Chapter 2
The Standard Model and Beyond

The Standard Model (SM) is a theory that describes the fundamental particles and their interactions, with the exception of gravitational interactions. Experimental observations over the past several decades have proven that the SM accurately describes the physics at energy levels accessible in the laboratory. The discovery of the Higgs boson during RunI of the LHC marks the completion of the theory, but various experimental hints and theoretical calculations also point to limitations of the SM.

This chapter is organized as follows: Sect. 2.1 starts by providing an overview of the Standard Model; the theory of the Higgs boson and its discovery is described in Sect. 2.2, and Sect. 2.3 sketches out the open questions and possible answers regarding physics beyond-the-Standard-Model that are most pertinent to the topics of this thesis.

2.1 The Standard Model

The Standard Model (SM) [1–4] of particle physics has been developed through the latter half of the twentieth century, guided by both theoretical predictions and experimental discoveries. It encompasses three of the four fundamental forces of nature with the exception of gravity, namely the strong, electromagnetic, and weak forces. In the SM, all matter is made up of two types of particles: fermions that have half-integer spin and are governed by Fermi–Dirac statistics, and bosons that have integer spin and follow Bose–Einstein statistics. The fundamental building blocks of matter are fermions in the SM, while the mediators of forces that dictate their interactions are bosons. Each particle in the SM, whether a fermion or a boson, has a corresponding antiparticle identical in mass but opposite in quantum charge: in most cases a particle and its antiparticle are different particles, but occasionally a
particle may be its own antiparticle. Figure 2.1 summarizes the different particles in the SM, their properties, and interactions.

### 2.1.1 Bosons

The different groups of bosons in the SM act as mediators for each of the three types of force described in the SM.

The photon is the mediator of the electromagnetic force, and couples to all fermions with a non-zero electromagnetic charge. The photon itself is massless, electromagnetic-charge-neutral, and has a spin of 1. The photon is its own antiparticle and was the first boson to be examined experimentally.

The gluon is the mediator of the strong force, and couples to all fermions with a color charge. The gluon carries color charge itself as well, which means unlike the photon, the gluon not only mediates the strong force, but also participates in it. Depending on the different combinations of the color charge, gluons come in eight varieties, given that the ninth possibility in the form of the singlet state \((r\bar{r} + b\bar{b} + g\bar{g})/\sqrt{3}\) does not exist, indicating that strong interactions happen on short distance scales. Gluons are massless and have a spin of 1. They were first discovered at DESY in the late 1970s.
The $W^\pm$ and $Z$ bosons are the mediators of the weak force, and couple to all fermions. The $W^\pm$ bosons carry the weak charged current, while the $Z$ boson is the mediator of the weak neutral current. The $W^\pm$ bosons have electromagnetic charges of $\pm 1$, and are each other's antiparticle. The $Z$ boson is electromagnetic-charge-neutral and its own antiparticle. The $W^\pm$ and $Z$ bosons have a spin of 1. They were discovered at the UA1 and UA2 experiments at CERN in the late 1980s.

The final boson, which was also the last missing piece of the SM until its discovery at the LHC in 2012, is the Higgs boson, or the boson of the Brout–Englert–Higgs mechanism. Its properties and discovery will be discussed in more detail in Sect. 2.2.

2.1.2 Fermions

The fermions in the SM are divided into two groups of very different properties, namely quarks and leptons, all of which have spin of $1/2$. Both quarks and leptons can be divided into three generations, where the first generation corresponds to what exists in common matter, and the second and third generations, having higher masses, can be accessed at increasingly higher energies. The quarks feel the strong force, while the leptons do not.

Quarks, regardless of the generation, can be divided into two types depending on the electromagnetic charge. The up-type quarks have a charge of $2/3$, and the down-type quarks have a charge of $-1/3$. Leptons can be categorized as charged leptons and neutrinos.

