# CHAPTER 1

# THE STANDARD MODELS

> The Higgs mechanism is just a reincarnation of the Communist party: it controls masses.
>
> V.I. Ulyanov

## 1.1 What we know

It is an ancestral belief that the Universe is composed of simple materials governed by a set of universal and unified laws. Our current understanding of the structure of the Universe is based on two basic pillars of modern physics: the Standard Model (SM) of particle physics and General Relativity (GR). The action of "everything we know" takes the form

$$S = \int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}R + \Lambda + \mathcal{L}_{SM}\right]\,, \tag{1.1}$$

with $M_P = (8\pi G)^{-1/2} = 2.48 \times 10^{18}$ GeV the reduced Planck mass, $R$ the Ricci scalar, $\Lambda$ a cosmological constant and $\mathcal{L}_{SM}$ the Standard Model Lagrangian density,

$$\begin{aligned}
\mathcal{L}_{SM} = & -\frac{1}{4g'^2}B_{\mu\nu}B^{\mu\nu} - \frac{1}{2g^2}\mathrm{Tr}(W_{\mu\nu}W^{\mu\nu}) - \frac{1}{2g_s^2}\mathrm{Tr}(G_{\mu\nu}G^{\mu\nu}) \\
& +\bar{Q}_i i\not{D}Q_i + \bar{L}_i i\not{D}L_i + \bar{u}_i i\not{D}u_i + \bar{d}_i i\not{D}d_i + \bar{e}_i i\not{D}e_i \\
& +(Y_u^{ij}\bar{Q}_i u_j\tilde{H} + Y_d^{ij}\bar{Q}_i d_j H + Y_l^{ij}\bar{L}_i e_j H + \text{h.c.}) \\
& +(D_\mu H)^\dagger(D^\mu H) - \lambda(H^\dagger H)^2 - m^2 H^\dagger H + \frac{\theta}{32\pi^2}\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}(G_{\mu\nu}G_{\rho\sigma})\,,
\end{aligned}$$

This Lagrangian density is based on the $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge symmetry group unifying the strong, weak and electromagnetic interactions. The gauge symmetry is spontaneously broken to $SU(3)_C \times U(1)_{EM}$ by a weak isodoublet complex scalar field, giving mass to the SM particles.[1] The intermediate $W^\pm$ and $Z$ gauge bosons acquire masses by absorbing three of the four components of the scalar field, the so-called Goldstone bosons. The

[1] In the original formulation of the SM the neutrinos remain massless.

| Bosons | |
|---|---|
| Gauge bosons<br>$\gamma$, $W^+$, $W^-$, $Z^0$, $g_{1...8}$ | Higgs boson<br>$\phi$ |
| **Fermions** | |
| Quarks | Leptons |
| $\begin{matrix} 2/3: \\ -1/3: \end{matrix} \begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix}$ | $\begin{matrix} 0: \\ -1: \end{matrix} \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$ |

Table 1.1: *The Standard model particle content. Numbers stand for electric charges.*

remaining degree of freedom becomes a physical particle: the Higgs, recently discovered. The many particle's experiments in the last 30 years gave rise to a vast array of data that allowed to test the interaction vertices, masses and cross sections of the model with unprecedented precision, see Fig. 1.1. The central principles of the SM have remained in place for decades and it is nowadays understood as an extremely successful description of particle physics at energies below TeV scales.

On the other hand, General Relativity (GR), a classical geometrical theory, constitutes a very elegant and coherent framework for the description of gravity and matter at the macroscopic level. Its predictions and deviations from Newtonian gravity have been tested in and out of the solar system, although its consequences go far beyond these scales. Indeed, it can be considered as the origin of modern cosmology. In General Relativity, space and time are promoted to dynamical quantities, whose evolution is dictated by the matter and energy content.

## 1.2 What we don't know

In spite of their success, strong experimental, observational and theoretical arguments lead us to believe that neither the SM nor GR should be understood as complete theories of nature. Before considering extensions, it is important to notice that we are facing different kinds of troubles.

