1
Setting the Scene

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In this chapter we introduce the basic features of the field of particle physics at the Terascale and give a short historical perspective. Given that we are experimentalists, we concentrate more on the landmark experimental measurements and leave the discussion of theoretical developments to the later chapters on the Standard Model (SM), supersymmetry (SUSY), physics beyond the Standard Model and so on. We also briefly cover a few topics that are otherwise not addressed in the rest of the book, such as the connection between particle physics and astrophysics, neutrinos and spin physics.

Throughout the book we use the usual particle physics units, that is, $\hbar = c = 1$, and use energy units for momenta and masses, for example $m_\mu = 0.105$ GeV and $p_\mathrm{T} > 10\,\mathrm{GeV}$.

1.1
From the 1970s into the Twenty-first Century

It is difficult to know where to start when writing an introduction to both a book and the field of particle physics. We decided that the 1970s would be the appropriate time, as this was when the Standard Model of particle physics started to establish itself as the theory of fundamental particles and their interactions; it was also the decade when one of us (ICB) entered the field.

The 1970s saw a whole slew of fundamental discoveries and theoretical developments, to name just a few:

- the discovery of weak neutral currents;
- the discovery of the J/ψ meson and further excited charmonium states;
- the discovery of the τ lepton;
- the discovery of the b quark;
- the discovery of the gluon at the end of the decade.

Within theory notable developments include:

Physics at the Terascale, First Edition. Edited by Ian C. Brock and Thomas Schörner-Sadenius

Published 2011 by WILEY-VCH Verlag GmbH & Co. KGaA.

- the proof that local gauge theories are renormalisable;
- the development of Quantum Chromodynamics (QCD), the theory of the strong interaction;
- the recognition that CP violation could be explained within the framework of the Standard Model, if there are at least three generations of quarks and leptons. In other words the Cabibbo–Kobayashi–Maskawa (CKM) matrix contains a non-trivial phase for three or more generations.

Although the pace of discoveries slowed in the last three decades, both the experimental measurements and the theoretical developments have been essential in establishing the Standard Model as the theory of fundamental particles and interactions as well as exposing weaknesses in the models and indicating directions for future accelerators, detectors and theory.

1.1.1 Weak Neutral Currents

The combination of a theory of the weak interactions which relied on the local gauge principle and the Higgs mechanism led to the formulation of the Standard Model by Glashow, Weinberg and Salam in the mid-1960s. Together with the proof of the renormalisability of such theories by 't Hooft and Veltman in 1971, the prediction of the existence of a neutral partner for the $W^{\pm}$ bosons (responsible for charged-current interactions) became a hot topic for the experimentalists.

Groups in the USA and at CERN looked for bubble chamber events in which a group of hadrons appear from nowhere! These were supposed to be due to reactions such as $\nu p \rightarrow \nu X$. A major difficulty in extracting a signal from such events was that neutron-induced interactions look very similar. Very detailed studies of neutron production in the detector surroundings were necessary before it was possible to convince both the collaborations and the community at large that such neutral-current events actually exist. First evidence was announced in 1973 by the Gargamelle collaboration and by June 1974 three different collaborations all showed clear evidence for weak neutral currents.

This discovery marked the beginning of a huge experimental and theoretical activity in the field of electroweak unification at CERN and around the world. By comparing the charged-current and neutral-current cross sections it was possible to determine the weak mixing angle, θ_{W}. This yielded a prediction for the mass of the W boson, which in turn led to the idea of building a proton–antiproton collider in order to be able to discover the W and Z bosons well before the start of the $e^{+}e^{-}$ collider, LEP.

