

Character Profile of The Higgs Boson

Lydia Brenner

Character Profile of the Higgs Boson

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Contents

I	Introduction	9
	Thesis structure and own contributions	10
1	Theory	13
1.1	The Standard Model of Particle Physics	13
1.1.1	Symmetries of the Standard Model	13
1.1.2	Electroweak Lagrangian	17
1.1.3	Spontaneous Symmetry Breaking and The Brout-Englert-Higgs Mechanism	19
1.1.4	Perturbative Quantum Chromodynamics and Renormalisation	21
1.1.5	Factorisation and Parton Distribution Functions	23
1.2	The SM Higgs Phenomenology in pp collisions	25
1.2.1	Production Modes	25
1.2.2	Decay Modes	28
1.3	Extensions to the Standard Model Higgs Sector	31
1.3.1	Additional Electroweak Singlet	32
1.3.2	Minimal Composite Higgs Model	33
1.3.3	Two Higgs Doublet Model	35
1.3.4	Simplified Minimal Supersymmetric Standard Model	37
1.3.5	Dark Matter and Higgs Portal Model	38
1.4	Effective Field Theory	40
1.5	Effective Models for Characterising the Higgs Boson	43
1.5.1	Kappa Framework	44
1.5.2	Simplified Template Cross Sections	45
1.5.3	Higgs characterisation Lagrangian	46
1.6	Monte Carlo Simulation	49
2	The LHC and the ATLAS detector	51
2.1	The Large Hadron Collider	51
2.1.1	Luminosity	52

2.1.2	Pile-up	53
2.2	The ATLAS detector	56
2.2.1	Particle Detection and Identification	57
2.2.2	Inner Detector	58
2.2.3	The Calorimeter System	59
2.2.4	The Muon Spectrometer	60
2.2.5	Trigger and Data Acquisition	62
2.3	Detector Simulation	64
3	Event and Object reconstruction	65
3.1	Data streams	65
3.2	Tracks and Vertices	66
3.2.1	Track Reconstruction	66
3.2.2	Resolution	67
3.2.3	Primary Vertex Reconstruction	69
3.3	Objects	70
3.3.1	Electrons and Photons	70
3.3.2	Muons	74
3.3.3	Jets	80
3.3.4	Missing Transverse Momentum	83
4	Statistics	85
4.1	Theories with parameters	86
4.2	Poisson counting experiments	86
4.3	Modelling distributions	87
4.4	Modelling uncertainties	87
4.4.1	Nuisance parameters and modelling uncertainties	87
4.5	Parameter and Variance Estimation	88
4.6	Interval Estimation	89
4.6.1	Observed limits and intervals	89
4.6.2	Expected limits and intervals	90
5	Analytic Lagrangian Morphing	91
5.1	Introduction	91
5.2	Signal morphing and comparison to ME reweighting	92
5.2.1	Morphing principles	92
5.2.2	Morphing with one non-SM coupling parameter in either the production or decay vertex	93
5.2.3	Morphing with one non-SM coupling parameter in both production and decay	96
5.2.4	Generalisation to higher-dimensional parameter space	97
5.2.5	Comparison to the matrix element reweighting method	100

5.3	Parametrisation in Higgs characterisation model	103
5.4	Extracting parameters	104
5.5	Validation results	105
5.5.1	Validation on MC truth information	105
5.5.2	Validation on MC reconstruction level with full analysis selection	118
5.6	Conclusions	121
5.7	Exploitation outside of high energy physics	121
6	Performance of Analytic Lagrangian Morphing	123
6.1	Dimensionality reduction	124
6.1.1	Setup	125
6.1.2	Performance of morphing	126
6.1.3	Rotation to Eigen space	133
6.1.4	Reduced model performance	135
6.1.5	Interference study	147
6.2	A methodology for optimisation of sample basis	150
6.2.1	Description of the algorithm	151
6.3	Conclusions	156
7	Gluon-Gluon Fusion with two Associated jets	157
7.1	Theoretical Framework for Higgs boson Parity	159
7.2	Data and Monte Carlo samples	160
7.2.1	Signal samples	160
7.2.2	Background processes and generators	160
7.3	Object Selection	161
7.4	Analysis procedure	163
7.4.1	Pre-selection	163
7.4.2	Signal Region Event Selection	165
7.4.3	Definition of Control Regions and Validation Regions	165
7.4.4	Usage of boosted decision trees	166
7.4.5	Fit Model and Parameter Extraction Procedure	178
7.5	Treatment of Uncertainties	179
7.5.1	Experimental uncertainties	179
7.5.2	Modelling uncertainties	181
7.6	Results	183
7.7	Conclusions	185
8	Couplings Measurement of the SM Higgs Boson	189
8.1	Simplified Template Cross Sections in Run 2	190
8.1.1	Sample generation	190
8.1.2	Individual Channels	191

8.1.3	Statistical Framework	193
8.1.4	Template Cross-section Measurements	195
8.1.5	Global signal strength Measurement	204
8.1.6	Total cross section combination	204
8.1.7	Conclusion	205
8.2	Prospects for Run 2 and HL-LHC	207
8.2.1	Input Channels	207
8.2.2	Coupling fit framework	208
8.2.3	Coupling fit results	212
8.2.4	Mass dependence of couplings	216
8.2.5	Theory uncertainties	216
8.2.6	Conclusions	220
9	BSM interpretations of Higgs Couplings	223
9.1	Introduction	223
9.2	Input Channels	223
9.2.1	Run 1	224
9.2.2	Prospects for Run 2 and HL-LHC	225
9.3	Analysis procedure	226
9.4	Mass dependence of couplings	228
9.5	Additional Electroweak Singlet	231
9.6	Minimal Composite Higgs Model	233
9.7	Two Higgs Doublet Model	236
9.8	Minimal Supersymmetric Standard Model	239
9.9	Higgs Portal to Dark Matter	246
9.10	Conclusions	251
O	Outlook	253
B	Bibliography	255
S	Summary	281
S	Samenvatting	287
A	Acknowledgements	295

I Introduction

Elementary particle physics describes and measures the properties of the smallest, most fundamental particles that make up the universe. The Standard Model of elementary particle physics (SM) provides a fundamental description of particles, their dynamics and interactions. Gravity is not included in the Standard Model. The particles embedded into the theory are, a priori, massless, while observed particles have mass. In order to explain the origin of the elementary particle masses, the Brout-Englert-Higgs mechanism is introduced. The complex Higgs field introduces a spontaneous breaking of the electroweak (EW) gauge group when it acquires a non-vanishing vacuum expectation value. The Brout-Englert-Higgs mechanism introduces the existence of one real scalar field, the Higgs boson, however it does not predict its mass. To verify that the Higgs mechanism is the origin of elementary particle masses is one of the main goals of the Large Hadron Collider (LHC) programs at CERN.

Before the start of the LHC, there was no experimental evidence of the existence of the Higgs boson, and limits on the Higgs boson mass were set by the Large Electron-Positron Collider (LEP) [1] and Tevatron [2]. The Higgs boson masses below 114 GeV and in the range of 158-175 GeV have been excluded by these experiments. The first run of the LHC (Run 1), which collected data between 2008 and 2012, discovered a new particle of a mass around 125 GeV in 2012. The particle was discovered by the ATLAS [3] and CMS [4] collaborations at the LHC. Precision measurements of the Higgs boson properties are ongoing in the second run of the LHC (Run 2), which started in 2015 after updates of the LHC detectors were performed.

The SM is not a complete theory of nature, as it does not answer several fundamental questions satisfactorily. Proposed solutions for open questions often predict modifications or extensions of the minimal scalar sector that is embedded in the SM. Models with fundamental physics beyond the SM, such as composite Higgs boson models, theories with two Higgs doublets, Supersymmetry (SUSY) and models with a dark matter candidate, make predictions

for the couplings of the observed Higgs boson with a mass around 125 GeV. This thesis gives further details on the models beyond the SM and compares these Beyond the Standard Model (BSM) theories with data coming from the detectors of the LHC.

Thesis structure and own contributions

Chapter 1 introduces the theory of the Standard Model of particle physics, including possible extensions to the Standard Model Higgs sector and models to characterise the Higgs boson.

Chapter 2 describes the LHC and the ATLAS detector as well as their performance during the first and second run of the LHC.

The event and object reconstruction with the ATLAS detector is described in chapter 3. I contributed to the optimisation of the algorithms to identify (tag) muons in Run 2, concentrating in particular on the optimisation in difficult areas of the detector, such as the area with bad coverage and the reconstruction of low energy muons. In this context I rewrote the tagger to be usable in Run 2, since a new data format is being used in the second Run of the LHC, which could not be read with the Run 1 software package.

Chapter 4 describes the statistical methods used for measurements discussed in this thesis.

Chapter 5 introduces the analytic Lagrangian morphing method. This method has been published as a note [5] by the ATLAS collaboration of CERN, and as part of the CERN's Handbook of LHC Higgs Cross Sections: 4; deciphering the nature of the Higgs sector (CERN Yellow Report 4) [6]. I developed the method and performed the needed mathematics and theory derivations for it. Together with one other person, I implemented the method in the LHC software (ROOT Class [7]). In a group of four, I generated samples needed for validation, as well as executing the validation of the method and writing the ATLAS note. I wrote the section of CERN Yellow Report 4 that describes the morphing method.

The performance of the analytic Lagrangian morphing method is discussed in chapter 6. I did the full study of the sensitivity that can be reached when looking for deviations from the SM in the Vector Boson Fusion production mechanism in the Higgs boson to $\mu\mu$ final state in the second run of the LHC, in particular in the context of Effective Field theories. I also studied the effect

of non linear correlations between the parameters of an effective field theory (EFT) and how they could affect the result of the analysis.

Chapter 7 focuses on the precision of the measurement of Higgs boson properties in the case the Higgs boson is produced through gluon-gluon Fusion (ggF) and decays to two W bosons with two associated jets. I performed the first optimisation of the cuts and the BDT. I applied the morphing and set statistical limits on the BSM parameters. In this context I wrote the statistical interpretation tool for this analysis and made it publicly available for any other hypothesis testing in the context of the Higgs properties measurements in Run 2.

Chapter 8 presents the combined measurements of the Higgs boson production and decay rates and coupling strengths with the ATLAS detector in Run 2 [8, 9] and prospects for these measurements in the future [10]. I performed all likelihood fits and produced the results and figures for the mu model, the cross-section model and the cross-section $\times$ branching ratio model for both the Run 2 and prospects studies. I also cross-checked the combined workspace and correlation scheme of the systematic parameters for the Run 2 study.

Chapter 9 presents the implications of the measured Higgs boson coupling strengths for selected scenarios with fundamental physics beyond the SM in Run 1 [11] as well as prospects for the future [12, 13]. I executed the combination of the different channels and created the correlation scheme between the systematic parameters for the Run 1 measurement. I performed the likelihood fits and produced the results and figures for the models with two Higgs boson doublets as well as for the minimal supersymmetric model for both the Run 1 measurement as well as for the prospect studies.

The final chapter concludes the thesis with an outlook to measurements that could be performed in the future.

1 Theory

1.1 The Standard Model of Particle Physics

In the second half of the twentieth century the theory model called Standard Model of particle physics was developed to describe the observed phenomena in particle physics. The goal of the Standard Model (SM) is to describe all particles in the universe including their (short-range) interactions. The last piece added to the Standard Model was the Higgs particle, which is a boson responsible for the mass of all particles.

This chapter will give an introduction to the Standard Model with emphasis on the role of the Higgs boson. This chapter also includes possible extensions to the SM Higgs sector that might be able to solve some of the shortcomings the Standard Model still faces today.

1.1.1 Symmetries of the Standard Model

Particles can be seen as excitations of their respective fields $\phi(x)$ in a Quantum Field Theory (QFT). The dynamics of particles can be described as a function of fields and their derivatives by the Lagrangian density:

$$\mathcal{L}(x) = \mathcal{L}(\phi, \partial_\mu \phi). \quad (1.1)$$

A theory is symmetric under a group if the Lagrangian describing the system is left invariant under transformations belonging to that group. The Standard Model of particle physics is built up out of internal and external symmetries. Internal symmetries are based on fields in a Lagrangian appearing symmetrically. This means that a Lagrangian that is build up out of two fields ϕ_1 and ϕ_2 has to be invariant under a mixing of the two fields with a constant α in the following way:

$$\begin{aligned} \phi_1 &\rightarrow \phi'_1 = \cos \alpha \phi_1 + \sin \alpha \phi_2 \\ \phi_2 &\rightarrow \phi'_2 = \cos \alpha \phi_1 - \sin \alpha \phi_2 \end{aligned} \quad (1.2)$$

There are two types of internal symmetries; global symmetries and local, or gauge, symmetries. For global symmetries the transformations are the same for

each point on space-time, while for local symmetries the transformations can differ between different points in space-time. Noether's theorem states that the invariance of the Lagrangian, $\partial\mathcal{L} = 0$, on a continuous global symmetry leads to conserved currents j_μ :

$$\partial_\mu j^\mu = 0. \quad (1.3)$$

Continuous local symmetries implicate the existence of gauge bosons, which appear in the Lagrangian as interactions between fields.

In QFT symmetries are described through groups. All continuous local symmetries form a Lie group, which is a continuous group where each element in a group can be expressed by an analytic function.

Quantum Electrodynamics -QED

The Dirac equation describes the dynamics of massive spin- $\frac{1}{2}$ particles - fermions:

$$(i\gamma^\mu \partial_\mu - m)\psi = 0. \quad (1.4)$$

The associated Dirac Lagrangian is defined as:

$$\mathcal{L} = i\bar{\psi}\gamma^\mu \partial_\mu \psi - m\psi\bar{\psi}, \quad (1.5)$$

where ψ is the Dirac spinor and $\bar{\psi} = \psi^\dagger \gamma^0$ is the Dirac field, with γ^μ the Dirac gamma matrices. The Dirac Lagrangian is invariant under the global phase transformation $U(1)_{EM}$. The fields and their derivatives transform as:

$$\begin{aligned} \psi &\rightarrow \psi' = e^{ig_{EM}\alpha(x)}\psi \\ \partial_\mu \psi &\rightarrow e^{ig_{EM}\alpha(x)}\partial_\mu \psi + ig_{EM}e^{ig_{EM}\alpha(x)}(\partial_\mu \alpha(x))\psi \end{aligned} \quad (1.6)$$

By introducing an additional gauge field $A_\mu = A_\mu(x)$ and replacing the derivative ∂_μ with the gauge-covariant derivative D_μ the local gauge invariance is restored. The gauge-covariant derivative is defined as:

$$D_\mu \equiv \partial_\mu + ig_{EM}A_\mu(x). \quad (1.7)$$

The local phase transformations become:

$$\begin{aligned} D_\mu &\rightarrow D_\mu' = e^{ig_{EM}\alpha(x)}D_\mu e^{-ig_{EM}\alpha(x)} \\ A_\mu &\rightarrow A_\mu' = A_\mu - \partial_\mu \alpha(x) \end{aligned} \quad (1.8)$$

The vector field A_μ is associated with the photon. The kinetic term of the photon is described by the field strength tensor $F_{\mu\nu}$ which is defined as:

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu. \quad (1.9)$$

The photon's mass term is proportional to $m_\gamma^2 A_\mu A^\mu$. The local gauge transformation of the mass term is:

$$m_\gamma^2 A_\mu A^\mu \rightarrow m_\gamma^2 (A^\mu - \partial^\mu \alpha(x))(A_\mu - \partial_\mu \alpha(x)) \neq m_\gamma^2 A_\mu A^\mu. \quad (1.10)$$

The mass term is only invariant if m_γ is zero.

In the Standard Model (SM) the equation of motion follows from a Lagrangian density which is constructed from the SM gauge group. The Standard Model is a non-abelian gauge theory (Yang-Mills Theory) [14], with the gauge group

$$SU(3)_C \times SU(2)_L \times U(1)_Y. \quad (1.11)$$

This gauge group describes the dynamics and interactions of the particles in the Standard Model. The internal symmetries of the Standard Model are the local $SU(2)_L \times U(1)_Y$ symmetry, corresponding to the electroweak (EW) interaction which combines the electromagnetic ($U(1)_Y$, hypercharge) and the weak interactions ($SU(2)_L$, isospin), and the remaining exact $SU(3)_C$ symmetry of the strong interaction which corresponds to the symmetry of the three colours (red, green and blue) of the six quarks in the Standard Model. In figure 1.1 the fermions are categorised according to their behaviour under these symmetries.

Transformations of spacetime cause the external symmetries of the Standard Model. The Standard Model is invariant when charge conjugation C , parity P and time T reversal are applied simultaneously. The SM is not invariant under these three discrete symmetries separately or any subset of two of these quantities, for example CP symmetry, but only under the combined CPT symmetry. Finally the Standard Model is also invariant under Lorentz transformations, rotations, boosts and translations. These symmetries are collected in the Poincaré symmetry group. The requirement of invariance under the Poincaré transformations implies that the Lagrangian must transform as tensors. This causes the Lagrangian to be scalar, with scalar, spinor and vector fields that are determined by the corresponding particles.

Gravity is missing from the gauge group and is covered instead by General Relativity (GR) [15]. Gravitation in GR deforms space-time, which is not analogous to the boson formalism. String theory introduces a spin 2 particle, called a graviton, to create a boson formalism for gravity [16]. Due to the relative strength of gravitation, it can safely be neglected when studying the other fundamental forces.

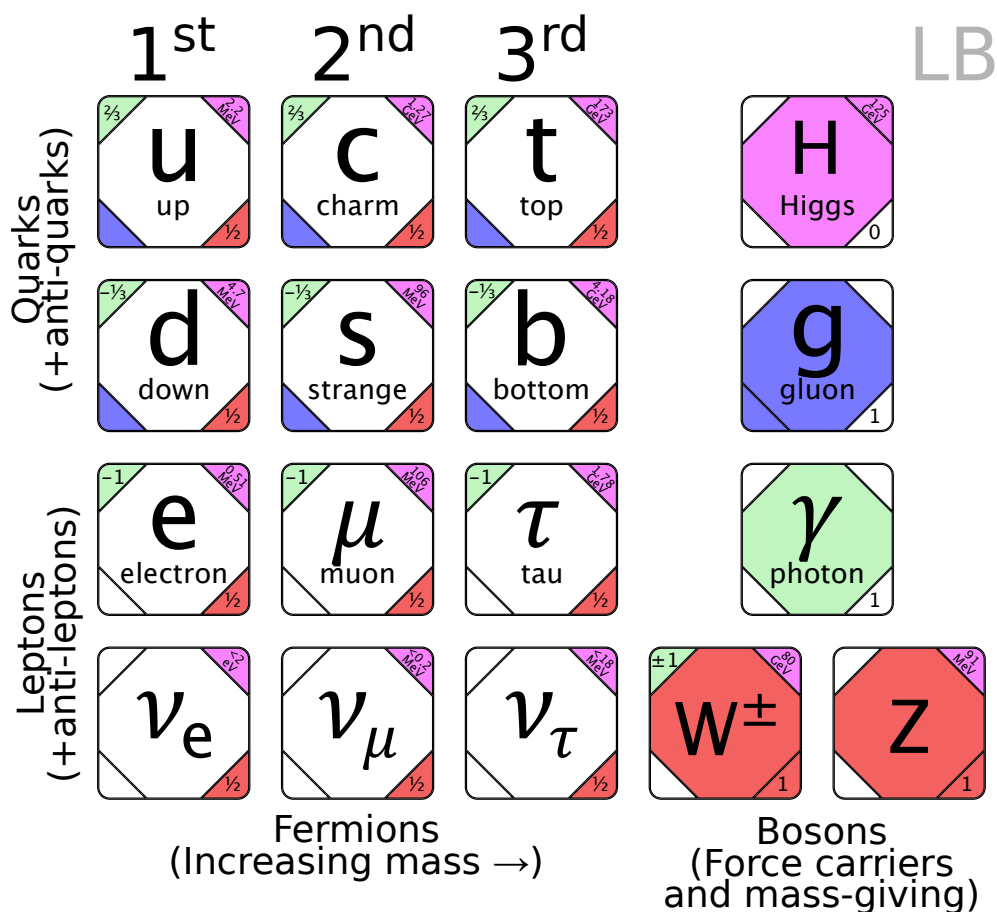


Figure 1.1: The particles in the Standard Model organised by spin and mass. Colours of the corners indicate couplings to corresponding force carrying particles. The number in the top right corresponds to the mass of the particle, the number in the top left corresponds to the charge of the particle, and the number on the bottom right corresponds to the spin of the particle.

1.1.2 Electroweak Lagrangian

The local $SU(2)_L \times U(1)_Y$ symmetry corresponds to the gauge invariance of the Lagrangian density that describes the electroweak interaction. [17, 18, 19]

Before the Lagrangian can be constructed, the preserved quantities of the electroweak interactions should be determined. The quantity associated with the weak interaction $SU(2)_L$ is the weak isospin. The third component of the weak isospin I_3 is conserved under weak interaction. The electroweak (EW) Lagrangian introduces the W -bosons which are the mediators of the weak force. These gauge bosons couple differently to left handed particles than to right handed particles due to the chirality of the particles. The only non-trivial transformation under the weak isospin $SU(2)_L$ are the transformations on the fermions left-handed chirality eigenstates ψ_L , which can be obtained by the projection operators P_L and P_R for left and right handed projections respectively:

$$\begin{aligned}\psi_L &= P_L \psi = \frac{1}{2}(1 - \gamma^5)\psi, \\ \psi_R &= P_R \psi = \frac{1}{2}(1 + \gamma^5)\psi.\end{aligned}\tag{1.12}$$

The difference in couplings to right-handed fermions, $I_3 = 0$, and left-handed fermion, $I_3 = \pm \frac{1}{2}$, fields cause the right-handed fermions fields to appear as singlets while the left-handed fermions appear as doublets. When describing fermions in the electroweak theory there is a difference between the mass eigenstates and the eigenstates of the weak isospin of the quarks. The unitary Cabibbo-Kobayashi-Maskawa (CKM) matrix can be used to obtain the weak isospin eigenstates. The CKM matrix is applied on the down-type component of the quark doublets, d , s and b , as:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{cd} & V_{td} \\ V_{us} & V_{cs} & V_{ts} \\ V_{ub} & V_{cb} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}\tag{1.13}$$

The mixing between the first two generation is large in comparison with the mixing with the third generation.

The quantity associated with the hypercharge $U(1)_Y$ symmetry is the weak hypercharge Y_W , which is a combination of the weak isospin and the electric charge Q :

$$Y_W = 2(Q - I_3)\tag{1.14}$$

The quarks and leptons including their quantum numbers are written as their doublets or singlets respectively in table 1.1. The quantum numbers between the three generations are the same, which in increasing masses of the particles.

	particles	particle type	Q	I_3	Y_W
Q_L	$((\begin{smallmatrix} u_L \\ d_L \end{smallmatrix}), (\begin{smallmatrix} c_L \\ s_L \end{smallmatrix}), (\begin{smallmatrix} t_L \\ b_L \end{smallmatrix}))$	left-handed quarks	$\frac{2}{3}$ or $-\frac{1}{3}$	$\frac{1}{2}$ or $-\frac{1}{2}$	$\frac{1}{3}$
u_R	(u_R, c_R, t_R)	right-handed up-type quarks	$\frac{2}{3}$	0	$\frac{4}{3}$
d_R	(d_R, s_R, b_R)	right-handed down-type quarks	$-\frac{1}{3}$	0	$-\frac{1}{3}$
L_L	$((\begin{smallmatrix} \nu_e L \\ e_L \end{smallmatrix}), (\begin{smallmatrix} \nu_\mu L \\ \mu_L \end{smallmatrix}), (\begin{smallmatrix} \nu_\tau L \\ \tau_L \end{smallmatrix}))$	left-handed leptons	0 or -1	$\frac{1}{2}$ or $-\frac{1}{2}$	-1
l_R	(e_R, μ_R, τ_R)	right-handed leptons	-1	0	-2

Table 1.1: Quantum numbers of fermions.

The preserved quantities of the electroweak (EW) interactions can now be used to construct the Lagrangian itself. The EW Lagrangian must be gauge-invariant under $SU(2)_L \times U(1)_Y$ and can be constructed from combining the gauge (G), fermion (F) and Higgs (H) Lagrangians in an additive matter:

$$\mathcal{L}_{EW} = \mathcal{L}_G + \mathcal{L}_F + \mathcal{L}_H \quad (1.15)$$

The Fermionic part has to include both the left-handed iso-doublets ψ_L and right-handed weak iso-singlet ψ_R :

$$\mathcal{L}_F = \sum_{\psi_L} \bar{\psi}_L i \not{D} \psi_L + \sum_{\psi_R} \bar{\psi}_R i \not{D} \psi_R. \quad (1.16)$$

A right-handed chiral fermion does not couple to isospin and is governed by the weak hypercharge Y_W which has been defined above. Its covariant derivative can be written in terms of the gauge-fields that couple to the weak isospin $\vec{W}_\mu = (W_\mu^1, W_\mu^2, W_\mu^3)$ and the weak hypercharge B_μ , in the form:

$$D_\mu \psi_R = (\partial_\mu + i \frac{g_1}{2} Y_W B_\mu) \psi_R. \quad (1.17)$$

This derivative is used to define the $U(1)$ coupling g_1 . The corresponding derivative of the left-handed chiral fermion is of the form:

$$D_\mu \psi_L = (\mathbf{I}(\partial_\mu + i \frac{g_1}{2} Y_W B_\mu) + i g_2 \frac{\vec{\tau}}{2} \vec{W}_\mu) \psi_L. \quad (1.18)$$

This derivative in turn defines the $SU(2)$ coupling g_2 and the 2×2 matrices $\mathbf{I}$ and $\vec{\tau}$.

For the gauge part of the Lagrangian we look at the pure contributions of the gauge-field couplings to the weak isospin and weak hypercharge. These fields contribute as

$$\mathcal{L}_G = -\frac{1}{4} F_i^{\mu\nu} F_{\mu\nu}^i - \frac{1}{4} B^{\mu\nu} B_{\mu\nu}. \quad (1.19)$$

Where $F_{\mu\nu}^i$ with $i = 1, 2, 3$ is the $SU(2)$ field strength and $B_{\mu\nu}$ the $U(1)$ field strength, which are defined as

$$\begin{aligned} F_{\mu\nu}^i &= \partial_\mu W_\nu^i - \partial_\nu W_\mu^i - g_2 \epsilon^{ijk} W_\mu^j W_\nu^k \\ B_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu. \end{aligned} \quad (1.20)$$

The four gauge-bosons entering into the Lagrangian here are massless. Adding a mass term for the gauge-bosons to the Lagrangian would break the gauge invariance and is therefore not a solution. In the next sections the solution to this problem including the Higgs Lagrangian are introduced.

1.1.3 Spontaneous Symmetry Breaking and The Brout-Englert-Higgs Mechanism

A solution to introduce mass for gauge bosons, while retaining gauge invariance, is to spontaneously break the electroweak symmetry through the Brout-Englert-Higgs mechanism [20, 21, 22, 23, 24, 25]. Brout and Englert formulated this mechanism in parallel to Higgs, however Higgs description included the postulation of a new boson. To this end a complex doublet is introduced of spin-zero Higgs fields with positive and zero electric charge. Each of these fields carry one unit of weak hypercharge.

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad (1.21)$$

The Higgs Lagrangian $\mathcal{L}_H$ is the sum of the Higgs-fermion couplings $\mathcal{L}_{HF}$ and the Higgs-gauge couplings $\mathcal{L}_{HG}$. The Higgs-gauge couplings can be written as:

$$\mathcal{L}_{HG} = (D^\mu \Phi)^* D_\mu \Phi - V(\Phi), \quad (1.22)$$

where

$$D_\mu \Phi = (\mathbf{I}(\partial_\mu + i\frac{g_1}{2}Y_W B_\mu) + ig_2 \frac{\vec{\tau}}{2} \vec{W}_\mu) \Phi \quad (1.23)$$

and V is the self interaction

$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \quad \text{with } \mu^2, \lambda > 0. \quad (1.24)$$

For the fermionic part of the Lagrangian the notation for the quarks and leptons from table 1.1 is used. The Higgs-fermion couplings can be written as:

$$\mathcal{L}_{HF} = \sum_{u\text{-type}} -g_u \bar{Q}_L \tilde{\Phi} u_R + \sum_{d\text{-type}} -g_d \bar{Q}_L \Phi d_R + \sum_{l\text{-type}} -g_\nu \bar{L}_L \tilde{\Phi} \nu_{l,R} - g_l \bar{L}_L \Phi l_R, \quad (1.25)$$

where the couplings constants g are arbitrary and

$$\tilde{\Phi} = i\tau_2 \Phi^* = (\phi^{0*}, -\phi^-)^T. \quad (1.26)$$

The Higgs-fermion Lagrangian is also referred to as the Yukawa Lagrangian and is written in the $SU(2)_L \times U(1)_Y$ invariant form. After electroweak symmetry breaking, the interaction $\tilde{\Phi}$ will look like a mass term.

The $\mathcal{L}_{HF}$ as well as the Higgs potential V do not contain a gauge field, however there is no principle that forbids such contributions and phenomenologically these terms are required. Without the Higgs potential V , electroweak symmetry breaking on the W gauge field would not result in a massive W . When we minimise the Higgs self-interaction potential V

$$\partial V(\Phi) = \partial(-\mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2) = 0, \quad (1.27)$$

the ground states of the Higgs are obtained. Solving this equation has two solutions, the trivial solution $\langle \Phi \rangle_0 = 0$ and the nontrivial solution

$$\langle \Phi^\dagger \Phi \rangle_0 = \frac{v^2}{2} \quad \text{with } v \equiv \sqrt{\frac{\mu^2}{\lambda}}, \quad (1.28)$$

where v corresponds to the vacuum expectation value of the ground state of Φ .

The masses of the fermions and gauge-bosons are determined by plugging the ground state solution of the Higgs into the Higgs Lagrangian $\mathcal{L}_H$. After this substitution, the mass contribution of the Lagrangian becomes:

$$\begin{aligned} \mathcal{L}_{mass} = & -\frac{v}{\sqrt{2}} \left(\sum_{u\text{-type}} g_{\bar{u}u} + \sum_{d\text{-type}} g_{\bar{d}d} + \sum_{l\text{-type}} g_{\bar{l}l} \right) + \left(\frac{vg_2}{2} \right)^2 W_\mu^+ W_-^\mu \\ & + \frac{v^2}{8} (W_\mu^3 \ B_\mu) \begin{pmatrix} g_2^2 & -g_1 g_2 \\ -g_1 g_2 & g_1^2 \end{pmatrix} \begin{pmatrix} W_3^\mu \\ B^\mu \end{pmatrix}. \end{aligned} \quad (1.29)$$

Using the fact that the mass appears in the Lagrangian as $m^2 \bar{\phi} \phi$, the masses of the fermions can be read from the mass contribution of the Lagrangian directly. This gives:

$$m_{l,u,d} = \frac{v}{\sqrt{2}} g_{l,u,d}. \quad (1.30)$$

The neutral gauge bosons, unlike the fermions, undergo mixing under symmetry breaking, since their mass matrix is not diagonal in the basis of W^3 and B states. The W boson appears separately in the mass Lagrangian and is therefore the only boson mass that can be read directly from the Lagrangian, in the same way as for the fermions.

$$M_W = \frac{v}{2} g_2. \quad (1.31)$$

The basis that corresponds to a diagonal mass matrix is:

$$\begin{aligned} Z_\mu &= \cos \theta_W W_\mu^3 - \sin \theta_W B_\mu, \\ A_\mu &= \sin \theta_W W_\mu^3 + \cos \theta_W B_\mu, \end{aligned} \quad (1.32)$$

where the mixing angle, or Weinberg angle, θ_W is defined by [19]

$$\tan \theta_W = \frac{g_1}{g_2}. \quad (1.33)$$

In this basis Z_μ corresponds to the Z^0 -boson and A_μ corresponds to the photon. From this the neutral gauge-boson masses are found

$$M_\gamma = 0 \quad \text{and} \quad M_Z = \frac{v}{2} \sqrt{g_1^2 + g_2^2}. \quad (1.34)$$

The ratio of the $W^\pm$ and Z^0 masses is now fixed by:

$$\frac{M_W}{M_Z} = \cos \theta_W. \quad (1.35)$$

1.1.4 Perturbative Quantum Chromodynamics and Renormalisation

In the beginning of this chapter, the standard model was introduced as a non-abelian gauge theory with the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$ after which the electroweak interaction was described. The last part of the SM gauge theory is the strong force. This force is described by quantum chromodynamics (QCD) though the gauge group $SU(3)_C$. The conserved quantum number of this gauge group is the colour, which is a property of quark and gluon fields. Although colour charge is a property of the gauge field, it is not a trivial consequence of the non-Abelian nature of $SU(3)_C$ [26].

A quark field of flavour f and colour k transforms as a triplet under a global $SU(3)_C$ transformation as

$$q_k^f \rightarrow q_k'^f \equiv U_k^i q_i^f \quad (1.36)$$

with

$$U = \exp(iT^a \theta_a) \quad \text{with} \quad T^a = \frac{\lambda^a}{2}. \quad (1.37)$$

In this transformation λ^a are the Gell-Mann matrices [27] which obey the commutation relation

$$[\lambda_a, \lambda_b] = 2if_{abc}\lambda_c. \quad (1.38)$$

The gauge invariant QCD Lagrangian can be written, when neglecting non-perturbative QCD effects and CP-symmetry breaking, as

$$\mathcal{L}_{QCD} = -\frac{1}{4}G_a^{\mu\nu}G_{\mu\nu}^a + \bar{q}_j^f(i\not{D}_{jk} - m_q^f\delta_{jk})q_k^f \quad \text{with} \quad D_\mu q^f = (\delta_\mu + ig_s G_\mu^a T^a)q^f, \quad (1.39)$$

where g_s is the strong coupling constant and the field strength tensor of the gluon fields can be written as

$$G_{\mu\nu}^a = \delta_\mu G_\nu^a - \delta_\nu G_\mu^a - g_s f^{abc} G_\mu^b G_\nu^c. \quad (1.40)$$

Cross sections of physics processes can be calculated using Feynman diagrams [28]. The dominant contribution comes from a direct vertex, however loop corrections to QCD, such as depicted in figure 1.2, have to be taken into account. The largest contributions come from loops of gluons or quarks due to the relatively high strength of the strong force compared to the electroweak force. The contribution from an additional loop is dependent on the energy of the particle in the loop, which creates issues in the perturbation theory. This problem is solved by replacing the coupling constant by a energy dependent coupling constant.

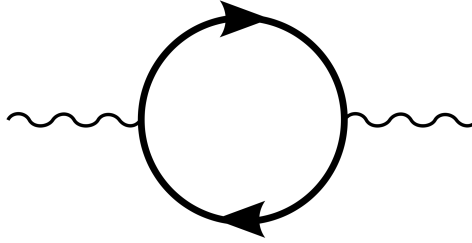


Figure 1.2: Example of a loop correction to a vertex in a Feynman diagram.

When taking higher order calculations into account, the calculation of the cross section diverges due to quantum loop corrections to the Green functions [29]. Parametrisation gives rise to singularities that need to be cancelled. The divergence can be removed by renormalisation which corresponds to subtracting the poles [30, 31] or because they do not appear in a physical observable.

One of the renormalised parameters is the strong coupling constant. After renormalisation the strong coupling constant g_s becomes a running coupling constant

$$\alpha_s \equiv \frac{g_s^2}{4\pi}, \quad (1.41)$$

which depends on the energy scale

$$Q \equiv \frac{\mu_R}{\lambda_{QCD}}. \quad (1.42)$$

This running coupling strength can be described up to leading order corrections by

$$\alpha_s(Q^2) = \frac{12\pi}{(11n_c - 2n_f) \ln Q^2}, \quad (1.43)$$

where n_c and n_f are the number of colour and quark flavours respectively. Due to asymptotic freedom, the coupling strength vanishes for increased energies. However, at low energies (soft QCD) the coupling diverges, which causes the quarks and gluons to form hadronic colour singlets, which is referred to as colour confinement. The main consequence of the absence of perturbation theory is that empirical calculations are needed to describe parton shower models.

1.1.5 Factorisation and Parton Distribution Functions

Hadronic interactions

Experiments such as the LHC collide protons, rather than free quarks. When colliding protons, each particle inside the proton, quarks and gluons, carries a fraction of the the proton's total momentum. The momentum of each parton, when assuming that the partons move collinear with the surrounding proton, can be written as: $\mathbf{p}_i = x_i \mathbf{p}_h$, where x_i lies between 0 and 1 and $\mathbf{p}_h$ is the momentum of the hadron.

The confinement scale Λ_{QCD} was introduced in the previous section to characterise the soft structure of a hadron. At the confinement scale the strong coupling constant in perturbative QCD would diverge, which is also referred to as the Landau pole. However perturbative QCD can be used to computer hard-scattering proceses, which take place at high energies, above the QCD scale.

The cross section of a general hadron-hadron process, $h_1 h_2 \rightarrow f$, is expressed as the convolution of a non-perturbative, but universal, parton distribution function (PDF) $f_{i/h}(x_i, Q^2)$, by using the factorisation theorem [32]. The PDF describes the probability for finding a parton i with longitudinal momentum fraction x_i , in a hadron h at energy scale Q with partonic cross section of the hard-scatter process, $\hat{\sigma}_{ij \rightarrow f}$. The cross section of the hadron-hadron process is calculated perturbatively:

$$\sigma_{h_1 h_2 \rightarrow f} = \sum_{i,j} \int dx_1 dx_2 f_{i/h_1}(x_1, \mu_F^2) f_{j/h_2}(x_2, \mu_F^2) \hat{\sigma}_{ij \rightarrow f}, \quad (1.44)$$

where μ_F is the factorisation scale that arises from infrared regularisation of the integral over the Lorentz-invariant phase space, Φ_f , which is accessible through the possible partonic final states f . The factorisation scale μ_F therefore separates the hard and soft processes.

Parton Distribution Functions

At an arbitrary scale μ_0 in well understood processes, such as deep inelastic scattering (DIS) [33, 34], Drell-Yann (DY) [35] and $pp \rightarrow jets$ [36], the PDFs, which are not calculable in QCD, can be measured. Due to their universality these PDFs can be extrapolated to other scales as a function of the factorisation scale μ_F . The Renormalisation Group Equation (RGE) evolution is given by the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) equations [37, 38, 39], which is a set of differential equations,

$$\mu_F^2 \frac{df_{i/h}(x_i, \mu_F^2)}{d\mu_F^2} = \frac{\alpha_s(\mu_F^2)}{2\pi} \sum_j \int_{x_i}^1 \frac{dx_j}{x_j} P_{i \leftarrow j} \left(\frac{x_i}{x_j} \right) f_{j/h}(x_j, \mu_F^2), \quad (1.45)$$

where $P_{i \leftarrow j}$ describes the splitting of parton j into parton i in the collinear limit.

1.2 The Standard Model Higgs Boson Phenomenology in pp collisions

One of the free parameters in the Standard Model is the mass of the Higgs boson. At the ATLAS and CMS experiments of the Large Hadron Collider at CERN this mass is measured at approximately 125 GeV [3, 4, 40]. The mass of the Higgs boson determines its coupling strength to other particles of the Standard Model.

1.2.1 Production Modes

The main production mechanisms for the Higgs boson are described below, the most dominant first. The quoted cross-sections in this section are obtained for a theory with a Higgs boson mass of 125 GeV [41, 6]. The production cross-sections are dependent of the centre-of-mass energy of the collision and the mass of the Higgs as depicted in figure 1.3.

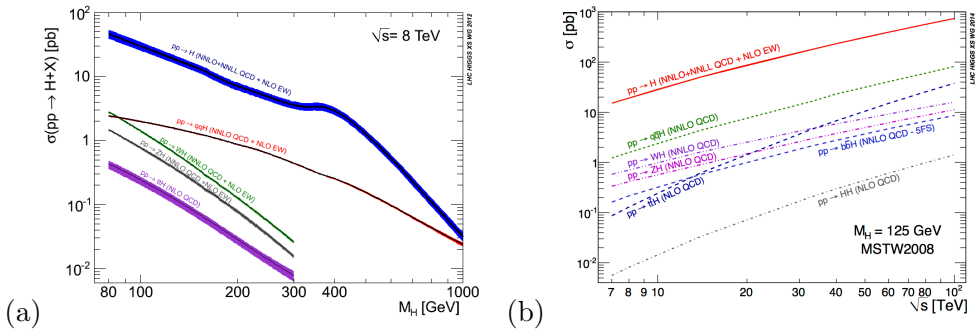


Figure 1.3: Higgs boson production cross section in proton-proton collisions as a function of (a) the Higgs mass assuming a centre-of-mass energy of 8 TeV and (b) as a function of the centre-of-mass energy assuming a Higgs mass of 125 GeV.

Gluon Fusion

The dominant production mode is gluon-gluon fusion (ggF), where the Higgs boson is produced through a quark loop. At high Q (LHC) gluons dominate the Parton Density Function (PDF), which drives the cross section. The ggF coupling is mediated by a virtual heavy quark loop. The most common heavy quark in the loop is a top quark, due to its high mass which causes the coupling to the Higgs to be large. The sub-leading correction comes from the b-quark, since it has the second highest mass. Measuring the ggF coupling

strength directly probes the Higgs couplings to heavy quarks. The Feynman diagram for this process is shown in figure 1.4. The production cross section of the ggF process is 19.3 pb for $\sqrt{s} = 8$ TeV and 48.6 pb for $\sqrt{s} = 13$ TeV [41]. The cross-sections are calculated at next-to-next-to-next-to leading order (N3LO) and next-to-next-to leading order + next-to-next-to leading logarithm (NNLO+NNLL) QCD and next-to leading order (NLO) EW accuracies. The theory uncertainty on the total cross section is 10% for $\sqrt{s} = 8$ TeV and 4% for $\sqrt{s} = 13$ TeV.

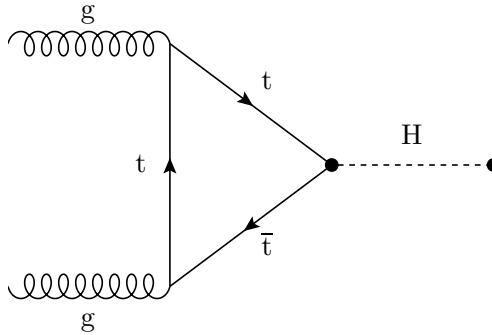


Figure 1.4: Leading order Feynman diagrams for Higgs production through gluon-gluon fusion.

Vector-Boson Fusion

The second largest production mode is vector boson fusion (VBF). This production mode probes the Higgs coupling to vector bosons. The VBF production is suppressed with respect to the ggF production, since this production is quark initiated and especially the $\bar{q}$ rate is low in practice. The leading order diagram for this process is shown in figure 1.5. The VBF process cross section is 1.58 pb for $\sqrt{s} = 8$ TeV and 3.78 pb for $\sqrt{s} = 13$ TeV. The cross-sections are calculated at NNLO QCD and NLO EW accuracies [41, 6]. The VBF process has a clean and distinctive signature in the detector due to the presence of two jets.

Associated Production with a Vector Boson

The associated production, or Higgs-strahlung, (VH) of a Higgs boson with a weak gauge boson can be produced with either a W boson or Z boson. This production mode, just as VBF, probes the Higgs coupling to vector bosons. The VH production is for the same reason suppressed with respect to the ggF production. The leading order diagram for this process is shown in figure 1.6. The VH process cross section is 0.70 pb for WH at $\sqrt{s} = 8$ TeV, 0.41 pb for

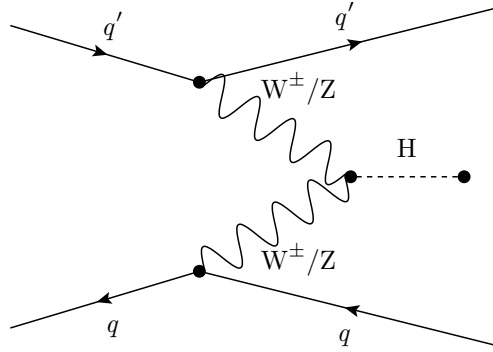


Figure 1.5: Leading order Feynman diagrams for Higgs production through vector boson fusion.

ZH at $\sqrt{s} = 8$ TeV, 1.37 pb for WH for $\sqrt{s} = 13$ TeV and 0.88 pb for ZH for $\sqrt{s} = 13$ TeV. The cross-sections are calculated at NNLO QCD and NLO EW accuracies.

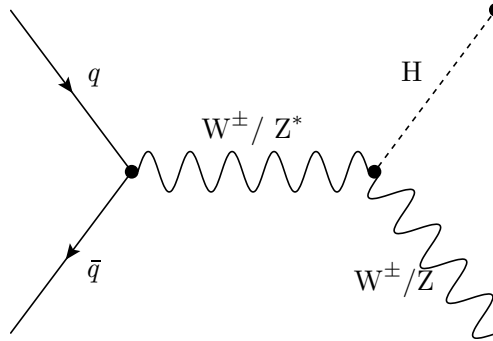


Figure 1.6: Leading order Feynman diagrams for Higgs production through associated production with a vector boson.

Production in Association with a Top Pair

Direct production in association with a top pair (ttH) is an important channel for direct measuring the couplings of the Higgs boson to top quarks. The Feynman diagram for this process is shown in figure 1.7. The ttH process cross section is 0.13 pb for $\sqrt{s} = 8$ TeV and 0.51 pb for $\sqrt{s} = 13$ TeV. The cross sections are calculated at NLO QCD and EW accuracies.

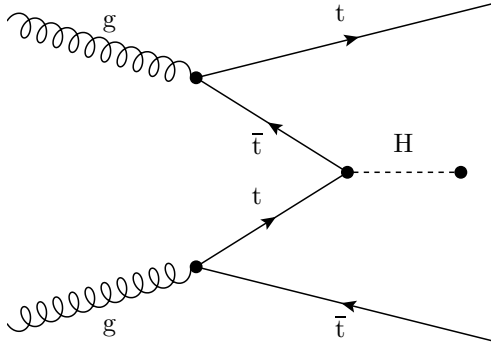


Figure 1.7: Leading order Feynman diagrams for Higgs production through production in association with a top pair.

1.2.2 Decay Modes

The mass of the Higgs boson fixes the branching ratio's (BRs) of the Higgs boson into massive particles, which are defined as

$$BR(H \rightarrow X_1) = \frac{\Gamma(H \rightarrow X_1)}{\sum_i \Gamma(H \rightarrow X_i)}, \quad (1.46)$$

where Γ is the partial width of the process and X_i are the particles the Higgs boson can decay into. The partial width is proportional to the couplings between the Higgs and its decay products squared, which in turn is proportional to the mass of the particles the Higgs boson decays into as well as the m_H through both the coupling g and kinematics effects at Leading Order. The partial width Γ is defined by theory, while the Branching Ratio's are an observed quantity. Figure 1.8 shows the BRs of the decay processes discussed in this thesis for different values of the SM Higgs boson mass.

Figure 1.8 shows that the Higgs boson mass around 125 GeV is ideal for measuring properties. If the Higgs boson had been above 160 GeV, it would have been easier to find, but there would have been little to measure in terms of couplings and the use of advanced methods such as effective field theories would have been pointless.

All Higgs boson decays discussed in this thesis are shown in figure 1.9

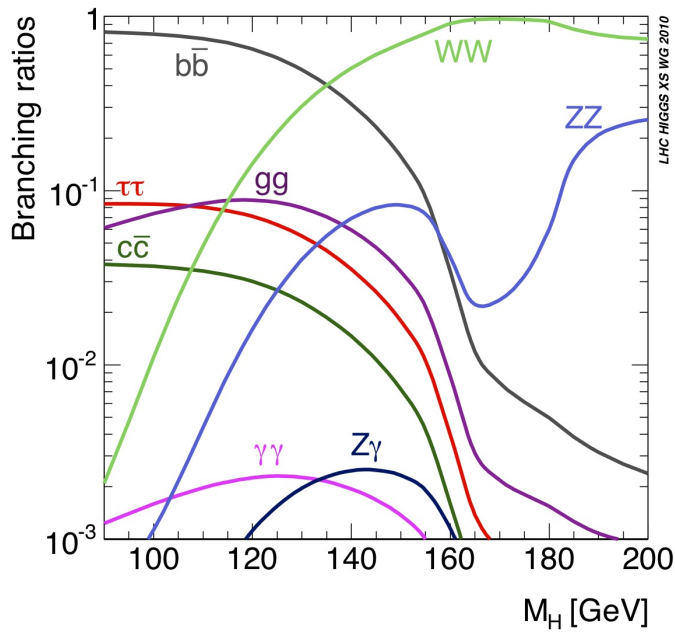


Figure 1.8: Branching ratio of the Higgs decays for different values of the Standard Model Higgs mass.

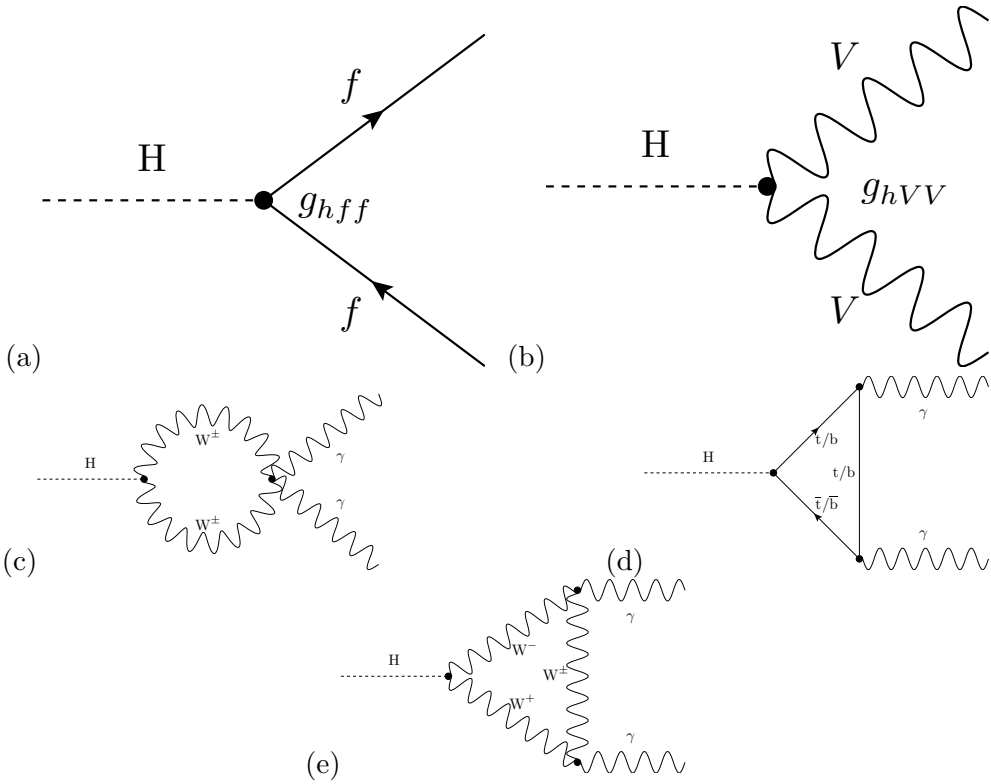


Figure 1.9: Feynman diagrams for Higgs decays to fermions (a), vector bosons (b) and photons (c, d and e)

1.3 Extensions to the Standard Model Higgs Sector

The Standard Model including the Higgs boson as described in the previous sections is a self-consistent theory, however it is incomplete. One of the missing pieces is **dark matter**: we know that it has to exist but we have no direct measurements of the particles that it consists of.

Another open point of the SM is the so called **naturalness problem**. A theory is considered natural when dimensionless ratios between free parameters of the theory are of the order of one. The standard model requires extensive fine-tuning with respect to naturalness, while also predicting properties that match those observed. Furthermore, due to the large energy gap between the EW scale and the scale of new physics, if it appears at the Planck scale (10^{19} GeV), is called the **hierarchy problem**. The hierarchy problem would not appear if the SM would be a complete description of nature.

A **grand unified theory (GUT)** predicts the unification of the three gauge interactions of the standard model. This theory would merge the electromagnetic, weak and strong interactions into one single force characterised by one larger gauge symmetry with one unified coupling constant. Any new particles predicted by a grand unified theory are expected to have masses well beyond the reach of any particle collider experiment and can therefore be only measured indirectly. The unification of the three gauge interactions of the Standard Model, which crates electroweak unification, is also the first step towards a combined theory that unites the Standard Model with gravity.

Observations show that the universe is dominated by matter, rather than have equal amount of matter and anti-matter which would be a natural assumption. Although the Standard Model contains CP-violating processes that can account for part of the matter-antimatter asymmetry, these are not strong enough to explain the observed asymmetry [42].

The substructure of particles is known as **compositeness**. Composite theories say that all particles described by the standard model are made up of even smaller units. [43]

Extensions to the Higgs boson sector play an important role in possible extensions of the symmetry group of the Standard Model. Extending the Higgs boson sector can be achieved by modifying the properties of the SM Higgs boson, with a mass of approximately 125 GeV, or adding more Higgs bosons. A selection of extended Higgs boson sector theories are discussed in this thesis.

1.3.1 Additional Electroweak Singlet

The simplest expansion to the SM Higgs boson sector is the addition of a heavy, real, electroweak singlet (EWS). Adding an additional electroweak singlet to the Higgs sector gives a solution for the naturalness problem and the strong CP problem. It is important to note that the EWS model is a composite model, which means that the Higgs boson is a bound state of new strong interactions and is not an elementary particle (or point-like) but has finite size, typically around 10^{-18} meters. This dimension is related to the Fermi scale (100 GeV) that determines the strength of the weak interactions. Microscopically the composite Higgs will be made of smaller constituents in the same way as nuclei are made protons and neutrons.

An additional electroweak singlet can be achieved by adding extra kinetic terms for the new scalar field X

$$\mathcal{L}_{scalar} = (D_\mu \Phi)^\dagger (D_\mu \Phi) + (D_\mu X)(D_\mu X) - V(\Phi, X), \quad (1.47)$$

with scalar potential

$$V(\Phi, X) = -\mu_1^2 \Phi^\dagger \Phi - \mu_2^2 X^2 + \lambda_1 (\Phi^\dagger \Phi)^2 + \lambda_2 X^4 + \lambda_3 \Phi^\dagger \Phi X^2. \quad (1.48)$$

The Potential is bound from below and the quartic couplings satisfy

$$\lambda_1, \lambda_2 > 0 \text{ and } \lambda_3 > -2\lambda_1 \lambda_2. \quad (1.49)$$

Spontaneous symmetry breaking calculations are done analogous to the SM, after which there are two CP-even Higgs bosons parametrised by the mixing angle α . The lighter Higgs, h , has the Standard Model (SM) decay modes with signal strengths μ . All Higgs couplings for the lighter Higgs, h , with is assumed to be the discovered Higgs boson with a mass of approximately 125 GeV, are uniformly suppressed by a factor κ , which is a coupling strength modifier.

$$\mu_h = \frac{\sigma_h \times BR_h}{(\sigma_h \times BR_h)_{SM}} = \kappa^2. \quad (1.50)$$

The heavier Higgs, H , has new non-SM decay modes such as $H \rightarrow hh$. Since the heavier Higgs, H , has non-SM decay modes, the signal strengths is not just suppressed by a factor κ' , but also needs to be parametrised by $BR_{H,new}$:

$$\mu_H = \frac{\sigma_H \times BR_H}{(\sigma_H \times BR_H)_{SM}} = \kappa'^2 (1 - BR_{H,new}). \quad (1.51)$$

Couplings of h and H together are proportional to SM couplings, but the couplings are reduced by the factors κ and κ' respectively, implying $\kappa^2 + \kappa'^2 = 1$. Indirect constraint on heavy Higgs boson coupling can be measured from the signal strength of the light Higgs boson using the relation $\kappa'^2 = 1 - \mu_h$.

1.3.2 Minimal Composite Higgs Model

The hierarchy problem can be sidestepped if the Higgs boson is not a fundamental particle, but a low energies manifestation of a theory at intermediate energy scale f . In such a theory the Higgs boson is a non-fundamental composite particle and is the realisation of a pseudo Nambu-Goldstone boson of a theory in which the EW symmetry is both spontaneously and directly broken. Higgs as a composite, pseudo Nambu-Goldstone boson also provides a solution for dark matter. In the Minimal Composite Higgs Models (MCHM), modifications to tree-level couplings are applied as a function of the compositeness scale f . These models are characterised by $\xi = v^2/f^2$ where f is the Higgs compositeness scale. There are several choices that can be made within this framework among which the spinorial representation of $SO(5)$. The version of MCHM that contains two complex doublets which transform under $SU(2)_L$ and $SU(2)_R$ is called MCHM4 [44]. The version of MCHM which gives a fundamental representation of $SO(5)$ is called MCHM5 [45].

These two models are used in the remainder of the thesis. For both models the coupling to vector bosons is adjusted with a coupling strength modifier:

$$\kappa_V = \sqrt{1 - \xi}, \quad (1.52)$$

while the fermion coupling is adjusted as

$$\begin{aligned} \kappa_F &= \sqrt{1 - \xi} \text{ for MCHM4} \\ \kappa_F &= \frac{1 - 2\xi}{\sqrt{1 - \xi}} \text{ for MCHM5.} \end{aligned} \quad (1.53)$$

For both models, the SM is found for $\xi \rightarrow 0$ which corresponds to $f \rightarrow \infty$. A graphical representation of the two models is shown in figure 1.10.

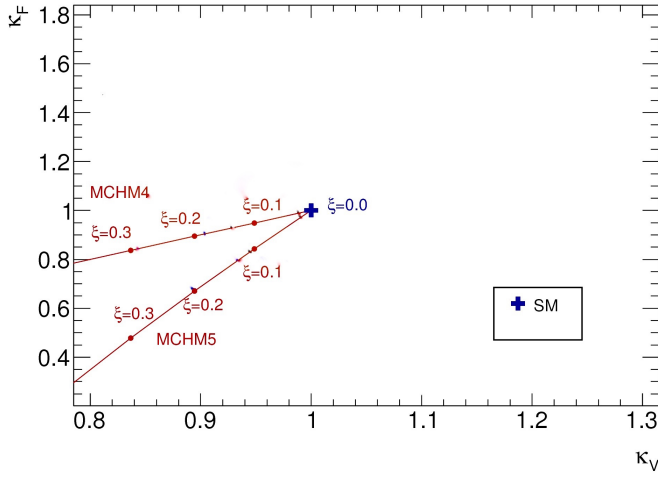


Figure 1.10: The SM as well as MCHM4 and MCHM5 for different values of ξ with respect to the coupling of the Higgs to fermions, on the y-axis, and vector bosons, on the x-axis.

1.3.3 Two Higgs Doublet Model

Instead of adding an additional electroweak singlet, the Two Higgs Doublet Model (THDM) adds an additional electroweak doublet to the standard model Higgs sector. Just as for the addition electroweak singlet model, the THDM model gives a solution for the naturalness problem and the strong CP problem. The most general gauge invariant scalar Higgs potential, under the Paschos-Glashow-Weinberg condition [46, 47], formed by the doublets Φ_1 and Φ_2 is given by:

$$V(\Phi_1, \Phi_2) = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - [m_{12}^2 \Phi_1^\dagger \Phi_2 + h.c.] + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\ + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) + [\frac{1}{2} (\Phi_1^\dagger \Phi_2)^2 + h.c.], \quad (1.54)$$

with all parameters real and containing eight scalar fields:

$$\Phi_a(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_a^+(x) \\ \nu_a + \eta_a + i\chi_a(x) \end{pmatrix} \text{ with } \langle \Phi_a \rangle_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu_a \end{pmatrix}, \text{ and } a = 1, 2. \quad (1.55)$$

These eight degrees of freedom contain three massless Goldstone bosons, which become the longitudinal polarisations of the $W^\pm$ and Z bosons when acquiring mass. This leaves five Higgs bosons: two CP-even bosons h and H , one neutral CP-odd boson A , two charged bosons $H^\pm$. In these theories the discovered Higgs particle is the light CP-even neutral Higgs boson h . The models are described by six parameters: the four masses, the ratio of the vacuum expectation values ($\tan \beta = \frac{v_1}{v_2}$), and the mixing angle α of the two neutral, CP-even Higgs states. Gauge invariance fixes the couplings of the two neutral, CP-even Higgs bosons (h and H) to vector bosons

$$\kappa_{hVV} = \frac{g_{hVV}^{THDM}}{g_{hVV}^{SM}} = \sin(\beta - \alpha) \\ \kappa_{HVV} = \frac{g_{HVV}^{THDM}}{g_{HVV}^{SM}} = \cos(\beta - \alpha) \quad (1.56)$$

where $V = W, Z$ and g^{THDM} are the THDM couplings.

The Paschos-Glashow-Weinberg condition is satisfied by two discrete symmetries,

$$\Phi_1 \rightarrow -\Phi_1 \text{ and } \Phi_1 \rightarrow -\Phi_1, \vec{d}_R \rightarrow -\vec{d}_R. \quad (1.57)$$

These symmetries define two types of THDMs, Type I and Type II. Conventionally all right handed fermions transform the same way under the imposed symmetry in this models. This convention makes one doublet in the Type I model fermiophobic in the limit of no mixing. However other conventions

leading to natural flavour conservation accommodate for different couplings which leads to a lepton specific (Type III) and flipped (Type IV) THDM. This leads to, in total, four types of two Higgs doublet models.

Type I One of the Higgs doublets couples to vector bosons, while the other couples to fermions. In the limit of no mixing, the first doublet is called fermiophobic.

Type II This model corresponds to a simplified Minimal Supersymmetric Standard Model (MSSM) which will be explained in a different matter in the next subsection. For this type one Higgs doublet couples to up-type quarks and the other to down-type quarks and charged leptons.

Type III This model is also called a lepton-specific model, where the Higgs bosons have the same couplings to quarks as in the Type I model and to charged leptons as in Type II.

Type IV This model is also called the flipped model, where the Higgs bosons have the same couplings to quarks as in the Type II model and to charged leptons as in Type I.

The couplings of the light Higgs boson h to vector bosons and fermions in each of the four types of two Higgs doublet models are summarised in table 1.2. The couplings are expressed as ratios relative to the Higgs boson couplings in the SM.

Coupling	Type I	Type II	Type III	Type IV
κ_V	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

Table 1.2: Couplings of the light Higgs boson h to weak vector bosons (κ_V), up-type quarks (κ_u), down-type quarks (κ_d), and charged leptons (κ_l), expressed as ratios to the Higgs boson couplings in the SM.

1.3.4 Simplified Minimal Supersymmetric Standard Model

In supersymmetric (SUSY) models a partner is introduced for each SM particle, differing from the SM particles by spin $\frac{1}{2}$. Softly broken SUSY solves the naturalness and hierarchy problems by canceling divergent loop contributions of the heavy SM particles to the Higgs boson mass, against those of corresponding SUSY partners. Enforcing lepton and baryon number conservation through introducing a discrete symmetry, R-parity, in the Minimal Supersymmetric Standard Model (MSSM), provides a candidate for a dark matter particle. The Higgs sector is, as with the THDM models, extended to five Higgs particles. The MSSM additionally has a strict upper bound on the mass of the lightest Higgs boson h , $m_h < m_Z$, at tree level, which is, however, broken by higher order radiative corrections. This thesis focuses on a version of supersymmetry with the additional constraint that the discovered Higgs boson is the light CP-even state h . This constrained model is called the Simplified Minimal Supersymmetric Standard Model (Simplified MSSM) [48, 49, 50, 51, 52, 53, 54].

The model is called simplified because of the assumption that the lightest Higgs has the same decay modes as the SM Higgs boson. This means that no Higgs boson decays to supersymmetric particles and the heavy Higgs bosons decay to lighter ones. Additionally, loop correction from stops, the supersymmetric partner of the top quark, in gluon fusion production and di-photon decays are neglected. Finally the universality of the down-type fermion couplings is assumed, and additionally it is hypothesised that the Higgs boson mass can be used to express the couplings in terms of the mass of the CP-odd Higgs particle, m_A and the ratio of the vacuum expectation values $\tan \beta = \frac{v_1}{v_2}$. This last assumption corresponds to $\kappa_b = \kappa_\tau = \kappa_\mu$. The mass squared mixing matrix of the neutral CP even Higgs bosons in this model is

$$\begin{aligned} \mathcal{M}_s^2 = & (m_Z^2 + \delta_1) \begin{pmatrix} \cos^2 \beta & -\cos \beta \sin \beta \\ -\cos \beta \sin \beta & \sin^2 \beta \end{pmatrix} \\ & + m_A^2 \begin{pmatrix} \sin^2 \beta & -\cos \beta \sin \beta \\ -\cos \beta \sin \beta & \cos^2 \beta \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ 0 & \frac{\delta}{\sin^2 \beta} \end{pmatrix}, \end{aligned} \quad (1.58)$$

where δ and δ_1 are radiative corrections from, primarily, top quark and top squark loops, and are given as a function of the mass of the CP odd boson A , m_A , and the ratio of the two doublet fields vacuum expectation factors $\tan \beta$. Neglecting sub-dominant corrections fixes the dominant radiative corrections to

$$\frac{\delta}{\sin^2 \beta} = \frac{(m_A^2 - m_h^2)(m_h^2 - m_Z^2) + m_A^2 m_Z^2 \sin^2 2\beta}{\sin^2 \beta m_A^2 - (m_h^2 - m_Z^2 + \sin^2 \beta m_Z^2)}, \quad (1.59)$$

which diagonalises the mass matrix. The eigenvectors of the diagonal mass matrix correspond to the physical states, which in turn fixes the Higgs boson

couplings to vector bosons (κ_V), up-type fermions (κ_u), and down-type fermions (κ_d). The couplings can be expressed as ratios to the corresponding SM expectations and can be determined as functions of m_A and $\tan\beta$.

$$\begin{aligned}\kappa_V &= \frac{s_d + \tan\beta s_u}{\sqrt{1 + \tan^2\beta}}, \\ \kappa_u &= s_u \frac{\sqrt{1 + \tan^2\beta}}{\tan\beta}, \\ \kappa_d &= s_d \sqrt{1 + \tan^2\beta},\end{aligned}\tag{1.60}$$

where s_u and s_d are given as a function of m_A and $\tan\beta$:

$$\begin{aligned}s_u(m_A, \tan\beta) &= \frac{1}{\sqrt{1 + \frac{(m_A^2 + m_Z^2)^2 \tan^2\beta}{(m_Z^2 + m_A^2 \tan^2\beta - m_h^2(1 + \tan^2\beta))^2}}}, \\ s_d(m_A, \tan\beta) &= s_u \frac{(m_A^2 + m_Z^2)^2 \tan^2\beta}{(m_Z^2 + m_A^2 \tan^2\beta - m_h^2(1 + \tan^2\beta))^2}.\end{aligned}\tag{1.61}$$

1.3.5 Dark Matter and Higgs Portal Model

In the Higgs portal model an additional weakly-interacting massive particle (WIMP) is introduced as a dark matter candidate. The WIMP particle is, in this model, assumed to interact very weakly with the SM particles, but strongly to the Higgs boson.

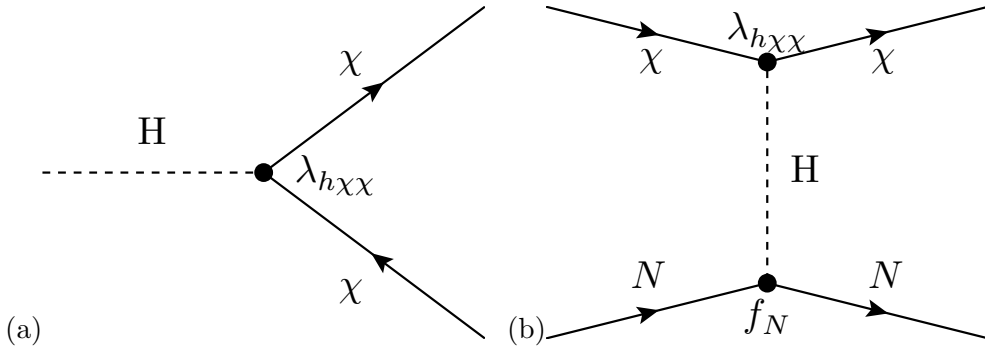


Figure 1.11: Direct production (a) and scattering (b) of WIMP particle through the Higgs sector.

The partial width for Higgs boson decays to a pair of dark matter particles depends on the assumed spin of the dark matter particle. The dark matter

candidate can be scalar S , spin 0, a Majorana fermion f , spin $\frac{1}{2}$, or a vector V , spin 1.

$$\begin{aligned}\mathcal{L}_S &= -\frac{1}{2}m_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_S \Phi^\dagger \Phi S^2, \\ \mathcal{L}_f &= -\frac{1}{2}m_f^2 \bar{f}f - \frac{1}{4}\frac{\lambda_f}{\Lambda}\Phi^\dagger \Phi \bar{f}f, \\ \mathcal{L}_V &= \frac{1}{2}m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{4}\lambda_V \Phi^\dagger \Phi V_\mu V^\mu,\end{aligned}\tag{1.62}$$

where λ_{hSS} , λ_{hVV} and λ_{hff}/Λ are the couplings of the Higgs boson to the dark matter candidates after electroweak symmetry breaking of the indicated spin and the mass scale Λ . The vacuum expectation value of the Φ field generates a 3-body interaction inside the Lagrangian in equation 1.62 and the couplings mentioned are expressed in terms of the vacuum expectation value of the Φ field. The Higgs partial decay widths into a pair of dark matter particles, as shown in figure 1.11a, are given by

$$\begin{aligned}\Gamma^{inv}(h \rightarrow SS) &= \lambda_{hSS}^2 \frac{v^2 \beta_S}{128\pi m_h}, \\ \Gamma^{inv}(h \rightarrow VV) &= \lambda_{hVV}^2 \frac{v^2 \beta_V m_h^3}{512\pi m_V^4} \left(1 - 4\frac{m_V^2}{m_h^2} + 12\frac{m_V^4}{m_h^4}\right), \\ \Gamma^{inv}(h \rightarrow ff) &= \frac{\lambda_{hff}^2}{\Lambda^2} \frac{v^2 \beta_f^3 m_h}{64\pi}.\end{aligned}\tag{1.63}$$

where $\beta_\chi = \sqrt{1 - 4m_\chi^2/m_h^2}$ which is a kinematic factor associated with the two-body $h \rightarrow \chi\chi$ decay.

The cross section for scattering between the WIMP and nucleons via Higgs boson exchange, as shown in figure 1.11b, $\sigma_\chi - N$ can be probed indirectly. The nucleon mass, $m_N \approx 0.94$ GeV, and the form factor associated with the Higgs-nucleon coupling, $f_N = 0.33 + 0.30 - 0.07$, computed using lattice QCD [55] are used to reinterpret measured couplings of the Higgs boson to dark matter candidates. The Cross section is given by

$$\begin{aligned}\sigma_S - N &= \lambda_{hSS}^2 \frac{m_N^4 f_N^2}{16\pi m_h^4 (m_S + m_N)^2}, \\ \sigma_V - N &= \lambda_{hVV}^2 \frac{m_N^4 f_N^2}{16\pi m_h^4 (m_V + m_N)^2}, \\ \sigma_f - N &= \frac{\lambda_{hff}^2}{\Lambda^2} \frac{m_N^4 f_N^2 m_f^2}{4\pi m_h^4 (m_f + m_N)^2}.\end{aligned}\tag{1.64}$$

1.4 Effective Field Theory

The idea behind an effective field theory (EFT) is to represent the dynamical content of the theory in the low energy limit in a simple way. This means that only those light degrees of freedom that are active at low energy are taken into account and their interactions are treated in the framework of a full field theory. Effects from high energy appear local at low energy, meaning that they are equivalent to terms in a local Lagrangian. An example of Feynman diagrams for a high order effect visible at low energy is shown in figure 1.12.

The coefficients of a Lagrangian, such as for example a couplings strength,

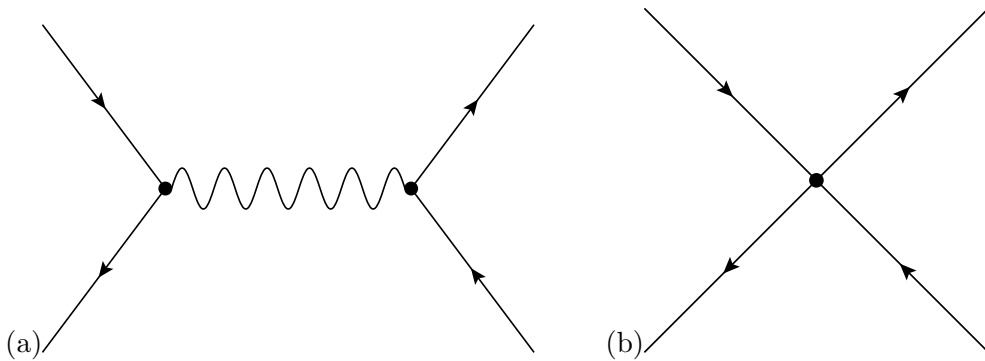


Figure 1.12: (a) Feynman diagram for a high energy mediating field (b) Feynman diagram for effective coupling.

are (usually) what is being measured in experiments. This means that the effects of physics at high energy is constrained by the parameters that are being measured at low energy by measuring effective couplings as depicted in figure 1.13.

Effective field theory uses the fact that high energy physics is constrained to perform calculations at low energy. There are two ways to use an EFT, first is a top-down approach which starts with a empirical theory and uses EFT to constrain complexities of the theory at lower energy scale, for example to perform QCD re-normalisations. The other way to use an EFT is in a bottom-up approach, which starts with a fundamental theory and uses EFT to constrain at higher energy, for example to constrain contributions of new-physics. When the high energy limit is known, the coefficients of the effective Lagrangian can be determined by matching. In theories where the high energy physics is not known, a parametrisation is applied by the most general local Lagrangian. Although effective field theories are not technically

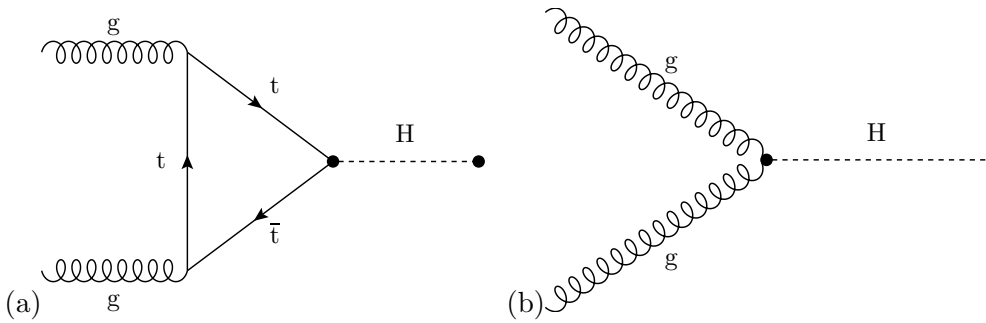


Figure 1.13: (a) Feynman diagram for the $gg \rightarrow H$ process (b) Feynman diagram for effective $gg \rightarrow H$ coupling.

re-normalisable, the decoupling theorem [56] shows that the high energy effect appears in renormalised coupling or in terms suppressed by powers of the heavy scale. The re-normalisable field theories are a subset of effective field theories in which the power suppressed Lagrangians are not needed.

When describing, for example, a field in the $SU(2)_L \times SU(2)_R$ chiral symmetry in terms of a parameterisation U , with left chirality, L , and right chirality, R , the symmetry transformation can be chosen such that the model is invariant under the $SU(2)_L \times SU(2)_R$ symmetry:

$$\phi_L \rightarrow L\phi_L, \phi_R \rightarrow R\phi_R, \text{ and } U \rightarrow LUR^\dagger. \quad (1.65)$$

Writing the effective Lagrangian for this model is unknown and not directly solvable due to the infinite number of possible terms in such a description. However effective field theory can make this task manageable. Using an energy expansion, candidate interactions can be generated that are invariant under the chiral $SU(2)$ transformations. The exponential parametrisation can be written in terms of the two-derivative, four-derivative, six-derivative and so on. In the exponential parametrisation, the two, four and six-derivative terms become

$$Tr(\partial_\mu U \partial^\mu U^\dagger), Tr(\partial_\mu U \partial_\nu U^\dagger) \cdot Tr(\partial^\mu U \partial^\nu U^\dagger), Tr(\partial_\mu U \partial^\mu U^\dagger) \cdot Tr(\partial_\nu U \partial^\nu U^\dagger) \quad (1.66)$$

Terms without a derivative can not be included in this list since $Tr(UU^\dagger) = 2$ is a constant. A general Lagrangian can now be organised by the dimensionality of the operators, such that a cut-off can be determined at a later stage

$$\mathcal{L} = \mathcal{L}_2 + \mathcal{L}_4 + \mathcal{L}_6 + \dots \quad (1.67)$$

For the $SU(2)_L \times SU(2)_R$ example the Lagrangian becomes

$$\mathcal{L} = \frac{F^2}{4} \text{Tr}(\partial_\mu U \partial^\mu U^\dagger) + l_1 [\text{Tr}(\partial_\mu U \partial^\mu U^\dagger)]^2 + l_2 \text{Tr}(\partial_\mu U \partial_\nu U^\dagger) \cdot \text{Tr}(\partial^\mu U \partial^\nu U^\dagger) + \dots \quad (1.68)$$

At sufficiently low energies the matrix elements of most of these terms are small, since each derivative becomes a factor of the momentum q when matrix elements are taken.

The number of derivatives can now be used to indicate the energy scale. This means that the Lagrangian with only the $\mathcal{L}_2$ term corresponding to the two derivatives is called of order $\mathcal{O}(E^2)$. Experiments are now needed, when matching to the full theory is not possible, to determine the coefficients of these terms.

In this thesis, effective field theories are used to look at Beyond the Standard Model (BSM) models, for which the Lagrangian can be written as a Standard Model (SM) Lagrangian plus a BSM Lagrangian. The effective Lagrangian can now be written as a sum of local operators O_i which contain the contributions from scales below an energy cut-off scale Λ as well as Wilson coefficients that depend on this energy scale $C_i(\Lambda)$ for long and short distance contributions respectively:

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_k \frac{1}{\Lambda^k} \sum_i C_{ik}(\Lambda) O_{ik}. \quad (1.69)$$

Most next to leading order terms in the BSM expansion are given by dimension-6, $\mathcal{O}(E^6)$, operators. In the calculation of loop diagrams, of an order of $\mathcal{O}(E^6)$ factors can be involved. This would create a problem for the counting of dimensions. However since an additional scalar field would be heavy, the propagation of the field will not reach very far and the resulting effective Lagrangian will be local. The higher order contribution from the loop diagram Lagrangian can therefore be renormalised to a Lagrangian at lower order. The renormalisation is done by using Weinberg's power-counting theorem [57].

The effective model becomes inadequate when the mass of the scalar particle in the theory is large enough to directly excite the scalar particle itself. This effect becomes clearly visible when the scattering matrix elements, which are the linear operators of a modified Hamiltonian using Dirac notation, are an expansion in the energy and take the schematic form

$$\mathcal{M} \approx \frac{q^2}{v^2} \left[1 + \frac{q^2}{m_\sigma^2} + \dots \right]. \quad (1.70)$$

This expansion shows that the scale of the energy dependence q^2 is determined by the mass of the scalar m^2 . When the corrections to the lowest-order result get larger, which corresponds to all terms in the energy expansion becoming equally important, the effective theory breaks down. [58, 59, 60, 61]

Effective field theories are used in this thesis to look at properties of the (SM) Higgs boson and as a framework for the BSM models described in the following sections.

