

DISSERTATION

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Measurement of Higgs-boson  
production cross-sections and test of  
CP invariance in vector-boson fusion  
production in the  $H \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$  decay  
mode with the ATLAS detector

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Fakultät für Mathematik und Physik  
Albert-Ludwigs-Universität Freiburg



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DISSERTATION

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*I was walking across a courtyard to breakfast at a conference and Erdős, who had just had breakfast, was walking in the opposite direction. When our paths crossed, I offered my customary greeting, 'Good morning, Paul. How are you today?' He stopped dead in his tracks. Out of respect and deference, I stopped too. We just stood there silently.... Finally, after much reflection, he said: 'Herbert, today I am very sad.' And I said, 'I am sorry to hear that. Why are you sad, Paul?' He said, 'I am sad because I miss my mother. She is dead you know.' I said, 'I know that, Paul. I know her death was very sad for you and for many of us, too. But wasn't that about five years ago?' He said, 'Yes, it was. But I miss her very much.'*

– Herbert Wilf in Joshua Hill's "Paul Erdős: Mathematical Genius, Human (In That Order)"



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# Introduction

In 2012, the ATLAS- and CMS collaborations at the Large Hadron Collider (LHC) announced the discovery of a new, scalar particle [1, 2]. Further studies revealed that its properties matched a particle predicted in 1964: the *Higgs boson*. The Higgs boson emerges from the *Brout–Englert–Higgs* (BEH) mechanism [3–7], a crucial part of the Standard Model since through this mechanism, masses for elementary particles are introduced to the theory.

The Standard Model is currently the best description of the kinematics and the strong-, electromagnetic-, and weak interactions of all known elementary particles. The interactions are based on local gauge symmetries and are mediated by gauge bosons, which are predicted to be massless prior to the BEH mechanism. However, the mediators of the weak interaction, the  $W^\pm$ - and  $Z$  bosons, are observed to have masses. The BEH mechanism introduces an additional field, the *Higgs field*, that causes spontaneous symmetry breaking. While the underlying gauge symmetry is maintained, the electroweak gauge bosons obtain masses. Masses for the charged fermions are generated by *Yukawa couplings* between the fermion fields and the Higgs field.

Another consequence of the BEH mechanism is the prediction of a new massive, scalar particle, the Higgs boson. Therefore, the discovery of the Higgs boson in 2012 was an important step in verifying that the BEH mechanism is indeed realised in nature.

While the discovery of the Higgs boson was established by analysing its decay into gauge bosons, the predicted Yukawa couplings to fermions still had to be observed. An important decay channel for this is the decay of the Higgs boson into a pair of  $\tau$ -leptons. The first observation of this decay was obtained by a combined measurement of the ATLAS- and CMS collaborations in 2016, using data collected in proton–proton collisions at center-of-mass energies of  $\sqrt{s} = 7$  TeV and  $\sqrt{s} = 8$  TeV [8]. With data collected in 2015 and 2016 at a center-of-mass energy of  $\sqrt{s} = 13$  TeV corresponding to an integrated luminosity of  $36.1 \text{ fb}^{-1}$ , this decay channel was analysed in more detail by the ATLAS collaboration, resulting in the measurement of the total cross-section and the individual cross-sections of the vector-boson-fusion- and gluon-gluon-fusion production modes of the Higgs boson in 2018 [9].

The first part of this thesis focuses on one portion of this measurement: the analysis of the semileptonic  $\tau_{\text{lep}}\tau_{\text{had}}$  final state of the  $H \rightarrow \tau\tau$  decay channel, where one of the  $\tau$ -leptons decays into an electron or a muon, and the other  $\tau$ -lepton decays hadronically.

Despite the success of the Standard Model, several observed phenomena remain unexplained. Amongst them is the *baryon asymmetry* in the universe. According to the Standard Model at low temperature, baryonic matter and antibaryonic matter (antimatter) was created in equal amounts at the beginning of the universe, but

more matter than antimatter is observed in the universe. Therefore, a process called *baryogenesis* that produces matter and antimatter at different rates has to be introduced. One of the *Sakharov conditions* [10] this process is required to fulfill is the violation of CP symmetry, where CP is the product of charge conjugation and parity. CP-violating processes are present in the Standard Model, but the measured size is too small to explain the observed baryon asymmetry, so additional sources of CP violation are required.

After the discovery of the Higgs boson, its couplings to fermions and gauge bosons provide new potential sources for CP violation. One of these possible sources is the coupling of the Higgs boson to the electroweak gauge bosons in the vector-boson-fusion production mode. This coupling was analysed by the ATLAS collaboration in 2016, based on data collected at a center-of-mass energy of  $\sqrt{s} = 8$  TeV and using the decay of the Higgs boson into a pair of  $\tau$ -leptons [11]. The *Optimal Observable* method was employed for the test of CP invariance. An *Effective Field Theory* approach was used to expand the Lagrangian of the Standard Model with additional, CP-odd terms. To select a phase space enriched with events originating from the vector-boson-fusion production mode, machine learning in form of *Boosted Decision Trees* (BDTs) was used. No sign of CP violation was observed and constraints on the relevant parameter  $\tilde{d}$  were derived.

This study of CP invariance with the Optimal Observable method was repeated in 2020, with data collected in 2015 and 2016 at a center-of-mass energy of  $\sqrt{s} = 13$  TeV corresponding to an integrated luminosity of  $36.1 \text{ fb}^{-1}$  [12]. Again, no sign of CP violation was observed, but tighter constraints on  $\tilde{d}$  were obtained.

The second part of this thesis presents, as in the case of the cross-section measurement, the analysis of the semileptonic  $\tau_{\text{lep}}\tau_{\text{had}}$  final state of the  $H \rightarrow \tau\tau$  decay channel.

## Structure of the thesis and contributions of the author

In Chapter 1, the theoretical concepts behind the topics of this thesis are introduced. A short overview of the Standard Model is given, including a description of the BEH mechanism, followed by a discussion of the various production- and decay modes of the Higgs boson at the LHC. After that, the concepts of CP violation and testing for CP invariance are introduced. An introduction to effective field theories and the definition of the Optimal Observable conclude the chapter.

Chapter 2 starts with an overview of the LHC and the ATLAS experiment, followed by a description of the various aspects of the simulation of proton–proton collisions. The chapter also contains a description of the dataset used for the analyses in this thesis.

Chapter 3 introduces the reconstruction, calibration, and identification of all objects that are used in the analyses.

The first analysis, the measurement of the production cross-section of the Higgs boson in the  $H \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$  decay mode, is described in Chapter 4. The author was involved in the implementation of this analysis in the common analysis framework *CAF* [13]. In the chapter, all relevant signal- and background processes are introduced, followed by the definition of the selection and categorisation of the events. After that, the methods used to estimate and validate the dominant background processes are described. Special focus is on the *Fake* background, where a jet in an event is misidentified as a hadronically decaying  $\tau$ -lepton. The data-driven *Fake Factor* method used for the estimation of this background process was developed, implemented, and validated by



the author, including the derivation of the relevant systematic uncertainties. This method was also adopted by an analysis searching for lepton-flavour-violating decays of the Higgs boson [14]. After the discussion of the background processes, the fit model and the systematic uncertainties are introduced, followed by the presentation of the results of the  $\tau_{\text{lep}}\tau_{\text{had}}$  channel and of the combination of all final states. All maximum-likelihood fits for the  $\tau_{\text{lep}}\tau_{\text{had}}$  channel presented in this thesis were performed and scrutinised by the author.

Chapter 5 contains the description of the second analysis presented in this thesis, the test of CP invariance in the coupling between the Higgs boson and the electroweak gauge bosons, using the vector-boson-fusion production mode in the  $H \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$  decay mode. The chapter starts with an introduction to the *Boosted Decision Tree* method and the definition of the event selection for the training of the BDTs, followed by a description of the training setup of this analysis. After that, the definitions of the signal- and control regions are presented, and the changes in the background estimation with respect to the cross-section measurement are discussed. The optimisation of the event selection and of the binning of the Optimal Observable distribution was carried out by the author. The author also adapted and validated the Fake Factor method for this analysis. The remaining sections of the chapter contain a discussion of the systematic uncertainties, an overview of the fit model, and the results of the  $\tau_{\text{lep}}\tau_{\text{had}}$  channel and of the combination of all final states. The author studied the behaviour of the systematic uncertainties regarding the energy resolution of jets and developed a special treatment to be used in this analysis. All maximum-likelihood fits in the  $\tau_{\text{lep}}\tau_{\text{had}}$  channel presented in this thesis were performed and scrutinised by the author.

The author implemented the analysis in the software framework, with exception of the training of the Boosted Decision Trees, the validation of the  $Z \rightarrow \tau\tau$  modelling, and parts of the fit model. Furthermore, the author was responsible for the documentation of the  $\tau_{\text{lep}}\tau_{\text{had}}$  part of the analysis in the internal supporting document.

The thesis concludes with a summary of the results and an outlook of future studies and improvements.



# Chapter 1

## Theory

This chapter provides an overview of the theoretical concepts that are important for the analyses presented in this thesis.

First, a short introduction to the theoretical framework of particle physics, the Standard Model, is given in Section 1.1. This includes a description of the electroweak symmetry breaking by which the Higgs boson is introduced to the theory.

The production- and decay modes of the Higgs boson at the LHC are discussed in Section 1.2 and the current status of searches for the Higgs boson and measurements of its properties are presented.

Section 1.3 introduces the concept of CP violation and the idea of CP tests, the sources of CP violation in the Standard Model, and hypothetical additional sources. Effective field theories and the Optimal Observable, the methods used in this thesis to study CP violation, are discussed in Sections 1.4 and 1.5, respectively.

### 1.1 The Standard Model

The Standard Model (SM) describes the properties and interactions of all known elementary particles. Particles are described as excitations of quantum fields, and their kinematics and interactions are described using the *Lagrange formalism*. The *Euler–Lagrange equation* is used to derive the equations of motion.

The SM consists of renormalisable quantum field theories (QFT) of the strong- and electroweak interactions, where the latter provides a combined description of the electromagnetic- and weak interactions. These QFTs are required to possess *local* gauge invariance, i.e. the Lagrangian has to be invariant under space-time dependent transformations of the fields. This requires the introduction of *gauge* fields and covariant derivatives to the theory, resulting in interaction terms in the Lagrangian. QFTs with such local gauge symmetries are referred to as *gauge field theories*.

The underlying symmetry group of the SM is  $SU(3)_C \times SU(2)_{I,L} \times U(1)_Y$ . Due to the local gauge invariance of the Lagrangian under transformations of this group, three conserved charges can be identified according to *Noether’s theorem* [15]. The strong interaction is described by *quantum chromodynamics* (QCD) [16–18] with the *colour* charge  $C$  as the conserved property under  $SU(3)_C$  transformations. The  $SU(2)_{I,L} \times U(1)_Y$  group is the basis for the *Glashow–Salam–Weinberg* (GSW) model [19–21], which describes the electroweak interactions. The conserved charges are the weak isospin  $I$  in  $SU(2)_{I,L}$  and the hypercharge  $Y$  in  $U(1)_Y$ . The subscript L denotes that  $SU(2)_{I,L}$  acts only on the left-chiral component of fields. The electrical charge  $Q$  is

also conserved since it is connected to the hypercharge and the third component of the weak isospin by the *Gell-Mann–Nishijima* formula [22, 23]:

$$Q = I_3 + \frac{Y}{2} \quad (1.1)$$

By incorporating an electroweak symmetry breaking (EWSB) mechanism, the *Brout–Englert–Higgs* (BEH) mechanism [3–7], into the SM, masses of the electroweak gauge bosons are introduced. This mechanism also results in a new scalar boson, the *Higgs boson*. Fermion masses are introduced by adding *Yukawa interaction* terms between the fermion fields and the Higgs field.

The  $SU(2)_{I,L} \times U(1)_Y$  symmetry is spontaneously broken by the BEH mechanism, but the symmetry under  $U(1)_Q$  remains unbroken.

The descriptions in the subsequent sections follow Ref. [24].

### 1.1.1 Elementary particles and interactions

The particles of the SM can be categorised according to their spin: the gauge bosons, the particles that mediate the interactions, have spin 1. The strong interaction is mediated by eight *gluons*  $g$ , the weak interaction by the  $W^\pm$ - and  $Z$  bosons, and the electromagnetic interaction by the photon  $\gamma$ . The Higgs boson, resulting from the BEH mechanism, is the only elementary particle with spin 0. The *matter* particles are fermions with spin  $\frac{1}{2}$ .

The fermions comprise six *quarks* and six *leptons*, where the twelve different particles are also referred to as *flavours*. Both quarks and leptons are paired into three *generations*. Between generations, the quantum numbers are the same, but the particles have different masses and flavours.

Each of the quark generations consists of an *up*-type quark and a *down*-type quark. For the first generation, these are the up quark  $u$  and the down quark  $d$ , for the second generation the charm quark  $c$  and the strange quark  $s$ , and for the third generation the top quark  $t$  and the bottom quark  $b$ . The up-type quarks have an electrical charge  $Q = \frac{2}{3}$ , while the down-type quarks have  $Q = -\frac{1}{3}$ . The quarks carry also colour charges, resulting in triplets of *red*-, *green*-, and *blue* colour states.

The lepton generations each consist of a lepton with electrical charge  $Q = -1$  and an associated neutral *neutrino* with  $Q = 0$ : the electron  $e$  and the electron-neutrino  $\nu_e$ , the muon  $\mu$  and the muon-neutrino  $\nu_\mu$ , and the tau-lepton  $\tau$  and the tau-neutrino  $\nu_\tau$ .

All electrically charged fermions interact through both the electromagnetic- and weak interactions, whereas the electrically neutral neutrinos only participate in the weak interaction. Since the quarks carry colour charges they also interact through the strong interaction.

Due to the  $V$ - $A$  structure of the weak interaction, only left-chiral particles (and right-chiral antiparticles) couple to the charged gauge bosons of the electroweak interaction. The left-chiral components of the quarks and leptons are grouped into doublets with weak isospin  $I = \frac{1}{2}$ , while the right-chiral components form singlets with weak isospin  $I = 0$ . Since neutrinos are considered massless in the SM, no right-chiral neutrinos are included.

The third component of the weak isospin is  $I_3 = \frac{1}{2}$  for the up-type quarks and the

neutrinos, whereas the down-type quarks and the charged leptons have  $I_3 = -\frac{1}{2}$ . The down-type quarks in the doublets are in their flavour eigenstates  $d'$ ,  $s'$ , and  $b'$ , which are related to the mass eigenstates  $d$ ,  $s$ , and  $b$  by the *Cabbibo–Kobayashi–Maskawa* (CKM) matrix  $V_{\text{CKM}}$  [25, 26]:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{\text{CKM}} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix} \quad (1.2)$$

with

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \quad (1.3)$$

This matrix describes the transition probabilities between different quark flavours under emission or absorption of a  $W$  boson.

An overview of the quarks and leptons and their quantum numbers is given in Table 1.1.

| 1st Gen.                                     | Particle<br>2nd Gen.                             | 3rd Gen.                                           | $Q$          | $I_3$        | $Y$          |
|----------------------------------------------|--------------------------------------------------|----------------------------------------------------|--------------|--------------|--------------|
| $\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$ | $\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$ | $\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$ | 0<br>-1      | +1/2<br>-1/2 | -1<br>-1     |
| $\begin{pmatrix} u \\ d' \end{pmatrix}_L$    | $\begin{pmatrix} c \\ s' \end{pmatrix}_L$        | $\begin{pmatrix} t \\ b' \end{pmatrix}_L$          | +2/3<br>-1/3 | +1/2<br>-1/2 | +1/3<br>+1/3 |
| $e_R$                                        | $\mu_R$                                          | $\tau_R$                                           | -1           | 0            | -2           |
| $u_R$                                        | $c_R$                                            | $t_R$                                              | +2/3         | 0            | +4/3         |
| $d_R$                                        | $s_R$                                            | $b_R$                                              | -1/3         | 0            | -2/3         |

**Table 1.1:** Overview of the left-chiral lepton- and quark doublets and the right-chiral singlets, and their respective electrical charge  $Q$ , third component of the weak isospin  $I_3$ , and hypercharge  $Y$ .  $d'$ ,  $s'$ , and  $b'$  indicate the flavour eigenstates.

In addition, each particle has a corresponding antiparticle with opposite charges and opposite chirality.

### 1.1.2 Quantum Chromodynamics

The  $\text{SU}(3)_C$  gauge group has eight gauge fields  $G_\mu^a$  with  $a = 1, \dots, 8$  and coupling strength  $g_s$ , corresponding to eight massless gluons. The non-abelian character of  $\text{SU}(3)_C$  results in self-coupling terms for the gluons. Therefore, also gluons carry colour charge.

The dependence of the coupling strength on the energy results in two special properties of QCD: *asymptotic freedom* and *confinement*. The *running coupling constant* can be written as

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f) \log(Q^2/\Lambda^2)} \quad (1.4)$$

where  $\alpha_s = \frac{g_s^2}{4\pi}$ ,  $Q$  is the energy scale at which  $\alpha_s$  is probed,  $n_f$  is the number of quark flavours available at the energy scale  $Q$ , and  $\Lambda$  is the energy scale that separates the *perturbative* and *non-perturbative* parts of QCD. The value of  $\Lambda$  is in the range 89 MeV-332 MeV [27], depending on the number of quark flavours taken into account. For  $Q^2 \leq \Lambda^2$ , the coupling strength is large and quarks are confined to bound states, i.e. hadrons. Non-perturbative methods have to be used to describe QCD at such energy scales.

For  $Q^2 \gg \Lambda^2$ , the coupling strength becomes small. Therefore, the quarks and gluons are asymptotically free and can be described perturbatively.

### 1.1.3 Electroweak Theory

The structure of the  $SU(2)_{I,L} \times U(1)_Y$  gauge group results in four gauge fields,  $W_\mu^1, W_\mu^2, W_\mu^3$  for  $SU(2)_{I,L}$ , and  $B_\mu$  for  $U(1)_Y$ , with coupling strengths  $g_W$  and  $g'$ . Combinations of these fields define the mass eigenstates, i.e. the  $W^\pm$  bosons, the photon  $A$ , and the  $Z$  boson:

$$\begin{aligned} W_\mu^\pm &= \frac{1}{\sqrt{2}} (W_\mu^1 \mp iW_\mu^2) \\ A_\mu &= W_\mu^3 \sin \theta_W + B_\mu \cos \theta_W \\ Z_\mu &= W_\mu^3 \cos \theta_W - B_\mu \sin \theta_W \end{aligned} \tag{1.5}$$

where  $\theta_W = \tan^{-1} \left( \frac{g'}{g_W} \right)$  is the *weak mixing angle*. The  $W^\pm$  bosons have an electrical charge of  $\pm 1$  and the third component of their weak isospin is  $\pm 1$ , whereas the photon and the  $Z$  boson are electrically neutral and have no isospin. The hypercharge of all electroweak gauge bosons is zero. An overview of the quantum numbers of the electroweak gauge bosons is given in Table 1.2.

| Particle | $Q$ | $I_3$ | $Y$ |
|----------|-----|-------|-----|
| $W^+$    | +1  | +1    | 0   |
| $W^-$    | -1  | -1    | 0   |
| $Z$      | 0   | 0     | 0   |
| $A$      | 0   | 0     | 0   |
| $H$      | 0   | -1/2  | 1   |

**Table 1.2:** Electrical charge  $Q$ , third component of the weak isospin  $I_3$ , and hypercharge  $Y$  of the electroweak gauge bosons and the Higgs boson.

The coupling strengths for the photon field  $A_\mu$  and the  $Z$  boson field  $Z_\mu$  can be expressed as

$$\begin{aligned} g_A &= g_W \sin \theta_W = g' \cos \theta_W \\ g_Z &= \frac{g_W}{\cos \theta_W} = \frac{g'}{\sin \theta_W} \end{aligned} \tag{1.6}$$

As  $SU(3)_C$ ,  $SU(2)_{I,L}$  is also non-abelian. Therefore, self-coupling terms for the gauge bosons are present in the Lagrangian.

### 1.1.4 Electroweak Symmetry Breaking

The  $W^\pm$ - and  $Z$  bosons are experimentally observed to be massive [28–31], but simply adding mass terms for the gauge bosons to the Lagrangian results in the violation of gauge invariance. To incorporate masses in the theoretical description while maintaining gauge invariance, the  $SU(2)_{I,L} \times U(1)_Y$  symmetry is broken to  $U(1)_Q$  via the BEH mechanism by introducing a weak isospin doublet of complex scalar fields  $\phi$  with hypercharge  $Y = 1$  and weak isospin  $I = \frac{1}{2}$ :

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \quad (1.7)$$

Here,  $\phi^+$  has electrical charge  $Q = +1$ , while  $\phi^0$  is neutral. The corresponding Lagrangian is

$$\mathcal{L} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi) \quad (1.8)$$

with

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2. \quad (1.9)$$

By choosing  $\lambda > 0$  and  $\mu^2 < 0$ , the minimum of  $V$  is at a non-vanishing value. A possible choice for the minimum is

$$\begin{aligned} \phi_1 &= \phi_2 = \phi_4 = 0 \\ \phi_3 &= \sqrt{\frac{-\mu^2}{\lambda}} = v \end{aligned} \quad (1.10)$$

where  $v \approx 246 \text{ GeV}$  [27] is the *vacuum expectation value* (vev).

Due to the choice of  $\phi_1 = \phi_2 = 0$ , the charged component of the doublet vanishes, resulting in a ground state with  $Q = 0$  and  $I_3 = -\frac{1}{2}$ :

$$\phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad (1.11)$$

By choosing this explicit minimum, the  $SU(2)_{I,L} \times U(1)_Y$  symmetry is broken and only the  $U(1)_Q$  symmetry of the electromagnetic interaction remains unbroken, i.e. the ground state is still invariant under  $U(1)_Q$  transformations, resulting in the masslessness of the corresponding gauge boson, the photon.

Expanding the field  $\phi$  about this ground state yields

$$\phi = \frac{1}{\sqrt{2}} e^{i \frac{\boldsymbol{\tau} \cdot \mathbf{G}(x)}{v}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \quad (1.12)$$

Here,  $\mathbf{G} = (G_1, G_2, G_3)$  and  $h$  are real fields and  $\boldsymbol{\tau} = (\tau_1, \tau_2, \tau_3)$  are the Pauli matrices. The  $\mathbf{G}$  correspond to three massless *Goldstone* bosons [32–34] that can be gauged away by a local  $SU(2)$  transformation, the *unitary gauge*, resulting in

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \quad (1.13)$$

Inserting Equation (1.13) into Equation (1.8) and replacing the derivative  $\partial_\mu$  with the *covariant derivative*  $D_\mu = \partial_\mu - ig_W \frac{\boldsymbol{\tau}}{2} \mathbf{W}_\mu + i \frac{g'}{2} B_\mu$  to keep the Lagrangian invariant

under local gauge transformations results in mass terms for the field combinations introduced in Equation (1.5):

$$\begin{aligned} m_W &= \frac{1}{2}vg_W \\ m_Z &= \frac{1}{2}vg_Z \\ m_A &= 0 \end{aligned} \tag{1.14}$$

As expected, the photon remains massless.

Another important consequence is the occurrence of a mass term  $m_H = \sqrt{2v^2\lambda}$  for the field  $h$ , corresponding to a massive, scalar, and electrical neutral particle, the *Higgs boson*  $H$ . The quantum numbers of the Higgs boson are included in Table 1.2. The resulting Lagrangian also includes several coupling terms: the triple- and quartic selfcoupling of the Higgs boson  $\lambda vh^3$  and  $\frac{1}{4}\lambda h^4$ , and the coupling between the Higgs boson and the vector bosons  $\frac{2m_V^2}{v}VVh$  and  $\frac{m_V^2}{v^2}VVhh$  with  $V = W^\pm, Z$ .

The doublet defined in Equation (1.7) can also be used to generate mass terms for the fermions. For this, *Yukawa couplings* between the scalar field  $\phi$  and the fermion fields  $\psi$  are introduced to the Lagrangian. For the leptons they have the form

$$\mathcal{L} = -g_\ell (\bar{\nu}_\ell, \bar{\ell})_L \phi \ell_R + \text{h.c.} \tag{1.15}$$

with  $\ell = e, \mu, \tau$  and  $g_\ell$  the corresponding coupling strength. *h.c.* indicates the Hermitian conjugate. After electroweak symmetry breaking, this part of the Lagrangian results in mass terms for the leptons with  $m_\ell = \frac{g_\ell v}{\sqrt{2}}$  and a coupling term  $\frac{m_\ell}{v}\bar{\ell}\ell h$ . The generation of mass terms for the down-type quarks is done in the same way, but to acquire mass terms for the up-type quarks, the charge conjugated field  $\phi_c = -i\tau_2\phi^*$  has to be introduced. Electroweak symmetry breaking results in

$$\phi_c = \frac{1}{\sqrt{2}} \begin{pmatrix} v + h(x) \\ 0 \end{pmatrix} \tag{1.16}$$

The corresponding part in the Lagrangian is then

$$\mathcal{L} = -g_d (\bar{u}, \bar{d})_L \phi d_R - g_u (\bar{u}, \bar{d})_L \phi_c u_R + \text{h.c.} \tag{1.17}$$

resulting in mass terms with  $m_d = \frac{g_d v}{\sqrt{2}}$  and  $m_u = \frac{g_u v}{\sqrt{2}}$ , and coupling terms  $\frac{m_d}{v}\bar{d}dh$  and  $\frac{m_u}{v}\bar{u}uh$ . The mass terms of the other quarks are generated in the same manner.

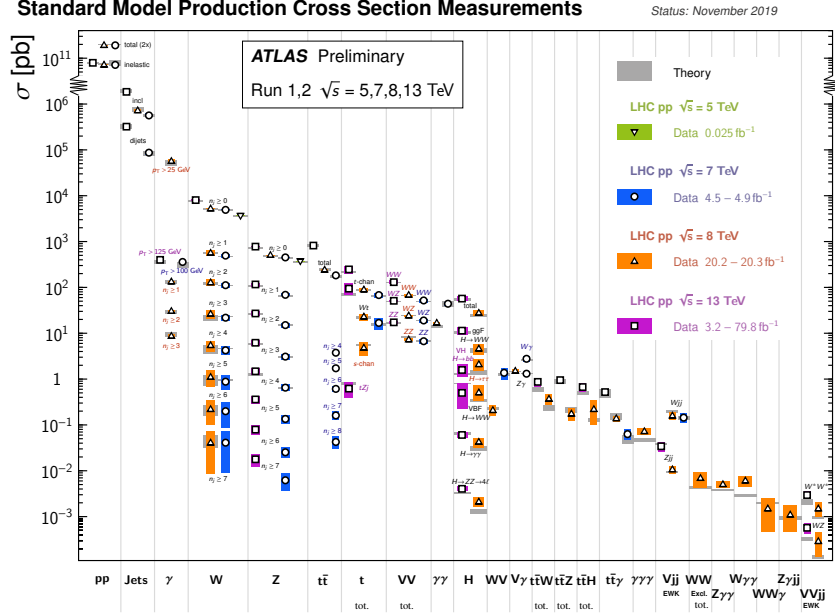
### 1.1.5 Limitations of the Standard Model

The Standard Model was able to correctly predict several particles and their properties, such as the  $W$ - and  $Z$  bosons [21, 28–31], the gluon [16, 35–39], the top- and bottom quarks [26, 40–42], and the Higgs boson [1, 2, 4, 5].

In addition, the predictions for the production cross-sections of a multitude of different particles agree very well with the measurements. This is shown in Figure 1.1, which summarises measurements with the ATLAS detector at the LHC.

Despite these successes, several observed phenomena cannot be explained within the theoretical framework of the SM.





**Figure 1.1:** Cross-section measurements with the ATLAS detector and the corresponding theoretical predictions. Taken from Ref. [43].

Gravitational interactions are not included in the SM. By adding the hypothesised mediating particle, the *graviton*, the theory becomes non-renormalisable, i.e. ultraviolet divergences occur [44]. Possible solutions for a quantum-mechanical description of gravity are e.g. *string theory* [45–47] or *loop quantum gravity* [48].

Neutrinos are considered massless in the SM, but observations of *neutrino oscillations* (e.g. [49–51]), i.e. a change in flavour while travelling through space, require the neutrinos to be massive. Analogous to the quark sector, the mixing of the neutrino flavours can be described by relating the flavour eigenstates of the neutrinos to their mass eigenstates by a matrix, in this case the *Pontecorvo–Maki–Nakagawa–Sakata* (PMNS) matrix [52, 53]. A possible way to generate neutrino masses is the *seesaw mechanism* [54–56].

Because of gravitational effects, observed in e.g. the rotation curves of galaxies [57], gravitational lensing [58], and the cosmic microwave background (CMB) [59], a new form of matter is assumed: *dark matter*. There can only be little interaction between dark matter and baryonic matter since no other type of interaction with dark matter besides gravitation was observed so far. In the past, neutrinos were considered as candidates for dark matter since they solely interact weakly, but their density in the universe is too low and they are too relativistic to explain the occurrent structure formation of dark matter. Therefore, no particle contained in the SM can explain dark matter. Hypothesised particle candidates are for example axions [60, 61] or *weakly interactive massive particles* (WIMPs), the latter predicted by e.g. supersymmetric extensions of the SM [62].

From measurements of the CMB, the amount of dark matter in the universe is extracted to be approximately 26 % of the total matter- and energy content, while baryonic matter only accounts for approximately 5 %. The remaining 69 % are composed of *dark energy* [59].

Dark energy was introduced to explain the observed acceleration of the expansion of the universe [63, 64]. It is hypothesised to be homogeneously distributed throughout the entire universe, to have a negative pressure, and to only interact gravitationally. A possible explanation for dark energy is its identification with the cosmological constant  $\Lambda$ , i.e. the energy density of the vacuum [65].

According to the SM, baryonic matter and antibaryonic matter (antimatter) should have been created in equal amounts at the beginning of the universe, but more matter than antimatter is observed in the universe [59]. To explain this *baryon asymmetry*, a process called *baryogenesis* has to be introduced that produces matter and antimatter at different rates. This process is required to fulfill the three *Sakharov conditions* [10]: violation of the baryon number  $B$ , violation of  $C$ - (charge conjugation) and  $CP$  (the product of charge conjugation and parity) symmetry, and interactions in absence of thermal equilibrium.

Baryon number violation is predicted in the SM via *sphalerons* [66–71]. Sphalerons also violate the conservation of the lepton number  $L$ , but conserve the difference  $B - L$ . No such processes have been observed so far.

Violation of both  $C$ - and  $CP$  symmetry is a feature of weak interactions. Charge conjugation of e.g. left-chiral neutrinos results in left-chiral antineutrinos, which are not observed [72] and not included in the SM. The violation of  $CP$  symmetry is introduced by a complex phase in the CKM matrix and has been observed in the interactions of  $K$ -,  $B$ -, and  $D$  mesons [73–83]. The measured size of the complex phase is too small to explain the observed baryon asymmetry [84–88], so new sources of  $CP$  violation are required.  $CP$  violation is discussed in more detail in Section 1.3 and a test for  $CP$  invariance in the coupling of the Higgs boson to electroweak gauge bosons is presented in Chapter 5.

Interactions out of thermal equilibrium can be achieved by a first-order phase transition [89]. In the SM, a phase transition is incorporated via the electroweak symmetry breaking, but the observed mass of the Higgs boson indicates a smooth cross-over between the unbroken and broken phase instead [90].

Since it is obviously not possible to explain baryogenesis within the SM, physics beyond the Standard Model is required.

## 1.2 The Higgs boson

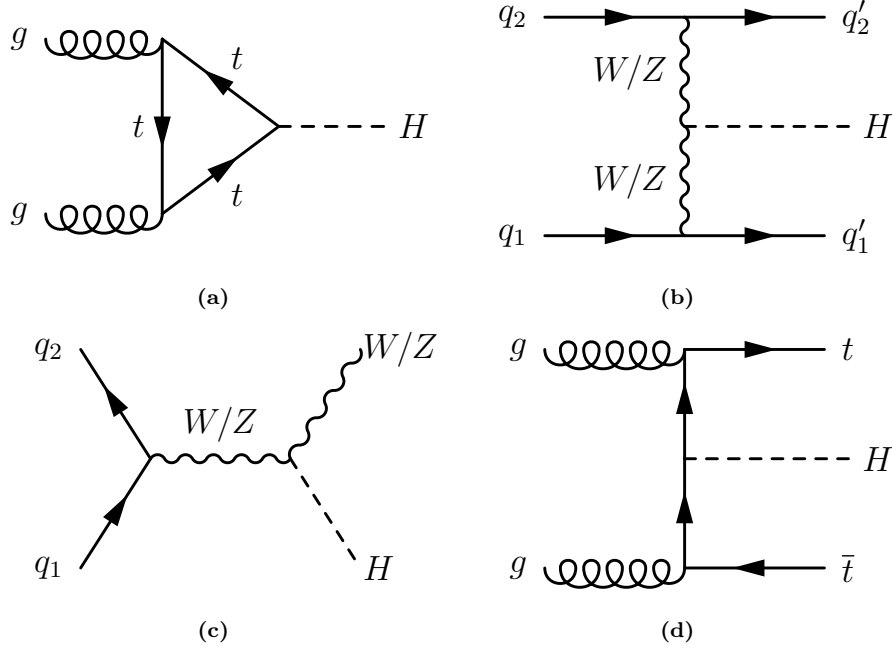
A consequence of the EWSB introduced in Section 1.1.4 is the prediction of a new scalar boson. Such a particle was observed in 2012 by the ATLAS and CMS experiments [1, 2]. Since then, a multitude of analyses have been carried out, each indicating that the discovered particle is indeed a Higgs boson with properties agreeing with the SM predictions within currently known uncertainties.

In the following, the important production- and decay modes of the Higgs boson at the LHC are introduced and an overview of the experimental results is given.

### 1.2.1 Production at the LHC

The Higgs boson is produced via several processes in proton–proton collisions. The leading-order *Feynman diagrams*, pictorial representations of particle interactions,

for the four main production processes are shown in Figure 1.2. Figure 1.3a shows the Higgs-boson production cross-sections at the LHC for a center-of-mass energy of  $\sqrt{s} = 13$  TeV as a function of the Higgs-boson mass  $m_H$ . The cross-sections and uncertainties quoted in the following text are taken from Ref. [91] and have all been evaluated at a center-of-mass energy of  $\sqrt{s} = 13$  TeV and a Higgs-boson mass of  $m_H = 125$  GeV.



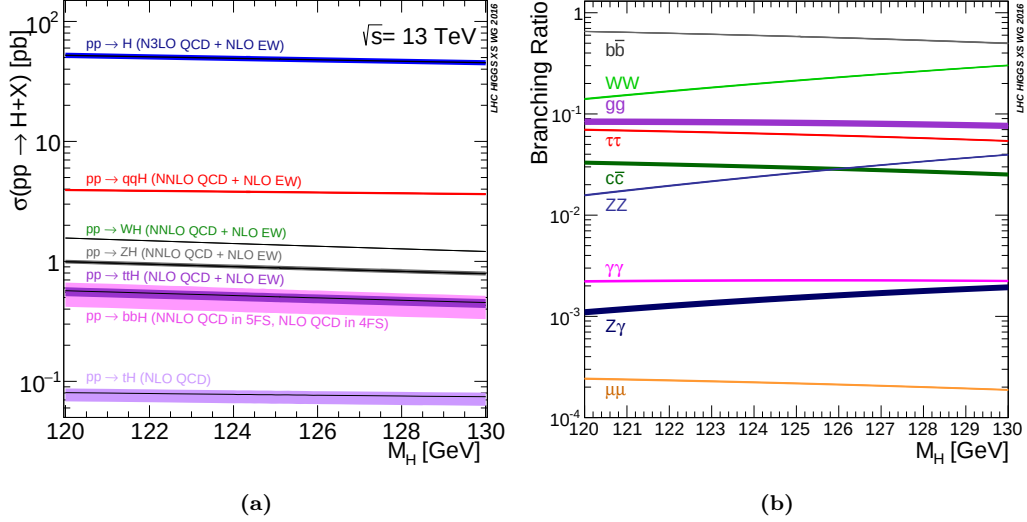
**Figure 1.2:** Leading-order Feynman diagrams for the four main production processes of the Higgs boson at the LHC: gluon-gluon fusion (a), vector-boson fusion (b), Higgs-strahlung (c), and associated production with a top-antitop quark pair.

The largest contribution to the production cross-section comes from gluon-gluon fusion ( $ggF$ ), where the Higgs boson couples to the gluons through a heavy quark loop. This loop is dominated by the top quark due to the mass scaling of the Yukawa coupling. The inclusive cross-section is calculated up to next-to-next-to-next-to-leading-order ( $N^3LO$ ) accuracy in  $\alpha_s$ , using fixed order and the heavy top-quark mass limit [92]. Electroweak corrections are included at next-to-leading-order (NLO) accuracy [93–96].

The resulting value is  $\sigma_{ggF} = 48.58$  pb, with theoretical uncertainties, including uncertainties on the QCD scales, of  $+4.56\%$ / $-6.72\%$ , and uncertainties of  $\pm 3.20\%$  from the *Parton density functions* (PDF) and  $\alpha_s$  [92].

The second most dominant production mode is the vector-boson fusion (VBF). Here, two incoming quarks (either or both can also be an antiquark) radiate vector bosons that fuse into a Higgs boson, hence resulting in two quarks in the final state. This process has been calculated up to next-to-next-to-leading-order (NNLO) accuracy in QCD and NLO accuracy in EW [97–100].

The obtained value is  $\sigma_{VBF} = 3.78$  pb, with PDF- and  $\alpha_s$  uncertainties of  $\pm 2.10\%$ , and QCD scale uncertainties of  $+0.43\%$ / $-0.33\%$ .



**Figure 1.3:** Production cross-sections of the Higgs boson at  $\sqrt{s} = 13$  TeV (a) and branching ratios (b) as function of  $m_H$ . Taken from Ref. [91].

In the Higgs-strahlung process ( $VH$ ), the Higgs boson is radiated off a vector boson  $V = W/Z$  produced through annihilation of an incoming quark-antiquark pair. As for the VBF production process, the calculation of the cross-section has been performed up to NNLO accuracy in QCD and NLO accuracy in EW [101–104].

The cross-section for  $WH$  is  $\sigma_{WH} = 1.37$  pb, with an uncertainty of  $+0.5\%/-0.7\%$  from the QCD scales and an uncertainty of  $\pm 1.9\%$  from the PDF- and  $\alpha_s$  values. The respective numbers for  $ZH$  are  $\sigma_{ZH} = 0.88$  pb,  $+3.8\%/-3.1\%$  and  $\pm 1.6\%$ .

The cross-section of the production in association with a top-antitop quark pair ( $t\bar{t}H$ ) has been calculated up to NLO accuracy for both QCD and EW [105–112].

The cross-section for  $t\bar{t}H$  production is  $\sigma_{t\bar{t}H} = 0.51$  pb, where the QCD scale uncertainties are  $+5.8\%/-9.2\%$  and the PDF- and  $\alpha_s$  uncertainty is  $\pm 3.6\%$ .

### 1.2.2 Decay of the Higgs boson

The Higgs boson decays into pairs of fermions or bosons. For a fixed mass of the Higgs boson, the individual decay widths depend on the mass and the type of the particles due to the coupling to the Higgs boson, as discussed in Section 1.1.4. Decay channels that contain massless particles, i.e.  $gg$ ,  $\gamma\gamma$  and  $Z\gamma$ , are possible via loops of e.g. top quarks or  $W^\pm$  bosons. The branching ratios (BR), i.e. the ratio between the individual decay width and the total decay width, as a function of  $m_H$  are shown in Figure 1.3b.

At  $m_H = 125$  GeV, the decay into a pair of  $b$ -quarks is dominating with a branching ratio of approximately 58%, followed by the decays into a pair of  $W$  bosons and a pair of gluons with branching ratios of approximately 22% and 9%, respectively.

The decay into a pair of  $\tau$ -leptons has a branching ratio of approximately 6%. This decay channel is the one considered in this analysis. Despite its relatively small BR compared to the decay into  $b$ -quarks, it is the most suitable channel to study the Yukawa coupling of the Higgs boson at the LHC, whereas the analysis of  $H \rightarrow b\bar{b}$  is challenging due to the amount of jet activity in  $pp$  collisions.

PROPHECY4F [113–115] and HDECAY [116, 117] are used to calculate the branching ratios. The  $H \rightarrow \tau\tau$  BR is calculated at N<sup>3</sup>LO accuracy in QCD, including the complete NLO EW corrections and mixed QCD-EW corrections. The uncertainty on the BR consists of theoretical uncertainties due to missing higher-order corrections, and parametric uncertainties. The resulting value is  $\text{BR}(H \rightarrow \tau\tau) = 0.06272$  with a relative uncertainty of 2.33 % [91].

### 1.2.3 Experimental results

The mass of the Higgs boson has been determined with a precision below the percent level, with values of  $124.97 \pm 0.24$  GeV [118] and  $125.38 \pm 0.14$  GeV [119] measured by ATLAS and CMS, respectively.

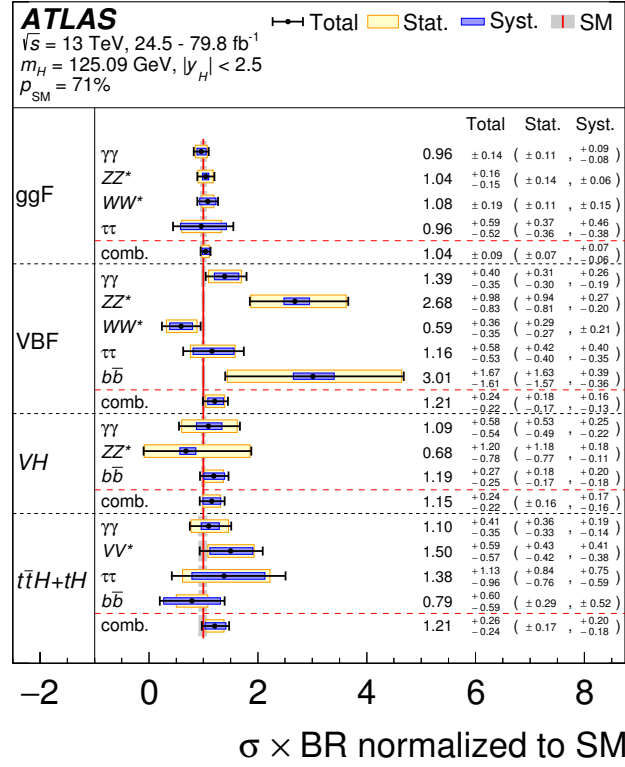
The SM prediction for the spin and parity of the Higgs boson has been tested against several alternative scenarios, which were all excluded at confidence levels above 99.9 % [120].

All major production processes and decay channels have been observed:  $ggF$ - [1, 2],  $VBF$ - [8],  $VH$ - [121], and  $t\bar{t}H$  production [122, 123], and the decays  $H \rightarrow WW$  [124],  $H \rightarrow \gamma\gamma$  [125, 126],  $H \rightarrow ZZ$  [127, 128],  $H \rightarrow \tau\tau$  [8], and  $H \rightarrow b\bar{b}$  [121, 129].

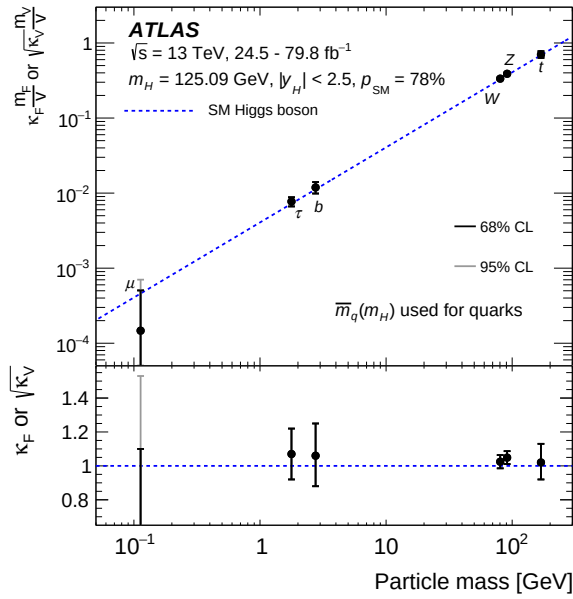
Measurements of the cross-sections of the various production- and decay modes have been carried out [130]. The results of a simultaneous maximum-likelihood fit to all channels are shown in Figure 1.4. Good agreement within uncertainties between the measurements and the SM prediction is observed.

The relation between the mass of a particle and its coupling strength to the Higgs boson, assuming a SM-like coupling structure, has been tested as well [130]. Figure 1.5 shows that the result for each particle agrees with the SM prediction of the Higgs boson.

A summary of the most recent results is given in Ref. [131].



**Figure 1.4:** Cross-sections times branching ratio for various production- and decay modes, normalised to the respective SM prediction. The values are extracted from a simultaneous maximum-likelihood fit to all channels. The total-, systematic-, and statistical uncertainties are indicated by black error bars, blue boxes, and yellow boxes, respectively. The grey boxes depict the theory uncertainties of the predictions. Taken from Ref. [130].



**Figure 1.5:** Reduced coupling-strength modifiers  $\kappa_F \frac{m_F}{v}$  for fermions and  $\sqrt{\kappa_V} \frac{m_V}{v}$  for bosons as a function of particle mass, where  $\kappa_{F/V}$  is the respective ratio between the measured cross-section and the SM prediction. The blue dotted line depicts the SM prediction. Taken from Ref. [130].

## 1.3 CP violation

As explained in Section 1.1.5, a sufficient amount of CP violation is one of the necessary criteria to explain the observed baryon asymmetry in the universe. The amount of CP violation in the SM, introduced via the CKM matrix, is not sufficient and additional sources are required.

To study potential new sources, CP-violating interactions can be added by expanding the SM Lagrangian with additional terms derived from an *effective field theory*.

This section first introduces the concepts of CP symmetry and CP violation, following closely the description in Ref. [132], and then gives an overview of CP-violating processes in the SM. After that, effective field theories in general and the approach used in this thesis are explained. The chapter concludes with the definition of CP-odd observables, including the one used in this thesis.

### 1.3.1 Basics of CP symmetry and CP tests

The  $CP$  operator combines the application of charge conjugation  $C$  and the parity operator  $P$ , where  $C$  flips the charges of particles, resulting in the respective antiparticle, and  $P$  changes the sign of all spatial coordinates and the chirality of particles. Another important operator for the following discussion is the time reversal operator  $T$ , which changes the sign of the time coordinate.

Using Dirac notation, applying  $C$ ,  $P$ ,  $T$ , and  $CP$  on a single-particle state with four-momentum  $p$  and spin  $s$  yields:

$$\begin{aligned} C |\phi(p, s)\rangle &= |\phi^*(p, s)\rangle \\ P |\phi(p, s)\rangle &= \eta_P |\phi(-p, s)\rangle \\ T |\phi(p, s)\rangle &= \langle\phi(-p, -s)| \\ CP |\phi(p, s)\rangle &= \eta_P |\phi^*(-p, s)\rangle \end{aligned} \tag{1.18}$$

where  $\eta_P$  is the intrinsic parity of  $\phi$ . Since  $T$  is anti-linear and  $C$  transforms fields in their Hermitian conjugates, no correspondent terms are present for these operators [133].

The application of  $T$  transforms an incoming particle  $|\phi\rangle$  into an outgoing particle  $\langle\phi|$ . To avoid this, the *naive time reversal*  $\hat{T}$  [134], which only changes the sign of the four-momentum and the spin, is used instead:

$$\hat{T} |\phi(p, s)\rangle = |\phi(-p, -s)\rangle \tag{1.19}$$

The eigenvalues of all these operators are  $\pm 1$ , since the respective dual application has to return the original state  $|\phi(p, s)\rangle$ . Therefore, a *CP-invariant* state is an eigenstate under CP transformation:

$$CP |\phi(p, s)\rangle = \pm 1 |\phi(-p, s)\rangle \tag{1.20}$$

where states with eigenvalue  $+1(-1)$  are denoted as CP-even (CP-odd). If the initial state  $|i\rangle$  and the final state  $|f\rangle$  of a process  $|i\rangle \rightarrow |f\rangle$  are eigenstates under CP transformation with different eigenvalues, CP invariance is violated, i.e. *CP violation* occurs.

Following the description in Ref. [132], an observable  $O$  of a process  $|i\rangle \rightarrow |f\rangle$  can also be defined to be CP-even or CP-odd:

$$O(CP|i\rangle \rightarrow CP|f\rangle) = \pm O(|i\rangle \rightarrow |f\rangle) \quad (1.21)$$

i.e. a CP-odd observable changes its sign under CP transformation.

If the initial state is an eigenstate under CP transformation and the underlying theory is CP-symmetric, the expectation value of a CP-odd observable vanishes, i.e.  $\langle O \rangle = 0$  [132]. Therefore, a non-vanishing mean value of a CP-odd observable indicates CP violation.

If the initial state is not CP-symmetric, a  $\hat{T}$ -odd observable has to be used instead, assuming CPT invariance. In addition, the initial state has to be  $\hat{T}$ -symmetric and *re-scattering effects*, i.e. complex-valued loops from particles on the mass shell, have to be absent. If these requirements are fulfilled and the underlying theory is CP-symmetric, the mean value of a  $\hat{T}$ -odd observable vanishes,  $\langle O \rangle = 0$ . Therefore, a non-vanishing mean value  $\langle O \rangle \neq 0$  can be interpreted as evidence for CP violation. If re-scattering effects are not neglected, a non-vanishing mean value can also indicate new physics beyond the Standard Model in form of new particles that are on the mass shell in the loops.

### 1.3.2 CP violation in the Standard Model

After the discovery of P violation in weak interactions in 1957 [135, 136] from which also C violation was implicit as a theoretical consequence [137–139], and the measurement of the helicity of the neutrino [72], the  $V-A$  structure of the weak interaction was established [140, 141], i.e. only left-chiral fermions and right-chiral antifermions take part in charged-current interactions. Since only the consecutive application of the  $C$ - and  $P$  operators conserves this structure, CP invariance was proposed [142] as the fundamental symmetry realised in nature.

But a few years later, in 1964, CP violation was discovered in the decays of neutral kaons [73]. The neutral kaons  $|K^0\rangle = |d\bar{s}\rangle$  and  $|\bar{K}^0\rangle = |s\bar{d}\rangle$  are produced in strong interactions but can only decay weakly. These are not CP eigenstates, since

$$\begin{aligned} CP|K^0\rangle &= |\bar{K}^0\rangle \\ CP|\bar{K}^0\rangle &= |K^0\rangle \end{aligned} \quad (1.22)$$

Therefore, CP eigenstates are defined as

$$\begin{aligned} |K_1\rangle &= \frac{1}{\sqrt{2}} (|K^0\rangle + |\bar{K}^0\rangle) \\ |K_2\rangle &= \frac{1}{\sqrt{2}} (|K^0\rangle - |\bar{K}^0\rangle) \end{aligned} \quad (1.23)$$

with

$$\begin{aligned} CP|K_1\rangle &= +|K_1\rangle & CP \text{ even} \\ CP|K_2\rangle &= -|K_2\rangle & CP \text{ odd} \end{aligned} \quad (1.24)$$

In the decay to pions, the  $2\pi$  final state is CP-even, whereas the  $3\pi$  final state is CP-odd. Additionally, the  $3\pi$  final state has a smaller phase space and the lifetime

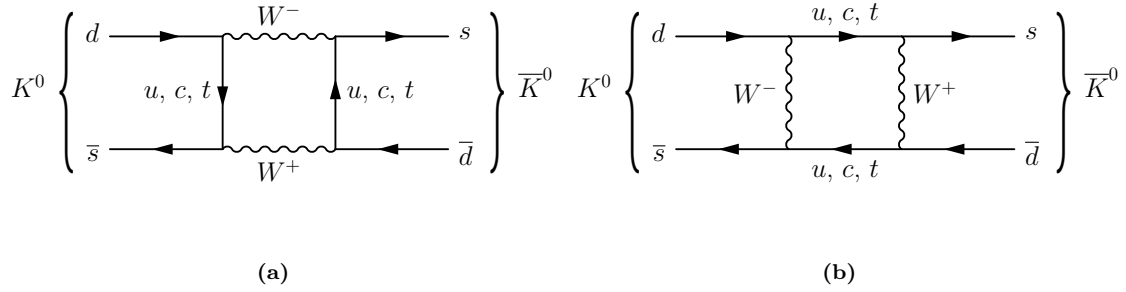


of the decaying particle is expected to be longer.

This matched the observations of a long-lived  $|K_L\rangle$  and a short-lived  $|K_S\rangle$ . Therefore, they were identified as  $|K_2\rangle$  and  $|K_1\rangle$ , respectively.

The experiment conducted in Ref. [73] analysed the decay products of a neutral kaon beam at a distance from the production point where only the long-lived, CP-odd  $|K_L\rangle$  component is expected. Therefore, no decay into two pions should be observed. Surprisingly, such decays were detected in a rate above the background expectation, implying a CP-violating decay  $K_L \rightarrow \pi\pi$ .

The reason for this is the mixing of  $|K^0\rangle$  and  $|\bar{K}^0\rangle$  via the box diagrams shown in Figure 1.6.



**Figure 1.6:** Box diagrams responsible for the mixing of  $K^0$  and  $\bar{K}^0$ .

This results in a contribution of the CP-even  $|K_1\rangle$  state to  $|K_L\rangle$ , which is responsible for the decay into two pions:

$$|K_L\rangle = \frac{1}{\sqrt{1 + |\varepsilon|^2}} (|K_2\rangle + \varepsilon |K_1\rangle) \quad (1.25)$$

where  $\varepsilon$  quantifies the contribution of  $|K_1\rangle$ .

Since the decay  $K_1 \rightarrow \pi\pi$  is not CP-violating, this type of CP violation where a mixing of states occurs is called *indirect* CP-violation. *Direct* CP-violation on the other hand is present in the decay  $K_2 \rightarrow \pi\pi$ , which was first observed in 1999 [74]. The reason for both types of CP violation is a complex phase in the CKM matrix  $V_{\text{CKM}}$  [25, 26], which is seen in this parameterisation [27]:

$$V_{\text{CKM}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \quad (1.26)$$

with the parameters  $s_{ij} = \sin \theta_{ij}$ ,  $c_{ij} = \cos \theta_{ij}$ , and  $\delta$ , the CP-violating phase.

CP violation was subsequently observed in further analyses of  $K$ -,  $B$ -, and  $D$ -meson decays [75–83].

The amount of CP violation introduced via the CKM matrix can be quantified by the *Jarlskog invariant*  $J$  [143]:

$$J = c_{12}c_{23}c_{13}^2 s_{12}s_{23}s_{13} \sin \delta \quad (1.27)$$

The value obtained with the most recent measurements of the CKM parameters is  $J = (3.18 \pm 0.15) \times 10^{-5}$  [27], which is too small to explain the observed baryon asymmetry in the universe [84–88]. Since all CP-violating effects observed so far are resulting from the CKM matrix, additional sources are required.

One possible source included in the SM is a CP-violating term in the Lagrangian of the QCD sector [68, 69, 144, 145], but measurements result in a far too small value  $|\theta| \lesssim 10^{-10}$  of the relevant parameter [27].

The observation of neutrino oscillations (e.g. [49–51]) suggests a relation between the flavour- and mass eigenstates of neutrinos similar to the one for quarks. In the case of neutrinos, this is described by the PMNS matrix [52, 53], which also contains a CP-violating phase. First searches for CP violation in the neutrino sector have been performed, e.g. [146], but no conclusive results are available yet.

After the discovery of the Higgs boson, the couplings to fermions and bosons provide new potential sources for CP violation. The coupling of the Higgs boson to the weak gauge bosons in the VBF production process is studied in this thesis. The next sections provide an introduction to the approach that is used.

## 1.4 Effective Field Theories

Physics beyond the SM may introduce new particles that are too heavy to be produced at the LHC. In that case, a direct observation is not possible and indirect effects due to the new particles have to be considered instead.

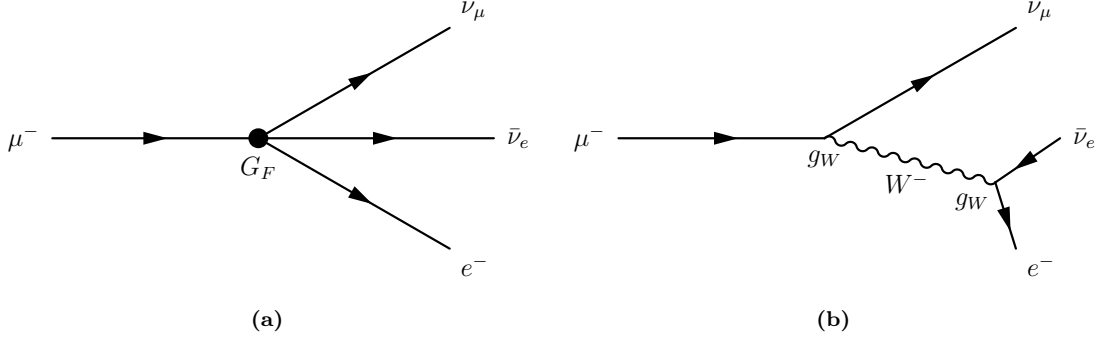
*Effective field theories* (EFT) provide a way to describe the impact of heavy particles with mass  $M$  at an energy scale  $\Lambda$  on observables at a much lower energy scale  $E \ll \Lambda$ , i.e. physics at the infrared (IR) scale can be described without knowing the full ultraviolet (UV) theory. This is possible due to the *decoupling theorem* [147]. Since the field content of the UV theory does not have to be known, this allows for model-independent tests at the low energy scale.

A prominent example for an EFT is *Fermi's interaction* [148]. This is a description of the charged-current processes of the weak interaction at energy scales below the mass of the  $W$  boson. Examples are the beta decay of a neutron  $n \rightarrow p + e^- + \bar{\nu}_e$  and the muon decay  $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$ , where a direct coupling with strength  $G_F$ , the *Fermi coupling constant*, between the four fermions is assumed. The four-fermion interaction for the muon decay is shown in Figure 1.7a.

This description breaks down close to energies of approximately 80 GeV. At this energy, the particle that is exchanged in the interaction has to be incorporated into the theory: the  $W$  boson with a mass of  $m_W \approx 80.4$  GeV [27], as shown in Figure 1.7b. The relation between the Fermi coupling constant  $G_F$  and the weak coupling strength  $g_W$  is

$$\frac{G_F}{\sqrt{2}} = \frac{g_W^2}{8m_W^2} \quad (1.28)$$

In the same spirit, the SM can be seen as an effective theory that is valid at the currently probed energy scales and up to a scale  $\Lambda$ , but is actually incomplete and



**Figure 1.7:** Muon decay in Fermi's interaction (a) and in the weak interaction with intermediate  $W$  boson (b).

breaks down at larger energy scales.

The effective Lagrangian of this *Standard Model Effective Field Theory* (SMEFT) is

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{f_i^{(5)}}{\Lambda} \mathcal{O}_i^{(5)} + \sum_i \frac{f_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \dots \quad (1.29)$$

where  $\mathcal{L}_{\text{SM}}$  is the SM Lagrangian, which is supplemented by additional terms. Each term consists of all gauge- and Lorentz invariant operators  $\mathcal{O}^{(D)}$  with mass dimension  $D$ , suppressed by the energy scale  $1/\Lambda^{(D-4)}$  and multiplied by the dimensionless, real-valued parameters  $f_i^{(D)}$ , called *Wilson coefficients*.

The operators are constructed using only the established field content of the SM. Complete, non-redundant sets of operators exist for mass dimensions up to  $D = 8$ , e.g. the *Warsaw basis* [149] or the *SILH basis* [150, 151], both for  $D = 6$ .

The construction of all mathematically valid operators results in a large number of operators. While only one operator, the *Weinberg operator* [152], is possible for  $D = 5$ , 2772 generators can be constructed for  $D = 6$ , assuming three fermion generations. The respective numbers for  $D = 7$  and  $D = 8$  are 1572 and 45800 [153].

Various assumptions can be made to reduce the numbers of considered operators. The requirement of  $B - L$  conservation excludes all operators with odd mass dimensions [154, 155]. The operators with  $D \geq 8$  can be neglected due to the large suppression in terms of  $1/\Lambda$ . If baryon number conservation is demanded and the number of fermion generations is limited to one, 59 operators for  $D = 6$  remain [153]. It has been shown [156–158] that the effective Lagrangian for  $D = 6$  is renormalisable at the one-loop level, resulting in a calculable scale dependence of the Wilson coefficients.

For the analysis of CP invariance in  $HVV$  couplings presented in Chapter 5, the number of operators is further reduced.

### 1.4.1 CP-odd operators in the $HVV$ vertex

The aim of the analysis presented in Chapter 5 is the test of CP invariance in the  $HVV$  vertex, i.e. the coupling of the Higgs boson to two electroweak gauge bosons. Therefore, only CP-violating operators that affect this vertex are of interest. All couplings between the Higgs boson and particles other than the electroweak gauge bosons are assumed to be as predicted by the SM, e.g. the couplings in the  $ggF$  production process and in the decay  $H \rightarrow \tau\tau$ . The approach used in this analysis follows the description and notation in Refs. [11, 159].

The tensor structure of the  $HVV$  vertex is

$$T^{\mu\nu}(q_1, q_2) = a_1(q_1, q_2) g^{\mu\nu} + a_2(q_1, q_2) [q_1 \cdot q_2 g^{\mu\nu} - q_2^\mu q_1^\nu] + a_3(q_1, q_2) \varepsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma} \quad (1.30)$$

where  $q_1$  and  $q_2$  are the momenta of the vector bosons. The form factors  $a_1$ ,  $a_2$ , and  $a_3$  quantify the different contributions to the vertex. The first term is the CP-even SM term, the second is an additional CP-even term, and the third term is CP-odd. The values of the form factors in the SM are  $a_1 = \frac{2m_V^2}{v}$  ( $V = W^\pm, Z$ ) and  $a_2 = a_3 = 0$ . In this analysis, operators are selected that result in a CP-odd contribution to the  $HVV$  vertex ( $a_3 \neq 0$ ) without additional CP-even contributions ( $a_2 = 0$ ).

The  $HVV$  vertex can be studied in the VBF- and  $VH$  production processes, and in the decay  $H \rightarrow VV$ . The cross-section of the  $VH$  production process is small compared to the VBF production process, and the sensitivity of  $H \rightarrow VV$  to CP-violating effects is small since the Higgs boson is selected to be on the mass shell, resulting in a limited momentum transfer in the  $HVV$  vertex [132]. Therefore, the VBF production process was chosen for this analysis.

From the 59 operators with  $D = 6$  only those are considered that result in CP violation, are  $SU(2)_{I,L} \times U(1)_Y$  invariant, and are constructed using the Higgs doublet  $\Phi$  and the gauge fields  $W_\mu^1, W_\mu^2, W_\mu^3$ , and  $B_\mu$ .

The resulting Lagrangian is

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{f_{\tilde{W}W}}{\Lambda^2} \mathcal{O}_{\tilde{W}W} + \frac{f_{\tilde{B}B}}{\Lambda^2} \mathcal{O}_{\tilde{B}B} + \frac{f_{\tilde{B}}}{\Lambda^2} \mathcal{O}_{\tilde{B}} \quad (1.31)$$

with the operators

$$\begin{aligned} \mathcal{O}_{\tilde{W}W} &= \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \\ \mathcal{O}_{\tilde{B}B} &= \Phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi \\ \mathcal{O}_{\tilde{B}} &= (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} D_\nu \Phi \end{aligned} \quad (1.32)$$

in the *HISZ basis* [160, 161] and the respective Wilson coefficients  $f_{\tilde{W}W}$ ,  $f_{\tilde{B}B}$ , and  $f_{\tilde{B}}$ . Here,  $\Phi$  is the Higgs doublet,  $D_\mu = \partial_\mu + i\frac{g}{2}B_\mu + i\frac{g'}{2}\sigma^a W_\mu^a$  the covariant derivative,  $\hat{W}_{\mu\nu}$  and  $\hat{B}_{\mu\nu}$  are the field-strength tensors of the gauge fields with  $\hat{B}_{\mu\nu} + \hat{W}_{\mu\nu} = i\frac{g'}{2}B_{\mu\nu} + i\frac{g}{2}\sigma^a W_{\mu\nu}^a$ ,  $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$  and  $W_{\mu\nu}^i = \partial_\mu W_\nu^i - \partial_\nu W_\mu^i + g\epsilon^{ijk}W_\mu^j W_\nu^k$ , and  $\tilde{V}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}V^{\rho\sigma}$  ( $V = B, W$ ) are the dual field-strength tensors.

The operator  $\mathcal{O}_{\tilde{B}}$  is already strongly constrained by previous measurements of CP-violating triple gauge-boson couplings [162–164]. Therefore, this operator is neglected

in this analysis.

The effective Lagrangian after electroweak symmetry breaking is [165]

$$\begin{aligned}\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} &+ \tilde{g}_{HAA} H \tilde{A}_{\mu\nu} A^{\mu\nu} + \tilde{g}_{HAZ} H \tilde{A}_{\mu\nu} Z^{\mu\nu} \\ &+ \tilde{g}_{HZZ} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HWW} H \tilde{W}_{\mu\nu}^+ W^{-\mu\nu}\end{aligned}\quad (1.33)$$

Due to  $\text{SU}(2)_{I,L} \times \text{U}(1)_Y$  invariance of the Lagrangian in Equation (1.31), the four coupling strengths can be expressed in terms of two dimensionless parameters  $\tilde{d}$  and  $\tilde{d}_B$ :

$$\begin{aligned}\tilde{g}_{HAA} &= \frac{g}{2m_W} \left( \tilde{d} \sin^2 \theta_W + \tilde{d}_B \cos^2 \theta_W \right) \\ \tilde{g}_{HAZ} &= \frac{g}{2m_W} \sin 2\theta_W \left( \tilde{d} - \tilde{d}_B \right) \\ \tilde{g}_{HZZ} &= \frac{g}{2m_W} \left( \tilde{d} \cos^2 \theta_W + \tilde{d}_B \sin^2 \theta_W \right) \\ \tilde{g}_{HWW} &= \frac{g}{m_W} \tilde{d}\end{aligned}\quad (1.34)$$

with

$$\begin{aligned}\tilde{d} &= -\frac{m_W^2}{\Lambda^2} f_{\tilde{W}W} \\ \tilde{d}_B &= -\frac{m_W^2}{\Lambda^2} f_{\tilde{B}B} \tan^2 \theta_W\end{aligned}\quad (1.35)$$

Since the contribution of  $\gamma\gamma$ ,  $\gamma Z$ ,  $ZZ$ , and  $WW$  to the VBF process cannot be distinguished experimentally, the arbitrary choice  $\tilde{d} = \tilde{d}_B$  results in

$$\begin{aligned}\tilde{g}_{HAA} = \tilde{g}_{HZZ} &= \frac{1}{2} \tilde{g}_{HWW} = \frac{g}{2m_W} \tilde{d} \\ \tilde{g}_{HAZ} &= 0\end{aligned}\quad (1.36)$$

Therefore, a single parameter describes the CP violation in the  $HVV$  coupling under these assumptions, resulting in the tensor structure

$$T^{\mu\nu}(q_1, q_2) = \sum_{V=W^\pm, Z} \frac{2m_V^2}{v} g^{\mu\nu} + \sum_{V=W^\pm, Z, \gamma} \frac{2g}{m_W} \tilde{d} \varepsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma} \quad (1.37)$$

The matrix element then consists of the CP-even SM part and an additional CP-odd part that scales with  $\tilde{d}$ :

$$\mathcal{M} = \mathcal{M}_{\text{SM}} + \tilde{d} \cdot \mathcal{M}_{\text{CP-odd}} \quad (1.38)$$

The squared matrix element used for the calculation of differential cross-sections is

$$|\mathcal{M}|^2 = |\mathcal{M}_{\text{SM}}|^2 + \tilde{d} \cdot 2\text{Re}(\mathcal{M}_{\text{SM}}^* \mathcal{M}_{\text{CP-odd}}) + \tilde{d}^2 \cdot |\mathcal{M}_{\text{CP-odd}}|^2 \quad (1.39)$$

The first and the last term are CP-even and do not contribute to CP violation. The interference term  $\text{Re}(\mathcal{M}_{\text{SM}}^* \mathcal{M}_{\text{CP-odd}})$  on the other hand is CP-odd and results in CP violation in the VBF production process of the Higgs boson. This term does not contribute to the total cross-section since it vanishes in the integration over a CP-symmetric phase space.

The last term increases the cross-section quadratically in  $\tilde{d}$ . This feature is not used in the analysis presented in Chapter 5, since an increase of the observed cross-section could also be caused by additional CP-even contributions.

## 1.5 Optimal Observable

The interference term in Equation (1.39) is used to define a CP-odd observable, called the *Optimal Observable* [166–168]:

$$\mathcal{OO} = \frac{2\text{Re}(\mathcal{M}_{\text{SM}}^* \mathcal{M}_{\text{CP-odd}})}{|\mathcal{M}_{\text{SM}}|^2} \quad (1.40)$$

The final state of the VBF production process consists of the Higgs boson and two quarks. The quarks hadronise and are reconstructed as jets in the analysis. By fixing the mass of the Higgs boson, neglecting the masses of the jets, and assuming momentum conservation in the transverse plane, this final state can be described by seven phase-space variables.

The Optimal Observable combines the full phase-space information in a single observable while maintaining the same sensitivity for small deviations from the SM, i.e. small values of  $\hat{d}$ , as shown in Ref. [167]. It is a CP-odd and  $\hat{T}$ -odd observable as defined in Section 1.3.1. The latter part is important since the dominant  $qq'$  initial states in the VBF production process are  $\hat{T}$ -symmetric, but not CP-symmetric. A non-vanishing mean value  $\langle \mathcal{OO} \rangle \neq 0$  can occur if re-scattering is caused by new particles, or if CP invariance is violated. Either case would be an indication for BSM physics. Under CP invariance and without re-scattering, the mean value vanishes:  $\langle \mathcal{OO} \rangle = 0$ .

The matrix elements in the definition of the Optimal Observable are calculated at LO accuracy with HAWK [99, 100, 102, 169, 170]. This requires the four-momenta of the Higgs boson and the two jets. The momentum fractions of the two initial-state partons can be derived by

$$x_{1,2} = \frac{m_{Hjj}}{\sqrt{s}} e^{\pm y_{Hjj}} \quad (1.41)$$

assuming energy-momentum conservation.  $x_1$  is the momentum fraction of the parton moving in positive  $z$ -direction, while  $x_2$  is the momentum fraction of the parton moving in negative  $z$ -direction.  $m_{Hjj}$  is the invariant mass and  $y_{Hjj}$  the rapidity of the final state, obtained from the vectorial sum of the Higgs boson and the two jets.

The four-momenta of the decay products of the Higgs boson are not directly used for the calculation of the Optimal Observable. Therefore, all analyses that select a VBF phase-space and that are able to provide the four-momentum of the Higgs boson can use the Optimal Observable method to study the  $HVV$  vertex.

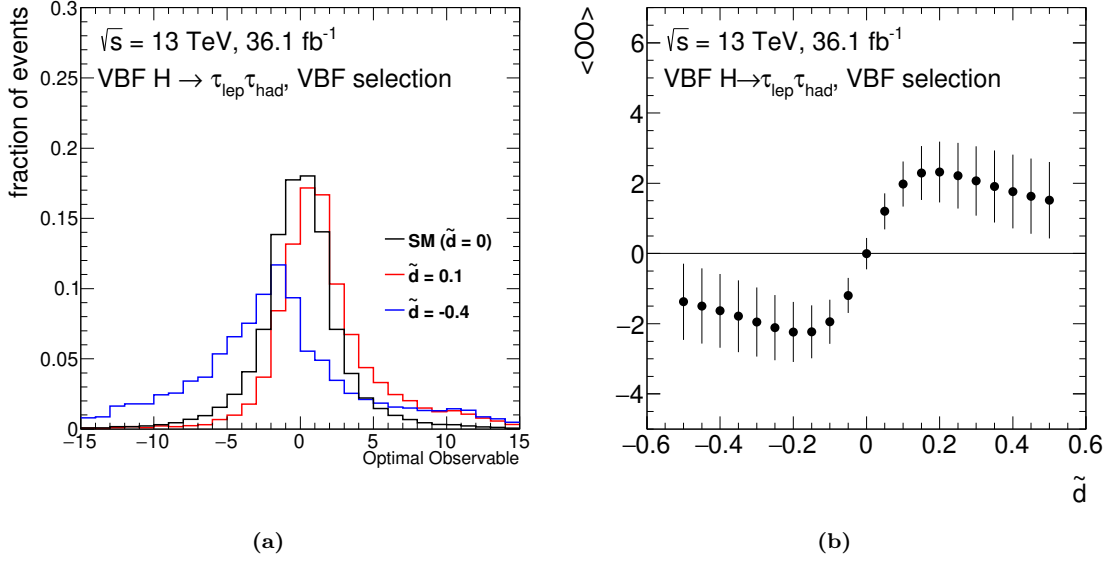
It is not possible to determine the flavours of the initial- and final-state partons. Therefore, the sum over all flavour configurations weighted by the CT10 parton distribution functions at LO accuracy [171] is used:

$$\begin{aligned} 2\text{Re}(\mathcal{M}_{\text{SM}}^* \mathcal{M}_{\text{CP-odd}}) &= \sum_{i,j,k,l} f_i(x_1) f_j(x_2) 2\text{Re} \left( \left( \mathcal{M}_{\text{SM}}^{ij \rightarrow klH} \right)^* \mathcal{M}_{\text{CP-odd}}^{ij \rightarrow klH} \right) \\ |\mathcal{M}_{\text{SM}}|^2 &= \sum_{i,j,k,l} f_i(x_1) f_j(x_2) \left| \mathcal{M}_{\text{SM}}^{ij \rightarrow klH} \right|^2 \end{aligned} \quad (1.42)$$

The Optimal Observable for simulated Higgs boson events produced in VBF after the VBF selection as introduced in Section 5.2 is shown in Figure 1.8a for three

values of  $\tilde{d}$ :  $\tilde{d} = 0.1$  (red),  $\tilde{d} = -0.4$  (blue), and  $\tilde{d} = 0$  (black), i.e. the SM case. The distribution is symmetric around zero for  $\tilde{d} = 0$  and is shifted to the right for  $\tilde{d} = 0.1$  and to the left for  $\tilde{d} = -0.4$ .

The behaviour of the mean value  $\langle \mathcal{OO} \rangle$  for different values of  $\tilde{d}$  is shown in Figure 1.8b. The mean value increases (decreases) for increasing positive (negative) values of  $\tilde{d}$  before reaching a maximum (minimum). After that, it converges back to zero, since for large values of  $\tilde{d}$  the dominating term in the matrix element is the CP-odd contribution, which is proportional to  $\tilde{d}^2$ .



**Figure 1.8:** (a) Distribution of the Optimal Observable for  $\tilde{d} = 0.1$  (red),  $\tilde{d} = -0.4$  (blue), and  $\tilde{d} = 0$  (black), i.e. the SM case. (b) The mean value  $\langle \mathcal{OO} \rangle$  of the Optimal Observable as function of  $\tilde{d}$ . In both figures simulated Higgs-boson events produced in VBF are used and the VBF selection discussed in Section 5.2 is applied. Statistical uncertainties are shown in (b)

In the analysis presented in Chapter 5, the Optimal Observable is calculated for events with a VBF selection applied. The value and confidence intervals of  $\tilde{d}$  are then extracted from data using maximum-likelihood fits.





# Chapter 2

## Experimental setup

In this chapter, the Large Hadron Collider (LHC), the ATLAS experiment, and the dataset used for this analysis are introduced. Section 2.1 describes the main features and the accelerator structure of the LHC, followed by a description of the different detector components and the trigger system of the ATLAS detector in Section 2.2. An overview of the simulation of proton–proton collisions is given in Section 2.3. The dataset used is described in Section 2.4.

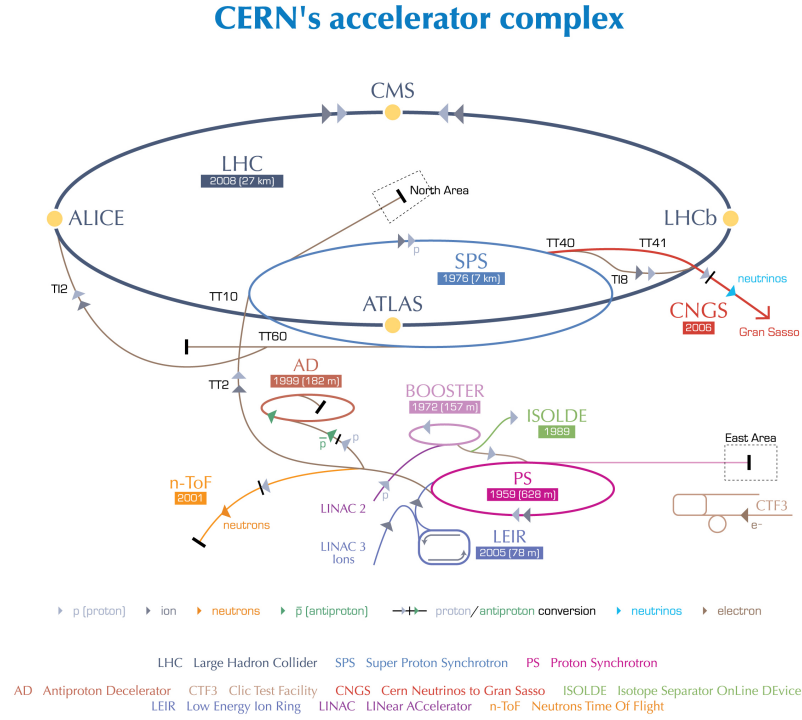
### 2.1 LHC

The LHC [172] is a particle accelerator located at the European Organisation for Nuclear Research (CERN) in Geneva, Switzerland. With a circumference of 26.7 km, it is placed in the underground tunnel that was formerly used for the Large Electron–Positron Collider (LEP) [173]. The tunnel consists of eight straight sections and eight arcs. 16 superconducting radiofrequency (RF) cavities operating at 400 MHz are located in the straight sections to accelerate the beams and keep them at their energy. The beams are travelling in opposite directions in two separate beam pipes and can be collided at four intersection points. To keep the beams on a circular path, 1232 dipole magnets are used. The magnets can generate a field strength of up to 8.33 T. For this, they are cooled down to 1.9 K using superfluid helium. 392 quadrupole magnets are used to keep the beams focused. Stronger quadrupole magnets are deployed directly before the intersection points to increase the focusing. Further magnets are used to separate the beams again after the collision, to correct for imperfections in the field geometry, and to deflect the beams for the beam dump. The LHC can accelerate and collide protons and heavy ions. So far, collisions took place between protons ( $p$ – $p$ ), lead nuclei (Pb–Pb), protons and lead nuclei ( $p$ –Pb), and xenon nuclei (Xe–Xe). The accelerator design allows center-of-mass energies of up to  $\sqrt{s} = 14$  TeV for  $pp$  collisions and instantaneous luminosities of up to  $\mathcal{L} = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ . The highest collision energy used so far was  $\sqrt{s} = 13$  TeV and the design instantaneous luminosity was exceeded by a factor of approximately two in 2017 and 2018 [174].

The proton beams are not continuous but consist of 2808 *bunches* with  $1.15 \cdot 10^{11}$  protons per bunch. 72 bunches with a spacing of 25 ns form a *bunch train*, whereas two bunch trains are separated by a gap of 320 ns.

The protons enter the LHC after being pre-accelerated by a chain of smaller accelerators. The source of the protons is ionised hydrogen gas. First, they are linearly

accelerated to 50 MeV and grouped into bunches by Linac2. After that, they are accelerated to 1.4 GeV by the Proton Synchrotron Booster (PSB), to 25 GeV by the Proton Synchrotron (PS), which also creates the bunch train structure, and to 450 GeV by the Super Proton Synchrotron (SPS). After that, the protons are injected into the LHC and accelerated to their collision energy. An overview of this acceleration chain is shown in Figure 2.1.



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**Figure 2.1:** A schematic overview of the LHC acceleration chain. Taken from Ref. [175].

Seven experiments are located at the interaction points of which the biggest are ATLAS [176], CMS [177], ALICE [178], and LHCb [179].

ATLAS and CMS are general-purpose detectors that are used to investigate a wide range of physics, e.g. precision measurements of the Standard Model and searches for new particles. ALICE aims to study the quark-gluon plasma produced by Pb-Pb collisions, whereas LHCb focuses on  $b$ -hadron physics.

The smaller experiments are TOTEM [180], MoEDAL [181], and LHCf [182]. LHCf and TOTEM are both used to study *forward* processes, i.e. particles that travel at small angles to the beamline. The focus of TOTEM is on the measurement of the total cross-section, elastic scattering, and diffractive processes, whereas LHCf uses the forward particles to study interactions similar to those caused by cosmic rays in the atmosphere. The aim of MoEDAL is the search for magnetic monopoles.

### 2.1.1 Luminosity

A large number of events is important for all physics analyses since this reduces the statistical errors and enables precise measurements. The rate of expected events for a specific process is given by the product of its cross-section  $\sigma$  and the instantaneous

luminosity  $\mathcal{L}$ :

$$R = \frac{\Delta N}{\Delta t} = \sigma \mathcal{L} \quad (2.1)$$

The cross-section is given by nature and can be predicted by theory, whereas the luminosity is provided by the collider. In the case of  $pp$  collisions, it is defined as

$$\mathcal{L} = \frac{n^2 n_b f_{\text{rev}}}{2\pi \Sigma_x \Sigma_y} \quad (2.2)$$

where  $n_b$  is the number of bunches in each beam,  $f_{\text{rev}}$  the revolution frequency of the beams,  $n$  is the number of protons per bunch, and  $\Sigma_x$  and  $\Sigma_y$  are the horizontal and vertical beam widths, respectively.

To determine the luminosity, inelastic collisions are used. The luminosity can be written as

$$\mathcal{L} = \frac{\mu_{\text{inel.}} n_b f_{\text{rev}}}{\sigma_{\text{inel.}}} \quad (2.3)$$

where  $\mu_{\text{inel.}}$  and  $\sigma_{\text{inel.}}$  are the average number of inelastic interactions per bunch crossing and the inelastic cross-section for  $pp$  collisions, respectively.

The cross-section  $\sigma_{\text{inel.}}$  is measured in special runs by *van der Meer* (vdM) scans, whereas  $\mu_{\text{inel.}}$  is determined during data taking for each bunch separately, resulting in the bunch luminosity

$$\mathcal{L}_b = \frac{\mu_{\text{inel.,b}} f_{\text{rev}}}{\sigma_{\text{inel.}}} \quad (2.4)$$

and in the total luminosity

$$\mathcal{L} = \sum_b \mathcal{L}_b \quad (2.5)$$

During vdM scans, the beam separation is varied in the horizontal and vertical direction. The cross-section  $\sigma_{\text{inel.}}$  is determined by using Equations (2.2) and (2.3):

$$\sigma_{\text{inel.}} = \mu_{\text{inel.}}^{\text{max}} \frac{2\pi \Sigma_x \Sigma_y}{n_1 n_2} \quad (2.6)$$

The LUCID-2 detector [183, 184] is used to measure  $\Sigma_x$ ,  $\Sigma_y$ , and  $\mu_{\text{inel.}}^{\text{max}}$ , where the latter is the maximum of the interaction rate during the scans.

## 2.2 The ATLAS detector

The ATLAS detector [176] surrounds the beamline in a cylindrical, symmetric shape. It is 44 m long, 25 m high and weighs 7 kt. The detector consists of various subsystems that are grouped in three main systems: the inner detector (ID), the calorimeter system, and the muon spectrometer (MS). Each subdetector is divided into separate systems in the central *barrel* region and the two forward *endcap* regions.