1.1.2 November Revolution

The discovery of the J/ψ meson in 1974 and the ψ' shortly thereafter have rightly been named the "November Revolution". Quite remarkably the J/ψ meson was observed in two very different experiments at the same time: e^+e^- collisions at a centre-of-mass energy of 3.1 GeV using the SPEAR storage ring at SLAC; a fixed-target experiment looking at the e^+e^- final state in p–Be collisions at Brookhaven. The identification of the resonances as bound states of a new quark, the charm quark, meant that there were now four quarks and four leptons, which could be classified into two generations of quarks and leptons. This provided a natural explanation for the non-existence of so-called *flavour changing neutral currents* (FCNC) via the GIM (Glashow, Iliopoulos, Maiani) mechanism. It is fair to say that this established the Standard Model as a serious theory for the interactions of fundamental particles and was also very instrumental in making particle physicists really believe that quarks were "real" particles rather than just abstract mathematical concepts.

This nice simple, symmetric picture was relatively short-lived, as the tau lepton was discovered only one year later through the decay chain where one τ lepton decays to an electron and accompanying neutrinos, while the other decays to a muon+neutrinos. Such an event signature – an $e\mu$ final state and missing energy – provided a clear signature for the existence of a third generation of leptons.

1.1.3 Third Generation

With the discovery of charm and then the τ lepton, it was natural to see if even more quarks existed. The highest energies could be reached with proton accelerators. This time the $\mu^+\mu^-$ final state was used to look for signs of new resonances. The location was Fermilab, and protons with energies up to 400 GeV were used. A clear signal for at least one resonance, with hints of a further two, was seen at an invariant mass of around 9.5 GeV, ushering in the existence of the fifth quark. Early in 1978, groups at DESY using the e^+e^- collider DORIS were able to separate the $\Upsilon(1S)$ and the $\Upsilon(2S)$. CESR, a new storage ring at Cornell University, extended the list of resonances to $\Upsilon(3S)$ and $\Upsilon(4S)$ a couple of years later.

The spectroscopy of both the $c\bar{c}$ and $b\bar{b}$ resonances has since been investigated in quite some detail. Masses and branching fractions can be compared to potential models, in order to study the strong interaction at intermediate energy scales. For many applications a non-relativistic quark model is sufficient, which simplifies the models considerably.

1.1.4 τ Lepton

Studies of the τ lepton produced a wealth of physics information that is not really covered in this book. Just to give a few examples:

- the measurement of the leptonic branching fractions of τ decays clearly shows the need for colour and yields a precise determination of the strong coupling, α_s;

- the hadronic mass spectra of the τ decay products yield important information on resonances in the 1 GeV range. This information is also useful for evaluating the running of the electromagnetic coupling, α, from a low energy scale to the mass of the Z boson;
- measurements of the τ lifetime and the branching fractions to electrons and muons are important tests of lepton universality.

1.1.5
B Mixing and CP Violation in *b*-Quark Systems

In the same way that the neutral kaon flavour eigenstates mix to form the mass eigenstates K^0 and $\overline{K}^0$, the neutral D and B hadrons should also mix. However, as the phase space for the decay is so much larger, the lifetimes of the two states are almost identical. One has to look for other signatures of such mixing, for example the observation of a $B^0 B^0$ event coming from the decay of $\Upsilon(4S)$. Such mixing was first observed by the ARGUS experiment at DESY in 1986. The observation was confirmed later by the CLEO experiment at Cornell University. Mixing in the D-hadron system is expected to be much smaller and was not observed until the B-factories KEK-B and PEP-II had been taking data for a number of years.

The machines that run at the centre-of-mass energy of the $\Upsilon(4S)$ observe mixing in the B_d^0 system; the Tevatron experiments have recently also observed mixing in the B_s^0 system, with the expected much higher oscillation frequency.

It is also possible for CP violation to occur in the B-hadron system. Theoretical studies showed that the most promising channel was the decay to the CP eigenstate $J/\psi\, K_S^0$. It was, however, necessary to measure the number of B^0 and $\overline{B}^0$ as a function of the time difference between their decay and the decay of the CP eigenstate in order to observe an effect. This made it necessary to build asymmetric machines, with different energies for the electron and positron beams. The BABAR and Belle experiments started taking data in 1999 and 3 years later produced clear evidence for CP violation. While the level of CP violation can be explained within the framework of the Standard Model, it is by far not enough to explain the matter–antimatter asymmetry in the universe, the origin of which is one of the big questions for both particle and astroparticle physics as well as cosmology.

