A Search for the Higgs boson produced in association with top quarks in multilepton final states at ATLAS

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ABSTRACT

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Abstract abstract.

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Preface

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Chris Lester
CERN, Fall 2014

Chapter 1

Introduction

Here is a citation [1].

CHAPTER 2

Theoretical Background

The Standard Model of particle physics (SM) is an extraordinarily successful description of the fundamental constituents of matter and their interactions. Experiments over the past 50 years have verified the extremely precise prediction of the SM. This success has culminated most recently in the discovery of the Higgs Boson. This chapter provides a brief introduction to the structure of the SM and how scientists are able to test it using hadron collider but focuses primarily on the physics of the Higgs boson and its decays to top quarks. Particular attention is given to the importance of a measurement of the rate at which Higgs Bosons are produced in association of top quarks in the context of testing the predictions the SM.

2.1 The Standard Model

2.1.1 The Standard Model Structure

The Standard Model (SM) [2, 3, 4, 5] is an example of a quantum field theory that describes the interactions of all of the known fundamental particles. Particles are understood to be excitations of the more fundamental object of the theory, the field. The dynamics and interactions of the fields are derived from the Standard Model Lagrangian, which is constructed to be symmetric under transformations of the group $SU(3) \times SU(2) \times U(1)$. $SU(3)$ is the group for the color, $SU(2)$ is the group for weak iso spin, and $U(1)$ is the group for weak hyper-charge.

Gauging the symmetries demands the introduction of 8 massless gluons, or the boson (full integer spin) carriers of the strong force [6] from the generators $SU(3)$ symmetry, and the 4 massless bosons, carriers for the weak and electromagnetic forces from the 3 generators of the $SU(2)$ and 1 generator of the $U(1)$ group. The weak and the electromagnetic forces are considered part of a larger single unified electroweak group $SU(2) \times U(1)$ and the associated generators mix.

The gauge symmetry allows the theory to be re-normalizable [7], meaning that unwanted infinities can be absorbed into observables from theory in a way that allows the theory to be able to predict physics at multiple energy scales. Singlets of the $SU(3)$ group are fermions (half-integer spin particles) called leptons and do not interact with the strong, where as doublets of the $SU(3)$ group are called quarks and do interact with the strong force. The SM is a chiral theory: the weak force violates parity, as it only couples to left-chiral particles or right-chiral antiparticles. This means that right-chiral and left-chiral fermions arise from different fields, which are different representations of the weak isospin group.

The discovery of particles and new interactions in various experiments is intertwined with the development of the theory that spans many decades and is not discussed in detail here.

So far, 3 separate generations of both quarks and leptons have been discovered, differing only by mass.The gluon and the 4 electroweak bosons have also been discovered(W^+, W^-, Z^0, and γ) [1]. The reason for this 3-fold replication is not known.

2.1.2 Electoweak Symmetry Breaking and the Higgs

Despite the simple structure of theory, the discovery of massive fundamental particles creates two sets of problems both related to $SU(2) \times U(1)$. First, the force-carrying bosons must enter the theory without mass or the symmetries will be explicitly broken in the Lagrangian. Second, adding fermion masses to theory in an ad-hoc way allows the right-chiral and left-chiral fermions to mix. Since they possesses different quantum numbers, as different representations of the weak-isospin group, this too breaks gauge invariance.

To solve these problems, spontaneous electro-weak symmetry breaking (EWSB) is introduced via the Brout-Englert-Higgs mechanism [8, 9, 10]. A massive scalar field in an electro-weak doublet is added to the theory with 4 new degrees of freedom and a potential which includes a quartic self-interaction term. Each fermion field interacts with the scalar field via a different Yukawa coupling, which unites the left and right chiral fields of a single particle type. This field explicitly preserves all of the symmetries, butt the minimum of the potential does not occur when the expectation of the field is zero. The field eventually falls to a state, where it acquires a vacuum-expectation value. However, a non-zero field must therefore point in a particular direction of weak-isospin space, breaking the symmetry.