On the one hand, there are well established facts, whose explanation is not satisfactory within the SM. The first, and maybe the most evident one, is the existence of neutrino masses. When the SM was formulated, the neutrinos were considered to be massless, and therefore, the particle content of the model was chosen to forbid the mass terms. Nevertheless, the situation changed dramatically with the discovery of neutrino oscillations, for which there is nowadays overwhelming evidence. These are transitions between neutrinos of different flavours and can occur only if neutrinos have non-degenerate masses. The initial version of the SM must then be extended in order to accommodate this fact.

Regarding also the particle content, one of the basic tenets of the SM is the symmetry between matter and antimatter. According to the CPT theorem, for any given particle there

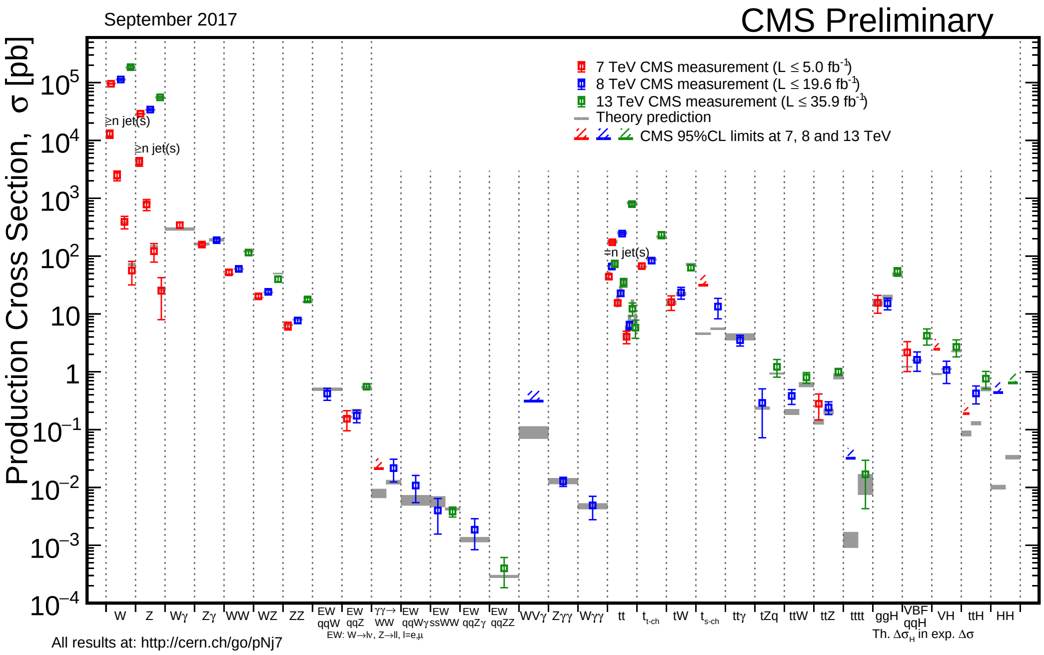


Figure 1.1: Comparison between SM predictions and data.

exists an antiparticle with opposite charges but identical masses and decay widths. This basic principle seems to be in contradiction with a variety of observations, ranging from the solar system to the whole observable Universe. For some unknown reason, there are many more protons than antiprotons and antimatter is indeed only detected in accelerators or cosmic rays. Moreover, the number of photons substantially exceed the number of protons.[2] This fact is usually called the baryon asymmetry problem. As established on general grounds by Sakharov in 1967, to successfully create the primeval baryon asymmetry, the particle processes violating baryon number conservation must take place out of thermal equilibrium. Besides, C and CP symmetries must be violated. Although the SM has *a priori* all the ingredients to generate the baryonic asymmetry, the absence of a first order electroweak phase transition and the smallness of the Jarlskog determinant in the quark sector excludes the possibility of generating the measured value within the standard theory.

