

Chapter 2

The Standard Model

The Standard Model (SM) is a successful description of particle physics nowadays. It is a quantum field theory that explains the dynamics of our universe through matter and forces. It incorporates three fundamental forces: the weak, the strong and the electromagnetic forces, and includes different types of particles. Mainly, the SM states that all the matter is composed by fermionic fields interacting among each other via vector fields. In order to understand the field content of the SM, it is necessary to begin with the definition of the symmetry group.

2.1 Symmetries, Gauge Theory and Particle Content

Symmetries have always played an important role in physics. The creation of the SM has not followed a different path: it is a theory based on a local symmetry. The first theorem of Noether assures that any differentiable symmetry of the action of a physical system leads to a corresponding conservation law [1]. Any conservation law of physics can be interpreted as resulting from the symmetries of a particular theory.

One example is the theory of Quantum Electrodynamics (or, QED). The invariance under local transformation implies the existence of gauge fields with specific properties. To demonstrate such remarkable consequence, let us begin by considering a free theory of fermions. The free lagrangian can be written as

$$\mathcal{L} = \bar{\psi}(i\gamma_{\mu}\partial^{\mu} - m)\psi, \quad (2.1)$$

with ψ being the spin-1/2 field, $\bar{\psi} = \psi^{\dagger}\gamma^0$, and γ^{μ} the Dirac matrices. The lagrangian is invariant under a global gauge transformation $\psi \rightarrow e^{-i\alpha}\psi$, with α a constant phase, which implies the conservation of the Dirac current $j^{\mu}(x)$:

$$\partial_{\mu}j^{\mu} = 0; \quad j^{\mu} = \bar{\psi}\gamma^{\mu}\psi. \quad (2.2)$$

However, Eq. (2.1) is not invariant under local gauge transformations, where now α depends on the space-time coordinates, and suggests that the derivative should be redefined as

$$\partial^\mu \rightarrow D^\mu \equiv \partial^\mu + i q A^\mu. \quad (2.3)$$

where A^μ is a vector field. The lagrangian (2.1) with the replacement $\partial^\mu \rightarrow D^\mu$ is now invariant under the following local transformations

$$\psi(x) \rightarrow \psi'(x) = e^{-i\alpha(x)} \psi(x), \quad (2.4)$$

$$A^\mu(x) \rightarrow A^{\mu'} = A^\mu(x) + \frac{1}{q} \partial^\mu \alpha(x), \quad (2.5)$$

and is finally given by

$$\mathcal{L} = \bar{\psi} (i \gamma_\mu \partial^\mu - m) \psi - q \bar{\psi} \gamma_\mu A^\mu \psi. \quad (2.6)$$

The second term has been derived from the imposition of local invariance. It describes the interaction of the fermionic matter ψ already existent on the theory, with the gauge field A^μ . Therefore, a theory that had in principle only matter fields, needs vector fields to provide interactions amongst fermions.

One could thus generalize this principle for all interactions, i.e. generate interaction terms for the weak, electromagnetic, strong (and later gravitational) forces through specific symmetries imposed on the theory. This is basically the idea for constructing the SM initially proposed by Glashow [2] and independently by Salam and Ward [3], extended later by Weinberg [4] and Salam [5]. Of course the complexity is larger than previously explained, since it works perfectly for abelian theories, however the world is not only described by them. Before going ahead, it is worth reminding that the SM of particle physics was created as a puzzle, and each piece was put together at different moments of History.

Initially, the electroweak theory was developed, and the gauge group $SU(2)_L \times U(1)_Y$ was used to relate electric charge with the isospin and the leptonic hypercharge of a particle. Besides matter fields, four gauge bosons are included due to the gauge symmetry: one triplet associated with the $SU(2)$ group and one singlet associated to the $U(1)$. The corresponding lagrangian, restricted to the leptonic fields, is given by

$$\mathcal{L} = \bar{L} \gamma^\mu D_\mu L + \bar{e}_R \gamma_\mu D'_\mu e_R - \frac{1}{4} W^{\mu\nu i} W_{\mu\nu}^i - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} \quad (2.7)$$

where the covariant derivatives are defined by

$$\begin{aligned} D_\mu &= \partial_\mu + i \frac{g}{2} \sigma^i W_\mu^i + i \frac{g'}{2} B_\mu, \\ D'_\mu &= \partial_\mu + i g' B_\mu, \end{aligned} \quad (2.8)$$

and L is the isospin doublet that contains the left-handed neutrino and electron, e_R is the right-handed electron,¹ σ^i are the Pauli matrices, and g and g' are the coupling constants. $W_{\mu\nu}^i$ and $B_{\mu\nu}$ are the field-strength tensors:

$$\begin{aligned} W_{\mu\nu}^i &= \partial_\mu W_\nu^i - \partial_\nu W_\mu^i - g\epsilon^{ijk} W_\mu^j W_\nu^k \\ B_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu. \end{aligned} \quad (2.9)$$