[1] The actual particles observed to be produced and propagate may be linear combinations of the underlying generators (for the bosons) or gauge representations (for the fermions).

The consequences of this spontaneous symmetry breaking are tremendous. First, the universe is filled with a field with a non-zero expectation value. The theory can be expanded around this new value and 3 of the degrees of freedom can be interpreted as the longitudinal polarizations of the W^+, W^-, and Z^0, while the 4th remains a scalar field, called the Higgs field with an associated particle called the Higgs particle or "Higgs" The weak bosons acquire a mass via their longitudinal polarizations and the Yukawa couplings of the scalar field to the fermions now behave like a mass term at the this new minimum.

2.1.3 The Standard Model Parameters

Although the SM structure is set by specifying the gauge groups, the EWSB mechanism, and acknowledging the 3-fold replication of the fermions, confronting the SM with experiment requires the measurement of 17[2] free parameters, which are unconstrained from the theory. These free parameters include the fermion masses (from the Yukawa coupling), the force coupling constants, the angles and phase of the mixing between quarks, and constants from the Higgs and electroweak sector[3].

Experiments have provided a number of measurements of the parameters of the SM[11]. Prior to the discovery of the Higgs boson (discussed later) the Higgs mass, however,was the only fully unconstrained parameter, although its value could be inferred via its involvement in loop corrections on the top mass (M_t) and the W mass (M_W). The GFitter collaboration assembles all relevant electroweak observable measurements into a statistical model and then allows certain measurements to float within their uncertainty to allow fora fit among multiple correlated measurements measurements [12]. Figure 2.1 shows the fitted constraints on 4 key SM parameters (M_H, M_W, M_t, $sin^2\theta_w$) with actual measurements overlaid. The addition to the fit of the measured Higgs mass from the ATLAS and CMS collaborations creates a small tension, as the other observables prefer the mass to be much lower ($\sim$ 80 GeV/c^2). The tension in the combined electroweak fit (including the Higgs) is not statistically significant with a p-value of 0.07.

2.2 Collider Physics and the Higgs

To test the theory, physicists accelerate particles to extremely high energies and force them to interact through collisions. Typically, the particles accelerated are electrons or protons, since they are stable.

[2]There are additional parameters from neutrino mass terms and mixing but it is unclear how to include these into the Standard Model, since it does not predict right-chiral neutrinos

[3] The electroweak sector includes parameters like mass of the $W^\pm$ and Z^0 bosons, the weak mixing angle,$sin^2\theta_w$, the fermi constant G_F, and Higgs Mass and vacuum expecation value. These parameters however are not wholly independent. As discussed above, it is only necessary theoretically to specify the two parameters relevant to the Higgs potential and the two coupling associated with the gauge groups