A superconducting solenoid magnet with a field strength of 2 T surrounds the ID and bends charged particles perpendicular to the beamline. Three superconducting toroid magnets are located around the calorimeter system, one in the barrel region and two in the endcap regions. Each toroid consists of eight symmetrically arranged coils, which produce magnetic fields in the muon detectors with field strengths of 0.5 T and 1 T in the barrel- and endcap regions, respectively. These magnetic fields

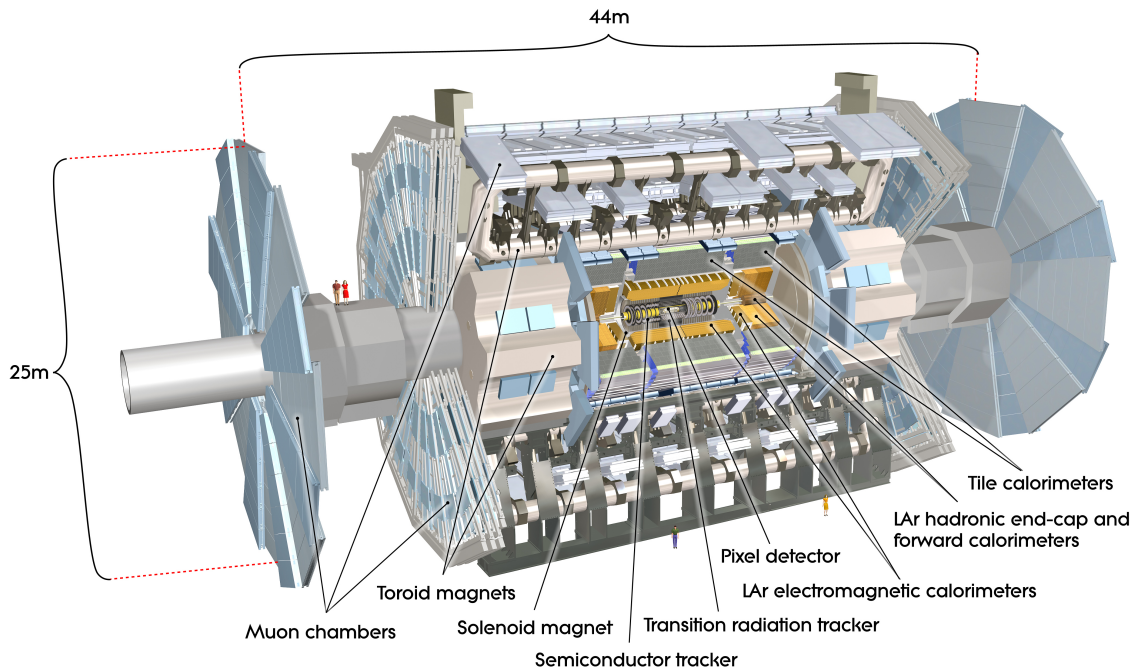
bend charged particles parallel to the beamline.

The ID provides the information for the reconstruction of the trajectories of charged particles, the measurement of their momenta, the determination of their charge, and the reconstruction of vertices. It is installed very close to the beamline and has a high granularity to achieve a good resolution of the measurements.

The calorimeter system consists of an electromagnetic calorimeter (ECAL) and a hadronic calorimeter (HCAL). The calorimeters measure the energies of particles and provide information about the emerging shower shape. Electrons and photons are measured by the ECAL, while hadrons are measured mostly in the HCAL. The calorimeters are located between the ID and the MS.

The MS constitutes the outermost layer of the ATLAS detector. Other particles than muons rarely reach the MS since they are already stopped in the calorimeter system. Therefore, the MS plays a crucial role in the measurement and identification of muons.

An overview of the ATLAS detector is shown in Figure 2.2.



**Figure 2.2:** Overview of the ATLAS detector. Taken from Ref. [176].

Due to the high collision rate delivered by the LHC, it is important to limit the rate of recorded events by only considering interesting events. These are selected by a combined hardware- and software *trigger* system.

### 2.2.1 Coordinate system

The origin of the coordinate system used in the ATLAS experiment (and in this thesis) is at the nominal interaction point. The  $x$ -axis points towards the center of the LHC ring, the  $y$ -axis upwards, and the  $z$ -axis counterclockwise along the beamline. This defines a right-handed coordinate system. The  $x$ - $y$  plane forms the

*transverse* plane and is used to define properties like the transverse momentum  $p_T$ , the transverse energy  $E_T$ , and the missing transverse energy  $E_T^{\text{miss}}$ .

The azimuthal angle  $\phi$  is measured around the beam axis and the polar angle  $\theta$  is measured from the beam axis. Instead of  $\theta$ , often the *pseudorapidity*  $\eta = -\ln\left(\tan\frac{\theta}{2}\right)$  is used. The value range goes from  $|\eta| = 0$  perpendicular to the beamline to  $|\eta| \rightarrow \infty$  when approaching the beamline.

For highly relativistic particles the pseudorapidity is equivalent to the *rapidity*  $y = \frac{1}{2} \ln\left(\frac{E+p_z}{E-p_z}\right)$  and the difference between pseudorapidities  $\Delta\eta$  becomes Lorentz invariant with respect to boosts in direction of the beamline. The angular distance between two points in the  $\eta$ - $\phi$  space is defined as  $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ .

### 2.2.2 Inner detector

The inner detector [176] consists of the silicon pixel detector and the semiconductor tracker (SCT) in the inner part, and the transition radiation tracker (TRT) in form of straw tubes in the outer part. The ID provides precise measurements of tracks with  $p_T > 0.5 \text{ GeV}$  and vertices due to the high resolutions of the pixel detector and the SCT, and the large number of hits in the TRT. Besides contributing to the reconstruction of tracks, the measurements of the TRT are used for the identification of electrons.

The total length of the ID is approximately  $\pm 3.5 \text{ m}$  around the interaction point with a radius of  $1.15 \text{ m}$ . The pixel detector and the SCT cover the region  $|\eta| < 2.5$ . In the barrel region, they are installed on concentric cylinders around the beam axis, while they are located on disks perpendicular to the beam axis in the endcap regions. The TRT covers the region  $|\eta| < 2$ . The straw tubes are installed parallel to the beamline in the barrel region, while they are arranged radially in wheels in the endcap regions. An overview of the inner detector with all subcomponents is shown in Figure 2.3.

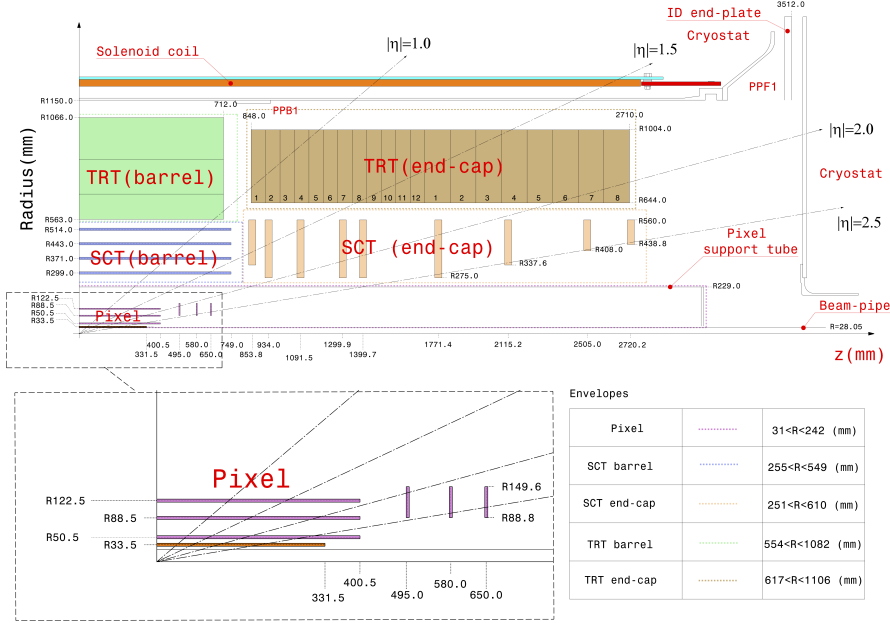
The design resolution for measurements of the transverse momenta with the ID is  $\sigma_{p_T}/p_T = 0.05 \% p_T \oplus 1 \%$  [176].

#### Pixel detector

The pixel detector is closest to the beamline and consists of three cylindrical layers in the barrel region and three disks in each endcap region. The pixel layers are segmented in  $R$ - $\phi$  and  $z$  with a size of  $R$ - $\phi \times z = 50 \times 400 \mu\text{m}^2$ . 47232 pixels are on each of the 1744 modules, resulting in approximately 80 million readout channels. The intrinsic accuracies, i.e. the minimal distances two hits can have so that they are still distinguishable, are  $10 \mu\text{m}$  ( $R$ - $\phi$ ) and  $115 \mu\text{m}$  ( $z$ ) in the barrel, and  $10 \mu\text{m}$  ( $R$ - $\phi$ ) and  $115 \mu\text{m}$  ( $R$ ) in the endcaps. Each track typically crosses three pixel layers. In addition to the three layers in the barrel region, a fourth layer, the *insertable b-layer* (IBL) [186], was installed as innermost layer next to the beamline after Run-1 of the LHC. The pixels have a smaller size of  $R$ - $\phi \times z = 50 \times 250 \mu\text{m}^2$  and additional 3D silicon sensors are used. The IBL adds approximately 12 million readout channels, resulting in improved performances of the tracking and the vertex reconstruction.

#### SCT

Outside the pixel detector, the SCT is installed. It has four layers in the barrel region and nine disks in each endcap region. It consists of 15912 silicon microstrip



**Figure 2.3:** Overview of the inner detector with the layout of the subcomponents in the barrel- and endcap regions. Taken from Ref. [185].

sensors, with 768 active strips of 6.4 cm length and a pitch of  $80 \mu\text{m}$  per sensor. A SCT module is formed by four sensors, where two daisy-chained sensors are mounted back-to-back. The strips of one sensor are aligned parallel to the beamline in the barrel region and perpendicular to the beamline in the endcap regions, while the other sensor is rotated by a stereo angle of  $40 \text{ mrad}$ . This rotation allows to obtain the  $z$ - and  $R$  components in the barrel- and endcap regions, respectively. Therefore, a measurement of three-dimensional space points is possible. 2112 modules are mounted in the barrel regions and 1976 modules are mounted in the endcap regions. The total amount of readout channels is approximately 6.3 million. The intrinsic accuracies are  $17 \mu\text{m}$  ( $R$ - $\phi$ ) and  $580 \mu\text{m}$  ( $z$ ) in the barrel, and  $17 \mu\text{m}$  ( $R$ - $\phi$ ) and  $580 \mu\text{m}$  ( $R$ ) in the endcaps. Each track crosses eight sensors and creates four space points.

## TRT

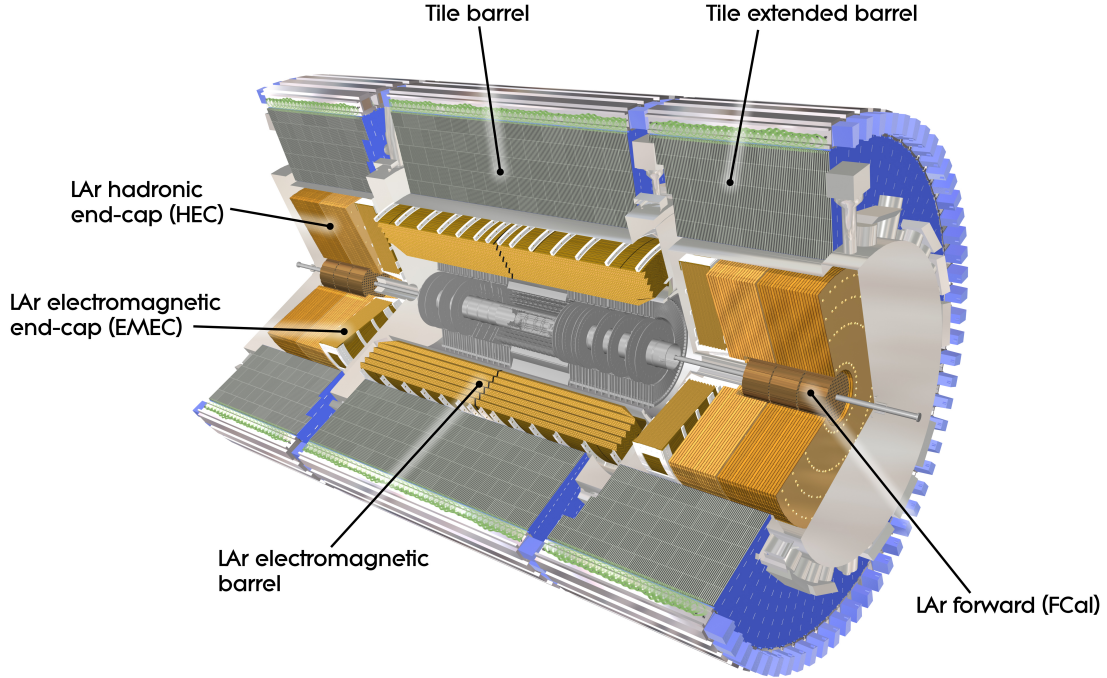
The outermost layer of the ID is the TRT. It consists of 298304 straw tubes with a diameter of 4 mm, filled with a  $\text{Xe}/\text{CO}_2/\text{O}_2$  gas mixture. In the barrel region, the straw tubes with a length of 144 cm are grouped in three rings parallel around the beamline, resulting in up to 72 layers of straw tubes. In each endcap region, the straw tubes are installed radially from the beamline and are grouped in 20 wheels with 8 layers, resulting in 160 planes of straw tubes. Each layer consists of 768 straw tubes with a length of 37 cm. The space between the straw tubes is filled with polypropylene fibres in the barrel region and foils in the endcap regions, which produce transition radiation. The total number of readout channels is approximately 351000. The TRT only provides information about  $R$ - $\phi$ , with an intrinsic accuracy of  $130 \mu\text{m}$  per straw tube. Each track results in approximately 36 hits in the TRT and due to this high number, the TRT contributes to the ID measurements despite its lower resolution.

### 2.2.3 Calorimeter system

The calorimeter system [176] is composed of electromagnetic (ECAL) and hadronic (HCAL) sampling calorimeters, which measure electromagnetic and hadronic showers with alternating layers of active material and absorber material. The system provides a coverage up to  $|\eta| = 4.9$  and full coverage in  $\phi$ . The ECAL covers up to  $|\eta| < 1.475$  in the barrel region and the electromagnetic endcap calorimeters (EMEC) cover the region  $1.375 < |\eta| < 3.2$ . The hadronic tile calorimeter is composed of a central barrel and two extended barrels, one on each side, covering the region  $|\eta| < 1.0$  and  $0.8 < |\eta| < 1.7$ , respectively, while the hadronic endcap calorimeter (HEC) covers  $1.5 < |\eta| < 3.2$ . The forward calorimeter (FCal) extends the coverage from  $3.1 < |\eta| < 4.9$  and is used for the measurement of both electromagnetic and hadronic showers.

The hadronic tile calorimeters use scintillating tiles as active material, while liquid argon (LAr) is used for all other calorimeters. Good energy and position resolutions are achieved due to the high granularity of the calorimeters. The granularity is finer in the region  $|\eta| < 2.5$ , which is the coverage of the ID, to allow for precise measurements of electrons and photons. The coarser granularity in the rest of the calorimeter system is still sufficient for the reconstruction of jets and  $E_T^{\text{miss}}$ . An overview of the calorimeter system is shown in Figure 2.4.

The energy resolution of the ECAL for electrons and photons is  $\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$ , while the resolution of the HCAL for the measurement of jets is  $\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$  in the barrel- and endcap regions, and  $\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$  for the forward calorimeter. [176].



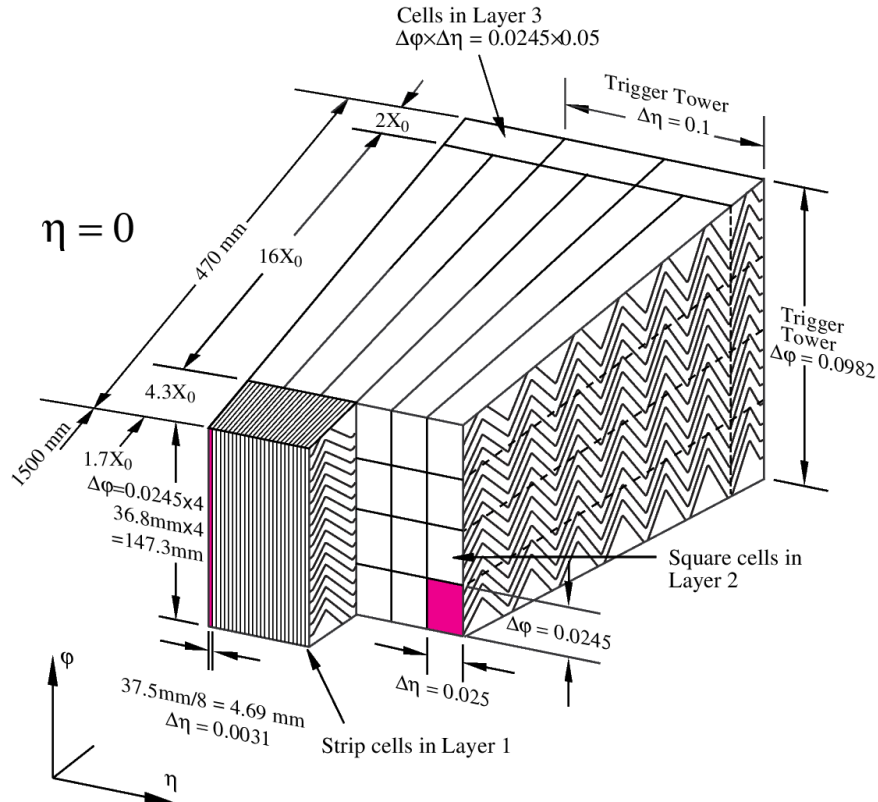
**Figure 2.4:** Overview of the calorimeter system in the ATLAS detector. Taken from Ref. [176].



### Electromagnetic calorimeter

The electromagnetic calorimeter uses liquid argon as active material and lead plates as absorber material. Full coverage in  $\phi$  is achieved by an accordion shape of the absorber plates. In the barrel region, the calorimeter is composed of two cylindrical half barrels that are centered around  $z = 0$ . Each half barrel contains 1024 absorbers. The calorimeter in both endcap regions is divided into two wheels. The outer wheels, covering the region  $1.375 < |\eta| < 2.5$ , contain 768 absorbers, whereas the inner wheels cover the region  $2.5 < |\eta| < 3.2$  and contain 256 absorbers. The radiation length of the ECAL is  $> 22 X_0$  in the barrel and  $> 24 X_0$  in the endcaps.

In the precision region  $|\eta| < 2.5$ , the calorimeter is segmented in three layers in depth with increasing granularity. The first layer consists of strip cells that are finely segmented in  $\eta$  with a maximum granularity of  $\Delta\eta \times \Delta\phi = 0.025/8 \times 0.1$ , allowing the identification of  $\pi^0 \rightarrow \gamma\gamma$  decays. The second layer collects the largest fraction of the EM showers and has a granularity of  $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$ . The last layer collects the tails of the showers and is less segmented in  $\eta$  with a granularity of  $\Delta\eta \times \Delta\phi = 0.050 \times 0.025$ . Only two layers with coarser granularities are used for the outermost region of the outer wheel, the inner wheel, and the edge zone of the barrel next to the inner wheel. There are 101760 readout channels in the barrel calorimeter and 62208 readout channels in the EMEC. An overview of a barrel module of the ECAL is shown in Figure 2.5.



**Figure 2.5:** An overview of a barrel module of the ECAL. Taken from Ref. [176].

To correct for the energy lost by electrons and photons in front of the calorimeter, a presampler, which consists of a thin active LAr layer, is installed in front of the first



layer, covering  $|\eta| < 1.52$  and  $1.5 < |\eta| < 1.8$  in the barrel region and the endcap regions, respectively, with a granularity of  $\Delta\eta \times \Delta\phi = 0.025 \times 0.1$ . The total amount of readout channels of the presampler is 9344.

### Hadronic calorimeter

The central- and extended barrels of the hadronic tile-calorimeter, which are located outside the ECAL, use steel as absorber material and scintillating tiles as active material. The barrels are divided into 64 modules and have three layers with depths at  $\eta = 0$  corresponding to interaction lengths of 1.5, 4.1, and  $1.8\lambda$  in the central barrel and 1.5, 2.6, and  $3.3\lambda$  in the extended barrels, respectively. The total thickness at the edge of the tile calorimeter is  $9.7\lambda$ . The granularity of the first two layers is  $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ , whereas the granularity of the last layer is  $\Delta\eta \times \Delta\phi = 0.2 \times 0.1$ . The coarser granularity of the HCAL is still sufficient to measure hadronic showers, which are wider with respect to EM showers.

The HEC consists of two wheels per endcap behind the EMEC. Each wheel is segmented in two layers in depth, resulting in four layers per endcap. Each of the layers consists of 32 wedge-shaped modules. The HEC uses copper plates as absorber material and LAr as active material. The thickness is about twelve interaction lengths. The granularity is  $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$  for  $|\eta| < 2.5$  and  $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$  for larger values of  $|\eta|$ . The total number of readout channels is 5632.

The FCal is located between the beamline and the HEC, consisting of three modules in each endcap with a total interaction length of  $10\lambda$ . The first module uses copper as absorber material and is used for the measurement of EM showers. The other two modules measure hadronic showers and use tungsten as absorber material. Each module is built as a metal matrix with longitudinal channels in which concentric rods and tubes parallel to the beamline are placed. LAr is used as active material in the gaps between the rods and the tubes. The total number of readout channels of the FCal is 3524. Behind the last layer is a shielding plug to reduce the leakage of showers into the muon system.

### 2.2.4 Muon spectrometer

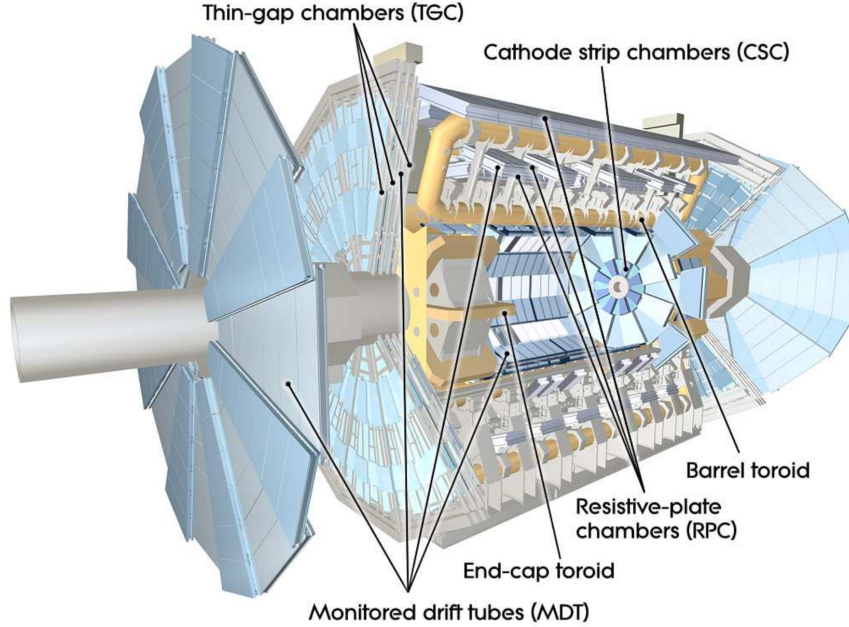
The muon spectrometer (MS) [176] forms the outermost part of the ATLAS detector. The MS measures the momentua and tracks of particles that leave the calorimeter system, mostly muons. It consists of two types of precision tracking chambers, Monitored Drift Tubes (MDT) and Cathode Strip Chambers (CSC), and two types of trigger chambers, Resistive Plate Chambers (RPC) and Thin Gap Chambers (TGC). The precision tracking chambers cover the region  $|\eta| < 2.7$ , while the triggering of muons is possible in  $|\eta| < 2.4$ .

The muons are bent parallel to the beamline by the toroid magnets. The large barrel toroid is responsible for the bending of the muons in the region  $|\eta| < 1.4$ , while the endcap toroids create the magnetic field in the region  $1.6 < |\eta| < 2.7$ . Inbetween these two regions, a combination of the fields provides the bending. Figure 2.6 shows the muon spectrometer and the toroid magnets.

The design momentum resolution of the MS is 10 % for the measurement of muon tracks with  $p_T = 1$  TeV [176]. For this, an alignment of the muon chambers with a precision of approximately 30 mm is required. This is achieved by an optical alignment system consisting of about 12000 sensors. 1800 Hall sensors are distributed

in the spectrometer for the reconstruction of the magnetic field to determine its bending power.

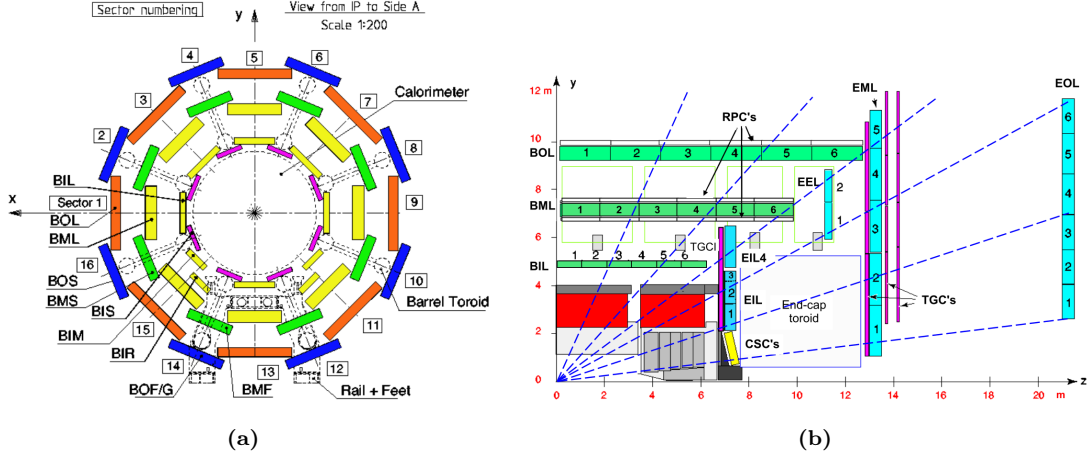
Three gaps are present in the coverage of the MS: one at  $\eta = 0$ , where services are located, and two at  $\phi = 240^\circ$  and  $\phi = 300^\circ$  for feet of the detector support structure.



**Figure 2.6:** An overview of the muon spectrometer and the toroid magnets. Taken from Ref. [176].

The 1088 MDT chambers cover the region  $|\eta| < 2.7$  and are installed in three cylindrical layers around the beam axis in the barrel region and in three wheels perpendicular to the beamline in the endcap regions. In each layer in the barrel region, large and small chambers are arranged in eight octants. In the innermost layer, the chambers contain four layers of MDTs, whereas the chambers contain only three layers of MDTs in the middle- and outer layers. The drift tubes are made of aluminium with a diameter of about 30 mm. They are filled with a gas mixture consisting of 93 % Ar and 7 % CO<sub>2</sub>. Electrons from the ionisation are collected at a tungsten-rhenium wire in the middle of the tube. The MDTs provide a precise measurement of the track coordinates in the bending direction. The achieved resolution is 80  $\mu\text{m}$  per tube and 35  $\mu\text{m}$  per chamber. The layout of the MDT chambers is shown in Figures 2.7a and 2.7b, where the latter also includes the other subsystems of the MS.

In the innermost wheel in the endcap region, the MDTs are replaced by CSCs in the region  $2 < |\eta| < 2.7$ . CSCs are multiwire proportional chambers with radially oriented wires and cathodes segmented into strips. The strips of one cathode are perpendicular to the wires for the measurement in the bending direction, while the strips of the other cathode are parallel to the wires, resulting in the facility to measure the transverse coordinate. The used gas is a mixture of Ar (80 %) and CO<sub>2</sub> (20 %). The CSCs can withstand the high particle flux in this region of the detector and have a higher granularity than the MDTs to handle the increased track density. In both endcap regions, the CSC system consists of two disks with eight large and small chambers, respectively. Each chamber contains four CSC planes, resulting in four measurements per traversing track. The resolution is 40  $\mu\text{m}$  in the bending



**Figure 2.7:** Layout of the MDT chambers (denoted as BIL, BML, BOL, EIL, EML and EOL) in the transverse plane (a) and the plane containing the beam axis (b). The latter also shows the position of the CSCs, RPCs, and TGCs. Taken from Ref. [176].

direction and 5 mm in the transverse plane.

A design criterion of the MS was the possibility to trigger on muon tracks. For this, the track information is required within a few tens of nanoseconds after the passage of the muon. Both the RPCs and the TGCs fulfill this requirement by delivering signals within 15-25 ns. In addition to measurements of  $\eta$  in the bending direction, both systems provide also measurements of  $\phi$  in the transverse direction.

The RPCs are located in the barrel region and cover  $|\eta| < 1.05$ . A RPC consists of two parallel resistive plates separated by a gas volume filled with the mixture  $\text{C}_2\text{H}_2\text{F}_4/\text{Iso-C}_4\text{H}_{10}/\text{SF}_6$  (94.7 %/5 %/0.3 %). The signal is read out by longitudinal strips on one plate and transverse strips on the other plate. In total, 962 RPCs are used in 544 chambers. The chambers are installed in front and behind the middle layer of the MDT chambers, and in the outer layer in front the small MDT chambers and behind the large MDT chambers.

The region  $1.05 < |\eta| < 2.4$  in the endcaps is covered by the TGCs. They are multiwire proportional chambers filled with a  $\text{CO}_2/\text{n-C}_5\text{H}_{12}$  (55 %/45 %) gas mixture. The coordinate in bending direction is read out by the wires, while the azimuthal coordinate is retrieved by radial strips on the cathode plates. Three or two chambers form a triplet- or doublet unit, respectively, with a total number of 744 units and 1704 chambers. The units are located at the inner- and middle layers of the MDT chambers. At the inner layer, one doublet layer is installed in front of the MDT chambers, while at the middle layer, a triplet layer is in front of the MDT chambers and two doublet layers are behind the MDT chambers.

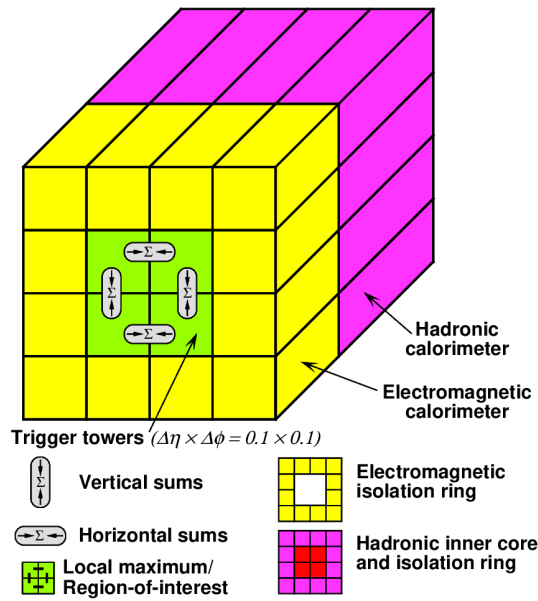
### 2.2.5 Trigger system

To limit the number of events that have to be processed and stored, a *trigger* system [176, 187] is responsible for the selection of interesting events. The trigger system consists of a hardware-based Level-1 (L1) trigger and a software-based high-level trigger (HLT). The initial bunchcrossing rate of approximately 40 MHz is reduced to an event rate of approximately 100 kHz by the L1 trigger, while the HLT further reduces the rate down to approximately 1 kHz.

The L1 trigger uses information from the muon trigger systems (L1Muon) and from the calorimeters (L1Calo), the latter with a coarser granularity.

The L1Calo system searches for energy deposits by electrons, photons,  $\tau_{\text{had}}$  candidates and jets, and can also identify  $E_{\text{T}}^{\text{miss}}$ . It is also possible to use the sum of all energy deposits  $E_{\text{T}}^{\text{sum}}$  as input for the trigger decision.

*Trigger towers* are defined by combining neighbouring cells throughout the layers of the calorimeters. The total amount of transverse energy deposited in a trigger tower has to exceed a predefined threshold. Additionally, isolation criteria can be defined by using information from neighbouring towers, denoted as *isolation ring*. An illustration of the trigger towers and the isolation ring is shown in Figure 2.8.



**Figure 2.8:** Illustration of the trigger towers in the calorimeter system. Taken from Ref. [176].

The L1Muon system finds hit patterns of muons from the interaction region by identifying coincidences between different trigger stations. The coincidences have to correspond to the possible trajectories of a muon with a predefined  $p_{\text{T}}$ . Therefore, the requirement for coincident hits defines effectively a  $p_{\text{T}}$  threshold.

The objects found by the L1Calo- and L1Muon systems are input to the L1Topo system. This allows to apply topological selections on properties such as the angular separation or the invariant mass of objects.

The central trigger processor (CTP) then collects the information from the L1Calo-, L1Muon-, and L1Topo systems and forms the final L1 trigger decision. For the accepted events, *regions of interest* (RoIs) are determined from the location of the objects found by the L1Muon- and L1Calo systems. The total decision time of the L1 system is about  $2.5 \mu\text{s}$  [188].

The RoIs are provided to the HLT system, which executes reconstruction- and identification algorithms by using the full granularity of the detector in the RoIs or by using the full detector system. A two-step approach is used: in the first step, a fast reconstruction which rejects the majority of events is applied. In the second

step, slower but more precise reconstruction- and identification algorithms are used. These algorithms are designed to have a minimum difference to the algorithms used in the offline reconstruction and identification. The total processing time of the HLT system is about 200 ms [188].

More details about the triggers for electrons and muons are found in Sections 3.3 and 3.4, respectively.

### Trigger nomenclature

The triggers listed in Table 4.3 are used in this analysis. No L1Topo requirement is applied since only triggers that require a single lepton in the event are used. The name of a trigger contains all information about the requirements on the objects in the accepted events [187].

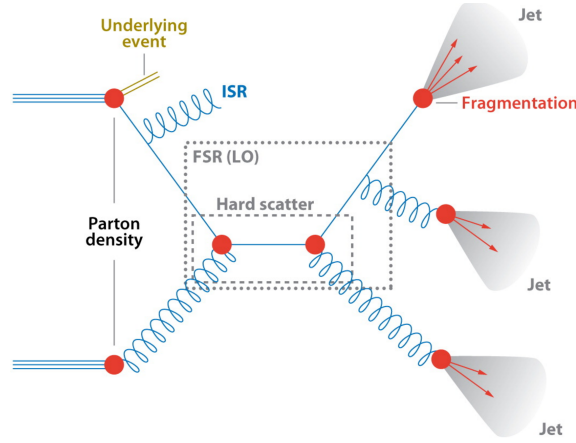
HLT denotes the requirements of the HLT system.  $e/\mu$  stands for electron/muon, the following number is the  $p_T$  requirement.  $1h^*$  and  $i^*$  indicate the identification and isolation criteria on the object.  $nod0$  means that no requirement on the distance between the primary vertex and the tracks of the object is imposed.

If a L1 term is included in the trigger name, the HLT was seeded by a non-default L1 trigger decision from the electromagnetic calorimeter EM or the muon spectrometer MU. The following number is again the  $p_T$  requirement. V indicates that the  $p_T$  threshold is depending on  $\eta$ , H that a  $p_T$  dependent veto against energy depositions in the hadronic calorimeter is applied, and I that the object is required to be isolated in the ECAL. The default L1 seeds for the triggers of this analysis are MU20 and EM22VHI.

## 2.3 Simulation of $pp$ collisions

In addition to the data collected with the ATLAS detector, the theoretical description and the simulation of the processes at a  $pp$  collider are necessary to compare the predictions of the Standard Model or of BSM theories with the data. The nature of the collisions makes this a complicated process: several phenomena with different scales of the momentum transfer  $Q$  have to be considered. These can be treated separately due to the *factorisation theorem* [189]. *Hard* processes with large  $Q$  like the *hardscatter event*, i.e. the interaction between the partons, can be calculated using *perturbation theory*. *Soft* processes with small  $Q$  on the other hand have to be described *non-perturbatively* by models which parameters are derived from data. Soft processes are the parton distribution functions (PDF) of the protons and the *fragmentation* (or *hadronisation*) of the coloured particles produced in the collision into colourless hadrons. In addition, initial- and final-state radiation (ISR and FSR) of the particles involved in the hardscatter event and the *underlying event* originating from beam remnants or multiple parton interactions have to be considered. All these aspects are incorporated into *Monte Carlo event generators* that use *random sampling* techniques. The different components that have to be simulated are shown in Figure 2.9.

Finally, the interaction between the final state particles and the detector has to be simulated.



**Figure 2.9:** The different components of a parton collision that have to be simulated. Taken from Ref. [190].

### 2.3.1 Partonic cross-section and PDFs

According to the factorisation theorem, the cross-section of two colliding protons producing a final state with  $n$  particles can be written as

$$\sigma_{pp \rightarrow n} = \sum_{a,b} \int_0^1 \int_0^1 dx_a dx_b f_a(x_a, \mu_F) f_b(x_b, \mu_F) \sigma_{ab \rightarrow n}(x_a, x_b, \mu_R, \mu_F) \quad (2.7)$$

Here,  $f_{a/b}$  are the *parton distribution functions* (PDFs), which describe the probability to find a parton of type  $a/b$  with a fraction  $x_{a/b}$  of the proton momentum when evaluated at the *factorisation scale*  $\mu_F$ . The *partonic cross-section*  $\sigma_{ab \rightarrow n}$  describes the interaction between the partons  $a$  and  $b$ , resulting in a final state with the particles  $n$ . As in the case of the PDFs, this depends on the momentum fractions and the factorisation scale but also on the *renormalisation scale*  $\mu_R$ .

The partonic cross-section can be expanded in a power series in the strong coupling strength  $\alpha_s$  as

$$\sigma = \sum_{n=1}^{\infty} \alpha_s^n \sigma_n \quad (2.8)$$

using perturbation theory of QCD. Higher orders in  $\alpha_s$  result in *real emissions* with additional particles in the final state, and *virtual contributions*, also called *loops*. The various  $\sigma_n$  can be calculated at the respective, fixed order with the *matrix element* that describes the process.

The collinear radiation of additional partons results in infrared (IR) divergences, which can be solved by *dimensional regularisation*. By this, the unphysical parameter  $\mu_F$ , the factorisation scale, is introduced. The probability for the radiation of a parton of type  $i$  from a parton of type  $j$  can be described by universal *splitting functions*  $P_{i \leftarrow j}$ . Since quarks and gluons can split into each other, the calculation of the probability  $f_i$  to find a parton of type  $i$  depends on the probability  $f_j$  to find a parton of type  $j$  and the splitting function  $P_{i \leftarrow j}$ , which results in a set of coupled differential equations named *DGLAP* equations [191–193] after Dokshitzer–Gribov–Lipatov–Altarelli–Parisi. The DGLAP equations depend on the momentum

fraction  $x$  and the factorisation scale  $\mu_F$  and describe the evolution of the PDFs in Equation (2.7) between different scales. The dependence on the momentum fraction has to be derived from measurements. The factorisation scale  $\mu_F$  effectively defines the energy scale that separates the perturbative and the non-perturbative parts of the calculation.

The integration of particle momenta in loops on the other hand results in ultraviolet (UV) divergences. These can also be solved by dimensional regularisation, and again, an unphysical parameter  $\mu_R$ , the renormalisation scale, is introduced. This parameter can be absorbed into a redefinition of the strong coupling strength  $\alpha_s$ , which becomes a function of  $\mu_R$ . This behaviour is called *running*. To describe the evolution of  $\alpha_s$  between different scales, the *renormalisation group equation* (RGE) is used.

Therefore, both types of divergences can be solved but not without the introduction of the unphysical parameters  $\mu_R$  and  $\mu_F$ . Cross-sections depend on these parameters because the perturbation series in Equation (2.8) is truncated when calculations are performed. For  $n \rightarrow \infty$ , the dependence vanishes.

Usually, both parameters are set to the scale of the hard scattering:  $\mu_R = \mu_F = Q$ . Since this choice is arbitrary, both scales are varied to obtain an estimate of missing higher-order contributions.

### 2.3.2 Parton showers

The splitting functions are also used to describe the final-state radiation of collinear- or soft partons. The successive emission of partons results in *parton showers*. Starting from the hard-scattering scale  $Q$ , the scale and the momentum fraction  $x$  decrease in each emission until a cutoff scale  $Q_0$  is reached and the hadronisation begins. To describe the evolution from scale  $Q$  to a lower scale  $q$ , the *Sudakov form factors* are used. These describe the probability that no emission happens between  $Q$  and  $q$ . Multiple emissions of collinear- and soft partons results in logarithmic terms that are effectively resummed to all orders by the parton-shower approach (in contrast to fixed-order matrix-element calculations).

The approach for ISR is slightly different since the initial parton originates from the proton, which is described by the PDFs. A backwards evolution is used, again going from the hard-scattering scale  $Q$  down to a cutoff scale  $Q_0$  while this time increasing the momentum fraction  $x$ . When the cutoff scale is reached, the backwards evolution stops and the description via PDFs sets in.

While parton-shower calculations provide a good description of regions with collinear and soft parton emissions, processes with energetic and widely separated partons are better described by matrix element calculations. Therefore, both approaches are combined in *matching-* or *merging* schemes. In matching schemes, a full next-to-leading-order (NLO) matrix-element calculation, including loop corrections, is combined with the parton shower. In merging schemes, leading-order (LO) matrix elements with an increasing number of emitted partons are used instead. In both approaches, a merging scale is defined to resolve any overlap in the phase space of the resulting jets. Jets above this scale are described by the matrix element, jets below by the parton shower.

### 2.3.3 Hadronisation

Due to colour confinement, quarks and gluons do not exist as free particles. Therefore, after the parton shower is finished, i.e. when  $Q$  reaches the IR cutoff scale  $Q_0$ , the hadronisation (also called fragmentation) begins. Hadronisation is the transformation of coloured partons to colourless hadrons. This is a universal process and is described by parametric models, which can be separated into two approaches: string fragmentation and cluster fragmentation.

The *Lund string model* [194] is the most prominent string fragmentation model and is used in the PYTHIA event generator [195]. In this model, the spatial separation of colour charges increases the potential energy between them. When the potential energy reaches a certain threshold, a new quark pair is created. This is repeated until the energy of the partons is low enough and colourless hadrons are formed. These hadrons are usually unstable and will decay into lighter, stable hadrons.

The SHERPA generator [196] uses a cluster fragmentation model [197, 198]. Here, gluons at the cutoff scale are split into quark pairs and colourless clusters are formed, which are interpreted as a superposition of hadron states. The clusters are then subsequently decayed into hadrons.

### 2.3.4 Underlying event

The *beam remnants*, i.e. the parts of the protons that are not involved in the hard interaction, undergo soft interactions, resulting in the *underlying event* (UE). This also includes *multiple parton interactions* (MPI) between the remaining partons in the beam remnants. Another effect which has an impact on the hadronisation is the colour connection between the partons of the hardscatter event and the beam remnants. Jets from the underlying event are usually soft and will not be reconstructed, but they contribute to the total energy of the event. As other soft interactions, the UE modelling is phenomenologically based.

### 2.3.5 Pile-up

Another soft QCD interaction is *pile-up* (PU), which consists of multiple proton–proton interactions. Additional interactions can happen in the same bunch-crossing as the hardscatter event, called *in-time pile-up*, or due to collisions in neighbouring bunch-crossings, called *out-of-time pile-up*. Both types are simulated as an inclusive sample of collision events and are overlayed with the simulation of the hardscatter event. The number of interactions per bunch-crossing  $\mu$  depends on the explicit beam conditions. Therefore, the simulated distribution of  $\mu$  is later reweighted to the distribution in data.

### 2.3.6 Detector simulation

The simulation of the interactions between the generated final-state particles and the detector materials is the last step in the simulation chain. For this, GEANT4 [199] is used. GEANT4 incorporates a detailed description of the complete ATLAS detector system, including the magnetic field configuration, expected noise levels, passive material such as cables, and known defects in detector components. The output format of this detector simulation is the same as when actual data is collected by

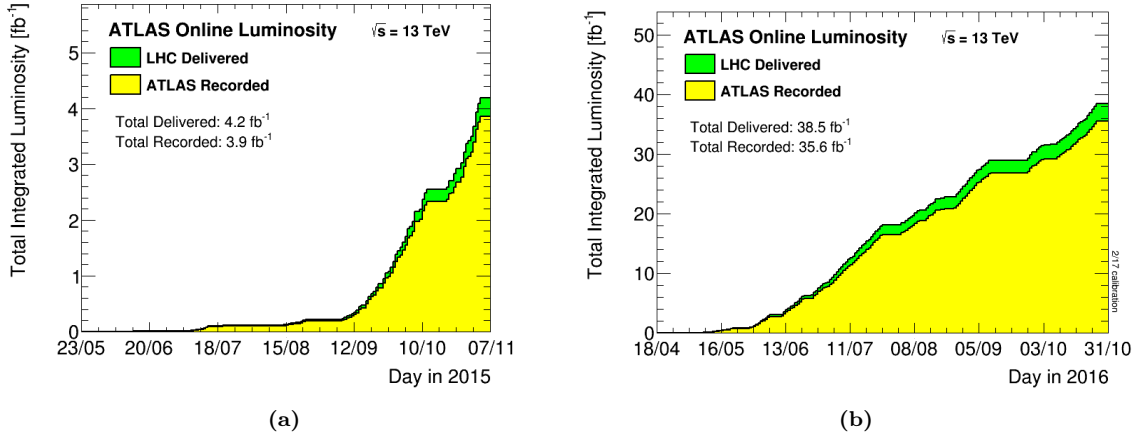


the real detector. Therefore, the same trigger-, identification-, and reconstruction software is used for the simulated events.

## 2.4 Dataset

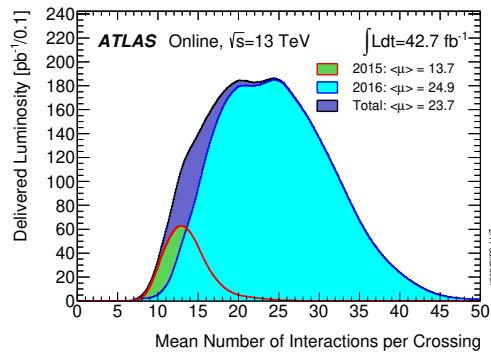
The data used in this analysis was collected in 2015 and 2016 at a center-of-mass energy of  $\sqrt{s} = 13$  TeV and with a bunch spacing of 25 ns. The total integrated luminosity in both years is  $36.1 \text{ fb}^{-1}$  of which  $3.2 \text{ fb}^{-1}$  were recorded in 2015 and  $32.9 \text{ fb}^{-1}$  in 2016. The cumulative delivered and recorded luminosity for both years is shown in Figure 2.10. The peak instantaneous luminosities are  $\mathcal{L} = 5 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$  in 2015 and  $\mathcal{L} = 1.4 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$  in 2016 [174].

Only data during which collection all detector subsystems and the magnetic system were fully operational is taken into account. Runs that satisfy all the quality criteria are stored in *Good Runs Lists* (GRL) and only these runs are used in analyses.



**Figure 2.10:** Cumulative delivered (green) and recorded (yellow) luminosity in 2015 (a) and 2016 (b). Taken from Ref. [174].

The mean number of interactions per bunch-crossing is  $\langle\mu\rangle = 13.7$  in 2015 and  $\langle\mu\rangle = 24.9$  in 2016, with peak values of 36.4 and 51.8, respectively. The distribution of  $\mu$  is shown in Figure 2.11. For this,  $\mu$  is obtained from Equation (2.4) using  $\sigma_{\text{inel.}} = 80 \text{ mb}$ .



**Figure 2.11:** Mean number of interactions per bunch-crossing in 2015 (green), 2016 (cyan), and combined (blue). Taken from Ref. [174].



# Chapter 3

## Object reconstruction and particle identification

This chapter describes the reconstruction, calibration, and identification of the objects that are used in this analysis: electrons, muons, jets, and hadronically decaying  $\tau$ -leptons. The basic components for the reconstruction are tracks of charged particles and clusters of energy deposits in the calorimeters, which are described in Section 3.1 and Section 3.2, respectively. The reconstruction, calibration, and identification of electrons, muons, jets, and hadronically decaying  $\tau$ -leptons is then described in Sections 3.3 to 3.6. For electrons and muons, the definition of the objects at trigger level and the definition of the isolation variables is described. The calculation of the missing transverse energy  $E_T^{\text{miss}}$  is explained in Section 3.7.

The various reconstruction-, identification-, trigger-, and isolation efficiencies are presented. These are usually different between data and simulation. Therefore, *scale factors*, defined as the ratio between the efficiencies in data over simulation, are applied to simulated events to correct for these differences.

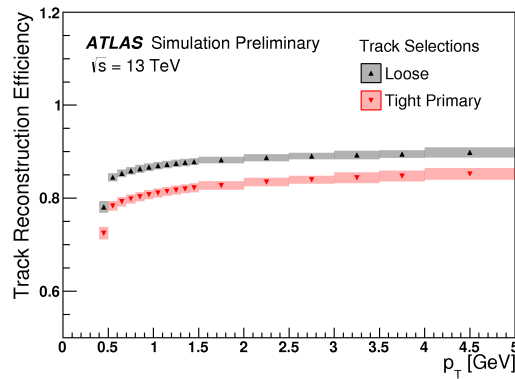
Efficiencies are typically measured in *tag-and-probe* analyses. For this, processes with characteristic signatures are used to obtain events free of background contamination. An example is the decay  $Z \rightarrow ee$  where the invariant mass  $m_{ee}$  is required to be close to the  $Z$ -boson mass. Strict selection criteria are applied on one electron, the *tag* electron, while the other electron, *probe* electron, is used for the efficiency measurement. The efficiency is then obtained as the ratio between the number of events after and before the application of the criterion of interest on the *probe* electron.

### 3.1 Tracks

The measurements of the inner detector, i.e. of the pixel detector, the SCT, and the TRT, are used for the reconstruction of tracks [200, 201]. In a first step, pixels and strips with hits that are on the same sensor are grouped into clusters. Track seeds are then formed from three clusters in different layers of the silicon detectors and a preliminary trajectory is constructed. Additional clusters that are compatible with this trajectory are used together with the seeds by a combinatorial Kalman filter [202] to build track candidates. Since multiple track candidates can emerge from

one set of seeds, an ambiguity solver [203] is used to reject candidates that fail certain quality measures. Example requirements are a transverse momentum  $p_T > 400$  MeV, a pseudorapidity of  $|\eta| < 2.5$ , and a minimum of seven clusters in the pixel detector and the SCT. The remaining track candidates are then extended into the TRT by a fit that tests for compatible hits in the TRT, i.e. the measured drift circles around the wires. The resulting tracks are the final output of this so-called *inside-out* chain. This approach is very efficient in finding tracks originating from hard-scatter particles or from the decays of short-lived particles. Tracks from decaying particles with a longer life time or from photon conversions may have an insufficient number of hits in the pixel detector and the SCT to fulfil the requirements of the *inside-out* chain. To recover these tracks, the *outside-in* chain is used. The *outside-in* chain constructs track segments with the hits in the TRT that were not used in the *inside-out* chain. These track segments are then extended back into the silicon detectors by adding compatible unused clusters.

The efficiency for the reconstruction of tracks is shown in Figure 3.1. The efficiency increases with the track  $p_T$  and reaches a plateau of approximately 90 % [204].



**Figure 3.1:** The track reconstruction efficiency evaluated with simulated events. The *Loose* track selection corresponds to the description in the text. Taken from Ref. [204].

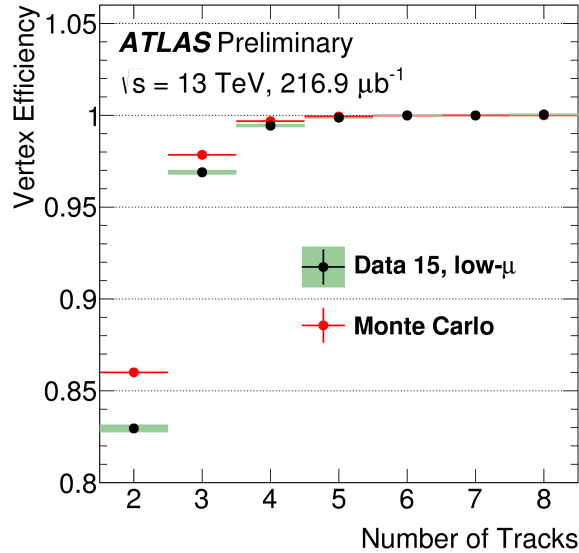
### 3.1.1 Primary vertices

The reconstructed tracks are used for the reconstruction of *primary vertices* [205, 206], i.e. candidates for the primary interaction point. Here, the tracks must fulfil tighter selection criteria to suppress fake tracks and tracks originating from secondary interactions. A seed for the first vertex is selected based on the position of the beam spot. The position of the seed and the parameters of the tracks are used in an iterative fit to determine the best position of the vertex. After each step, the input tracks are weighted based on the compatibility with the current vertex position and the position is recalculated with the weighted tracks. After the fit is finished, tracks that are incompatible with the resulting vertex position are removed from the vertex and can be used as input for further vertex reconstructions. The starting position for the next fit is then calculated from the remaining tracks and this procedure is repeated until all tracks are used or no further vertex can be reconstructed. A vertex is then finally considered as valid candidate if it has at least two associated tracks. The vertex with the highest sum of squared transverse momenta of the associated tracks  $\sum p_{T,\text{track}}^2$  is considered as the vertex of the hard scattering; the other vertices

are considered as pile-up vertices.

The vertex reconstruction efficiency is greater than 80 % and increases with the number of associated tracks [206], which is shown in Figure 3.2.

*Secondary vertices* originating from the decay of hadrons are discussed in Section 3.5.3.



**Figure 3.2:** The vertex reconstruction efficiency in data (green) and simulation (red). Taken from Ref. [206].

## 3.2 Calorimeter clusters

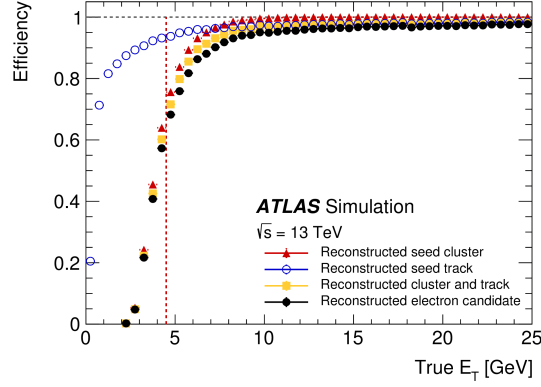
Energy deposits in the cells of the electromagnetic and hadronic calorimeters are used for the reconstruction of jets and electrons. The cells are first grouped into clusters by using two different methods: the *sliding-window* algorithm for electrons and photons, and *topological clustering* for jets and hadronically decaying  $\tau$ -leptons.

For the sliding-window algorithm [207, 208], *towers* of the size  $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$  are built by summing the energy deposits in all layers of the EM calorimeter. A window with the size of  $3 \times 5$  towers and a minimum transverse energy of  $E_T > 2.5$  GeV is defined and moved across all elements of the tower grid to search for local maxima of the energy deposits. These local maxima are called *seed clusters* and are used for the reconstruction of electrons, discussed in Section 3.3, and photons.

Figure 3.3 shows the efficiency for the reconstruction of the seed clusters, evaluated with simulation. The efficiency is between 65 % and 99 % for energies above 4.5 GeV [208].

Topological clustering [207, 209] uses both the EM and the hadronic calorimeters. The important value for this algorithm is the signal significance of a cell, defined as the ratio between the measured energy and the average expected noise in the cell:  $\varsigma_{\text{cell}} = \frac{E_{\text{cell}}}{\sigma_{\text{noise, cell}}}$ , where  $\sigma_{\text{noise, cell}}$  is composed of electronic noise and energy deposited by pile-up. The electromagnetic energy scale is used for both the measured energy and the noise term.

The clustering begins by searching for seed cells with a high absolute signal significance of  $|\varsigma_{\text{cell}}| > 4$ . Each seed cell is considered as a *proto-cluster* and all its



**Figure 3.3:** The efficiencies of the various electron reconstruction steps as a function of the truth transverse energy, evaluated with simulation: the seed cluster reconstruction (red), the track reconstruction before (blue) and after (yellow) the GSF fit, and the full electron reconstruction (black). Taken from Ref. [208].

neighbouring cells are added to this proto-cluster. If a neighbouring cell has a signal significance of  $|\varsigma_{\text{cell}}| > 2$ , all its neighbours are also added to the proto-cluster. This is repeated until no newly added cell satisfies  $|\varsigma_{\text{cell}}| > 2$ . Proto-clusters are merged if a neighbouring cell is also a seed cell or if a neighbouring cell with  $|\varsigma_{\text{cell}}| > 2$  is shared by two proto-clusters.

During the formation, spatial signal structures inside a cluster are not taken into account. Therefore, the energy deposits of multiple particles could be contained in a single cluster. To split the clusters accordingly, local signal maxima are defined by a cell energy of  $E_{\text{cell}} > 500$  MeV with at least four neighbouring cells of which none contains a larger signal. The local maxima serve as seed cells for a new clustering, this time without any signal significance thresholds and without merging proto-clusters. Instead, neighbouring cells can be shared by two proto-clusters. For this, a shared cell is added to the two proto-clusters with weights  $w_1 = \frac{E_1}{E_1 + r E_2}$  and  $w_2 = 1 - w_1$ , where  $E_{1,2}$  are the energies of the two proto-clusters and  $r = \exp(d_1 - d_2)$ .  $d_{1,2}$  are the distances from the cell to the centres of the proto-clusters.

After the splitting is finished, all proto-clusters are considered as *topo-clusters*. Since only the absolute value of the signal significance is used for the thresholds, topo-clusters can have a total energy below zero due to fluctuations of pile-up and electronic noise. Only topo-clusters with  $E_{\text{clus}} > 0$  are used for the reconstruction of objects.

To correct for energy losses due to e.g. the non-compensating calorimeters and dead material, a calibration scheme called *local hadronic cell weighting* (LCW) [210] is applied to each topo-cluster. For each cell in a cluster, electromagnetic and hadronic calibrations are applied, where the calibration weights are scaled by the probability, based on shower shape variables, of the corresponding cluster to be generated by an electromagnetic- or a hadronic shower.

## 3.3 Electrons

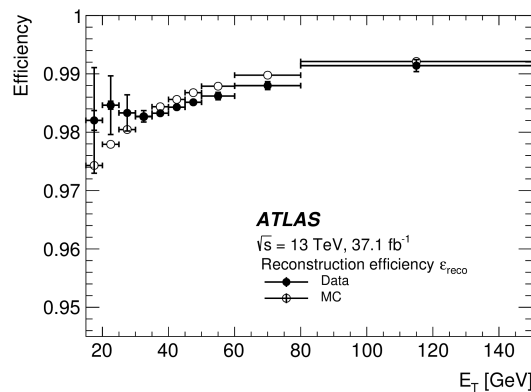
### 3.3.1 Reconstruction

For the electron reconstruction [208], tracks are loosely matched to the seed clusters in the EM calorimeter discussed in Section 3.2. To account for the energy loss of electrons due to bremsstrahlung in the detector material, the matched tracks are refitted with a Gaussian-sum filter (GSF) [211]. If multiple refitted tracks are associated to the same seed cluster, a primary track is selected by taking into account several quality criteria, e.g. the distance in  $\phi$  and  $\eta$  between the track and the cluster, or the number of hits in the silicon detectors. The efficiencies for the track reconstruction both before and after the GSF step are shown in Figure 3.3. For energies larger than 10 GeV, efficiencies above 98 % are obtained [208].

Reconstructed clusters are then built around the seed clusters by increasing the window sizes to  $3 \times 7$  and  $5 \times 5$  in the barrel region and in the endcap region, respectively. The energy of the reconstructed clusters needs to be calibrated to correspond to the original energy of the electron. The calibration procedure [212] takes into account the energy loss due to material in front of the calorimeter and due to energy not contained in the clusters, the differences in the energy response of the different calorimeter layers, and local non-uniformities in the calorimeter due to e.g. geometric effects at the boundaries between modules.

The four-momentum of the final electron candidate is then constructed by taking the energy from the calibrated cluster and the  $\eta$  and  $\phi$  directions from the track.

The efficiency for the complete electron reconstruction is shown in Figure 3.3. Above  $E_T > 15$  GeV, efficiencies larger than 97 % are obtained [208]. A comparison of the reconstruction efficiencies in data and simulation, using a  $Z \rightarrow ee$  tag-and-probe analysis, is shown in Figure 3.4.

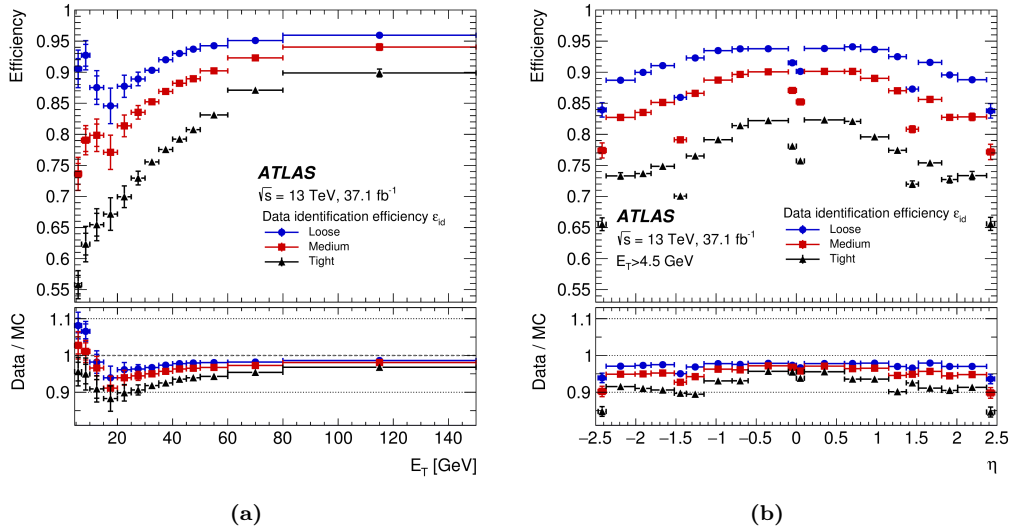


**Figure 3.4:** The electron reconstruction efficiencies in data (closed circles) and simulation (open circles), measured in  $Z \rightarrow ee$  events. Statistical and total uncertainties are shown. Taken from Ref. [208].

### 3.3.2 Identification

To reject jets misidentified as electrons and non-prompt electrons from photon conversions or from the decay of  $b$ - and  $c$ -hadrons, prompt electrons are identified using a likelihood-based method [208]. Measurements from the tracking and the calorimeter

system serve as input for the likelihood. For each input quantity, probability density functions (pdfs) are constructed using simulation for the background and the signal. The products of the pdfs for background and signal define the respective likelihoods  $L_B$  and  $L_S$  from which the discriminant  $d_L = \frac{L_S}{L_S + L_B}$  is built. By requiring the electron candidates to return values greater than a chosen value of the log-transformed  $d_L$ ,  $d'_L = -\frac{1}{15} \ln(d_L^{-1} - 1)$ , *loose*, *medium*, and *tight* working points with different efficiencies are defined. The efficiencies in data, obtained from  $Z \rightarrow ee$  and  $J/\psi \rightarrow ee$  tag-and-probe analyses, and the data-to-simulation efficiency ratios are shown in Figure 3.5a as a function of the transverse energy of the electron. The efficiencies for  $E_T > 20$  GeV are in the range from 70 % to 90 %, 80 % to 94 % and 85 % to 96 % for the *tight*, *medium* and *loose* working points, respectively, increasing with  $E_T$ . Compared to the *loose* working point, the efficiencies are lower for the *medium* and *tight* working points, but they provide a better background rejection [208]. A typical rejection rate for jets at the *medium* working point used in this analysis is approximately 1500 [213].



**Figure 3.5:** The electron identification efficiencies in data (top panel) and the ratio between data and simulation (bottom panel) for the *loose* (blue), *medium* (red), and *tight* (black) working points as a function of  $E_T$  (a) and  $\eta$  (b). Statistical and total uncertainties are shown. Taken from Ref. [208].

The longitudinal track impact-parameter  $d_0$  and its significance  $|d_0/\sigma(d_0)|$  are used as inputs for the likelihood function, where  $d_0$  is the closest distance between a given track and the hard-scatter vertex in the  $r$ - $\phi$  plane. Non-prompt electrons from  $\tau$ -lepton decays tend to have larger track parameters than electrons from e.g.  $Z \rightarrow ee$  decays. Since the scale factors are derived using the latter process, an observed mismodelling in the simulation of the  $H \rightarrow \tau\tau$ - and  $Z \rightarrow \tau\tau$  processes is not covered by these scale factors. Therefore, a likelihood without the two track parameter variables is used to derive correct scale factors as a function of the electron  $p_T$ . These scale factors are applied by default. For a conservative estimate of the systematic uncertainty, the scale factors are applied a second time.



### 3.3.3 Isolation

To further suppress non-prompt electrons and misidentified jets, the electron candidate is required to be isolated, i.e. a limit on the amount of detector activity around the electron candidate is inflicted. Calorimeter- and track-based isolation criteria are defined [208].

For the calorimeter-based isolation, topological clustering as introduced in Section 3.2 is performed. The seed cells are required to have  $|\zeta_{\text{cell}}| > 4$  and all neighbouring cells with  $|\zeta_{\text{cell}}| > 2$  are added to the cluster. This is iteratively repeated until no further cells satisfy the requirement and a final shell of cells around the cluster is added. The energies of all clusters with a positive energy and their barycentre inside a cone of size  $\Delta R$  around the cluster position of the electron are summed. Since this sum also contains the energy of the electron candidate, the energy of the cells in the  $\Delta\eta \times \Delta\phi = 0.125 \times 0.175$  rectangle around the position of the electron is subtracted. Additional energy deposited by the electron outside this rectangle is estimated by simulation and also subtracted. Finally, the contribution from pile-up is estimated from the ambient energy density [214] and subtracted.

For the track-based isolation, the transverse momenta of the tracks inside a cone of size  $\Delta R$  around the electron track are summed, excluding the contribution from the electron track and further contributions due to bremsstrahlung. The cone size for the track-based isolation is not fixed but decreases with increasing transverse momentum of the electron:

$$\Delta R = \min \left( \frac{10 \text{ GeV}}{E_{\text{T}} [\text{GeV}]}, R_{\text{max}} \right) \quad (3.1)$$

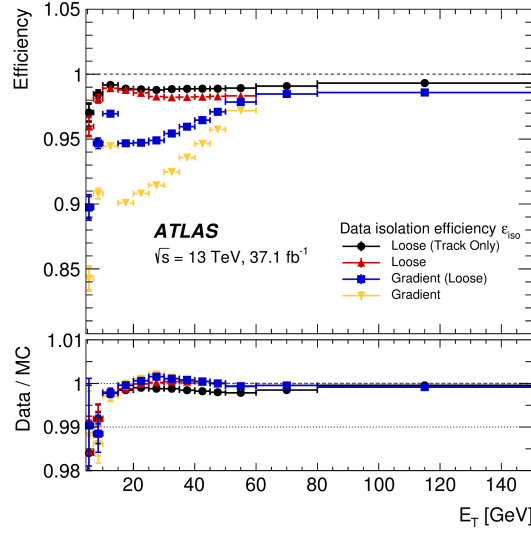
where  $R_{\text{max}}$  is the maximum cone size. This is done to take into account decays of particles with a high  $p_{\text{T}}$  where other objects can be close to the electron.

The efficiencies of different isolation working points in data, measured in a  $Z \rightarrow ee$  tag-and-probe analysis, and the ratio between the efficiencies in simulation, are shown in Figure 3.6 as a function of  $E_{\text{T}}$ . The isolation efficiency of the *gradient* working point used in this analysis is in the range from 90 % to 99 % for  $E_{\text{T}} > 20 \text{ GeV}$  [208]. The *relative* isolation variables, defined as the ratio between the isolation variables described above to the  $p_{\text{T}}$  of the electron, are used for the isolation requirements. For the *gradient* isolation, cuts are applied on the relative isolation variables to reach a certain efficiency, which depends on the  $p_{\text{T}}$  of the electron. The (maximum) cone size used for both the calorimeter- and track-based isolation variables is  $\Delta R = 0.2$  and  $R_{\text{max}} = 0.2$ , respectively.

### 3.3.4 Trigger

The L1 part of the electron triggers [215] builds a region of interest (RoI) of  $4 \times 4$  towers with a granularity of  $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ . The sum of the energy of at least one of the four possible pairs of  $2 \times 1$  and  $1 \times 2$  towers in the central  $2 \times 2$  region has to be larger than a given threshold, which can be  $\eta$ -dependent. Hadronic activity can be rejected by setting a threshold to the sum of energy contained in the hadronic towers matched to the central  $2 \times 2$  towers. Also, an isolation criteria can be defined by limiting the sum of energy contained in the twelve towers around the central region.

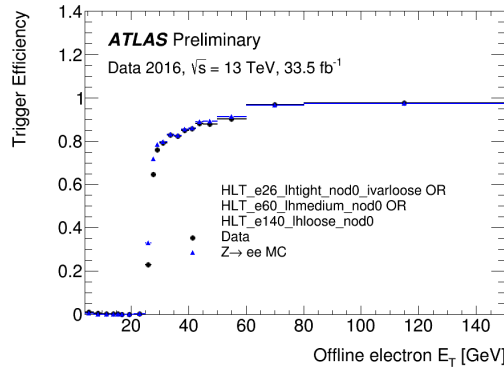
As a first step at the HLT, a fast calorimeter algorithm reconstructs clusters from



**Figure 3.6:** The electron isolation efficiencies in data (top panel) and the ratio between data and simulation (bottom panel) for different isolation working points as a function of  $E_T$ . The *gradient* working point used in this analysis is shown in yellow. Statistical and total uncertainties are shown. Taken from Ref. [208].

calorimeter cells in the RoI. The clusters need to be matched to tracks built in a fast tracking stage. The cluster energy and cluster shape parameters are used to identify the electrons and to reject backgrounds. After that, offline-like algorithms are used in a precision step. The energy of the clusters is calibrated and precision tracks are required to match the clusters. For the identification, a likelihood-based method similar to the one described in Section 3.3.2 is used. Additionally, a track-based isolation can be required at the HLT.

The combined efficiency for the electron triggers used for data-taking in 2016 for this analysis is shown in Figure 3.7 as a function of the transverse energy of the reconstructed electron, where the lowest threshold of the triggers is  $E_T = 26$  GeV. A  $Z \rightarrow ee$  tag-and-probe analysis is used to measure the efficiencies. The efficiency is steeply rising to approximately 80 % after the lowest  $E_T$  threshold of the triggers is passed and then reaches a plateau at approximately 97 % [216].



**Figure 3.7:** The combined electron trigger efficiency used for data-taking in 2016 for this analysis in data (black) and simulation (blue) as a function of the transverse energy of the reconstructed electron. The lowest threshold is  $E_T = 26$  GeV. Statistical uncertainties are shown. Taken from Ref. [216].

## 3.4 Muons

### 3.4.1 Reconstruction

The information from the ID and the MS, and to some extent from the calorimeters, is used for the reconstruction of muons [217]. Track segments are built from hits in each of the muon chambers. The segments from the different detector layers are then combined by a fit to form muon track candidates, where the selection criteria for the segments are based on the hit multiplicity and the quality of the fit. At least two track segments are needed to build the tracks, with exception of the barrel-endcap transition region, where one segment with a high quality is sufficient. When the same segment is shared by multiple tracks, an overlap removal algorithm is used to assign the segment to the best fitting track or to limit the number of tracks to two. A global  $\chi^2$  fit is then performed to build a track candidate of the hits. Additional hits consistent with the resulting trajectory can be added and a new fit is performed.

Depending on the detector region and on the available hits in the MS, additional information of other detectors is used, resulting in four types of muons:

1. Combined muons (CB) are built from the hits in the MS and the ID. The reconstructed MS tracks are extrapolated to the ID and matched to ID tracks. The hits in both detectors are then used in a global refit by taking into account the energy loss in the calorimeters. A complementary approach extrapolates the ID tracks outward to the MS.
2. Segment-tagged muons (ST) are used when only one layer of the MS chambers contains hits due to a low transverse momentum of the muon or due to a low acceptance in the region. For ST muons, an ID track has to be matched to at least one segment in the MDT or CSC chambers.
3. Calorimeter-tagged muons (CT) are used in the region  $|\eta| < 0.1$  where cables and services are located and the MS is not fully instrumented. A track in the ID needs to be matched with an energy deposit in the calorimeters compatible with a minimum-ionizing particle.
4. Extrapolated muons (ME) are used for the reconstruction in the region not covered by the ID,  $2.5 < |\eta| < 2.7$ . Hits in at least two layers of the MS chambers are required in the barrel region and hits in three layers in the forward region. The extrapolated track has to be compatible with the interaction point while taking into account an estimated energy loss in the calorimeters.

The first three types can share the same ID track. In that case, the order in choosing the type is CB, ST, CT. To resolve a possible overlap with ME muons in the MS, the hits of the tracks are analysed and the one with better fit quality and a larger number of hits is selected.

Due to the selection criteria defined in Sections 4.4 and 4.5, only CB muons are used in this analysis.

The  $p_T$  of the muons is calibrated to take into account several effects on the momentum scale and resolution [217]. The calibration is done separately for the transverse momenta of the ID- and MS tracks. The momentum scale is affected by an inaccurate description of the magnetic field and by an inaccurate simulation of the energy loss in the calorimeters and due to other materials. The momentum resolution is broadened by taking into account multiple scattering, inhomogeneities of the magnetic field, the spatial resolution of the hit measurements, and the misalignment of the MS. For the determination of the alignment parameter, special runs without the toroidal magnetic fields are used. All other calibration parameters are determined from data by performing maximum-likelihood fits in the invariant mass of  $J/\psi \rightarrow \mu\mu$  and  $Z \rightarrow \mu\mu$  candidates for which the templates are derived from simulation. Only CB type muons are used for this and the parameters are determined binned in  $\eta$  and  $\phi$  separately for the ID and the MS.

### 3.4.2 Identification

Four muon identification selections are defined to suppress backgrounds from pion- and kaon decays, and to ensure a good measurement of the muon momentum [217]. In all four selections, a minimum number of hits in the ID is required.

All muon types are considered for *loose* muons. CT- and ST muons are restricted to the region  $|\eta| < 0.1$ . CB muons are required to have at least three hits in at least two MDT layers. This requirement is softer in the region  $|\eta| < 0.1$ , where only hits in one layer are needed. The momentum measurement of muons that originate from decays of hadrons is often not compatible between the ID and the MS. Therefore, the  $q/p$  *significance* is required to be less than seven for CB muons. This quantity is defined as the absolute value of the difference between the ratios between the charge- and momentum measurements in the ID and MS, divided by the sum of squares of their uncertainties. ME muons are restricted to the region  $2.5 < |\eta| < 2.7$  and need to have hits in at least three MDT/CSC layers.

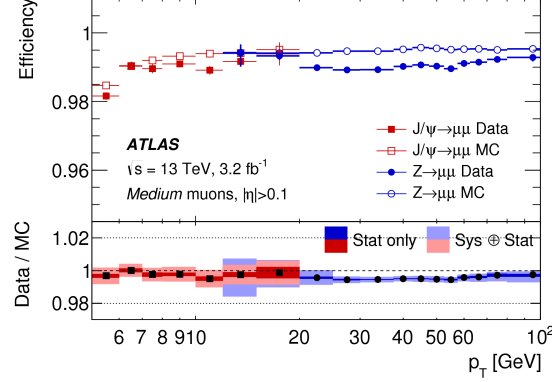
For *medium* muons, only CB- and ME muons that fulfil the *loose* requirements are considered.

*Tight* muons are restricted to CB muons that fulfil the *medium* requirements. They need to have hits in at least two layers of the MS and the  $\chi^2$  of the combined track fit has to be smaller than eight. For a better background rejection at low transverse momenta,  $p_T$ -dependent cuts are applied to the  $q/p$  significance and to  $\rho'$ , the absolute value of the difference between the  $p_T$  measurements in the ID and the MS, divided by the  $p_T$  of the combined track.

By defining the identification selections this way, all *tight* muons are included in the *medium* selection, and both selections are included in the *loose* selection.

Additionally, a *high- $p_T$*  selection is defined by requiring *medium* CB muons with hits in at least three layers in the MS. This increases the momentum resolution for muons with  $p_T > 100$  GeV.

The combined efficiency of the reconstruction and identification for *medium* muons used in this analysis for data and simulation and their ratio is shown in Figure 3.8 as a function of  $p_T$ . The efficiencies in data are obtained with  $J/\Psi \rightarrow \mu\mu$  and  $Z \rightarrow \mu\mu$  tag-and-probe analyses for low and high values of muon  $p_T$ , respectively. The efficiency is above 98 % over the whole  $p_T$  range. [217].



**Figure 3.8:** Combined reconstruction- and identification efficiency (top panel) for *medium* muons for data (closed points) and simulation (open points) and their ratio (bottom panel) as a function of muon  $p_T$ . Statistical and systematic uncertainties are shown. Taken from Ref. [217].

### 3.4.3 Isolation

The same track- and calorimeter-based isolation variables as in the case for electrons are defined for muons to suppress background contributions [217].

For the track-based isolation, the transverse momenta of the tracks inside a cone of size  $\Delta R$  around the muon track are summed, excluding the contribution from the muon track. The cone size is not fixed but decreases with increasing transverse momentum of the muon to take into account decays of particles with a high  $p_T$  where other objects can be close to the muon:

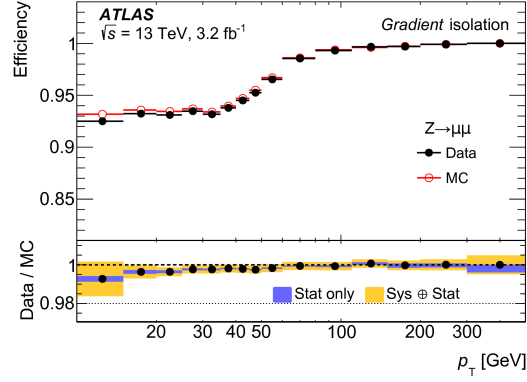
$$\Delta R = \min \left( \frac{10 \text{ GeV}}{p_T [\text{GeV}]}, R_{\text{max}} \right) \quad (3.2)$$

where  $R_{\text{max}}$  is the maximum cone size.

The calorimeter-based isolation is defined as the sum of the energies of all topological clusters, described in Section 3.2, with a positive energy and their barycentre inside a cone of size  $\Delta R$  around the position of the muon. The energy deposits of the muon are subtracted, as is the contribution from pile-up, estimated from the ambient energy density [214].

The efficiency of the *gradient* isolation used in this analysis in data and simulation, measured in a  $Z \rightarrow \mu\mu$  tag-and-probe analysis, and their ratio is shown for *medium* muons in Figure 3.9 as a function of  $p_T$ . The efficiency is approximately 93 % for  $p_T < 40$  GeV and then increases to values above 99 % for  $p_T > 80$  GeV [217].

The *relative* isolation variables, defined as the ratio between the isolation variables described above and the  $p_T$  of the muon, are used for the isolation requirements. For the *gradient* isolation, cuts are applied on the relative isolation variables to reach a certain efficiency, which depends on the  $p_T$  of the muon. The cone size used for the calorimeter-based isolation variable is  $\Delta R = 0.2$ , while the maximum cone size for the track-based isolation variable is  $R_{\text{max}} = 0.3$ .

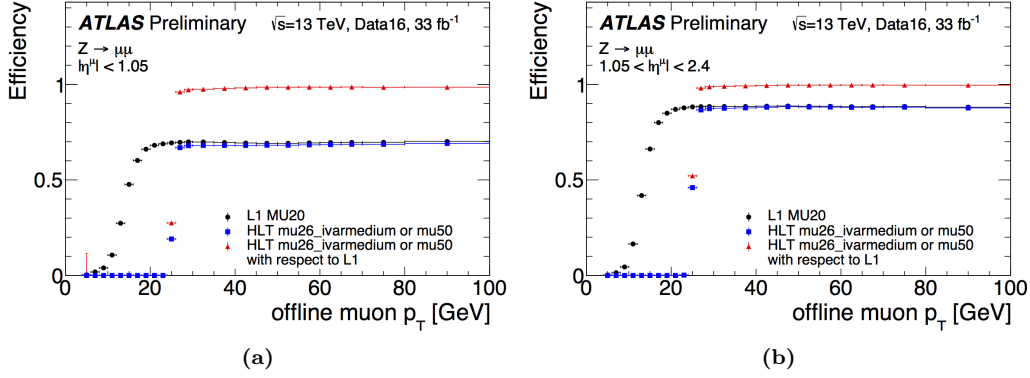


**Figure 3.9:** The muon isolation efficiency for the *gradient* working point (top panel) in data (black) and simulation (red) and their ratio (bottom panel) for *medium* muons as a function of  $p_T$ . Statistical and total uncertainties are shown. Taken from Ref. [217].

### 3.4.4 Trigger

The muon trigger [187] requires at L1 coincident hits in the layers of the RPCs or the TGCs. The transverse momentum is estimated by comparing the hit pattern with the expected track of a muon with infinite  $p_T$ . A RoI around the hit pattern is the starting point for the HLT step. In a fast reconstruction step, the information from the MDTs in the RoI is used to build a MS-only muon candidate. The transverse momentum is assigned according to predefined look-up tables. The MS-only track is then extrapolated to the interaction point, combined with matching tracks in the ID, and the RoI is redefined. In the precision reconstruction step, all subdetectors of the MS are used to reconstruct tracks in the new RoI. These tracks are again extrapolated to the ID and combined tracks are built. If no matching ID track is found, an inside-out approach is tried by extrapolating ID tracks to the MS. After the combined muon candidate is reconstructed, a track-based isolation criteria can be applied in addition.

The combined efficiencies for the muon triggers used for data-taking in 2016 for this analysis are shown in Figure 3.10a and Figure 3.10b for the barrel region ( $|\eta| < 1.05$ ) and for the endcap region ( $1.05 < |\eta| < 2.4$ ), respectively, as a function of the transverse momentum of the reconstructed muon. A  $Z \rightarrow \mu\mu$  tag-and-probe analysis is used to measure the efficiencies. The efficiencies are very steeply rising to plateaus of approximately 70 % and 88 % for the barrel- and endcap regions, respectively, after the lowest  $p_T$  threshold of the triggers is passed. The reduced efficiency in the barrel region is caused by the toroid coils and the two feet sectors [218].



**Figure 3.10:** The combined muon trigger efficiencies used for data-taking in 2016 for this analysis in the barrel region (a) and in the endcap region (b) as a function of the muon  $p_T$ . Shown are the efficiencies for the L1 trigger (black), the HLT triggers (blue), and their ratio (red). Statistical uncertainties are shown. Taken from Ref. [218].

## 3.5 Jets

### 3.5.1 Reconstruction

Almost immediately after the production of quarks and gluons, their fragmentation and hadronisation is taking place, resulting in a collimated spray of colour-neutral hadrons called *jets*. The main component for the reconstruction of jets is the energy deposited in the electromagnetic and hadronic calorimeters. For this, the topoclusters discussed in Section 3.2 are used as input for the reconstruction algorithm and are referred to as *particles* for the rest of this section.

Jets for this analysis are reconstructed using the anti- $k_t$  algorithm [219] implemented in FASTJET [220]. The distance measures  $d_{ij}$  and  $d_{iB}$  between two particles and between a particle and the beamline, respectively, are defined as

$$d_{ij} = \min(p_{T,i}^{-2}, p_{T,j}^{-2}) \frac{\Delta R_{ij}^2}{R^2} \quad (3.3)$$

$$d_{iB} = p_{T,i}^{-2}$$

where  $p_{T,i}$ ,  $p_{T,j}$  and  $\Delta R_{ij}$  are the transverse momenta and the geometrical distance of the particles, respectively. The radius parameter  $R$  controls the size of the jets and is set to 0.4.