These topics are discussed in much more detail in Chapter 8.

1.1.6
Gluon Discovery

One of the main goals of the PETRA (DESY) and PEP (SLAC) accelerators was to discover the top quark. Although they ultimately failed in this goal, they did discover the gluon! The discovery put the theory of the strong interaction, QCD, on a much stronger footing and was the result of a very productive interplay between experimentalists and theorists. There is some controversy over which of the PETRA collaborations discovered the gluon first. The European Physical Society credited four members of the TASSO collaboration with the discovery, for which they received the EPS prize in 1995. However, they also awarded a complementary prize to the four PETRA collaborations: JADE, MARK J, PLUTO and TASSO in recognition of their combined efforts.

A 1976 paper from J. Ellis, M. Gaillard and G. Ross had suggested that 3-jet events with hard gluon bremsstrahlung should be observable in e^+e^- collisions. First data were taken by the PETRA experiments at centre-of-mass energies of 13 and 17 GeV in 1978. Later that year the energy was increased up to 30 GeV. One of the keys to the discovery was to investigate how the jet shapes changed as a function of energy. Do the jets get wider and is the topology of the jet-widening consistent with a general increase of the intrinsic transverse momentum of the particles in the jet? Or, is the broadening confined to a plane, as would be expected if hard gluons are emitted? By summer 1979 there was clear evidence that the latter was the case, and all experiments had textbook pictures of events in which three clear jets were seen. More data allowed the spin of the gluon to be determined in the following year.

1.1.7
W and *Z* Discoveries

As discussed above, the relative rate of neutral-current and charged-current interactions of neutrinos could be used to measure the weak mixing angle and make a prediction for the masses of the W and Z bosons. At CERN, the SPS came into operation in 1976 with beam energies of 350–400 GeV, insufficient to produce W or Z bosons in fixed-target experiments. In the same year, D. Cline, C. Rubbia and P. McIntyre proposed changing the SPS into the Sp$\bar{\text{p}}$S, that is, a proton–antiproton collider with enough energy and intensity to produce the weak bosons and detect their production in collider detectors.

While the proposal was certainly controversial, one may even say audacious, it led to the W and Z being discovered at least 6 years before the Z boson could have been produced at LEP. It is also clear from all accounts of this period that without the drive, enthusiasm and skill of Carlo Rubbia the Sp$\bar{\text{p}}$S would not have been approved or built. And without the invention of stochastic cooling by Simon van der Meer it would not have been possible to produce enough "cooled" antiprotons to achieve the necessary luminosity.

Both the experiments and the collider were built in an impressively short time. Machine and detectors were both ready by summer 1981, just three years after the project had been approved. The luminosity increased rapidly and the collider run at the end of 1982 yielded enough luminosity (18 nb^{-1}) to see clear W-boson events in both the UA1 and UA2 detectors (time was shared between fixed-target and collider running). A further increase in luminosity in 1983 (118 nb^{-1}) led to Z-boson decays being observed, and the electroweak Standard Model was established as the correct description of electromagnetic and weak processes.

1.1.8
LEP and the Standard Model

One of the major achievements of LEP was undoubtedly the precise determination of the number of light neutrino families, which also put severe constraints on possible extensions of the Standard Model which contain other weakly interacting light particles.

LEP also saw clear evidence for the self-coupling of both gluons and the vector bosons, W and Z, one of the key predictions of non-Abelian theories like the electroweak Standard Model and QCD.

The measurements at LEP, as well as input from SLC and Tevatron, all feed into a global fit of all Standard Model parameters that impressively demonstrates the validity of the Standard Model and also gives a prediction for the mass of the Higgs boson.

As these measurements are discussed in detail in Chapter 3, we will not go into them further here.