1.5 Effective Models for Characterising the Higgs Boson

The first run of the LHC lead to the discovery of the existence of a new boson. By testing the properties of the bosons such as the spin and parity, it is possible to assess that the new boson is the scalar, parity-even particle predicted in the Brout-Englert-Higgs mechanism in the Standard Model. Current measurements are compatible with the SM Higgs boson. Since no clear hint for a particular new physics model is seen, an agnostic framework to measure possible new physics is needed. Manifestations of possible high energy new physics effects at low energy can be measured with two different approaches. The requirement for an approach to measure manifestations of possible new physics effect, is that the method is as model independent as possible. The main difficulty is that the SM does not have any degrees of freedom in the Higgs sector, other than the mass, which means that additional degrees of freedom have to be introduced. A first realisation of an extension of the SM with new degrees of freedom is the kappa framework. The idea of this method is to introduce a scaling factor as a degree of freedom for each coupling. The kappa framework is not able to see differences in shapes, since it uses overall scaling factors. By introducing a scaling factor per bin, for example for p_T bins, some shape sensitivity can be recovered. This last step is done in a recent extension of the kappa framework: the simplified template method. The main feature of the kappa framework is that its parameters generally align well with observed quantities. The second approach is an effective field theory inspired approach, the Higgs characterisation Lagrangian model. The idea of this method is to find a way to build a model from a field theory directly and align parameters with theoretical rather than observable concepts. The requirement for this second method is that the SM can be recovered with the right choice of parameters.

1.5.1 Kappa Framework

The kappa framework is set up to measure deviations of Higgs couplings from the Standard Model. The method is inspired by the Leading Order (LO) diagrams of the Higgs couplings. [41, 10] The kappa framework is based on the following assumptions:

- The signals observed in the different search channels originate from a single resonance with a mass of around 125 GeV.
- The width of the Higgs boson is narrow. The narrow-width approximation predicts a rate for a given channel in the following way:

$$\sigma \times BR(i \rightarrow H \rightarrow f) = \frac{\sigma_i \times \Gamma_f}{\Gamma_H} \quad (1.71)$$

where σ_i is the production cross section through the initial state i , BR is the branching ratio into the final state f , Γ_f is the partial decay width into the final state f , and Γ_H is the total width of the Higgs boson.

- The tensor structure of the Lagrangian is assumed to be the same as that in the SM. This means only modifications of coupling strengths are considered. In particular this means that the observed state is a CP-even scalar.

The SM couplings in the kappa framework are calculated with NNLO QCD and NLO EW. The kappa framework is then parametrised with LO degrees of freedom, by scaling each coupling g_i with a value κ_i

$$g_i \rightarrow \kappa_i g_i. \quad (1.72)$$

The scale factors κ_i for the couplings are defined such that the cross sections σ_i and the partial decay widths Γ_j scale with κ_i^2 compared to the SM prediction. Using this scaling the signal strength, for example, for the $gg \rightarrow H \rightarrow \gamma\gamma$ process is expressed in the kappa framework as:

$$(\sigma \times BR)(gg \rightarrow H \rightarrow \gamma\gamma) = \sigma_{SM}(gg \rightarrow H) \times BR_{SM}(H \rightarrow \gamma\gamma) \times \frac{\kappa_g^2 \kappa_\gamma^2}{\kappa_H^2}, \quad (1.73)$$

where κ_g and κ_γ are the scaling factors for Higgs boson coupling to gluons and photons, respectively, and κ_H is the scaling of the total width. The best available SM predictions for all $(\sigma \times BR)$ are recovered for $\kappa_i = 1$.

Scaling of the total width

The sum of all Higgs partial decay widths is the total width Γ_H . Assuming that neither invisible or undetectable final states contribute to the total width, meaning no additional BSM Higgs decay modes, Γ_H can be expressed as the sum of the scaled partial Higgs decay widths to SM particles. The scaled partial Higgs decay widths combines to a total scale factor κ_H^2 for the SM total width Γ_{SM} :

$$\kappa_H^2(\kappa_i, m_H) = \sum_j \frac{\Gamma_j(\kappa_j, m_H)}{\Gamma_H^{SM}(m_H)} \quad (1.74)$$

with $j = WW^{(*)}, ZZ^{(*)}, b\bar{b}, \tau^-\tau^+, \mu^-, \mu^+, \gamma\gamma, Z\gamma, gg, t\bar{t}, c\bar{c}, s\bar{s}$.

Contributions from electrons, first generation quarks and neutrinos are assumed to have a negligible effect on the total width due to their mass. In case invisible or undetectable final states contribute to the total width, the branching ratio for Higgs to invisible final states, BR_{inv} , can be used to parametrise the total width.

$$\Gamma_H = \frac{\kappa_H^2 \Gamma_{SM}}{1 - BR_{inv}} \quad (1.75)$$

1.5.2 Simplified Template Cross Sections

The main limitation of the kappa framework is that only scalar modifications are allowed within the framework, which neglects possible changes in shapes of distributions of parameters and only finds model modifications that influence the total signal strengths. The simplified template cross section framework[62] adds an effective parametrisation of differential effects.

The cross sections are measured for specific production modes with the SM production serving as kinematic template. Measurements are performed in simplified fiducial volumes, hence the name simplified template cross section framework. This means that individual scaling factors are introduced for separated parts of the data. The primary goals of the framework are to maximise the sensitivity of the measurements while at the same time minimising their theory dependence. The exclusive regions of phase space that can be measured are specific to the different production modes and are called *bins* for simplicity. The bins are constructed to optimise the following:

- To minimise the dependence on theoretical uncertainties that are directly folded into the measurements.
- To maximise experimental sensitivity.
- To isolate possible BSM effects.

- To minimise the number of bins without loss of experimental sensitivity.

Figure 1.14 shows the simplest, called stage 0, splitting into bins for simplified cross sections. In following stages the splitting level is increased to introduce additional parameters. This has the benefit that the sensitivity for deviations increases, however splitting the data decreases the statistical sensitivity. Due to the decrease of statistical sensitivity, additional splitting stages should only be introduced when a sufficient amount of data has been collected.

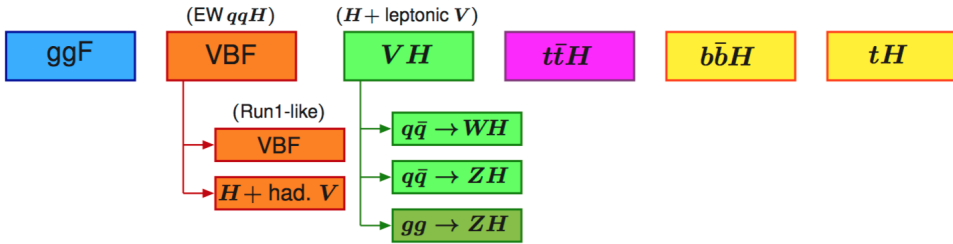


Figure 1.14: The stage 0 splitting for simplified template cross sections.

1.5.3 Higgs characterisation Lagrangian

The Higgs characterisation Lagrangian model [63] is a field theory based on a standard model part, that does not include the Higgs sector, and an effective field theory for a Higgs sector that can contain new physics with an energy cutoff scale Λ . The Lagrangian of this effective field theory for a boson with spin/parity assignment J^P can be written as:

$$\mathcal{L}_{HC,J} = \mathcal{L}_{SM-H} + \mathcal{L}_J, \quad (1.76)$$

where $\mathcal{L}_{SM-H}$ is the SM Lagrangian as describes in chapter 1 without the Higgs sector, meaning the Higgs particle and its interactions with the SM. The Higgs particle and interaction terms of the Higgs boson with the SM particles are contained in $\mathcal{L}_J$, described below.

The Higgs characterisation Lagrangian is dependent on the spin of the assumed Higgs boson. Preliminary studies indicate that the discovered boson is compatible with a spin 0 hypothesis [64, 65, 66, 67, 68, 69, 70, 71, 72]. For this reason this thesis will focus on $\mathcal{L}_J$ for a spin 0 particle version of the Lagrangian. [63]

A list of guiding principles for the construction of the Higgs part of the Lagrangian is:

1. All possible interactions generated by gauge-invariant dimension-six operators above the electroweak scale are included.

2. It is easy to recover the SM case of the Lagrangian.
3. The Lagrangian includes the 0^- state couplings typical of SUSY and generic Two Higgs Doublet Models (THDMs).
4. The Lagrangian allows CP-mixing between 0^+ and 0^- states, which will be parametrised in terms of a mixing angle α . This is particularly important since the CP state of the Higgs has not yet been measured with sufficient precision.

The effective Lagrangian for the spin 0 state is constructed by including all possible interactions that are generated by gauge-invariant dimension six operators that are invariant under $SU(2)_L \times U(1)_Y$. The requirement of gauge invariance under $SU(2)_L \times U(1)_Y$ mean that only those terms that act above the electroweak scale are included. The Lagrangians for the Higgs interactions with SM particles will be restricted, for simplicity, to three-point interactions. [73, 74, 75]

The notations used for a CP-even, 0^+ , Higgs is H , while a CP-odd, 0^- , Higgs is denoted by A . Other used notations are:

$$\begin{aligned} c_\alpha &\equiv \cos \alpha \\ s_\alpha &\equiv \sin \alpha \end{aligned} \tag{1.77}$$

The Lagrangian for a generic spin 0 Higgs boson $X_0 = H, A$ coupling to fermions is written as

$$\mathcal{L}_0^f = - \sum_{f=t,b,\tau} \bar{\phi}_f (c_\alpha \kappa_{Hff} g_{Hff} + i s_\alpha \kappa_{Aff} g_{Aff} \gamma_5) \phi_f X_0, \tag{1.78}$$

where the coupling strength of the scalar is $g_{Hff} = m_f/v$ in the SM, and the coupling strength of the pseudo-scalar coupling in a THDM, g_{Aff} , with $\tan \beta = 1$ is $g_{Aff} = m_f/v$. The SM is obtained by setting $c_\alpha = 1$ and $\kappa_{Hff} = 1$ while the pseudo-scalar state of a type-II CP-conserving THDM or SUSY is obtained by setting $s_\alpha = 1$ and $\kappa_{Aff} = \cot \beta$ or $\tan \beta$ for up or down components of the $SU(2)$ fermion doublet respectively.

For simplicity, only the couplings to third generation fermions are taken into account, however extensions to the other fermion families as well as flavour-changing structures are trivial to implement, but not important for the work presented in this thesis. The interaction of the Lagrangian also parametrises the effects of a $\mathcal{L}_Y^{dim=6}$ operator. For fermions the only operator that modifies the Yukawa interaction comes from the top quark:

$$\mathcal{L}_Y^{dim=6} = (\phi^\dagger \phi) Q_L \tilde{\phi} t_R, \tag{1.79}$$

where Q_L is the $SU(2)_L$ doublet (t_L, b_L) and ϕ is the spin-0 particle field with particle excitation X_0 .

The effective Lagrangian for the interactions of the Higgs with vector bosons is written as:

$$\begin{aligned}
\mathcal{L}_0^V = & \{ \underline{c_\alpha \kappa_{SM}} [\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu}] \\
& - \frac{1}{4} [\underline{c_\alpha \kappa_{H\gamma\gamma}} g_{H\gamma\gamma} A_{\mu\nu} A^{\mu\nu} + \underline{s_\alpha \kappa_{A\gamma\gamma}} g_{A\gamma\gamma} A_{\mu\nu} \tilde{A}^{\mu\nu}] \\
& - \frac{1}{2} [\underline{c_\alpha \kappa_{HZ\gamma}} g_{HZ\gamma} Z_{\mu\nu} A^{\mu\nu} + \underline{s_\alpha \kappa_{AZ\gamma}} g_{AZ\gamma} Z_{\mu\nu} \tilde{A}^{\mu\nu}] \\
& - \frac{1}{4} [\underline{c_\alpha \kappa_{Hgg}} g_{Hgg} G_{\mu\nu}^a G^{a,\mu\nu} + \underline{s_\alpha \kappa_{Agg}} g_{Agg} G_{\mu\nu}^a \tilde{G}^{a,\mu\nu}] \\
& - \frac{1}{4} \frac{1}{\Lambda} [\underline{c_\alpha \kappa_{HZZ}} Z_{\mu\nu} Z^{\mu\nu} + \underline{s_\alpha \kappa_{AZZ}} Z_{\mu\nu} \tilde{Z}^{\mu\nu}] \\
& - \frac{1}{2} \frac{1}{\Lambda} [\underline{c_\alpha \kappa_{HWW}} W_{\mu\nu}^+ W^{-\mu\nu} + \underline{s_\alpha \kappa_{AWW}} W_{\mu\nu}^+ \tilde{W}^{-\mu\nu}] \\
& - \frac{1}{\Lambda} \underline{c_\alpha} [\underline{\kappa_{H\partial\gamma}} Z_\nu \partial_\mu A^{\mu\nu} + \underline{\kappa_{H\partial Z}} Z_\nu \partial_\mu Z^{\mu\nu} + (\underline{\kappa_{H\partial W}} W_\nu^+ \partial_\mu W^{-\mu\nu} + h.c.)] \} X_0
\end{aligned} \tag{1.80}$$

where the (reduced) field strength tensors are defined as:

$$\begin{aligned}
V_{\mu\nu} &= \partial_\mu V_\nu - \partial_\nu V_\mu \text{ with } V = A, Z, W^\pm \\
G_{\mu\nu}^a &= \partial_\mu G_\nu^a - \partial_\nu G_\mu^a + g_s f^{abc} G_\mu^b G_\nu^c
\end{aligned} \tag{1.81}$$

and the dual tensor is:

$$\tilde{V}_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu\rho\sigma} V^{\rho\sigma} \tag{1.82}$$

All underlined terms are parameters, while the other terms are fixed to their SM values. The κ_i are scaling factors for the couplings g_{XVV} . The couplings $g_{Xyy'}$ are chosen such that they reproduce the SM Higgs boson when $\kappa_i = 1$, and the couplings $g_{Xyy'}$ are chosen such that they reproduce a pseudo-scalar in a THDM with $\tan\beta = 1$. The terms with a $1/\Lambda$ suppression term are for new physics processes that are not included in the THDM. Setting the $\kappa_i = 0$ for these terms, while for the other terms $\kappa_i = 1$ and $c_\alpha = 1$, reduces the Lagrangian to the SM Lagrangian. Any new-physics deviations from the SM predictions can be accounted for by setting $\kappa_i \neq 1$ for terms without a $1/\Lambda$ suppression term, and $\kappa_i \neq 0$ for terms with a $1/\Lambda$ suppression scale. The values for g_{XVV} for a SM Higgs boson and a pure BSM Higgs boson are shown in table 1.3. For the values in the table it is assumed that no new particles contribute to loop couplings of Higgs to VV . With the exception of $\kappa_{H\partial W}$, all κ_i can be taken as real without loss of generality. In this parametrisation, non-vanishing $\kappa_{Hff}, \kappa_{Aff}, \kappa_{HVV}, \kappa_{AVV}$ with $\alpha \neq 0$ and $\alpha \neq \pi/2$ imply CP violation.

Table 1.4 lists the parameters and includes example values for each parameter.

$g_{Xyy'} \times v$	ff	WW	ZZ	$\gamma\gamma$	$Z\gamma$	gg
H	m_f	$2m_W^2$	$2m_Z^2$	$47\frac{\alpha_{EM}}{18\pi}$	$C\frac{94\cos^2\theta_W-13}{9\pi}$	$-\frac{\alpha_s}{3\pi}$
A	m_f	0	0	$4\frac{\alpha_{EM}}{3\pi}$	$2C\frac{8\cos^2\theta_W-5}{3\pi}$	$-\frac{\alpha_s}{2\pi}$

Table 1.3: Values of the coupling $g_{Xyy'}$ in units of v where $C = \sqrt{\frac{\alpha_{EM}G_F m_Z^2}{8\sqrt{2}\pi}}$.

Parameter	Example value	Description
$\Lambda [TeV]$	1	Energy cutoff scale
$c_\alpha \equiv \cos \alpha$	between 0 and 1	Mixing between 0^+ and 0^-
κ_i	0 or 1	Coupling scaling parameter

Table 1.4: Free parameters of the Higgs characterisation Lagrangian framework with example values.

1.6 Monte Carlo Simulation

Predictions for observable processes at LHC collisions are needed. Theories, such as (effective) field theories, that describe the Higgs boson at high energy in a collision are just one of the ingredients. To compare the observations in the detector with theory, additional collision information is simulated. Specific processes from pp collisions are generated using Monte Carlo (MC) methods. Monte Carlo methods simulate hard scattered events, parton showers, hadronisation and the decays of outgoing particles. MC uses random number generators to simulate the process under consideration according to theoretical prescriptions.

Hard scattering events with high p_T objects in the final state are rare in pp collisions. Therefore sub-processes are simulated independently, rather than simulating the proton collision inclusively. The cross-section of the hard scattering is constructed as an integral over the product of the sub-processes. To reduce the statistical uncertainty of the sample, more hard scattering processes can be simulated than expected in the collision. The simulated hard scattering processes are therefore normalised to their respective cross sections so they can be compared to data. The partons, which make up the incoming protons, radiate gluons, which can either radiate off more gluons or split into quark-antiquark pairs. This process is known as parton showering. Jets, meaning clusters of particles, hadronise when the partons reach a certain energy. The underlying event of the process are the parts of the protons that

do not participate in the hard scattering, but that do interact.

There are two types of Monte Carlo generators, general purpose generators and matrix element generators. General purpose generators simulate the entire proton collision including parton showering and hadronisation. The general purpose generators are limited to two-to-one and two-to-two processes, but can use external Matrix Element information. Any additional particles must come from parton shower models.

Matrix element generators simulate the hard scattering only. Matrix element generators rely on general purpose generators for the parton showering process. A specified number of final and initial state radiation particles can be calculated at matrix element level, since two-to- n processes are included in the model. Examples of generators are listed in table 1.5.

MC generator	Matrix Element	functionality
PYTHIA [77, 78]	LO	PS, UE, H, PU
HERWIG [79]	LO	PS, UE if interfaced with JIMMY [80], H
SHERPA [81]	NLO+multi-leg	HS, PS, UE, H
ALPGEN [82]	LO+multi-leg	HS, PS if interfaced with PYTHIA or HERWIG, UE, H
ACERMC [83]	LO	HS, PS if interfaced with PYTHIA or HERWIG, UE, H
POWHEG [84, 85, 86]	NLO	HS, PS if interfaced with PYTHIA or HERWIG, UE, H
MG5_MC@NLO [87, 88]	NLO+multi-leg	HS, PS if interfaced with HERWIG, UE, H

Table 1.5: Overview of MC generators. The following abbreviations are used: HS for hard scattering, PS for parton showering, UE for the underlying event, PU for pileup, H for hadronisation, LO for leading-order and NLO for next-to-leading-order. The abbreviation multileg is used to refer to generators that provide additional partons in the matrix element calculation. [76]

2 The LHC and the ATLAS detector

Underneath the border between France and Switzerland lies the Large Hadron Collider (LHC) [89, 90, 91, 92]. The LHC is an accelerator at the European Organisation for Nuclear Research (CERN), where collisions between highly energetic particles are produced. Two protons, two lead ions or one proton and one lead ion are accelerated in a circular accelerator in opposite directions. Collisions are possible at four places along the circle, at these four places detectors are built. There are two general purpose detectors, ATLAS [93, 94, 95] and CMS [96, 97, 98], and two detectors for specialised purposes, LHCb [99], with the purpose of measuring the matter /anti-matter imbalance of the universe and ALICE [100], with the purpose of measuring the properties of the Quark Gluon Plasma by colliding lead nuclei. The data studied in this thesis are collected with the ATLAS detector. The LHC and the ATLAS detector, including the subsystems that the detector consists of, are described in the remainder of this chapter.

2.1 The Large Hadron Collider

The Large Hadron Collider (LHC) is a circular accelerator and collider. The accelerator is located approximately 100 m under the ground in a tunnel with a 26.7 km circumference [89, 90, 91]. The LHC was designed to run at a centre of mass energy of $\sqrt{s} = 14$ TeV for p-p collisions and $\sqrt{s} = 2.76$ TeV for Pb-Pb collisions. The first run of the LHC ran at a lower energy with p-p collisions at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV and Pb-Pb collisions at $\sqrt{s} = 1.15$ PeV. At the beginning of the second run, the LHC ran at $\sqrt{s} = 13$ TeV for p-p collisions. In this thesis the focus will be on p-p collisions.

To create the protons, hydrogen atoms are separated. The protons are then accelerated to 50 MeV in a linear accelerator (LINAC2). After the linear accelerator, the protons are injected into a series of circular pre-accelerators;

the Proton Synchrotron Booster (PSB), which increases the energy to 1.4 GeV, the Proton Synchrotron (PS), to push the energy up to 25 GeV and the Super Proton Synchrotron (SPS), to accelerate the protons up to 450 GeV. The accelerator complex is shown in figure.

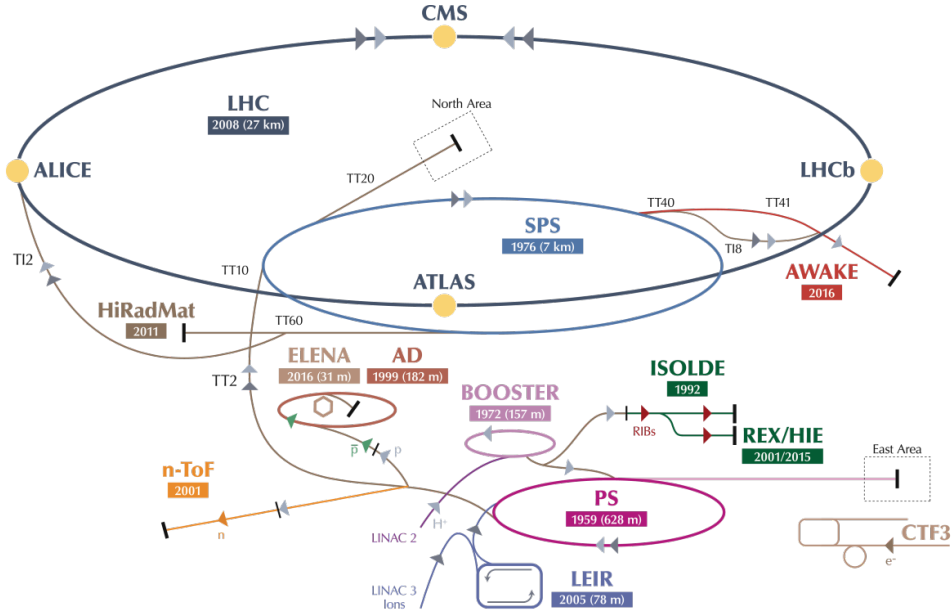


Figure 2.1: Cern Accelerator Complex.

The LHC is designed to arrange the protons in bunches with, nominally, 1.15×10^{11} protons per bunch. When the beam is fully populated there are 2808 bunches per beam which are separated by 25 ns. Superconducting dipole magnets are used to keep the protons in orbit with a field of 8.33 T. Sextupole and quadrupole magnets are used to stabilise the particle beam and to focus the beam, respectively.

2.1.1 Luminosity

The number of interactions a particle accelerator is able to produce per unit of time is called the luminosity. The number of events per second, N , is related to the instantaneous luminosity, L , and the cross-section, σ :

$$N \equiv \frac{dn}{dt} = L \times \sigma. \quad (2.1)$$

The LHC is designed for an instantaneous luminosity of $L = 10^{34} \text{cm}^{-2} \text{s}^{-1}$. The luminosity of the LHC is calculated as [92]:

$$L = \frac{N_b^2 n_b f_{rev} \gamma_r}{4\pi \epsilon_n \beta^*} F, \quad (2.2)$$

where N_b is the number of particles per bunch, n_b the number of bunches per beam, γ_r the relativistic gamma factor and ϵ_n the normalised transverse beam emittance. The revolution frequency, f_{rev} , the geometric luminosity reduction factor due to the crossing angle at the interaction point (IP), F , and the beta function at the collision point, β^* , are given by:

$$\begin{aligned} f_{rev} &= \frac{\beta c}{2\pi R}, \\ F &= (1 + (\frac{\theta_c \sigma_z}{2\sigma^*})^2)^{-\frac{1}{2}}, \\ \beta^* &= \frac{\pi \sigma^{*2}}{\epsilon_n}, \end{aligned} \quad (2.3)$$

where θ_c is the full crossing angle at the IP, σ_z the RMS bunch length, and σ^* the transverse RMS beam size at the IP. All equations for the luminosity assume a Gaussian beam distribution, round beams with $\sigma_z \ll \beta$ and identical beam parameters for both beams. Some typical parameters of the LHC performance are shown in table 2.1.

The total number of events generated in collisions is:

$$N_{event} = \mathcal{L} \sigma_p \text{ with } \mathcal{L} = \int L dt, \quad (2.4)$$

where $\mathcal{L}$ is the integrated luminosity, measured in inverse barns¹ and σ_p is the cross section for a process in a proton-proton collision. The integrated luminosity, $\mathcal{L}$, is shown in figure 2.2.

2.1.2 Pile-up

One of the challenges the detectors of the LHC face is called pile-up, which is multiple collisions in the same readout window. Pile-up manifests itself as a high occupancy in a sub-detector. There are two types of pile-up, which is the result of an intentional choice to increase the luminosity, in-time pile-up and out-of-time pile-up.

In-time pile-up refers to the number of inelastic proton-proton collisions per bunch crossing. The number of collisions per bunch crossing follows a Poissonian

¹1b = 10^{-28}m^2

Parameter	Run 1		Run 2	design
Centre-of mass energy $\sqrt{s}$ [TeV]	7	8	13	14
Minimum bunch spacing for physics [ns]	150	50	25	25
Peak instantaneous luminosity [10^{33} cm $^{-2}$ s $^{-1}$]	3.65	7.73	13.8	10
Delivered integrated luminosity [fb $^{-1}$ /year]	5.6	23.1	38.5	8-120
Average number of interactions $<\mu>$	9.1	20.7	24.9	19.02

Table 2.1: Performance of the LHC during the first and second run of proton-proton collision, including the main beam and machine parameters [101, 89]. For Run 2 the integrated luminosity for is shown for 2016.

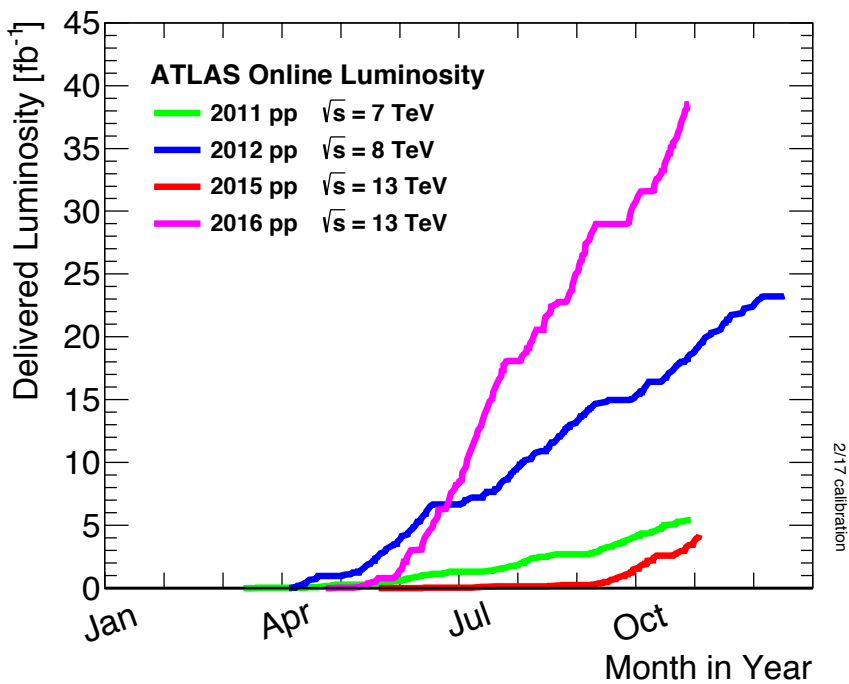


Figure 2.2: Cumulative luminosity versus day delivered to ATLAS during stable beams and for high energy p-p collisions. [101]

distribution. The mean value μ of this Poissonian distribution is related to the instantaneous luminosity in the following way:

$$\mu = \frac{L\sigma_{ie}}{n_b f_{rev}}, \quad (2.5)$$

where σ_{ie} is the total inelastic cross-section of proton collisions, n_b is the number of bunches per beam, and f_{rev} is the revolution frequency. The revolution frequency $f_{rev} = \beta c / 2\pi R$, with R the machine radius and β a measure of the squeezing of the beam.

The out of time pile-up comes from neighbouring bunch crossings, which can occupy the detector. The mean number of interactions per bunch crossing is shown for Run 1 and Run 2 of the LHC in figure 2.3.

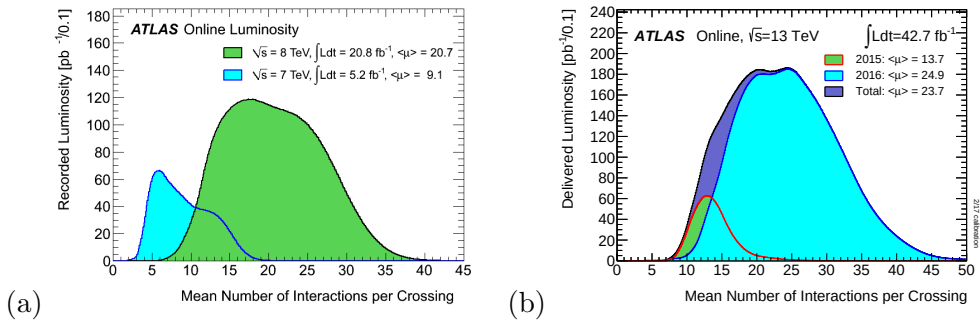


Figure 2.3: The luminosity-weighted distribution of the mean number of interactions per crossing for (a) Run 1 and (b) Run 2. [102, 101]

2.2 The ATLAS detector

The ATLAS detector is designed as a general purpose detector. The detector is in particular optimised for searches at high energy, TeV scale, and precision measurements of Standard Model particles. The design of ATLAS is nearly cylindrically symmetric and is built up in layers of different detector types around the beam of the LHC. A cut-away representation of the detector is shown in figure 2.4. The detector weighs approximately 7000 tonnes and is approximately 44m long with a diameter of approximately 25m. It is the largest detector of the four LHC experiments.

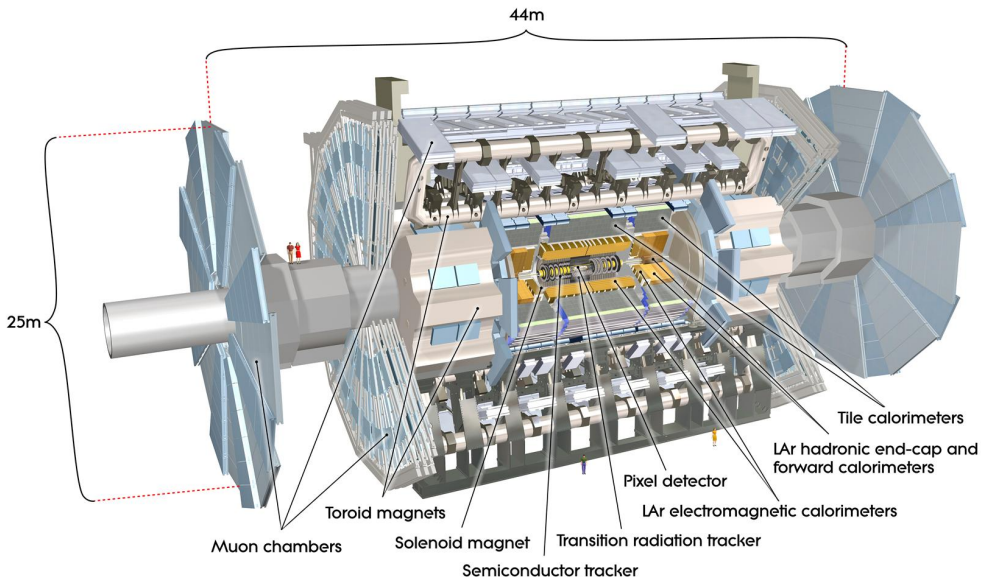


Figure 2.4: The ATLAS detector partially cut-away to show the different subsystems of the detector. This figure is taken from [94].

The detector is invariant under rotations around the beam axis and has forward-backward symmetry. The interaction point is located in the centre of the detector and is used as the centre of the coordinate system. Due to the geometry of the detector, a cylindrical coordinate system is used.

The beam axis is defined as the z -direction. The azimuthal angle, $\phi \in [-\pi, \pi]$, is the angle around the beam axis z . The polar angle, $\theta \in [0, \pi]$, is the angle from the beam axis. The pseudo-rapidity is often used to describe the direction of the massless particle and is defined as $\eta = -\ln \tan(\theta/2)$. For massive particles the rapidity is used rather than the pseudo-rapidity. The rapidity is defined as

$y = \frac{1}{2} \ln[(E + p_z)/(E - p_z)]$. For massless particles there is an exact relation between the rapidity and the pseudo-rapidity. The rapidity distributions of processes are invariant under boosts in the z -direction.

From the cylindrical coordinate system a right-handed coordinate system can be defined, with the $x - y$ plane transverse to the beam axis. The x -axis points radially inward to the centre of the LHC-ring, the y -axis points upwards. The $x - y$ plane is used to define several experimental quantities; the transverse momentum, $p_T = p \sin \theta$, the transverse energy, $E_T = E \sin \theta$, and the missing transverse energy, E_T^{miss} . The missing transverse energy is used to measure the imbalance of the energy in the transverse plane.

2.2.1 Particle Detection and Identification

The different layers of the detector each have their own purpose for particle detection and identification. The layer closest to the beam is important for vertexing, i.e. finding the interaction point of the protons. The second layer from the beam is the tracker, which is used to reconstruct the trajectory of a particle from the interaction point outwards. The tracker is surrounded by the calorimeter system, which measure the energy of the particle through absorption. The outermost layer is the muon tracker, which is ideal for measuring muons. Magnets are used to bend the trajectory of the charged particles, which is used to reconstruct the energy of the charged particles. After reconstructing the path of the charged particles, the helix in the magnetic field can be used to reconstruct the momentum and the charge of the particle, since the radius of the helix is inversely proportional to the transverse momentum of the particle. The trajectories are reconstructed using the high-resolution tracker which lies close to the interaction point and the muon spectrometer which is the most outer sub-detector of the ATLAS detector.

The calorimeters are used to measure the energy of all particles, charged and neutral. The calorimeters consist of successive thin layers of alternating active material and absorbing material, which can be used to measure the number of particles produced in a shower. A shower of particles refers to a particle decaying in a cascade of electromagnetic or hadronic particles. From the shower of particles the initial particle can be reconstructed and its energy can be approximated. This process is complicated due to the high local particle density in the detector, which makes it difficult to separate the particles in the shower from other particles nearby.

Each subsystem is further described in the following subsections.

2.2.2 Inner Detector

The inner detector (ID) is designed to measure the tracks of charged particles while slowing down the particles as little as possible and minimising the material that the particles travel through. It is positioned inside the magnetic field of the solenoid magnet such that the curvature of the trajectory enables measurements of the p_T of the charged particles. The ID is made up of three layers. The layers closest to the beam are two silicon-based detectors; the Pixel components and the Semiconductor Tracker (SCT). The outer layer is the Transition Radiation Tracker (TRT). In the long shutdown of the LHC in 2013 and 2014 an additional pixel layer was installed between the beam and the already existing pixel layers. The new pixel layer, the insertable B-layer (IBL), improves the vertexing. A cut-away view of the ATLAS ID is shown in figure 2.5. [103, 104]

The Insertable b-layer is a single layer of pixel detector in cylindrical form. The IBL lies at a distance of $31 \text{ mm} < R < 40 \text{ mm}$ from the interaction point. The pixel size is $50 \times 250 \mu\text{m}^2$. The resolution of the IBL detector is $8, 5 \mu\text{m}$ in the transverse direction ($R - \phi$) and $47 \mu\text{m}$ in the longitudinal direction (z).

The pixel Detector consists of 1744 silicon pixel modules. The modules are arranged in three layers in the form of three concentric cylinders in the barrel region and three disks perpendicular to the beam line in the end-cap region. The sensor tile area is composed of $250 \mu\text{m}$ thick silicon wafer readout pixels with a nominal size of $50 \times 400 \mu\text{m}^2$. Each particle is expected to hit three layers of the pixel detector. The resolution of the pixel detector is $10 \mu\text{m}$ in the transverse direction ($R - \phi$) and $115 \mu\text{m}$ in the longitudinal direction (z in the barrel and R in the end-cap region).

The Semiconductor Tracker is a strip detector consisting of silicon sensors. The SCT has approximately 6.3 million readout channels distributed over 4088 modules. The resolution of the SCT detector is $17 \mu\text{m}$ in the transverse direction ($R - \phi$) and $580 \mu\text{m}$ in the longitudinal direction (z in the barrel and R in the end-cap region).

The Transition Radiation Tracker is a straw tube detector. The TRT consists of approximately 351000 readout channels with an intrinsic accuracy of $130 \mu\text{m}$ per straw. The straws are filled with a gas mixture of 70% Xenon, 27% CO_2 and 3% O_2 . The tubes themselves are 4mm in diameter and contain a $31 \mu\text{m}$ gold-plated tungsten anode wire. The tubes have a length of 144 cm in the barrel and 37 cm in the end-caps. The resolution of the TRT detector is $130 \mu\text{m}$ in the transverse direction ($R - \phi$).

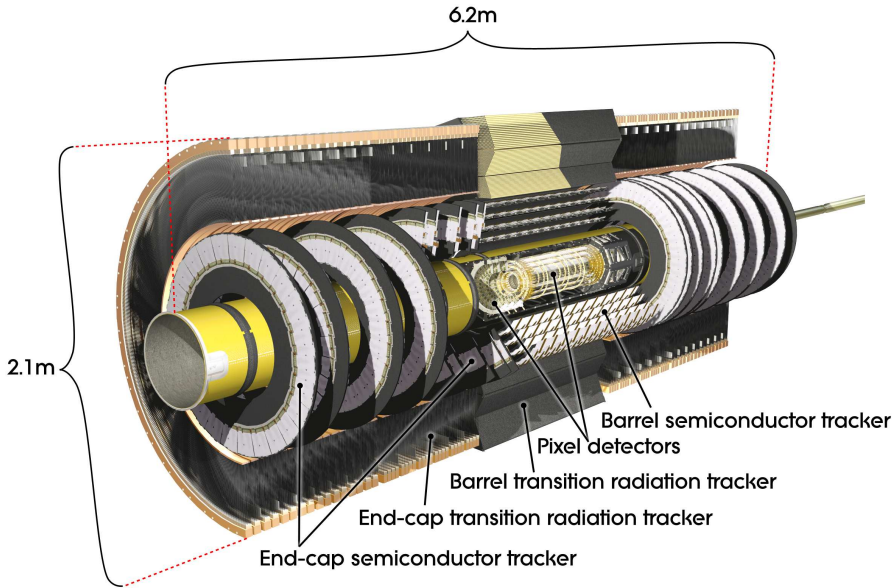


Figure 2.5: Cut-away view of the ATLAS ID [94].

2.2.3 The Calorimeter System

Calorimeters are used to measure the energy of particles. There are two types of calorimeters, each designed for different types of particles: electromagnetic and hadronic particles. The Electromagnetic calorimeter measures processes on the characteristic radiation length for electromagnetic interactions, while the Hadronic calorimeter measures processes on the characteristic nuclear interaction length for strong interactions. The ATLAS calorimeters cover a range up to $|\eta| < 4.9$. The calorimeters are built up from alternating layers of active and passive material. The passive material, observer, interacts heavily with the passing particles, which starts the showering process. The active layers detect the produced particles and measure their energy. The measurement of the energy of all particles inside the calorimeter system is important to be able to calculate the total energy deposit.

The Electromagnetic Calorimeter (ECAL) is designed to stop electromagnetic particles, in particular electrons and photons, and measure their energy. The absorbing material of the ECAL is lead and the active material is liquid argon (LAr), which extends over more than 22 radiation lengths, X_0 . In the barrel region the ECAL covers up to $|\eta| < 1.475$, while the endcap region covers $1.375 < |\eta| < 3.2$. To optimise the energy resolution, the thickness of

the lead and the granularity vary as a function of η .

Hadronic Calorimeter (HCAL) is designed to stop hadronic particles, in particular hadronic jets, and measure their energy. The absorbing material of the HCAL is steel. The active material is made up out of scintillators that are organised in a harmonic structure. In the end-cap the absorbing material is made of copper and the active material is LAr. The total depth is 9.7 nuclear interaction lengths, λ . The use of LAr in the endcap region close to the beam pipe, allows for constant refreshing of the active material, which makes the detector more radiation-hard.

2.2.4 The Muon Spectrometer

The Muon Spectrometer (MS) is a tracking system that forms the outermost layer of ATLAS detector. Most particles have either decayed or have been stopped by the calorimeter system. Most muons are neither stopped nor decayed and are therefore identified as muons when they leave a hit in the MS. These muons can originate from the primary vertex, jets and cosmics.

The barrel and end-cap regions of the MS are installed within the toroid magnets as shown in figure 2.6. The magnets are used to reconstruct the p_T of the particle. The MS also contains two large and two small wheels of muon detectors. The MS contains two types of detectors: the precision chambers, that can be used to measure the p_T of the muons through a precise particle reconstruction, and the trigger chambers, which are detectors with a fast readout for the trigger system. A good measurement of the total energy deposit is needed to correctly calculate E_T^{miss} .

The Precision Chambers can be found in the barrel and end-cap regions. In the barrel region three layers of slightly overlapping Monitored Drift Tubes (MDTs) are installed at approximately 5 m, 7.5 m and 10 m from the interaction. In the end-cap region the MDTs have been mounted on four large wheels that are positioned perpendicular to the beam axis at a distance of approximately 7.4 m, 10.8 m, 14 m and 21.5 m from the interaction point. Due to the need for higher rate capability and time resolution, the wheel closest to the interaction point contains, in addition to the MDTs, Cathode Strip Chambers (CSCs).

The MDTs are pressurised aluminium tubes filled with a mixture of Argon and CO_2 . Each tube contains a tungsten-rhenium anode wire. The size of the MDT chambers increase with the distance to the interaction point.

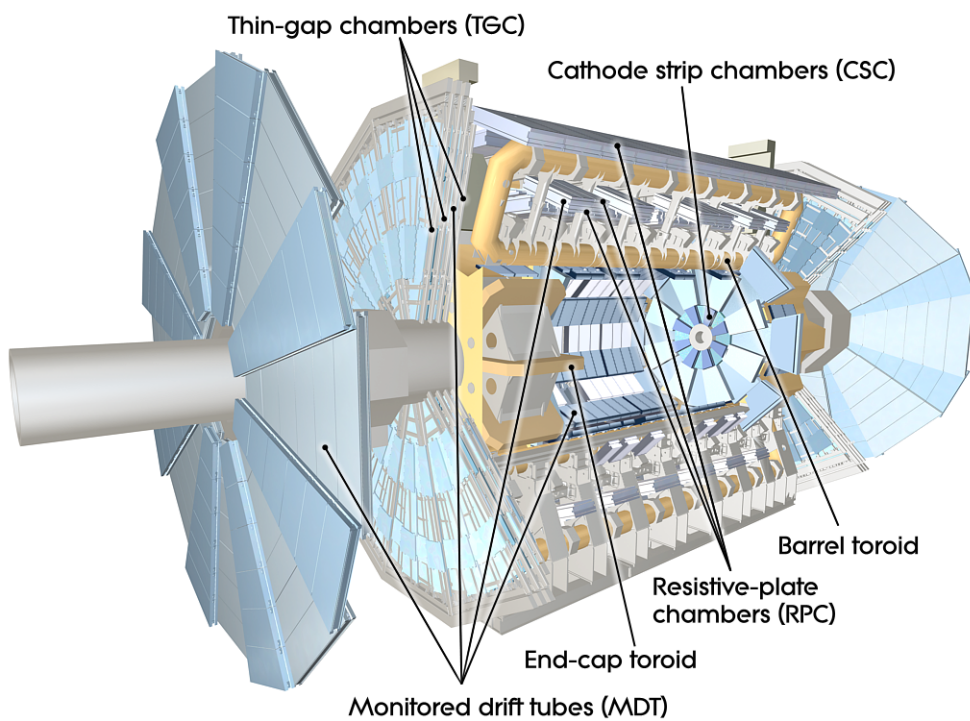


Figure 2.6: The muon spectrometer of the ATLAS detector partially cut-away to show the different subsystems of the spectrometer. This figure is taken from [94].

The CSCs are trapezium shaped multi-wire proportional chambers containing two cathode strips per plane. The CSCs are installed perpendicular to each other.

The Trigger Chambers of the MS are used to trigger the muon tracks and complement the precision tracking chambers. The trigger system of the MS is composed of three stations of two layers each in the barrel region. Each layer contains a gaseous parallel electrode-plate detector called the Resistive-Plate Chambers (RPCs). The RPCs have a time resolution of 1.5 ns and a spacial resolution of 10 mm. In the end-cap region the trigger chambers are composed of four layers of Thin-Gap Chambers (TGCs). One TGC is located on the innermost precision tracking wheel and the other three surround the third MDT wheel.

2.2.5 Trigger and Data Acquisition

The ATLAS trigger system and data acquisition system (DAQ) are needed to reduce the amount of data from the detector significantly. In Run 1 the time spacing between the proton bunching was 50 ns with a bunch crossing rate of 20 MHz. With on average around 20 interactions per bunch crossing, the rate is of the order of GHz for individual proton interactions. For each of these events tens of thousands read-out channels of the ATLAS detector deliver information, which sums up to approximately 1.5 MB per event. It is not possible to process and store in the order of petabytes of data per second. Therefore a quick selection is needed to select events that are interesting to lower the rate to maximally 1.6 GB/s. This is equivalent to a rate around 1kHz. In the second run of the LHC the rate is increased further due to increased luminosity, which means an even stronger data reduction is needed.

The trigger system contains three stages: the Level-1 (L1) and Level-2 (L2) trigger and the Event Filter (EF). The L2 and EF stages are also referred to as the High-Level trigger (HLT). In the second run of the LHC the L2 and EF stages have been merged into one trigger stage. The stages are set up to do fast reconstruction of physics objects and make a decision. Each stage refines the decision making of the previous stage and significantly reduces the event rate, but is also slower than the stage before it. This is a trade-off between speed and accuracy. After the incoming data has gone through the L1 trigger they are stored by the Data Acquisition System (DAQ). Recording for offline data analysis occurs after all trigger levels are passed. A diagram of the ATLAS trigger and DAQ is shown in figure 2.7.

The L1 trigger is hardware based and reduces the data approximately by a factor 400. The L1 trigger is based on hits in the trigger chambers in the

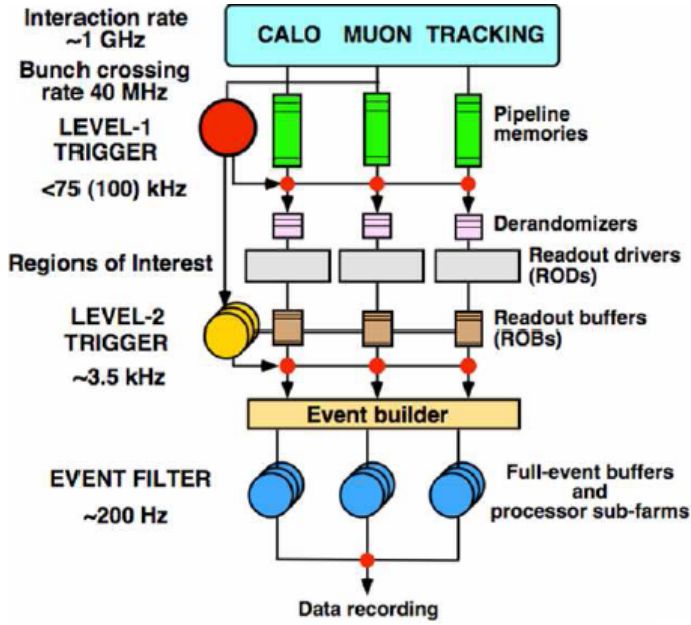


Figure 2.7: Diagram of the ATLAS trigger and Data Acquisition Systems in Run 1 of the LHC. This figure is taken from [103].

MS as well as in the calorimeter. The trigger in the calorimeter (LICALO) is able to trigger separately on electrons, photons, taus, jets and E_T^{miss} while the MS trigger is able to identify the high- p_T muons. The L1 trigger uses this information to define Regions of Interest (RoI) corresponding to a cone in the $\eta - \phi$ region in the detector, from the interaction point towards the MS system. The events that pass the L1 trigger are used in the software based L2 trigger. The L2 trigger reduces the data approximately by another factor 30. The L2 trigger performs a fast reconstruction of the full event. The events that pass the L2 trigger are sent to the Event Builder (EB) and after that to the EF. The EF uses the full detector to perform an event reconstruction, which is done offline. After all the trigger levels the data rate is reduced to 400 Hz in the first run of the LHC and to 1 kHz in the second run of the LHC. The full trigger system and DAQ takes approximately 4 s, after which the data is stored for offline analysis.

2.3 Detector Simulation

To accurately compare the collected data with predictions from MC, the detector response for each process has to be simulated. The paths of particles emerging from the collision that traverse the ATLAS detector are simulated after the event generation as described in section 1.6. The simulation of a collision event includes the simulation of a hard scattering, followed by the decays of short lived particles and showering. A full simulation of the ATLAS detector is built in GEANT4 [105]. GEANT4 simulates the response of the detector as particles interact with matter. The full simulation of the ATLAS detector is computationally expensive. In particular the simulation of the calorimeters takes a lot of time. A fast parametrised simulation of the calorimeter system, the ID and muons, is provided by ATLEFASTII [106]. Although the fast simulation is not as accurate as the full simulation, since it does not use the full granularity of the calorimeters, it does reduce computing time considerably. The fast simulation is used for high statistics samples and is extensively validated against full simulation.

After the generated events passed the detector simulation they are run through the same calibration and reconstruction algorithms that are used for data. This way, the simulated data resembles the data produced by the interactions as accurately as possible. Generated collision events before running the detector simulation are referred to as *truth level*, while after simulation the events are referred to as reconstructed, or *reco level*.

3 Event and Object reconstruction

The goal of event and object reconstruction is to reconstruct final state particles that are produced in the LHC collisions in the centre of the ATLAS detector as accurately as possible. The object is a physics object, such as for example a reconstructed electron or jet. To reconstruct events and objects, information in the form of hits in the sub-detector systems of the ATLAS detector is used. The detector hits of charged particles are used to reconstruct tracks of these particles in the inner detector and muon spectrometer, and energy clusters in the calorimeters. Since each type of particle leaves a different trace in the detector, the particles can be identified. Before the particles can be identified for use in an analysis, the detector information has to go through three steps. First the data has to be selected using trigger information. Secondly hits in the detector have to be combined to reconstruct tracks of particles and reconstruct the vertices. Lastly the tracks, vertices and calorimeter clusters are combined to create physics objects and identify particles. These steps are needed for all physics objects, however throughout this chapter, a particular focus will be on the muon reconstruction as an example for the reconstruction details.

3.1 Data streams

Info from the ATLAS trigger system is used to sort collision events in multiple slices, based on the triggers that select the event. These slices are stored in inclusive *streams* that are used to select the data. There are four types of primary physics streams based on different physics information: Egamma, Muons, JetTauEtmis and MinBias, and several additional calibration streams. The sequence, called the trigger chain, reconstructs and selects steps that have to be followed to efficiently trigger upon certain signatures. The trigger chain includes two types of algorithms. The first algorithm, Feature Extraction (FEX), is used to create an object, such as clusters in the calorimeter. The second algorithm, Hypothesis (HYPO), is used to apply a specific selection

criteria to the objects, such as requiring $p_T > 20$ GeV. The trigger sequence includes different trigger classes:

- *Single Object Triggers* are used for final states with at least one characteristic object.
- *Multiple Object Triggers* are used for final states with two or more characteristic objects of the same type.
- *Combined Triggers* are used for final states with two or more characteristic objects of different types.
- *Topological Triggers* are used for final states that require a selection based on information from more than one region of interest.

Trigger rates are controlled by periodically changing the thresholds, or by changing the selection criteria. Pre-scale factors can be applied to each trigger chain, such that only a percentage of the events pass the trigger. The pre-scale changes are adjusted during the fill of the LHC, taking advantage of the decrease in instantaneous luminosity, to maximise the bandwidth and ensure a constant trigger rate, which is useful for monitoring and calibration. The pre-scale changes in Run 2 are used to cope with the increasing trigger rates, due to the increasing luminosity and pile-up.

3.2 Tracks and Vertices

Hits in the Inner Detector (ID) are combined into tracks. The point from which the tracks originate, the vertex, must be reconstructed. Each bunch crossing usually contains multiple vertices, since multiple pp collisions occur at each bunch crossing.

3.2.1 Track Reconstruction

Tracks are reconstructed from hits in the ID. Tracks in the ID are parametrised by helices, which are reconstructed using the New Tracking (NEWT) algorithm [107]. The NEWT algorithm consists of multiple sequences of algorithms to efficiently identify the trajectories of primary charged particles. Primary charged particles are particles with a lifetime greater than 3×10^{-11} s directly originating from a pp interaction, or from subsequent decays or interactions of particles with a lifetime shorter than 3×10^{-11} s. The track reconstruction efficiency is measured as the fraction of reconstructed tracks corresponding to simulated particles with $p_T > 400$ MeV and $|\eta| < 2.5$ as a function of the track p_T and η .

An **inside-out** algorithm is used to reconstruct the trajectories of primary charged particles. Inside-out tracking uses hits in the silicon detectors, Pixel and SCT, as the seed for the track candidate. Hits are added to the track candidate from the centre of the detector moving outwards. The additional points are chosen by a combinatorial Kalman Filter [108]. The seeds of track candidates consist of three hits in the silicon detectors, which are translated into three-dimensional space points. The seeds are classified according to their sub-detector location. There are four types of combinations of space points:

- Three hits in the pixel detector; PPP
- Three hits in the SCT detector; SSS
- Two hits in the pixel detector and one hit in the SCT detector; PPS
- One hit in the pixel detector and two hits in the SCT detector; PSS.

A single seed can be used to form more than one track candidate. Fake tracks can occur when the same space point is assigned to more than one track candidate. These ambiguities in the track reconstruction must be resolved to remove fake tracks. This is done with dedicated algorithms. The quality of a track candidate can be influenced by holes, outliers and hits. Holes are space points where a hit in the detector is expected, but no hit is observed. Outliers are space points assigned to the track candidate which results in a poor track fit. The reconstructed tracks from the pixel detector and the SCT, are extended in the TRT. The inside-out algorithm is the baseline algorithm designed for the efficient reconstruction of primary charged particles. As a second step, **back-tracking** is designed to reconstruct secondary particles, which are particles produced in the interactions of primary particles with a large lifetime. Back-tracking is a method to search for tracks, starting from segments reconstructed in the TRT and extending these tracks inwards by adding silicon hits. Tracks with a TRT segment, but no extension into the silicon detectors, are referred to as TRT-standalone tracks [109].

3.2.2 Resolution

The momentum scale and resolution of the ID are studied using a tag-and-probe approach. This method identifies pairs of isolated, oppositely charged muons from Z decays by matching independently reconstructed ID and MS tracks. The tag-and-probe approach exploits well known di-muon resonances and works as follows. A combined muon track, which is described in 3.3.2, is required in the event as the tag. The tag is then paired with a track reconstructed in the ID, the probe, giving an invariant mass close to the considered resonance mass.

The fraction of reconstructed signal probes measures the muon identification efficiency. Each muon had a transverse momentum of at least 25 GeV in the central region of $|\eta| < 2.5$. The fractional ID momentum scale resolution, $\sigma(1/p)/(1/p)$, is measured using a un-binned maximum likelihood fit. For this fit $1/p$ is used, rather than p , since this is proportional to the track radius. The fit is done on a parametric function that describes the Z bosons intrinsic spacial resolution and multiple scattering effects in the traversed material and the invariant mass distribution of the Z boson reconstructed with ID tracks only. The result of this fit is shown in figure 3.1.

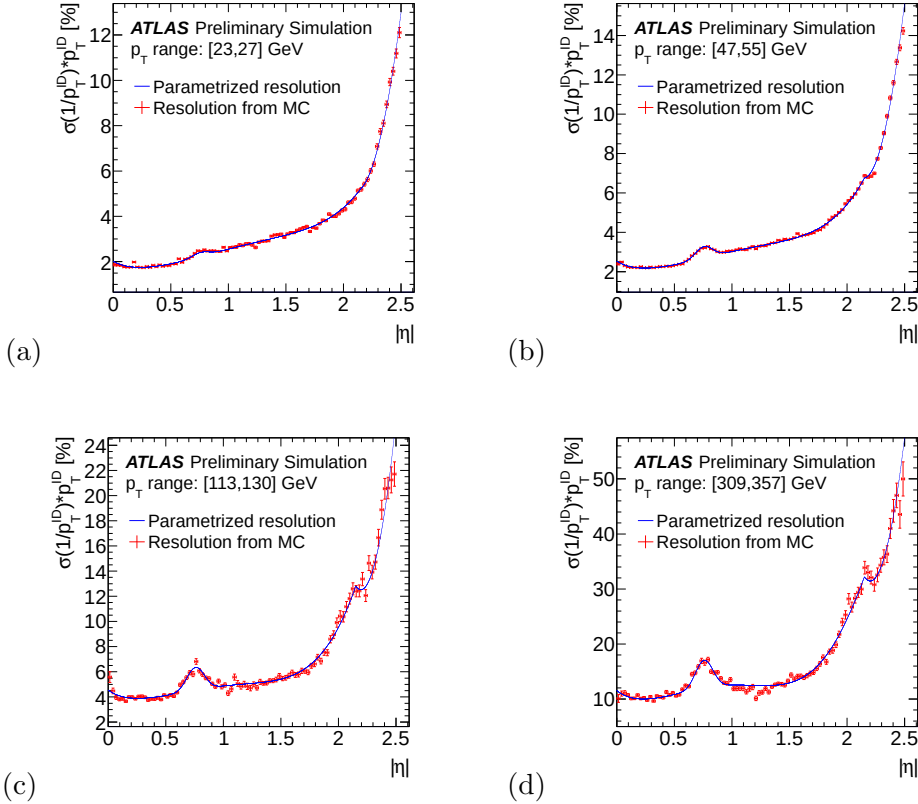


Figure 3.1: Fractional ID momentum resolution as a function of pseudo-rapidity in four p_T intervals [110]. The dots with error bars show the fractional resolution in MC simulation and the line shows the projection of the fit. The effects of multiple scattering in the traversed material is taken into account.

The impact parameter resolution is important for processes relying on heavy flavour tagging of jets, in jets originating from a b-quark. For example, processes relying on b-jet identification are top quark pair production and Higgs decays to a pair of bottom quarks. Multiple scattering effects can degrade the impact parameter resolution. Therefore, the transverse impact parameter, d_0 , and modified longitudinal impact parameter, $z_0 \sin \theta$, are measured as a function of the pseudo-rapidity for two different regions in $p_T \sqrt{\sin \theta}$, which is directly proportional to multiple scattering effects [110]. The efficiency to tag the flavour of the jet is shown in figure 3.2, as a function of the p_T of the jet.

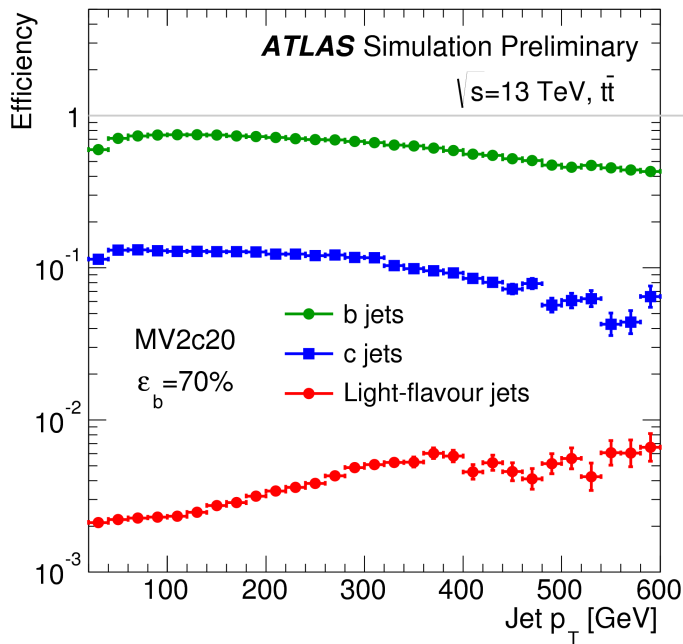


Figure 3.2: The efficiency to tag b (green), c (blue) and light-flavour (red) jets for the MV2c20 tagging algorithm with the 70% operating point. Efficiencies are shown as a function of the jet p_T [111].

3.2.3 Primary Vertex Reconstruction

Primary vertices from pp interactions in the ATLAS ID detector are reconstructed using an iterative search strategy. Vertices are reconstructed from tracks with 9 hits in the silicon trackers, which is the SCT and Pixel detectors combined, with at least 4 hits in the SCT, and with the requirement that there are no holes in the pixel detector [112].

The vertex reconstruction is composed of five stages.

1. A set of tracks is defined that fulfil the following requirements: Each track is required to have $p_T > 400$ MeV, $d_0 < 4$ mm and a resolution of the transverse and longitudinal impact parameters of $\sigma(d_0) < 5$ mm and $\sigma(z_0) < 10$ mm. In Run 2 the vertex reconstruction has the additional requirements of at least 1 hit in the IBL or in the first layer of the pixel detector and not more than one hole in the SCT.
2. The seed position of the vertex originates from the beam spot position.
3. An adaptive χ^2 fit is used to precisely estimate the true vertex position. The fit uses a set of tracks and the seed position of the vertex as input. In the fit, each track is assigned a weight that corresponds to the compatibility of the track with the position of the vertex. The best estimate position of the vertex is re-fitted using the weighted set of tracks.
4. The tracks that are incompatible with the reconstructed vertex are removed. The removed vertices can be used to find another vertex.
5. The remaining tracks of the event are used to perform the vertex reconstruction again.

In order to have a high efficiency, each vertex is required to be associated with at least four tracks. The vertex reconstruction efficiency for the hard scattering process, as well as the efficiency to reconstruct and select the primary vertex, as a function of the average number of inelastic interactions per bunch crossing, is shown in figure 3.3.

3.3 Objects

The reconstructed tracks and vertices are combined with calorimeter information to construct physics objects and identify particles.

3.3.1 Electrons and Photons

A typical electron signature has an associated track in the ID, as well as a deposit in the electromagnetic calorimeter. Particle showers that are fully contained in the electromagnetic calorimeter can originate from electrons or photons. Electrons are expected to have a track associated with the energy deposit in the calorimeter. A photon typically has a deposit in the electromagnetic calorimeter as well, however, due to the lack of charge, has no associated track. The calorimeter signals for electrons and photons are indistinguishable, which makes track information of vital importance.

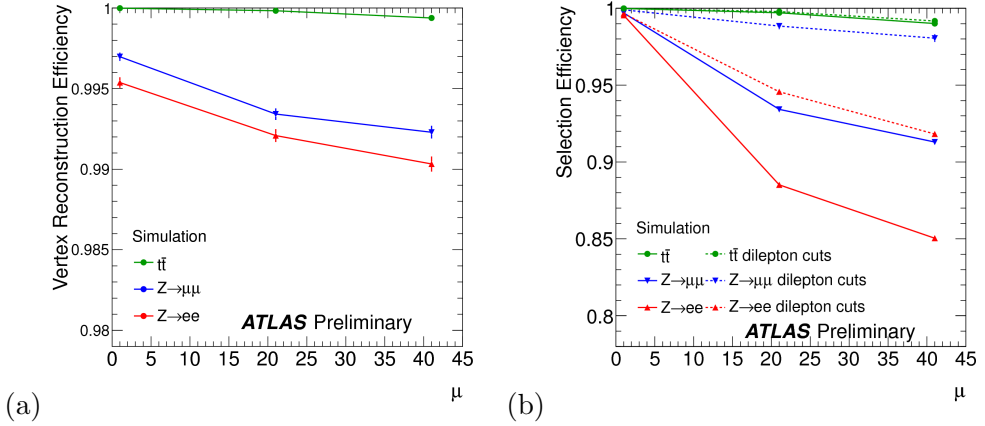


Figure 3.3: (a) The vertex reconstruction efficiency for the hard scattering process, as a function of the average number of inelastic interactions per bunch crossing and (b) the efficiency to reconstruct and select the true primary vertex, as a function of the average number of inelastic interactions per bunch crossing [113, 114, 115].

Electrons

Electrons are reconstructed from cluster seeds in the electromagnetic calorimeter in the central region of the detector where $|\eta| < 2.47$. Each electron candidate must have at least one track associated to the cluster's energy deposit. When more than one track is associated to the electron candidate, the track with hits in the silicon detectors is prioritised. The track with the smallest distance to the centre of the cluster is then picked. In the forward region, $|\eta| > 2.47$, there are no tracks associated to the cluster's energy deposit, and electrons are not distinguishable from photons.

The electron energy scale is calibrated using $Z \rightarrow e^+e^-$ events from data and simulation. The electron identification is based on variables that are sensitive to the longitudinal and transverse shape of the shower in the calorimeter, the properties of the tracks and the matching of the tracks to the cluster [116, 117, 118].

Various discriminating variables are combined into selection criteria in order to identify real prompt electrons with high efficiency. Prompt electrons are electrons originating from the primary vertex, while non-prompt electrons originate from additional scattering interactions in the detector. There are three efficiency working points, loose, medium and tight, with increasing background rejection power. The loose working point uses shower shape variables in the first and second layer of the ECAL and variables that quantify

the amount of leakage into the HCAL. To improve the rejection of hadronic particles, requirements on the track quality and the track cluster matching are added. The medium working point additionally requires a hit in the innermost layer of the pixel detector to have a better separating power between electrons and photons. Furthermore, a loose selection on the impact parameter is added and extra information from the TRT is used to reject background from charged hadrons. The background rejection power of the medium working point is an order of magnitude better than the loose working point background rejection. The tight working point uses the selection criteria of the medium working point, while also taking the ratio of cluster energy over track momentum (E/p) into account. The tight working point also applies a veto on reconstructed photon conversion vertices associated with the cluster. The background rejection power of the tight working point is around a factor two better than the rejection power of the medium working point [116, 119, 120]. To better identify prompt electron and reject fakes and non-prompt electrons, typically light jets or non-prompt electrons coming from semi-leptonic decays of heavy hadrons, isolation criteria can be used. The isolation criteria require that only a small amount of energy is deposited in a narrow cone around the electron candidate. The electron reconstruction and identification efficiency is shown in figure 3.4 as a function of the transverse energy and η .

Photons

In the same way as for the electrons, photons are reconstructed from energy deposits in the clusters of cells in the electromagnetic calorimeter. A converted photon is reconstructed if a track associated to a cluster is found to originate from a conversion vertex where a photon has split into a electron-positron pair. A conversion vertex typically has two oppositely charged tracks emerging from the vertex in parallel in the ID, or with a single track where the energy deposit in the calorimeter is much larger than the momentum of the track. An unconverted photon is reconstructed from a cluster with no track associated to it.

Reconstructed photons can either be prompt, meaning that they originate from the primary vertex, or originate from jets. Prompt showers typically leave a narrow and contained shower in the electromagnetic calorimeter with limited leakage into the hadronic calorimeter. Just as for the electrons, the shape of the shower in the electromagnetic calorimeter and the leakage into the hadronic calorimeter are therefore used to identify prompt photons [121].

Two sets of cut-based selections are defined to identify photons, loose and tight. The loose selection is based on the shower shape and energy deposit in the hadronic calorimeter. The tight selections adds information from the first layer of the ECAL, which in particular provides good rejection of neutral

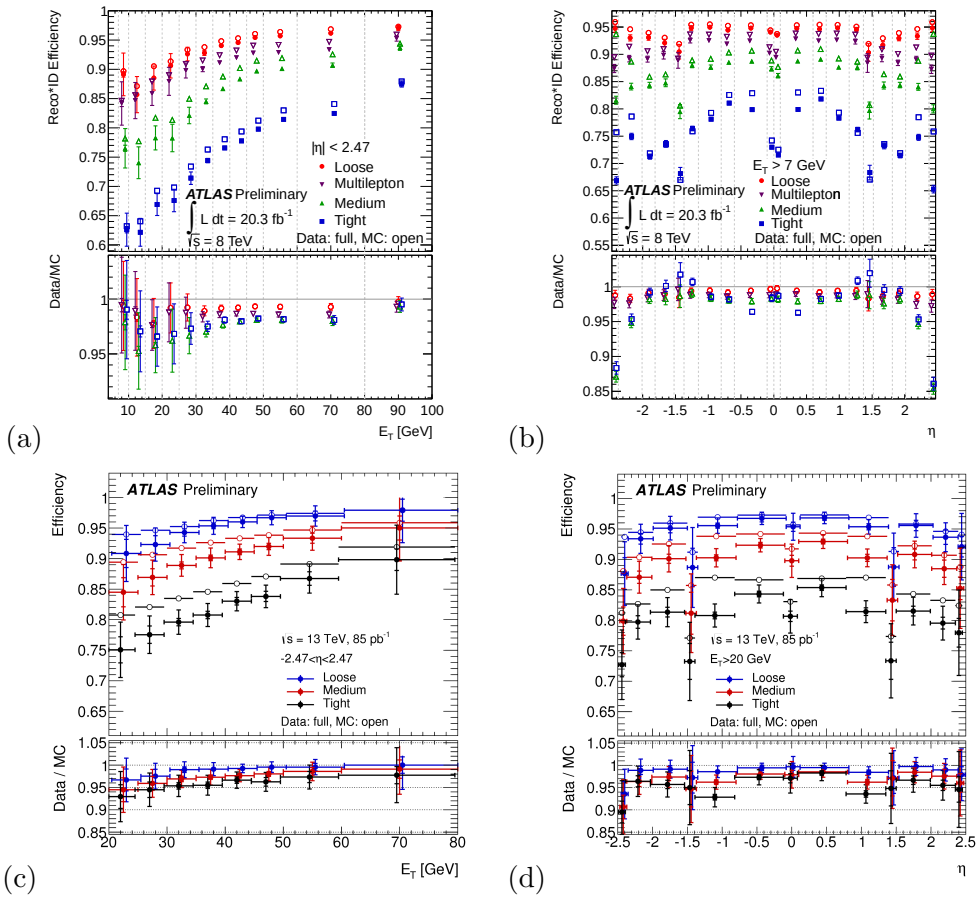


Figure 3.4: Electron reconstruction and identification efficiency as a function of transverse energy for (a) Run 1 [117] and (c) Run 2 [118], and as a function of η for (b) Run 1 and (d) Run 2.

hadrons decaying into photons, $\pi^0 \rightarrow \gamma\gamma$. In addition an isolation requirement is required, which requires that the transverse energy in a cone of size $\Delta R = 0.4$ around the photon candidate should be $E_T^{iso} < 4$ GeV.

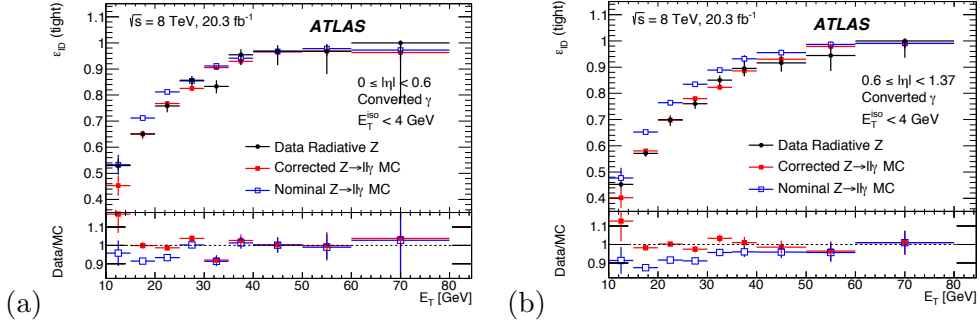


Figure 3.5: Photon identification efficiency as a function of transverse energy for (a) unconverted photons and (b) converted photons [122].

3.3.2 Muons

Reconstruction and identification

For the reconstruction and identification of muons, information from the Inner Detector (ID), the Muon Spectrometer (MS) and the calorimeter are used. Two independent software packages exist to reconstruct muon trajectories; Muid and Staco. They both follow the general points strategy below.

- 1) A global search for patterns in the hit distribution in the MDT (Monitor Drift Tube) of the MS is performed.
- 2) The identified patterns, called segments, in the MS are fitted by straight lines.
- 3) Segments are combined to form track candidates that are extrapolated to the interaction point.
- 4) In the **First Chain** the MS track candidates are combined with ID tracks.
- 5) In the **Second Chain** the remaining ID tracks are combined with single, or multiple, MS segments without requiring a full MS track.

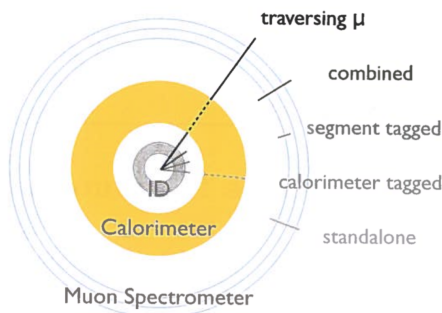
The first chain combines an inner detector track with a muon spectrometer track using a statistical method. The second chain, however, combines an inner detector track with a muon spectrometer track using a global refit of the two tracks. ID tracks without any MS segments are fit with the MuGirl package. For Run 2 a third chain is introduced which replace the first and second chain. The third chain combines the first and second chain in a combined fit where

ID and MS information is used simultaneously. The combined tracks that are the results of the first, second or third chain, are required to pass a number of cuts to determine if this is a muon track. This process, as well as a description of the pattern recognition, is explained below.

The selection criteria on the quality of the muon track to identify muons in Run 1 are based on a minimum number of hits and a maximum number of holes [123]. For Run 2 a dedicated identification algorithm was optimised to select muons produced in the hard scattering (prompt muons), and suppress muons formed inside hadronic jets (non-prompt muons) [124]. The muon identification is based on several quality cuts. The first cut is on the difference between the charge over momentum ratio, (p/q) , measured in the ID and MS, divided by the combined uncertainty on p/q . The difference between the p_T measured in the ID and MS divided by the p_T of the combined track and the quality of the fit of the combined track are used for the identification. Four working points are defined, loose, medium, tight and high- p_T . Loose muon identification is optimised to recover identification efficiency in the crack region of the muon spectrometer, $|\eta| < 0.1$. The medium working point is the default for Run 2. The tight muon selection has a higher purity, but lower efficiency and the high- p_T working point is optimised for a better momentum resolution of muons with $p_T > 100$ GeV.

Muon tagging

There are four different ways to tag a muon, depending on what detector information is used. A diagram is shown to illustrate and summarise the different muons in figure 3.6.



1. Calorimeter tagged muons use muon identification algorithms that are completely independent of the MS. This method is useful for areas where there is limited MS coverage, such as at $\eta = 0$. Two algorithms are used to identify calorimeter tagged muons; *CaloMuonTag* and *CaloLikelihood ratio*. Both of these algorithms use the ID tracks that are extrapolated to the calorimeter. When the ID tracks are matched with the calorimeter hits, the measured energy deposits in the calorimeter are used to distinguish muons from electrons, since electrons deposit all their energy in the calorimeter, and the muons typically do not.

2. Standalone muons are the muons that are tagged before information from the MS is combined with ID track information. These muons use only the MS tracks.

For Muid and Staco, different track identification and reconstructing algorithms are used. These two algorithms are purely based on MS measurements and work as described in section *Pattern recognition*. Tracks identified and reconstructed by the Moore algorithm for Muid and by the MuonBoy algorithm for Staco.

3. Combined muons are the muons that are tagged after the MS tracks are combined with ID tracks. The standalone muons are combined with ID tracks to get combined muons. There are again two algorithms, one for Muid and one for Staco. Both of the algorithms use χ^2_{match} to find possible matches of pairs of standalone and ID tracks. The definition of χ^2_{match} is

$$\chi^2_{match} = (t_{MS} - t_{ID})^T (cov_{MS} + cov_{ID})^{-1} (t_{MS} - t_{ID}), \quad (3.1)$$

where t are the track parameters, such as the p_T of the track, and cov the corresponding covariance matrix.

Muid combined tracks are obtained by combining the track parameters and fitting the ID and MS measurements of the two tracks. Staco combined tracks are obtained by a statistical combination of ID and MS tracks which is defined as $t_{staco} = (cov_{ID}^{-1} + cov_{MS}^{-1})^{-1} (cov_{ID}^{-1} t_{ID} + cov_{MS}^{-1} t_{MS})$. Due to the efficiency of the combined fit, t_{staco} is not used anymore in Run 2.

4. Segment tagged muons are the muons that are tagged after ID tracks are combined with MS segments, without requiring a full MS track. In the overlap region between the barrel and the endcaps at $|\eta| \approx 1.2$, the standalone muon reconstruction is difficult. In this region the third MDT stations are missing which leads to less available measurements. Low momentum muons can also produce hits and segments in the MS, that are not found by the standalone algorithm. This happens if these muons have a large curvature. For these regions, segment tagged muons recover the efficiency losses. This is done by extrapolating the ID tracks and matching those to track segments in

the MS. For this method a full MS track, as is used for the combined muons, is not needed. This method requires at least one MS segment.

Staco uses for this the MuTag tool. In general it extrapolates ID tracks only to the inner station. For $|\eta| < 1.4$ the MuTagTool also extrapolates to the middle stations and around the eta gap the outer stations are added. Important to note is that the MuTagTool uses only ID tracks and MS segments that are not already part of a Staco Combined muon. In this way less ambiguities need to be solved.

MuTagIMO is the segment tagging tool for Muid. It extrapolates ID tracks to all three muon stations; the Inner, Middle and Outer stations. Segments are matched to the extrapolated track at every station. It is an independent identification algorithm, which means it also uses ID tracks and MS segments that are already part of a Muid Combined muon. For MuTagIMO, this method is described in more detail below.

ID track selection for muons

Most tracks in the ID do not originate from a muon. To distinguish the muons a few selection cuts are applied. Muons with low momenta will not be able to reach the MS. To lower the mis-tagging rate a momentum cut of at least 3 GeV is applied. Dana analysts can add a cut at 5 GeV or 10 GeV to reduce the fakes even further, however these cuts could also cut some real muons. For this reason these higher thresholds on the momentum are not added to the tagger as standard.

To further reduce the fake-rate, a cut on the p_T is applied on the ID tracks which requires a p_T of at least 2 GeV. Only ID tracks with at least one pixel hit and at least three SCT hits are accepted.

MS segment selection for muon tagging

After the selection on the ID tracks, a selection on the MS segments is applied. The cuts on the segments are made to reduce the fake-rate, in particular to reject MS hits coming from b-jets produced in the detector.

There Run 1 cuts for this purpose are listed below.

- Reject MDT segments that are not close to chamber edges, which have more holes than hits and no trigger hits. A hole is a place where a hit is expected but not found. Close is defined as the requirement that the distance between the shortest tube and the corresponding chamber is less than 10 cm.
- Reject MDT segments in middle end-caps that have no trigger hits, in situations where trigger hits are expected.

- Reject MDT segments with less than 3 hits.

For Run 2 some cuts need to be adjusted to accommodate for the higher event rate. The changes to these cuts are listed in table 3.1.