Even if a satisfactory baryogenesis mechanism was known, the baryonic matter would not be able to account for all the matter content in the Universe. Several astrophysical and cosmological observations, coming from many different scales, seem to suggest that our Universe should contain a new type of invisible or dark matter component. The new species would help to explain processes so unrelated as primordial nucleosynthesis, large-scale structure formation, or galactic rotation curves. However, the concept of dark matter does not find a satisfactory explanation within the framework of the Standard Model, since all the SM particles either emit photons or would have left an imprint at nucleosynthesis. The now

[2]This is usually defined in terms of the quantity $\eta = n_B/n_\gamma$ where $n_B$ is the difference between the number of baryons and antibaryons per unit volume and $n_\gamma$ is the photon number density at temperature $T$. The value of $\eta$ is severely constrained by nucleosynthesis, $5.1 \times 10^{-11} \leq \eta \leq \times 6.5 \times 10^{-11}$ at 95 % C.L.

massive neutrinos would constitute a natural choice, but they are essentially ruled out by observations. As relativistic species, neutrinos erase density fluctuations at scales below their free-streaming length, of order 40 Mpc $\times m_\nu/30$ eV. This erasing would imply a top-down process for the structure formation in the Universe. As a consequence, galaxies would only appear at redshifts $z \leq 1$, which is in clear contradiction with the observation of galaxies at redshifts $z > 4$. A new dark candidate beyond the Standard Model matter content, or a substantial modification of GR, seems therefore unavoidable.

This invisible matter is indeed not the only dark or unknown component in our Universe. In the concordance ΛCDM model, the redshift dependence of the luminosity of type Ia Supernovae is interpreted as a consequence of a present accelerated expansion of the Universe. The present energy content is dominated by a cosmological constant term Λ, which, as happens with dark matter, has been only inferred by its gravitational interaction on cosmological scales. Although this term is a completely natural part of Einstein equations, it encounters consistency or interpretation problems when particle physics, in its standard formulation, is taken into account. In the usual quantum field theory approach, the Λ term cannot be distinguished from vacuum energy fluctuations. When the standard renormalization procedure in flat space-time is applied, it fails to reproduce the observed value by many orders of magnitude. Also, no explanation is known for the so called *coincidence problem*, which wonders about why the cosmological constant started to dominate *right now*, in our present epoch. These difficulties have motivated the study of alternatives such as Modified Gravity, Extra Dimensions, Dark Energy or inhomogeneous Lemaître-Tolman-Bondi cosmologies.

Finally, we believe that the early Universe also underwent a period of accelerated expansion. In the hot Big Bang theory questions such as the origin of the surprising flatness, homogeneity and isotropy of the present Universe remain unexplained. Our Universe should have been originated from very unnatural and non-generic initial conditions.

Any fundamental or effective theory beyond the SM and GR should try to solve, or at least alleviate, the previously described troubles. They clearly constitute a *smoking gun* for physics Beyond the Standard Model.

On the other hand, there are man-made or aesthetic problems. The SM contains many parameters, which are unrelated, at least in the context of the theory itself. In addition to the Yukawa couplings for quark and lepton masses, one should specify three mixing angles and a complex phase in the CKM matrix, as well as other CP violation parameters. Something similar happens in the neutrino sector. If mass terms are allowed, three further mixing angles together with three phases must be considered. This counting gives rise to 26 free parameters. The amount and strange hierarchy of the parameters, or the non-unification of the gauge couplings, are usually invoked to justify new physics beyond the SM, such as Grand Unified Theories. The large set of couplings is thought to be the dynamical outcome of a simpler and more fundamental structure, as happens for instance with the transport coefficients of fluids.

There is a large number of proposals for extending the Standard Model, commonly referred to as *Beyond the Standard Model* (BSM) theories. Inspired by the success of weak interactions, they share the belief that new energy scales, and their associated physics, should appear beyond the electroweak scale. The new symmetries and particles introduced would allow to partially alleviate some of the SM problems, providing candidates for dark matter, new Baryogenesis mechanisms or flat inflationary potentials. Given the huge difference between the weak and gravitational scales, the relevance of gravity in those theories is usually neglected and new physics is expected to appear at energies well below the Planck scale.