The matter content of the world is not only formed by leptons but also by hadrons, and it has been discovered that hadrons are composed by quarks. The symmetry that relates the color charge in quarks is $SU(3)_c$. The SM is consequently defined to have $SU(3)_c \times SU(2)_L \times U(1)_Y$ as the gauged symmetry group. Each gauge boson field is associated to the generator of the algebra of each group. Therefore, eight coloured spin-1 particles associated to the $SU_c(3)$ gauge group exist and are also known as gluons. In addition, there are still the four un-coloured particles, $W_{\mu\nu}^i$ and $B_{\mu\nu}$ quoted previously, that will mix to form the massive $W^\pm$ and Z^0 gauge bosons and the massless photon.

In a nutshell, the final particle content of the SM is summarized in Fig. 2.1 [6]. The masses and most significant quantum numbers of each particle are stated in the figure. One important piece of the SM, the scalar field, has not yet been mentioned. It has been stated that conservation laws are a consequence of imposed symmetries. The SM theory is therefore based on gauge symmetries, and lagrangians are constructed from the assumption of massless fields. The mechanism to generate mass to the particles requires the existence of at least one scalar particle, the Brout-Englert-Higgs boson.² This is the so-called BEH mechanism [7–9], which will be explained in what follows.

Fig. 2.1 An illustration of the particle content of the Standard Model, excluding scalar fields. This is an interpretation of the periodic table of elements adapted to fundamental particle physics based on [6]

Quarks			Leptons		
up $\frac{1}{2}$ $\frac{2}{3}$ u 2.4 MeV	charm $\frac{1}{2}$ $\frac{2}{3}$ c 1.27 GeV	top $\frac{1}{2}$ $\frac{2}{3}$ t 171.2 GeV	electron neutrino $\frac{1}{2}$ 0 ν_e < 2.2 eV	muon neutrino $\frac{1}{2}$ 0 ν_μ < 0.17 eV	tau neutrino $\frac{1}{2}$ 0 ν_τ < 15.5 MeV
down $\frac{1}{2}$ $-\frac{1}{3}$ d 4.8 MeV	strange $\frac{1}{2}$ $-\frac{1}{3}$ s 104 MeV	bottom $\frac{1}{2}$ $-\frac{1}{3}$ b 4.2 GeV	electron $\frac{1}{2}$ -1 e 0.511 MeV	muon $\frac{1}{2}$ -1 μ 105.7 MeV	tau $\frac{1}{2}$ -1 τ 1.77 GeV
gluon 1 0 g 0 eV	photon 1 0 γ 0 eV	Higgs 0 0 H ~126 GeV			
Z boson 1 0 Z^0 91.2 GeV	W boson 1 ± 1 $W^\pm$ 80.4 GeV				

Gauge bosons

Legend

Name

spin charge

Symbol

mass
(natural units)

¹ Right-handed neutrinos are not included in the theory.

² From the present moment on we shall abbreviate Brout-Englert-Higgs boson by Higgs boson, which is the usual shortened form used in the literature.

2.2 The Brout–Englert–Higgs Mechanism

It is known from Noether's theorem that symmetries imply conservation laws. It is a consequence of the invariance of both the lagrangian and the vacuum of a theory. However, there could be a situation where the lagrangian is invariant under a symmetry in which the vacuum is not. If such circumstance occurs, the symmetry is defined as to be broken, or hidden.

Consider for instance a scalar field ϕ whose lagrangian is given by [10]:

$$\mathcal{L}_\phi = \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - V(\phi), \quad \text{with} \quad V(\phi) = \frac{1}{2}\mu^2 \phi^2 + \frac{1}{4}\lambda \phi^4, \quad (2.10)$$

where ϕ is real and $\lambda > 0$. The lagrangian is clearly invariant under the transformation $\phi \rightarrow -\phi$. When the vacuum expected value (vev) is calculated, two separated situations arise:

- (a) If $\mu^2 > 0$, the vacuum is invariant under such symmetry,

$$\langle \phi \rangle_0 \equiv \langle 0 | \phi | 0 \rangle = 0 \quad (\mu^2 > 0). \quad (2.11)$$

- (b) However, if $\mu^2 < 0$:

$$\langle \phi \rangle_0 = \pm \sqrt{\frac{-\mu^2}{2\lambda}} \equiv \pm \frac{v}{\sqrt{2}} \quad (\mu^2 < 0). \quad (2.12)$$

The vacuum state in this case is degenerated, and it depends on the choice between $+v$ and $-v$.

