

1

Historical Introduction

The most incomprehensible thing about the universe is that it is comprehensible.

(Albert Einstein)

Physics at the shortest scales deals with the study of the elementary constituents of matter as produced in particle accelerators or within astrophysical and cosmological environments. In broad terms, particle physics seeks to determine the properties of the Universe at large, starting from the microphysics describing the interactions among quarks and leptons, the basic building blocks of matter. The underlying theory is the so-called standard model (SM), which puts together quantum mechanics and Einstein's relativity along with the principle of gauge invariance. These basic pillars constitute the three revolutions in physics that took place in the past century. The SM describes the electromagnetic, weak and strong interactions among the elementary constituents of matter in terms of a quantum field theory merging quantum mechanics with special relativity and incorporating interactions via gauge symmetry. In this picture, all basic forces other than gravity are mediated by the exchange of intermediate vector bosons associated with the SM gauge symmetry group $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$, that is, the photon, the gluons and the weak gauge bosons $W^\pm$ and Z [7–9]. Its theoretical formulation was developed from the mid- to the late twentieth century, and its current form has gained general acceptance after the experimental confirmation of the existence of quarks in the mid-1970s. Quarks carry colour and hence couple to gluons, while leptons do not. Today we know for certain that there are three types or 'generations' of elementary constituents of matter.

The gauge bosons associated with the electroweak $SU(2)_L \otimes U(1)_Y$ part of the symmetry are the photon and $W^\pm$, Z gauge bosons. The latter were directly produced for the first time at CERN (the European Organization for Nuclear Research) in 1983 [10–13]. On the other hand, the gluons are associated with the $SU(3)$ colour symmetry and were discovered at DESY (German Electron Synchrotron) [14].

In order to provide masses for the gauge bosons and fermions, the SM gauge symmetry must be broken spontaneously down to the $SU(3)_c \otimes U(1)_Q$ subgroup, where $SU(3)_c$ describes the strong colour force amongst quarks holding the

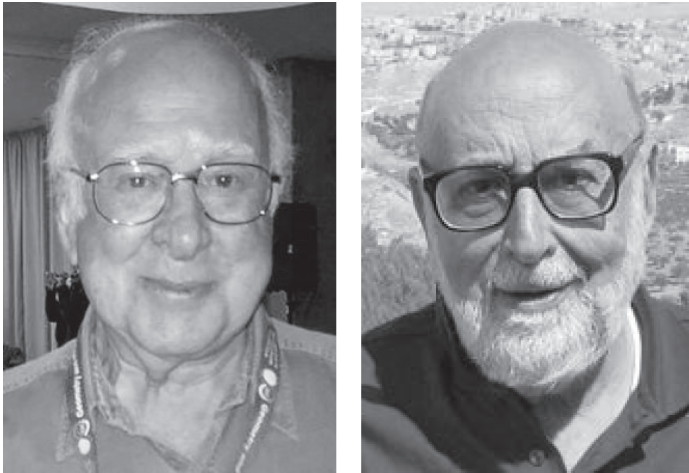


Figure 1.1 Peter Higgs and Francois Englert shared the 2013 physics Nobel Prize for their pioneering work on spontaneous symmetry-breaking in the standard model. Adapted from the Wikimedia Commons

nucleus together, while $U(1)_Q$ describes the long-range electromagnetic force between charged particles. The formulation of the spontaneous gauge symmetry-breaking mechanism was pioneered by Englert, Brout, Higgs, Guralnik, Hagen and Kibble (Figure 1.1) [15–17] and will be referred to in this book simply as the *Higgs mechanism*. It implies the existence of a physical elementary scalar particle, the so-called Higgs boson. Its recent discovery by the ATLAS and CMS experiments at the Large Hadron Collider (LHC) at CERN [18–20] constitutes an outstanding achievement in particle physics, and a triumph for elementary particle theory, and was awarded the 2013 physics Nobel Prize. While the mass ~ 125 GeV and current data on decay branching ratios seem, in general, to be in accordance with expectations, a better understanding of its properties from further data will be required in order to underpin the nature of the associated dynamics and possibly uncover new principles in Nature.