The distances  $d_{ij}$  and  $d_{iB}$  are computed for all particles and the minimum is determined. If one of the  $d_{iB}$  is the minimum, particle  $i$  is considered as a jet and removed from the input particles; if one of the  $d_{ij}$  is the minimum, the particles  $i$  and  $j$  are merged to a new particle and added to the input particles. This procedure is repeated until no input particles are left.

### 3.5.2 Jet energy scale calibration

A calibration of the jets is applied to restore the jet energy scale (JES) to the energy of a *truth* jet built from truth particles after the hadronisation [221]. The calibration is carried out in multiple stages: in a first step, the jet four-momenta are recalculated to point to the hard-scatter vertex while keeping the energy fixed.

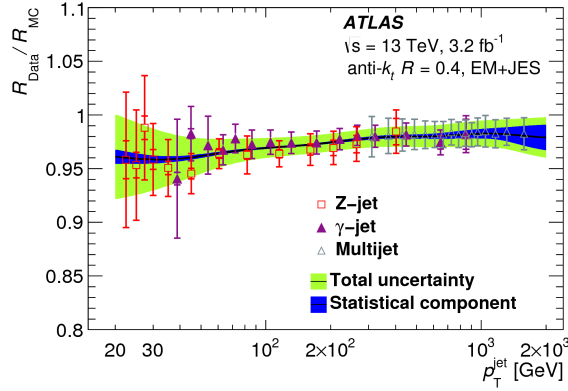
After that, two corrections are applied to subtract the contributions from pile-up

from the energy.

The third stage in the calibration corrects the reconstructed jet energy to the truth jet energy and accounts for biases in the reconstructed jet  $\eta$  due to transitions between different calorimeters or changes in the calorimeter granularity.

Differences between the fragmentation of gluons and quarks lead to differences between the measured- and the truth energy of jets depending on the flavour of the initiating particle. A correction is applied to reduce those dependencies. Additionally, the energy loss of jets that are not fully contained in the calorimeter is reduced.

Finally, a residual calibration is applied to data using in-situ measurements to account for differences in the jet energy response between data and simulation. The ratio between the responses in data and simulation is shown in Figure 3.11 for the individual measurements and for their combination. The applied calibration is approximately 4% for jets with low  $p_T$  and decreases to approximately 2% at 2 TeV [221].



**Figure 3.11:** Ratio of the jet energy response between data and simulation as a function of jet  $p_T$  for  $Z$ +jet- (red square),  $\gamma$ +jet- (purple triangle), and multijet (grey triangle) measurements. The black line shows the combination of these measurements. Total and statistical uncertainties are shown. Taken from Ref. [221].

### 3.5.3 $b$ -jets

It is possible to identify jets that contain  $b$ -hadrons, called  $b$ -jets. This identification procedure is referred to as  $b$ -tagging. By requiring the absence of  $b$ -tagged jets in an event, the contribution from top quark backgrounds is suppressed.

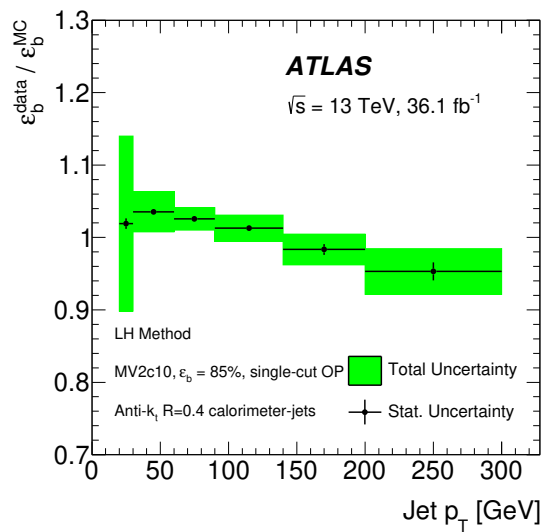
$b$ -hadrons have a relatively long lifetime of approximately 1.5 ps, which results in an average flight path length of 3 mm in the transverse direction for a  $b$ -hadron with  $p_T = 50$  GeV [222]. Therefore, the decay of the  $b$ -hadron results in at least one *secondary* vertex that is displaced from the hard-scatter vertex discussed in Section 3.1.1.

This special topology is exploited by *vertex-based*  $b$ -tagging algorithms by reconstructing the secondary vertex and using its properties, and by *impact-parameter based* algorithms by using the transversal and longitudinal track impact-parameters  $d_0$  and  $z_0$ , where  $d_0$  is the closest distance between a given track and the hard-scatter vertex in the  $r$ - $\phi$  plane and  $z_0$  is the difference between the  $z$ -coordinates of this point and the hard-scatter vertex. The impact parameters of tracks originating from a secondary vertex are in general larger than those of tracks from the hard-scatter vertex.



Vertex-based algorithms have a lower mistag rate than impact-parameter based algorithms but are limited by the efficiency of the secondary vertex reconstruction of approximately 70 % [222]. Therefore, the outputs of several algorithms are combined by using them as input variables, in addition to the transverse momentum and the pseudorapidity of the jet, for *MV2c20* [222, 223], a *Boosted Decision Trees* algorithm. The algorithms that provide the inputs are the impact-parameter based IP2D and IP3D [223], and the vertex-based SV1 [224] and JetFitter [225].

Depending on the cut placed on the final discriminant, working points with different efficiencies for correctly tagging a  $b$ -jet are defined. Figure 3.12 shows the scale factors measured in  $t\bar{t}$  events as a function of the jet  $p_T$  for the 85 % working point [226] used in this analysis. Rejection rates for  $c$ -jets,  $\tau$ -jets, and light-flavour jets are 3.3, 8, and 27, respectively.



**Figure 3.12:** The  $b$ -tagging scale factors for the 85 % working point of the MV2 algorithm. Statistical and total uncertainties are shown. Taken from Ref. [226].

## 3.6 Hadronically decaying $\tau$ -leptons

The  $\tau$ -lepton can decay leptonically and, due to its mass of 1.777 GeV [27], also hadronically. The dominating decay modes and their branching ratios are listed in Table 3.1.

Approximately 35 % of the  $\tau$ -leptons decay leptonically in an electron or a muon, with two neutrinos. The decay into a hadron  $h$  and one neutrino has a BR of approximately 65 %. Here,  $h$  stands for a pion  $\pi$  or a kaon  $K$ , where the decay into pions is dominating the branching ratios. Exactly one charged particle is present in approximately 77 % of the hadronic decays, whereas exactly three charged particles are present in approximately 23 % of these decays.

### 3.6.1 Reconstruction

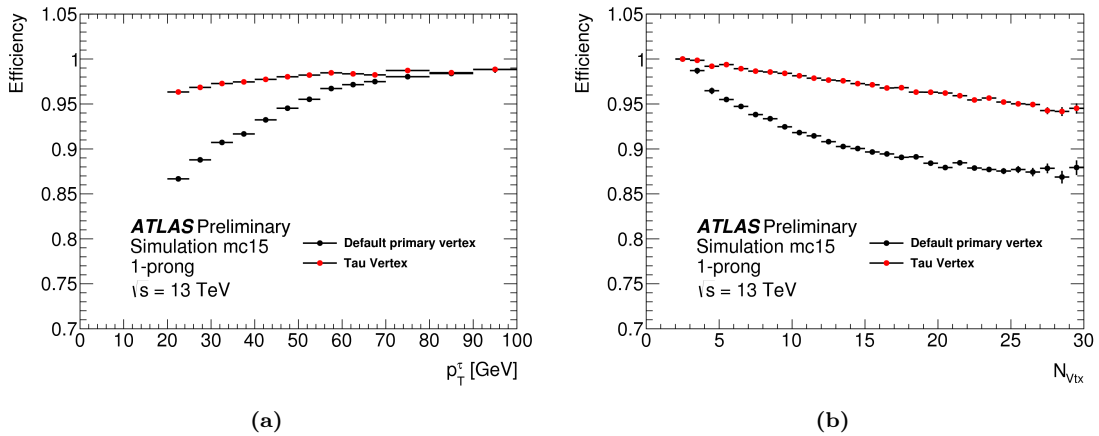
The reconstruction of a hadronically decaying  $\tau$ -leptons [227] is seeded by reconstructed jets. Seed jets are required to have a transverse momentum  $p_T > 10$  GeV

| Decay mode                     | BR [%]           |
|--------------------------------|------------------|
| leptonic                       | $35.21 \pm 0.06$ |
| $e^- \bar{\nu}_e \nu_\tau$     | $17.82 \pm 0.04$ |
| $\mu^- \bar{\nu}_\mu \nu_\tau$ | $17.39 \pm 0.04$ |
| hadronic                       | $64.79 \pm 0.17$ |
| $h^- \nu_\tau$                 | $11.51 \pm 0.05$ |
| $h^- \pi^0 \nu_\tau$           | $25.93 \pm 0.09$ |
| $h^- \pi^0 \pi^0 \nu_\tau$     | $9.48 \pm 0.10$  |
| $h^- h^+ h^- \nu_\tau$         | $9.80 \pm 0.05$  |
| $h^- h^+ h^- \pi^0 \nu_\tau$   | $4.76 \pm 0.05$  |
| other hadr.                    | $3.31 \pm 0.05$  |

**Table 3.1:** Decay modes and branching ratios for a  $\tau^-$ -lepton. The decay modes for a  $\tau^+$ -lepton are charge conjugated. Here,  $h^-$  stands for  $\pi^-$  or  $K^-$ . Values taken from Ref. [27].

and a pseudorapidity  $|\eta| < 2.5$ , and are calibrated using the LCW scheme [210].  $\tau_{\text{had}}$  candidates in the transition region  $1.37 < |\eta| < 1.52$  are vetoed. In events with multiple interactions, the selected primary vertex is not always the vertex where the  $\tau$ -lepton is produced. To increase the reconstruction efficiency, the production vertex of the  $\tau$ -lepton, the  $\tau$  vertex (TV), is identified among the primary vertices of the event. For this, the considered tracks are required to have an angular distance  $\Delta R < 0.2$  around the seed jet direction,  $p_T > 1$  GeV, and satisfy requirements on the number of hits in the ID. The transverse momenta of these tracks are summed and the TV is defined as the primary vertex to which the largest fraction of this sum is matched.

When using this TV instead of the hard-scatter vertex, the efficiency for assigning the correct vertex is especially improved for low  $p_T$ -values of the  $\tau$ -lepton and for high numbers of reconstructed vertices  $N_{\text{vtx}}$ , and is above 95 %. This is shown in Figures 3.13a and 3.13b, respectively.

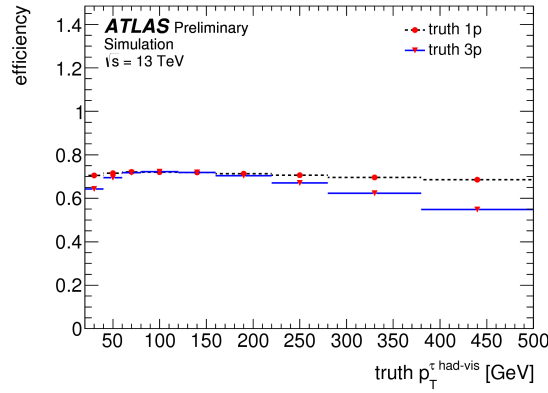


**Figure 3.13:** The efficiencies for correctly assigning the  $\tau_{\text{had}}$  production vertex when using the  $\tau$  vertex (red) and when using the default primary vertex (black) as a function of the transverse momentum  $p_T$  (a) and the number of reconstructed vertices (b). Taken from Ref. [227].

The direction of the  $\tau_{\text{had}}$  candidate is calculated with the vectorial sum of the topological clusters within  $\Delta R < 0.2$  of the seed jet, using the TV as origin. The  $\tau_{\text{had}}$  candidate is assumed to be massless.

New impact parameters are calculated with respect to the TV. The requirements on the transversal and longitudinal impact-parameters are  $|d_0| < 1$  mm and  $|z_0 \sin \theta| < 1.5$  mm, respectively. Associated tracks need to have a transverse momentum  $p_T > 1$  GeV, satisfy requirements on the number of hits in the ID, and have to be within the *core region*  $\Delta R < 0.2$  around the direction of the  $\tau_{\text{had}}$  candidate. Tracks in the *isolation region*  $0.2 < \Delta R < 0.4$  are used in the identification step.

The efficiencies for the reconstruction of 1-track- and 3-track  $\tau_{\text{had}}$  are shown in Figure 3.14. The efficiency for the 1-track  $\tau_{\text{had}}$  reconstruction is almost constant at 70 % over the complete  $p_T$  range, whereas the 3-track  $\tau_{\text{had}}$  reconstruction efficiency is between 55 % and 70 %, and is reduced for low and high  $p_T$  values [227].



**Figure 3.14:** Efficiencies for the reconstruction of 1-track- and 3-track  $\tau_{\text{had}}$ . Taken from Ref. [227].

The energy of the reconstructed  $\tau_{\text{had}}$  candidate needs to be calibrated back to the true energy of the visible decay products. First, the contribution from pile-up is subtracted, which is increasing linearly with the number of primary vertices in the event. Then, a detector response calibration function is applied to correct for decay products that do not reach the calorimeter, that do not deposit enough energy to create a topological cluster, or that are not within  $\Delta R = 0.2$  of the reconstructed  $\tau_{\text{had}}$  candidate. This response function is extracted from simulation, using the true visible energy  $E_{\text{vis}}^{\text{true}}$ . The pile-up- and response corrections are computed and applied depending on the track multiplicity and  $|\eta|$  of the  $\tau_{\text{had}}$  candidate.

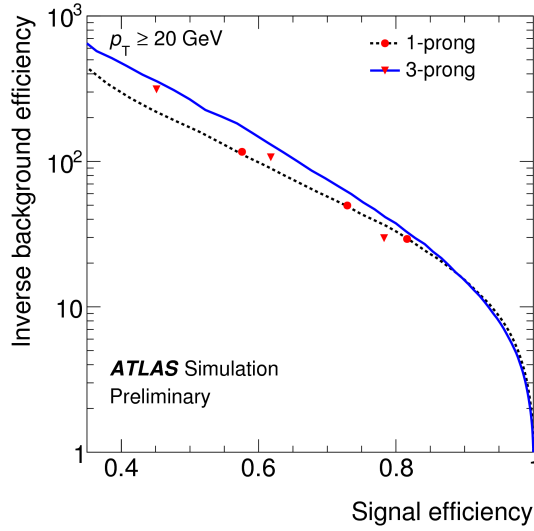
### 3.6.2 Identification

To reject backgrounds from quark- and gluon-initiated jets, Boosted Decision Trees are trained separately for  $\tau_{\text{had}}$  candidates with one and three tracks [227]. Simulated  $Z/\gamma^* \rightarrow \tau\tau$  events are used as signal, while di-jet events from data are used as background.

Variables based on properties of the tracks and topological clusters inside the core- and isolation regions of the  $\tau_{\text{had}}$  candidate are used as input for the BDTs. In total, twelve input variables are used, e.g. the scalar sum of track  $p_T$  in the isolation region divided by the sum of the  $p_T$  of all tracks associated with the  $\tau_{\text{had}}$  candidate, the maximum  $\Delta R$  between the tracks in the core region and the direction of the  $\tau_{\text{had}}$  candidate, and the energy deposited in the region  $\Delta R < 0.1$  divided by the energy

deposited in the region  $\Delta R < 0.2$  around the  $\tau_{\text{had}}$  candidate. A pile-up correction is applied to the variables so that the mean of the distributions for the signal samples is constant as a function of pile-up.

Three working points corresponding to different identification efficiencies, *loose*, *medium* and *tight*, are defined. The efficiencies of the working points are approximately 80 %, 75 % and 65 % for 1-track  $\tau_{\text{had}}$  candidates and approximately 80 %, 60 % and 45 % for 3-track  $\tau_{\text{had}}$  candidates, respectively. The respective jet rejection rates are approximately 30, 50, and 100, and 30, 100, and 300 [227]. The efficiencies and rejection rates are shown in Figure 3.15. Specific values of the BDT score are chosen such that the  $p_T$  dependency of the efficiencies is reduced.

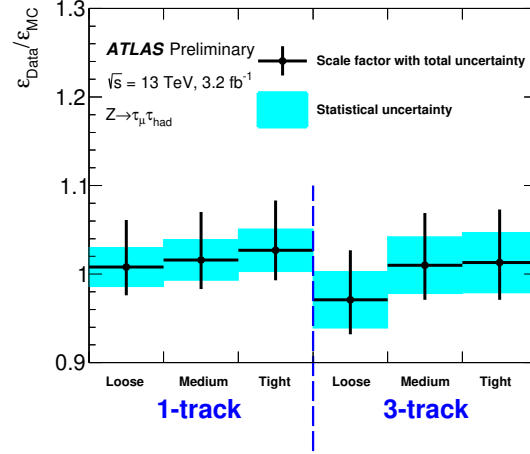


**Figure 3.15:** Inverse background efficiency, i.e. the rejection rate, as function of the identification efficiency of 1-track- (black, dashed) and 3-track (blue, solid)  $\tau_{\text{had}}$ . The *loose*, *medium* and *tight* working points are shown in red. The working points are not on the lines due to a cut on the BDT score to reduce  $p_T$  dependencies. Taken from Ref. [227].

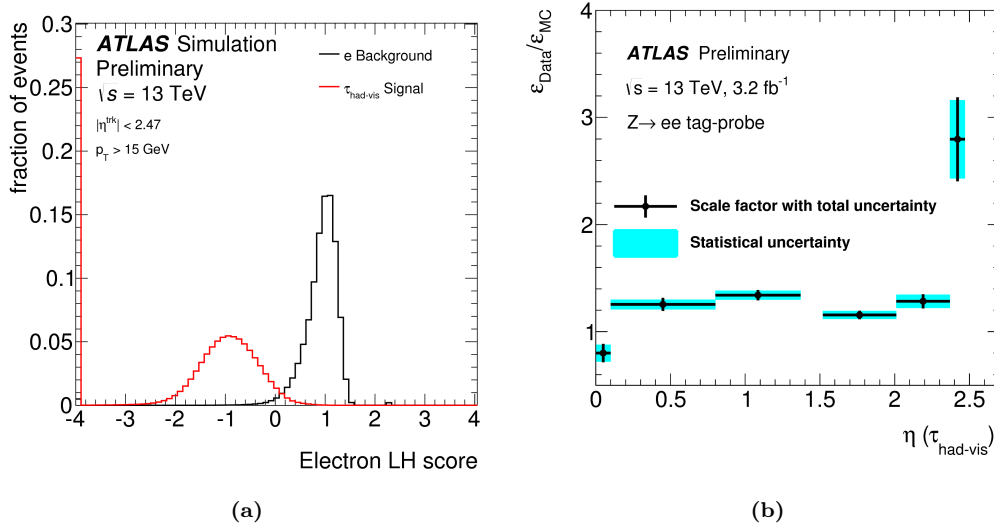
To evaluate the performance of the identification, a  $Z \rightarrow \tau_\mu \tau_{\text{had}}$  tag-and-probe analysis is used [228]. The events are selected by the presence of a muon and have to contain a  $\tau_{\text{had}}$  candidate. The efficiencies are calculated in data and in simulation, and scale factors are derived. The scale factors for all working points are shown in Figure 3.16.

To distinguish 1-track  $\tau_{\text{had}}$  candidates from electrons, the likelihood score used for the electron identification described in Section 3.3.2 is used [227]. 1-track  $\tau_{\text{had}}$  candidates within  $\Delta R < 0.4$  of an electron with  $p_T > 5$  GeV are rejected if the electron has a high likelihood score. This value depends on the  $p_T$  and  $|\eta|$  of the  $\tau_{\text{had}}$  candidate such that the resulting  $\tau_{\text{had}}$  efficiency is a constant 95 % with respect to  $\tau_{\text{had}}$  candidates passing the *loose* identification. The likelihood score for  $\tau_{\text{had}}$  candidates and electrons is shown in Figure 3.17a.

A  $Z \rightarrow ee$  tag-and-probe analysis is used to evaluate the performance. Events are required to contain an electron and a 1-track  $\tau_{\text{had}}$  candidate. The efficiencies are calculated in data and in simulation, and scale factors are derived, which are shown in Figure 3.17b.



**Figure 3.16:** Scale factors for the  $\tau_{\text{had}}$  identification. Systematic and statistical uncertainties are shown. Taken from Ref. [228].



**Figure 3.17:** (a) The electron likelihood score for simulated  $\tau_{\text{had}}$  candidates (red) and for electrons (black). Taken from Ref. [227]. (b) Scale factors for the discrimination between electrons and  $\tau_{\text{had}}$  candidates. Systematic and statistical uncertainties are shown. Taken from Ref. [228].

## 3.7 Missing transverse energy

Missing transverse energy  $E_T^{\text{miss}}$  can arise from various sources. Real missing energy occurs when a neutrino (or a BSM particle) is produced in the hard-scatter event and leaves the detector without interaction. Fake missing energy can be the result of pile-up, energy mismeasurements, particles that hit the detector in a region with low acceptance, or particles that are not detected due to a low reconstruction efficiency.

### 3.7.1 Reconstruction

For the reconstruction of  $E_T^{\text{miss}}$  [229, 230], the momentum conversion transverse to the beam line and the measurement of all detected particles are used. Additionally, ID tracks that are not associated to any reconstructed particle are taken into account. Therefore, the vector of the missing transverse energy is calculated as the negative vectorial sum of the transverse momenta of all reconstructed- and calibrated objects,

i.e. electrons, muons, jets, and  $\tau_{\text{had}}$ , called the *hard term*, and of the tracks associated with the hard scatter vertex but not with any of the objects, called the *soft term*:

$$\mathbf{E}_T^{\text{miss}} = - \sum_{i \in \{\text{hard term objects}\}} \mathbf{p}_{T,i} - \sum_{j \in \{\text{soft term objects}\}} \mathbf{p}_{T,j} \quad (3.4)$$

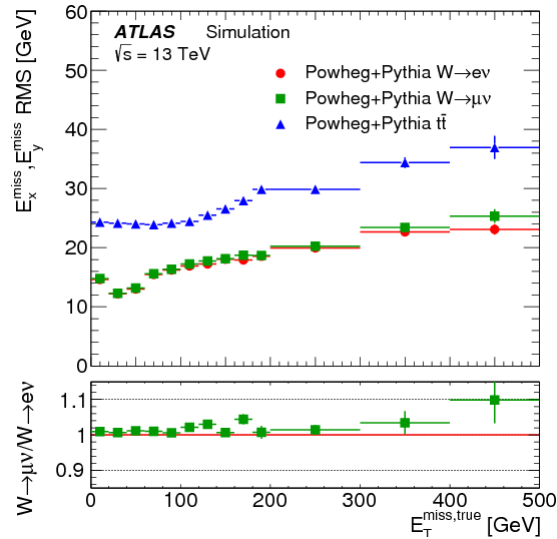
The object selections applied in a given analysis must also be applied on the objects entering the  $E_T^{\text{miss}}$  reconstruction.

$E_T^{\text{miss}}$  is then defined as the magnitude of  $\mathbf{E}_T^{\text{miss}}$ :

$$E_T^{\text{miss}} = |\mathbf{E}_T^{\text{miss}}| = \sqrt{(E_x^{\text{miss}})^2 + (E_y^{\text{miss}})^2} \quad (3.5)$$

A procedure to remove ambiguities due to overlapping objects of the hard term is applied to avoid any double-counting of detector signals. The commonly used order of priority is electrons, photons,  $\tau_{\text{had}}$ , and jets. All electrons are used in the  $E_T^{\text{miss}}$  reconstruction. If any of the other particles shares calorimeter signals with particles of higher priority, it is rejected. Muons are typically reconstructed from MS- and ID tracks alone, but large energy losses of them in the calorimeter can be reconstructed as jets. For such cases and for cases where a jet overlaps only marginal with an electron or a photon, refined overlap removal procedures as described in Ref. [229] are used.

The resolution of the missing transverse energy as a function of the truth  $E_T^{\text{miss}}$ , i.e. the transverse momentum of the neutrino(s), is shown in Figure 3.18 for simulated  $W \rightarrow e\nu$ ,  $W \rightarrow \mu\nu$ , and  $t\bar{t}$  events. The resolution is approximately between 10 GeV and 25 GeV for the  $W$  boson decays and approximately between 25 GeV and 40 GeV for the  $t\bar{t}$  events [229].



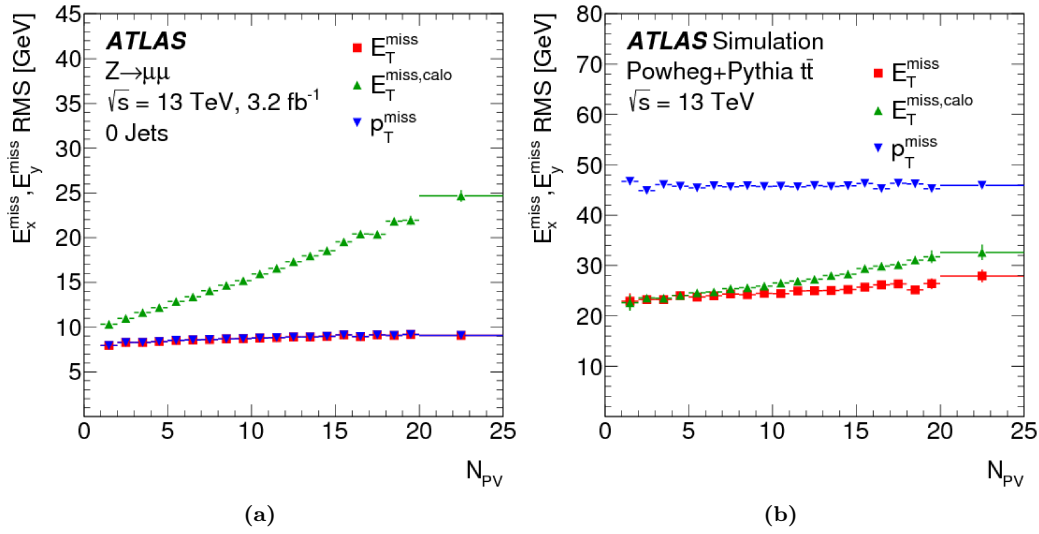
**Figure 3.18:** The resolution of the missing transverse energy as a function of truth  $E_T^{\text{miss}}$  for simulated  $W \rightarrow e\nu$  (red),  $W \rightarrow \mu\nu$  (green), and  $t\bar{t}$  (blue) events. The lower panel shows the ratio between the  $W \rightarrow \mu\nu$ - and the  $W \rightarrow e\nu$  resolution. The ratio is close to one over the entire range. Statistical uncertainties are shown. Taken from Ref. [229].

### 3.7.2 Alternative $E_T^{\text{miss}}$ definitions

The soft term of the missing transverse energy can also be reconstructed from topo-clusters. For this, only topo-clusters that are not used in the reconstruction of the objects in the hard term are considered. The missing transverse energy using this topo-cluster soft term is referred to as  $E_T^{\text{miss,calo}}$ .

Another definition of the missing transverse energy is  $p_T^{\text{miss}}$ , which uses only ID tracks from the hard-scatter vertex. No signals from the calorimeter or the MS are included in this definition.

The resolutions of  $E_T^{\text{miss,calo}}$ ,  $p_T^{\text{miss}}$ , and the default  $E_T^{\text{miss}}$  as a function of the number of reconstructed primary vertices  $N_{\text{PV}}$ , i.e. for different amounts of pile-up, are shown in Figure 3.19a for  $Z \rightarrow \mu\mu$  events and in Figure 3.19b for  $t\bar{t}$  events.



**Figure 3.19:** Resolution of  $E_T^{\text{miss}}$  (red squares),  $E_T^{\text{miss,calo}}$  (green triangles), and  $p_T^{\text{miss}}$  (blue triangles) as function of the number of reconstructed primary vertices  $N_{\text{PV}}$  for  $Z \rightarrow \mu\mu$  (a) and  $t\bar{t}$  events. Statistical uncertainties are shown. Taken from Ref. [229].

In  $Z \rightarrow \mu\mu$  events, where no real missing energy is expected, the resolution of  $E_T^{\text{miss,calo}}$  degrades with increasing  $N_{\text{PV}}$ , while the resolutions of  $p_T^{\text{miss}}$  and  $E_T^{\text{miss}}$  are stable and very similar.

In events with real missing energy and high jet multiplicity, such as  $t\bar{t}$ ,  $E_T^{\text{miss}}$  and  $E_T^{\text{miss,calo}}$  have a much better resolution than  $p_T^{\text{miss}}$ , but both show a slight sensitivity to pile-up while the latter remains stable. The best resolution at high  $N_{\text{PV}}$  is obtained for the default  $E_T^{\text{miss}}$ .





# Chapter 4

## Cross-section measurement

This chapter describes the measurement of the  $H \rightarrow \tau\tau$  cross-section in the  $\tau_{\text{lep}}\tau_{\text{had}}$  final state. For this, the events are divided into categories that target the specific kinematics of the  $ggF$ - and VBF production processes, called signal regions. Several control regions are defined to validate the modelling of the background processes and obtain their normalisation from data, and to constrain systematic uncertainties. The most important background processes are the production of a  $Z$  boson that decays into a pair of  $\tau$ -leptons, and events that contain a jet misidentified as a hadronically decaying  $\tau$ -lepton (called *Fakes* or *Fake* background). A maximum-likelihood fit in the reconstructed di- $\tau$  mass is performed in the signal- and control regions to extract the  $H \rightarrow \tau\tau$  cross-section and to normalise background processes to data.

The relevant signal- and background processes are introduced in Sections 4.1 and 4.2. In Section 4.3, several methods to reconstruct the mass of the di- $\tau$  system are explained, including the final discriminant  $m_{\tau\tau}^{\text{MMC}}$ . Section 4.4 contains the object selection. The event selection and the definitions of the signal- and control regions are detailed in Section 4.5. After that, the methods used to estimate and validate the dominant background processes are described in Section 4.6. Section 4.7 contains a description of the fit model used to extract the  $H \rightarrow \tau\tau$  cross-section, followed by a discussion of the considered systematic uncertainties in Section 4.8. The measured cross-sections are presented in Section 4.9, including the combination with the  $\tau_{\text{lep}}\tau_{\text{lep}}$ - and  $\tau_{\text{had}}\tau_{\text{had}}$  final states taken from Ref. [9].

All distributions in this chapter, except those in Section 4.9, are shown before the maximum-likelihood fit is performed, i.e. all signal- and background processes are normalised to their respective theoretical cross-section and the shapes of the distributions are taken from simulation, except for the data-driven estimate of the Fake background.

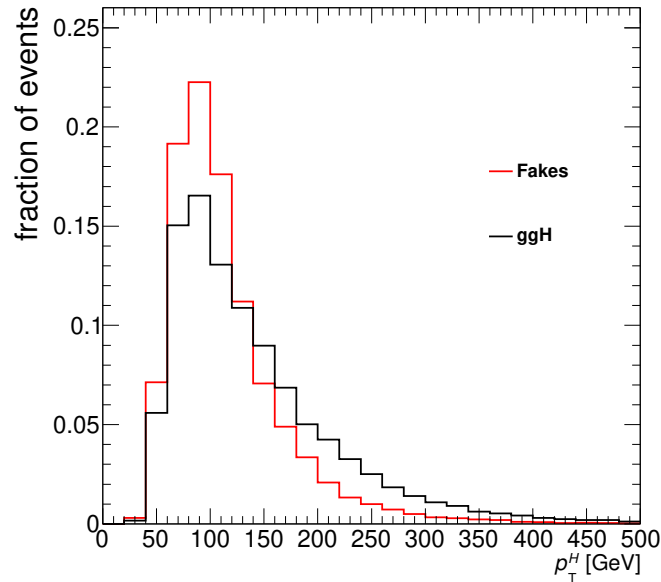
### 4.1 Signal processes

As discussed in Section 1.2.1, the four main production processes of the Higgs boson at the LHC are  $ggF$ , VBF,  $VH$  and  $t\bar{t}H$ . These production processes can be distinguished depending on the particles in the final state and their kinematic properties. Only the  $ggF$ - and VBF production processes are targeted by the event selection in this analysis. The other production processes are taken into account, but no special categories are defined for these and they are suppressed by the selection criteria.

In addition to the final-state particles specific to the different production modes, the decay products of the Higgs boson constitute the final state.

The decay considered in this analysis is the semileptonic final state of the di- $\tau$  decay of the Higgs boson,  $H \rightarrow \tau\tau \rightarrow \ell + \tau_{\text{had}} + 3\nu$ . The decay products are a lepton  $\ell$ , which is either an electron  $e$  or a muon  $\mu$ , the visible part of a hadronically decaying  $\tau$ -lepton  $\tau_{\text{had}}$  and three neutrinos  $\nu$ . Since it is not possible to detect neutrinos with the ATLAS detector, they add an amount of missing transverse energy  $E_{\text{T}}^{\text{miss}}$  to the final state. The opposite electric charges of the lepton  $\ell$  and the  $\tau_{\text{had}}$  candidate are another feature of the final state.

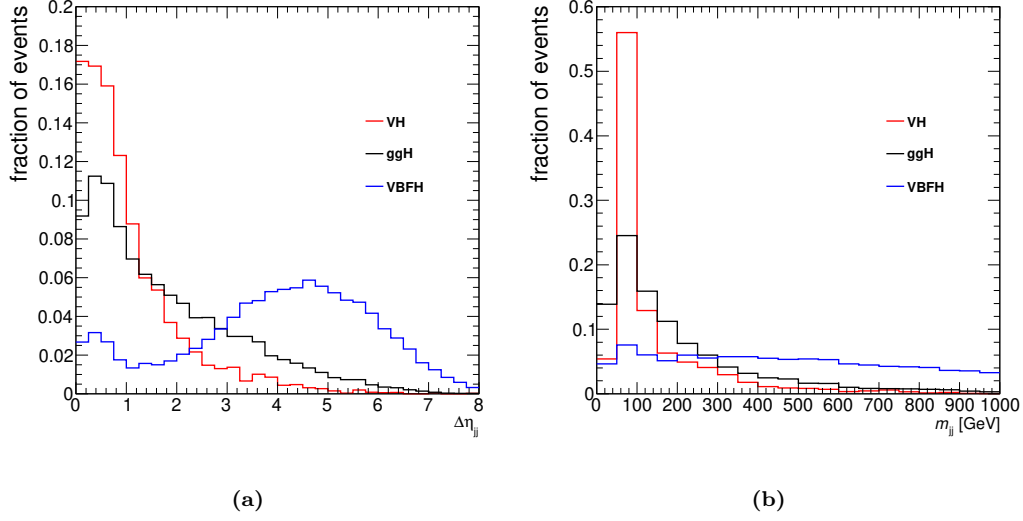
There are no additional final-state partons present at LO accuracy in the  $ggF$  production process, but radiative corrections at higher-order accuracy in QCD contribute significantly to the total cross-section and result in additional jets in the final state. In case of such radiations, the Higgs boson recoils against the resulting jet system and receives a boost in the transverse direction. Therefore, to suppress background processes at least one jet and a high transverse momentum of the Higgs boson  $p_{\text{T}}^H$  are required, where the latter is defined as the transverse momentum of the vectorial sum of the lepton, the  $\tau_{\text{had}}$ , and the missing transverse energy. Figure 4.1 shows  $p_{\text{T}}^H$  for the  $ggF$  production process and the Fake background after the preselection defined in Section 4.5.2. The method described in Section 4.6.1 is used to estimate the Fake background.



**Figure 4.1:** The transverse momentum of the Higgs boson  $p_{\text{T}}^H$  for the  $ggF$  production process (black) and the Fake background (red) after the preselection.

The VBF production process has already at LO accuracy two partons in the final state. The resulting jets have a large separation in pseudorapidity  $\eta$ . This process is targeted and separated from the  $ggF$  process by requiring at least two jets with a large difference in pseudorapidity  $|\Delta\eta_{jj}|$  between the two jets with highest  $p_{\text{T}}$  and a

large invariant mass  $m_{jj}$  of the two jets. This is shown in Figure 4.2.



**Figure 4.2:**  $|\Delta\eta_{jj}|$  (a) and  $m_{jj}$  (b) for the  $VH$ - (red),  $ggF$ - (black), and the VBF (blue) production processes.

The decay of the vector boson in the  $VH$  production process results in leptons or quarks in the final state. In the case of a hadronic decay of the vector boson, this process is suppressed by cuts on  $|\Delta\eta_{jj}|$  and  $m_{jj}$ , as shown in Figure 4.2. When the vector boson decays leptonically, cutting on the transverse mass  $m_T$ , defined in Equation (4.1), suppresses the  $VH$  production process.

Finally, the top quarks in the  $t\bar{t}H$  production process decay either leptonically or hadronically via the weak interaction and almost always with accompanying bottom quarks. Therefore, this process is heavily suppressed by a veto on  $b$ -tagged jets, which is applied to reduce top-quark backgrounds.

POWHEG-BOX v2 [231–236] is used to simulate the  $ggF$ -, VBF- and  $VH$  production processes, using the MINLO approach [237]. With this, the VBF- and  $VH$  production processes are simulated at NLO accuracy in QCD. For  $ggF$ , NNLO accuracy with matching to a parton shower is achieved by using the *NNLOPS* method [238, 239], where the rapidity of the Higgs boson is reweighted with the distribution obtained from HNNLO [240]. For these signal production processes, the PDF4LHC15 [241] PDF parameterisation is used in the matrix element, at NNLO accuracy for  $ggF$  and at NLO accuracy for VBF and  $VH$ . PYTHIA 8.212 [195] is used to model the parton showering, hadronisation and underlying event (UEPS). For modelling the non-perturbative effects, the AZNLO [242] set of tuned parameters is used with the CTEQ6L1 [243] PDF set. EVTGEN v.1.6.0 [244] is used for the decay of  $b$ - and  $c$ -hadrons.

For the  $t\bar{t}H$  production process, MADGRAPH5\_aMC@NLO v2.2.3 [245] is used with NLO accuracy in QCD. NNPDF3.0NLO [246] is used for the PDF parameterisation in the matrix element. For the UEPS modelling, PYTHIA 8.210 with the A14 [247] set of tuned parameters and the NNPDF2.3LO [248] PDF set is used. For  $b$ - and  $c$ -hadron decays, EVTGEN v.1.2.0 is used.

The cross-sections used to normalise the signal samples are described in Section 1.2.1.

## 4.2 Background processes

Background processes are separated in *irreducible* and *reducible* processes. Irreducible processes have the same final state and a very similar topology as the signal processes, while reducible processes have different final states and topologies. Therefore, reducible processes can be distinguished more easily. However, jets in the final state can be misidentified as  $\tau_{\text{had}}$ , resulting in a signal-like final state. Events that contain such *fake*  $\tau_{\text{had}}$  are estimated using a data-driven *Fake Factor* method, described in Section 4.6.1. The jets are either quark- or gluon-initiated, resulting in a different shower shape and thus a different misidentification probability.

The dominant and irreducible background process is the production of a  $Z/\gamma^*$  boson decaying into two  $\tau$ -leptons with additional jets,  $Z/\gamma^* \rightarrow \tau_{\text{lep}}\tau_{\text{had}} + 3\nu + \text{jets}$ , with a real  $\tau_{\text{had}}$ . This production can happen similar to the VBF production process of the Higgs boson by the fusion of two  $W$  bosons, which is called electroweak (EWK) production.

Example Feynman diagrams for this process are shown in Figure 4.3. Due to the different masses of the  $Z$  boson and the Higgs boson, the di- $\tau$  mass can be used to distinguish these two processes, which is shown in Figure 4.4.

Since simulation is used to estimate the dominant  $Z \rightarrow \tau\tau$  background, the modelling is validated in a dedicated study which is explained in Section 4.6.2.

The normalisation of the  $Z \rightarrow \tau\tau$  background is constrained by data since it is free-floating in the maximum-likelihood fit.

The decay of  $Z/\gamma^*$  bosons into a pair of electrons or muons can also contribute as a background if e.g. one of the two leptons is not detected and a jet is misidentified as  $\tau_{\text{had}}$ . No real missing energy is expected in the final state of this process, so placing a lower cut on  $E_{\text{T}}^{\text{miss}}$  can reduce this background, as shown in Figure 4.5.

The production of a leptonically decaying  $W$  boson with additional jets is an important source for events with a fake  $\tau_{\text{had}}$  in the final state since one of the jets can be misidentified. Therefore, this background process is estimated by the Fake Factor method. The jets in this process are mostly quark-initiated. Example Feynman diagrams for this process are shown in Figure 4.6.

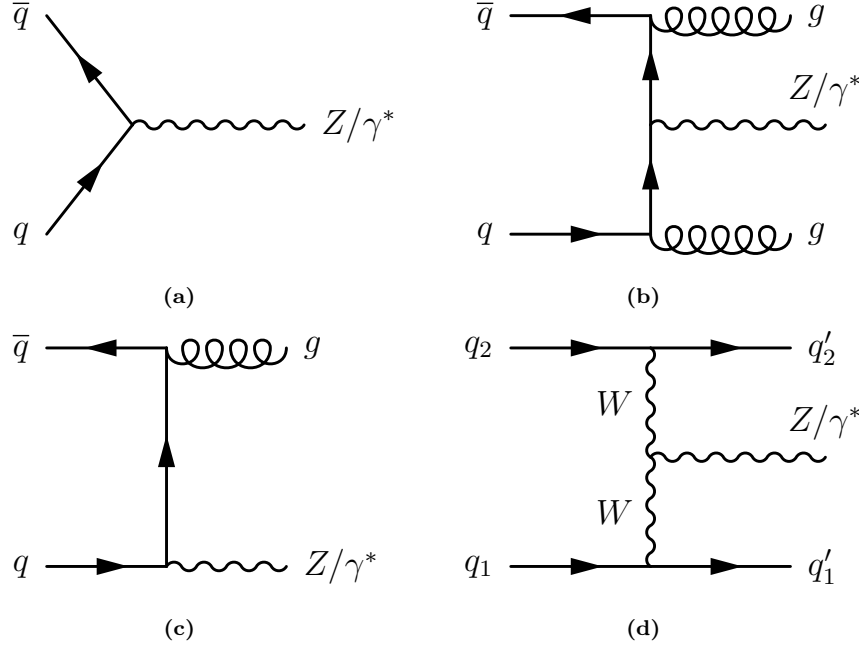
This process is suppressed by placing a cut on the mass of the  $W$  boson. Since the neutrino from the decay leaves the detector undetected, the missing transverse energy  $E_{\text{T}}^{\text{miss}}$  has to be used to calculate the transverse mass  $m_{\text{T}}$ :

$$m_{\text{T}} = \sqrt{2p_{\text{T}}^{\text{lep}} E_{\text{T}}^{\text{miss}} (1 - \cos \Delta\phi_{\text{lep}, E_{\text{T}}^{\text{miss}}})} \quad (4.1)$$

Here,  $\Delta\phi_{\text{lep}, E_{\text{T}}^{\text{miss}}}$  is the azimuthal angle between the lepton and the missing transverse energy, and  $p_{\text{T}}^{\text{lep}}$  is the transverse momentum of the lepton.

The  $m_{\text{T}}$  distribution is shown in Figure 4.7. Placing a cut on this distribution also suppresses the  $VH$  production process.

Diboson production, where all combinations of  $W$ - and  $Z/\gamma^*$  bosons can appear, can have final states with real or fake  $\tau_{\text{had}}$  and a lepton. Example Feynman diagrams are shown in Figure 4.8.



**Figure 4.3:** Example Feynman diagrams for the production of  $Z/\gamma^*$  bosons with different numbers of partons in the final state (a-c), and the electroweak production (d).

This background is suppressed by placing cuts on the angular properties of the lepton- $\tau_{\text{had}}$  system, e.g.  $|\Delta\eta_{\ell, \tau_{\text{had}}}|$ , as shown in Figure 4.9.

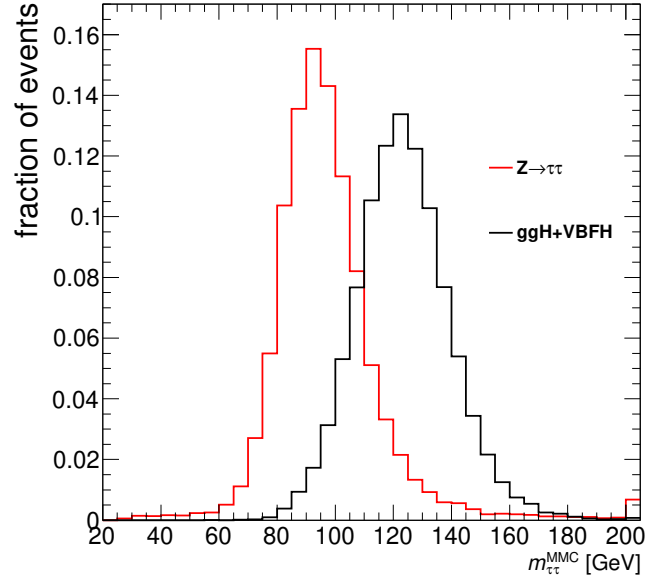
Top quarks can decay both leptonically and hadronically. Therefore, the production of a single top-quark in association with a  $W$  boson ( $Wt$ ) and the production of a top- and antitop-quark pair ( $t\bar{t}$ ) can result in a final state with a lepton and a real or fake  $\tau_{\text{had}}$  candidate. Example Feynman diagrams for these production modes are shown in Figure 4.10.

If an event from the s-channel- or t-channel production of a top quark is selected in the analysis, a jet in the final state was misidentified as  $\tau_{\text{had}}$ . Therefore, these processes are covered by the Fake Factor method.

Since top quarks decay via the weak interaction, which involves almost always an accompanying bottom quark, this background is suppressed by requiring a veto on  $b$ -tagged jets, as shown in Figure 4.11.

Multijet production processes have a large cross-section at the LHC and result in events with a high multiplicity of jets. The jets, which are mostly gluon-initiated in these processes, can be misidentified as leptons or  $\tau_{\text{had}}$  candidates and thus these multijet events contribute to the background processes of this analysis. Figure 4.12 shows example Feynman diagrams for this type of process.

The selection criteria, e.g. the isolation requirement for leptons and the  $E_{\text{T}}^{\text{miss}}$  requirement, suppress the contribution of this background, but it is, together with  $W + \text{jets}$  production, the largest source for events containing fake  $\tau_{\text{had}}$  and is also estimated by the Fake Factor method.



**Figure 4.4:** The di- $\tau$  mass reconstructed with the MMC method, discussed in Section 4.3.3, for the VBF- and  $ggF$  production processes (black) and for the  $Z \rightarrow \tau\tau$  background (red).

The SHERPA 2.2.1 [196, 249] generator is used for the simulation of diboson processes and  $W/Z$  bosons in association with jets, and SHERPA 2.2.0 is used for the EWK production of  $W/Z$  bosons. The matrix elements are calculated with COMIX [250] and OPENLOOPS [251], and are merged with the SHERPA UEPS model [252] using the ME+PS@NLO prescription [253]. The PDF set NNPDF3.0NNLO [246] is used. The matrix elements for  $W/Z$ +jets production are calculated at NLO accuracy in QCD for up to two partons and at LO accuracy for up to four partons, whereas the matrix elements for diboson production are calculated at NLO accuracy in QCD for up to one parton and at LO accuracy for up to three partons. For EWK  $W/Z$ -boson production, the matrix elements are calculated at LO accuracy for up to three partons.

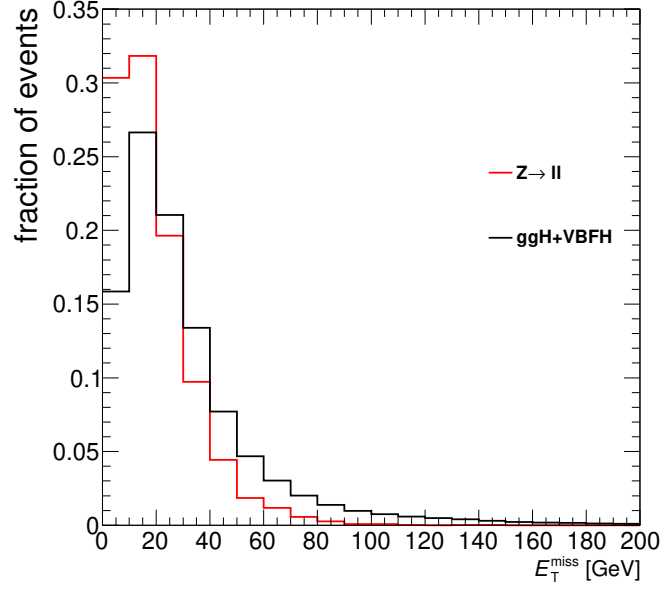
The cross-section for  $W/Z$ +jets production is calculated at NNLO accuracy in QCD [254] and NLO accuracy in EW [255–260] using FEWZ 3.1 [261] with the PDF set CT10 [171]. For the diboson- and EWK  $W/Z$ -boson processes, the cross-sections are taken directly from SHERPA at NLO- and LO accuracy, respectively.

$t\bar{t}$  production is simulated with the POWHEG-BOX v2 [231–233, 262] generator with the CT10 [171] PDF set in the matrix element calculation.

For the production of single top-quarks in association with a  $W$  boson, POWHEG-BOX v1 [263, 264] with the CT10 [171] PDF set is used.

PYTHIA 6.428 [265] with the CTEQ6L1 [243] PDF set and the Perugia 2012 [266] tune is used to simulate the parton shower, the hadronisation, and the underlying event. For  $b$ - and  $c$ -hadron decays, EVTGEN v.1.2.0 [244] is used. Photon emissions are simulated with PHOTOS 2.6 [267–269],  $\tau$ -lepton decays with TAUOLA 2.7 [270, 271].

The cross-section of the  $t\bar{t}$  production process is calculated with TOP++ 2.0 [272] at NNLO accuracy in QCD [273–277] with next-to-next-to-leading logarithmic (NNLL)



**Figure 4.5:**  $E_T^{\text{miss}}$  for the VBF- and  $ggF$  production processes (black) and for the  $Z \rightarrow \ell\ell$  background (red).

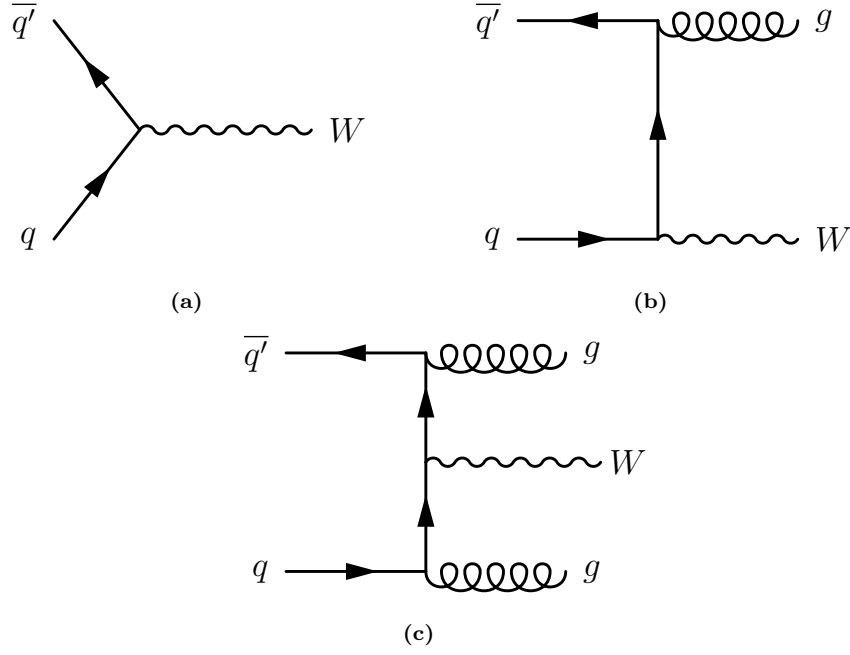
soft-gluon resummation [278, 279]. For production in association with a  $W$  boson, the cross-section is calculated at NLO accuracy with NNLL soft-gluon corrections [280].

The multijet background is estimated by the Fake Factor method and no simulated samples are used.

The cross-sections for the simulated background processes are listed in Table 4.1. These include the production cross-section, the respective branching ratio, and filter efficiencies due to kinematic requirements at generation level.

| Process                     | Cross-section [pb] | Order             | Generator                  | PDF          |
|-----------------------------|--------------------|-------------------|----------------------------|--------------|
| $W \rightarrow e\nu$        | 19 866.55          | NNLO QCD + NLO EW | SHERPA 2.2.1               | NNPDF3.0NNLO |
| $W \rightarrow \mu\nu$      | 19 869.27          | NNLO QCD + NLO EW | SHERPA 2.2.1               | NNPDF3.0NNLO |
| $W \rightarrow \tau\nu$     | 19 892.30          | NNLO QCD + NLO EW | SHERPA 2.2.1               | NNPDF3.0NNLO |
| $W \rightarrow e\nu$ EW     | 6.75               | LO                | SHERPA 2.2.0               | NNPDF3.0NNLO |
| $W \rightarrow \mu\nu$ EW   | 6.74               | LO                | SHERPA 2.2.0               | NNPDF3.0NNLO |
| $W \rightarrow \tau\nu$ EW  | 6.75               | LO                | SHERPA 2.2.0               | NNPDF3.0NNLO |
| $Z \rightarrow ee$          | 4 513.35           | NNLO QCD + NLO EW | SHERPA 2.2.1               | NNPDF3.0NNLO |
| $Z \rightarrow \mu\mu$      | 4 503.42           | NNLO QCD + NLO EW | SHERPA 2.2.1               | NNPDF3.0NNLO |
| $Z \rightarrow \tau\tau$    | 2 719.91           | NNLO QCD + NLO EW | SHERPA 2.2.1               | NNPDF3.0NNLO |
| $Z \rightarrow ee$ EW       | 0.64               | LO                | SHERPA 2.2.0               | NNPDF3.0NNLO |
| $Z \rightarrow \mu\mu$ EW   | 0.64               | LO                | SHERPA 2.2.0               | NNPDF3.0NNLO |
| $Z \rightarrow \tau\tau$ EW | 0.63               | LO                | SHERPA 2.2.0               | NNPDF3.0NNLO |
| Diboson                     | 99.76              | NLO               | SHERPA 2.2.1               | NNPDF3.0NNLO |
| $t\bar{t}$                  | 831.11             | NNLO+NNLL QCD     | POWHEG-Box v2+PYTHIA 6.428 | CT10         |
| $Wt$                        | 71.67              | NLO+NNLL QCD      | POWHEG-Box v1+PYTHIA 6.428 | CT10         |

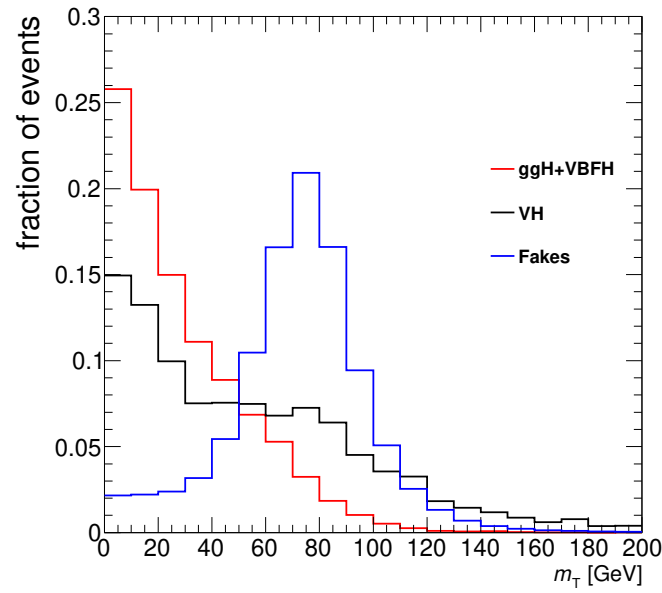
**Table 4.1:** Cross-sections, order of the cross-sections, and the generators and PDFs used to simulate the background processes. The cross-sections include the production cross-section, the respective branching ratio, and filter efficiencies due to kinematic requirements at generation level.



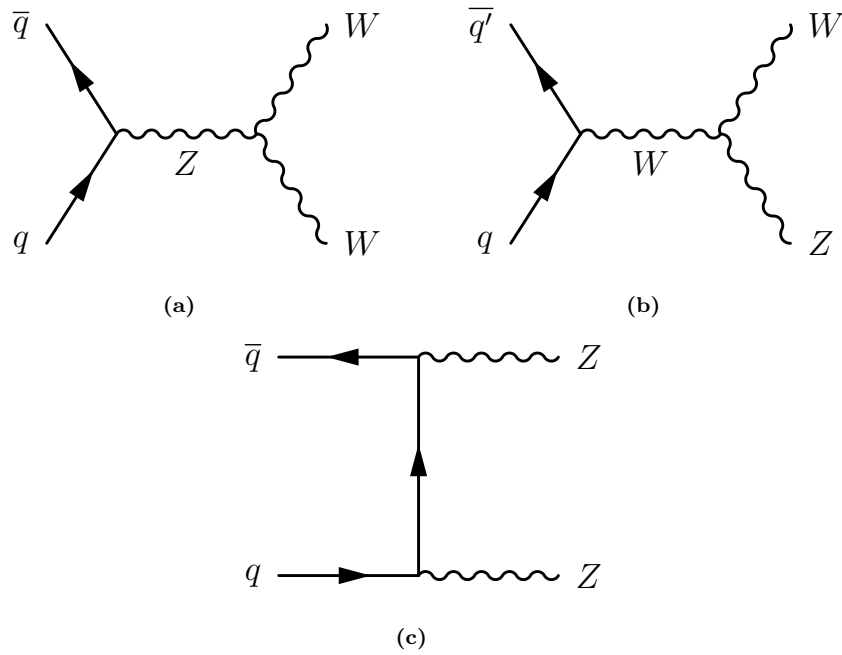
**Figure 4.6:** Example Feynman diagrams for the production of  $W$  + jets with different numbers of partons in the final state.

GEANT4 [199] is used for a full simulation of the ATLAS detector response for all signal- and background samples. All samples are overlaid with minimum-bias events to include the effect of pile-up interactions. These events are simulated with PYTHIA 8.186 [281] with the MSTW2008LO [282] PDF and the A2 [283] parameter set.

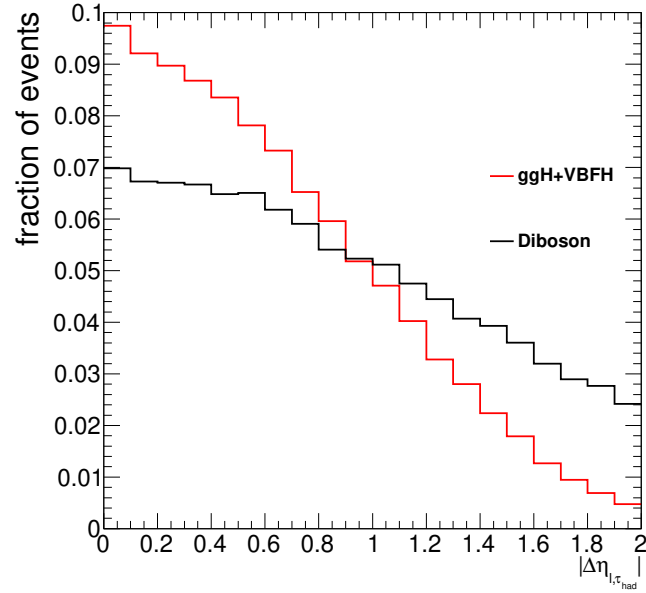




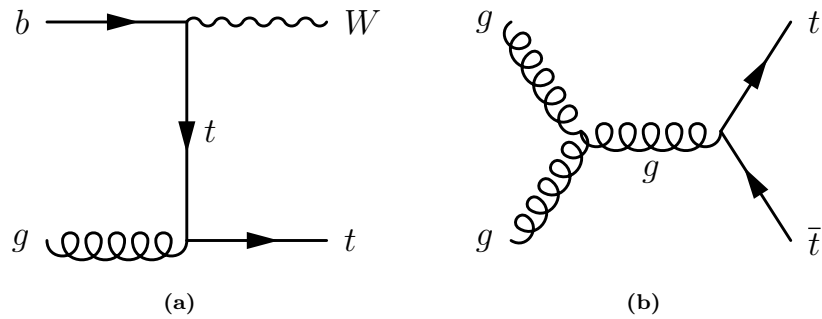
**Figure 4.7:** The transverse mass  $m_T$  for the VBF- and  $ggF$  production processes (red), for the  $VH$  production process (black), and for the Fake background (blue).



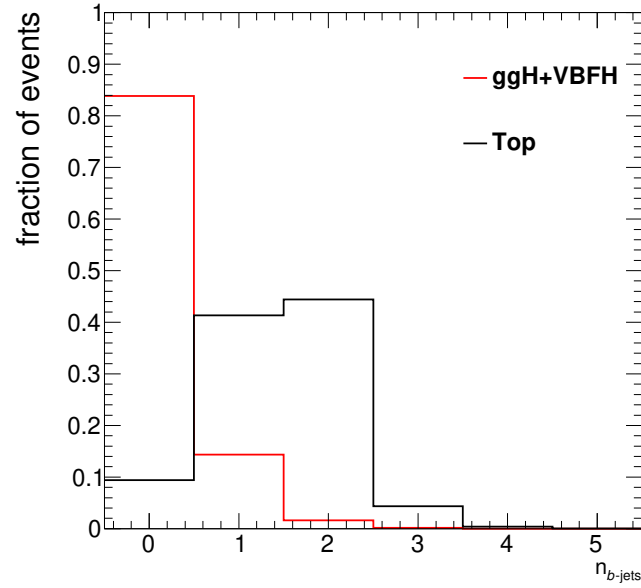
**Figure 4.8:** Example Feynman diagrams for diboson production.



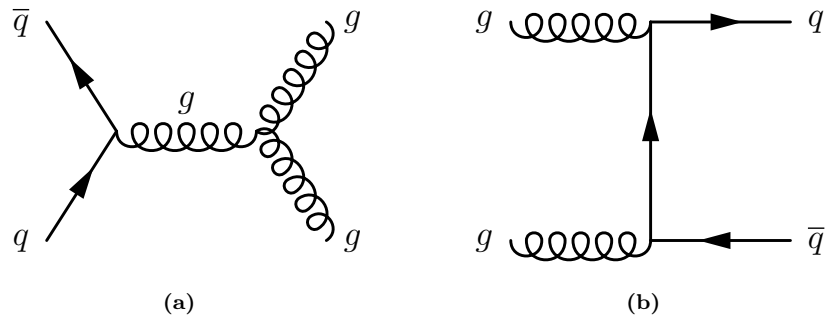
**Figure 4.9:**  $|\Delta\eta_{\ell,\tau_{\text{had}}}|$  for the VBF- and  $ggF$  production processes (red), and for the diboson background (black).



**Figure 4.10:** Example Feynman diagrams for  $Wt$  (a) and  $t\bar{t}$  (b) production.



**Figure 4.11:** Number of  $b$ -tagged jets for the VBF- and  $ggF$  production processes (red), and for the top-quark background (black).



**Figure 4.12:** Example Feynman diagrams for QCD multijet production.

### 4.3 Mass reconstruction

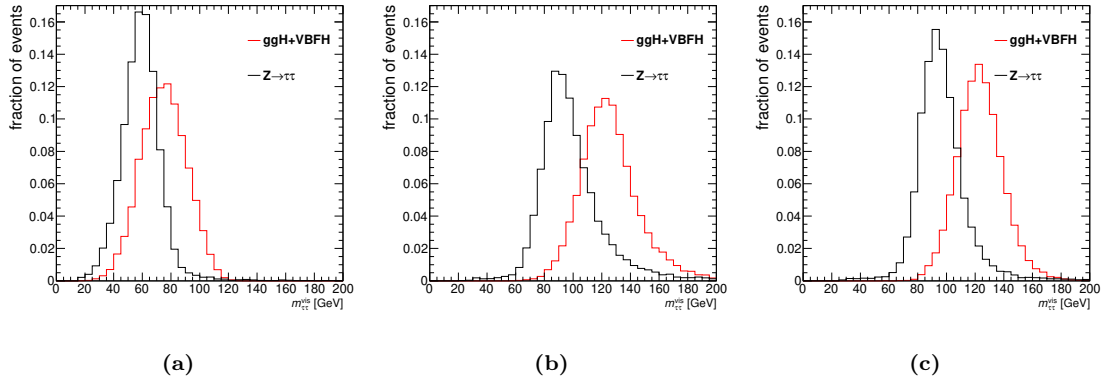
It is not possible to directly reconstruct the invariant mass of the di- $\tau$  system due to the final-state neutrinos, which escape the detector undetected. Therefore, several methods to estimate the invariant mass are used in the analysis.

#### 4.3.1 Visible mass

Only the information of the visible decay products of the two  $\tau$ -leptons is used to calculate the visible mass  $m_{\tau\tau}^{\text{vis}}$ :

$$m_{\tau\tau}^{\text{vis}} = \sqrt{(E_\ell + E_{\tau_{\text{had}}})^2 - (\vec{p}_\ell + \vec{p}_{\tau_{\text{had}}})^2} \quad (4.2)$$

where  $E_{\ell/\tau_{\text{had}}}$  and  $\vec{p}_{\ell/\tau_{\text{had}}}$  are the energy and the momentum of the visible decay products of the  $\tau$ -lepton decays. Since the missing energy is completely neglected in the calculation, the distribution of  $m_{\tau\tau}^{\text{vis}}$  is shifted to lower masses. This is shown in Figure 4.13a.



**Figure 4.13:** The di- $\tau$  mass distributions of the  $ggF$ - and  $VBF$  production processes (red) and the  $Z \rightarrow \tau\tau$  background (black) after the preselection, reconstructed with different techniques: the visible mass (a), the collinear mass (b), and the MMC mass (c).

#### 4.3.2 Collinear mass

One possibility to include the missing energy due to the neutrinos in the reconstruction of the mass is the use of the collinear approximation [284]. For this, it is assumed that the missing energy in the event arises solely from the neutrinos in the  $\tau$ -lepton decays and that the neutrinos propagate in the same direction as the visible decay products. With these assumptions, equations for the  $x$ - and  $y$ -components of the  $E_{\text{T}}^{\text{miss}}$  vector can be set up:

$$\begin{aligned} E_{\text{T},x}^{\text{miss}} &= p_{\text{lep}}^{\text{miss}} \sin \theta_{\text{lep}}^{\text{vis}} \cos \phi_{\text{lep}}^{\text{vis}} + p_{\text{had}}^{\text{miss}} \sin \theta_{\text{had}}^{\text{vis}} \cos \phi_{\text{had}}^{\text{vis}} \\ E_{\text{T},y}^{\text{miss}} &= p_{\text{lep}}^{\text{miss}} \sin \theta_{\text{lep}}^{\text{vis}} \sin \phi_{\text{lep}}^{\text{vis}} + p_{\text{had}}^{\text{miss}} \sin \theta_{\text{had}}^{\text{vis}} \sin \phi_{\text{had}}^{\text{vis}} \end{aligned} \quad (4.3)$$

where  $p_{\text{lep/had}}^{\text{vis}}$ ,  $\theta_{\text{lep/had}}^{\text{vis}}$  and  $\phi_{\text{lep/had}}^{\text{vis}}$  are the momentum, invariant mass, polar angle, and azimuthal angle of the visible decay products of the leptonically or hadronically decaying  $\tau$ -lepton. The unknown total momentum of all invisible decay products is denoted by  $p_{\text{lep/had}}^{\text{miss}}$ .

These equations can be solved for  $p_{\text{lep}}^{\text{miss}}$  and  $p_{\text{had}}^{\text{miss}}$ . The momentum fractions carried by the visible decay products of the  $\tau$ -leptons are calculated by

$$x_{\text{lep/had}} = \frac{p_{\text{lep/had}}^{\text{vis}}}{p_{\text{lep/had}}^{\text{vis}} + p_{\text{lep/had}}^{\text{miss}}} \quad (4.4)$$

Neglecting the masses of the  $\tau$ -lepton and of the visible decay products, the collinear mass of the di- $\tau$  system can then be calculated by

$$m_{\tau\tau}^{\text{coll}} = \frac{m_{\tau\tau}^{\text{vis}}}{\sqrt{x_{\text{lep}} x_{\text{had}}}} \quad (4.5)$$

where  $m_{\tau\tau}^{\text{vis}}$  is the visible mass defined in Equation (4.2). This technique relies on a boosted di- $\tau$  system where the visible decay products are not back-to-back since otherwise the equation system in Equation (4.3) becomes linearly dependent and can no longer be solved for  $p_{\text{lep}}^{\text{miss}}$  and  $p_{\text{had}}^{\text{miss}}$ . Another limiting factor is the resolution of the missing energy, resulting in a broad  $m_{\tau\tau}^{\text{coll}}$  distribution and a long tail. The peak of the distribution is at the correct mass in contrast to  $m_{\tau\tau}^{\text{vis}}$  and a better separation of signal and background is visible, as shown in Figure 4.13b.

### 4.3.3 Missing Mass Calculator

A technique that does not depend on the boost of the di- $\tau$  system is the *Missing Mass Calculator* (MMC) method [285]. It is still assumed that the neutrinos from the  $\tau$ -lepton decays are the only source of missing energy in the event, but the requirement on the collinearity of the decay products is dropped. The  $x$ - and  $y$ -components of the  $E_{\text{T}}^{\text{miss}}$  vector can then be expressed by

$$\begin{aligned} E_{\text{T},x}^{\text{miss}} &= p_{\text{lep}}^{\text{miss}} \sin \theta_{\text{lep}}^{\text{miss}} \cos \phi_{\text{lep}}^{\text{miss}} + p_{\text{had}}^{\text{miss}} \sin \theta_{\text{had}}^{\text{miss}} \cos \phi_{\text{had}}^{\text{miss}} \\ E_{\text{T},y}^{\text{miss}} &= p_{\text{lep}}^{\text{miss}} \sin \theta_{\text{lep}}^{\text{miss}} \sin \phi_{\text{lep}}^{\text{miss}} + p_{\text{had}}^{\text{miss}} \sin \theta_{\text{had}}^{\text{miss}} \sin \phi_{\text{had}}^{\text{miss}} \end{aligned} \quad (4.6)$$

where, in contrast to Equation (4.3), the polar- and azimuthal angles of the invisible decay products,  $\theta_{\text{lep/had}}^{\text{miss}}$  and  $\phi_{\text{lep/had}}^{\text{miss}}$ , have to be used. Additionally, the invariant masses of the  $\tau$ -leptons are

$$\begin{aligned} m_{\tau_{\text{lep}}}^2 &= (m_{\text{lep}}^{\text{miss}})^2 + (m_{\text{lep}}^{\text{vis}})^2 + 2\sqrt{(p_{\text{lep}}^{\text{vis}})^2 + (m_{\text{lep}}^{\text{vis}})^2} \sqrt{(p_{\text{lep}}^{\text{miss}})^2 + (m_{\text{lep}}^{\text{miss}})^2} \\ &\quad - 2p_{\text{lep}}^{\text{vis}} p_{\text{lep}}^{\text{miss}} \cos(\theta_{\text{lep}}^{\text{vis}} - \theta_{\text{lep}}^{\text{miss}}) \end{aligned} \quad (4.7)$$

$$m_{\tau_{\text{had}}}^2 = (m_{\text{had}}^{\text{vis}})^2 + 2p_{\text{had}}^{\text{miss}} \left( \sqrt{(p_{\text{had}}^{\text{vis}})^2 + (m_{\text{had}}^{\text{vis}})^2} - p_{\text{had}}^{\text{vis}} \cos(\theta_{\text{had}}^{\text{vis}} - \theta_{\text{had}}^{\text{miss}}) \right)$$

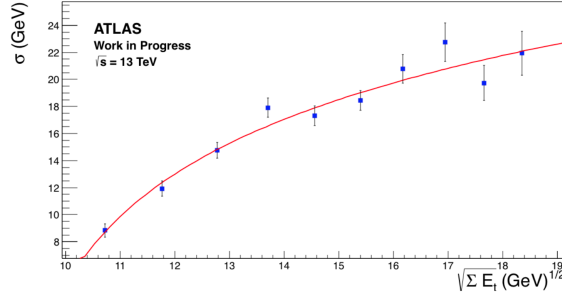
with  $m_{\tau_{\text{lep}}} = m_{\tau_{\text{had}}} = m_{\tau} = 1.777 \text{ GeV}$ . Since only one neutrino is present in the case of a hadronically decaying  $\tau$ -lepton,  $m_{\text{had}}^{\text{miss}}$  drops out of the equation for  $m_{\tau_{\text{had}}}^2$ . There are in total seven unknowns in the four Equations (4.6) and (4.7),  $p_{\text{lep}}^{\text{miss}}$ ,  $p_{\text{had}}^{\text{miss}}$ ,  $\theta_{\text{lep}}^{\text{miss}}$ ,  $\theta_{\text{had}}^{\text{miss}}$ ,  $\phi_{\text{lep}}^{\text{miss}}$ ,  $\phi_{\text{had}}^{\text{miss}}$ , and  $m_{\text{lep}}^{\text{miss}}$ , resulting in an underdetermined system. To solve the system, a scan in a subset of the unknown variables is performed. It would be sufficient to scan the parameter space of three variables, in this case  $\phi_{\text{lep}}^{\text{miss}}$ ,  $\phi_{\text{had}}^{\text{miss}}$ , and  $m_{\text{lep}}^{\text{miss}}$ , to find solutions for the four equations, but since the resolution

of  $E_T^{\text{miss}}$  has an impact on the efficiency of the MMC method,  $E_{T,x}^{\text{miss}}$  and  $E_{T,y}^{\text{miss}}$  are included in the scan. For each scan point,  $\vec{p}_{\text{lep}}^{\text{miss}}$  and  $\vec{p}_{\text{had}}^{\text{miss}}$  are reconstructed and a value for the mass of the di- $\tau$  system  $m_{\tau\tau}^{\text{MMC}}$ , also called the *MMC mass*, is obtained. Not every configuration in the parameter space is equally likely. Therefore, every solution is weighted by its probability depending on the angle between the visible and invisible decay products, the ratio between the visible and invisible momenta, and the resolution of the missing transverse energy. The probability density functions are obtained from simulated  $Z/\gamma^* \rightarrow \tau\tau$  events.

The  $E_T^{\text{miss}}$  resolution is parameterised as a function of  $\sqrt{\sum E_T}$  [286], where  $\sum E_T$  is the scalar sum of the transverse momenta of all objects contributing to the calculation of  $E_T^{\text{miss}}$ :

$$\sum E_T = \sum_{i \in \{\text{hard term objects}\}} p_{T,i} + \sum_{j \in \{\text{soft term objects}\}} p_{T,j} \quad (4.8)$$

The resulting parameterisation is shown in Figure 4.14.



**Figure 4.14:** The parameterisation of the  $E_T^{\text{miss}}$  resolution as a function of  $\sqrt{\sum E_T}$ . Taken from Ref. [286].

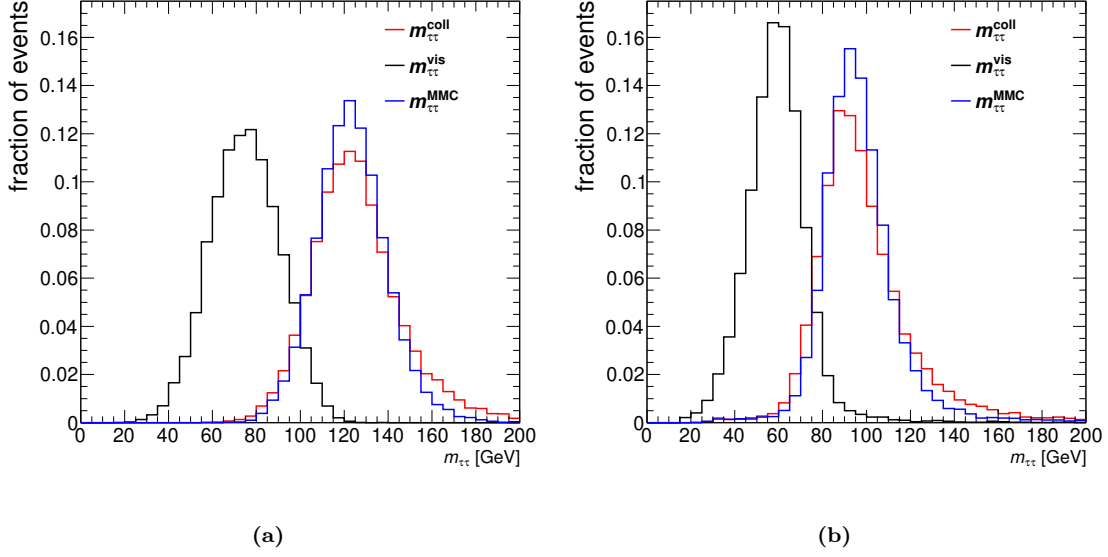
After scanning the parameter space using a Markov chain Monte Carlo method [287], a  $m_{\tau\tau}^{\text{MMC}}$  distribution with all solutions is produced and the position of the maximum of this distribution is chosen as the final  $m_{\tau\tau}^{\text{MMC}}$  value. The  $m_{\tau\tau}^{\text{MMC}}$  distributions for  $H \rightarrow \tau\tau$  and  $Z \rightarrow \tau\tau$  are shown in Figure 4.13c.

A comparison of the resulting distributions of the three techniques after the preselection defined in Section 4.5.2 is shown in Figures 4.15a and 4.15b for the  $ggF$ - and the VBF production processes, and for the  $Z \rightarrow \tau\tau$  background, respectively. The respective mean values and root mean square (RMS) values are shown in Table 4.2.

|                              | $m_H$ [GeV] | $\sigma_H$ [GeV] | $m_Z$ [GeV] | $\sigma_Z$ [GeV] | $\frac{m_H - m_Z}{\sqrt{\sigma_H^2 + \sigma_Z^2}}$ |
|------------------------------|-------------|------------------|-------------|------------------|----------------------------------------------------|
| $m_{\tau\tau}^{\text{vis}}$  | 74.9        | 15.8             | 59.3        | 14.6             | 0.73                                               |
| $m_{\tau\tau}^{\text{coll}}$ | 125.6       | 20.2             | 98.3        | 21.7             | 0.92                                               |
| $m_{\tau\tau}^{\text{MMC}}$  | 123.5       | 16.2             | 96.7        | 17.5             | 1.04                                               |

**Table 4.2:** Mean values, RMS values, and the separation power for the distributions shown in Figure 4.15.

The visible mass has the smallest RMS values of  $\sigma_H = 15.8$  GeV and  $\sigma_Z = 14.6$  GeV but is clearly shifted to lower masses due to the neglected missing energy in the



**Figure 4.15:** The di- $\tau$  mass distributions of the  $ggF$ - and the  $VBF$  production processes (a) and the  $Z \rightarrow \tau\tau$  background (b) after the preselection, reconstructed with different techniques: the visible mass (black), the collinear mass (red) and the MMC mass (blue). The respective RMS is shown in the legend.

calculation: the mean values of the distributions are at  $m_H = 74.9$  GeV and at  $m_Z = 59.4$  GeV.

Both the collinear mass and the MMC mass on the other hand are able to approximately reproduce the mass of the respective boson. The resulting mean values are  $m_H = 125.6$  GeV and  $m_Z = 98.3$  GeV for the collinear mass, and  $m_H = 123.5$  GeV and  $m_Z = 96.7$  GeV for the MMC mass. The distributions obtained with the MMC method have smaller RMS values of  $\sigma_H = 16.2$  GeV and  $\sigma_Z = 17.5$  GeV compared to the values when using the collinear mass:  $\sigma_H = 20.2$  GeV and  $\sigma_Z = 21.7$  GeV.

To quantify the separation power of the different methods,  $\frac{m_H - m_Z}{\sqrt{\sigma_H^2 + \sigma_Z^2}}$  is used, where larger values imply better separation of the distributions. The resulting values are also included in Table 4.2. The largest separation power of 1.04 is obtained from the MMC method, followed by the collinear mass with a value of 0.92. The visible mass provides the worst separation with a value of 0.73.

The MMC method thus provides the best separation between the mass distributions of the Higgs-boson signal and the  $Z \rightarrow \tau\tau$  background. Therefore, the  $m_{\tau\tau}^{\text{MMC}}$  distribution is used as the final discriminant in the maximum-likelihood fits.

## 4.4 Object selection

In this section, the requirements on the objects introduced in Chapter 3 are summarised. The same object can be reconstructed by multiple algorithms. Therefore, an overlap removal is applied to remove any ambiguities between close objects.

Electrons are required to pass the *loose* working point, to have transverse momentum  $p_T > 15$  GeV, and to be in the detector region  $|\eta| < 2.47$ , excluding the transition region  $1.37 < |\eta| < 1.52$ . Electrons are rejected if they share a track with a muon or if their distance from a jet is within  $0.2 < \Delta R < 0.4$ .

Muons have to pass the *loose* identification criteria. They are required to have transverse momentum  $p_T > 10$  GeV and to be in the detector region  $|\eta| < 2.5$ . Muons are rejected if their distance from a jet is  $0.2 < \Delta R < 0.4$ . The jet is removed instead if the muon track is associated with the jet and if the jet has less than three tracks or if it has less than twice the muon  $p_T$ .

Jets are required to have  $p_T > 20$  GeV and to be in the region  $|\eta| < 4.9$ . A *Jet Vertex Tagger* (JVT) [288] is used to reject jets originating from pileup. The JVT uses the tracks associated with the jet to determine its likelihood to originate from pileup. This is done for jets with  $p_T < 50$  GeV and  $|\eta| < 2.4$ . The *medium* working point is used, corresponding to the cut  $|JVT| > 0.59$ . The efficiency for selecting a jet from the hard-scatter event is 92 %, while the rejection rate for pile-up jets is 100.

Pileup jets in the forward region are rejected by a *forward JVT* [289] for jets with  $p_T < 50$  GeV and  $|\eta| > 2.5$ . This algorithm uses shape information from the calorimeter clusters. The *tight* working point is used, corresponding to the cut  $fJVT < 0.4$ . The efficiency for selecting a jet from the hard-scatter event is 85 %, while the rejection rate for pile-up jets is 2.

Jets within  $\Delta R = 0.2$  of an electron or  $\tau_{\text{had}}$  candidate are rejected. *b*-tagging is applied to jets with  $|\eta| < 2.5$ , using a working point with 85 % efficiency.

$\tau_{\text{had}}$  candidates are required to have  $p_T > 20$  GeV and to pass the *loose* identification requirements.  $\tau_{\text{had}}$  candidates are rejected if they are within  $\Delta R = 0.2$  of an electron or muon.

## 4.5 Event selection

As explained in Section 4.2, several background processes with much higher cross-sections than for the production of a Higgs boson are present in the data. A preselection is applied to suppress the various background components and after that, the remaining events are categorised according to their kinematic properties to separate the *ggF*- and VBF production processes. To validate the modelling of the simulation, to constrain systematic uncertainties, and to normalise the top-quark background, several background-enriched control regions are defined.

### 4.5.1 Trigger

Only events passing a single-lepton trigger during data-taking are taken into account. A logical *or* between the triggers listed in Table 4.3 is performed. The naming of the triggers is explained in Section 2.2.5. Due to the higher luminosity and increased pileup during data-taking in 2016, the HLT objects had to satisfy stricter requirements, e.g. higher  $p_T$  thresholds and tighter isolation criteria.