Both situations are illustrated in Fig. 2.2. On the left side, the potential is shown as a function ϕ for $\mu^2 > 0$. As Eq. 2.11 revealed, only one vev is obtained. However, on the right, the plot of same potential is shown for the choice of $\mu^2 < 0$. Equation 2.12 exhibits a degenerate vacuum state, displayed by the two local minimums in Fig. 2.2b.

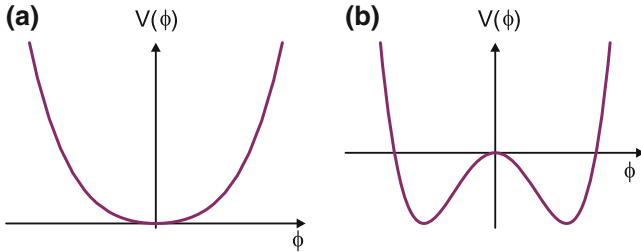


Fig. 2.2 Potential $V(\phi)$ of Eq. 2.10 as a function of ϕ for the two situations presented: **a** with $\mu^2 > 0$ and **b** for $\mu^2 < 0$. For case **(a)**, the minimum is at $\phi_0 = 0$ and for case **(b)** $\phi_0 = \pm v$, where the vacuum is degenerated

We could therefore choose one state, for instance $\langle\phi\rangle_0 = +v$, and re-define the field in order for the vacuum to be at the origin:

$$\xi(x) \equiv \phi(x) - \langle\phi\rangle_0 = \phi(x) - v. \quad (2.13)$$

Now $\langle\xi\rangle_0 = 0$, and the lagrangian (2.10) becomes

$$\mathcal{L}_\xi = \frac{1}{2}(\partial_\mu\xi)(\partial^\mu\xi) - \lambda v^2\xi^2 - \lambda v\xi^3 - \frac{1}{4}\lambda\xi^4. \quad (2.14)$$

This is the lagrangian of a free scalar field ξ with mass term³ $m_\xi = \sqrt{-2\mu^2}$. The symmetry was therefore hidden behind the primary definition of the field. By redefining the field ϕ it was possible to obtain the massive ξ . This concept is named *spontaneous symmetry breaking* and it illustrates the main mechanism used to generate the mass of fermionic and bosonic fields of the SM.

In the SM, it is necessary to define a doublet composed of two complex scalar fields. Suppose the doublet ϕ can be defined in a Hermitian basis as [11–13]

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 - i\phi_2 \\ \phi_3 - i\phi_4 \end{pmatrix} \quad (2.15)$$

The scalar lagrangian to be added to (2.7) will be similar to the one given in (2.10). However, in order to maintain the gauge invariance under $SU(2)_L \times U(1)_Y$, the covariant derivative (2.8) should be used:

$$\mathcal{L}_{BEH} = |D_\mu\phi|^2 - V(\phi). \quad (2.16)$$

In the new basis, the potential is

$$V(\phi) = \frac{1}{2}\mu^2 \left(\sum_{i=1}^4 \phi_i^2 \right) + \frac{1}{4}\lambda \left(\sum_{i=1}^4 \phi_i^2 \right)^2. \quad (2.17)$$

We can choose the position of the minimum as $\phi_1 = \phi_2 = \phi_4 = 0$ and $\phi_3 = v$, being v the Higgs vev. A new field h can be defined to be a radial excitation around the vev. The symmetry $SU(2)_L \times U(1)_Y$ is broken to $U(1)_{em}$ if we choose the specific value for the vev to be $\sqrt{-\mu^2/2\lambda}$. The field can thus be re-written as

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}, \quad (2.18)$$

The potential $V(\phi)$ of the lagrangian becomes

³ Notice the mass is positive, since we are analysing the case where $\mu^2 < 0$.

$$V_{BEH} = -\frac{1}{4}\lambda v^4 + \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4. \quad (2.19)$$

The second term indicates the mass of the Higgs field, $m_h^2 = 2v^2\lambda$. The third and the forth terms, i.e. the terms related to h^3 and h^4 , indicate self-couplings of the Higgs boson.