Indeed, although recognized as an excellent approximation at energy scales below a few hundred gigaelectronvolts (GeV) [21], the $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ theory is not believed to be the ultimate theory of elementary particle interactions. For example, supersymmetry or strong dynamics has been suggested to explain the naturalness of the electroweak breaking mechanism. The former [22, 23] is a symmetry that relates the SM states to a hypothetical set of supersymmetric partners so that these cancel quadratically divergent contributions to the Higgs squared-mass, ‘solving’ the so-called hierarchy problem. The new states are odd under a new quantum number called *R-parity*, under which all the SM particles are even. The so-called minimal supersymmetric standard model (MSSM) assumes *ad hoc* conservation of *R-parity* [24]. In order to be phenomenologically viable, supersymmetry must be broken in a way that is not yet fully understood, but which should be ‘soft’ [25]. If sufficiently light, the states

corresponding to partners of the SM particles would be produced at the LHC, current data already placing important restrictions on the model parameters.

While we eagerly wait for positive signs of new physics, such as supersymmetry, in the next run of the LHC, we turn to the neutrino sector, which provides one of the most solid present-day evidences for physics beyond the SM. Among the elementary building blocks of matter, neutrinos are unique in that they do not carry an electric charge and as a result interact only weakly; hence their experimental elusiveness. Neutrinos may pass through ordinary matter almost unaffected. As a result, they constitute a unique probe of the very early Universe, and the precise determination of their properties may hold the clue for what lies beyond the SM of particle physics. Neutrinos come from ‘natural’ sources such as nuclear fusion inside the Sun, cosmic ray interactions in the Earth’s atmosphere, the Earth’s natural radioactivity, supernova explosions, not to mention neutrinos produced primordially in the Big Bang itself.

There is one neutrino ‘flavour’ within each SM generation. The first neutrino ν_e was discovered in nuclear reactors in 1956 [26], while the ν_μ [27] and the ν_τ [28] were discovered in particle accelerators in 1961 and 2000, respectively. Three neutrino species also fit well with the good measurement of the Z-boson ‘invisible’ width at LEP as well as with the primordial abundance of helium in the early Universe [29].

The Sun and most visible stars produce their energy by the conversion of hydrogen to helium and are copious sources of neutrinos. Pontecorvo was the first to speculate that such neutrinos might be detectable through radiochemical means in a large volume of chlorine-bearing liquid [30]. In 1964, Bahcall and Davis argued that a solar neutrino experiment would be feasible in a large enough detector volume placed deep underground so as to reduce cosmic-ray-associated backgrounds [31, 32]. In the late 1960s, Ray Davis proposed his pioneer geochemical experiment at Homestake [33], which captured fewer neutrinos than expected in the standard solar model (Figure 1.2) ([34]). Understanding the observed solar neutrino deficit remained a challenge until its final resolution over ten years ago, which gave us irrefutable proof for the existence of neutrino mass, a possibility always present ever since Pauli proposed the neutrino idea in order to account for energy conservation in nuclear beta decays. However, the success of the V–A hypothesis [35] in accounting for the observed parity violation in the weak interaction [36] was taken as an indication for massless neutrinos and incorporated into the manifestly chiral formulation of the $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ theory.

The 1980s saw a thriving period in neutrino physics. On the theory side, motivated by the idea of grand unification [37–39], one started to question the assumption of lepton (and baryon) number conservation [40]. The unification idea inspired the seesaw mechanism as a way to understand the tiny neutrino masses as resulting from the exchange of superheavy ‘messengers’, either fermions

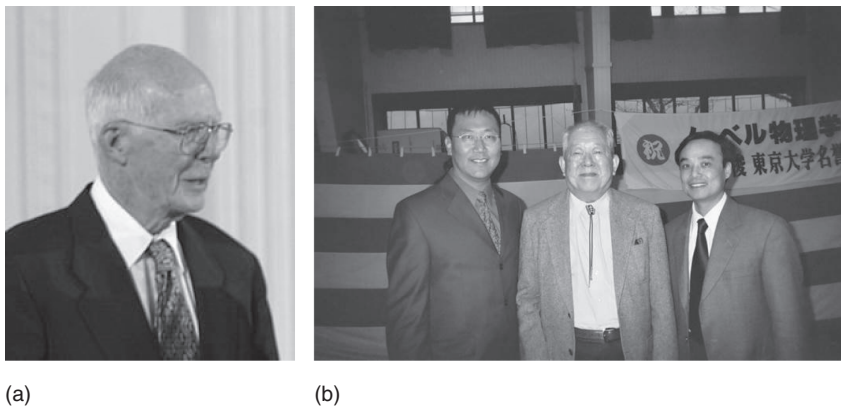


Figure 1.2 Ray Davis (a) and Masatoshi Koshihara (b) (with C. K. Jung and C. Yanagisawa) were recognized for their pioneering contributions to astrophysics, including the detection of solar and supernova neutrinos.

