Dissertation
submitted to the
Combined Faculties of the Natural Sciences and Mathematics
of the Ruperto-Carola-University of Heidelberg, Germany
for the degree of
Doctor of Natural Sciences

Put forward by

Marco Bellagente
born in Desio
Oral examination: XX.XX.2022

Go with the Flow

Normalizing Flow applications for High Energy Physics

Referees: Prof. Dr. Jan-Martin Pawlowski
Prof. Dr. Monica Dunford (?)

Abstract

bla bla

Zusammenfassung

bla bla Auf Deutsch

Contents

Preface

The research presented in this thesis was conducted at the Institute for Theoretical Physics at Heidelberg University from February 2019 to February 2022. The contents of the Chapters **??**-**??** are based on work in collaboration with other authors and have previously been published as

[1] M. Bellagente, A. Butter, G. Kasieeczka, T. Plehn and R. Winterhalder,
"How to GAN away Detector Effects",
SciPost Phys. **8** (2020) no. 4, 070, `arXiv:1912.00477 [hep-ph]`

[2] M. Bellagente, A. Butter, G. Kasieeczka, T. Plehn, R. Winterhalder, L. Ardizzone and U. Köthe,
"Invertible networks or partons to detector and back again",
SciPost Phys. **9** (2020) 074, `arXiv:2006.06685 [hep-ph]`

[3] M. Bellagente, M. Luchmann, M. HauSSmann and T. Plehn,
"Understanding Event- Generation Networks via Uncertainties",
`arXiv:2104.04543 [hep-ph]`

[4] R. Winterhalder, M. Bellagente, and B. Nachmann
"Latent Space Refinement for Deep Generative Models",
`arXiv:2106.00792 [stat.ML]`

1 | Introduction

The motivation behind the prediction of a fundamental scalar particle in the Standard Model (SM), the Higgs boson, was to grant a mechanism for the generation of the masses of the electroweak gauge bosons via electroweak symmetry breaking (EWSB) [?, ?, ?]. The discovery of a Higgs boson at the Large Hadron Collider (LHC) [?, ?] strongly hints at EWSB indeed being the mechanism behind the mass generation of the SM particles. One of the pivotal tasks of the LHC and future colliders is to probe both the local and global structure of the Higgs potential, which is reflected in the couplings of the Higgs boson to other SM particles and in its self-coupling, respectively. In this thesis, we present a global view on Higgs couplings at the LHC to extend our understanding of the EWSB sector and to set universal constraints on new physics that might be hiding in it.

The couplings of the Higgs boson to other SM particles manifest the local properties of its potential in the vicinity of the electroweak vacuum after EWSB. LHC measurements of the various predicted Higgs production and decay channels are crucial to explore and constrain these couplings. So far, the (preliminary) results of LHC Run II are compatible with the couplings predicted for the SM Higgs boson [?, ?]. Its four dominant production modes at the LHC have been observed with no significant deviation from the SM expectations. Moreover, LHC Run II has established the Higgs decays into the kinematically accessible third generation fermions in addition to the decays into pairs of the electroweak gauge bosons. Tight constraints have been set on the Higgs branching ratio to a pair of muons, to $Z\gamma$ or to *invisible*, i.e. to undetectable, particles.

While single-Higgs production measurements probe the local structure of the Higgs potential and provide only indirect constraints on the realization of EWSB, the examination of the global structure of the potential requires (at least) di-Higgs production. This process is sensitive to the trilinear Higgs self-coupling, which the LHC will only constrain to multiple times its SM value, even after its high-luminosity run [?]. For measurements in the percent range, future colliders are required [?, ?]. In any collider experiment, precise measurements of Higgs couplings to other SM particles are a crucial ingredient for the extraction of Higgs self-coupling from multi-Higgs production [?, ?, ?], which emphasizes the relevance of the local properties of the Higgs potential on a global scale.

The exploration of the structure of the Higgs potential is not only indispensable to gain a deeper understanding of EWSB on a fundamental level, it also provides important constraints for physics beyond the SM (BSM). The motivations for extension of the SM Higgs sector and their impact on Higgs couplings are versatile: The Higgs boson might be the mediator to a dark sector [?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?] resulting in, for instance, an increased Higgs branching ratio to invisible particles and global rescalings of its couplings to other SM particles. A modified Higgs potential or an extended Higgs sector has direct implications for vacuum stability [?, ?, ?, ?] and electroweak baryogenesis [?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?], which requires a strong first-order phase transition to ensure a deviation from thermal equilibrium [?]. If in fact electroweak baryogenesis is the mechanism responsible for the baryon-antibaryon asymmetry in the universe, the remnants of the electroweak phase transition may have observable consequences, e.g. , in the form of gravitational waves [?, ?, ?, ?].

