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 $pp \to H$ 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.

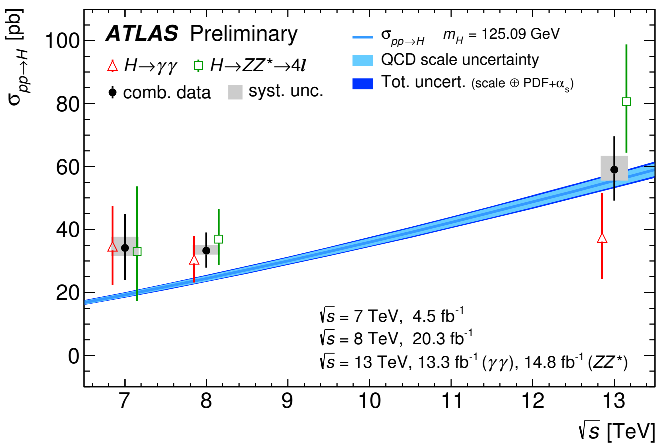

Figure S.1: Total $pp \to H$ cross sections measured at different centre-of-mass energies, compared to SM predictions at up to N^{3}LO in QCD. The grey bands on the combined measurements represent the systematic uncertainty, while the black lines are the total uncertainties. The light blue band represents 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.

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.

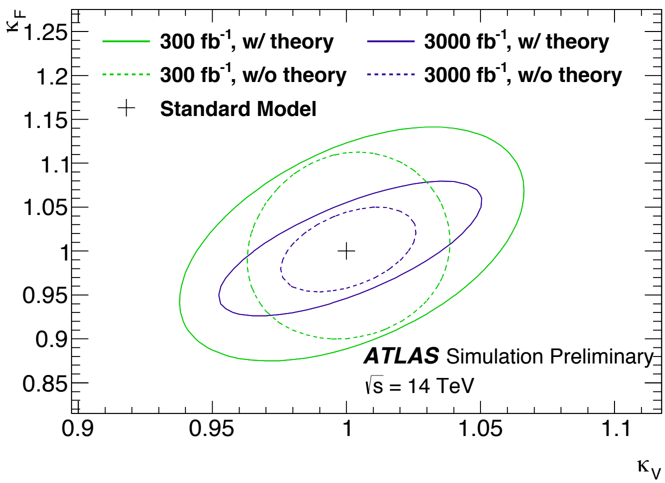

Figure S.2: 68% CL expected likelihood contour for κ_V and κ_f in a minimal coupling fit at 14 TeV for an assumed integrated luminosity of 300 fb^{-1} and 3000 fb^{-1}.

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.

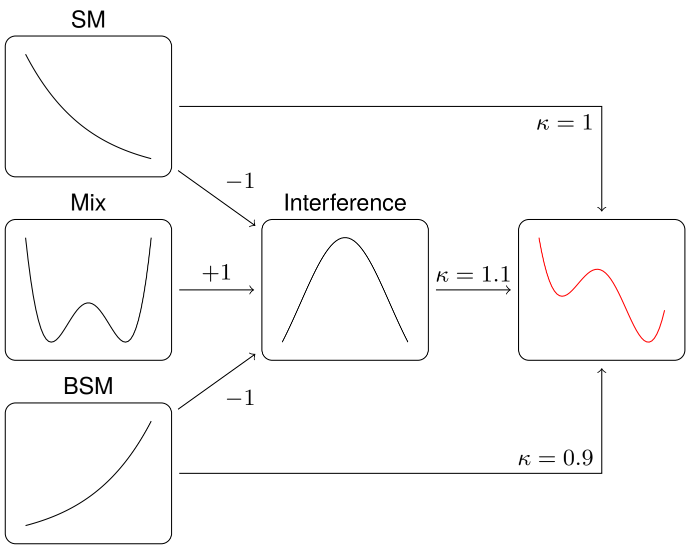

Figure S.3: Illustration of the morphing procedure in a simple showcase.

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 $\sqrt{s} = 7$ TeV and 20.3 fb^{-1} at $\sqrt{s} = 8$ 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 $\sqrt{s} = 14$ 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.

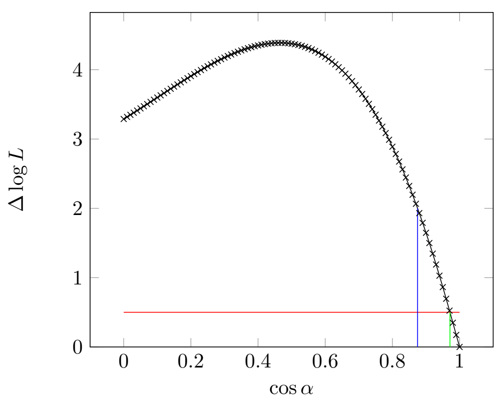

Figure S.4: Scan of the mixing angle, $\cos\alpha$, for an Asimov dataset created for a SM CP even Higgs boson. The mixing angle, $\cos\alpha$, mixes between a CP even and CP odd Higgs boson of the coupling of the Higgs boson to top quarks.

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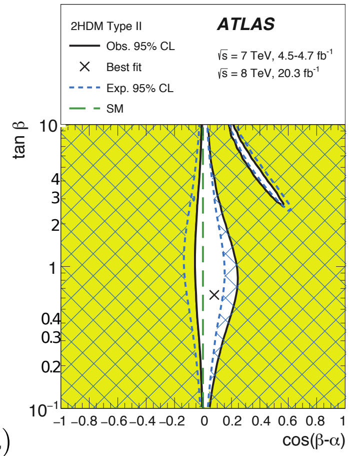
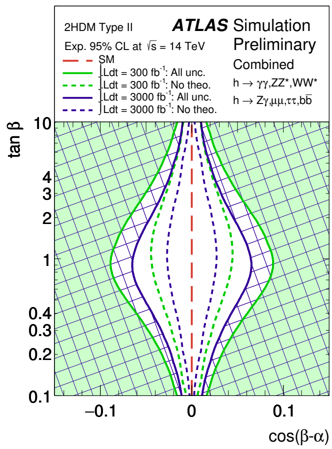


(a)



(b)

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.