

# CHAPTER 1

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## Introduction and Theoretical Background

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The Standard Model of particle physics has been tested by many experiments and has been shown to accurately describe high energy particle interactions. The existence of a scalar particle, known as the Higgs boson, is central to the theory. The Higgs boson breaks electro-weak symmetry and provides mass to the elementary particles in a consistent way. Prior to the turn-on of the LHC, the Higgs boson was the only fundamental particle in the Standard Model that had not been observed.

The remainder of the chapter is organized as follows: Section 1.1 gives a basic introduction to the Standard Model of particle physics and the role of the Higgs. Section 1.2 describes several tests of the Standard Model, and implications for the Higgs. Section 1.3 describes Higgs production at the LHC.

### 1.1 Standard Model and the Higgs

The Standard Model (SM) [1, 2, 3, 4] is a description of nature in terms of fundamental particles and their interactions. It has been developed over a number of decades, and has been guided both by theoretical predictions and experimental discoveries. The SM encompasses three of the four fundamental forces of nature: electromagnetism, the strong interaction, and the weak interaction. Apart from gravity, the interactions described by the SM are responsible for all aspects of daily life. Electromagnetism describes the interaction of electrons with nuclei, and is thus responsible for all of chemistry and biology. The strong force describes the interactions within the nucleus. The weak force provides a description of radioactivity and nuclear fusion, which powers the stars.

The SM describes nature using a mathematical formalism known as quantum field theory [5]. The fundamental particles are represented by quantum fields. Quarks and leptons constitute matter, and are represented by fields with half integer spin, referred to as “fermion” fields. The dynamics of this system, i.e. the motion and interactions of excitations in the fields, is governed by a mathematical

function referred to as the Lagrangian.

The SM is a particular type of quantum field theory known as a gauge theory. The Lagrangian of the SM is invariant under continuous internal transformations of the group  $SU(3) \times SU(2) \times U(1)$ . This invariance is referred to as gauge invariance, and is critical for ensuring that the theory is consistent. Additional quantum fields, corresponding to each of the internal symmetry generators, are required to ensure gauge invariance. These fields are of integer spin and are referred to as “gauge fields”. The excitations of the gauge fields correspond to particles referred to as “gauge bosons”. In the standard model twelve gauge fields are included in the Lagrangian, eight for the generators of  $SU(3)$ , three for the generators of  $SU(2)$ , and one for the  $U(1)$  generator.

In principle, what has been described above is enough to define a consistent theory of particles and their interactions. In fact, the  $SU(3)$  gauge symmetry coupled to the quarks correctly describes the strong interaction, with the eight  $SU(3)$  gauge fields associated to the different colored states of the gluon. Gluons have been observed experimentally [6, 7] and interact with quarks as predicted in the SM.

A problem arises when considering the part of the SM that describes the electromagnetic and weak interactions, governed by the  $SU(2) \times U(1)$  symmetry. To preserve gauge invariance, the gauge fields must be added without mass terms. This implies that the gauge bosons should appear as mass-less particles, as is the case for gluons. However, to properly describe the weak force, the gauge bosons associated to it are required to have a large mass, seemingly in contradiction with the prediction.

The masses of the quarks and leptons pose another problem. The weak interaction violates parity, coupling differently to left and right-handed quark and lepton helicity states. To account for this in the SM, the left and right-handed fermions are treated as different fields, with different couplings. A fermion mass term in the Lagrangian would couple these different fields, and thus break gauge invariance. A gauge invariant left-handed weak interaction implies that the fermion fields should not have mass terms, and that the quarks and leptons which appear in nature should be mass-less particles. This, again, is in direct conflict with observation.