The offline reconstructed lepton has to be geometrically matched to the object that caused the event to pass the trigger: the distance between them has to be  $\Delta R < 0.1$ . The minimum offline  $p_T$  requirement for the lepton depends on the flavour and the year of data-taking and is summarised in Table 4.3. The values are chosen such that the  $p_T$  is in the plateau of the respective trigger efficiency curve.



|                 | Data period | Trigger                        | offline $p_T$ [GeV] |
|-----------------|-------------|--------------------------------|---------------------|
| Single electron | 2015        | HLT_e24_lhmedium_L1EM20VH      | 25                  |
|                 |             | HLT_e60_lhmedium               |                     |
|                 |             | HLT_e120_lhloose               |                     |
|                 | 2016        | HLT_e26_lhtight_nod0_ivarloose | 27                  |
|                 |             | HLT_e60_lhmedium_nod0          |                     |
|                 |             | HLT_e140_lhloose_nod0          |                     |
| Single muon     | 2015        | HLT_mu20_iloose_L1MU15         | 21                  |
|                 |             | HLT_mu40                       |                     |
|                 | 2016        | HLT_mu26_ivarmedium            | 27                  |
|                 |             | HLT_mu50                       |                     |

**Table 4.3:** Triggers and offline- $p_T$  requirements used in the analysis.

### 4.5.2 Preselection

A preselection is applied to suppress hardware problems and non-collision events (e.g. cosmic radiation, beam-halo events) in the recorded data, and the various background processes.

Only events that are contained in a *Good Runs List* (GRL) are used in the analysis. This rejects events that were recorded while the detector was not fully operational. To reject non-collision events, events are required to contain at least one primary vertex. Events are rejected if they contain a jet associated with energy deposits from hardware problems or non-collision events.

Events are required to contain exactly one  $\tau_{\text{had}}$  candidate with  $p_T > 30$  GeV satisfying the *medium* identification criterion and exactly one electron or muon satisfying the respective *medium* identification criterion and the *gradient* isolation criterion. The identification- and isolation criteria are defined in Chapter 3. The lepton and the  $\tau_{\text{had}}$  are required to have opposite electric charge. To suppress  $Z \rightarrow ee$  events, electrons misidentified as  $\tau_{\text{had}}$  candidates are rejected using Boosted Decision Trees [290]. A cut on the resulting score  $\text{BDT}_{\text{score}}^{e\text{-Veto}} > 0.15$  is applied for events that contain a 1-track  $\tau_{\text{had}}$  candidate.

To reduce the  $W$ +jets background, a cut on the transverse mass, as introduced in Section 4.2,  $m_T < 70$  GeV is applied. A veto on  $b$ -tagged jets is required to suppress processes with top quarks. Since the final state of all signal production processes contains three neutrinos due to the  $\tau$ -lepton decays, a minimum missing transverse energy  $E_T^{\text{miss}} > 20$  GeV is required. At least one jet with a  $p_T > 40$  GeV is required. Since the lepton and the  $\tau_{\text{had}}$  in signal events arise from the Higgs boson decay, they are expected to have a small angular separation. To ensure this and suppress non-resonant background events, cuts on the difference in pseudorapidity  $|\Delta\eta_{\ell, \tau_{\text{had}}}| < 1.5$  and on  $\Delta R_{\ell, \tau_{\text{had}}} < 2.5$  are applied. To reduce backgrounds where the neutrinos, and hence the missing transverse energy, and the lepton and  $\tau_{\text{had}}$  are not from the same source, cuts on the momentum fractions  $x_1$  and  $x_2$  carried by the visible decay products of the  $\tau$ -leptons are applied:  $0.1 < x_1 < 1.4$  and  $0.1 < x_2 < 1.2$ , where the  $x_i$  are calculated with Equation (4.4) using the collinear

approximation.

The definition of the preselection is summarised in Table 4.4. The event yields of all signal- and background processes and of the observed data after the preselection are listed in Table 4.5. The dominant background is  $Z \rightarrow \tau\tau$ , followed by the Fakes. The signal-to-background ratio s/b after the preselection is only 0.014. The relative signal composition is shown in Table 4.6. Most of the signal is composed of  $ggF$  events, whereas the contribution from the  $t\bar{t}H$  production process is negligible, as expected.

Figure 4.16 shows the  $m_{\tau\tau}^{\text{MMC}}$  distribution after the preselection. The  $Z \rightarrow \tau\tau$ - and signal distributions are peaking at the respective masses and the peak of the  $Z \rightarrow \tau\tau$  distribution is much higher even after scaling the signal by 20.

| Preselection                                                                          |               |                                                |                  |
|---------------------------------------------------------------------------------------|---------------|------------------------------------------------|------------------|
| $\tau_{\text{had}}$ : <i>medium</i> ID, $p_{\text{T}} > 30$ GeV                       |               | $ \Delta\eta_{\ell, \tau_{\text{had}}}  < 1.5$ |                  |
| $e/\mu$ : <i>medium</i> ID, <i>gradient</i> isolation, $p_{\text{T}}$ as in Table 4.3 |               | $\Delta R_{\ell, \tau_{\text{had}}} < 2.5$     |                  |
| $N_{\tau_{\text{had}}} = 1$ , $N_{e/\mu} = 1$                                         |               | $0.1 < x_1 < 1.4$                              |                  |
| $\text{BDT}_{\text{score}}^{\text{e-Veto}} > 0.15$                                    |               | $0.1 < x_2 < 1.2$                              |                  |
| Opposite charge of lepton and $\tau_{\text{had}}$                                     |               | $N_{b\text{-jets}} = 0$                        |                  |
| $m_{\text{T}} < 70$ GeV                                                               |               | $p_{\text{T}}^{j_1} > 40$ GeV                  |                  |
| $E_{\text{T}}^{\text{miss}} > 20$ GeV                                                 |               |                                                |                  |
| VBF                                                                                   |               | Boosted                                        |                  |
| $p_{\text{T}}^{j_2} > 30$ GeV                                                         |               | Not VBF                                        |                  |
| $\eta_{j_1} \cdot \eta_{j_2} < 0$                                                     |               | $p_{\text{T}}^H > 100$ GeV                     |                  |
| $ \Delta\eta_{jj}  > 3$                                                               |               |                                                |                  |
| $m_{jj} > 400$ GeV                                                                    |               |                                                |                  |
| Central leptons                                                                       |               |                                                |                  |
| Tight                                                                                 | Loose         | High                                           | Low              |
| $m_{jj} > 500$ GeV                                                                    | Not VBF Tight | $p_{\text{T}}^H > 140$ GeV                     | Not Boosted High |
| $p_{\text{T}}^H > 100$ GeV                                                            |               | $\Delta R_{\ell, \tau_{\text{had}}} < 1.5$     |                  |

**Table 4.4:** Preselection and categorisation

| Category      | VBF              | $ggF$           | $VH$              | $t\bar{t}H$       | Signal           |
|---------------|------------------|-----------------|-------------------|-------------------|------------------|
| Preselection  | 69.1 $\pm$ 0.4   | 211.3 $\pm$ 1.8 | 18.0 $\pm$ 0.4    | 0.41 $\pm$ 0.06   | 298.8 $\pm$ 1.9  |
| VBF incl.     | 32.17 $\pm$ 0.27 | 10.8 $\pm$ 0.4  | 0.29 $\pm$ 0.05   | 0.014 $\pm$ 0.013 | 43.2 $\pm$ 0.5   |
| VBF Tight     | 25.12 $\pm$ 0.24 | 6.93 $\pm$ 0.31 | 0.159 $\pm$ 0.035 | 0.001 $\pm$ 0.011 | 32.2 $\pm$ 0.4   |
| VBF Loose     | 7.05 $\pm$ 0.12  | 3.84 $\pm$ 0.26 | 0.13 $\pm$ 0.04   | 0.013 $\pm$ 0.006 | 11.04 $\pm$ 0.29 |
| Boosted incl. | 25.67 $\pm$ 0.23 | 124.3 $\pm$ 1.3 | 13.14 $\pm$ 0.30  | 0.33 $\pm$ 0.06   | 163.5 $\pm$ 1.4  |
| Boosted High  | 13.70 $\pm$ 0.17 | 63.7 $\pm$ 0.9  | 7.60 $\pm$ 0.22   | 0.17 $\pm$ 0.05   | 85.2 $\pm$ 1.0   |
| Boosted Low   | 11.97 $\pm$ 0.16 | 60.6 $\pm$ 1.0  | 5.55 $\pm$ 0.20   | 0.157 $\pm$ 0.032 | 78.3 $\pm$ 1.0   |

| Category      | $Z \rightarrow \tau\tau$ | Fake           | Top            | $Z \rightarrow \ell\ell$ | Diboson         | Background       | Data   | s/b   |
|---------------|--------------------------|----------------|----------------|--------------------------|-----------------|------------------|--------|-------|
| Preselection  | 15 160 $\pm$ 120         | 5 290 $\pm$ 40 | 288 $\pm$ 10   | 760 $\pm$ 110            | 348 $\pm$ 6     | 21 840 $\pm$ 170 | 22 836 | 0.014 |
| VBF incl.     | 472 $\pm$ 16             | 172 $\pm$ 7    | 18.8 $\pm$ 2.4 | 21 $\pm$ 5               | 14.0 $\pm$ 1.6  | 698 $\pm$ 18     | 814    | 0.062 |
| VBF Tight     | 294 $\pm$ 11             | 86 $\pm$ 5     | 13.6 $\pm$ 2.0 | 11 $\pm$ 4               | 10.6 $\pm$ 1.5  | 416 $\pm$ 13     | 496    | 0.077 |
| VBF Loose     | 177 $\pm$ 12             | 86 $\pm$ 4     | 5.3 $\pm$ 1.3  | 10.1 $\pm$ 2.5           | 3.4 $\pm$ 0.7   | 282 $\pm$ 13     | 318    | 0.039 |
| Boosted incl. | 9 050 $\pm$ 80           | 2 494 $\pm$ 24 | 189 $\pm$ 8    | 270 $\pm$ 40             | 253 $\pm$ 5     | 12 260 $\pm$ 90  | 12 903 | 0.013 |
| Boosted High  | 5 100 $\pm$ 50           | 610 $\pm$ 13   | 58 $\pm$ 5     | 108 $\pm$ 15             | 134.4 $\pm$ 3.2 | 6 020 $\pm$ 60   | 6 347  | 0.014 |
| Boosted Low   | 3 950 $\pm$ 60           | 1 884 $\pm$ 21 | 132 $\pm$ 7    | 165 $\pm$ 33             | 119.0 $\pm$ 3.4 | 6 250 $\pm$ 70   | 6 556  | 0.013 |

**Table 4.5:** Event yields after the preselection and in all signal regions. *Signal* and *Background* are the sum of all signal- and background processes, respectively. All samples are normalised to their respective theoretical cross-section except for the data-driven Fake estimate.

|              | VBF [%] | $ggF$ [%] | $VH$ [%] | $t\bar{t}H$ [%] |
|--------------|---------|-----------|----------|-----------------|
| Preselection | 23      | 71        | 6        | 0.1             |
| VBF          | 74      | 25        | 0.7      | <0.1            |
| VBF Tight    | 78      | 22        | 0.5      | <0.1            |
| VBF Loose    | 64      | 35        | 1.2      | 0.1             |
| Boosted      | 16      | 76        | 8        | 0.2             |
| Boosted High | 16      | 75        | 9        | 0.2             |
| Boosted Low  | 15      | 77        | 7        | 0.2             |

**Table 4.6:** Relative signal-composition after the preselection and in all signal regions.

### 4.5.3 Categorisation

After the preselection, more selection criteria are applied to categorise the signal events according to their production process and to further reduce background events. As already mentioned, this analysis focuses on the productions via  $ggF$  and VBF.

To target Higgs bosons produced via VBF, a second jet with  $p_T > 30$  GeV is required. The two jets with highest  $p_T$  have to be in opposite detector hemispheres with a large separation in pseudorapidity  $|\Delta\eta_{jj}| > 3$  and an invariant mass  $m_{jj} > 400$  GeV. Additionally, *central  $\tau$ -leptons* are required: the lepton and the  $\tau_{\text{had}}$  candidate are required to have  $\eta$  values between those of the two jets. This category is referred to as *VBF category*. The distributions of  $|\Delta\eta_{jj}|$  and  $m_{jj}$  before the application of the respective selection criterion are shown in Figure 4.17.

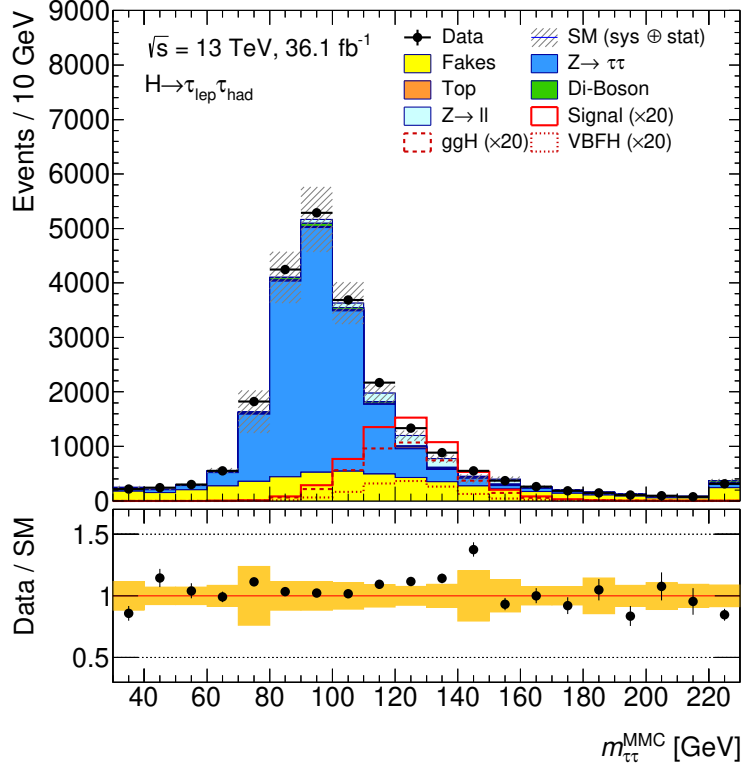
To increase the sensitivity, the VBF category is split further into orthogonal subcategories.

The *VBF Tight* category is defined by requiring a higher invariant mass of the two jets,  $m_{jj} > 500$  GeV, and by adding the requirement for a high transverse momentum of the Higgs boson,  $p_T > 100$  GeV. The *VBF Loose* category is composed of all events failing these additional criteria. The distributions of  $m_{jj}$  and  $p_T^H$  before the application of the respective selection criterion are shown in Figure 4.18.

The event yields and the relative signal-compositions in the VBF categories are listed in Table 4.5 and Table 4.6, respectively. The signal is dominated by the VBF production process, but the  $ggF$  production process has contributions between 22 % and 35 %. The  $t\bar{t}H$ - and  $VH$  production processes are negligible. The signal-to-background ratio improves with respect to the preselection: in the VBF category it is 0.062, while it is 0.077 and 0.039 for the VBF Tight- and VBF Loose categories, respectively.

The  $m_{\tau\tau}^{\text{MMC}}$  distributions in the VBF categories are shown in Figure 4.19. The signal processes are scaled by 10. The peak of the signal distribution is now more pronounced than after the preselection.

For the production via  $ggF$ , all events falling into the VBF category are vetoed to ensure full orthogonality of the categories. The Higgs boson recoils against additional jets arising from QCD radiation and receives a boost in the transverse direction. To target this feature of the  $ggF$  production process, a cut on the transverse momentum



**Figure 4.16:** The  $m_{\tau\tau}^{\text{MMC}}$  distribution after the preselection. All samples are normalised to their respective theoretical cross-section prediction except for the data-driven Fake estimate. The signal contributions are scaled by 20. Statistical and systematic uncertainties are included in the uncertainty band.

of the Higgs boson  $p_T > 100$  GeV is applied. This category is referred to as *Boosted category*. The distribution of  $p_T^H$  before the application of the selection criterion is shown in Figure 4.20.

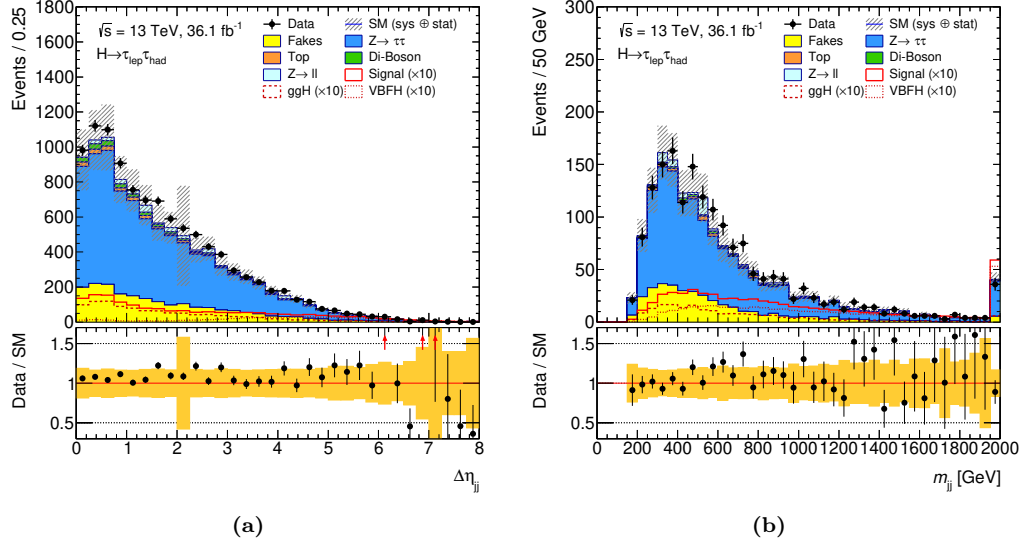
Additional subcategories are also defined for the Boosted category.

The *Boosted High* category is defined by increasing the requirement for the transverse momentum of the Higgs boson to  $p_T > 140$  GeV and by tightening the requirement for the angular separation of the lepton and the  $\tau_{\text{had}}$  to  $\Delta R_{\ell, \tau_{\text{had}}} < 1.5$ . The *Boosted Low* category is composed of all events failing the definition of the *Boosted High* category. The distributions of  $p_T^H$  and  $\Delta R_{\ell, \tau_{\text{had}}}$  before the application of the respective selection criterion are shown in Figure 4.21.

The event yields in the Boosted categories are listed in Table 4.5 and the relative signal-compositions are shown in Table 4.6. The  $ggF$  production process is dominating, while the contributions of the VBF- and  $VH$  production processes are between 15 % and 16 %, and between 7 % and 9 %, respectively. The signal-to-background ratio in the inclusive Boosted category is 0.013, while it is 0.014 and 0.013 for the Boosted High- and Boosted Low categories, respectively. These ratios are comparable to the ratio after the preselection, but the fraction of  $ggF$  events is increased.

The  $m_{\tau\tau}^{\text{MMC}}$  distributions in the Boosted categories are shown in Figure 4.22.

The definitions of all categories are summarised in Table 4.4.



**Figure 4.17:** Distributions of  $|\Delta\eta_{jj}|$  (a) and  $m_{jj}$  (b) in the VBF category before the application of the respective selection criterion. Statistical and systematic uncertainties are included in the uncertainty band.

The background predictions in Figures 4.19 and 4.22 are in good agreement with data within the uncertainties. The statistics in the VBF regions are rather low, resulting in large uncertainties. Some upwards fluctuation in data are present in the region around  $m_{\tau\tau}^{\text{MMC}} = 125$  GeV, especially in Figures 4.19c, 4.22b and 4.22c. The results of the maximum-likelihood fit presented in Section 4.9 provide more insight into this.

#### 4.5.4 Control regions

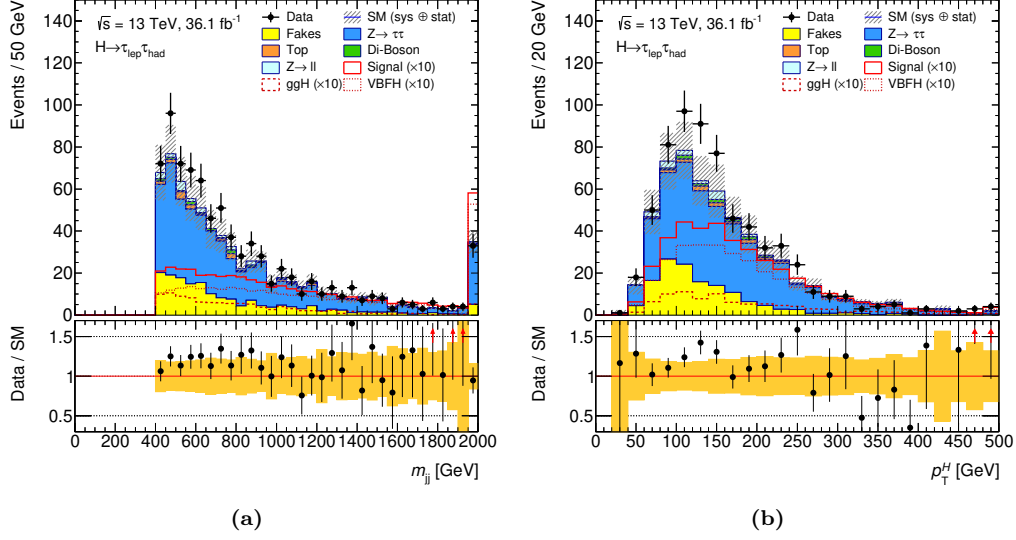
Additional regions are defined to validate the modelling of the backgrounds, to estimate the Fake background, to constrain systematic uncertainties and, in the case of the top-quark background, to normalise the background to data in the maximum-likelihood fit. The definition of these control regions is chosen such that they remain kinematically as close as possible to the signal regions but are enriched in the targeted background processes.

##### Top-quark background

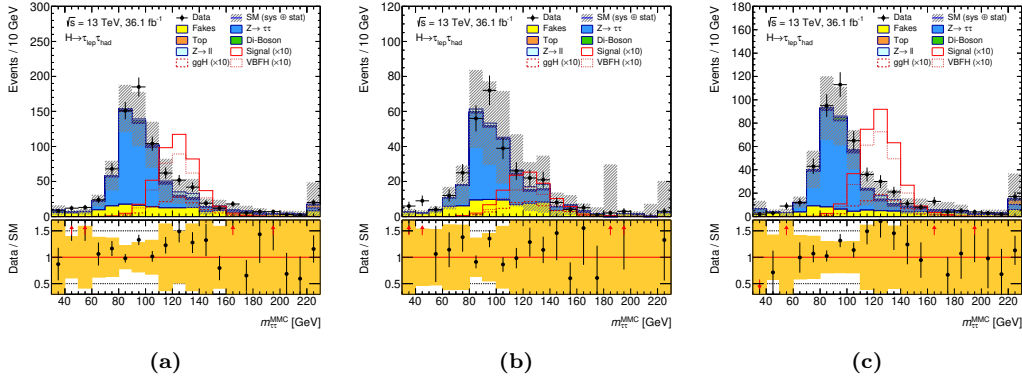
For the definition of the control region for top-quark backgrounds (TopCR), at least one  $b$ -tagged jet is required. Additionally, the cut on the transverse mass is changed from  $m_T < 70$  GeV to  $m_T > 40$  GeV to reject the  $Z \rightarrow \tau\tau$  background in the TopCR, as shown in Figure 4.23. This region is used to normalise the top-quark background to data in the maximum-likelihood fit.

##### $W$ +jets background

To construct a region enriched with events containing a quark-initiated jet misidentified as  $\tau_{\text{had}}$ , the main source being the  $W$ +jets process, the cut on the transverse mass is inverted to  $m_T > 70$  GeV. The  $W$ +jets control region (WCR) is used in the



**Figure 4.18:** Distributions of  $m_{jj}$  (a) and  $p_T^H$  (b) in the VBF Tight category before the application of the respective selection criterion. Statistical and systematic uncertainties are included in the uncertainty band.



**Figure 4.19:**  $m_{\tau\tau}^{\text{MMC}}$  distribution in the inclusive VBF- (a), VBF Loose- (b), and VBF Tight (c) categories. The signal contributions are scaled by 10. Statistical and systematic uncertainties are included in the uncertainty band.

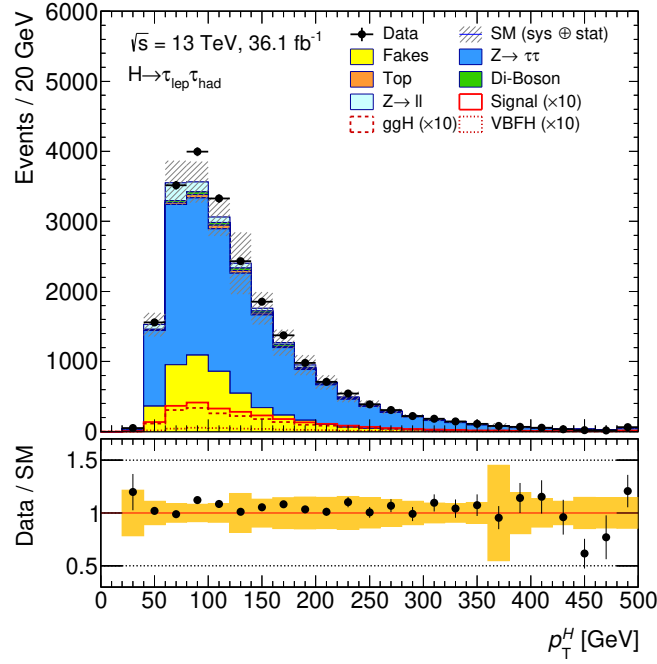
Fake Factor method to estimate the contribution of quark-initiated jets to the Fake background.

### Multijet background

For the control region for the multijet background (QCD CR), the isolation requirement of the lepton is inverted. This region is enriched with multijet events where a gluon-initiated jet is misidentified as  $\tau_{\text{had}}$ . The QCD CR is used in the Fake Factor method to estimate the contribution of gluon-initiated jets to the Fake background.

The event yields, the fractions of the respective targeted background, and the fractions of the signal in the control regions are shown in Tables 4.7 to 4.9. The signal contamination in the control regions is very low with a maximum of 2.8% in the multijet control region of the VBF Tight category.

The purities of the control regions, i.e. the relative amount of events of the targeted background with respect to the total amount of events, are good. They are between



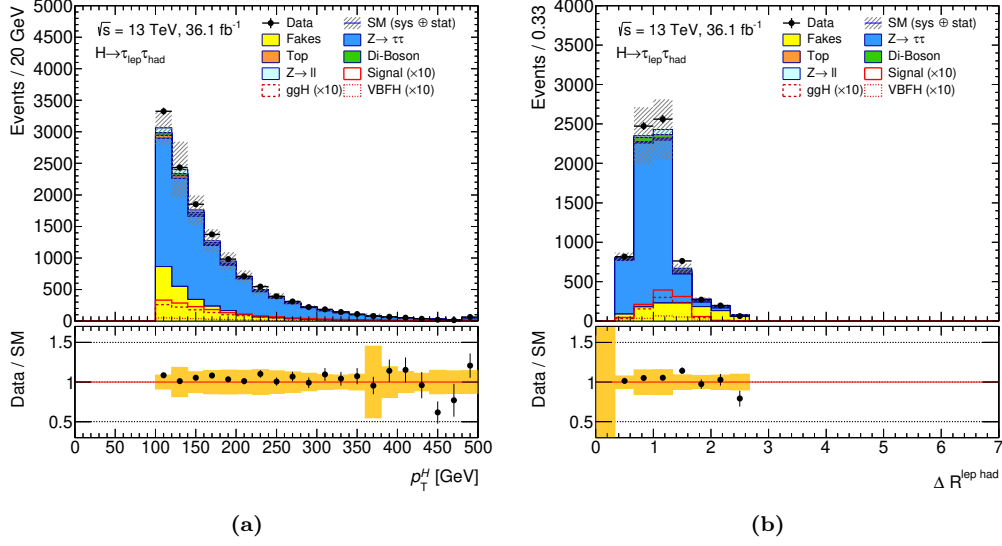
**Figure 4.20:** Distribution of  $p_T^H$  in the Boosted category before the application of the selection criterion. Statistical and systematic uncertainties are included in the uncertainty band.

41 % and 63 % for the TopCRs, between 39 % and 72 % for the QCDCRs, and between 52 % and 71 % for the WCRs, depending on the category. For all CRs, the Boosted High category is the category with the lowest purity.

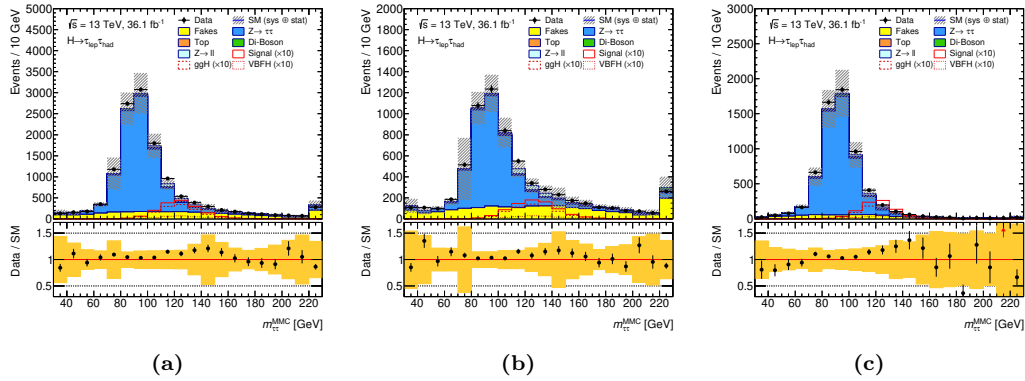
In the TopCRs, the Fake background is the second largest background, whereas  $Z \rightarrow \tau\tau$  is the second largest background in the QCDCRs. In the WCRs, the  $Z \rightarrow \tau\tau$ -,  $Z \rightarrow \ell\ell$ -, diboson-, and top-quark backgrounds contribute in similar amounts.

The negative yield for  $t\bar{t}H$  in the WCR of the VBF Loose category is caused by a single event with negative weight. Negative weights occur in the event generation with MC@NLO [291].

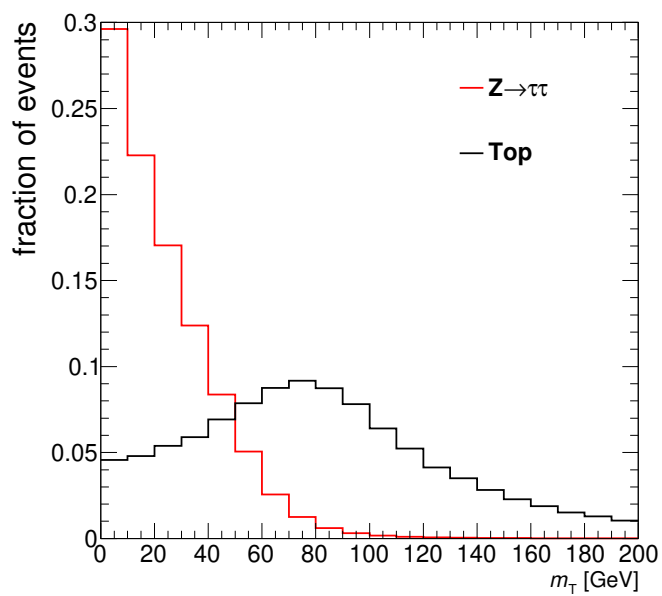




**Figure 4.21:** Distributions of  $p_T^H$  (a) and  $\Delta R_{\ell, \tau_{\text{had}}}$  (b) in the Boosted High category before the application of the respective selection criterion. Statistical and systematic uncertainties are included in the uncertainty band.



**Figure 4.22:**  $m_{\tau\tau}^{\text{MMC}}$  distribution in the inclusive Boosted- (a), Boosted Low- (b), and Boosted High (c) categories. The signal contributions are scaled by 10. Statistical and systematic uncertainties are included in the uncertainty band.



**Figure 4.23:** The transverse mass  $m_T$  for the  $Z \rightarrow \tau\tau$  background (red) and for the top-quark background (black) after the preselection without the requirement on  $m_T$  but with the requirement of at least one  $b$ -tagged jet.

| Category      | VBF               | $ggF$           | $VH$              | $t\bar{t}H$       | Signal          |
|---------------|-------------------|-----------------|-------------------|-------------------|-----------------|
| VBF incl.     | $1.08 \pm 0.06$   | $1.12 \pm 0.19$ | $0.041 \pm 0.021$ | $0.20 \pm 0.04$   | $2.43 \pm 0.21$ |
| VBF Tight     | $0.79 \pm 0.05$   | $0.76 \pm 0.16$ | $0.013 \pm 0.008$ | $0.17 \pm 0.04$   | $1.73 \pm 0.18$ |
| VBF Loose     | $0.285 \pm 0.028$ | $0.36 \pm 0.10$ | $0.028 \pm 0.019$ | $0.023 \pm 0.012$ | $0.70 \pm 0.11$ |
| Boosted incl. | $1.37 \pm 0.07$   | $7.2 \pm 0.4$   | $1.71 \pm 0.12$   | $6.64 \pm 0.23$   | $16.9 \pm 0.5$  |
| Boosted High  | $0.69 \pm 0.05$   | $3.96 \pm 0.30$ | $1.01 \pm 0.10$   | $1.91 \pm 0.13$   | $7.56 \pm 0.35$ |
| Boosted Low   | $0.68 \pm 0.05$   | $3.21 \pm 0.29$ | $0.70 \pm 0.07$   | $4.73 \pm 0.18$   | $9.33 \pm 0.35$ |

| Category      | $Z \rightarrow \tau\tau$ | Fake            | Top             | $Z \rightarrow \ell\ell$ | Diboson        | Background      | Data   | Top fraction [%] | Signal fraction [%] |
|---------------|--------------------------|-----------------|-----------------|--------------------------|----------------|-----------------|--------|------------------|---------------------|
| VBF incl.     | $25 \pm 5$               | $66 \pm 4$      | $157 \pm 9$     | $19 \pm 10$              | $5.2 \pm 0.9$  | $272 \pm 15$    | 324    | 57               | 0.9                 |
| VBF Tight     | $13.8 \pm 3.2$           | $41.6 \pm 3.0$  | $107 \pm 7$     | $14 \pm 10$              | $3.6 \pm 0.7$  | $180 \pm 13$    | 223    | 59               | 1.0                 |
| VBF Loose     | $11 \pm 4$               | $24.7 \pm 2.0$  | $49 \pm 5$      | $5.5 \pm 1.7$            | $1.5 \pm 0.6$  | $92 \pm 7$      | 101    | 53               | 0.7                 |
| Boosted incl. | $409 \pm 19$             | $1\,439 \pm 19$ | $2\,900 \pm 40$ | $50 \pm 8$               | $65.1 \pm 2.8$ | $4\,860 \pm 50$ | 4\,934 | 59               | 0.3                 |
| Boosted High  | $208 \pm 12$             | $252 \pm 8$     | $347 \pm 13$    | $22.0 \pm 3.2$           | $20.2 \pm 1.3$ | $848 \pm 20$    | 871    | 41               | 0.9                 |
| Boosted Low   | $201 \pm 15$             | $1\,187 \pm 17$ | $2\,550 \pm 34$ | $28 \pm 7$               | $44.9 \pm 2.5$ | $4\,010 \pm 40$ | 4\,063 | 63               | 0.2                 |

**Table 4.7:** Event yields, fraction of the top-quark background, and the fraction of the signal in the TopCR. *Signal* and *Background* are the sum of all signal- and background processes, respectively. The fractions are relative to the total signal- and background yield. All samples are normalised to their respective theoretical cross-section except for the data-driven Fake estimate.

| Category      | VBF               | $ggF$           | $VH$              | $t\bar{t}H$         | Signal          |
|---------------|-------------------|-----------------|-------------------|---------------------|-----------------|
| VBF incl.     | $1.35 \pm 0.06$   | $0.52 \pm 0.09$ | $0.023 \pm 0.013$ | $0.0010 \pm 0.0007$ | $1.90 \pm 0.11$ |
| VBF Tight     | $0.99 \pm 0.06$   | $0.31 \pm 0.07$ | $0.023 \pm 0.013$ | $0.0010 \pm 0.0007$ | $1.33 \pm 0.09$ |
| VBF Loose     | $0.360 \pm 0.029$ | $0.21 \pm 0.05$ | $0.0 \pm 0.0$     | $0.0 \pm 0.0$       | $0.57 \pm 0.06$ |
| Boosted incl. | $1.07 \pm 0.05$   | $5.43 \pm 0.33$ | $0.56 \pm 0.06$   | $0.035 \pm 0.013$   | $7.09 \pm 0.34$ |
| Boosted High  | $0.494 \pm 0.034$ | $2.49 \pm 0.20$ | $0.35 \pm 0.05$   | $0.018 \pm 0.009$   | $3.36 \pm 0.21$ |
| Boosted Low   | $0.571 \pm 0.034$ | $2.94 \pm 0.26$ | $0.208 \pm 0.032$ | $0.018 \pm 0.010$   | $3.73 \pm 0.26$ |

| Category      | $Z \rightarrow \tau\tau$ | Fake           | Top             | $Z \rightarrow \ell\ell$ | Diboson         | Background      | Data   | Fake fraction [%] | Signal fraction [%] |
|---------------|--------------------------|----------------|-----------------|--------------------------|-----------------|-----------------|--------|-------------------|---------------------|
| VBF incl.     | $28.4 \pm 3.5$           | $70.8 \pm 3.3$ | $1.5 \pm 0.7$   | $0.6 \pm 0.4$            | $0.13 \pm 0.12$ | $101 \pm 5$     | 101    | 69                | 1.8                 |
| VBF Tight     | $14.3 \pm 2.2$           | $30.8 \pm 2.2$ | $1.2 \pm 0.6$   | $0.36 \pm 0.30$          | $0.04 \pm 0.10$ | $46.7 \pm 3.2$  | 50     | 64                | 2.8                 |
| VBF Loose     | $14.1 \pm 2.7$           | $40.0 \pm 2.4$ | $0.26 \pm 0.26$ | $0.21 \pm 0.21$          | $0.09 \pm 0.05$ | $55 \pm 4$      | 51     | 72                | 1.0                 |
| Boosted incl. | $369 \pm 17$             | $646 \pm 10$   | $16.0 \pm 2.2$  | $10 \pm 9$               | $8.5 \pm 0.7$   | $1\,049 \pm 22$ | 1\,051 | 61                | 0.7                 |
| Boosted High  | $197 \pm 11$             | $140 \pm 5$    | $6.0 \pm 1.4$   | $2.9 \pm 1.0$            | $4.3 \pm 0.5$   | $350 \pm 12$    | 372    | 39                | 0.9                 |
| Boosted Low   | $172 \pm 13$             | $506 \pm 9$    | $10.0 \pm 1.7$  | $7 \pm 9$                | $4.2 \pm 0.5$   | $699 \pm 18$    | 679    | 72                | 0.5                 |

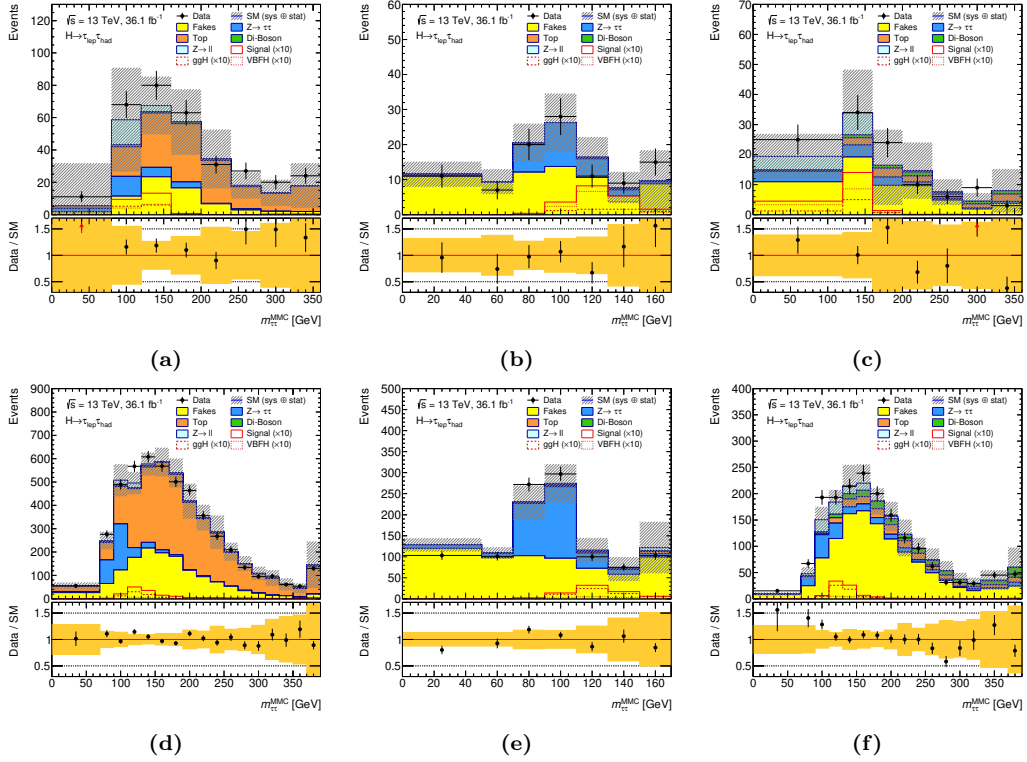
**Table 4.8:** Event yields, fraction of the Fake background, and the fraction of the signal in the QCDCR. *Signal* and *Background* are the sum of all signal- and background processes, respectively. The fractions are relative to the total signal- and background yield. All samples are normalised to their respective theoretical cross-section except for the data-driven Fake estimate.

| Category      | VBF               | $ggF$           | $VH$              | $t\bar{t}H$          | Signal          |
|---------------|-------------------|-----------------|-------------------|----------------------|-----------------|
| VBF incl.     | $1.25 \pm 0.05$   | $0.69 \pm 0.12$ | $0.061 \pm 0.017$ | $0.010 \pm 0.006$    | $2.01 \pm 0.13$ |
| VBF Tight     | $0.95 \pm 0.05$   | $0.44 \pm 0.09$ | $0.018 \pm 0.007$ | $0.011 \pm 0.006$    | $1.41 \pm 0.10$ |
| VBF Loose     | $0.300 \pm 0.024$ | $0.26 \pm 0.07$ | $0.044 \pm 0.016$ | $-0.0016 \pm 0.0011$ | $0.60 \pm 0.08$ |
| Boosted incl. | $1.16 \pm 0.05$   | $5.58 \pm 0.30$ | $1.23 \pm 0.12$   | $0.184 \pm 0.030$    | $8.15 \pm 0.33$ |
| Boosted High  | $0.453 \pm 0.031$ | $2.52 \pm 0.22$ | $0.43 \pm 0.08$   | $0.054 \pm 0.015$    | $3.46 \pm 0.24$ |
| Boosted Low   | $0.70 \pm 0.04$   | $3.06 \pm 0.20$ | $0.80 \pm 0.09$   | $0.131 \pm 0.026$    | $4.69 \pm 0.22$ |

| Category      | $Z \rightarrow \tau\tau$ | Fake           | Top            | $Z \rightarrow \ell\ell$ | Diboson         | Background    | Data | Fake fraction [%] | Signal fraction [%] |
|---------------|--------------------------|----------------|----------------|--------------------------|-----------------|---------------|------|-------------------|---------------------|
| VBF incl.     | $12.9 \pm 3.0$           | $60 \pm 6$     | $12.7 \pm 1.9$ | $12 \pm 5$               | $6.3 \pm 0.6$   | $103 \pm 8$   | 111  | 57                | 1.9                 |
| VBF Tight     | $8.1 \pm 2.6$            | $36.5 \pm 2.5$ | $9.6 \pm 1.6$  | $5.2 \pm 2.0$            | $4.8 \pm 0.4$   | $64 \pm 4$    | 54   | 56                | 2.2                 |
| VBF Loose     | $4.8 \pm 1.5$            | $23 \pm 5$     | $3.1 \pm 0.9$  | $7 \pm 4$                | $1.5 \pm 0.5$   | $39 \pm 7$    | 57   | 59                | 1.5                 |
| Boosted incl. | $173 \pm 10$             | $1134 \pm 16$  | $148 \pm 7$    | $80 \pm 23$              | $132.4 \pm 3.4$ | $1668 \pm 31$ | 1737 | 68                | 0.5                 |
| Boosted High  | $58 \pm 5$               | $154 \pm 6$    | $18.8 \pm 2.7$ | $36 \pm 5$               | $25.6 \pm 1.3$  | $292 \pm 10$  | 317  | 52                | 1.2                 |
| Boosted Low   | $116 \pm 9$              | $980 \pm 15$   | $130 \pm 7$    | $44 \pm 22$              | $106.8 \pm 3.1$ | $1376 \pm 29$ | 1420 | 71                | 0.3                 |

**Table 4.9:** Event yields, fraction of the Fake background, and the fraction of the signal in the WCR. *Signal* and *Background* are the sum of all signal- and background processes, respectively. The fractions are relative to the total signal- and background yield. All samples are normalised to their respective theoretical cross-section except for the data-driven Fake estimate.

The  $m_{\tau\tau}^{\text{MMC}}$  distribution in the control regions is shown in Figure 4.24. A good modelling of the backgrounds within uncertainties is observed.



**Figure 4.24:** The  $m_{\tau\tau}^{\text{MMC}}$  distribution in the control regions for the inclusive VBF- (top) and Boosted (bottom) categories. Shown are the top-quark- (a)+(d), QCD- (b)+(e), and  $W$ +jets (c)+(f) control regions. Statistical and systematic uncertainties are included in the uncertainty band.

## 4.6 Background estimation

A precise estimation of both the yields and the modelling of the backgrounds is important for the signal extraction. The estimation for all background processes except Fakes is taken from simulation. The normalisations of the top-quark- and  $Z \rightarrow \tau\tau$  background processes are obtained from data in the maximum-likelihood fit. This is done separately in the inclusive VBF- and Boosted categories since the phase spaces in the two categories are very different. The respective theoretical predictions are used for all other background processes. A data-driven *Fake Factor* method is used for the estimation of the Fake background, discussed in Section 4.6.1. The modelling of the simulated  $Z \rightarrow \tau\tau$  background is validated in a dedicated validation region which is introduced in Section 4.6.2.

### 4.6.1 Fake estimation

One of the dominant background processes in this analysis are events with a jet that is misidentified as a hadronically decaying  $\tau$ -lepton. This process is difficult to simulate with precise modelling. An accurate description of the quark-to-gluon ratio in the events is required since the  $\tau_{\text{had}}$  misidentification probability differs due to the

different shower shapes of the energy depositions of quark- and gluon-initiated jets in the calorimeters. However, the  $\tau_{\text{had}}$  identification criteria depend on the shower shape, so only a specific subset of jets is selected. This can lead to a bias of the quark-to-gluon ratio. It is also very challenging to achieve a good modelling in the simulation of the shower shapes separately for quark- and gluon-initiated jets.

Additionally, a large amount of simulated multijet events is required due to the high production cross-section at the LHC on one hand and the low efficiency of selecting events with misidentified  $\tau_{\text{had}}$  candidates on the other hand. The production of these large samples is computationally very intensive and only a small fraction of the simulated events would be used in the analysis. Therefore, these samples do not exist and a data-driven method, the *Fake Factor* method, to estimate this background has to be used.

The aim of the Fake Factor method is to estimate the number of misidentified  $\tau_{\text{had}}$  candidates in the signal region that pass the identification criteria,  $N_{\text{Fake}}^{\text{pass, SR}}$ . For this, the number of events in data that fail this criteria,  $N_{\text{data}}^{\text{fail, SR}}$ , is multiplied with the Fake Factor FF. Both the yield and the shapes of distributions are estimated by this method since the FF is applied per event.

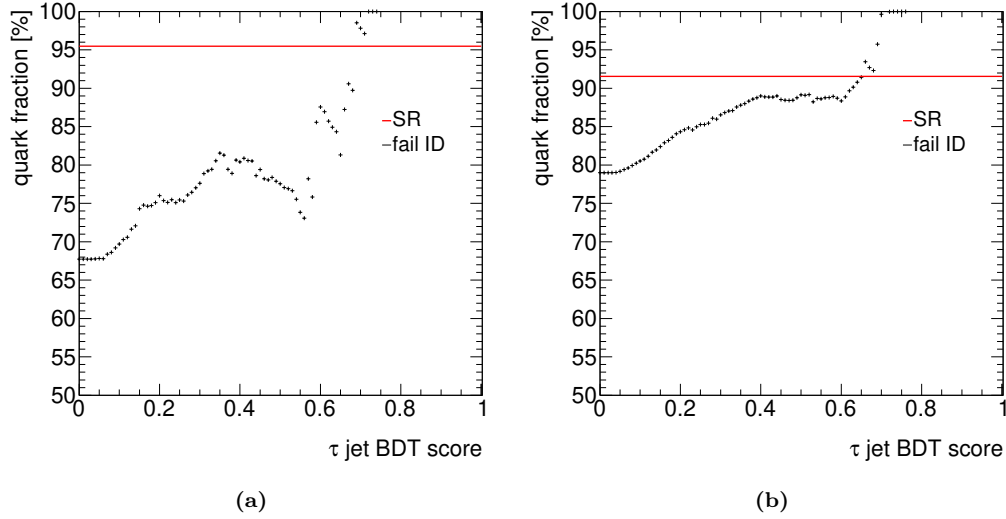
For the estimation of the FF, a region enriched with fake  $\tau_{\text{had}}$  is defined by inverting the identification criterion: the  $\tau_{\text{had}}$  candidate has to fail the *medium* identification (ID) working point. Since the BDT that is used to define the identification working points assigns a low score to  $\tau_{\text{had}}$  candidates that originate from a gluon-initiated jet, a minimum value of the  $\text{BDT}_{\text{score}}$  is required to suppress this gluon-dominated region and to obtain a quark-to-gluon ratio similar to that in the signal region.

Figure 4.25 shows the quark fraction in  $W$ +jets events in the VBF- and Boosted categories for the signal region, where the  $\tau_{\text{had}}$  candidate is required to pass the *medium* ID, and the quark fraction as a function of the  $\text{BDT}_{\text{score}}$  for events that fail the *medium* ID and after cutting on the respective value of the  $\text{BDT}_{\text{score}}$ . The quark fraction is defined as the number of events that contain a quark-initiated jet faking a  $\tau_{\text{had}}$  divided by the number of all events with a jet faking a  $\tau_{\text{had}}$ ,  $\frac{N_{q\text{-jet} \rightarrow \tau_{\text{had}}}}{N_{q\text{-jet} \rightarrow \tau_{\text{had}}} + N_{g\text{-jet} \rightarrow \tau_{\text{had}}}}$ . The classification of a  $\tau_{\text{had}}$  candidate as quark- or gluon-initiated jet is done by a geometric matching within an angular distance  $\Delta R < 0.2$  between the reconstructed  $\tau_{\text{had}}$  and particles at the generator level of the simulation.

A cut on a rather high value of the  $\text{BDT}_{\text{score}}$  would be required to reach the same quark fraction as in the signal regions. This would limit the number of events available for the estimation of the FF and increase the statistical uncertainty. Therefore, the cut  $\text{BDT}_{\text{score}} > 0.25$  is chosen to obtain quark fractions similar to those in the signal regions and to preserve reasonable statistics at the same time. The resulting quark fractions are listed in Table 4.10.

The Fake Factor is then defined as the ratio between the number of events with a  $\tau_{\text{had}}$  that passes the identification  $N^{\text{pass}}$  and the number of events with a  $\tau_{\text{had}}$  that fails the identification  $N^{\text{fail}}$ :

$$\text{FF} = \frac{N^{\text{pass}}}{N^{\text{fail}}} \quad (4.9)$$



**Figure 4.25:** Quark fractions in  $W$ +jets events in the VBF- (a) and Boosted (b) categories for the signal region (red), and the quark fraction as a function of the  $\text{BDT}_{\text{score}}$  for events that fail the *medium* ID and after cutting on the respective value of the  $\text{BDT}_{\text{score}}$  (black).

|                                              | VBF [%] | Boosted [%] |
|----------------------------------------------|---------|-------------|
| SR                                           | 95      | 92          |
| fail ID & $\text{BDT}_{\text{score}} > 0.25$ | 75      | 85          |

**Table 4.10:** Quark fractions in  $W$ +jets events in the VBF- and Boosted categories for the signal region, and for events that fail the *medium* ID with a  $\text{BDT}_{\text{score}} > 0.25$ .

Since the misidentification probability is different for quark- and gluon-initiated jets, Fake Factors are calculated in control regions that are enriched with the respective jets.  $W$ +jets,  $Z \rightarrow \ell\ell$  + jets, and top quarks are primarily produced with a gluon in the initial state. Therefore, these processes have mainly quark-initiated jets in the final state.  $W$ +jets is the dominant background of these processes and thus the WCR is used to derive the Fake Factor. For the Fake Factor of gluon-initiated jets, multijet events in the QCDCR are used.

When calculating the Fake Factors, contributions from events that contain a  $\tau_{\text{had}}$  that is not faked by a jet, e.g. a true  $\tau_{\text{had}}$  or a misidentified lepton, are subtracted. Simulation is used to estimate this subtraction part. The resulting equations are:

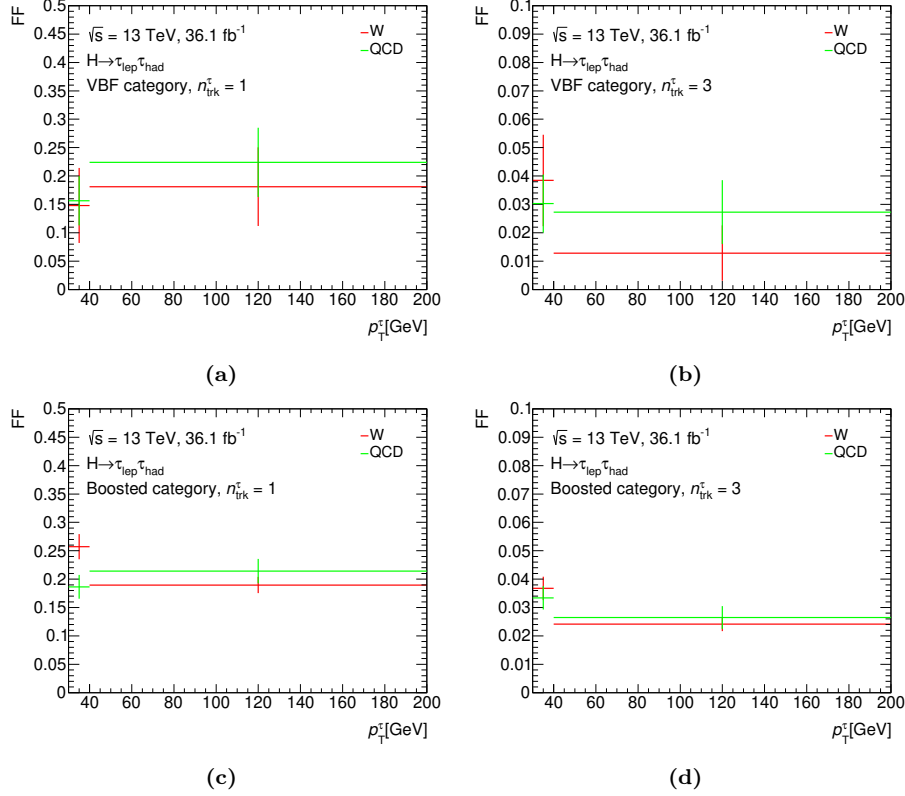
$$\text{FF}_W = \frac{N_{\text{data}}^{\text{pass, WCR}} - N_{\text{MC, no jet} \rightarrow \tau_{\text{had}}}^{\text{pass, WCR}}}{N_{\text{data}}^{\text{fail, WCR}} - N_{\text{MC, no jet} \rightarrow \tau_{\text{had}}}^{\text{fail, WCR}}} \quad (4.10)$$

$$\text{FF}_{\text{QCD}} = \frac{N_{\text{data}}^{\text{pass, QCDCR}} - N_{\text{MC, no jet} \rightarrow \tau_{\text{had}}}^{\text{pass, QCDCR}}}{N_{\text{data}}^{\text{fail, QCDCR}} - N_{\text{MC, no jet} \rightarrow \tau_{\text{had}}}^{\text{fail, QCDCR}}}$$

The Fake Factors are calculated separately for the inclusive VBF- and Boosted categories, and depend on the  $p_T$  and on the track multiplicity of the  $\tau_{\text{had}}$ , as shown in Figure 4.26. The numerical values are listed in Table 4.11.

The Fake Factors of the two categories are in agreement within their statistical uncertainty, which is rather large for the VBF category due to low statistics. The





**Figure 4.26:** Fake Factors  $FF_W$  (red) and  $FF_{QCD}$  (green) for the VBF category with a 1-track  $\tau_{had}$  (a) and a 3-track  $\tau_{had}$  (b), and for the Boosted category with a 1-track  $\tau_{had}$  (c) and a 3-track  $\tau_{had}$  (d). The statistical uncertainty of the Fake Factors is shown.

FFs are larger for 1-track  $\tau_{had}$  than for 3-track  $\tau_{had}$ , likely due to the smaller background rejection of the *medium* ID working point for 1-track  $\tau_{had}$ , as shown in Figure 3.15. For  $p_T < 40$  GeV,  $FF_W$  tends to be larger than  $FF_{QCD}$ . This trend is reverted for  $p_T > 40$  GeV, but they are consistent within statistical uncertainties. A possible explanation is the dependence of the shower properties, e.g. the width or the track multiplicity, on  $p_T$ . Higher statistics are required to reduce the statistical uncertainty and to study this behaviour in more detail, i.e. with a finer binning in  $p_T$ .

For the estimation of the Fake background in the signal region, a combined Fake Factor is constructed as the sum of  $FF_W$  and  $FF_{QCD}$ , weighted by the expected

|         |         | $FF_W$         |                | $FF_{QCD}$     |                |
|---------|---------|----------------|----------------|----------------|----------------|
|         |         | $p_T < 40$ GeV | $p_T > 40$ GeV | $p_T < 40$ GeV | $p_T > 40$ GeV |
| VBF     | 1-track | 0.148          | 0.181          | 0.156          | 0.224          |
|         | 3-track | 0.038          | 0.013          | 0.030          | 0.027          |
| Boosted | 1-track | 0.257          | 0.190          | 0.186          | 0.214          |
|         | 3-track | 0.037          | 0.024          | 0.033          | 0.026          |

**Table 4.11:** Fake Factors for the VBF- and Boosted categories, and for 1-track- and 3-track  $\tau_{had}$ .

contributions of the two processes:

$$FF = R_W FF_W + R_{QCD} FF_{QCD} \quad (4.11)$$

where  $R_W$  is the contribution from  $W$ +jets events and  $R_{QCD}$  is the contribution from multijet events in the SR.  $R_{QCD}$  is obtained from data and since it is assumed that other sources of fake  $\tau_{had}$  are negligible, the contribution of  $W$ +jets is taken to be  $R_W = 1 - R_{QCD}$ .

$R_{QCD}$  is calculated by

$$R_{QCD} = \frac{N_{QCD}^{fail, SR}}{N_{data}^{fail, SR} - N_{MC, no\ jet \rightarrow \tau_{had}}^{fail, SR}} \quad (4.12)$$

$R_{QCD}$  is calculated separately for electrons and muons, for 1- and 3-track  $\tau_{had}$  candidates, and as function of the azimuthal angle between the  $\tau_{had}$  and the missing energy  $\Delta\phi_{\tau_{had}, E_T^{miss}}$ , and the  $p_T$  of the  $\tau_{had}$ .

The number of multijet events in the signal region  $N_{QCD}^{fail, SR}$  is taken from data in the QCD control region. To account for the difference in lepton isolation between the two regions, this number is multiplied by a transfer factor, the *Isolation Factor* (IF):

$$N_{QCD}^{fail, SR} = \left( N_{data}^{fail, QCDCR} - N_{MC, true\ lepton}^{fail, QCDCR} \right) \cdot IF \quad (4.13)$$

where the number of events that contain a true lepton is estimated from simulation and subtracted. The Isolation Factor is defined as the ratio between events passing the lepton isolation requirement ( $N^{iso}$ ) and the events failing it ( $N^{non-iso}$ ), and is derived after the preselection but with the requirement of same charge of the lepton and the  $\tau_{had}$  candidate (SSCR) to avoid overlap with the nominal event selection. The contribution of events that contain a true lepton is again subtracted in the calculation:

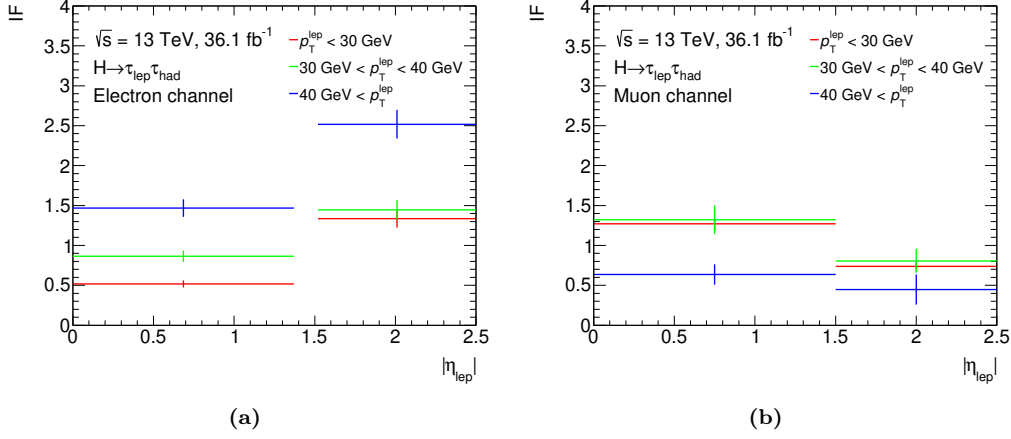
$$IF = \frac{N_{data}^{iso, SSCR} - N_{MC, true\ lepton}^{iso, SSCR}}{N_{data}^{non-iso, SSCR} - N_{MC, true\ lepton}^{non-iso, SSCR}} \quad (4.14)$$

The Isolation Factors are calculated separately for electrons and muons, and depend on the transverse momentum  $p_T$  and the rapidity  $|\eta|$  of the lepton, excluding the transition region  $1.37 < |\eta| < 1.52$  between the barrel- and the endcap calorimeter. The Isolation Factors are shown in Figure 4.27 and the numerical values are listed in Table 4.12,

|                                 | Electron        |                 | Muon           |                |
|---------------------------------|-----------------|-----------------|----------------|----------------|
|                                 | $ \eta  < 1.37$ | $ \eta  > 1.52$ | $ \eta  < 1.5$ | $ \eta  > 1.5$ |
| $p_T < 30$ GeV                  | 0.518           | 1.335           | 1.271          | 0.739          |
| $30 \text{ GeV} < p_T < 40$ GeV | 0.865           | 1.447           | 1.322          | 0.806          |
| $40 \text{ GeV} < p_T$          | 1.467           | 2.518           | 0.636          | 0.448          |

**Table 4.12:** Isolation Factors for the electron channel and the muon channel, and for different  $p_T$  values.

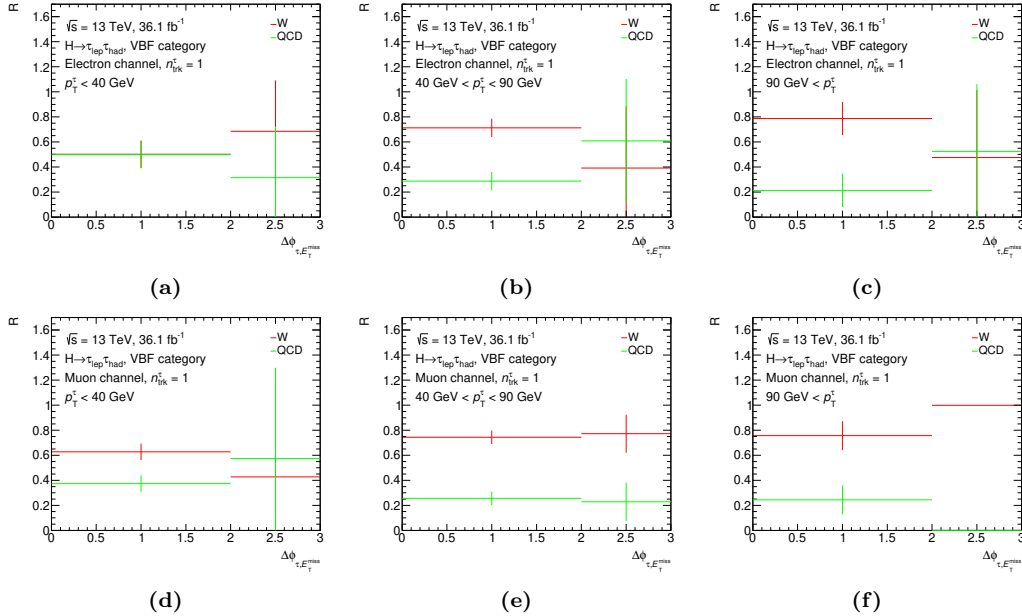
In the electron channel, the IFs are smallest for  $p_T < 30$  GeV and highest for  $p_T > 40$  GeV, and they are increasing with  $|\eta_{lep}|$  for all three  $p_T$  regions, likely due



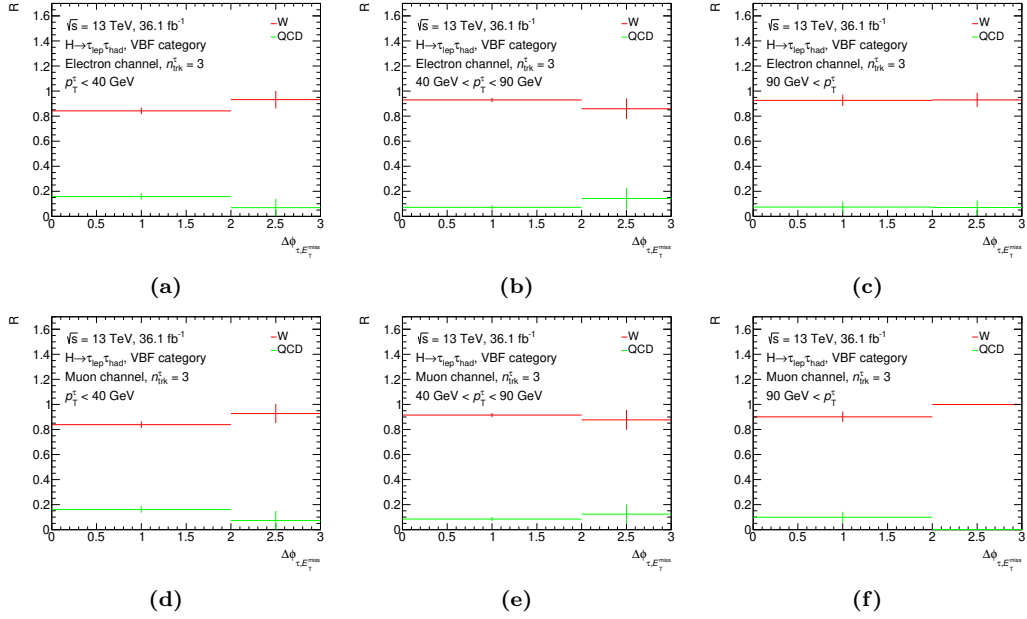
**Figure 4.27:** Isolation Factors as a function of  $|\eta_{\text{lep}}|$  for the electron channel (a) and the muon channel (b) and for different bins in  $p_T$ . The statistical uncertainty of the Isolation Factors is shown.

to the lower identification efficiency for high  $|\eta_{\text{lep}}|$ , as shown in Figure 3.5b. In the muon channel, the highest IFs are found in the intermediate  $p_T$  region,  $30 \text{ GeV} < p_T < 40 \text{ GeV}$ , statistically agreeing with the IFs for  $p_T < 30 \text{ GeV}$ , whereas the smallest ones are in the  $p_T > 40 \text{ GeV}$  region. This can possibly be explained by the lower isolation efficiency for small  $p_T$ , as shown in Figure 3.9. The Isolation Factors in the muon channel are decreasing with  $|\eta_{\text{lep}}|$ .

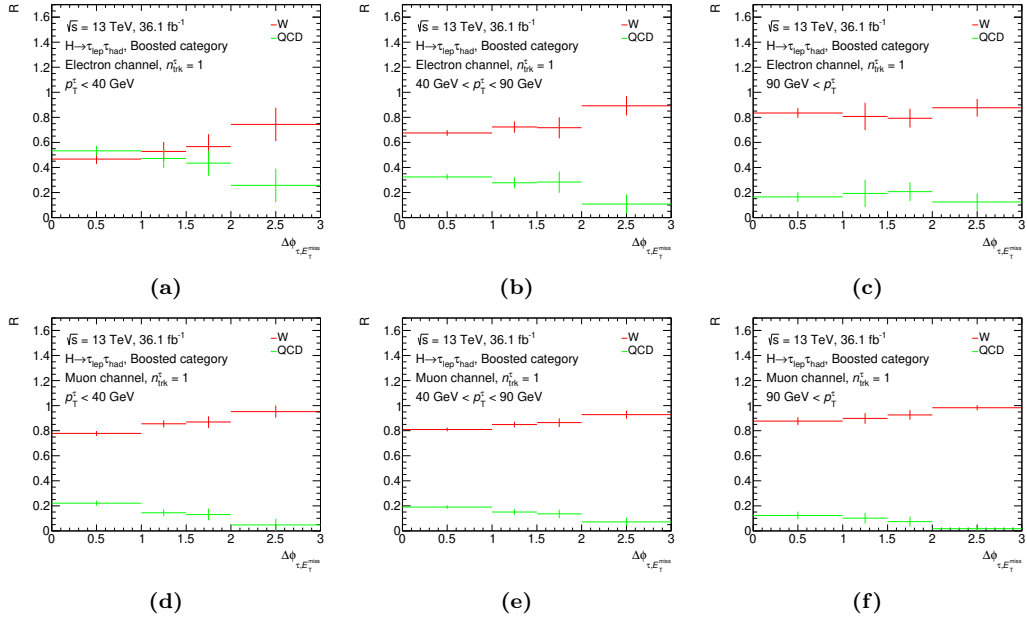
The relative contributions  $R_{\text{QCD}}$  and  $R_W$  are then calculated for the inclusive VBF- and Boosted categories and are shown in Figures 4.28 to 4.31. The numerical values are given in Table 4.13.



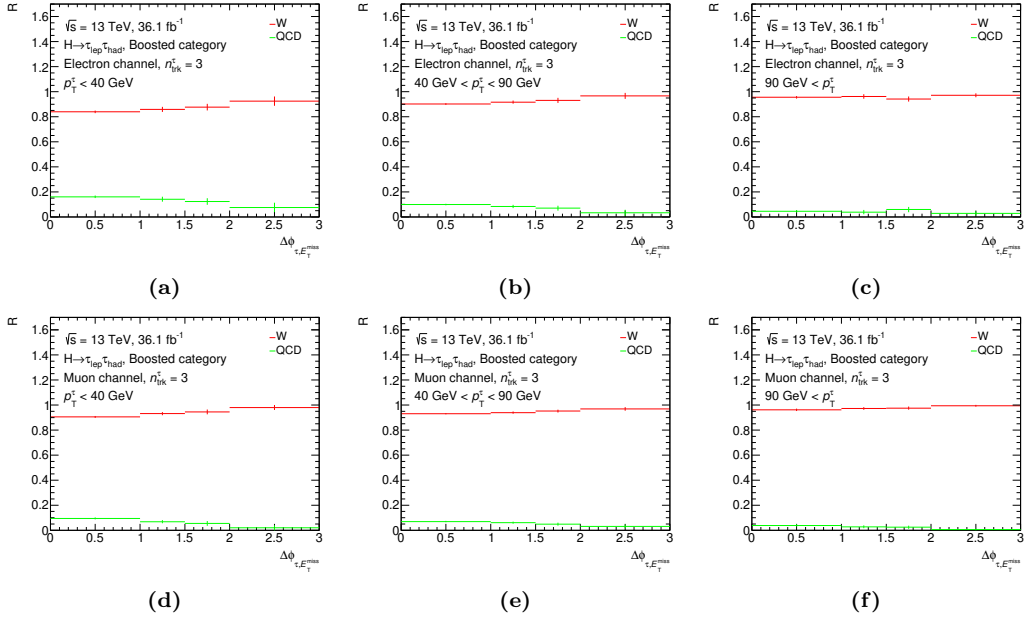
**Figure 4.28:** The relative contributions of multijet- (green) and  $W$ +jets (red) events in the VBF category for 1-track  $\tau_{\text{had}}$ , in the electron channel for  $p_T^{\tau} < 40 \text{ GeV}$  (a),  $40 \text{ GeV} < p_T^{\tau} < 90 \text{ GeV}$  (b) and  $90 \text{ GeV} < p_T^{\tau}$  (c), and in the muon channel for  $p_T^{\tau} < 40 \text{ GeV}$  (d),  $40 \text{ GeV} < p_T^{\tau} < 90 \text{ GeV}$  (e) and  $90 \text{ GeV} < p_T^{\tau}$  (f).



**Figure 4.29:** The relative contributions of multijet- (green) and  $W$ +jets (red) events in the VBF category for 3-track  $\tau_{\text{had}}$ , in the electron channel for  $p_T^\tau < 40$  GeV (a),  $40 \text{ GeV} < p_T^\tau < 90$  GeV (b) and  $90 \text{ GeV} < p_T^\tau$  (c), and in the muon channel for  $p_T^\tau < 40$  GeV (d),  $40 \text{ GeV} < p_T^\tau < 90$  GeV (e) and  $90 \text{ GeV} < p_T^\tau$  (f).



**Figure 4.30:** The relative contributions of multijet- (green) and  $W$ +jets (red) events in the Boosted category for 1-track  $\tau_{\text{had}}$ , in the electron channel for  $p_T^\tau < 40$  GeV (a),  $40 \text{ GeV} < p_T^\tau < 90$  GeV (b) and  $90 \text{ GeV} < p_T^\tau$  (c), and in the muon channel for  $p_T^\tau < 40$  GeV (d),  $40 \text{ GeV} < p_T^\tau < 90$  GeV (e) and  $90 \text{ GeV} < p_T^\tau$  (f).



**Figure 4.31:** The relative contributions of multijet- (green) and  $W$ +jets (red) events in the Boosted category for 3-track  $\tau_{\text{had}}$ , in the electron channel for  $p_T^\tau < 40$  GeV (a),  $40 \text{ GeV} < p_T^\tau < 90$  GeV (b) and  $90 \text{ GeV} < p_T^\tau$  (c), and in the muon channel for  $p_T^\tau < 40$  GeV (d),  $40 \text{ GeV} < p_T^\tau < 90$  GeV (e) and  $90 \text{ GeV} < p_T^\tau$  (f).

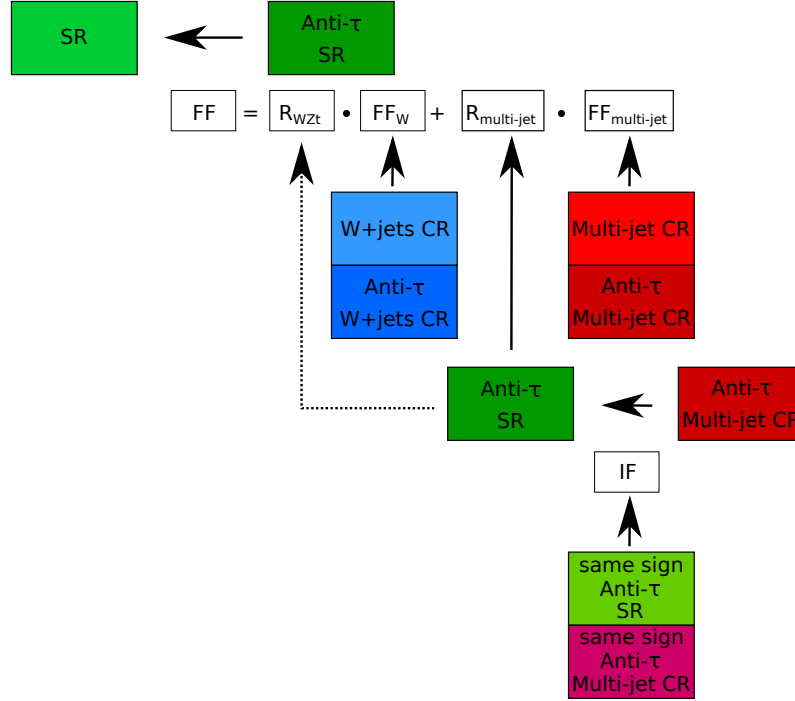
|          |         |                                         | $R_W$            |                  |                  |                        |                        |                  | $R_{QCD}$        |                  |                  |                        |                        |                  |
|----------|---------|-----------------------------------------|------------------|------------------|------------------|------------------------|------------------------|------------------|------------------|------------------|------------------|------------------------|------------------------|------------------|
|          |         |                                         | VBF              |                  | Boosted          |                        |                        |                  | VBF              |                  | Boosted          |                        |                        |                  |
|          |         |                                         | $\Delta\phi < 2$ | $\Delta\phi > 2$ | $\Delta\phi < 1$ | $1 < \Delta\phi < 1.5$ | $1.5 < \Delta\phi < 2$ | $\Delta\phi > 2$ | $\Delta\phi < 2$ | $\Delta\phi > 2$ | $\Delta\phi < 1$ | $1 < \Delta\phi < 1.5$ | $1.5 < \Delta\phi < 2$ | $\Delta\phi > 2$ |
| Electron | 1-track | $p_T < 40$ GeV                          | 0.502            | 0.685            | 0.467            | 0.528                  | 0.566                  | 0.743            | 0.498            | 0.315            | 0.533            | 0.472                  | 0.434                  | 0.257            |
|          |         | $40 \text{ GeV} < p_T < 90 \text{ GeV}$ | 0.713            | 0.391            | 0.675            | 0.723                  | 0.717                  | 0.892            | 0.287            | 0.609            | 0.325            | 0.277                  | 0.283                  | 0.108            |
|          |         | $90 \text{ GeV} < p_T$                  | 0.787            | 0.476            | 0.835            | 0.807                  | 0.793                  | 0.876            | 0.213            | 0.524            | 0.165            | 0.193                  | 0.207                  | 0.124            |
|          | 3-track | $p_T < 40$ GeV                          | 0.842            | 0.931            | 0.839            | 0.859                  | 0.877                  | 0.924            | 0.158            | 0.069            | 0.161            | 0.141                  | 0.123                  | 0.076            |
|          |         | $40 \text{ GeV} < p_T < 90 \text{ GeV}$ | 0.929            | 0.858            | 0.901            | 0.916                  | 0.930                  | 0.967            | 0.071            | 0.142            | 0.099            | 0.084                  | 0.070                  | 0.033            |
|          |         | $90 \text{ GeV} < p_T$                  | 0.926            | 0.930            | 0.955            | 0.962                  | 0.941                  | 0.971            | 0.074            | 0.070            | 0.045            | 0.038                  | 0.059                  | 0.029            |
| Muon     | 1-track | $p_T < 40$ GeV                          | 0.627            | 0.427            | 0.778            | 0.855                  | 0.869                  | 0.953            | 0.373            | 0.573            | 0.222            | 0.145                  | 0.131                  | 0.047            |
|          |         | $40 \text{ GeV} < p_T < 90 \text{ GeV}$ | 0.744            | 0.772            | 0.810            | 0.849                  | 0.864                  | 0.928            | 0.256            | 0.228            | 0.190            | 0.151                  | 0.136                  | 0.072            |
|          |         | $90 \text{ GeV} < p_T$                  | 0.756            | 0.999            | 0.877            | 0.898                  | 0.926                  | 0.983            | 0.244            | 0.001            | 0.123            | 0.102                  | 0.074                  | 0.017            |
|          | 3-track | $p_T < 40$ GeV                          | 0.838            | 0.927            | 0.905            | 0.932                  | 0.945                  | 0.980            | 0.162            | 0.073            | 0.095            | 0.068                  | 0.055                  | 0.020            |
|          |         | $40 \text{ GeV} < p_T < 90 \text{ GeV}$ | 0.915            | 0.876            | 0.930            | 0.940                  | 0.952                  | 0.969            | 0.085            | 0.124            | 0.070            | 0.060                  | 0.048                  | 0.031            |
|          |         | $90 \text{ GeV} < p_T$                  | 0.901            | 0.999            | 0.962            | 0.972                  | 0.976                  | 0.994            | 0.099            | 0.001            | 0.038            | 0.028                  | 0.024                  | 0.006            |

**Table 4.13:** Relative contributions of multijet- and  $W$ +jets events  $R_{QCD}$  and  $R_W$  in the VBF- and Boosted categories. They depend on the type of lepton in the event, the number of tracks and the transverse momentum of the  $\tau_{\text{had}}$  candidate, and the angle  $\Delta\phi$  between  $E_T^{\text{miss}}$  and the  $\tau_{\text{had}}$  candidate.

Only two bins in  $\Delta\phi_{\tau_{\text{had}}, E_T^{\text{miss}}}$  are considered since the statistics are again low in the VBF category.

The contribution of multijet events is in general lower for events with a 3-track  $\tau_{\text{had}}$ . This can again be likely explained by the larger background rejection of the *medium* ID working point for 3-track  $\tau_{\text{had}}$ , as shown in Figure 3.15. A decreasing  $R_{\text{QCD}}$  is observed for higher values of  $p_T^\tau$ . A possible explanation is the better rejection of gluon-initiated Fakes for higher  $p_T^\tau$  due to the shower properties.

The combined Fake Factors calculated with Equation (4.11) are listed in Table 4.14. A sketch of the complete Fake Factor method is shown in Figure 4.32.



**Figure 4.32:** Sketch of the Fake Factor method. Taken from Ref. [292].

The yield and the distribution of events with fake  $\tau_{\text{had}}$  in the signal region can be estimated by multiplying the events that contain a  $\tau_{\text{had}}$  that failed the identification with the combined Fake Factors of Equation (4.11) after subtracting simulated events that do not contain a fake  $\tau_{\text{had}}$ :

$$N_{\text{Fake}}^{\text{pass, SR}} = \left( N_{\text{data}}^{\text{fail, SR}} - N_{\text{MC, no jet} \rightarrow \tau_{\text{had}}}^{\text{fail, SR}} \right) \cdot \text{FF} \quad (4.15)$$

|          |         |                                 | FF = R <sub>W</sub> FF <sub>W</sub> + R <sub>QCD</sub> FF <sub>QCD</sub> |                  |                  |                        |                        |                  |
|----------|---------|---------------------------------|--------------------------------------------------------------------------|------------------|------------------|------------------------|------------------------|------------------|
|          |         |                                 | VBF                                                                      |                  | Boosted          |                        |                        |                  |
|          |         |                                 | $\Delta\phi < 2$                                                         | $\Delta\phi > 2$ | $\Delta\phi < 1$ | $1 < \Delta\phi < 1.5$ | $1.5 < \Delta\phi < 2$ | $\Delta\phi > 2$ |
| Electron | 1-track | $p_T < 40$ GeV                  | 0.152                                                                    | 0.151            | 0.219            | 0.224                  | 0.226                  | 0.239            |
|          |         | $40 \text{ GeV} < p_T < 90$ GeV | 0.193                                                                    | 0.207            | 0.198            | 0.196                  | 0.197                  | 0.192            |
|          |         | $90 \text{ GeV} < p_T$          | 0.190                                                                    | 0.204            | 0.194            | 0.194                  | 0.195                  | 0.193            |
|          | 3-track | $p_T < 40$ GeV                  | 0.037                                                                    | 0.038            | 0.036            | 0.036                  | 0.036                  | 0.037            |
|          |         | $40 \text{ GeV} < p_T < 90$ GeV | 0.014                                                                    | 0.015            | 0.024            | 0.024                  | 0.024                  | 0.024            |
|          |         | $90 \text{ GeV} < p_T$          | 0.014                                                                    | 0.014            | 0.024            | 0.024                  | 0.024                  | 0.024            |
| Muon     | 1-track | $p_T < 40$ GeV                  | 0.151                                                                    | 0.153            | 0.242            | 0.247                  | 0.248                  | 0.254            |
|          |         | $40 \text{ GeV} < p_T < 90$ GeV | 0.192                                                                    | 0.191            | 0.194            | 0.193                  | 0.193                  | 0.191            |
|          |         | $90 \text{ GeV} < p_T$          | 0.192                                                                    | 0.181            | 0.193            | 0.192                  | 0.191                  | 0.190            |
|          | 3-track | $p_T < 40$ GeV                  | 0.037                                                                    | 0.038            | 0.036            | 0.037                  | 0.037                  | 0.037            |
|          |         | $40 \text{ GeV} < p_T < 90$ GeV | 0.014                                                                    | 0.015            | 0.024            | 0.024                  | 0.024                  | 0.024            |
|          |         | $90 \text{ GeV} < p_T$          | 0.014                                                                    | 0.013            | 0.024            | 0.024                  | 0.024                  | 0.024            |

**Table 4.14:** Combined Fake Factors in the VBF- and Boosted categories. They depend on the type of lepton in the event, the number of tracks and the transverse momentum of the  $\tau_{\text{had}}$  candidate, and the angle  $\Delta\phi$  between  $E_T^{\text{miss}}$  and the  $\tau_{\text{had}}$  candidate.