Additionally to these changes in the cuts, some additional cuts are applied for Run 2. These are listed below.

- Reject segments with a lone outer end-cap hit.
- Reject segments in all detector regions with no trigger hits when trigger hits are expected.

In collision events with many interactions, extrapolated tracks can often be matched to multiple segments in a single MS station. It is not physically possible that the muon crosses the MDT station more than once. Therefore it is mismatched to all MS tracks except for one. A segment can also be matched to multiple ID tracks. The selection cuts that are used, such as the cut on the number of holes, are described in section *Segment selection*. These cuts are used to reduce ambiguities such as the double matching of an ID track or MS segment. Further cuts are applied to solve these ambiguities.

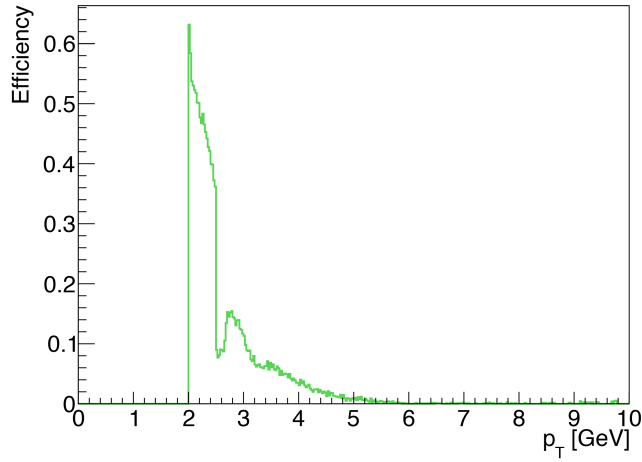
In the case that one ID track is associated to multiple segments in the same MS station, the segment with the smallest R_Y is taken. When multiple ID tracks are associated to the same MS segment, a quality factor is calculated based on R_Y , R_{YZ} and the number of segments that were associated to that ID track.

In Run 2 the events are busier, which will make solving these ambiguities even more important. Because of this, some of the cuts have been tightened. At the same time the geometry modules are updated and the segment and track selection are moved to one tool. Advanced track and segment matching is moved into the MuTagIMO tool directly. The new MuTagIMO tool still writes out a MuTagObject, but can now run on xAOD [125], which is the data format used in ATLAS in the second run of the LHC. All ambiguity solving is now done in one tool. The switch from the first and second chain to the third chain combined fit improved the tagging of muons dramatically. Therefore the

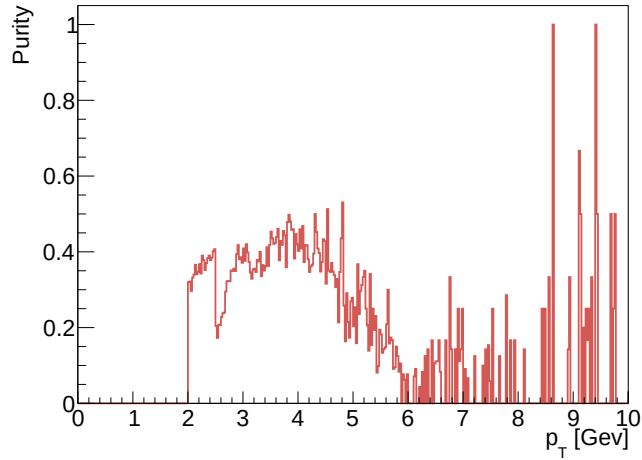
cut	Run 1	Run 2
MDT segments with combined pull	> 5	> 3
segments with $nTrigHit = 0$		
$\&nMDTHoles$	> 3	> 2
CSC segments with	$n\eta Hits + n\phi Hits = 0$	$n\eta Hits = 0$
CSC segments with		
$n\eta Hits + n\phi Hits$	< 4	$< 1 \&nExpTrigHit > 0$

Table 3.1: Changes in the rejection cuts from Run 1 to Run 2.

MuTagIMO tool is only called in the when there is insufficient information to run the third chain effectively, meaning in the eta rapidity gaps of the muon system of the ATLAS detector, and for low p_T muons. The efficiency and purity of the MuTagIMO tool for low p_T muons are shown in figure 3.6. The reconstruction efficiency of the full muon tagger is shown in figure 3.7



(a)



(b)

Figure 3.6: (a) The efficiency of the MuTagIMO tool (b) The purity of the MuTagIMO tool for $p_T < 10$ GeV.

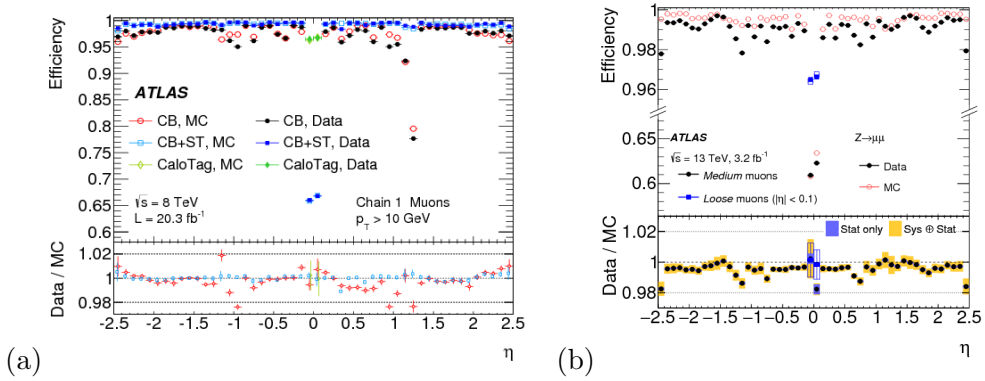


Figure 3.7: The muon reconstruction efficiency as a function of η with (a) 20.3 fb $^{-1}$ at $\sqrt{s} = 8$ TeV [123] and (b) 3.2 fb $^{-1}$ at $\sqrt{s} = 13$ TeV [124].

3.3.3 Jets

Jets are observed as clusters of topologically related energy deposits in the calorimeter system and are associated with tracks of charged particles that are reconstructed in the ID. The reconstruction of the jets can start either from the track, which are referred to as track jets, or from the calorimeter information, which are referred to as calorimeter jets. Track jets are built from ID tracks. Calorimeter jets are reconstructed from topo-clusters using collinear and infrared safe clustering algorithms [126]. Topo-clusters are energy deposits in topologically connected calorimeter cells with significant signal above a threshold to suppress electronic noise or noise from pile-up interactions.

The jet finding algorithm most commonly used in ATLAS is the anti- k_T clustering algorithm [127]. The anti- k_T algorithm is a sequential recombination algorithm, which means that the input objects are grouped together depending on the distance between them, d_{ij} , and the distance to the beam line, d_{iB} , where the distances are:

$$d_{ij} = \min((k_T^i)^{2p}, (k_T^j)^{2p}) \frac{\Delta R_{ij}^2}{R^2}, \quad (3.2)$$

$$d_{iB} = (k_T^i)^{2p},$$

where k_T^i and k_T^j are the transverse momenta of objects i and j . The ΔR_{ij}^2 is defined as

$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2, \quad (3.3)$$

where y_i and y_j are the rapidity of objects i and j and ϕ_i and ϕ_j are the azimuthal angle of objects i and j . The ΔR_{ij}^2 value is dependent on the specific algorithm used. For the anti- k_T algorithm p has the value -1, to ensure that

the clustering begins with the highest k_T object, in this case object i . The distances between the objects in the vicinity of object i , d_{ij} are compared to d_{iB} . When $d_{ij} < d_{iB}$, a combined object k is created from the combination of i and j , otherwise object i is defined as a jet.

Calibration and systematic uncertainties

Topo-clusters are calibrated to the energy scale of EM showers [128, 129]. In a second step jets are calibrated to the hadronic energy scale by classifying topo-clusters as either electromagnetic or hadronic based on the energy density and the longitudinal shower depth. The reconstructed jet energies are also corrected for the effects of pile-up. The jet energy calibration procedure exploits the balance between the jet transverse momenta and the transverse momenta of reference objects. The uncertainty on the jet energy scale (JES) is derived by a combination of test beam measurements, simulations and in-situ measurements [128]. The uncertainty on the jet energy resolution (JER) varies from 5% to 20% depending on p_T and η .

A tag-and-probe method, using tagged jets in data and the nominal inclusive jet in a Monte Carlo simulated sample, is used to derive the reconstruction efficiency for jets. The systematic uncertainty on the reconstruction efficiency for jets with $p_T < 30$ GeV is determined at 2%. At higher p_T the systematic is determined to be negligible.

Jet cleaning and vertex fraction

Several quality criteria are applied to the reconstructed jets, consisting of energy thresholds on the electromagnetic and hadronic calorimeters as well as the shape of electrical signals. These criteria reject calorimetric noise, beam-gas interactions and cosmic ray contamination of showers.

To identify jets originating from the primary vertex, an additional requirement on the Jet Vertex Fraction (JVF) can be applied to select high quality jets. The JVF is defined as the sum of the transverse momenta of all tracks arising from the primary vertex, and the sum of transverse momenta are matched to a jet divided by the total jet-matched track p_T from all vertices. Cutting on JVF rejects jets from pile-up interactions.

b-tagged jets

A jet originating from a b-quark is called a b-jet. The b-jets can be identified through various algorithms, based on impact parameters or secondary vertices. These algorithms all exploit the distinguishable feature of a b-quark, which is the lifetime. The topologies of the b-jet can be exploited to further improve the identification of b-jets. The MV1 algorithm [130], which is the most commonly

used b-tagging algorithm, combines the most discriminating variables in a multivariate algorithm. The output of the MV1 algorithm is a weight, related to the probability of the jet originating from b , c or light flavour quark. There are different b-tagging efficiency working points. Each analysis can choose a different working point, depending on their needs, which are a trade-off between higher efficiency and higher purity. The b-tagging efficiency at the 77% working point, and the jet flavour composition are shown in figure 3.8.

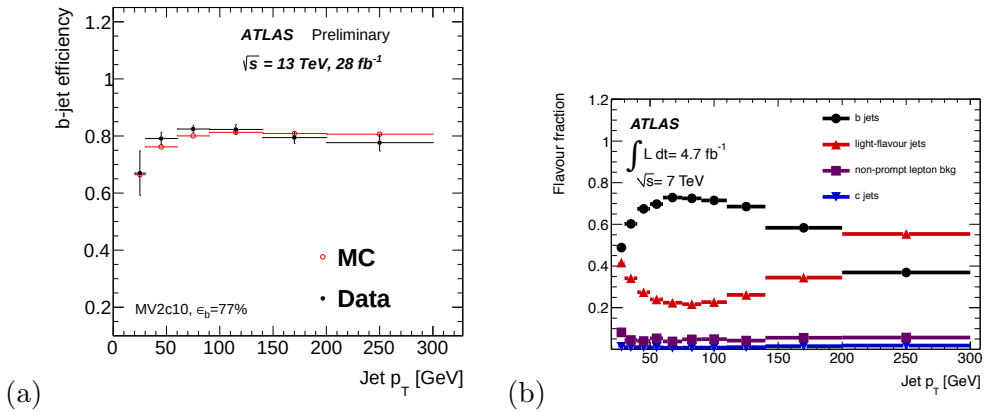


Figure 3.8: (a) b-tagging efficiency for the b-tagging algorithm at the 77% working point as a function of jet p_T , extracted from data (black) using the $t\bar{t}$ Probability Distribution Function method and in simulation (red) [131, 132]. Error bars indicating the combined statistical and systematic uncertainty are shown. (b) Expected jet flavour composition of the two leading jets in selected dilepton events as a function of jet p_T .

τ -leptons

The τ -lepton has a short lifetime, and is heavy enough to decay to either lighter leptons or light quarks. The hadronically decaying τ -leptons leave a jet-like signature in the detector. Information from the ID and the calorimeters is combined in a multivariate discriminant to reconstruct hadronic tau decays. Quantities that describe the shower shape in the calorimeter and ID are used to distinguish between hadronically decaying τ -leptons and jets coming from quarks or gluons. τ -lepton signals can be faked by electrons or QCD jets, which can be rejected by imposing a veto based on the emission of the transition radiation and by the measured shower shape in the calorimeter.

Hadronic tau decays are characterised by the number of charged particles in the final state, called prongs. Tracks from taus are expected to be collimated and

isolated and the substructure of the energy deposit of a tau in the calorimeter. The number of neutral pions and the energy deposited by neutral pions differs from a strongly produced jet. Independently trained BDTs are used to optimise a multivariate discriminant for 1-prong and 3-prong taus.

Three working points are defined for τ -lepton identification, loose, medium and tight, for three different cuts on the multivariate discriminant for 1-prong and 3-prong taus. The signal efficiencies for the three working points are dependent of the p_T of the tau. For the loose working point the efficiency is around 0.7, while for the medium working point the efficiency is reduced to around 0.6. For the tight working point the efficiency is further reduced to around 0.4. While the efficiency of the working points reduces, the purity increases.

3.3.4 Missing Transverse Momentum

Weakly interacting particles, such as neutrinos, traverse the ATLAS detector without any interactions and can therefore not be measured. The imbalance in the transverse momentum of particles that can be identified gives information on the transverse energy of particles that can not be measured directly. Reconstructing the vectorial sum of the calibrated energy of all objects gives the calorimeter based missing transverse energy, E_T^{miss} . The x and y components of the E_T^{miss} are a sum over the reconstructed physics objects,

$$E_{x,y}^{\text{miss}} = \sum_i E_{x,y}^{\text{miss},i} \text{ with } i = e, \gamma, \mu, \tau, \text{jets, soft,} \quad (3.4)$$

where soft objects are those with a transverse energy below the selection criteria used in the particle identification algorithms. The soft term can be estimated from deposits in the calorimeter and tracks. The x and y coordinates of the missing transverse momentum are used to calculate the total missing transverse momentum

$$E_T^{\text{miss}} = \sqrt{(E_x^{\text{miss}})^2 + (E_y^{\text{miss}})^2}. \quad (3.5)$$

A track-based reconstruction of the missing transverse momentum, p_T^{miss} , significantly improves the resolution by guiding the momentum measurement of soft objects, which are tracks with less than 0.5 GeV and associated with the primary vertex, using track information from selected leptons and jets that are associated to the primary vertex. The improvement of the resolution is about 20% with this method. The reconstructed transverse mass benefits from the enhanced missing transverse momentum resolution.

The E_T^{miss} resolution depends on the scalar sum of the transverse energy in an event, $\sum E_T$. The resolution is estimated using events without E_T^{miss} and in events containing neutrinos. The resolution of $E_{x,y}^{\text{miss}}$, using the track-based reconstruction of p_T^{miss} , as a function of $\sum E_T$ is shown in figure 3.9.

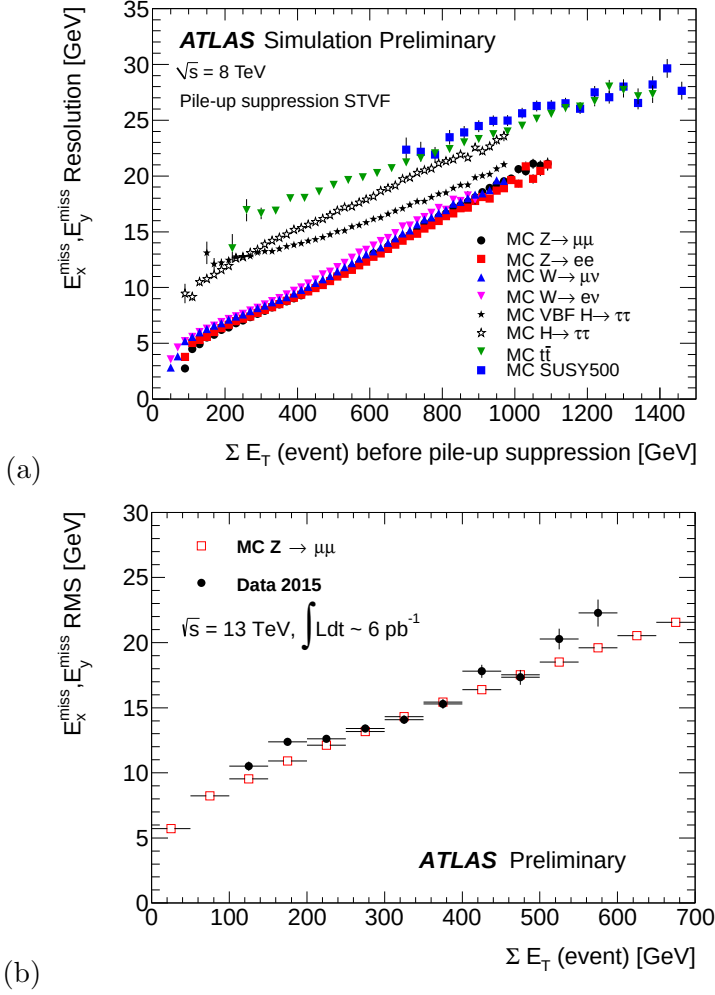


Figure 3.9: Resolution of the x and y components of E_T^{miss} (a) for several models estimated from MC simulations and (b) for a sample with neutrinos in the final state [133, 134].

4 Statistics

Data collected at the LHC, for example by the ATLAS detector, is used to test theories. An example of a theory that is tested at the LHC is the postulation of the existence of the Higgs boson. The theory gives a probability $P(x)$ for an observable x that can be measured. Strictly speaking, the probability $P(x)$ is a conditional probability of finding the measured data given the theory, $P(\text{data}|\text{theory})$, which can be studied at the LHC. The measured probability

$$P(\text{data}_{\text{observed}}|\text{theory})$$

is called the likelihood,

$$L(x) \equiv P(\text{data}|\text{theory}). \quad (4.1)$$

The probability $P(\text{theory}|\text{data})$ has a more intuitive meaning than $P(\text{data}|\text{theory})$. Bayes' theorem relates the conditional probabilities $P(A|B)$ and $P(B|A)$ as:

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}. \quad (4.2)$$

If A is interpreted as a certain theory, and B is the hypothesis that an experiment has a particular result, i.e. data, Bayes' theorem takes the form:

$$P(\text{theory}|\text{data}) \propto P(\text{data}|\text{theory}) \cdot P(\text{theory}). \quad (4.3)$$

Here $P(\text{theory})$ represents the prior probability that the theory is true and $P(\text{data}|\text{theory})$ is the likelihood. The posterior probability that the theory is correct after seeing the result of the experiment is then given by $P(\text{theory}|\text{data})$. In particle physics, results of experiments are nevertheless usually communicated in the form of $P(\text{data}|\text{theory})$, as $P(\text{theory}|\text{data})$ is always dependent on the inherently subjective notion of $P(\text{theory})$, which is the prior belief in the theory.

4.1 Theories with parameters

Often a theory has one or more parameters, denoted as μ . These theories are called composite hypotheses in statistics, as apposed to simple hypotheses which have no parameters. In this case, instead of studying the probability of finding the data under a hypothesis with a certain value of μ , the most likely value for parameter μ , denoted as $\hat{\mu}$, can be measured or, a confidence interval $[\mu_-, \mu_+]$, can be calculated. A confidence interval is defined as the range of μ for which, if the experiment is repeated many times, the intervals obtained will include the true value at the specified rate a , for example, 68% or 95%. In the example of the search for the Higgs boson, the μ parameter represents the signal strength and a can be chosen such that the confidence interval spans 2σ .

4.2 Poisson counting experiments

For a counting analysis the observable x corresponds to the observed count n in a given selection of collision events. The data set corresponding to the observed count is denoted $D = \{n\}$. Given an expected count v , the likelihood for this analysis is given by a Poisson distribution

$$L(D|H_\mu) = \text{Poisson}(n|v). \quad (4.4)$$

In this case a null hypothesis can be created,

$$H_0 = P(D|v_b), \quad (4.5)$$

where $v_b = \sum_k v_b^{(k)}$ is the expected count under the hypothesis that there is only the SM background and no new physics. A signal hypothesis can be created as

$$H_1 = P(D|v_b + v_s), \quad (4.6)$$

where v_s is the expected count for the new physics process. Alternatively a composite hypothesis can be created by introducing a parameter that controls the signal strength, μ , as

$$H(\mu) = P(D|v_b + \mu v_s), \quad (4.7)$$

which corresponds to H_0 for $\mu = 0$ and to H_1 for $\mu = 1$.

4.3 Modelling distributions

When designing an experiment it is often beneficial to not only use the continuous observables x in the data to define an event selection that is interpreted as a counting experiment with event count n , but to use a subset of these continuous observables in the statistical analysis of the data. If the distributions of these observables are analytically known, one can replace $P(n|v)$ with a continuous probability density function $f(x|v)$ to express the likelihood. At the LHC, such analytical expressions are generally not known, and knowledge of these expected distributions for signal and background is inferred from MC simulation and expressed in histograms. As a histogram is effectively a collection of counting experiments, the probability model for binned datasets in a continuous observable x can be expressed as a product of Poisson distributions

$$L(D|H_\mu) = \prod_{i=1}^n \text{Poisson}(n_i|v_i). \quad (4.8)$$

This likelihood can be rewritten as a function of μ as:

$$L(D|H_\mu) = \prod_{i=1}^n \text{Poisson}(n_i|v_b + \mu v_s). \quad (4.9)$$

4.4 Modelling uncertainties

The expected counts v_i are generally not known perfectly, but depend on uncertainties in the simulation chain, as well as MC statistical uncertainties. The uncertainties in the MC simulations chain range from effects in the matrix element theory calculations to experimental uncertainties in the modelling of the detector, such as for example track reconstruction. To be able to express these uncertainties, each is quantified into one or more model parameters that describe the effect of these uncertainty parameters on the probability model of the measurement. As these parameters, while necessary, are not of interest in the final result, these are collectively referred to as nuisance parameters. The physics parameters are known as the *parameters of interest*. The parameter of interest, POI, of the tested model is denoted by μ , and indicates a continuous set of hypotheses as defined in equation 4.7, while the nuisance parameters are denoted by θ .

4.4.1 Nuisance parameters and modelling uncertainties

The relation between the data and the POI is influenced by systematic uncertainties. These uncertainties need to be incorporated into the statistical model

of a physics measurement. To be able to incorporate these uncertainties into the likelihood, there are several requirements:

- One or more degrees of freedom must be identified that are uncertain. These degrees of freedom will be expressed in the form of nuisance parameters.
- The response function, $v_s(\alpha)$, needs to be measured, to measure the response of the physics likelihood to the change of nuisance parameter values.
- A separate likelihood that describes the external knowledge on the nuisance parameters is needed if such information exists. These likelihoods are called the subsidiary measurements and are expressed as likelihood functions that measure the nuisance parameters α in a simplified representation of the actual measurement. A commonly used form is to define the meaning of the parameter α such that the value 0 corresponds to the nominal representation and the values ± 1 correspond to the prediction at $\pm 1\sigma$ deviations allowed by the external information. In this representation the form of the subsidiary measurement reduces to a unit Gaussian.

The full likelihood including the constraint terms explicitly, using the ingredients described above, is:

$$L_{full}(D|H_\mu, \alpha) = L_{phys}(D|v_b(\alpha) + \mu v_s(\alpha)) \times L_{sub}(0|1, \alpha), \quad (4.10)$$

where L_{phys} is the likelihood as shown in equation 4.9 and L_{sub} is the likelihood of the subsidiary measurements. The joint distribution of subsidiary measurements represents an uncorrelated estimate of each nuisance parameter, as each underlying case is a-priori assumed to be independent. If however two or more nuisance parameters have a very similar response in the physics model, the maximum likelihood estimates of the nuisance parameters on the full likelihood of equation 4.10 may become correlated.

4.5 Parameter and Variance Estimation

Maximising a likelihood function $L(\alpha) = L(D|H_\mu, \alpha)$ as in equation 4.10, with respect to the parameters α_i , gives the value of α_i for which the data is most probable. The maximum likelihood estimators, MLEs, for α are denoted as $\hat{\alpha}$. Maximising $L(\alpha)$ is equivalent to minimising $-\ln L(\alpha)$, and are the solutions of equations

$$\frac{\partial \ln L(\alpha)}{\partial \alpha_i} = 0 \quad \forall \alpha_i \in \alpha. \quad (4.11)$$

When the solution to equation 4.11 can not be found analytically, it needs to be calculated numerically. For LHC analyses the numerical minimisation is done using MINUIT [135].

The effect of all nuisance parameters on μ that are correlated with α are incorporated in the variance-covariance matrix $V_{ij} = \text{cov}(\hat{\alpha}_i, \hat{\alpha}_j)$. The HESSE algorithm in MINUIT measures the Hessian matrix from finite steps in the likelihood function to obtain the variance-covariance matrix as

$$H_{ij}(\hat{\alpha}) = -(V)_{ij}^{-1}(\hat{\alpha}) = \left. \frac{\partial^2 \ln L(\alpha)}{\partial \alpha_i \partial \alpha_j} \right|_{\hat{\alpha}}. \quad (4.12)$$

As is apparent from equation 4.12, nuisance parameters θ for which $\frac{\partial^2 \ln L(\alpha)}{\partial \theta \partial \mu}$ is non-zero will increase for the variance estimation on μ .

4.6 Interval Estimation

4.6.1 Observed limits and intervals

To create an interval estimation with a calibrated confidence level of a parameter μ , first a function of the data, called a *test statistic*, is formulated to express the compatibility of the data with hypothesis $H_\mu = H(\mu)$. A confidence interval in μ can be calculated from the values of T_μ for each value of μ . A practical way to create such a test statistic for a hypothesis with one parameter of interest is a likelihood ratio:

$$T_\mu = \frac{L(\mu)}{L(\hat{\mu})}. \quad (4.13)$$

The compatibility of the hypothesis is expressed in the p-value, the probability to observe a signal as large as observed in the data, or larger¹, under the assumption that H_μ is true. This probability is calculated as:

$$p = \int_{t_{\text{observed}}}^{\infty} f(T_\mu) dt. \quad (4.14)$$

The p -value can be translated into a significance, Z , which is defined as the number of standard deviations corresponding to the p -value as:

$$\begin{aligned} Z &= \Phi^{-1}(1 - p) \text{ for a one - sided distribution,} \\ Z &= \Phi^{-1}(1 - 2p) \text{ for a two - sided distribution,} \end{aligned} \quad (4.15)$$

where Φ is the quantile of the cumulative distribution of a gaussian distribution. In general the distribution $f(T_\mu)$ is not known analytically, however asymptotically the p.d.f. of test statistic T_μ is a $\log \chi^2$ distribution with one degree

¹With larger precisely defined by the ordering defined by the test statistic T_μ .

of freedom for one parameter of interest, and in that case equation 4.14 can be solved analytically. If the distribution of T_μ is independent of μ , as is asymptotically the case, the practical procedure to construct an interval in μ from an observed T_μ is to find the values of μ for which T_μ is exactly equal to the value of the stated confidence level (e.g. $\frac{1}{2}$ for $Z = 1$). In MINUIT the MINOS procedure is designed to measure intervals following this concept.

For a hypothesis $H(\mu)$ with nuisance parameters $\alpha = (\mu, \theta)$ in addition to a POI, the test statistic shown in equation 4.13 can be generalised to

$$t_\mu = \frac{L(\mu, \hat{\hat{\theta}})}{L(\hat{\mu}, \hat{\theta})}, \quad (4.16)$$

known as the profiled likelihood ratio. This procedure is applied in the MINOS method. The conditional maximum likelihood estimators $\hat{\hat{\theta}}$ maximise the likelihood function $L(\alpha) = L(\mu, \theta)$ for a fixed value of the POI μ . Asymptotically, the distribution of t_μ will also become a χ^2 distribution [136], similar to T_μ , and thus test statistic t_μ is independent of the true values of θ in the asymptotic limit.

4.6.2 Expected limits and intervals

When calculating the expected limit or significance for an experiment, the relevant distribution of the test statistic is $f(t_\mu|\mu')$, where μ' expected value of μ in the hypothesis. Asymptotically $f(t_\mu|\mu')$ follows a non-central χ^2 distribution, which is a generalisation of the χ distribution [136], with centrality parameter Λ . If Λ is known, the expected limits can again be calculated analytically. The value of Λ for such calculations can be obtained from a fit to a so-called Asimov dataset [137] as follows:

$$t_\mu(Asimov) = \sqrt{(\Lambda)}, \quad (4.17)$$

where the Asimov dataset is a dataset that respects the median of the expected distribution, i.e. it is a dataset without statistical fluctuations. An Asimov dataset can be created from the conditional MLEs with all statistical fluctuations suppressed.

5 Analytic Lagrangian Morphing

5.1 Introduction

The properties of the newly discovered Higgs boson have been extensively probed by the ATLAS and CMS experiments using LHC Run 1 proton-proton collision data at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV [138, 139, 40, 140]. The studies of the tensor structure of the Higgs boson couplings to gauge bosons were based on signal models including at most one or two beyond-the-standard-model coupling parameters at a time, with all remaining Beyond the Standard Model (BSM) parameters set to zero. For Run 2, it is envisioned to have signal models which depend on a larger number of coupling parameters, in order to account for possible correlations among them. Additional coupling parameters in the Higgs coupling to Standard Model (SM) particles change the predicted cross section, as well as the shape of differential distributions. In this context, it is necessary to revise the existing signal modelling methods and provide alternatives which are better suited for such a multidimensional parameter space. Section 1.5 introduces some models that are suited for a multidimensional parameter space.

For this purpose, a morphing method, *Analytic Lagrangian morphing*, has been developed and implemented. It provides a continuous description of arbitrary physical signal observables such as cross sections or differential distributions in a multidimensional space of coupling parameters. The morphing-based signal model is a linear combination of a minimal set of orthogonal base samples (templates) spanning the full coupling parameter space. The weight of each template is derived from the coupling parameters appearing in the signal matrix element.

Morphing is more than a simple interpolation technique, in that it is not limited to the points in the range spanned by the input samples. In fact, the choice of the input samples is arbitrary, and any set of input samples satisfying the required conditions to build the morphing function will span the entire space,

independent of their precise coordinates.

All studies in sections 5.5 are on generator level only, with the exception of the morphing validation described in section 5.5.2. This section uses the final discriminating distributions of the ATLAS Run 1 $H \rightarrow ZZ^* \rightarrow 4\ell$ tensor structure analysis [138] as input for the validation of the morphing technique. Backgrounds are explicitly not taken into account in the example studies.

Higher order QCD and EW corrections are not considered. In the presented work a single resonance with a mass of 125 GeV is assumed. The total width of the Higgs boson is fixed to the SM expectation of 4 MeV and a modification to this width caused by the coupling parameters is not taken into account. For a correct modelling of the total width all coupling parameters of a model need to be considered, not only the parameters that enter in the Higgs boson production or decay, such as for example Higgs boson self couplings. If all parameters that influence the total width are known, the morphing technique can be used to describe the dependence of the total width on the coupling parameters of a model.

5.2 Signal morphing and comparison to matrix element reweighting

5.2.1 Morphing principles

The morphing procedure is based on the concepts of the morphing of (possibly multi-dimensional) histograms described in Reference [141]. It is introduced to describe the dependence of a given physical observable T on an arbitrary configuration of a set of non-SM Higgs boson couplings $\vec{g}_{\text{target}} \equiv \{g_{\text{SM}}, g_{\text{BSM},1}, \dots, g_{\text{BSM},n}\}$ to known particles. This dependence is described by a morphing function

$$T_{\text{out}}(\vec{g}_{\text{target}}) = \sum_i w_i(\vec{g}_{\text{target}}; \vec{g}_i) T_{\text{in}}(\vec{g}_i), \quad (5.1)$$

which linearly combines the values or differential distributions T_{in} at a number of selected discrete coupling configurations $\vec{g}_i = \{g_{\text{SM},i}, \vec{g}_{\text{BSM},i}\}$. The input distributions T_{in} are normalised to their expected cross sections such that T_{out} includes not only the correct shape, but also the correct cross section prediction. Here, g_{SM} denotes the Higgs boson coupling predicted by the Standard Model. Morphing only requires that any differential cross section can be expressed as a polynomial in coupling parameters. For calculation at lowest order and using the narrow-width approximation for a resonance, this yields a second order polynomial each in production and decay.

In practice, the template distributions T_{in} are obtained from the Monte Carlo (MC) simulation of the signal process for a given coupling configuration $\vec{g}_i$.

The minimal number N of Monte Carlo samples needed to describe the signal at all possible coupling configurations, depends on the number n of studied non-SM coupling parameters. The contribution of each sample T_{in} is weighted by a factor w_i based on the assumption that the value of a physical observable is proportional to the squared matrix element for the studied process

$$T \propto \mathcal{M}^2. \quad (5.2)$$

The weights w_i can therefore be expressed as functions of the coupling parameters in the matrix element $\mathcal{M}$. In this case T can be anything derived from the Matrix element, for example a whole MC sample.

The described procedure allows for a continuous description in an n -dimensional parameter space. A feature-complete implementation has been developed within the RooFit package [142], making use of HistFactory [143]. The provided signal model can therefore be used in commonly used RooFit workspaces.

In the remainder of this section, several examples for the construction of the model with the morphing method will be shown for the case of Higgs boson production and decay with only one or two non-SM coupling parameters. Subsequently, a generalisation to an n -dimensional coupling parameter space will be presented. Finally, the method is compared and contrasted with the well-established matrix element reweighting approach [144].

5.2.2 Morphing with one non-SM coupling parameter in either the production or decay vertex

As the simplest case, a morphing function is determined with only one non-SM Higgs coupling g_{BSM} contributing to either the production or decay in addition to the SM Higgs boson coupling g_{SM} . A typical example is a mixture of the SM and CP-odd Higgs boson couplings to two vector bosons, studied in detail in LHC Run 1 [138, 139].

The matrix element of such a scenario for given values of $\{g_{\text{SM}}, g_{\text{BSM}}\}$ can be written as a sum of the pure SM and the pure BSM contribution¹

$$\mathcal{M}(g_{\text{SM}}, g_{\text{BSM}}) = g_{\text{SM}} \cdot \mathcal{O}_{\text{SM}} + g_{\text{BSM}} \cdot \mathcal{O}_{\text{BSM}}. \quad (5.3)$$

This translates into the description of a physical observable T from the above signal process,

$$T(g_{\text{SM}}, g_{\text{BSM}}) \propto |\mathcal{M}(g_{\text{SM}}, g_{\text{BSM}})|^2 = \quad (5.4)$$

$$g_{\text{SM}}^2 \cdot \mathcal{O}_{\text{SM}}^2 + g_{\text{BSM}}^2 \cdot \mathcal{O}_{\text{BSM}}^2 + g_{\text{SM}} \cdot g_{\text{BSM}} \cdot 2\Re(\mathcal{O}_{\text{SM}}^* \mathcal{O}_{\text{BSM}}). \quad (5.5)$$

¹In this and the following section, the notation $\mathcal{O}$ will be used for the amplitude, whereas the notation $\mathcal{M}$ will be used for fully computed matrix elements. However, since the difference is only conceptual, the symbols are used interchangeably.

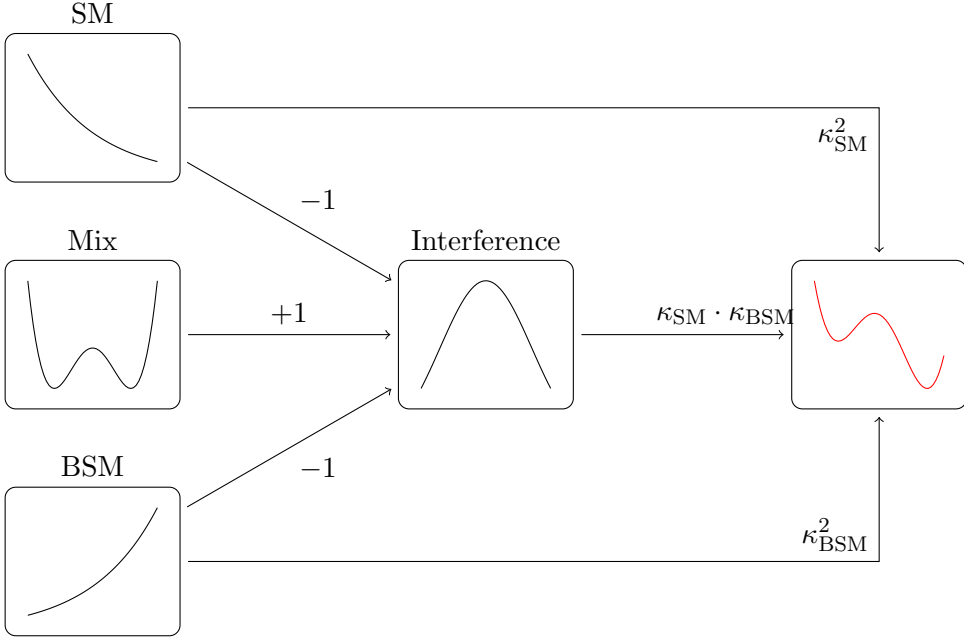


Figure 5.1: Illustration of the morphing procedure in a simple showcase.

The physical observable T can be used to morph to an arbitrary parameter point.

The number of input distributions required to morph to an arbitrary parameter point $\vec{g}_{\text{target}} = \{g_{\text{SM}}, g_{\text{BSM}}\}$ is equal to the unique terms in the matrix element squared, which is three in this case. It is sufficient to generate a pure SM distribution $T_{\text{in}}(1, 0)$, a pure BSM distribution $T_{\text{in}}(0, 1)$ and a mixed distribution $T_{\text{in}}(1, 1)$. Using the proportionalities to the matrix element squared one obtains

$$\begin{aligned} T_{\text{in}}(1, 0) &\propto |\mathcal{O}_{\text{SM}}|^2, \\ T_{\text{in}}(0, 1) &\propto |\mathcal{O}_{\text{BSM}}|^2, \\ T_{\text{in}}(1, 1) &\propto |\mathcal{O}_{\text{SM}}|^2 + |\mathcal{O}_{\text{BSM}}|^2 + 2\mathcal{R}(\mathcal{O}_{\text{SM}}^* \mathcal{O}_{\text{BSM}}). \end{aligned} \quad (5.6)$$

Applying these three equations to Equation 5.5 results in the morphing function for a distribution at an arbitrary parameter point

$$T_{\text{out}}(g_{\text{SM}}, g_{\text{BSM}}) = \underbrace{(g_{\text{SM}}^2 - g_{\text{SM}}g_{\text{BSM}})}_{=w_1} T_{\text{in}}(1, 0) + \quad (5.7)$$

$$+ \underbrace{(g_{\text{BSM}}^2 - g_{\text{SM}}g_{\text{BSM}})}_{=w_2} T_{\text{in}}(0, 1) + \underbrace{g_{\text{SM}}g_{\text{BSM}}}_{=w_3} T_{\text{in}}(1, 1). \quad (5.8)$$

The derivation of this is graphically depicted in Figure 5.1.

The output distribution can be created by only using the three input distributions multiplied by the appropriate weight factor w_i . Since fixed parameters for the input distributions were used, the weights only depend on the desired parameters for the output distribution.

To be able to minimise statistical uncertainty in the considered parameter space in a later stage, it is favourable to be flexible in choosing the parameters for the input distributions. In order to develop a generalisation for a morphing function with arbitrary input parameters $\vec{g}_i$, the proportionality to the matrix element squared of the three input distributions can be written in the following way:

$$T_{\text{in}}(g_{\text{SM},i}, g_{\text{BSM},i}) \propto g_{\text{SM},i}^2 |\mathcal{O}_{\text{SM}}|^2 + g_{\text{BSM},i}^2 |\mathcal{O}_{\text{BSM}}|^2 + 2g_{\text{SM},i}g_{\text{BSM},i} \mathcal{R}(\mathcal{O}_{\text{SM}}^* \mathcal{O}_{\text{BSM}}), \quad (5.9)$$

with $i = 1, 2, 3$. Now, the following ansatz can be made for the morphing function:

$$\begin{aligned} T_{\text{out}}(g_{\text{SM}}, g_{\text{BSM}}) = & \underbrace{(a_{11}g_{\text{SM}}^2 + a_{12}g_{\text{BSM}}^2 + a_{13}g_{\text{SM}}g_{\text{BSM}})}_{w_1} T_{\text{in}}(g_{\text{SM},1}, g_{\text{BSM},1}) \\ & + \underbrace{(a_{21}g_{\text{SM}}^2 + a_{22}g_{\text{BSM}}^2 + a_{23}g_{\text{SM}}g_{\text{BSM}})}_{w_2} T_{\text{in}}(g_{\text{SM},2}, g_{\text{BSM},2}) \\ & + \underbrace{(a_{31}g_{\text{SM}}^2 + a_{32}g_{\text{BSM}}^2 + a_{33}g_{\text{SM}}g_{\text{BSM}})}_{w_3} T_{\text{in}}(g_{\text{SM},3}, g_{\text{BSM},3}). \end{aligned} \quad (5.10)$$

This Ansatz contains unknown variables a_{ij} . For any of the input parameters, the morphing function should regain the input distribution

$$T_{\text{out}} = T_{\text{in}} \quad \text{for} \quad \vec{g}_{\text{target}} = \vec{g}_i. \quad (5.11)$$

This results in exactly the right number of constraints needed to recover the unknown variables a_{ij}

$$\begin{aligned} 1 &= a_{11}g_{\text{SM},1}^2 + a_{12}g_{\text{BSM},1}^2 + a_{13}g_{\text{SM},1}g_{\text{BSM},1} \\ 0 &= a_{21}g_{\text{SM},1}^2 + a_{22}g_{\text{BSM},1}^2 + a_{23}g_{\text{SM},1}g_{\text{BSM},1} \end{aligned} \quad (5.12)$$

...

All constraints can be written in a compact matrix form

$$\begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \cdot \begin{pmatrix} g_{\text{SM},1}^2 & g_{\text{SM},2}^2 & g_{\text{SM},3}^2 \\ g_{\text{BSM},1}^2 & g_{\text{BSM},2}^2 & g_{\text{BSM},3}^2 \\ g_{\text{SM},1}g_{\text{BSM},1} & g_{\text{SM},2}g_{\text{BSM},2} & g_{\text{SM},3}g_{\text{BSM},3} \end{pmatrix} = \mathbb{1} \quad (5.13)$$

$$\Leftrightarrow A \cdot G = \mathbb{1}.$$

The unique solution $A = G^{-1}$ requires the input parameters to fulfil the condition $\det(G) \neq 0$.

5.2.3 Morphing with one non-SM coupling parameter in both production and decay

In, for example, the VBF Higgs boson production with a decay to two vector boson, the same coupling appears in the production and decay vertex. Having a BSM parameter applied in production and decay requires certain adjustments in calculating the morphing function. For simplicity a scenario is discussed for two parameters g_{SM} and g_{BSM} , which are now (in contrast to the previous section) applied in the production and decay vertex. An example for such a scenario would be Higgs boson production via VBF with decays into two vector bosons V using the SM and one BSM HVV operator.

Again the matrix element squared can be factorised in the following way, assuming the narrow width approximation:

$$\mathcal{M}(g_{\text{SM}}, g_{\text{BSM}}) = (g_{\text{SM}} \cdot \mathcal{O}_{\text{SM},p} + g_{\text{BSM}} \cdot \mathcal{O}_{\text{BSM},p}) \cdot (g_{\text{SM}} \cdot \mathcal{O}_{\text{SM},d} + g_{\text{BSM}} \cdot \mathcal{O}_{\text{BSM},d}). \quad (5.14)$$

By squaring the matrix element additional interference terms emerge

$$\begin{aligned} |\mathcal{M}(g_{\text{SM}}, g_{\text{BSM}})|^2 &= (g_{\text{SM}} \mathcal{O}_{\text{SM},p} + g_{\text{BSM}} \mathcal{O}_{\text{BSM},p})^2 \cdot (g_{\text{SM}} \mathcal{O}_{\text{SM},d} + g_{\text{BSM}} \mathcal{O}_{\text{BSM},d})^2 \\ &= g_{\text{SM}}^4 \cdot \mathcal{O}_{\text{SM},p}^2 \mathcal{O}_{\text{SM},d}^2 + g_{\text{BSM}}^4 \cdot \mathcal{O}_{\text{BSM},p}^2 \mathcal{O}_{\text{BSM},d}^2 \\ &\quad + g_{\text{SM}}^3 g_{\text{BSM}} \cdot (\mathcal{O}_{\text{SM},p}^2 \Re(\mathcal{O}_{\text{SM},d}^* \mathcal{O}_{\text{BSM},d}) + \Re(\mathcal{O}_{\text{SM},p}^* \mathcal{O}_{\text{BSM},p}) \mathcal{O}_{\text{SM},d}^2) \\ &\quad + g_{\text{SM}}^2 g_{\text{BSM}}^2 \cdot (\mathcal{O}_{\text{SM},p}^2 \mathcal{O}_{\text{BSM},d}^2 + \mathcal{O}_{\text{BSM},p}^2 \mathcal{O}_{\text{SM},d}^2) \\ &\quad + g_{\text{SM}} g_{\text{BSM}}^3 \cdot (\mathcal{O}_{\text{BSM},p}^2 \Re(\mathcal{O}_{\text{SM},d}^* \mathcal{O}_{\text{BSM},d}) + \Re(\mathcal{O}_{\text{SM},p}^* \mathcal{O}_{\text{BSM},p}) \mathcal{O}_{\text{BSM},d}^2). \end{aligned} \quad (5.15)$$

Equation 5.15 is a 4th order polynomial in the coupling parameters g . Each unique term in coupling parameters requires an input distribution for the morphing, which results in 5 different samples for this scenario. The morphing function for arbitrary values of g_{SM} and g_{BSM} for the input distributions is obtained in a similar way as for the previous case. First the input distributions are proportional to the matrix element squared

$$T_{\text{in}}(g_{\text{SM},i}, g_{\text{BSM},i}) \propto |\mathcal{M}(g_{\text{SM}}, g_{\text{BSM}})|^2, \quad i = 1, \dots, 5. \quad (5.16)$$

Again, an Ansatz is used for the morphing function

$$\begin{aligned}
T_{\text{out}}(g_{\text{SM}}, g_{\text{BSM}}) &= \underbrace{(a_{11}g_{\text{SM}}^4 + a_{12}g_{\text{SM}}^3g_{\text{BSM}} + a_{13}g_{\text{SM}}^2g_{\text{BSM}}^2 + a_{14}g_{\text{SM}}g_{\text{BSM}}^3 + a_{15}g_{\text{BSM}}^4)}_{w_1} T_{\text{in}}(g_{\text{SM},1}, g_{\text{BSM},1}) \\
&= \underbrace{(a_{21}g_{\text{SM}}^4 + a_{22}g_{\text{SM}}^3g_{\text{BSM}} + a_{23}g_{\text{SM}}^2g_{\text{BSM}}^2 + a_{24}g_{\text{SM}}g_{\text{BSM}}^3 + a_{25}g_{\text{BSM}}^4)}_{w_2} T_{\text{in}}(g_{\text{SM},2}, g_{\text{BSM},2}) \\
&= \underbrace{(a_{31}g_{\text{SM}}^4 + a_{32}g_{\text{SM}}^3g_{\text{BSM}} + a_{33}g_{\text{SM}}^2g_{\text{BSM}}^2 + a_{34}g_{\text{SM}}g_{\text{BSM}}^3 + a_{35}g_{\text{BSM}}^4)}_{w_3} T_{\text{in}}(g_{\text{SM},3}, g_{\text{BSM},3}) \\
&= \underbrace{(a_{41}g_{\text{SM}}^4 + a_{42}g_{\text{SM}}^3g_{\text{BSM}} + a_{43}g_{\text{SM}}^2g_{\text{BSM}}^2 + a_{44}g_{\text{SM}}g_{\text{BSM}}^3 + a_{45}g_{\text{BSM}}^4)}_{w_4} T_{\text{in}}(g_{\text{SM},4}, g_{\text{BSM},4}) \\
&= \underbrace{(a_{51}g_{\text{SM}}^4 + a_{52}g_{\text{SM}}^3g_{\text{BSM}} + a_{53}g_{\text{SM}}^2g_{\text{BSM}}^2 + a_{54}g_{\text{SM}}g_{\text{BSM}}^3 + a_{55}g_{\text{BSM}}^4)}_{w_5} T_{\text{in}}(g_{\text{SM},5}, g_{\text{BSM},5}).
\end{aligned} \tag{5.17}$$

Requiring that the output distribution reproduces the input distributions at their respective parameters, constraints are set to calculate the unknown variables a_{ij} in the morphing function.

In matrix form, all constraints are written as

$$\begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} \\ a_{41} & a_{42} & a_{43} & a_{44} & a_{45} \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} \end{pmatrix} \cdot \begin{pmatrix} g_{\text{SM},1}^4 & g_{\text{SM},2}^4 & g_{\text{SM},3}^4 & g_{\text{SM},4}^4 & g_{\text{SM},5}^4 \\ g_{\text{SM},1}^3g_{\text{BSM},1} & g_{\text{SM},2}^3g_{\text{BSM},2} & g_{\text{SM},3}^3g_{\text{BSM},3} & g_{\text{SM},4}^3g_{\text{BSM},4} & g_{\text{SM},5}^3g_{\text{BSM},5} \\ g_{\text{SM},1}^2g_{\text{BSM},1}^2 & g_{\text{SM},2}^2g_{\text{BSM},2}^2 & g_{\text{SM},3}^2g_{\text{BSM},3}^2 & g_{\text{SM},4}^2g_{\text{BSM},4}^2 & g_{\text{SM},5}^2g_{\text{BSM},5}^2 \\ g_{\text{SM},1}g_{\text{BSM},1}^3 & g_{\text{SM},2}g_{\text{BSM},2}^3 & g_{\text{SM},3}g_{\text{BSM},3}^3 & g_{\text{SM},4}g_{\text{BSM},4}^3 & g_{\text{SM},5}g_{\text{BSM},5}^3 \\ g_{\text{BSM},1}^4 & g_{\text{BSM},2}^4 & g_{\text{BSM},3}^4 & g_{\text{BSM},4}^4 & g_{\text{BSM},5}^4 \end{pmatrix} = \mathbb{I}$$

$$\Leftrightarrow A \cdot G = \mathbb{I}. \tag{5.18}$$

Again, the input parameters must be chosen such that the requirement $\det(G) \neq 0$ is satisfied.

5.2.4 Generalisation to higher-dimensional parameter space

After the instructional examples provided above in sections 5.2.2 and 5.2.3, it is now straightforward to spell out a step-by-step explanation on how to construct the morphing function for processes with an arbitrary number of free coupling parameters in two vertices.

1. Construct a general matrix element squared

$$|\mathcal{M}(\vec{g})|^2 = \underbrace{\left(\sum_{x \in p,b} g_x \mathcal{O}(g_x) \right)^2}_{\text{production}} \cdot \underbrace{\left(\sum_{x \in d,b} g_x \mathcal{O}(g_x) \right)^2}_{\text{decay}}. \tag{5.19}$$

2. Expand the matrix element squared to a 4th degree polynomial in the coupling parameters

$$|\mathcal{M}(\vec{g})|^2 = \sum_{i=1}^N X_i \cdot P_i(\vec{g}), \tag{5.20}$$

X_i is a prefactor, which will be represented by an input distribution. In the 4th degree polynomial $P_i(\vec{g}) = g_a g_b g_c g_d$ of the coupling parameters $\vec{g}$, the same coupling can occur multiple times (e.g. g_{SM}^4 or $g_{\text{BSM},1} g_{\text{BSM},2} g_{\text{BSM},3}^2$). The number of different expressions in the polynomial N is equal to the number of samples needed for the morphing.

3. Generate input distributions at arbitrary but fixed parameter points $\vec{g}_i$

$$T_{\text{in},i} \propto |\mathcal{M}(\vec{g}_i)|^2. \quad (5.21)$$

4. Construct the morphing function with an Ansatz

$$T_{\text{out}}(\vec{g}) = \sum_{i=1}^N \underbrace{\left(\sum_{j=1}^N A_{ij} P_j(\vec{g}) \right)}_{w_i(\vec{g})} T_{\text{in},i}. \quad (5.22)$$

$$= \vec{P}(\vec{g}) \cdot A \vec{T}, \quad (5.23)$$

where the second line is the first one recast in matrix notation. The matrix A has to be calculated to obtain the full morphing function.

5. Exploit that the output distribution should be equal to the input distribution at the respective input parameters

$$T_{\text{out}}(\vec{g}_i) = T_{\text{in},i} \quad \text{for} \quad i = 1, \dots, N. \quad (5.24)$$

which can also be cast in matrix notation as

$$\begin{aligned} A \cdot (P_j(\vec{g}_i))_{ij} &= \mathbb{1} \\ \Leftrightarrow A \cdot G &= \mathbb{1}. \end{aligned} \quad (5.25)$$

6. The unique solution $A = G^{-1}$ requires the input parameters to fulfil the condition $\det(G) \neq 0$.

The number of base samples increases if there are additional coupling parameters to be considered in the production or decay vertex, for example in the case of a combination of measurements in several production and decay modes. However, the general morphing principle remains the same and the method can be generalised to a higher-dimensional coupling parameter space. The number N of input base samples depends on how many of the n studied coupling parameters enter the production and/or the decay vertex.

In case of the gluon fusion process with subsequent decays to vector bosons, the production and decay will have a completely disjoint set of couplings, and the number of input samples will be

$$N_{\text{ggF}} = n_p \cdot \frac{n_p + 1}{2} \cdot n_d \cdot \frac{n_d + 1}{2}, \quad (5.26)$$

where n_p are the number of parameters included for the production and n_d the number of parameters included for the decay.

For the VBF Higgs boson production with subsequent decay into vector bosons, when considering the exact same set of couplings in the production and the decay vertex, the number of samples is given by

$$N_{\text{VBF}} = \binom{4 + n_s - 1}{4}, \quad (5.27)$$

where n_s is the number samples that are shared in production and decay. Both expressions are just the number of terms in the polynomial obtained upon calculation of the matrix element. A general expression for n_p couplings appearing only in production, n_d couplings appearing only in decay and n_s couplings shared in production and decay can be obtained by careful counting as

$$N = \frac{n_p(n_p + 1)}{2} \cdot \frac{n_d(n_d + 1)}{2} + \binom{4 + n_s - 1}{4} \quad (5.28)$$

$$+ \left(n_p \cdot n_s + \frac{n_s(n_s + 1)}{2} \right) \cdot \frac{n_d(n_d + 1)}{2} \quad (5.29)$$

$$+ \left(n_d \cdot n_s + \frac{n_s(n_s + 1)}{2} \right) \cdot \frac{n_p(n_p + 1)}{2} \quad (5.30)$$

$$+ \frac{n_s(n_s + 1)}{2} \cdot n_p \cdot n_d + (n_p + n_d) \binom{3 + n_s - 1}{3}. \quad (5.31)$$

In this expression the counting is split for (5.28) terms pure in production and decay, or pure in shared, (5.29) terms pure in decay and mixed in production and shared or purely shared, (5.30) terms pure in production and mixed in decay and shared or purely shared, and (5.31) terms mixed in both, and terms mixed in one and purely shared in the other.

This is a general definition of the number of samples N in terms of number of coupling parameters n . For example Equation 5.26 can be reproduced by setting $n_s = 0$ and Equation 5.27 by $n_p = 0$ and $n_d = 0$.

The full generality of this method is not exploited in the remainder of this chapter. The discussed examples are outlined in table 5.1.

When the aim is to perform a likelihood fit on some (pseudo-)data T_d , the minimisation condition is

$$\hat{g}(T_d) = \arg \min_{\vec{g}} -2 \ln P \left(T_d \mid \mu = \sum_{i=1}^N \left(\sum_{j=1}^N A_{ij} P_j(\vec{g}) \right) T_{\text{in},i} \right). \quad (5.32)$$

Only the polynomials $P_j(\vec{g})$ depend on $\vec{g}$ and therefore need to be recalculated during the minimisation process, while the quantities A_{ij} and $T_{\text{in},i}$ stay fixed.

Section,	Process	n_p	n_d	n_s	N
5.5.1	ggF $H \rightarrow ZZ^* \rightarrow 4\ell$ truth	1	2	0	3
5.5.1	VBF $H \rightarrow ZZ^* \rightarrow 4\ell$ truth	0	0	3	15
5.5.1	ggF $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ truth	1	3	0	6
5.5.1	VBF $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ truth	0	0	3	15
5.5.2	ggF $H \rightarrow ZZ^* \rightarrow 4\ell$ reconstructed	1	3	0	6

Table 5.1: Overview of the examples presented in terms of the n -dimensional generalisation.

The error propagation of statistical uncertainties of the simulated samples to the output T_{out} is conceptually straightforward. Since the $\vec{g}_i$ are free parameters, the matrix A carries no uncertainty besides numerical fluctuations. Thus, uncertainties only propagate via linear combinations. The question of how the input parameters $\vec{g}_i$ need to be chosen such that the expected uncertainty of the output is minimal, within some parameter region of interest, is non-trivial and is discussed in chapter 6.

5.2.5 Comparison to the matrix element reweighting method

To be able to compare the morphing method to the matrix element reweighting method used in the past, the matrix element reweighting method is briefly summarised. The intent of the summary is to highlight the differences between the methods, as well as indicate how the two methods complement each other.

The calculation of theory predictions for e.g. differential cross sections is most conveniently performed via Monte Carlo integration techniques. In these techniques the distribution in question is probed with a finite set of phase space points, which are then treated analogously to observed collision events in data analysis. These probing points, or Monte Carlo events, may carry a certain weight – a number assigned by the generator to encode the magnitude of the contribution of this phase space point to the distribution of interest. Some generators choose to use adaptive Monte Carlo techniques to adjust their sampling distribution according to the probed distribution. This ensures that the event weights generated are within a certain (narrow) acceptance band, thus reducing uncertainty of the result.

Since the weight of an event is a measure of the probability assigned to this phase space point (taking into account the sampling distribution of the generator), it is related to the matrix element of the process in question. For some theoretical framework α , the event weight depends on the parton distribution functions f_1

and f_2 as well as on the transfer or (detector) resolution function $W(x, y)$:

$$\omega_\alpha(x) \propto P_\alpha(x) = \frac{1}{\sigma} \int d\phi(y) |\mathcal{M}_\alpha(y)|^2 dw_1 dw_2 f_1(w_1) f_2(w_2) W(x, y). \quad (5.33)$$

This translates the true quantities of the simulated particles y to the observable quantities x of the same particles after detector simulation and reconstruction and, most notably, on the modulus square of the matrix element M_α of this transition within the given theoretical framework [144].

As the detector resolution simulation is highly non-trivial and commonly the most expensive part of the event generation process, it has become common practice to generate and simulate events for some theoretical setup α and then, afterwards, translate them to a different theoretical setup α' by considering the ratio between the matrix elements, i. e.

$$\omega_{\alpha'}(y) = \omega_\alpha(y) \frac{|\mathcal{M}_{\alpha'}(y)|^2}{|\mathcal{M}_\alpha(y)|^2}, \quad (5.34)$$

where the knowledge of the generator information y for the simulated events is exploited to be able to reweight them according to the matrix element values. This method is related to the morphing technique presented here in that it allows to exploit precomputed results to perform a exact translation into a different theoretical framework. However the matrix element reweighting is a technique that only requires a single input sample and performs the translation on an event-by-event basis to another single point in the parameter space. The morphing technique, on the other hand, requires several input samples, but is capable of morphing entire distributions of observables in a continuous way such that no additional interpolation is needed. For the matrix element reweighting method additional interpolation between the points in the parameter space that have been created with the method are done with interpolation techniques implement in **HistFactory** [143], like Moment Morphing [141]. These interpolation methods are intended for use on physical observables such as cross sections or distributions retrieved after the full processing of event generation, simulation, digitisation, reconstruction and selection. Given the expense of iterating over large input datasets and performing the matrix element calculation on every event, the new morphing method is several orders of magnitude faster in a typical scenario and thus provides the ability to (precisely) approximate the matrix-element weighting in iterative procedures like fits. In order to achieve the same interpolation power with matrix element reweighting, one would need to produce a vast number of reweighted samples, hugely exceeding the number of input samples for the morphing.

However, as the morphing technique requires a (possibly large) number of input samples, it still requires a large amount of resources to be provided upfront for

generating and especially simulating the input samples. Therefore a hybrid approach using both methods in a complementary fashion by using matrix element reweighting to save time on detector simulation when creating input samples for applications of morphing is very promising.

5.3 Parametrisation in the frame of the Higgs characterisation model

The morphing method itself is completely independent from the parametrisation that is chosen to model non-SM couplings and the interaction of the non-SM particles with SM particles.

For a validation of the morphing method in Section 5.5.1 the parametrisation of the Higgs Characterisation Model [63] is chosen. This model has been used in the recently published ATLAS Run 1 analysis [138].

The Higgs characterisation model describes the non-SM couplings of the Higgs boson based on an effective field theory approach, as described in section 1.5.3. Within this model, the effective Lagrangian for the interaction of a spin-0 particle with gauge bosons is given by

$$\begin{aligned}
\mathcal{L}_0^V = & \{ \underline{c_\alpha} \underline{\kappa_{SM}} [\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu}] \\
& - \frac{1}{4} [\underline{c_\alpha} \underline{\kappa_{H\gamma\gamma}} g_{H\gamma\gamma} A_{\mu\nu} A^{\mu\nu} + \underline{s_\alpha} \underline{\kappa_{A\gamma\gamma}} g_{A\gamma\gamma} A_{\mu\nu} \tilde{A}^{\mu\nu}] \\
& - \frac{1}{2} [\underline{c_\alpha} \underline{\kappa_{HZ\gamma}} g_{HZ\gamma} Z_{\mu\nu} A^{\mu\nu} + \underline{s_\alpha} \underline{\kappa_{AZ\gamma}} g_{AZ\gamma} Z_{\mu\nu} \tilde{A}^{\mu\nu}] \\
& - \frac{1}{4} [\underline{c_\alpha} \underline{\kappa_{Hgg}} g_{Hgg} G_{\mu\nu}^a G^{a,\mu\nu} + \underline{s_\alpha} \underline{\kappa_{Agg}} g_{Agg} G_{\mu\nu}^a \tilde{G}^{a,\mu\nu}] \\
& - \frac{1}{4} \frac{1}{\Lambda} [\underline{c_\alpha} \underline{\kappa_{HZZ}} Z_{\mu\nu} Z^{\mu\nu} + \underline{s_\alpha} \underline{\kappa_{AZZ}} Z_{\mu\nu} \tilde{Z}^{\mu\nu}] \\
& - \frac{1}{2} \frac{1}{\Lambda} [\underline{c_\alpha} \underline{\kappa_{HWW}} W_{\mu\nu}^+ W^{-\mu\nu} + \underline{s_\alpha} \underline{\kappa_{AWW}} W_{\mu\nu}^+ \tilde{W}^{-\mu\nu}] \\
& - \frac{1}{\Lambda} \underline{c_\alpha} [\underline{\kappa_{H\partial\gamma}} Z_\nu \partial_\mu A^{\mu\nu} + \underline{\kappa_{H\partial Z}} Z_\nu \partial_\mu Z^{\mu\nu} + (\underline{\kappa_{H\partial W}} W_\nu^+ \partial_\mu W^{-\mu\nu} + h.c.)] \} X_0
\end{aligned} \tag{5.35}$$

where the notation

$$c_\alpha \equiv \cos(\alpha), \quad s_\alpha \equiv \sin(\alpha) \tag{5.36}$$

is used. All underlined terms are parameters, while the other terms are fixed to their SM values.

All couplings $\kappa_{Hxx'}$ describe CP-even interactions, and coupling strengths $\kappa_{Axx'}$ CP-odd interactions. Here, c_α is the mixing angle between CP-even and CP-odd couplings.

Λ is the cut-off scale of the effective theory and BSM couplings are suppressed by a factor $\frac{1}{\Lambda}$. For a more detailed description of the model see Reference [63]. In this chapter, the cut-off scale Λ is fixed to 1 TeV and c_α to $\frac{1}{\sqrt{2}}$.

5.4 Extracting parameters

The morphing method is implemented in RooFit [142].

The implementation has been performed as a single class by the name of `RooEFTMorphFunc`, analogous to other interpolation techniques already implemented in the RooStats statistics framework. The input is retrieved from an external file, which should contain the physical quantities subject to the morphing (total or differential cross sections) as well as the sets of input parameters. The user is expected to provide details on the model in which the morphing should be performed, either by providing a list of available couplings and vertices in which they appear manually, or by using one of the pre-made constructors for different Higgs boson production and decay mechanisms that are currently implemented that include VBF and ggF Higgs boson production with weak bosonic decay modes.

The implementation uses the procedure outlined in Section 5.2.4 to construct a morphing function on the setup provided, where the physical inputs T are typically incorporated by histograms. The couplings g , which might have been provided by the user or created by the class internally, can either be free parameters or be incorporated as derived quantities depending on some other parameter set, most notably the set of coupling strength parameters κ . The matrix inversion required for the construction of the morphing function is usually performed via the standard matrix implementation of the ROOT software framework [7], but this can be replaced by the more sophisticated boost linear algebra library uBLAS [145] at compile-time, which allows higher numeric accuracy of the result, if required.

The `RooEFTMorphFunc` adheres to the standard RooStats interface of interpolation functions, thus standard minimisation techniques to perform likelihood fits of the morphing function to some target distribution can be applied. With these techniques the couplings act as free parameters to be constrained by the fit, independent of whether they were user-provided or automatically generated.

For the purpose of the studies presented in the following sections, backgrounds, treatment of the total width, and systematic uncertainties have been neglected. As a test statistic for the fits, the profile likelihood ratio is used: $\tilde{t}_\mu = -2 \ln \frac{L(\vec{\mu}, \hat{\theta})}{L(\hat{\mu}, \hat{\theta})}$ [137], with the signal parameter(s) constrained to be in the physical region, has been used.

5.5 Validation results

The validation of the morphing method is presented in two parts. In the first part the validation is performed on distributions from MC truth information. The second part of the validation is based on simulated distributions at reconstruction level after full Run 1 analysis selections of the ATLAS $H \rightarrow ZZ^* \rightarrow 4\ell$ analysis group described in Reference [138].

Samples have been produced for the validation described in Section 5.5.1, which is performed on the generator level after the parton showering and hadronisation, but without accounting for the detector effects. Samples of events from gluon fusion and VBF Higgs production processes with subsequent decays into two W or Z bosons have been produced for the SM and several non-SM coupling configurations with the MADGRAPH5_AMC@NLO [146] event generator. Parton showers and their hadronisations are generated with Pythia8 [147].

The Higgs characterisation (HC) model [63] has been used as a framework for the BSM configurations within the generator. Two different versions of the model are available. The default HC model is used for the VBF processes, whereas for the gluon fusion only the SM production via a heavy quark loop is assumed and no BSM particles contribute to the gluon fusion loop. All processes are generated at the leading order and with $\sqrt{s} = 13$ TeV, using the leading-order PDF set NNPDF23.

Distributions of several variables sensitive to non-SM couplings are used for validation. Definitions for the angular observables shown here can be found in Reference [148]. In addition, for VBF production the azimuthal angle between the tagging jets $\Delta\phi_{jj}$ is used, which has good discriminant power between CP-odd and CP-even BSM parameters as shown in Reference [149]. Jet candidates have been reconstructed using the anti- k_t algorithm [127, 150] with a distance parameter of $R = 0.4$. All input and validation distributions are used at the generator-level, except the ones in the morphing validation described in Section 5.5.2. This study is using the final discriminating distributions of the ATLAS Run 1 $H \rightarrow ZZ^* \rightarrow 4\ell$ tensor structure analysis [138], which is a CP measurement, for the validation of the morphing technique.

5.5.1 Validation on MC truth information

Before applying the morphing to a full analysis, it is useful to test the morphing in a controlled environment where all parameters are known, as is the case for truth-level. The truth-level validation is based on a reduced parameter set that consists of the SM coupling, one additional non-SM CP-even ($c_\alpha \cdot \kappa_{HVV}$)

and one CP-odd coupling ($s_\alpha \cdot \kappa_{AVV}$), using equation 5.35. The parameters for the input samples are chosen to reduce the statistical uncertainty from the morphing function in the desired parameter space. All SM couplings are set to one and the non-SM parameter limits are taken such that a pure non-SM sample would have the SM cross section.

Validation in ggF $H \rightarrow WW^* \rightarrow e\nu\mu\nu$

In gluon fusion production for the decay to WW , the azimuthal angle between two leptons $\Delta\phi_{ll}$, which has already been used in the spin and parity measurement by ATLAS [59], is taken as the distribution on which to run the validation. In addition to the SM coupling κ_{SM} two non-SM couplings, κ_{HWW} and κ_{AWW} , are used. All three operators act on the decay vertex which results in 6 input samples needed for the morphing. Besides these 6 input samples additional validation samples are produced to have statistically independent distributions.

An overview of all generated samples in the parameter space is presented in figure 5.2 and table 5.2. The samples consist of 50.000 Monte Carlo events each. The cross sections using the morphing technique is presented in figure 5.3 (left). These figures illustrate that using larger absolute non-SM coupling values results in larger rates for both non-SM coupling parameters. The relative Monte Carlo statistical uncertainty arising from the morphing function on the number of events is shown in Figure 5.3 (right). In the tested parameter space the relative Monte Carlo statistical uncertainty remains very small, in the range of ca. 2-3%. The uncertainty grows proportionally with the distance to the samples used as input for the morphing. This explains both the local maxima in the central parameter region and the rapid increase in the outer region.

For this process the kinematic observable used is the azimuthal angle between

	κ_{SM}	κ_{Hgg}	κ_{Aww}	κ_{Hww}	$\cos \alpha$
Input Sample 0	$\sqrt{2}$	$\sqrt{2}$	-2.83	-4.73	$\frac{1}{\sqrt{2}}$
Input Sample 1	$\sqrt{2}$	$\sqrt{2}$	-2.50	4.79	$\frac{1}{\sqrt{2}}$
Input Sample 2	$\sqrt{2}$	$\sqrt{2}$	7.07	2.86	$\frac{1}{\sqrt{2}}$
Input Sample 3	$\sqrt{2}$	$\sqrt{2}$	6.88	-3.02	$\frac{1}{\sqrt{2}}$
Input Sample 4	$\sqrt{2}$	$\sqrt{2}$	-8.62	0.10	$\frac{1}{\sqrt{2}}$
Validation Sample v0	1.40	1.38	-0.75	-4.28	$\frac{1}{\sqrt{2}}$
Validation Sample v1	1.42	1.39	7.46	1.39	$\frac{1}{\sqrt{2}}$

Table 5.2: Overview of the samples used in the ggF $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ study.

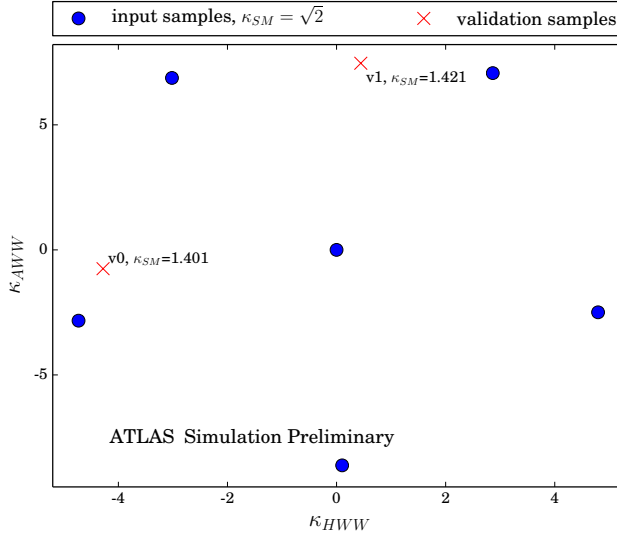


Figure 5.2: Overview of produced samples for morphing validation in the ggF $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ channel. The SM couplings g_{Hgg} and g_{SM} are set to 1 for all input samples and the limits for the BSM parameters are taken such that a pure BSM sample would have the SM cross section. The parameters for the validation samples are taken randomly in the desired parameter space.

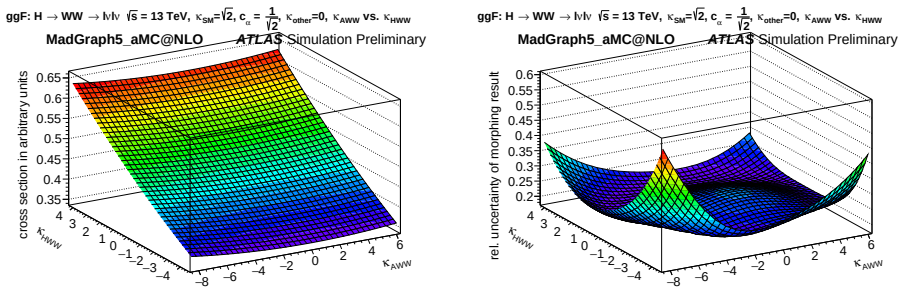


Figure 5.3: The number of expected events in the considered parameter space for ggF $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ calculated with the morphing method is shown on the left. The relative Monte Carlo statistical uncertainty on the number of expected events propagated from the morphing function can be seen on the right.

the two leptons $\Delta\phi_{ll}$. All input distributions for morphing and validation are scaled to their respective cross section in arbitrary units and shown in Figure 5.4. Two tests of the morphing method are covered. First the morphing to the input distributions is tested (cf. Figure 5.5). Since the validation samples are among the inputs a perfect agreement is seen, as expected. Similar results are obtained for the other input samples, but are not shown here. Second the morphing is tested on statistically independent validation samples (figure 5.6), which shows agreement of the input samples and the morphing within the statistical errors.

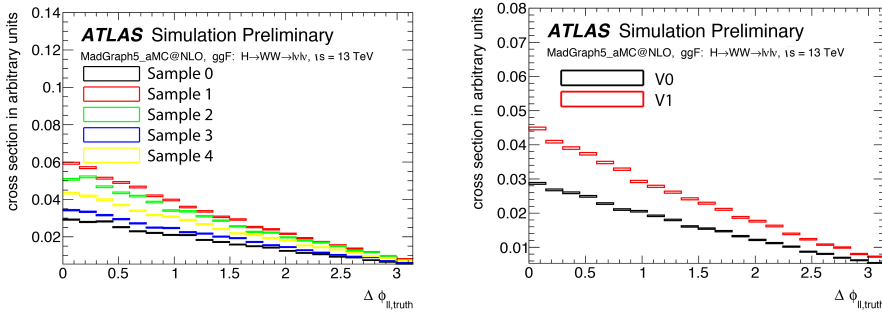


Figure 5.4: Input and validation distributions used for the morphing validation, generated from 50.000 Monte Carlo events each. The size of the boxes correspond to the Monte Carlo statistical uncertainties.

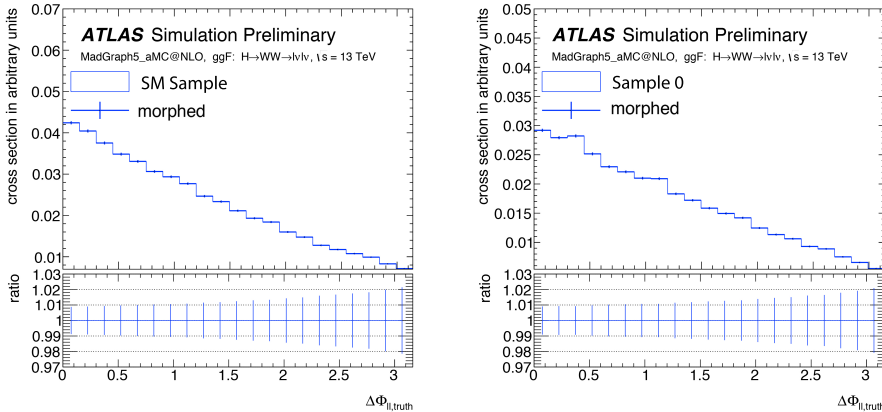


Figure 5.5: Validation of the morphing using input distributions. The SM distribution (left) and one input distribution (right) show perfect agreement as expected for statistically dependent samples.

Finally, the fitting procedure is tested. Fitting to the $\Delta\phi_{ll}$ distribution of a dataset that is the sample from the SM hypothesis or one of the other BSM

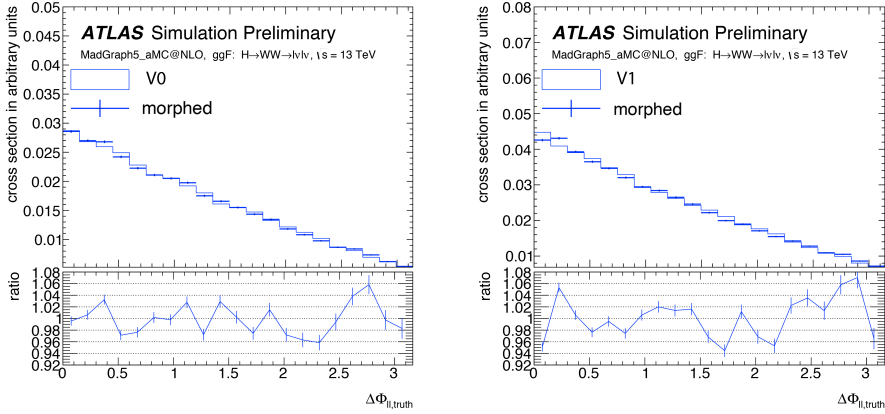


Figure 5.6: Validation of the morphing using statistically independent distributions. Both morphing results agree within the statistical uncertainty of the morphing.

input samples used as pseudo-data is shown in Figure 5.7. Again a perfect agreement is obtained and the nominal parameter values are recovered. The fitted values for the parameters are shown in Table 5.3. For comparison, the morphing result is also shown. The Monte Carlo statistical uncertainty is used both for display of the error bars and in the fit. The uncertainties on the fit parameters give an idea of the sensitivity on the parameter. The correlations between the parameters are shown in Table 5.4.

The same fitting procedure is applied to the statistically independent validation distributions and is shown in Figure 5.8. The fitted values for the parameters are shown in Table 5.3 and the correlation for these fits are listed in Table 5.5.

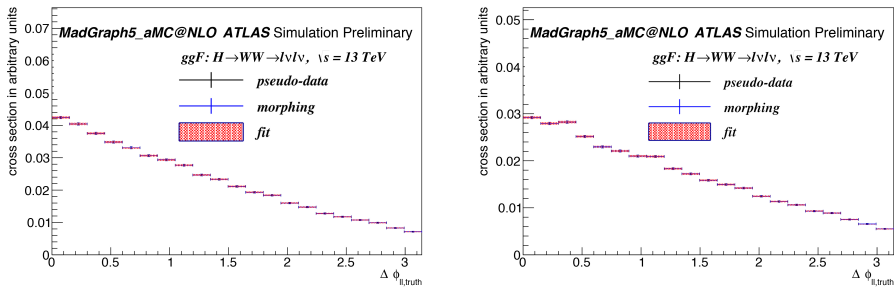


Figure 5.7: Fit validation to the SM input sample (left) and one of the BSM input samples (right).

	κ_{SM}	κ_{Aww}	κ_{Hww}
SM sample	1.41291 ± 0.01423	0.00000 ± 0.30961	-0.00001 ± 1.61594
Input sample 0	1.41421 ± 0.01236	-4.73015 ± 0.28268	-2.83060 ± 0.47713
Validation Sample v0	1.41291 ± 0.01108	-4.54363 ± 0.26892	0.00549 ± 0.68506
Validation Sample v1	1.45677 ± 0.01597	-0.03135 ± 0.36602	5.59299 ± 0.65238

Table 5.3: Fit results in the ggF $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ study.

left	κ_{SM}	κ_{HWW}	κ_{Aww}	right	κ_{SM}	κ_{HWW}	κ_{Aww}
κ_{SM}	1.00	-0.16	0.16	κ_{SM}	1.00	-0.53	0.60
κ_{HWW}	-0.16	1.00	-0.99	κ_{HWW}	-0.53	1.00	-0.99
κ_{Aww}	0.16	-0.99	1.00	κ_{Aww}	0.60	-0.99	1.00

Table 5.4: Correlation matrix for the SM input sample and one BSM sample corresponding to the fits in Figure 5.7.