From a theoretical point of view, both of the these problems can be overcome by what is referred to as “spontaneous symmetry breaking” [8, 9, 10, 11, 12, 13].. The idea is that additional quantum fields are added to the theory that couple to the electro-weak  $SU(2) \times U(1)$  gauge fields. These fields have zero spin, and are referred to as “scalar” fields. The scalar fields are included in a way that respects the  $SU(2) \times U(1)$  symmetry, and preserves the gauge invariance of the Lagrangian. The trick is that the scalar fields are added with a special form of interaction such that zero values of the fields do not correspond to the lowest energy state. While the actual interaction in the Lagrangian preserves

the  $SU(2) \times U(1)$  symmetry, the ground state of the field will necessarily break it. As a result, the Lagrangian preserves gauge invariance, despite the fact that the particular state that describes nature does not exhibit  $SU(2) \times U(1)$  symmetry. In this sense the symmetry is said to be “spontaneously broken”.

The upshot of the spontaneous symmetry breaking is that in nature the scalar fields will take on a non-zero value, referred to as the “vacuum expectation value”, or vev. The vev will couple to the fermion and gauge fields in a way that is equivalent to having mass terms, but nevertheless preserves gauge invariance. As a result, the fermions and weak gauge bosons can appear in nature as massive particles, consistent with observation. The masses of the gauge bosons are set by the vev and by the couplings associated to the gauge symmetry, and are thus constrained by the theory. The fermion masses, on the other-hand, depend on arbitrary coupling parameters that must be input to the theory. Through spontaneous symmetry breaking, massive fermions and weak bosons can be accommodated in a gauge invariant way.

The SM as sketched above provides a consistent theory for describing massive fermions interacting via the electromagnetic, the strong, and the parity-violating weak force. The predictions of the SM have been tested over many years, by many different experiments, and have been shown to accurately describe all of the observed data. Focusing on the electro-weak sector, examples of the impressive agreement of SM predictions with observed data are shown in Figures 1.1 and 1.2. Figure 1.1 shows the hadronic cross-section in  $e^+e^-$  collisions as a function of the center-of-mass energy [14]. The black curve shows the  $e^+e^- \rightarrow f\bar{f}$  cross section prediction by the SM, and the points give the measurements from various different experiments. The falling cross-section at low center-of-mass energy, and the peak due to  $Z$  boson production, are accurately described by the SM. The figure also shows the agreement of the observed LEP-II data with the SM prediction for  $e^+e^- \rightarrow WW$ . This process is sensitive to the  $ZWW$  coupling, which is a direct consequence of the gauge structure of the theory. Figure 1.2 shows a summary of various SM cross section predictions and their measurements in  $\sqrt{s} = 7$  TeV  $pp$  collisions at the LHC [15]. An impressive agreement is found over many orders of magnitude.

Another consequence of the spontaneous symmetry breaking is the prediction of a massive scalar particle. The interactions that generate the vev give mass to one of the additional scalar fields. This field should appear in nature as a neutral massive spin-zero boson, referred to as the “Higgs” boson. The mass of the Higgs boson depends on an arbitrary parameter associated to the symmetry breaking, and is thus an input to the theory. The interactions of the Higgs boson with the fermions and gauge bosons are, however, fixed by the theory. The couplings to gauge bosons are fixed by the gauge couplings, and the couplings to fermions are fixed by the fermion masses; the Higgs boson couples to