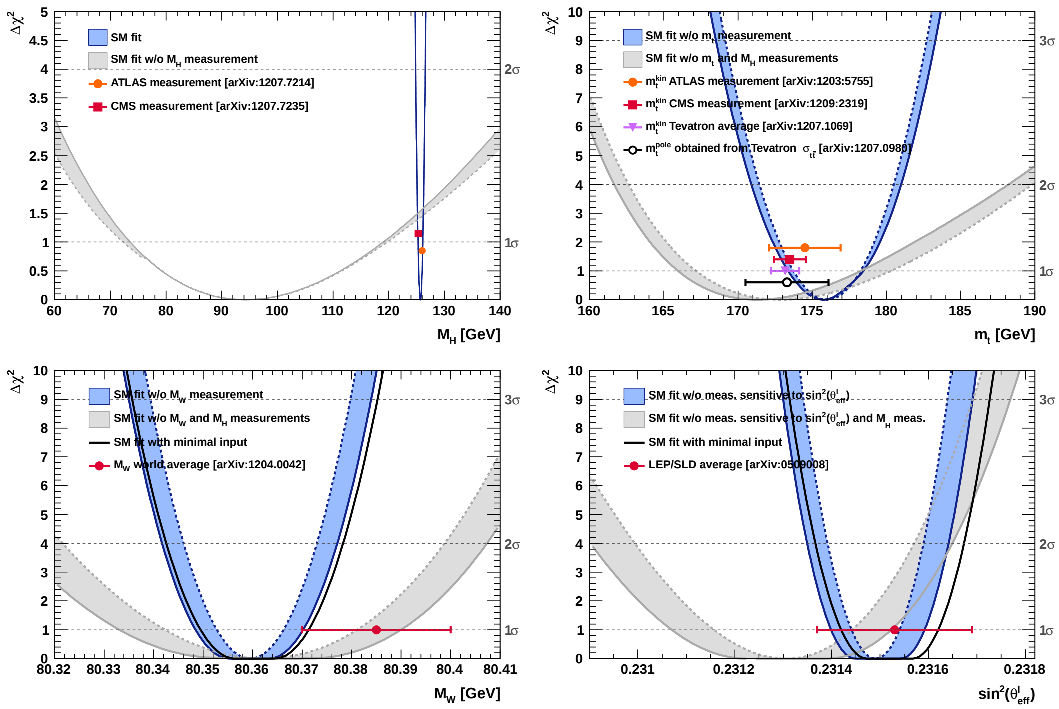

Figure 2.1: χ^2 as a function of the Higgs mass (top left), the top quark mass (top right), the W boson mass (bottom left) and the effective weak mixing angle (bottom right) for the combined SM fit from the GFitter group. The data points placed along $\chi^2 = 1$ represent direct measurements of the respective observable and their $\pm 1\sigma$ uncertainties. The grey (blue) bands show the results when excluding (including) the new M_H measurements from (in) the fits.

Electron-positron collider machines have a rich history of discovery and measurement in particle physics. The advantage of electron accelerators is that the colliding element is itself a fundamental particle. However, due synchrotron radiation, curvature of the beam line becomes problematic for high energy beams. Hadron colliders, specifically, proton-proton and proton-anti-proton colliders can be accelerated in rings without large losses due to synchrotron radiation, but the actual colliding objects at high energies are the constituent quarks and gluons. This complicates analysis because the initial state of the system is not discernible on a per-collision basis and momentum of hard scatter system is unknown along the beam direction.

Collider physics rely on form-factor descriptions of the colliding hadrons that describe the fraction of momentum carried by the hadrons constituent 'partons'. These are called parton-distribution functions, seen in Figure 2.2, and are factorized and integrated through the theoretical calculations of various collision processes [13].

At the Large Hadron Collider or LHC (discussed in detail in Chapter 3 a proton-proton colluder,