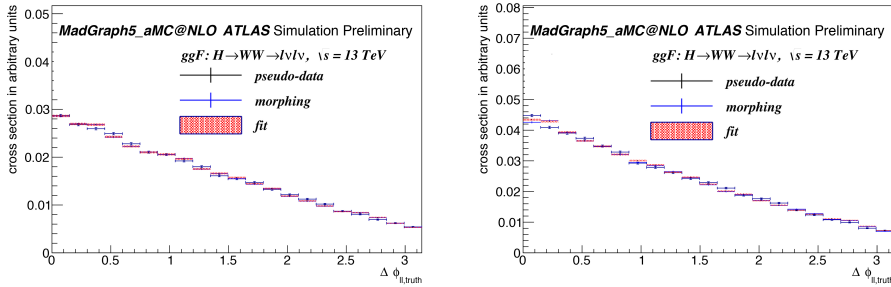


Figure 5.8: Fit validation to validation samples v0 (left) and v1 (right).

v0	κ_{SM}	κ_{HWW}	κ_{Aww}	v1	κ_{SM}	κ_{HWW}	κ_{Aww}
κ_{SM}	1.00	-0.12	0.11	κ_{SM}	1.00	-0.37	0.18
κ_{HWW}	-0.12	1.00	-0.99	κ_{HWW}	-0.37	1.00	-0.97
κ_{Aww}	0.11	-0.99	1.00	κ_{Aww}	0.18	-0.97	1.00

Table 5.5: Correlation matrix for the validation distributions v0 and v1 corresponding to the fits in Figure 5.8.

Validation in ggF $H \rightarrow ZZ^* \rightarrow 4\ell$

For completeness a study has been performed on the ggF $H \rightarrow ZZ^* \rightarrow 4\ell$ channel for only one parameter of interest, the non-SM coupling parameter κ_{Azz} . For this study truth distributions of $\cos(\theta_1)$ and Φ , which are sensitive to the presence of non-SM couplings, are used. θ_1 is the angle between the on-shell Z boson and its negatively charged lepton, ϕ is the angle between the decay planes of the two Z bosons calculated in the rest frame of the Higgs boson [138]. The parameters of the samples used for this study are listed in table 5.6.

All samples are produced with the SM couplings set to their nominal values, e.g $\cos(\alpha) \cdot \kappa_{Hgg} = 1$. The error bars shown reflect the Monte Carlo statistical uncertainty from a total of 50.000 generated events. In figure 5.9 the comparison between morphing function output (dashed) and distributions of two reference points as listed in table 5.6 are shown.

For both validation samples, which incorporate SM and CP-odd admixtures with positive and with negative non-SM coupling strength, the morphing output agrees very well within the statistical uncertainty with the distributions of the dedicated validation samples.

Validation in VBF $H \rightarrow WW^* \rightarrow e\nu\mu\nu$

A more complicated example is the VBF vertex, which shares a coupling in the production and decay. In addition to the SM coupling κ_{SM} , two non-SM couplings κ_{HWW} and κ_{AWW} are used for validation. All three operators act on the production and decay vertex which results in 15 input samples needed for the morphing. Besides these 15 input samples additional validation samples are produced to have statistically independent distributions. The kinematic observable used is the azimuthal angle between the two tagging jets $\Delta\phi_{jj}$

An overview of all generated samples in the parameter space can be found in figure 5.10 and table 5.7, where the two additional validation samples have been highlighted and dubbed v0 and v1. Their parameters have been chosen arbitrarily to cover the parameter space evenly. For each sample, 50.000 Monte

	κ_{SM}	κ_{Azz}	κ_{Hgg}	$\cos \alpha$
Input Sample 0	1.000	0.000	1.000	1.000
Input Sample 1	0.000	13.938	1.414	0.707
Input Sample 2	1.414	13.938	1.414	0.707
Validation Sample v1	1.000	0.250	1.414	0.707
Validation Sample v2	1.414	-2.000	1.414	0.707

Table 5.6: Overview of the samples used in the ggF $H \rightarrow ZZ^* \rightarrow 4\ell$ study.

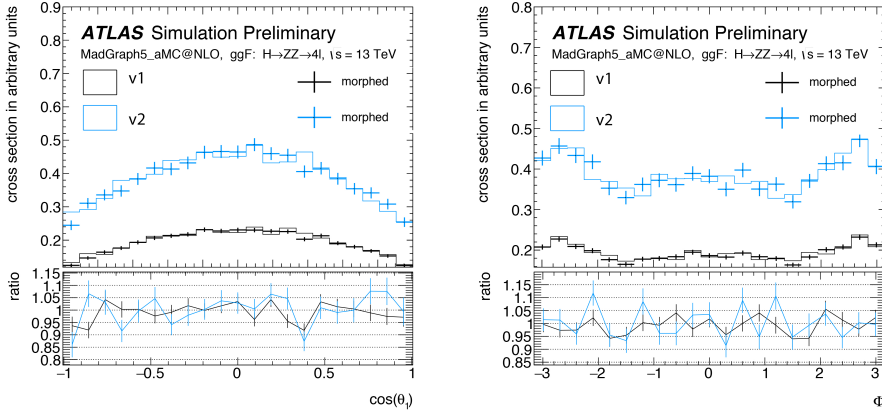


Figure 5.9: Distributions of $\cos(\theta_1)$, where θ_1 is the angle between the on-shell Z boson and its negatively charged lepton (left) and the angle ϕ (right) between the decay planes of the two Z bosons for events generated in the $ggF\ H \rightarrow ZZ^* \rightarrow 4\ell$ process at 13 TeV, calculated in the rest frame of the Higgs boson [138]. Generated validation samples (solid) as well as predictions calculated via morphing (dashed) are shown. The ratios between the morphing output and the validation distributions are shown in the lower panels.

Carlo events have been generated. The cross sections calculated in arbitrary units using the morphing technique can be seen in figure 5.11 (left). The cross-section increases for larger absolute non-SM coupling values.

The relative uncertainty arising from the MC statistical uncertainty from propagation of morphing function on the number of events is shown in figure 5.11 (right). In the considered parameter space the relative Monte Carlo statistical uncertainty remains very small, in the range of ca. 2-3%. Outside the considered parameter space, the uncertainty grows with the distance to the input sample parameters. This explains both the local maxima in the central parameter region and the rapid increase in the outer region.

All input distributions for morphing and validation are scaled to their respective cross section in arbitrary units and shown in figure 5.12. When morphing to one of the input samples a perfect match is obtained as expected. The morphing is also tested against statistically independent validation samples, as shown in figure 5.13, exhibiting agreement within $\sim 5\%$ of the input samples and the morphing.

In addition, the fitting procedure is tested. When fitting to the SM or one of the other BSM input samples used as pseudo-data, again a perfect agreement is obtained and the nominal parameter values are recovered. The correlations between the parameters are shown in table 5.8.

The same fitting procedure is applied to the statistically independent validation

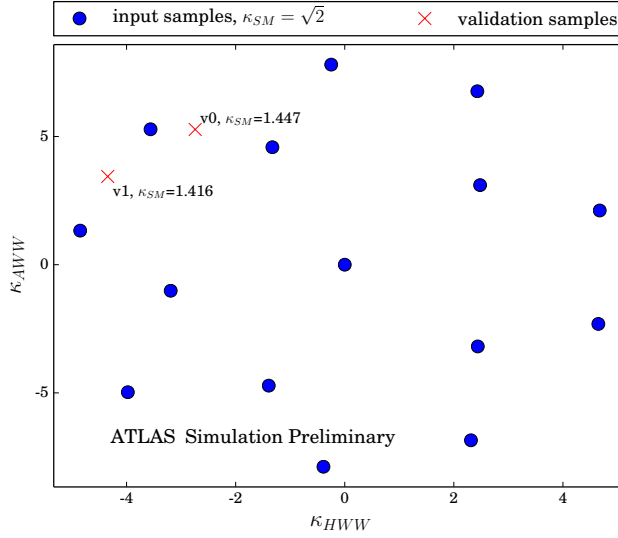


Figure 5.10: Overview of produced samples for morphing validation in the $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ channel. The SM coupling g_{SM} is set to 1 for all input samples and the limits for the BSM parameters are taken such that a pure BSM sample would have the SM cross section. The parameters for the validation samples are taken arbitrarily in the desired parameter space.

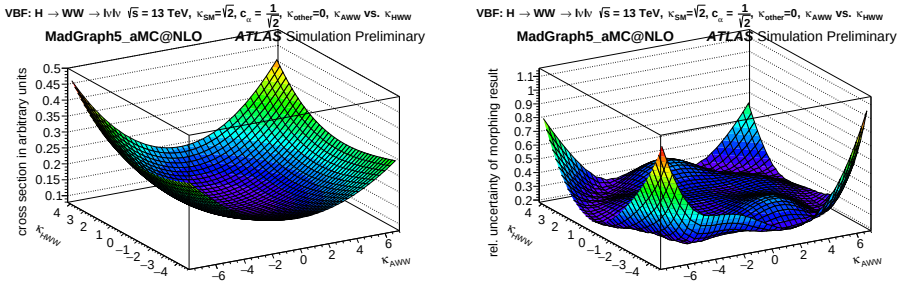


Figure 5.11: The number of expected events in the considered parameter space for $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ calculated with the morphing method is shown on the left. The relative uncertainty on the number of expected events propagated from the morphing function can be seen on the right.

	κ_{SM}	κ_{Aww}	κ_{Hww}	$\cos \alpha$
Input Sample 0	$\sqrt{2}$	-1.02	-3.19	$\frac{1}{\sqrt{2}}$
Input Sample 1	$\sqrt{2}$	6.76	2.43	$\frac{1}{\sqrt{2}}$
Input Sample 2	$\sqrt{2}$	-4.72	-1.39	$\frac{1}{\sqrt{2}}$
Input Sample 3	$\sqrt{2}$	2.11	4.67	$\frac{1}{\sqrt{2}}$
Input Sample 4	$\sqrt{2}$	-4.97	-3.98	$\frac{1}{\sqrt{2}}$
Input Sample 5	$\sqrt{2}$	1.33	-4.85	$\frac{1}{\sqrt{2}}$
Input Sample 6	$\sqrt{2}$	-3.19	2.44	$\frac{1}{\sqrt{2}}$
Input Sample 7	$\sqrt{2}$	7.80	-0.25	$\frac{1}{\sqrt{2}}$
Input Sample 8	$\sqrt{2}$	-2.31	4.65	$\frac{1}{\sqrt{2}}$
Input Sample 9	$\sqrt{2}$	0.00	0.00	$\frac{1}{\sqrt{2}}$
Input Sample 10	$\sqrt{2}$	3.10	2.48	$\frac{1}{\sqrt{2}}$
Input Sample 11	$\sqrt{2}$	-6.85	2.31	$\frac{1}{\sqrt{2}}$
Input Sample 12	$\sqrt{2}$	-7.88	-0.39	$\frac{1}{\sqrt{2}}$
Input Sample 13	$\sqrt{2}$	5.28	-3.56	$\frac{1}{\sqrt{2}}$
Input Sample 14	$\sqrt{2}$	4.58	-1.33	$\frac{1}{\sqrt{2}}$
Validation Sample v0	1.447	5.27	-2.74	$\frac{1}{\sqrt{2}}$
Validation Sample v1	1.416	3.44	-4.35	$\frac{1}{\sqrt{2}}$

Table 5.7: Overview of the samples used in the ggF $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ study.

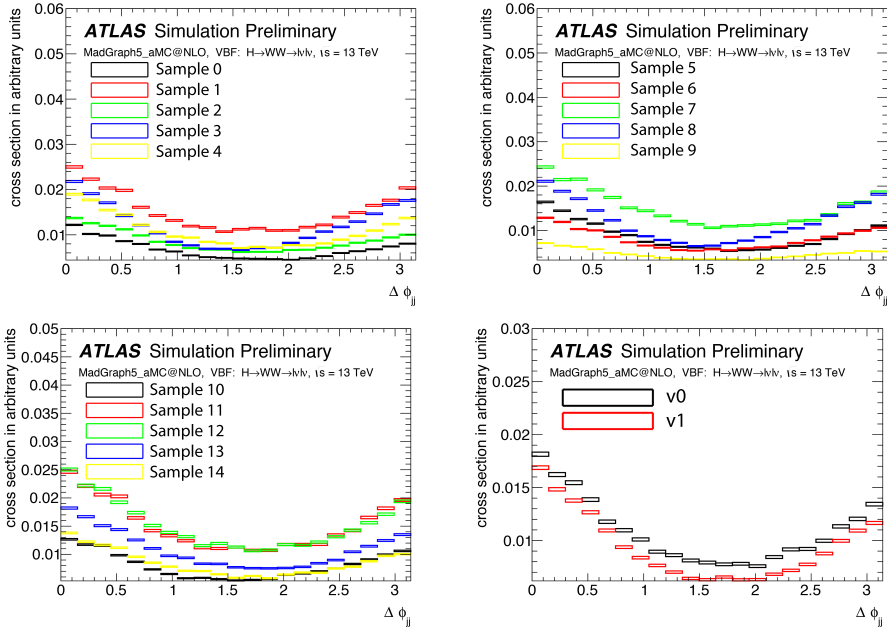


Figure 5.12: Input and validation distributions used for the morphing validation, using 50.000 Monte Carlo events each. The size of the boxes correspond to the Monte Carlo statistical uncertainties.

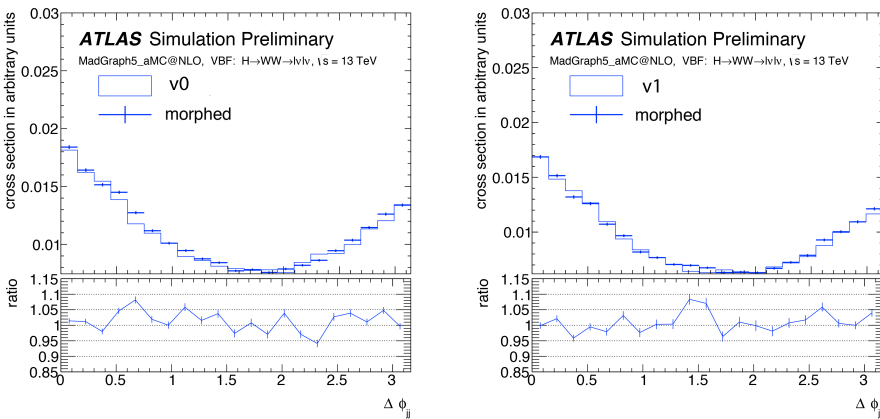


Figure 5.13: Validation of the morphing using statistically independent distributions. Both morphing results agree within the statistical uncertainty of the morphing.

distributions and is shown in figure 5.14 and table 5.9. The correlation results of these fits are listed in Table 5.10. As changing the SM and BSM κ_{AWW} coupling parameter have a similar effect on the observed distribution, their maximum likelihood estimators are correlated.

	κ_{SM}	κ_{HWW}	κ_{AWW}		κ_{SM}	κ_{HWW}	κ_{AWW}
κ_{SM}	1.00	0.15	-0.23	κ_{SM}	1.00	0.20	0.77
κ_{HWW}	0.15	1.00	0.36	κ_{HWW}	0.20	1.00	0.75
κ_{AWW}	-0.23	0.36	1.00	κ_{AWW}	0.77	0.75	1.00

Table 5.8: Correlation matrix for the SM input sample (left) and one BSM sample (right)

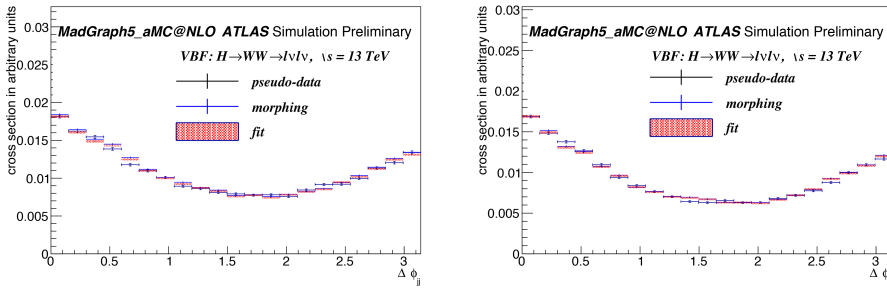


Figure 5.14: Results obtained by morphing with the known input parameters as well as morphing obtained with the parameters extracted from the fit for the v0 validation sample (left) and v1 validation sample (right).

Validation in VBF $H \rightarrow ZZ^* \rightarrow 4\ell$

For completeness VBF $H \rightarrow ZZ^* \rightarrow 4\ell$ is studied with two non-SM coupling parameters, κ_{HZZ} and κ_{AZZ} , in production and decay. As a validation variable $\Delta\Phi_{jj}$ as defined at the beginning of this section has been chosen.

As listed in Table 5.1, 15 morphing input samples are needed in order to model such a mixture. The parameters of the the input samples, as well as a set of of 5 validation samples are listed in Table 5.11. Each sample was produced with 50.000 Monte Carlo events.

	κ_{SM}	κ_{Aww}	κ_{Hww}
Validation Sample v0	1.46482 ± 0.01890	-2.47606 ± 0.17699	5.03605 ± 0.26935
Validation Sample v1	1.42924 ± 0.01043	-4.23819 ± 0.10548	3.19053 ± 0.30144

Table 5.9: Fit results in the VBF $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ study.

v0	κ_{SM}	κ_{HWW}	κ_{AWW}	v1	κ_{SM}	κ_{HWW}	κ_{AWW}
κ_{SM}	1.00	0.20	-0.95	κ_{SM}	1.00	0.49	-0.93
κ_{HWW}	0.20	1.00	0.09	κ_{HWW}	0.49	1.00	-0.16
κ_{AWW}	-0.95	0.09	1.00	κ_{AWW}	-0.93	-0.16	1.00

Table 5.10: Correlation matrix from the fit to the v0 (left) and v1 (right) samples as defined in Figure 5.10, corresponding to the fits shown in Figure 5.14 and Table 5.7.

	$\cos \alpha$	κ_{Azz}	κ_{Hzz}	κ_{SM}
Input Sample 0	0.707	-9.366	0.952	1.414
Input Sample 1	0.707	3.655	5.189	1.414
Input Sample 2	0.707	-5.510	-7.817	1.414
Input Sample 3	0.707	-4.574	4.922	1.414
Input Sample 4	0.707	7.739	-3.261	1.414
Input Sample 5	0.707	0.513	-5.612	1.414
Input Sample 6	0.707	-11.654	4.921	1.414
Input Sample 7	0.707	-0.781	8.461	1.414
Input Sample 8	0.707	9.135	1.544	1.414
Input Sample 9	0.707	-13.764	-2.333	1.414
Input Sample 10	0.707	-7.100	-3.737	1.414
Input Sample 11	0.707	10.696	5.635	1.414
Input Sample 12	0.707	14.112	-1.435	1.414
Input Sample 13	0.707	0.000	0.000	1.414
Input Sample 14	0.707	6.898	-7.420	1.414
Validation Sample v0	0.707	8.494	0.862	1.385
Validation Sample v1	0.707	-0.039	7.104	1.400
Validation Sample v2	0.707	1.814	-2.976	1.424
Validation Sample v3	0.707	-10.565	1.343	1.449
Validation Sample v4	0.707	10.735	5.051	1.391

Table 5.11: Overview of the samples used in the VBF $H \rightarrow ZZ^* \rightarrow 4\ell$ study

The morphing to two validation points (2 and 4 in Table 5.11) in comparison to the generated distribution, is shown in Figure 5.15. All distributions are shown normalised to their respective cross sections.

The morphing function describes shape and cross section, depending on the non-SM coupling parameters, in reasonable agreement with the validation distributions.

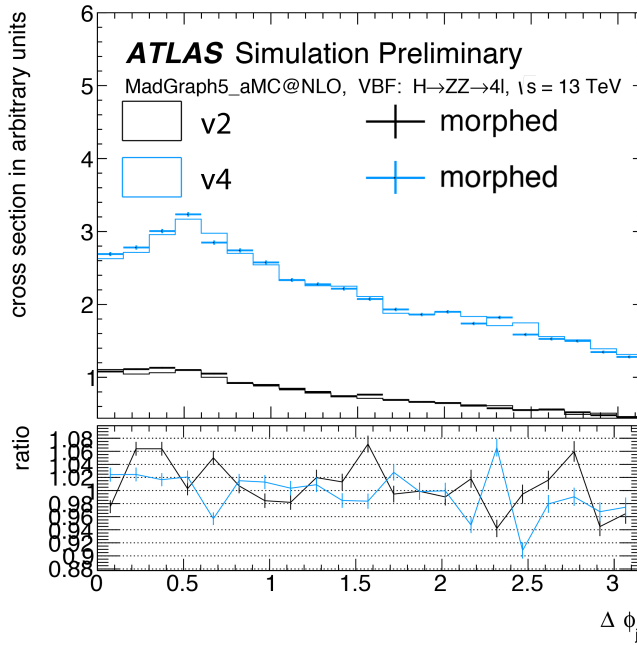


Figure 5.15: Distributions of the $\Delta\phi_{jj}$, the angle between leading and sub leading jet for events generated in the VBF $H \rightarrow ZZ^* \rightarrow 4\ell$ process at 13 TeV. Generated validation samples (solid) as well as predictions calculated via morphing (dashed) are shown. The ratio between morphing output and validation distribution is depicted in the lower panel.

5.5.2 Validation on MC reconstruction level with full analysis selection

In order to validate the morphing procedure after taking detector effects into account, the fully reconstructed Monte Carlo samples of the Run 1 $H \rightarrow ZZ^* \rightarrow 4\ell$ tensor structure analysis [138] have been used as a showcase example. This validation is also used to check the validity of morphing on more complicated observables.

Mixing of the SM with one additional non-SM parameter, κ_{HZZ} or κ_{AZZ} , has been studied in this publication using the parametrisation of the Higgs

characterisation model described in Section 5.3 with the following notation

$$\tilde{\kappa}_{HZZ} = \frac{1}{4} \cdot \frac{v}{\Lambda} \cdot \kappa_{HZZ}, \quad \tilde{\kappa}_{AZZ} = \frac{1}{4} \cdot \frac{v}{\Lambda} \cdot \kappa_{AZZ}. \quad (5.37)$$

This check of the morphing is based on the analysis described in [138], where only the dominant production process, gluon fusion Higgs production, has been taken into account. The inputs to the morphing validation in this section are the final distributions of the $H \rightarrow ZZ^* \rightarrow 4\ell$ tensor structure analysis. The used distributions are of physical observables Φ and $\text{TO}(\tilde{\kappa}_{AZZ}, \alpha)$. The angle Φ is between the decay planes of the two intermediate Z bosons, which has also been used for the validation described in section 5.5.1. The other used observable is $\text{TO}(\tilde{\kappa}_{AZZ}, \alpha)$ [138], which is one of the final discriminating variables of the $H \rightarrow ZZ^* \rightarrow 4\ell$ tensor structure measurement. This observable is sensitive to the amplitude of CP-odd admixtures in the HZZ coupling structure. A more detailed description of both variables can be found on pages 17 and 24 in the original publication [138]. The full analysis selection described in the before mentioned publication has been applied. For the Run 1 tensor structure measurement a range of $[-10, 10]$ in a step size of 0.25 for the non-SM coupling parameters was probed.

Distributions from the ggF $H \rightarrow 4\mu$ channel at 8 TeV have been chosen for the validation. The configuration of the morphing input samples, as well of the validation samples, is shown in Table 5.12.

	$\tilde{\kappa}_{\text{SM}}$	$\tilde{\kappa}_{HZZ}$	$\tilde{\kappa}_{AZZ}$
Input sample 1	1	0	0
Input sample 2	0	1	0
Input sample 3	0	0	1
Input sample 4	1	1	0
Input sample 5	0	1	1
Input sample 6	1	0	1
Validation sample Φ v1	1	-1.25	0
Validation sample Φ v2	1	-2	0
Validation sample $\text{TO}(\tilde{\kappa}_{AZZ}, \alpha)$ v3	1	0	5
Validation sample $\text{TO}(\tilde{\kappa}_{AZZ}, \alpha)$ v4	1	0	3.25

Table 5.12: Values of the coupling parameters for the morphing input and validation samples

The configuration of the input samples can be chosen arbitrarily, the only condition being that the corresponding morphing matrix is invertible, as derived in Section 5.2.4.

The validation sample used for Φ uses a SM-like CP-even scenario, whereas the validation sample used for $\text{TO}(\tilde{\kappa}_{AZZ}, \alpha)$ employs a CP-odd scenario to

show that morphing works in both cases. A comparison of the distribution of the validation samples and the output of the morphing function is shown in Figure 5.16.

The perfect agreement of the morphed distributions with the validation samples is expected, since they are not statistically independent. The input samples as well as the validation samples were obtained by ME-reweighting of a single, large sample, as discussed in Section 5.2.5. Figure 5.16 shows that more complicated observables can be morphed with this method as well. The correlations between the spin-CP variable distributions used as inputs to the observables are fully reproduced by the morphing.

Overall the morphing validation in this section demonstrates that the described morphing technique is not restricted to generator level. As long as analysis acceptance and detector effects are correctly described in the input distributions, the morphing function is able to describe arbitrary coupling parameter configurations.

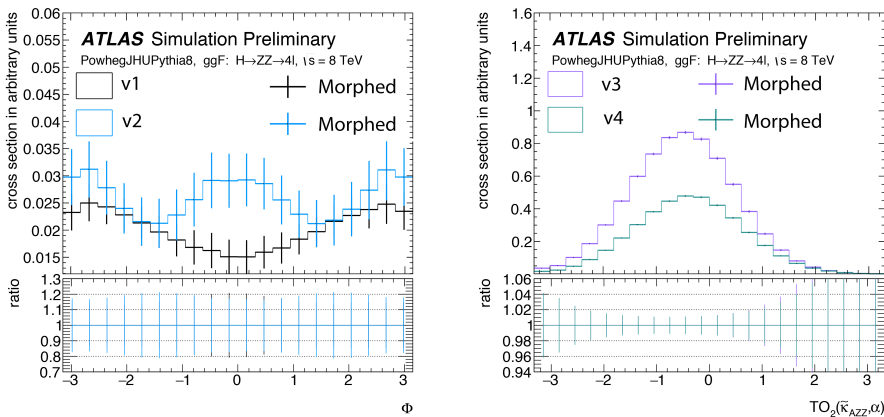


Figure 5.16: ggF $H \rightarrow ZZ \rightarrow 4\mu$ distributions at 8 TeV published in Reference [138] comparing the shapes of physical observables Φ and $\text{TO}(\tilde{\kappa}_{AZZ}, \alpha)$ for two validation points obtained via Matrix Element reweighting with the output of the morphing function. The perfect agreement is due to the fact both distributions stem from the same original sample.

5.6 Conclusions

The morphing method has been shown to perform as expected using generator-level and reconstruction-level distributions. In addition, a preliminary study on the impact of BSM coupling parameters in the context of VBF Higgs boson production has been performed, acting both as a proof-of-concept for elaborate studies using this method and as a showcase for the performance of the morphing method. This method is capable of continuously morphing signal distributions and rates based on a minimal orthogonal set of independent base samples. Therefore it allows to directly fit for the coupling parameters that describe the SM and possibly non-SM interaction of the Higgs boson with fermions and bosons of the SM.

This method can be utilised to measure the properties of the Higgs boson during the LHC Run 2 data-taking period and beyond.

5.7 Exploitation of morphing tool outside of high energy physics

Although morphing has been developed for high energy physics, the method is not restricted to this area of physics, or to physics at all. The morphing tool requires that a Lagrangian can be constructed to describe the process and that the parameters in this Lagrangian are written in a linear form.

For example, for describing path integrals and symmetry breaking for optimal control theory [151], the process can be described by a Lagrangian and MC methods are used. An optimal control is a set of differential equations describing the paths of the control variables that minimise this cost function, meaning that it is a set of equations to optimise the path from A to B. The passible paths integrals could be computed using morphing to reduce the size of the MC samples needed, while maintaining full coverage of the parameter space. This is useful for several examples in physiology, electronics, climate modelling, machine design, ecosystems, navigation, neural networks, predator-prey interaction, gene expression, and production theory.

An example where morphing could be used outside of the field of physics, is in the use of sensors in robotics [152]. Since Lagrangians are used to describe the location of objects that the sensors measure, a good and fast interpolation between measured points can be achieved using the morphing tool. This might result in either higher performance sensors, or the possibility to reduce the number of sensors needed. In particular the morphing method could be used in the Optotrak software [153], which measures eye movements, since high precision measurements are of vital importance in this context.

6 Performance of Analytic Lagrangian Morphing

The newly developed technique of Analytic Lagrangian Morphing [154] is used for some early measurements [155] of Higgs properties as well as for the development of better Higgs measurements through information geometry [156].

The only way in which Analytic Lagrangian Morphing falls short of the capabilities of Matrix Element Reweighting, the tool used in Run1, is that Matrix Element (ME) Reweighting has the additional feature to model non-coupling-like parameters, such as masses, widths and variations in parton density functions. Analytic Lagrangian Morphing can only model parameters which depend on the cross section in a polynomial form. This means that parameters such as for example m_H cannot be modelled. Analytic Lagrangian Morphing will therefore not be able to replace Matrix Element Reweighting completely, as the latter will remain an indispensable tool for the estimation of systematic uncertainties connected to the limited accuracy of the parton density functions, for non-EFT approaches to deriving limits on the masses of new particles, and to studies concerning the decay widths of particles. However, in so far as an EFT captures the parameters of the underlying theory in polynomial form parameters, Analytic Lagrangian Morphing still allows to model their effects. The additional functionality of the Analytic Lagrangian Morphing with respect to ME reweighting is that the method is fast and efficient enough to be performed in the context of a likelihood fit of the parameters, and that it accurately models the underlying physics without making any additional approximations beyond the stated Analytic Lagrangian Morphing approximation. The only internal uncertainty of the method originates from the numerical accuracy with which the matrix inversion can be performed, and the MC stat uncertainties of the samples used as templates.

The main drawbacks of the Analytic Lagrangian Morphing method is the large number of samples that need to be produced. A study to reduce the

number of free parameters in the tested model is discussed in section 6.1. Reducing the number of free parameters in the model reduces both the number of samples needed to be produced and the free parameters, dimensions, in a likelihood fit.

The method for choosing which samples are produced as an input to the morphing is discussed in section 6.2. To reduce the error coming from the morphing method, it is important to choose a sample basis that results in low errors in the interested area of the parameter phase-space.

6.1 Dimensionality reduction

Reducing the number of free parameters in the tested model reduces both the number of samples needed to be produced and the free parameters, dimensions, in a likelihood fit. The simplest method to reduce the dimensionality of the method is to fix parameters to the SM values when the fit is not sensitive to those parameters, for example due to low statistics. Instead of fixing parameters to their respective SM values, parameters can be related to each other to create a reduced model. Another approach to reduce the dimensionality is exploiting properties of the Lagrangian, which decreases by construction the number of terms in the matrix element squared. This applies for interference terms that include CP- odd and CP-even contributions.

Production of the Higgs boson via vector boson fusion (VBF) is sensitive to SM higher order or non-SM contributions in the HVV production vertex. So far there are no, or very loose experimental constraints on the contribution of the BSM coupling parameters to the VBF production. Therefore the purpose of this work is to study the VBF vertex and identify, with the help of the morphing method, a set of relevant non-SM contributions. As a benchmark for the parameters, a fit to pseudo-data generated for an SM scenario at 13 TeV has been performed, assuming an uncertainty of 8% on the measured cross section, which is the expected Run 2 uncertainty at the LHC (the ATLAS and CMS combined results from Run 1 [157] have a roughly 20% uncertainty for comparison). All studied distributions are generator level only and no backgrounds are taken into account.

For the purpose of this study, the Lagrangian of the Higgs characterisation model, as detailed in section 1.5.3, is used which describes the interaction of a scalar (Higgs) particle coupling to a pair of gauge bosons is used, including operators up to dimension 6 and their cross terms. The cut-off scale Λ is chosen at 1 TeV.

6.1.1 Setup

In order to study the BSM contributions in the VBF production, a Higgs boson decay that does not interfere with the production is chosen. For this publication $H \rightarrow \mu\mu$ has been used for purely technical reasons.

The VBF Higgs production process with subsequent decays into two muons has been produced for the SM and several BSM coupling configurations with MADGRAPH5_AMC@NLO [146] event generator. To retain gauge invariance the VBF production also includes the diagrams of the Higgs boson production in association with a hadronically decaying vector boson. Parton showers and their hadronisations are generated with Pythia8 [147] using the A14 tune [158]. The Higgs characterisation (HC) model [63] has been used as a framework for the BSM configurations within the MADGRAPH5_AMC@NLO generator.

In total there are 15 non-SM coupling parameters in the HVV vertex described as in the Higgs characterisation model in Equation 5.35. A subset of 13 parameters contributes to the VBF production vertex, listed in Table 6.1.

coupling scale factor	
κ_{SM}	1
$\kappa_{H\gamma\gamma}$	203.22
$\kappa_{A\gamma\gamma}$	408.62
$\kappa_{HZ\gamma}$	109.13
$\kappa_{AZ\gamma}$	986.88
κ_{HZZ}	5.75
κ_{AZZ}	6.96
κ_{HWW}	3.36
κ_{AWW}	3.92
$\kappa_{H\partial WR} = \Re(\kappa_{H\partial W})$	0.76
$\kappa_{H\partial WI} = \Im(\kappa_{H\partial W})$	0.84
$\kappa_{H\partial A}$	1.77
$\kappa_{H\partial Z}$	1.37

Table 6.1: The listed values of the coupling parameters reproduce the Standard Model cross section at $\sqrt{s} = 13$ TeV for the pure BSM sample. A combination of these parameters, where either the positive or the negative of the listed value is taken, is used to construct the 91 input samples for the presented VBF production vertex study.

In order to describe all BSM parameters in production with the morphing method, 91 input samples are generated with the above described setup. Each sample corresponds to 30.000 Monte Carlo events. The configurations of those

samples were chosen with the following requirements:

1. Experimental sensitivity: Chose values of BSM parameters within experimental sensitivity. The Run 1 limit on VBF cross section is $\sigma_{\text{VBF}} \lesssim (1 + \frac{1}{4}) \cdot \sigma_{\text{VBF,SM}}$. Values of the coupling parameters have been calculated to reproduce the SM cross section for pure BSM samples [157]. The values are listed in Table 6.1.
2. Since no large deviations from the SM were found in Run 1 [157], the input samples, with the exception of the pure SM sample itself, are all mixtures of SM with one or two additional BSM parameters.
3. Well defined coverage of BSM parameter phase space: Mixtures of SM plus one additional BSM parameter have been used as input with both positive and negative values for the BSM coupling strength.
4. Input samples can also represent smaller morphing input sets: Parameter configurations were chosen in such a way that also input sample sets which allow morphing of distributions with fewer than the maximal number of parameters are well represented.

6.1.2 Performance of morphing using truth level simulation samples

A provisional event selection is made to be able to test the performance of the morphing in a realistic analysis setting, even though no backgrounds are considered in this study. Events with a $H \rightarrow \mu\mu$ candidate and at least two jets are selected. Muons are required to be oppositely charged and to be within the ATLAS detector acceptance defined by $p_{T,\mu} > 6 \text{ GeV}$ and $|\eta_\mu| < 2.7$. Jets on generator truth level are reconstructed using the anti- k_t algorithm [127, 150] with a distance parameter of $R = 0.4$. A minimum transverse momentum of 20 GeV is required for jets, as well as a pseudo-rapidity of $|\eta_j| < 5.0$. Additionally the jets have to have a minimum distance of $\Delta R_{jj} > 5$. This results in the selection of an VH suppressed phase space, for future studies this requirement will be removed in order to ensure an inclusive selection.

This study will aim to model the following observable distributions with the morphing approach: $\Delta\eta_{jj}$, $\Delta\Phi_{jj}$, m_{jj} and $p_{T,j1}$. Figure 6.1 shows these distributions. Distributions for the comparison of SM with mixing of SM plus BSM CP-even coupling κ_{HWW} are shown in Figure 6.1. It should be noted that the distributions of m_{jj} and $\Delta\eta_{jj}$ are correlated for the signal. The observable $\Delta\Phi_{jj}$ includes sign information of the BSM coupling parameters κ_{HZZ} , κ_{HZA} and κ_{HWW} . The distributions $p_{T,j1}$ and $\Delta\eta_{jj}$ are sign-sensitive for $\kappa_{H\partial Z}$ and $\kappa_{H\partial W_R}$.

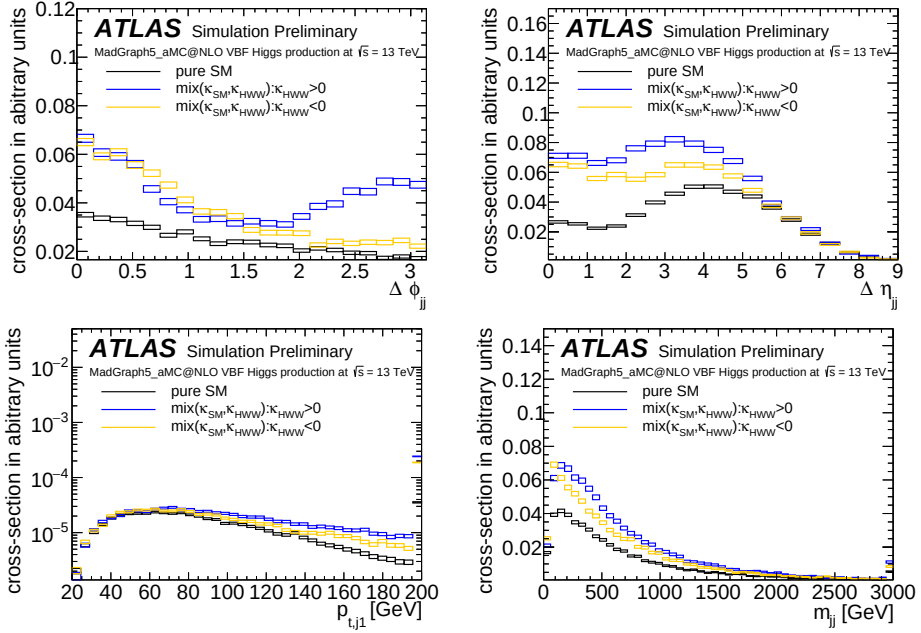


Figure 6.1: VBF $H \rightarrow \mu\mu$ distributions for $\Delta\Phi_{jj}$ (top left), $p_{T,j1}$ (bottom left), m_{jj} (top right) and $\Delta\eta_{jj}$ (bottom right) with mixing of SM and BSM CP-even HWW couplings. The size of the boxes correspond to the Monte Carlo statistical uncertainties.

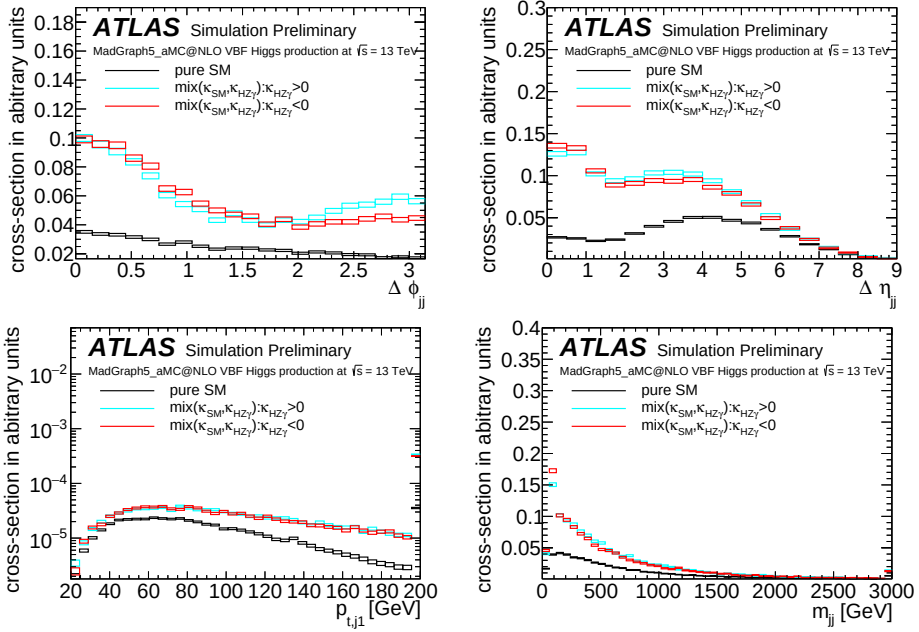


Figure 6.2: VBF $H \rightarrow \mu\mu$ distributions for $\Delta\Phi_{jj}$ (top left), $p_{T,j1}$ (bottom left), m_{jj} (top right) and $\Delta\eta_{jj}$ (bottom right) with mixing of SM and BSM CP-even $HZ\gamma$ couplings. The size of the boxes correspond to the Monte Carlo statistical uncertainties.

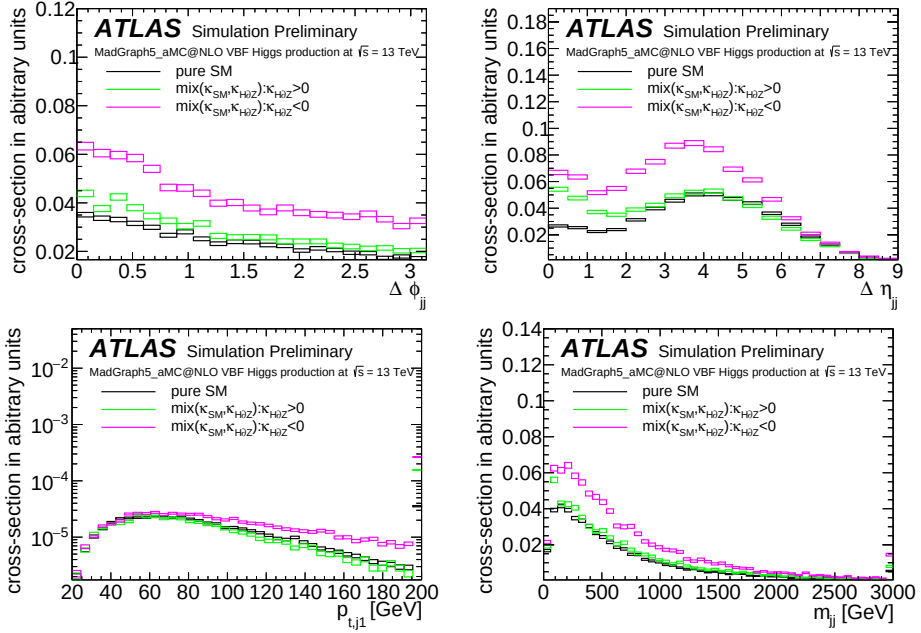


Figure 6.3: VBF $H \rightarrow \mu\mu$ distributions for $\Delta\Phi_{jj}$ (top left), $p_{T,j1}$ (bottom left), m_{jj} (top right) and $\Delta\eta_{jj}$ (bottom right) with mixing of SM and BSM CP-even $H\partial Z$ couplings. The size of the boxes correspond to the Monte Carlo statistical uncertainties.

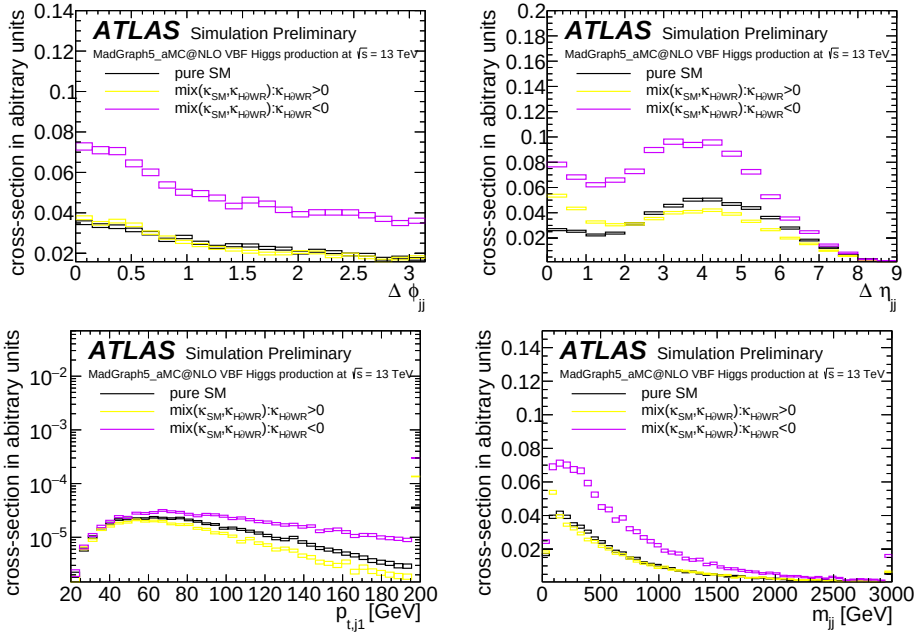


Figure 6.4: VBF $H \rightarrow \mu\mu$ distributions for $\Delta\Phi_{jj}$ (top left), $p_{T,j1}$ (bottom left), m_{jj} (top right) and $\Delta\eta_{jj}$ (bottom right) with mixing of SM and BSM CP-even $H\partial W_R$ couplings. The size of the boxes correspond to the Monte Carlo statistical uncertainties.

For the study of the VBF production the above observables are concatenated into one final binned distribution var_{4d} shown in Figure 6.5, which takes the correlations between the input variables into account by constructing the combined variable var_{4d} in the following manner;

$$\text{var}_{4d} = 3^3 \cdot i_{\Delta\eta_{jj}} + 3^2 \cdot i_{m_{jj}} + 3 \cdot i_{p_{T,j1}} + i_{\Delta\Phi_{jj}},$$

where the values of each of the four variables are divided into three bins

$$i_{\text{var}} = \begin{cases} 0 & \text{var} < (\min_{\text{var}} + \frac{1}{3} \cdot (\max_{\text{var}} - \min_{\text{var}})) \\ 1 & (\min_{\text{var}} + \frac{1}{3} \cdot (\max_{\text{var}} - \min_{\text{var}})) \leq \text{var} < (\min_{\text{var}} + \frac{2}{3} \cdot (\max_{\text{var}} - \min_{\text{var}})) \\ 2 & \text{var} \geq (\min_{\text{var}} + \frac{2}{3} \cdot (\max_{\text{var}} - \min_{\text{var}})) \end{cases}.$$

The minimum and maximum values of each variable are listed in Table 6.2.

	$\Delta\eta_{jj}$	m_{jj} [GeV]	$p_{T,j1}$ [GeV]	$\Delta\Phi_{jj}$
min	0	0	20	0
max	6	1000	200	π

Table 6.2: Minimum and maximum values of the VBF production jet variables $\Delta\eta_{jj}$, m_{jj} , $p_{T,j1}$ and $\Delta\Phi_{jj}$.

The sensitivity to the coupling parameters and their correlations are retrieved by fitting a SM pseudo-dataset simulated at 13 TeV, with a samples size that corresponds to a statistical uncertainty of 8% on the inclusive cross section.

In Table 6.3 the post-fit values of all coupling parameters and their respective fit uncertainties are listed. The value of the fit uncertainty provides insight about the sensitivity to the BSM parameters in a SM-like Higgs scenario.

The post-fit correlation matrix is shown in Table 6.4. Depicted values can be compared, for example, to theoretical predictions of BSM coupling parameter correlations. The correlation matrix, like the sensitivity, may vary substantially over the parameter pace of the model. The matrix shown in table 6.4 is only valid for scenarios close to the SM.

As can be seen in figure 6.1, there are many parameters with varying sensitivity for Run 2, hence it may be desirable to eliminate these very insensitive parameters from the model in the near future. However, the presence of strong correlations, as shown in table 6.4, implies that it may not be optimal to simply eliminate a subset of the chosen insensitive parameters, as the data may still be sensitive to linear combinations of parameters that are individually insensitive. Based on these findings it is foreseen to be able to reduce the dimensionality of the required parameter space by means of a principal component analysis and subsequent reparametrisation and neglecting of parameters to which there is

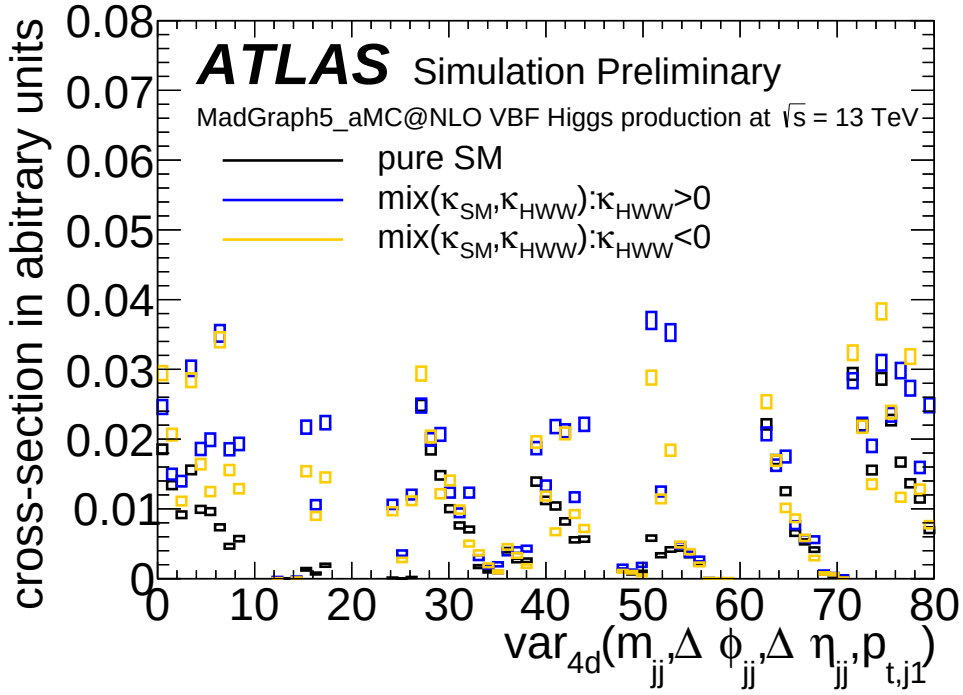


Figure 6.5: VBF $H \rightarrow \mu\mu$ distribution of var_{4d} , which is a combination of $\Delta\eta_{jj}$, $\Delta\Phi_{jj}$, m_{jj} and $p_{T,j1}$ into one discriminating variable, shown for SM and mixing of SM with BSM CP-even HWW couplings. The size of the boxes correspond to the Monte Carlo statistical uncertainties.

parameter	post-fit value	+	−
Λ	1000.		
$\cos \alpha$	0.71		
$\kappa_{H\ell\ell}$	1.41		
$\kappa_{A\gamma\gamma}$	0	+219	−441
κ_{Aww}	0	+3	−2.6
$\kappa_{Az\gamma}$	0	+441	−398
κ_{Azz}	0	+2.7	−1.3
$\kappa_{H\gamma\gamma}$	0	+236	−91
$\kappa_{H\partial\gamma}$	0	+0.3	−0.6
$\kappa_{H\partial wI}$	0	+1.6	−0
$\kappa_{H\partial wR}$	0	+0.5	−0.3
$\kappa_{H\partial z}$	0	+1.2	−0.5
κ_{Hww}	0	+1.5	−3
$\kappa_{Hz\gamma}$	0	+38	−49
κ_{Hzz}	0	+8	−2.5
κ_{SM}	1.41	+0.22	−0.11

Table 6.3: Values of the coupling parameters and their respective errors after fitting to SM pseudo-data with 8% cross section uncertainty. The top rows list the input parameters that were fixed to their nominal values during the fit.

little to no sensitivity. Also, careful study might allow to choose a set of input samples that provide a smaller statistical uncertainty on the fit results.

6.1.3 Rotation to Eigen space

New parameters are constructed without correlations between the parameters to be able to reduce the number of parameters in a way that eliminates parameters, or linear combinations of parameters, with low sensitivity. To this end a rotation to the Eigen basis of the covariance matrix is performed. A re-parametrisation in eigenvectors is performed as illustrated in figure 6.6.

The eigenvalues of the rotated parameter correspond to a larger variation in the data, which corresponds to less sensitivity to this parameter. After a re-parameterisation in eigenvectors is performed, a fit can be done on the new parameter space. The rotated parameters with low sensitivity can be fixed to their SM value. The result of the fit on the rotated parameters is expected to have a near $\mathbb{1}$ correlation matrix, since the correlations of the fit on the κ parameter space are used to create an orthogonal rotated parameter space through the eigenvectors. The Eigen rotation assumes a mostly multivariate

	$\kappa_{A\gamma\gamma}$	κ_{AWW}	$\kappa_{AZ\gamma}$	κ_{AZZ}	$\kappa_{H\gamma\gamma}$	$\kappa_{H\theta\gamma}$	$\kappa_{H\theta W I}$	$\kappa_{H\theta W R}$	$\kappa_{H\theta Z}$	$\kappa_{HW W}$	$\kappa_{H Z \gamma}$	$\kappa_{H Z Z}$	κ_{SM}
$kAaa$	1.000	0.125	-0.092	0.027	0.117	-0.348	-0.059	0.131	-0.116	-0.178	0.064	0.072	-0.173
$kAw w$	0.125	1.000	0.327	-0.303	-0.352	0.179	-0.104	-0.468	0.689	0.313	0.087	-0.263	-0.143
$kAza$	-0.092	0.327	1.000	-0.088	0.173	-0.048	-0.055	0.133	-0.001	-0.026	0.208	-0.090	-0.056
$kAzz$	0.027	-0.303	-0.088	1.000	-0.262	0.230	0.405	0.124	-0.223	0.341	0.203	-0.480	0.111
$kHaa$	0.117	-0.352	0.173	-0.262	1.000	-0.127	-0.221	0.159	-0.264	-0.464	-0.010	0.256	-0.008
$kHda$	-0.348	0.179	-0.048	0.230	-0.127	1.000	-0.116	-0.352	0.343	0.264	0.279	-0.338	0.202
$kHdwI$	-0.059	-0.104	-0.055	0.405	-0.221	-0.116	1.000	0.020	-0.029	0.259	-0.132	-0.194	0.012
$kHdwR$	0.131	-0.468	0.133	0.124	0.159	-0.352	0.020	1.000	-0.922	-0.151	-0.290	0.242	0.029
$kHdz$	-0.116	0.689	-0.001	-0.223	-0.264	0.343	-0.029	-0.922	1.000	0.246	0.246	-0.227	0.091
$kHww$	-0.178	0.313	-0.026	0.341	-0.464	0.264	0.259	-0.151	0.246	1.000	-0.121	-0.754	-0.041
$kHza$	0.064	0.087	0.208	0.203	-0.010	0.279	-0.132	-0.290	0.246	-0.121	1.000	-0.409	0.231
$kHzz$	0.072	-0.263	-0.090	-0.480	0.256	-0.338	-0.194	0.242	-0.227	-0.754	-0.409	1.000	0.010
kSM	-0.173	-0.143	-0.056	0.111	-0.008	0.202	0.012	0.029	0.091	-0.041	0.231	0.010	1.000

Table 6.4: Correlation matrix of the coupling parameters after fitting to SM pseudo-data with 8% cross section uncertainty. The colours roughly indicate the size of the correlation, where a correlation larger than 30% shown in red, a correlation between 10% and 30% is shown in blue and correlations smaller than 10% are shown in black.

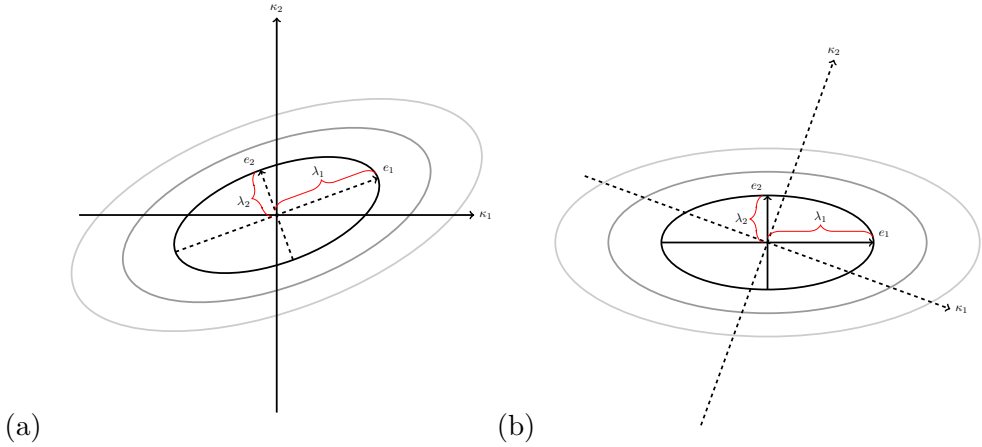


Figure 6.6: Illustration of the re-parametrisation into the Eigen basis of the covariance matrix, (a) before the rotation and (b) after the rotation. The ellipses indicate the likelihood contours coming from a fit. The e_i vectors indicate the Eigen directions with Eigenvalue λ_i .

Gaussian structure of the likelihood. If this assumption is not true, residual correlations may occur and the beneficial effect of the rotation may be lost.

6.1.4 Reduced model performance

To be able to take a closer look at what happens during the diagonalisation, reduced models where only three parameters are taking into account are considered. In these reduced models the other parameters are set to the SM values. All the reduced models have κ_{SM} as one of the parameters, and two other parameters. Three examples are discussed in detail.

1. Example of reduced model with κ_{HWW} , $\kappa_{H\partial WI}$ and κ_{SM}

As a first examples a reduced model is considered with κ_{HWW} , $\kappa_{H\partial WI}$ and κ_{SM} . Figure 6.7 shows the profiled likelihood after a fit is performed on the reduced model. Figure 6.7(c) shows the correlation between the three parameters. The correlation matrix is calculated is the minimum of the fit, assuming a hessian distribution. The hessian approximation of the likelihood is shown in green lines in the likelihood plots.

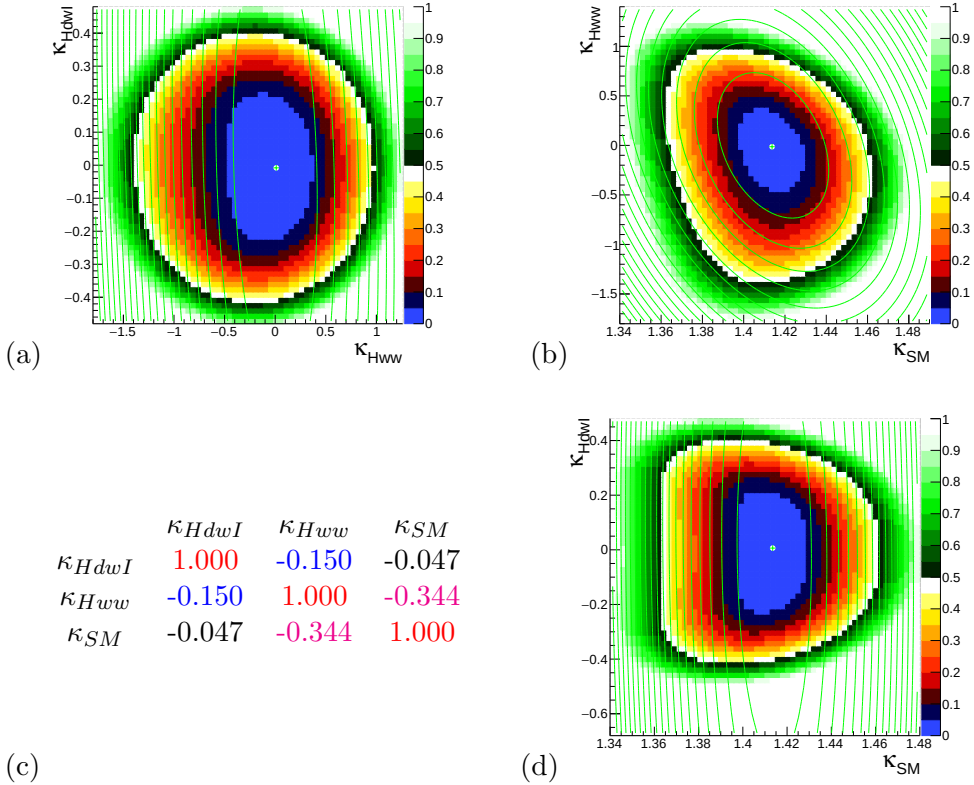


Figure 6.7: The profiled likelihood plots after a fit is performed on the reduced model are shown for (a) κ_{HWW} versus κ_{HdWI} , (b) κ_{HWW} versus κ_{SM} and (d) κ_{HdWI} versus κ_{SM} . The correlation matrix is shown in (c). The z-axis indicates the likelihood and the overlaid green lines show the hessian approximation of the likelihood as calculated in the fit minimum.

The correlation matrix of the fit is used to calculate the diagonalisation transformation:

$$\begin{aligned}\kappa_{HdwI} &= +0.990000 \cdot \text{EV}_0 - 0.130000 \cdot \text{EV}_1 + 0.002200 \cdot \text{EV}_2 \\ \kappa_{Hww} &= -0.130000 \cdot \text{EV}_0 - 0.990000 \cdot \text{EV}_1 + 0.013000 \cdot \text{EV}_2 \\ \kappa_{SM} &= -0.000410 \cdot \text{EV}_0 + 0.013000 \cdot \text{EV}_1 + 1.000000 \cdot \text{EV}_2\end{aligned}$$

After this transformation is performed, a fit on the diagonalised model to the data is performed. The profiled likelihood of the fit after diagonalisation is shown in figure 6.8. The correlation between the parameters after the diagonalisation is shown in figure 6.8(c). This correlation matrix is close to the expected $\mathbb{1}$ matrix. This shows that the diagonalisation works as expected.

2. Example of reduced model with $\kappa_{H\gamma\gamma}$, $\kappa_{A\gamma\gamma}$ and κ_{SM}

As a second example a reduced model is considered with $\kappa_{H\gamma\gamma}$, $\kappa_{A\gamma\gamma}$ and κ_{SM} . Figure 6.9 shows the profiled likelihood after a fit is performed on the reduced model. Figure 6.9(c) shows the correlation between the three parameters. The correlation matrix is calculated is the minimum of the fit, assuming a hessian distribution. The hessian approximation of the likelihood is shown in green lines in the likelihood plots. A sign ambiguity is present in the likelihood when taking a closer look at the profiled likelihoods shown in figure 6.9(b) and (d). From the structure that this sign ambiguity introduces in the likelihood it can be assumed that the hessian likelihood approximation is incorrect, and therefore the wrong diagonalisation transformation is constructed.

A brute-force application of the diagonalisation algorithm, ignoring the issue with the likelihood structure, results in:

$$\begin{aligned}\kappa_{Aaa} &= -1.000000 \cdot \text{EV}_0 - 0.054000 \cdot \text{EV}_1 - 0.000004 \cdot \text{EV}_2 \\ \kappa_{Haa} &= -0.054000 \cdot \text{EV}_0 + 1.000000 \cdot \text{EV}_1 + 0.000022 \cdot \text{EV}_2 \\ \kappa_{SM} &= -0.000003 \cdot \text{EV}_0 - 0.000022 \cdot \text{EV}_1 + 1.000000 \cdot \text{EV}_2\end{aligned}$$

After this transformation is performed, a fit of the diagonalised model to the data is performed. The profiled likelihood of the fit after diagonalisation is shown in figure 6.10. The correlation between the parameters of the diagonalised model is shown in figure 6.10(c). This correlation shows correlations of similar order of magnitude as before the diagonalisation was performed and sign ambiguities are present also in this diagonalised parameter space. In this example the diagonalisation of the full model did not work due to the effect of sign ambiguities. These sign ambiguities can be resolved by increasing the

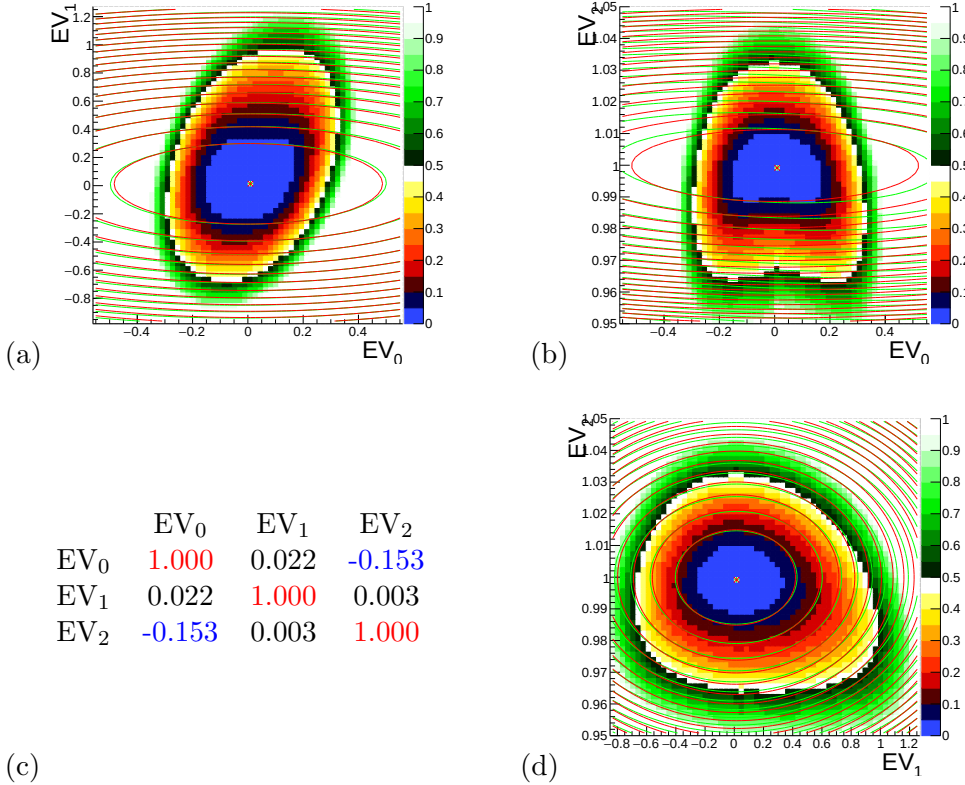


Figure 6.8: The profiled likelihood plots after a fit is performed on the diagonalised reduced model are shown for (a) EV_0 versus EV_1 , (b) EV_0 versus EV_2 and (d) EV_1 versus EV_2 . The correlation matrix after diagonalisation is shown in (c). The z-axis indicates the likelihood and the overlaid green lines show the hessian approximation of the likelihood as calculated in the fit minimum. The overlaid red lines show the shape of the likelihood when the transformation is applied to the hessian approximation before diagonalisation.

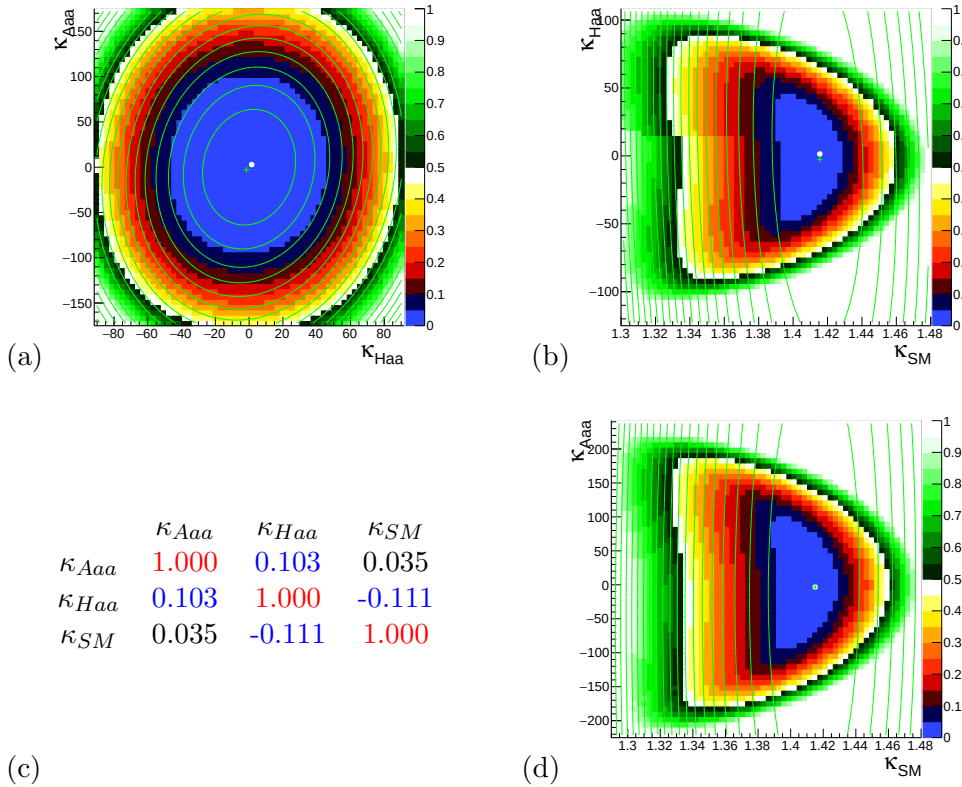


Figure 6.9: The profiled likelihood plots after a fit is performed on the reduced model are shown for (a) κ_{Haa} versus κ_{Aaa} , (b) κ_{Haa} versus κ_{SM} and (d) κ_{Aaa} versus κ_{SM} . The correlation matrix is shown in (c). The z-axis indicates the likelihood and the overlaid green lines show the hessian approximation of the likelihood as calculated in the fit minimum.

sensitivity to these parameters. This can be done, for example, by changing the histogram on which this analysis is done to a histogram with higher sensitivity to (one of these) parameters, or possibly by increasing the statistics.

3. Example of reduced model with κ_{HWW} , κ_{AWW} and κ_{SM}

As the final example a reduced model is considered with κ_{HWW} , κ_{AWW} and κ_{SM} . Figure 6.11 shows the profiled likelihood after a fit is performed on the reduced model. Figure 6.11(c) shows the correlation between the three parameters. The correlation matrix is calculated at the minimum of the fit, assuming a hessian distribution. The hessian approximation of the likelihood is shown in green lines in the likelihood plots.

The correlation matrix of the fit is used to calculate the diagonalisation transformation:

$$\begin{aligned}\kappa_{Aww} &= +0.980000 \cdot EV_0 - 0.170000 \cdot EV_1 + 0.024000 \cdot EV_2 \\ \kappa_{Hww} &= -0.170000 \cdot EV_0 - 0.980000 \cdot EV_1 + 0.013000 \cdot EV_2 \\ \kappa_{SM} &= -0.021000 \cdot EV_0 + 0.017000 \cdot EV_1 + 1.000000 \cdot EV_2\end{aligned}$$

After this transformation is performed, a fit of the diagonalised model to the data is performed. The profiled likelihood of the fit after diagonalisation is shown in figure 6.12. The correlation between the parameters after the diagonalisation is shown in figure 6.12(c). This correlation shows larger correlations than before the diagonalisation was performed and especially the profiled likelihood shown in 6.12(b) shows a clear non-hessian shape. This is surprising since the likelihoods shown in figure 6.11 show no abnormal behaviour and the hessian approximation seems to match well with the profiled likelihood.

As a first check to better understand the strange behaviour of the diagonalisation, a three dimensional plot is made of the likelihood as shown in 6.13. This three dimensional likelihood does not show any unexpected behaviour either.

It is possible that there are higher order correlations between the considered parameters, which are not taken into account in the transformation. One way these higher correlations could manifest themselves is if the correlation calculated with the use of the hessian approximation changes depending on where in the parameter space the approximation is made. In the regular analysis of the data, only the covariance matrix measured at the point of maximum likelihood is evaluated and used. To investigate this particular problem case, the covariance matrix over a wider range of parameters that bracket the point of maximum likelihood are evaluated. The correlation calculated per point in the parameter space is shown in figure 6.14. The correlation matrix as calculated in the fit minimum before the transformation is performed is shown

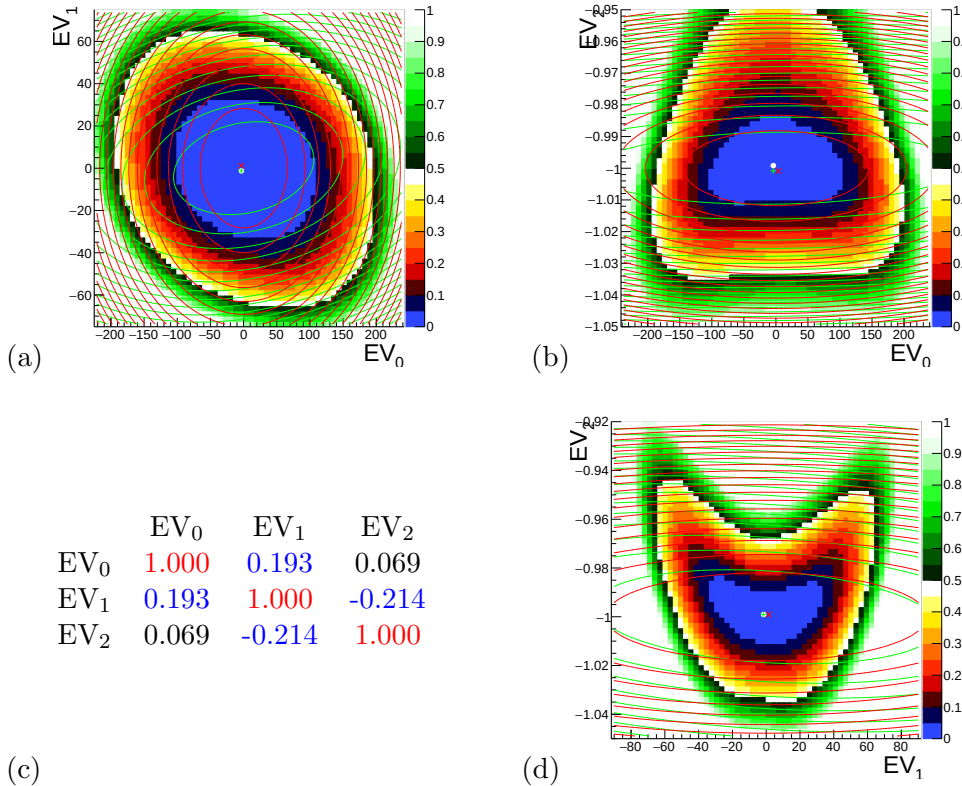


Figure 6.10: The likelihood plots after a fit is performed on the diagonalised reduced model are shown for (a) EV_0 versus EV_1 , (b) EV_0 versus EV_2 and (d) EV_1 versus EV_2 . The correlation matrix after diagonalisation is shown in (c). The z-axis indicates the likelihood and the overlaid green lines show the hessian approximation of the likelihood as calculated in the fit minimum. The overlaid red lines show the shape of the likelihood when the transformation is applied to the hessian approximation before diagonalisation.

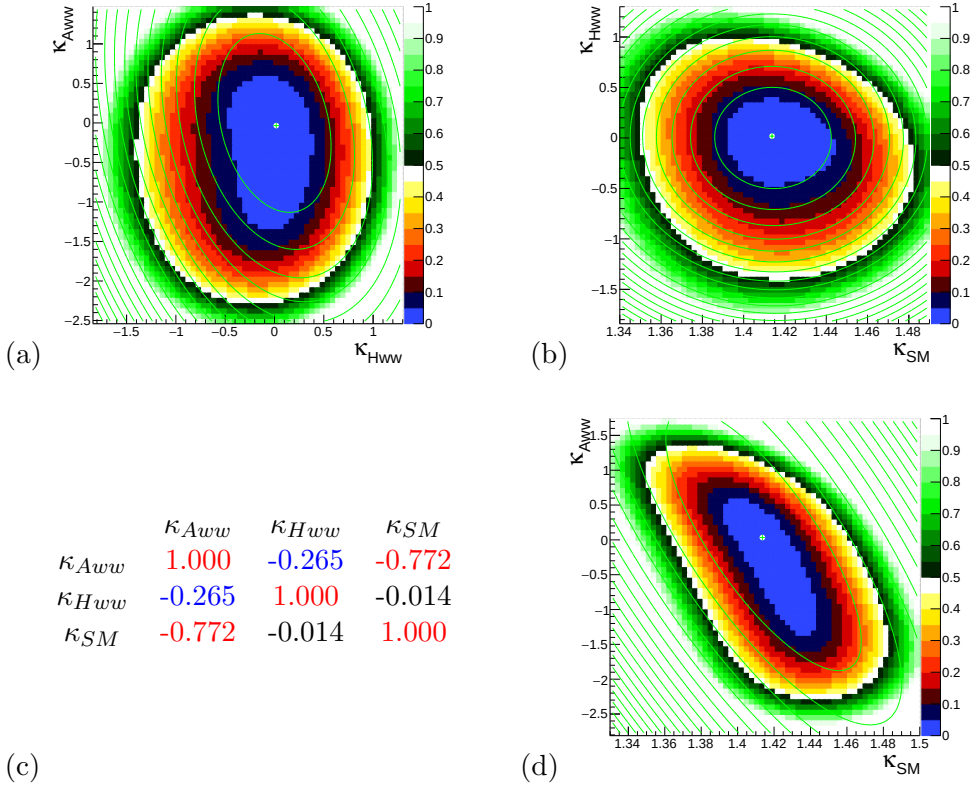


Figure 6.11: The profiled likelihood plots after a fit is performed on the reduced model are shown for (a) κ_{HWW} versus κ_{AWW} , (b) κ_{HWW} versus κ_{SM} and (d) κ_{AWW} versus κ_{SM} . The correlation matrix is shown in (c). The z-axis indicates the likelihood and the overlaid green lines show the hessian approximation of the likelihood as calculated in the fit minimum.

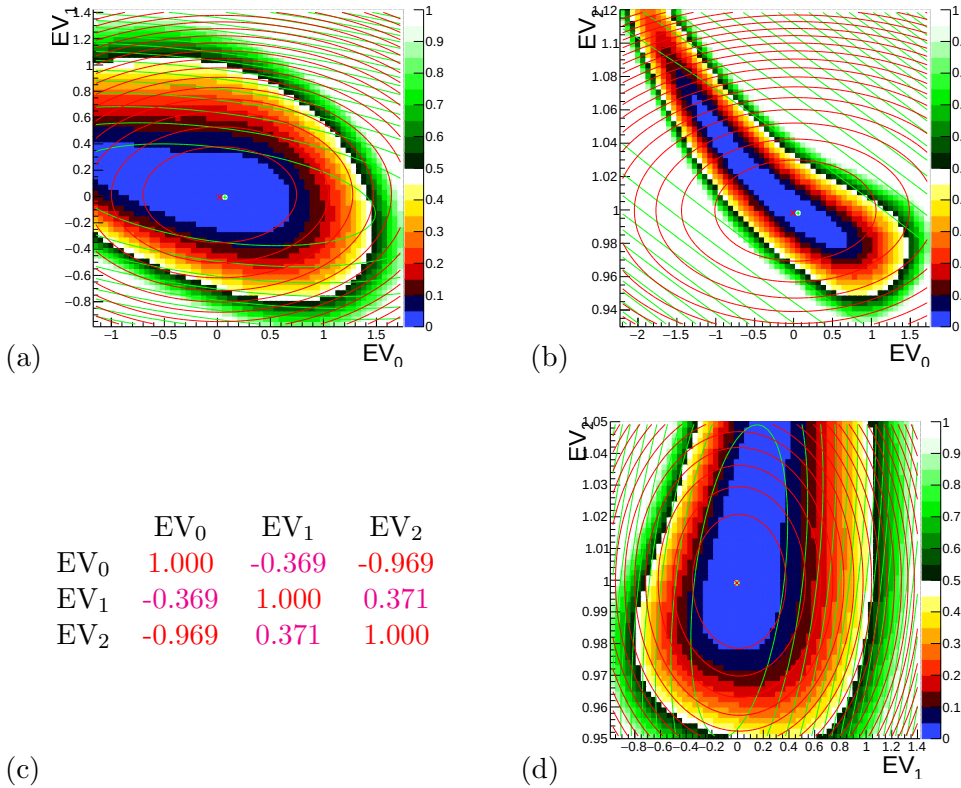


Figure 6.12: The likelihood plots after a fit is performed on the diagonalised reduced model are shown for (a) EV_0 versus EV_1 , (b) EV_0 versus EV_2 and (d) EV_1 versus EV_2 . The correlation matrix after diagonalisation is shown in (c). The z-axis indicates the likelihood and the overlaid green lines show the hessian approximation of the likelihood as calculated in the fit minimum. The overlaid red lines show the shape of the likelihood when the transformation is applied to the hessian approximation before diagonalisation.