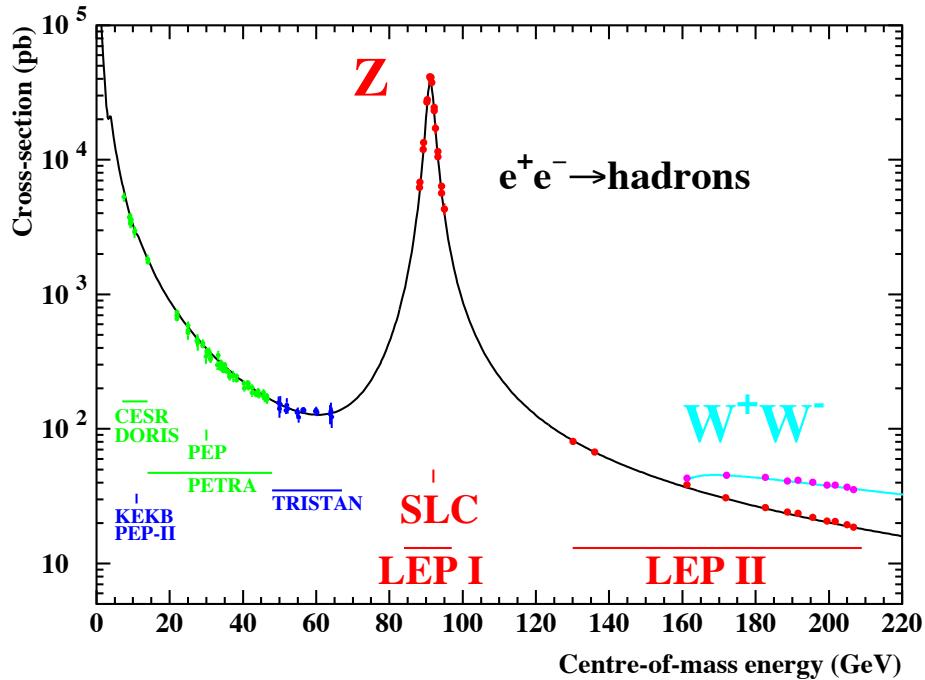


Figure 1.1: The hadronic cross-section as a function of center-of-mass energy. The solid line is the prediction of the SM, and the points are the experimental measurements. Also indicated are the energy ranges of various  $e^+e^-$  accelerators. The cross-sections have been corrected for the effects of photon radiation.

fermions proportionally to their mass. As of the beginning of the LHC running, the Higgs boson had not been observed experimentally.

As mentioned above, the mass of the Higgs boson is not predicted by the SM. There are no rigorous bounds on the Higgs mass from theory alone [16]. The Higgs must be massive to generate the spontaneous symmetry breaking, and if it is assumed that perturbation theory is valid, the a mass of the Higgs should be below about a TeV. The next section will describe constraints on the Higgs mass from measurements of the other electro-weak parameters.

The Higgs boson is a necessary ingredient in the SM for ensuring gauge invariance. Masses for the fermions and gauge bosons are allowed at the price of an additional scalar particle, the Higgs boson. A search for the Higgs bosons at the LHC is the subject of this thesis. The following section describes constraints and experimental limits on the Higgs boson mass prior to 2011.

The SM presented above is the minimal version that spontaneously breaks the electro-weak symmetry. More complex arrangements of scalar fields can be added to the theory. In general, these lead to additional physical particles, but serve the purpose of gauge invariant mass generation. These