2.1.3 Gauge Theory

The SM is based on a mathematical framework called quantum field theory \cite{5}, which is used to construct quantum mechanical models of particles. Within the framework, particles are represented by states of quantized fields. Interactions among particles are governed by a Lagrangian. The SM is a gauge theory, meaning the Lagrangian is invariant under a continuous group of local transformations. In particular, the SM Lagrangian is invariant under transformations of the group $SU(3)_c \times SU(2)_L \times U(1)_Y$.

Gauge fields with integer spin are included in the model to maintain this invariance, and excitations in these fields correspond to gauge bosons. There are a total of twelve gauge bosons: eight gluons corresponding to the generators of $SU(3)_c$, two oppositely charged $W$ bosons corresponding to generators of $SU(2)_L$, and a neutral $Z$ boson and a photon ($\gamma$), which correspond to linear combinations of generators for $SU(2)_L$ and $U(1)_Y$. The gauge bosons ensure that the SM is renormalizable, which is a form of consistency that is necessary for the model to have predictive power.
To match the gauge theory, the left-handed fermions exist as doublets under SU(2)_L, while the right-handed fermions are singlets. This gives rise to the three generations of quark doublets and singlets, as shown in Eq. (2.1), as well as the three generations of lepton doublets and singlets, with the caveat that there are no right-handed neutrinos or left-handed anti-neutrinos [Eq. (2.2)].

\[
\begin{pmatrix}
  u' \\
  d'
\end{pmatrix}_L,
\begin{pmatrix}
  c' \\
  s'
\end{pmatrix}_L,
\begin{pmatrix}
  t' \\
  b'
\end{pmatrix}_L,
\begin{array}{cccc}
  u_R & d_R & c_R & s_R & t_R & b_R \\
  v_e & v_\mu & v_\tau & \tau^- & \mu^- & \tau^- \\
  e^- & \mu^- & \tau^- & \tau^- & \mu^- & \tau^- \\
  d' & s' & b' & b'
\end{array}
\] (2.1)

The quarks which are primed are **weak eigenstates** related to **mass eigenstates** by the Cabibbo–Kobayashi–Maskawa (CKM) matrix [Eq. (2.3)].

\[
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix}_L = \begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix} \begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix}_L = \hat{V}_{\text{CKM}} \begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix} (2.3)
\]

The diagonal elements in the CKM matrix [Eq. (2.3)] are nearly 1, showing the dominance of the same generation. However, the non-zero off-diagonal elements indicate the possibility of generation-changing and flavor-changing processes, mediated by the W± bosons unique to the weak force.

2.2 **Spontaneous Symmetry Breaking and the Higgs Boson**

The theory described in Sect. 2.1 presents a fairly good framework of particles and their interactions; however, it also poses a number of problems when compared with experimental observations, especially in terms of the masses of the particles discovered. First, consider the part of the SM that describes the electromagnetic and weak interactions, governed by the SU(2)_L × U(1)_Y symmetry. To preserve gauge invariance the gauge bosons need to be massless (i.e., the gauge fields must be included without mass terms). However, the W± and Z bosons responsible for mediating weak interactions need to have large masses to properly describe the weak force. The masses of the quarks and leptons show another problem. Weak interactions are found to violate parity, coupling differently to left- and right-handed fermion helicity states. This is accounted for in the SM by treating left- and right-handed fermions as different fields with different couplings. A fermion mass term in the Lagrangian would couple these different fields, hence breaking the gauge invariance. Thus, the fermions should be massless as implied by a gauge invariant left-handed interaction, which is inconsistent with observations.
These problems can be resolved by the mechanism called “spontaneous symmetry breaking” \cite{6–10}. Additional quantum fields with zero-spin (scalar) that couples to the $SU(2)_L \times U(1)_Y$ electroweak gauge fields are added to the Lagrangian. The scalar fields are constructed such that the zero values do not correspond to the lowest energy state. Instead, the potential takes on the shape of a Mexican Hat. Starting from the origin which has a local maximum, the potential drops to the minimum before rising again, and the local minimum is identical around the ring of the local potential. As a result, while the Lagrangian preserves gauge invariance under $SU(2)_L \times U(1)_Y$, the symmetry is broken in the ground state and the scalar fields take on a non-zero value, referred to as the vacuum expectation value, or $vev$. The $vev$ couples to fermion and gauge fields while preserving gauge invariance, giving rise to the masses of gauge bosons and fermions observed in nature.

