Chapter 1
Introduction

This thesis will describe several analyses measuring the properties of the Higgs boson. As this chapter will describe, the Higgs boson was predicted to exist in 1967 as part of a theoretical explanation of the weak nuclear force. The theory that is now known as the Standard Model of particle physics, or the "SM," was built over the next 20 years, and it describes almost all known particles and interactions. Although the SM is not a *complete* description of the universe—its most obvious omission is gravity—almost all measurements of processes the SM covers agree with the theoretical predictions to incredible precision, with some especially precise measurements reaching 9 digits of agreement.

For a long time, the Higgs boson was the only elementary particle that was predicted by the SM but not observed. After almost 50 years of searching by building experiments designed to probe higher and higher energies, it was finally discovered by the CMS and ATLAS collaborations in 2012. As the most recently discovered fundamental particle, the Higgs boson is a natural target for higher-precision experimental tests of the SM's predictions. If deviations from the SM are detected, they would be a hint to further beyond SM, or "BSM," physics, such as new particles or interactions, and possibly open doors to understanding other mysteries of physics, such as the identity of dark matter.

1.1 Elementary Particles

Philosophical arguments for the idea that matter can only be divided up to a certain fundamental limit, known as an atom, go back to the ancient Greeks. Ultimately, the word "atom" ended up with a slightly different connotation than the Greek philosophers intended. The objects now known as atoms, although they form a useful basic unit in describing how matter interacts under many normal circumstances, are made of protons, neutrons, and electrons. The electron, isolated

J. Roskes, *A Boson Learned from its Context, and a Boson Learned from its End*,
Springer Theses, https://doi.org/10.1007/978-3-030-58011-7_1

by J.J. Thomson in 1897, was the first particle discovered that, as far as we know, is actually an elementary particle. A few years later, in the results that are considered to be the birth of quantum mechanics, Planck [1] and Einstein [2] showed that light is quantized in packets of energy, which came to be known as photons.

With these two discoveries, we have examples of each of the two types of elementary particles: fermions, which have half-integer spin, obey the Pauli exclusion principle, and therefore make up matter; and bosons, which have integer spin and transmit forces between fermions.

Further developments in particle physics over the next few decades came through experiments probing atomic structure. Rutherford proposed in 1911, based on the famous gold foil experiments, that an atom's positive charge is concentrated in the central nucleus [3], and his subsequent experiments revealed that the nucleus contains protons [4]. The existence of neutrons was suspected for years and finally confirmed experimentally in 1932 [5]. Around the same time, to reconcile the energy spectrum of β-decay with conservation of energy, Pauli proposed the existence of another very light, neutral particle, known as the neutrino [6].

To explain all of these observations, two new interactions were required. The weak force makes β decay possible by allowing neutrons to change into protons. However, calculations showed that this force is too weak to explain how the nucleus, with many positively-charged protons in close proximity, remains bound. Yukawa [7] proposed an additional force, the strong nuclear force, mediated by a particle with a mass between the masses of the proton and the electron. The first particle discovered that fit this criterion was the muon, which surprised everybody because it has nothing to do with the strong force and is actually a lepton—except for its mass, it behaves exactly like the electron. The pion, which really is the particle predicted by Yukawa, was discovered in 1947 [8, 9]. Over the next decades, a large number of other strongly-interacting bosons, known as mesons, and fermions, known as baryons, were discovered. Collectively, these strongly interacting particles are known as hadrons. (Yukawa's description of the strong nuclear force should not be confused with the later development of the quark model and quantum chromodynamics, which will be described in Sect. 1.5.)

1.2 Gauge Symmetry

In the SM's current form, its forces are all derived from gauge symmetries of the interacting particles. The electromagnetic force, mediated by the photon A_μ, is generated by a $U(1)$ gauge symmetry α of the charged fermion fields ψ: its Lagrangian

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi - \frac{1}{4}F_{\mu\nu}^2, \tag{1.1}$$

where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$, $D_\mu = \partial_\mu - iqA_\mu$, q and m are the fermion's charge and mass, and γ^μ are the Dirac matrices, is invariant under the transformation

$$\begin{aligned} \psi &\to e^{-i\alpha(x)}\psi \\ A_\mu &\to A_\mu + \frac{i}{q}\partial_\mu \alpha(x) \end{aligned} \tag{1.2}$$

Since the photon is massless, everything works well.

However, trying to apply the same procedure to a short-range force leads to trouble. If a force has short range, this implies that the particle that transmits has mass. A mass term in the Lagrangian, proportional to $A_\mu A^\mu$, would violate this gauge symmetry.