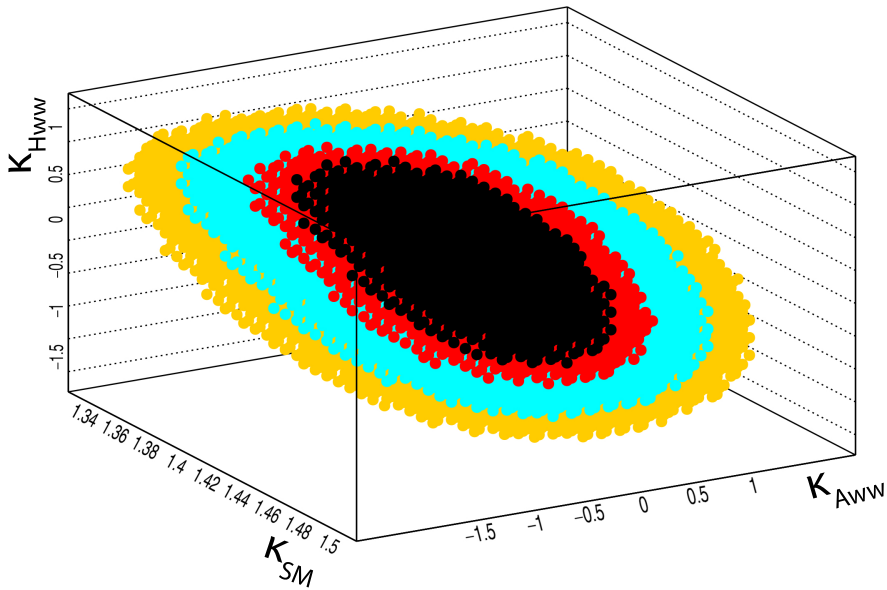


Figure 6.13: The profiled likelihood plots after a fit is performed on the reduced model are shown for κ_{HWW} versus κ_{AWW} versus κ_{SM} . The colour indicates the likelihood.

in 6.14(c) for comparison.

The correlations are calculated by fitting a Gaussian function to the likelihood of two parameters x and y . The fitted function is

$$-\ln(A) + c_{xx} * (x - \hat{x})^2 + c_{yy} * (y - \hat{y})^2 - 2 * c_{xy} * (x - \hat{x}) * (y - \hat{y}), \quad (6.1)$$

where c_{xx} is the variance of the first parameter (x), c_{yy} is the variance of the first parameter (y), c_{xy} is the covariance between the two parameters (x and y) and A is a scale factor that corresponds to the maximum of the likelihood [159, 160]. This Gaussian parabola is fitted to the likelihood at different points in the parameter space and c_{xx} , c_{yy} and c_{xy} are extracted, which are used to calculate the correlation between the two parameters. Figure 6.14 shows that the correlation is not constant throughout the parameter space. For comparison the method of fitting the Gaussian parabola is applied to the hessian approximation of the likelihood as well. The fluctuation of the correlations calculated with this hessian approximation of the likelihood is smaller than 5%. The non-constant behaviour of the correlations throughout the parameter space may explain why the diagonalisation transformation does not work.

Using the diagonalisation as a method to reduce the number of parameters taken into account can be complicated due to sign ambiguities shown in example 2. Another complication arises from non-constant correlations throughout the parameter space as shown in example 3. Especially the effects shown in example 3 imply that taking a reduced model into account will not always be accurate.

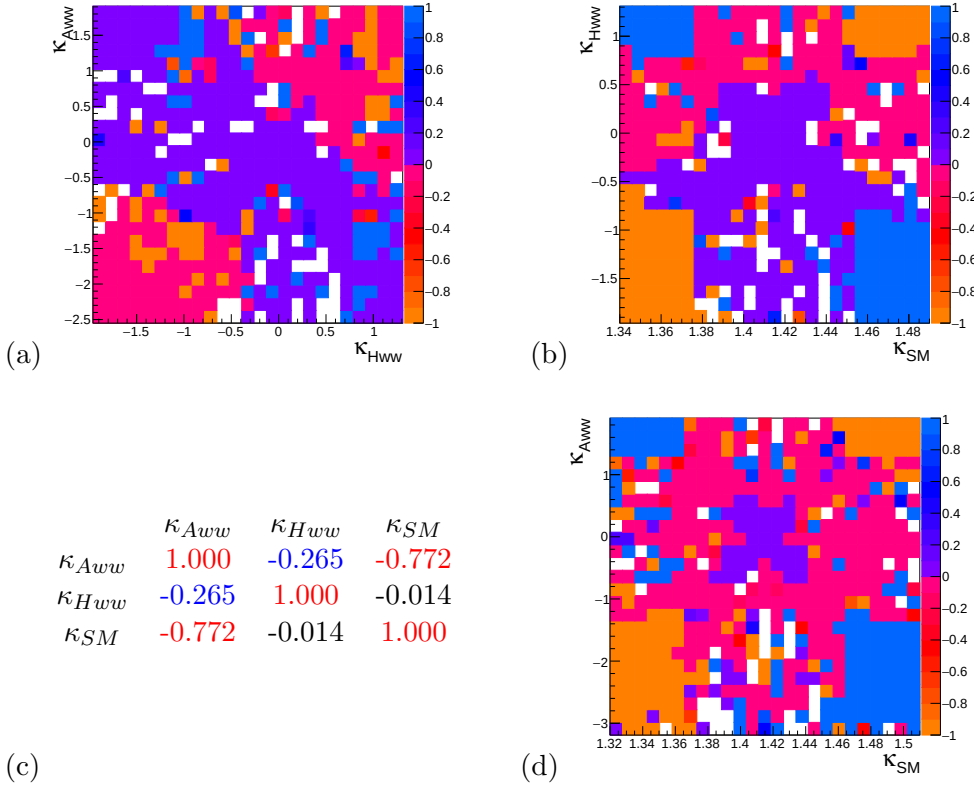


Figure 6.14: The correlation between the parameters calculated at different places in the parameter space are shown for (a) κ_{HWW} versus κ_{AWW} , (b) κ_{HWW} versus κ_{SM} and (d) κ_{AWW} versus κ_{SM} . The correlation matrix is shown in (c). The z-axis indicates the correlation.

6.1.5 Interference study

An additional physics validation of the model which can be used to reduce the dimensionality of the model is by exploiting properties of the Lagrangian. The number of terms in the matrix element squared are, for example, decreased for interference terms that include CP-odd and CP-even contribution. The Lagrangian describing the interaction between the Higgs boson field X_0 and some vector boson V (like W or Z) takes the form

$$\mathcal{L} = \left\{ a_1 V_\mu V^\mu + a_2 V_{\mu\nu} V^{\mu\nu} + b V_{\mu\nu} \tilde{V}^{\mu\nu} \right\} X_0, \quad (6.2)$$

where

$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu \quad (6.3)$$

is the reduced field strength tensor, and

$$\tilde{V}^{\mu\nu} = \frac{1}{2} \epsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} \quad (6.4)$$

is the dual tensor. The couplings a_1 and a_2 are the SM and non-SM CP-even couplings, and b is a non-SM CP-odd coupling. Considering the tree-level $H \rightarrow VV$ decay, the tensor structure of this vertex is

$$\mathcal{V}^{\mu\nu} \propto a_1 g^{\mu\nu} + a_2 (q_1^\mu q_2^\nu - q_1 q_2 g^{\mu\nu}) + b \epsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma}, \quad (6.5)$$

which will be a factor in the Matrix Element. However, the contraction of the totally antisymmetric tensor $\epsilon^{\mu\nu\rho\sigma}$ with $g^{\mu\nu}$ will make any interference terms between CP-even and CP-odd terms vanish when calculating cross sections or partial widths.

This section is to demonstrate that this physics effect is correctly modelled by *Effective Lagrangian Morphing*. Figure 6.1.5 shows a Feynman diagram of Higgs boson production via vector boson fusion with subsequent decay to vector bosons, with the exact same effective vertex with two available $H \rightarrow VV$ couplings g_1 and g_2 being allowed for both production and decay. The Matrix Element in this case will take the form

$$\begin{aligned} \mathcal{M} &\propto (g_1 \mathcal{M}_1 + g_2 \mathcal{M}_2)^2, \\ |\mathcal{M}|^2 &\propto g_1^4 |\mathcal{M}_1|^4 + g_2^4 |\mathcal{M}_2|^4 + 2g_1^2 g_2^2 \left(|\mathcal{M}_1|^2 |\mathcal{M}_2|^2 + \Re \mathcal{M}_1 \mathcal{M}_2^{*2} \right) \\ &\quad + 4g_1^3 g_2 |\mathcal{M}_1^2| \Re \mathcal{M}_1 \mathcal{M}_2^* + 4g_1 g_2^3 \Re \mathcal{M}_1 \mathcal{M}_2^* |\mathcal{M}_2|^2. \end{aligned} \quad (6.6)$$

The number of terms is five, as expected in this case. Assuming now that one of these couplings is CP-odd and the other one CP-even, the term $\Re \mathcal{M}_1 \mathcal{M}_2^*$ vanishes by construction which reduces the matrix element square to the form

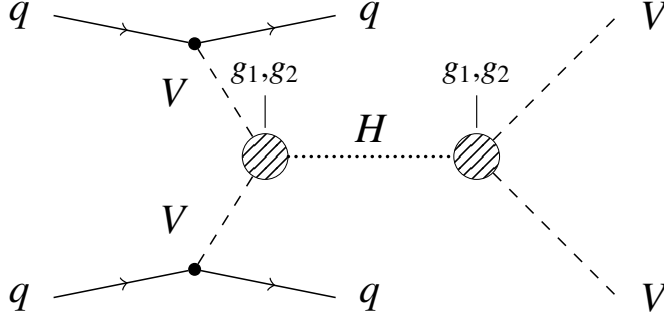


Figure 6.15: Feynman diagram for Higgs boson production via VBF and subsequent decay $H \rightarrow VV$, employing effective $H \rightarrow VV$ couplings with two couplings g_1 and g_2 .

$$|\mathcal{M}|^2 \propto g_1^4 |\mathcal{M}_1|^4 + g_2^4 |\mathcal{M}_2|^4 + 2g_1^2 g_2^2 |\mathcal{M}_1|^2 |\mathcal{M}_2|^2, \quad (6.7)$$

which reduces the number of terms to three.

In order to prove experimentally that this is possible, two sets of samples have been generated with MGMCatNLO 2.3.3.p1 [87] in the Higgs Characterisation Model (introduced in 1.5.3) using the leading-order PDF set NNPDFXXLO [158]. Hadronisation and showering were again performed with Pythia8.212 [78] using the A14 tune [158]. One of the sets includes the CP-even BSM coupling κ_{HWW} , the other one includes the CP-odd BSM coupling κ_{AWW} . Then, two versions of the morphing function have been constructed on each sample set, one standard version including the interference terms, and another one excluding vanishing interference terms. The sample configurations as well as the resulting predictions in comparison with an independent validation sample are shown in figure 6.16. Notably, the full calculation including the interference terms requires five samples, whereas the calculation of the morphing function without the interference terms only requires three. The reduced base sets are true subsets of the full ones, hence the uncertainty bands shown are not uncorrelated. However, they are still useful for comparison with the statistically independent validation sample.

While in the CP-odd case, the modelling of the validation sample is equally good with and without the interference terms, the modelling breaks down entirely without the interference terms in the CP-even case. This is completely expected, as the $\kappa_{AWW}\kappa_{SM}$ interference terms are expected to vanish either way for the CP-odd scenario, whereas the $\kappa_{HWW}\kappa_{SM}$ interference terms do not vanish in the CP-even case. Hence, this result illustrates that Effective

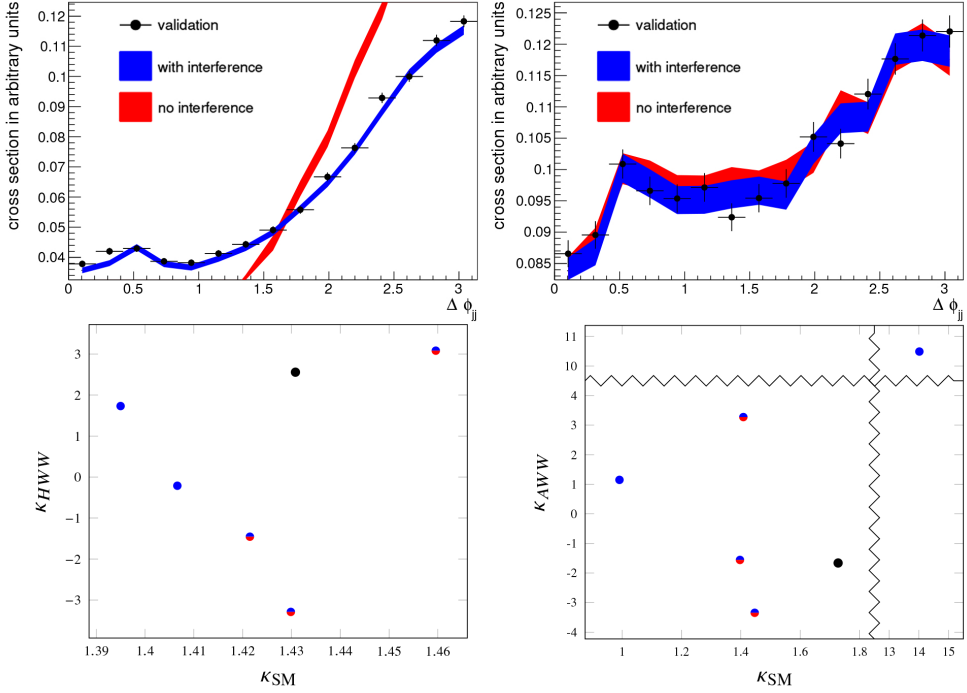


Figure 6.16: Comparison of Effective Lagrangian Morphing for VBF HWW, including either the CP-even HWW coupling (left) or the CP-odd AWW coupling (right) in addition to the Standard Model coupling. For each scenario, the morphing is constructed with (blue) or without (red) the interference terms. Also shown is an independent validation sample (black). The top panels show the predicted distributions in the azimuthal angular separation of the jets $\Delta\phi_{jj}$, whereas the bottom panels show the coupling parameter choices of the samples. The bi-colour markers indicate samples that are used in both cases. All samples are using $\cos\alpha = \frac{1}{\sqrt{2}}$ and $\Lambda = 1\text{ TeV}$. The zig-zag lines indicate discontinuities in the axes.

Lagrangian Morphing correctly models the interference terms, even in cases where they contribute significantly to the final result, and that physical insights into the tensor structure of the Matrix Element can be used to effectively reduce the dimensionality of the setup.

6.2 A methodology for optimisation of sample basis

Besides the possibility of reducing the number of couplings, the only freedom left to further minimise the uncertainty of the morphing model description of BSM Higgs signal is to choose well suited sample points of the coupling parameters for the input samples. To do this, an analysis is performed which analyses the formula expressing the uncertainty of the morphing output. For each bin of a binned morphed distribution, this is written as:

$$T_{\text{out}}^{\text{bin}}(\vec{g}_{\text{target}}) = \sum_{i=1}^N w_i \left(\vec{g}_{\text{target}}; \{\vec{g}_l\}_{l=1}^N \right) T_{\text{in}}^{\text{bin}}(\vec{g}_i). \quad (6.8)$$

The value of the bin in the input distribution is given by the number $N_{\text{in,MC}}^{\text{bin}}(\vec{g}_i)$ of events in the input sample produced at the parameter point $\vec{g}_i$ that fall into that bin, as well as the cross section $\sigma_{\text{in}}(\vec{g}_i)$ and the target luminosity $\mathcal{L}$.

Let $N_{\text{in,MC}}^{\text{tot}}$ be the number of events requested when running the MC event generator for this specific input sample. The bin value $T_{\text{in}}^{\text{bin}}$ is obtained as

$$T_{\text{in}}^{\text{bin}}(\vec{g}_i) = N_{\text{in,MC}}^{\text{bin}}(\vec{g}_i) \cdot \frac{\sigma_{\text{in}}(\vec{g}_i)\mathcal{L}}{N_{\text{in,MC}}^{\text{tot}}}, \quad (6.9)$$

where $N_{\text{in,MC}}^{\text{bin}}$, the only non-trivial quantity on the right-hand-side, is simply multiplied with a sample-specific, cross-section-dependent normalisation factor. The quantity $N_{\text{in,MC}}^{\text{bin}}$ follows a poisson distribution. In addition, the generator might assign an uncertainty to the cross section σ_{in} . Assume that all other quantities are exact or have uncertainties that are negligible, the uncertainty on the bin value $T_{\text{in}}^{\text{bin}}$ is then given as:

$$\Delta T_{\text{in}}^{\text{bin}}(\vec{g}_i) = \frac{\mathcal{L}}{N_{\text{in,MC}}^{\text{tot}}} \left(N_{\text{MC}}^{\text{bin}} \Delta \sigma_i + \sqrt{N_{\text{in,MC}}^{\text{bin}}(\vec{g}_i)} \sigma_i(\vec{g}_i) \right) \quad (6.10)$$

$$= \frac{\sigma_i(\vec{g}_i)\mathcal{L}}{N_{\text{in,MC}}^{\text{tot}}} \left(N_{\text{MC}}^{\text{bin}} \Delta_{\text{rel}} \sigma_i + \sqrt{N_{\text{in,MC}}^{\text{bin}}(\vec{g}_i)} \right). \quad (6.11)$$

The relative uncertainty of the total cross section, $\Delta \sigma_i$, is generator dependent and can be taken as constant and parameter independent in first approximation, since this uncertainty is proportional to number of generated events in each sample. Assuming this approximation, $\Delta \sigma_i$ primarily acts as a global scale

factor in the total uncertainty. For MadGraph the approximate uncertainty on the total cross section is expected to be $\approx 8\%$.

Since only the choice of sampling point of the input parameters for the input templates are the focus of optimising the uncertainty, and not the statistics of the individual samples (which are all assumed to be the same), the total cross section morphing can be simplified as follows.

$$\Delta\sigma_{\text{out}}(\vec{g}_{\text{target}}) = \sqrt{\sum_{i=1}^N w_i^2 (\vec{g}_{\text{target}}, \{\vec{g}_l\}_{l=1}^N) \sigma_i^2(\vec{g}_i) \cdot (\Delta_{\text{rel}}\sigma_i)^2} \quad (6.12)$$

The lowest uncertainty can only be achieved if both the weights, w_i^2 , and the total cross sections, σ_i , are small for all input samples in the parameter region where the morphing will be performed.

There are two approaches to reduce the uncertainty on the measurement. The first approach is to choose the sampling point of the input parameters close to the best measured value so far, which leads to small cross sections for morphed models in the parameter space of interest. For example, one can take the region of interest defined by $|\sigma|$ as $0.75\sigma_{\text{SM}} < |\sigma| < 1.25\sigma_{\text{SM}}$. This results in a small input cross section, however the weights used to morph events to the desired point in the parameter space get large. The second approach is to use input parameters also outside of parameter space of interest. This approach has the advantage that it does not apply any additional restrictions on the sample points of the coupling parameters for the input samples. The disadvantage of this method is that the cross section grows quickly with larger BSM parameters. An iterative method has been developed to apply the tradeoff between large weights and large cross sections. This iterative method is elaborated on below.

6.2.1 Description of the algorithm

The assumption that all the base samples have comparable statistical power is very reasonable in practice, as this relates to an equal number of events and thus an equal amount of computing time for the production of all base samples. Under this assumption, the actual numerical values of the cross sections are equally as important as the entries of the morphing matrix, as both types of quantities ultimately act as scaling factors for the relative statistical uncertainties.

Since the goal is to reduce the error arising from the morphing method, the uncertainty on prediction obtained from the morphing function with N samples is used as a figure of merit.

$$\Delta\sigma^2 g = \sum_j^N (w_j \vec{g} \Delta\xi_j)^2 \quad \text{with} \quad w_j g = \sum_i^N P_i \vec{g} \quad (6.13)$$

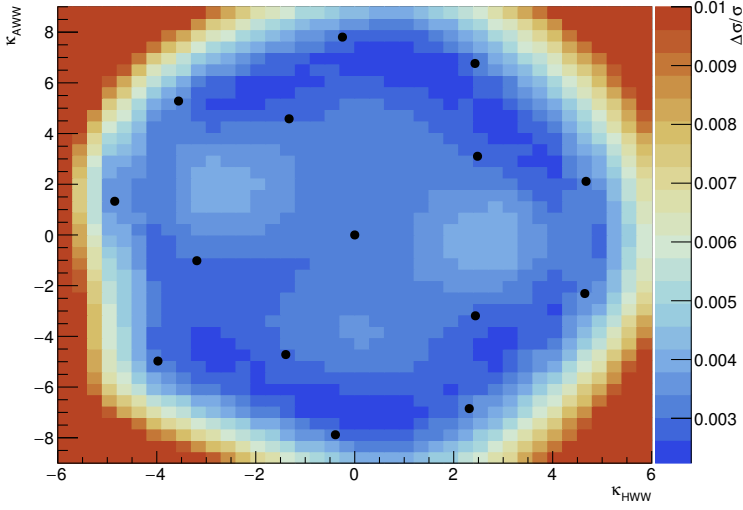


Figure 6.17: Relative uncertainty on the morphing prediction in colour-code. Blue colours (inner) correspond to smaller relative uncertainties, red colours (outer) correspond to larger relative uncertainties. The positions of the input template samples are indicated with black markers.

However, this quantity is a function of the point, $\vec{g}$, in parameter space that is the target of the morphing. As the underlying idea of the morphing technique is to provide full coverage of a region $\mathcal{A} \subset \mathbb{R}^{N \times N}$ of parameter space with a finite (and small) set of base samples, it is questionable which is the correct strategy to minimise the uncertainty in the entire region. One could argue that the maximum

$$f(\vec{g}_1, \dots, \vec{g}_N) = \max_{\vec{g} \in \mathcal{A}} \sqrt{\Delta\sigma^2(g \mid \vec{g}_1, \dots, \vec{g}_N)} \quad (6.14)$$

would be a viable figure of merit, but considering 6.17 reveals that such a choice would make the figure of merit entirely dependent on the chosen boundary of the region of interest, as uncertainties usually diverge strongly at the bounds of the region. Instead, it seems appropriate to consider the integral

$$f(\vec{g}_1, \dots, \vec{g}_N) = \int_{\vec{g} \in \mathcal{A}} \sqrt{\Delta\sigma^2(\vec{g} \mid \vec{g}_1, \dots, \vec{g}_N)} d\mathcal{A} \quad (6.15)$$

over the uncertainty in the region of interest. The uncertainty is a function of many parameters, and it is not clear whether the calculation of the integral in a symbolic fashion is feasible. Thus, it needs to be evaluated at a finite set $\mathcal{B} = \{\vec{b}_1, \dots, \vec{b}_M\}$ of M benchmark samples, i.e.,

$$f(\vec{g}_1, \dots, \vec{g}_N) = \sum_{b \in \mathcal{B}} \sqrt{\Delta\sigma^2 \vec{g}_b \mid \vec{g}_1, \dots, \vec{g}_N}. \quad (6.16)$$

Additionally, the evaluation of the uncertainty at these benchmarks for some *test basis* requires the knowledge of the cross sections of the constituent samples, and thus their production with a Monte Carlo generator. With this approach, the optimisation would essentially boil down to trying out a couple of different basis sets, and settling for the best one, which is not very satisfactory. In order to circumvent this, one would need a technique to estimate the cross sections at any given point in parameter space. Luckily, the method of Effective Lagrangian Morphing is itself such a technique. From this, it becomes apparent that in order to find the optimal set of base samples, two layers of Effective Lagrangian Morphing need to be concatenated to a chain. The underlying layer, the *cross section morphing*, provides the cross sections for the test basis. The top layer, the *test morphing*, then calculates the predictions at the benchmarks. Of course, the cross section morphing itself needs a basis, and the precision of the prediction will depend on the choice of this basis. Any imprecisions in the prediction of the cross sections of the test basis will bias the results of the optimisation.

The benchmarks themselves need not necessarily be generated as real samples, they may just be defined as points in the parameter space. However, if they are generated as real samples, this allows to estimate the bias from the imprecision of the cross section morphing with a bias term

$$B_b = (\sigma(\vec{g}_b | \vec{g}_1, \dots, \vec{g}_N) - \sigma_b)^2, \quad (6.17)$$

which can be included in the figure of merit to avoid convergence to regions of parameter space that are subject to large systematic biases in the calculation of the figure of merit.

It would of course be best to start the optimisation with a close to optimal basis. It thus seems desirable to restart the optimisation, using the optimised basis as the new basis of the cross section morphing. This is, however, only

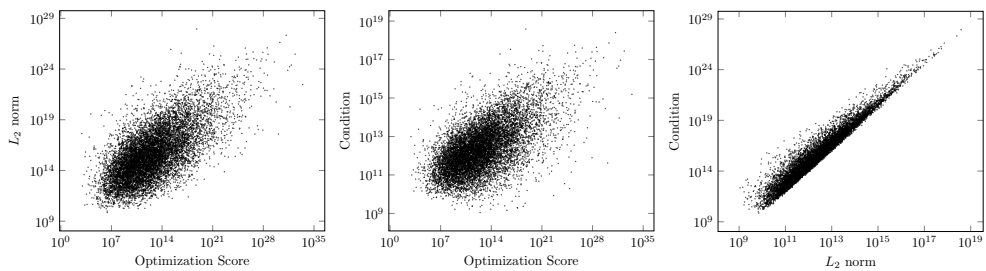


Figure 6.18: Correlation between L_2 -norm, condition number and optimisation score for randomly generated basis sets for a VBF $H \rightarrow VV$ scenario with two shared coupling parameters.

partially true, as samples of the optimised basis need not themselves lie in the region of interest covered by the benchmark samples. Nevertheless, the algorithm may be restarted with the optimised basis used for the cross section inputs to obtain improved results.

Further effects might influence the result of the uncertainty calculation. For example, the benchmark might be placed at a point in parameter space that is difficult to model for the specific Monte Carlo generator or the concrete implementation of the model in question and thus associated to large uncertainties. In order to account for this effect, the uncertainty obtained from the test morphing can be normalised to the uncertainty found in the benchmark sample.

Thus, the suggested figure of merit is

$$f(\vec{g}_1, \dots, \vec{g}_N) = \sum_{b \in \mathcal{B}} \sqrt{\frac{\Delta\sigma^2(\vec{g}_b | \vec{g}_1, \dots, \vec{g}_N)}{\Delta\sigma_b^2}} \cdot (\sigma(\vec{g}_b | \vec{g}_1, \dots, \vec{g}_N) - \sigma_b)^2. \quad (6.18)$$

This optimisation score has been evaluated on 10.000 test sets for a $H \rightarrow VV$ configuration with two free coupling parameters and compared with the L_2 -norm and the condition number of the morphing matrices. The L_2 -norm is defined as:

$$\sqrt{\vec{g} \cdot \vec{g}}, \quad (6.19)$$

where the dot represents the inner product, and the condition number is defined on a matrix A as:

$$C(A) = \|A^{-1}\| \cdot \|A\|. \quad (6.20)$$

The result of the evaluation of the optimisation score is shown in 6.18. As expected, the quantities are correlated, but significant deviations from a one-to-one correspondence can be observed.

With this technique, it is possible to evaluate the performance of a test basis with sufficiently low computational effort to allow for a numeric optimisation of the sample choice to take place. This is, of course, a natural consequence from the fact that Effective Lagrangian Morphing has been designed to provide the means of obtaining predictions sufficiently performant to facilitate a likelihood minimisation. The resulting algorithm is schematically displayed in 6.19.

One very subtle point is the question how exactly the uncertainties on the test basis should be defined. The morphing function predicting X at the coupling values $\vec{g}$ can be cast as

$$X(\vec{g}) = P(\vec{g})A\vec{\xi}, \quad (6.21)$$

where P is a vector of polynomials in $\vec{g}$, A is the morphing Matrix, and $\vec{\xi}$ are the predictions at the base samples. If the base samples are themselves results

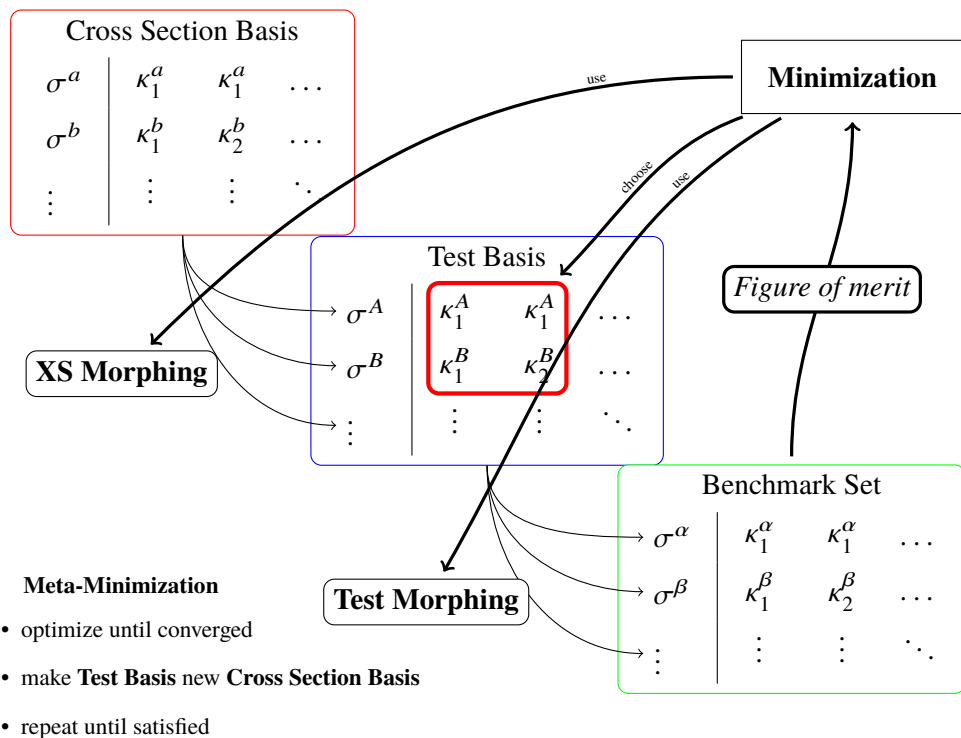


Figure 6.19: Schematic view of the base optimisation algorithm.

of morphing, this becomes

$$X(\vec{g}) = P(\vec{g}) \underbrace{AP(\vec{g}')A'}_{\tilde{A}} \vec{\xi}, \quad (6.22)$$

where the expression indicated by the under-brace can be identified as a matrix $\tilde{A}$. Thus, it appears that effective Lagrangian morphing is *transitive* in the sense that inserting an additional layer should not change the final result, and the uncertainties of the predictions for X will only depend on the uncertainties of the cross section basis $\vec{\xi}$. However, if the intermediate results are actually projected onto the intermediate test basis ξ_i , the correlations between the uncertainties of the respective ξ_i will vanish from the calculation. This is not an accident, but an intended effect, as the uncertainties on the test basis would also be uncorrelated in the case of actually generated samples. In principle, the statistical fluctuations on the test basis $\vec{\xi}$ propagated from the cross section basis $\vec{\xi}$ are already accounted for by the bias term in 6.17. This, however, begs the question whether the uncertainty predictions obtained by the cross section morphing for the test basis $\vec{\xi}$ should at all be used, or whether they should be replaced by some fixed value corresponding to the envisioned uncertainties on the actual samples.

6.3 Conclusions

The morphing method has is shown to perform in a complete VBF $H \rightarrow \mu\mu$ MC analysis. Methods for reducing the number of the parameters in this analysis have been investigated and have proved unsuccessful. These methods also show that reducing the number of parameters should not be done and could give incorrect results due to underlying physics. A method for optimising the sample basis has been proposed which could reduce the error arising from statistical precision of the input samples.

7 Gluon-Gluon Fusion with two Associated jets

Within the Standard Model (SM) the Higgs boson must be a CP even scalar, a spin 0 particle that obeys the CP symmetry. However, many BSM theories predict the existence of additional Higgs bosons which can be CP even, CP odd, or, as a result from the superposition of CP eigenstates, partially violate the CP symmetry. Examples of extended Higgs sectors are introduced in section 1.3. The presence of CP violating Higgs bosons in BSM theories makes probing the CP properties of the Higgs boson of high importance for the search for new physics.

Previous studies of the CP nature of the Higgs boson have been performed in the decay of the Higgs boson to WW^* [59] and ZZ^* [67], which excluded the pure CP odd and large CP mixing scenarios. However, the top Yukawa coupling, present in gluon gluon fusion (ggF) and in associated production with a top quark pair ($t\bar{t}H$), has not been exploited yet. While the $t\bar{t}H$ production process is not yet sensitive enough for observation [161], the ggF production process has a significantly larger production rate. With the data collected at the ATLAS detector during Run 2 of the LHC it is possible to measure the CP properties of the top Yukawa coupling for the first time. The sensitivity of this measurement is discussed in this chapter.

To reveal the CP structure of the top Yukawa coupling, CP sensitive observables have to be considered to perform a direct measurement. The properties of the top Yukawa coupling will be propagated via the matrix element to the properties of the final state particles. Because of the conservation of angular momentum of the hard scattering process, a particularly promising CP sensitive observable is the azimuthal angle between two spectator jets of the ggF process ($\Delta\Phi_{jj}$). As a result ggF accompanied by two jets will be a very promising channel in which the CP structure of the top Yukawa coupling can be measured [162]. The leading corresponding Feynman diagrams at next to leading order (NLO) are shown in Figure 7.1 and clearly show that each process results in two identifiable spectator jets. The $\Delta\Phi_{jj}$ distribution as expected from

the simulation in reference [162] is shown in figure 7.2. To perform a first measurement of this process, it is advisable to search in a decay mode of the Higgs boson with both a high branching ratio and a clearly identifiable Higgs boson decay signature. Given that the $H \rightarrow b\bar{b}$ final state would have too large backgrounds, a reasonable compromise is to perform the study in the second largest $H \rightarrow WW^* \rightarrow l\nu l\nu$ final state. To simplify the identification of spectator jets originating from the Higgs boson production, rather than the outgoing quarks of the Higgs boson decay, final states with leptons are preferred.

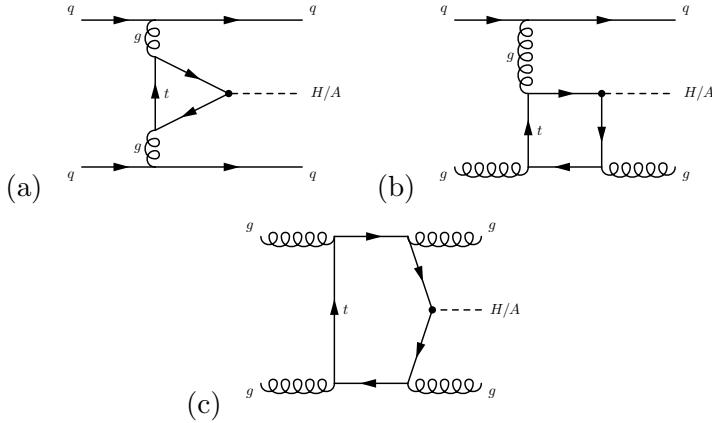


Figure 7.1: A selection Feynman diagrams contributing to the production of a Higgs boson in association of two jets via the fusion of two gluons.

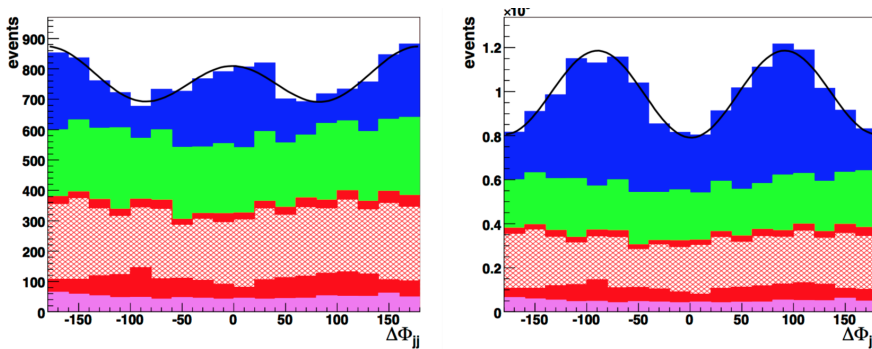


Figure 7.2: The distribution of the $\Delta\Phi_{jj}$ observable corresponding to the procedure of reference [162] for a pure CP even hypothesis (left) and a pure CP-odd hypothesis (right) for an integrated luminosity of 300fb^{-1} . Figure taken from [162].

The NLO description of ggF Higgs boson production in association with two

jets is incorporated into the the MadGraph5_aMC@NLO [88] event generator and is used in order to simulate various Higgs-boson hypotheses.

7.1 Theoretical Framework for Studying the Parity of the Higgs-Boson

To describe the possible CP scenarios for a Higgs-like resonance, an effective field theory (EFT) approach is adopted. The effective Lagrangian that describes the top Yukawa coupling is expressed as:

$$\mathcal{L}_0^t = -\bar{\psi}_t(c_\alpha\kappa_{Htt}g_{Htt} + is_\alpha\kappa_{Att}g_{Att}\gamma_5)\psi_t X_0, \quad (7.1)$$

where g_{Htt} and g_{Att} represent the respectively CP even and CP odd Yukawa couplings, α the mixing angle between an CP even and CP odd state, X_0 a Lorentz scalar field, ψ the top field and γ_5 the multiplication of the four contravariant gamma matrices. The coefficients $c_\alpha \equiv \cos\alpha$ and $s_\alpha \equiv \sin\alpha$ are pre-factors of the effective Lagrangian. The real dimensionless coupling parameters κ_{Htt} and κ_{Att} are scale factors of the effective Lagrangian. If $\kappa_{Htt} = 1$ and $c_\alpha = 1$, the SM coupling of the Higgs field to top quarks is obtained.

The top Yukawa coupling induces an effective coupling in $ggF + 2$ jets of the gluons with the Higgs boson through the top-quark loop. The effective coupling description of this process is only valid when the transverse momentum of the jets is not larger than the top mass [161]. This heavy-top limit is implemented in the Higgs Characterisation model [63], as described in section 1.5.3, which is used to generate the various signal hypotheses. In this model, the effective Lagrangian for a coupling of the Higgs boson with gluons reads:

$$\mathcal{L}_0^g = -\frac{1}{4}(c_\alpha\kappa_{Hgg}g_{Hgg}G_{\mu\nu}^a G^{a,\mu\nu} + \frac{1}{2}s_\alpha\kappa_{Agg}g_{Agg}G_{\mu\nu}^a G_{\rho\sigma}^a \epsilon^{\mu\nu\rho\sigma})X_0, \quad (7.2)$$

where $G_{\mu\nu}^a$ is the gluon field strength tensor, g_{Hgg} and g_{Agg} represent the respectively CP even and CP odd effective gluon couplings and $\epsilon^{\mu\nu\rho\sigma}$ is the Levi-Civita symbol. The real dimensionless coupling parameters κ_{Hgg} and κ_{Agg} have been introduced for practical reasons as scale factors of the effective Lagrangian. If $\kappa_{Hgg} = 1$ and $c_\alpha = 1$, the SM coupling of the Higgs field to gluons is obtained. This effective Lagrangian does not only introduce the ggX_0 coupling, but also an $gggX_0$ and $ggggX_0$ coupling which are present in Figures 7.1(b) and 7.1(c).

Three benchmark scenarios are used, which are summarised in table 7.1. These benchmarks will be used to test against the data collected at the ATLAS detector, as well as used as input for the morphing to be able to measure the Effective Lagrangian parameters directly as explained in chapter 5.

Scenario	Parameters
CP even (SM)	$\kappa_{Hgg} = 1, \kappa_{Agg} = 0, c_\alpha = 1$
CP odd	$\kappa_{Hgg} = 0, \kappa_{Agg} = 1, c_\alpha = 0$
CP mix	$\kappa_{Hgg} = 1, \kappa_{Agg} = 1, c_\alpha = \frac{1}{\sqrt{2}}$

Table 7.1: Definition of the three benchmark scenarios used in this section. The parameter settings correspond to the Spin-0 benchmark models and one CP mixing scenario. The parameters κ_i , that are not explicitly mentioned are considered to be equal to 0.

7.2 Data and Monte Carlo samples

Candidate events in data are selected from the full 2015 and 2016 dataset, collected by ATLAS with $\sqrt{s} = 13$ TeV pp collisions, only including events where all ATLAS sub-detectors were fully operational. The corresponding total integrated luminosity [163] is 36.07 fb^{-1} .

All simulated events are generated at a centre-of-mass energy $\sqrt{s}$ of 13 TeV and passed through the full ATLAS detector simulation [164, 105]. The simulated events are overlaid with additional inelastic pp interactions that are typically simulated with PYTHIA8 [147] in order to match the pile-up conditions observed in the ATLAS data recorded during the beginning of the second run of the LHC.

7.2.1 Signal samples

Dedicated MC samples are generated to evaluate the $ggF + 2$ jets signal for the three benchmark scenarios in section 7.1. The MADGRAPH5_AMC@NLO[146] generator is used to generate the signal events at NLO in two jets using the Higgs Characterisation model. The procedure is similar to the one deployed in reference [161]. The PDF set used is NNPDF23_nnlo_as_0118. Subsequently the events are showered with PYTHIA8[147] using CTQ10 PDFs in conjunction with the A14 tune. PYTHIA8 is also used to decay $H \rightarrow WW^* \rightarrow l\nu l\nu$ since only the CP nature of the Top Yukawa coupling is tested. The morphing method introduced in chapter 5 is used to obtain a complete representation of all intermediate mixing scenarios with respect to the benchmark scenarios.

7.2.2 Background processes and generators

The Monte Carlo (MC) generators used to model background processes are listed in Table 7.2. For most processes, separate programs are used to generate the hard scattering process and to model the parton showering (PS), hadronisation, and the underlying event (UE). The $t\bar{t}$ process is the main background in

this analysis, followed by the SM WW process, the $Z \rightarrow \tau\tau$ process and other diboson processes. A further background originates from $W + jets$ events that enter in the selection due to light jets which are often misidentified as leptons. The multijet background is included in the fake estimate.

PYTHIA 8.210, PYTHIA 8.186 or PYTHIA 6.428 [78] are used for the PS, hadronisation and UE for some of the background processes. HERWIG [79] is used for PS and hadronisation in estimating systematic uncertainties with UE being modelled with JIMMY [165]. The CT10 parton distribution function (PDF) set is used for the hard scattering process in POWHEG-BOX v2 [84] while for MG5_aMC@NLO [87] the NNPDF23LO PDF set is used. The CTEQ6L1 PDF set is used for the PYTHIA showering, with the AZNLO tune when interfaced to POWHEG-BOX v2 and with the A14 tune when interfaced to MG5_aMC@NLO. Sherpa2.2.1 [81] is calculated using CT10 PDF set in conjunction with a dedicated set of tuned parameters from the parton shower developed by the SHERPA authors [81]. The samples are normalised to higher order calculations and the details can be found in table 7.2.

Process	Generator	$\sigma \cdot \text{Br}$ (pb)	Precision $\sigma_{\text{incl.}}$
VBF $H \rightarrow WW$	POWHEG+PYTHIA8	0.808	NNLO
$WH H \rightarrow WW$	POWHEG+PYTHIA8(MINLO)	0.293	NNLO
$ZH H \rightarrow WW$	POWHEG+PYTHIA8(MINLO)	0.189	NNLO
inclusive $Z/\gamma^* \rightarrow \ell\ell$ ($m_{\ell\ell} \geq 40\text{GeV}$)	MG5_aMC@NLO	6.04×10^3	NNLO
inclusive $Z/\gamma^* \rightarrow \ell\ell$ ($40 \geq m_{\ell\ell} \geq 10\text{GeV}$)	MG5_aMC@NLO	8.01×10^3	NNLO
$(W \rightarrow \ell\nu)\gamma$ ($p_T^{\gamma} > 10\text{GeV}$)	SHERPA	453	LO
$(Z \rightarrow \ell\ell)\gamma$ ($p_T^{\gamma} > 10\text{GeV}$)	SHERPA	175	LO
$t\bar{t}$ leptonic	POWHEG+PYTHIA8	87.6	NNLO+NNLL
Wt leptonic	POWHEG+PYTHIA6	7.55	NLO
$Z^{(*)}Z^{(*)} \rightarrow 2\ell 2\nu$ ($m_{\ell\ell} \geq 4\text{GeV}$)	SHERPA	0.925	LO
diboson: $gg \rightarrow 2\ell 2\nu$	SHERPA	0.72	NLO
diboson: $q\bar{q}/g \rightarrow \ell\nu\ell\ell$	SHERPA	11.9	NLO
diboson: $q\bar{q}/g, gg \rightarrow \ell\ell\ell\ell$	SHERPA	11.5	NLO

Table 7.2: MC generators used to model the background processes, and corresponding cross sections. The column *Precision* $\sigma_{\text{incl.}}$ gives the calculation order of the inclusive cross section applied to the sample.

7.3 Object Selection

The object definition requirements used in this analysis are chosen to select events that are consistent with a final state containing two charged leptons, two neutrinos and two jets. Every event must at least contain one primary vertex (PV) with at least two associated tracks connected to it. Only tracks with a $p_T > 400$ MeV are considered. If there is more than one PV, the one with the largest track p_T sum, $\sum p_T^2$, is chosen. The main physical objects in this analysis, electrons, muons, jets and missing transverse momentum, are

considered to be originating from this PV.

Electrons are selected from a reconstructed track in the Inner Detector (ID) that is matched with topological clusters of energy deposit in the electromagnetic (EM) calorimeter. The pseudorapidity is required to be lower than 2.47, excluding the gap between the barrel and endcaps in the liquid argon (LAr) calorimeter ($1.37 < |\eta| < 1.52$). The transverse momentum of the electrons must be at least 15 GeV. Electron candidates with a $p_T < 25$ GeV have to pass the *TightLH* likelihood-based identification criteria, while electrons with $p_T > 25$ GeV must pass the *MediumLH* selection [166]. The absolute value of the longitudinal impact parameter of each electron track, calculated with respect to the vertex and multiplied with $\sin \theta$ of the track ($|z_0 \sin \theta|$), is required to be at most 0.5 mm. The transverse impact parameter significance ($|d_0|/\sigma_{d_0}$), calculated with respect to the beam line, is required to be less than five for electrons. Furthermore the p_T and η dependent *Gradient* isolation criterion is applied defined to produce a nominal efficiency of 90% on leptons derived from $Z \rightarrow ll$ simulated events with p_T of 25 GeV, rising to 99% at 60 GeV.

Muons are selected from a combined track in the ID and the Muon Spectrometer (MS) that have a consistent trajectory and curvature, taking into account the energy loss in the calorimeters. The absolute value of the pseudorapidity is required to be lower than 2.5. The transverse momentum of the muons must be at least 15 GeV. All muon candidates have to pass the *Medium* identification selection [167]. The requirements for the longitudinal and transverse impact parameter are $|z_0 \sin \theta| < 0.5$ mm and $|d_0|/\sigma_{d_0} < 3$. As for electrons, the *Gradient* isolation working point is applied. The *Gradient* working point with the *Medium* identification selection is tuned to produce a nominal efficiency of 90% for leptons with p_T of 25 GeV, rising to 99% at 60 GeV.

A jet is reconstructed from topological clusters of energy deposit in the calorimeter system using the anti- k_T algorithm [127] with a distance parameter of $R = 0.4$. Jets are calibrated to the EM scale using p_T and η dependent correction factors, which account for e.g. losses in passive material, the non-compensating response of the calorimeters, and contributions from pile-up interactions [126]. The pseudorapidity is required to be lower than 4.5 and the transverse momentum has to be at least 25 GeV. For forward jets, situated in the region $2.4 < |\eta| < 4.5$, the transverse momentum has to be at least 30 GeV. To reduce the number of jets originating from pile-up vertices, jets with $p_T < 50$ GeV and $|\eta| < 2.4$ are required to have the jet vertex tagger (JVT) variable larger than 0.64, which is a multivariable tagger [168]. An overlap removal procedure for jets is used to prevent double-counting of leptons and jets. Jets within a cone of size $\Delta R < 0.2$ of an electron candidate are removed, while for cone sizes in the region $0.2 < \Delta R < 0.4$ the electron candidate is discarded. Jets within a cone of size $\Delta R < 0.2$ of a muon candidate are discarded only if

they have less than three associated tracks in that cone. If the jet is within $\Delta R < 0.4$ of a muon candidate and has more or equal to three associated tracks, the muon candidate is removed.

The b -jets are identified using the MV2c20 b -tagging algorithm [169] with an efficiency of 85% determined from $t\bar{t}$ simulated events. The background was composed of 20% c -jets and 80% light-jets. 24 input variables, including η and p_T of the jet, are used in the training of the boosted decision tree discriminant. The missing transverse momentum, E_T^{miss} , in each event is calculated from the negative vectorial sum of the transverse momenta of all calibrated selected objects, such as electrons, muons, and jets. Tracks compatible with the primary vertex and not matched to any of the other objects are also included in the E_T^{miss} reconstruction.

7.4 Analysis procedure

To optimise the separation power between different CP mixing scenarios, cuts are applied to observables. Cuts are also applied to get rid of mismodelling, reduce backgrounds or to select a specific channel.

To reduce the uncertainties on the modelling of the backgrounds, several control regions (CR), which are regions enhanced in a particular background, are created. The data in the CR are used to normalise, or correct, the shape of the backgrounds, since the data would otherwise only be modelled by the simulations. Additionally, validation regions are defined. The validation regions are not used to correct the simulated background samples, but to validate them. A description of the uncertainties is given in section 7.5.

7.4.1 Pre-selection

The pre-selection cuts are optimised to reduce the effect of mismodelling, reduce the contribution from backgrounds, as well as to select the $H \rightarrow WW \rightarrow l^+l^-\nu\nu$ decay channel. The pre-selection cuts and their purpose are explained below.

- **Good Run List (GRL)** Select only events for successful LHC runs.
- **Trigger selection** Select events that are triggered by either a medium or loose single lepton trigger (electron or muon) or the loose di-lepton trigger, to maximise the total trigger efficiency. The di-lepton triggers have been added because the single lepton triggers need to be prescaled as the instantaneous luminosity increased during the Run-2 period, and when a trigger gets prescaled we have to use the next un-prescaled trigger, which typically has a higher p_T threshold. The selected leptons offline are always matched to a corresponding trigger object. The lowest un-prescaled single lepton trigger has a p_T of 24 GeV, therefore offline a 25

GeV cut-off has to be used to avoid the turn on curve of the trigger. A di-lepton trigger has smaller background contributions and can therefore stay un-prescaled with lower p_T thresholds. The present di-lepton trigger has a p_T threshold of 17 GeV for electrons and 14 GeV for muons. Therefore by using the di-lepton triggers, the offline threshold of the p_T can be lowered to 22 GeV, which is above the di-lepton p_T threshold, to avoid to be in the turn on of the trigger. The efficiency gain, expressed in percentage, after pre-selection for ggF with two jets and a leading lepton p_T , $p_T^{\text{leading}} > 22$ GeV of adding the di-lepton trigger is 8%.

- **Jet Cleaning** Select clean jets to reduce jet mismodelling. The jet quality is determined from variables such as the difference between the measured pulse shape and the predicted pulse shape of the energy deposit corresponding to LAr cells [170].
- **$V\gamma V$ jet overlap removal** Remove events that are tagged as γ and a jet [171].
- **≥ 2 leptons** Require at least two leptons to select the $H \rightarrow WW \rightarrow l^+l^-\nu\nu$ decay channel. The two leading leptons in p_T are required to have opposite flavour (one electron and one muon) and opposite sign.
- **$p_T^{\text{leading lepton}} > 22$ GeV** Select events where the leading lepton (highest p_T) has a $p_T > 22$ GeV.
- **$p_T^{\text{sublead lepton}} > 15$ GeV** Select events where the second highest p_T lepton has a $p_T > 15$ GeV.
- **$m_{ll} > 10$ GeV** Select events where the invariant mass of the two lepton system is larger than 10 GeV. This cut is used to reject events where one or more of the leptons is faked by a jet.

Fake factor application After these pre-selection cuts are applied, a factor is applied for fakes. A data driven method is used to model the kinematic variables of events with fake leptons. This method derives a fake factor from di-jet events, which is then applied to data in a special control region. This method is applied after the full selection in the full $ee + \mu\mu$ sample. The fake factor is derived as the ratio between the number of ID and Anti-ID leptons as a function of the transverse momentum and pseudorapidity [171].

7.4.2 Signal Region Event Selection

The signal region for the $ggF+2$ jets process is obtained by applying additional cuts to reduce backgrounds.

- **≥ 2 jet** Select events with at least 2 jets to select the $ggF+2$ jets production channel.
- **$m_{ll} < 90$ GeV** Mainly removes contributions from top backgrounds.
- **$m_T < 150$ GeV** Mainly removes contributions from top backgrounds. The transverse mass m_T is defined as

$$m_T = \sqrt{(E_T^{ll} + E_T^{miss})^2 + |p_T^{ll} + E_T^{miss}|^2}, \quad (7.3)$$

where

$$E_T^{ll} = \sqrt{|p_T^{ll}|^2 + m_{ll}^2}, \quad (7.4)$$

and p_T^{ll} is the transverse mass of the two lepton system.

- **$n_{b\text{jets}} = 0$** Defined in the following also as b-jet veto. Select events with the number of b jets (n_{jets}) equal to 0, to reject top background.
- **$Z \rightarrow \tau\tau$ veto** Remove contributions from $Z \rightarrow \tau\tau$. Cuts out a band of 25 GeV around the Z mass, specifically $|m_{\tau\tau} - m_Z| < 25$ GeV ($m_{\tau\tau} < 66$ GeV). The $\tau\tau$ invariant mass $m_{\tau\tau}$ is calculated using the collinear approximation [172].
- **$p_T^{ll} > 20$ GeV** A cut on the p_T of the di-lepton system, that removes contributions from fakes originating from $W + \text{jets}$, since these typically have a low p_T .

7.4.3 Definition of Control Regions and Validation Regions

Data is used to correct the normalisation or shape of some of the main backgrounds that would otherwise be obtained from simulation. In this way the systematic uncertainty associated to the theory mismodelling of the backgrounds as described by the simulation, are reduced since they are only included as an extrapolation factor between the signal region and the control region. In order to make the extrapolation error as small as possible, the CR are designed to be very close to the signal regions and typically feature only a couple of different or inverted cuts with respect to the signal region selection. Validation regions are used to check the correctness of the MC simulation of the data.

Control region for $t\bar{t}$ dilepton events

The control region for $t\bar{t}$ dilepton events is obtained by requiring at least one b -tagged jet in the event instead of zero b -tagged jets, while keeping the other signal selection cuts. The comparison between data and simulation in this region is shown in figure 7.3.

Control region for $Z \rightarrow \tau\tau$ events

The control region for $Z \rightarrow \tau\tau$ events is obtained by requiring a mass of the two lepton system of $66 \text{ GeV} < m_{ll} < 116 \text{ GeV}$ instead of the $Z \rightarrow \tau\tau$ veto. The p_T^{ll} cut and m_{ll} cuts are not applied either, while keeping the other signal selection cuts. The comparison between data and simulation in this region is shown in figure 7.4.

Validation region for dibosonic WW events

The WW validation region is obtained by requiring a mass of the two lepton system $m_{ll} > 90 \text{ GeV}$ instead of the $Z \rightarrow \tau\tau$ veto, the m_T cut and the $m_{ll} < 90 \text{ GeV}$ cut, while keeping the other signal selection cuts. The comparison between data and simulation in this validation region is shown in figure 7.5.

The choice is made to use this region as a validation region because it is not pure enough for a control region, since it is heavily contaminated by $t\bar{t}$ events as can be seen from figure 7.5. Several studies have been done, but no improvement on the purity of WW events was obtained.

Validation region for W +jets events

The W +jets control region is obtained by requiring that the selected events contain two leptons with the same electric charge instead of opposite charge, while all other selection requirements are the same with respect to the signal region. The comparison between data and simulation in this validation region is shown in figure 7.6.

For all control and validation regions a reasonable pre-fit agreement between the data and MC simulation is obtained.

7.4.4 Usage of boosted decision trees

After the cuts are applied in the signal region, control regions and validation regions, a multivariate method is used to reduce the backgrounds even further, namely a boosted decision tree (BDT) [173]. The event yields obtained before applying cuts on the BDT response are shown in tables 7.3 and 7.4. The BDT is trained for a SM CP even Higgs boson hypothesis versus the background.

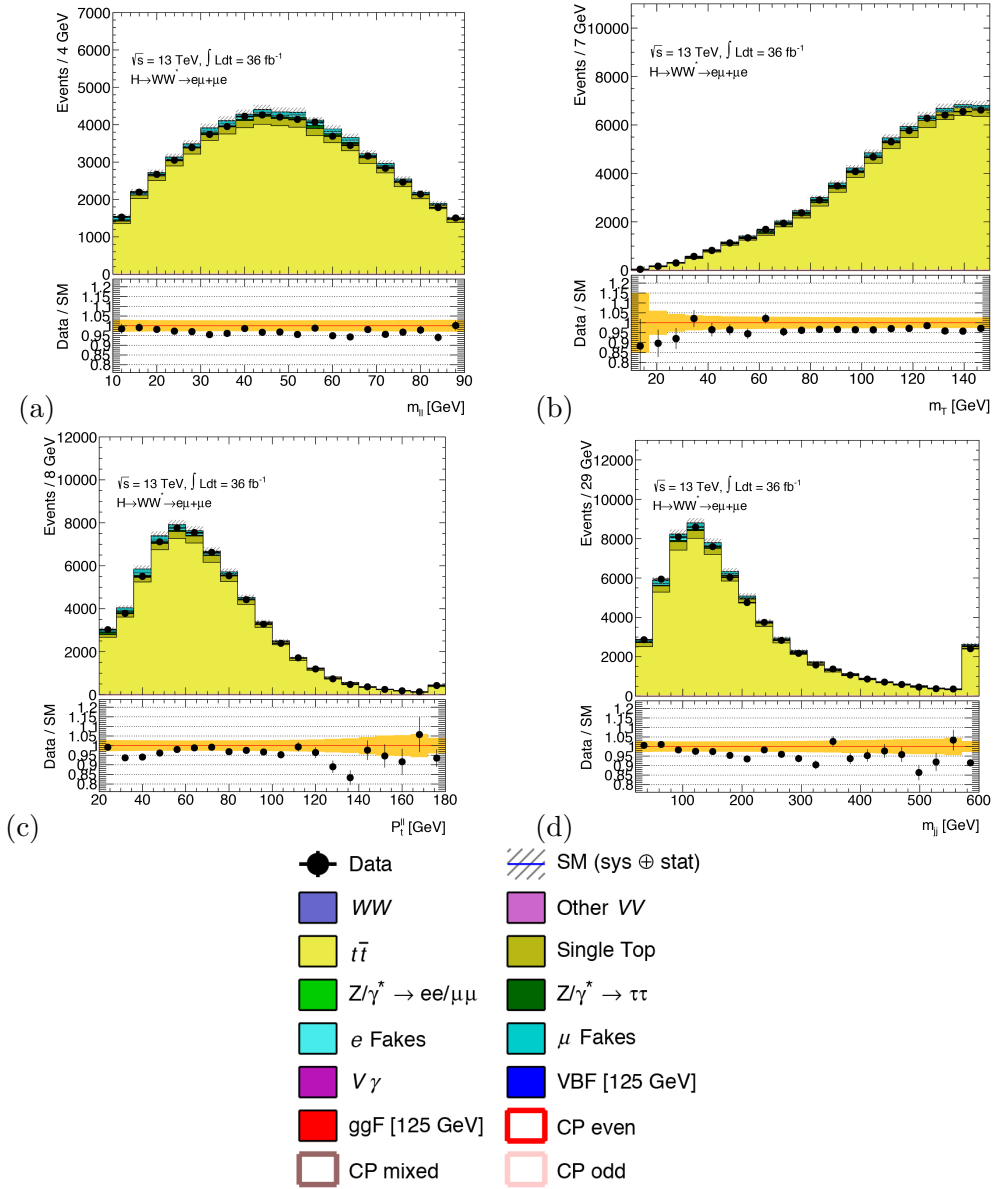


Figure 7.3: Distribution of observables (a) $m_{\ell\ell}$ (b) m_T (c) p_T^l and (d) M_{jj} , in the top control region. The yellow band indicates the statistical uncertainty plus the experimental systematic uncertainties.

Several tens of kinematic distributions have been tested and, out of these, seven variables have shown to perform well in terms of signal over background separation. The use of additional observables does not improve the performance

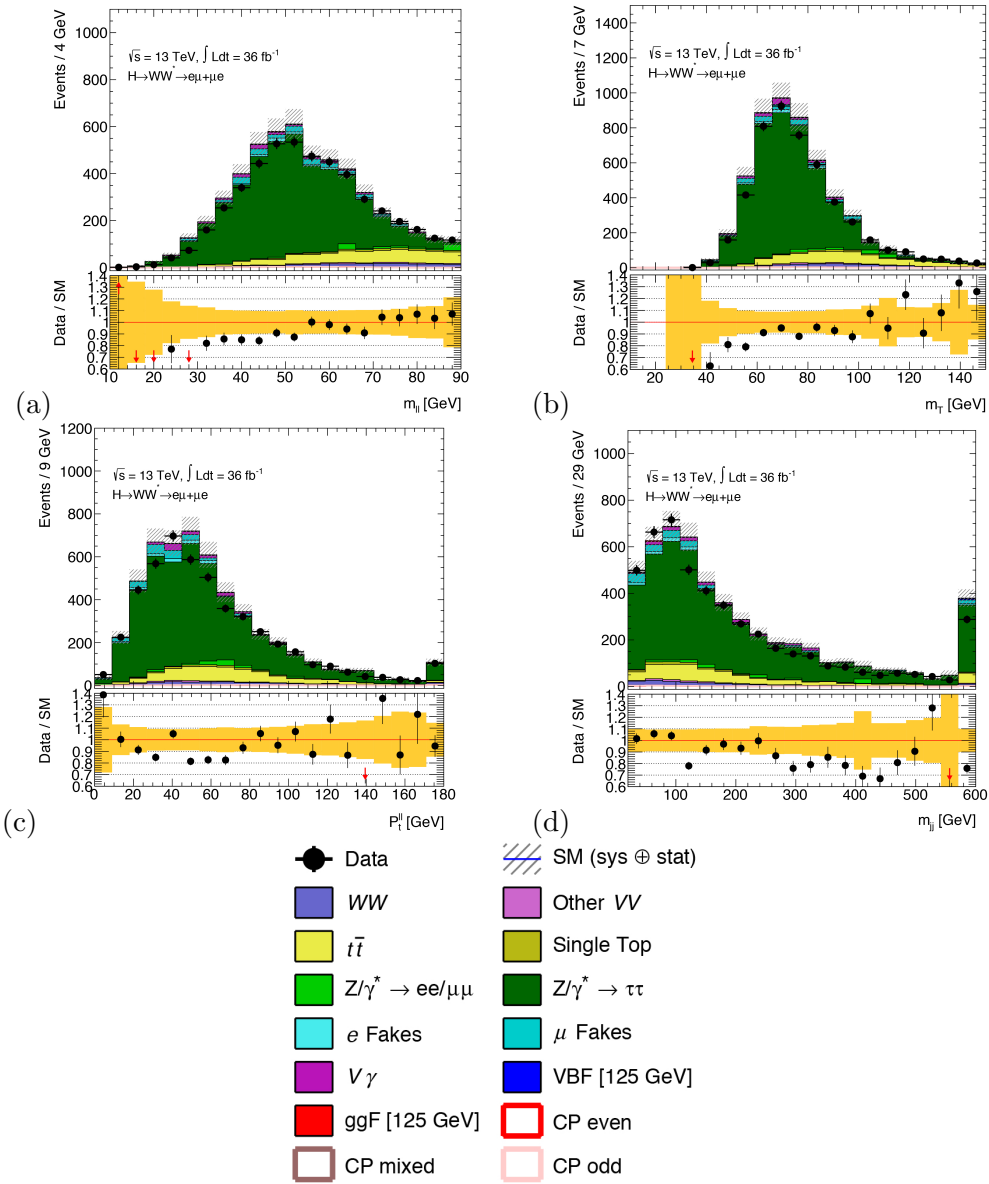


Figure 7.4: Distribution of observables (a) $m_{\ell\ell}$ (b) m_T (c) p_T^H and (d) m_{jj} , in the $Z \rightarrow \tau\tau$ control region. The yellow band indicates the statistical uncertainty plus the experimental systematic uncertainties.

of the BDT further, while it could introduce overtraining. The seven variables, that are chosen due to their sensitivity to the separation between background and the CP even Higgs boson, are:

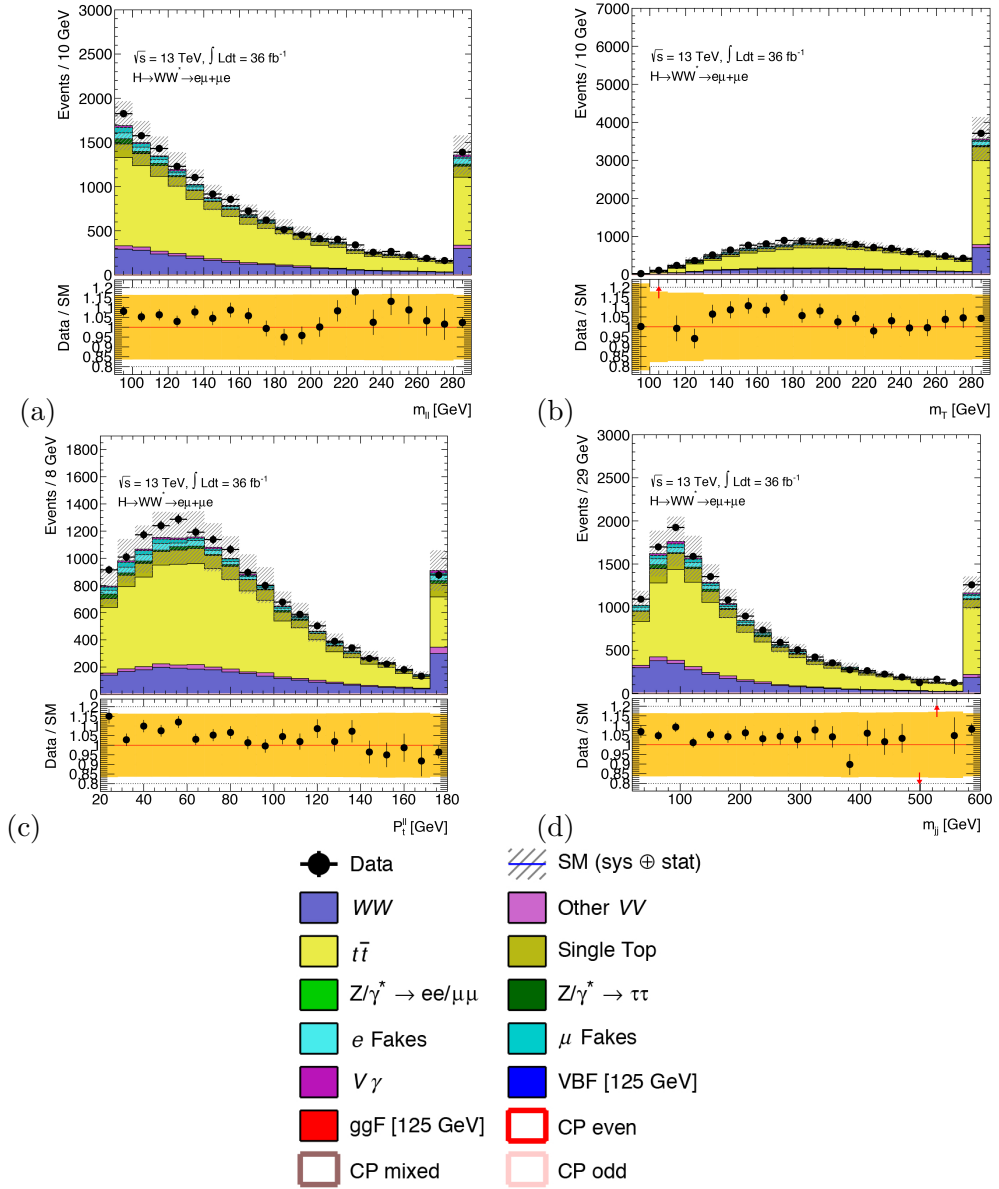


Figure 7.5: Distribution of observables (a) m_{ll} (b) m_T (c) p_T^l and (d) M_{jj} , in the WW validation region. The yellow band indicates the statistical uncertainty plus the experimental systematic uncertainties.

- $\Delta\phi_{ll}$ The azimuthal angle between the two leptons. This variable is sensitive to the boost of the system that produced them, and therefore allows to separate the signal from the WW background.

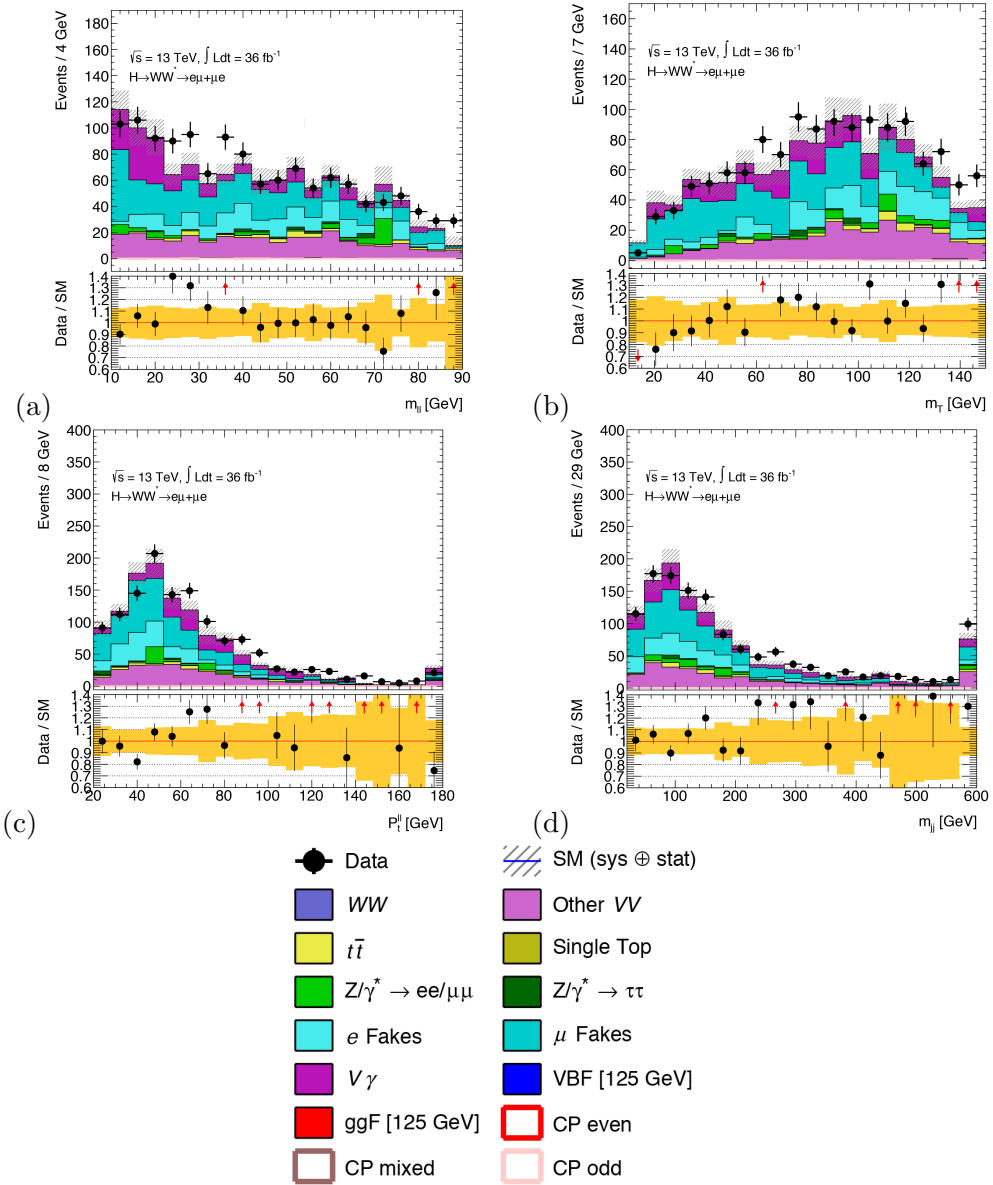


Figure 7.6: Distribution of observables (a) m_{ll} (b) m_T (c) p_T^l and (d) M_{jj} , in the W +jets validation region. The yellow band indicates the statistical uncertainty plus the experimental systematic uncertainties.

- $\mathbf{m_T}$ The transverse sum of the mass of all particles in the event.
- $\mathbf{m_{ll}}$ The invariant mass of the two lepton system.

$\sqrt{s} = 13\text{TeV}, \mathcal{L} = 36\text{fb}^{-1}$	VBF [125 GeV]	ggF [125 GeV]	Total Bkg	Data/bkg	Data
Channel Selection	282.98 ± 1.44	1130.65 ± 8.53	2297202.64 ± 4020.30	0.47 ± 0.00	1072233
GRL Selection	282.98 ± 1.44	1130.65 ± 8.53	1744337.16 ± 2728.16	0.59 ± 0.00	1033849
Jet Cleaning	280.75 ± 1.43	1127.13 ± 8.51	1736540.93 ± 2724.79	0.59 ± 0.00	1028868
Overlap: Vgamma/Vjets	280.75 ± 1.43	1127.13 ± 8.51	1723076.54 ± 2672.97	0.60 ± 0.00	1028868
Trigger Selection	252.56 ± 1.36	1006.15 ± 8.03	1447313.55 ± 2287.28	0.64 ± 0.00	926237
Only two Leptons	248.06 ± 1.34	987.51 ± 7.90	1435145.98 ± 2090.08	0.63 ± 0.00	902483
$p_t^{\text{lead}} > 22 \text{ GeV}$	248.06 ± 1.34	987.51 ± 7.90	1435145.98 ± 2090.08	0.63 ± 0.00	902483
$p_t^{\text{sublead}} > 15$	221.45 ± 1.27	875.40 ± 7.43	1251470.48 ± 1995.34	0.62 ± 0.00	774264
$m_{\ell\ell} > 10 \text{ GeV}$	208.95 ± 1.23	824.99 ± 7.22	839699.88 ± 1655.02	0.77 ± 0.00	647411
Apply fake factor	190.92 ± 1.18	743.53 ± 6.84	520565.58 ± 1038.32	1.00 ± 0.00	518876
$\geq 2\text{-jets}$	123.80 ± 0.95	382.53 ± 4.27	345057.66 ± 425.21	0.96 ± 0.00	330818
$m_{\ell\ell} < 90 \text{ GeV}$	123.70 ± 0.95	382.18 ± 4.27	164103.52 ± 325.05	0.98 ± 0.00	160029
$m_T \leq 150\text{GeV}$	119.93 ± 0.93	367.32 ± 4.17	114377.72 ± 292.65	0.97 ± 0.00	111314
$b\text{-jet veto}$	102.70 ± 0.85	301.60 ± 3.72	19117.39 ± 199.22	0.99 ± 0.01	18959
$Z \rightarrow \tau\tau$ veto	87.63 ± 0.79	261.97 ± 3.45	10002.30 ± 140.89	1.05 ± 0.02	10547
$p_T^{\ell\ell} > 20 \text{ GeV}$	86.20 ± 0.78	256.62 ± 3.41	8495.32 ± 91.96	1.07 ± 0.02	9084
$Z \rightarrow \tau\tau$ CR	8.84 ± 0.26	23.84 ± 1.07	5262.12 ± 97.89	0.92 ± 0.02	4840
Top CR	13.31 ± 0.34	50.55 ± 1.67	64455.54 ± 168.66	0.97 ± 0.00	62462
WW VR	0.08 ± 0.02	0.30 ± 0.10	14204.19 ± 74.08	1.05 ± 0.01	14891
W+jets VR	0.51 ± 0.07	1.39 ± 0.26	1198.17 ± 34.67	1.09 ± 0.04	1310

Table 7.3: Numbers of events passing the event selection. The various simulated Monte Carlo samples are normalised to the integrated luminosity. The event yields are shown separately for the predicted signal processes, the total background and the observations in data. The uncertainties correspond to the statistical uncertainties.

- $\mathbf{p}_T^{\text{ll}}$ The p_T of the two lepton system.
- $\min(\Delta\mathbf{R}(\ell_0, \mathbf{j}))$ The angular distance between the leading p_T lepton (ℓ_0) and each jet is calculated and the minimal angular distance is chosen.
- $\min(\Delta\mathbf{R}(\ell_1, \mathbf{j}))$ The angular distance between the sub-leading p_T lepton (ℓ_1) and each jet is calculated and the minimal angular distance is chosen.
- $\min(\mathbf{m}_T^\ell)$ The minimum of the two transverse masses of the lepton- E_T^{miss} system. This quantity is calculated for each lepton as:

$$\sqrt{2 * MET * p_T^{\text{lep}} * (1 - \cos \phi_{\text{lep}}^{\text{MET}})}, \quad (7.5)$$

where $\phi_{\text{lep}}^{\text{MET}}$ is the ϕ angle between the lepton and E_T^{miss} .