The kinetic term of the lagrangian, $|D_\mu\phi|^2$ includes terms with the W_μ^i and B_μ fields,

$$\left| \left(i\frac{g}{2}\sigma^i W_\mu^i + i\frac{g'}{2}B_\mu \right) \phi \right|^2 = \frac{(v+h)^2}{8} [g^2(W_\mu^1)^2 + g^2(W_\mu^2)^2 + (-gW_\mu^3 + g'B_\mu)^2]. \quad (2.20)$$

If four new vector fields are defined as:

$$\begin{aligned} Z_\mu^0 &= \frac{1}{\sqrt{g^2 + g'^2}} (gW_\mu^3 - g'B_\mu), & W_\mu^\pm &= \frac{1}{\sqrt{2}} (W_\mu^1 \mp iW_\mu^2), \\ A_\mu &= \frac{1}{\sqrt{g^2 + g'^2}} (g'W_\mu^3 + gB_\mu), \end{aligned} \quad (2.21)$$

Equation 2.20 can be written in terms of the new fields. The boson masses can be identified by the following terms of the lagrangian

$$m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} (m_Z^2 Z_\mu Z^\mu + m_A^2 A_\mu A^\mu). \quad (2.22)$$

With the above expression, it is straightforward to find the masses related to the W_μ , Z_μ and A_μ fields [11]:

$$m_W = \frac{vg}{2}, \quad m_Z = \frac{v}{2}\sqrt{g^2 + g'^2} \quad \text{and} \quad m_A = 0. \quad (2.23)$$

Notice however that covariant derivatives can now be written in terms of the new bosonic fields. Consequently, it is possible to re-write Eq. 2.8 in a more useful format, in terms of the electromagnetic coupling, given by

$$g_e = \frac{gg'}{\sqrt{g^2 + g'^2}} \quad (2.24)$$

or in terms of the *weak mixing angle*,

$$g_e = g \sin \theta_w, \quad \cos \theta_w = \frac{g}{\sqrt{g^2 + g'^2}}, \quad \text{and} \quad \sin \theta_w = \frac{g'}{\sqrt{g^2 + g'^2}}. \quad (2.25)$$

The mass of the $W^\pm$ and Z bosons are therefore related through the expression

$$m_W = m_Z \cos \theta_w. \quad (2.26)$$

As a result, all effects of $W^\pm$ and Z exchange processes (at tree level) can be exhibited as a function of the g_e , θ_w and m_W parameters.

Finally, to find the value for the vev v we can replace the expression found for the mass of the $W^\pm$ bosons in terms of the Fermi constant:

$$G_F = \sqrt{2} \frac{g^2}{8m_W^2} = \frac{\sqrt{2}}{2v^2}. \quad (2.27)$$

Because the Fermi constant is experimentally known with a very good accuracy, $G_F = 1.16637(1) \times 10^{-5} \text{ GeV}^{-2}$ [14], the value for the Higgs vev can be deduced as $v \sim 246 \text{ GeV}$. This is the value where the $SU(2)_L \times U(1)_Y$ is broken. However, because the parameter λ is not known, the mass of the Higgs boson cannot be predicted.

A similar mechanism is used to obtain the mass of the fermions. The invariant lagrangian that should be added to (2.7) can be exhibited as

$$\mathcal{L}_{yuk} = -\lambda_e \bar{L} \phi e_R - \lambda_d \bar{Q}_L \phi d_R - \lambda_u \bar{Q}_L \tilde{\phi} u_R + h.c. \quad (2.28)$$

where Q_L is the isospin doublet that contains the left-handed up and down quarks, u_R and d_R are the right-handed up and down quarks, $\tilde{\phi} = i\sigma_2 \phi^*$, and σ_2 is one of the Pauli matrices. After spontaneous symmetry breaking, the mass of the fermions (except neutrinos) are generated as $m_f = \lambda_f v/2$, and neutrinos continue to be massless. The couplings λ_f are called Yukawa couplings [11], and are determined depending on the experimental values of fermionic masses.

2.3 Experimental Facts and Standard Model Constraints

As it has been stated, the SM is one of the most tested theories in physics. It has been experimentally investigated through different methods, and nowadays particle colliders are used for such task.

The final missing piece is, with no doubt, the experimental observation of the scalar sector of the SM through the Higgs particle. Very recent developments have been made in order to limit and constrain the mass of the Higgs particle using data from the Large Hadron Collider (LHC), the revolutionary proton-proton collider experiment situated in Switzerland. At this stage, we limit ourselves to display the most advanced SM results obtained from LHC data. A detailed description related to such collider will be presented in Chap. 4.