Explanations for the weak force, which is a short-range force, face this difficulty. On the other hand, because the weak force involves charged currents, which turn electrons into neutrinos or protons into neutrons, the particles that transmit it, now known as W bosons, must be charged, meaning that its theory has to be combined with the electromagnetic force in some way. In 1959, Glashow, Salam, and Ward developed a theory of the electroweak interaction [10, 11], but the difficulty of assigning mass to the W and Z bosons, and hence limiting the range of the force, remained.

1.3 Symmetry Breaking

In the meantime, an early attempt to understand the nature of the strong force was undertaken by Yochiro Nambu in 1960 [12, 13] by analogy with a similar feature in superconductivity. In the ground state of a superconductor, all of the electrons in the material form correlated Cooper pairs. The underlying theory describing how the electrons interact with each other and with the nuclei is the electromagnetic force, which respects gauge symmetry. However, the ground state of the system involves correlated electrons, which requires a fixed relative phase. Although there is no preference for any particular phase, once a phase is chosen at the time the material becomes a superconductor, it is fixed. As will be described later in the context of the Higgs potential, this "spontaneous symmetry breaking" implies the existence of massless bosons that transmit interactions between excitations from the ground state. In a superconductor, excitations take the form of linear combinations between electrons and holes.

Similarly to Cooper pairs of electrons in a superconductor, Nambu suggested that protons and neutrons are mixture states between more fundamental particles, one left-handed and one right-handed. Nucleon interactions are invariant under rotations between left- and right-handed states; however, the nucleon's mass term breaks this symmetry. Therefore, as in the superconductor, there should exist a massless boson that transmits a force between nucleons. Nambu identified this boson with the pion, and suggested that the underlying theory of nucleons, unknown at the time, does not exactly respect chiral symmetry, making the pion mass small but nonzero. Using this model, Nambu was able to explain several features of pions and heavier mesons.

1.4 The Higgs Mechanism

Nambu's result was generalized over the next few years by Goldstone, Weinberg, and Salam [14, 15]. The result is that any spontaneously broken symmetry generates a massless particle, known as a Goldstone boson.

In simultaneous papers by Brout and Englert [17], Higgs [18, 19], and Guralnik et al. [20] in 1964, it was shown that spontaneous symmetry breaking can result in massive gauge bosons, which would be necessary to describe the short-range weak force as a gauge theory. They considered a complex scalar field ϕ with interactions following the Mexican hat potential parameterized by constants λ and μ,

$$V(\phi) = \frac{1}{4}\lambda^2|\phi|^4 - \frac{1}{2}\mu^2|\phi|^2, \tag{1.3}$$

illustrated in Fig. 1.1. Before any interactions with other fields are included, the corresponding Lagrangian is

$$\mathcal{L} = \frac{1}{2}|d_\mu\phi|^2 - \frac{1}{4}\lambda^2|\phi|^4 + \frac{1}{2}\mu^2|\phi|^2 \tag{1.4}$$

The vacuum, or ground state, is where the energy is minimized: a circle at $\phi^\dagger\phi = \left(\frac{\mu}{\lambda}\right)^2$. Again, the symmetry of the Lagrangian, which was invariant under $\phi \to e^{i\alpha}\phi$, is broken by choosing one of these ground states.

Rewriting the Lagrangian by starting from one of these ground states, we can set

$$\phi = v + h + i\xi,$$

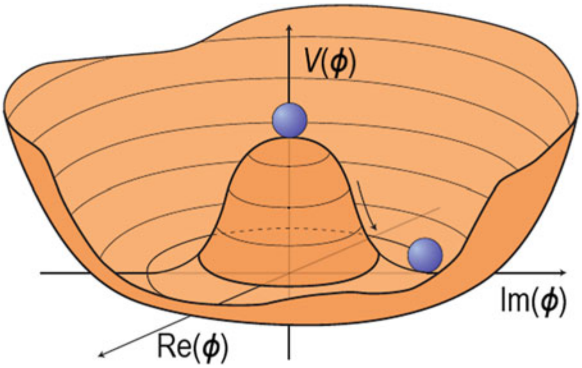

Fig. 1.1 Plot of the Mexican hat potential, Eq. (1.3). This plot is from [16]

where

$$v = \frac{\mu}{\lambda}$$

and h and ξ are real scalar fields. Substituting this into Eq. (1.4), we find, among other terms,

$$\frac{1}{2}(d_\mu h)^2 - \mu^2 h^2 + \frac{1}{2}(d_\mu \xi)^2. \tag{1.5}$$

Of two particles in this parameterization, one, ξ, is massless as expected for a Goldstone boson, and the other, h, has a mass of $\sqrt{2}\mu$. The other terms are cubic or quartic in the fields and give various interactions of the form hhh, $h\xi\xi$, $hhhh$, $\xi\xi\xi\xi$, and $hh\xi\xi$, with coupling strengths that are functions of μ and λ.