The distributions of the BDT input variables in the signal region are shown in figure 7.7. Since the analysis is not yet finalised and changes to the analysis might still be introduced after a full evaluation of the results based on the control regions and expected results, the plots in the signal region are shown without the data. This is done in order not to bias the analysis with the data. A cut is introduced on the output of the BDT which is optimised to give the best signal/background ratio. The optimal value to cut on the BDT output

Cut	WW	Other VV	$t\bar{t}$	Single Top	$Z/\gamma^* \rightarrow e\ell/\mu\mu$	$Z/\gamma^* \rightarrow \tau\tau$	e Fakes	μ Fakes	V_γ
Channel Selection	45418.14 $\pm$ 61.58	24552.11 $\pm$ 89.70	404864.66 $\pm$ 401.21	36556.69 $\pm$ 75.32	41557.49 $\pm$ 900.86	170074.93 $\pm$ 1204.19	779093.72 $\pm$ 2614.97	779093.72 $\pm$ 2614.97	17891.19 $\pm$ 172.77
GR1 Selection	45418.14 $\pm$ 61.58	24552.11 $\pm$ 89.70	404864.66 $\pm$ 401.21	36556.69 $\pm$ 75.32	41557.49 $\pm$ 900.86	170074.93 $\pm$ 1204.19	81353.64 $\pm$ 1817.22	521768.31 $\pm$ 1286.03	17891.19 $\pm$ 172.77
Jet Cleaning	45392.79 $\pm$ 61.52	24472.01 $\pm$ 89.53	40655.47 $\pm$ 400.48	36752.92 $\pm$ 78.18	41499.31 $\pm$ 908.02	169746.37 $\pm$ 1203.23	478500.47 $\pm$ 1814.86	518836.92 $\pm$ 1284.06	17832.74 $\pm$ 172.56
Overlap: $V_{\text{gamma}}/V_{\text{jets}}$	45392.73 $\pm$ 61.52	24473.01 $\pm$ 89.53	40655.47 $\pm$ 400.48	36752.92 $\pm$ 78.18	29548.14 $\pm$ 748.08	168143.15 $\pm$ 1197.73	478500.47 $\pm$ 1814.86	518836.92 $\pm$ 1284.06	17833.74 $\pm$ 172.56
Trigger Selection	42474.32 $\pm$ 59.39	2076.68 $\pm$ 82.27	379901.56 $\pm$ 388.95	34858.45 $\pm$ 70.21	24040.92 $\pm$ 673.09	132470.95 $\pm$ 1055.47	388906.70 $\pm$ 1541.76	411163.76 $\pm$ 1048.85	1220.00 $\pm$ 141.63
Only two Leptons	41961.14 $\pm$ 58.99	1203.98 $\pm$ 60.61	372988.60 $\pm$ 384.03	34341.84 $\pm$ 75.40	13678.67 $\pm$ 557.39	128495.04 $\pm$ 1026.75	405964.40 $\pm$ 1374.25	415355.65 $\pm$ 967.69	10746.66 $\pm$ 134.96
$p_T^{\text{lead}} > 22$ GeV	41961.14 $\pm$ 58.99	1203.98 $\pm$ 60.61	372988.60 $\pm$ 384.03	34341.84 $\pm$ 75.40	13678.67 $\pm$ 557.39	128495.04 $\pm$ 1026.75	405964.40 $\pm$ 1374.25	415355.65 $\pm$ 967.69	10746.66 $\pm$ 134.96
$p_T^{\text{sublead}} > 15$ GeV	40178.89 $\pm$ 57.75	10054.64 $\pm$ 55.73	353779.52 $\pm$ 374.03	32648.38 $\pm$ 73.46	10850.96 $\pm$ 541.50	110629.97 $\pm$ 961.71	366259.73 $\pm$ 1357.11	317377.51 $\pm$ 868.19	9690.88 $\pm$ 126.71
$m_{\ell\ell} > 10$ GeV	39537.50 $\pm$ 57.29	4639.42 $\pm$ 37.54	347249.07 $\pm$ 370.68	32115.24 $\pm$ 72.84	6402.29 $\pm$ 428.32	109374.83 $\pm$ 958.46	165426.27 $\pm$ 1018.62	130361.63 $\pm$ 667.22	4593.67 $\pm$ 82.54
Apply fake factor	37165.85 $\pm$ 55.55	3346.44 $\pm$ 30.76	322186.29 $\pm$ 357.52	30201.47 $\pm$ 70.63	3429.48 $\pm$ 286.54	9585.07 $\pm$ 896.69	8865.63 $\pm$ 138.38	14831.40 $\pm$ 175.92	3534.02 $\pm$ 70.78
> 2 -jets	5893.00 $\pm$ 22.01	1013.83 $\pm$ 18.37	298180.40 $\pm$ 351.88	18587.88 $\pm$ 56.69	402.85 $\pm$ 51.93	11654.47 $\pm$ 200.39	3563.94 $\pm$ 60.38	4925.30 $\pm$ 71.72	835.99 $\pm$ 36.16
$m_{\ell\ell} < 90$ GeV	2578.24 $\pm$ 14.42	552.02 $\pm$ 12.65	135099.41 $\pm$ 233.70	7621.68 $\pm$ 35.88	351.34 $\pm$ 50.48	11416.48 $\pm$ 198.03	2108.52 $\pm$ 48.37	3733.52 $\pm$ 64.78	642.32 $\pm$ 32.99
$m_{\tau\tau} < 150$ GeV	1825.05 $\pm$ 12.10	483.91 $\pm$ 12.11	89673.83 $\pm$ 189.96	4961.41 $\pm$ 28.96	349.71 $\pm$ 50.46	11385.62 $\pm$ 197.81	1701.02 $\pm$ 45.01	3300.65 $\pm$ 60.69	606.52 $\pm$ 32.31
b -jet veto	1547.50 $\pm$ 10.96	383.83 $\pm$ 10.79	4734.00 $\pm$ 40.39	634.69 $\pm$ 9.55	284.80 $\pm$ 45.58	9075.03 $\pm$ 178.24	596.51 $\pm$ 34.02	1358.91 $\pm$ 42.98	502.03 $\pm$ 29.49
$Z \rightarrow \tau\tau$ veto	1095.73 $\pm$ 9.17	287.96 $\pm$ 9.51	3442.11 $\pm$ 34.71	472.18 $\pm$ 8.55	126.73 $\pm$ 31.64	2952.50 $\pm$ 128.29	421.71 $\pm$ 25.58	897.19 $\pm$ 32.29	306.79 $\pm$ 32.31
$p_T^{\ell\ell} > 20$ GeV	1024.87 $\pm$ 8.80	271.55 $\pm$ 9.34	3277.94 $\pm$ 33.98	446.15 $\pm$ 8.26	117.64 $\pm$ 31.32	1925.09 $\pm$ 67.46	374.18 $\pm$ 23.61	773.30 $\pm$ 22.50	284.59 $\pm$ 21.71
$Z \rightarrow \tau\tau$ CR	181.94 $\pm$ 3.70	50.51 $\pm$ 3.58	560.59 $\pm$ 13.56	74.92 $\pm$ 3.46	95.14 $\pm$ 27.26	3910.87 $\pm$ 87.63	69.04 $\pm$ 15.47	106.27 $\pm$ 20.65	113.84 $\pm$ 16.51
Top CR	160.92 $\pm$ 3.87	57.11 $\pm$ 3.97	58647.26 $\pm$ 156.38	2960.33 $\pm$ 22.69	27.59 $\pm$ 12.28	50.39 $\pm$ 33.82	702.86 $\pm$ 23.95	1265.20 $\pm$ 32.32	538.7 $\pm$ 9.58
WW VR	2630.77 $\pm$ 14.61	347.75 $\pm$ 12.07	8865.93 $\pm$ 58.32	1345.00 $\pm$ 14.96	35.06 $\pm$ 10.72	183.44 $\pm$ 28.31	446.83 $\pm$ 17.28	267.26 $\pm$ 11.97	144.13 $\pm$ 12.04
W+Jets VR	7.39 $\pm$ 0.69	268.29 $\pm$ 8.67	35.92 $\pm$ 3.83	2.97 $\pm$ 0.59	55.75 $\pm$ 14.80	13.98 $\pm$ 4.98	200.43 $\pm$ 19.04	383.90 $\pm$ 13.15	219.54 $\pm$ 18.23

Table 7.4: Numbers of events passing the event selection split to the different background processes. The various simulated Monte Carlo samples are normalised to the integrated luminosity. The uncertainties correspond to the statistical uncertainties.

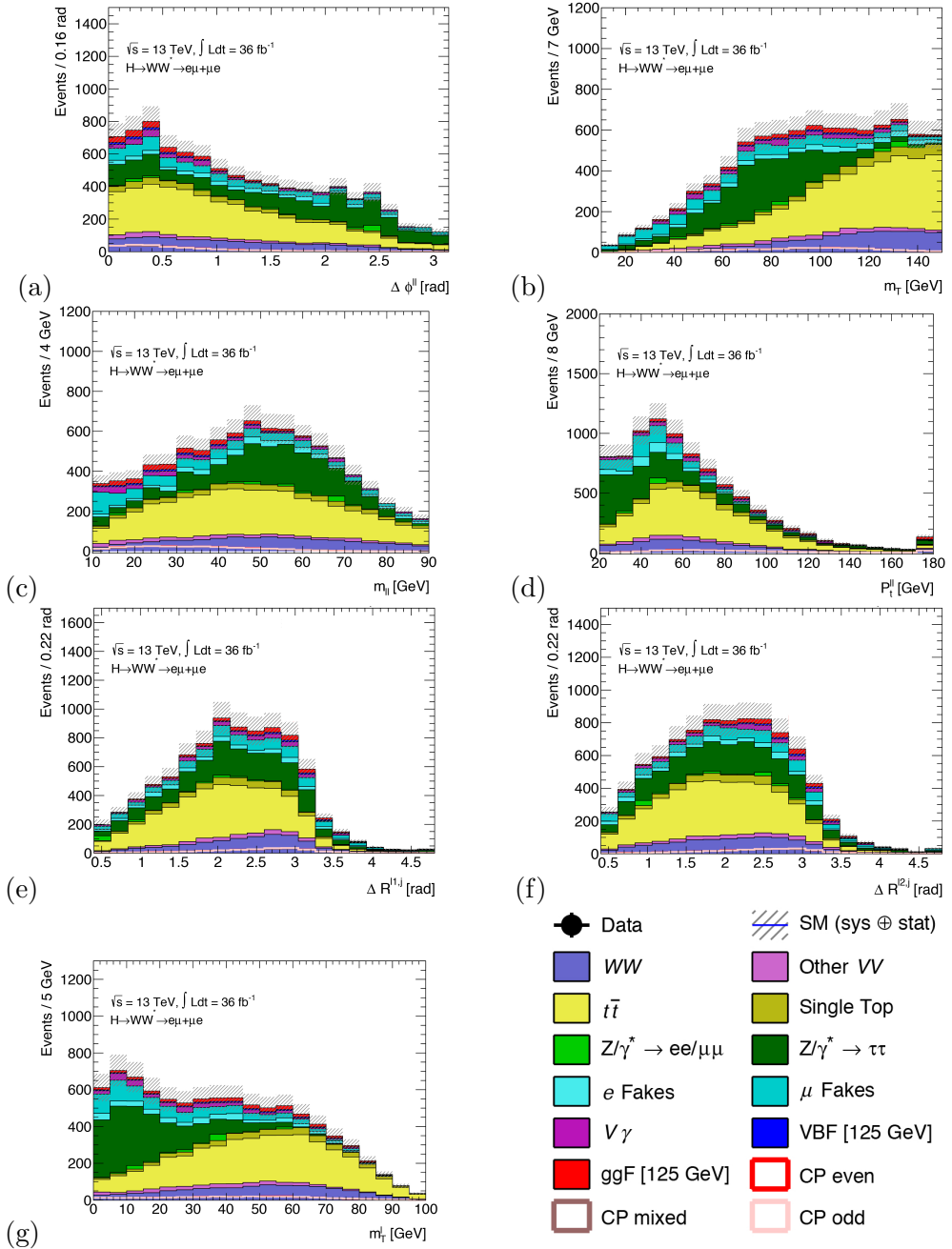


Figure 7.7: Distribution of the BDT input observables: (a) $\Delta\phi_{\Pi}$ (b) m_T (c) m_{Π} (d) p_T^{Π} (e) $\min(\Delta R(\ell_0, j))$ (f) $\min(\Delta R(\ell_1, j))$ (g) $\min(m_T^{\ell})$.

is found to be at $\mathbf{BDT} > 0$. The BDT output for the signal region, control

regions and validation regions is shown in figure 7.8.

The $\Delta\phi_{jj}$ distribution after the cut on the BDT is applied in the control regions and validation regions is shown in figure 7.9. The $\Delta\phi_{jj}$ distribution after the cut on the BDT is applied in the signal region, as well as the distribution at this cut level for the different CP benchmark scenarios, is shown in figure 7.10. The event yields obtained after applying cuts on the BDT response are shown in table 7.5.

$\sqrt{s} = 13\text{TeV}, \mathcal{L} = 36\text{fb}^{-1},$	BDT cut
VBF [125 GeV]	70.7 ± 0.7
ggF [125 GeV]	196 ± 3.0
WW	421 ± 5.7
Other VV	132 ± 5.3
$t\bar{t}$	1147 ± 20.0
Single Top	156 ± 4.8
$Z/\gamma^* \rightarrow ee/\mu\mu$	28.5 ± 8.2
$Z/\gamma^* \rightarrow \tau\tau$	249.8 ± 20.2
e Fakes	112.4 ± 14.5
μ Fakes	275.6 ± 11.9
$V\gamma$	130.8 ± 13.4
Total Bkg	2653 ± 38.6

Table 7.5: Expected numbers of events passing the BDT cut corresponding to the full event selection for a integrated luminosity of 36fb^{-1} . The various simulated Monte Carlo samples are normalised to the integrated luminosity. The event yields are shown separately for the predicted signal and background processes. The uncertainties correspond to the uncertainty due to MC statistics.

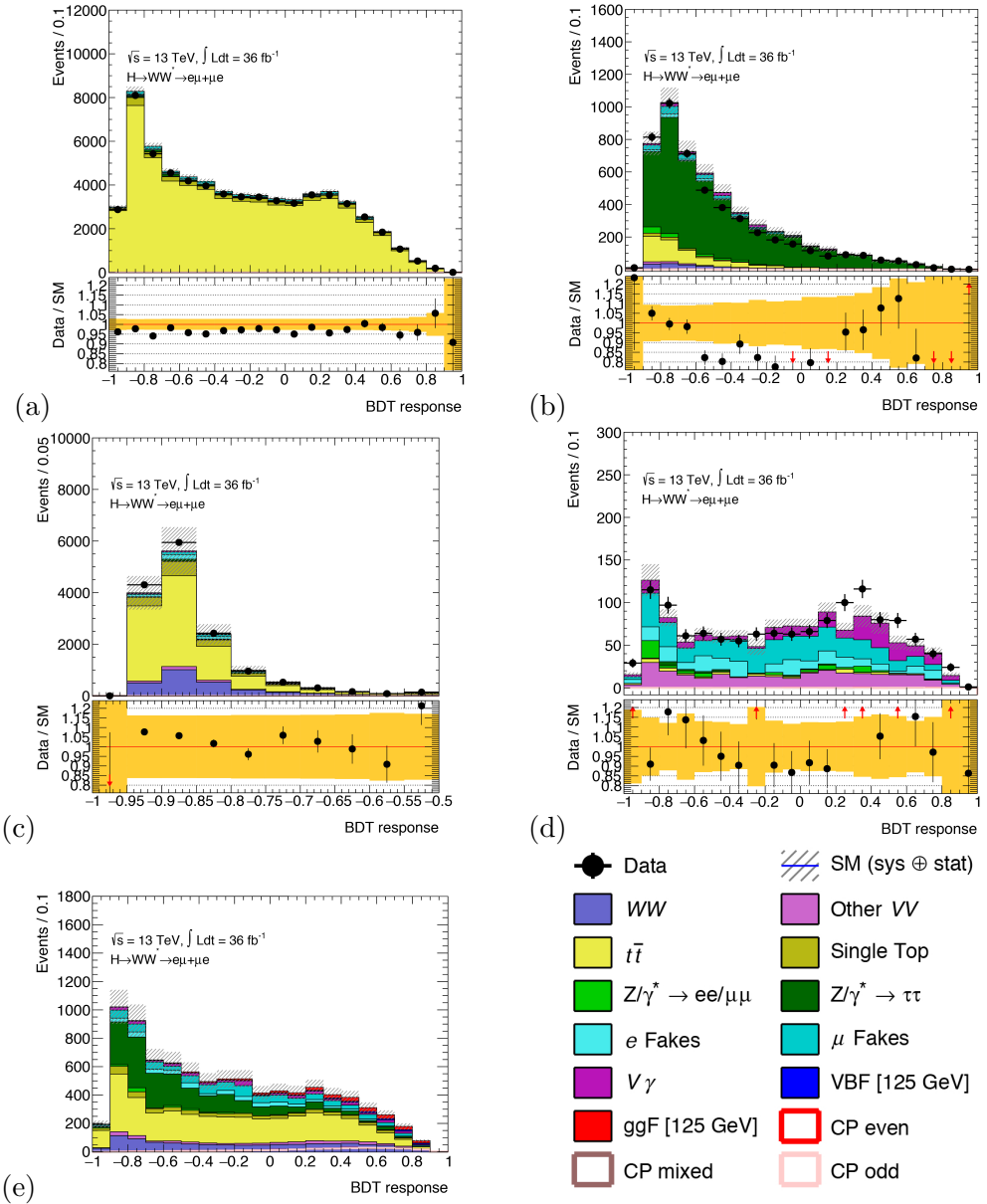


Figure 7.8: Distribution of the BDT output for (a) the top control region (b) the $Z \rightarrow \tau\tau$ control region (c) the WW validation region (d) the W +jets validation region and (e) the signal region.

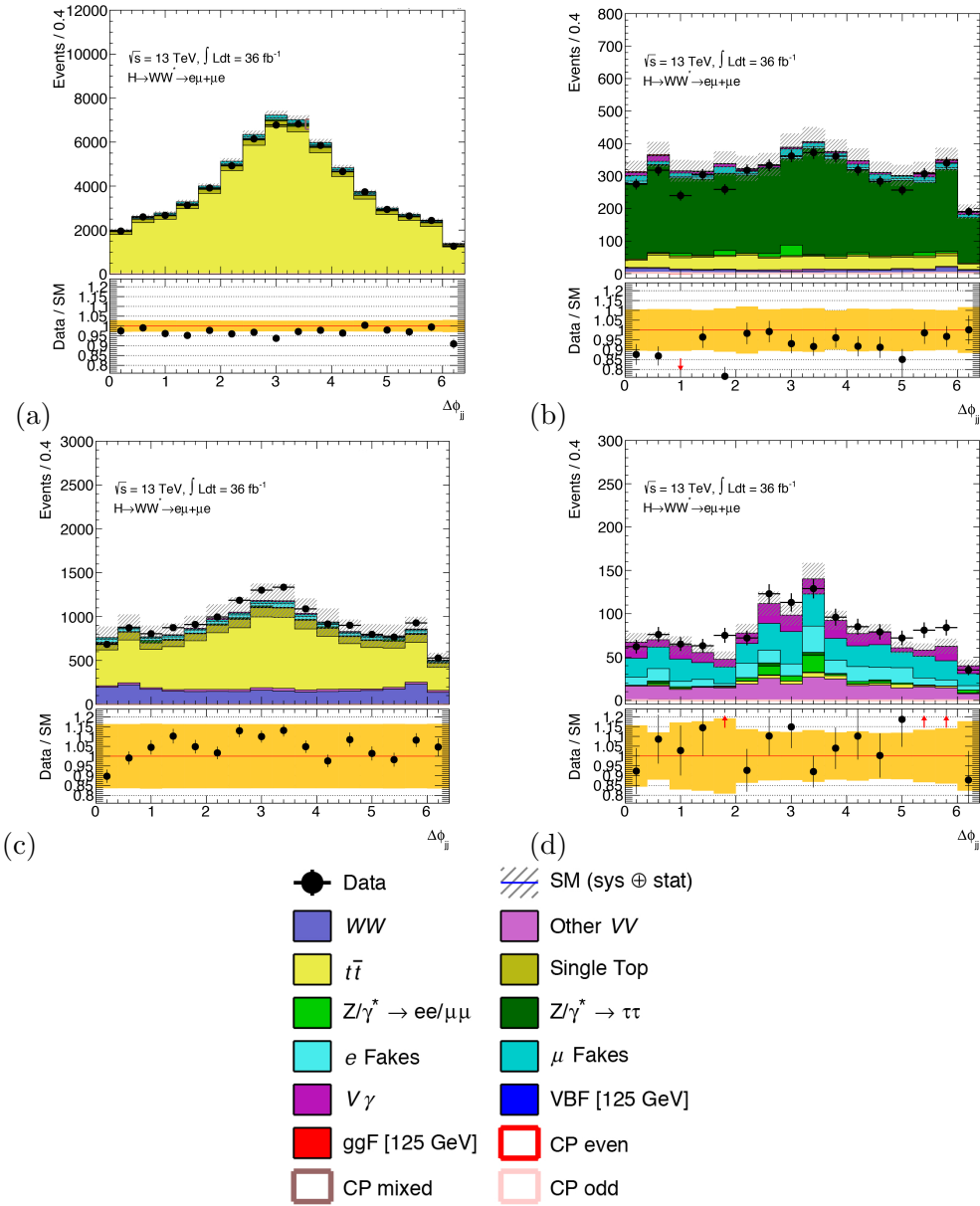
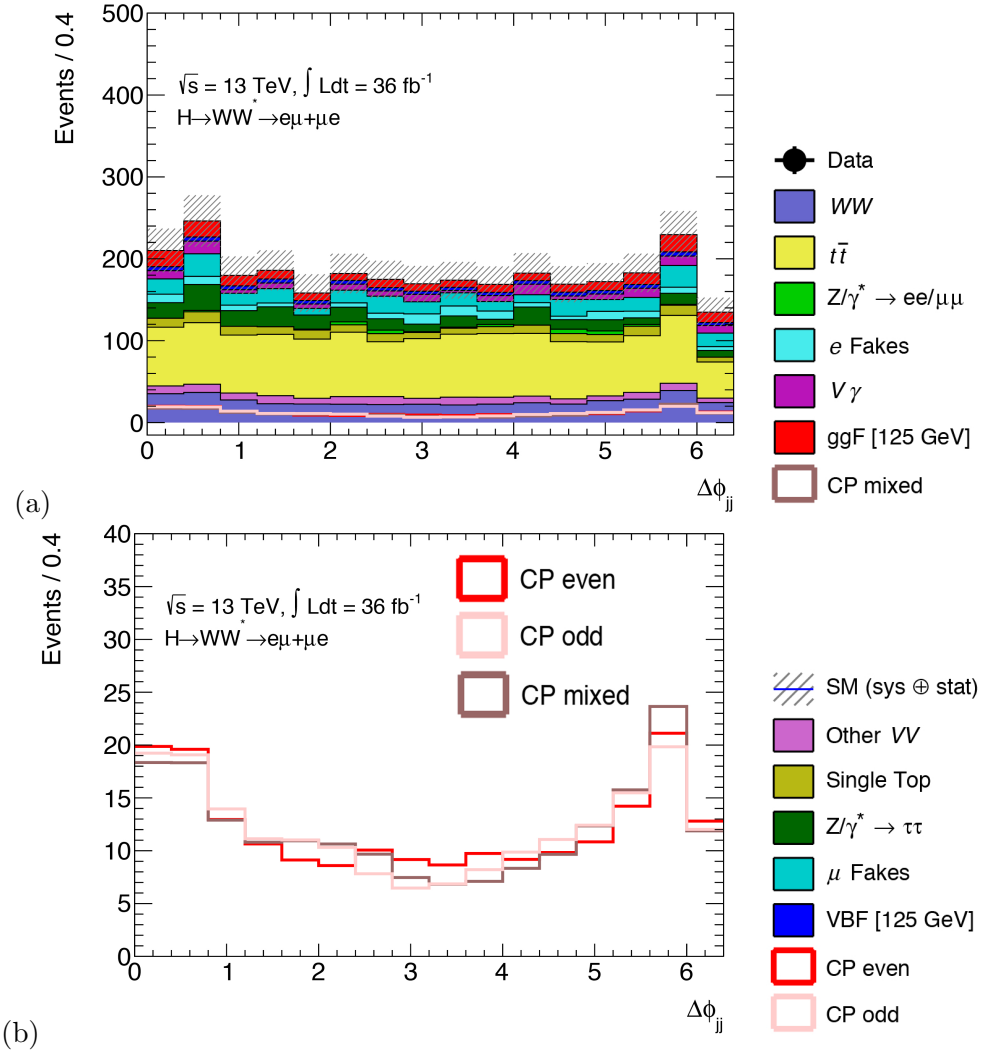


Figure 7.9: Distribution of $\Delta\phi_{jj}$ for (a) the top control region (b) the $Z \rightarrow \tau\tau$ control region (c) the WW validation region and (d) the W +jets validation region after the BDT cut is applied. The yellow band indicates the statistical and experimental systematic uncertainty.



7.4.5 Fit Model and Parameter Extraction Procedure

A general description of the maximum likelihood procedure is given in chapter 4. The discriminant variable used into the fit is the $\Delta\phi_{jj}$ distribution. The fit uses the SM CP even Higgs boson sample in the signal region. The top control region and the $Z \rightarrow \tau\tau$ control region are included as a counting experiment in the likelihood¹. These control regions are used to estimate the normalisation factor for these background to be applied in the signal region.

Several sources of systematic uncertainties are considered that can affect the normalisation of signal and background and/or the shape of their corresponding final discriminant distributions. The individual systematic uncertainties are described in detail in section 7.5. Individual sources of systematic uncertainty are considered uncorrelated. A coherent description of the effect of each systematic uncertainties is maintained.

All applicable experimental systematic uncertainties are included in the likelihood fit. Due to the low statistic regime, all the NPs describing the systematic uncertainties are included into the fit by using a LogNormal constraint such that expected event counts remain positive for all values of the corresponding NPs.

The expected performance of the fit has been studied using so-called Asimov dataset approach; this procedure replaces the ensemble testing performed with Monte Carlo pseudo-experiments with a single 'representative' dataset on which an Maximum Likelihood estimate of the parameter returns exactly the median of the ensemble expectation with a single fit. The Asimov dataset allows to study the constraints on the nuisance parameters that could be obtained with the expected data uncertainties distributions and statistical uncertainties. This is used to check if the implementation of the nuisance parameters is done properly.

The parameter extraction is done in the form of likelihood scans over the $\cos\alpha$ parameter and the ratio $\frac{\kappa_{Agg}}{\kappa_{Hgg}} \tan\alpha$. Although the scans of $\cos\alpha$ and the ratio $\frac{\kappa_{Agg}}{\kappa_{Hgg}} \tan\alpha$ both indicate the compatibility with different CP scenarios, the two scans have a different purpose. The scan of $\cos\alpha$ is directly interpretable in terms of the mixing angle between a SM CP even Higgs boson and a CP odd Higgs boson, while the scan of the ratio $\frac{\kappa_{Agg}}{\kappa_{Hgg}} \tan\alpha$ allows an easier extraction of the results for theorists. The κ_{Hgg} and κ_{Agg} parameters are set to one in the scan of $\cos\alpha$. The analytic morphing method is used, as described in chapter 5, to model the signal and its dependence on the parameters κ_{Hgg} , κ_{Agg} and $\cos\alpha$ in the full parameter space spanned by the parameters. For these fits the shape of the different CP mixing scenarios is tested. The shape information is fitted and no result is extracted based on normalisation of the signal in order

¹This is implemented as a single-bin histogram for each control region.

to be more model independent. In any case, the different signal hypotheses differ only marginally in terms of yields.

Additionally, the probability of the data under the pure SM CP even and pure CP odd hypotheses has been evaluated using the hypothesis test as described in section 4.6. For this test the Asimov data is compared to a pure CP even Higgs boson scenario and a pure CP odd Higgs boson scenario.

7.5 Treatment of Statistical and Systematic Uncertainties

The systematic uncertainties considered in this analysis are divided into two categories: experimental uncertainties and theoretical uncertainties.

In the likelihood fit, the experimental uncertainties are varied in a coherent way across all backgrounds and across signal and control regions, so that the uncertainties on the extrapolation factors are correctly propagated. All sources are analysed to evaluate their impact on both the yield normalisation and on the shape of the $\Delta\phi_{jj}$ distributions. The uncertainties on the extrapolation factors from the control regions to the signal regions, which are obtained from the generators, are correctly propagated.

7.5.1 Experimental uncertainties

A-priori, the largest sources of experimental uncertainty in this category are the jet-energy scale and resolution, the b -tagging efficiency, the lepton resolution, identification and trigger efficiencies and the missing transverse momentum measurement. The ranking of the considered experimental uncertainties and their effect on the signal region yield are shown in table 7.6.

Systematic	Effect on signal yield [%]
b-tagging efficiency	10.2
Jet energy scale	4.0
Jet energy resolution	3.8
Light-jet tagging efficiency	1.5
Luminosity	1.4
Lepton reconstruction	1.0
E_T^{miss}	0.4

Table 7.6: Summary of the main experimental systematics considered and their effect on the signal yield.

Jet energy scale and resolution

There are various contributions to the systematic uncertainty due to the jet energy scale (JES) calibration. The modelling and statistical uncertainties on the jet calibration, pile-up and calorimeter response on jet flavour composition contribute to the systematic uncertainty due to the JES calibration. The jet energy scale, jet energy resolution, and their uncertainties are derived and their uncertainties are obtained by combining information from simulation, test-beam data, and in-situ measurements [174]. The total uncertainty due to JES is less than 7%. The uncertainty on the jet energy resolution (JER) is determined from in-situ measurements as a function of p_T and η . The uncertainty due to JER varies between 2% and 40%.

Flavour (b -)tagging efficiency

Systematic uncertainties on the measured b -tagging efficiencies and the corresponding scale factors are evaluated individually by replacing the nominal jet sample with a modified sample obtained after varying the relevant properties of the simulated objects. The whole event selection and reconstruction as well as the measurement of the b -tagging efficiencies and scale factors is repeated taking each systematic variation into account.

Uncertainties on the c -tagging efficiencies and mis-tag rate [130] are also taken into account, since the analysis makes use of b -tagging.

Luminosity

The integrated luminosity of the data collected by ATLAS in the 2016 run is measured with a precision of 3.2%, as calculated from a preliminary calibration of the luminosity scale using x-y beam-separation scans at $\sqrt{s}=13$ TeV using similar techniques to those described in reference [163].

Missing transverse momentum

Uncertainties due to the scaling and smearing of the electron, muon and jet energies and momenta also include a re-calculation of the missing transverse momentum, which has an additional effect on the event selection acceptance and the BDT input variables. Further sources for systematic uncertainties that are only related to the E_T^{miss} calculation procedure correspond to the energy scale and resolution of calorimeter cells not associated to any reconstructed lepton or jet candidate [175].

Lepton reconstruction

The uncertainties coming from lepton reconstruction, identification and isolation are estimated by a tag-and-probe method in $Z \rightarrow ll$ events [123]. The uncertainties arising from the lepton energy scale and resolution depend on p_T and η . These uncertainties have a small effect on the signal and background event yields.

Fake factor estimation

The following sources of uncertainties on the measurement of the fake factors need to be taken into account [176]:

- The uncertainty associated to the real lepton contamination from electroweak processes in the di-jet data sample. It is estimated by varying the subtracted MC predictions.
- The difference in fake factor in the di-jet data sample and in the $Z + jets$ data sample, i.e. the different flavour composition of the jets. This is done to model the difference between $W + jets$ and di-jet events.
- The statistical uncertainty on the fake factor measurement.

The uncertainty originating from the fake factor calculation is not taken into account, and must be added to get a complete picture of the experimental uncertainty on the measurement for future analyses.

7.5.2 Modelling uncertainties

The theory systematics related to physics modelling considered are summarised in table 7.7.

Model uncertainties on the signal samples

The systematic uncertainties on the modelling of the $H \rightarrow WW$ signal sample depend on the choice of PDF set, the process of parton showering and QCD scale uncertainties. Uncertainties on the modelling of the signal samples are not taken into account for the sensitivity study presented here. The theoretical uncertainties that will be assessed in future analyses are:

- **QCD scales** This is done by independently varying the values of the renormalisation scale μ_R and the factorisation scales μ_F , in MG5_aMC@NLO calculations. Both scales are independently multiplied by a factor of 2.0 or 0.5 relative to the nominal value $\mu_0 = m_H$.

Systematic type	Alternate generator	Effect on yield [%] SR	Top CR	$Z \rightarrow \tau\tau$ CR
Top	SHERPA			
MC generator choice		10.48	8.22	8.91
Parton Shower		15.45	5.39	18.41
A14 tune (up)		-1.85	-2.34	0.44
A14 tune (down)		5.33	0.71	-1.63
$Z \rightarrow \tau\tau$	ALPGEN			
MC generator choice		-19.52	10.0	19.18
$V\gamma$	SHERPA			
QCD scale (up)		+6.67	+6.67	+6.67
QCD scale (down)		-10.47	-10.47	-10.47
WW	POWHEG+PYTHIA8			
QCD Scale ($\mu_R=0.5, \mu_F=0.5$)		28.78	29.24	29.77
QCD Scale ($\mu_R=2.0, \mu_F=2.0$)		-19.57	-20.15	-20.22
$\alpha_S = 0.117$		-2.45	-2.39	-2.44
$\alpha_S = 0.119$		2.30	2.30	2.37
MMHT2014nnlo68cl		1.29	1.23	1.40
MC/PS Generator		-7.43	-19.29	-0.97

Table 7.7: Summary of the theory systematics considered and their effect on the yield.

- PDF uncertainties** This is done from the envelope of the CT10 68% CL eigenvectors added in quadrature with the maximal difference between the results obtained with CT10 and those obtained with either MSTW [158] or NNPDF [177].
- Choice of parton-shower and underlying-event models (PS/UE)**
 The uncertainties corresponding to the parton shower tune and the underlying event are derived by shifting independently, up or down, the PYTHIA internal parameters that are associated with the final state radiation (FSR) or the multiple parton interactions (MPI) to study their influence on the various signal hypotheses separately. These uncertainties are compared for each CP state to the parton shower model uncertainties, which are estimated by comparing the results obtained for the nominal parton shower generator to those obtained using Herwig++ instead of PYTHIA8. These uncertainties include migration effects between the 0- and 1-jet production modes into the 2-jet channel due to an increase or decrease of the final state radiation.

Top-quark modelling

In order to obtain the parton shower uncertainties for the top backgrounds the $t\bar{t}$ sample generated with POWHEG+PYTHIA8 is compared to a sample generated with POWHEG+HERWIG7. In order to obtain the uncertainties on the Matrix element the $t\bar{t}$ sample generated with POWHEG+PYTHIA8 is compared to a sample generated with MG5_aMC@NLO+PYTHIA8. For

the uncertainties in the initial and final state radiation two samples from POWHEG+PYTHIA8 are used where the shower parameters are varied. In these samples the parameters used to control the initial and final state radiation are chosen such that the amount of additional radiation is increased (decreased) in a range consistent with experimental findings [178].

Z + jets modelling

The systematic uncertainty due to the choice of the matrix element and parton shower generators for $Z + jets$ events is evaluated by comparing the nominal MG5_aMC@NLO sample with a sample generated with Sherpa.

$V\gamma$ modelling

The systematic uncertainty for the choice of parton-shower and underlying-event models for the $V\gamma$ background is evaluated by comparing the Sherpa sample with a sample generated with MG5_aMC@NLO. The QCD scale uncertainty is calculated by varying both scales by a factor of 2.0 or 0.5 relative to the nominal value.

VV modelling

The systematic uncertainty on the choice of the matrix element and the parton shower for the VV background is evaluated by comparing the nominal Sherpa sample with a sample generated with MG5_aMC@NLO. QCD scale uncertainties are calculated by independently varying the factorisation and normalisation scales by a factor of 2.0 or 0.5 relative to the nominal value.

Modelling of other background

The systematic uncertainties for the other backgrounds are currently not included. The VBF production is treated as a background in this analysis, and the modelling uncertainties corresponding to this background should be calculated in the same way as for the signal.

7.6 Results

All the results shown for this analysis are on a Asimov dataset, which represents a result on the sensitivity obtained for such an analysis to measure the properties of the top Yukawa Higgs boson coupling. The result of the pull from the nuisance parameters (NPs) from the fit to the Asimov dataset under the pure SM CP even Higgs boson hypothesis is shown in figure 7.11.

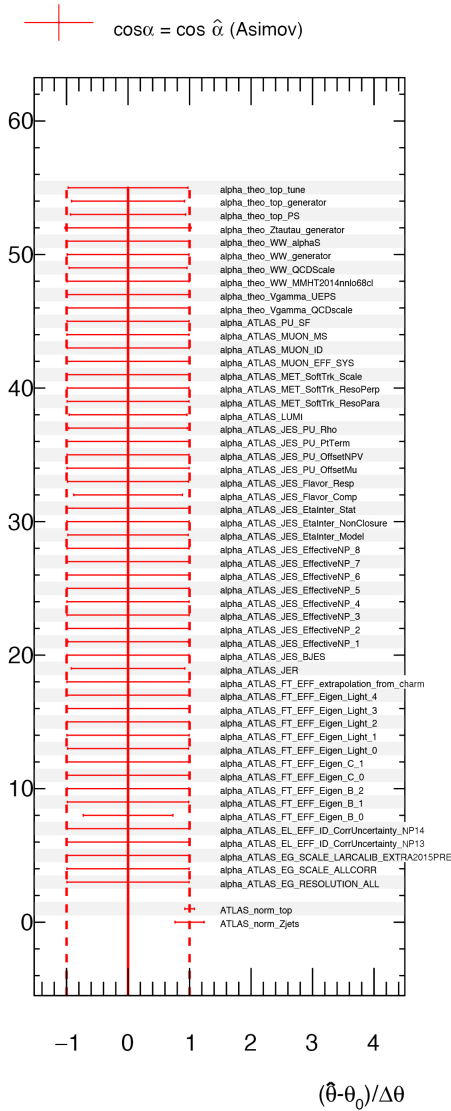


Figure 7.11: Fitted nuisance parameters to Asimov data set under the pure SM CP even Higgs boson hypothesis (assuming $m_H = 125$ GeV). If no NPs are constrained beyond their uncertainty defined in the subsidiary measurement, the interval for all NPs will exactly span the range $[-1,1]$.

As expected, nuisance parameters corresponding to the main experimental systematic uncertainties are all centred on zero and the normalisation scale factors are centred around one. The majority of the parameters (especially the ones related to the detector performance) are not constrained beyond their

expectation. This shows that there is no unexpected behaviour in the analysis procedure.

The sensitivity for the parameter scan of $\cos \alpha$ and the ratio $\frac{\kappa_{Agg}}{\kappa_{Hgg}} \tan \alpha$ on an Asimov dataset are shown in figure 7.12. The SM CP even Higgs boson hypothesis corresponds to a mixing angle $\cos \alpha = 1$, $\kappa_{Agg} = 0$ and $\kappa_{Hgg} = 1$. The SM values for $\cos \alpha$, κ_{Agg} and κ_{Hgg} correspond to $\frac{\kappa_{Agg}}{\kappa_{Hgg}} \tan \alpha = 0$. The parameter scans allow to exclude mixing parameters at 2σ . The resulting exclusion limits of the parameter scans is summarised in table 7.8. The sensitivity for the parameter scan of $\cos \alpha$ is shown for an Asimov dataset created for a SM CP even Higgs boson hypothesis and a CP mixing with predominant CP odd fraction for the Higgs boson ($\cos \alpha = 0.5$). The Asimov dataset with a CP mixing of $\cos \alpha = 0.5$ is used to test the sensitivity in case a non-SM result is measured. From the SM CP even Higgs boson Asimov dataset, mixings with a CP odd fraction larger than 13.9% can be excluded at 95%CL.

In the Run 1 of the LHC, the method for testing the separation power between a SM CP even Higgs boson hypothesis and a CP odd Higgs boson hypothesis was a hypothesis test with the use of toys [59]. This method is implemented as a consistency check. The result of the hypothesis test is shown in figure 7.13. The expected sensitivity, obtained from the hypothesis test between a SM CP even Higgs boson and a CP odd Higgs boson shown in figure 7.13, shows a good separation power between the two CP scenarios. As expected, the separation power between the two hypotheses as a result of the hypothesis test corresponds with the separation power found at the extremes of the CP-even versus CP-odd parameters scans. As can be seen from both methods, shown in figures 7.12 and 7.13, there is a high exclusion power for a CP odd Higgs boson or a strong CP mixing scenario when a SM CP even Higgs boson is measured. The inclusion of additional systematic uncertainties for the signal modelling and modelling of the VBF and $W + jets$ backgrounds will slightly reduce the exclusion power of a future analysis performed on data to measure the properties of the top Yukawa Higgs boson coupling.

7.7 Conclusions

The gluon-gluon fusion Higgs boson production mode in association with two jets is shown to be a promising way to assess the top Yukawa coupling, which has never been measured before. The precision achieved for a study of the properties of the top Yukawa Higgs boson coupling in the $H \rightarrow WW$ decay channel is shown to have a good separation power between a SM CP even Higgs boson and a CP odd Higgs boson. The analysis also shows that a precision

Parameter	Central value	1σ range	2σ range
$\cos \alpha = 1$	1.00	[0.97 – 1.00]	[0.87 – 1.00]
$\cos \alpha = 0.5$	0.50	[0.16 – 0.83]	[-0.07 – 0.96]
$\frac{\kappa_{Agg}}{\kappa_{Hgg}} \tan \alpha = 0$	0.00	[-0.34 – 0.33]	[-0.64 – 0.61]

Table 7.8: The best fit value for the parameter scans of $\cos \alpha$ and the ratio $\frac{\kappa_{Agg}}{\kappa_{Hgg}} \tan \alpha$ performed on an Asimov dataset created with parameter values quoted in the *Parameter* column. The maximum value for $\cos \alpha$ is one, which creates a cut-off at this value of the scan. The SM CP even Higgs boson hypothesis corresponds to $\cos \alpha = 1$ and $\frac{\kappa_{Agg}}{\kappa_{Hgg}} \tan \alpha = 0$, while a pure CP odd Higgs boson hypothesis corresponds to $\cos \alpha = 0$ and $\frac{\kappa_{Agg}}{\kappa_{Hgg}} \tan \alpha = \infty$. This table corresponds to the parameter scan in figure 7.12.

measurement can be achieved through the use of the analytic morphing method with a comparable precision to previous measurement methods.

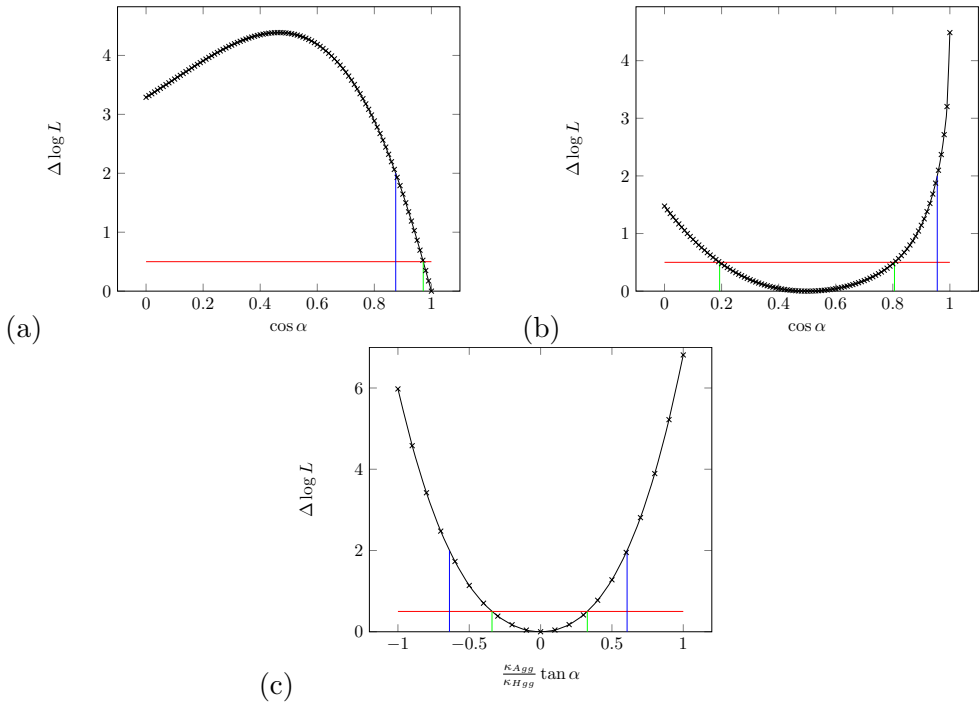


Figure 7.12: The sensitivity obtained in this analysis for the parameter scan of (a) $\cos \alpha$ with an Asimov dataset created for the SM CP even Higgs boson, (b) $\cos \alpha$ with an Asimov dataset created for a CP mixed Higgs boson with mixing value $\cos \alpha = 0.5$ and (c) the ratio $\frac{\kappa_{Agg}}{\kappa_{Hgg}} \tan \alpha$ for an Asimov dataset created for the SM CP even Higgs boson. The green lines indicate the 1σ confidence interval and the blue lines indicate the 2σ confidence interval. The best fit values and the 1σ and 2σ confidence intervals are summarised in table 7.8.

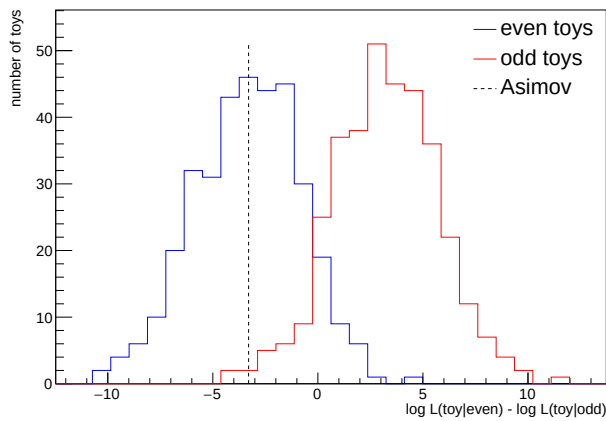


Figure 7.13: The Distribution of the likelihood ratio of toy datasets evaluated under the CP-odd and CP-even analysis for toy datasets sampled under the CP-even hypothesis (blue) and the CP-odd hypothesis (red). A large separation of the distributions implies a good separation power between the hypothesis.

8 Couplings Measurement of the Standard Model Higgs Boson

The SM does not predict the value of the Higgs boson mass, m_H . However when the mass is known, the production cross sections and decay branching ratios of the Higgs boson can be calculated to high precision. Therefore, precisely measuring the coupling strengths of the Higgs boson is critical in ascertaining whether the discovered particle is fully responsible for electroweak symmetry breaking (EWSB). Precision measurements of the coupling strengths also directly measure whether there are potential deviations from SM predictions. A measurement of the Higgs boson production and decay rates and coupling strengths using pp collision data at $\sqrt{s} = 7$ and 8 TeV in the ATLAS experiment has been performed in the first run of the LHC [179]. The Run 1 analysis included the results of the analysis of the Higgs boson decays to $\gamma\gamma$, ZZ^* , WW^* , $Z\gamma$, $b\bar{b}$, $\tau\tau$ and $\mu\mu$. The measured signal yield, normalised to the SM expectation and combining all production and decay channels, is $1.18^{+0.15}_{-0.14}$. The observed Higgs production and decay rates in Run 1 are interpreted in a leading-order coupling framework as described in section 1.5.1. The Run 1 results are compatible with the SM expectations for a Higgs boson with a mass of 125.36 GeV.

8.1 Simplified Template Cross Sections in Run 2

For the simplified template cross section analysis, LHC data at $\sqrt{s} = 13$ TeV recorded by the ATLAS detector are used. The measurement is performed by combining the individual $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^*$ decay channels [180, 181].

The analysis considers the combination of five production processes: ggF ($gg \rightarrow H$ and $b\bar{b}H$), VBF ($qq' \rightarrow qq'H$), VHhad ($q\bar{q}/gg \rightarrow ZH$ and $q\bar{q}' \rightarrow WH$ with hadronic decays of W/Z), VHlep ($q\bar{q}/gg \rightarrow ZH$ and $q\bar{q}' \rightarrow WH$ with leptonic decays of W/Z) and top ($q\bar{q}/gg \rightarrow t\bar{t}H$ and tH). The mass of the Higgs boson is chosen to be $m_H = 125$ GeV and the natural width of the Higgs boson is chosen to be $\Gamma_H = 4.07$ MeV [41].

The proton-proton collision data used in this analysis was collected by the ATLAS experiment in 2015 and 2016. The dataset amounts to 9.5 fb^{-1} , of which 3.2 fb^{-1} were collected in 2015 and 6.3 fb^{-1} in 2016. The pileup was 13.7 in the 2015 dataset and 21.9 in the 2016 dataset.

8.1.1 Sample generation

Higgs production via ggF is simulated at NLO accuracy in QCD using POWHEG Box [84, 85, 86, 182], with the CT10 pdf. The parton-level events produced in the POWHEG Box go through parton showering, hadronisation and multiple parton interactions (MPI) in Pythia8. The sample is normalised to reproduce the total cross section predicted by a N3LO QCD calculation with NLO electroweak corrections [6, 183]. Additional corrections are applied to the Higgs boson transverse momentum distribution to reproduce the distribution predicted by HRES2.1 at NNLO+NNLL, which includes the effects of top-quark and bottom-quark masses and uses dynamical renormalisation and factorisation scales.

Higgs boson production via VBF is generated to NLO accuracy in QCD using POWHEG box [184] with the CT10 pdf. The parton-level events produced in the POWHEG Box go through parton showering, hadronisation and multiple parton interactions (MPI) in Pythia8. The VBF sample is normalised to approximate NNLO QCD cross section with NLO electroweak corrections applied [6, 185, 186, 187, 188, 189, 190]. VH Higgs bosons are produced at LO accuracy in QCD using Pythia8 with the NNPDF2.3LO pdf set [177]. The samples are normalised to cross sections calculated at NNLO in QCD with NLO electroweak correction [6, 191, 192, 193].

Higgs boson production $t\bar{t}H$ is produced at NLO accuracy in QCD using MG5_aMC [146] with the NNPDF2.3 pdf and interfaced to Pythia8 to provide parton showering, hadronisation and MPO. The $t\bar{t}H$ sample is normalised to a cross section calculation accurate to NLO in QCD with NLO corrections applied [6, 194, 195, 196, 197].

Higgs boson production $b\bar{b}H$ is produced using MG5_aMC interfaced to Pythia8 and normalised to a cross section calculated to NNLO accuracy in QCD [6]. The sample includes the effect of interference with the ggF mechanism. Higgs boson production tHW is produced at LO accuracy using MG5_aMC interfaced to Herwig++ [198]. Higgs boson production $tHjb$ is produced at LO accuracy using MG5_aMC interfaced to Pythia8. The tHW and $tHjb$ samples are normalised to calculations accurate to NLO in QCD [6].

The simulated events are passed through a Geant4 [105] simulation of the ATLAS detector [106] and reconstructed using the same analysis software as used for the data. The mean number of additional pp interactions per bunch crossing, is included in the simulation by adding inelastic pp collisions, such that the average number of interactions per bunch crossing reproduces the number of interactions observed in the data. The inelastic pp collisions are produced using Pythia8.

8.1.2 Individual Channels

Each decay channel, $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^*$, divides the events into a number of mutually exclusive categories based on reconstructed event kinematics and topology. The categories are defined such that each category is sensitive primarily to a given production mode. A further subdivision is made based on the number of jets in the final state. The categories are taken as templates, as described in section 1.5.2. Table 8.1 gives an overview of the event categories for both decay modes used for the measured simplified template cross sections and the inclusive signal strength.

$H \rightarrow ZZ^* \rightarrow 4l$

The $H \rightarrow ZZ^* \rightarrow 4l$ analysis [181] reconstructs the Z and Z^* bosons in their decays to electrons and muons. Five event categories are used, as categorised in table 8.1, to separate the different Higgs boson production modes. The VH leptonic category requires the presence of at least one additional lepton with $p_T > 8$ GeV. The remaining events are categorised according to their jet multiplicity. In the jet-multiplicity based categories boosted decision trees (BDTs) based on kinematic jet and Z variables are used to separate the different Higgs production processes from the SM ZZ^* background. Only events with an invariant four-lepton mass between 118 GeV and 129 GeV are considered in the analysis. In the jet categories, the signal is extracted through a binned fit to the BDT discriminant. The jets are required to have a minimum p_T of 30 GeV. In the VH leptonic category the signal estimation is based on event counting. The remaining $ZZ^* \rightarrow 4l$ background is estimated from the Monte Carlo simulation, while the Z +jets and $t\bar{t}$ backgrounds are estimated from

$H \rightarrow ZZ^* \rightarrow 4l$		$H \rightarrow \gamma\gamma$	
Category	Target	Category	Target
VH -leptonic	VHlep	$t\bar{t}H$ leptonic	top
		$t\bar{t}H$ hadronic	top
		VH dilepton	VHlep
		VH one-lepton	VHlep
		VH Emiss	VHlep
2-jet VH -like	VHhad	VH hadronic loose	VHhad
		VH hadronic tight	VHhad
2-jet VBF-like	VBF	VBF loose	VBF
		VBF tight	VBF
		ggH central low- p_{Tt}	ggF
0-jet	ggF	ggH central high- p_{Tt}	ggF
1-jet	ggF	ggH fwd low- p_{Tt}	ggF
		ggH fwd high- p_{Tt}	ggF

Table 8.1: Categories entering in the combined measurements for the $H \rightarrow ZZ^* \rightarrow 4l$ and $H \rightarrow \gamma\gamma$ decay modes as described in [180] and [181] respectively. Each category is designed to separate a specific production process, as summarised in the columns named target. For VH hadronic and VBF in the $H \rightarrow \gamma\gamma$ analysis two working points are used, loose and tight, based on the level of background rejection. For ggH in the $H \rightarrow \gamma\gamma$ analysis, the signal selection is separated for the forward and central region of the detector, as well as for low- and high- p_{Tt} , which is defined as the orthogonal component of the diphoton momentum when projected on the axis given by the difference of the momenta of the two photons.

control regions in the data.

$H \rightarrow \gamma\gamma$

The $H \rightarrow \gamma\gamma$ analysis [180] is based on thirteen exclusive event categories targeting the five Higgs boson production mode combinations as described in table 8.1. The leptonic selection requires at least one lepton, with a minimum p_T of 20 GeV for electrons and 15 GeV for muons. and at least two jets of which one should be identified as originating from a b -quark, as well as missing transverse momentum E_T^{miss} or at least two b -tagged jets. Five categories are enriched in VH production. The dilepton category required two same-flavour opposite-sign leptons consistent with a Z -boson decay, with the mass of the two leptons $m_{ll} > 10$ GeV. The one-lepton category requires exactly one lepton and a minimum E_T^{miss} significance. The Emiss category required zero leptons, high E_T^{miss} significance, $E_T^{\text{miss}} > 50$ GeV, and a minimum diphoton transverse momentum $p_T > 10$ GeV. The two hadronic VH categories require two jets consistent with a V decay and employ a BDT based on diphoton and dijet variables. In the hadronic selection events with at least five jets are required of which at least one is b -tagged. The used b -tag working point lies between the Loose and Medium working points. The selection of the two categories enriched in VBF events requires two jets loosely consistent with VBF topology, where jets lie within $|\eta| < 4.5$, and is based on a BDT combining six kinematic variables. The remaining events are separated according to the pseudo-rapidity of the two photons and the p_{Tt} of the diphoton system, which is defined as the orthogonal component of the diphoton momentum when projected on the axis given by the difference of the momenta of the two photons, which separates events with different diphoton invariant mass resolution and further discriminates VBF and gluon fusion production. The signal is extracted by a fit to the diphoton invariant mass distribution in a combined fit to all event categories. The background shape is parametrised in each event category and determined from data.

8.1.3 Statistical Framework

The statistical treatment is described in chapter 4 and [199, 200, 201, 143, 142, 202]. Each of the parameters of interest represent a product of a Higgs production cross section and a branching ratio in the fit. The present analysis considers the five combinations of production modes and two Higgs decay channels, giving initially ten parameters to be estimated. These parameters can be used to predict the mean numbers of events in bins corresponding to different kinematic regions for several event topologies. A likelihood function is constructed that treats the number of events found in each bin as an indepen-

dent Poisson-distributed value, or is based on the un-binned diphoton invariant mass distribution in the case of low-statistic event categories in $H \rightarrow \gamma\gamma$.

The predicted mean number of events in each bin depends on additional nuisance parameters, corresponding to the uncertainty on the electromagnetic and jet energy scale systematic uncertainties, luminosity and background shape. In total this analysis consists of about 200 nuisance parameters, which are determined by the fit. Some of these are constrained by the same data. Other nuisance parameters are constrained by auxiliary information such as independent control measurements. In this case, the estimated value of the nuisance parameter is treated as following either a Gaussian or a log-normal distribution, and a corresponding multiplicative term is included in the likelihood function [200, 202].

The nuisance parameters are grouped into four classes: nuisance parameters associated with experimental systematic uncertainties, nuisance parameters associated with the theoretical modelling of the Higgs boson signal, nuisance parameters associated with the theoretical modelling of the background, and nuisance parameters related to the background yield and shape. Uncertainties are treated as either uncorrelated or fully (anti-)correlated. Uncertainties that are fully (anti-)correlated between different event categories or between different decay channels share the same nuisance parameter.

The sources of the theoretical uncertainties, related to the Higgs boson signal, considered in the measurements of the cross sections are uncertainties in the acceptance of the different categories due to missing higher-order QCD corrections, uncertainties in the pdfs [203], and uncertainties in the modelling of the underlying event and parton shower (UE/PS). The nuisance parameter related to the uncertainties due to missing higher-order QCD corrections for the inclusive 2-jet acceptance in the VBF categories is shared between the two decay channels, and so is the nuisance parameter associated to the effect of the uncertainties due to missing higher-order QCD corrections in the splitting of the signal in the p_{Tt} categories in $H \rightarrow \gamma\gamma$ and the 0- and 1-jet categories in $H \rightarrow ZZ^*$ [204, 205, 206, 207, 208]. The nuisance parameters associated with UE/PS uncertainties are also correlated between the two decay channels. For the measurement of the signal strength, uncertainties on the predicted cross section are taken into account, including uncertainties from missing higher-order QCD corrections, as well as uncertainties on the pdfs and α_s . These uncertainties are fully correlated between the different decay channels. In addition, theoretical and parametric uncertainties on the decay branching ratios are included [6]. All experimental sources of uncertainties shared by the two analyses are correlated in the combined fit, notably the uncertainties on the electromagnetic energy scale and resolution, the muon energy scale, the jet energy scale and resolution, as well as uncertainties related to the reconstruc-

tion and isolation efficiencies of electrons, and the uncertainties related to the identification and isolation efficiencies of muons. Possible improvements that reduce the largest uncertainties are discussed in section 8.2.5.

8.1.4 Template Cross-section Measurements

The combined analysis of the different decay channels is performed with $(\sigma \times BR)_i^f = \sigma_i \times BR^f$, where σ_i is the cross section for production process i , for $|y_H| < 2.5$, and BR^f is the branching fraction for the final state f .

Due to the limited statistics, the combined analysis is only sensitive to a subset of all possible production processes, which motivates the combination of production processes as follows:

- $b\bar{b}H$ is coupled with $gg \rightarrow H$ by assuming SM predictions for the ratios of the two processes and the combined cross section of the two processes will be reported, labelled ggF .
- tH is coupled with $t\bar{t}H$ by assuming SM predictions for the ratios of the $pp \rightarrow tH$ and the $pp \rightarrow t\bar{t}H$ cross sections, labelled top .
- WH and ZH are merged for the leptonic and the hadronic V decays, separately. $V(\rightarrow q\bar{q})H$ is labelled $VHhad$ and $V(\rightarrow leptons)H$ is labelled $VHlep$. The merging assumes the SM prediction for the ratio of the production cross sections and includes the contributions from both $q\bar{q} \rightarrow VH$ and $gg \rightarrow ZH$.

The values of the process cross sections are adjusted to take the fraction between the central, $|y_H| < 2.5$, and total cross sections into account. These fractions are used to calculate the values of the SM prediction for the measured cross sections [6]. The fractions are shown in table 8.2. The uncertainties related to the finite size of the simulated samples used to calculate the fractions are of the order of 5 ‰. The values of the fraction between the central and the total cross section for $b\bar{b}H$ and tH are assumed to have negligible impact on the calculation of the SM predictions and are set to one.

Measurement of $\sigma \times BR$ products

Seven $(\sigma \times BR)_i^f$ are measured in the central region. The $H \rightarrow ZZ^*$ analysis does not have any event category sensitive to Higgs production in association with top quarks, and very few events in the category sensitive to VH production. For categories that are not sensitive enough, the SM cross sections are assumed. The parameters of interest for the measurements in this model are summarised in table 8.3.

Process	Contributing to	$\sigma_i(y_H < 2.5)/\sigma_i$
$gg \rightarrow H$	ggF	0.907
$qq' \rightarrow qq'H$	VBF	0.932
$q\bar{q}' \rightarrow WH(W \rightarrow had.)$	VHhad	0.870
$q\bar{q}/gg \rightarrow ZH(Z \rightarrow had.)$	VHhad	0.900
$q\bar{q}' \rightarrow WH(W \rightarrow lep.)$	VHlep	0.869
$q\bar{q} \rightarrow ZH(Z \rightarrow lep.)$	VHlep	0.900
$gg \rightarrow ZH(Z \rightarrow lep.)$	VHlep	0.965
$q\bar{q}/gg \rightarrow t\bar{t}H$	top	0.985

Table 8.2: Fraction between the central, $|y_H| < 2.5$, and total cross section per production process.

Decay mode	ggF	VBF	VHhad	VHlep	top
$H \rightarrow \gamma\gamma$	$(\sigma \times BR)_{ggF}^{\gamma\gamma}$	$(\sigma \times BR)_{VBF}^{\gamma\gamma}$	$(\sigma \times BR)_{VHhad}^{\gamma\gamma}$	$(\sigma \times BR)_{VHlep}^{\gamma\gamma}$	$(\sigma \times BR)_{top}^{\gamma\gamma}$
$H \rightarrow ZZ$	$(\sigma \times BR)_{ggF}^{ZZ}$	$(\sigma \times BR)_{VBF}^{ZZ}$	Fixed to SM	Fixed to SM	Fixed to SM

Table 8.3: Parameters of interest for the measurement of $(\sigma \times BR)_i^f$.

The results of this measurement are shown in figure 8.1 and table 8.4. In general, a good agreement with the SM is found, and the uncertainties are comparable to the SM expectation with the current statistics. For VBF, both decay channels measure a higher $(\sigma \times BR)_{VBF}^f$ than expected from the SM. This corresponds to the increased signal strengths for VBF that has been measured.

The ggF and VBF cross sections are measured with the best precision. The contours in the $(\sigma \times BR)_{ggF}^f - (\sigma \times BR)_{VBF}^f$ plane for the two decay channels are shown in figure 8.2. The two measurements are compatible with each other and with the SM expectation at the 2σ level.

Decay mode	$H \rightarrow \gamma\gamma$		$H \rightarrow ZZ^* \rightarrow 4l$	
	Expected (pb)	Observed (pb)	Expected (pb)	Observed (pb)
ggF	$0.098^{+0.031}_{-0.029}$	$0.063^{+0.030}_{-0.029}$	$1.19^{+0.40}_{-0.34}$	$1.58^{+0.46}_{-0.39}$
VBF	$0.0084^{+0.0057}_{-0.0051}$	$0.018^{+0.006}_{-0.006}$	$1.12^{+0.19}_{-0.11}$	$1.35^{+0.26}_{-0.20}$
VHhad	$0.0035^{+0.0084}_{-0.0074}$	$0.0025^{+0.0068}_{-0.0058}$	-	-
VHlep	$0.0014^{+0.0025}_{-0.0018}$	$0.0010^{+0.0025}_{-0.0019}$	-	-
top	$0.0013^{+0.0017}_{-0.0014}$	$0.00025^{+0.0016}_{-0.0012}$	-	-

Table 8.4: Best fit values for $(\sigma \times BR)_i^f$.

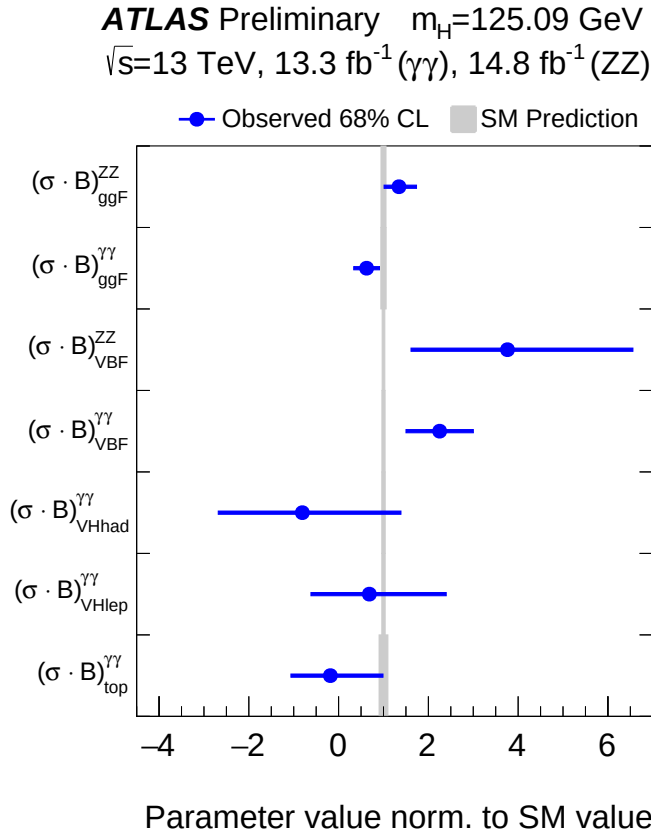


Figure 8.1: Cross sections $(\sigma \times BR)_i^f$ split to production mode and decay channel. The fit results are normalised to the SM predictions for the various parameters. The shaded bands indicate the theoretical uncertainties in these predictions.

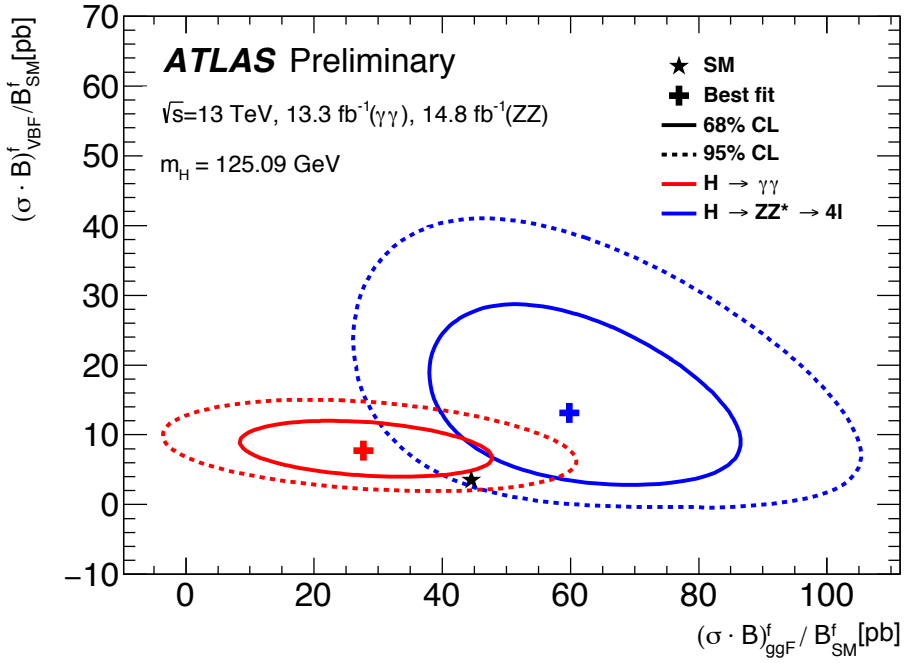


Figure 8.2: Contours in the $(\sigma \times BR)_{ggF}^f$ vs $(\sigma \times BR)_{VBF}^f$ plane for two decay channels, as well as the SM prediction. The branching ratios are normalised to the SM.

Measurement of Production Cross Sections.

The cross sections of the five production modes are measured in the central region, assuming SM Higgs decay branching fractions. Figure 8.3 and table 8.5 show the cross section measurement results. The fit results displayed in figure 8.3 are normalised to the SM prediction for the various parameters and the shaded bands indicate the theoretical uncertainties in these prediction. All channels give a result compatible with the SM within 2σ . The likelihood scan for the cross sections of the five production modes are shown in figure 8.6.

The largest uncertainties on the ggF measurement are coming from the luminosity and the photon identification efficiency. For the VBF measurement the largest uncertainties are coming from the ggF QCD scale calculation and the photon identification efficiency. The uncertainties for the VHhad and top categories are coming mainly from the QCD scale of the ggF production, while the VHlep uncertainties come mainly from the photon calibration effect common in Run 1 and Run 2.

Production mode	SM prediction (pb)	Observed σ_i (pb)
σ_{ggF}	44.5 ± 2.3	$47.8^{+9.8}_{-9.4}$
σ_{VBF}	3.52 ± 0.07	$7.9^{+2.8}_{-2.4}$
σ_{VHhad}	1.36 ± 0.03	$-2.5^{+2.9}_{-2.6}$
σ_{VHlep}	0.64 ± 0.02	$0.32^{+1.07}_{-0.79}$
σ_{top}	0.60 ± 0.06	$-0.11^{+0.67}_{-0.54}$

Table 8.5: Best fit values for the production cross sections σ_i assuming SM Higgs decay branching fractions.

Measurement of Production Cross Sections and Partial Width Ratios

Measurements of the ratios of production cross-sections and ratios of partial widths are used to parametrise the per-channel cross-sections. The cross-section σ_{ggF}^{ZZ} is used to provide an overall normalisation. The product of the cross section and the branching fraction $(\sigma \times BR)_i^f$ are expressed using the ratios as:

$$(\sigma \times BR)_i^f = (\sigma \times BR)_{ggF}^{ZZ} \cdot \left(\frac{\sigma_i}{\sigma_{ggF}} \right) \cdot \left(\frac{BR^f}{BR^{ZZ}} \right), \quad (8.1)$$

where σ_i are the cross sections of the five production modes. The measurements of $(\sigma \times BR)_{ggF}^{ZZ}$, $\sigma_{VBF}/\sigma_{ggF}$ and $BR^{\gamma\gamma}/BR^{ZZ}$ are shown in figure 8.5. The individual likelihood scans are shown in figure 8.6.

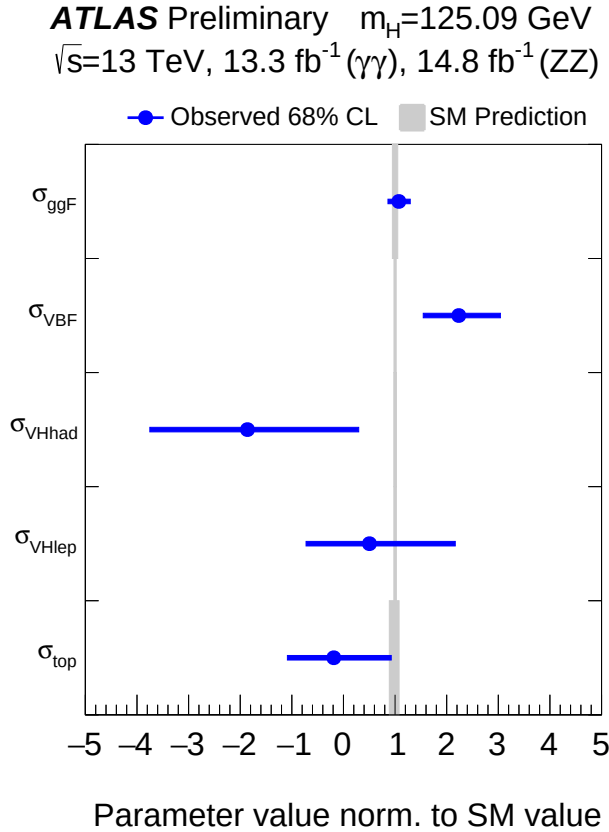


Figure 8.3: Cross sections split to production mode. The fit results are normalised to the SM predictions for the various parameters. The shaded bands indicate the theoretical uncertainties in these predictions.

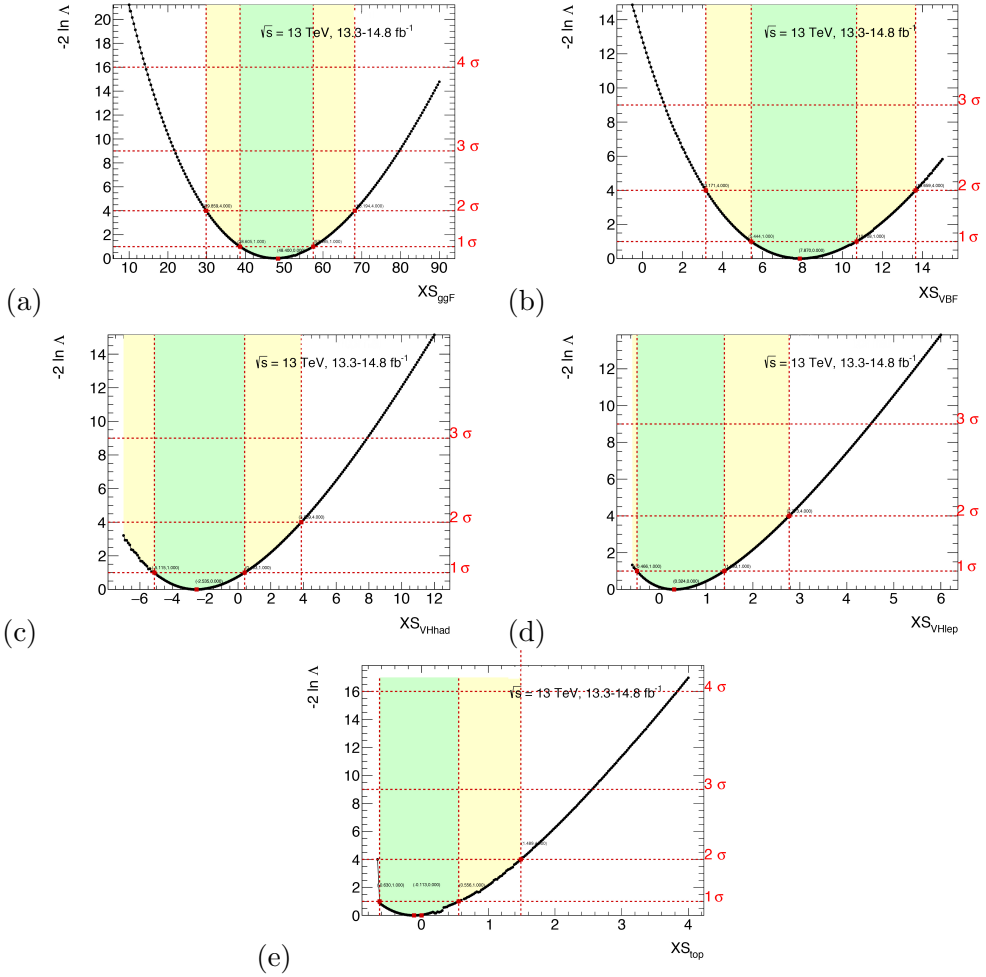


Figure 8.4: The likelihood scans for (a) ggF (b) VBF (c) VHhad (d) VHlep and (e) top cross section production modes. The decay branching fractions are assumed to be SM.

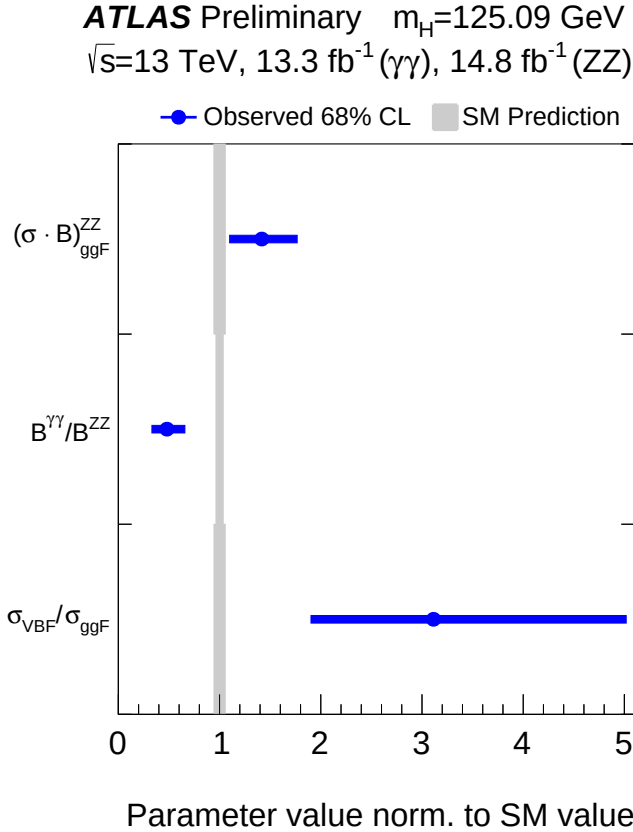


Figure 8.5: Measurement of $(\sigma \times BR)_{ggF}^{ZZ}$, $\sigma_{VBF}/\sigma_{ggF}$ and $BR^{\gamma\gamma}/BR^{ZZ}$. The fit results are normalised to the SM predictions for the various parameters. The shaded bands indicate the theoretical uncertainties in these predictions.

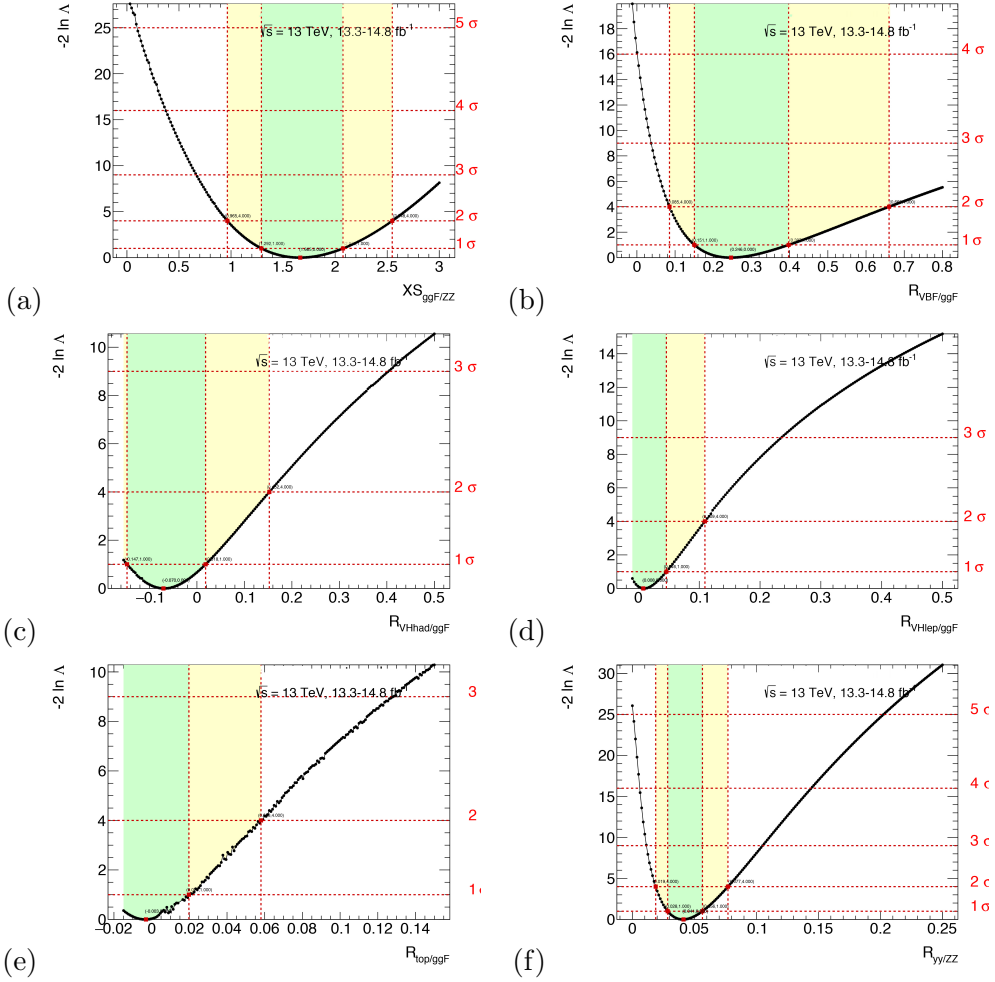


Figure 8.6: The likelihood scans for (a) $(\sigma \times BR)_{ggF}^{ZZ}$ (b) $\sigma_{VBF}/\sigma_{ggF}$ (c) $\sigma_{VHhad}/\sigma_{ggF}$ (d) $\sigma_{VHlep}/\sigma_{ggF}$ (e) $\sigma_{top}/\sigma_{ggF}$ and (f) $BR^{\gamma\gamma}/BR^{ZZ}$.