1.1.9
HERA and Proton Structure

The idea for an electron–proton collider had been around since the early 1970s. It was decided to build the accelerator at DESY, and the project was officially launched in 1984. After the start of the machine in 1990, first physics results came from the running in 1992. Protons with energies of 820 or 920 GeV were brought into collision with electrons or positrons of 27.5 GeV, which implies a centre-of-mass energy of 300–320 GeV.

The early running already brought two surprises: at the small distance scales probed by HERA, many more gluons and quark–antiquark pairs from the sea inside the proton were observed than expected; a proton could participate in a hard interaction while remaining intact in a much larger fraction of events than it was reasonable to expect at such high momentum transfers. For the physics at the LHC, such a large number of gluons enhances many cross sections substantially and so is very relevant for "Physics at the Terascale". The origin of the "diffractive" events is still not fully understood and has spawned a whole series of studies and theoretical models (see Chapter 11 for a discussion of diffractive physics).

The lasting legacy of HERA though is certainly the very precise measurements of the structure functions of the proton; the clear demonstration of electroweak unification through the measurement of both neutral-current and charged-current cross sections over a very wide range of squared four-momentum transfer, Q^2, and the precise measurements of the strong coupling, also showing a clear running of the coupling as a function of the energy scale within a single experiment.

In recent years the two collider experiments, H1 and ZEUS, have started to produce combined results in the same spirit as the LEP and Tevatron experiments. This has led to an impressive improvement in the precision of the structure func-

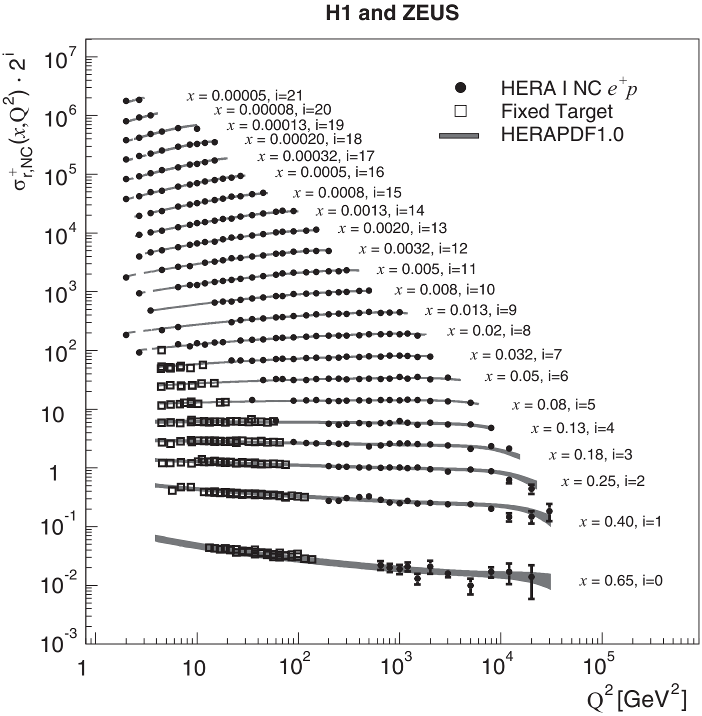

Figure 1.1 Combined measurements of the ZEUS and H1 collaborations of the proton structure function (adapted from H1 Collaboration and ZEUS Collaboration (F.D. Aaron et al.), Combined Measurement and QCD Analysis of the Inclusive $e^{\pm}p$ Scattering Cross Sections at HERA. JHEP 1001:109 (2010)).

tion measurements, which form the basis for cross-section predictions for the LHC (and any other hadron collisions).