If the original field Φ couples to a gauge field A_μ, then the rewritten Lagrangian, derived from Eq. (1.4) with $d_\mu \rightarrow D_\mu$, will also contain terms that look like $A_\mu d^\mu \xi$. This term means that A_μ can turn into ξ and vice versa. By further reparameterization by choosing a particular gauge, ξ can be removed from the equation entirely. The $A_\mu d^\mu \xi$ terms become a mass term for A_μ. We now have a way to introduce massive gauge bosons.

In Peter Higgs' paper, he pointed out an important consequence of this model: the scalar field h should be observable as a particle. Although he personally downplays his role and prefers to share credit with the others who independently discovered this possibility, this type of particle is generally known as a Higgs boson.

Although fermions are allowed to have a mass term without affecting gauge invariance, a coupling between fermions and Φ would also naturally introduce a mass term proportional to the coupling strength as well as couplings to h and A_μ. From experiments so far, it seems to be the case that the Higgs mechanism also generates fermion masses.

Using the Higgs mechanism and building on Glashow and Salam's earlier work, the full theory of the weak force and its combination with electromagnetism came through Weinberg and Salam in 1967 [21, 22]. Because there needed to be three massive vector bosons, the full electroweak theory involves a complex scalar doublet instead of a single complex scalar as described here. Three of the four degrees of freedom get "eaten" to form the masses of the Z and W bosons, and the fourth is left as a Higgs boson.

Electroweak theory, combined with earlier experiments revealing how the weak force affects leptons and baryons, predicted properties of the Z and W bosons. The first interaction mediated by the Z boson, neutrino scattering, was observed in 1973, and the Z and W bosons themselves were observed in 1983.

1.5 The Strong Force and QCD

Around the same time as the weak force, the strong force also came to be understood better. Gell-Mann [23] and Zweig [24, 25] predicted in 1964 that baryons and mesons are made of one of three types of more fundamental particles, known as the up, down, and strange quarks. This theory explained the structure and interactions of the many, many types of baryons and mesons in existence. Each quark carries a "color charge," and the differently colored quarks can be rotated into each other by an $SU(3)$ symmetry, similar to the way the simpler electric charge and electromagnetic force are invariant under a $U(1)$ symmetry.

The fundamental strong force, known as quantum chromodynamics or QCD, is transmitted between these quarks by eight gluons. The strong nuclear force, which affects baryons and mesons and is responsible for holding nuclei together, comes from interactions between the quarks and gluons that make up the nucleons involved. Because gluons are massless, there is no need for a Higgs mechanism here.

The strong force is observed to only act at short distances for a different reason. Unlike the electromagnetic force, the mathematical description of QCD behaves well at high energy and badly at low energy. At the shortest distances, quarks do not interact, and this is known as "asymptotic freedom". However, when quarks move too far away from each other, the interaction energy increases significantly. The result is "color confinement": free particles with color charge do not exist. Instead, when a process with high enough energy splits a baryon or meson, more quark-antiquark pairs are produced from the vacuum to create more baryons and mesons, all of which are colorless and do not directly interact via the strong force.

This presents experimental advantages and disadvantages. In a high energy process, QCD effects are small; they can be expanded around the lowest order contribution and in many cases can be neglected entirely. On the other hand, when a process produces quarks or gluons, they split into many more quarks and gluons. Many more quark-antiquark pairs are produced to neutralize the remaining color charge. The result is a jet containing baryons and mesons, which is more complicated to detect and measure than electrons or muons.

The existence of a fourth quark, known as charm, was proposed shortly after the quark model itself, and in 1970 Glashow, Iliopoulos, and Maiani used the possibility to explain why flavor changing neutral currents, which would involve strange quarks decaying to down quarks, are suppressed [26]. Once it was discovered in the form of the J/ψ meson in 1974, there were four known quarks, up, down, charm, and strange, corresponding to four leptons, the electron and its neutrino and the muon and its neutrino.

1.6 The Standard Model

The combined description of the electromagnetic and strong forces was developed in the 1970s and became known as the Standard Model. Since its initial inception, an additional generation of quarks and leptons was proposed and discovered, consisting of the tau lepton and an associated neutrino and the top and bottom quarks.