8.1.5 Global signal strength Measurement

The global signal strength μ is determined in the same manner as in the first run of the LHC [199]. The signal strength is defined as the ratio of the observed yield and its SM expectation

$$\mu = \frac{\sigma \times BR}{\sigma^{SM} \times BR^{SM}}. \quad (8.2)$$

The global signal strength μ is a single scaling factor for all production processes and decay modes simultaneously. The likelihood scan for μ is shown in figure 8.7. The expected value for μ is $1.0^{+0.166}_{-0.177}$ and the observed value is $1.13^{+0.18}_{-0.17}$. Higgs boson production is observed with a local significance around 10σ , where 8.6σ was expected, assuming an asymptotic distribution of the test statistic.

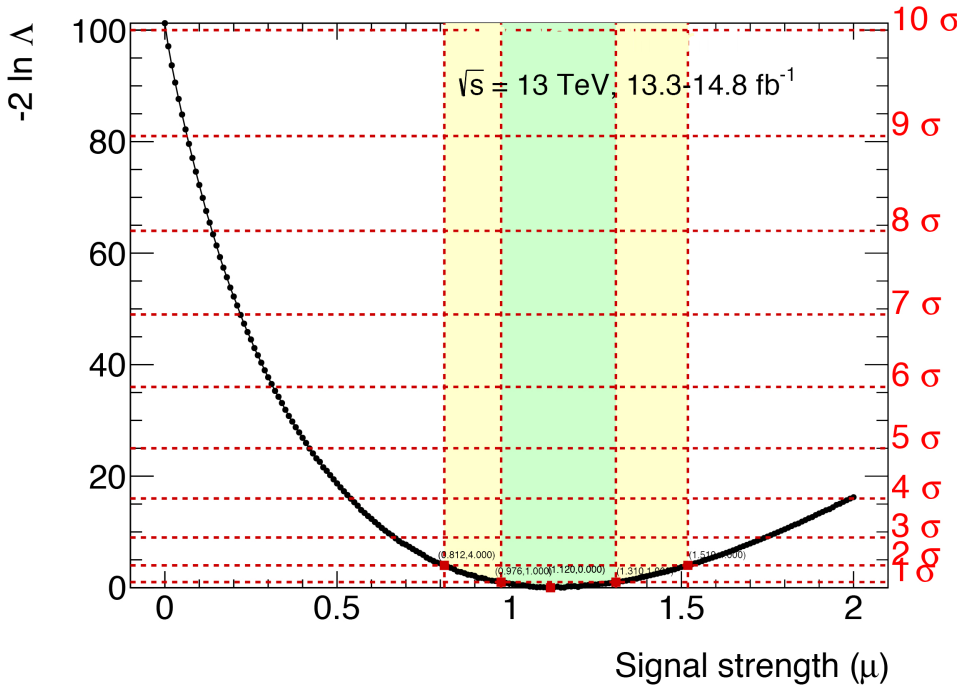


Figure 8.7: The likelihood scan for the global signal strength μ .

8.1.6 Total cross section combination

For the measurement of the total cross section, the signal yields are measured inclusively in both channels and no attempt is made to disentangle the different Higgs boson production modes. This method causes the measurement to

be as independent on the model as possible. The corrections for acceptance and detector effects are computed assuming the ratio between the different production modes follows the SM prediction. Results are shown for centre-of-mass energies of 7 TeV with an integrated luminosity of 4.5 fb^{-1} , 8 TeV with an integrated luminosity of 20.3 fb^{-1} [209] and 13 TeV with an integrated luminosity of 9.5 fb^{-1} . A summary of the measured total $pp \rightarrow H + X$ cross sections is shown in table 8.6 and figure 8.8 for the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$ decay channels and their combination, compared to the SM predictions. The results of the two decay channels are compatible within the quoted uncertainties and no deviation from the SM prediction is observed.

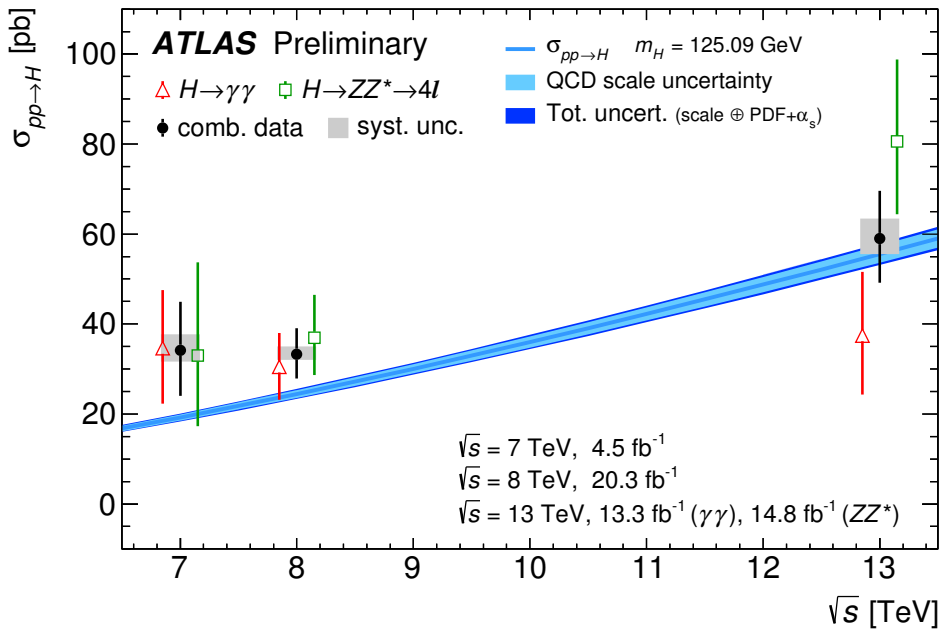


Figure 8.8: Total $pp \rightarrow H$ cross sections measured at different centre-of-mass energies, compared to SM predictions at up to $N^3\text{LO}$ in QCD. The grey bands on the combined measurements represent the systematic uncertainty, while the black lines are the total uncertainties. The light blue band represents the QCD scale uncertainty and the dark blue band represents the total uncertainty on the theory prediction, assuming a Higgs boson mass of 125.09 GeV [40].

8.1.7 Conclusion

Combined measurements based on the products of Higgs boson production cross sections and branching ratios using proton-proton collision data produced by

Total cross section [pb]	7 TeV	8 TeV	13 TeV
$H \rightarrow \gamma\gamma$	35^{+13}_{-12}	$30.5^{+7.5}_{-7.4}$	37^{+14}_{-13}
$H \rightarrow ZZ^* \rightarrow 4l$	33^{+21}_{-16}	37^{+9}_{-8}	81^{+18}_{-16}
Combination	$34 \pm 10(\text{stat.})^{+4}_{-2}(\text{syst.})$	$33.3^{+5.5}_{-5.3}(\text{stat.})^{+1.7}_{-1.3}(\text{syst.})$	$59.0^{+9.7}_{-9.2}(\text{stat.})^{+4.4}_{-3.5}(\text{syst.})$
SM prediction	19.2 ± 0.9	24.5 ± 1.1	$55.5^{+2.4}_{-3.4}$

Table 8.6: Total $pp \rightarrow H + X$ cross sections measured using $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$ decays, and their combination, for centre-of-mass energies of 7 TeV, 8 TeV and 13 TeV. The SM predictions [6] are computed for a Higgs boson mass of 125.09 GeV [40].

the LHC at $\sqrt{s} = 13$ TeV and recorded by the ATLAS detector are shown. The analysis is based on the measurements performed in the individual $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$ decay channels. No significant deviation from the Standard Model predictions is observed.

8.2 Prospects for Run 2 and HL-LHC

Precise measurements of the Higgs boson properties is one of the main opportunities of an upgrade of the LHC to high luminosity, the High-Luminosity LHC (HL-LHC). A comprehensive study of the projected precision of measurements of the Higgs boson production cross section times branching ratios and Higgs boson couplings was presented at the ECFA HL-LHC workshop [210].

The present LHC programme is expected to deliver a total integrated luminosity around 300 fb^{-1} by the year 2022. The peak instantaneous luminosity will be in the range from $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ to $3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. The average number of pile-up events per bunch crossing, μ , is 50-60. The HL-LHC will deliver a total luminosity around 3000 fb^{-1} , with a peak luminosity of $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and $\mu = 140$.

The particle-level quantities were modified by applying efficiency and resolution (smearing) functions to physics objects [211]. The assumptions regarding the performance are described in [212].

The measurements of the cross sections times branching ratio are expressed in terms of the ratio with respect to the SM expectation, $\mu = (\sigma \times BR)/(\sigma_{SM} \times BR_{SM})$. The expected precision is given as the relative uncertainty in the signal strength, $\Delta\mu/\mu$. These measurements are interpreted in terms of the Higgs boson couplings to elementary particles.

8.2.1 Input Channels

The combination is performed on the prospects of the $H \rightarrow \mu\mu$, $H \rightarrow \tau\tau$, $H \rightarrow ZZ$, $H \rightarrow WW$ and $H \rightarrow \gamma\gamma$ (0, 1 and 2-jets categories, which corresponds to respectively 0, 1 and 2 additional jets in the final state) channels as presented in reference [210], the updates of $H \rightarrow Z\gamma$ and VH/ttH $H \rightarrow \gamma\gamma$ categories presented in references [213] and [214], respectively, and the study of $VH \rightarrow b\bar{b}$ prospects documented in reference [215]. For HL-LHC the projections for $H \rightarrow \tau\tau$ are presented in reference [210], and [216] for the $H \rightarrow \tau\tau \rightarrow l\nu\tau_{had}\nu$ decay mode, where τ_{had} is a hadronically decaying tau, assuming $\mu = 140$. The theory uncertainties in all channels aim to reflect the current estimates [41]. The uncertainty on the Higgs boson branching ratios from the future precision on the Higgs mass measurement is not accounted for, but is expected to be very small.

The expected precision on the signal strengths for each category is shown in figure 8.9 and in table 8.7. Table 8.8 shows the precision reachable for different production modes from combining different final states, under the assumption of SM Higgs branching ratios.

The cross section measurements of the dominant production mode, $gg \rightarrow H$, reach an ultimate experimental precision around 4%. This precision is close

to the limit given by the assumed luminosity uncertainty, which is assumed for both the 300 fb^{-1} and the 3000 fb^{-1} scenarios to be 3%. The measurement precision will provide a stringent constraint of possible BSM contribution to the $gg \rightarrow H$ process, dominated in the SM by loop diagrams via top and bottom quarks. Additional information about the Higgs boson coupling properties can be gained through the search for invisible Higgs decays [210, 217] and measurements of the off-shell Higgs production in final states containing two vector bosons with invariant masses above the WW and ZZ on-shell production threshold [218, 219, 220, 221].

The statistical treatment of the input channels used to extract information about the Higgs boson couplings is described in references [210, 222, 223, 202, 201, 143, 142]. The inclusive signal theory uncertainties for missing higher orders, QCD scale variations, $\text{pdf} + \alpha_s$, and branching ratios (BR) are included as given in references [41]. The correlations in the BR uncertainties for the different final states are accounted for. The (anti-)correlated uncertainty contributions for different jet multiplicities and Higgs p_T in the $gg \rightarrow H$ and $VH \rightarrow b\bar{b}$ processes, are assumed to be the same numbers as for the 7 TeV and 8 TeV analysis [41, 224, 225, 226]. All common signal theory uncertainties are treated as 100% correlated between all channels. Other systematic uncertainties are considered to be analysis-specific and treated as uncorrelated between channels. The results are shown using the current theory uncertainties and assuming no theory uncertainties, which is the expected experimental limit for a measurement.

8.2.2 Coupling fit framework

The leading-order tree-level motivated κ -framework, as described in section 1.5.1 is used for the measurements of the Higgs coupling scale factors. Since this framework does not take higher order electroweak corrections beyond the SM into account, it is not suitable for precision measurements, and an EFT approach is the most promising way for future Higgs precision measurements. An EFT approach allows to consistently calculate higher order corrections and also includes CP-odd couplings in a natural extension. The main degrees of freedom in such an EFT measurement will be similar to the degrees of freedom present in the leading-order κ -framework, so the precision projections presented here for the HL-LHC should stay *approximately* valid.

In some of the fits, κ_H and the effective scale factors κ_γ , $\kappa_{Z\gamma}$ and κ_g for the loop induced $H \rightarrow \gamma\gamma$, $H \rightarrow Z\gamma$ and $gg \rightarrow H$ processes are expressed as a function of the more fundamental factors κ_W , κ_Z , κ_t , κ_b , κ_τ and κ_μ . Only the dominant fermion contributions are indicated here for simplicity, but other terms are included as well. The effective scale factors for the loop induced

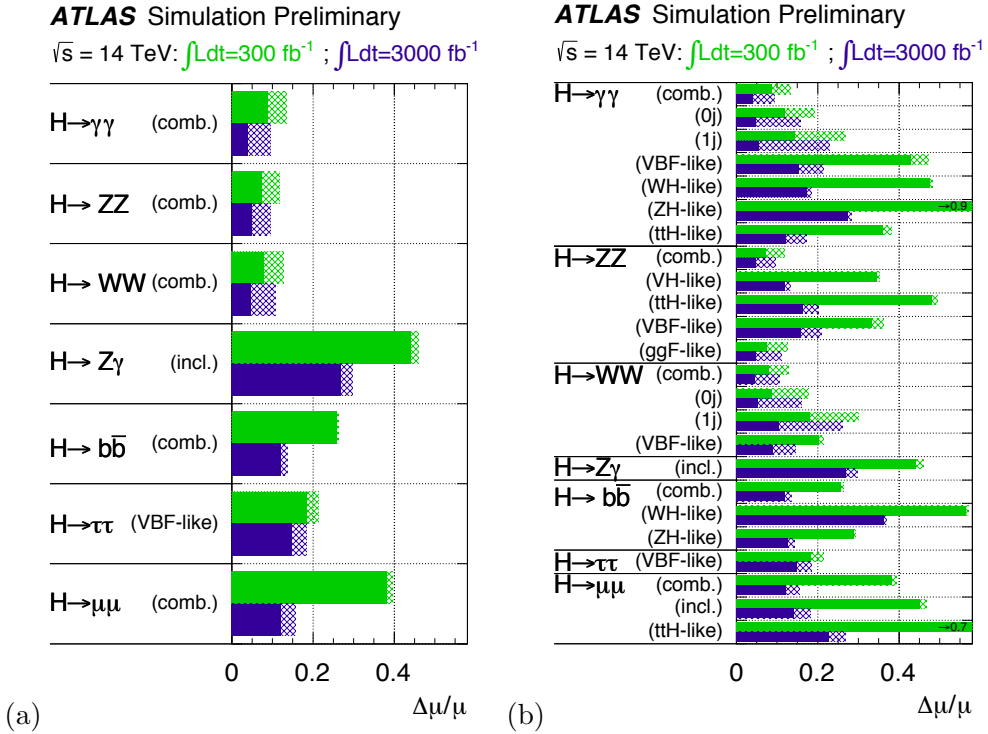


Figure 8.9: Relative uncertainty on the signal strength μ for all Higgs final states considered in the different experimental categories used in the combination for 300 fb^{-1} and 3000 fb^{-1} of 14 TeV LHC data. A SM Higgs boson mass of 125 GeV is assumed. The uncertainty pertains to the number of events passing the experimental selection, not to the particular Higgs boson process targeted. The hashed areas indicate the increase of the estimated error due to current theory systematic uncertainties. The abbreviation *comb* indicates that the precision on μ is obtained from the combination of the measurements from the different sub-categories for the same final state. The abbreviation *incl* indicates that the measurement from the inclusive analysis was used. (a) Shows only the combined signal strength in the considered final states, while (b) also shows the signal strength in the main experimental sub-categories within each final state.

$\Delta\mu/\mu$	300 fb ⁻¹		3000 fb ⁻¹	
	All unc.	No theory unc.	All unc.	No theory unc.
$H \rightarrow \gamma\gamma$				
comb.	0.13	0.09	0.09	0.04
0-jet	0.19	0.12	0.16	0.05
1-jet	0.27	0.14	0.23	0.05
VBF-like	0.47	0.43	0.22	0.15
WH-like	0.48	0.48	0.19	0.17
ZH-like	0.85	0.85	0.28	0.27
ttH-like	0.38	0.36	0.17	0.12
$H \rightarrow ZZ$				
comb.	0.11	0.07	0.09	0.04
VH-like	0.35	0.34	0.13	0.12
ttH-like	0.49	0.48	0.20	0.16
VBF-like	0.36	0.33	0.21	0.16
ggF-like	0.12	0.07	0.11	0.04
$H \rightarrow WW$				
comb.	0.13	0.08	0.11	0.05
0-jet	0.18	0.09	0.16	0.05
1-jet	0.30	0.18	0.26	0.10
VBF-like	0.21	0.20	0.15	0.09
$H \rightarrow Z\gamma$				
incl.	0.46	0.44	0.30	0.27
$H \rightarrow b\bar{b}$				
comb.	0.26	0.26	0.14	0.12
WH-like	0.57	0.56	0.37	0.36
ZH-like	0.29	0.29	0.14	0.13
$H \rightarrow \tau\tau$				
VBF-like	0.21	0.18	0.19	0.15
$H \rightarrow \mu\mu$				
comb.	0.39	0.38	0.16	0.12
incl.	0.47	0.45	0.18	0.14
ttH-like	0.74	0.72	0.27	0.23

Table 8.7: Relative uncertainty on the signal strength μ for all Higgs final states considered in the different experimental categories used in the combination for 300 fb⁻¹ and 3000 fb⁻¹ of 14TeV LHC data. A SM Higgs boson mass of 125 GeV is assumed. The abbreviation *comb* indicates that the precision on μ is obtained from the combination of the measurements from the different sub-categories for the same final state. The abbreviation *incl* indicates that the measurement from the inclusive analysis was used.

$\Delta\mu/\mu$	300 fb ⁻¹		3000 fb ⁻¹	
	All unc.	No theory unc.	All unc.	No theory unc.
$gg \rightarrow H$	0.12	0.06	0.11	0.04
VBF	0.18	0.15	0.15	0.09
WH	0.41	0.41	0.18	0.18
qqZH	0.80	0.79	0.28	0.27
ggZH	3.71	3.62	1.47	1.38
ttH	0.32	0.30	0.16	0.10

Table 8.8: Relative uncertainty on the signal strength μ for different production modes used in the combination of Higgs final states for 300 fb⁻¹ and 3000 fb⁻¹ of 14TeV LHC data. A SM Higgs boson mass of 125 GeV is assumed.

processes are written as:

$$\kappa_g^2(\kappa_b, \kappa_t) = \frac{\kappa_t^2 \sigma_{ggH}^{tt} + \kappa_b^2 \sigma_{ggH}^{bb} + \kappa_t \kappa_b \sigma_{ggH}^{tb}}{\sigma_{ggH}^{tt} + \sigma_{ggH}^{bb} + \sigma_{ggH}^{tb}} \quad (8.3)$$

$$\kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W) = \frac{\sum_{i,j} \kappa_i \kappa_j \Gamma_{\gamma\gamma}^{ij}}{\sum_{i,j} \Gamma_{\gamma\gamma}^{ij}} \quad (8.4)$$

$$\kappa_{Z\gamma}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W) = \frac{\sum_{i,j} \kappa_i \kappa_j \Gamma_{Z\gamma}^{ij}}{\sum_{i,j} \Gamma_{Z\gamma}^{ij}} \quad (8.5)$$

$$\kappa_H^2 = \sum_{jj} \frac{\kappa_j^2 \Gamma_H^{SM}}{\Gamma_H^{SM}} \quad \text{with } jj = WW, ZZ, b\bar{b}, \tau^-\tau^+, \gamma\gamma, Z\gamma, gg, t\bar{t}, c\bar{c}, s\bar{s}, \mu^-\mu^+ \quad (8.6)$$

where σ_{ggH}^{ij} are the ggH production cross-sections with particles ij in the loop, $\Gamma_{Z\gamma}^{ij}$ are the $Z\gamma$ decay widths with particles ij in the loop, and Γ_{ff}^{SM} is the SM decay to two fermions, which are theoretically predicted [41]. The relations above are used in the fits, except for some parameterisations where κ_γ , $\kappa_{Z\gamma}$ or κ_g have dedicated fit parameters assigned to them.

8.2.3 Coupling fit results

This analysis uses two different benchmark parameterisations, following the recommendations in reference [41], depending on the assumptions on the total width of the Higgs boson. When no assumption on the total width is made, a measurement of ratios $\lambda_{ij} = \kappa_i/\kappa_j$ of coupling scale factors is performed. When there is a total width assumption, it allows for extracting absolute couplings κ_i . A minimal coupling fit is shown in the parametrisation that assumes one universal coupling to vector bosons, $\kappa_V \equiv (\kappa_Z = \kappa_W)$, and one universal coupling to fermions, $\kappa_f \equiv (\kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu)$. This measurement is most sensitive to different deviations from the SM between the Higgs boson gauge- and Yukawa-coupling sectors. The $H \rightarrow \gamma\gamma$ and $gg \rightarrow H$ loops and the Higgs boson width depend only on κ_V and κ_f in this parametrisation, with no contributions from BSM physics. With 3000 fb^{-1} of integrated luminosity, experimental precisions around 1.7% on κ_V and 3.2% on κ_f are expected. The results are shown in figure 8.10 and in model 2 in table 8.9.

Models 3 through 8 in table 8.9 are extensions of this minimal coupling fit, which all assume no BSM Higgs decay modes. Model 3 removes the assumption on the identical scaling between the W and Z bosons to probe custodial symmetry. Model 4 keeps a common scaling for vector bosons, but separates couplings to up-type and down-type fermions. Model 5 separates couplings to quarks and leptons. Model 6 separates couplings to quarks, the τ lepton and the muon in order to probe differences between second and third generation fermion couplings. Model 7 removes the assumption on identical scaling between the different gauge and Yukawa couplings, while the assumption that no BSM particles contribute to the loops is kept. Finally model 8 removes the assumption on BSM particles in loops in order to allow contributions from new physics, which results in a fit that includes the effective coupling scale factors κ_g , κ_γ and $\kappa_{Z\gamma}$.

The precision on a given coupling parameter is specific to the particular parameterisation in which it is probed. General parameterisations with more parameters and fewer simplifying assumptions generally result in the parameters being determined with larger uncertainties. When too many parameters are introduced, the model stops being constraint enough to make conclusions. The models discussed in this thesis are constraint enough to be able to measure the parameters.

The expected precision for a coupling parametrisation to probe loop-induced Higgs couplings, κ_g , κ_γ and $\kappa_{Z\gamma}$, and invisible or undetectable Higgs decays through their branching ratio $BR_{i,u}$ are described in table 8.10. All other couplings to massive particles that do not proceed via a loop in lowest order are assumed to be equal to their SM values. This model, model 9, allows to

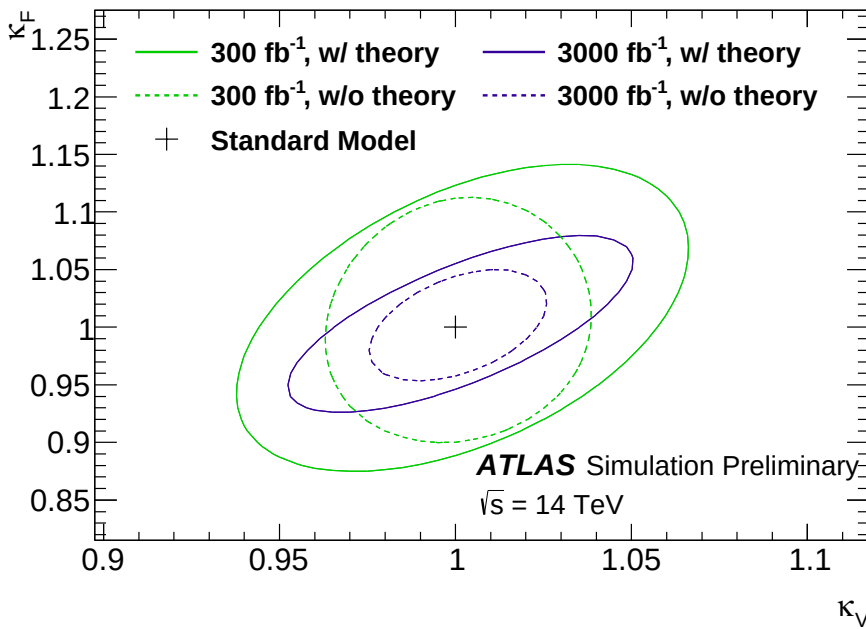


Figure 8.10: 68% CL expected likelihood contour for κ_V and κ_f in a minimal coupling fit at 14 TeV for an assumed integrated luminosity of 300 fb⁻¹ and 3000 fb⁻¹.

Model	Coupling	Theory unc. [%] 300 fb ⁻¹			Theory unc. [%] 3000 fb ⁻¹		
		All	Half	None	All	Half	None
1	κ	4.2	3.0	2.4	3.2	2.2	1.7
2	κ_V	4.3	3.0	2.5	3.3	2.2	1.7
	κ_f	8.8	7.5	7.1	5.1	3.8	3.2
3	κ_Z	4.7	3.7	3.3	3.3	3.2	1.9
	κ_W	4.9	3.6	3.1	3.6	2.4	1.8
	κ_f	9.3	7.9	7.3	5.4	4.0	3.4
4	κ_V	5.9	5.4	5.3	3.7	3.2	3.0
	κ_u	8.9	7.7	7.2	5.4	4.0	3.4
	κ_d	12	12	12	6.7	6.2	6.1
5	κ_V	4.3	3.1	2.5	3.3	2.2	1.7
	κ_q	11	8.7	7.8	6.6	4.5	3.6
	κ_l	10	9.6	9.3	6.0	5.3	5.1
6	κ_V	4.3	3.1	2.5	3.3	2.2	1.7
	κ_q	11	9.0	8.1	6.7	4.7	3.8
	κ_τ	12	11	11	9.2	8.4	8.1
	κ_μ	20	20	19	6.9	6.3	6.1
7	κ_Z	8.1	7.9	7.8	4.3	3.9	3.8
	κ_W	8.5	8.2	8.1	4.8	4.1	3.9
	κ_t	14	12	11	8.2	6.1	5.3
	κ_b	23	22	22	12	11	10
	κ_τ	14	13	13	9.8	9.0	8.7
	κ_μ	21	21	21	7.3	7.1	7.0
8	κ_Z	8.1	7.9	7.9	4.4	4.0	3.8
	κ_W	9.0	8.7	8.6	5.1	4.5	4.2
	κ_t	22	21	20	11	8.5	7.6
	κ_b	23	22	22	12	11	10
	κ_τ	14	14	13	9.7	9.0	8.8
	κ_μ	21	21	21	7.5	7.2	7.1
	κ_g	14	12	11	9.1	6.5	5.3
	κ_γ	9.3	9.0	8.9	4.9	4.3	4.1
	$\kappa_{Z\gamma}$	24	24	24	14	14	14

Table 8.9: Expected precision on Higgs coupling scale factors with 300 fb⁻¹ and 3000 fb⁻¹ of $\sqrt{s} = 14$ TeV data for selected parameterisations, assuming no BSM decay modes. The coupling scale factor κ represents all SM particles, κ_V represents the gauge bosons W and Z , κ_f represents all fermions, κ_u represents all up-type fermions, κ_d represents all down-type fermions, κ_q represents all quarks and κ_l represents all leptons. The results are reported for the assumption that the theory uncertainties stay the same size as in Run 1, become half of the Run 1 size and without theory uncertainties.

probe $BR_{i,u}$.

Model	Parameter	Theory unc. [%] 300 fb ⁻¹			Theory unc. [%] 3000 fb ⁻¹		
		All	Half	None	All	Half	None
9	κ_g	8.9	7.1	6.3	6.6	4.1	2.8
	κ_γ	4.9	4.8	4.7	2.1	1.8	1.7
	$\kappa_{Z\gamma}$	23	23	23	14	14	14
	$BR_{i,u}$	<22	<20	<20	<14	<11	<10

Table 8.10: Expected precision on loop-induced Higgs couplings, κ_g , κ_γ and $\kappa_{Z\gamma}$, along with the expected 95% CL upper limit on the branching ratio for invisible or undetectable decays, $BR_{i,u}$, with 300 fb⁻¹ and 3000 fb⁻¹ of $\sqrt{s} = 14$ TeV data. The results are reported for the assumption that the theory uncertainties stay the same size as in Run 1, become half of the Run 1 size and without theory uncertainties.

When the assumption on the total width is removed and no other assumption is made, only ratios of coupling scale factors can be determined at the LHC. In this case $\sigma \times BR(i \rightarrow H \rightarrow f)$ is a function of products of ratios of coupling scale factors, $\lambda_{XY} = \kappa_X / \kappa_Y$, for all signal channels. This gives the proportionality $\sigma \times BR(i \rightarrow H \rightarrow f) \sim \lambda_{iY}^2 \cdot \lambda_{YY'}^2 \cdot \lambda_{fY}^2$, where $\kappa_{YY'}^2 = \kappa_Y \cdot \kappa_{Y'} / \kappa_H$ is a suitable chosen overall scale parameter common to all signal channels and λ_{iY}^2 and λ_{fY}^2 are the coupling scale factor ratios involving the initial and final state particles, respectively.

Measuring ratios of scale factors has the advantage that many experimental and theoretical systematic uncertainties, such as the uncertainty on the integrated luminosity, cancel. Table 8.11 shows the expected precision on the ratios of coupling parameters for selected benchmark parameterisations. Models 10 through 14 are targeted at specific aspects of the SM: model 10 for the ratio of fermion and gauge boson couplings, model 11 for the ratio of W and Z couplings, model 12 for the ratio of up-type and down-type couplings, model 13 for the ratio of lepton and quark couplings and model 14 for the ratio of second and third generation lepton couplings. The impact of the cancelation of uncertainties can, for example, be seen in model 11 when comparing the uncertainty on κ_{ZZ} with the uncertainty on λ_{WZ} .

The experimental precision on the ratios of coupling scale factors for a fully generic benchmark parametrisation is shown in model 15 in table 8.11 and in figure 8.11. This model does not use any additional assumptions than the ones listed in section 8.2.2, and makes no assumption on new particles

contributing through loops. The ratio of the photon and Z boson couplings, $\lambda_{\gamma Z}$ is important to look for indications of new charged particles contributing in the $H \rightarrow \gamma\gamma$ loop in comparison to $H \rightarrow ZZ$ decays. The ratio of the top quark and gluon couplings, λ_{tg} , is crucial for possible new coloured particles contributing through the gluon fusion loop as compared to ttH .

Differential measurements of Higgs production, for example of the Higgs boson transverse momentum and rapidity [227, 228], are not included in this analysis. These measurements will further decrease the uncertainties in the coupling measurement. The ttH process is expected to be measured in additional decay channels to those studies here. These and other improvements are expected to further improve the Higgs coupling precision attained in the future. With the inclusion of the full 2016 dataset, additional splitting based on the p_T of the system can be measured due to the increase in statistics. With increasing luminosity, more information can be obtained on the differential distributions by increasing the number of bins.

8.2.4 Mass dependence of couplings

The relationship between the Higgs boson couplings and the SM particle masses is tested by using *reduced* coupling scale factors y_i as

$$y_{V,i} = \sqrt{\kappa_{V,i} \frac{g_{V,i}}{2v}} = \sqrt{\kappa_{V,i}} \frac{m_{V,i}}{v}, \quad (8.7)$$

for the weak bosons $V = W, Z$ and

$$y_{f,i} = \kappa_{f,i} \frac{g_{f,i}}{\sqrt{2}} = \kappa_{f,i} \frac{m_{f,i}}{v}, \quad (8.8)$$

for the fermions $f = \mu, \tau, b, t$, and where $g_{V,i}$ denotes the absolute gauge couplings to various bosons and $g_{f,i}$ the absolute Yukawa couplings to various fermions. The fit results for a model assuming no new Higgs decay modes, with loop-induced couplings resolved in terms of the couplings to particles in the loop are used. This model is shown as model 7 in table 8.9. Figure 8.12 shows the reduced coupling scale factors y_i as a function of the mass of particle i .

8.2.5 Theory uncertainties

Estimates of how much each source of theory uncertainty would have to be reduced to be small compared to the expected experimental uncertainties are calculated. *Small* is arbitrarily defined for each theory systematic uncertainty as 30% of the expected total experimental uncertainty, which would lead to an increase of the total uncertainty by $\sim 10\%$ due to this source. As the theory

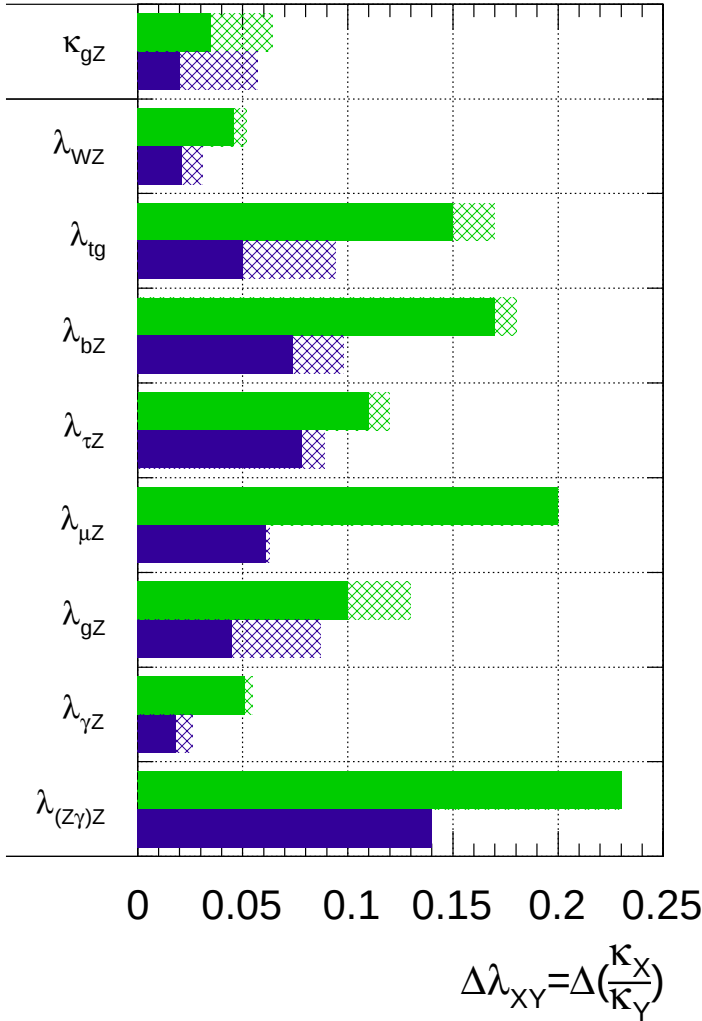
ATLAS Simulation Preliminary
 $\sqrt{s} = 14 \text{ TeV}$: $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$; $\int \mathcal{L} dt = 3000 \text{ fb}^{-1}$


Figure 8.11: Relative uncertainty expected for determining the coupling scale factor ratios λ_{XY} in a generic fit without assumptions at 14 TeV for an assumed integrated luminosity of 300 fb^{-1} and 3000 fb^{-1} , with an assumed Higgs boson mass of 125 GeV. The hashed areas indicate the increase of the estimated error due to current theory systematic uncertainties.

Model	Coupling ratio	Theory unc. [%] 300 fb ⁻¹			Theory unc. [%] 3000 fb ⁻¹		
		All	Half	None	All	Half	None
10	κ_{VV}	7.3	6.7	6.5	4.0	3.2	2.9
	λ_{fV}	7.8	7.4	7.2	3.6	3.1	2.9
11	κ_{ZZ}	9.8	9.1	8.9	5.1	4.3	3.9
	λ_{WZ}	4.3	4.0	3.9	2.3	1.8	1.6
	λ_{fZ}	9.2	8.5	8.3	4.4	3.7	3.5
12	κ_{uu}	14	11	9.7	8.7	5.7	4.2
	λ_{Vu}	9.4	8.3	7.9	5.1	3.8	3.2
	λ_{dV}	9.7	8.2	7.7	6.0	4.6	4.0
13	κ_{qq}	14	11	9.9	8.1	5.6	4.5
	λ_{Vq}	9.6	8.5	8.1	5.2	3.9	3.4
	λ_{lq}	12	10	9.4	7.3	6.0	5.4
14	$\kappa_{\tau\tau}$	21	19	19	17	15	15
	$\lambda_{V\tau}$	11	11	11	8.5	7.8	7.6
	$\lambda_{q\tau}$	12	10	9.8	9.3	7.9	7.4
	$\lambda_{\mu\tau}$	22	22	22	11	9.8	9.6
15	κ_{gZ}	6.4	4.4	3.5	5.7	3.3	2.0
	λ_{WZ}	5.2	4.8	4.6	3.1	2.4	2.1
	λ_{tg}	17	16	15	9.4	6.4	5.0
	λ_{bZ}	18	17	17	9.8	8.1	7.4
	$\kappa_{\tau Z}$	12	12	11	8.9	8.1	7.8
	$\lambda_{\mu Z}$	20	20	20	6.3	6.2	6.1
	λ_{gZ}	13	11	10	8.7	5.8	4.5
	$\lambda_{\gamma Z}$	5.5	5.2	5.1	2.6	2.0	1.8
	$\lambda_{(Z\gamma)Z}$	23	23	23	14	14	14

Table 8.11: Expected precision on ratios of Higgs coupling scale factors with 300 fb⁻¹ and 3000 fb⁻¹ of $\sqrt{s} = 14$ TeV data for selected parameterisations, without assumptions on the Higgs total width. The results are reported for the assumption that the theory uncertainties stay the same size as in Run 1, become half of the Run 1 size and without theory uncertainties.

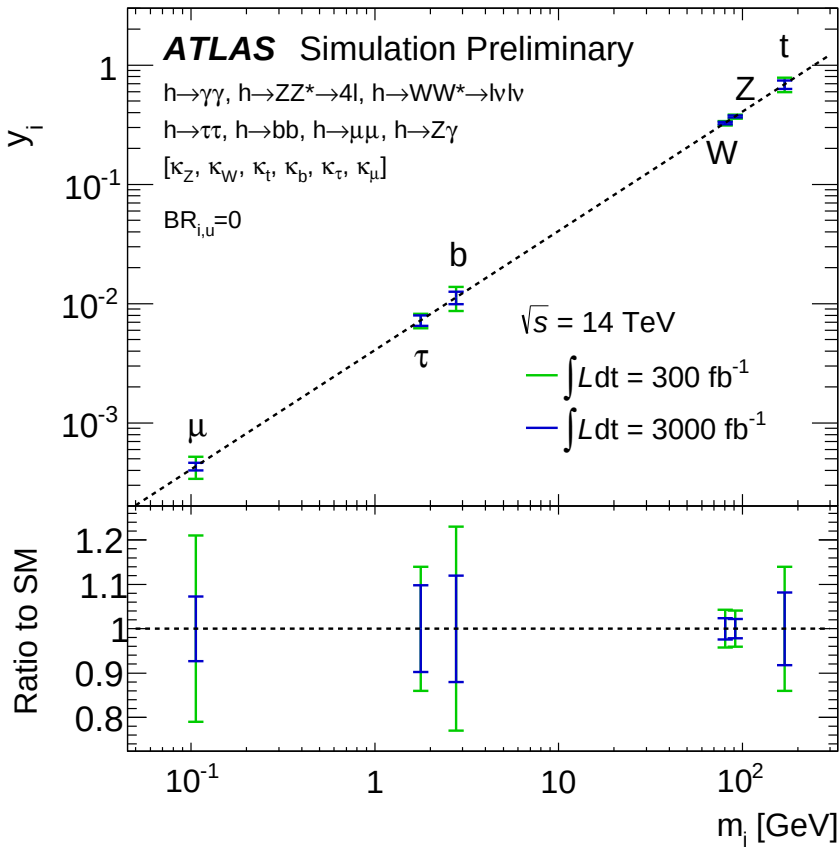


Figure 8.12: Fit results for the reduced coupling scale factors $y_{V,i}$ for weak bosons and $y_{f,i}$ for fermions as a function of the mass of particle i at 14 TeV for an assumed integrated luminosity of 300 fb^{-1} and 3000 fb^{-1} , with an assumed Higgs boson mass of 125 GeV. The diagonal dashed line indicates the predicted mass dependence for the SM Higgs boson.

uncertainties are uncorrelated to the experimental uncertainties, a sum in quadrature with the experimental uncertainties is valid to good approximation. The Higgs boson signal theory uncertainties [41] give a sizeable contribution to the expected total uncertainty, as seen from the expected precision of the coupling parameter measurements in tables 8.9, 8.10 and 8.11. The estimation of the size of theory uncertainties is only approximate and is intended as guideline to indicate where improvements are needed, rather than as a precise prediction. The values of the uncertainties are in some cases, such as the jet-bin and p_T uncertainties for the $gg \rightarrow H$ process, specific to the analysis selection, but are treated as 100% correlated between the different analysis, since this is the best approximation currently possible. However, high statistics fits in the HL-LHC allow scenarios to reduce the input theory uncertainty by up to a factor of two, by exploiting the consistency of the signal strength between different experimental analyses, categories and bins in distributions. More detailed correlation measurements will need to be developed in the future to either address this issue or to demonstrate where measured data can be used to reduce the Higgs boson signal theory uncertainties. The deduced theory uncertainties given here are corrected to compensate for these excessive reductions in uncertainty.

Table 8.12 shows the deduced size of different Higgs boson signal theoretical uncertainties given the measurements presented in the generic model 15, which uses as few theory assumptions as possible at the LHC. Models 2 and 8 were also examined, but no stronger constraints were found. Both inclusive and differential signal theory uncertainties on the $gg \rightarrow H$ process are found to be the most limiting for future measurements of this production mode. The uncertainties on the $t\bar{t}H$ and VBF production contribute to a lesser degree. Other uncertainties, such as the parametric m_b or $H \rightarrow \gamma\gamma$ and $H \rightarrow Z\gamma$ theory uncertainties entering the branching ratio calculation increase the total uncertainty on the measurements by only 5 to 10% and are hence already below the goal of an increase by 10% and are therefore not explicitly mentioned in table 8.12. However, several of these smaller sources together will help improve the ultimate precision of future LHC Higgs measurements.

8.2.6 Conclusions

The precision of all channels can be improved and several new Higgs boson production and decay modes can be observed by the ATLAS detector with 300 fb^{-1} in the second run of the LHC and 3000 fb^{-1} at the HL-LHC. The projected measurements of the cross section times branching ratio using the combination of all channels studied are used to derive the expected precision on Higgs boson couplings to fermions and bosons, and on the ratios of couplings in a variety of parameterisations. The expected limit on the branching ratio

Scenario Theory uncertainty [%]	Status 2014 [41]	Deduced size of uncertainty to increase total uncertainty by $\lesssim 10\%$ for 300 fb $^{-1}$ by $\lesssim 10\%$ for 3000 fb $^{-1}$									
		κ_{gZ}	λ_{gZ}	$\lambda_{\gamma Z}$	κ_{gZ}	λ_{gZ}	$\lambda_{\gamma Z}$	$\lambda_{\tau Z}$	λ_{tg}		
$gg \rightarrow H$											
pdf	8	2			1.3						
incl. QCD scale (MHO)	7	2			1.1						
p_T shape and 0j $\rightarrow$ 1j mig.	10-20		3.5-7			1.5-3					
1j $\rightarrow$ 2j mig.	13-28			6.5-14		3.3-7					
1j $\rightarrow$ VBF 2j mig.	18-58						6-19				
VBF 2j $\rightarrow$ VBF 3j mig.	15-38							6-19			
VBF											
pdf	3.3						2.8				
$t\bar{t}H$											
pdf	9									3	
incl. QCD scale (MHO)	9									2	

Table 8.12: Estimation of the deduced size of theory uncertainties, in percent (%), for different coupling measurements in the generic model 15, with 300 fb $^{-1}$ and 3000 fb $^{-1}$ of $\sqrt{s} = 14$ TeV data. Each source of theory systematic uncertainty is required to affect the measurement by less than 30% of the total experimental uncertainty and hence increase the total uncertainty by less than 10%. MHO stands for missing higher order uncertainty and mig. stands for migration. When no number is given, the theory uncertainty from existing calculations is already sufficiently small. The impact of the jet-bin and p_T related uncertainties in the $gg \rightarrow H$ depends on the analysis selections and hence no single number can be quoted, therefore the range of uncertainty values used in the different analyses is shown.

for Higgs to invisible is also determined. The improvements at high luminosity compared to Run 2 are a factor of 2-3, particularly without the inclusion of theoretical systematic uncertainties, which are expected to improve in the future.

9 BSM interpretations of Higgs Couplings

9.1 Introduction

Combined coupling fits of the measured Higgs boson production and decay rates within the SM framework, as shown in chapter 8, have not found any significant deviation from the SM expectations [229, 222, 179]. These results suggest that the discovered particle is indeed a Higgs boson and that a non-zero vacuum expectation value of a Higgs doublet is responsible for electroweak symmetry breaking [20, 21, 22, 23, 24]. The observed CP-even Higgs boson is denoted as h .

The SM postulates only one Higgs doublet, however many BSM theories introduce a more complex Higgs sector as described in section 1.3. Searches for deviations from the rates of Higgs boson production and decay predicted by the SM, including both the visible and invisible decay channels, can be probed through Higgs couplings.

9.2 Input Channels

The determination of the couplings are based on a combination of different Higgs boson decays. Each decay channel is split into categories sensitive to different production modes. Direct searches for additional heavy Higgs bosons, H , A and $H^\pm$, are not used in the fits discussed here, but their results are interpreted in the Run 1 analysis for the hMSSM benchmark model for comparison.

This chapter contains two studies with slightly different inputs which will be described here.

9.2.1 Run 1

For the determination of the couplings in the visible Higgs boson decay channels, the experimental inputs include search results and measurements of Higgs boson decays:

- $h \rightarrow \gamma\gamma$ [230] For this decay channel results from $t\bar{t}h$ associated production are included [231]. The notation $t\bar{t}h$ is used instead of $t\bar{t}H$ to specify that the particle produced is the lightest Higgs boson in a multi-Higgs model, rather than the SM Higgs boson.
- $h \rightarrow ZZ^* \rightarrow 4l$ with $l = e, \mu$ [232]
- $h \rightarrow WW^* \rightarrow l\nu l\nu$ with $l = e, \mu$ [233, 234]
- $h \rightarrow Z\gamma$ [235]
- $h \rightarrow b\bar{b}$ [225] For this decay channel results from $t\bar{t}h$ associated production are included [236].
- $h \rightarrow \tau\tau$ [237]
- $h \rightarrow \mu\mu$ [238]
- Search results from final states with multiple leptons [239].

In addition, the constraints on the Higgs boson invisible decay branching ratio use direct searches for Higgs boson decays to invisible particles in events with dileptons or dijets with large missing transverse momentum, E_T^{miss} .

- The search for a Higgs boson, produced through VBF, and thus accompanied by dijets, that decays invisibly and results in missing transverse momentum, $VBF \rightarrow jj + E_T^{\text{miss}}$ [240].
- The search for a Higgs boson that subsequently decays invisibly, produced in association with a Z boson that decays to dileptons, $Zh \rightarrow ll + E_T^{\text{miss}}$ [217].
- The search for a Higgs boson which afterwards decays invisibly, produced together with a W or Z boson that decays hadronically, $W/Zh \rightarrow jj + E_T^{\text{miss}}$ [241].

These searches are based on up to 4.7fb^{-1} of pp collision data at $\sqrt{s} = 7$ TeV and up to 20.3fb^{-1} at $\sqrt{s} = 8$ TeV.

Each measurement or search classifies candidate events into exclusive categories based on the expected kinematic properties of different Higgs boson production processes. This both improves the sensitivity and enables discrimination

between different Higgs boson production modes. Each search channel is designed to be mostly sensitive to the product of a Higgs boson production cross section and a decay branching ratio. The combination of the visible decay search channels is used [179] to determine the couplings of the Higgs boson to other SM particles.

9.2.2 Prospects for Run 2 and HL-LHC

In this prospective study the following decay channels have been included as described in reference [10], with each being split into categories sensitive to different production modes:

- $h \rightarrow \gamma\gamma$ in the inclusive 0-jet, 1-jet and 2-jet final states, the last with a VBF selection, as well as 1-lepton and 2-lepton selections with other criteria to separate Wh , Zh and $t\bar{t}h$ production modes [214, 210].
- $h \rightarrow ZZ^* \rightarrow 4l$ with $l = e, \mu$ separated into categories sensitive to ggF, VBF, Zh/Wh and $t\bar{t}h$ production [210]
- $h \rightarrow WW^* \rightarrow l\nu l\nu$ with $l = e, \mu$ in the 0jet and 2jet final states, the 2-jet final state with a VBF selection [210]
- $h \rightarrow Z\gamma$ in inclusive and 2jet (VBF) final states [213]
- $h \rightarrow bb$ with one-lepton and two-lepton selections to identify Wh and Zh productions, respectively [215]
- $h \rightarrow \tau\tau$ in the 2-jet final state with a VBF selection [210]
- $h \rightarrow \mu\mu$ in inclusive and $t\bar{t}h$ final states [210]
- $h \rightarrow ll$ with $l = e, \mu$ in inclusive and 2jet (VBF) final states [213].

In each channel, the trigger and the photon and lepton requirements are adjusted to keep misidentification rates at a level that is believed to be acceptable in the future high-luminosity environment. For the VBF jet selection the cuts are tightened to reduce the expected fake rate induced by pileup [212].

Differential measurements of Higgs production, for examples of the Higgs boson transverse momentum and rapidity [227, 228], are not included here but would further decrease the uncertainties in the coupling measurements. The $t\bar{t}h$ process is expected to be measured in additional decay channels to those studies here. The $t\bar{t}h$ process is for example expected to be measured in the $h \rightarrow bb$ channel. These and other improvements are expected to allow to reach a better precision in the Higgs coupling measurement in the future.

9.3 Analysis procedure

In the benchmark models considered, which are introduced in section 1.3, the couplings of the Higgs boson to fermions and vector bosons are modified by functions of the model parameters. In all cases, it is assumed that the modifications of the couplings do not change the Higgs boson production or decay kinematics significantly. Thus the expected rate of any given process can be obtained through a simple rescaling of the SM couplings and no acceptance change due to kinematics in each BSM scenario is included. A simultaneous fit of the measured rates in multiple production and decay modes is used to constrain the BSM model parameters.

The statistical treatment of that data is described in reference [200, 202, 201, 143, 142]. Confidence intervals use the test statistic $t_\alpha = -2 \ln \Lambda(\alpha)$ which is based on the profile likelihood ratio as described in section 4.3. The likelihood function for the Higgs boson coupling measurements is built as a product of the likelihoods of all measured Higgs boson channels, where for each channel the likelihood is built using sums of signal and background probability density functions in the discriminating variables.

Confidence intervals are extracted by taking t_α to follow an asymptotic χ^2 distribution with the corresponding number of degrees of freedom [137].

The measured values in Run 1 and expected values for Run 2 and the HL-LHC, from one-dimensional likelihood scans are given in table 9.1. Table 9.1 summarises the relevant best-fit value, interval at 68% confidence level (CL), and/or upper limit at the 95% CL for physical quantities of interest. These include the overall signal strength, the scale factors for the Higgs boson couplings and total width, and the Higgs boson invisible decay branching ratio in various parameterisations. The BSM models probed with these parameters are also indicated. The overall signal strength measured in Run 1 is larger than 1, where exactly 1 is expected for the SM.

Model	Coupling Parameter	Measurement Run 1	expected precision in %			
			All syst.	300 fb ⁻¹ w/o theory	All syst.	3000 fb ⁻¹ w/o theory
1 Mass scaling Parameterisation	κ_Z	$[-1.06, -0.82] \cup [0.84, 1.12]$	8.1	7.8	4.3	3.8
	κ_W	0.91 ± 0.14	8.5	8.1	3.8	3.9
	κ_t	0.94 ± 0.21	14	11	8.2	5.3
	κ_b	$[-0.90, -0.33] \cup [0.28, 0.96]$	23	22	12	10
	κ_τ	$[-1.22, -0.80] \cup [0.80, 1.22]$	14	13	9.8	8.7
	κ_μ	< 2.28 at 95% CL	21	21	7.3	7.0
2 MCHM4	μ_h	$1.18^{+0.15}_{-0.14}$	8.5	4.8	6.5	3.4
3 MCHM5 THDM Type I	κ_V/μ_h					
	κ_f	1.09 ± 0.07 1.11 ± 0.16	4.3	2.5	3.3	1.7
4 THDM Type II (h)MSSM	$\lambda_{Vu} = \kappa_V/\kappa_u$	$0.92^{+0.18}_{-0.16}$				
	$\kappa_{uu} = \kappa_u^2/\kappa_h$	1.25 ± 0.33				
	$\lambda_{du} = \kappa_d/\kappa_u$	$[-1.08, -0.81] \cup [0.75, 1.04]$				
	κ_V		5.9	5.3	3.7	3.0
	κ_u		8.9	7.2	5.4	3.4
5 THDM Type III lepton-specific	κ_d		12	12	6.7	6.1
	$\lambda_{Vq} = \kappa_V/\kappa_q$	$1.03^{+0.18}_{-0.15}$				
	$\kappa_{qq} = \kappa_q^2/\kappa_h$	$1.03^{+0.33}_{-0.20}$				
	$\lambda_{du} = \kappa_d/\kappa_u$	$[-1.34, -0.94] \cup [0.94, 1.34]$				
	κ_V		4.3	2.5	3.3	1.7
6 THDM Type IV flipped	κ_q		11	7.8	6.6	3.6
	λ_l		10	9.3	6.0	5.1
	κ_V		7.9	7.6	4.3	3.7
	κ_{ul}		11	10	5.6	4.5
	λ_d'		21	21	11	9.6
7 Higgs portal	κ_Z	0.99 ± 0.15				
	κ_W	0.92 ± 0.14				
	λ_t	$1.26^{+0.32}_{-0.34}$				
	κ_b	0.61 ± 0.28				
	λ_τ	$0.98^{+0.20}_{-0.18}$				
	λ_μ	< 2.25 at 95% CL				
	κ_g	$0.92^{+0.18}_{-0.15}$	8.9	6.3	6.7	2.8
	κ_γ	$0.90^{+0.15}_{-0.14}$	4.9	4.7	2.1	1.7
	$\kappa_Z\gamma$	< 3.15 at 95% CL	23	23	14	14
	BR_{inv}	< 0.23 at 95% CL	< 22	< 20	< 14	< 10

Table 9.1: Observed Run 1 measurements and expected measurements for Run 2 and the HL-LHC of the overall signal strength, μ , scale factors (s.f.), κ , for the Higgs boson couplings and total width, $\kappa + h$, and the Higgs boson invisible decay branching ratio, BR_{inv} , in different coupling parameterisations, along with the BSM models or parameterisations they are used to probe. Ratios of scale factors are noted as λ . For the Higgs portal model no additional assumption of the vector boson couplings are made.

9.4 Mass dependence of couplings

The observed rates in Run 1 and the expected rates for Run 2 and the HL-LHC in different channels are used to determine the sensitivity to the couplings of the Higgs boson to the other particles, which scale with the Higgs mass. The Higgs boson mass for Run 1 uses the ATLAS measurement of $m_h = 125.36 \pm 0.37(\text{stat}) \pm 0.18(\text{syst})$ GeV [242] while for Run 2 and the HL-LHC a mass of $m_h = 125.0$ GeV is assumed. The precision of the scale factors to different fermions and vector boson are expressed in terms of a mass scaling parameter ϵ and the vacuum expectation value parameter, M whose SM value is $v \approx 246$ GeV [243], and are given in model 1 of table 9.1. The coupling scale factors to fermions and vector bosons, respectively, are expressed as:

$$\begin{aligned}\kappa_{f,i} &= v \frac{m_{f,i}^\epsilon}{M^{1+\epsilon}}, \\ \kappa_{V,j} &= v \frac{m_{V,j}^{2\epsilon}}{M^{1+2\epsilon}},\end{aligned}\tag{9.1}$$

where $m_{f,i}$ denotes the mass of each fermion species (indexed i) and $m_{V,j}$ denotes each vector boson mass (indexed j). The mass scaling of the couplings as well as the vacuum expectation values of the SM are recovered with parameter values $\epsilon = 0$ and $M = v$, which produce $\kappa_{f,i} = \kappa_{V,j} = 1$. The values $\epsilon = -1$ corresponds to light Higgs boson couplings that are independent of the particle mass.

The production and decay rates are modified from their SM expectations accordingly. For example, assuming the narrow-width approximation [244, 245], the rate for the process $gg \rightarrow h \rightarrow ZZ^* \rightarrow 4l$ relative to the SM prediction can be parametrised [41] as:

$$\mu = \frac{\sigma \times BR}{(\sigma \times BR)_{SM}} = \frac{\kappa_g^2 \kappa_Z^2}{\kappa_h^2},\tag{9.2}$$

where κ_g is the scale factor for the loop-induced coupling to the gluon through the top and bottom quarks, where the top and bottom couplings are scaled by κ_f , and κ_Z is the couplings scale factor for the Z boson. The scale factor for the total width of the Higgs boson, κ_h^2 is calculated as a squared effective coupling scale factor. It is defined as the sum of squared coupling scale factors for all decay modes, κ_i^2 , each weighted by the corresponding SM branching ratio:

$$\kappa_h^2 = \sum_{jj} \frac{\kappa_{jj}^2 \Gamma_{jj}^{SM}}{\Gamma_h^{SM}} \text{ with } jj = WW, ZZ, b\bar{b}, \tau^+\tau^-, \gamma\gamma, Z\gamma, gg, t\bar{t}, c\bar{c}, s\bar{s}, \mu^+\mu^-\tag{9.3}$$

where $\Gamma_{\gamma\gamma}^{ij}$, $\Gamma_{Z\gamma}^{ij}$ and Γ_{ff}^{SM} are theoretically predicted [41]. It is assumed that there are no new production and decay modes beyond those in the SM. Production or decays through loops are resolved in terms of the contributing particles in the loops, assuming contributions from SM particles only. For example, the W boson provides the dominant contribution to the loop in the $h \rightarrow \gamma\gamma$ decay, followed by the top quark, such that the effective coupling scale factor κ_γ is given by:

$$\kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W) = \frac{\sum_{i,j} \kappa_i \kappa_j \Gamma_{\gamma\gamma}^{ij}}{\sum_{i,j} \Gamma_{\gamma\gamma}^{ij}}, \quad (9.4)$$

where the negative interference between the W and the top loops, as well as the contributions from other charged particles in the loops, are accounted for. Similarly, for the loop induced $h \rightarrow Z\gamma$ and $gg \rightarrow h$ processes the effective coupling scale factors are given by respectively:

$$\begin{aligned} \kappa_{Z\gamma}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W) &= \frac{\sum_{i,j} \kappa_i \kappa_j \Gamma_{Z\gamma}^{ij}}{\sum_{i,j} \Gamma_{Z\gamma}^{ij}}, \\ \kappa_g^2(\kappa_b, \kappa_t) &= \frac{\kappa_t^2 \sigma_{ggh}^{tt} + \kappa_b^2 \sigma_{ggh}^{bb} + \kappa_t \kappa_b \sigma_{ggh}^{tb}}{\sigma_{ggh}^{tt} + \sigma_{ggh}^{bb} + \sigma_{ggh}^{tb}}. \end{aligned} \quad (9.5)$$

Combined fits to the rates are performed with the mass scaling factor ϵ and the vacuum expectation value parameter M as the two parameters of interest. Figure 9.1 shows contours of the two-dimensional likelihood as a function of these parameters. The measured and expected values in Run 1 from one-dimensional likelihood scans are given in table 9.2. The extracted value of ϵ is close to 0, the SM value, indicating that the measured couplings to fermions and vector bosons are consistent with the linear and quadratic mass dependence, respectively, predicted in the SM. The best-fit value for M in Run 1 is less than $v \approx 246$ GeV, which corresponds to the measured overall signal strength μ_h which is measured to be greater than 1. The data is compatible with the SM within about 1.5 standard deviations. With 300 fb^{-1} of data with the inclusion of theoretical uncertainties, the two-dimensional region of parameter space outside of approximately $|\epsilon| < 0.04$ is expected to be excluded at 95% CL. The corresponding expected compatible region that is still allowed with an exclusion of 95% CL, decreases to about $|\epsilon| < 0.02$ with 3000 fb^{-1} . The two-dimensional parameter region with values of M that differ more than 15 (10) GeV from $v \approx 246$ GeV are expected to be excluded at 95% CL with 300 (3000) fb^{-1} if no theory uncertainties are included.

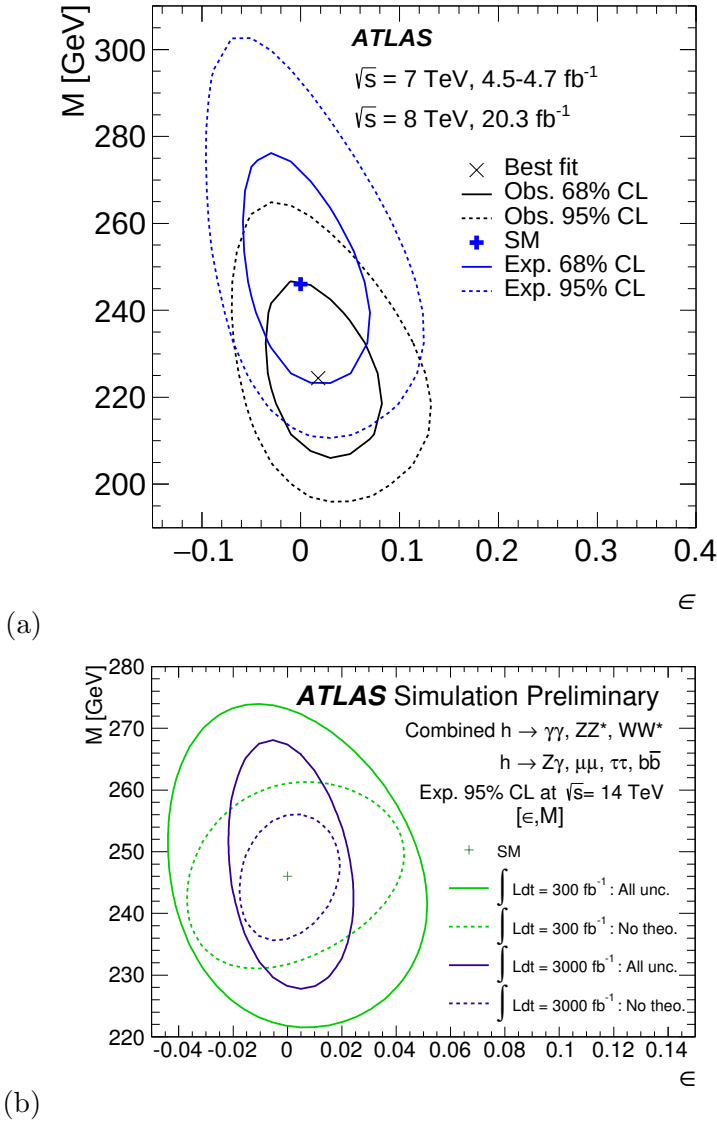


Figure 9.1: Two-dimensional confidence intervals as a function of the mass scaling factor, ϵ , and the vacuum expectation value parameter M . The likelihood contours are shown, where $-2 \ln \Lambda = 2.3$ corresponding to approximately 68% CL (1 standard deviation) is shown for (a) the Run 1 measurement, and where $-2 \ln \Lambda = 6.0$ corresponding to 95% CL (2 standard deviations) is shown for (a) the Run 1 measurement and (b) as expected for 300 fb^{-1} and 3000 fb^{-1} of integrated luminosity, with and without inclusion of theory uncertainties, assuming a SM Higgs boson. The best fit to the data of Run 1 is indicated as $\times$ and the SM expectation indicated as $+$.

Parameter	Observed	Expected
ϵ	0.018 ± 0.039	0.000 ± 0.042
M	$224^{+14}_{-12} \text{ GeV}$	$246^{+19}_{-16} \text{ GeV}$

Table 9.2: Observed and expected measurements of the mass scaling parameter ϵ and the vacuum expectation value parameter M for Run 1.

9.5 Additional Electroweak Singlet

The addition of a scalar electroweak singlet field, as described in section 1.3.1, results in two non-zero vacuum expectation values for the two fields. Spontaneous symmetry breaking leads to mixing between the singlet state and the state of the doublet field, resulting in two CP-even Higgs bosons. The notation h is used for the lighter Higgs boson, while H denotes the heavier of the pair. The two Higgs bosons are assumed to be non-degenerate. They couple to fermions and vector bosons in a similar way as the SM Higgs boson, but each with a strength reduced by a common scale factor, denoted by κ and κ' for h and H , respectively. The unitarity constraint implies that:

$$\kappa^2 + \kappa'^2 = 1. \quad (9.6)$$

The lighter Higgs boson h is assumed to be the observed Higgs boson with mass $m_h \approx 125 \text{ GeV}$. It is assumed to have the same production and decay modes as the SM Higgs boson, with only SM particles contributing to loop-induced production or decay. The decays of the heavy Higgs boson to the light Higgs boson, for example $H \rightarrow hh$, are assumed to contribute negligibly to the light Higgs boson production rate. The contamination from heavy Higgs boson decays, such as $H \rightarrow WW$, in the light Higgs boson signal regions, such as $h \rightarrow WW$, is also taken to be negligible. In this model, the h production and decay rates are modified according to:

$$\begin{aligned} \sigma_h &= \kappa^2 \times \sigma_{h,SM}, \\ \Gamma_h &= \kappa^2 \times \Gamma_{h,SM}, \\ BR_{h,i} &= BR_{h,SM,i}, \end{aligned} \quad (9.7)$$

where σ denotes the production cross section, Γ denotes the total decay width, BR denotes the branching ratio, and i indexes the different decay modes. For the heavier Higgs boson H , new decay modes such as $H \rightarrow hh$ are possible if they are kinematically accessible. In this case, the production and decay rates of the H boson are modified with respect to those of a SM Higgs boson

with equal mass by the branching ratio of all BSM decay modes $BR_{H,new}$, as:

$$\begin{aligned}\sigma_H &= \kappa'^2 \times \sigma_{H,SM}, \\ \Gamma_H &= \frac{\kappa'^2}{1 - BR_{H,new}} \times \Gamma_{H,SM}, \\ BR_{H,i} &= (1 - BR_{H,new}) \times BR_{H,SM,i}.\end{aligned}\tag{9.8}$$

Here $\sigma_{H,SM}$, $\Gamma_{H,SM}$ and $BR_{H,SM,i}$ denote the cross section, total width, and branching ratio for a given decay mode, indexed i , predicted for a SM Higgs boson with mass m_H .

The overall signal strengths, namely the ratio of production and decay rates in the measured channels relative to the expectations for a SM Higgs boson with corresponding mass, is given for h and H , assuming the narrow with approximation, by:

$$\begin{aligned}\mu_h &= \frac{\sigma_h \times BR_h}{(\sigma_h \times BR_h)_{SM}} = \kappa^2, \\ \mu_H &= \frac{\sigma_H \times BR_H}{(\sigma_H \times BR_H)_{SM}} = \kappa'^2(1 - BR_{H,new}).\end{aligned}\tag{9.9}$$

Combining equations 9.6 and 9.9, the squared coupling of the heavy Higgs boson can be expressed in terms of the signal strength of the light Higgs boson as:

$$\kappa'^2 = 1 - \mu_h.\tag{9.10}$$

This equation for the squared coupling scale factor takes the same form as equation 9.11, so the same parameter constraints are expected. The observed and expected signal strength precision of the light Higgs boson is given in model 2 of table 9.1. The measured and expected 95% CL upper limit on κ'^2 are shown in table 9.3.

Run 1		300 fb ⁻¹		3000 fb ⁻¹	
Obs.	Exp.	All unc.	No theory unc.	All unc.	No theory unc.
0.12	0.23	0.17	0.10	0.13	0.06

Table 9.3: Observed and expected upper limits at the 95% CL on the squared coupling scale factor of the heavy Higgs boson, κ'^2 , in a model with an additional electroweak singlet.

This corresponds, according to equation 9.9, to the maximum signal strength for contamination of a heavy Higgs boson into a light Higgs boson signal. Figure 9.2 shows the expected limits in the $(\mu_H, BR_{H,new})$ plane of the heavy Higgs boson. Expected contours of the scale factor for the total width $\Gamma_H/\Gamma_{H,SM}$,

and κ'^2 are also indicated. These results are independent of the mass and $BR_{H,new}$ of the heavy Higgs boson.

The relative improvement with 3000 fb^{-1} compared to 300 fb^{-1} is lower if all systematic uncertainties are included. The correlation between the ϵ and M uncertainties with all systematic uncertainties is different from the case without including the theory uncertainties. This is due to the different relative impact of the theory uncertainties on different channels.

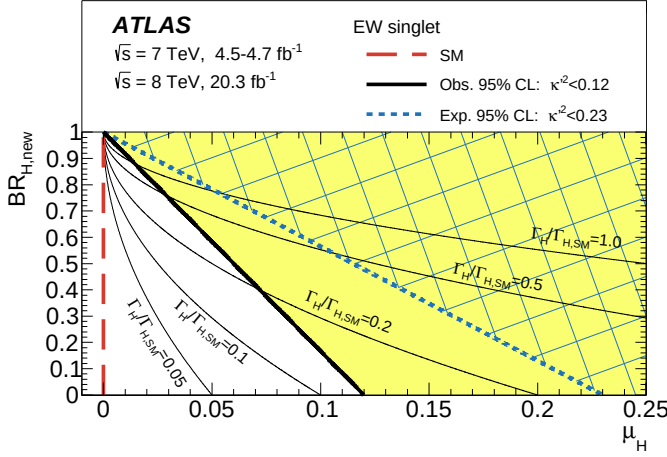
9.6 Minimal Composite Higgs Model

The Minimal Composite Higgs Models (MCHM) is described in section 1.3.2. The MCHM4 model is a minimal $SO(5)/SO(4)$ model where the SM fermions are embedded in spinorial representations of $SO(5)$. The ratio of the predicted coupling scale factors to their SM expectations, κ , can be written in the particularly simple form:

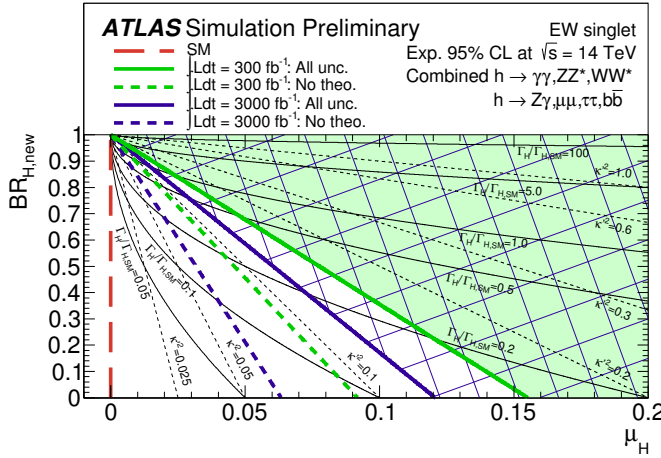
$$\kappa = \kappa_V = \kappa_f = \sqrt{1 - \xi}, \quad (9.11)$$

where $\xi = v^2/f^2$ is a scaling parameter, with v being the SM vacuum expectation value and f the Higgs boson compositeness scale. The SM is recovered in the limit $\xi \rightarrow 0$, which corresponds to $f \rightarrow \infty$. The combined signal strength, μ_h , and equivalent coupling scale factor, $\kappa = \sqrt{\mu_h}$, expected and measured using the combination of all channels considered are listed in model 2 of table 9.1. The experimental and expected measurements are interpreted in the MCHM4 scenario by rescaling the rates in different production and decay modes as function of the coupling scale factors $\kappa = \kappa_V = \kappa_f$, taking the same production and decay modes as in the SM. The scale factors are in turn expressed as a function of ξ using equation 9.11.

Assuming the SM Higgs boson, which corresponds to $\xi = 0$, the scaling parameter is measured to be $\xi = 1 - \mu_h = -0.18 \pm 0.14$ in Run 1, while the Run 1 expectation for the SM Higgs boson is $\xi = 0 \pm 0.14$. The best-fit value observed for ξ is negative because $\mu_h > 1$ is measured. The statistical and systematic uncertainties are of similar size. The model contains a physical boundary restricting $\xi \geq 0$. This boundary is ignored for the measurement, but can be used to produce an upper limit for the parameters. Taking the lower boundary into account produces an observed (expected) upper limit in Run 1 at 95% CL of $\xi < 0.12$ (0.23), corresponding to a Higgs boson compositeness scale of $f > 710$ (510) GeV. The observed and expected likelihood scans of the Higgs compositeness scaling parameter ξ in the MCHM4 model are shown in figure 9.3(a). Assuming the SM Higgs boson, the scaling parameter is expected to be measured as $\xi = 1 - \mu_h = 0.000 \pm 0.085$ (0.064) using 300 fb^{-1} (3000 fb^{-1}) of data. With 300 fb^{-1} of data and with (without) including theory uncertainties,



(a)



(b)

Figure 9.2: Observed and expected upper limits at 95% CL on the squared coupling scale factor of the heavy Higgs boson, κ'^2 , in a model with an additional electroweak singlet, shown in the $(\mu_H, BR_{H,new})$ plane of the heavy Higgs boson, for (a) Run 1 and (b) for 300fb^{-1} and 3000fb^{-1} . The light shaded and hashed regions indicate the observed and expected exclusions. Contours of the scale factor for the total width $\Gamma_H/\Gamma_{H,SM}$, and κ'^2 are also indicated.

the expected 95% CL upper limit is $\xi < 0.16$ (0.092), corresponding to a Higgs boson compositeness scale of $f > 620$ (810) GeV. The limits with 3000 fb^{-1} are $\xi < 0.12$ (0.063) and $f > 710$ (980) GeV. The results are limited by the theoretical uncertainties on the Higgs production rates through ggF and VBF [10].

The MCHM5 model is an $\text{SO}(5)/\text{SO}(4)$ model where the SM fermions are embedded in fundamental representations of $\text{SO}(5)$. Here the measured rates are expressed in terms of ξ by rewriting the coupling scale factors as:

$$\begin{aligned}\kappa_V &= \sqrt{1 - \xi}, \\ \kappa_f &= \frac{1 - 2\xi}{\sqrt{1 - \xi}},\end{aligned}\tag{9.12}$$

where $\xi = v^2/f^2$. The observed and expected measurements of κ_V and κ_f are given in model 3 of table 9.1. The likelihood scans of ξ in MCHM5 for the Run 1 measurement are shown in figure 9.3(b). Ignoring the physical boundary restricting $\xi \geq 0$, the composite Higgs boson scaling parameter is determined to be $\xi = -0.12 \pm 0.10$, while $\xi = 0.00 \pm 0.10$ is expected for the SM Higgs boson in the Run 1 measurement. Accounting for the boundary produces an observed (expected) upper limit at 95% CL of $\xi < 0.10$ (0.17), corresponding to a Higgs boson compositeness scale of $f > 780$ (600) GeV. Assuming the SM Higgs boson, the composite Higgs boson scaling parameter is expected to be measured as $\xi = 0.000 \pm 0.057$ (0.033) for 300fb^{-1} (3000fb^{-1}) of data. With 300 fb^{-1} of data and with (without) including theory uncertainties, the expected 95% CL upper limit is $\xi < 0.10$ (0.067), corresponding to a Higgs boson compositeness scale of $f > 780$ (950) GeV. The limits with 3000 fb^{-1} are $\xi < 0.060$ (0.039) and $f > 1.0$ (1.2) TeV. Figure 9.4 shows the expected and measured two-dimensional likelihood for vector boson and fermion coupling measurements in the (κ_V, κ_f) space, overlaid with predictions as parametric functions of ξ for the MCHM4 and MCH5 models. A secondary minimum in the likelihood at $\kappa_f < 0$ is rejected at more than 95% CL. Table 9.4 summarises the lower limits at 95% CL on the Higgs boson compositeness scale for Run 1 and with 300 fb^{-1} and 3000 fb^{-1} in the MCHM4 and MCHM5 models.

Model	Run 1		300 fb^{-1}		3000 fb^{-1}	
	Observed	Expected	All unc.	No theory unc.	All unc.	No theory unc.
MCHM4	710 GeV	510 GeV	620 GeV	810 GeV	710 GeV	980 GeV
MCHM5	780 GeV	600 GeV	780 GeV	950 GeV	1.0 TeV	1.2 TeV

Table 9.4: Observed and expected lower limits at the 95% CL on the Higgs boson compositeness scale f in the MCHM4 and MCHM5 models.

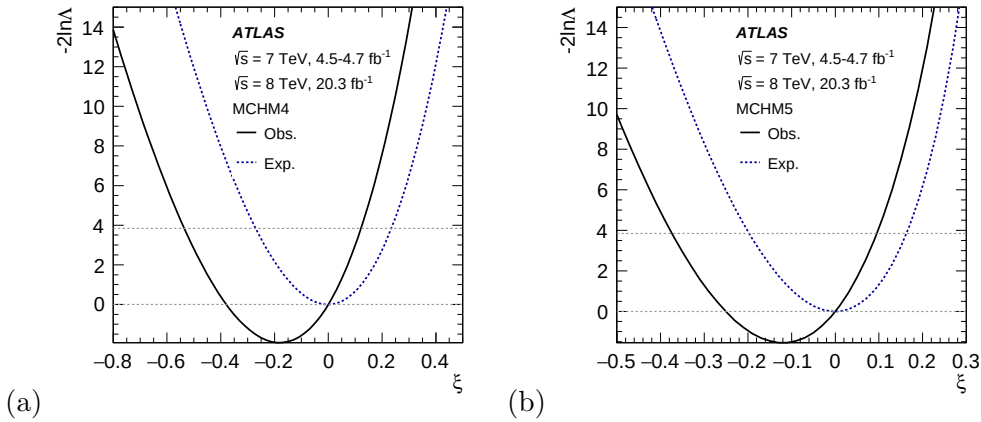


Figure 9.3: Likelihood scans of the Higgs boson compositeness parameter, $\xi = v^2/f^2$, in the (a) MCHM4 and (b) MCHM5 models. The observed and expected likelihoods are shown. Ignoring the physical boundary ξ greater than or equal to 0, the lines at $-2 \ln \Lambda = 1.0$ and $-2 \ln \Lambda = 4.0$ correspond approximately to 68% CL (1σ) and 95% CL (2σ), respectively.