Driven by the question what current data reveal about the EWSB sector and new physics that might be hiding in it, in this thesis we aim at increasing the precision of Higgs-coupling measurements and combining them in a comprehensive framework. This requires us to rethink the way we perform, interpret and combine experimental analyses in a way that fully exploits the available data. To tackle this challenge, we take a multi-prong approach: First, we focus on the improvement of an individual Higgs-production and decay channel by applying modern analysis techniques. Second, we perform global analyses of the Higgs-gauge sector for the LHC and a potential future upgrade of the LHC in a model-independent framework.

Data driven analysis techniques are applied to the experimental analyses of individual search channels more and more frequently. They replace simple cut-and-count strategies and vetoes by more advanced multivariate analyses and machine learning to profit from to the full information provided by the data. A prime test bed for the application of these new approaches is given by jets, not only because the LHC generates ample of them, but also because their substructure relies on relatively simple physical principles. In Chapter **??**, we apply a multivariate analysis to the tagging jets in weak-boson-fusion Higgs production with an invisible decay of the Higgs boson. Based on the observation that the tagging jets in the weak-boson-fusion Higgs signal are more likely to be quark-initiated, we examine the potential of variables targeting quark/gluon discrimination to suppress the gluon-dominated QCD backgrounds.

An economic use of the available Higgs data calls for a combination of measurements from different experiments, sectors and scales. Such comprehensive study can aid in making small effects of new physics visible on a global scale and demands for a universal parametrization of those. Historically, deviations from the SM Higgs couplings were described by coupling modifiers in the Δ-framework [**?**] (or the closely related κ-framework introduced in Ref. [**?**]). A phenomenologically more powerful framework to probe the data for hints of possible BSM physics in an almost model-independent way is given by SM effective field theory (SMEFT) [**?**, **?**, **?**, **?**, **?**, **?**], introduced in Chapter **??**. It directly links the Higgs and gauge sectors and allows for the modelling of modified Lorentz structures. We confront the SMEFT framework with data using the fitting tool SFitter [**?**]. As discussed in Chapter **??**, SFitter allows for an exhaustive treatment of statistical, systematic and theoretical uncertainties as well as their correlations.

Motivated by the experimental advances of LHC Run II, we perform a global fit of the Higgs-gauge sector based on Higgs and di-boson measurements as well as electroweak precision data in Chapter **??**. We include momentum-related kinematic distributions and examine the impact of the different LHC Run II measurements on the reach of our global analysis in detail. On the theory side, we broaden our view on the Higgs sector by expanding the set of considered dimension-six operators from 10 to 18 with respect to previous SFitter analyses [**?**, **?**]. This extension of our operator set will bring us a significant step closer to a global SMEFT fit at dimension six. We discuss how the additional fermionic Higgs-gauge operators have a relevant impact on a global fit of the Higgs-gauge sector despite the strong constraints from electroweak precision data.

An upgrade of the LHC to an energy of 27 TeV is among the realistic proposals for future colliders following the high-luminosity LHC era. The capability of such a 27 TeV hadron collider to produce a statistically relevant number of di-Higgs events prompts us to perform a global fit of the Higgs-gauge sector including a modified Higgs potential. In Chapter **??**, we assess the sensitivity of a high-energy upgrade of the LHC to the Wilson coefficients of dimension-six operators in the SMEFT framework. We thoroughly examine the correlations of operators influencing the extraction of the trilinear Higgs self-coupling and thereby probe the relevance of precise constraints on the local properties of the Higgs potential for the study of its global structure.

In Chapter **??**, we will summarize our results and give an outlook to further improvements and extensions of the concepts discussed in this thesis. Each of the lines of research mentioned above will aid in constructing a global view of Higgs couplings at the LHC as well as its proposed future upgrade and will bring us one step closer to probing if EWSB is indeed described by the simple structure of the SM Higgs potential. The derived limits on Higgs couplings in the SMEFT framework can be mapped onto constraints for UV-complete BSM models [**?**, **?**]. Furthermore, they provide a key ingredient for future tests of the global structure of the Higgs potential. In summary, the thorough investigation of Higgs couplings at the LHC is crucial to gain a deeper understanding of the structure of the Higgs sector and EWSB on a fundamental level.

2 | Generative Models

3 | Generative Adversarial Networks

4 | Invertible Neural Networks

5 | Bayesian Neural Networks

bla bla

6 | Latent Space Refinement

7 | Summary