They shared the 2002 Nobel Prize with Riccardo Giacconi for the discovery of X-ray sources. Credit photo: Wikimedia Commons (a) and courtesy of Chiaki Yanagisawa (b).

(type I) [41–47] or triplet scalars (type II seesaw) [46, 47].¹⁾ In order to describe the phenomenology of neutrino oscillations, the multi-generation description of the $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ seesaw mechanism was formulated,²⁾ leading to the current form of the lepton mixing matrix, presented in terms of 1–2, 2–3 and 1–3 mixing angles θ_{ij} [46, 47, 58] as well as Dirac and Majorana CP phases affecting oscillations and lepton number violation processes, respectively.³⁾ The last ingredient required in order to describe neutrino propagation was the proper description of matter effects that are present in the interior of the Sun or the Earth, formulated by Mikheev, Smirnov and Wolfenstein [59, 60]. On the experimental front, the use of water Cherenkov detectors paved the way to the historic detection of neutrinos from SN1987a in the Large Magellanic Cloud [61–63]. Measurements of the zenith angle dependence and recoil energy spectrum of solar neutrinos [64, 65] brought on a firmer observational basis the long-standing problem of solar neutrinos indicated by geochemical experiments since Homestake [33, 66–68]. Also, the observations of neutral current neutrino interactions on deuterium at the Sudbury Neutrino Observatory (SNO) gave strong evidence for solar ν_e flavour conversions [69], contributing also to the determination of the oscillation parameters [70]. The ultimate elucidation of the solar neutrino puzzle had to wait for the confirmation of the oscillation hypothesis by the nuclear reactor experiment KamLAND. This experiment

- 1) Note that the seesaw idea was first given in a phenomenological $\mu \rightarrow e\gamma$ paper [41], while in Ref. [46] the suggested type I versus type II terminology was opposite to what became subsequently established.
- 2) This also led to low-scale seesaw realizations where messengers can be accessible to collider searches [48–51] and also induce charged lepton flavour violation [52–54].
- 3) The most general seesaw form of the lepton mixing matrix given in [46, 47] also describes a class of non-standard neutrino conversion effects in matter [55–57].

measured not only the flux of $\bar{\nu}_e$'s from distant nuclear reactors in Japan but also the spectrum distortion [71] matching the one expected from large mixing angle oscillations. This was crucial to exclude non-standard solutions, thus establishing robustness of large angle oscillations driven by θ_{12} [72–74].

Cosmic ray interactions with atomic nuclei in the Earth's atmosphere produces particle showers, which end up in (anti)neutrinos. Large underground experiments such as IMB, MACRO and Kamiokande-II indicated a deficit in the muon-to-electron neutrino event ratio. The elucidation of this 'anomaly' had to wait till the commissioning of the Super-K experiment, which gave a very high statistics measurement over a wide energy range from hundreds of megaelectronvolts to a few teraelectronvolts. It showed that the observed deficit in the μ -like atmospheric events is due to ν_μ oscillations driven by θ_{23} [75], a discovery later confirmed by accelerator experiments such as K2K [76] and MINOS [77].

Recent reactor experiments, especially at Daya Bay, have observed the disappearance of electron-anti-neutrinos at a distance of about 2 km from the reactors, providing a robust determination of the third neutrino mixing angle, θ_{13} [78], seen also at accelerator experiments such as T2K [79]. This opens the door to a new generation of oscillation experiments [80] probing CP violation in neutrino oscillations [81], and may shed light on the mystery of flavour.

Note that in both solar and atmospheric 'sectors' there is independent confirmation of the oscillation hypothesis by experiments based at reactors and accelerators. Neutrino oscillation physics is now a mature field brought to the precision era. Dedicated fits [82, 83] indicate a pattern of mixing angles quite different from the Cabibbo–Kobayashi–Maskawa (CKM) [84, 85] matrix which characterizes quark mixing. Altogether, the discovery of neutrino oscillations constitutes a historic landmark in particle physics, which not only implies new physics but is also likely to pave the way for a deep understanding of the flavour puzzle. In particular, lepton flavour violation may also be seen in the charged lepton sector, irrespective of neutrino mass, bringing complementary information [52–54, 86]. Moreover, it is likely that there is total lepton number violation, as highlighted in the modern gauge theoretical formulation of neutrino masses. Proving the Majorana nature of neutrinos requires searching for lepton number violation processes such as neutrinoless double beta decay [87, 88].