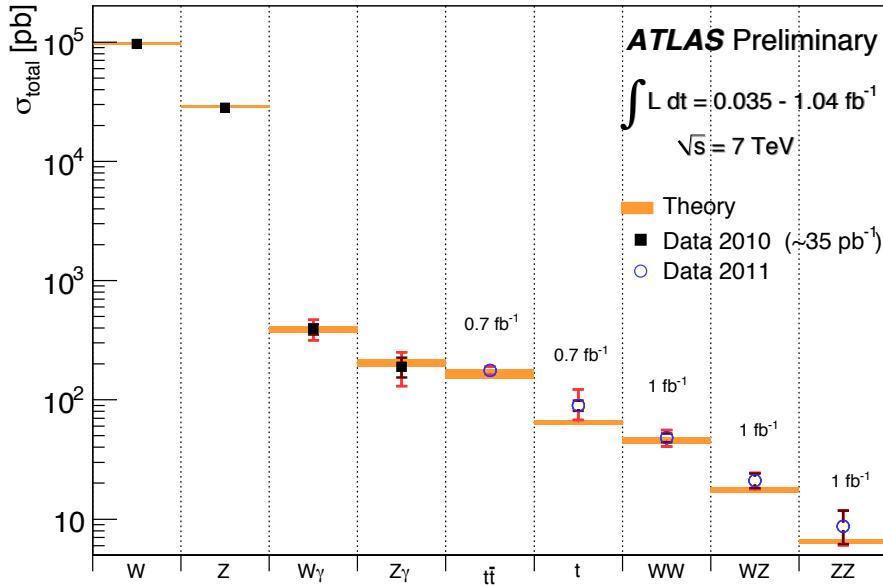


Figure 1.2: Summary of several Standard Model total production cross section measurements compared to the corresponding theoretical expectations. The dark error bar represents the statistical uncertainty. The red error bar represents the full uncertainty, including systematics and luminosity uncertainties. The W and Z vector-boson inclusive cross sections were measured with  $35 \text{ pb}^{-1}$  of integrated luminosity from the 2010 data-set. All other measurements were performed using the 2011 data-set. The top quark pair production cross-section is based on a statistical combination of measurements in the single-lepton, di-lepton and all-hadronic channels using up to  $0.7 \text{ fb}^{-1}$  of data. The single-top measurement uses  $0.7 \text{ fb}^{-1}$  of data. The WW and WZ and ZZ measurements were made using  $1.02 \text{ fb}^{-1}$ .

more complicated extensions are not considered in this thesis. The reader is directed to References [16, 17, 18] for more information.

## 1.2 Standard Model Predictions

The SM had been established in its current form by 1972. It has predicted many phenomena that were later observed experimentally. The existence of a weak neutral interactions is one consequence of SM. At the time, no such interactions, referred to as “neutral currents”, were known. In 1973, the Gargamelle bubble chamber [19] observed weak neutral currents in neutrino scattering.

Another consequence of the SM is the existence of the massive gauge bosons associated to the weak force. The SM gives an unified description of the electromagnetic and weak interactions. As a result, the weak and electromagnetic couplings are related to the masses of the weak gauge bosons. Based on

the measurements of the electromagnetic coupling, the muon lifetime, and neutral currents, the masses of the  $W$  and  $Z$  bosons are predicted by the SM. In 1983, the  $W$  and  $Z$  bosons were discovered by the UA1 and UA2 experiments [20, 21] [22, 23] with masses consistent with the theoretical expectation, another triumph of the SM.

In the 1990s, the LEP [24] and SLC [25]  $e^+e^-$  colliders began measuring  $Z$  boson parameters with high precision. These measurements were all found to be consistent with SM predictions. Assuming the validity of the SM, these accurate measurements can be used to estimate parameters not directly observable in  $e^+e^-$  collisions. Unobserved particles can effect measured quantities through quantum loop corrections. The SM predicts the form of these corrections, so measured quantities can be used to infer properties of the particles participating in the loops.

An example of this type of analysis for the top-quark mass is shown in Figure 1.3. The value of the top mass enters into loop corrections in  $e^+e^- \rightarrow b\bar{b}$  events, and in the  $W$  mass and width. The bottom two points in the figure show the predicted values of the top-quark mass from using measurements of the  $e^+e^-$  data (LEP1/SLD), and including direct measurements of the  $W$  mass and width (LEP1/SLD/ $m_W/\Gamma_W$ ). These predictions are self consistent, and agree with direct measurements of the top-quark mass by the CDF and D0 experiments [26, 27, 28], shown in the top of the figure. Before the discovery of the top-quark in 1994, the electro-weak measurements allowed the top-quark mass to be predicted, again showing the power of the SM.

Figure 1.4 is a more complicated version, showing the predictions of both the top-quark and  $W$  masses. The SM with the LEP/SLC data give the indirect prediction of  $m_t$  and  $m_W$  shown by the dashed red curve. The direct measurements of the top mass, from the Tevatron, and the  $W$  mass, from LEP-II and the Tevatron, are shown in blue. The observed consistency is a critical test of the SM.