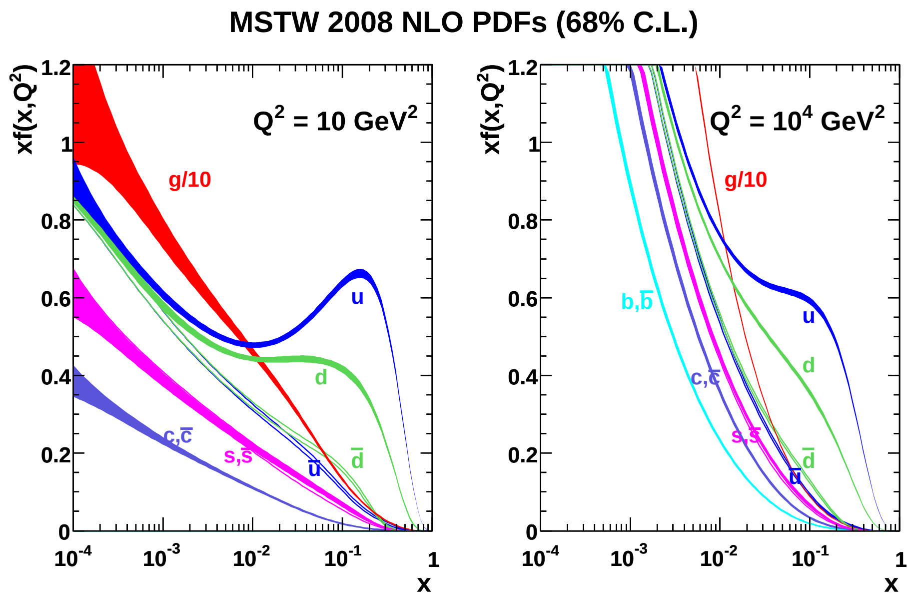

Figure 2.2: Proton Parton Distribution Functions (PDFs) form the MSTW Collaboration at $Q^2 = 10$ GeV^2 and $Q^2 = 10^4$ GeV^2

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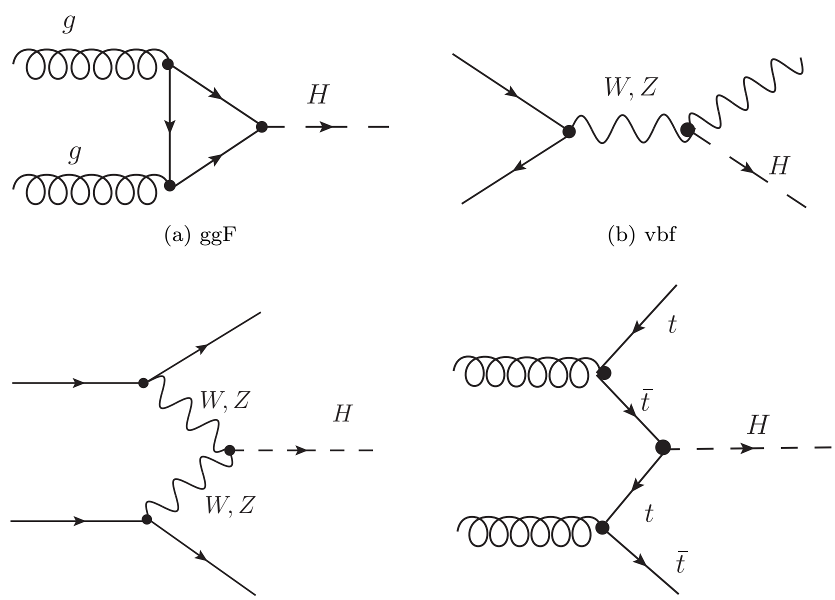
the types of initial states are quark-quark, quark-gluon, and gluon-gluon. Gluon collisions dominate overall, due to the large number of gluons inside the proton, though the relative importance of different initial states changes with the energy scale of the collision and the type of final state sought after.

A prime motivation for the construction of the Large Hadron Collider was the discovery or exclusion of the Higgs boson[14]. LEP and the Tevatron excluded large swaths of possible Higgs boson masses, especially below 114 GeV/$c^2$and the unitarity of certain diagrams including the $WWWW$ vertex required the mass to be below about 1 TeV, a range that was achievable at the LHC with high luminosity running [11].

Despite the ubiquity of Higgs couplings, Higgs boson production at the LHC is a low rate process. Because it couples to fermions proportional to mass and because the colliding particles must be stable and therefore light, production of the Higgs must occur through virtual states.

The Higgs boson can be produced through collision at the LHC via 4 mechanisms: gluon-fusion (ggF), vector-boson fusion (VBF), Higgsstrahlung (VH), and production in association with top quarks ($t\bar{t}H$). The diagrams are shown in Figure 2.3 and the production cross-sections as a function of Higgs mass for the 8 TeV LHC proton-proton runinng are shown in Figure 2.4 [15]. The largest production cross-section is via the gluon fusion channel at 20 pb, which proceeds through a fermion loop that is dominated by the top quark, because of its large Yukawa coupling to the Higgs.