Further hints for new physics come from cosmology, which has made fast progress over the last few years [89, 90]. Indeed, it is truly remarkable that $< 5\%$ of the entire Universe consists of stuff we know, and all the rest remains a complete mystery, dubbed dark matter and dark energy. As an example, we mention dark matter, whose detailed nature remains elusive, despite strong evidence in favour of its existence, ever since the pioneering observations of the astronomer Fritz Zwicky in the 1930s. Dark matter neither emits nor scatters light or other electromagnetic radiation, hence cannot be detected directly by optical or radio astronomy. However, most of the mass in the Universe is indeed non-luminous, and its existence is also inferred by the modelling of structure formation and galaxy evolution. However, we still do not know its composition. Viable dark matter particle physics candidates must be electrically neutral and provide the

correct relic abundance, hence they must be stable over cosmological time scales. The most popular candidate is a weakly interacting massive particle (WIMP), for example, the lightest supersymmetric particle in models with conserved R-parity [91, 92].

Although neutrinos cannot provide the required dark matter, the physics through which they acquire their small masses may be closely connected, providing a fascinating link between neutrinos and early Universe cosmology [93–96]. One interesting possibility is that dark matter is stabilized by a remnant of the flavour symmetry which explains the oscillation pattern [97, 98]. Many other types of relations between dark matter and neutrinos [99, 100] are considered in Chapter 17. Another open issue in cosmology is the understanding of the matter–antimatter asymmetry [101]. An attractive mechanism is to generate a primordial lepton–anti-lepton asymmetry through the out-of-equilibrium CP-violating decays of the messenger particles responsible for neutrino mass. This would take place very early on in the evolution of the Universe, while subsequent non-perturbative processes would convert the lepton number (B-L) asymmetry into a baryon asymmetry. In such a *leptogenesis* picture, neutrinos are responsible for the origin of matter.

To sum up, over the last century neutrinos have provided a crucial tool in our understanding of weak interactions and guidance in the formulation of today’s SM of particle physics. It is not risky to imagine that they may also help in directing us towards the ‘theory of everything’ that lies ahead. Among the challenges in present-day particle physics, many are coming from the neutrino sector. Some of them are as follows:

- 1) *The Nature of Neutrinos*. Is lepton number violated in nature? Are neutrinos their own anti-particles? The observation of neutrinoless double beta decay ($\beta\beta_{0\nu}$) would provide the answer [87, 88] and many experiments are going on [102–104].
- 2) *The Origin of Neutrino Mass*. Why are neutrinos so light when compared the other elementary fermions? Is this a hint for some sort of unification of the gauge interactions [37–39]? Are neutrino masses a low-scale phenomenon? [48–51, 105–107]
- 3) *The Pattern of Neutrino Mixing*. Why are lepton mixing angles so different from the CKM mixing angles? Is there an underlying symmetry of flavour? [108–114]
- 4) *Probing Non-standard Neutrino Interactions*. Is there lepton flavour violation beyond that seen in oscillations? Do they show up in neutrino propagation? [55–57, 115, 116]
- 5) *Charged Lepton Flavour Violation and CP Violation*. Do processes such as $\mu \rightarrow e + \gamma$ take place? [117] Is leptonic CP violated? Does lepton flavour violation take place at LHC energies? This would be truly complementary to the oscillation studies.
- 6) *Probing Neutrinos at High Energy Accelerators*. Can neutrino properties be probed at LHC energies and higher? [118–122] Is teraelectronvolt-scale supersymmetry the origin of neutrino mass? [123–126]

- 7) *Neutrino Cosmology*. Owing to their weak interaction, neutrinos constitute an ideal probe of the early Universe, and may shed light on the origin of dark matter [93–96]. Can the origin of dark matter and neutrino mass be related?

Such are some of the challenges of today, which should inspire our research efforts in searching for hints of the theory of tomorrow. The purpose of this book is to provide a graduate text in which to learn basic model-building techniques, while at the same time be introduced to state-of-the-art research topics.