The LHC has started colliding protons for physics analyses in 2009, breaking energy records ever since. For more than a year starting in 2010, it has collided protons with a center-of-mass energy of 7 TeV, achieving a considerably high sensitivity. For this reason, many of the SM parameters have already been very precisely measured by the LHC. A summary of the most recent values due to electroweak constraints can be,

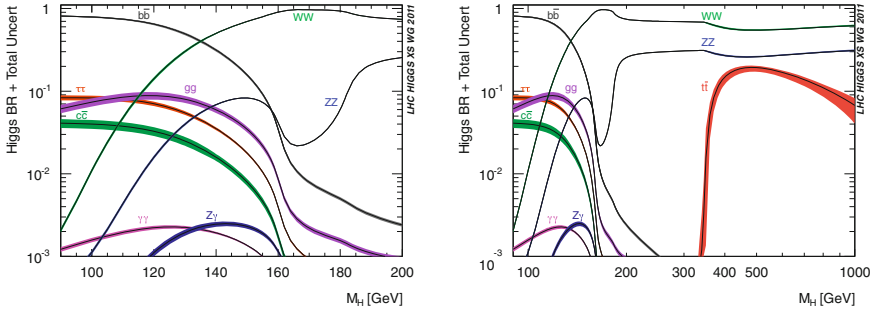


Fig. 2.3 Higgs branching ratio for contributing decay channels as a function of the Higgs mass. These plots are made by the Higgs cross section working group, extracted from [17]

for example, found in Ref. [15]. As it has been stated, within the SM the only missing aspect is now the Higgs boson mass. However, it has been further constrained at the LHC by the end of 2011.

For a Higgs boson with a mass above 125 GeV, the search is dominated by bosonic modes, where Higgs decays to W^+W^- and ZZ . For lower masses, the most important channels are $b\bar{b}$, $\tau\tau$ and $\gamma\gamma$ [16]. This is explicitly displayed on Fig. 2.3 extracted from [17] that shows the Higgs branching ratio of each decay channel as a function of its expected mass.

The largest decay mode of the SM Higgs bosons is $h \rightarrow W^+W^-$. If the Higgs boson would have a mass between 160 and 170 GeV, an excess would most probably (95 % of confidence level) have already been observed by the Tevatron, proton-anti-proton hadron collider situated in the United States of America. Within the W^+W^- channel, purely leptonic ($h \rightarrow W^+W^- \rightarrow \ell\nu\ell\nu$) and semi-leptonic ($h \rightarrow W^+W^- \rightarrow \ell\nu qq$) decay modes are being searched at the LHC. The decay of the Higgs boson to a pair of Z bosons has also been very attractive due to the production of a very clean signal. If the Z boson would decay as $Z \rightarrow \ell\ell$, $h \rightarrow ZZ$ would produce 4ℓ signature, which is very uncommon for the SM, leading to very small background. The production of $h \rightarrow ZZ \rightarrow \ell\ell qq$ and $h \rightarrow ZZ \rightarrow \ell\ell qq$ are also being analysed. At the low mass region, direct analyses of $h \rightarrow \gamma\gamma$, $h \rightarrow b\bar{b}$ and $h \rightarrow \tau\tau$ have been taken care of by the collaborations of the LHC experiments. Limits for the Higgs boson mass could therefore be set taking into account these analyses.

In July 2012 two collaborations of the LHC experiment have announced the discovery of a new boson state that, in principle, could be the Higgs boson [18, 19]. However, it is yet very early to state whether it is the so-expected Higgs particle, or a new bosonic particle with different properties.

We are living therefore in a historical moment for particle physics. If the Higgs is not discovered by the LHC very soon, the SM will not have a mechanism to explain the generation of mass for fermions and bosons. Fortunately, it has been shown that the LHC has very strong indicators for a low mass Higgs boson of approximately 126 GeV. For the moment, only time can provide us these answers.

2.4 Why to go Beyond the Standard Model?

In the previous sections, it has been shown why the SM of particle physics is one of the most successful theories in physics, which explains with great accuracy the experimental data we have so far. However, the SM suffers from few shortcomings, which led theorists to believe there could be new physics lying at the TeV scale. Here, we present some of these issues, which will be addressed in further chapters by the introduction of extensions of the SM.

2.4.1 The Hierarchy Problem

Many features of the SM arise from the BEH mechanism, the procedure to generate masses for the particles observed. However, only calculations at the lowest level of perturbation theory, also known as tree-level contributions, have yet been discussed. In reality, radiative corrections to the mass of a particle should be computed when one-loop corrections to the propagator are considered.