(a) ggF (b) vbf (c) vh (d) $t\bar{t}H$

Figure 2.3: Dominant Higgs production modes at the LHC

Because the Higgs' couples to every massive particle, it has a rich set of decays also seen in Figure 2.4, especially for $m_H = 125$. Studies of Higgs properties at hadron colliders offers many tests of the Standard Model and ample room for searches for new physics. These tests specifically can verify the link between Yukawa coupling and the particles mass and further constrain details of EWSB by examining Higgs coupling to the weak bosons.

2.2.1 Higgs Discovery at the LHC

In 2012 both ATLAS and CMS announced the discovery of a new boson consistent with the Higgs by examining the results of Higgs searches in a number of decay channels ($H \to W^+W^-$,$H \to Z^0Z^0$, and $H \to \gamma\gamma$) in the 2011 dataset at $\sqrt{s}$ =7 TeV and part of the 2012 dataset at $\sqrt{s}$ =8 TeV. By 2013 and 2014, both experiments have updated and/or finalized their results for the full 2011 and 2012 datasets [16, 17]. I will focus on the ATLAS results in the following. The ATLAS measurements constrain both the Higgs mass[18] and spin[19], as well as provide constraints to the Higgs couplings to different particles.

Figure 2.5 show the results of the searches in all of the measurement channels as well as constraints on the SM Higgs coupling parameters in an example fit, where the couplings to the top-quark, bottom-

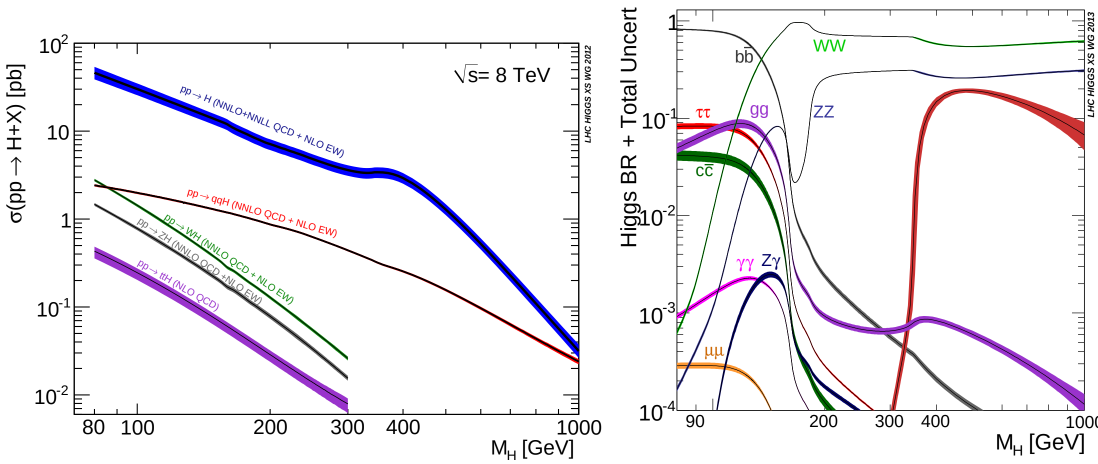


Figure 2.4: 8 TeV LHC Higgs production cross-sections (left) and decay branching fractions

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quark, W,Z, and τ are allowed to fluctuate independently. These rely on measurements binned in different production and decay channels. They are dominated by higher statistics results in the gluon-fusion production modes, but measurements in the VH and VBF modes are close to SM sensitivity.

The combined results show basic agreement with the SM with much room for improvement with the addition of new production and decay modes and higher statistics. The coupling constraints are particularly strong for the W and Z, which are the most sensitive decay channels, and top quark due to the dominance of the top Yukawa in the ggF loop.