### Systematic uncertainties

Several systematic uncertainties of the Fake Factor method are taken into account:

1. The statistical uncertainty of the Fake Factors FF<sub>W</sub> and FF<sub>QCD</sub> due to the limited statistics in the regions that are used to derive the Fake Factors. The relative uncertainties of the Fake Factors are between 27 % and 76 % in the VBF category and between 8 % and 15 % in the Boosted category.
2. Uncertainties on R<sub>QCD</sub>. Three uncertainties are considered that arise from the estimation of the Isolation Factor:
  - (a) The statistical uncertainty of the Isolation Factors due to the limited statistics in the regions that are used to derive the Isolation Factors. The relative uncertainties are between 7 % and 42 %.
  - (b) The use of the SSCR to derive the Isolation Factors. The difference to the Isolation Factors calculated with the nominal selection is assigned as a systematic uncertainty, which is between 1 % and 54 %.
  - (c) The contamination of the SSCR with events that contain a true lepton. The subtraction part in the calculation of the Isolation Factors is varied by the total uncertainty of the simulated backgrounds of  $\pm 35$  % to estimate this.

The three uncertainties are added in quadrature and are propagated through the full background estimate.

The relative impact of the uncertainties on the Fake yield in the four signal regions is shown in Table 4.15. The statistical uncertainty is dominant in the VBF categories, while the non-closure uncertainty, introduced in the next section, is the largest uncertainty in the Boosted categories.

Since a variation of R<sub>QCD</sub> results in an opposed variation of R<sub>W</sub> due to the relation



$R_W = 1 - R_{QCD}$ , the effect on the combined FF also depends on  $FF_W$  and  $FF_{QCD}$ . This is the reason for the opposite effect on the yields in the VBF- and Boosted categories. Since  $FF_W$  and  $FF_{QCD}$  are rather similar, the effect on the yields is small in all categories.

|              | stat. [%]  | $R_{QCD}$ [%] | non-closure [%] |
|--------------|------------|---------------|-----------------|
| VBF Tight    | $\pm 36.0$ | $+3.3 / -3.1$ | —               |
| VBF Loose    | $\pm 36.7$ | $+2.4 / -2.3$ | —               |
| Boosted High | $\pm 8.3$  | $\mp 0.8$     | $\pm 16.5$      |
| Boosted Low  | $\pm 9.1$  | $-1.8 / +1.7$ | $\pm 13.3$      |

**Table 4.15:** Relative impact of the systematic uncertainties of the Fake Factor method on the Fake yield in the signal regions.

### Closure test

To test the validity of the Fake Factor method, a closure test in the SSCR is performed. For this, the full procedure as described above is repeated in the SSCR, with Isolation Factors derived with the nominal selection. The Fake Factors are then applied to events in the SSCR and the resulting distribution is compared to data. The event yields in SSCR are shown in Table 4.16. Since the SSCR is very pure in events with fake  $\tau_{had}$  and has very little signal contamination, it is sensitive to the modelling of this background component.

The MMC mass  $m_{\tau\tau}^{MMC}$  in the inclusive VBF- and Boosted categories is shown in Figure 4.33. While the background model agrees well within uncertainties with the data in the VBF category, some mismodelling is observed at small values of  $m_{\tau\tau}^{MMC}$  in the Boosted category. By splitting the selection into the number of tracks of the  $\tau_{had}$ ,  $n_{trk}^\tau$ , and the flavour of the lepton, the source of this mismodelling is found to be the electron channel with  $n_{trk}^\tau = 1$ . All combinations of lepton flavour and  $n_{trk}^\tau$  are shown in Figure 4.34.

| Category      | VBF               | $ggF$           | $VH$              | $t\bar{t}H$       | Signal          |
|---------------|-------------------|-----------------|-------------------|-------------------|-----------------|
| VBF incl.     | $0.234 \pm 0.022$ | $0.10 \pm 0.06$ | $0.022 \pm 0.010$ | $0.007 \pm 0.005$ | $0.37 \pm 0.07$ |
| Boosted incl. | $0.197 \pm 0.019$ | $0.84 \pm 0.12$ | $0.85 \pm 0.08$   | $0.15 \pm 0.04$   | $2.03 \pm 0.15$ |

| Category      | $Z \rightarrow \tau\tau$ | Fake          | Top            | $Z \rightarrow \ell\ell$ | Diboson        | Background    | Data | Fake fraction [%] | Signal fraction [%] |
|---------------|--------------------------|---------------|----------------|--------------------------|----------------|---------------|------|-------------------|---------------------|
| VBF incl.     | $2.0 \pm 1.3$            | $136 \pm 4$   | $0.6 \pm 0.4$  | $1.5 \pm 1.3$            | $2.4 \pm 0.7$  | $142 \pm 5$   | 131  | 96                | 0.3                 |
| Boosted incl. | $82 \pm 8$               | $1090 \pm 12$ | $20.7 \pm 3.1$ | $22 \pm 9$               | $22.6 \pm 0.9$ | $1237 \pm 17$ | 1452 | 88                | 0.2                 |

**Table 4.16:** Event yields, fraction of the Fake background, and the fraction of the signal in the SSCR. *Signal* and *Background* are the sum of all signal- and background processes, respectively. The fractions are relative to the total signal- and background yield. All samples are normalised to their respective theoretical cross-section except for the data-driven Fake estimate.

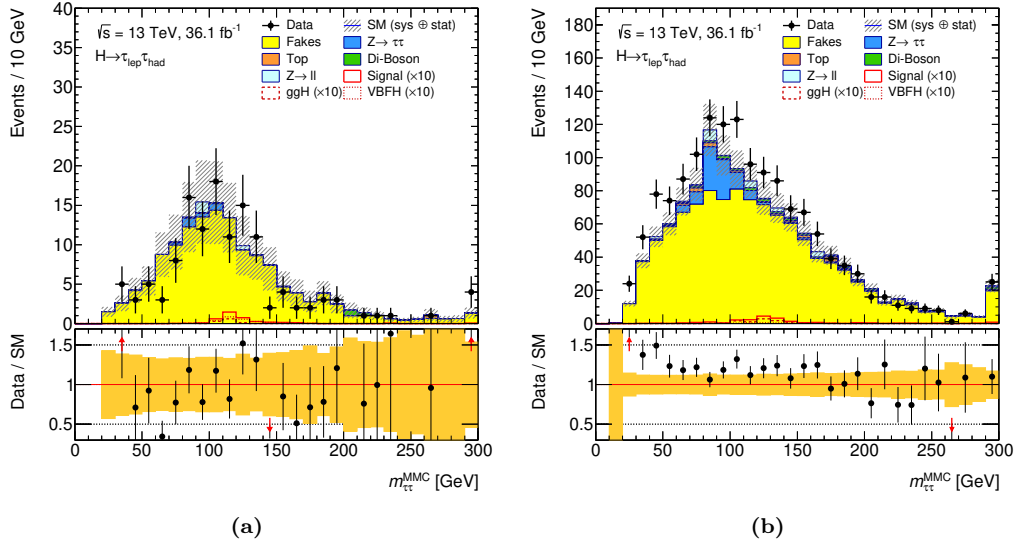
To account for this mismodelling, an additional *non-closure* systematic uncertainty is introduced. A correction factor CF depending on the MMC mass  $m_{\tau\tau}^{\text{MMC}}$  is derived for events in the electron channel with  $n_{\text{trk}}^\tau = 1$ :

$$\text{CF} = \frac{N_{\text{data}}^{\text{SSCR}} - N_{\text{MC}}^{\text{SSCR}} - N_{\text{Fake}}^{\text{SSCR}}}{N_{\text{Fake}}^{\text{SSCR}}} \quad (4.16)$$

When this systematic uncertainty is evaluated, the correction factor is applied to events with fake  $\tau_{\text{had}}$  in the electron channel with  $n_{\text{trk}}^\tau = 1$  and with the nominal selection applied:

$$N_{\text{Fake}}^{\text{SR, syst}} = (1 + \text{CF}) N_{\text{Fake}}^{\text{SR}} \quad (4.17)$$

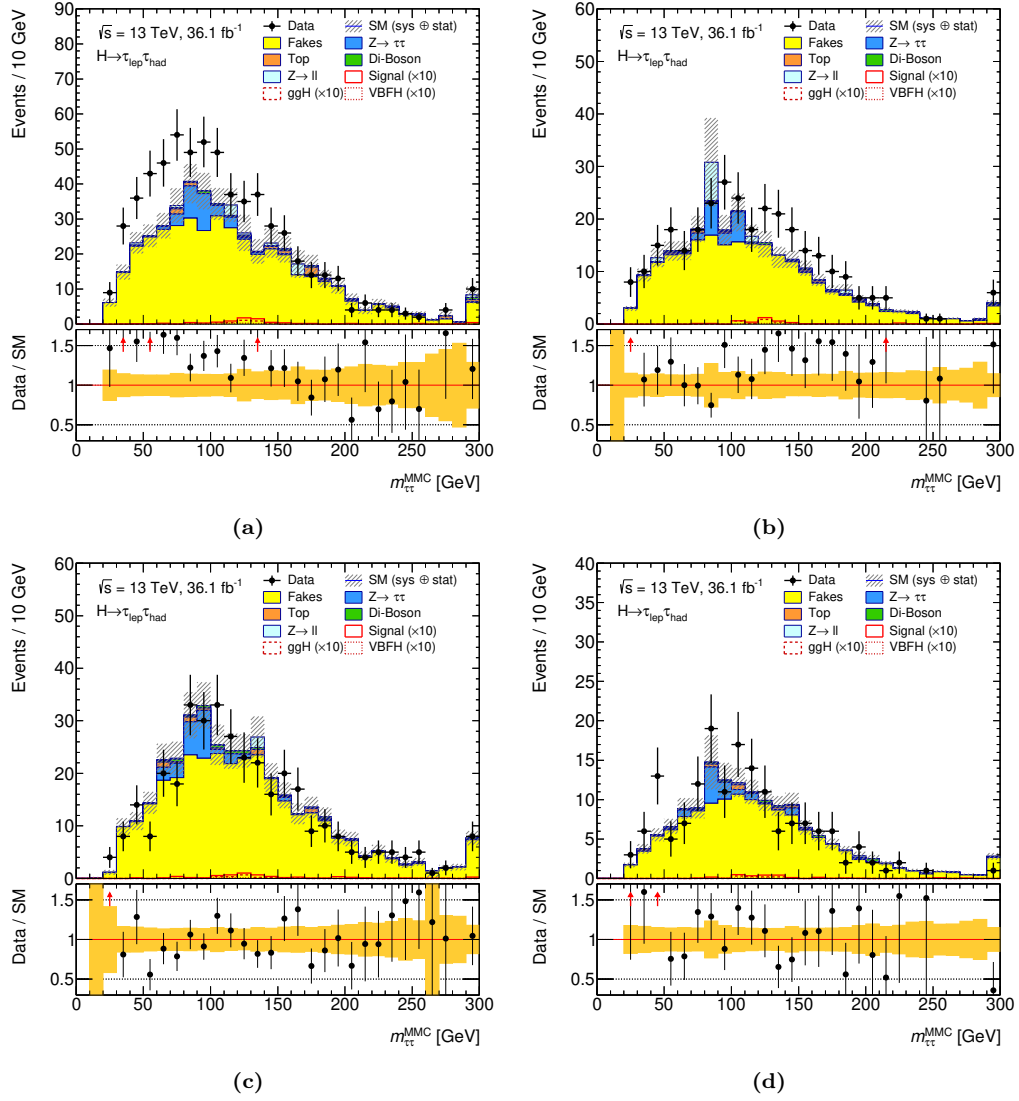
The relative impact on the Fake yield is included in Table 4.15. This source of uncertainty is dominant for the Fake estimation in the Boosted categories.



**Figure 4.33:** The MMC mass  $m_{\tau\tau}^{\text{MMC}}$  in the SSCR for the VBF category (a) and the Boosted category (b). Statistical uncertainties and all systematic uncertainties related to Fakes are included in the uncertainty band.

### 4.6.2 $Z \rightarrow \tau\tau$ modelling

The dominant irreducible background of this analysis is the production of  $Z/\gamma^*$  decaying into two  $\tau$ -leptons with additional jets. Since this process is estimated by simulation, the modelling has to be validated with data. It is not possible to define a region that is very pure in  $Z \rightarrow \tau\tau$  events and at the same time free from  $H \rightarrow \tau\tau$  signal contribution, but since the most challenging part of this process is the modelling of the jets,  $Z \rightarrow \ell\ell$  events can be used for the validation of the simulation. Therefore, a validation region close to the signal region is defined. Instead of one lepton and one  $\tau_{\text{had}}$ , exactly two leptons with same lepton flavour and opposite charge are required. The  $\tau_{\text{had}}$  is replaced by a lepton in the definitions of all variables used for selection requirements. The invariant mass of the leptons  $m_{\ell\ell}$  has to be greater than 80 GeV to ensure a region rich in  $Z \rightarrow \ell\ell$  events. The full definition of the validation region is summarised in Table 4.17. Plots of  $p_{\text{T}}^{\ell\ell}$  and of jet properties in the  $Z \rightarrow \tau\tau$  validation region are shown in Figure 4.35.

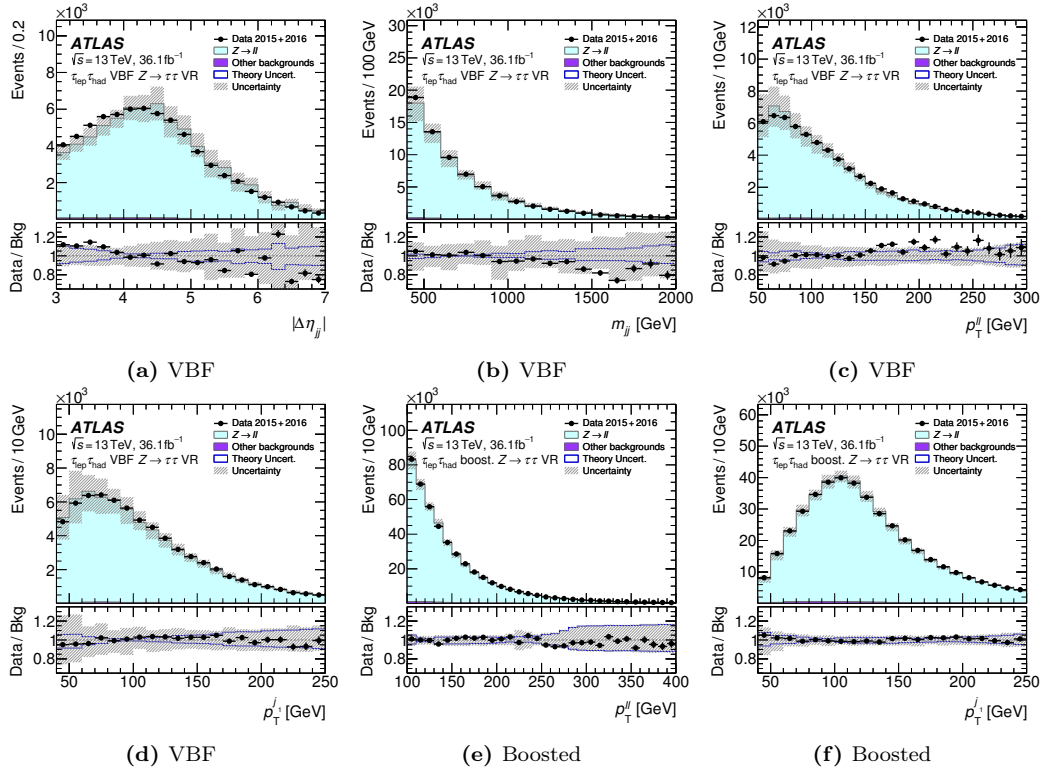


**Figure 4.34:** The MMC mass  $m_{\tau\tau}^{\text{MMC}}$  in the SSCR for the Boosted category for the electron channel with  $n_{\text{trk}}^{\tau} = 1$  (a) and with  $n_{\text{trk}}^{\tau} = 3$  (b), and for the muon channel with  $n_{\text{trk}}^{\tau} = 1$  (c) and with  $n_{\text{trk}}^{\tau} = 3$  (d). Statistical uncertainties and all systematic uncertainties related to Fakes are included in the uncertainty band.

A good modelling of the distributions within statistical and systematic uncertainties is observed, except for a trend in the ratio between data and simulation for  $|\Delta\eta_{jj}|$  and  $m_{jj}$ . Reweighting the simulation with the observed  $m_{jj}$  distribution has no impact on the modelling of  $m_{\tau\tau}^{\text{MMC}}$  and on the measurement [9].

The systematic uncertainties regarding the  $Z \rightarrow \tau\tau$  modelling are discussed in Section 4.8.2.

| Preselection                                  |                                    |
|-----------------------------------------------|------------------------------------|
| 2 leptons with same flavour & opposite charge |                                    |
| $m_{\ell\ell} > 80 \text{ GeV}$               |                                    |
| $ \Delta\eta_{\ell\ell}  < 1.5$               |                                    |
| $\Delta R_{\ell\ell} < 2.5$                   |                                    |
| $p_T^{j_1} > 40 \text{ GeV}$                  |                                    |
| $N_{b\text{-jets}} = 0$                       |                                    |
| VBF                                           | Boosted                            |
| $p_T^{j_2} > 30 \text{ GeV}$                  | Not VBF                            |
| $\eta_{j_1} \cdot \eta_{j_2} < 0$             | $p_T^{\ell\ell} > 100 \text{ GeV}$ |
| $ \Delta\eta_{jj}  > 3$                       |                                    |
| $m_{jj} > 400 \text{ GeV}$                    |                                    |

**Table 4.17:** Preselection and categorisation of the  $Z \rightarrow \tau\tau$  validation region.**Figure 4.35:** Distributions in the  $Z \rightarrow \tau\tau$  validation region for the inclusive VBF category (a)–(d) and the inclusive Boosted category (e)–(f). Shown are  $|\Delta\eta_{jj}|$  (a),  $m_{jj}$  (b),  $p_T^{\ell\ell}$  (c)–(e), and  $p_T^{1,\text{Jet}}$  (d)–(f). The hatched bands include statistical and systematic uncertainties. The expected distribution is normalised to the event yield in data. Taken from Ref. [9].

## 4.7 Fit model

Maximum-likelihood fits are performed in data to extract the parameters of interest. The likelihood function and the definition of the test statistics used in this analysis are introduced in this section. The aim of this analysis is to measure the total cross-section of the process  $H \rightarrow \tau\tau$ ,  $\sigma_{H \rightarrow \tau\tau}$ , and the VBF- and  $ggF$  production cross-sections  $\sigma_{H \rightarrow \tau\tau}^{\text{VBF}}$  and  $\sigma_{H \rightarrow \tau\tau}^{\text{ggF}}$ . For this, maximum-likelihood fits with one- and two parameters of interest are performed, respectively. The respective signal strengths  $\mu$  are defined by normalizing the measured cross-sections to the expected cross-sections  $\sigma_{\text{SM}}$ :  $\mu = \frac{\sigma}{\sigma_{\text{SM}}}$ . The results of these maximum-likelihood fits are presented in Section 4.9.

This section follows the explanations in Ref. [293] and the HISTFACTORY User's Guide [294], and one parameter of interest called  $\mu$  will be used in the descriptions.

### 4.7.1 Likelihood function

The expected event count in bin  $i$  can be expressed as the sum of expected signal- and background events in this bin:

$$n_i^{\text{exp}} = \mu s_i(\boldsymbol{\theta}) + b_i(\boldsymbol{\theta}) \quad (4.18)$$

where  $s_i$  and  $b_i$  are the number of signal- and background events, respectively,  $\mu$  is the signal strength, and  $\boldsymbol{\theta}$  represents the set of nuisance parameters on which the number of signal- and background events depend. The probability to observe  $n_i$  events in data can be expressed by the Poisson probability

$$P_{\text{Pois}}(n_i|\mu, \boldsymbol{\theta}) = \frac{(\mu s_i(\boldsymbol{\theta}) + b_i(\boldsymbol{\theta}))^{n_i}}{n_i!} e^{-(\mu s_i(\boldsymbol{\theta}) + b_i(\boldsymbol{\theta}))} \quad (4.19)$$

If the number of data events  $n_i$  is considered as fixed, this probability is called the *likelihood function* for the parameters  $\mu$  and  $\boldsymbol{\theta}$ :  $L(\mu, \boldsymbol{\theta}|n_i)$ . The likelihood function for the full distribution is the product of the likelihood functions for each bin  $i$ :

$$L(\mu, \boldsymbol{\theta}|n) = \prod_i \frac{(\mu s_i(\boldsymbol{\theta}) + b_i(\boldsymbol{\theta}))^{n_i}}{n_i!} e^{-(\mu s_i(\boldsymbol{\theta}) + b_i(\boldsymbol{\theta}))} \quad (4.20)$$

where  $n$  is the total number of events. In this analysis, the product includes the bins of the  $m_{\tau\tau}^{\text{MMC}}$  distributions in all signal regions and a single bin, effectively the event yield, in the top-quark control region.

### Systematic uncertainties

To include systematic uncertainties in the measurement, the likelihood function has to be modified. This is done by adding terms that reflect the information obtained from auxiliary measurements of the systematic uncertainty and hence of the nuisance parameter  $\theta$ . For this, a constraint term in form of a Gaussian probability density function is introduced for each of the nuisance parameters  $\theta$ :

$$P_{\text{Gauss}}(\theta|\tilde{\theta}, \sigma_\theta) = \frac{1}{\sqrt{2\pi}\sigma_\theta} \exp\left(-\frac{(\theta - \tilde{\theta})^2}{2\sigma_\theta^2}\right) \quad (4.21)$$

where  $\tilde{\theta}$  is the best estimate for the nuisance parameter and  $\sigma_\theta$  is the variance.

A systematic uncertainty can have an effect on the overall normalisation, denoted by  $\eta$ , and on the shape of the distribution, denoted by  $\sigma_i$  for the effect on bin  $i$ . The inputs provided to the maximum-likelihood fit are the nominal normalisation  $\eta^0 = 1$  and the nominal shape  $\sigma_i^0$ , and the variations  $\eta^\pm$  and  $\sigma_i^\pm$ , resulting from the auxiliary measurements of the systematic uncertainty. An interpolation scheme is used to obtain a continuous parameterisation of  $\eta$  and  $\sigma_i$  in the parameter  $\alpha$ . For the normalisation uncertainties  $\eta$ , an exponential interpolation is used:

$$\eta(\alpha) = \begin{cases} (\eta^+)^{\alpha}, & \alpha \geq 0 \\ (\eta^-)^{-\alpha}, & \alpha < 0 \end{cases} \quad (4.22)$$

This ensures  $\eta \geq 0$ , as expected for a normalisation.

A linear interpolation is used for the shape uncertainties  $\sigma_i$ :

$$\sigma_i(\alpha) = \begin{cases} \sigma_i^0 + \alpha (\sigma_i^+ - \sigma_i^0), & \alpha \geq 0 \\ \sigma_i^0 + \alpha (\sigma_i^0 - \sigma_i^-), & \alpha < 0 \end{cases} \quad (4.23)$$

For  $\alpha = 0$ , the nominal values are returned,  $\eta(0) = 1 = \eta^0$  and  $\sigma_i(0) = \sigma_i^0$ , whereas  $\alpha = \pm 1$  results in the variations  $\eta^\pm$  and  $\sigma_i^\pm$ .

In this parameterisation, Equation (4.21) becomes

$$P_{\text{Gauss}}(\alpha|0, 1) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{\alpha^2}{2}\right) \quad (4.24)$$

### Statistical uncertainties

Another necessary term in the likelihood function is one for the statistical uncertainty of the sum of background processes per bin  $b_i^w$ . Since the background processes are estimated using Monte Carlo simulation, this is a sum of  $N$  weighted events,

$b_i^w = \sum_{j=1}^N w_j$ , with uncertainty  $\sigma_i = \sqrt{\sum_{j=1}^N w_j^2}$ , where  $w_j$  are the weights of the events

in bin  $i$ . The relative uncertainty  $\sigma_i^{\text{rel}}$  of the background estimation is larger than the relative uncertainty  $1/\sqrt{N}$  obtained from unweighted Poisson statistics [295].

To obtain an estimate for the number of events that would be measured in an auxiliary measurement with the same relative uncertainty  $\sigma_i^{\text{rel}}$  and that can be described by Poisson statistics, the number of unweighted events  $b_i^{\text{unw}}$  is defined as

$$b_i^{\text{unw}} = \left(\frac{b_i^w}{\sigma_i}\right)^2 = (\sigma_i^{\text{rel}})^{-2} \quad (4.25)$$

with uncertainty  $\sqrt{b_i^{\text{unw}}}$ . The Poisson distribution with true mean  $\gamma_i b_i^{\text{unw}}$  is then

$$P_{\text{Pois}}(b_i^{\text{unw}}|\gamma_i) = \frac{(\gamma_i b_i^{\text{unw}})^{b_i^{\text{unw}}}}{b_i^{\text{unw}}!} e^{-(\gamma_i b_i^{\text{unw}})} \quad (4.26)$$

The *gamma factor*  $\gamma_i$  is the parameter that has to be estimated to obtain the true mean in bin  $i$ .

Since  $b_i^{\text{unw}}$  is not ensured to be an integer, the gamma probability distribution  $P_\Gamma$  has to be used instead of the Poisson distribution:

$$P_\Gamma(b_i^{\text{unw}}|\gamma_i) = \frac{b_i^{\text{unw}} (\gamma_i b_i^{\text{unw}})^{b_i^{\text{unw}}-1}}{\Gamma(b_i^{\text{unw}}-1)} e^{-(\gamma_i b_i^{\text{unw}})} \quad (4.27)$$

where  $\Gamma(x)$  is the gamma function. This term is added to the likelihood function as  $L(\gamma_i|b_i^{\text{unw}})$  to obtain an estimate for  $\gamma_i$ .

### Full likelihood function

With these extensions, the full likelihood function for the signal strength  $\mu$ , the set of nuisance parameters  $\boldsymbol{\theta}$ , and the set of gamma factors  $\boldsymbol{\gamma}$  can be defined:

$$L(\mu, \boldsymbol{\theta}, \boldsymbol{\gamma}) = \prod_i P_{\text{Pois}}(n_i|\mu, \boldsymbol{\theta}) \prod_{\boldsymbol{\theta}} P_{\text{Gauss}}(\boldsymbol{\theta}|\tilde{\boldsymbol{\theta}}, \sigma_{\boldsymbol{\theta}}) \prod_i P_\Gamma(b_i^{\text{unw}}|\gamma_i) \quad (4.28)$$

with products over the bins  $i$  and the nuisance parameters  $\boldsymbol{\theta}$ .

The likelihood function  $L$  can then be maximised with respect to  $\mu$ ,  $\boldsymbol{\theta}$ , and  $\boldsymbol{\gamma}$  to obtain their best-fit values  $\hat{\mu}$ ,  $\hat{\boldsymbol{\theta}}$ , and  $\hat{\boldsymbol{\gamma}}$ . Usually, the negative logarithm of the likelihood function  $-\ln L$  is minimised instead since this is computationally easier while yielding the same result.

### 4.7.2 Test statistics

To test hypotheses for the signal strength  $\mu$  against data, the profile likelihood ratio  $\lambda(\mu)$  is defined:

$$\lambda(\mu) = \frac{L(\mu, \hat{\boldsymbol{\theta}})}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})} \quad (4.29)$$

Here,  $\hat{\boldsymbol{\theta}}$  are the values of the nuisance parameters, now including the gamma factors  $\boldsymbol{\gamma}$ , that maximise the likelihood function for the specific value of  $\mu$  corresponding to the *null hypothesis*. The profile likelihood ratio can take values  $0 < \lambda(\mu) \leq 1$ , with smaller values indicating a disagreement between the data and the null hypothesis, while larger values indicate a good agreement.

Again, the negative logarithm of the likelihood function can be used instead, resulting in the test statistic  $t_\mu$ :

$$t_\mu = -2 \ln \lambda(\mu) \quad (4.30)$$

Larger values of  $t_\mu$  indicate a larger disagreement between the data and the tested value of  $\mu$ . The  $p$ -value is used to quantify the disagreement:

$$p_\mu = \int_{t_\mu^{\text{obs}}}^{\infty} f(t_\mu|\mu) dt_\mu \quad (4.31)$$

Here,  $t_\mu^{\text{obs}}$  is the observed value of  $t_\mu$  and  $f(t_\mu|\mu)$  is the probability density function of  $t_\mu$  for the signal strength  $\mu$ . The  $p$ -value  $p_\mu$  represents the probability to observe a value  $t_\mu \geq t_\mu^{\text{obs}}$ . Approximations for the profile likelihood ratio and thus for the



pdf  $f(t_\mu|\mu)$  are derived in [293].

The  $p$ -value is usually converted into the significance  $Z_\mu$  by

$$Z_\mu = \Phi^{-1}(1 - p_\mu) \quad (4.32)$$

where  $\Phi^{-1}$  is the quantile of the standard Gaussian. The  $p$ -value becomes smaller for larger values of  $t_\mu$ , corresponding to a larger significance  $Z_\mu$ .

Usually, a value of  $\mu \geq 0$  is expected in the case of a signal strength, and the test statistic  $\tilde{t}_\mu$  is used:

$$\tilde{t}_\mu = \begin{cases} -2 \ln \lambda(\mu) & \hat{\mu} \geq 0 \\ -2 \ln \tilde{\lambda}(\mu) & \hat{\mu} < 0 \end{cases} \quad (4.33)$$

with

$$\tilde{\lambda}(\mu) = \frac{L(\mu, \hat{\boldsymbol{\theta}})}{L(0, \hat{\boldsymbol{\theta}})} \quad (4.34)$$

Hence, if the best-fit value  $\hat{\mu}$  turns out to be negative, it is set to 0 instead. This test statistic is used in this analysis for the measurement of the cross-section and the signal strength.

To quantify the significance of an excess, the test statistic  $q_0 = \tilde{t}_0$  is used:

$$q_0 = \begin{cases} -2 \ln \lambda(0) & \hat{\mu} \geq 0 \\ 0 & \hat{\mu} < 0 \end{cases} \quad (4.35)$$

This tests if the background-only hypothesis with  $\mu = 0$  can be rejected. Also here, only non-negative values of  $\hat{\mu}$  are considered and even if a deviation from the background-only hypothesis is observed with a signal strength  $\hat{\mu} < 0$ ,  $q_0$  is set to 0 and the background-only hypothesis is not rejected.

For increasing values of  $\hat{\mu}$ , the incompatibility of the data with the background-only hypothesis increases, corresponding to a larger value of  $q_0$ . The  $p$ -value defined in Equation (4.31) is used to quantify this incompatibility:

$$p_0 = \int_{q_0^{\text{obs}}}^{\infty} f(q_0|0) dq_0 \quad (4.36)$$

with significance  $Z_0 = \Phi^{-1}(1 - p_0)$ .

To test the sensitivity of an analysis, the expected significance  $Z_{\text{exp}}$  is used. For this, simulation is used to construct an *Asimov* data set with parameters  $\mu'$  and  $\boldsymbol{\theta}$ . The parameters are chosen such that when the Asimov data set is used in the profile likelihood ratio, the resulting best-fit values are equal to the values used for its construction, i.e.  $\hat{\mu} = \mu'$  and  $\hat{\boldsymbol{\theta}} = \boldsymbol{\theta}$ . Therefore, the Asimov likelihood-ratio is

$$\lambda_A(\mu) = \frac{L_A(\mu, \hat{\boldsymbol{\theta}})}{L_A(\hat{\mu}, \hat{\boldsymbol{\theta}})} = \frac{L_A(\mu, \hat{\boldsymbol{\theta}})}{L_A(\mu', \boldsymbol{\theta})} \quad (4.37)$$

For the expected discovery significance,  $\mu' = 1$  is chosen, corresponding to the nominal signal-plus-background hypothesis, which is tested against the background-only hypothesis with  $\mu = 0$ .

## 4.8 Systematic uncertainties

Various sources of systematic uncertainties are taken into account in this analysis. These are grouped into theoretical uncertainties, experimental uncertainties, and uncertainties on the estimation of the Fake background. The latter are described in Section 4.6.1.

The experimental uncertainties are related to the pile-up reweighting, the luminosity measurement, and to all objects that are used in the analysis: electrons, muons, hadronically decaying  $\tau$ -leptons, jets, and the missing transverse energy  $E_T^{\text{miss}}$ .

Theoretical uncertainties are considered for the signal modelling and the modelling of the  $Z \rightarrow \tau\tau$  +jets background. Uncertainties on the other background contributions are neglected since the yields are small in comparison.

The uncertainties with the largest impact on the result are related to the jet energy resolution, the normalisation of the  $Z \rightarrow \tau\tau$  background, the modelling of the parton shower, hadronisation, and underlying event in the  $ggF$  signal, and the limited number of simulated events for the background samples.

### 4.8.1 Experimental uncertainties

#### Electrons

For the energy calibration of electrons, more than 70 systematic variations decorrelated in bins of  $\eta$  are taken into account. This uncertainty model was developed and used in Run-1 of the LHC. The results have been checked for Run-2 and updated where necessary [212].

Since this analysis is not very sensitive to the energy scale of electrons, a simplified model is used where all effects are considered as fully correlated across  $\eta$  and the linear sum of them is used. This results in one systematic variation for the energy scale and one for the energy resolution. The uncertainty on the energy scale is less than 1 %, while the uncertainty on the energy resolution increases with  $p_T$  from 5 % to 40 % [212].

For the energy scale, additional uncertainties are considered in Run-2. These take into account varying temperature of the liquid argon between 2015 and 2016, the additional use of scintillator information and the intercalibration between the first two layers of the electromagnetic calorimeter, with respective sizes of 0.05 %, 5 %, and 1.5 % [212].

Further uncertainties, all less than 1 %, are considered for the efficiencies of the trigger, reconstruction, identification, and isolation. [187, 208].

As explained in Section 3.3.2, custom scale factors for non-prompt electrons from  $\tau$ -lepton decays are derived for this analysis. For a conservative estimate of the systematic uncertainty, the scale factors are applied a second time.

#### Muons

For uncertainties on the momentum resolution of the muons, the tracks in the inner detector and in the muon spectrometer are varied. The uncertainties are between 2.3 % and 2.9 %, depending on the pseudorapidity [217].

Variations are also applied to the momentum scale, taking into account charge-

dependent effects due to possible misalignments in the detector, resulting in uncertainties less than 1 % [217].

Both statistical and systematic uncertainties are considered for efficiencies of the trigger, identification, and isolation. All these uncertainties are less than 1 % [187, 217].

### $\tau$ -leptons

The energy scale of hadronically decaying  $\tau$ -leptons is varied due to uncertainties in the modelling of the detector geometry, the measurement in the tag-and-probe analysis, and the GEANT4 detector model. The resulting uncertainty on the energy scale is between 2 % and 3 % [227].

Uncertainties of the efficiencies are considered for the identification and the reconstruction of  $\tau$ -leptons, and for the removal of overlapping electrons, where the latter is independently estimated for the misidentification of true electrons as  $\tau_{\text{had}}$  and true hadronically decaying  $\tau$ -leptons as electrons. The uncertainty on the identification efficiency is 5 % for 1-track  $\tau$ -leptons, and 6 % for 3-track  $\tau$ -leptons. The uncertainty on the reconstruction efficiency is between 2 % and 4.5 %, depending on the transverse momentum, while the uncertainty on the electron overlap removal is between 3 % and 14 %, depending on the pseudorapidity [228].

An uncertainty for the trigger efficiency is not required, since no  $\tau$ -lepton triggers are used in this analysis.

### Jets

Eleven nuisance parameters are taken into account for the jet energy resolution (JER). This set of parameters is a reduction from 17 parameters, from which 9 are taken from the Run-1 calibration, 7 cover the cross calibrations from Run-1 to Run-2, and 1 is for the forward region, derived in Run-1. The total uncertainty is between 1 % and 4 %, depending on the pseudorapidity and the transverse momentum [296, 297].

Uncertainties of the jet energy scale (JES) are covered by 88 nuisance parameters. 75 of those are estimated by in-situ analyses of  $Z$ +jet,  $\gamma$ +jet, and multijet data, and are reduced to a set of 8 parameters for this analysis. The rest of the uncertainties cover corrections depending on  $\eta$ , the behaviour of jets with  $p_T > 1.8$  TeV, the effects from pileup, flavour-related effects, and high- $p_T$  jets that are not fully contained in the calorimeter. The total uncertainty is between 1 % and 4.5 %, depending on the pseudorapidity and the transverse momentum [221].

Uncertainties on the efficiencies of the jet vertex tagger and the forward jet vertex tagger are between 1 % and 2 % [288], and less than 1 % [289], respectively, depending on the pseudorapidity and the transverse momentum.

The jet energy resolution has the largest impact on the result due to the impact on  $m_{\tau\tau}^{\text{MMC}}$ . Jets with a high  $p_T$  recoiling against the di- $\tau$  system are present in both the Boosted- and the VBF category. The JER nuisance parameters lead to a variation in the  $p_T$  of the jets, which also causes a change of the missing transverse energy  $E_T^{\text{miss}}$ . As  $E_T^{\text{miss}}$  is an input to the MMC method,  $m_{\tau\tau}^{\text{MMC}}$  is impacted by the jet energy resolution.

The impact of the JER uncertainties on the  $ggF$ - and VBF acceptance is up to 18 %, while it is up to 16 % on the  $Z \rightarrow \tau\tau$  background. The JER- and JES uncertainties have the largest impacts on the  $m_{\tau\tau}^{\text{MMC}}$  shapes of the signal processes.

### **$b$ -tagged jets**

Systematic uncertainties for the efficiency of the  $b$ -tagging algorithm are considered independently for  $b$ -,  $c$ - and light-flavour jets, where the initial number of uncertainties is reduced to eleven by using an eigenvalue decomposition of the covariance matrix of systematic and statistical variations. The uncertainties for  $b$ -,  $c$ - and light-flavour jets are between 2 % and 12 %, between 5 % and 7 %, and between 15 % and 28 %, respectively, depending on the transverse momentum [226, 298, 299]. Two further uncertainties cover the extrapolation of the scale factor to jets with  $p_T > 300$  GeV or  $p_T > 140$  GeV for  $b$ -jets and  $c$ -jets respectively, and the application of the  $c$ -jet scale factors to  $\tau$ -jets.

The impact of the  $b$ -tagging uncertainties on the acceptance of the top-quark background is up to 17 %.

### **$E_T^{\text{miss}}$**

Uncertainties on the missing transverse energy arise from varying the scale and resolution of the soft term, the latter separately for the contributions parallel and perpendicular to the direction of the hard term. These uncertainties are between 10 % and 30 %, depending on the transverse momentum [229, 230]. Additionally, the uncertainties on the hard objects in the event, as described above, are propagated to the calculation of  $E_T^{\text{miss}}$ .

### **Pileup reweighting**

As explained in Section 2.3, the simulated events have to be reweighted to match the observed pileup profile in the 2015 and 2016 dataset. To account for uncertainties of the measured fiducial inelastic cross-section [300], the scale factor applied in the reweighting is varied by 9 %.

### **Luminosity**

The combined error on the luminosity measurement for the 2015 and 2016 datasets is 2.1 %, with the assumption of a partial correlation between the two datasets. It is derived from the calibration of the luminosity scale using  $x$ - $y$  beam-separation scans [184].

## **4.8.2 Theoretical uncertainties**

Several theoretical uncertainties are considered for the modelling of the signal and the  $Z \rightarrow \tau\tau$  background. Since the contribution of the other backgrounds is small in the signal regions, no additional uncertainties are included for them. The TopCR is used to normalise the top-quark background to data in the maximum-likelihood fit.

## Signal modelling

The implementation of the uncertainties on the signal modelling follows the recommendations of the LHCHSWG [91]. The sources of the uncertainties are the QCD- and EW scales due to missing higher orders in the perturbation theory, the non-perturbative parts of the modelling (underlying event and hadronisation), and the experimental input parameters for the calculation of the PDFs and  $\alpha_s$ .

The uncertainties are separated into the uncertainty on the total cross-section, the uncertainty on the acceptances into the signal regions, and the uncertainty on the shape of the  $m_{\tau\tau}^{\text{MMC}}$  distribution, which is input for the maximum-likelihood fit. The latter two are treated as correlated for each source of uncertainty. Since the number of  $t\bar{t}H$  events in the signal regions is very small, as shown in Table 4.6, only the total cross-section uncertainties are considered for the  $t\bar{t}H$  process.

The values of the uncertainties on the total cross-sections are taken from Ref. [91] and are summarised in Table 4.18. No uncertainty on the QCD scale is included for the  $ggF$  process, since this is already covered in the method described in the next paragraph. The uncertainty on the EW scale is only included for the VBF production process.

These uncertainties are not used for the measurement of the cross-section  $\sigma_{H\rightarrow\tau\tau}$  and are only included when the signal strength  $\mu$  is the fit parameter.

| Production process | QCD scale [%] | EW scale [%] | PDF [%]   | $\alpha_s$ [%] |
|--------------------|---------------|--------------|-----------|----------------|
| $ggF$              | —             | —            | $\pm 1.9$ | $\pm 2.6$      |
| VBF                | $+0.4 / -0.3$ | $\pm 2.0$    | $\pm 2.1$ | $\pm 0.5$      |
| $WH$               | $+0.5 / -0.7$ | —            | $\pm 1.7$ | $\pm 0.9$      |
| $ZH$               | $+3.8 / -3.1$ | —            | $\pm 1.3$ | $\pm 0.9$      |
| $t\bar{t}H$        | $+5.8 / -9.2$ | —            | $\pm 3.0$ | $\pm 2.0$      |

**Table 4.18:** Theoretical uncertainties on the total cross-section of the signal production processes. Taken from Ref. [91].

Higher-order QCD corrections introduce large uncertainties for the  $ggF$  production cross-section when placing a requirement on the number of jets as done in this analysis for the VBF- and Boosted categories. Bin-to-bin migrations in the number of jets due to the uncertainties have to be taken into account. Therefore, a special treatment of the  $ggF$  uncertainties is required, using in total nine uncertainty sources. To account for uncertainties of the jet multiplicity due to missing higher-order corrections, four sources are included of which one accounts for uncertainties due to the variation of the renormalisation and factorisation scales, one for the variation of the resummation scale and two for bin-to-bin migrations from zero to one jet, and from one to two or more jets [301–304].

Three uncertainties are considered for the modelling of the transverse momentum of the Higgs boson: one for the migration from the 0–60 GeV region to the 60– $\infty$  GeV region, one for the migration from the 0–120 GeV region to the 120– $\infty$  GeV region, both estimated using POWHEG NNLOPS [238, 239], and one for the effects of the assumption of a finite mass of the top quark, which becomes important at a  $p_T^H$  of around 200 GeV [91].

The VBF categories contain a sizeable amount of  $ggF$  events, as shown in Table 4.6.

Therefore, uncertainties on the acceptance of  $ggF$  production in the VBF phase space are taken into account by requiring exactly two jets and at least three jets, respectively [305, 306].

The resulting impact of these nine uncertainties on the acceptance of the  $ggF$  production process is between 1 % and 14 %.

A simpler uncertainty scheme is used for the VBF-,  $ZH$ -, and  $WH$  samples: the renormalisation and factorisation scales  $\mu_R$  and  $\mu_F$  are varied in POWHEG by factors 1/2 and 2 with the constraint  $1/2 \leq \mu_R/\mu_F \leq 2$  on the ratio. For each bin, the largest of these variations is then taken as the final uncertainty.

These uncertainties impact the acceptance of the VBF production process between 1 % and 2 %, and the acceptance of the  $VH$  production process up to 14 %.

To obtain an estimate for the uncertainty of the parton shower-, underlying event-, and hadronisation modelling, two parton shower algorithms, PYTHIA 8.212 [195] and HERWIG 7.0.3 [307, 308], are compared, using fast simulation. This is done for the VBF-,  $ggF$ -, and  $VH$  samples.

The effect on the  $ggF$  acceptance varies between 3 % and 12 %, while it is 1 % for VBF and 2 % for  $VH$ .

The PDF uncertainties follow the recommendations of the PDF4LHC collaboration [241], which consist of 30 eigenvector variations and 2 variations of  $\alpha_s$ .

The effect on the signal acceptance is between 1 % and 3 %.

Due to missing higher order corrections and parametric uncertainties on the  $H \rightarrow \tau\tau$  branching ratio, an uncertainty on the total cross-section of  $\pm 2.3$  % is added for all signal production processes.

Of the theoretical uncertainties, the UEPS modelling in the statistically dominant  $ggF$  signal has the largest impact on the result.

### $Z \rightarrow \tau\tau$ + jets modelling

The normalisation of the  $Z \rightarrow \tau\tau$  background is free-floating in the maximum-likelihood fit, separately for the inclusive VBF- and Boosted categories. Therefore, each systematic uncertainty of the  $Z \rightarrow \tau\tau$  modelling is decorrelated between the inclusive categories.

The considered uncertainties are renormalisation- and factorisation scale variations by factors 1/2 and 2 with the constraint  $1/2 \leq \mu_R/\mu_F \leq 2$  on the ratio, the PDF parameterisation, variations of the resummation scale for soft gluon emissions  $\mu_Q$  by factors 1/2 and 2, variations of the merging scale, which defines the maximum  $p_T$  of jets from the parton shower, to 15 GeV and 30 GeV (the nominal being 20 GeV), all directly provided by SHERPA [196], and the comparison with a different parton shower model using samples simulated with MADGRAPH5\_aMC@NLO v2.2.2 [245] interfaced to PYTHIA 8.186 [281].

The impact on the acceptance of the scale variations, the merging scale variation, and the parton shower comparison are up to 4 %, 6 %, and 4 %, respectively. The variations of the PDF parameterisation and the resummation scale have negligible impact.

For the electroweak production of a  $Z$  boson with two associated jets, an uncertainty on the cross-section of 25 % is assumed, taken from the measurement in Ref. [309].

The impact of the experimental- and theoretical uncertainties on the signal- and background acceptance and on the shape of the  $m_{\tau\tau}^{\text{MMC}}$  distribution is shown in Appendix A.1. The naming of the uncertainties in Appendix A.1 is explained in Table A.1.

Tables A.2 to A.13 show the impact on the acceptance, excluding the uncertainties already shown in Tables 4.15 and 4.18. Only uncertainties with an impact larger than 0.1 % are included in the tables.

In the VBF categories, the largest impacts on the acceptance are observed for uncertainties on the jet energy resolution,  $ggF$  QCD scale,  $ggF$  UEPS, VBF parton shower,  $b$ -tagging, and  $VH$  scale variations.

The largest impacts in the Boosted categories are from uncertainties on the jet energy resolution,  $ggF$  parton shower,  $ggF$  QCD scale, and  $b$ -tagging.

The impact of the systematic uncertainties on the shape of the  $m_{\tau\tau}^{\text{MMC}}$  distribution is shown in Figures A.1 to A.4. Only the six uncertainties with the largest impact on the shape are shown per category. For this, the compatibility of the nominal distribution with the distribution after the application of the respective uncertainty was evaluated with a  $\chi^2$  test [310] and the tests with the lowest resulting p-values were selected.

The resulting 24 uncertainties all impact the shape of signal distributions, in most of the cases the VBF production process. The majority of the uncertainties are related to the jet energy resolution and the jet energy scale, but uncertainties on the VBF parton shower,  $E_T^{\text{miss}}$ , and  $\tau_{\text{had}}$  energy scale are also included.

## 4.9 Results

Maximum-likelihood fits as described in Section 4.7 with one- and two free parameters are performed in data to measure the total cross-section of  $H \rightarrow \tau\tau$  production and the  $ggF$ - and VBF production cross-sections, respectively. The  $m_{\tau\tau}^{\text{MMC}}$  distribution is used in the VBF- and Boosted signal regions to extract the signal strength, and the event yields in the corresponding top-quark control regions are used to obtain the normalisation of this background. The normalisation of the  $Z \rightarrow \tau\tau$  background is obtained from the  $Z$ -boson peak in the  $m_{\tau\tau}^{\text{MMC}}$  distributions in the signal regions.

The observed significance of the signal excess under the background-only hypothesis is 2.4 standard deviations, whereas the expected significance is 2.6 standard deviations. For the measurement of the total cross-section,  $\sigma_{H \rightarrow \tau\tau} = \sigma_H \cdot \mathcal{B}(H \rightarrow \tau\tau)$  is used as fit parameter, where  $\sigma_H$  is the total cross-section of all considered production processes and  $\mathcal{B}(H \rightarrow \tau\tau)$  is the branching fraction of the Higgs boson decaying to  $\tau$ -leptons. It is assumed that the relative contributions from the different production processes are as predicted in the SM. The uncertainties on the signal cross-sections

are excluded for this fit and the resulting value is

$$\sigma_{H \rightarrow \tau\tau} = 3.13_{-0.84}^{+0.86} \text{ (stat.)}_{-1.03}^{+1.26} \text{ (syst.) pb} \quad (4.38)$$

This is in agreement with the SM prediction of  $\sigma_{H \rightarrow \tau\tau}^{\text{SM}} = 3.46 \pm 0.13 \text{ pb}$  [91]. The measurement has a relative uncertainty of 46 % and is dominated by the systematic uncertainties, especially by uncertainties related to jets and the theoretical uncertainty of the signal. The normalisation factors are consistent with one and are shown in Table 4.19. The event yields obtained from the maximum-likelihood fit are summarised in Table 4.20 and Table 4.21.

|                          | VBF             | Boosted         |
|--------------------------|-----------------|-----------------|
| Top                      | $1.29 \pm 0.30$ | $1.00 \pm 0.09$ |
| $Z \rightarrow \tau\tau$ | $1.06 \pm 0.18$ | $1.04 \pm 0.09$ |

**Table 4.19:** Normalisation factors obtained from the fit to data, including all statistical and systematic uncertainties.

|                          | VBF SR |             |       |             | Boosted SR |            |            |            |
|--------------------------|--------|-------------|-------|-------------|------------|------------|------------|------------|
|                          | Loose  |             | Tight |             | low $p_T$  |            | high $p_T$ |            |
| $Z \rightarrow \tau\tau$ | 184    | $\pm 20$    | 336   | $\pm 25$    | 4 210      | $\pm 100$  | 5 370      | $\pm 90$   |
| $Z \rightarrow \ell\ell$ | 12     | $\pm 4$     | 11.2  | $\pm 3.4$   | 130        | $\pm 40$   | 112        | $\pm 24$   |
| Top                      | 8.2    | $\pm 3.4$   | 17    | $\pm 6$     | 140        | $\pm 29$   | 50         | $\pm 11$   |
| Fake                     | 98     | $\pm 17$    | 97    | $\pm 16$    | 1 870      | $\pm 90$   | 603        | $\pm 33$   |
| Diboson                  | 3.5    | $\pm 1.7$   | 9.5   | $\pm 2.1$   | 122        | $\pm 12$   | 137        | $\pm 12$   |
| $ggF$                    | 3.5    | $\pm 1.6$   | 6.3   | $\pm 2.8$   | 56         | $\pm 24$   | 61         | $\pm 28$   |
| VBF                      | 5.7    | $\pm 2.6$   | 22    | $\pm 10$    | 11         | $\pm 5$    | 12         | $\pm 6$    |
| $WH$                     | 0.12   | $\pm 0.07$  | 0.12  | $\pm 0.07$  | 3.5        | $\pm 1.5$  | 4.5        | $\pm 2.0$  |
| $ZH$                     | 0.029  | $\pm 0.018$ | 0.041 | $\pm 0.022$ | 1.6        | $\pm 0.7$  | 2.3        | $\pm 1.0$  |
| $t\bar{t}H$              | 0.009  | $\pm 0.006$ | —     |             | 0.15       | $\pm 0.07$ | 0.23       | $\pm 0.11$ |
| Total background         | 306    | $\pm 18$    | 470   | $\pm 25$    | 6 480      | $\pm 90$   | 6 280      | $\pm 80$   |
| Total signal             | 9      | $\pm 4$     | 28    | $\pm 12$    | 72         | $\pm 30$   | 81         | $\pm 35$   |
| Data                     | 318    |             | 496   |             | 6556       |            | 6347       |            |

**Table 4.20:** Observed event yields and predicted yields by the fit in the signal regions, including all statistical and systematic uncertainties.

The impact of the different groups of uncertainties on the relative uncertainty of  $\sigma_{H \rightarrow \tau\tau}$  is summarised in Table 4.22. For this, all nuisance parameters in the respective group are fixed to their best-fit values and the maximum-likelihood fit is repeated. The resulting uncertainty on  $\sigma_{H \rightarrow \tau\tau}$  is subtracted quadratically from the uncertainty obtained from the full maximum-likelihood fit. The resulting value, divided by  $\sigma_{H \rightarrow \tau\tau}$ , is shown in the table.

The systematic uncertainties with the largest impacts are related to jets, theoretical uncertainties of the signal, and the limited amount of simulated background events.



|                          | VBF TopCR |             | Boosted TopCR |            |
|--------------------------|-----------|-------------|---------------|------------|
| $Z \rightarrow \tau\tau$ | 27        | $\pm 9$     | 440           | $\pm 50$   |
| $Z \rightarrow \ell\ell$ | 18        | $\pm 16$    | 35            | $\pm 26$   |
| Top                      | 200       | $\pm 40$    | 2 930         | $\pm 160$  |
| Fake                     | 68        | $\pm 30$    | 1 440         | $\pm 130$  |
| Diboson                  | 6.1       | $\pm 1.3$   | 65            | $\pm 8$    |
| $ggF$                    | 1.2       | $\pm 0.6$   | 6.8           | $\pm 3.2$  |
| VBF                      | 1.1       | $\pm 0.5$   | 1.3           | $\pm 0.6$  |
| $WH$                     | 0.028     | $\pm 0.021$ | 1.0           | $\pm 0.5$  |
| $ZH$                     | 0.013     | $\pm 0.013$ | 0.63          | $\pm 0.29$ |
| $t\bar{t}H$              | 0.18      | $\pm 0.08$  | 5.9           | $\pm 2.6$  |
| Total background         | 321       | $\pm 18$    | 4 920         | $\pm 70$   |
| Total signal             | 2.5       | $\pm 1.1$   | 16            | $\pm 7$    |
| Data                     | 324       |             | 4934          |            |

**Table 4.21:** Observed event yields and predicted yields by the fit in the top-quark control regions, including all statistical and systematic uncertainties.

Figure 4.36 shows the impact of the leading ten uncertainties on  $\sigma_{H \rightarrow \tau\tau}$ , and their post-fit *pulls*. For the evaluation of the impact, the maximum-likelihood fit is repeated with the respective nuisance parameter fixed to  $\pm 1\sigma$  of the best-fit value. The relative difference between the resulting value of  $\sigma_{H \rightarrow \tau\tau}$  and the value obtained from the full maximum-likelihood fit is defined as the impact.

A pull of a nuisance parameter  $\theta$  is defined as

$$\text{pull} = \frac{\hat{\theta} - \theta_0}{\Delta\theta} \quad (4.39)$$

where  $\hat{\theta}$  is the best-fit value,  $\theta_0$  the nominal input value, and  $\Delta\theta$  the input uncertainty of the respective auxiliary measurement. The post-fit uncertainties of the nuisance parameters are extracted from the covariance matrix  $V_{i,j}$ , defined as [293]

$$V_{i,j} = \text{cov}(\theta_i, \theta_j) = - \left[ \frac{\partial^2 \ln L(\boldsymbol{\theta})}{\partial \theta_i \partial \theta_j} \right]^{-1} \quad (4.40)$$

evaluated at  $\hat{\mu}$  and  $\hat{\boldsymbol{\theta}}$ .

One of the systematic uncertainties related to the jet energy resolution has the largest impact, followed by the variation of the normalisation of the  $Z \rightarrow \tau\tau$  background in the Boosted category within its uncertainties obtained from the maximum-likelihood fit. The other important uncertainties are related to the jet energy scale, the  $\tau_{\text{had}}$  identification, the modelling of the  $ggF$ - and  $Z \rightarrow \tau\tau$  processes, and to the statistical uncertainty of the Fakes in the Boosted category.

The signal strength  $\mu_{H \rightarrow \tau\tau}$ , defined as the ratio between the measured cross-section and the Standard Model prediction, is obtained by performing another maximum-likelihood fit including the uncertainties on the signal cross-sections. The resulting

| Source of uncertainty                  | Impact on:                |                                       |                                       |
|----------------------------------------|---------------------------|---------------------------------------|---------------------------------------|
|                                        | $\Delta\sigma/\sigma$ [%] | $\Delta\sigma_{ggF}/\sigma_{ggF}$ [%] | $\Delta\sigma_{VBF}/\sigma_{VBF}$ [%] |
| Jets                                   | +24.1 / -19.9             | +50.9 / -39.2                         | +48.7 / -35.4                         |
| Theo. uncert. signal                   | +20.2 / -8.4              | +59.8 / -11.1                         | +28.3 / -14.9                         |
| Background statistics                  | +16.6 / -15.8             | +11.5 / -8.9                          | +49.5 / -51.4                         |
| Background normalisation               | +12.4 / -9.0              | +12.3 / -12.7                         | +21.4 / -9.1                          |
| Hadronic $\tau$ -lepton decays         | +10.2 / -4.9              | +13.6 / -5.9                          | +14.2 / -3.9                          |
| Fakes                                  | +9.0 / -8.2               | +25.2 / -19.7                         | +23.6 / -25.6                         |
| Theo. uncert. $Z \rightarrow \tau\tau$ | +6.0 / -6.3               | +20.7 / -18.9                         | +12.6 / -10.8                         |
| $E_T^{\text{miss}}$                    | +5.5 / -5.6               | +5.2 / -4.7                           | +10.9 / -10.8                         |
| Luminosity                             | +4.4 / -2.8               | +6.6 / -3.6                           | +4.2 / -0.6                           |
| Flavour tagging                        | +3.9 / -3.1               | +7.2 / -4.9                           | +1.9 / -0.4                           |
| Pileup reweighting                     | +1.9 / -1.4               | +11.1 / -8.1                          | +17.4 / -12.7                         |
| Electrons and Muons                    | +1.3 / -1.4               | +3.1 / -3.0                           | +0.8 / -0.8                           |
| Total syst. uncertainty                | +40.4 / -33.0             | +83.9 / -56.9                         | +85.4 / -75.4                         |
| Data statistics                        | +27.5 / -26.9             | +46.7 / -45.7                         | +71.8 / -67.9                         |
| Total uncertainty                      | +48.9 / -42.5             | +96.1 / -73.0                         | +111.6 / -101.4                       |

**Table 4.22:** Impact of the different sources of uncertainty on the relative cross-section uncertainties as computed by the maximum-likelihood fits, both for the fit with one parameter of interest,  $\sigma$ , and for the fit with two parameters of interest,  $\sigma_{ggF}$  and  $\sigma_{VBF}$ .

value is

$$\mu_{H \rightarrow \tau\tau} = 0.90^{+0.25}_{-0.24} \text{ (stat.) }^{+0.37}_{-0.30} \text{ (syst.)} \quad (4.41)$$

The  $m_{\tau\tau}^{\text{MMC}}$  distributions for the signal and the backgrounds predicted by the maximum-likelihood fit are shown along with the data in Figure 4.37, where the signal is scaled by the best-fit value for  $\mu_{H \rightarrow \tau\tau}$ . A good agreement between the data and the signal-plus-background expectation is observed.

To extract values for the VBF- and  $ggF$  production cross-sections, a maximum-likelihood fit with the two parameters  $\sigma_{H \rightarrow \tau\tau}^{\text{VBF}}$  and  $\sigma_{H \rightarrow \tau\tau}^{\text{ggF}}$  is performed, while the  $VH$ - and  $t\bar{t}H$  production processes are fixed to the values predicted by the Standard Model. The values obtained by the maximum-likelihood fit are

$$\begin{aligned} \sigma_{H \rightarrow \tau\tau}^{\text{VBF}} &= 0.18^{+0.13}_{-0.12} \text{ (stat.) }^{+0.16}_{-0.14} \text{ (syst.) pb} \\ \sigma_{H \rightarrow \tau\tau}^{\text{ggF}} &= 3.1 \pm 1.4 \text{ (stat.) }^{+2.6}_{-1.8} \text{ (syst.) pb} \end{aligned} \quad (4.42)$$

Both are consistent with the Standard Model predictions of  $\sigma_{VBF, H \rightarrow \tau\tau}^{\text{SM}} = 0.237 \pm 0.006$  pb and  $\sigma_{ggF, H \rightarrow \tau\tau}^{\text{SM}} = 3.05 \pm 0.13$  pb [91]. Again, the systematic uncertainties are dominant with respect to the statistical uncertainty. The breakdown of the different sources of uncertainties is shown in Table 4.22. The relative uncertainties are very high, above 80 % for  $\sigma_{H \rightarrow \tau\tau}^{\text{ggF}}$  and above 100 % for  $\sigma_{H \rightarrow \tau\tau}^{\text{VBF}}$ . The largest uncertainties are originating from uncertainties on the signal, jets, and the estimation of the Fake background. For  $\sigma_{H \rightarrow \tau\tau}^{\text{VBF}}$ , the statistical uncertainty of the simulated background processes is the largest uncertainty.

### 4.9.1 Combination with the $\tau_{\text{lep}}\tau_{\text{lep}}$ - and $\tau_{\text{had}}\tau_{\text{had}}$ channels

Similar analyses to the one presented in this thesis are performed in the full leptonic- and full hadronic decay channels of  $H \rightarrow \tau\tau$ . The same maximum-likelihood fits as mentioned above are performed but using in total 13 signal regions and 6 control regions. The combined analysis of the three final states is documented in Ref. [9]. All numbers and figures presented in this section are taken from there.

The observed significance obtained with the combination is 4.4 standard deviations with an expected significance of 4.1 standard deviations. The resulting values for the total signal cross-section and the signal strength are

$$\begin{aligned}\sigma_{H \rightarrow \tau\tau} &= 3.77^{+0.60}_{-0.59} \text{ (stat.)}^{+0.87}_{-0.74} \text{ (syst.) pb} \\ \mu_{H \rightarrow \tau\tau} &= 1.09^{+0.18}_{-0.17} \text{ (stat.)}^{+0.26}_{-0.22} \text{ (syst.)}^{+0.16}_{-0.11} \text{ (theory syst.)}\end{aligned}\tag{4.43}$$

The best-fit values of the two-parameter fit are

$$\begin{aligned}\sigma_{H \rightarrow \tau\tau}^{\text{VBF}} &= 0.28 \pm 0.09 \text{ (stat.)}^{+0.11}_{-0.09} \text{ (syst.) pb} \\ \sigma_{H \rightarrow \tau\tau}^{ggF} &= 3.1 \pm 1.0 \text{ (stat.)}^{+1.6}_{-1.3} \text{ (syst.) pb}\end{aligned}\tag{4.44}$$

Again, all these results are in agreement with the Standard Model predictions and systematic uncertainties are dominating. The combination with the other channels reduces the relative uncertainties with respect to the analysis of the  $\tau_{\text{lep}}\tau_{\text{had}}$  channel. The relative uncertainty on the total signal cross-section is 27 %, while it is 48 % and 57 % for  $\sigma_{H \rightarrow \tau\tau}^{\text{VBF}}$  and  $\sigma_{H \rightarrow \tau\tau}^{ggF}$ , respectively.

Figure 4.38 shows the  $m_{\tau\tau}^{\text{MMC}}$  distribution for the combination of all 13 signal region. The contribution of each region is weighted by  $\ln(1 + s/b)$ , where  $s/b$  is the expected signal-to-background ratio of the respective signal region.

The impact of the leading ten uncertainties on  $\sigma_{H \rightarrow \tau\tau}$  and their post-fit pulls are shown in Figure 4.39. One component of the uncertainties related to the QCD calculation of the  $ggF$  process has the largest impact, followed by an uncertainty related to the jet energy resolution. Three other components of the QCD calculation uncertainty are also included in these important uncertainties, as well as the normalisation factors for the  $Z \rightarrow \tau\tau$ - and  $Z \rightarrow \ell\ell$  processes in the Boosted categories, and uncertainties related to the  $b$ -mistag rate, the jet energy scale, and the uncertainty of the luminosity.

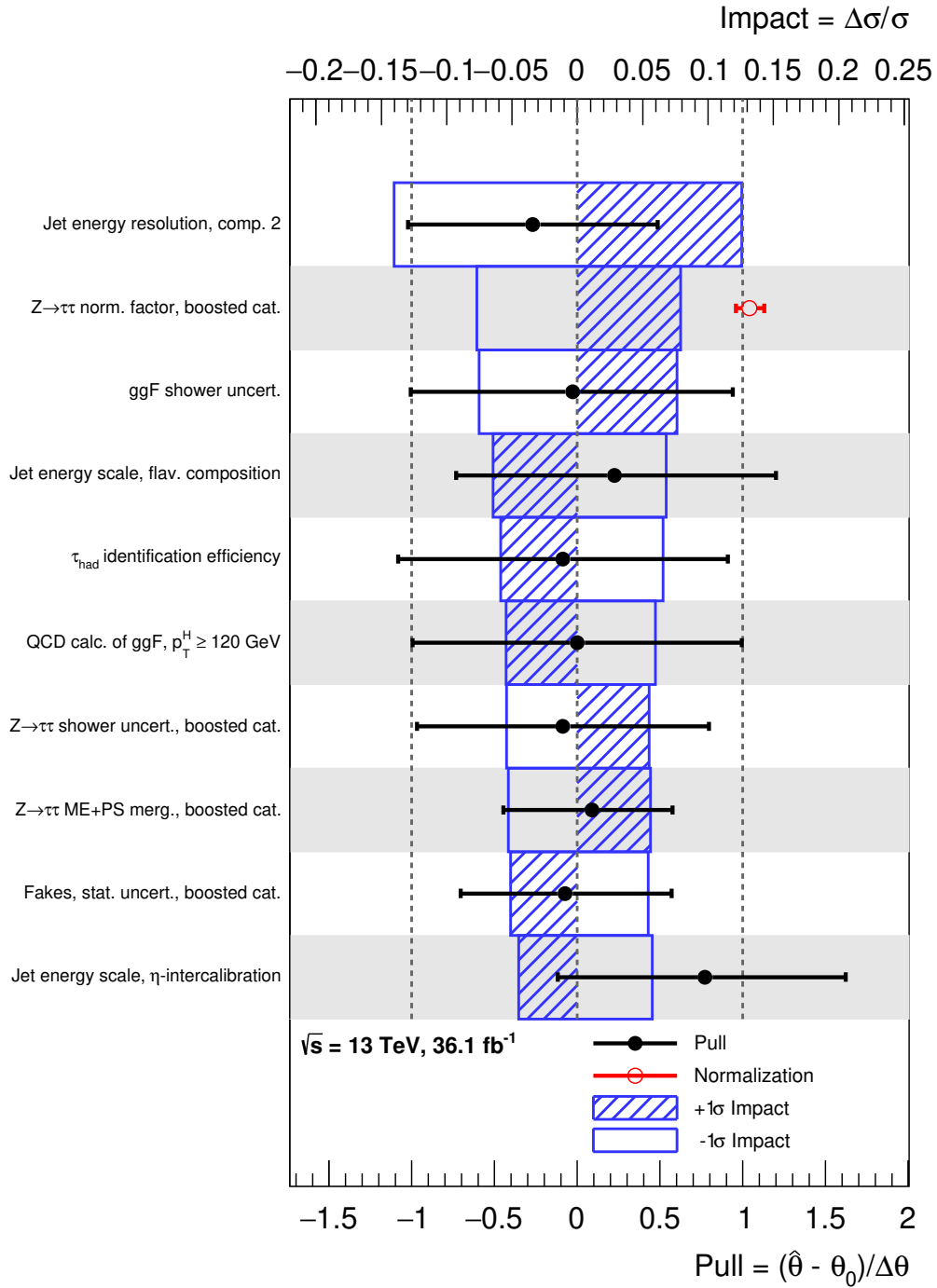
The  $\tau_{\text{lep}}\tau_{\text{had}}$  channel is an important contribution in the combination: it has the largest signal-to-background ratio, the largest individual significance, and lies between the other two channels with respect to the relative uncertainty on the cross-section, as shown in Figure 4.40.

A combination with the result of the search for  $H \rightarrow \tau\tau$  with data recorded at center-of-mass energies of 7 and 8 TeV [311] was performed. The resulting observed significance is 6.4 standard deviations with an expected significance of 5.4 standard deviations.

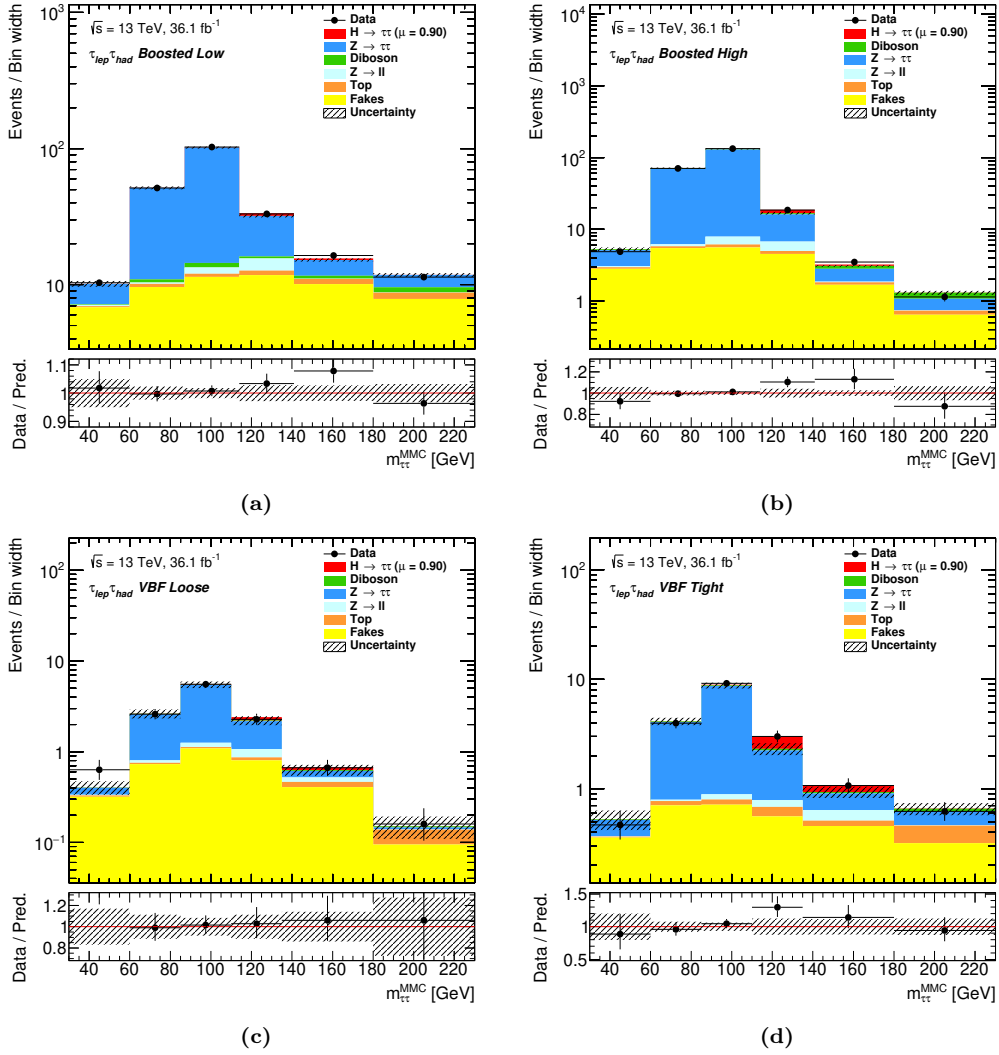
The CMS collaboration also performed a measurement of the  $H \rightarrow \tau\tau$  decay, using  $35.9 \text{ fb}^{-1}$  of data collected at a center-of-mass energy of  $\sqrt{s} = 13 \text{ TeV}$  [312]. The

reported observed significance is 4.9 standard deviations, while the expected significance is 4.7 standard deviations. By combining with the corresponding measurement with data collected at center-of-mass energies of  $\sqrt{s} = 7$  TeV and  $\sqrt{s} = 8$  TeV, an observed significance of 5.9 standard deviations is obtained, equal to the expected significance.

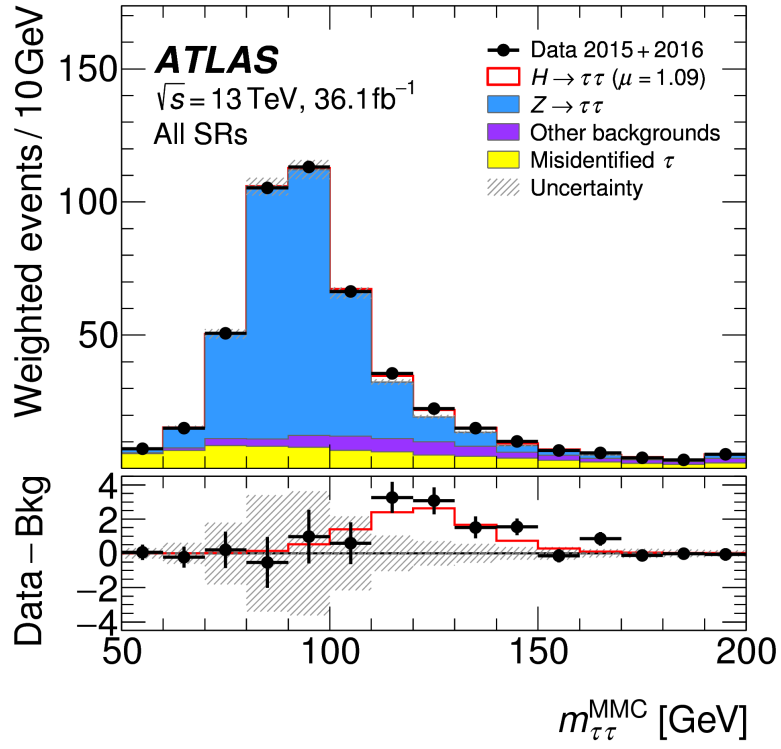
The best-fit value for the signal strength is  $\mu = 1.09^{+0.27}_{-0.26}$ , with a relative uncertainty of 24 %. A measurement of the cross-sections is not reported.



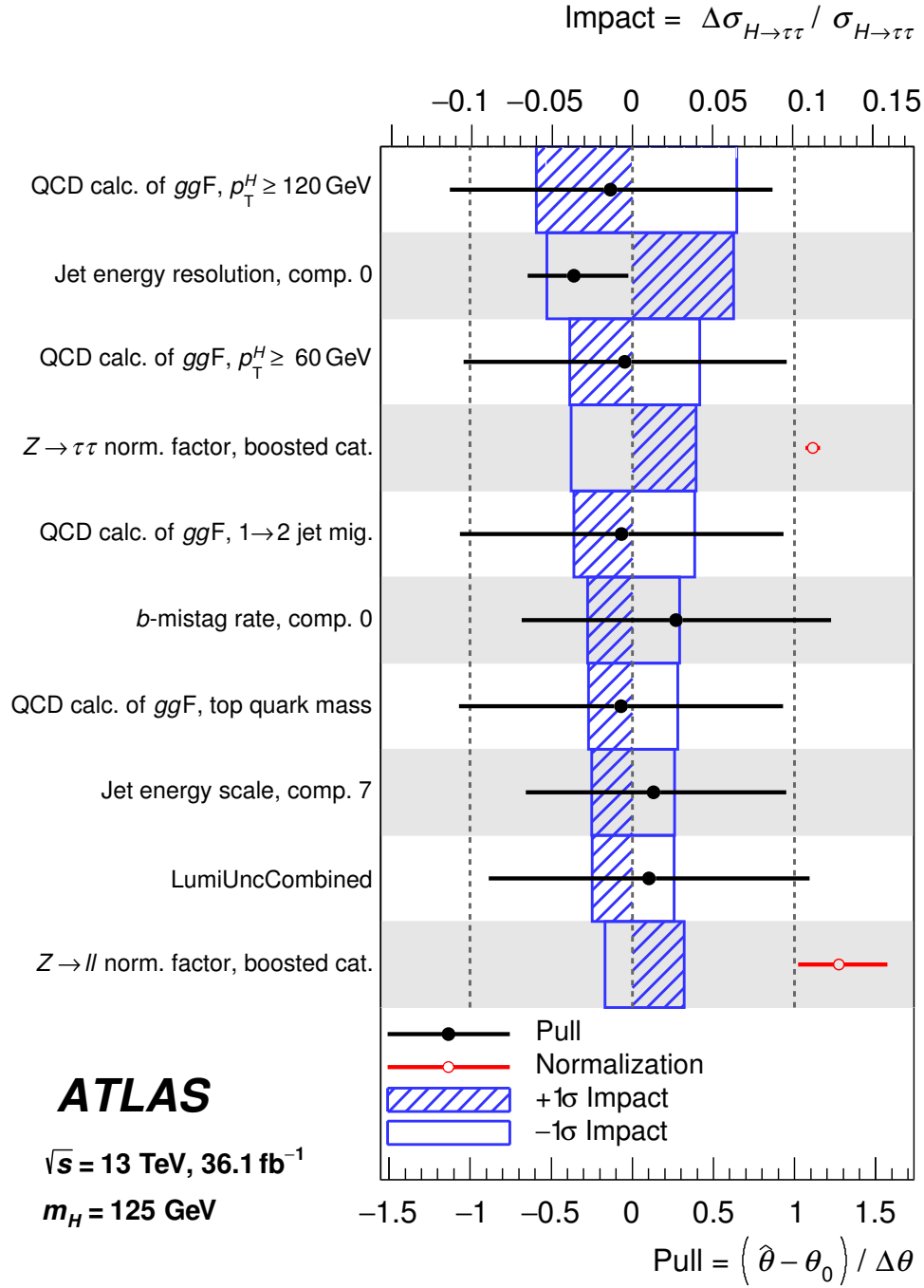
**Figure 4.36:** Relative impact of systematic uncertainties on the cross-section in decreasing order of the size of the impact as computed by the maximum-likelihood fit, shown by the blue boxes. Only the leading ten uncertainties are shown. The black dots and error bars show the pulls and uncertainties of the fitted nuisance parameters. The red dot and error bar show the  $Z \rightarrow \tau\tau$  normalisation factor in the Boosted category and its uncertainty.



**Figure 4.37:**  $m_{\tau\tau}^{MMC}$  distributions and the ratio between the data and the Standard Model prediction in the Boosted Low- (a), Boosted High- (b), VBF Loose- (c), and VBF Tight (d) signal regions. The signal and the backgrounds are determined by the maximum-likelihood fit and the signal is scaled by the best-fit value for  $\mu_{H \rightarrow \tau\tau}$ . The hatched bands include all statistical, experimental, and theoretical uncertainties.

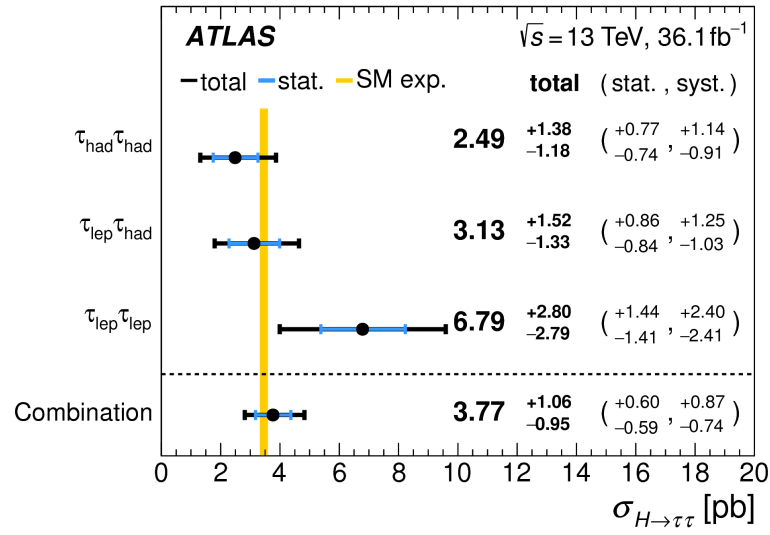


**Figure 4.38:**  $m_{\tau\tau}^{\text{MMC}}$  distribution and the difference between the data and background for the sum of all signal regions. The contribution of each region is weighted by  $\ln(1 + s/b)$ , where  $s/b$  is the expected signal-to-background ratio of the region. The signal and the backgrounds are determined by the maximum-likelihood fit and the signal is scaled by the best-fit value for  $\mu_{H \rightarrow \tau\tau}$ . The hatched bands include all statistical, experimental, and theoretical uncertainties. Taken from Ref. [9].



**Figure 4.39:** Relative impact of systematic uncertainties on the cross-section in decreasing order of the size of the impact as computed by the maximum-likelihood fit, shown by the blue boxes. Only the leading ten uncertainties are shown. The black dots and error bars show the pulls and uncertainties of the fitted nuisance parameters. The red dots and error bars show the  $Z \rightarrow \tau\tau$ - and  $Z \rightarrow \ell\ell$  normalisation factors in the Boosted categories and their uncertainties. Taken from Ref. [9].





**Figure 4.40:** Measured values for  $\sigma_{H \rightarrow \tau\tau}$  for maximum-likelihood fits in the individual channels and for the combined maximum-likelihood fit. The black error bars indicate the total uncertainty, whereas the statistical uncertainty is indicated by the blue error bars. The yellow band represents the theory uncertainty of the predicted cross-section. Taken from Ref. [9].



# Chapter 5

## Test of CP invariance

The aim of this analysis is the test of CP invariance in the coupling between the Higgs boson and the electroweak gauge bosons. In this analysis, the production of the Higgs boson via VBF is used to study this coupling. Hence, only the VBF production process is regarded as signal process in this analysis, the  $ggF$ -,  $VH$ -, and  $t\bar{t}H$  production processes on the other hand are treated as background processes. All couplings between the Higgs boson and particles other than the electroweak gauge bosons are assumed to be as predicted by the SM, e.g. the couplings in the  $ggF$  production process and in the decay  $H \rightarrow \tau\tau$ . The CP-odd *Optimal Observable* ( $OO$ ), introduced in Section 1.5, is used in maximum-likelihood fits to test for CP violation and to measure or set constraints on the parameter  $\tilde{d}$ . The distribution of the MMC mass is used in a control region to constrain systematic uncertainties and to obtain the normalisation of the  $Z \rightarrow \tau\tau$  background.

The same techniques to estimate the backgrounds as in Chapter 4 are used, and the same experimental and theoretical uncertainties are considered. An additional uncertainty on the veto of a third jet is included for the  $ggF$  process, and a different approach for the usage of the uncertainty on the jet energy resolution is taken.

It is critical to select a part of the phase space that is enriched with VBF signal events. Although the cross-section measurement described in Chapter 4 also targets the VBF production process, the achieved signal-to-background ratios in the VBF categories are not high enough to allow for a precise measurement of the CP properties. Therefore, instead of following the cut-based approach of Chapter 4, a machine learning approach using *Boosted Decision Trees* (BDTs) is chosen after the application of a loose preselection.