Given the consistency seen thus far, this analysis can be repeated, using the top and  $W$  masses as inputs, to predict the mass of the Higgs boson. The Higgs boson also contributes to measured quantities through loop corrections. The measured  $W$  and top-quark masses are particularly sensitive to the size of the Higgs mass. The shaded band in Figure 1.4, shows the dependence of the Higgs mass on  $m_W$  and  $m_t$ . The SM can predict the value of Higgs mass, using other measured quantities, even though the Higgs boson has not been observed,

The blue band in Figure 1.5 shows the SM prediction of the Higgs boson mass using all relevant data, as of July 1011 [29]. The minimum value shows the SM best fit, which gives a prediction slightly below 100 GeV. The width of the curve gives the uncertainty associated to the prediction. The yellow areas show the values of Higgs mass excluded by direct searches. As of 2011, the relevant exclusions

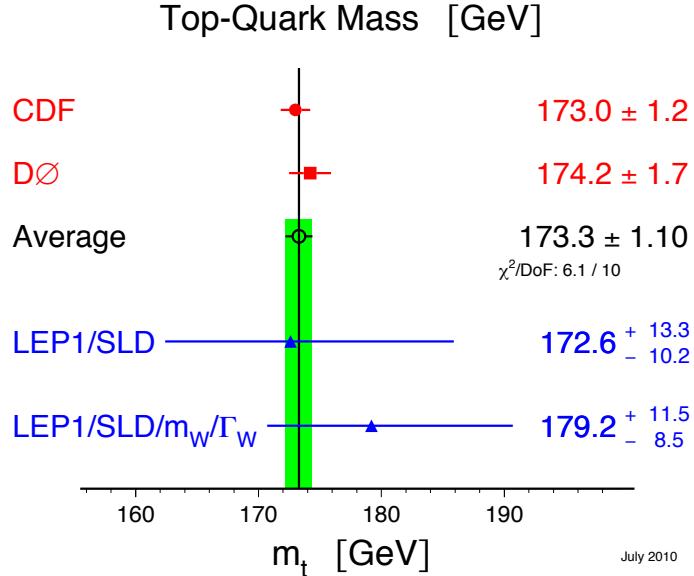


Figure 1.3: Results on the mass of the top quark. The direct measurements of  $m_t$  from Run-I of the Tevatron (top) are compared with the indirect SM predictions (bottom)

were from LEP-II [30] and the Tevatron [31, 32, 33]. LEP-II has excluded Higgs boson masses below 114 GeV, and the Tevatron has excluded Higgs boson masses in the range 158-175 GeV. Considering these exclusions, the SM predicts a Higgs boson with mass below  $\sim 160$  GeV at the 95% confidence level, and below  $\sim 200$  GeV at the 99% confidence level [14]. As further discussed in Chapter 8, the SM prediction of the Higgs boson mass guides the analyses presented in this thesis.

The SM provides a consistent theoretical framework for describing high energy particle interactions. It has made several predictions which have been borne out by data. A single set of electro-weak parameters adequately describes all electro-weak measurements. The SM predicts the existence of Higgs boson with a mass less than 200 GeV. Prior to the turn on of the LHC, no such particle had been observed. Higgs masses up-to 115 GeV were searched for, and excluded, at LEP-II. The Tevatron has excluded the Higgs in a mass range of 158-175 GeV. The goal of the work presented in this thesis is to discover or exclude the presence of a SM Higgs boson.

### 1.3 Higgs at the LHC

A primary motivation for the construction of the LHC was to discover or exclude the Higgs boson. One of the main reasons the Higgs has remained elusive is that it couples weakly to ordinary matter. As mentioned above, the Higgs couples to fermions proportionally to their mass. The particles collided