The resulting theory involves 61 fundamental particles. There are six flavors of quarks, each of which comes in three colors, and six leptons. Each of these particles also has a corresponding antiparticle, so the total comes to 48 fermions. There are 12 vector bosons, which transmit forces: 8 gluons for the strong force, the $W^{\pm}$ and Z bosons for the weak force, and the photon for the electromagnetic force. Finally, the scalar Higgs boson brings the total to 61.

The quarks, which have color charge, interact through the strong force, mediated by the octet of gluons, which also interact among themselves. The quarks and charged leptons, which have electric charge, interact through the electromagnetic force, mediated by the photon. Finally, all types of fermions interact through the weak force, mediated by the Z and W bosons. The Z and W bosons also interact with each other, and the W boson, which has electric charge, interacts with the photon. The relationships and interactions between the SM particles are summarized in Fig. 1.2.

1.7 Limitations of the Standard Model

As mentioned in the introduction to this chapter, almost all experiments probing the SM find agreement with the theoretical predictions, although there are a few outliers

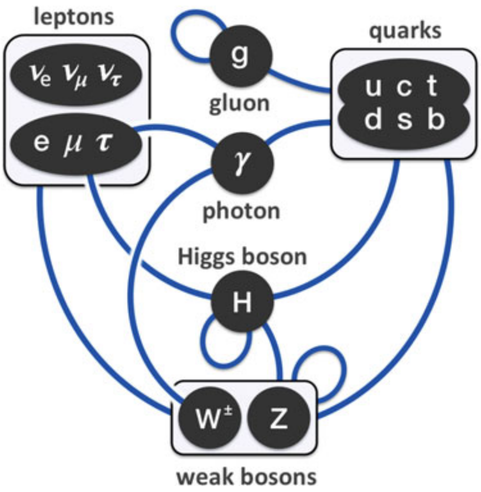

Fig. 1.2 Particles of the Standard Model, shown in the black circles and ovals, and their interactions with each other, shown as blue lines connecting them. Lines looping from a particle back to itself indicate self-interactions. This clever illustration is from [27]

under further investigation, such as the muon's anomalous magnetic moment. However, many phenomena are left unexplained by the SM. This is a list of a few important holes that may be better understood by examining the Higgs boson, which can reveal properties of the Higgs field.

From astrophysics, we know that dark matter exists, and observations place limits on how strongly or weakly it can interact with regular matter. No experiment has managed to detect dark matter particles on Earth other than through their gravitational influence on astrophysics and cosmology. If dark matter's mass is generated through interactions with the Higgs field, then it should also interact with the Higgs boson.

The universe contains much more matter than antimatter, which can again be determined from astrophysical observations. Electromagnetism, the strong force, and gravity treat matter and antimatter identically. The weak force does interact differently with matter than with antimatter, violating CP symmetry. However, calculations show that the small magnitude of CP violation in the weak force is insufficient to produce the huge ratio of matter to antimatter that we observe. The SM predicts that the Higgs boson is CP even. If this predication fails and a CP odd component is present as well, the Higgs boson's interactions would be an additional source of CP violation.

Another mystery of the Standard Model is the hierarchy problem. Quantum corrections to the Higgs boson's mass, generated by loop interactions with other particles, are of order 10^{19} GeV. This means that to produce the value that we observe, the "bare" mass, before those corrections, must be exactly $(x \times 10^{19} + 125)$ GeV. There is no known mechanism for this fine-tuning. Several theories exist that would explain it, and predict new particles and/or interactions as part of that explanation.

A similar puzzle relates to dark energy, which accelerates the expansion of the universe. All of the fields of the Standard Model, including the Higgs field, should contribute to the zero-point energy density of empty space, but calculations result in an energy density 50–100 orders of magnitude larger than what is observed.

There are any number of other theoretical reasons to suggest that new particles, breaking or producing one symmetry or another, might exist.

The nature of quantum field theory is that a change in the behavior of one particle, through the twisty lines in Fig. 1.2, has effects on all other particles' behavior as well. The existence of another particle that interacts with SM particles would be observable not just by seeing the particle itself, but also by measuring other particles' interactions to higher precision.

The analyses described here search for changes to the Higgs boson's behavior, whether they are produced through a new particle or some other mechanism, by examining both particles produced in association with it (its "context") and its decay products (its "end"). Any deviation from the SM predictions would be interesting both experimentally and theoretically and may help to explain one or more of the puzzles of the SM.

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