2.2.2 $t\bar{t}H$ Production

Notably absent thus far in the SM are searches for the Higgs in the $t\bar{t}H$ production channel, due to the lack of statistics. Searches are underway and initial results are close to SM sensitivity for ATLAS and CMS. More will be discussed about particular searches later. $t\bar{t}H$ production depends on the top Yukawa coupling at tree level. Comparison of the gluon-fusion and the $t\bar{t}H$ modes would allow for disentangling the effects of of new particles in the gluon-fusion loop[20]. For instance, generic models would allow for the introduction of new colored particles into the loop. The simplest of these models would be the addition of a new generation of quarks. Fourth generation quarks, which obtain mass from a Higgs Yukawa coupling are already largely excluded due to their enormous effects on the Higgs production cross-section[21]. Other exotic scenarios allow for new colored particles in the gluon-fusion loop, which are not entirely constrained by present measurements[22, 23, 24]. These include, for instance, Supersymmetric models involving the stop quark.

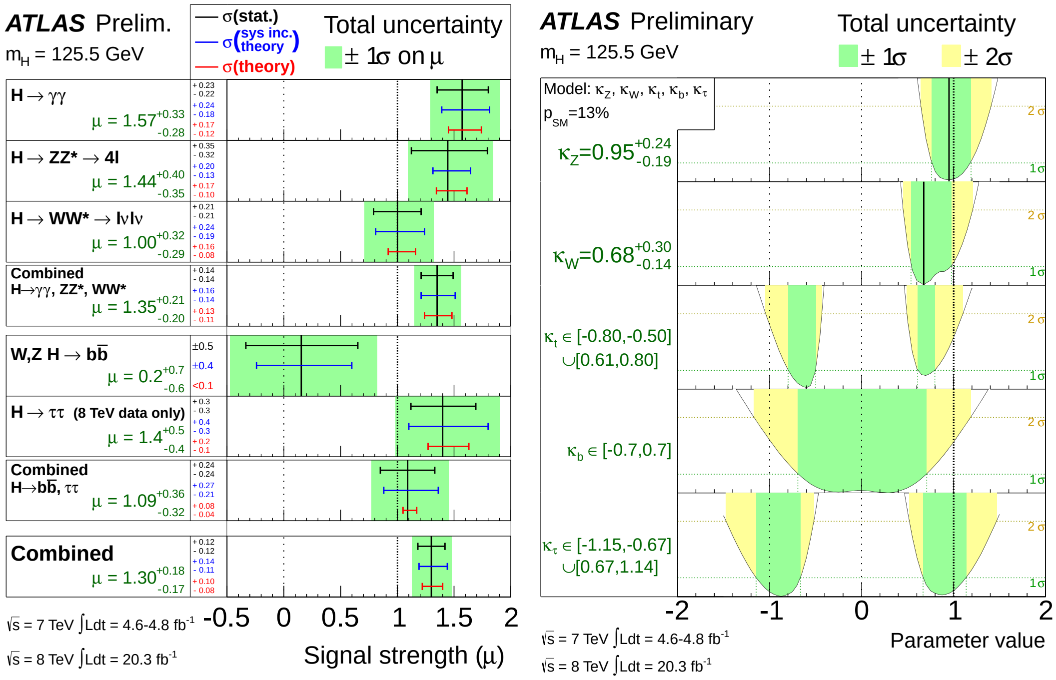

Figure 2.5: ATLAS Higgs combination results for all SM measurement channels as ratios of the measured to SM production cross-sections (left) and extracted Higgs coupling constraint scale-factors for a combined fit to the measurement channels, where the W,Z, top-quark, b-quark, and τ couplings are allowed to float. The p-value of this particular model is 0.13 and in agreement with SM expectations

Aside from the loop effects, measurement of the $t\bar{t}H$ production cross-section would provide a precise measurement of the top Yukawa coupling. When compared with the measured top quark mass, this tests the Higgs mass generation properties for up-type quarks. Despite similar uncertainties on the overall production cross-sections for $t\bar{t}H$ and the gluon-fusion modes, both of which depend on the top Yukawa, most of these uncertainties would cancel for $t\bar{t}H$ if normalized to the topologically similar $t\bar{t}Z$. Finally, the uniqueness of the experimental signature means that searches for $t\bar{t}$ signatures can be performed for a variety of Higgs decays ($\gamma\gamma$, $b\bar{b}$, WW,ZZ, and $\tau\bar{\tau}$ with roughly similar degrees of sensitivity (within a factor of 10)[20].