Take for example a toy-theory with a single fermion ψ coupled to a massive scalar ϕ [20]. The lagrangian is given by

$$\mathcal{L}_\phi = i \bar{\psi} \gamma_\mu \partial^\mu \psi + |\partial_\mu \phi|^2 - m_s^2 |\phi|^2 - \lambda_f \bar{\psi} \psi \phi. \quad (2.29)$$

As it has been done for the SM, we suppose the symmetry is spontaneously broken and the fermion obtains the mass $m_f = \lambda_f v / \sqrt{2}$ at the lowest order.

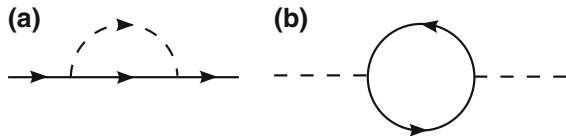
To compute corrections to the fermion mass within this toy-theory, it is necessary to consider one-loop contributions to the fermion propagator due to the scalar particle, as illustrated in Fig. 2.4a. The renormalized fermion mass is given by

$$m_f = m_f^{(0)} + \delta m_f \quad (2.30)$$

where $m_f^{(0)} = \lambda_f v / \sqrt{2}$, and the correction to the mass depends on the introduction of a cutoff Λ to the theory:

$$\delta m_f = -\frac{3\lambda_f^2 m_f}{64\pi^2} \log \frac{\Lambda^2}{m_f^2} + \dots \quad (2.31)$$

Fig. 2.4 **a** Example of a fermionic loop on a scalar particle, **b** illustration of a scalar loop on a fermionic particle



where ... indicates terms that vanish when $\Lambda \rightarrow \infty$ or terms independent of the cutoff. Notice that the correction to the mass of the fermion depends explicitly on m_f . In the limit where the mass of the fermions are very small, the lagrangian (2.29) is invariant under chiral transformations. Therefore, decreasing the mass of the fermion increases the symmetry of the theory. It is thus usually said that fermionic masses are protected by chiral symmetry.

Similarly, we could compute corrections to the scalar propagator due to the fermion loop, as shown on Fig. 2.4b. When this is done, the mass of the scalar obtains a δm_s correction, which can be written as:

$$\delta m_s^2 = -\frac{\lambda_f^2}{8\pi} \left[\Lambda^2 - 6m_f^2 \log \frac{\Lambda}{m_f} + 2m_f^2 + \dots \right] \quad (2.32)$$

Differently from corrections for fermionic masses, the mass correction for a scalar particle is found to be quadratically divergent. For this reason, nothing can actually protect the mass of the scalar particle of having very large corrections. If we assume the theory to be valid until the Planck scale, i.e. scale at which quantum corrections to gravity become important, corrections to the scalar particles will be of such order of magnitude. Unless the mass of the particle and its correction are at most of the same order, the theory is considered to have a naturalness problem.

For the SM Higgs boson the same fact occurs. Obviously, corrections to the propagator due to all types of particles on the loop must be considered. However, the largest contributions come from fermionic loops, where quadratic divergences appear.

Since unitarity requires the Higgs boson to have a mass smaller than 1 TeV, quadratic divergences would indicate a large problem, considering corrections would have a much larger order of magnitude than the mass at lowest order. A counter term to cancel these quadratic divergences could solve the problem. However, such large cancellations would be highly un-natural. Conversely, one could adjust the cutoff down to 1 TeV. The result would be a theory that ceases to being valid at this energy scale. This is known as the *hierarchy problem*, and it is one of the reasons for which it is believed that new physics could indeed lie above the TeV scale.

2.4.2 Fermionic Mass Hierarchy

Another issue not well explained by the SM is related to the order of magnitude of the fermion masses. We have seen that fermionic lagrangian is defined by the Yukawa term, or Eq. 2.28, and they should acquire mass from spontaneous symmetry breaking. Concentrating on the quark terms, we have:

$$\mathcal{L}_{yuk}^q = -\lambda_d \bar{Q}_L \phi d_R - \lambda_u \bar{Q}_L \tilde{\phi} u_R + h.c., \quad (2.33)$$

which can be decomposed as

$$\mathcal{L}_{yuk}^q = (\bar{u}'_R \bar{c}'_R \bar{t}'_R) \mathcal{M}_U \begin{pmatrix} u'_L \\ c'_L \\ t'_L \end{pmatrix} + (\bar{d}'_R \bar{s}'_R \bar{b}'_R) \mathcal{M}_D \begin{pmatrix} d'_L \\ s'_L \\ b'_L \end{pmatrix} + h.c.$$