Given that both of us spent the last 10–15 years of our careers working in either the H1 or the ZEUS collaborations we cannot resist showing the comparison of the cross-section measurements in neutral-current processes with the parton distribution function (PDF) extracted from the HERA data, Figure 1.1. The plot shows in fact the reduced cross section, σ_r, as a function of Q^2, over a wide range of x, where the so-called Bjorken x can be interpreted as the fraction of the proton's longitudinal momentum that participates in the hard interaction. The reduced cross section is closely related to the structure function F_2. As discussed at the end of Chapter 17 it even appears feasible to use W-boson production to measure the LHC integrated luminosity, thanks to next-to-next-to-leading-order QCD calculations and the accurate determinations of the structure functions. It is always interesting to see the Nobel prizes of the past being used for "bread and butter" physics in the next generation of colliders!

The neutral-current and charged-current cross sections for electrons and positrons are shown in Figure 1.2. At low Q^2, the neutral-current cross section is dom-

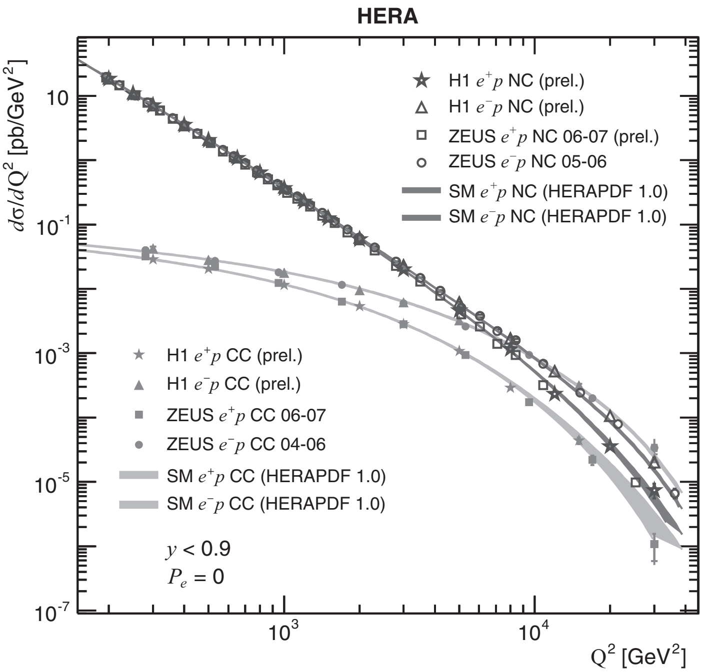

Figure 1.2 Electroweak unification at HERA. Neutral-current and charged-current cross sections for both electrons and positrons as a function of Q^2 are shown (adapted from https://www.desy.de/h1zeus/combined_results/index.php?do=nc_cc).

inated by photon exchange. At high $Q^2 \sim M_W^2$ both weak and electromagnetic process contribute with similar strength, as can be clearly seen in the figure – a real textbook demonstration of electroweak unification.

When it comes to measurements of the strong coupling, α_s, at HERA, theory lags behind experiment. The experimental precision is substantially better than the theoretical uncertainties in the extraction of α_s. Progress here is slow, as higher-order QCD calculations are notoriously difficult to perform and higher-order Monte Carlo simulations for ep collisions are not at the top of the priority list for most theorists.

1.1.10
Top-Quark Discovery

After the discovery of the b quark in 1977 and the τ lepton in 1975, it was clear that a sixth quark, the top quark, should exist. Studies of the properties of B-hadron decays using the CESR accelerator at Cornell provided further evidence that the b quark was a member of a weak isospin doublet.

One of the main physics goals of the subsequent e^+e^- colliders, PETRA, PEP, TRISTAN and LEP was therefore to discover the top quark. Despite heroic efforts, fine energy scans to look for $t\bar{t}$ resonances and pushing the accelerator energies to the maximum possible, no direct evidence for the top quark was found.

After the failures to find the top quark at PEP, PETRA and TRISTAN, one of the first indications that the top quark was very heavy came from the discovery of $B^0\overline{B}^0$ mixing by the ARGUS experiment at DESY in 1986. Such a large mixing could be explained by a large top-quark mass, as terms such as $m_\mathrm{t}^2 - m_\mathrm{c}^2$ appear in the calculation (here, m_t and m_c are the masses of the top and the charm quark, respectively).