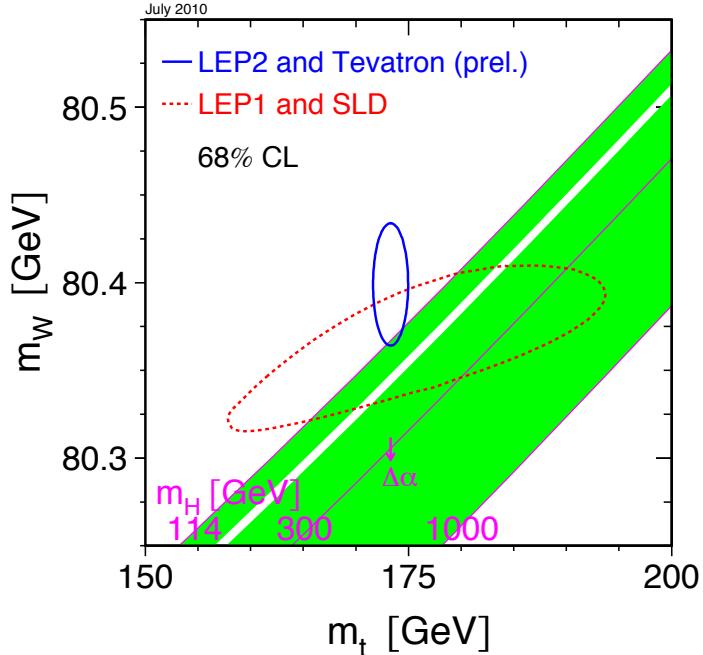


Figure 1.4: The comparison of the indirect constraints on  $m_W$  and  $m_t$  based on LEP-I/SLD data (dashed contour) and the direct measurements from the LEP-II/Tevatron experiments (solid contour). In both cases the 68% CL contours are given. The shaded band shows the SM relationship for the masses as a function of the Higgs mass. The regions excluded by direct searches,  $< 114$  GeV and  $158$  GeV –  $175$  GeV, or disfavored by theory,  $> 1$  TeV, are not shown. The arrow labeled  $\Delta\alpha$  shows the variation of this relation with one of the SM parameters. This variation gives an additional uncertainty to the SM band shown in the figure.

in  $e^+e^-$  and hadron machines either have relatively small mass, e.g. electrons and first-generation quarks, or do not directly couple to the Higgs, e.g. gluons. As a result, Higgs production is a rare process. However, the large data sets of high energy collisions, produced by the LHC, will provide sensitivity to Higgs production throughout the relevant mass range.

The important Higgs production diagrams at the LHC are shown in Figure 1.6. The cross sections of these various processes are shown in Figure 1.7, as a function of Higgs mass [34, 35]. The “gluon fusion” process, shown in Figure 1.6a, is the dominate Higgs production mechanism. Gluon fusion is shown, in blue, at the top in Figure 1.7. It has a production cross section of  $\sim 20$  pb for  $m_h = 120$  GeV in  $\sqrt{s} = 7$  TeV collisions. Higgs production is orders of magnitude smaller than many electro-weak processes, as can be seen by comparison with Figure 1.2. Searching for this small Higgs signal under