where we have used the *prime* notation to represent the weak eigenstates. However, there is no reason, in principle, for the matrices $\mathcal{M}_u = \frac{v}{\sqrt{2}} \lambda_u^{ij}$ and $\mathcal{M}_d = \frac{v}{\sqrt{2}} \lambda_d^{ij}$ to be diagonal. In fact, the weak eigenstates are linear superposition of mass eigenstates and the transformation can be given as

$$\begin{pmatrix} u' \\ c' \\ t' \end{pmatrix} = V_u \begin{pmatrix} u \\ c \\ t \end{pmatrix}, \quad \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_d \begin{pmatrix} d \\ s \\ b \end{pmatrix} \quad (2.34)$$

where V_u and V_d are unitary matrices that diagonalize the mass matrices $\mathcal{M}_u$ and $\mathcal{M}_d$.

In the SM lagrangian, charged currents (processes intermediated by a charged particle, such as $W^\pm$) are proportional to

$$(\bar{u}'_L \bar{c}'_L \bar{t}'_L) \gamma^\mu \begin{pmatrix} d'_L \\ s'_L \\ b'_L \end{pmatrix} = (\bar{u}_L \bar{c}_L \bar{t}_L) (V_u^\dagger V_d) \gamma^\mu \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} \quad (2.35)$$

while neutral currents are proportional to

$$(\bar{u}'_L \bar{c}'_L \bar{t}'_L) \gamma^\mu \begin{pmatrix} d'_L \\ s'_L \\ b'_L \end{pmatrix} = (\bar{u}_L \bar{c}_L \bar{t}_L) (V_u^\dagger V_u) \gamma^\mu \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}. \quad (2.36)$$

Notice that $V_u^\dagger V_u = 1$, and there is no flavour mixing terms (at tree level) for neutral currents. However, flavour changing terms appear for charged currents coming from the CKM matrix defined to be $V_{CKM} = V_u^\dagger V_d$ [10].

Experimentally, the CKM matrix is constrained and its parameters are defined according to the observed mass values for the fermions. It has been also realized that the CKM matrix follows a hierarchy and can be parametrized following the Wolfenstein parametrization [21].

In principle there is no natural explanation for the hierarchy observed in the CKM matrix. This can be related to the hierarchy observed in the experimental values obtained for the mass of the fermions. In particular, note that fermionic masses are generated from the same mechanism. It is therefore un-natural to obtain masses with so different order of magnitude. For instance the ratio $m_{\text{electron}}/m_{\text{top}}$ is of the order of 3×10^{-6} . This issue is usually known as the *fermionic mass hierarchy*, and it could be one more indication of new physics at the TeV scale.

2.4.3 CP Violation

CP symmetry is the combination of charge (C) conjugation and parity (P) symmetries. These symmetries state that the laws of physics must be the same if:

- charge is conjugated, i.e. particles are replaced by anti-particles;
- parity is exchanged, i.e. left-handed particles are replaced by right-handed particles.

Both symmetries hold for electromagnetic interactions. It has been discovered however that they can be separately violated for weak interactions [22, 23]. The CP symmetry has been proposed to solve the problem of individual C and P violations, with the statement that the CP should be the real symmetry between matter and anti-matter.

Violation of CP has been experimentally discovered in 1964 by Cronin and Fitch [24, 25], through experiments made with K^0 . Later on, CP violation in B mesons has also been observed [26–28].

The main question regarding the subject nowadays is why is the strong force CP-invariant? The QCD lagrangian contain one term that could be responsible for a possible CP violation. This term is set to zero due to the non-existence of such events. The issue is also known as *strong CP problem*, and presents one more evidence for new physics at TeV scale. Besides, CP violation is often used to explain the unbalance of matter/anti-matter of the Universe.

The most famous solution has been proposed by Peccei and Quinn [29, 30]. This theory postulates the existence of a new particle named axion, generated from the spontaneous symmetry breaking of a new symmetry.

2.4.4 Dark Matter

A different indication of new physics at the TeV scale is the evidence of dark matter existence. Dark matter is defined to be an undetermined type of matter that does not emit or reflect electromagnetic radiation. In fact, the subatomic composition of this new type of matter is not yet known, neither are its interactions.

The first evidence was postulated by Jan Oort in 1932, in a study related to the search of orbital velocities of stars in the Milky Way. In 1933, when calculating orbital velocities of galaxies and clusters, Fritz Zwicky discovered that part of the mass expected by his calculations was missing, and denominated it dark matter [31].