This method is described in Section 5.1 and the event selection for the training of the Boosted Decision Trees is given in Section 5.2, followed by the setup of the training framework in Section 5.3. The definition of the signal region is presented in Section 5.4. The changes in the background estimation with respect to the cross-section measurement are detailed in Section 5.5. The method to produce signal templates with CP-mixing is explained in Section 5.6. The systematic uncertainties and their impact are discussed in Section 5.7. After that follows an overview of the used fit model in Section 5.8. The results of the analysis are presented in Section 5.9.

All distributions in this chapter, with exception of those in Section 5.9, are shown before the maximum-likelihood fit is performed, i.e. all signal- and background processes are normalised to their respective theoretical cross-section and the shapes of the distributions are taken from simulation, except for the data-driven estimate of the Fake background.

## 5.1 Boosted Decision Trees

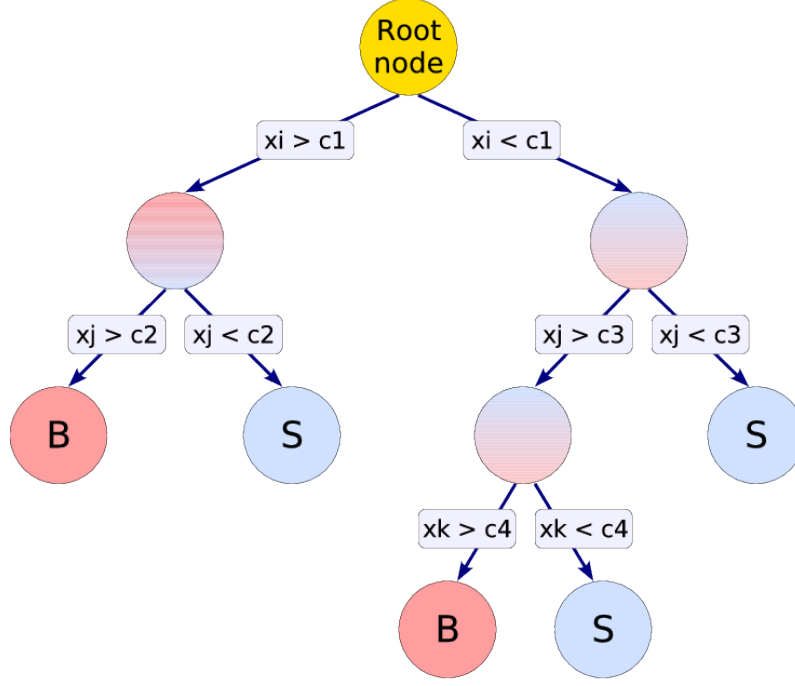
In a cut-based approach, every single selection criterion discards a set of events. These events are then no longer available for the maximum-likelihood fit, resulting in an increased statistical uncertainty. Instead of discarding events, *supervised machine learning classification* classifies them as signal- or background-like. The resulting distribution can either be directly used as input for the maximum-likelihood fit, or a cut can be applied to select a phase space dominated by signal-like events. The latter option, which is used in this analysis, also discards events, but since the machine learning technique exploits correlations between the selection criteria in the event classification, a higher signal-to-background ratio than the one of a pure cut-based approach is expected.

First, a model is constructed in a *training* step by using input that is labelled with the desired output, i.e. as either signal or background. After that, the accuracy of the model is evaluated in a test step by using input that is separate from the training input. If the model satisfies the requirements, it can be used to classify arbitrary, unlabelled input.

In this analysis, the TMVA [313] implementation of the BDT method is used to separate the signal- and background processes.

The input to a decision tree in the training, or *growing*, step is a set of events, labelled as signal or background, and a list of variables. All input variables are scanned with cut values according to a given step size, where each cut divides the original set of events, the root node, into two new nodes. For each of these nodes, the separation power is determined by using the *Gini index* [314]  $G = p \cdot (1 - p)$ , with the purity  $p = \frac{s}{s+b}$ , where  $s$  and  $b$  are the amount of signal- and background events in the node, respectively. The variable and corresponding cut value that maximises the increase between the Gini index of the parent node and the sum of the Gini indices of the resulting daughter nodes, weighted by the fraction of events they contain, is then chosen. After this, the daughter nodes are the starting point for the next iteration of this procedure. This is repeated until a stopping criterion is fulfilled. The final nodes, the *leaf* nodes, are then classified as either signal- or background nodes, according to the majority of the events they contain. Each event can thus be assigned an output value of +1 (signal-like) or -1 (background-like), depending on the classification of the leaf node that contains the event. Figure 5.1 shows a visualisation of this procedure.

In the test step, another set of events is used as input for the trained decision tree. The responses of the decision tree to this test set should be similar to the responses to the training set, otherwise *overtraining* has occurred, i.e. the decision tree was trained on features specific to the training set. This can happen when statistical fluctuations are present in the training set that impact the decisions during the



**Figure 5.1:** Visualisation of a decision tree.  $x_i, x_j$ , and  $x_k$  are variables and  $c_1, c_2, c_3$ , and  $c_4$  are the respective cut values. The leaf nodes are classified as either signal (S) or background (B). Taken from Ref. [313].

training. Another downside of decision trees are the fact that they are *weak learners*, i.e. their outcome is only slightly better than a random guess. *Boosting* [315, 316] can be used to combine multiple weak learners into a strong learner and improve the training performance.

When using Boosted Decision Trees, multiple trees are trained with the same training set. The final output  $F(\vec{x})$  is a weighted sum of the responses of the individual decision trees  $h(\vec{x}; \vec{a})$ :

$$F(\vec{x}; \{\rho_m, \vec{a}_m\}_1^M) = \sum_{m=1}^M \rho_m h(\vec{x}; \vec{a}_m) \quad (5.1)$$

Here,  $M$  is the total number of decision trees,  $h(\vec{x}; \vec{a}_m)$  is the response of one tree, where  $\vec{a}_m$  denotes the parameters that are used, i.e. the variables and cut values, and  $\rho_m$  are the respective weights. The output of  $F(\vec{x})$  can now take values between  $-1$  and  $+1$ .

An additive model is used to construct  $F(\vec{x})$ : at each step, one additional decision tree is added and the existing trees are left unchanged:

$$F_m(\vec{x}) = F_{m-1}(\vec{x}) + \rho_m h(\vec{x}; \vec{a}_m) \quad (5.2)$$

The parameters  $\vec{a}_m$  and the weights  $\rho_m$  are chosen such that the deviation between the output of  $F(\vec{x})$  and the true classification  $\vec{y}$ , i.e.  $-1$  for a background event and  $+1$  for a signal event, is minimised. The deviation is quantified by a *loss-function*  $L(y, F)$ , i.e. by minimizing the loss-function, the deviation is minimised.

In this analysis, the TMVA implementation of the *Gradient Boost* [317] method is used, with the binomial log-likelihood loss-function:

$$L(y, F) = \ln(1 + e^{-2yF(\vec{x})}) \quad (5.3)$$

A *steepest-descent* approach is used to numerically approximate the minimisation of the loss-function via the calculation of its gradient after adding a new tree.

To avoid overtraining, the learning rate can be limited by reducing the impact of each tree. This is done by multiplying the output of the tree by a *shrinkage* parameter  $\nu < 1$  when the tree is added:

$$F_m(\vec{x}) = F_{m-1}(\vec{x}) + \nu \rho_m h(\vec{x}; \vec{a}_m) \quad (5.4)$$

## 5.2 Training selection

To achieve a good performance of the BDTs, it is important to have a high number of events available for the training step to reduce the impact of statistical fluctuations. Because of this, a looser event selection than the one defined for the measurement of the cross-section introduced in Section 4.5 is used in this analysis.

In the preselection, the cuts on  $E_T^{\text{miss}}$ ,  $|\Delta\eta_{\ell, \tau_{\text{had}}}|$ ,  $\Delta R_{\ell, \tau_{\text{had}}}$ ,  $x_1$  and  $x_2$  are removed, whereas in the definition of the VBF category, the cut on  $\eta_{j_1} \cdot \eta_{j_2}$  and the requirement on the lepton centrality are removed, and the cut on  $m_{jj}$  is loosened from 400 GeV to 300 GeV. The remaining cuts are listed in Table 5.1 and the event yields after this selection are shown in Table 5.2.

| Training selection                                                           |
|------------------------------------------------------------------------------|
| $\tau_{\text{had}}$ : <i>medium</i> ID, $p_T > 30$ GeV                       |
| $e/\mu$ : <i>medium</i> ID, <i>gradient</i> isolation, $p_T$ as in Table 4.3 |
| $N_{\tau_{\text{had}}} = 1$ , $N_{e/\mu} = 1$                                |
| $\text{BDT}_{\text{score}}^{\text{e-Veto}} > 0.15$                           |
| Opposite charge of lepton and $\tau_{\text{had}}$                            |
| $m_T < 70$ GeV                                                               |
| $N_{b\text{-jets}} = 0$                                                      |
| $p_T^{j_1} > 40$ GeV                                                         |
| $p_T^{j_2} > 30$ GeV                                                         |
| $ \Delta\eta_{jj}  > 3$                                                      |
| $m_{jj} > 300$ GeV                                                           |

**Table 5.1:** Definition of the training selection.

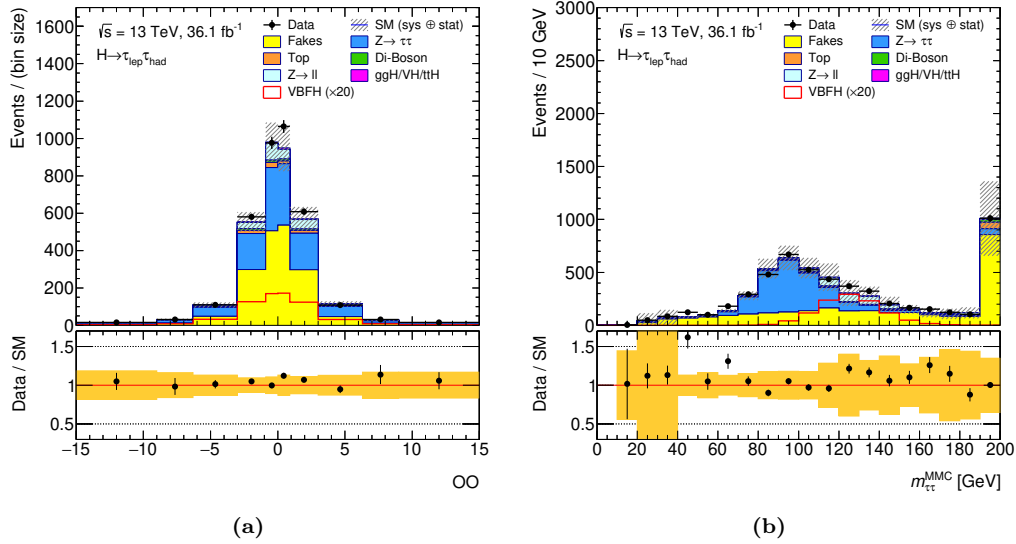
Table 5.2 shows both the *unweighted* and the *weighted* event yields. The unweighted yield is the raw number of generated events that is available for the training of the BDTs, while the weighted yield represents the expected number of events, i.e. all scale factors are applied and the yield is normalised to the respective expected cross-section and a luminosity of  $36.1 \text{ fb}^{-1}$ .

|            | VBF              | $ggF/VH/t\bar{t}H$ | $Z \rightarrow \tau\tau$ | Fake            | Top         | $Z \rightarrow \ell\ell$ | Diboson        | Background      | s/b   |
|------------|------------------|--------------------|--------------------------|-----------------|-------------|--------------------------|----------------|-----------------|-------|
| Unweighted | 34510            | 3098               | 22637                    | 61520           | 553         | 2099                     | 7890           | 97797           | 0.353 |
| Weighted   | $56.38 \pm 0.35$ | $35.4 \pm 0.8$     | $1\,920 \pm 40$          | $2\,621 \pm 34$ | $151 \pm 7$ | $350 \pm 40$             | $85.5 \pm 3.3$ | $5\,160 \pm 70$ | 0.011 |

**Table 5.2:** Unweighted and weighted event yields after the training selection. *Background* is the sum of all background processes, including the  $ggF$ -,  $VH$ -, and  $t\bar{t}H$  production processes.

After this selection, the dominating backgrounds are Fakes and the  $Z \rightarrow \tau\tau$  process. The signal-to-background ratio is 0.011, which is rather low compared to the numbers of the cross-section measurement shown in Table 4.5. This is expected since a loose selection without much separation power is applied deliberately to increase the event yields for the training.

The distributions of the Optimal Observable and the MMC mass after the training selection are shown in Figure 5.2.



**Figure 5.2:** Distributions of the Optimal Observable (a) and the MMC mass (b) after the training selection. Statistical and systematic uncertainties are included in the uncertainty band.

The same control regions as in the cross-section measurement introduced in Section 4.5.4 are defined. For the definition of the control region for top-quark backgrounds (TopCR), at least one  $b$ -tagged jet is required and the cut on the transverse mass is changed from  $m_T < 70$  GeV to  $m_T > 40$  GeV. For the  $W$ +jets control region (WCR), the cut on the transverse mass is inverted to  $m_T > 70$  GeV. For the control region for the multijet background (QCD CR), the isolation requirement of the lepton is inverted.

### 5.3 Setup used in this analysis

Several parameters can be adjusted for the training of (boosted) decision trees and the choice of these parameters impacts the performance and overtraining of the classifier. To obtain a good configuration, a scan in the space of parameter values is performed. Three parameters are scanned: the *minimal node size*, which impacts the complexity of the individual decision trees, and the *number of trees* and the *shrinkage*, which impact the complexity of the boosting.

The minimal node size stops the growing of a decision tree if the remaining number of events in a node is too small. This parameter is given as the relative fraction of the total number of events in the training set. Another parameter, the *maximum depth* of the tree, is set to a fixed value of five so that the depth of the tree is fully controlled by the minimal node size.



The number of trees defines the total number of trees used during boosting. The shrinkage parameter controls the learning rate of the algorithm by reducing the weight of the individual decision trees.

Table 5.3 shows the tested values of the parameters. The values that resulted in the best configuration are a minimal node size of 5 %, a number of 100 trees, and a shrinkage of 0.1.

| Parameter          | Scanned values                                     |
|--------------------|----------------------------------------------------|
| Min. node size [%] | 0.1, 0.2, 0.5, 1, 2, <u>5</u> , 10, 20             |
| Number of trees    | 10, 20, 50, <u>100</u> , 200, 400, 800, 1000, 1200 |
| Shrinkage          | 0.03, <u>0.1</u> , 0.3, 0.8, 1                     |

**Table 5.3:** Parameters and the tested values in the optimisation of the BDTs. The chosen values are underlined.

This scan can, like the scan of variables and cut values, lead to overtraining. To avoid this, instead of splitting the events into a training- and a test set as described above, they are split into three disjoint sets:

1. the *training* set to train the BDTs
2. the *validation* set to test the performance of the trained BDTs. For this, a maximum-likelihood fit is performed, including the most important systematic uncertainties
3. the *test* set is the input to the selected best performing BDTs. The resulting BDT score is used in the analysis

With this procedure, the events in the test set are only used as input for the final BDTs, so any potential bias due to the training and optimisation is avoided. As a drawback, not all available simulated events are used in the training, again limiting the performance. Therefore, *k-fold cross-validation* is used.

The idea behind *k-fold cross-validation* is to split the events into *k* disjoint sets, which are then divided into training-, test- and, validation sets in *k* different ways. The simulated events are split into the sets by using a random number. Later in the test step, the data events are split depending on their unique event number *n* and the set *i* they end up in is defined by  $i = n \bmod k$ .

When performing the parameter scan, *k* BDTs are trained for each point, where a different combination of all event sets, excluding two of them, is used as input for each training, i.e. in the training of BDT<sub>*i*</sub> for  $i \in \{0, \dots, k-1\}$ , all sets are used except set *i* and set  $(i+1) \bmod k$ , as they are used as the validation- and test set, respectively. With this method, all events are used for training, validation, and testing.

In this analysis, *k* = 10 is used, resulting in the usage of 80 % of all events in each training. All background processes are used in the training- and validation steps, while only the VBF production process is included as signal.

When using the ten resulting BDTs in the analysis, the events are distributed among them with the same splitting method as in the training- and test steps: a random number between 0 and 1 is used for simulated events, and  $n \bmod 10$  is used for data, where  $n$  is the unique event number.

In total, 23 observables were tested as input variables and only those with the highest impact are used in the final training. For this, the BDTs are first trained with all 23 observables and the binned significance  $Z_{\text{binned}}$  is calculated:

$$Z_{\text{binned}} = \sqrt{\sum_{i \in \text{bins}} Z(s_i, b_i)^2} \quad (5.5)$$

where  $s_i$  and  $b_i$  are the number of signal- and background events in bin  $i$ , respectively.  $Z(s, b)$  is the asymptotic significance [293]:

$$Z(s, b) = \sqrt{2 \left( (s + b) \ln \left( 1 + \frac{s}{b} \right) - s \right)} \quad (5.6)$$

After this, the variable with the lowest *importance* is removed. The importance is calculated by counting how often the variable was used to split a node. Each occurrence is weighted by the number of events in the node and by the gain in separation power, determined by the Gini index. The average importance is calculated using the values of all ten BDTs.

The training of the BDTs is then repeated with the remaining variables,  $Z_{\text{binned}}$  is calculated again, and the variable with the lowest importance is removed. This procedure is repeated until the removal of a further variable would result in a significant drop of  $Z_{\text{binned}}$ .

The remaining nine variables are:

- $m_{\tau\tau}^{\text{vis}}$   
the visible mass of the di- $\tau$  system (defined in Section 4.3.1)
- $m_{\tau\tau}^{\text{MMC}}$   
the mass of the di- $\tau$  system, calculated with the MMC (defined in Section 4.3.3)
- $m_{jj}$   
the invariant mass of the two jets with the highest transverse momenta
- $\Delta R_{\ell, \tau_{\text{had}}}$   
the angular distance between the lepton and the  $\tau_{\text{had}}$
- $\Delta \eta_{\ell, \tau_{\text{had}}}$   
the difference in pseudorapidity  $\eta$  between the lepton and the  $\tau_{\text{had}}$
- $p_{\text{T}}^{\text{total}}$   
the transverse momentum of the vectorial sum of all objects in an event: lepton,  $\tau_{\text{had}}$ ,  $j_1$ ,  $j_2$ ,  $E_{\text{T}}^{\text{miss}}$

- $E_T^{\text{miss}} \phi$  centrality  $/\sqrt{2}$   
the centrality of the missing transverse energy with respect to the azimuthal angles of the lepton and the  $\tau_{\text{had}}$ , defined as

$$E_T^{\text{miss}} \phi \text{ centrality} = \frac{r + s}{\sqrt{r^2 + s^2}} \quad (5.7)$$

with

$$\begin{aligned} r &= \frac{\sin(\phi^{\text{miss}} - \phi^{\tau_{\text{had}}})}{\sin(\phi^\ell - \phi^{\tau_{\text{had}}})} \\ s &= \frac{\sin(\phi^\ell - \phi^{\text{miss}})}{\sin(\phi^\ell - \phi^{\tau_{\text{had}}})} \end{aligned} \quad (5.8)$$

and takes values between  $\pm\sqrt{2}$ .

- $C_{jj}(\ell)$   
the centrality of the lepton with respect to the pseudorapidity of the two jets with the highest transverse momenta
- $C_{jj}(\tau_{\text{had}})$   
the centrality of the  $\tau_{\text{had}}$  with respect to the pseudorapidity of the two jets with the highest transverse momenta

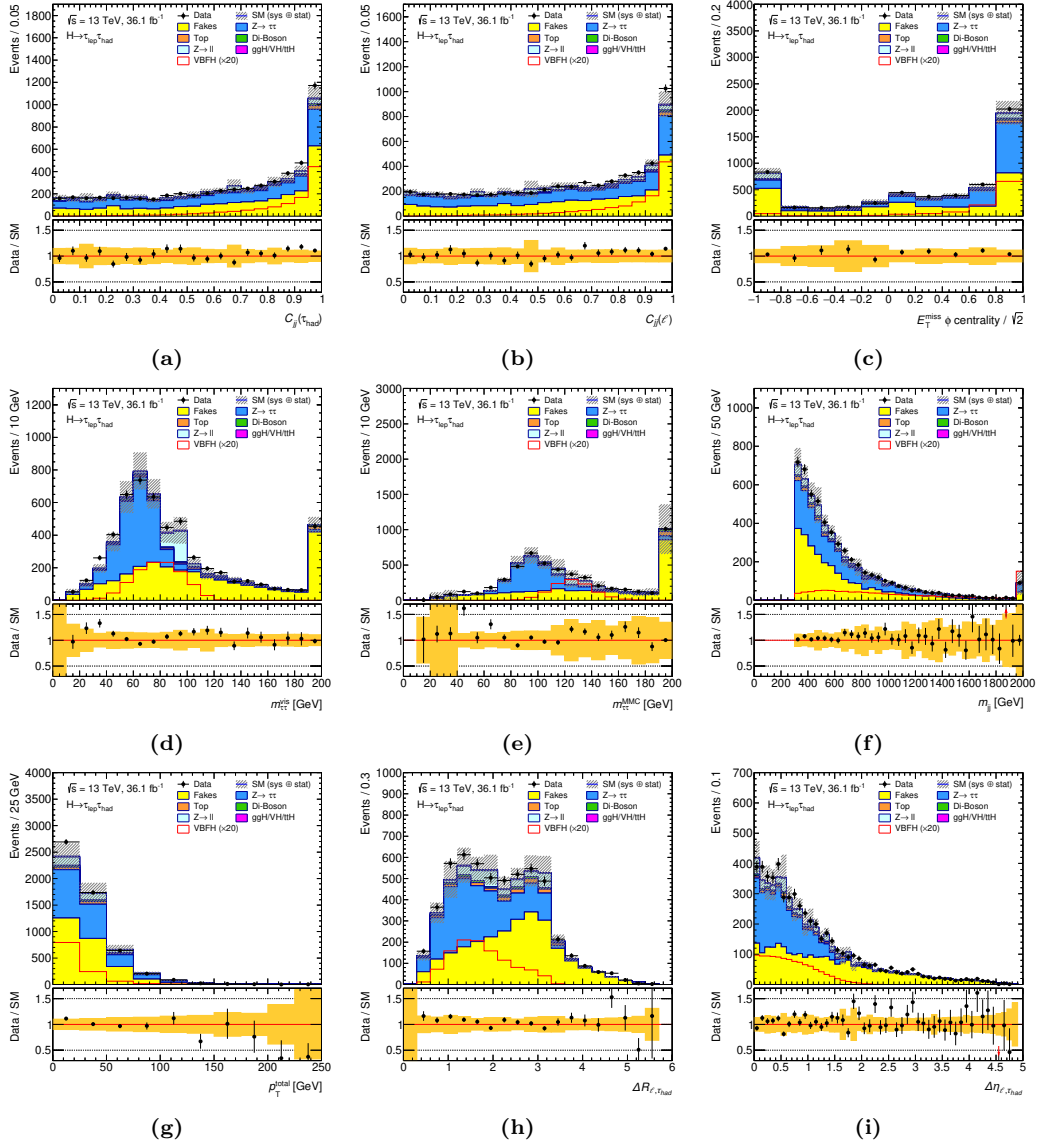
The centrality  $C_{jj}(x)$  for an object  $x$  is defined as

$$C_{jj}(x) = \exp \left[ \frac{-4}{(\eta_{j1} - \eta_{j2})^2} \left( \eta_x - \frac{\eta_{j1} + \eta_{j2}}{2} \right)^2 \right] \quad (5.9)$$

This quantity is one if the object is exactly between the jets and is smaller than  $1/e$  if the object is not located between the jets.

Figure 5.3 shows that all the variables used in the training are well modelled. The ranking of the variables in the training according to their importance is shown in Table 5.4. The variable with the largest importance is the centrality of the lepton  $C_{jj}(\ell)$ , followed by the  $E_T^{\text{miss}} \phi$  centrality and the MMC mass  $m_{\tau\tau}^{\text{MMC}}$ . The first two describe the spatial distribution of the objects in an event and help to suppress backgrounds for which the direction of the objects is not as correlated as in the VBF production process. The MMC mass describes the mass of the di- $\tau$  system and helps to distinguish the non-resonant backgrounds and the  $Z \rightarrow \tau\tau$  background from the  $H \rightarrow \tau\tau$  process.

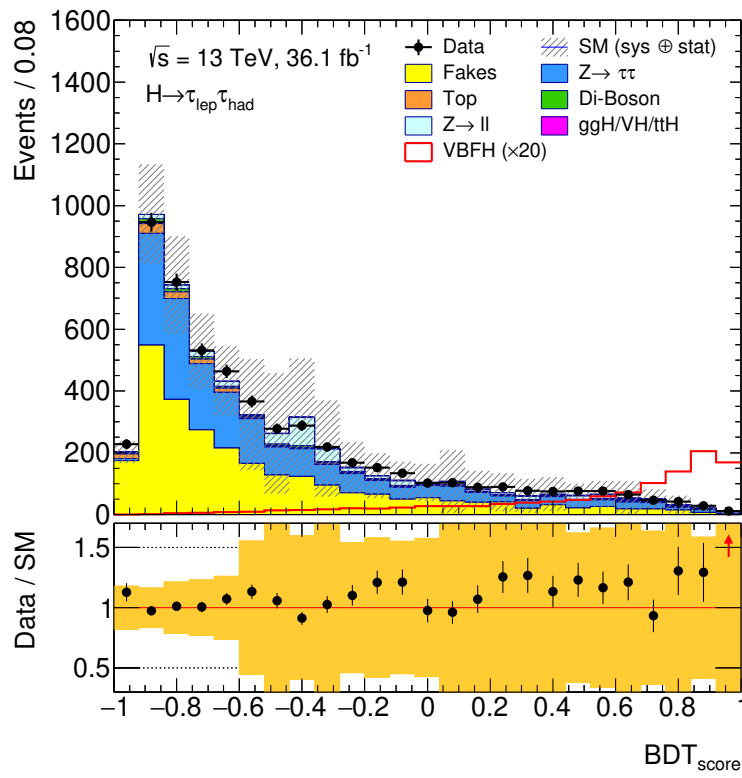
No significant overtraining occurred in the training of the BDTs [318]. The distributions of the resulting BDT score after the training selection in the signal region and in the control regions are shown in Figures 5.4 and 5.5.



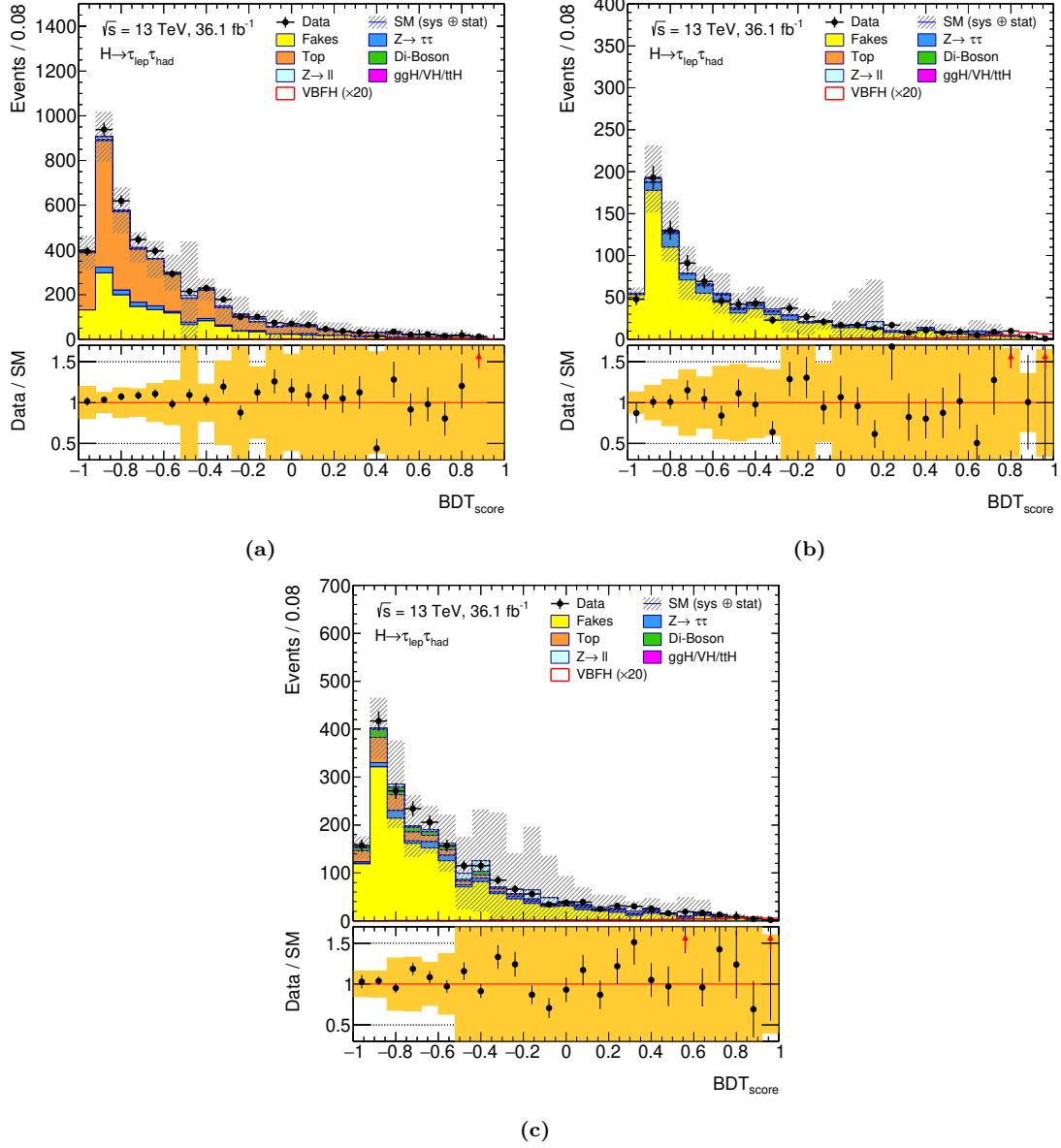
**Figure 5.3:** The variables used in the training of the BDTs after the training selection:  $C_{jj}(\tau_{\text{had}})$  (a),  $C_{jj}(\ell)$  (b),  $E_{\text{T}}^{\text{miss}} \phi \text{ centrality} / \sqrt{2}$  (c),  $m_{\tau\tau}^{\text{vis}}$  (d),  $m_{\tau\tau}^{\text{MMC}}$  (e),  $m_{jj}$  (f),  $p_{\text{T}}^{\text{total}}$  (g),  $\Delta R_{\ell, \tau_{\text{had}}}$  (h), and  $\Delta \eta_{\ell, \tau_{\text{had}}}$  (i). Statistical and systematic uncertainties are included in the uncertainty band.

| Variable                                                        | Importance |
|-----------------------------------------------------------------|------------|
| $C_{jj}(\ell)$                                                  | 0.21       |
| $E_{\text{T}}^{\text{miss}} \phi \text{ centrality} / \sqrt{2}$ | 0.18       |
| $m_{\tau\tau}^{\text{MMC}}$                                     | 0.15       |
| $C_{jj}(\tau_{\text{had}})$                                     | 0.12       |
| $m_{jj}$                                                        | 0.10       |
| $\Delta R_{\ell, \tau_{\text{had}}}$                            | 0.08       |
| $m_{\tau\tau}^{\text{vis}}$                                     | 0.06       |
| $p_{\text{T}}^{\text{total}}$                                   | 0.05       |
| $\Delta \eta_{\ell, \tau_{\text{had}}}$                         | 0.04       |

**Table 5.4:** Ranking of the input variables used in the  $\tau_{\text{lep}}\tau_{\text{had}}$  VBF BDTs.



**Figure 5.4:** The BDT<sub>score</sub> distribution after the training selection in the signal region. Statistical and systematic uncertainties are included in the uncertainty band.



**Figure 5.5:** The  $\text{BDT}_{\text{score}}$  distribution after the training selection in the top-quark control region (a), the QCD control region (b), and the  $W$ +jets control region (c). Statistical and systematic uncertainties are included in the uncertainty band.

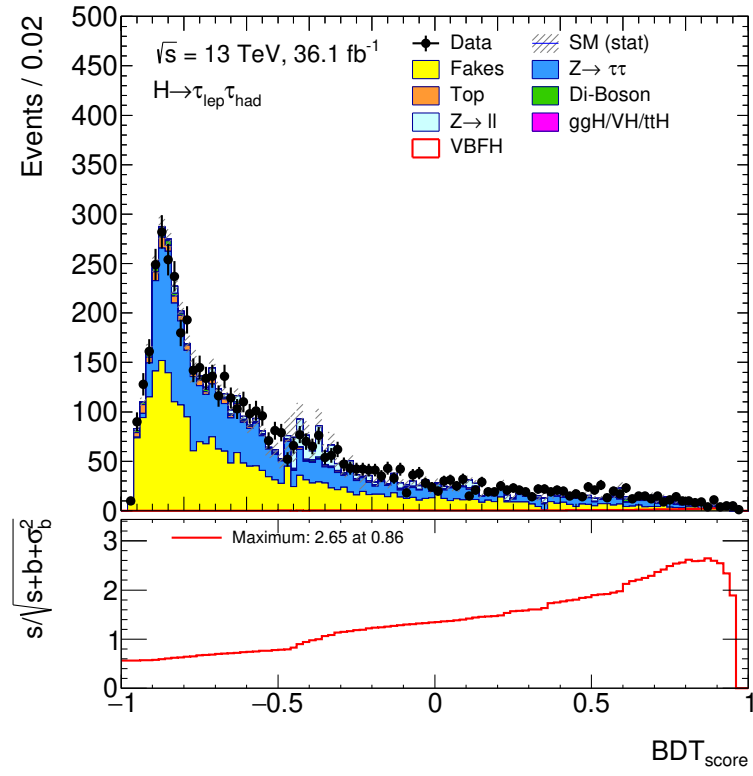
## 5.4 VBF signal region and control regions

Table 5.2 shows that the signal-to-background ratio after the training selection is  $\frac{s}{b} = 0.01$ , where  $s$  is the number of VBF signal events and  $b$  is the number of background events. It is important to increase this number to be sensitive for possible CP violation in the VBF production process. Therefore, a cut on the  $\text{BDT}_{\text{score}}$  is applied to select a region enriched with signal-like events.

The cut on the  $\text{BDT}_{\text{score}}$  is defined by maximizing the value of  $\frac{s}{\sqrt{s+b+\sigma_b^2}}$ , evaluated by a scan of different cut values on a finely binned distribution of the  $\text{BDT}_{\text{score}}$ , where  $\sigma_b$  is the statistical error of the background. This procedure is visualised in Figure 5.6. The resulting cut value is  $\text{BDT}_{\text{score}} > 0.86$ , corresponding to an  $\frac{s}{\sqrt{s+b+\sigma_b^2}}$  of 2.65. The signal efficiency of this cut is 29 %, while the background efficiency is only 0.4 %. This results in a large signal-to-background ratio of 0.913, which is more than 80 times higher than the ratio of 0.011 after the training selection in Table 5.2. The event yields in the VBF SR are listed in Table 5.5. The dominating background is the  $Z \rightarrow \tau\tau$  process, followed by Fakes.

The inverse cut,  $\text{BDT}_{\text{score}} < 0.86$ , defines the *low BDT* control region (lowBDTCR). The event yields in the lowBDTCR are listed in Table 5.5. This region is dominated by the Fake- and  $Z \rightarrow \tau\tau$  background processes. The Fake background constitutes 50 % of the events in the lowBDTCR, while the contribution from the  $Z \rightarrow \tau\tau$  background is 37 %. The signal contribution is less than 1 %. The  $m_{\tau\tau}^{\text{MMC}}$  distribution in this control region is used in the maximum-likelihood fit to obtain the free-floating normalisation of the  $Z \rightarrow \tau\tau$  background and to constrain systematic uncertainties. Although the  $Z \rightarrow \tau\tau$  background is not the dominating background in this region, the lowBDTCR is convenient for this due to the peak structure in the  $m_{\tau\tau}^{\text{MMC}}$  distribution, which is shown in Figure 5.9.

As in the cross-section measurement, top-quark-,  $W$ +jets-, and QCD control regions are used to check the modelling of the top-quark- and Fake background processes. Since the majority of background events has a small  $\text{BDT}_{\text{score}}$ , these control regions are defined after the training selection, i.e. without applying a cut on the  $\text{BDT}_{\text{score}}$ . The event yields in the control regions are listed in Table 5.5. The signal contribution is less than 1 % in all regions. In the TopCR, 58 % of the events are from top-quark processes, while the fraction of Fake background in the WCR and in the QCD is 75 % and 86 %, respectively. The second largest background in the TopCR is the Fake background, while the top-quark background and the  $Z \rightarrow \tau\tau$  background are the second largest backgrounds in the WCR and the QCDCR, respectively.



**Figure 5.6:** The distribution of the  $\text{BDT}_{\text{score}}$  with  $\frac{s}{\sqrt{s+b+\sigma_b^2}}$  for different cut values. Only statistical uncertainties are included in the uncertainty band.

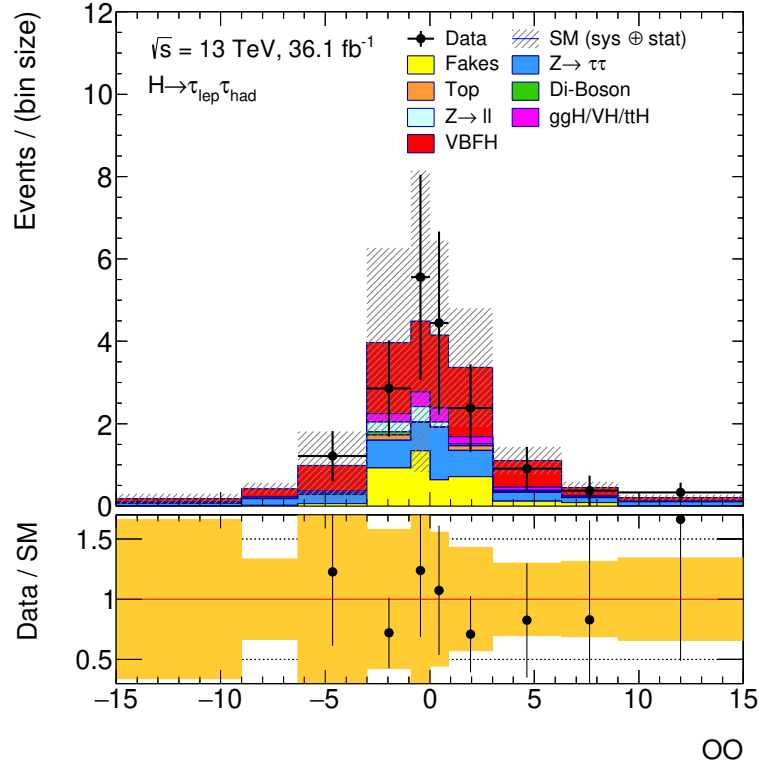


| Category | VBF              | $ggF/VH/t\bar{t}H$ | $Z \rightarrow \tau\tau$ | Fake          | Top             | $Z \rightarrow \ell\ell$ | Diboson         | Background     | Data | s/b   |
|----------|------------------|--------------------|--------------------------|---------------|-----------------|--------------------------|-----------------|----------------|------|-------|
| VBF SR   | $16.57 \pm 0.19$ | $2.24 \pm 0.21$    | $7.7 \pm 1.5$            | $6.2 \pm 1.0$ | $0.50 \pm 0.35$ | $1.0 \pm 1.0$            | $0.51 \pm 0.14$ | $18.1 \pm 2.1$ | 30   | 0.913 |

| Category | VBF              | $ggF/VH/t\bar{t}H$ | $Z \rightarrow \tau\tau$ | Fake          | Top           | $Z \rightarrow \ell\ell$ | Diboson        | Background    | Data | Background fraction [%]                   | Signal fraction [%] |
|----------|------------------|--------------------|--------------------------|---------------|---------------|--------------------------|----------------|---------------|------|-------------------------------------------|---------------------|
| lowBDTCR | $39.81 \pm 0.30$ | $33.2 \pm 0.8$     | $1920 \pm 40$            | $2615 \pm 34$ | $150 \pm 7$   | $350 \pm 40$             | $85.0 \pm 3.3$ | $5150 \pm 70$ | 5375 | 37 ( $Z \rightarrow \tau\tau$ )/50 (Fake) | 0.8                 |
| TopCR    | $2.20 \pm 0.09$  | $5.13 \pm 0.31$    | $141 \pm 13$             | $1467 \pm 17$ | $2422 \pm 33$ | $75 \pm 16$              | $31.9 \pm 2.1$ | $4140 \pm 40$ | 4372 | 58 (Top)                                  | 0.1                 |
| WCR      | $2.83 \pm 0.08$  | $3.28 \pm 0.24$    | $112 \pm 11$             | $1580 \pm 20$ | $198 \pm 8$   | $103 \pm 30$             | $90 \pm 4$     | $2090 \pm 40$ | 2182 | 75 (Fake)                                 | 0.1                 |
| QCDCR    | $2.36 \pm 0.08$  | $1.93 \pm 0.22$    | $89 \pm 9$               | $770 \pm 13$  | $8.3 \pm 1.6$ | $23 \pm 8$               | $3.8 \pm 0.5$  | $896 \pm 17$  | 898  | 86 (Fake)                                 | 0.3                 |

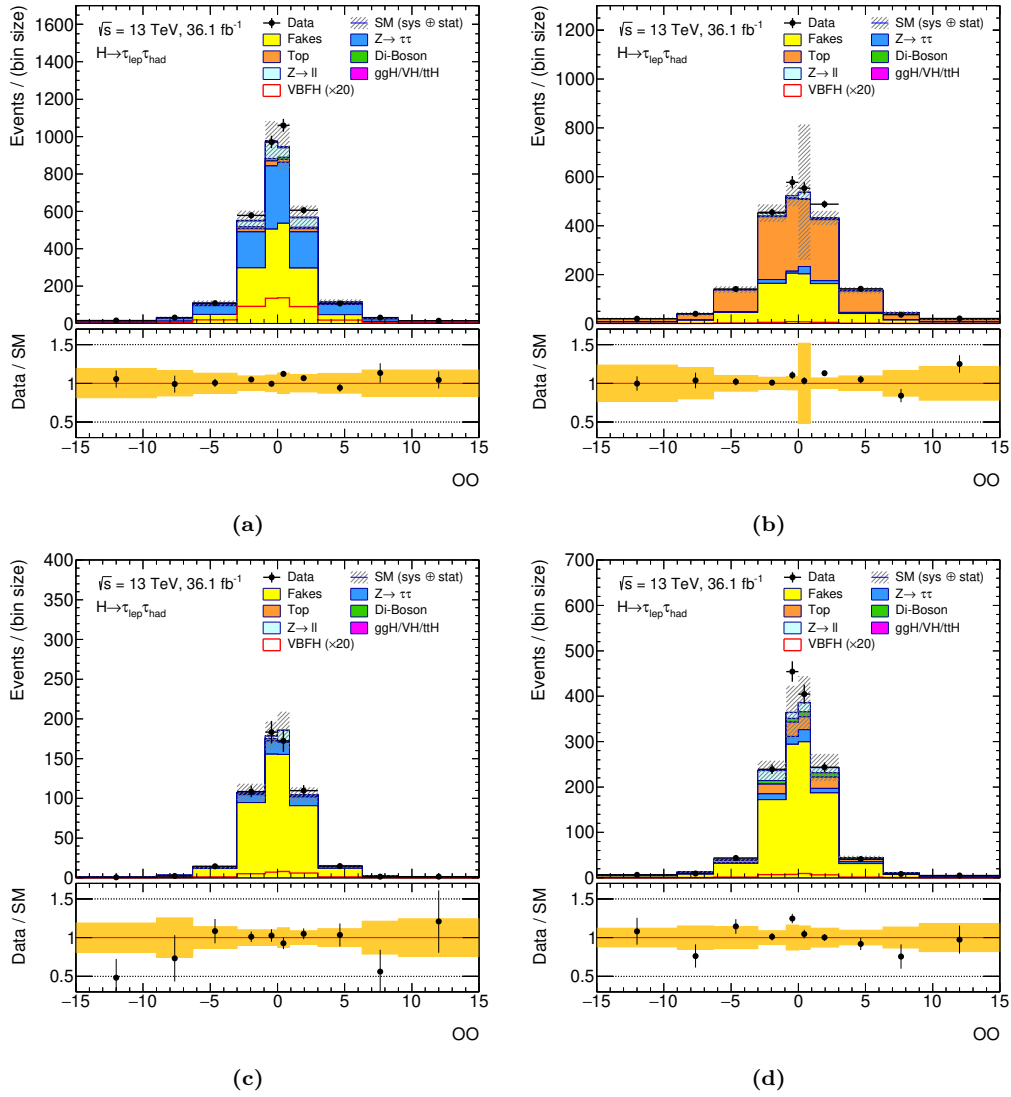
**Table 5.5:** Event yields in the VBF signal region and in the control regions. *Background* is the sum of all background processes. For the control regions, the signal fraction and the fraction of the relevant backgrounds are given. The fractions are relative to the total signal- and background yield. All samples are normalised to their respective theoretical cross-section except for the data-driven Fake estimate.

The Optimal Observable in the signal region and the various control regions is shown in Figures 5.7 and 5.8, respectively. The MMC mass in the lowBDTCR is shown in Figure 5.9. All control regions show a good modelling and no asymmetry is observed in the distributions.

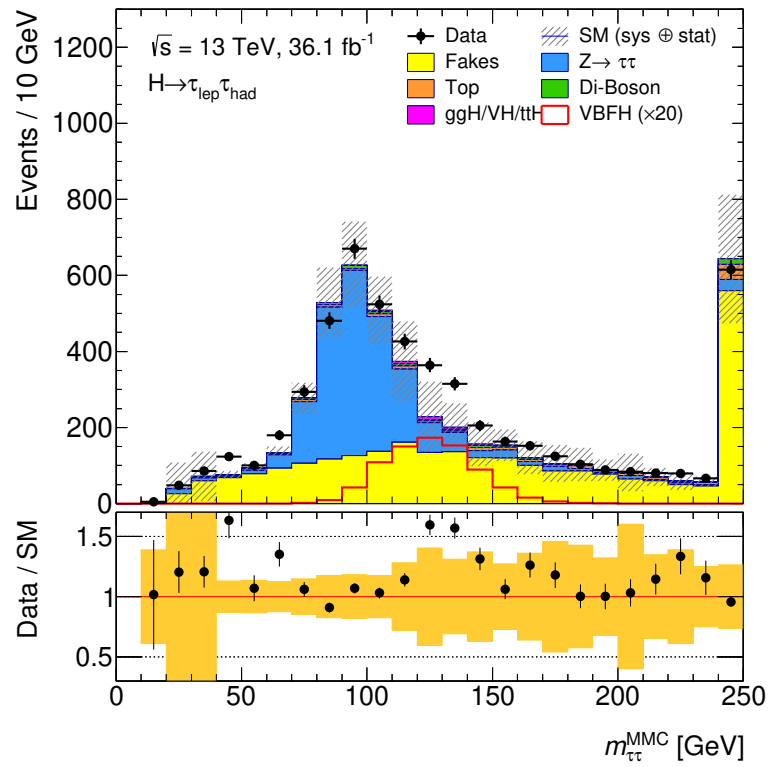


**Figure 5.7:** Optimal Observable in the VBF SR. Statistical and systematic uncertainties are included in the uncertainty band.

The displayed number and size of the bins of the Optimal Observable distribution in Figure 5.7 is also used in the maximum-likelihood fit and is chosen such that each bin contains a positive yield of every background process. To achieve this, a finely binned Optimal Observable distribution is used as starting point. Starting at zero, bins to the left and the right are combined symmetrically until a positive yield of all background processes is obtained in both bins, before the procedure is repeated for the remaining bins.



**Figure 5.8:** Optimal Observable distributions in the low BDT control region (a), the top-quark control region (b), the QCD control region (c), and the W+jets control region (d). Statistical and systematic uncertainties are included in the uncertainty band.



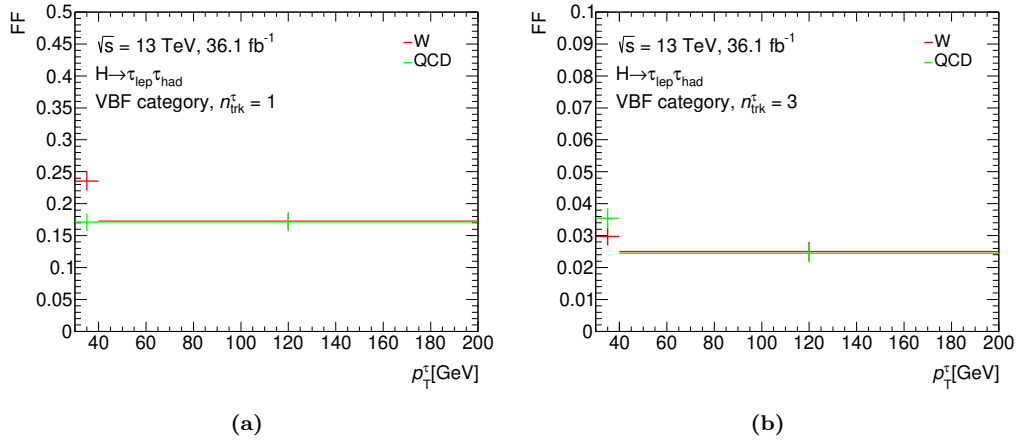
**Figure 5.9:** MMC mass in the low BDT control region. Statistical and systematic uncertainties are included in the uncertainty band.

## 5.5 Background estimation

The same methods as in the cross-section measurement introduced in Section 4.6 are used for the background estimation of this analysis. The differences are described in the following sections.

### 5.5.1 Fake estimation

Since the event selection is changed for this analysis, the complete calculation of the Isolation Factors, the Fake Factors, and the relative contributions from  $W$ +jets- and multijet events is repeated after applying the training selection defined in Table 5.1. The Fake Factors are shown in Figure 5.10, the Isolation Factors in Figure 5.11, and the relative contributions in Figures 5.12 and 5.13. The respective values are listed in Tables 5.6 to 5.9.



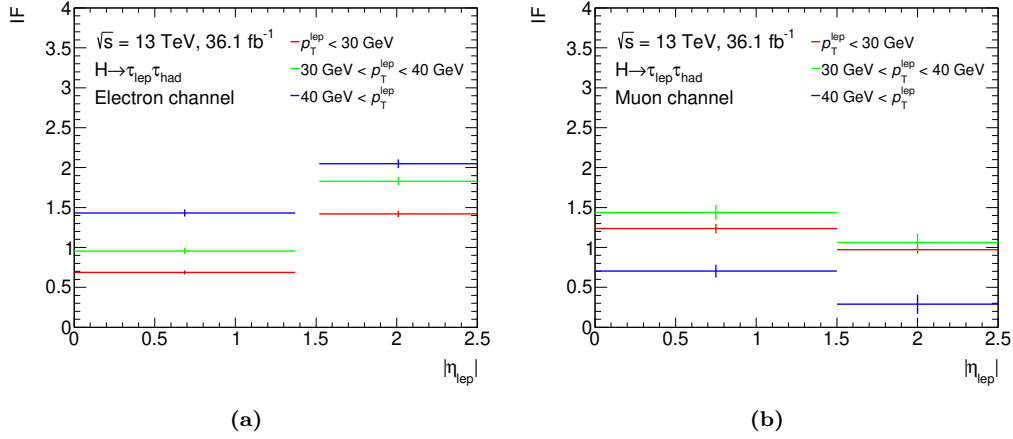
**Figure 5.10:** Fake Factors for the VBF category with a 1-track  $\tau_{\text{had}}$  (a) and a 3-track  $\tau_{\text{had}}$  (b). The statistical uncertainty of the Fake Factors is shown.

|         | FF <sub>W</sub>        |                        | FF <sub>QCD</sub>      |                        |
|---------|------------------------|------------------------|------------------------|------------------------|
|         | $p_T < 40 \text{ GeV}$ | $p_T > 40 \text{ GeV}$ | $p_T < 40 \text{ GeV}$ | $p_T > 40 \text{ GeV}$ |
| 1-track | 0.235                  | 0.173                  | 0.171                  | 0.172                  |
| 3-track | 0.030                  | 0.025                  | 0.035                  | 0.024                  |

**Table 5.6:** Fake Factors for 1-track- and 3-track  $\tau_{\text{had}}$  after the training selection.

The same systematic uncertainties of the Fake Factor method as in the cross-section measurement are considered in this analysis. The relative impact of these uncertainties on the Fake yield in the signal region is shown in Table 5.10.

The closure test is repeated in the SSCR of this analysis. The modelling of the  $\text{BDT}_{\text{score}}$  distribution and of  $m_{\tau\tau}^{\text{MMC}}$  is checked after the training selection and in the lowBDTCR, respectively. It is not possible to check the modelling of the Optimal Observable after the application of the SR cut  $\text{BDT}_{\text{score}} > 0.86$  due to the very low amount of events in this region. A cut of  $\text{BDT}_{\text{score}} > 0.1$  and a suitable binning is used instead. All the distributions are shown in Figure 5.14.



**Figure 5.11:** Isolation Factors for the electron channel (a) and the muon channel (b). The statistical uncertainty of the Isolation Factors is shown.

|                                 | Electron        |                 | Muon           |                |
|---------------------------------|-----------------|-----------------|----------------|----------------|
|                                 | $ \eta  < 1.37$ | $ \eta  > 1.52$ | $ \eta  < 1.5$ | $ \eta  > 1.5$ |
| $p_T < 30$ GeV                  | 0.687           | 1.421           | 1.236          | 0.972          |
| $30 \text{ GeV} < p_T < 40$ GeV | 0.956           | 1.829           | 1.436          | 1.063          |
| $40 \text{ GeV} < p_T$          | 1.430           | 2.047           | 0.703          | 0.288          |

**Table 5.7:** Isolation Factors for the electron channel and the muon channel, and for different  $p_T$  values.

Good agreement between data and the background model is seen for the  $\text{BDT}_{\text{score}}$  distribution and the Optimal Observable, but a mismodelling is observed for small values of the  $m_{\tau\tau}^{\text{MMC}}$  distribution. Therefore, also for this analysis a non-closure systematic uncertainty is included and a correction factor depending on the MMC mass  $m_{\tau\tau}^{\text{MMC}}$  is derived with same-sign events in the lowBDTCR. This factor is then applied to events with fake  $\tau_{\text{had}}$  in the lowBDTCR with the nominal selection applied. The relative impact on the Fake yield is shown in Table 5.10.

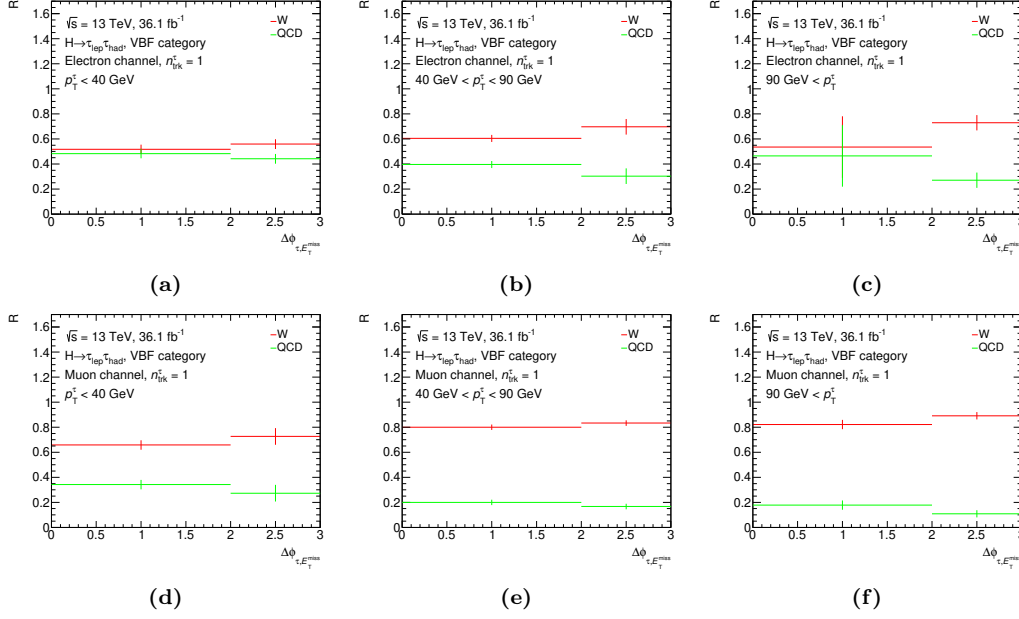
### 5.5.2 Electroweak $Z$ -boson production

As in the cross-section measurement, an uncertainty on the cross-section of electroweak  $Z$ -boson production of 25 % is assumed, following the measurement in [309]. During this analysis it was found that the SHERPA samples underestimate the cross-section of this process. To correct for the difference with the measurement, a factor of 1.7 is applied to the cross-section.

### 5.5.3 $Z \rightarrow \tau\tau$ modelling

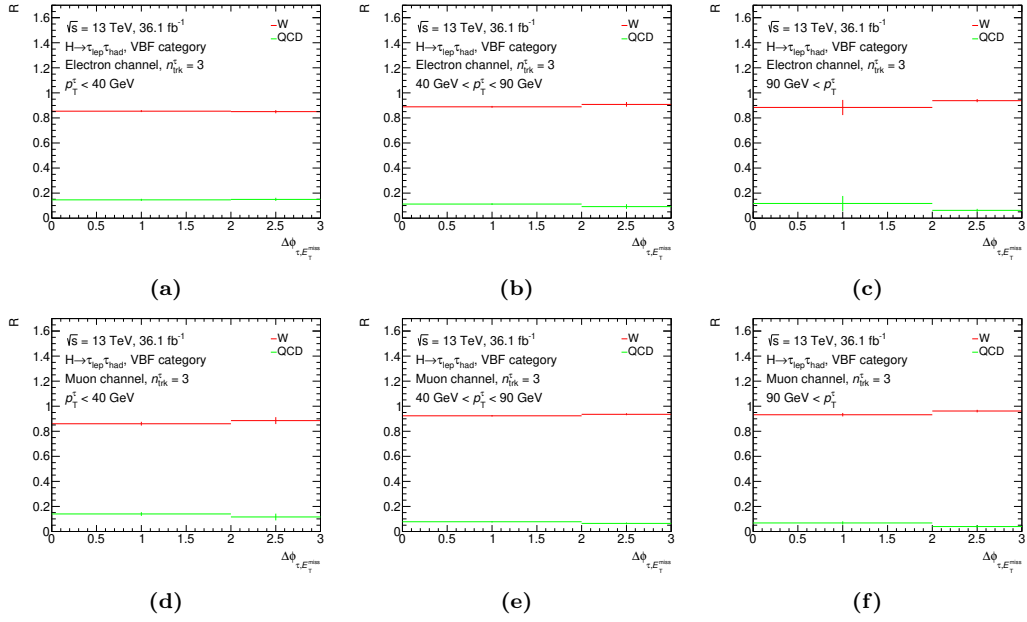
As in the cross-section measurement, the modelling of the  $Z \rightarrow \tau\tau$  process is validated with  $Z \rightarrow \ell\ell$  events in a validation region close to the training selection of this analysis. The definition of the validation region is given in Table 5.11.

The modelling of all jet related input variables that are used for the training of the BDTs, i.e.  $C_{jj}(\ell)$ ,  $C_{jj}(\tau_{\text{had}})$  (with the  $\tau_{\text{had}}$  candidate replaced by the second lepton



**Figure 5.12:** The relative contributions in the VBF category for 1-track  $\tau_{\text{had}}$ , in the electron channel for  $p_T^\tau < 40$  GeV (a),  $40 \text{ GeV} < p_T^\tau < 90$  GeV (b) and  $90 \text{ GeV} < p_T^\tau$  (c), and in the muon channel for  $p_T^\tau < 40$  GeV (d),  $40 \text{ GeV} < p_T^\tau < 90$  GeV (e) and  $90 \text{ GeV} < p_T^\tau$  (f).

in the event),  $m_{jj}$ , and  $p_T^{\text{total}}$ , is validated. A good agreement with data is obtained within uncertainties, but a slope in the  $m_{jj}$  distribution is observed, as in the  $Z \rightarrow \tau\tau$  validation of the cross-section measurement. Reweighting factors depending on  $m_{jj}$  are derived by using the ratio between data and  $Z \rightarrow \ell\ell$  events in the validation region. In contrast to the cross-section measurement, applying these reweighting factors to the  $Z \rightarrow \tau\tau$ - and  $Z \rightarrow \ell\ell$  events in the SR and the lowBDTCR has an impact on the results of this analysis due to the reduced number of background events entering the maximum-likelihood fit. Therefore, the reweighting is applied by default with the full difference in the yields serving as systematic uncertainty. The change in yields in the SR caused by the reweighting is 8% for  $Z \rightarrow \tau\tau$  and 19% for  $Z \rightarrow \ell\ell$ , whereas the impact in the lowBDTCR is less than 1% for both processes.



**Figure 5.13:** The relative contributions in the VBF category for 3-track  $\tau_{\text{had}}$ , in the electron channel for  $p_T^\tau < 40$  GeV (a),  $40 \text{ GeV} < p_T^\tau < 90$  GeV (b) and  $90 \text{ GeV} < p_T^\tau$  (c), and in the muon channel for  $p_T^\tau < 40$  GeV (d),  $40 \text{ GeV} < p_T^\tau < 90$  GeV (e) and  $90 \text{ GeV} < p_T^\tau$  (f).

|          |         |                                         | $R_W$            |                  | $R_{QCD}$        |                  |
|----------|---------|-----------------------------------------|------------------|------------------|------------------|------------------|
|          |         |                                         | $\Delta\phi < 2$ | $\Delta\phi > 2$ | $\Delta\phi < 2$ | $\Delta\phi > 2$ |
| Electron | 1-track | $p_T < 40 \text{ GeV}$                  | 0.517            | 0.559            | 0.483            | 0.441            |
|          |         | $40 \text{ GeV} < p_T < 90 \text{ GeV}$ | 0.604            | 0.697            | 0.396            | 0.303            |
|          |         | $90 \text{ GeV} < p_T$                  | 0.535            | 0.729            | 0.465            | 0.271            |
|          | 3-track | $p_T < 40 \text{ GeV}$                  | 0.854            | 0.850            | 0.146            | 0.150            |
|          |         | $40 \text{ GeV} < p_T < 90 \text{ GeV}$ | 0.888            | 0.908            | 0.112            | 0.092            |
|          |         | $90 \text{ GeV} < p_T$                  | 0.883            | 0.938            | 0.117            | 0.062            |
| Muon     | 1-track | $p_T < 40 \text{ GeV}$                  | 0.658            | 0.727            | 0.342            | 0.273            |
|          |         | $40 \text{ GeV} < p_T < 90 \text{ GeV}$ | 0.800            | 0.833            | 0.200            | 0.167            |
|          |         | $90 \text{ GeV} < p_T$                  | 0.822            | 0.891            | 0.178            | 0.109            |
|          | 3-track | $p_T < 40 \text{ GeV}$                  | 0.860            | 0.885            | 0.140            | 0.115            |
|          |         | $40 \text{ GeV} < p_T < 90 \text{ GeV}$ | 0.923            | 0.936            | 0.077            | 0.064            |
|          |         | $90 \text{ GeV} < p_T$                  | 0.932            | 0.961            | 0.068            | 0.039            |

**Table 5.8:** Relative contributions of multijet- and  $W$ +jets events  $R_{QCD}$  and  $R_W$  after the training selection. They depend on the type of lepton in the event, the number of tracks and the transverse momentum of the  $\tau_{\text{had}}$  candidate, and the angle  $\Delta\phi$  between  $E_T^{\text{miss}}$  and the  $\tau_{\text{had}}$  candidate.



|          |         |                                         | FF = R <sub>W</sub> FF <sub>W</sub> + R <sub>QCD</sub> FF <sub>QCD</sub> |                  |
|----------|---------|-----------------------------------------|--------------------------------------------------------------------------|------------------|
|          |         |                                         | $\Delta\phi < 2$                                                         | $\Delta\phi > 2$ |
| Electron | 1-track | $p_T < 40 \text{ GeV}$                  | 0.204                                                                    | 0.207            |
|          |         | $40 \text{ GeV} < p_T < 90 \text{ GeV}$ | 0.172                                                                    | 0.172            |
|          |         | $90 \text{ GeV} < p_T$                  | 0.172                                                                    | 0.172            |
|          | 3-track | $p_T < 40 \text{ GeV}$                  | 0.031                                                                    | 0.031            |
|          |         | $40 \text{ GeV} < p_T < 90 \text{ GeV}$ | 0.025                                                                    | 0.025            |
|          |         | $90 \text{ GeV} < p_T$                  | 0.025                                                                    | 0.025            |
| Muon     | 1-track | $p_T < 40 \text{ GeV}$                  | 0.213                                                                    | 0.218            |
|          |         | $40 \text{ GeV} < p_T < 90 \text{ GeV}$ | 0.173                                                                    | 0.173            |
|          |         | $90 \text{ GeV} < p_T$                  | 0.173                                                                    | 0.173            |
|          | 3-track | $p_T < 40 \text{ GeV}$                  | 0.031                                                                    | 0.030            |
|          |         | $40 \text{ GeV} < p_T < 90 \text{ GeV}$ | 0.025                                                                    | 0.025            |
|          |         | $90 \text{ GeV} < p_T$                  | 0.025                                                                    | 0.025            |

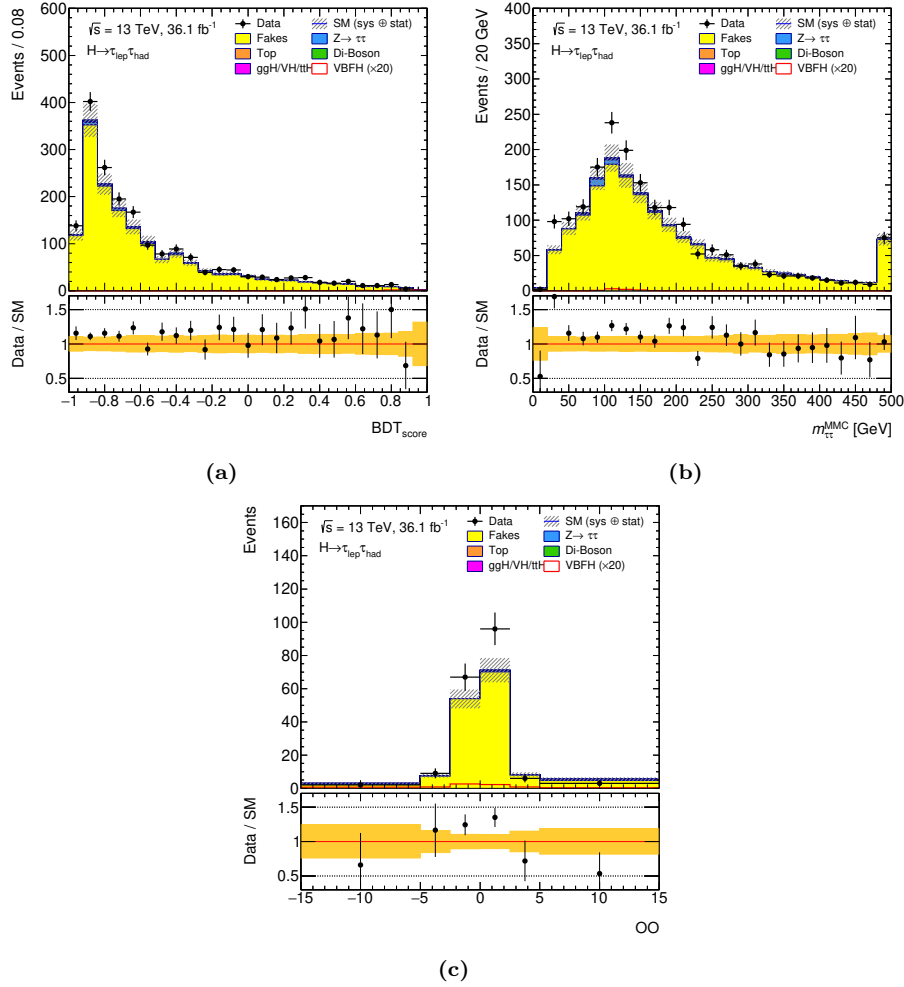
**Table 5.9:** Combined Fake Factors after the training selection. They depend on the type of lepton in the event, the number of tracks and the transverse momentum of the  $\tau_{\text{had}}$  candidate, and the angle  $\Delta\phi$  between  $E_T^{\text{miss}}$  and the  $\tau_{\text{had}}$  candidate.

|          | stat. [%] | R <sub>QCD</sub> [%] | non-closure [%] |
|----------|-----------|----------------------|-----------------|
| SR       | $\pm 9.1$ | $\mp 1.6$            | —               |
| lowBDTCR | $\pm 8.7$ | $-3.4 / +3.2$        | $\pm 5.0$       |

**Table 5.10:** Relative impact of the systematic uncertainties of the Fake Factor method on the Fake yield in the signal region and the lowBDTCR. The non-closure systematic is only considered for the lowBDTCR.

| $Z \rightarrow \tau\tau$ validation region    |
|-----------------------------------------------|
| 2 leptons with same flavour & opposite charge |
| $m_{\ell\ell} > 80 \text{ GeV}$               |
| $E_T^{\text{miss}} < 55 \text{ GeV}$          |
| $p_T^{j_1} > 40 \text{ GeV}$                  |
| $p_T^{j_2} > 30 \text{ GeV}$                  |
| $ \Delta\eta_{jj}  > 3$                       |
| $m_{jj} > 300 \text{ GeV}$                    |
| $N_{b\text{-jets}} = 0$                       |

**Table 5.11:** Definition of the  $Z \rightarrow \tau\tau$  validation region.



**Figure 5.14:** The  $\text{BDT}_{\text{score}}$  after the training selection (a), the MMC mass  $m_{\tau\tau}^{\text{MMC}}$  in the lowBDTCR (b), and the Optimal Observable with a cut of  $\text{BDT}_{\text{score}} > 0.1$  applied. All three figures are derived with the same-sign selection. Statistical uncertainties and all systematic uncertainties related to Fakes are included in the uncertainty band.

## 5.6 Signal reweighting

To obtain the distribution of the Optimal Observable for non-vanishing values of  $\tilde{d}$ , a matrix-element based reweighting is applied to the SM VBF Higgs boson sample. The weights are defined by

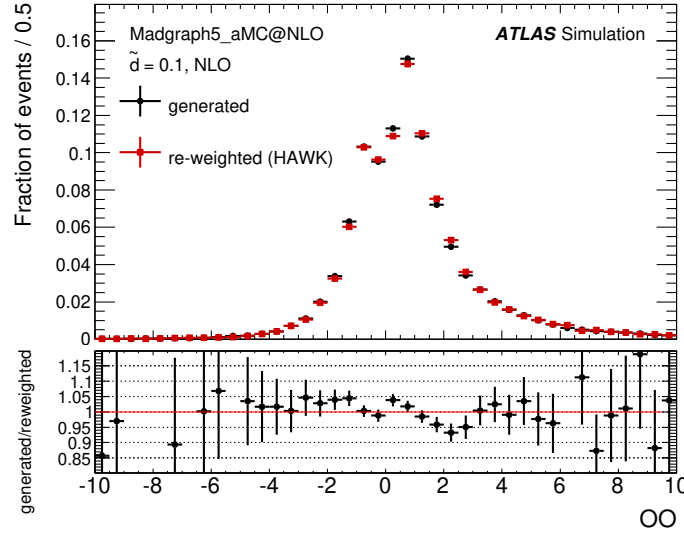
$$\begin{aligned} w(\tilde{d}) &= \frac{|\mathcal{M}|^2}{|\mathcal{M}_{\text{SM}}|^2} \\ &= 1 + \tilde{d} \cdot \frac{2\text{Re}(\mathcal{M}_{\text{SM}}^* \mathcal{M}_{\text{CP-odd}})}{|\mathcal{M}_{\text{SM}}|^2} + \tilde{d}^2 \cdot \frac{|\mathcal{M}_{\text{CP-odd}}|^2}{|\mathcal{M}_{\text{SM}}|^2} \\ &= 1 + \tilde{d} \cdot w_1 + \tilde{d}^2 \cdot w_2 \end{aligned} \quad (5.10)$$

where  $w_1$  and  $w_2$  are calculated once per event and an arbitrary value for  $\tilde{d}$  can be chosen afterwards. The events are simulated with POWHEG-BOX v2 [231–236] at NLO accuracy. The resulting  $2 \rightarrow 2 + H$ - and  $2 \rightarrow 3 + H$  processes, i.e.  $qq \rightarrow qqH$  and  $qq \rightarrow gqqH$  or  $qg \rightarrow qqgH$ , are input to HAWK [99, 100, 102, 169, 170], which is used to calculate the matrix elements for the reweighting at LO accuracy. The inputs for the calculation of the matrix elements are the four-momenta and the flavours of the initial- and final-state partons and the four-momentum of the Higgs boson. The cross-section of the reweighted signal is increased quadratically in  $\tilde{d}$  by the CP-even component  $|\mathcal{M}_{\text{CP-odd}}|^2$  of the matrix element. Since the rate information is not used in this analysis, the reweighted signals are normalised back to the SM cross-section.

This reweighting procedure was already used in the Run-1 analysis [11] and was validated with VBFNLO [319–321] and MADGRAPH5\_aMC@NLO [245]. It is possible to directly generate events with anomalous couplings in the  $HVV$  vertex at LO accuracy with both programs, whereas MADGRAPH5\_aMC@NLO can also generate events at NLO accuracy.

To validate the reweighting procedure, events corresponding to the SM prediction of  $\tilde{d} = 0$  were generated and reweighted as described above, using different values for  $\tilde{d}$ . Events with anomalous couplings corresponding to these  $\tilde{d}$  values were also directly generated and the resulting distributions of the Optimal Observable were compared to those from the reweighted events. This was done at LO accuracy with VBFNLO, and at LO- and NLO accuracy with MADGRAPH5\_aMC@NLO.

For all three comparisons it was found that the reweighting of the SM process provides a good approximation of the directly generated BSM process. The comparison of the Optimal Observable distributions for the events generated at NLO accuracy with MADGRAPH5\_aMC@NLO is shown in Figure 5.15. Good agreement of the two distributions is observed. This validates the usage of the reweighting procedure with LO accuracy to approximate the simulation of processes with anomalous coupling at NLO accuracy.



**Figure 5.15:** Distribution of the Optimal Observable for  $\tilde{d} = 0.1$ . The SM sample generated with MADGRAPH5\_MC@NLO at NLO accuracy is reweighted to  $\tilde{d} = 0.1$  using the procedure described in the text, and is compared to a sample directly generated with anomalous couplings using the same generator. Taken from Ref. [11].

## 5.7 Systematic uncertainties

All systematic uncertainties described in Section 4.8, besides those related to the Boosted categories, are also taken into account in this analysis and their effects are evaluated in the VBF SR and the lowBDTCR. The implementation of the uncertainties on the jet energy resolution is changed with respect to the cross-section measurement, and an additional uncertainty due to a veto on a third jet is introduced.

### 5.7.1 Veto on a third jet

The requirement for high values of the  $\text{BDT}_{\text{score}}$  for the VBF SR results in a VBF phase-space. Therefore, this requirement is effectively a veto on the presence of a third jet in addition to the two jets of the VBF production process. To account for this, an uncertainty of  $+36.6\%/-30.4\%$  is applied on the  $ggF$  signal in the signal region. The uncertainty is evaluated with the *Stewart-Tackmann* method [305, 306] using cross-sections obtained from MADGRAPH5\_aMC@NLO [245].

### 5.7.2 JER uncertainties

In the standard implementation of the JER uncertainties, variations of both the data and the simulated samples are applied. In each bin of the considered distribution, in this case the Optimal Observable, the larger variation is selected and applied on the simulated samples. This is done separately for each of the eleven nuisance parameters.

This implementation results in very large uncertainties in this analysis due to the limited data statistics in the tails of the Optimal Observable distribution. Therefore, only the variations derived from the simulated samples are used.

Unfortunately, also some simulated backgrounds samples have limited statistics in the VBF SR. Therefore, a special treatment is applied for the JER acceptance uncertainties of the  $Z \rightarrow \tau\tau$  process and the sum of the diboson-, top-quark-, and  $Z \rightarrow \ell\ell$  processes.

The acceptance uncertainties are evaluated using fits to the trend of the relative effect on the yield over the distribution of the  $\text{BDT}_{\text{score}}$ . For this, histograms of the  $\text{BDT}_{\text{score}}$  are created where each bin is filled with the relative difference of the yields when applying the JER uncertainties in each bin. For every nuisance parameter, separately for the up- and down variations, three fits are performed, using polynomials of first-, second-, and third order. The resulting functions are evaluated at the VBF SR cut value of  $\text{BDT}_{\text{score}} = 0.86$ . The largest variation of the six obtained values is then symmetrised and applied in the signal region.

Table 5.12 shows the statistical uncertainty of the simulated samples in the signal region, the acceptance uncertainties derived in the signal region, and the acceptance uncertainties derived with the fit method as described above. The uncertainties derived in the signal region are of a similar size as the statistical uncertainty or even larger due to the limited statistics of the samples. When the fit method is used, the uncertainties are reduced.

| Systematic              | $Z \rightarrow \tau\tau$ |               | Others        |             |
|-------------------------|--------------------------|---------------|---------------|-------------|
| MC stat. in SR          | +21.1 / -21.1            |               | +51.3 / -51.3 |             |
|                         | SR                       | fit method    | SR            | fit method  |
| ATLAS_JER_CROSSCALIBFWD | +21.2 / -21.2            | +8.9 / -8.9   | +44.7 / -44.7 | +3.0 / -3.0 |
| ATLAS_JER_NOISEFWD      | +18.2 / -18.2            | +7.2 / -7.2   | +10.8 / -10.8 | +7.1 / -7.1 |
| ATLAS_JER_NP_0          | +19.5 / -19.5            | +13.9 / -13.9 | +14.2 / -14.2 | +5.2 / -5.2 |
| ATLAS_JER_NP_1          | +15.4 / -15.4            | +5.7 / -5.7   | +45.7 / -45.7 | +9.0 / -9.0 |
| ATLAS_JER_NP_2          | +17.5 / -17.5            | +7.0 / -7.0   | +72.4 / -72.4 | +7.8 / -7.8 |
| ATLAS_JER_NP_3          | +33.6 / -33.6            | +8.5 / -8.5   | +20.4 / -20.4 | +8.4 / -8.5 |
| ATLAS_JER_NP_4          | +20.8 / -20.8            | +6.1 / -6.1   | +26.6 / -26.6 | +7.3 / -7.3 |
| ATLAS_JER_NP_5          | +32.4 / -34.4            | +6.9 / -6.9   | +18.0 / -18.0 | +5.9 / -5.9 |
| ATLAS_JER_NP_6          | +21.4 / -21.4            | +12.0 / -12.0 | +36.9 / -36.9 | +5.5 / -5.5 |
| ATLAS_JER_NP_7          | +10.6 / -10.6            | +7.1 / -7.1   | +22.1 / -22.1 | +5.7 / -5.7 |
| ATLAS_JER_NP_8          | +27.4 / -27.4            | +7.1 / -7.1   | +39.7 / -39.7 | +6.5 / -6.5 |

**Table 5.12:** Comparison of relative JER acceptance uncertainties evaluated in the VBF SR and with the fit method, and the statistical uncertainty for the  $Z \rightarrow \tau\tau$ - and *Others* processes.

The impact of the experimental- and theoretical uncertainties on the signal- and background acceptance and on the shapes of the Optimal Observable- and the  $m_{\tau\tau}^{\text{MMC}}$  distributions is shown in Appendix A.2. The naming of the uncertainties in Appendix A.2 is explained in Table A.1.

Tables A.14 to A.17 show the impact on the acceptance, excluding the uncertainties already shown in Tables 4.18 and 5.10. Only uncertainties with an impact larger than 0.1 % are included in the tables.

The largest impacts in the VBF signal region are from uncertainties on the  $ggF$ - and VBF parton showers, and the third-jet veto. Several large uncertainties on the  $Z \rightarrow \ell\ell$ -, top-quark-, and diboson backgrounds are observed, likely resulting from

the limited statistics of the simulated samples in the signal region.

In the lowBDT control region, the largest impacts are from uncertainties on the  $ggF$  parton shower and the JES due to the flavour composition of jets in  $Z \rightarrow \ell\ell$ .

The impact of the systematic uncertainties on the shapes of the Optimal Observable- and  $m_{\tau\tau}^{\text{MMC}}$  distributions is shown in Figure A.5. Only the six uncertainties with the largest impact on the shapes are shown. For this, the compatibility of the nominal distribution with the distribution after applying the respective uncertainty was evaluated with a  $\chi^2$  test [310] and the tests with the lowest resulting p-values were selected.

The only significant impact in the signal region is from the uncertainty on the VBF parton shower. This and two further uncertainties impact the shape of the VBF signal distributions in the lowBDT control region, where also the  $ggF$  parton-shower uncertainty and the non-closure systematic of the Fake background have significant impacts.

## 5.8 Fit model

To obtain the best estimate for the parameter  $\tilde{d}$ , maximum-likelihood fits are performed for values of  $\tilde{d}$  between  $-0.2$  and  $0.2$  in steps of  $0.01$ , and for values of  $\pm 0.25, 0.3, 0.35, 0.4, 0.45$  and  $0.50$ . These maximum-likelihood fits follow the description in Section 4.7, including the definition of the likelihood function. For each value of  $\tilde{d}$ , the minimum of the negative log-likelihood (NLL) is calculated. An NLL curve is constructed out of the values of these minima, where the minimum of this curve indicates the best estimator  $\hat{\tilde{d}}$ . For intermediate points where no maximum-likelihood fit is performed, an interpolation between fitted points is used.

Confidence intervals for  $\tilde{d}$  are obtained by reading off where the NLL curve takes values above a certain difference from the minimum value. The 68.3 % confidence level (CL) interval is obtained by  $\Delta\text{NLL} = \text{NLL} - \text{NLL}_{\text{min}} = 0.5$  and the 95 % CL interval by  $\Delta\text{NLL} = \text{NLL} - \text{NLL}_{\text{min}} = 1.92$  [322].

To obtain expected confidence intervals, an Asimov dataset is constructed by taking the signal-plus-background expectation, where the signal strength  $\mu$  of the VBF signal and the parameter  $\tilde{d}$  can be set to arbitrary values, which will be detailed in the next section.

The maximum-likelihood fits are performed in distributions of the Optimal Observable in the SR and of  $m_{\tau\tau}^{\text{MMC}}$  in the lowBDTCR, where the latter one helps to constrain systematic uncertainties and to obtain the free-floating normalisation of the  $Z \rightarrow \tau\tau$  background. The signal strength  $\mu$  of the VBF production process is free floating in the maximum-likelihood fits, so only the shape of the Optimal Observable is used to obtain an estimate for  $\tilde{d}$ . The other Higgs boson production processes, which are treated as background, are normalised to their SM predictions.

## 5.9 Results

Since the Optimal Observable is a CP-odd observable, its mean value  $\langle OO \rangle$  is expected to vanish when CP violation is absent. A non-vanishing value on the other hand would indicate CP violation under the assumption that re-scattering effects can be neglected. The observed mean value of the Optimal Observable in the signal region and its statistical uncertainty are found to be

$$\langle OO \rangle = 0.74 \pm 0.78 \quad (5.11)$$

No sign of CP violation is observed since the mean value is consistent with 0.

Several  $\Delta\text{NLL}$  curves, obtained from maximum-likelihood fits as discussed in Section 5.8, are shown in Figure 5.16a, and the respective confidence intervals are listed in Table 5.13.

The grey curve, "Pre-fit expected", shows the result of maximum-likelihood fits to a pure Asimov dataset, corresponding to the SM expectation for the signal ( $\tilde{d} = 0$  and  $\mu = 1$ ) and the backgrounds.