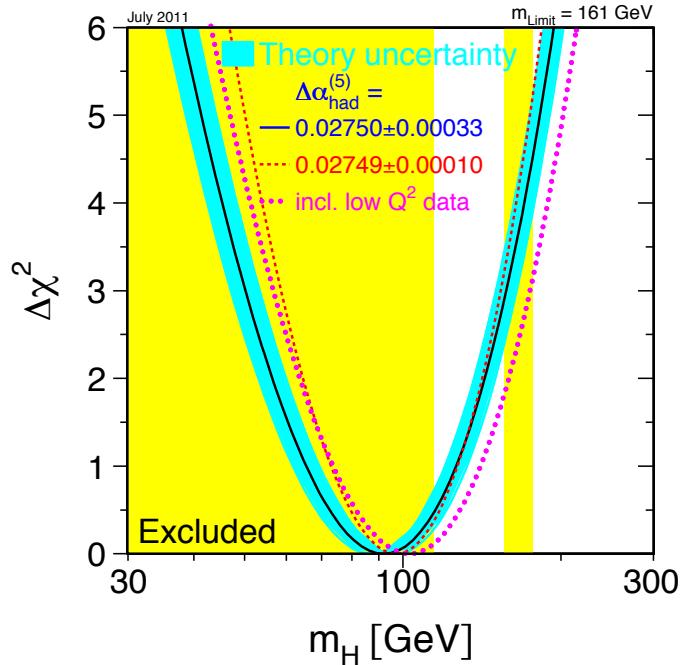


Figure 1.5: Standard Model prediction of the Higgs mass. The line is the result of the fit using data at the  $Z$  pole, and direct determinations of  $m_t, m_W, \Gamma_w$ . The band represents an estimate of the theoretical error due to missing higher order corrections. The vertical band shows the 95% CL exclusion limit on  $m_h$  from the direct searches at LEP-II (up to 114 GeV) and the Tevatron (158 to 175 GeV). The dashed curve shows the result of using a different values of  $\Delta\alpha_{had}^{(5)}$ . The dotted curve corresponds to a fit including lower energy data.

the pile of other electro-weak processes is one of the biggest challenges of the Higgs searches presented in this thesis.

## 1.4 Conclusion

This concludes the basic introduction to the SM and the Higgs boson. The SM provides a theoretically consistent, and experimentally verified, framework for describing the strong and electro-weak forces. The theory predicts the existence of an additional particle, the Higgs boson, which was unobserved before the turn on of the LHC. The work documented in this thesis builds to a search for, and a discovery of, the Higgs boson. Chapters 2 to 7 describe the experimental inputs, and what it takes to be able to use them effectively. Chapter 8 motivates the particular Higgs search strategy employed

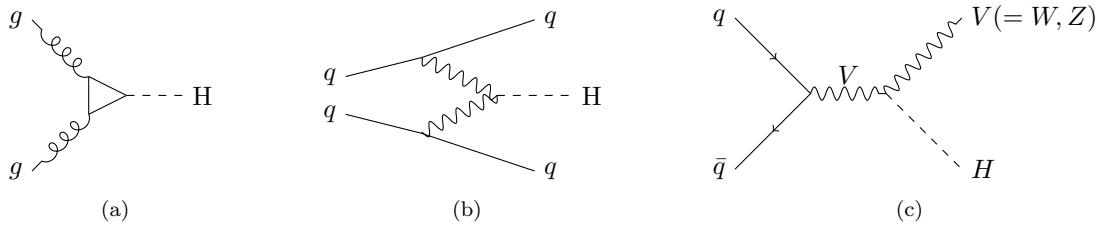


Figure 1.6: Leading order Feynman diagrams for Higgs production at the LHC. (a) The gluon fusion diagram proceeds via top-quark loop. (b) The vector-boson fusion diagram results in a final state with the Higgs and two jets. (c) The associated production diagram results in a final state with the Higgs and a  $W$  or  $Z$  boson. The relative size of the cross-sections of the different processes is shown in Figure 1.7.

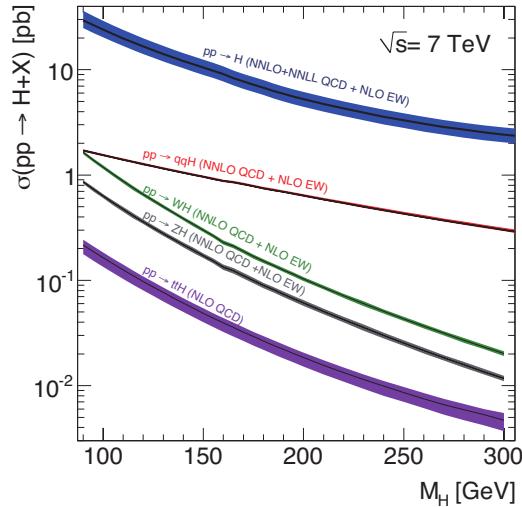


Figure 1.7: Standard Model Higgs boson cross sections for the various production mechanisms shown in Figure 1.6. The process in Figure 1.6a is shown in blue, Figure 1.6b in red, and the processes corresponding to Figure 1.6c are shown in green and black.

in this thesis. Chapters 9 and 10 sharpen the analysis tools needed for the search. And finally, Chapters 11 and 12 give the search results, and present the discovery of the Higgs boson.

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