With the high-precision data collected by the four LEP experiments in the early 1990s it was possible to make a prediction for the value of the top-quark mass with an error of around 20 GeV. This prediction was stunningly confirmed when the top quark was finally discovered by the CDF and DØ collaborations in 1995 with a mass in excellent agreement with the prediction from LEP. This topic is discussed in more detail in Chapter 9.

1.1.11 Searches for Higgs Particles and Supersymmetry

The Higgs mechanism discussed in Chapters 2 and 6 was invented almost 50 years ago to explain how mass could be generated within the framework of spontaneous symmetry breaking in local gauge theories. It is the only mechanism thought up so far that has withstood the test of time. However, one of its key predictions is that at least one massive scalar boson should exist. Again here, measurements of the free parameters in the Standard Model lead to a prediction for the Higgs mass, which will certainly be within the reach of future colliders. However, no clear evidence for a Higgs particle has been found so far. Indeed no fundamental scalar particles have ever been discovered, so a Higgs boson would be a major new aspect of the Standard Model of particle physics.

Supersymmetry is the favoured theoretical model for physics beyond the Standard Model. It is discussed in detail in Chapter 7. Unbroken supersymmetry would imply a partner particle for every Standard Model particle with the same mass. Such particles clearly do not exist, hence supersymmetry must be broken and the supersymmetric particles must in general be significantly heavier than their Standard Model counterparts. Unsuccessful searches for such particles have been made at all colliders over the past decades. As the LHC can cover the scale of electroweak symmetry breaking, evidence for supersymmetry, if it exists, should finally be discovered there!

1.1.12 Tau-Neutrino Discovery

After the discovery of the top quark, and ignoring for now the Higgs boson, the only other missing particle in the Standard Model was the tau neutrino. Decays of the τ lepton indicated that a partner neutrino almost certainly existed. However, direct interactions of the tau neutrino are very difficult to observe. First one has to produce such neutrinos. This can happen through the decay of tau leptons or D_S mesons; producing an intense beam of tau leptons in a fixed-target experiment requires both high intensity and high energy. A handful of events which demonstrate directly the existence of the tau neutrino via a charged-current interaction which produced a tau lepton were observed in the DONUT experiment at Fermilab in 2000.

1.2 Problems of the Standard Model

So far, the history of the Standard Model (see also Chapter 2) as told above is a story of successes. However, the Standard Model also has numerous shortcomings which are one of the main motivations for the construction of future collider facilities like the LHC. In this section, the most striking of the deficiencies are mentioned briefly; more details can be found in Chapters 2, 7 and 10.

First of all, the Standard Model has a number of conceptional shortcomings: one fundamental problem is the so-called hierarchy problem – the question why the scale of electroweak symmetry breaking (or alternatively the expected Higgs mass) is $\mathcal{O}$ (100 GeV), when in principle this scale should receive corrections of the order of the largest scale relevant in the Standard Model (like the Planck scale or the grand unification scale). This discrepancy can either be explained by a fine tuning of tree-level and loop contributions to the Higgs mass (hence also the term "fine-tuning problem"), or by the introduction of a new symmetry (like supersymmetry, see Chapter 7). The onset of "new physics" should then be within the reach of the LHC. Putting it another way, despite the invention of the Higgs mechanism, the puzzle of electroweak symmetry breaking (i. e. the question how gauge bosons acquire their observed masses) is far from being understood.

A second conceptual (and also aesthetic) problem is the large number of parameters of the Standard Model: in a fundamental theory one would expect explanations of the values that certain parameters take. However, in the Standard Model, the values of about 30 parameters have to be put in by hand (masses, mixing angles, couplings). In addition, from a phenomenological point of view, the values of some of the parameters are rather puzzling. There is, for example, a huge spread in fermion masses (from meV for neutrinos to more than 170 GeV for the top quark) and no obvious mechanism for the generation of these masses. Similarly, the different mixing behaviour of quarks (almost diagonal) and neutral leptons (very large mixing) is a challenge.