Nowadays, several observations have confirmed dark matter evidence [32]. For instance, analyses combining galaxy cluster dynamics, supernova data and Cosmic Microwave Background (CMB) radiation with Big Bang nucleosynthesis are good indicators for its existence. Besides, precise measurements have been performed and recently confirmed the existence of dark matter at larger scales than the size of galaxies and clusters. It is believed that approximately 5 % of the known matter in the Universe is formed of atoms, while 23 % is dark. A relation of the matter

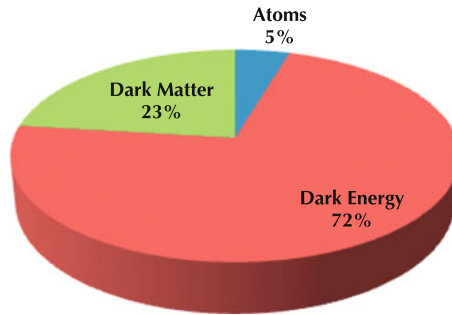


Fig. 2.5 WMAP data shows that the content of the present Universe is formed by approximately 5 % of baryonic matter, i.e. atoms that compose planets and stars; 23 % of dark matter; and 72 % by dark energy, subject not discussed within this study. Dark energy should be different from dark matter, and responsible for the experimentally observed acceleration of the Universe. This image is based on the one produced by the NASA/WMAP Science Team [33]

content of the Universe as of today, extracted from WMAP results, are displayed on Fig. 2.5 [33].

In principle, dark matter could be formed of either baryonic, non-baryonic content or yet by a combination of both. It could consist of planets, black-holes or even burnt-out stars in the galactic halo, for example. These are so-called MACHOS, i.e. massive compact halo objects, and are the most probable constituent of the dark matter if it is found to be formed of baryonic content [34].

Nevertheless, there are reasons to believe that dark matter could not consist of only baryonic content. Studies have shown that there is more dark matter in the Universe than the maximum number that can be calculated. The theory of Big Bang nucleosynthesis and acoustic peaks in the CMB can be used to accurately determine the fraction of baryons in the Universe, and therefore to predict how much dark matter is expected to be baryonic. For this reason, it is widely believed that a significant part of the dark matter content is likely to be exotic, i.e. composed by non-baryonic content. From the SM of particle physics, only the neutrino would fill in all the requirements to be a non-baryonic dark matter candidate. Since it does not carry electric charge and it interacts very weakly to the particles of the SM, the cross section for neutrino production is very small. However, the mass density of neutrinos in the Universe has been calculated and is not enough to explain the matter fraction of the cosmic average density. Besides, there are studies of galaxies structure affirming that neutrinos with a very small mass cannot be entirely responsible for the measured dark matter composition. As a solution, there could exist different types of neutrinos not yet observed, such as sterile neutrinos, to account for part of the dark matter content. In this case, clearly new physics is expected.

There are usually three categories to separate possible non-baryonic dark matter content: (i) hot dark matter, which encompass theories with sterile neutrinos, (ii) warm dark matter and (iii) cold dark matter. These categories are related through the velocity of propagation of the particles, rather than their actual temperature. Particles

moving ultra relativistically fit in the first category, particles moving relativistically fit in the second category and finally, particles moving at classical velocities are categorized as cold dark matter.

Different (and most probable) options are available. If dark matter is non-baryonic and not formed by neutrinos, it should be composed by new particle(s). The most common suggestions are axions and WIMPs (or weakly interacting massive particles). The axion is the hypothetical particle postulated by Peccei and Quinn to solve the strong CP problem that appears in QCD [29, 30], as explained previously. They are supposed to be scalar particles generated from the spontaneous symmetry breaking of a new symmetry.

WIMPs are massive particles, predicted by some theories Beyond the Standard Model (BSM), i.e. theory extensions to the SM. Examples of such theories are supersymmetry or theories with extra dimensions, both to be detailed on subsequent chapters. Candidates for WIMPs should interact only via the weak or gravitational forces, and not through the strong force. These are for example the neutralino or the gravitino in different variations of supersymmetric (SUSY) theories. SUSY theories not only predict a stable particle to be the dark matter candidate, but also solve several other issues presented here (for example the hierarchy problem). It is therefore one of the most studied BSM theories giving rise to different branches. More details on SUSY theories will be presented in Chap. 6. Finally, WIMPs candidates could also be for example new and unpredicted particles coupled to the SM only via gravitational interaction.

All the options briefly discussed here to find the best candidate for dark matter largely indicate the existence of new constituents of fundamental particles. Moreover, an extended version of the SM would be necessary to incorporate such exotic particles. If this is true, chances are that these particles will be at the LHC energy range. Therefore, hints of new physics existence could appear very soon.

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