It is important to note the importance of the top Yukawa coupling to the overall structure of the SM, due to its enormous size compared to other couplings. The top Yukawa is for instance 350000x as large as the electron Yukawa coupling. Because of this the top Yukawa coupling, along with the Higgs mass, is one of the most important pieces of the renormalization group equations (RGE) responsible for the running of the parameter that determines the Higgs self-coupling λ. If this parameter runs negative, then the potential responsible for the entire mechanism of EWSB no longer has a minimum and becomes unbounded, resulting in instability in the universe [25]. Metastability occurs when the

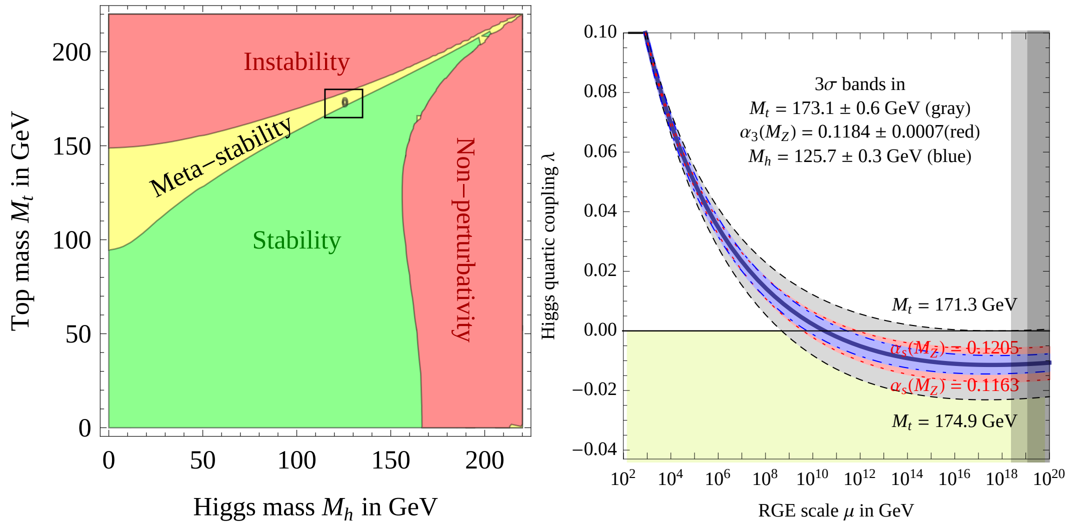

Figure 2.6: RGE for the running of the SM parameter, λ for the Higgs self-coupling term with present values and uncertainty bands for M_H and M_t (left). The two-dimensional plot colored (right) shows regions for which the SM is stable, unstable, and metastable based on this RGE

shape of the potential allows for a false local minimum. Figure 2.6 shows the running of this parameter, the regions for which the universe is stable, unstable and metastable. Current measurements suggest that universe lies in a metastable island[4].

2.3 Conclusion

The Standard Model, despite its success in providing a unified description of fundamental particles and interactions into single theory, has its flaws. These have been discussed in depth elsewhere, but include issues like the description of massive neutrinos, the failure to include gravity, and the unnaturalness of large quantum corrections to Higgs parameters. For these reasons, it seems the SM might be a lower energy approximation to a more fundamental theory. The discovery of the Higgs boson at the LHC provided a stunning verification of one of the fundamental aspects of the theory but at the same time offers new area to search for glimpses of something grander. The production of samples of Higgs bosons allows for a rich array of new tests of the Standard Model, which is now finally over-constrained by experiment. Searches for the $t\bar{t}H$ production, one category of which is the topic of this thesis, provide tree-level access to a central parameter of the theory, the top Yukawa coupling, as well as access a variety of Higgs decays, which will eventually provide a rigorous new test of the SM.

[4] The RGE assumed that there is no new physics at all energy scales

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Chapter 4

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