9.7 Two Higgs Doublet Model

The Two Higgs Doublet Models (THDMs), as described in section 1.3.3, extend the SM Higgs sector by an additional doublet of the complex field. Five Higgs bosons are predicted in the THDM: two neutral CP-even bosons h and H , one neutral CP-odd boson A , and two charged bosons $H^\pm$. The most general THDMs can accommodate CP-violating Higgs boson couplings as well as tree-level flavour-changing neutral currents in the Higgs sector. Since the latter are strongly constrained by existing data, the models considered have additional requirements imposed, such as the Glashow-Weinberg condition [46, 47], in order to evade existing experimental bounds. Gauge invariance fixed the couplings of the two neutral CP-even Higgs bosons to vector bosons relative to their SM values to be:

$$\begin{aligned} g_{hVV}^{THDM}/g_{hVV}^{SM} &= \sin(\beta - \alpha), \\ g_{HVV}^{THDM}/g_{HVV}^{SM} &= \cos(\beta - \alpha). \end{aligned} \quad (9.13)$$

Here g_{XVV}^{THDM} with $X = h, H$ and $V = W, Z$ denote the SM Higgs boson couplings to vector bosons, $\tan \beta = v_2/v_1$ where v_1 and v_2 denote the vacuum expectation values of the Higgs doublets, and α denotes the mixing angle of the two neutral CP-even Higgs states. The Glashow-Weinberg condition is satisfied by four types of THDM, which are described in section 1.3.3. The Higgs boson rate measurements in different production and decay modes are

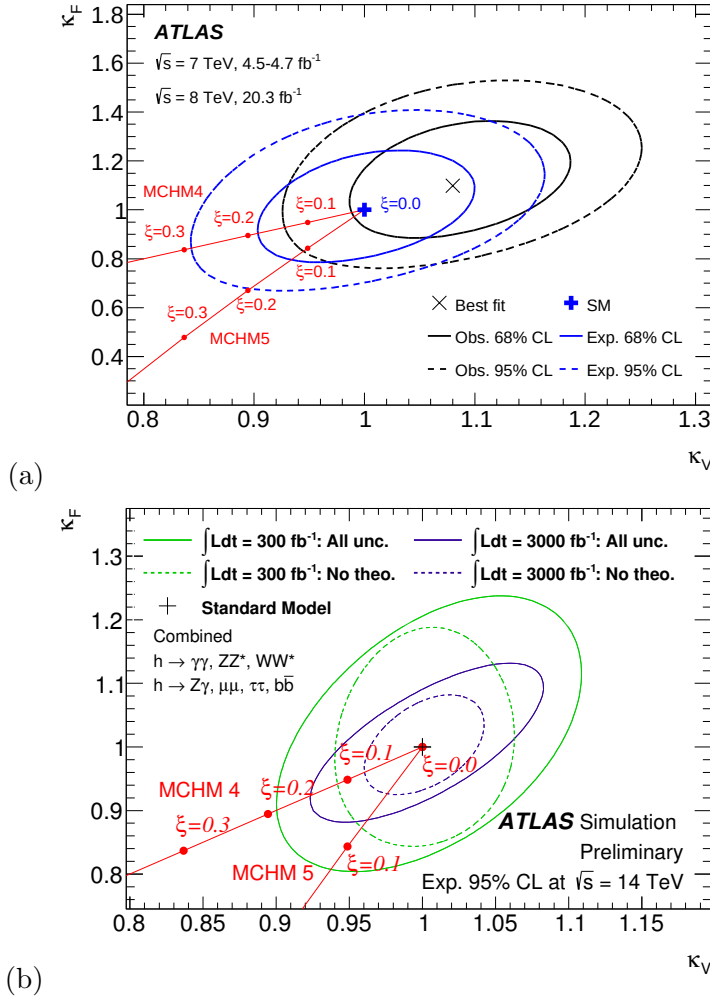


Figure 9.4: Two-dimensional likelihood contours in the (κ_V, κ_f) coupling plane for (a) Run 1 and (b) prospects, where $-2 \ln \Lambda = 2.3$ and $-2 \ln \Lambda = 6.0$ correspond approximately to 68% CL (1σ) and 95% CL (2σ) respectively. The coupling predictions in the MCHM4 and MCHM5 models are shown as parametric functions of the Higgs boson compositeness parameter $\xi = v^2/f^2$. The two-dimensional likelihood contours are shown for reference ξ and should not be used to estimate the exclusion for the single parameter ξ .

interpreted in each of these four types of THDMs assuming that the observed new particle with mass $m_h \approx 125$ GeV is the light CP-even neutral Higgs boson h . This is done by rescaling the production and decay rates as functions of the couplings $\kappa_V, \kappa_u, \kappa_d$ and κ_l . The expected measurements of these couplings, which assume the same production and decay modes as in the SM, are given in models 3-6 in table 9.1. These couplings are in turn expressed as a function of the underlying parameters, the two angles β and α . Here it is assumed that the decay modes are the same as those for the SM Higgs boson.

The rescaled coupling predictions agree with those obtained using the SUSHI [246] and 2HDMC [247] programs, which calculate Higgs boson production and decay rates respectively in two Higgs doublet models. The rescaled ggF rate agrees with the SUSHI prediction to better than a percent, and the rescaled decay rates show a similar level of agreement. The cross section for bbh associated production is calculated using SUSHI and includes a correction that scales with the square of the Yukawa coupling to the b -quark, assuming that it produces differential distributions that are the same as those in ggF. The correction is a small fraction of the total production rate for the regions of parameter space where the data would be compatible with the SM at 95% CL. Figure 9.5 shows the regions of the $(\cos(\beta - \alpha), \tan \beta)$ plane that are excluded at a CL of at least 95% for each of the four types of THDMs, overlaid with the exclusion limits expected for the SM Higgs sector. Figure 9.6 shows the regions of the $(\cos(\beta - \alpha), \tan \beta)$ plane that are expected to be excluded at 95% CL or greater assuming the SM Higgs sector. The expected exclusions are shown for 300fb^{-1} and 3000fb^{-1} at $\sqrt{s} = 14$ TeV, with and without the inclusion of theory uncertainties, and for each of the four types of THDMs described in section 1.3.3. The α and β parameters are taken to satisfy $0 \leq \beta \leq \pi/2$ and $0 \leq \beta - \alpha \leq \pi$ without loss of generality. The expected exclusion regions in $\cos(\beta - \alpha)$ depend on the particular functional dependence of the coupling on β and α , which are different for each of the four types of THDMs. The SM-like alignment limit is achieved for $\cos(\beta - \alpha) = 0$. The range $0.1 \leq \tan \beta \leq 10$ is shown.

The regions of compatibility, which is the region of phase space that is not excluded at a 95% CL, extend to larger and smaller $\tan \beta$ values, but with a correspondingly narrower range of $\cos(\beta - \alpha)$. The confidence intervals drawn are derived from a χ^2 distribution with two parameters of interest, corresponding to the quantities $\cos(\beta - \alpha)$ and $\tan \beta$. However, at $\cos(\beta - \alpha) = 0$ the likelihood is independent of the model parameter β , effectively reducing the number of parameters of interest locally to one. Hence the assumed test-statistic distribution for two parameters of interest that is used may lead to some over-coverage near $\cos(\beta - \alpha)$.

The Run 1 results are shown in figure 9.5. In each of the four THDM types a

similar petal is possible at the lower right of the $(\cos(\beta - \alpha), \tan \beta)$ plane. For the Type I, Type II, Type II and Type IV models, this lower petal corresponds respectively to an inverted coupling to fermions, up-type quarks, all quarks and lastly the up-type quarks and leptons. In all four cases, the lower petal is rejected since an inverted top quark coupling sign is disfavoured. The top quark coupling is extracted primarily through its dominant effect in ggF Higgs production, as well as by resolving the Higgs boson decays to diphotons, with one contribution from the top quark.

In Type II, Type III and Type IV there is narrow petal of allowed parameter space, with surrounding region being excluded, at the upper right of the $(\cos(\beta - \alpha), \tan \beta)$ plane. These three allowed upper petals correspond respectively to an inverted sign of the couplings to down-type fermions, leptons or the bottom quark. These couplings are measured with insufficient precision to be excluded. There is no upper petal at high $\tan \beta$ in Type I, since all the Yukawa couplings are identical. With the luminosity increase to 300 fb^{-1} and 3000 fb^{-1} these couplings can be measured with sufficient precision to exclude all petals.

Figures 9.7 and 9.8 show which coupling excludes which region in the $(\cos(\beta - \alpha), \tan \beta)$ plane for the four types of THDM at 300 fb^{-1} and 3000 fb^{-1} .

9.8 Minimal Supersymmetric Standard Model

The minimal supersymmetric Standard Model, as described in section 1.3.4, introduces a mass mixing matrix for the neutral CP-even Higgs bosons, h and H . The mass squared mixing matrix of the neutral CP even Higgs bosons can be written as:

$$\begin{aligned} \mathcal{M}_s^2 = & (m_Z^2 + \delta_1) \begin{pmatrix} \cos^2 \beta & -\cos \beta \sin \beta \\ -\cos \beta \sin \beta & \sin^2 \beta \end{pmatrix} \\ & + m_A^2 \begin{pmatrix} \sin^2 \beta & -\cos \beta \sin \beta \\ -\cos \beta \sin \beta & \cos^2 \beta \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ 0 & \frac{\delta}{\sin^2 \beta} \end{pmatrix}, \end{aligned} \quad (9.14)$$

where δ and δ_1 are radiative corrections from, primarily, top quark and top squark loops, and are given as a function of the mass of the CP odd boson A , m_A , and the ratio of the two doublet fields vacuum expectation factors $\tan \beta$. Neglecting sub-dominant corrections fixes the dominant radiative corrections to

$$\frac{\delta}{\sin^2 \beta} = \frac{(m_A^2 - m_h^2)(m_h^2 - m_Z^2) + m_A^2 m_Z^2 \sin^2 2\beta}{\sin^2 \beta m_A^2 - (m_h^2 - m_Z^2 + \sin^2 \beta m_Z^2)}, \quad (9.15)$$

which diagonalises the mass matrix. The eigenvectors of the diagonal mass matrix correspond to the physical states, which in turn fixes the Higgs boson

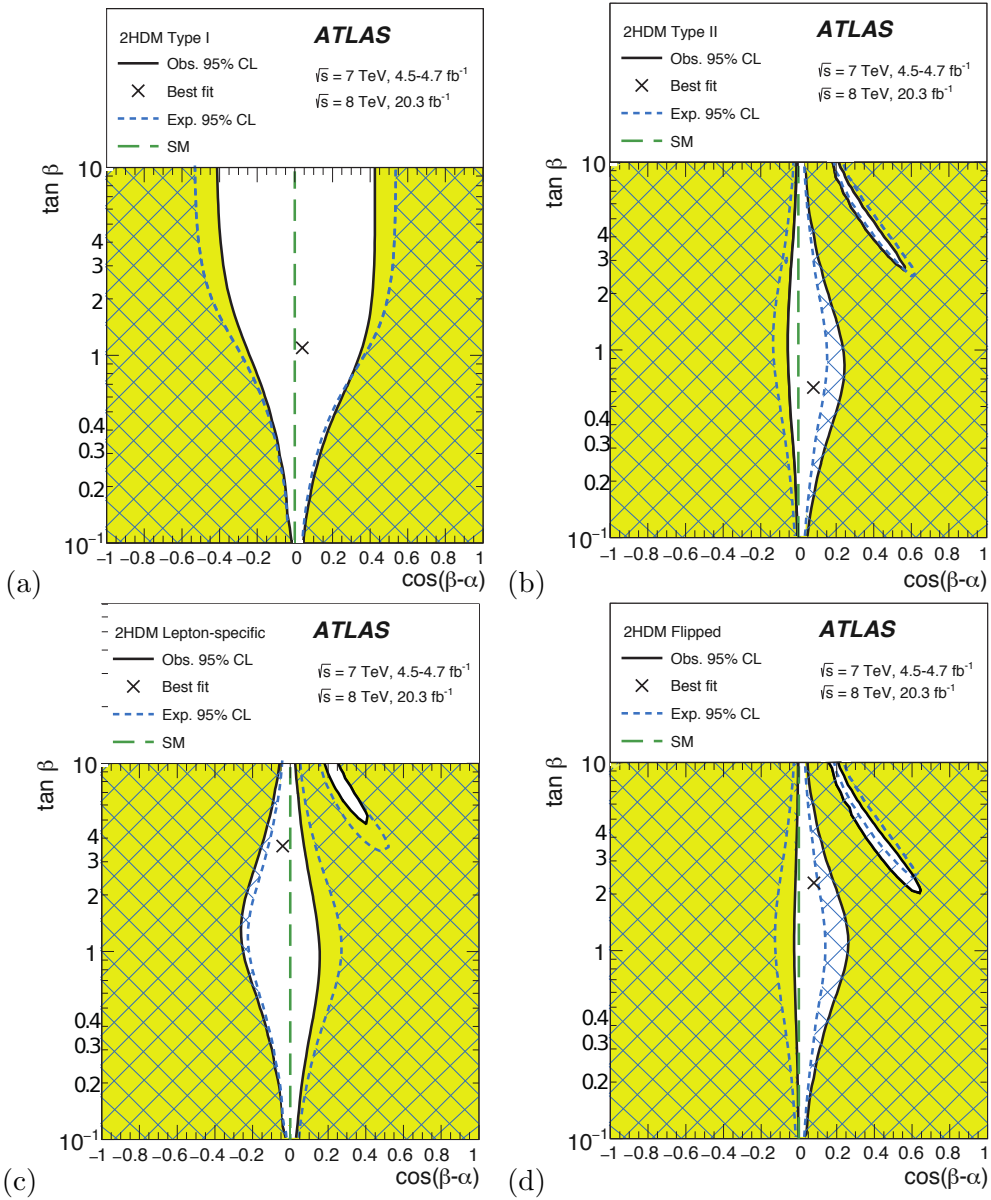


Figure 9.5: Regions of the $(\cos(\beta - \alpha), \tan \beta)$ plane of four types of THDMs excluded by fits to the measured rates of Higgs boson production and decays. The confidence intervals account for a possible relative sign between different couplings. The expected likelihood contours where $-2 \ln \Lambda = 6.0$, corresponding approximately to 95% CL (2σ), are indicated assuming the SM Higgs sector. The light shaded and hashed regions indicate the observed and expected exclusions, respectively.

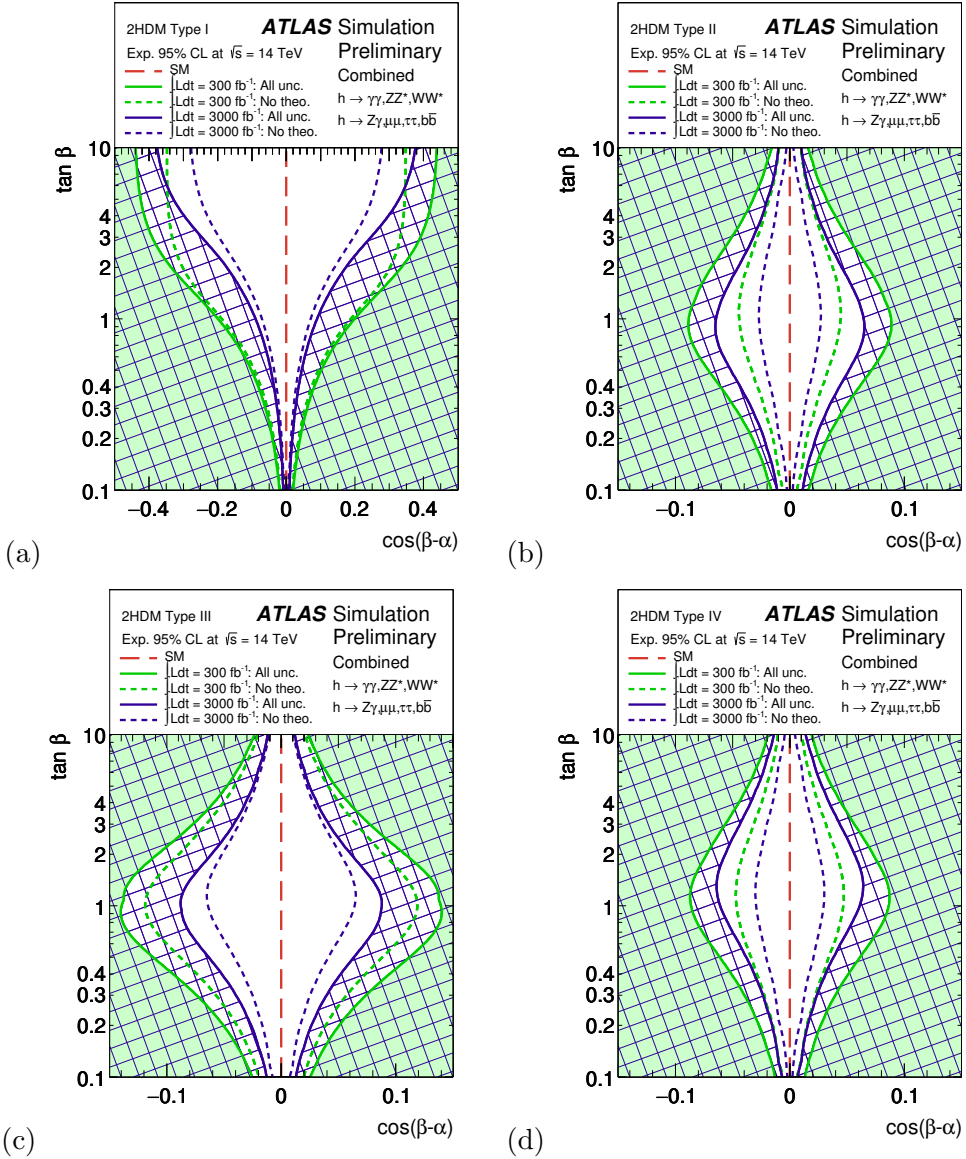


Figure 9.6: Regions of the $(\cos(\beta - \alpha), \tan \beta)$ plane of four types of THDMs expected to be excluded by fits to the measured rates of Higgs boson production and decays. The confidence intervals account for a possible relative sign between different couplings. The expected likelihood contours where $-2 \ln \Lambda = 6.0$, corresponding approximately to 95% CL (2σ), are indicated assuming the SM Higgs sector. The light shaded and hashed regions indicate the expected exclusions.

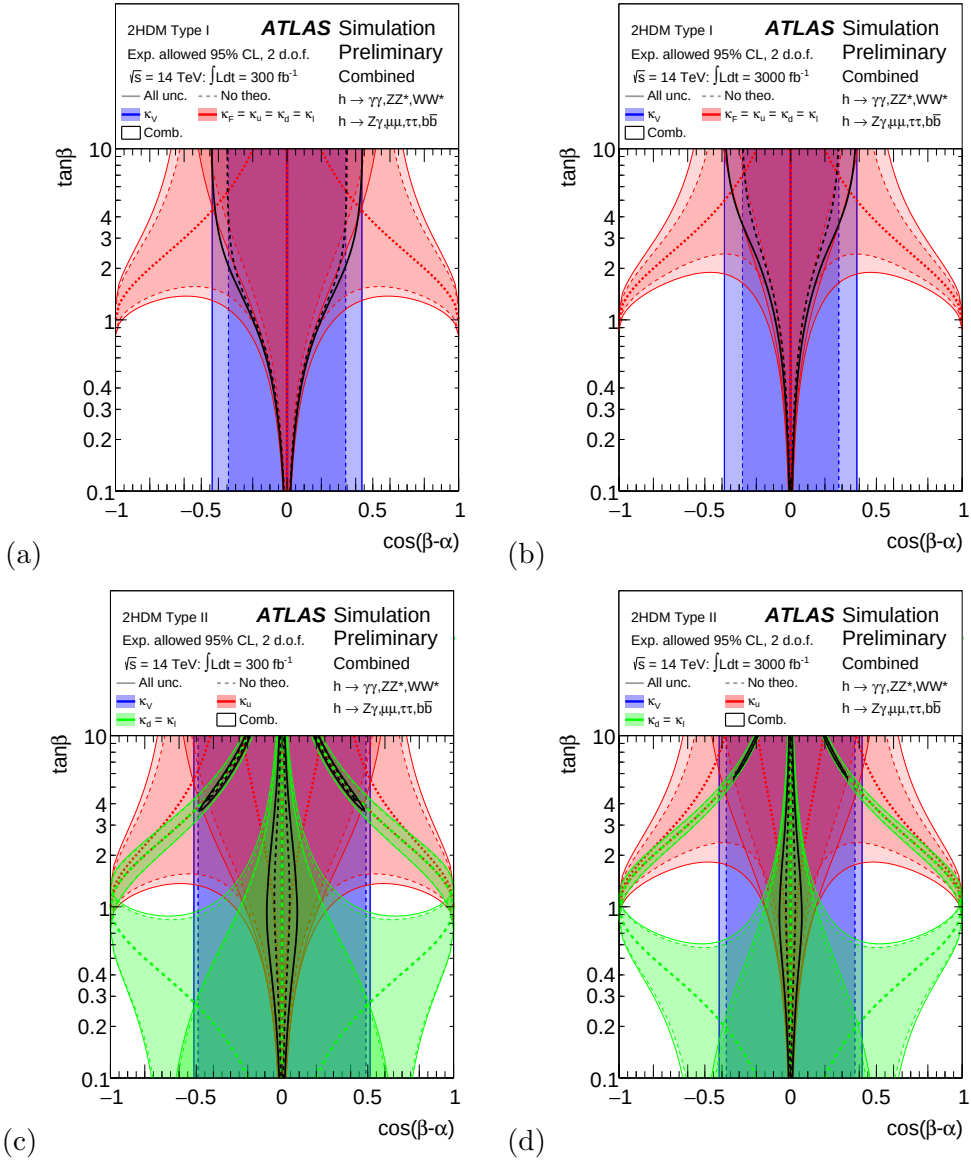


Figure 9.7: Regions of the $(\cos(\beta - \alpha), \tan\beta)$ plane for 2HDM type I (a) with 300 fb^{-1} and (b) with 3000 fb^{-1} and Type II (c) with 300 fb^{-1} and (d) with 3000 fb^{-1} , expected to be compatible with the measured rates of Higgs boson production and decays, assuming the data follows the SM. The expected likelihood contours where $-2 \ln \Lambda = 6.0$, corresponding approximately to 95% CL (2σ), are indicated assuming the SM Higgs sector. The light (dark) shaded regions are with (without) the inclusion of theory uncertainties in the Higgs boson coupling precision. For 2HDM type II, the confidence intervals for $\kappa_d = \kappa_l$ at large $\tan\beta$ correspond to a negative sign relative to κ_u . The second set of confidence intervals similarly corresponds to a positive sign relative to κ_u .

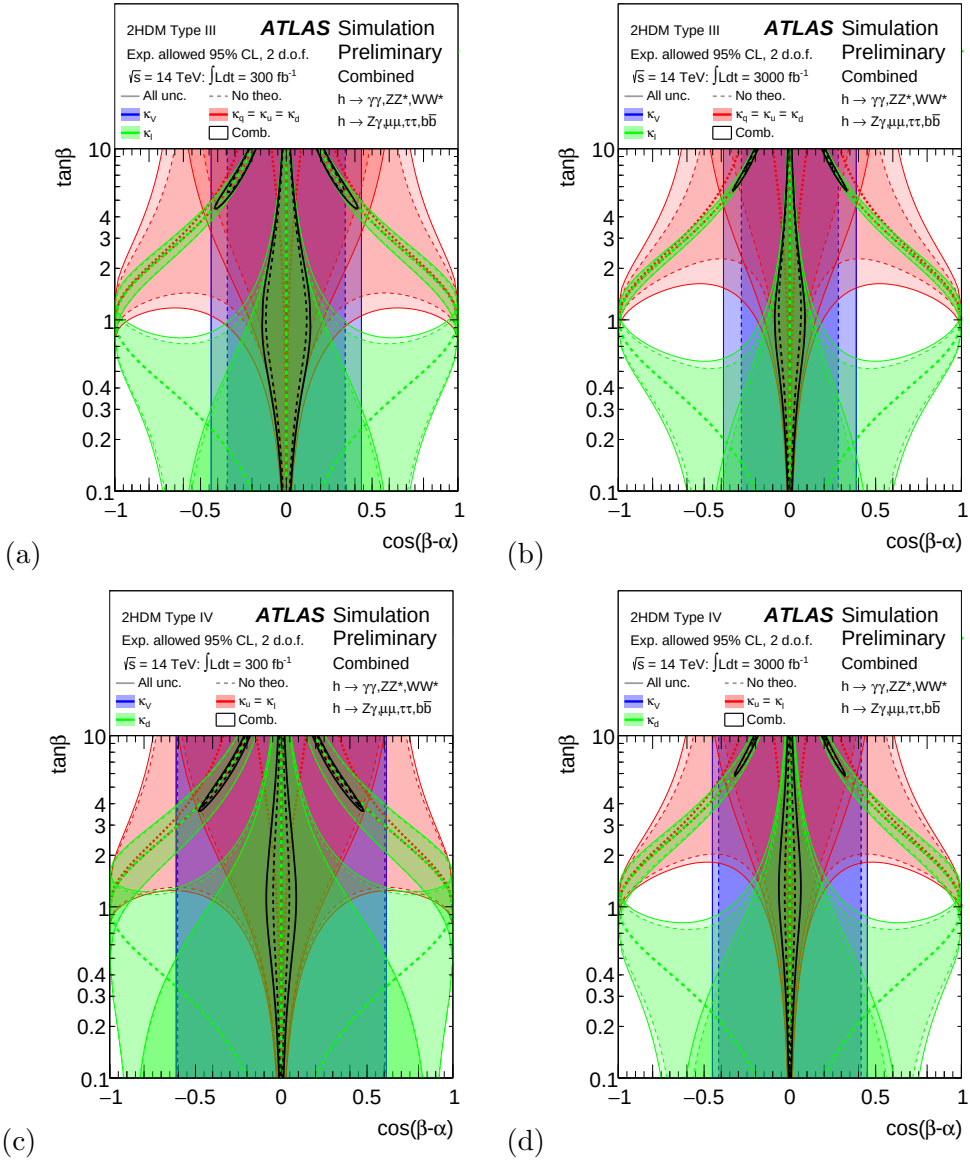


Figure 9.8: Regions of the $(\cos(\beta - \alpha), \tan \beta)$ plane for 2HDM type III (a) with 300 fb^{-1} and (b) with 3000 fb^{-1} and Type IV (c) with 300 fb^{-1} and (d) with 3000 fb^{-1} , expected to be compatible with the measured rates of Higgs boson production and decays, assuming the data follows the SM. The expected likelihood contours where $-2 \ln \Lambda = 6.0$, corresponding approximately to 95% CL (2σ), are indicated assuming the SM Higgs sector. The light (dark) shaded regions are with (without) the inclusion of theory uncertainties in the Higgs boson coupling precision. For 2HDM type III (IV) the confidence intervals for $\kappa_d = \kappa_l$ at large $\tan \beta$ correspond to a negative sign relative to κ_q ($\kappa_u = \kappa_l$). The second set of confidence intervals similarly corresponds to a positive sign relative to κ_q ($\kappa_u = \kappa_l$).

couplings to vector bosons (κ_V), up-type fermions (κ_u), and down-type fermions (κ_d). The scale factors for the Higgs boson couplings to vector bosons, up-type fermions, and down-type fermions, $\kappa_V, \kappa_u, \kappa_d$, can be expressed as functions of the free parameters m_A and $\tan \beta$, which are in this case the only two free parameters, as:

$$\begin{aligned}\kappa_V &= \frac{s_d + \tan \beta s_u}{\sqrt{1 + \tan^2 \beta}}, \\ \kappa_u &= s_u \frac{\sqrt{1 + \tan^2 \beta}}{\tan \beta}, \\ \kappa_d &= s_d \sqrt{1 + \tan^2 \beta},\end{aligned}\tag{9.16}$$

where s_u and s_d are given as a function of m_A and $\tan \beta$:

$$\begin{aligned}s_u(m_A, \tan \beta) &= \frac{1}{\sqrt{1 + \frac{(m_A^2 + m_Z^2)^2 \tan^2 \beta}{(m_Z^2 + m_A^2 \tan^2 \beta - m_h^2(1 + \tan^2 \beta))^2}}}, \\ s_d(m_A, \tan \beta) &= s_u \frac{(m_A^2 + m_Z^2)^2 \tan^2 \beta}{(m_Z^2 + m_A^2 \tan^2 \beta - m_h^2(1 + \tan^2 \beta))^2}.\end{aligned}\tag{9.17}$$

To test this model, the measured and expected production and decay rates are expressed in terms of the corresponding couplings. The observed new particle with mass $m_h \approx 125$ GeV is assumed to be the light CP-even neutral Higgs boson h . Model 4 of table 9.1 lists the observed and expected ratios of the coupling scale factors, $\kappa_V, \kappa_u, \kappa_d$. The coupling scale factors are in turn written in terms of m_A and $\tan \beta$ using equation 9.16. A correction is applied for bbh associated production as a function of the b -quark Yukawa coupling as described for the THDM models. Loop corrections from stops in gluon fusion production and diphoton decays are expected to be small, less than about 5% for $m_{stop} > 500$ GeV [54], and are neglected. Additional correction in the MSSM that would break the universality of the down-type fermion couplings, such that for example $\kappa_b \neq \kappa_\tau$, are generally sub-dominant effects [53] and are not included. The MSSM includes other possibilities such as Higgs boson decays to supersymmetric particles, decays of heavy Higgs boson to lighter ones [248], and effects from light supersymmetric particles [249], which are not investigated here. This model is therefore not fully general but serves as a useful benchmark, particularly if no direct observation of supersymmetry is made.

The observed and expected two-dimensional likelihood scan in the $(m_A, \tan \beta)$ plane for this simplified MSSM model are shown in figure 9.9. The region $1 \leq \tan \beta \leq 10$ is shown. At significantly smaller or larger values of $\tan \beta$, the hMSSM model is not a good approximation of the MSSM. For $\tan \beta < 1$, the

coupling to SM particles receive potentially large corrections related to the top sector that have not been included [250].

The Run 1 data are consistent with the SM decoupling limit, $m_A \rightarrow \infty$. The observed (expected) lower limit at the 95% CL on the CP-odd Higgs boson mass at Run 1 is at least $m_A > 370$ (310) GeV for $1 \leq \tan \beta \leq 50$, increasing to 440 (330) GeV at $\tan \beta = 1$. The observed limit is stronger than expected because the measured rates in the $h \rightarrow \gamma\gamma$, which is expected to be dominated by a W boson loop in the SM, and $h \rightarrow ZZ^* \rightarrow 4l$ channels are higher than predicted by the SM. The hMSSM model has a physical boundary $\kappa_V \leq 1$, so the vector-boson coupling cannot be larger than the SM value. The physical boundary is accounted for by computing the profile likelihood ratio with respect to the maximum likelihood obtained within the physical region of the parameter space, $m_A > 0$ and $\tan \beta > 0$. Figure 9.10 overlays the constraints in the $(m_A, \tan \beta)$ plane of the hMSSM model from various direct searches for heavy Higgs bosons. The constraints from the following searches are shown:

- $H/A \rightarrow \tau\tau$ search via both ggF and bbh associated production [251].
- Heavy CP-odd Higgs boson A produced via ggF and decaying to Zh with $Z \rightarrow ee, \mu\mu$ or $\nu\nu$ and $h \rightarrow bb$ [252].
- Heavy CP-even Higgs boson H produced via ggF and decaying to $WW \rightarrow \nu l \nu, l \nu q q$ [253] or $ZZ \rightarrow 4l, ll \nu \nu, ll q q, ll b b$ [254] with $l = e, \mu$ and $q = u, d, c, s$.
- Charged Higgs boson $H^\pm$ production in association with a top quark [255].

The cross sections for ggF and bbh associated production in the five-flavour scheme hMSSM model are calculated with SUSHI. The calculation for ggF includes the complete massive top and bottom loop corrections at NLO QCD [256], the top quark loop corrections in the heavy-quark limit of QCD at NNLO [257, 258, 259], and EW loop corrections due to light quarks up to NLO [260, 261]. The bbh associated production in the five-flavour scheme includes corrections up to NNLO in QCD [262]. The production of a heavy Higgs boson has also been calculated in the four-flavour scheme at NLO in QCD [263, 264], and the result has been combined with the five-flavour scheme using an empirical matching procedure [265]. The branching ratios have been calculated using HDECAY.

With 300fb^{-1} of data, the expected lower limit at 95% CL on the CP-odd Higgs boson mass is $m_A > 390$ (490) GeV for $2 \leq \tan \beta \leq 10$ with (without) the inclusion of theory uncertainties, with the limit increasing to larger masses for $\tan \beta < 2$. With 3000fb^{-1} of data, the expected limit is $m_A > 480$ (640) GeV.

Figure 9.11 shows which coupling excludes which region of the $(m_A, \tan \beta)$ plane for 300 fb^{-1} and 3000 fb^{-1} .

9.9 Higgs Portal to Dark Matter

Many "Higgs Portal" models [266, 267, 268, 55, 269, 217, 270] introduce an additional weakly-interacting massive particle (WIMP) as a dark matter candidate, as introduced in section 1.3.5. It is assumed to interact very weakly with the SM particles, except for the Higgs boson. In this study, the coupling of the Higgs boson to the WIMP is taken to be a free parameter. The Higgs portal model, where the Higgs boson is taken to be the only mediator, is a special case of the spin-independent limits obtained by direct detection experiments. To compare with direct searches, the observed upper limit combining all the visible and invisible Higgs boson decay channels using the most general baseline parameterisation is calculated at 90% CL, which results in a limit on the branching ratio of the Higgs boson to invisible final states of $BR_{inv} < 0.22$. With 300 fb^{-1} of data and with (without) the inclusion of theory uncertainties, the expected 95% CL upper limit on the branching ratio of the Higgs boson to invisible final states is $BR_i < 0.22$ (0.19). With 3000 fb^{-1} , the expected limit decreases to $BR_i < 0.13$ (0.09). The expected measurements for the $\kappa_g, \kappa_\gamma, \kappa_{Z\gamma}, BR_{inv}$ parameterisation are listed in model 7 of table 9.1. This limit is translated into constraints on the coupling of the WIMP to the Higgs boson as a function of its mass [55]. This is done for WIMP masses less than half the Higgs boson mass, under the assumption that the resulting Higgs boson decays to WIMP pairs account entirely for BR_{inv} . Any additional contributions to BR_{inv} from other new phenomena would produce a more stringent limit. The partial width for Higgs boson decays to a pair of dark-matter particles depends on the spin of the dark-matter particle as explained in section 1.3.5. Upper limits at the 90% CL on the WIMP-nucleon scattering cross section $\sigma_{\chi-N}$ are derived as a function on the WIMP mass m_χ , as shown in figure 9.12. The hashed bands indicate the uncertainty resulting from the systematic variation of the form factor f_N . They are compared with limits from direct searches for dark matter [271, 272, 273, 274, 275, 276, 277, 278, 279] at the confidence levels indicated.

The ATLAS limits on the WIMP nucleon scattering cross section are proportional to those on the invisible decay branching ratio. They are weaker (stronger) at low m_χ mass for scalar (Majorana and vector) WIMPs, and degrade as m_χ approaches $m_h/2$ as expected from kinematics. The limits are shown for $m_\chi \geq 1 \text{ GeV}$, but extend to WIMP masses small than this value.

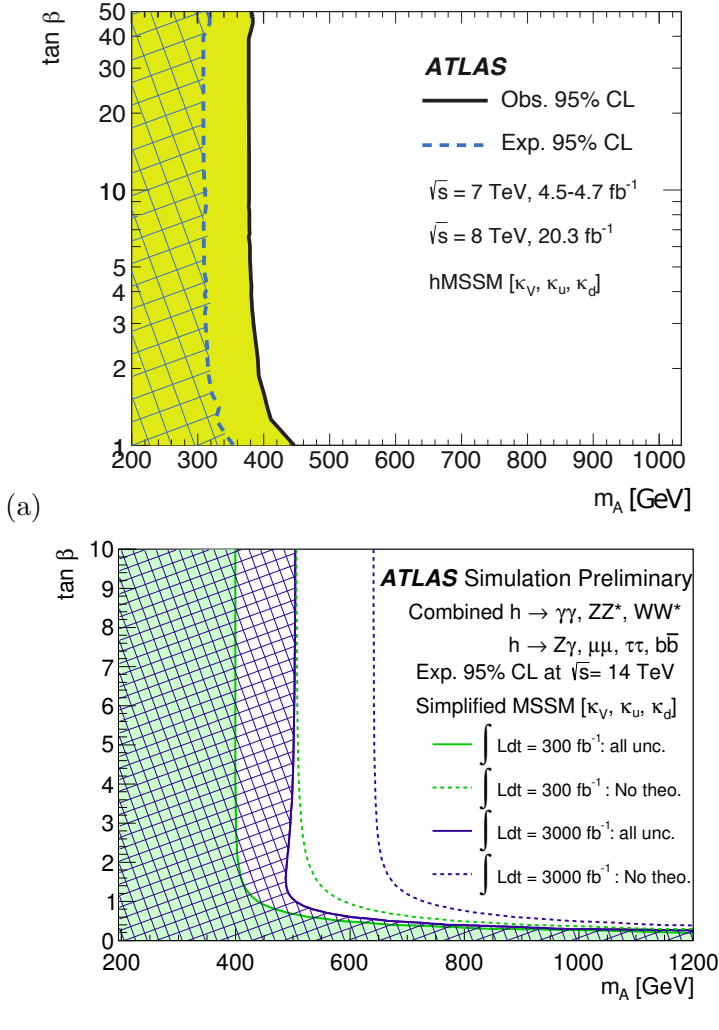


Figure 9.9: Regions of the $(m_A, \tan\beta)$ plane expected to be excluded in a simplified MSSM model via fits to the measured rates of Higgs boson production and decays. The likelihood contours where $-2\ln\Lambda = 6.0$, corresponding approximately to 95% CL (2σ), are indicated assuming the SM Higgs sector. The light shaded and hashed regions indicate the observed and expected exclusions, respectively. The SM decoupling limit is $m_A \rightarrow \infty$.

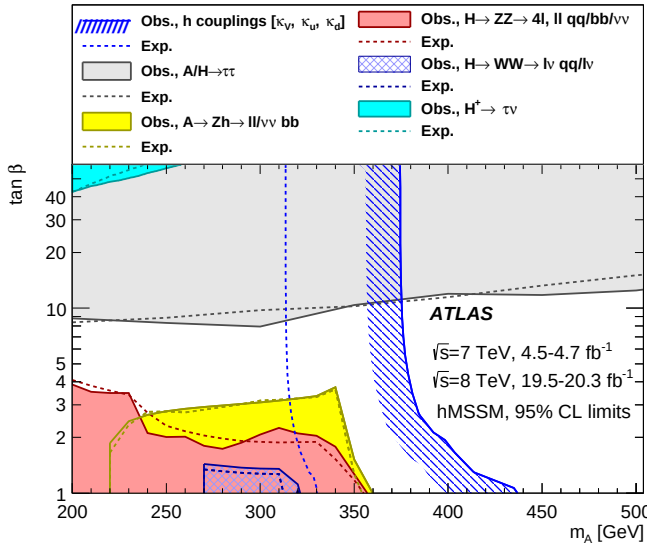


Figure 9.10: Regions of the $(m_A, \tan \beta)$ plane excluded in a simplified MSSM model via fits to the measured rates of Higgs boson production and decays. The likelihood contours where $-2\ln\Lambda = 6.0$, corresponding approximately to 95% CL (2σ), are indicated for the data and expectation assuming the SM Higgs sector. The light shaded and hashed regions indicate the observed and expected exclusions, respectively. The SM decoupling limit is m_A going to infinity. The light shaded or hashed regions indicate the observed exclusions.

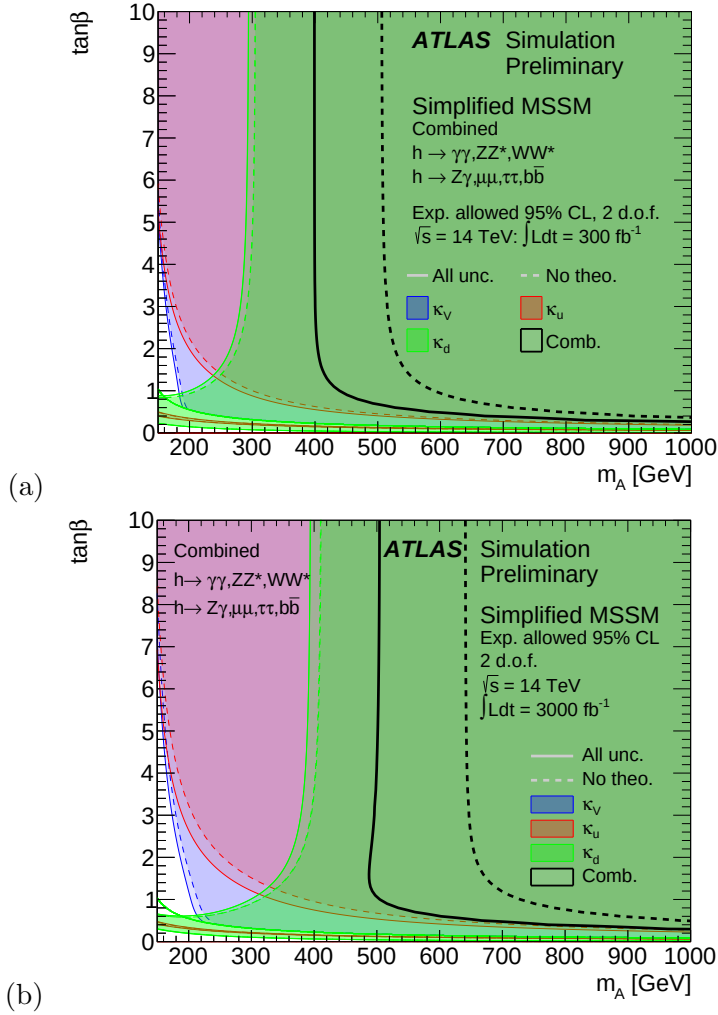


Figure 9.11: Regions of the $(m_A, \tan \beta)$ plane of the simplified MSSM expected to be compatible with the measured rates of Higgs boson production and decays, assuming the data follows the SM for (a) 300 fb^{-1} and (b) 3000 fb^{-1} of integrated luminosity. The expected 95% CL (2σ) regions are indicated. The light (dark) shaded regions are with (without) the inclusion of theory uncertainties in the Higgs boson coupling precision. The confidence interval for $\kappa_d = \kappa_l$ at large $\tan \beta$ corresponds to a positive sign relative to κ_u . The second confidence interval at low $\tan \beta$ similarly corresponds to a negative sign relative to κ_u . The confidence interval for κ_u at low $\tan \beta$ corresponds to a second solution of the equation $\kappa_u = s_u(m_A, \tan \beta)(1 + \tan^2 \beta)^{1/2} / \tan \beta$.

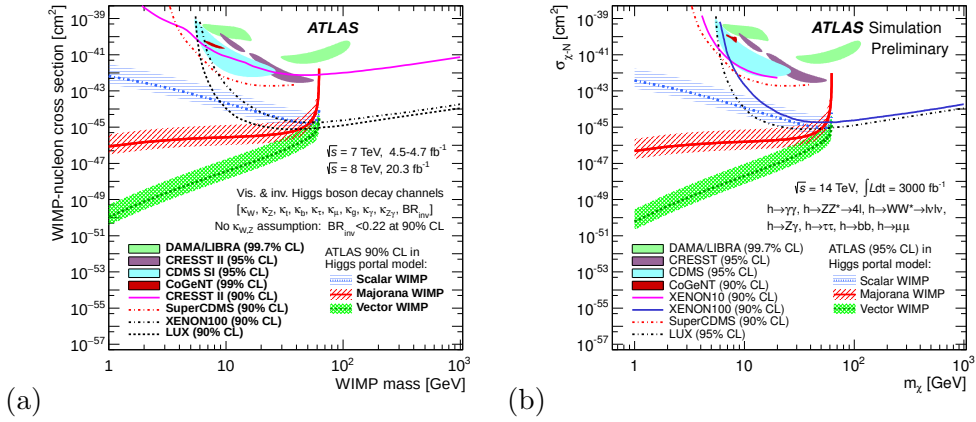


Figure 9.12: Observed and expected upper limit at 95% CL on the WIMP-nucleon scattering cross section in a Higgs portal model as a function of the mass of the dark matter particle, shown separately for a scalar, Majorana fermion, or vector boson WIMP, for (a) Run1 and (b) with 3000 fb^{-1} of data at $\sqrt{s} = 14 \text{ TeV}$ and including all systematic uncertainties. The hashed bands indicate the uncertainty resulting from the form factor f_N . Excluded and allowed regions from direct detection experiments at the confidence levels indicated are also shown [271, 272, 273, 274, 275, 276, 277, 278, 279]. These are spin-independent results obtained directly from searches for nuclei recoils from elastic scattering of WIMPs, rather than being inferred indirectly through Higgs boson exchange in the Higgs portal model.

9.10 Conclusions

Higgs boson coupling measurements from the combination of multiple production and decay channels have been used to indirectly search for new physics. The results are based on up to 4.7 fb^{-1} of pp collision data at $\sqrt{s} = 7 \text{ TeV}$ and 20.3 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$ recorded by the ATLAS experiment at the LHC. No significant deviation from the SM expectation is found in the observables studied, which are used to constrain various models of new phenomena. Projections are derived for 300 fb^{-1} and 3000 fb^{-1} of pp collision data at $\sqrt{s} = 14 \text{ TeV}$ expected to be collected by the ATLAS experiment, assuming the data follows the SM expectation. The inclusion of additional channels, as well as future improvements in the understanding of experimental and theoretical systematic uncertainties on the coupling measurements, would provide additional potential for sensitivity gains at the High-Luminosity LHC.

O Outlook

Higgs physics at the ATLAS detector has reached an exciting new phase of precision measurements, but the analyses are still mostly set up for conducting searches. The current strategy for the interpretation and combination of results follows either a BSM-specific model, as shown in chapter 9, or are setup in a BSM-agnostic way by the use of the kappa framework, introduced in section 1.5.1. Due to the absence of hints of BSM physics, an agnostic approach is valuable, however the theoretical interpretation of the kappa model suffers from its semi-empirical nature. In particular, a much more precise numeric determination of the parameters of the kappa framework with future larger datasets does not necessarily result in a better understanding of the Higgs Lagrangian due to the models intrinsic uncertainties.

A promising opportunity to improve the modelling of the Higgs boson signal in a BSM agnostic way, is the concept of analytic Lagrangian morphing, as introduced in chapters 5 and 6. The use of these new techniques will allow to extract more information on Higgs properties from the same data, by virtue of exploiting more kinematic features of that data, as shown in chapter 7. Another benefit of this method of signal modelling is that parameters can in such a model have a clearer connection with the parameters of an Effective Higgs Lagrangian, which makes the results better interpretable for high precision measurements.

As current predictions for Higgs precision measurement are based only on the extrapolation of Higgs boson rate measurements in the kappa model, it is expected that future measurements that also exploit the kinematic distributions will exceed these current projections [10, 12, 13].

Another strategy for future measurements is the use of the simplified cross-section method, as shown in chapter 8, which offers a more incremental way forward from the kappa model. From a technical viewpoint, the simplified cross-section measurement gives a more adiabatic evolution of the structure of the measurement model than the effective Lagrangian model. However a simplified cross-section measurement requires more effort in the interpretation

of the results.

General improvements in scope of the Higgs measurement programme will benefit all types of interpretation efforts. The inclusion of additional channels, such as the $t\bar{t}H$ production channel and the $H \rightarrow \mu\mu$ decay, as well as future improvements in the understanding of experimental and theoretical systematic uncertainties on the coupling measurements, would provide additional potential for sensitivity gains in future measurements. The systematical uncertainty on the analyses will improve due to the introduction of a-priori correlation of nuisance parameters in subsidiary measurement, which more accurately models reality.

BSM-specific models remain a promising approach to look into BSM physics, since they indicate to what degree future data restricts the parameter space of a specific BSM hypothesis. Independent of the choice of approach, an exciting, interesting and productive new phase of precision measurements in Higgs physics at the ATLAS detector has started.

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S Summary

Elementary particle physics describes and measures the properties of the smallest, most fundamental particles that make up the universe. The Standard Model of elementary particle physics (SM) provides a fundamental description of particles, their dynamics and interactions. The particles embedded into the theory are, a priori, massless, while observed particles have mass. In order to explain the origin of the elementary particle masses, the Brout-Englert-Higgs mechanism is introduced. The complex Higgs field introduces a spontaneous breaking of the electroweak (EW) gauge group when it acquires a non-vanishing vacuum expectation value. The Brout-Englert-Higgs mechanism introduces the existence of one real scalar field, with the Higgs boson as excitation, however it does not predict its mass. To verify that the Higgs mechanism is the origin of elementary particle masses is one of the main goals of the Large Hadron Collider (LHC) programs at CERN.

Before the start of the LHC, there was no experimental evidence of the existence of the Higgs boson, and limits on the Higgs boson mass were set by the Large Electron-Positron Collider (LEP) [1] and Tevatron [2]. The Higgs boson masses below 114 GeV and in the range of 158-175 GeV have been excluded by these experiments. The first run of the LHC (Run 1), which collected data between 2010 and 2012, discovered a new particle of a mass around 125 GeV in 2012 [3, 4]. Precision measurements of the Higgs boson properties are ongoing in the second run of the LHC (Run 2) with an increased beam energy.

This thesis gives an overview of the precision measurements of the Higgs boson properties, with reinterpretations of the Run 1 results, results of the ongoing Run 2 and prospects for the full second run and the High Luminosity LHC (HL-LHC).

With the measured mass of the Higgs boson, all other properties of the SM Higgs boson, such as its production cross section and decay widths, are predicted by the SM. In the ongoing second run of the LHC (Run 2) the couplings of the Higgs boson are further studied, including the production cross sections and decay widths. The measured total $pp \rightarrow H$ cross sections measured in Run 1 and Run 2 are summarised in figure S.1. No significant deviation from the Standard Model predictions is observed.

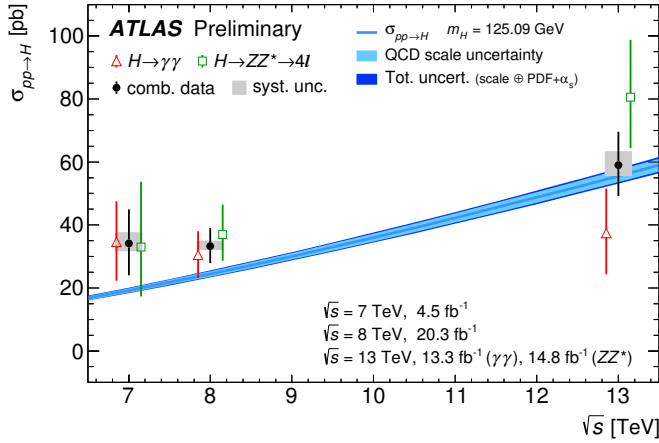


Figure S.1: Total $pp \rightarrow H$ cross sections measured at different centre-of-mass energies, compared to SM predictions at up to N³LO in QCD. The grey bands on the combined measurements represent the systematic uncertainty, while the black lines are the total uncertainties. The light blue band represents the QCD scale uncertainty and the dark blue band represents the total uncertainty on the theory prediction, assuming a Higgs boson mass of 125.09 GeV.

The expected improvement on the measurement of the coupling of the Higgs boson to vector bosons, κ_V , and the coupling to fermions, κ_f , is shown in figure S.2. The improvements at high luminosity compared to Run 2 are a factor of 2-3, particularly without the inclusion of the current theoretical systematic uncertainties. The scenario without systematics is included as a benchmark, since systematic uncertainties are expected to improve in the future, but no firm prediction exists on the expected rate of improvement.

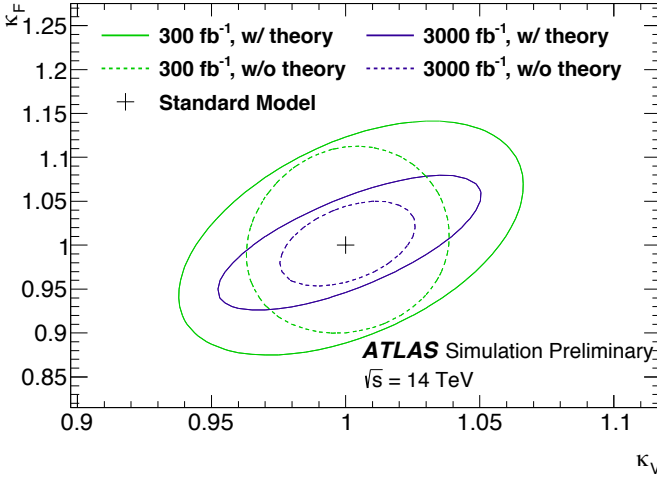


Figure S.2: 68% CL expected likelihood contour for κ_V and κ_f in a minimal coupling fit at 14 TeV for an assumed integrated luminosity of 300 fb⁻¹ and 3000 fb⁻¹.

Even with the discovery of the Higgs boson, the SM is not a complete theory of nature, as it does not answer several fundamental questions satisfactory. Proposed solutions for open questions often predict modifications or extensions of the minimal scalar sector that is embedded in the SM. Models with fundamental physics beyond the SM, such as composite Higgs boson models, theories with two Higgs doublets, Supersymmetry (SUSY) and models with a dark matter candidate, make predictions for modified couplings of the observed Higgs boson with a mass around 125 GeV. Data coming from the detectors of the LHC can be compared with these Beyond the Standard Model (BSM) theories.

The studies of the tensor structure of the Higgs boson couplings to gauge bosons are based on signal models including at most one or two beyond-the-standard-model couplings contributing at a time, with all remaining Beyond the Standard Model (BSM) parameters set to zero. For Run 2, it is envisioned to have signal models which depend on a larger number of coupling parameters simultaneously considered. These coupling parameters in the Higgs coupling to SM particles change the predicted cross section, as well as the shape of differential distributions. In this context, it is necessary to revise the existing signal modelling methods that only modify signal rates and provide alternatives which are better suited to describe both signal rate and shape changes in a n-dimensional parameter space. For this purpose, a morphing method has been developed and implemented. It provides a continuous description of arbitrary physical signal observables such as cross sections or differential distributions in a multidimensional space of coupling parameters. The morphing-based signal model is a linear combination of a minimal set of orthogonal base samples (templates) spanning the full coupling parameter space. The weight of each template

is derived from the coupling parameters appearing in the signal matrix element. A simplified illustration of the morphing procedure is shown in figure S.3.

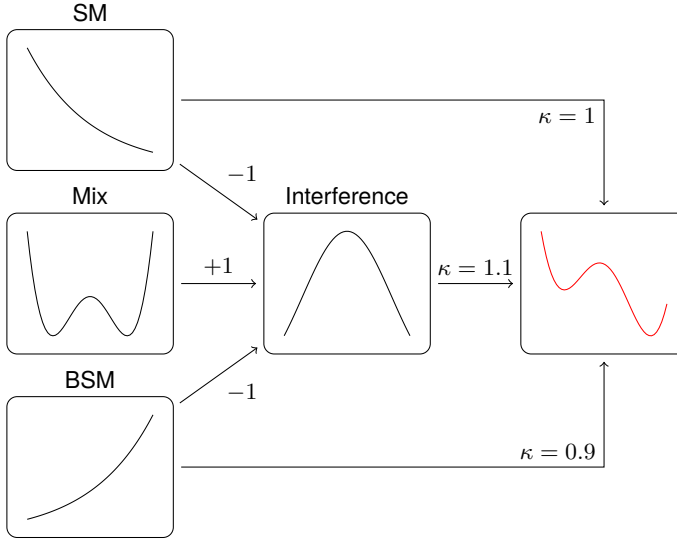


Figure S.3: Illustration of the morphing procedure in a simple showcase.

The morphing method has been shown to perform as expected using generator-level and reconstruction-level distributions. In addition, a preliminary study on the impact of BSM coupling parameters in the context of VBF Higgs boson production has been performed, acting both as a proof-of-concept for elaborate studies using this method and as a showcase for the performance of the morphing method. This method is capable of continuously morphing signal distributions and rates based on a minimal orthogonal set of independent base samples. Therefore it allows to directly fit for the coupling parameters that describe the SM and possibly non-SM interaction of the Higgs boson with fermions and bosons of the SM.

A method for optimising the sample basis has been proposed which could reduce the error arising from statistical precision of the input samples.

Within the Standard Model (SM) the Higgs must be a CP even scalar, a spin 0 particle. However, many BSM theories predict the existence of additional Higgs bosons which can be CP even, CP odd, or, as a result from the superposition of CP eigenstates, partially violating the CP symmetry. With the data collected at the ATLAS detector during Run 2 of the LHC it is possible to measure the CP properties of the coupling of the Higgs boson to top quarks for the first time. To reveal the CP structure of the Higgs boson coupling to top quarks, CP sensitive observables have to be considered to perform a direct measurement. Due to the conservation of angular momentum, a particularly promising CP sensitive observable is the azimuthal angle between two final state jets ($\Delta\Phi_{jj}$). As a result gluon-gluon fusion accompanied by two jets will be a very promising channel in which the CP structure of the Higgs boson coupling to top quarks can be measured [162]. Using the morphing method described in this thesis, a direct measurement is performed on the sensitivity of mixing angle α between a CP even and a CP odd Higgs boson. The expected result of this measurement is shown in figure S.4.

Higgs boson coupling measurements from the combination of multiple production and decay channels have been used to indirectly search for new physics. The results are based on up to 4.7 fb^{-1} of pp collision data at $\sqrt{s} = 7 \text{ TeV}$ and 20.3 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$ recorded by the ATLAS experiment at the LHC. No significant derivation from the SM expectation is found in the observables studied, which are used to constrain various models of new phenomena. Projections have been derived for 300 fb^{-1} and 3000 fb^{-1} of pp collision data at $\sqrt{s} = 14 \text{ TeV}$ expected to be collected by the ATLAS experiment, assuming the data follows the SM expectation. Figure S.5 shows as an example the region of the parameter space of a two Higgs doublet model that can be excluded with 300 fb^{-1} and 3000 fb^{-1} of data, assuming the data follows the expectation of a standard model Higgs boson.

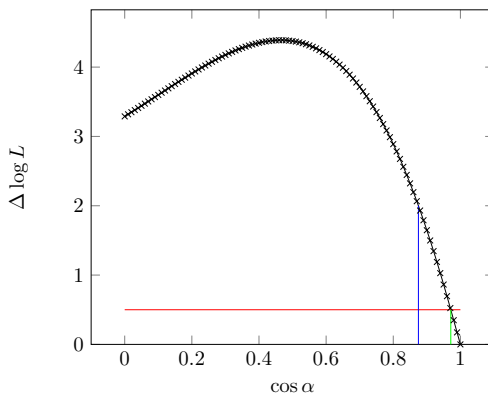


Figure S.4: Scan of the mixing angle, $\cos \alpha$, for an Asimov dataset created for a SM CP even Higgs boson. The mixing angle, $\cos \alpha$, mixes between a CP even and CP odd Higgs boson of the coupling of the Higgs boson to top quarks.

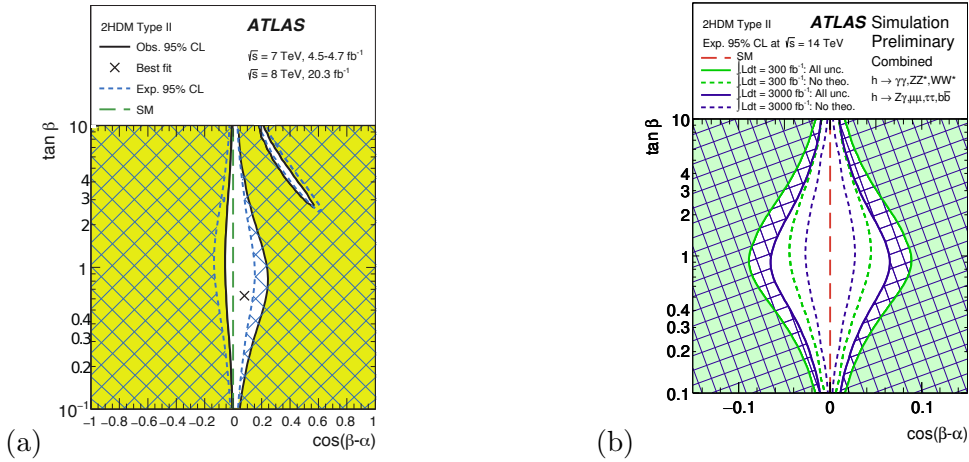


Figure S.5: Regions of the $(\cos(\beta-\alpha), \tan \beta)$ plane of a model with an additional Higgs doublet, where α is the angle between a CP even and CP odd Higgs boson and β is the ratio of the vacuum expectation values of the two Higgs boson. (a) Shows the excluded region by fits to the measured rates of Higgs boson production and decays and (b) shows the expected region to be excluded by fits to the measured rates of Higgs boson production and decays. The confidence intervals account for a possible relative sign between different couplings. The expected likelihood contours where $-2 \ln \Lambda = 6.0$, corresponding approximately to 95% CL (2σ), are indicated assuming the SM Higgs sector. The light shaded and hashed regions indicate the observed and expected exclusions, respectively.

Higgs physics at the ATLAS detector has reached an exciting new phase of precision measurements, but the analyses are still mostly set up for conducting searches. The research shown in this thesis has provided measurements in the Higgs sector, placed limits on new physics, and, with the Analytic Lagrangian Morphing tool, opened the door for precision measurements of Higgs physics at the LHC. Searches for extensions to the standard model can be performed with this tool, and will provide accurate possible predictions for any Standard Model and beyond the standard model parameters. Whilst this technique for analytic morphing is becoming widely accepted within the ATLAS Higgs group and was included in the recommendation in the Handbook of LHC Higgs Cross Sections (Yellow Report 4) [6], it can also be used within searches for BSM contributions to top-quark physics, precision measurements of EW processes and for measurements of processes such as triple gauge couplings. An exciting, interesting and productive new phase of precision measurements in Higgs physics at the ATLAS detector has started.

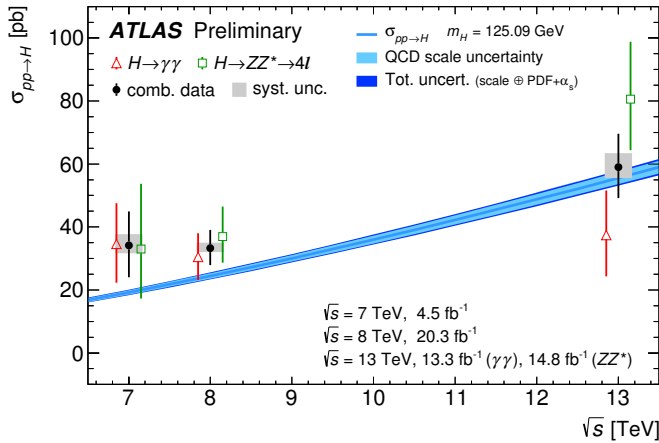
S Samenvatting

Elementairedeeltjesfysica beschrijft en meet de eigenschappen van de kleinste, meest fundamentele deeltjes waaruit ons universum bestaat. Het standaardmodel der deeltjesfysica (SM) biedt een fundamentele beschrijving van deeltjes en hun dynamica en interacties. De deeltjes in de theorie zijn, a priori, massaloos, in tegenstelling tot deeltjes die in experimenten worden gemeten. Om de oorsprong van de massa van elementaire deeltjes te beschrijven is het Brout-Englert-Higgs-mechanisme geïntroduceerd. Het complexwaardige Higgsveld introduceert een spontane breking van de elektrozwakke ijkgroep indien deze een niet-verdwijvende vacuümverwachtingswaarde verkrijgt. Het Brout-Englert-Higgs-mechanisme introduceert een reëel scalair veld, met als excitatie het Higgsboson, zonder de massa hiervan te voorspellen. Een van de hoofddoelen van de Large Hadron Collider (LHC) programma's van CERN is om te verifiëren dat het Higgsmechanisme de oorsprong van de massa van elementaire deeltjes is.

Voor de start van de LHC waren er geen experimentele bewijzen voor het bestaan van het Higgsboson, en de limieten aan de massa van dit deeltje waren vastgesteld door de Large Electron-Positron Collider (LEP) [1] en Tevatron [2]. Een Higgsboson met een massa onder 114 GeV of in het bereik van 158-175 GeV is uitgesloten door deze experimenten. De eerste periode van data-acquisitie van de LHC (Run 1), die data verzamelde tussen 2010 en 2012, ontdekte een nieuw deeltje met een massa rond 125 GeV in 2012 [3, 4]. Precisiemetingen aan het Higgsboson zijn gaande in de tweede periode van data-acquisitie van de LHC (Run 2), met een verhoogde energie van de protonbundels.

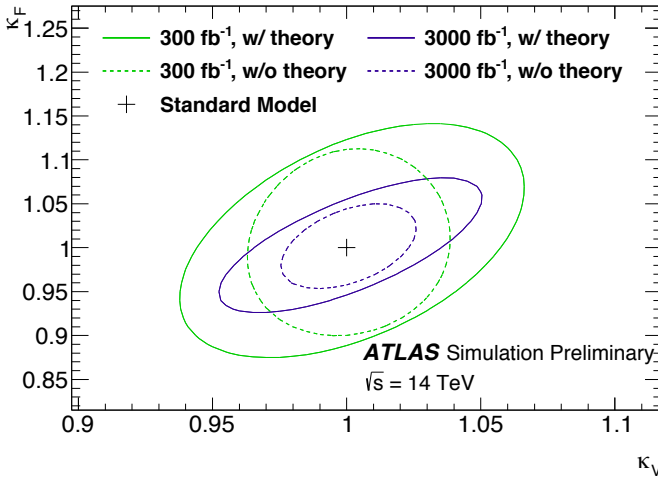
Dit proefschrift geeft een overzicht van de precisiemetingen aan de eigenschappen van het Higgsboson: reïnterpretatie van Run 1 resultaten, resultaten van de huidige Run 2 en voorspellingen voor de volledige tweede periode van data-acquisitie en de High Luminosity LHC (HL-LHC).

Met de gemeten massa van het Higgsboson zijn alle andere eigenschappen van het SM Higgsboson, zoals de werkzame doorsnede en vervalbreedte, voorspeld door het standaardmodel. In Run 2 zijn de koppelingen van het Higgsboson verder onderzocht, inclusief de werkzame doorsnede en vervalbreedte. De gemeten totale werkzame doorsnede van $pp \rightarrow H$ in Run 1 en Run 2 zijn samengevat in figuur S.1. Er is geen significante afwijking van de voorspellingen van het standaardmodel gemeten.



Figuur S.1: Totale werkzame doorsnede van $pp \rightarrow H$ gemeten op verschillende massamiddelpuntenergieën en vergeleken met SM-voorspellingen tot N³LO in QCD. De grijze banden rondom de gecombineerde metingen (zwarte punten) zijn de systematische onzekerheden en de zwarte lijnen de totale onzekerheden. De lichtblauwe band is de QCD-schaalonzekerheid en de donkerblauwe band de totale theoretische onzekerheid onder de aanname van een Higgsbosonmassa van 125,09 GeV.

De verwachte verbetering in de meting van de koppelingen van het Higgsboson aan vectorbosonen, κ_V , en de koppelingen aan fermionen, κ_f , zijn afgebeeld in figuur S.2. De verbeteringen bij hoge luminositeit vergeleken met Run 2 zijn een factor 2-3, in het bijzonder zonder de toevoeging van de huidige theoretische systematische onzekerheden. Het geval zonder systematische onzekerheden is meegenomen als ijkpunt, aangezien verwacht wordt dat de systematische onzekerheden in de toekomst verbeteren. Er bestaan echter geen eenduidige voorspellingen over hoe groot deze verbetering zal zijn.

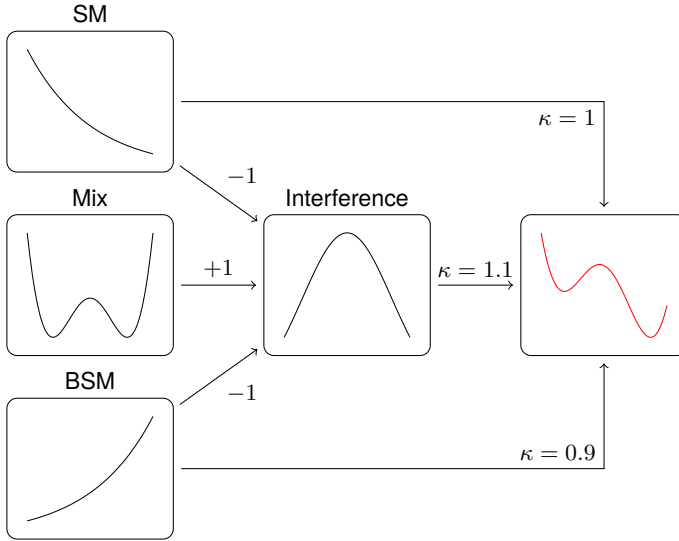


Figuur S.2: 68% CL verwachte waarschijnlijkheidscontour voor κ_V en κ_f in een minimale koppelingsfit met een massamiddelpuntsenergie van 14 TeV onder de aanname van een geïntegreerde luminositeit van 300 fb^{-1} en 3000 fb^{-1} .

Zelfs met de ontdekking van het Higgsboson is het SM niet een complete beschrijving van de natuur en beantwoordt het verschillende fundamentele vragen niet op een bevredigende manier. Voorgestelde oplossingen voor de openstaande vragen voorspellen vaak aanpassingen of uitbreidingen van de minimale scalaire sector van het SM. Modellen met fundamentele fysica buiten het SM, zoals modellen met samengestelde Higgsbosonen, theorieën met twee Higgsdoubletten, supersymmetrie (SUSY) en modellen met een kandidaat voor donkere materie, geven voorspellingen voor gemodificeerde koppelingen van het geobserveerde Higgsboson met een massa rond 125 GeV. Data verzameld door de detectors van de LHC kan worden vergeleken met deze modellen buiten het SM (BSM).

De studies naar de tensorstructuur van de koppeling van Higgsbosonen met ijkbosonen zijn gebaseerd op signaalmodellen met maximaal twee BSM koppelingen, zonder contributies van alle andere BSM-parameters. Voor de tweede periode van data-acquisitie staan signaalmodellen die afhankelijk zijn van een groter aantal simultane koppelingsparameters in het vooruitzicht. Deze koppelingsparameters in de koppeling van het Higgsboson aan SM-deeltjes veranderen de voorspelling voor de werkzame doorsnede en de vorm van de differentiële distributies. In deze context is het nodig om de bestaande signaalmodellerings methodes, die alleen de hoeveelheid signaal aanpassen, te herzien en alternatieven te geven die beter zijn in het beschrijven van de hoeveelheid signaal en hoe de vorm van de distributies veranderen in een n -dimensionale parameter ruimte. Om dit doel te bereiken is een morphingmethode ontwikkeld. Deze methode geeft een continue beschrijving van een arbitraire fysische observabele, zoals de werkzame doorsnede of differentiële distributies in een multidimensionale

ruimte van koppelingsparameters. Het op morphing gebaseerde signaalmodel is een lineaire combinatie van een minimale set van orthogonale basissjablonen, die de volledige koppelingsparameter ruimte opspannen. De schalingsfactor van elk sjabloon is afgeleid van de koppelingsparameters die in het matrixelement van het signaal voorkomen. Een versimpelde illustratie van de morphingmethode is te zien in figuur S.3.



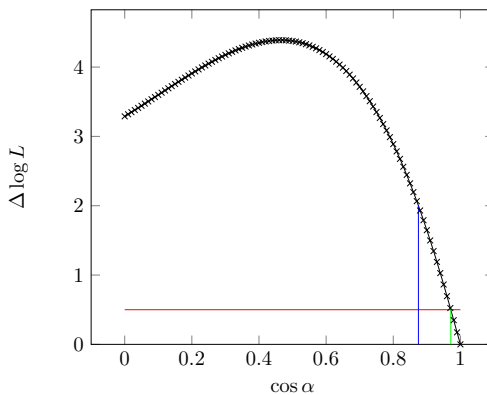
Figuur S.3: Illustratie van de morphingmethode in een simpel voorbeeldgeval.

Er is aangetoond dat de morphingmethode werkt naar verwachting met behulp van distributies op generatorniveau en reconstructieniveau. Een voorlopige studie naar de impact van BSM koppelingsparameters in de context van VBF Higgsbosonproductie is ook uitgevoerd. Deze studie is gebruikt als *proof-of-concept* voor uitgebreide studies met deze methode en als voorbeeld voor de prestaties van de morphingmethode. Deze methode is in staat om een continue signaaldistributie te vervormen en de hoeveelheden data gebaseerd op een minimale orthogonale set van onafhankelijke sjablonen. Hierdoor is het mogelijk om een koppelingsparameter die de SM - en mogelijke niet-SM - interacties van het Higgsboson met fermionen en bosonen van het standardmodel beschrijven, direct te fitten.

Een voorstel is gedaan voor het optimaliseren van de sjabloonkeuze, wat de statistische fouten van de sjablonen kan verkleinen.

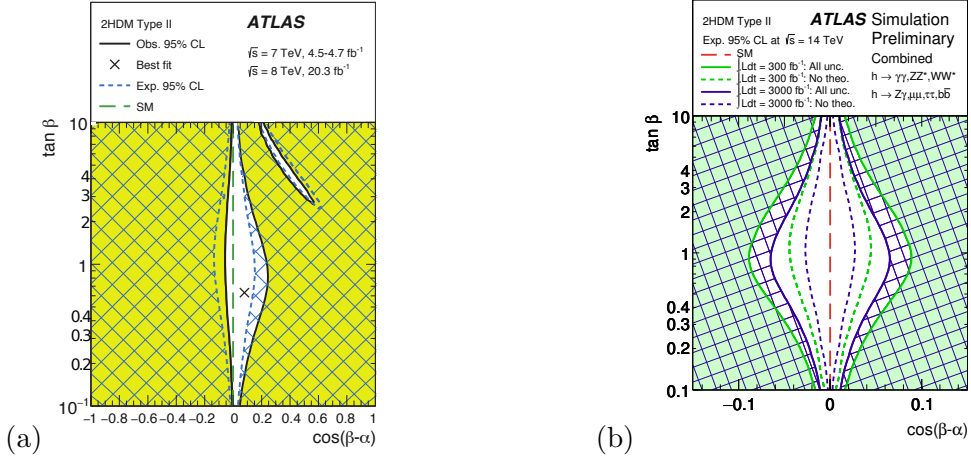
In het standaardmodel moet het Higgsboson een CP-even scalar, een spin-0 deeltje, zijn. Veel BSM-theorieën voorspellen echter het bestaan van extra Higgsbosonen die CP-even, CP-oneven of, als resultaat van een superpositie van CP-eigentoestanden, deels CP schendend kunnen zijn. Met de data verzameld door de ATLAS-detector tijdens Run 2 van de LHC is het mogelijk om de CP-eigenschappen van de koppeling van het Higgsboson met top quarks voor het eerst te meten. Om de CP-structuur van deze koppeling te achterhalen, zijn observabelen gebruikt die gevoelig zijn voor CP om een directe meting uit te voeren. Door het behoud van hoekmoment is de azimuthale hoek tussen de twee stralen in de eindtoestand ($\Delta\Phi_{jj}$) een veelbelovende observabele, die gevoelig is voor de CP-structuur van het deeltje. Hierdoor is gluon-gluonfusie met twee vergezellende stralen een veelbelovend kanaal om de CP-structuur van de koppeling van het Higgsboson aan top quarks te meten [162]. Een directe meting is uitgevoerd, met behulp van de morphingmethode zoals beschreven in dit proefschrift, naar de gevoeligheid van de mengingshoek α tussen een CP-even en een CP-oneven Higgsboson. Het verwachte resultaat van deze meting is afgebeeld in figuur S.4.

Metingen aan de koppelingen van het Higgsboson van de combinatie van meerdere productie- en vervalsskanalen zijn gebruikt om indirect te zoeken naar nieuwe fysica. De resultaten zijn gebaseerd op tot 4.7 fb^{-1} van pp -botsingsdata met een massamiddelpuntsenergie van $\sqrt{s} = 7 \text{ TeV}$ en 20.3 fb^{-1} met $\sqrt{s} = 8 \text{ TeV}$, verzameld door het ATLAS-experiment. Er is geen significante afwijking van de SM-verwachting gevonden in de observabelen die gebruikt zijn om de verschillende modellen van nieuwe fenomenen in te perken. Voorspellingen zijn afgeleid voor 300 fb^{-1} en 3000 fb^{-1} van pp -botsingsdata met een massamiddelpuntsenergie van $\sqrt{s} = 14 \text{ TeV}$, die verwacht wordt te worden verzameld door het ATLAS experiment, onder de aanname dat de data



Figuur S.4: Scan van de mengingshoek, $\cos \alpha$, voor een Asimov-dataset gecreëerd voor een SM CP-even Higgsboson. De mengingshoek, $\cos \alpha$, mixt tussen een CP-even en CP-oneven Higgsboson in de koppeling tussen het Higgsboson en top quarks.

de SM voorspellingen volgt. Figuur S.5 laat een voorbeeld zien van een regio van de parameterruimte van een model met twee Higgsdoubletten, welke kan worden uitgesloten met 300 fb^{-1} en 3000 fb^{-1} data, onder de aanname dat de data de voorspellingen voor het SM Higgsboson volgt.



Figuur S.5: Regio's van het $(\cos(\beta - \alpha), \tan \beta)$ -vlak voor een model met een extra Higgsdoublet, waar α de hoek tussen een CP-even en CP-oneven Higgsboson is en β de ratio van de vacuümverwachtingwaarden van de twee Higgsbosonen. (a) Laat de regio zien die is uitgesloten door fits aan de gemeten hoeveelheden Higgsbosonproducties en -vervalen en (b) laat de regio zien die wordt verwacht te worden uitgesloten door zulke fits. De verwachte waarschijnlijkheidscontouren waar $-2 \ln \Lambda = 6.0$, wat overeenkomt met ongeveer 95% CL (2σ), zijn aangegeven onder de aanname van een SM Higgssector. De licht ingekleurde en gearceerde regio's geven de geobserveerde respectievelijk verwachte uitgesloten regio's aan.

Higgsfysica bij de ATLAS-detector heeft een spannende nieuwe fase van precisie-metingen bereikt, maar de analyses zijn nog steeds grotendeels opgezet voor het uitvoeren van een zoektocht. Het onderzoek gepresenteerd in dit proefschrift heeft metingen in de Higgssector gegeven, limieten geplaatst op nieuwe fysica en, met de hulp van analytische Lagrangiaan morphing, de deur opengezet voor precisie-metingen van Higgsfysica bij de LHC. Zoektochten voor uitbreidingen van het standaardmodel kunnen worden uitgevoerd met behulp van deze morphingmethode en zullen nauwkeurige voorspellingen mogelijk maken voor parameters in en buiten het standaardmodel. Terwijl deze methode breed geaccepteerd wordt binnen de ATLAS-Higgsgroep en is toegevoegd aan de aanbevelingen in het handboek voor LHC-Higgs werkzame doorsneden (Yellow Report 4) [6], kan deze methode ook gebruikt worden in zoektochten

naar BSM-bijdragen in topquark fysica, precisiemetingen van elektrozwakke processen en voor metingen van processen zoals drievoudige ijk koppelingen. Een spannende, interessante en productieve nieuwe fase van precisiemetingen in Higgsfysica bij de ATLAS-detector is begonnen.

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Thank you also to Michael Duehrssen-Debling for supervising me even though it wasn't his job and having an enormous amount of patience.

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