Spontaneous symmetry breaking also predicts a neutral, massive scalar boson called the Higgs boson $h$. The couplings of the Higgs to gauge bosons in the SM are determined by the gauge couplings, and the couplings to fermions are proportional to the fermion masses. The mass of the Higgs itself depends on an arbitrary parameter associated with the symmetry breaking and thus is not fixed in the SM.

At the time of the turn-on of the LHC, the Higgs boson was the last missing piece of the SM. The monumental moment in the search for the SM Higgs boson came on July 4, 2012, when the ATLAS and CMS collaborations both announced discoveries of a new “SM Higgs–like” particle with a mass near 125 GeV \cite{11, 12}. Extensive experimental studies of the properties of the new boson, and how it interacts with other particles ensued, all of which yielding results consistent with SM predictions (Fig. 2.2), including its couplings to fermions and bosons, production rate, decay width, spin, and CP quantum numbers. With the increase in energy and luminosity at RunII of the LHC resulting in orders of magnitude larger production rates, future measurements of the Higgs properties could reveal deviations from the SM.

2.3 Physics Beyond the Standard Model

Despite being one of the most robust and successful physics models in describing the world we know of, the SM has its limitations. Increasing experimental evidence and theoretical conjectures point to a widely accepted view that a more fundamental theory exists with the SM being its low-energy realization.

One open question is the striking asymmetry of matter versus antimatter. Basic laws of symmetry and thermal equilibrium should have resulted in the production of an equal amount of matter and antimatter at the creation of the universe. However, the visible universe today is dominated by matter while antimatter has essentially vanished. This is known as Charge–Parity–Violation (CPV). While the SM provides CPV terms that can account for part of the asymmetry, it is an open topic for investigation as whether the parameters are sufficient to present the level of matter–antimatter asymmetry in the current universe.
The phenomenon of neutrino oscillations, observed in both atmospheric neutrinos originating from electromagnetic cascades initiated by cosmic rays, and solar neutrinos, poses another serious challenge. This indicates that neutrinos do have mass and the flavor of the neutrino may oscillate under a rotation matrix (the PMNS matrix) similar to the CKM matrix for quarks, while the SM stipulates that neutrinos are massless.

As mentioned in Sect. 2.2, the discovery of the Higgs boson completes the SM, though the SM gives no prediction of the Higgs boson mass, which is currently measured to be $125.09 \pm 0.21 \text{(stat)} \pm 0.11 \text{(syst)}$ GeV [13] (the “stat” denotes the statistical uncertainty and “syst” refers to the systematic uncertainty). This means the electroweak scale is $\mathcal{O}(100 \text{ GeV})$, while the Planck scale is at $\mathcal{O}(10^{19} \text{ GeV})$. The enormous difference is called the hierarchy problem, indicating that either the universe is incredibly fine-tuned, or there is some form of new physics that can cancel out the divergence and stabilize the Higgs boson mass. Another fundamental question is the so-called grand unification, concerning whether there is a unified description addressing the three gauge interactions in the SM, i.e., electromagnetic, weak, and strong interactions. How gravity might be able to be merged into a greater symmetry adds another layer of mystery to our understanding of the universe.

Finally, the SM provides no viable candidate to account for the abundance of DM in the universe, let alone the case of dark energy. The neutrinos, despite being electromagnetically neutral and weakly interacting particles with non-zero masses, have been essentially ruled out as dominant DM candidates because they are simply
not abundant enough. The existence of DM is hence a strong motivation to search for physics beyond the SM (BSM). Various BSM theories predict new particles that may be DM candidates, which can be tested through experiments that in turn constrain such theories.

References

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