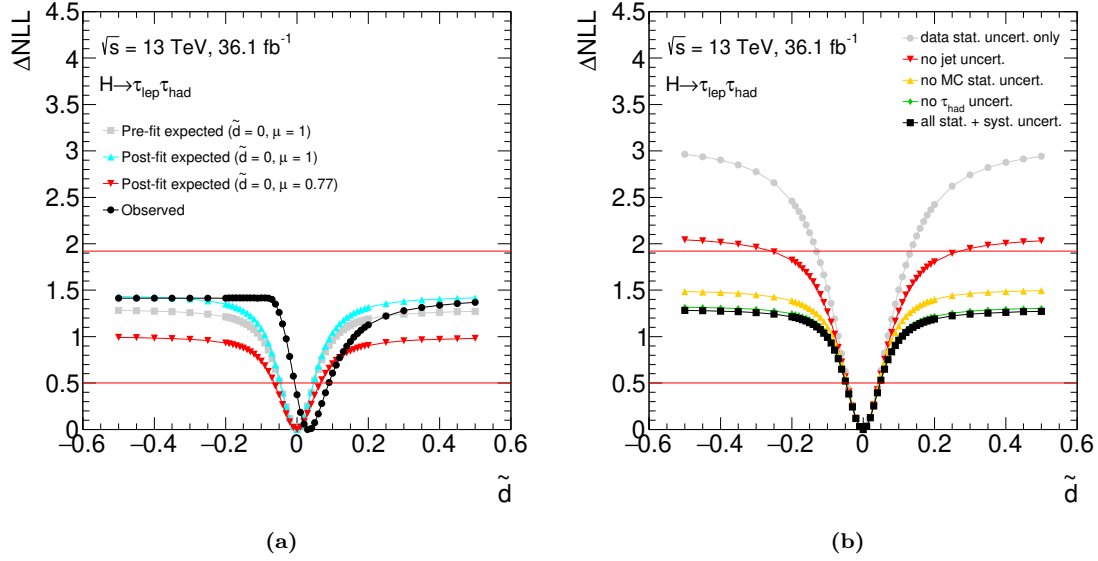
For the red and cyan curves, the constraints of the nuisance parameters and the normalisation factors are first determined in a maximum-likelihood fit to observed data in the lowBDTCR, excluding the SR. The resulting normalisation factor for the  $Z \rightarrow \tau\tau$  background is 0.91. This normalisation factor and the constraints are then used to create an Asimov dataset for maximum-likelihood fits in the SR and the lowBDTCR from which the "Post-fit expected"  $\Delta\text{NLL}$  curves are constructed. For the cyan curve, the SM expectation for the signal ( $\tilde{d} = 0$  and  $\mu = 1$ ) is used. For the red curve, the best-fit value of the signal strength  $\hat{\mu} = 0.77$  from the maximum-likelihood fit to observed data for the point  $\tilde{d} = 0$  is used.

The sensitivity increases when going from the pre-fit expected to the post-fit expected curve with  $\mu = 1$  since the constraints result in a reduced number of background events. Setting  $\mu = 0.77$  on the other hand results in a lower sensitivity since the number of signal events decreases.

| Fit               |                                 | 68.3 % CL      |
|-------------------|---------------------------------|----------------|
| Pre-fit expected  | ( $\tilde{d} = 0, \mu = 1$ )    | [-0.048,0.048] |
| Post-fit expected | ( $\tilde{d} = 0, \mu = 1$ )    | [-0.046,0.046] |
| Post-fit expected | ( $\tilde{d} = 0, \mu = 0.77$ ) | [-0.064,0.065] |
| Observed          |                                 | [-0.006,0.089] |

**Table 5.13:** 68.3 % CL intervals of the various  $\Delta\text{NLL}$  curves in Figure 5.16a.

The observed  $\Delta\text{NLL}$  curve is shown in black. The minimum of the curve is located at  $\tilde{d} = 0.03$  and the best-fit value of the signal strength of the corresponding maximum-likelihood fit is  $\hat{\mu} = 0.85$ . The resulting normalisation factor for the  $Z \rightarrow \tau\tau$  background is 0.91. The event yields and distributions obtained from the maximum-likelihood fit for these best-fit values are shown in Table 5.14 and Figure 5.17, respectively.



**Figure 5.16:** (a) Observed (black) and expected  $\Delta\text{NLL}$  curves. The pre-fit expected curve (grey) is constructed using a pure Asimov dataset both in the SR and the lowBDTCR, assuming  $\tilde{d} = 0$  and  $\mu = 1$ . For the post-fit expected curves (cyan and red), a maximum-likelihood fit to observed data in the lowBDTCR is performed and the resulting constraints are used to create an Asimov dataset for maximum-likelihood fits in the SR and lowBDTCR. For the cyan curve, a signal strength of  $\mu = 1$  and  $\tilde{d} = 0$  is assumed, whereas for the red curve the best-fit signal strength  $\hat{\mu} = 0.77$  from the maximum-likelihood fit to observed data for the point  $\tilde{d} = 0$  is used. (b) The impact of several groups of systematic uncertainties on the pre-fit expected  $\Delta\text{NLL}$  curves. Shown are the curves after removing the jet related systematic uncertainties, the  $\tau_{\text{had}}$  related systematic uncertainties, the MC statistical uncertainties, and all systematic uncertainties.

No data is observed in the first two bins of the Optimal Observable, which is the reason for the behaviour of the observed  $\Delta\text{NLL}$  curve at negative values of  $\tilde{d}$ . The best-fit value of the signal strength  $\mu$  is zero for these points. Therefore, only the background expectation contributes. The  $\Delta\text{NLL}$  curve plateaus since the expectation of the background processes is not depending on  $\tilde{d}$ .

Figure 5.16b shows the impact on the sensitivity when several groups of systematic uncertainties, i.e. uncertainties related to jets,  $\tau_{\text{had}}$  candidates, and MC statistics, or all systematic uncertainties are excluded from the maximum-likelihood fit. For all curves, a pure Asimov dataset with  $\tilde{d} = 0$  and  $\mu = 1$  is used. The respective 68.3%- and 95 % CL intervals are listed in Table 5.15. The systematic uncertainties related to jets have the largest impact on the sensitivity of this analysis, followed by the statistical uncertainties of the Monte Carlo samples.

When all statistical and systematic uncertainties are considered, the 68.3 % CL interval is  $[-0.048, 0.048]$ . The removal of the systematic uncertainties related to  $\tau_{\text{had}}$  has almost no impact on the interval, but removing the statistical uncertainties of the Monte Carlo samples improves the interval to  $[-0.046, 0.044]$ . The same effect is achieved when removing the systematic uncertainties related to jets, but in this case, also a 95 % CL interval of  $[-0.256, 0.268]$  is reached. When only the statistical uncertainty of the data is considered, the 68.3 %- and 95 % CL intervals are further improved to  $[-0.043, 0.043]$  and  $[-0.130, 0.133]$ , respectively.



|                                              | SR               | lowBDTCR             |
|----------------------------------------------|------------------|----------------------|
| VBF ( $\tilde{d} = 0.03, \hat{\mu} = 0.85$ ) | $13.54 \pm 7.27$ | $33.75 \pm 19.93$    |
| $Z \rightarrow \tau\tau$                     | $6.33 \pm 3.46$  | $1801.76 \pm 108.31$ |
| Fake                                         | $6.25 \pm 0.97$  | $2939.28 \pm 131.27$ |
| Others                                       | $1.77 \pm 2.24$  | $568.53 \pm 80.78$   |
| $ggF/VH/t\bar{t}H$                           | $2.14 \pm 1.60$  | $33.88 \pm 9.09$     |
| Total background                             | $16.48 \pm 5.16$ | $5343.44 \pm 75.95$  |
| Data                                         | 30               | 5375                 |

**Table 5.14:** Observed event yields and predicted yields by the maximum-likelihood fit for  $\tilde{d} = 0.03$  and  $\hat{\mu} = 0.85$ , including all statistical and systematic uncertainties.

| Fit                            | 68.3 % CL      | 95 % CL        |
|--------------------------------|----------------|----------------|
| data stat. uncert. only        | [-0.043,0.043] | [-0.130,0.133] |
| no jet uncert.                 | [-0.046,0.044] | [-0.256,0.268] |
| no MC stat. uncer.             | [-0.046,0.044] | —              |
| no $\tau_{\text{had}}$ uncert. | [-0.048,0.047] | —              |
| all stat. + syst. uncert.      | [-0.048,0.048] | —              |

**Table 5.15:** 68.3 % CL intervals of the various  $\Delta\text{NLL}$  curves in Figure 5.16b.

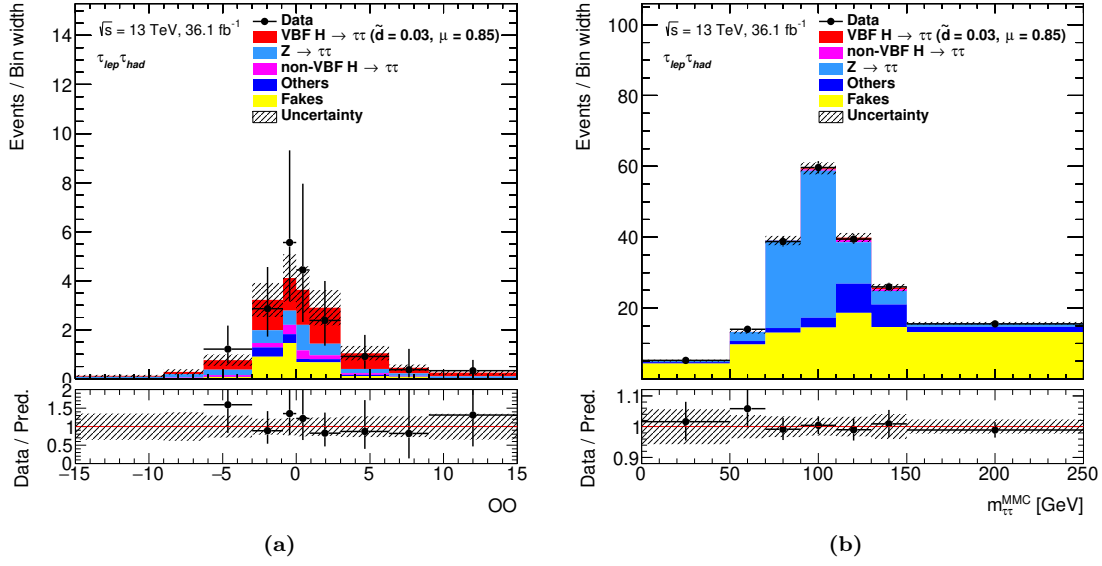
From the observed  $\Delta\text{NLL}$  curve in Figure 5.16a, the observed 68.3 % CL interval of  $\tilde{d} \in [-0.006, 0.089]$  is retrieved, which contains the SM expectation of  $\tilde{d} = 0$ , whereas the expected 68.3 % CL interval obtained from the post-fit expected curve with  $\tilde{d} = 0$  and  $\mu = 1$  is  $\tilde{d} \in [-0.046, 0.046]$ .

### 5.9.1 Combination with the $\tau_{\text{lep}}\tau_{\text{lep}}$ - and $\tau_{\text{had}}\tau_{\text{had}}$ channels

As in the case of the cross-section measurement presented in Chapter 4, a combined analysis including the  $\tau_{\text{lep}}\tau_{\text{lep}}$ - and  $\tau_{\text{had}}\tau_{\text{had}}$  channels was performed. This analysis is documented in Ref. [12] and all number and figures presented in this section are taken from there.

Table 5.16 summarises the mean value of the Optimal Observable in data for each channel and their combination. For the combination, the mean values of the individual channels are weighted by the inverse of their respective variance. Every mean value is consistent with zero. Therefore, no evidence for CP violation is observed.

The expected and observed  $\Delta\text{NLL}$  curves for the combined maximum-likelihood fit are shown in Figure 5.18a. Figure 5.18b shows again the observed  $\Delta\text{NLL}$  curve for the combined maximum-likelihood fit and as well the observed  $\Delta\text{NLL}$  curves for the individual channels.



**Figure 5.17:** Post-fit distributions of the Optimal Observable and the MMC mass  $m_{\tau\tau}^{\text{MMC}}$  in the SR (a) and in the lowBDTCR (b), respectively. The signal prediction for the best-fit value  $\hat{d} = 0.03$  is used. The signal and backgrounds are determined by the maximum-likelihood fit and the signal is scaled by the best-fit value of the signal strength  $\hat{\mu} = 0.85$ . The hatched bands include all statistical, experimental and theoretical uncertainties.

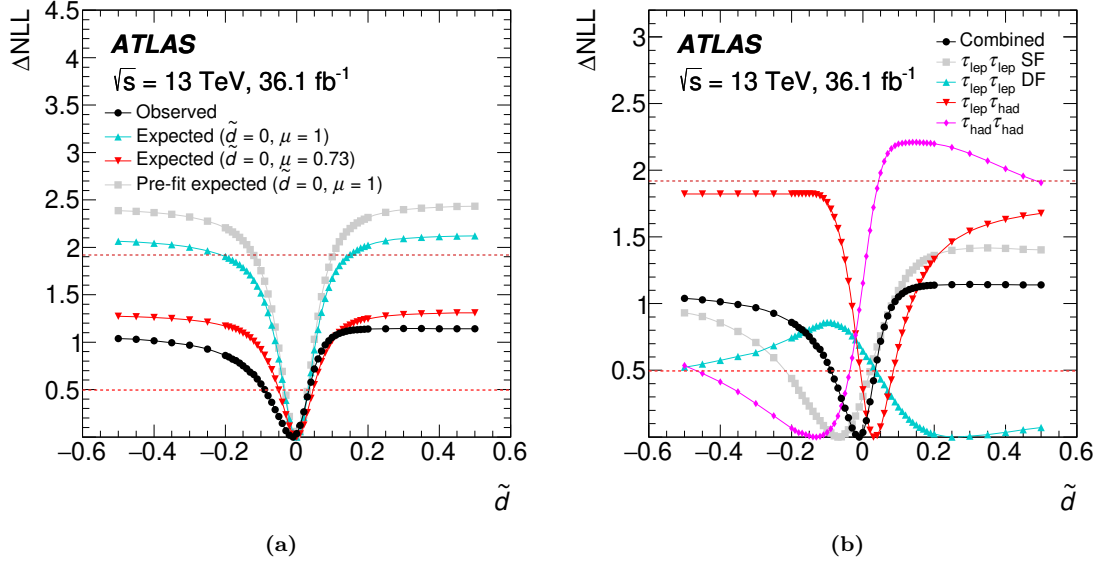
| Channel                                 | $\langle \mathcal{OO} \rangle$ |
|-----------------------------------------|--------------------------------|
| $\tau_{\text{lep}}\tau_{\text{lep}}$ SF | $-0.54 \pm 0.72$               |
| $\tau_{\text{lep}}\tau_{\text{lep}}$ DF | $0.71 \pm 0.81$                |
| $\tau_{\text{lep}}\tau_{\text{had}}$    | $0.74 \pm 0.78$                |
| $\tau_{\text{had}}\tau_{\text{had}}$    | $-1.13 \pm 0.65$               |
| Combined                                | $-0.19 \pm 0.37$               |

**Table 5.16:** Mean value of the Optimal Observable in data for all channels and their combination. The statistical uncertainties are shown. Taken from Ref. [12].

The  $\Delta\text{NLL}$  curves of the  $\tau_{\text{had}}\tau_{\text{had}}$ - and the  $\tau_{\text{lep}}\tau_{\text{lep}}$  different-flavour channel are observed to be very asymmetric with wide 68.3 % CL intervals, while the curve of the  $\tau_{\text{lep}}\tau_{\text{lep}}$  same-flavour channel is more symmetric and has a smaller 68.3 % CL interval. The  $\tau_{\text{lep}}\tau_{\text{had}}$  channel constitutes an important contribution in the combination: it has the smallest 68.3 % CL interval of all channels and reaches large  $\Delta\text{NLL}$  values.

The minimum of the observed  $\Delta\text{NLL}$  curve for the combination of all channels is at  $\tilde{d} = -0.01$  with a best-fit value of the signal strength of  $\hat{\mu} = 0.73$ . The distributions of the Optimal Observable in the signal regions of the  $\tau_{\text{lep}}\tau_{\text{lep}}$ - and  $\tau_{\text{had}}\tau_{\text{had}}$  channels are shown in Figure 5.19, while the distribution in the  $\tau_{\text{lep}}\tau_{\text{had}}$  channel was already shown in Figure 5.17.

The observed 68.3 % CL interval is  $\tilde{d} \in [-0.090, 0.035]$ . The expected 68.3 % CL interval obtained from the post-fit expected curve with  $\tilde{d} = 0$  and  $\mu = 1$  is  $\tilde{d} \in [-0.035, 0.033]$ . In addition, an expected 95 % CL interval of  $\tilde{d} \in [-0.21, 0.15]$  is extracted from the curve.



**Figure 5.18:** (a) Observed (black) and expected  $\Delta\text{NLL}$  curves. The pre-fit expected curve (grey) is constructed using a pure Asimov dataset both in the SR and the lowBDTCR, assuming  $\tilde{d} = 0$  and  $\mu = 1$ . For the post-fit expected curves (cyan and red), a maximum-likelihood fit to observed data in the lowBDTCR is performed and the resulting constraints are used to create an Asimov dataset for maximum-likelihood fits in the SR and lowBDTCR. For the cyan curve, a signal strength of  $\mu = 1$  and  $\tilde{d} = 0$  is assumed, whereas for the red curve the best-fit signal strength  $\hat{\mu} = 0.73$  from the maximum-likelihood fit to observed data for the point  $\tilde{d} = 0$  is used. (b) Observed  $\Delta\text{NLL}$  curves for the combined maximum-likelihood fit and for the maximum-likelihood fits of the individual channels. For the maximum-likelihood fits of the individual channels, only the yield information in the other SRs is used. Taken from Ref. [12]

These results are a significant improvement compared to the corresponding intervals obtained with the Run-1 analysis [11]. The observed and expected 68.3 % CL intervals were  $\tilde{d} \in [-0.11, 0.05]$  and  $\tilde{d} \in [-0.08, 0.08]$ , respectively.

### Comparison with other analyses

The results of this analysis can be compared to other analyses by the ATLAS- and CMS collaborations that also neglect any rate information. The ATLAS collaboration studied the CP invariance in the coupling between the Higgs boson and the electroweak gauge bosons in the decays  $H \rightarrow WW$  and  $H \rightarrow ZZ$  with the data collected in Run-1 [120]. The parameter  $(\tilde{\kappa}_{AVV}/\kappa_{SM}) \cdot \tan \alpha$  is used, which is related to  $\tilde{d}$  by [323]

$$\tilde{d} = -(\tilde{\kappa}_{AVV}/\kappa_{SM}) \cdot \tan \alpha \quad (5.12)$$

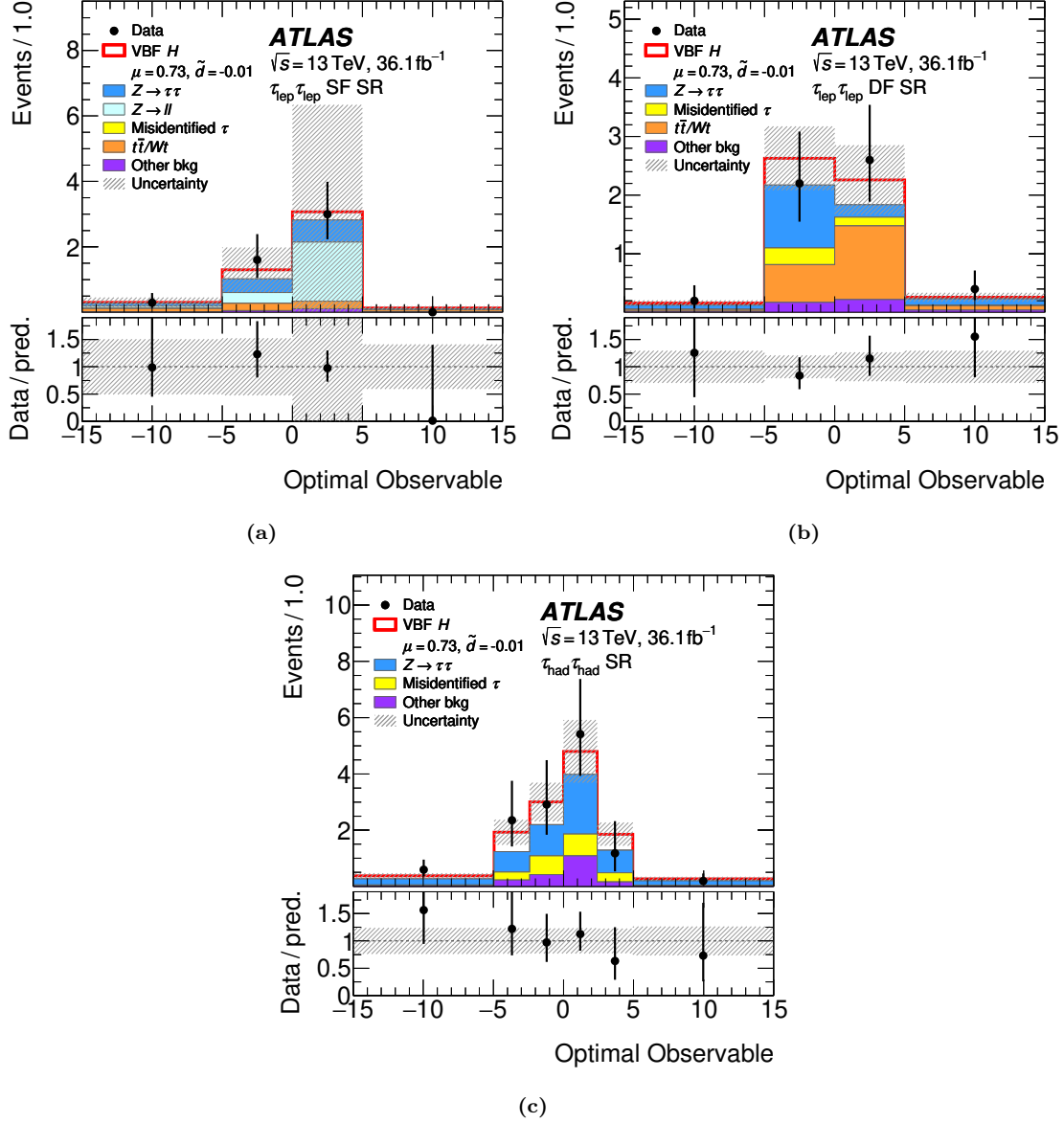
These decays were also studied by the CMS collaboration, using data collected in Run-1 and Run-2 [324, 325]. In Run-2, CP invariance was also studied in the  $HVV$  coupling in the VBF production process with the decay  $H \rightarrow \tau\tau$ , and a combination of the  $H \rightarrow VV$ - and  $H \rightarrow \tau\tau$  analyses was performed [326].

The parameter  $f_{a3} \cos(\phi_{a3})$  is used in these analyses. The relation to  $\tilde{d}$  is [323]

$$\tilde{d} = \frac{f_{a3} \cos(\phi_{a3})}{|f_{a3} \cos(\phi_{a3})|} \sqrt{\frac{|f_{a3} \cos(\phi_{a3})|}{|1 - f_{a3} \cos(\phi_{a3})|} \frac{\sigma_{SM}}{\sigma_{CP}}} \quad (5.13)$$

with  $\phi_{a3} = 0$  or  $\pi$ .  $\sigma_{SM}$  and  $\sigma_{CP}$  are the cross-sections for a pure SM-like- and a pure CP-odd contribution to the  $HVV$  vertex, respectively. The value of  $\frac{\sigma_{SM}}{\sigma_{CP}}$  is 6.99 at a center-of-mass energy of  $\sqrt{s} = 8$  TeV and 6.54 for  $\sqrt{s} = 13$  TeV.

The resulting 68.3 %- and 95 % CL intervals are shown in Table 5.17. The analysis of CP invariance in the VBF production process of  $H \rightarrow \tau\tau$  in Run-2 presented in this chapter has the smallest expected 68.3 % CL interval. In general, the analyses of the VBF production process have higher sensitivities than the analyses of the Higgs-boson decay into two gauge bosons.



**Figure 5.19:** Post-fit distributions of the Optimal Observable in the signal regions of the  $\tau_{lep}\tau_{lep}$  same-flavour channel (a), the  $\tau_{lep}\tau_{lep}$  different-flavour channel (b), and the  $\tau_{had}\tau_{had}$  channel (c). The signal prediction for the best-fit value  $\hat{d} = -0.01$  is used. The signal and backgrounds are determined by the maximum-likelihood fit and the signal is scaled by the best-fit value of the signal strength  $\hat{\mu} = 0.73$ . The ratio of the data to the prediction is shown in the lower panels. The hatched bands include all statistical, experimental, and theoretical uncertainties. Taken from Ref. [12]

| Analysis |                                             | Data set                               | exp. 68.3 % CL | obs. 68.3 % CL | exp. 95 % CL   | obs. 95 % CL |
|----------|---------------------------------------------|----------------------------------------|----------------|----------------|----------------|--------------|
| CMS      | $H \rightarrow VV$                          | Run-1                                  | [-1.45,1.45]   | [-0.78,0.78]   | [-2.81,2.81]   | [-1.61,1.65] |
| CMS      | $H \rightarrow VV$                          | Run-1 + Run-2 ( $80 \text{ fb}^{-1}$ ) | [-0.11,0.11]   | [-0.10,0.05]   | [-0.76,0.76]   | [-1.13,0.80] |
| CMS      | $H \rightarrow \tau\tau$                    | Run-2 ( $80 \text{ fb}^{-1}$ )         | [-0.042,0.043] | [-0.053,0.078] | [-0.154,0.154] | —            |
| CMS      | $H \rightarrow VV + H \rightarrow \tau\tau$ | Run-1 + Run-2 ( $80 \text{ fb}^{-1}$ ) | [-0.039,0.039] | [-0.042,0.042] | [-0.089,0.089] | [-0.81,0.30] |
| ATLAS    | $H \rightarrow VV$                          | Run-1                                  | [-1.2,1.2]     | [-0.1,1.4]     | [-2.30,2.33]   | [-0.83,2.18] |
| ATLAS    | $H \rightarrow \tau\tau$                    | Run-1                                  | [-0.08,0.08]   | [-0.11,0.15]   | —              | —            |
| ATLAS    | $H \rightarrow \tau\tau$                    | Run-2 ( $36.1 \text{ fb}^{-1}$ )       | [-0.035,0.033] | [-0.090,0.035] | [-0.21,0.15]   | —            |

**Table 5.17:** Expected and observed confidence intervals for  $\tilde{d}$ . Equations (5.12) and (5.13) were used to convert the parametrisations to  $\tilde{d}$ . A dash denotes that no sensitivity was reached. Values taken from Refs. [11, 12, 120, 324–327]

# Conclusion and outlook

The Higgs boson is an essential part of the Standard Model: it is predicted by the Brout–Englert–Higgs mechanism, which is incorporated into the Standard Model to break the electroweak symmetry, resulting in masses for the electroweak gauge bosons and the charged fermions.

Since the discovery of the Higgs boson in 2012, a multitude of analyses had and still have the aim to measure its properties. Any deviation with respect to the Standard Model prediction would be a sign of new physics beyond the Standard Model, but so far, all measurements are in agreement with the predictions.

All relevant production- and decay modes of the Higgs boson have been observed and the coupling strengths to the respective particles have been determined. With the increasing size of available data, precise measurements of the cross-sections and the mass of the Higgs boson have become possible.

This thesis contributes to two aspects in the study of the Higgs boson: the measurement of production cross-sections and a test for CP invariance in VBF production. Both analyses are using the  $H \rightarrow \tau\tau$  decay channel, with focus on the semileptonic  $\tau_{\text{lep}}\tau_{\text{had}}$  final state. The data for the analyses was collected in proton–proton collisions at a center-of-mass energy of  $\sqrt{s} = 13 \text{ TeV}$  by the ATLAS detector at the LHC, corresponding to an integrated luminosity of  $36.1 \text{ fb}^{-1}$ .

For the measurement of the cross-sections, selection criteria are defined to target the respective kinematics of the VBF- and  $ggF$  production processes and to suppress background processes. Events containing a jet that is misidentified as a hadronically decaying  $\tau$ -lepton, called *Fakes*, constitute an important background process for this analysis. A major part of the work done during the course of this thesis was the development and implementation of the data-driven *Fake Factor* method to estimate the Fake background. This method was successfully validated and the relevant systematic uncertainties were derived.

The final discriminant of this analysis is the mass determined by the *Missing Mass Calculator* (MMC). The missing energy due to the neutrinos in the final state is taken into account by this technique, resulting in the capability to distinguish the signal process from the background processes, especially  $Z \rightarrow \tau\tau$  decays. The distribution of the MMC mass is used in maximum-likelihood fits to determine the signal strength and the cross-section of the Higgs boson. The resulting values for the total signal cross-section and for the signal strength are

$$\begin{aligned}\sigma_{H \rightarrow \tau\tau} &= 3.13^{+0.86}_{-0.84} \text{ (stat.) }^{+1.26}_{-1.03} \text{ (syst.) pb} \\ \mu_{H \rightarrow \tau\tau} &= 0.90^{+0.25}_{-0.24} \text{ (stat.) }^{+0.37}_{-0.30} \text{ (syst.)}\end{aligned}\tag{5.14}$$

The best-fit values for the VBF- and  $ggF$  cross-sections are

$$\begin{aligned}\sigma_{H \rightarrow \tau\tau}^{\text{VBF}} &= 0.18_{-0.12}^{+0.13} \text{ (stat.)}_{-0.14}^{+0.16} \text{ (syst.) pb} \\ \sigma_{H \rightarrow \tau\tau}^{ggF} &= 3.1 \pm 1.4 \text{ (stat.)}_{-1.8}^{+2.6} \text{ (syst.) pb}\end{aligned}\tag{5.15}$$

The corresponding results for the combination with the  $\tau_{\text{lep}}\tau_{\text{lep}}$ - and  $\tau_{\text{had}}\tau_{\text{had}}$  channels are

$$\begin{aligned}\sigma_{H \rightarrow \tau\tau} &= 3.77_{-0.59}^{+0.60} \text{ (stat.)}_{-0.74}^{+0.87} \text{ (syst.) pb} \\ \mu_{H \rightarrow \tau\tau} &= 1.09_{-0.17}^{+0.18} \text{ (stat.)}_{-0.22}^{+0.26} \text{ (syst.)}_{-0.11}^{+0.16} \text{ (theory syst.)}\end{aligned}\tag{5.16}$$

$$\begin{aligned}\sigma_{H \rightarrow \tau\tau}^{\text{VBF}} &= 0.28 \pm 0.09 \text{ (stat.)}_{-0.09}^{+0.11} \text{ (syst.) pb} \\ \sigma_{H \rightarrow \tau\tau}^{ggF} &= 3.1 \pm 1.0 \text{ (stat.)}_{-1.3}^{+1.6} \text{ (syst.) pb}\end{aligned}$$

All results are consistent with the Standard Model predictions. Systematic uncertainties are dominating, in particular uncertainties related to jets, theoretical uncertainties of the signal, and the limited amount of simulated background events. When combining with data recorded at center-of-mass energies of 7 and 8 TeV, an observed significance of 6.4 standard deviations with an expected significance of 5.4 standard deviations is obtained.

The second analysis presented in this thesis is a test for CP invariance in the  $HVV$  vertex of the VBF production process. The motivation behind this analysis is the observed baryon asymmetry in the universe. One of the Sakharov criteria to explain this asymmetry is CP violation. Since the amount of CP violation present in the Standard Model is not sufficient, additional sources are required.

To define a phase space that is enriched with events originating from the VBF production process, machine learning in form of *Boosted Decision Trees* is employed. An *Effective Field Theory* approach is adopted to keep the analysis model independent. With this approach, an additional CP-odd component to the  $HVV$  vertex is quantified in terms of the single parameter  $\tilde{d}$ . A method based on matrix elements, the *Optimal Observable* method, is used to test for CP invariance. A non-vanishing mean value, under the assumption that re-scattering effects can be neglected, would indicate CP violation. The observed mean value of the Optimal Observable is

$$\langle OO \rangle = 0.74 \pm 0.78\tag{5.17}$$

Since this result is consistent with zero, no sign of CP violation is observed.

To set constraints on the possible values of  $\tilde{d}$ , maximum-likelihood fits are performed in the distribution of the Optimal Observable. The resulting confidence interval at 68.3 % confidence level is

$$\tilde{d} \in [-0.006, 0.089]\tag{5.18}$$

The Standard Model prediction of  $\tilde{d} = 0$  is contained in this interval. The systematic uncertainties with the largest impact on the size of the interval are uncertainties related to jets and the limited amount of simulated background events.

The corresponding results for the combination with the  $\tau_{\text{lep}}\tau_{\text{lep}}$ - and  $\tau_{\text{had}}\tau_{\text{had}}$  channels are

$$\begin{aligned}\langle OO \rangle &= -0.19 \pm 0.37 \\ \tilde{d} &\in [-0.090, 0.035]\end{aligned}\tag{5.19}$$



Again, the mean value of the Optimal Observable is consistent with zero and  $\tilde{d} = 0$  is contained in the 68.3 % CL confidence interval.

In both analyses, the  $\tau_{\text{lep}}\tau_{\text{had}}$  channel is an important contribution in the combination with the  $\tau_{\text{lep}}\tau_{\text{lep}}$ - and  $\tau_{\text{had}}\tau_{\text{had}}$  channels due to its large signal-to-background ratio in the signal regions.

Several improvements for both analyses are expected in the future. At the time this thesis is written, the complete dataset of Run-2 of the LHC, corresponding to an integrated luminosity of  $139\text{ fb}^{-1}$ , is being analysed. The increased amount of data will result in reduced statistical uncertainties. Since systematic uncertainties are the dominating source of uncertainty in the analyses presented in this thesis, it is important to reduce those as well.

One possibility to improve the systematic uncertainties associated with the  $Z \rightarrow \tau\tau$  process is the employment of the *Embedding* method [328] instead of using simulated samples. In this method,  $Z \rightarrow \mu\mu$  events are selected in data. The muons are removed from the event and simulated  $\tau$ -leptons are embedded in their place. By doing this, the jets, pile-up, and missing energy of the event are taken completely from data, and the systematic uncertainties related to them are rendered unnecessary. To reduce the statistical uncertainty on the simulated samples, larger amounts of events have to be simulated. To limit the necessary computing resources for this, generator filters with higher efficiency could be developed, targeting only the kinematics of the phase space required for the analyses.

In the case of the cross-section measurement, the increased amount of data will enable the measurement of *differential*- and *fiducial* cross-sections. Differential cross-sections are determined as a function of a variable and for fiducial cross-sections, experimental effects such as reconstruction efficiencies are removed from the measurement.

Another approach is represented by the *STXS* method. Here, the cross-sections are measured in pre-defined phase-space regions. The definition of these regions are common between different analyses of the Higgs boson, and between the ATLAS- and CMS collaborations. This provides the possibility of combining several measurements and of comparing the results with theoretical predictions, especially in phase-space regions where the effects of BSM physics are expected to be large.

For the test of CP invariance in the  $HVV$  vertex, a combination with other analyses promises an increase in sensitivity. Only the four-momenta of the Higgs boson and of the two jets are input for the construction of the Optimal Observable. The four-momenta of the decay products are not used and therefore, all analyses of the Higgs boson that select a VBF phase-space can use the Optimal Observable method to study the  $HVV$  vertex.

In addition, CP invariance can also be tested in other production- and decay modes of the Higgs boson, e.g. in  $ggF$  production or in the  $H \rightarrow \tau\tau$  decay-vertex. After the observation of neutrino oscillations, the neutrino sector also provides the opportunity to search for CP violation. Since the detectors at the LHC are not designed to detect neutrinos, other experiments will be important for this type of searches.

There are still many phenomena that cannot be explained by the Standard Model. The origin of the observed baryon asymmetry in the universe is one of them. Therefore, the search for CP-violating processes remains an important task in the future.



# Appendix A

## Impact of systematic variations

### A.1 Cross-section measurement

#### A.1.1 Impact on acceptance

| Nuisance parameter                    | Description                                                                       |
|---------------------------------------|-----------------------------------------------------------------------------------|
| <b>Experimental</b>                   |                                                                                   |
| ATLAS_EG_RESOLUTION_ALL               | Electron energy resolution                                                        |
| ATLAS_EG_SCALE_ALLCORR                | Electron energy scale                                                             |
| ATLAS_EG_SCALE_E4SCINTILLATOR         | Electron energy scale, scintillator                                               |
| ATLAS_EG_SCALE_LARCALIB_2015PRE       | Electron energy scale, intercalibration 2015                                      |
| ATLAS_EG_SCALE_LARTEMP_2015PRE        | Electron energy scale, LAr temperature 2015                                       |
| ATLAS_EG_SCALE_LARTEMP_2016PRE        | Electron energy scale, LAr temperature 2016                                       |
| ATLAS_EL_EFF_ID_NONPROMPT_D0          | Electron identification efficiency, non-prompt electrons                          |
| ATLAS_FT_EFF_Eigen_b_0-2              | $b$ -tagging efficiency, $b$ -jets                                                |
| ATLAS_FT_EFF_Eigen_c_0-2              | $b$ -tagging efficiency, $c$ -jets                                                |
| ATLAS_FT_EFF_Eigen_light_0-4          | $b$ -tagging efficiency, light quark jets                                         |
| ATLAS_FT_EFF_extrapolation_from_charm | Extrapolation of scale factors from $c$ -jets to $\tau$ -jets                     |
| ATLAS_JER_CROSSCALIBFWD               | Jet energy resolution, Run-1 calibration, forward region                          |
| ATLAS_JER_NOISEFWD                    | Jet energy resolution, noise forward region                                       |
| ATLAS_JER_NP_0-8                      | Jet energy resolution                                                             |
| ATLAS_JES_BJES                        | Jet energy scale, $b$ -jets                                                       |
| ATLAS_JES_EffectiveNP_1-8             | Jet energy scale                                                                  |
| ATLAS_JES_EtaInter_Model              | Jet energy scale, $\eta$ -intercalibration, model                                 |
| ATLAS_JES_EtaInter_NonClosure         | Jet energy scale, $\eta$ -intercalibration, non-closure                           |
| ATLAS_JES_EtaInter_Stat               | Jet energy scale, $\eta$ -intercalibration, statistical uncertainties             |
| ATLAS_JES_Flavor_Comp                 | Jet energy scale, flavour-dependent jet composition                               |
| ATLAS_JES_Flavor_Comp_zll             | Jet energy scale, flavour-dependent jet composition, $Z \rightarrow \ell\ell$     |
| ATLAS_JES_Flavor_Resp                 | Jet energy scale, flavour-dependent jet response                                  |
| ATLAS_JES_HighPt                      | Jet energy scale, jets with $p_T > 1.8$ TeV                                       |
| ATLAS_JES_PU_OffsetMu                 | Jet energy scale, pile-up, interactions per crossing                              |
| ATLAS_JES_PU_OffsetNPV                | Jet energy scale, pile-up, number primary vertices                                |
| ATLAS_JES_PU_PtTerm                   | Jet energy scale, pile-up, $p_T$ dependence                                       |
| ATLAS_JES_PU_Rho                      | Jet energy scale, pile-up, jet $p_T$ density                                      |
| ATLAS_JES_PunchThrough                | Jet energy scale, jets not fully contained in calorimeter                         |
| ATLAS_JVT                             | Efficiency jet vertex tagger                                                      |
| ATLAS_MET_SoftTrk_ResoPara            | $E_T^{\text{miss}}$ soft term resolution, parallel                                |
| ATLAS_MET_SoftTrk_ResoPerp            | $E_T^{\text{miss}}$ soft term resolution, perpendicular                           |
| ATLAS_MET_SoftTrk_Scale               | $E_T^{\text{miss}}$ soft term scale                                               |
| ATLAS_MUONS_ID                        | Muon momentum resolution, inner detector                                          |
| ATLAS_MUONS_MS                        | Muon momentum resolution, muon spectrometer                                       |
| ATLAS_MUONS_SAGITTA_RESBIAS           | Muon momentum scale, sagitta, residual bias                                       |
| ATLAS_MUONS_SAGITTA_RHO               | Muon momentum scale, sagitta, $p_T$ imbalance ID and MS                           |
| ATLAS_MUONS_SCALE                     | Muon momentum scale                                                               |
| ATLAS_PRW_DATASF                      | Pile-up reweighting, scale factor                                                 |
| ATLAS_TAU_EFF_ELEORL_TRUEELE          | $\tau_{\text{had}}$ electron overlap removal efficiency, true electron            |
| ATLAS_TAU_EFF_ELEORL_TRUEHADTAU       | $\tau_{\text{had}}$ electron overlap removal efficiency, true $\tau_{\text{had}}$ |
| ATLAS_TAU_EFF_ID_TOTAL                | $\tau_{\text{had}}$ identification efficiency                                     |
| ATLAS_TAU_EFF_RECO_TOTAL              | $\tau_{\text{had}}$ reconstruction efficiency                                     |
| ATLAS_TAU_TES_DETECTOR                | $\tau_{\text{had}}$ energy scale, detector geometry                               |
| ATLAS_TAU_TES_INSITU                  | $\tau_{\text{had}}$ energy scale, in-situ measurement                             |
| ATLAS_TAU_TES_MODEL                   | $\tau_{\text{had}}$ energy scale, GEANT4 model                                    |
| <b>Theoretical</b>                    |                                                                                   |
| Theo_ggH_shower                       | $ggF$ , parton shower, parametrization                                            |
| Theo_ggH_sig_qcd_0-8                  | $ggF$ , QCD corrections                                                           |
| Theo_ggH_jetveto                      | $ggF$ , third-jet veto due to cut on $\text{BDT}_{\text{score}}$                  |
| Theo_boost_ggH_PSUE                   | $ggF$ , parton shower and underlying event, Boosted categories, MC comp.          |
| Theo_boost_VBFH_PSUE                  | VBF, parton shower and underlying event, Boosted categories, MC comp.             |
| Theo_vbf_ggH_PSUE                     | $ggF$ , parton shower and underlying event, VBF categories, MC comp.              |
| Theo_vbf_VBFH_PSUE                    | VBF, parton shower and underlying event, VBF categories, MC comp.                 |
| Theo_VH_PSUE                          | $VH$ , parton shower and underlying event, MC comparison                          |
| Theo_sig_alphaS                       | $\alpha_s$ uncertainty                                                            |
| Theo_sig_pdf_0-29                     | PDF uncertainties                                                                 |
| Theo_VBFH_MUR_MUF                     | VBF, scale uncertainties                                                          |
| Theo_VBFH_shower                      | VBF, parton shower, parametrization                                               |
| Theo_VH_MUR_MUF                       | $VH$ , scale uncertainties                                                        |
| Z_EWK_proportion                      | Electroweak $Z$ -boson production, cross-section uncertainty                      |
| ZttTheory_CKK_boost                   | $Z \rightarrow \tau\tau$ , merging scale, Boosted categories                      |
| ZttTheory_CKK_vbf                     | $Z \rightarrow \tau\tau$ , merging scale, VBF categories                          |
| ZttTheory_MGvsSH_boost                | $Z \rightarrow \tau\tau$ , parton shower, Boosted categories, MC comparison       |
| ZttTheory_MGvsSH_vbf                  | $Z \rightarrow \tau\tau$ , parton shower, VBF categories, MC comparison           |
| ZttTheory_MUR_MUF_boost               | $Z \rightarrow \tau\tau$ , scale uncertainties, Boosted categories                |
| ZttTheory_MUR_MUF_vbf                 | $Z \rightarrow \tau\tau$ , scale uncertainties, VBF categories                    |
| ZttTheory_QSF_boost                   | $Z \rightarrow \tau\tau$ , resummation scale, Boosted categories                  |
| Ztt_mjj_rew                           | $Z \rightarrow \tau\tau$ , $m_{jj}$ reweighting                                   |
| Zll_mjj_rew                           | $Z \rightarrow \ell\ell$ , $m_{jj}$ reweighting                                   |

**Table A.1:** Description of the nuisance parameter naming used in Tables A.2 to A.17 and Figs. A.1 to A.4

|                               | <i>ggF</i>    |  | <i>VBF</i>    |  | <i>WH</i>     |               | <i>ZH</i>     |  |
|-------------------------------|---------------|--|---------------|--|---------------|---------------|---------------|--|
| ATLAS_EG_SCALE_ALLCORR        |               |  |               |  |               |               | +15.0 / -15.1 |  |
| ATLAS_FT_EFF_Eigen_c_0        |               |  |               |  | +1.4 / -1.4   |               |               |  |
| ATLAS_FT_EFF_Eigen_light_0    | +1.6 / -1.6   |  | +1.1 / -1.1   |  | +2.2 / -2.2   | +2.1 / -2.0   |               |  |
| ATLAS_FT_EFF_Eigen_light_3    |               |  |               |  | -1.0 / +1.0   |               |               |  |
| ATLAS_JER_CROSSCALIBFWD       | +3.8 / -3.0   |  |               |  | -2.7 / +2.7   | -7.9 / +7.9   |               |  |
| ATLAS_JER_NOISEFWD            | +0.6 / +0.2   |  |               |  | -2.7 / +2.7   | -7.9 / +7.9   |               |  |
| ATLAS_JER_NP_0                | -6.4 / +6.8   |  | -6.6 / +3.2   |  | +26.3 / -15.8 | +11.9 / +18.3 |               |  |
| ATLAS_JER_NP_1                | +2.6 / -2.6   |  | +5.8 / -5.8   |  | -20.9 / +20.9 |               |               |  |
| ATLAS_JER_NP_2                | -7.0 / +4.6   |  | -4.7 / +4.7   |  | +12.9 / -12.9 | -29.1 / +29.1 |               |  |
| ATLAS_JER_NP_3                | -8.8 / +8.9   |  | -9.1 / +9.1   |  | -20.7 / +20.2 |               |               |  |
| ATLAS_JER_NP_4                | -0.7 / +1.1   |  | +8.5 / -8.5   |  | -15.7 / +15.7 | -3.6 / +2.9   |               |  |
| ATLAS_JER_NP_5                | +2.8 / -4.0   |  | +2.4 / -3.6   |  |               |               |               |  |
| ATLAS_JER_NP_6                | +6.6 / -6.6   |  | +7.5 / -7.5   |  |               |               |               |  |
| ATLAS_JER_NP_7                | +8.0 / -7.7   |  | +5.8 / -5.8   |  | -12.1 / +6.2  | -5.3 / +4.6   |               |  |
| ATLAS_JER_NP_8                | -7.6 / +3.8   |  | -7.7 / +5.9   |  |               |               |               |  |
| ATLAS_JES_EffectiveNP_1       | +1.2 / -2.6   |  | +0.5 / -1.4   |  | +2.9 / +6.4   |               |               |  |
| ATLAS_JES_EffectiveNP_2       | -1.2 / +1.2   |  | -0.2 / -0.3   |  |               |               |               |  |
| ATLAS_JES_EffectiveNP_3       | -1.4 / +1.9   |  | -0.3 / +0.3   |  |               |               |               |  |
| ATLAS_JES_EffectiveNP_4       | +0.1 / -1.0   |  |               |  |               |               |               |  |
| ATLAS_JES_EffectiveNP_6       | +3.3 / -1.0   |  |               |  |               |               |               |  |
| ATLAS_JES_EffectiveNP_7       | +0.2 / -0.1   |  |               |  |               |               |               |  |
| ATLAS_JES_EffectiveNP_8       |               |  | 0.0 / +0.1    |  |               |               |               |  |
| ATLAS_JES_EtaInter_Model      | +3.8 / -4.6   |  | +2.4 / -3.0   |  | -0.1 / -0.3   | -7.1 / +1.2   |               |  |
| ATLAS_JES_EtaInter_NonClosure |               |  |               |  | -5.2 / 0.0    |               |               |  |
| ATLAS_JES_EtaInter_Stat       | +1.1 / -1.8   |  | +0.3 / -0.4   |  |               |               |               |  |
| ATLAS_JES_Flavor_Comp         | +3.1 / -2.9   |  | +1.7 / -0.3   |  | +11.1 / -8.4  | +11.1 / +0.7  |               |  |
| ATLAS_JES_Flavor_Resp         | -1.3 / +4.6   |  | 0.0 / +0.2    |  | +2.8 / -2.8   |               |               |  |
| ATLAS_JES_PU_OffsetMu         | -0.4 / +0.9   |  | -1.1 / +1.1   |  | +10.4 / -8.4  |               |               |  |
| ATLAS_JES_PU_PtTerm           | +3.8 / -4.9   |  | +1.4 / -1.3   |  | +5.3 / -8.1   |               |               |  |
| ATLAS_JES_PU_Rho              | +2.6 / -2.4   |  | +1.3 / +0.2   |  | +5.4 / +1.7   |               |               |  |
| ATLAS_MET_SoftTrk_ResoPara    | -0.3 / +1.0   |  |               |  |               | +0.8 / +7.1   |               |  |
| ATLAS_MET_SoftTrk_ResoPerp    | +1.3 / -1.3   |  |               |  |               | +0.8 / +7.1   |               |  |
| ATLAS_MET_SoftTrk_Scale       | +1.4 / -0.9   |  | +1.5 / -1.3   |  |               |               |               |  |
| ATLAS_PRW_DATASF              | -3.2 / +2.7   |  | -3.2 / +1.8   |  | -2.5 / -5.8   | -13.1 / +12.8 |               |  |
| ATLAS_TAU_EFF_ID_TOTAL        | +5.8 / -5.8   |  | +5.8 / -5.8   |  | +5.9 / -5.9   | +5.9 / -5.9   |               |  |
| ATLAS_TAU_EFF_RECO_TOTAL      | +3.0 / -3.0   |  | +3.0 / -3.0   |  | +2.8 / -2.8   | +3.4 / -3.4   |               |  |
| ATLAS_TAU_TES_DETECTOR        | -0.2 / -2.6   |  | -1.5 / +1.5   |  | +0.2 / 0.0    | -8.0 / 0.0    |               |  |
| ATLAS_TAU_TES_INSITU          | +1.5 / -0.9   |  | +1.7 / -2.2   |  |               |               |               |  |
| ATLAS_TAU_TES_MODEL           |               |  | 0.0 / -0.4    |  |               | -8.0 / +0.8   |               |  |
| Theo_VBFH_MUR_MUF             |               |  | +1.1 / -1.1   |  |               |               |               |  |
| Theo_VBFH_shower              |               |  | -10.2 / +10.2 |  |               |               |               |  |
| Theo_VH_MUR_MUF               |               |  |               |  | +13.0 / -10.9 | +14.1 / -12.0 |               |  |
| Theo_ggH_shower               | +2.7 / -2.7   |  |               |  |               |               |               |  |
| Theo_ggH_sig_qcd_0            | +4.3 / -4.3   |  |               |  |               |               |               |  |
| Theo_ggH_sig_qcd_1            | +4.3 / -4.3   |  |               |  |               |               |               |  |
| Theo_ggH_sig_qcd_2            | +2.8 / -2.8   |  |               |  |               |               |               |  |
| Theo_ggH_sig_qcd_3            | +6.8 / -6.8   |  |               |  |               |               |               |  |
| Theo_ggH_sig_qcd_4            | +9.2 / -9.2   |  |               |  |               |               |               |  |
| Theo_ggH_sig_qcd_6            | +7.8 / -7.8   |  |               |  |               |               |               |  |
| Theo_ggH_sig_qcd_7            | +10.9 / -10.9 |  |               |  |               |               |               |  |
| Theo_ggH_sig_qcd_8            | +6.1 / -6.1   |  |               |  |               |               |               |  |
| Theo_VH_PSUE                  |               |  |               |  | +1.2 / -1.2   | +1.2 / -1.2   |               |  |
| Theo_vbf_VBFH_PSUE            |               |  | +2.3 / -2.3   |  |               |               |               |  |
| Theo_vbf_ggH_PSUE             | +12.1 / -12.1 |  |               |  |               |               |               |  |
| Theo_sig_alphaS               | +1.6 / -1.4   |  |               |  |               |               |               |  |
| Theo_sig_pdf_14               |               |  |               |  |               | -1.2 / +1.2   |               |  |
| Theo_sig_pdf_3                |               |  |               |  |               | -1.4 / +1.4   |               |  |
| Theo_sig_pdf_4                | -1.9 / +1.9   |  |               |  |               |               |               |  |

**Table A.2:** Relative impact of up- and downward fluctuations of the nuisance parameters on the acceptance of the signal processes in the signal region of the VBF Tight category. Variations less than 0.1 % are ignored.

|                                 | $Z \rightarrow \tau\tau$ | $Z \rightarrow \ell\ell$ | Top           | Diboson       |
|---------------------------------|--------------------------|--------------------------|---------------|---------------|
| ATLAS_EG_SCALE_ALLCORR          |                          |                          | 0.0 / +1.4    |               |
| ATLAS_EG_SCALE_LARCALIB_2015PRE |                          |                          | +1.4 / 0.0    |               |
| ATLAS_FT_EFF_Eigen_b_0          |                          |                          | +11.5 / -10.5 |               |
| ATLAS_FT_EFF_Eigen_b_1          |                          |                          | +3.2 / -3.2   |               |
| ATLAS_FT_EFF_Eigen_c_0          |                          |                          |               | +1.3 / -1.2   |
| ATLAS_FT_EFF_Eigen_light_0      | +1.9 / -1.8              | +2.2 / -2.2              | +1.8 / -1.8   | +1.9 / -1.8   |
| ATLAS_JER_CROSSCALIBFWD         | +3.4 / -3.4              | +17.3 / -17.3            | -9.2 / +9.2   | -2.4 / +2.4   |
| ATLAS_JER_NOISEFWD              | +3.9 / -3.9              | +9.8 / -9.8              | -9.2 / +9.2   | -2.4 / +2.4   |
| ATLAS_JER_NP_0                  | -7.8 / +7.5              |                          | -4.1 / +8.1   | -7.4 / +5.5   |
| ATLAS_JER_NP_1                  | +3.0 / -4.5              |                          | -15.0 / +15.0 |               |
| ATLAS_JER_NP_2                  | -6.3 / +0.6              |                          |               | -4.8 / -0.4   |
| ATLAS_JER_NP_3                  | -7.3 / +7.5              |                          | +8.4 / -8.6   | -14.6 / +10.9 |
| ATLAS_JER_NP_4                  | -9.2 / +9.3              | -11.3 / +12.4            |               |               |
| ATLAS_JER_NP_5                  | -4.0 / +4.0              |                          | -8.0 / +8.0   |               |
| ATLAS_JER_NP_6                  | +1.1 / -1.1              |                          |               |               |
| ATLAS_JER_NP_7                  |                          | +12.6 / -12.6            | -11.5 / +10.9 |               |
| ATLAS_JER_NP_8                  | -5.4 / +6.3              |                          | -1.2 / +2.1   | -1.5 / -0.5   |
| ATLAS_JES_EffectiveNP_1         | +2.4 / -3.4              | -0.8 / +3.6              |               | +2.7 / +9.6   |
| ATLAS_JES_EffectiveNP_2         | -1.4 / +1.0              |                          |               |               |
| ATLAS_JES_EffectiveNP_5         |                          | -13.1 / +13.1            |               |               |
| ATLAS_JES_EffectiveNP_7         |                          | -6.0 / -0.8              |               |               |
| ATLAS_JES_EtaInter_Model        | +5.6 / -5.7              |                          | +7.4 / -9.4   | +2.8 / -2.7   |
| ATLAS_JES_EtaInter_NonClosure   |                          |                          |               | -5.4 / +5.1   |
| ATLAS_JES_EtaInter_Stat         | +3.6 / -3.9              |                          |               |               |
| ATLAS_JES_Flavor_Comp           |                          | +12.1 / -8.6             | +0.4 / -2.9   | +13.4 / -8.5  |
| ATLAS_JES_Flavor_Resp           | -4.1 / +4.1              | +8.6 / -1.4              |               | +6.2 / +2.0   |
| ATLAS_JES_PU_OffsetMu           | +2.2 / -2.4              |                          |               |               |
| ATLAS_JES_PU_OffsetNPV          | +1.8 / -1.9              | +5.1 / -3.7              | -8.0 / +8.9   | +0.2 / +1.2   |
| ATLAS_JES_PU_PtTerm             | +2.0 / -0.9              | +7.8 / -1.6              | +7.2 / -7.2   | +0.7 / -1.1   |
| ATLAS_JES_PU_Rho                | +3.8 / -5.0              | -0.1 / +4.8              | -5.1 / +5.5   | +8.3 / -3.6   |
| ATLAS_MET_SoftTrk_ResoPara      |                          | +1.9 / -1.8              | +2.9 / -2.9   |               |
| ATLAS_MET_SoftTrk_ResoPerp      | +1.5 / -1.5              | +2.6 / -2.6              |               | +2.3 / -2.3   |
| ATLAS_MET_SoftTrk_Scale         | +2.2 / -0.9              |                          | +1.1 / -1.9   |               |
| ATLAS_MUONS_MS                  |                          | +3.7 / +1.7              |               |               |
| ATLAS_PRW_DATASF                | -2.1 / +0.3              |                          | -4.8 / +3.7   | +15.2 / -13.6 |
| ATLAS_TAU_EFF_ELEORL_TRUEELE    |                          | +3.0 / -3.0              |               |               |
| ATLAS_TAU_EFF_ID_TOTAL          | +5.9 / -5.9              |                          | +5.2 / -5.2   | +5.6 / -5.6   |
| ATLAS_TAU_EFF_RECO_TOTAL        | +3.1 / -3.1              |                          | +2.8 / -2.8   | +3.3 / -3.3   |
| ATLAS_TAU_TES_DETECTOR          |                          |                          | -1.3 / -3.3   |               |
| ATLAS_TAU_TES_INSITU            | +2.7 / -2.2              |                          | +6.3 / -6.0   | +1.6 / +5.0   |
| ATLAS_TAU_TES_MODEL             |                          |                          |               | +0.1 / -8.6   |
| Z_EWK_proportion                | +1.6 / -1.6              |                          |               |               |
| ZttTheory_CKK_vbf               | -2.5 / +1.7              |                          |               |               |
| ZttTheory_MGvsSH_vbf            | +3.5 / -3.5              |                          |               |               |
| ZttTheory_MUR_MUF_vbf           | +1.7 / -1.7              |                          |               |               |

**Table A.3:** Relative impact of up- and downward fluctuations of the nuisance parameters on the acceptance of the background processes in the signal region of the VBF Tight category. Variations less than 0.1 % are ignored.

|                               | <i>ggF</i>    | VBF           | <i>WH</i>     | <i>ZH</i>     | <i>t<math>\bar{t}</math>H</i> |
|-------------------------------|---------------|---------------|---------------|---------------|-------------------------------|
| ATLAS_EL_EFF_ID_NONPROMPT_D0  | -1.0 / +1.0   |               |               |               |                               |
| ATLAS_FT_EFF_Eigen_b_0        |               |               |               |               | +12.9 / -12.9                 |
| ATLAS_FT_EFF_Eigen_b_1        |               |               |               |               | +2.2 / -2.2                   |
| ATLAS_FT_EFF_Eigen_c_0        |               |               | +1.5 / -1.5   |               | +2.6 / -2.6                   |
| ATLAS_FT_EFF_Eigen_light_0    | +1.3 / -1.3   |               | +1.2 / -1.2   | +1.3 / -1.3   | +1.8 / -1.7                   |
| ATLAS_JER_CROSSCALIBFWD       |               |               | -15.9 / +15.9 | -10.1 / +10.1 |                               |
| ATLAS_JER_NOISEFWD            | -1.2 / +1.2   |               | -15.9 / +15.9 | -10.1 / +10.1 |                               |
| ATLAS_JER_NP_0                | -18.3 / +10.9 | -17.4 / +13.4 | +51.4 / -38.5 | +15.4 / -5.4  | -33.0 / +24.2                 |
| ATLAS_JER_NP_1                | +5.6 / -0.8   | +9.4 / -9.4   |               |               | +16.7 / -16.7                 |
| ATLAS_JER_NP_2                | -7.1 / +5.6   | -11.1 / +11.1 | +10.1 / -0.3  | -0.5 / -0.3   |                               |
| ATLAS_JER_NP_3                | +11.1 / -11.1 | -11.4 / +11.4 | +8.1 / -0.9   | +16.9 / -17.4 |                               |
| ATLAS_JER_NP_4                | +5.6 / -6.7   | +12.4 / -12.5 |               |               |                               |
| ATLAS_JER_NP_5                |               | +4.7 / -4.8   |               | +29.3 / -29.3 | -24.5 / +24.5                 |
| ATLAS_JER_NP_6                | +10.0 / -9.8  | +9.3 / -9.4   | +3.7 / -5.1   | +4.0 / -13.5  | +33.5 / -33.5                 |
| ATLAS_JER_NP_7                | -5.9 / +4.5   | -5.3 / +5.3   | -1.7 / +9.0   |               |                               |
| ATLAS_JER_NP_8                | -5.7 / +5.0   | -3.6 / +3.7   | -10.3 / +15.8 | -6.7 / 0.0    |                               |
| ATLAS_JES_EffectiveNP_1       | +9.4 / -9.4   | +0.7 / -0.7   | +12.7 / -12.7 |               |                               |
| ATLAS_JES_EffectiveNP_5       |               | +1.9 / -2.0   |               |               | 0.0 / +3.7                    |
| ATLAS_JES_EtaInter_Model      | +10.0 / -8.3  | +3.4 / -3.4   |               | +7.7 / -7.7   | -0.2 / +3.8                   |
| ATLAS_JES_EtaInter_NonClosure | +3.6 / -2.2   | +3.5 / -3.4   |               | -1.1 / +7.7   |                               |
| ATLAS_JES_EtaInter_Stat       | +4.3 / -3.6   |               |               |               |                               |
| ATLAS_JES_Flavor_Comp         | +7.7 / -5.9   | +2.0 / -1.5   |               | -9.2 / +9.2   |                               |
| ATLAS_JES_Flavor_Resp         | -7.9 / +7.9   | -0.7 / +0.4   | -1.1 / -0.6   |               |                               |
| ATLAS_JES_PU_OffsetMu         | -4.4 / +5.6   | -0.1 / +0.1   |               |               |                               |
| ATLAS_JES_PU_OffsetNPV        | -1.8 / +1.8   |               |               |               |                               |
| ATLAS_JES_PU_PtTerm           | +1.9 / -0.9   | -0.9 / +1.3   | -10.0 / +5.2  | +7.8 / -7.8   |                               |
| ATLAS_JES_PU_Rho              | +5.8 / -5.0   | -1.1 / +1.1   | +1.1 / -1.1   |               |                               |
| ATLAS_JVT                     |               |               |               |               | +1.0 / -1.0                   |
| ATLAS_MET_SoftTrk_ResoPara    | -4.3 / +4.3   |               | +9.4 / -5.6   |               |                               |
| ATLAS_MET_SoftTrk_ResoPerp    | +3.2 / -3.2   |               | -7.0 / +7.0   |               |                               |
| ATLAS_MET_SoftTrk_Scale       | +1.8 / -0.7   | -1.0 / +1.0   | -8.4 / 0.0    |               |                               |
| ATLAS_PRW_DATASF              |               | -2.7 / +0.8   | +4.3 / -6.9   | -3.3 / +3.5   | -6.6 / +9.4                   |
| ATLAS_TAU_EFF_ID_TOTAL        | +5.8 / -5.8   | +5.9 / -5.9   | +5.8 / -5.8   | +5.7 / -5.7   | +6.0 / -6.0                   |
| ATLAS_TAU_EFF_RECO_TOTAL      | +3.3 / -3.3   | +3.4 / -3.4   | +3.1 / -3.1   | +3.2 / -3.2   | +2.7 / -2.7                   |
| ATLAS_TAU_TES_DETECTOR        | -2.0 / +4.8   | -0.2 / +0.2   | 0.0 / -13.2   |               | 0.0 / -20.6                   |
| ATLAS_TAU_TES_INSITU          | +2.5 / -2.9   | +2.6 / -3.0   | 0.0 / -20.6   | -9.9 / 0.0    |                               |
| Theo_VBFH_shower              |               | -12.8 / +12.8 |               |               |                               |
| Theo_VH_MUR_MUF               |               |               | +8.7 / -8.1   | +19.0 / -11.9 |                               |
| Theo_ggH_shower               | +3.5 / -3.5   |               |               |               |                               |
| Theo_ggH_sig_qcd_0            | +2.8 / -2.8   |               |               |               |                               |
| Theo_ggH_sig_qcd_1            | +2.7 / -2.7   |               |               |               |                               |
| Theo_ggH_sig_qcd_2            | +2.7 / -2.7   |               |               |               |                               |
| Theo_ggH_sig_qcd_3            | +1.6 / -1.6   |               |               |               |                               |
| Theo_ggH_sig_qcd_4            | +11.7 / -11.7 |               |               |               |                               |
| Theo_ggH_sig_qcd_5            | -1.2 / +1.2   |               |               |               |                               |
| Theo_ggH_sig_qcd_6            | +3.0 / -3.0   |               |               |               |                               |
| Theo_ggH_sig_qcd_7            | +3.4 / -3.4   |               |               |               |                               |
| Theo_VH_PSUE                  |               |               | +1.2 / -1.2   | +1.2 / -1.2   |                               |
| Theo_vbf_VBFH_PSUE            |               | +2.3 / -2.3   |               |               |                               |
| Theo_vbf_ggH_PSUE             | +12.1 / -12.1 |               |               |               |                               |
| Theo_sig_alphaS               | +1.4 / -1.3   |               |               | +1.0 / -1.0   |                               |

**Table A.4:** Relative impact of up- and downward fluctuations of the nuisance parameters on the acceptance of the signal processes in the signal region of the VBF Loose category. Variations less than 0.1 % are ignored.

|                               | $Z \rightarrow \tau\tau$ |               | $Z \rightarrow \ell\ell$ |  | Top           | Diboson       |
|-------------------------------|--------------------------|---------------|--------------------------|--|---------------|---------------|
| ATLAS_FT_EFF_Eigen_b_0        |                          |               |                          |  | +5.4 / -5.4   |               |
| ATLAS_FT_EFF_Eigen_b_1        |                          |               |                          |  | +1.8 / -1.8   |               |
| ATLAS_FT_EFF_Eigen_b_2        |                          |               |                          |  | -1.5 / +1.5   |               |
| ATLAS_FT_EFF_Eigen_light_0    | +1.4 / -1.4              |               | +2.9 / -2.9              |  | +1.4 / -1.4   | +1.5 / -1.5   |
| ATLAS_FT_EFF_Eigen_light_3    |                          |               |                          |  | -1.1 / +1.1   |               |
| ATLAS_JER_CROSSCALIBFWD       | +1.9 / -1.8              |               |                          |  | -11.6 / +11.6 |               |
| ATLAS_JER_NOISEFWD            | +3.3 / -3.1              | -4.4 / +4.4   |                          |  | -11.6 / +11.6 | -2.0 / +2.0   |
| ATLAS_JER_NP_0                | -7.9 / +6.1              | +3.7 / +27.2  |                          |  | +14.7 / +0.6  | -9.1 / +6.8   |
| ATLAS_JER_NP_1                | -7.2 / +7.9              | +4.6 / -3.3   |                          |  | +6.2 / +6.4   | +15.1 / -9.0  |
| ATLAS_JER_NP_2                | +8.9 / -8.9              | +2.5 / +3.1   |                          |  | +13.8 / -3.5  | -9.1 / +20.4  |
| ATLAS_JER_NP_3                | +8.7 / -6.1              | +5.9 / -16.1  |                          |  | +26.5 / -26.5 | -31.7 / +19.1 |
| ATLAS_JER_NP_4                | +7.5 / -7.6              |               |                          |  | +0.8 / -10.2  | +17.8 / -13.2 |
| ATLAS_JER_NP_5                | -16.3 / +15.7            | -17.0 / +16.7 |                          |  |               | +6.7 / -1.1   |
| ATLAS_JER_NP_6                | -9.4 / +9.0              |               |                          |  | +1.7 / -7.7   | +10.0 / -2.3  |
| ATLAS_JER_NP_7                | +11.7 / -11.8            |               |                          |  | +13.0 / -4.4  |               |
| ATLAS_JER_NP_8                | -0.9 / +2.7              | -5.3 / +23.4  |                          |  | -4.5 / +10.5  | +2.8 / +16.7  |
| ATLAS_JES_EffectiveNP_1       | +6.2 / -6.4              | +7.0 / -4.8   |                          |  | +8.1 / -8.1   | +17.3 / -12.4 |
| ATLAS_JES_EffectiveNP_2       |                          |               |                          |  | +7.5 / -7.5   | -1.0 / +3.5   |
| ATLAS_JES_EffectiveNP_3       |                          | -0.4 / -0.3   |                          |  |               |               |
| ATLAS_JES_EffectiveNP_4       | +2.3 / -2.2              | +9.0 / -7.7   |                          |  | +7.5 / -7.5   | +6.1 / -6.4   |
| ATLAS_JES_EffectiveNP_7       |                          |               |                          |  | +3.7 / -3.7   |               |
| ATLAS_JES_EtaInter_Model      | +5.2 / -11.4             | +10.5 / -18.9 |                          |  | +7.9 / -6.7   | -7.9 / +1.2   |
| ATLAS_JES_EtaInter_NonClosure | +4.3 / -4.5              | +0.5 / -1.3   |                          |  | +5.6 / -10.4  | -22.5 / +22.6 |
| ATLAS_JES_EtaInter_Stat       | -0.9 / -4.1              | +4.1 / -6.1   |                          |  | +7.6 / -7.6   | +1.7 / -0.9   |
| ATLAS_JES_Flavor_Comp         | -0.4 / -4.3              | +16.1 / -23.8 |                          |  | +3.4 / -1.5   | -8.8 / +15.9  |
| ATLAS_JES_Flavor_Resp         | -1.4 / +3.1              | -5.8 / +5.3   |                          |  | -2.8 / +0.2   | +8.5 / +15.1  |
| ATLAS_JES_PU_OffsetMu         | -2.8 / -0.1              | -0.3 / -7.0   |                          |  | -3.6 / +3.6   | -8.5 / +7.4   |
| ATLAS_JES_PU_OffsetNPV        | +0.5 / -1.2              |               |                          |  |               | -7.4 / +8.2   |
| ATLAS_JES_PU_PtTerm           | +0.4 / -3.2              |               |                          |  | +7.6 / -7.9   | -10.2 / +9.8  |
| ATLAS_JES_PU_Rho              | +7.9 / -4.2              | +20.8 / -6.2  |                          |  | +13.3 / -13.3 | +9.6 / +5.1   |
| ATLAS_MET_SoftTrk_ResoPara    | +2.2 / -2.2              | -8.4 / +8.4   |                          |  | +5.6 / -5.6   | +2.2 / -2.2   |
| ATLAS_MET_SoftTrk_ResoPerp    |                          | +4.0 / -2.7   |                          |  | +5.6 / -5.6   | +2.9 / -2.9   |
| ATLAS_MET_SoftTrk_Scale       | +1.4 / -1.3              | +5.6 / -18.1  |                          |  | +5.8 / -3.7   | +7.0 / -8.1   |
| ATLAS_PRW_DATASF              | +3.1 / -1.9              | +1.9 / -3.6   |                          |  | -2.2 / -2.1   | -7.8 / +3.8   |
| ATLAS_TAU_EFF_ID_TOTAL        | +5.9 / -5.9              |               |                          |  | +5.2 / -5.2   | +5.6 / -5.6   |
| ATLAS_TAU_EFF_RECO_TOTAL      | +3.6 / -3.6              |               |                          |  | +2.6 / -2.6   | +3.3 / -3.3   |
| ATLAS_TAU_TES_INSITU          | +4.1 / -1.5              |               |                          |  | +7.1 / -3.7   | -15.8 / +16.6 |
| ATLAS_TAU_TES_MODEL           |                          |               |                          |  | +0.7 / -3.7   | -6.3 / +3.2   |
| Z_EWK_proportion              | +0.7 / -0.7              |               |                          |  |               |               |
| ZttTheory_CKK_vbf             | +4.9 / -3.4              |               |                          |  |               |               |
| ZttTheory_MGvsSH_vbf          | -2.1 / +2.0              |               |                          |  |               |               |
| ZttTheory_MUR_MUF_vbf         | -3.7 / +3.4              |               |                          |  |               |               |

**Table A.5:** Relative impact of up- and downward fluctuations of the nuisance parameters on the acceptance of the background processes in the signal region of the VBF Loose category. Variations less than 0.1 % are ignored.



|                                       | <i>ggF</i>    | VBF         | <i>WH</i>     | <i>ZH</i>     | $t\bar{t}H$   |
|---------------------------------------|---------------|-------------|---------------|---------------|---------------|
| ATLAS_EG_RESOLUTION_ALL               |               |             | 0.0 / +17.7   |               |               |
| ATLAS_FT_EFF_Eigen_b_0                |               |             |               | -4.7 / +4.8   |               |
| ATLAS_FT_EFF_Eigen_c_0                |               | -1.7 / +1.7 | -12.9 / +12.9 | -8.5 / +7.7   |               |
| ATLAS_FT_EFF_Eigen_c_2                |               |             | +1.3 / -1.3   |               |               |
| ATLAS_FT_EFF_Eigen_light_0            | -8.7 / +8.7   | -6.7 / +6.6 |               | +1.8 / -1.7   | +3.4 / -3.3   |
| ATLAS_FT_EFF_Eigen_light_1            | +2.3 / -2.3   | +1.7 / -1.7 |               |               |               |
| ATLAS_FT_EFF_Eigen_light_2            | +1.0 / -1.0   |             |               |               |               |
| ATLAS_FT_EFF_Eigen_light_3            | +2.9 / -2.9   | +1.3 / -1.3 |               | -1.2 / +1.2   |               |
| ATLAS_FT_EFF_extrapolation_from_charm |               |             | +12.6 / -12.6 | +6.4 / -7.2   |               |
| ATLAS_JER_CROSSCALIBFWD               | -1.8 / +1.8   | +3.6 / -3.6 |               | -16.7 / +16.7 | +2.4 / -2.4   |
| ATLAS_JER_NOISEFWD                    |               | +2.8 / -2.8 |               | -16.7 / +16.7 | +3.5 / -3.5   |
| ATLAS_JER_NP_0                        | +14.1 / -14.1 | -3.9 / +4.0 | -4.4 / +20.7  | +36.0 / -36.0 |               |
| ATLAS_JER_NP_1                        |               | +2.3 / -2.3 |               | -36.6 / +36.6 | +16.6 / -16.6 |
| ATLAS_JER_NP_2                        | +8.1 / -8.1   | -1.7 / +5.4 | +15.4 / -1.0  | +36.3 / -36.3 | -2.5 / +10.2  |
| ATLAS_JER_NP_3                        |               | -4.3 / +3.8 | -3.7 / +40.2  | +38.7 / -38.7 | +4.0 / -12.6  |
| ATLAS_JER_NP_4                        | -11.2 / +11.2 | +2.7 / -0.7 | -2.0 / +16.7  | -39.1 / +39.1 |               |
| ATLAS_JER_NP_5                        |               | +1.7 / -1.5 | -0.6 / +16.2  |               | +5.7 / -5.7   |
| ATLAS_JER_NP_6                        |               |             | -0.6 / +16.4  | +39.0 / -39.0 | +10.9 / -1.0  |
| ATLAS_JER_NP_7                        |               | -1.4 / +2.7 | -1.0 / +16.4  | +39.0 / -39.0 | -2.3 / +6.6   |
| ATLAS_JER_NP_8                        | +10.6 / -10.6 | -0.3 / +3.4 |               | +36.5 / -36.5 | -0.3 / +5.5   |
| ATLAS_JES_EffectiveNP_1               |               | +2.7 / -2.2 |               | +0.2 / -19.8  |               |
| ATLAS_JES_EffectiveNP_2               | +2.0 / -7.4   |             |               |               | +3.5 / -1.3   |
| ATLAS_JES_EffectiveNP_3               | -5.9 / +0.1   |             |               |               |               |
| ATLAS_JES_EtaInter_Model              |               | +6.0 / -2.9 | 0.0 / -54.3   | +0.2 / -19.8  |               |
| ATLAS_JES_EtaInter_NonClosure         | -7.8 / +7.8   |             | 0.0 / +17.7   | +19.7 / -19.7 | 0.0 / +6.4    |
| ATLAS_JES_EtaInter_Stat               | -5.9 / +5.9   | +0.8 / -2.0 |               |               |               |
| ATLAS_JES_Flavor_Comp                 | +15.4 / -15.4 | +3.6 / -4.9 | +18.3 / -71.9 |               | +3.5 / -5.3   |
| ATLAS_JES_Flavor_Resp                 | -15.4 / +15.4 | -2.0 / +0.8 |               | -19.8 / +0.4  |               |
| ATLAS_JES_PU_OffsetMu                 | -9.6 / +0.1   |             | +17.7 / -17.7 | -19.8 / 0.0   |               |
| ATLAS_JES_PU_OffsetNPV                |               | +1.1 / -1.1 |               |               |               |
| ATLAS_JES_PU_PtTerm                   | +0.9 / -11.7  | +1.5 / -2.3 |               |               | +6.0 / -1.9   |
| ATLAS_JES_PU_Rho                      | +11.5 / -11.5 | +3.8 / -2.7 | +17.8 / -0.4  | +0.5 / -19.9  | -6.8 / +6.8   |
| ATLAS_MET_SoftTrk_ResoPara            | +3.7 / -3.7   | -1.0 / +1.0 |               |               |               |
| ATLAS_MET_SoftTrk_ResoPerp            |               |             |               |               | +2.2 / -2.2   |
| ATLAS_MET_SoftTrk_Scale               |               |             | 0.0 / +17.7   |               |               |
| ATLAS_MUONS_SAGITTA_RESBIAS           | +1.4 / 0.0    |             |               |               |               |
| ATLAS_PRW_DATASF                      | +11.6 / -9.3  |             | -19.5 / +4.6  | -15.6 / +3.2  | +13.4 / -3.0  |
| ATLAS_TAU_EFF_ELEORL_TRUEHADTAU       |               |             |               | +1.0 / -1.0   |               |
| ATLAS_TAU_EFF_ID_TOTAL                | +5.7 / -5.7   | +5.8 / -5.8 | +5.6 / -5.6   | +5.6 / -5.6   | +6.1 / -6.1   |
| ATLAS_TAU_EFF_RECO_TOTAL              | +3.5 / -3.5   | +3.1 / -3.1 | +4.2 / -4.2   | +3.8 / -3.8   | +3.1 / -3.1   |
| ATLAS_TAU_TES_DETECTOR                | -5.6 / +2.7   | -3.3 / +6.7 | 0.0 / +22.5   |               | -15.2 / +1.5  |
| ATLAS_TAU_TES_INSITU                  | 0.0 / -5.2    | -0.1 / +3.4 | 0.0 / +17.7   | -19.8 / 0.0   | -5.7 / +5.7   |
| ATLAS_TAU_TES_MODEL                   |               | -0.7 / +1.2 |               |               | -1.2 / +0.3   |
| Theo_VBFH_MUR_MUF                     |               | +1.1 / -1.3 |               |               |               |
| Theo_VH_MUR_MUF                       |               |             | +43.8 / -17.9 | +3.7 / -4.0   |               |
| Theo_ggH_sig_qcd_0                    | +3.3 / -3.3   |             |               |               |               |
| Theo_ggH_sig_qcd_1                    | +3.3 / -3.3   |             |               |               |               |
| Theo_ggH_sig_qcd_2                    | +1.9 / -1.9   |             |               |               |               |
| Theo_ggH_sig_qcd_3                    | +6.2 / -6.2   |             |               |               |               |
| Theo_ggH_sig_qcd_4                    | +12.2 / -12.2 |             |               |               |               |
| Theo_ggH_sig_qcd_6                    | +6.0 / -6.0   |             |               |               |               |
| Theo_ggH_sig_qcd_7                    | +9.2 / -9.2   |             |               |               |               |
| Theo_ggH_sig_qcd_8                    | +6.2 / -6.2   |             |               |               |               |
| Theo_VH_PSUE                          |               |             | +1.2 / -1.2   | +1.2 / -1.2   |               |
| Theo_vbf_VBFH_PSUE                    |               | +2.3 / -2.3 |               |               |               |
| Theo_vbf_ggH_PSUE                     | +12.1 / -12.1 |             |               |               |               |
| Theo_sig_alphaS                       | +1.5 / -1.3   |             | +1.7 / -1.9   |               |               |
| Theo_sig_pdf_0                        |               |             |               | +1.5 / -1.5   |               |
| Theo_sig_pdf_14                       |               |             |               | -1.3 / +1.3   |               |
| Theo_sig_pdf_16                       | +1.2 / -1.2   |             |               |               |               |
| Theo_sig_pdf_3                        | -1.3 / +1.3   |             | -2.5 / +2.5   |               |               |
| Theo_sig_pdf_4                        | -2.0 / +2.0   |             | +2.6 / -2.6   |               |               |
| Theo_sig_pdf_5                        |               |             | -1.1 / +1.1   |               |               |

**Table A.6:** Relative impact of up- and downward fluctuations of the nuisance parameters on the acceptance of the signal processes in the top-quark control region of the VBF category. Variations less than 0.1 % are ignored.

|                               | $Z \rightarrow \tau\tau$ | $Z \rightarrow \ell\ell$ | Top         | Diboson       |
|-------------------------------|--------------------------|--------------------------|-------------|---------------|
| ATLAS_FT_EFF_Eigen_b_0        | -1.4 / +1.4              |                          | -1.3 / +1.1 |               |
| ATLAS_FT_EFF_Eigen_c_0        |                          | -3.0 / +3.0              |             | -2.5 / +2.5   |
| ATLAS_FT_EFF_Eigen_light_0    | -5.5 / +5.4              | -1.9 / +1.8              |             | -8.0 / +8.0   |
| ATLAS_FT_EFF_Eigen_light_1    | +1.5 / -1.5              |                          |             | +2.2 / -2.2   |
| ATLAS_FT_EFF_Eigen_light_3    | +3.4 / -3.4              |                          |             | +3.5 / -3.2   |
| ATLAS_FT_EFF_Eigen_light_4    | +1.4 / -1.3              |                          |             | +1.1 / -1.1   |
| ATLAS_JER_CROSSCALIBFWD       | +5.1 / -5.1              | -8.7 / +8.7              |             | -2.2 / +2.2   |
| ATLAS_JER_NOISEFWD            | +6.6 / -6.6              | -8.6 / +8.6              |             | -1.9 / +1.9   |
| ATLAS_JER_NP_0                | +13.8 / -13.8            | +56.6 / -56.6            | -3.7 / +1.5 | +18.4 / -18.4 |
| ATLAS_JER_NP_1                | -9.4 / +9.4              |                          |             | -10.6 / +10.6 |
| ATLAS_JER_NP_2                | +14.7 / -14.7            | +55.3 / -55.3            | -1.8 / +0.1 | +11.3 / -11.3 |
| ATLAS_JER_NP_3                | +20.5 / -20.5            | -8.8 / +1.2              | -3.4 / +3.4 |               |
| ATLAS_JER_NP_4                |                          |                          |             | -7.5 / +7.5   |
| ATLAS_JER_NP_5                | -7.1 / +1.1              |                          | +2.2 / -0.9 | -7.2 / +7.2   |
| ATLAS_JER_NP_6                |                          |                          | +1.9 / -2.4 |               |
| ATLAS_JER_NP_7                |                          |                          | +2.3 / -2.3 | +7.3 / -7.3   |
| ATLAS_JER_NP_8                | -0.1 / +3.2              |                          | -0.3 / +1.0 | +8.3 / -8.3   |
| ATLAS_JES_EffectiveNP_1       | -3.6 / +5.8              |                          | +1.2 / -1.1 | +5.6 / -5.6   |
| ATLAS_JES_EffectiveNP_2       | +5.4 / -3.9              |                          |             |               |
| ATLAS_JES_EffectiveNP_3       | -0.3 / +1.7              | -3.7 / +0.1              |             |               |
| ATLAS_JES_EffectiveNP_4       |                          | 0.0 / -3.7               |             |               |
| ATLAS_JES_EffectiveNP_7       |                          | 0.0 / -3.7               |             |               |
| ATLAS_JES_EffectiveNP_8       |                          | -3.7 / 0.0               |             |               |
| ATLAS_JES_EtaInter_Model      | -3.8 / +6.1              |                          | +4.2 / -3.5 | +0.9 / -3.8   |
| ATLAS_JES_EtaInter_NonClosure | +5.3 / -5.3              |                          | -1.1 / +0.8 |               |
| ATLAS_JES_EtaInter_Stat       | -1.3 / +4.1              |                          | +2.3 / -1.3 |               |
| ATLAS_JES_Flavor_Comp         | -2.2 / +1.5              |                          | +2.5 / -2.1 | +0.2 / -9.3   |
| ATLAS_JES_Flavor_Resp         | +10.2 / -2.8             |                          | -1.2 / +0.2 | -2.1 / +0.1   |
| ATLAS_JES_PU_OffsetMu         | +2.1 / -2.9              | +0.4 / -4.3              | -1.9 / +1.5 | -1.9 / +0.1   |
| ATLAS_JES_PU_OffsetNPV        | -0.1 / +6.0              |                          |             |               |
| ATLAS_JES_PU_PtTerm           | +5.2 / -0.2              |                          | +1.6 / -1.0 | +1.5 / -0.9   |
| ATLAS_JES_PU_Rho              | -0.6 / +7.5              |                          | +1.4 / -1.0 | +5.5 / -5.5   |
| ATLAS_JVT                     |                          | +1.1 / -1.1              |             |               |
| ATLAS_MET_SoftTrk_ResoPara    | -8.1 / +8.1              | -52.8 / +52.8            |             | -2.4 / +2.4   |
| ATLAS_MET_SoftTrk_ResoPerp    | -1.7 / +1.7              | -53.0 / +53.0            |             | -1.7 / +1.8   |
| ATLAS_MET_SoftTrk_Scale       |                          | 0.0 / -2.0               |             | +1.1 / -0.2   |
| ATLAS_MUONS_MS                | 0.0 / -1.2               |                          |             |               |
| ATLAS_MUONS_SAGITTA_RESBIAS   |                          |                          |             | +1.2 / -0.7   |
| ATLAS_PRW_DATASF              | -15.0 / +4.7             | +26.2 / -25.6            |             | -7.5 / +5.7   |
| ATLAS_TAU_EFF_ID_TOTAL        | +5.7 / -5.7              |                          | +5.6 / -5.6 | +5.3 / -5.3   |
| ATLAS_TAU_EFF_RECO_TOTAL      | +3.6 / -3.6              |                          | +3.1 / -3.1 | +2.9 / -2.9   |
| ATLAS_TAU_TES_DETECTOR        | -1.4 / +3.9              |                          | -1.2 / +0.6 |               |
| ATLAS_TAU_TES_INSITU          | +6.2 / -2.3              |                          | +3.8 / -4.6 |               |
| ATLAS_TAU_TES_MODEL           | +0.8 / -2.9              |                          | +1.6 / -0.7 |               |
| Z_EWK_proportion              | +0.9 / -0.9              |                          |             |               |
| ZttTheory_CKK_vbf             | -5.9 / +4.0              |                          |             |               |
| ZttTheory_MUR_MUF_vbf         | +6.1 / -4.3              |                          |             |               |

**Table A.7:** Relative impact of up- and downward fluctuations of the nuisance parameters on the acceptance of the background processes in the top-quark control region of the VBF category. Variations less than 0.1% are ignored.

|                                       | $ggF$         |  | VBF         | $WH$        | $ZH$         | $t\bar{t}H$   |
|---------------------------------------|---------------|--|-------------|-------------|--------------|---------------|
| ATLAS_FT_EFF_Eigen_b_0                |               |  |             |             |              | +13.9 / -13.8 |
| ATLAS_FT_EFF_Eigen_b_1                |               |  |             |             |              | +3.0 / -3.1   |
| ATLAS_FT_EFF_Eigen_c_0                |               |  |             | +1.3 / -1.3 |              | +2.7 / -2.6   |
| ATLAS_FT_EFF_Eigen_light_0            | +1.8 / -1.8   |  | +1.5 / -1.4 | +1.8 / -1.7 | +2.0 / -2.0  | +2.0 / -2.0   |
| ATLAS_FT_EFF_extrapolation_from_charm |               |  |             |             |              | -1.3 / +1.3   |
| ATLAS_JER_CROSSCALIBFWD               |               |  |             |             |              | +3.5 / -3.5   |
| ATLAS_JER_NOISEFWD                    |               |  |             |             |              | +3.5 / -3.5   |
| ATLAS_JER_NP_0                        | +0.2 / +2.1   |  | -1.4 / +1.3 | -2.6 / +4.0 | -3.0 / +10.3 | -1.2 / +26.0  |
| ATLAS_JER_NP_1                        | +1.5 / -1.5   |  | +1.8 / -1.8 | +0.3 / -1.5 | -0.4 / +1.6  | +10.2 / -11.2 |
| ATLAS_JER_NP_2                        | +1.6 / -1.7   |  | +1.2 / -1.3 | -0.3 / +1.2 | -1.8 / -2.0  | -1.6 / +27.9  |
| ATLAS_JER_NP_3                        | +3.7 / -3.7   |  | -1.2 / +1.2 | +2.3 / -1.7 | +3.3 / -3.1  | +0.9 / +2.5   |
| ATLAS_JER_NP_4                        | -0.7 / +0.7   |  | -1.3 / +1.3 |             | +4.2 / -4.2  | +15.4 / +1.3  |
| ATLAS_JER_NP_5                        | -0.2 / +0.2   |  | -1.7 / +1.4 | -0.4 / +1.5 | -3.0 / +3.2  |               |
| ATLAS_JER_NP_6                        | +1.6 / -1.6   |  | -0.1 / +0.1 |             | -1.8 / +2.9  | +1.9 / +6.0   |
| ATLAS_JER_NP_7                        | -3.9 / +3.9   |  | -2.2 / +2.2 | -1.8 / -1.1 | +1.9 / -0.8  | -2.0 / +6.1   |
| ATLAS_JER_NP_8                        | -0.2 / -0.1   |  | +1.4 / -1.3 | -0.7 / +0.7 | +1.6 / +0.1  | +5.2 / +10.7  |
| ATLAS_JES_EffectiveNP_1               | +1.6 / -1.8   |  | -0.6 / +0.3 |             |              |               |
| ATLAS_JES_EffectiveNP_2               | +1.9 / -1.6   |  | -1.3 / +0.8 |             |              | -4.1 / -3.0   |
| ATLAS_JES_EffectiveNP_3               | -1.3 / +0.2   |  |             |             |              |               |
| ATLAS_JES_EffectiveNP_4               | -0.1 / -0.4   |  |             |             |              |               |
| ATLAS_JES_EffectiveNP_6               | +0.4 / -0.7   |  |             |             |              |               |
| ATLAS_JES_EffectiveNP_7               | +0.4 / -1.0   |  |             |             |              |               |
| ATLAS_JES_EtaInter_Model              | +2.5 / -2.3   |  | +0.5 / -0.8 |             |              | +1.3 / -0.5   |
| ATLAS_JES_EtaInter_NonClosure         | -2.0 / +2.4   |  | -0.9 / +0.5 |             |              |               |
| ATLAS_JES_EtaInter_Stat               | +0.3 / -0.3   |  | -1.4 / +1.4 |             |              | +1.3 / -2.1   |
| ATLAS_JES_Flavor_Comp                 | +0.5 / -1.1   |  | +0.1 / 0.0  | +2.1 / -0.1 | -0.8 / -0.5  | +33.8 / -13.6 |
| ATLAS_JES_Flavor_Resp                 | +0.3 / +0.9   |  |             | +0.2 / +1.8 | +1.6 / +0.5  | -1.8 / +5.2   |
| ATLAS_JES_PU_OffsetMu                 |               |  | +2.1 / -2.4 |             |              | +4.7 / -3.5   |
| ATLAS_JES_PU_OffsetNPV                | +0.5 / -0.7   |  | -0.3 / +0.4 |             |              |               |
| ATLAS_JES_PU_PtTerm                   | +2.3 / -2.4   |  | -0.4 / +0.3 |             |              |               |
| ATLAS_JES_PU_Rho                      | +1.1 / -0.5   |  | -0.1 / +0.7 |             | +0.7 / -1.0  | +12.1 / -10.5 |
| ATLAS_MET_SoftTrk_ResoPara            |               |  | -0.7 / +0.7 | +4.1 / -4.1 | +1.5 / -1.5  | +7.5 / -6.9   |
| ATLAS_MET_SoftTrk_ResoPerp            | +1.4 / -1.4   |  |             | -0.9 / +1.0 |              |               |
| ATLAS_MET_SoftTrk_Scale               | +1.1 / -1.4   |  | +1.0 / 0.0  | +1.5 / -0.5 |              | +5.6 / -5.7   |
| ATLAS_PRW_DATASF                      | -3.9 / +2.3   |  | -2.3 / +0.8 | -0.3 / -0.1 | -4.8 / +3.6  | -10.0 / +23.1 |
| ATLAS_TAU_EFF_ELEORL_TRUEHADTAU       |               |  |             |             |              | +1.1 / -1.1   |
| ATLAS_TAU_EFF_ID_TOTAL                | +5.8 / -5.8   |  | +5.8 / -5.8 | +5.8 / -5.8 | +5.8 / -5.8  | +6.3 / -6.3   |
| ATLAS_TAU_EFF_RECO_TOTAL              | +2.9 / -2.9   |  | +2.9 / -2.9 | +2.9 / -2.9 | +2.8 / -2.8  | +3.3 / -3.3   |
| ATLAS_TAU_TES_DETECTOR                | -1.2 / +1.4   |  | -0.7 / +0.6 | -0.4 / +1.3 | +0.5 / +0.1  |               |
| ATLAS_TAU_TES_INSITU                  | +0.7 / -0.2   |  | +0.9 / -1.2 | +1.6 / -0.7 | +1.6 / -2.4  |               |
| ATLAS_TAU_TES_MODEL                   | +1.9 / -1.9   |  | +0.1 / -0.1 |             |              | -1.7 / +0.2   |
| Theo_VBFH_MUR_MUF                     |               |  | +1.5 / -1.1 |             |              |               |
| Theo_VBFH_shower                      |               |  | +6.6 / -6.6 |             |              |               |
| Theo_VH_MUR_MUF                       |               |  |             | +3.5 / -6.0 | +3.5 / -2.7  |               |
| Theo_ggH_shower                       | -23.6 / +23.6 |  |             |             |              |               |
| Theo_ggH_sig_qcd_0                    | +7.4 / -7.4   |  |             |             |              |               |
| Theo_ggH_sig_qcd_1                    | +7.2 / -7.2   |  |             |             |              |               |
| Theo_ggH_sig_qcd_2                    | +5.6 / -5.6   |  |             |             |              |               |
| Theo_ggH_sig_qcd_3                    | +9.1 / -9.1   |  |             |             |              |               |
| Theo_ggH_sig_qcd_6                    | +9.7 / -9.7   |  |             |             |              |               |
| Theo_ggH_sig_qcd_7                    | +13.8 / -13.8 |  |             |             |              |               |
| Theo_ggH_sig_qcd_8                    | +7.9 / -7.9   |  |             |             |              |               |
| Theo_VH_PSUE                          |               |  |             | +1.2 / -1.2 | +1.2 / -1.2  |               |
| Theo_boost_VBFH_PSUE                  |               |  | +1.8 / -1.8 |             |              |               |
| Theo_boost_ggH_PSUE                   | +2.9 / -2.9   |  |             |             |              |               |
| Theo_sig_alphaS                       | +1.5 / -1.2   |  |             |             |              |               |
| Theo_sig_pdf_16                       | +1.1 / -1.1   |  |             |             |              |               |
| Theo_sig_pdf_4                        | -1.8 / +1.8   |  |             |             |              |               |

**Table A.8:** Relative impact of up- and downward fluctuations of the nuisance parameters on the acceptance of the signal processes in the signal region of the Boosted High category. Variations less than 0.1 % are ignored.

|                                 | $Z \rightarrow \tau\tau$ | $Z \rightarrow \ell\ell$ | Top           | Diboson     |
|---------------------------------|--------------------------|--------------------------|---------------|-------------|
| ATLAS_EG_SCALE_ALLCORR          |                          | -1.4 / +0.9              |               |             |
| ATLAS_EG_SCALE_LARCALIB_2015PRE |                          | +2.6 / -2.6              |               |             |
| ATLAS_FT_EFF_Eigen_b_0          |                          |                          | +16.3 / -14.9 |             |
| ATLAS_FT_EFF_Eigen_b_1          |                          |                          | +3.1 / -3.1   |             |
| ATLAS_FT_EFF_Eigen_b_2          |                          |                          | -1.5 / +1.5   |             |
| ATLAS_FT_EFF_Eigen_light_0      | +1.8 / -1.8              | +1.9 / -1.8              | +1.8 / -1.8   | +2.0 / -2.0 |
| ATLAS_JER_CROSSCALIBFWD         |                          | +3.7 / -3.7              | +1.9 / -1.9   |             |
| ATLAS_JER_NOISEFWD              |                          | +3.3 / -3.3              | +1.8 / -1.8   |             |
| ATLAS_JER_NP_0                  | -0.8 / +0.7              | -1.4 / +12.9             | +0.5 / +2.9   | -2.2 / +2.0 |
| ATLAS_JER_NP_1                  |                          | +10.3 / -1.3             | +0.7 / +1.5   |             |
| ATLAS_JER_NP_2                  | 0.0 / +0.1               | -17.8 / +17.5            | -0.7 / +2.1   | -1.5 / +1.8 |
| ATLAS_JER_NP_3                  | -0.3 / +0.2              | +7.5 / -8.0              | +4.3 / +1.3   | -1.4 / +0.3 |
| ATLAS_JER_NP_4                  | +1.1 / -1.3              | +12.8 / -0.2             |               | -0.5 / +0.3 |
| ATLAS_JER_NP_5                  |                          | +10.0 / -10.5            | +4.7 / -4.3   | +0.8 / -1.1 |
| ATLAS_JER_NP_6                  |                          | -7.3 / +7.8              | +4.8 / -4.7   | +0.5 / -0.5 |
| ATLAS_JER_NP_7                  |                          | -1.2 / +7.1              |               | -2.0 / +2.0 |
| ATLAS_JER_NP_8                  |                          | -0.4 / +7.4              |               | -0.8 / +0.4 |
| ATLAS_JES_EffectiveNP_1         | +1.2 / -1.9              |                          | -7.4 / +8.0   |             |
| ATLAS_JES_EffectiveNP_2         | -0.1 / +0.2              |                          |               |             |
| ATLAS_JES_EffectiveNP_3         | -0.8 / +0.9              |                          |               |             |
| ATLAS_JES_EtaInter_Model        | +1.0 / -1.6              | -3.3 / -0.1              | -2.9 / +3.5   | +1.3 / -1.1 |
| ATLAS_JES_EtaInter_NonClosure   |                          |                          | -2.6 / +4.0   |             |
| ATLAS_JES_Flavor_Comp           | 0.0 / +0.8               |                          | -2.2 / +1.3   | +4.1 / -3.0 |
| ATLAS_JES_Flavor_Resp           | -2.0 / +1.3              |                          | +3.3 / -3.2   | -2.0 / +0.4 |
| ATLAS_JES_PU_OffsetMu           |                          | +2.6 / +1.0              |               |             |
| ATLAS_JES_PU_OffsetNPV          |                          | -2.5 / +2.4              |               |             |
| ATLAS_JES_PU_PtTerm             | +0.5 / +0.3              |                          |               | +2.1 / -1.5 |
| ATLAS_JES_PU_Rho                | -0.2 / +0.1              |                          | -8.5 / +7.8   | +0.1 / -1.0 |
| ATLAS_MET_SoftTrk_ResoPara      | +1.4 / -1.4              | +4.7 / -4.7              | +1.1 / -1.1   |             |
| ATLAS_MET_SoftTrk_ResoPerp      |                          | +4.2 / -4.2              |               |             |
| ATLAS_MET_SoftTrk_Scale         | +1.1 / -1.0              | +5.9 / -1.0              | -6.1 / +5.6   |             |
| ATLAS_PRW_DATASF                | -2.7 / +2.3              | +2.1 / -3.3              | -1.5 / +1.0   | -3.1 / +2.7 |
| ATLAS_TAU_EFF_ELEORL_TRUEELE    |                          | +2.3 / -2.3              |               |             |
| ATLAS_TAU_EFF_ID_TOTAL          | +5.8 / -5.8              |                          | +4.7 / -4.7   | +5.8 / -5.8 |
| ATLAS_TAU_EFF_RECO_TOTAL        | +3.1 / -3.1              |                          | +2.5 / -2.5   | +3.0 / -3.0 |
| ATLAS_TAU_TES_INSITU            | +2.8 / -3.6              |                          | +0.6 / -2.5   | +1.9 / -1.1 |
| ATLAS_TAU_TES_MODEL             |                          |                          | +0.6 / -1.1   |             |
| Z_EWK_proportion                | +0.2 / -0.2              |                          |               |             |
| ZttTheory_CKK_boost             | -3.5 / +2.9              |                          |               |             |
| ZttTheory_MGvsSH_boost          | +1.7 / -1.7              |                          |               |             |
| ZttTheory_MUR_MUF_boost         | +1.1 / -1.3              |                          |               |             |

**Table A.9:** Relative impact of up- and downward fluctuations of the nuisance parameters on the acceptance of the background processes in the signal region of the Boosted High category. Variations less than 0.1 % are ignored.

|                                       | <i>ggF</i>  | <i>VBF</i>  | <i>WH</i>   | <i>ZH</i>    | <i>t<math>\bar{t}</math>H</i> |
|---------------------------------------|-------------|-------------|-------------|--------------|-------------------------------|
| ATLAS_FT_EFF_Eigen_b_0                |             |             |             |              | +23.8 / -20.5                 |
| ATLAS_FT_EFF_Eigen_b_1                |             |             |             |              | +4.6 / -4.5                   |
| ATLAS_FT_EFF_Eigen_b_2                |             |             |             |              | -2.4 / +2.4                   |
| ATLAS_FT_EFF_Eigen_c_0                |             |             | +1.5 / -1.5 |              | +2.1 / -2.2                   |
| ATLAS_FT_EFF_Eigen_light_0            | +1.3 / -1.3 | +1.0 / -1.0 | +1.4 / -1.4 | +1.5 / -1.5  | +2.3 / -2.3                   |
| ATLAS_FT_EFF_Eigen_light_3            |             |             |             |              | -1.0 / +1.0                   |
| ATLAS_FT_EFF_extrapolation_from_charm |             |             |             |              | -1.3 / +1.3                   |
| ATLAS_JER_CROSSCALIBFWD               |             |             |             | +1.3 / -1.3  |                               |
| ATLAS_JER_NOISEFWD                    |             |             |             | +1.0 / -1.0  | -1.0 / +1.0                   |
| ATLAS_JER_NP_0                        | -2.9 / +3.1 | -2.9 / +3.1 | +0.4 / +1.4 | -2.6 / 0.0   |                               |
| ATLAS_JER_NP_1                        | +2.8 / -2.8 | +3.2 / -3.6 | +1.0 / -1.1 | +1.2 / -3.7  | -0.2 / -1.7                   |
| ATLAS_JER_NP_2                        | -1.6 / +1.7 | +1.0 / -1.9 | -4.7 / +4.6 | -2.1 / +2.2  | -19.6 / +19.3                 |
| ATLAS_JER_NP_3                        | +4.9 / -4.9 | -2.8 / +2.8 | +5.1 / -5.1 | +5.5 / -5.4  | +6.2 / 0.0                    |
| ATLAS_JER_NP_4                        | +1.9 / -2.0 | +0.7 / -1.3 | +1.2 / -0.7 | +0.8 / -1.2  | +8.0 / -7.5                   |
| ATLAS_JER_NP_5                        | -3.0 / +3.0 | +1.1 / -1.0 | -3.4 / +4.4 |              | -5.8 / +0.5                   |
| ATLAS_JER_NP_6                        |             |             |             | +1.9 / -1.2  | +4.6 / -0.2                   |
| ATLAS_JER_NP_7                        | -0.6 / +0.6 | +0.5 / -1.2 | +1.7 / +0.2 | +0.2 / +0.3  | +5.5 / -4.8                   |
| ATLAS_JER_NP_8                        | -2.5 / +1.1 | -2.5 / +2.6 | +2.0 / -2.3 | +0.1 / -0.1  |                               |
| ATLAS_JES_EffectiveNP_1               | +0.2 / -0.7 | -0.2 / -0.8 | -3.8 / +0.7 | +2.6 / -1.3  | +6.5 / -10.2                  |
| ATLAS_JES_EffectiveNP_2               |             | +0.2 / +0.3 |             |              | +1.2 / -0.3                   |
| ATLAS_JES_EffectiveNP_7               |             | -0.1 / +0.1 |             |              |                               |
| ATLAS_JES_EffectiveNP_8               |             |             | +1.3 / 0.0  |              |                               |
| ATLAS_JES_EtaInter_Model              | +0.6 / -0.9 | +0.5 / -1.5 | +0.1 / -0.5 | +2.7 / -0.3  |                               |
| ATLAS_JES_EtaInter_NonClosure         |             | -1.0 / -0.1 | +0.4 / +1.1 | +3.6 / -5.3  | -5.3 / +1.5                   |
| ATLAS_JES_EtaInter_Stat               | +1.0 / -1.0 | +0.7 / -0.7 |             |              |                               |
| ATLAS_JES_Flavor_Comp                 | +2.2 / -2.4 | +1.2 / -1.3 | +5.7 / -5.7 | +10.1 / -3.8 | +22.6 / -8.1                  |
| ATLAS_JES_Flavor_Resp                 | -2.5 / +1.3 |             | +0.2 / -0.6 | -1.5 / +2.9  | +0.7 / +0.2                   |
| ATLAS_JES_PU_OffsetMu                 |             |             | -0.9 / -0.1 | -3.4 / +3.3  | +0.1 / -1.9                   |
| ATLAS_JES_PU_OffsetNPV                |             |             | -1.5 / +0.7 | +0.7 / -0.7  | +5.0 / -4.3                   |
| ATLAS_JES_PU_PtTerm                   | +0.5 / -0.6 | +0.6 / -1.4 | +0.7 / -0.7 | -0.4 / -0.8  | +2.4 / -6.0                   |
| ATLAS_JES_PU_Rho                      | +1.3 / -2.3 | -0.2 / -0.9 | -1.4 / +2.4 | +1.6 / -0.9  | +16.2 / -17.8                 |
| ATLAS_JVT                             |             |             |             |              | +1.2 / -1.2                   |
| ATLAS_MET_SoftTrk_ResoPara            |             |             | -1.4 / +1.4 |              | +7.9 / -7.9                   |
| ATLAS_MET_SoftTrk_ResoPerp            |             |             | -3.8 / +3.8 | +2.4 / -2.4  | -4.3 / +4.3                   |
| ATLAS_MET_SoftTrk_Scale               | +0.5 / -0.1 |             | +1.2 / +1.9 | +3.8 / -4.1  |                               |
| ATLAS_PRW_DATASF                      | -3.1 / +2.3 | -3.0 / +2.5 | +0.8 / -1.5 | -5.8 / +4.6  | +6.2 / -4.2                   |
| ATLAS_TAU_EFF_ID_TOTAL                | +5.8 / -5.8 | +5.8 / -5.9 | +5.9 / -5.9 | +5.8 / -5.8  | +6.2 / -6.2                   |
| ATLAS_TAU_EFF_RECO_TOTAL              | +3.3 / -3.3 | +3.3 / -3.3 | +3.2 / -3.2 | +3.3 / -3.3  | +2.6 / -2.6                   |
| ATLAS_TAU_TES_DETECTOR                |             | -0.6 / +0.1 |             |              | +5.0 / -7.9                   |
| ATLAS_TAU_TES_INSITU                  | +2.3 / -2.6 | +2.9 / -3.9 | +1.5 / -4.4 | +6.7 / -5.1  | +11.1 / -4.7                  |
| ATLAS_TAU_TES_MODEL                   |             |             | +1.8 / -2.0 | +0.7 / 0.0   | +0.1 / -0.9                   |
| Theo_VBFH_shower                      |             | +9.6 / -9.6 |             |              |                               |
| Theo_VH_MUR_MUF                       |             |             | +3.0 / -3.7 | +4.3 / -2.2  |                               |
| Theo_ggH_shower                       | -6.1 / +6.1 |             |             |              |                               |
| Theo_ggH_sig_qcd_0                    | +6.7 / -6.7 |             |             |              |                               |
| Theo_ggH_sig_qcd_1                    | +6.3 / -6.3 |             |             |              |                               |
| Theo_ggH_sig_qcd_2                    | +6.2 / -6.2 |             |             |              |                               |
| Theo_ggH_sig_qcd_3                    | +4.5 / -4.5 |             |             |              |                               |
| Theo_ggH_sig_qcd_6                    | +6.9 / -6.9 |             |             |              |                               |
| Theo_ggH_sig_qcd_7                    | +6.0 / -6.0 |             |             |              |                               |
| Theo_VH_PSUE                          |             |             | +1.2 / -1.2 | +1.2 / -1.2  |                               |
| Theo_boost_VBFH_PSUE                  |             | +1.8 / -1.8 |             |              |                               |
| Theo_boost_ggH_PSUE                   | +2.9 / -2.9 |             |             |              |                               |
| Theo_sig_alphaS                       | +1.5 / -1.4 |             |             |              |                               |

**Table A.10:** Relative impact of up- and downward fluctuations of the nuisance parameters on the acceptance of the signal processes in the signal region of the Boosted Low category. Variations less than 0.1 % are ignored.

|                               | $Z \rightarrow \tau\tau$ | $Z \rightarrow \ell\ell$ | Top           | Diboson     |
|-------------------------------|--------------------------|--------------------------|---------------|-------------|
| ATLAS_FT_EFF_Eigen_b_0        |                          |                          | +17.3 / -15.9 |             |
| ATLAS_FT_EFF_Eigen_b_1        |                          |                          | +3.7 / -3.7   |             |
| ATLAS_FT_EFF_Eigen_b_2        |                          |                          | -2.1 / +2.2   |             |
| ATLAS_FT_EFF_Eigen_light_0    | +1.3 / -1.3              | +1.3 / -1.3              | +1.2 / -1.2   | +1.6 / -1.6 |
| ATLAS_JER_CROSSCALIBFWD       |                          |                          |               | +1.2 / -1.2 |
| ATLAS_JER_NOISEFWD            |                          | +4.1 / -1.8              |               | +1.2 / -1.2 |
| ATLAS_JER_NP_0                | -1.0 / +1.8              | +1.1 / +11.2             | +5.5 / -5.8   | -3.8 / +2.4 |
| ATLAS_JER_NP_1                | +2.2 / -2.4              | +0.5 / +1.2              | +2.9 / -2.4   | +0.7 / -1.8 |
| ATLAS_JER_NP_2                | -1.1 / +1.2              |                          | +1.2 / -0.6   | -1.2 / +1.1 |
| ATLAS_JER_NP_3                |                          |                          | +2.6 / -6.4   | -2.2 / +2.8 |
| ATLAS_JER_NP_4                |                          | -3.4 / -9.0              | -1.7 / +0.2   | +0.6 / -2.3 |
| ATLAS_JER_NP_5                |                          | +2.7 / -3.0              |               |             |
| ATLAS_JER_NP_6                | -1.2 / +1.1              | +7.3 / -6.0              | 0.0 / -1.4    | 0.0 / -0.2  |
| ATLAS_JER_NP_7                |                          |                          |               | +1.4 / -1.6 |
| ATLAS_JER_NP_8                | -1.8 / +1.4              | +1.0 / +5.5              | -1.5 / +1.5   | -1.6 / +0.5 |
| ATLAS_JES_EffectiveNP_1       |                          |                          |               | +1.8 / -1.0 |
| ATLAS_JES_EffectiveNP_2       |                          | -1.6 / +7.3              |               |             |
| ATLAS_JES_EffectiveNP_3       |                          | -5.1 / +6.0              |               |             |
| ATLAS_JES_EffectiveNP_4       |                          | +4.4 / -1.3              |               |             |
| ATLAS_JES_EffectiveNP_5       |                          | -9.4 / +12.5             |               |             |
| ATLAS_JES_EffectiveNP_6       |                          | +5.6 / -7.0              |               |             |
| ATLAS_JES_EffectiveNP_7       |                          | +0.3 / +11.6             |               |             |
| ATLAS_JES_EffectiveNP_8       |                          | -6.0 / +7.4              |               |             |
| ATLAS_JES_EtaInter_Model      | +0.4 / -0.6              |                          | +3.5 / -2.8   | +2.8 / -1.7 |
| ATLAS_JES_EtaInter_NonClosure |                          | -10.9 / +13.9            |               |             |
| ATLAS_JES_EtaInter_Stat       |                          |                          | +1.3 / -0.4   |             |
| ATLAS_JES_Flavor_Comp         |                          | +14.1 / -8.2             |               | +5.0 / -2.3 |
| ATLAS_JES_Flavor_Resp         | -1.7 / +1.5              |                          | -0.8 / +1.8   | -1.2 / +1.6 |
| ATLAS_JES_PU_OffsetMu         |                          | +1.7 / -5.3              | +0.1 / -2.3   | +0.7 / +0.1 |
| ATLAS_JES_PU_OffsetNPV        |                          |                          | -0.7 / +2.5   | +1.1 / -0.7 |
| ATLAS_JES_PU_PtTerm           |                          | +15.4 / -16.5            | +2.3 / -0.4   |             |
| ATLAS_JES_PU_Rho              | +1.2 / -1.0              | -1.2 / -0.5              |               | +1.4 / -1.3 |
| ATLAS_MET_SoftTrk_ResoPara    |                          | +10.1 / +2.7             | -3.1 / +3.1   |             |
| ATLAS_MET_SoftTrk_ResoPerp    |                          | -5.1 / +6.4              |               |             |
| ATLAS_MET_SoftTrk_Scale       | -0.2 / +0.1              | -19.2 / +30.3            |               |             |
| ATLAS_MUONS_MS                |                          | +3.7 / -3.7              |               |             |
| ATLAS_MUONS_SAGITTA_RESBIAS   |                          | +2.9 / -3.3              |               |             |
| ATLAS_MUONS_SAGITTA_RHO       |                          | -1.6 / +3.2              |               |             |
| ATLAS_PRW_DATASF              | -3.5 / +1.3              | +19.0 / -18.8            | -2.0 / +1.4   | -2.7 / +2.0 |
| ATLAS_TAU_EFF_ELEORL_TRUEELE  |                          | +1.6 / -1.6              |               |             |
| ATLAS_TAU_EFF_ID_TOTAL        | +5.9 / -5.9              |                          | +5.1 / -5.1   | +5.7 / -5.7 |
| ATLAS_TAU_EFF_RECO_TOTAL      | +3.4 / -3.4              |                          | +2.8 / -2.8   | +3.1 / -3.1 |
| ATLAS_TAU_TES_INSITU          | +5.9 / -5.2              |                          | +5.6 / -4.6   | +4.2 / -3.2 |
| ATLAS_TAU_TES_MODEL           |                          |                          | +1.6 / -1.3   | +2.1 / -1.6 |
| Z_EWK_proportion              | +0.1 / -0.1              |                          |               |             |
| ZttTheory_CKK_boost           | +6.4 / -5.2              |                          |               |             |
| ZttTheory_MGvsSH_boost        | -2.1 / +2.1              |                          |               |             |
| ZttTheory_MUR_MUF_boost       | -0.9 / +0.6              |                          |               |             |

**Table A.11:** Relative impact of up- and downward fluctuations of the nuisance parameters on the acceptance of the background processes in the signal region of the Boosted Low category. Variations less than 0.1 % are ignored.

|                                       | <i>ggF</i>  | <i>VBF</i>  | <i>WH</i>   | <i>ZH</i>    | <i>t<math>\bar{t}</math>H</i> |
|---------------------------------------|-------------|-------------|-------------|--------------|-------------------------------|
| ATLAS_EG_RESOLUTION_ALL               |             |             | -1.1 / +0.7 |              |                               |
| ATLAS_EG_SCALE_ALLCORR                |             |             | +0.1 / -1.2 |              |                               |
| ATLAS_FT_EFF_Eigen_c_0                | -1.1 / +1.1 | -1.8 / +1.8 | -4.4 / +4.4 | -2.2 / +2.1  |                               |
| ATLAS_FT_EFF_Eigen_light_0            | -6.9 / +6.8 | -6.4 / +6.4 | -3.7 / +3.6 | -2.8 / +2.7  |                               |
| ATLAS_FT_EFF_Eigen_light_1            | +1.9 / -1.9 | +1.7 / -1.7 | +1.0 / -1.0 |              |                               |
| ATLAS_FT_EFF_Eigen_light_3            | +2.1 / -2.1 | +1.5 / -1.6 |             |              |                               |
| ATLAS_FT_EFF_extrapolation_from_charm |             |             | +2.5 / -2.5 |              |                               |
| ATLAS_JER_CROSSCALIBFWD               | -1.7 / +1.7 |             |             |              | -1.2 / +1.2                   |
| ATLAS_JER_NOISEFWD                    | -3.3 / +3.3 | -1.1 / +1.1 |             |              |                               |
| ATLAS_JER_NP_0                        |             |             | -1.1 / +1.7 | -1.1 / +7.2  | -1.1 / +2.5                   |
| ATLAS_JER_NP_1                        | -2.9 / +2.9 |             | +1.1 / -1.8 | +1.0 / -0.8  |                               |
| ATLAS_JER_NP_2                        | +3.6 / -3.6 |             |             | -5.7 / +5.7  |                               |
| ATLAS_JER_NP_3                        |             | -1.3 / +1.3 | -2.4 / +2.4 | -4.4 / +4.4  |                               |
| ATLAS_JER_NP_4                        | -3.5 / +0.1 | -2.0 / +2.0 | +0.2 / -1.0 | -3.0 / +3.0  |                               |
| ATLAS_JER_NP_5                        |             |             | +0.9 / -2.9 |              |                               |
| ATLAS_JER_NP_6                        |             |             | +0.5 / -3.1 |              | +2.0 / -2.0                   |
| ATLAS_JER_NP_7                        |             | -1.6 / +0.2 |             | -0.5 / +1.1  |                               |
| ATLAS_JER_NP_8                        | +3.7 / -3.7 |             | +3.0 / -3.0 | -0.1 / +1.4  |                               |
| ATLAS_JES_EffectiveNP_1               | +4.2 / -4.2 | +1.8 / -1.1 |             | +2.5 / -1.8  | +1.2 / -1.2                   |
| ATLAS_JES_EffectiveNP_2               |             | +0.2 / -1.4 | +1.4 / -2.6 | +1.8 / -0.7  |                               |
| ATLAS_JES_EffectiveNP_8               |             |             | 0.0 / -1.1  |              |                               |
| ATLAS_JES_EtaInter_Model              | +1.4 / -2.8 | +1.3 / -1.8 | -2.1 / +0.3 | +1.3 / -0.6  |                               |
| ATLAS_JES_EtaInter_NonClosure         | -1.7 / +1.2 | -2.3 / +1.1 | -2.2 / +1.1 |              | -1.4 / +1.4                   |
| ATLAS_JES_EtaInter_Stat               | +1.5 / -1.0 |             |             |              |                               |
| ATLAS_JES_Flavor_Comp                 | +5.4 / -5.1 | +2.4 / -2.9 | +4.6 / -6.5 | +3.1 / -10.4 | +0.9 / -2.4                   |
| ATLAS_JES_Flavor_Resp                 | -3.9 / +5.7 |             | +0.7 / -3.4 | -0.7 / +2.1  | -1.5 / +1.5                   |
| ATLAS_JES_PU_OffsetMu                 |             |             | -1.9 / +1.7 | -2.1 / +0.5  |                               |
| ATLAS_JES_PU_OffsetNPV                | +1.1 / -0.5 |             | -2.7 / +2.7 |              | +1.7 / -1.7                   |
| ATLAS_JES_PU_PtTerm                   | +1.6 / -1.6 | +0.9 / -2.2 | +1.4 / -3.2 | +2.8 / -2.8  |                               |
| ATLAS_JES_PU_Rho                      | +5.3 / -6.1 | +2.0 / -2.3 | +3.5 / -3.5 | +3.4 / -4.1  | +0.4 / -1.9                   |
| ATLAS_JVT                             |             |             |             |              | +1.1 / -1.1                   |
| ATLAS_MET_SoftTrk_ResoPara            |             | -1.9 / +1.9 | -4.8 / +4.8 | -4.6 / +4.6  |                               |
| ATLAS_MET_SoftTrk_ResoPerp            | +1.7 / -1.7 | -2.6 / +2.6 | -3.6 / +3.6 | -2.4 / +2.4  |                               |
| ATLAS_MET_SoftTrk_Scale               | +0.9 / -1.3 | -1.9 / +0.3 | -3.1 / 0.0  |              | -1.7 / +1.7                   |
| ATLAS_PRW_DATASF                      |             | -1.5 / +1.5 | -6.5 / +4.5 | -8.7 / +6.9  | -2.3 / +1.2                   |
| ATLAS_TAU_EFF_ID_TOTAL                | +5.8 / -5.8 | +5.8 / -5.8 | +5.8 / -5.8 | +5.8 / -5.8  | +5.6 / -5.6                   |
| ATLAS_TAU_EFF_RECO_TOTAL              | +3.1 / -3.1 | +3.2 / -3.2 | +3.0 / -3.0 | +3.1 / -3.1  | +3.0 / -3.0                   |
| ATLAS_TAU_TES_DETECTOR                | -3.7 / +4.6 | -3.4 / +3.4 | -4.8 / +3.1 | -5.4 / +16.5 | -1.4 / +1.7                   |
| ATLAS_TAU_TES_INSITU                  | -1.4 / +0.3 | -0.7 / +1.2 |             |              | +1.7 / -1.2                   |
| ATLAS_TAU_TES_MODEL                   | -2.0 / +0.2 |             |             | -1.0 / 0.0   |                               |
| Theo_VH_MUR_MUF                       |             |             | +3.3 / -2.9 | +6.0 / -3.0  |                               |
| Theo_ggH_sig_qcd_0                    | +7.5 / -7.5 |             |             |              |                               |
| Theo_ggH_sig_qcd_1                    | +7.2 / -7.2 |             |             |              |                               |
| Theo_ggH_sig_qcd_2                    | +5.4 / -5.4 |             |             |              |                               |
| Theo_ggH_sig_qcd_3                    | +9.8 / -9.8 |             |             |              |                               |
| Theo_ggH_sig_qcd_6                    | +7.7 / -7.7 |             |             |              |                               |
| Theo_ggH_sig_qcd_7                    | +9.8 / -9.8 |             |             |              |                               |
| Theo_ggH_sig_qcd_8                    | +4.2 / -4.2 |             |             |              |                               |
| Theo_VH_PSUE                          |             |             | +1.2 / -1.2 | +1.2 / -1.2  |                               |
| Theo_boost_VBFH_PSUE                  |             | +1.8 / -1.8 |             |              |                               |
| Theo_boost_ggH_PSUE                   | +2.9 / -2.9 |             |             |              |                               |
| Theo_sig_alphaS                       | +1.6 / -1.4 |             |             |              |                               |
| Theo_sig_pdf_1                        |             | +1.3 / -1.3 |             |              |                               |
| Theo_sig_pdf_16                       | +1.0 / -1.0 |             |             |              |                               |
| Theo_sig_pdf_3                        | -1.1 / +1.1 |             |             |              |                               |
| Theo_sig_pdf_4                        | -1.3 / +1.3 |             |             |              |                               |

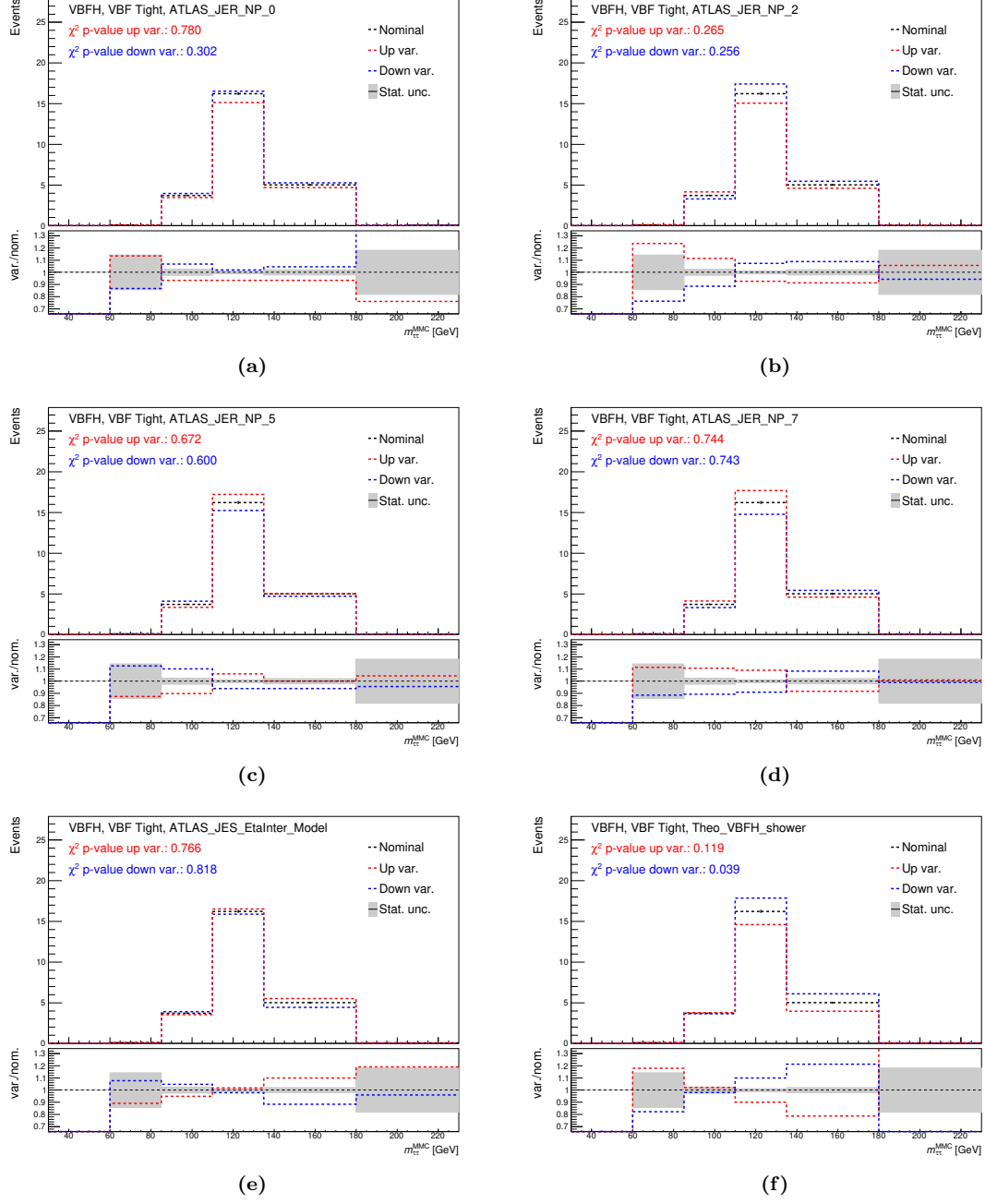
**Table A.12:** Relative impact of up- and downward fluctuations of the nuisance parameters on the acceptance of the signal processes in the top-quark control region of the Boosted category. Variations less than 0.1 % are ignored.

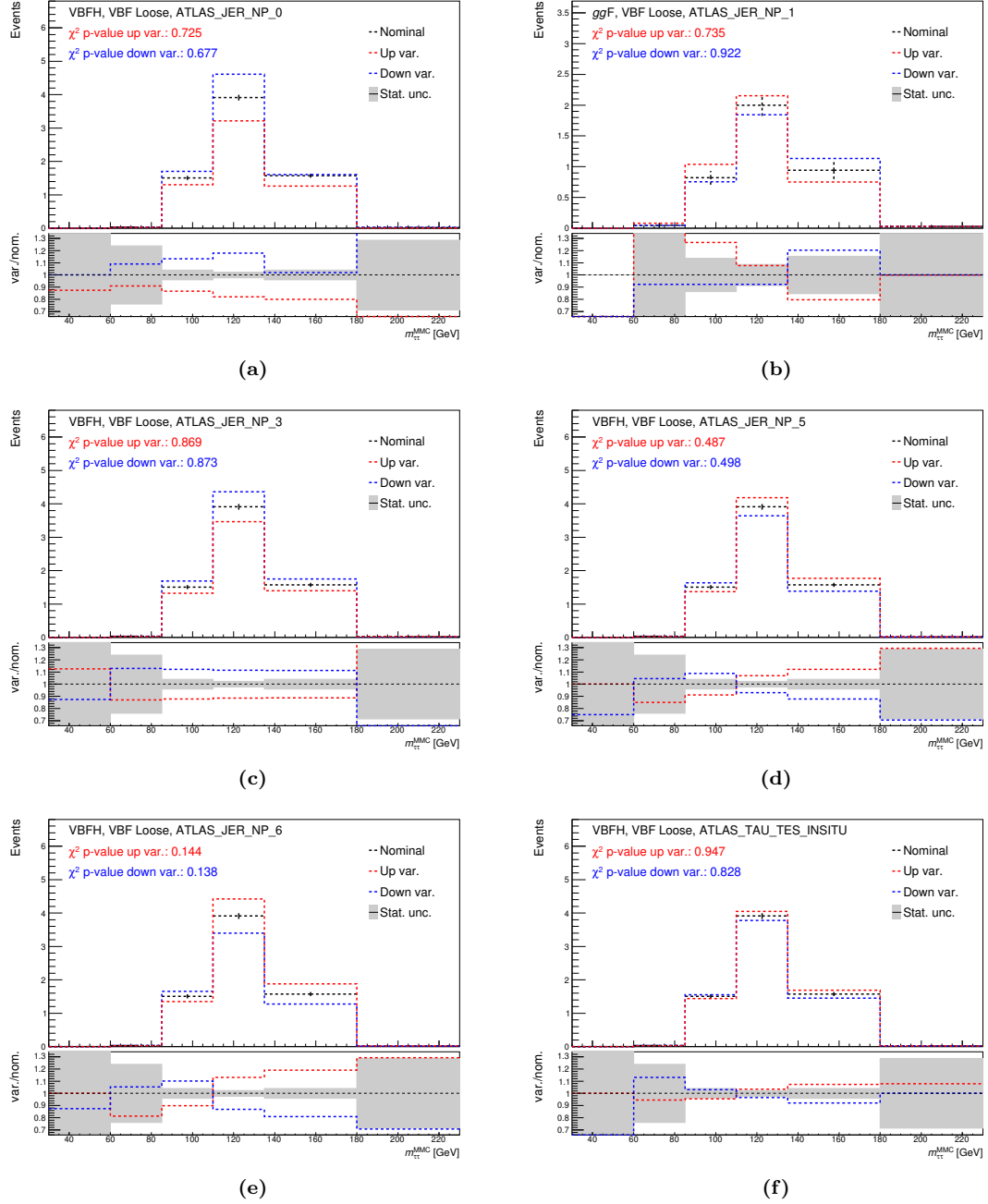
|                               | $Z \rightarrow \tau\tau$ | $Z \rightarrow \ell\ell$ | Top         | Diboson     |
|-------------------------------|--------------------------|--------------------------|-------------|-------------|
| ATLAS_EG_SCALE_ALLCORR        |                          | +1.5 / -0.5              |             |             |
| ATLAS_FT_EFF_Eigen_b_0        |                          |                          | -1.2 / +1.1 |             |
| ATLAS_FT_EFF_Eigen_c_0        | -1.0 / +1.0              |                          |             | -2.1 / +2.1 |
| ATLAS_FT_EFF_Eigen_light_0    | -5.7 / +5.6              | -6.4 / +6.4              |             | -6.7 / +6.6 |
| ATLAS_FT_EFF_Eigen_light_1    | +1.5 / -1.5              | +1.7 / -1.7              |             | +1.7 / -1.7 |
| ATLAS_FT_EFF_Eigen_light_3    | +1.9 / -1.9              | +3.1 / -3.1              |             | +1.3 / -1.3 |
| ATLAS_FT_EFF_Eigen_light_4    |                          | +1.0 / -1.0              |             |             |
| ATLAS_JER_CROSSCALIBFWD       | -2.3 / +2.3              | +4.8 / -4.8              |             |             |
| ATLAS_JER_NOISEFWD            | -1.1 / +1.1              | +4.6 / -4.6              |             |             |
| ATLAS_JER_NP_0                | +2.6 / -2.6              | -1.0 / +23.9             | -1.1 / +0.4 | -1.1 / +1.8 |
| ATLAS_JER_NP_1                |                          |                          |             | -2.4 / +2.4 |
| ATLAS_JER_NP_2                | +3.9 / -3.9              | +62.6 / -62.6            |             | +1.6 / -1.6 |
| ATLAS_JER_NP_3                | -1.2 / +0.8              | +2.6 / -67.7             |             | -1.3 / +1.3 |
| ATLAS_JER_NP_4                | -1.9 / +1.9              | +1.2 / -68.0             |             | -2.2 / +0.1 |
| ATLAS_JER_NP_5                |                          | +6.3 / -0.9              |             |             |
| ATLAS_JER_NP_6                |                          |                          |             | +2.0 / -2.0 |
| ATLAS_JER_NP_7                | +0.1 / -1.4              | -1.2 / +8.6              |             | +1.6 / -1.6 |
| ATLAS_JER_NP_8                |                          | -0.1 / +8.3              |             | +1.6 / -1.6 |
| ATLAS_JES_EffectiveNP_1       | +2.8 / -2.7              | +5.9 / -3.4              | +0.9 / -1.1 | +0.9 / -2.1 |
| ATLAS_JES_EffectiveNP_2       |                          | -5.4 / +5.4              |             |             |
| ATLAS_JES_EffectiveNP_4       |                          | -4.8 / +4.8              |             |             |
| ATLAS_JES_EffectiveNP_5       |                          | +3.4 / -3.4              |             |             |
| ATLAS_JES_EtaInter_Model      |                          | +2.2 / -4.3              |             | +0.3 / -1.2 |
| ATLAS_JES_EtaInter_NonClosure | -1.1 / +1.1              |                          |             |             |
| ATLAS_JES_EtaInter_Stat       | +1.5 / -0.1              | +6.7 / -6.7              |             |             |
| ATLAS_JES_Flavor_Comp         | +1.1 / -0.2              | +9.8 / -7.2              | +1.6 / -1.9 | +3.4 / -4.9 |
| ATLAS_JES_Flavor_Resp         | -2.7 / +2.6              | -4.9 / +6.3              |             | -1.7 / +0.8 |
| ATLAS_JES_PU_OffsetMu         |                          | -0.1 / +1.3              |             |             |
| ATLAS_JES_PU_OffsetNPV        | -1.0 / +0.3              | +2.5 / -0.9              |             |             |
| ATLAS_JES_PU_PtTerm           | +1.4 / -1.8              | -4.2 / +4.2              |             |             |
| ATLAS_JES_PU_Rho              | +4.2 / -3.8              | +8.3 / -6.4              | +1.4 / -1.6 | +1.7 / -2.5 |
| ATLAS_MET_SoftTrk_ResoPerp    | -1.1 / +1.1              | -1.8 / +1.8              |             |             |
| ATLAS_MET_SoftTrk_Scale       | -1.1 / +1.7              | -6.1 / +3.4              |             |             |
| ATLAS_MUONS_MS                |                          | +0.6 / -1.2              |             |             |
| ATLAS_PRW_DATASF              | -1.3 / +1.3              | +1.5 / -3.7              | -2.2 / +1.8 | -1.9 / +2.1 |
| ATLAS_TAU_EFF_ELEORL_TRUEELE  |                          | +1.7 / -1.7              |             |             |
| ATLAS_TAU_EFF_ID_TOTAL        | +5.8 / -5.8              |                          | +5.5 / -5.5 | +5.5 / -5.5 |
| ATLAS_TAU_EFF_RECO_TOTAL      | +3.3 / -3.3              |                          | +3.1 / -3.1 | +3.0 / -3.0 |
| ATLAS_TAU_TES_DETECTOR        | -2.4 / +3.7              |                          | -1.0 / +0.9 |             |
| ATLAS_TAU_TES_INSITU          |                          |                          | +2.5 / -2.4 | +2.7 / -0.5 |
| ATLAS_TAU_TES_MODEL           | -1.2 / +0.8              |                          |             | +1.1 / -0.1 |
| Z_EWK_proportion              | +0.1 / -0.1              |                          |             |             |
| ZttTheory_CKK_boost           | -6.5 / +5.3              |                          |             |             |
| ZttTheory_MUR_MUF_boost       | +5.5 / -3.9              |                          |             |             |
| ZttTheory_QSF_boost           | +2.3 / -2.3              |                          |             |             |

**Table A.13:** Relative impact of up- and downward fluctuations of the nuisance parameters on the acceptance of the background processes in the top-quark control region of the Boosted category. Variations less than 0.1 % are ignored.



## A.1.2 Impact on shapes

Figure A.1: Shape uncertainties with the lowest  $\chi^2$  p-values in the VBF Tight category.



**Figure A.2:** Shape uncertainties with the lowest  $\chi^2$  p-values in the VBF Loose category.

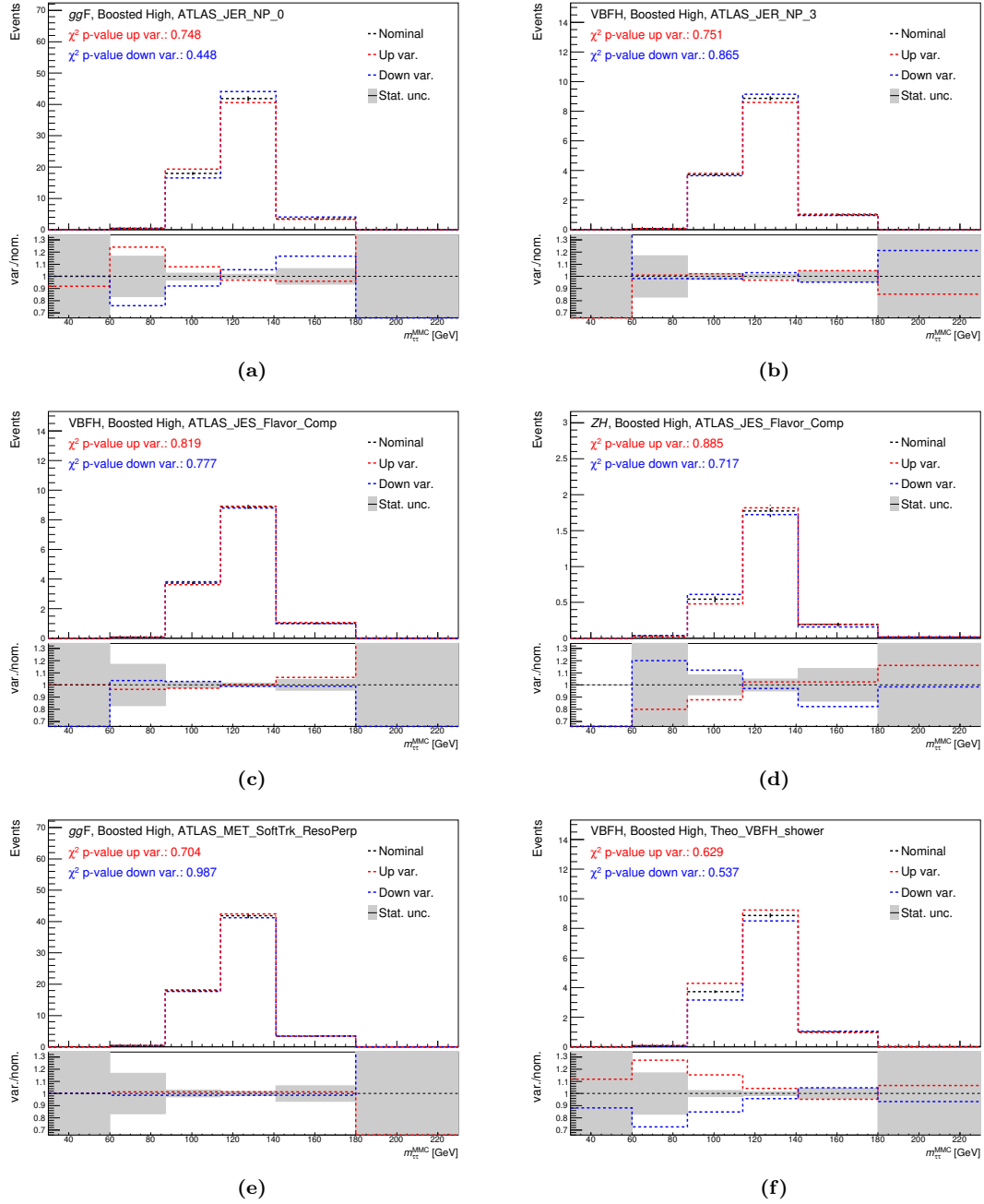
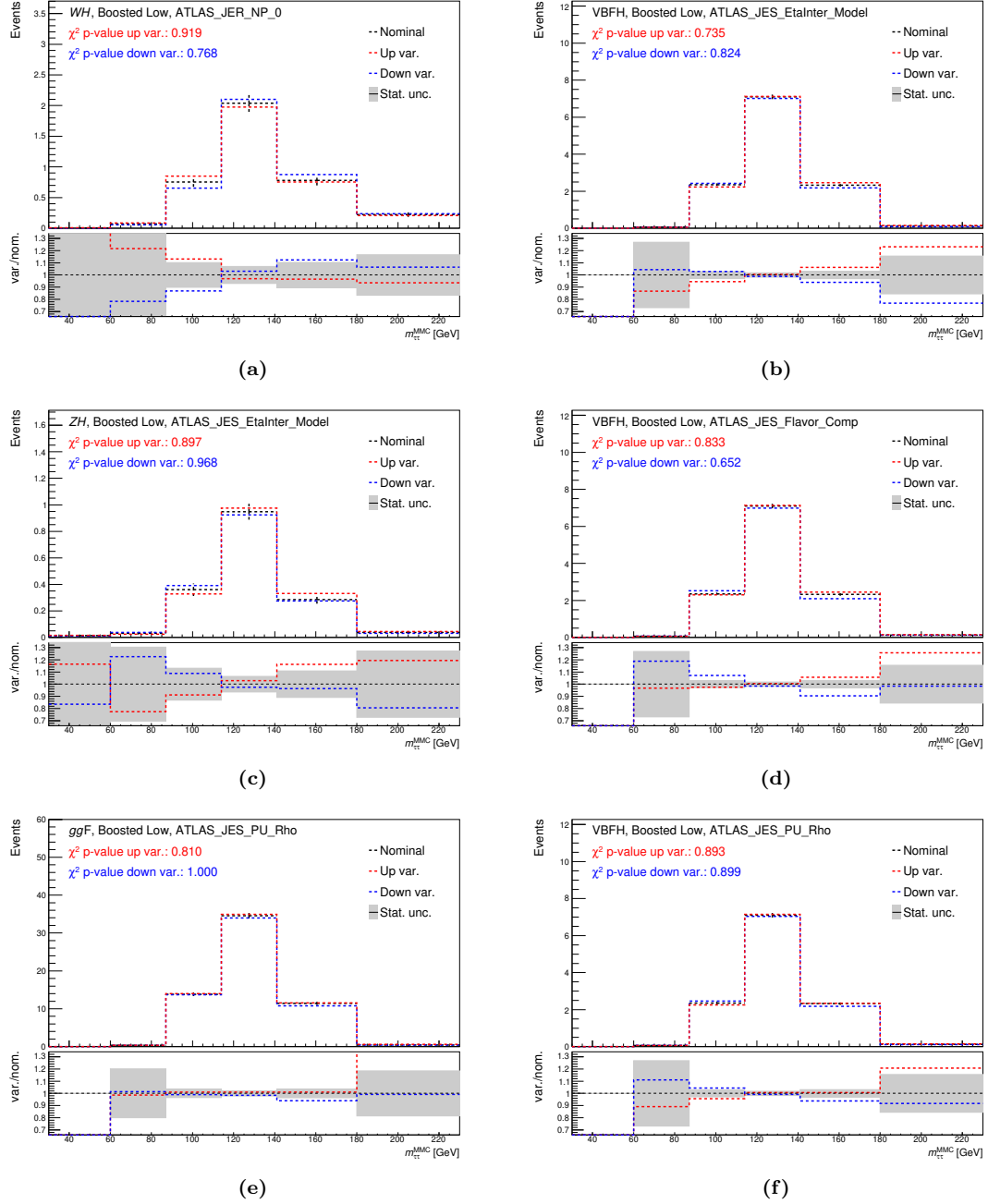


Figure A.3: Shape uncertainties with the lowest  $\chi^2$  p-values in the Boosted High category.



**Figure A.4:** Shape uncertainties with the lowest  $\chi^2$  p-values in the Boosted Low category.

## A.2 Test of CP invariance

### A.2.1 Impact on acceptance

|                                 | VBF           | $ggF/VH/t\bar{t}H$ |
|---------------------------------|---------------|--------------------|
| ATLAS_EG_RESOLUTION_ALL         |               | +0.3 / -1.8        |
| ATLAS_EG_SCALE_ALLCORR          |               | -4.1 / +5.1        |
| ATLAS_EG_SCALE_E4SCINTILLATOR   |               | -0.4 / +2.1        |
| ATLAS_EG_SCALE_LARCALIB_2015PRE | +0.5 / -0.5   | +1.2 / -1.2        |
| ATLAS_EG_SCALE_LARTEMP_2015PRE  |               | +2.2 / -3.7        |
| ATLAS_EG_SCALE_LARTEMP_2016PRE  |               | +1.1 / -4.2        |
| ATLAS_FT_EFF_Eigen_light_0      |               | +1.4 / -1.4        |
| ATLAS_JER_CROSSCALIBFWD         |               | +3.0 / -3.0        |
| ATLAS_JER_NOISEFWD              |               | +11.1 / -11.1      |
| ATLAS_JER_NP_0                  | +1.8 / -1.8   | +3.2 / -3.2        |
| ATLAS_JER_NP_1                  |               | +2.9 / -2.9        |
| ATLAS_JER_NP_2                  |               | +9.2 / -9.2        |
| ATLAS_JER_NP_4                  |               | +7.2 / -7.2        |
| ATLAS_JER_NP_5                  |               | +2.8 / -2.8        |
| ATLAS_JER_NP_7                  |               | +2.7 / -2.7        |
| ATLAS_JER_NP_8                  |               | +4.6 / -4.6        |
| ATLAS_JES_BJES                  |               | +0.9 / -0.9        |
| ATLAS_JES_EffectiveNP_2         | +1.6 / -0.1   | +2.8 / -1.8        |
| ATLAS_JES_EffectiveNP_3         | -0.2 / +1.1   | +1.3 / -1.3        |
| ATLAS_JES_EffectiveNP_4         |               | +1.5 / -1.5        |
| ATLAS_JES_EffectiveNP_5         |               | +4.0 / -0.6        |
| ATLAS_JES_EffectiveNP_6         |               | +2.4 / -2.4        |
| ATLAS_JES_EtaInter_Model        | +2.8 / -2.7   | +0.3 / -5.7        |
| ATLAS_JES_EtaInter_NonClosure   | -0.8 / +1.3   | -4.0 / +3.5        |
| ATLAS_JES_EtaInter_Stat         |               | +1.3 / -1.3        |
| ATLAS_JES_Flavor_Comp           | +3.0 / -1.8   | -1.2 / +1.0        |
| ATLAS_JES_Flavor_Resp           |               | -2.5 / +8.8        |
| ATLAS_JES_PU_OffsetMu           |               | +1.0 / -1.0        |
| ATLAS_JES_PU_PtTerm             | +2.4 / -1.4   | +4.4 / -1.9        |
| ATLAS_JES_PU_Rho                |               | +1.1 / -1.1        |
| ATLAS_JES_PunchThrough          |               | -1.6 / +0.7        |
| ATLAS_MET_SoftTrk_ResoPara      |               | +3.2 / -3.2        |
| ATLAS_MET_SoftTrk_Scale         | +0.6 / -0.6   | +3.9 / -4.3        |
| ATLAS_MUONS_ID                  | +0.3 / -0.3   |                    |
| ATLAS_MUONS_MS                  |               | +1.5 / -3.7        |
| ATLAS_MUONS_SAGITTA_RESBIAS     |               | +0.8 / -2.5        |
| ATLAS_PRW_DATASF                | -3.8 / +3.2   | -5.4 / +2.1        |
| ATLAS_TAU_EFF_ID_TOTAL          | +5.8 / -5.8   | +5.9 / -5.9        |
| ATLAS_TAU_EFF_RECO_TOTAL        | +3.0 / -3.0   | +2.9 / -2.9        |
| ATLAS_TAU_TES_DETECTOR          |               | +0.9 / -0.9        |
| ATLAS_TAU_TES_INSITU            | +3.3 / -2.3   |                    |
| ATLAS_TAU_TES_MODEL             | +1.1 / -0.6   |                    |
| Theo_VBFH_MUR_MUF               | +1.3 / -2.0   |                    |
| Theo_VBFH_shower                | -14.9 / +14.9 |                    |
| Theo_ggH_shower                 |               | -57.0 / +57.0      |
| Theo_ggH_sig_qcd_1              |               | +1.8 / -1.8        |
| Theo_ggH_sig_qcd_2              |               | +2.5 / -2.5        |
| Theo_ggH_sig_qcd_3              |               | +6.5 / -6.5        |
| Theo_ggH_sig_qcd_4              |               | +9.0 / -9.0        |
| Theo_ggH_sig_qcd_5              |               | -6.4 / +6.4        |
| Theo_ggH_sig_qcd_6              |               | +7.6 / -7.6        |
| Theo_ggH_sig_qcd_7              |               | +10.6 / -10.6      |
| Theo_ggH_sig_qcd_8              |               | +6.9 / -6.9        |
| Theo_ggH_PSUE                   |               | +11.8 / -11.8      |
| Theo_ggH_jetveto                |               | +36.0 / -29.9      |
| Theo_sig_alphaS                 |               | +1.7 / -1.5        |
| Theo_sig_pdf_16                 |               | +1.0 / -1.0        |
| Theo_sig_pdf_4                  |               | -2.0 / +2.0        |

**Table A.14:** Relative impact of up- and downward fluctuations of the nuisance parameters on the total number of events of the VBF signal process and the other Higgs boson production processes in the VBF signal region. Variations less than 0.1 % are ignored.

|                                 | $Z \rightarrow \tau\tau$ | Others        |
|---------------------------------|--------------------------|---------------|
| ATLAS_EG_RESOLUTION_ALL         | +2.3 / -2.3              | 0.0 / +2.0    |
| ATLAS_EG_SCALE_ALLCORR          | +3.4 / -3.4              | +33.9 / -10.8 |
| ATLAS_EG_SCALE_E4SCINTILLATOR   |                          | -4.2 / +62.5  |
| ATLAS_EG_SCALE_LARCALIB_2015PRE | -5.6 / +11.1             |               |
| ATLAS_EG_SCALE_LARTEMP_2015PRE  | -18.3 / +2.1             | -3.8 / +50.2  |
| ATLAS_EG_SCALE_LARTEMP_2016PRE  | +2.3 / -2.3              | +12.7 / -16.7 |
| ATLAS_EL_EFF_ID_NONPROMPT_d0    | -1.3 / +1.3              |               |
| ATLAS_FT_EFF_Eigen_light_0      | +1.2 / -1.2              |               |
| ATLAS_JER_CROSSCALIBFWD         | +8.9 / -8.9              | +3.0 / -3.0   |
| ATLAS_JER_NOISEFWD              | +7.2 / -7.2              | +7.1 / -7.1   |
| ATLAS_JER_NP_0                  | +13.9 / -13.9            | +5.2 / -5.1   |
| ATLAS_JER_NP_1                  | +5.7 / -5.7              | +9.0 / -9.0   |
| ATLAS_JER_NP_2                  | +7.0 / -7.0              | +7.8 / -7.8   |
| ATLAS_JER_NP_3                  | +8.5 / -8.5              | +8.4 / -8.4   |
| ATLAS_JER_NP_4                  | +6.1 / -6.1              | +7.3 / -7.3   |
| ATLAS_JER_NP_5                  | +7.0 / -7.0              | +5.9 / -5.9   |
| ATLAS_JER_NP_6                  | +12.0 / -12.0            | +5.5 / -5.5   |
| ATLAS_JER_NP_7                  | +7.1 / -7.1              | +5.6 / -5.6   |
| ATLAS_JER_NP_8                  | +7.1 / -7.1              | +6.0 / -6.0   |
| ATLAS_JES_BJES                  |                          | -5.1 / +71.0  |
| ATLAS_JES_EffectiveNP_1         | +6.4 / -6.4              | +6.4 / -6.4   |
| ATLAS_JES_EffectiveNP_2         | +11.9 / -11.9            | +10.9 / -10.9 |
| ATLAS_JES_EffectiveNP_3         | +5.3 / -5.3              | +64.8 / -6.5  |
| ATLAS_JES_EffectiveNP_4         | +4.3 / -4.3              | +45.1 / -45.1 |
| ATLAS_JES_EffectiveNP_5         | +3.4 / -3.4              |               |
| ATLAS_JES_EffectiveNP_6         | +10.4 / -7.1             | +8.8 / -8.8   |
| ATLAS_JES_EffectiveNP_7         | +4.6 / -4.6              | -14.9 / +13.3 |
| ATLAS_JES_EffectiveNP_8         | -1.0 / +5.1              | -42.4 / +39.1 |
| ATLAS_JES_EtaInter_Model        | +5.8 / -8.2              | -19.8 / +34.3 |
| ATLAS_JES_EtaInter_NonClosure   | -9.4 / +9.6              | -16.6 / +18.9 |
| ATLAS_JES_EtaInter_Stat         | +5.7 / -5.7              | +27.8 / -27.2 |
| ATLAS_JES_Flavor_Comp           | +2.6 / -2.6              | -5.9 / +6.7   |
| ATLAS_JES_Flavor_Comp_zll       |                          | +83.7 / -22.1 |
| ATLAS_JES_Flavor_Resp           | -17.5 / +20.0            | +5.1 / -1.5   |
| ATLAS_JES_HighPt                | -17.4 / +2.8             | +38.0 / -38.0 |
| ATLAS_JES_PU_OffsetMu           | +4.4 / -0.9              |               |
| ATLAS_JES_PU_OffsetNPV          | +8.4 / -8.4              | -4.8 / +45.7  |
| ATLAS_JES_PU_PtTerm             |                          | +9.0 / -9.0   |
| ATLAS_JES_PU_Rho                | +11.3 / -11.3            | +46.5 / -11.3 |
| ATLAS_JES_PunchThrough          | +8.9 / -8.9              | -5.9 / +35.9  |
| ATLAS_MET_SoftTrk_ResoPara      | -7.8 / +7.7              | -37.4 / +50.9 |
| ATLAS_MET_SoftTrk_ResoPerp      | -11.6 / +11.6            | +21.1 / -21.1 |
| ATLAS_MET_SoftTrk_Scale         | +10.3 / -10.3            | -23.3 / +5.3  |
| ATLAS_MUONS_ID                  | +7.6 / -7.6              | +6.7 / -6.7   |
| ATLAS_MUONS_MS                  | +1.1 / -13.0             | +9.2 / -9.2   |
| ATLAS_MUONS_SAGITTA_RESBIAS     | +8.9 / -8.9              | +24.3 / -6.8  |
| ATLAS_MUONS_SAGITTA_RHO         | -19.6 / +3.8             | +6.5 / -6.5   |
| ATLAS_MUONS_SCALE               |                          | +7.0 / -7.0   |
| ATLAS_PRW_DATASF                |                          | -8.5 / +5.5   |
| ATLAS_TAU_EFF_ELEORL_TRUEELE    |                          | +2.1 / -2.1   |
| ATLAS_TAU_EFF_ID_TOTAL          | +5.9 / -5.9              | +2.0 / -2.0   |
| ATLAS_TAU_EFF_RECO_TOTAL        | +2.6 / -2.6              | +1.1 / -1.1   |
| ATLAS_TAU_TES_DETECTOR          | +2.7 / -27.2             |               |
| ATLAS_TAU_TES_INSITU            | +1.9 / -2.5              | +29.5 / -29.5 |
| ATLAS_TAU_TES_MODEL             | +3.9 / -3.9              | +6.2 / -6.2   |
| Z_EWK_proportion                | +5.6 / -5.6              | +1.2 / -1.2   |
| Zll_mjj_rew                     |                          | +9.8 / -9.6   |
| ZttTheory_CKK                   | -1.3 / +0.9              |               |
| ZttTheory_MUR_MUF               | +7.9 / -7.9              |               |
| ZttTheory_PDF                   | +2.9 / -3.5              |               |
| ZttTheory_QSF                   | -1.0 / +1.0              |               |
| Ztt_mjj_rew                     | +8.3 / -8.3              |               |

**Table A.15:** Relative impact of up- and downward fluctuations of the nuisance parameters on the total number of events of the background processes in the VBF signal region. Variations less than 0.1 % are ignored.

|                               | VBF         | $ggF/VH/t\bar{t}H$ |
|-------------------------------|-------------|--------------------|
| ATLAS_FT_EFF_Eigen_light_0    | +1.0 / -1.0 | +1.4 / -1.3        |
| ATLAS_JER_CROSSCALIBFWD       |             | +2.2 / -2.2        |
| ATLAS_JER_NOISEFWD            |             | +3.2 / -3.2        |
| ATLAS_JER_NP_0                |             | +3.2 / -3.2        |
| ATLAS_JER_NP_2                |             | +1.0 / -1.0        |
| ATLAS_JER_NP_3                |             | +1.2 / -1.2        |
| ATLAS_JER_NP_4                |             | +1.4 / -1.4        |
| ATLAS_JES_EffectiveNP_1       |             | +3.0 / -2.3        |
| ATLAS_JES_EtaInter_Model      | +1.2 / -1.8 | +6.3 / -4.9        |
| ATLAS_JES_EtaInter_NonClosure | +1.1 / -1.6 | +3.6 / -1.4        |
| ATLAS_JES_EtaInter_Stat       |             | +1.8 / -0.3        |
| ATLAS_JES_Flavor_Comp         | +0.5 / -1.2 | +4.9 / -3.9        |
| ATLAS_JES_Flavor_Resp         |             | -3.0 / +3.8        |
| ATLAS_JES_PU_OffsetMu         |             | -1.2 / +2.3        |
| ATLAS_JES_PU_PtTerm           |             | +1.8 / -0.6        |
| ATLAS_JES_PU_Rho              | +1.0 / -1.5 | +3.4 / -3.1        |
| ATLAS_PRW_DATASF              | -2.3 / +1.1 |                    |
| ATLAS_TAU_EFF_ID_TOTAL        | +5.8 / -5.8 | +5.8 / -5.8        |
| ATLAS_TAU_EFF_RECO_TOTAL      | +3.3 / -3.3 | +3.3 / -3.3        |
| ATLAS_TAU_TES_INSITU          | +2.9 / -4.1 | +3.8 / -3.4        |
| Theo_VBFH_shower              | -2.8 / +2.8 |                    |
| Theo_ggH_shower               |             | +18.2 / -18.2      |
| Theo_ggH_sig_qcd_1            |             | +1.5 / -1.5        |
| Theo_ggH_sig_qcd_2            |             | +2.6 / -2.6        |
| Theo_ggH_sig_qcd_3            |             | +4.6 / -4.6        |
| Theo_ggH_sig_qcd_4            |             | +8.4 / -8.4        |
| Theo_ggH_sig_qcd_6            |             | +1.9 / -1.9        |
| Theo_ggH_sig_qcd_7            |             | +3.9 / -3.9        |
| Theo_ggH_sig_qcd_8            |             | +1.7 / -1.7        |
| Theo_ggH_PSUE                 |             | +11.6 / -11.6      |
| Theo_sig_alphaS               |             | +1.4 / -1.2        |
| Theo_sig_pdf_4                |             | -1.1 / +1.1        |

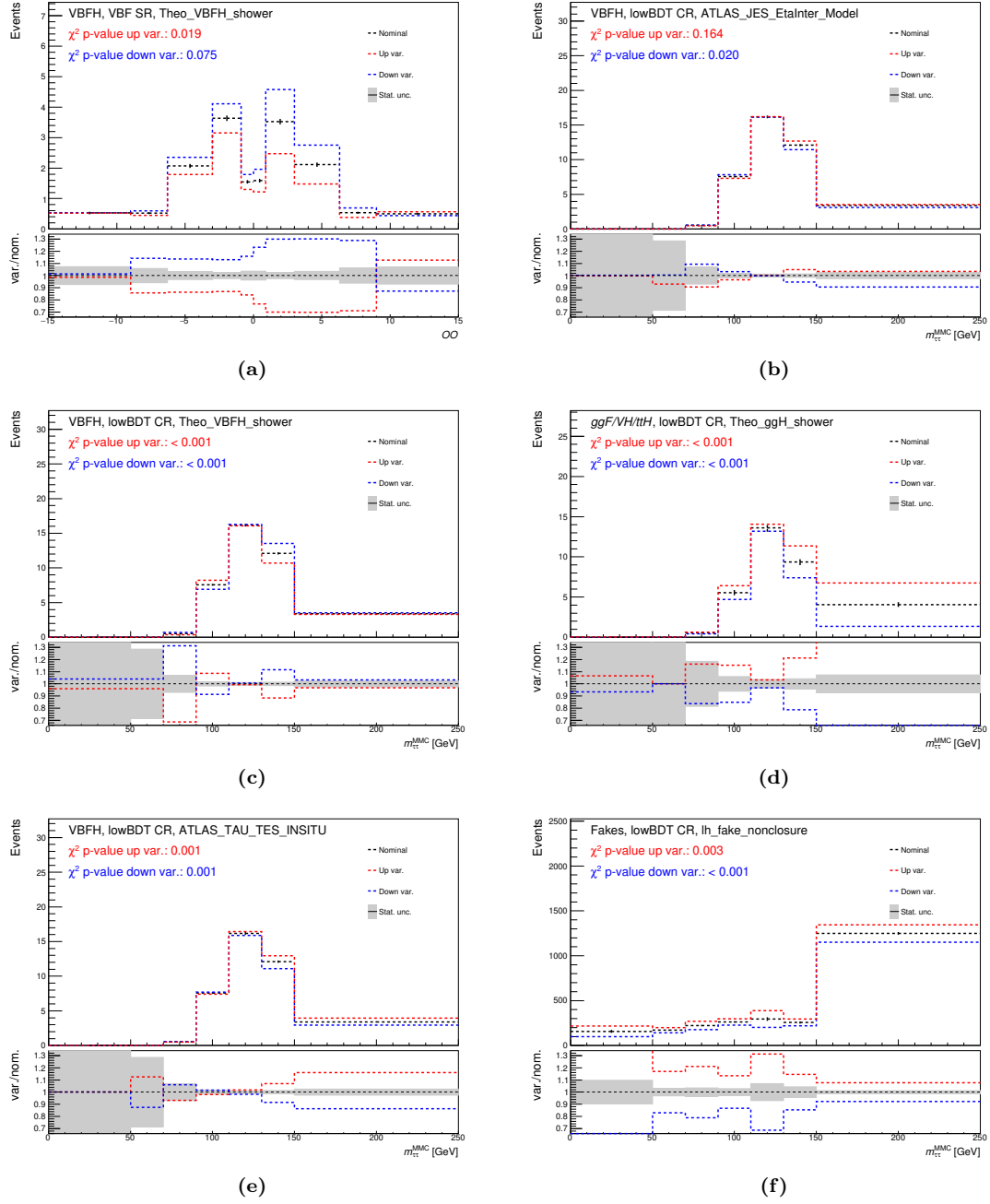
**Table A.16:** Relative impact of up- and downward fluctuations of the nuisance parameters on the total number of events of the VBF signal process and the other Higgs boson production processes in the lowBDT control region. Variations less than 0.1 % are ignored.



|                               | $Z \rightarrow \tau\tau$ | Others       |
|-------------------------------|--------------------------|--------------|
| ATLAS_FT_EFF_Eigen_b_0        |                          | +4.0 / -3.8  |
| ATLAS_FT_EFF_Eigen_light_0    | +1.5 / -1.4              | +1.4 / -1.3  |
| ATLAS_JER_CROSSCALIBFWD       | +2.4 / -2.4              | +3.4 / -3.4  |
| ATLAS_JER_NOISEFWD            | +2.7 / -2.7              | +4.1 / -4.1  |
| ATLAS_JER_NP_0                | +3.5 / -3.5              | +1.4 / -1.4  |
| ATLAS_JER_NP_1                |                          | +3.2 / -3.2  |
| ATLAS_JER_NP_2                |                          | +1.4 / -1.4  |
| ATLAS_JER_NP_3                |                          | +3.4 / -3.4  |
| ATLAS_JER_NP_4                |                          | +4.2 / -4.2  |
| ATLAS_JER_NP_5                |                          | +2.9 / -2.9  |
| ATLAS_JER_NP_6                |                          | +3.9 / -3.9  |
| ATLAS_JER_NP_7                |                          | +2.7 / -2.7  |
| ATLAS_JER_NP_8                |                          | +5.0 / -5.0  |
| ATLAS_JES_EffectiveNP_1       | +2.0 / -2.3              | +0.9 / -0.9  |
| ATLAS_JES_EffectiveNP_2       |                          | +0.8 / -0.8  |
| ATLAS_JES_EtaInter_Model      | +4.7 / -4.7              | +7.0 / -7.5  |
| ATLAS_JES_EtaInter_NonClosure | +1.6 / -2.0              |              |
| ATLAS_JES_EtaInter_Stat       | +1.1 / -1.0              |              |
| ATLAS_JES_Flavor_Comp         | +1.0 / -1.1              | +2.0 / -1.5  |
| ATLAS_JES_Flavor_Comp_zll     |                          | +12.5 / -8.0 |
| ATLAS_JES_Flavor_Resp         | -2.8 / +2.3              |              |
| ATLAS_JES_PU_OffsetMu         | -1.3 / +0.8              | -1.6 / +1.5  |
| ATLAS_JES_PU_PtTerm           | +1.2 / -1.6              | +1.1 / -1.1  |
| ATLAS_JES_PU_Rho              | +3.2 / -2.8              | +3.4 / -3.2  |
| ATLAS_MET_SoftTrk_ResoPerp    |                          | -2.4 / +2.4  |
| ATLAS_TAU_EFF_ELEORL_TRUEELE  |                          | +2.0 / -2.0  |
| ATLAS_TAU_EFF_ID_TOTAL        | +5.9 / -5.9              | +2.1 / -2.1  |
| ATLAS_TAU_EFF_RECO_TOTAL      | +3.4 / -3.4              | +1.2 / -1.2  |
| ATLAS_TAU_TES_INSITU          | +5.3 / -5.7              | +1.4 / -1.8  |
| ATLAS_TAU_TES_MODEL           | +1.6 / -1.0              |              |

**Table A.17:** Relative impact of up- and downward fluctuations of the nuisance parameters on the total number of events of the background processes in the lowBDT control region. Variations less than 0.1 % are ignored.

## A.2.2 Impact on shapes



**Figure A.5:** Shape uncertainties with the lowest  $\chi^2$  p-values in the VBF SR (a) and the lowBDTCR (b)-(f).

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*And yet, and yet... To deny temporal succession, to deny the self, to deny the astronomical universe, appear to be acts of desperation and are secret consolations. Our destiny (unlike the hell of Swedenborg and the hell of Tibetan mythology) is not terrifying because it is unreal; it is terrifying because it is irreversible and iron-bound. Time is the substance of which I am made. Time is a river that sweeps me along, but I am the river; it is a tiger that mangles me, but I am the tiger; it is a fire that consumes me, but I am the fire. The world, unfortunately, is real; I, unfortunately, am Borges.*

– Jorge Luis Borges in "A New Refutation of Time"