Talking about neutrino masses, also the question of the particle character of the neutrino is open: due to its zero electric charge, the neutrino is special among the fermions and might, eventually, be its own antiparticle (a "Majorana" neutrino instead of a "Dirac" particle like the other fermions). This question is still unanswered (see Section 1.3.1).

There are further far-reaching questions to the Standard Model, of which we only mention two. In the Standard Model the quantisation of electric charge can only be explained if magnetic monopoles exist – which so far have not been observed.

Furthermore, the Standard Model does not provide charge and mass unification (the three fundamental interactions do not unify at some large unification scale), and it is unclear why atoms are neutral when quarks and leptons belong to different multiplets. However, a truly fundamental theory should include such a unification of forces.

Also from the cosmological side, the Standard Model is challenged: first, it is obvious that the Standard Model does not contain a theory for the description of the interactions that govern the large-scale structure of the universe – there is no renormalisable quantum theory of gravity. Second, and of more direct consequence for particle physics, the Standard Model does not provide a candidate particle to explain the large dark-matter content of the universe of close to 25%. The dark matter is necessary to account for, among other features, the rotation curves of galaxies and is also favoured by measurements of the cosmic microwave background (CMB). Finally, also the baryon asymmetry as observed in the universe still awaits an explanation.

Current efforts in high energy physics are focused on solving at least some of these questions and a few definite experimental answers are expected from the Large Hadron Collider. An attractive theoretical alternative to or extension of the Standard Model which provides satisfactory answers to many of the questions is supersymmetry which is discussed in more detail in Chapter 7.

1.3 Other Topics Connected to High Energy Physics

This book focuses on recent and near-future collider-based high energy physics experiments, their organisation, construction, operation, and results. However, high energy particle physics is of course a much wider field, and there are numerous topics which, because of space limitations, cannot be covered in detail. In this section, a number of these topics are briefly touched upon. At the end of the chapter we include a few suggestions for further reading.

1.3.1 Neutrino Physics

Neutrinos as elementary particles were first suggested by W. Pauli in the 1930s in order to explain the spectrum of nuclear β decay; the first experimental observation (of the electron neutrino) was in 1956 by Cowan and Reines; the muon and tau neutrinos were discovered in 1962 and 2000, respectively. However, the neutrino is still a mystery.

Firstly, for some time now the neutrino mass has been known to be extremely small, but distinctly different from zero (the evidence for neutrino oscillations which gives rise to this knowledge is discussed below). This fact is theoretically interesting since it (somewhat contrary to intuition) points to a new large fundamental mass scale and thus to new physics beyond the Standard Model of particle physics. Consequently, a number of experiments have been devised to precisely measure the masses of the neutrinos and to determine their mass hierarchy. Three different methods are used: measurement of the β decay energy spectrum, the detection of neutrinoless double-β decay and cosmological measurements of the cosmic microwave background.

The last method relies on determining the influence of neutrino masses on structure formation in the universe and on primordial nucleosynthesis. Although the model uncertainties are rather large, an upper limit for the sum of the three neutrino masses of less then 0.28 eV has been derived.

In the case of β decay measurements, a precise measurement of the endpoint in the decay energy spectrum is aimed for. The relevant experiments, like the Mainz–Troitsk experiment, have achieved precisions of the order of 2 eV, and new experiments like KATRIN aim at a measurement with a precision of about 0.2 eV for the electron neutrino[1].

Neutrinoless double-β decay experiments search for extremely rare decays of certain isotopes which can only take place if the neutrino has mass and is at the same time its own antiparticle. Past or running experiments to be mentioned here are the Heidelberg–Moscow collaboration, CUORICINO and EXO-200[2]. The question whether the neutrino (the only neutral fermion in the Standard Model!) is its own antiparticle or not (Majorana neutrino instead of Dirac neutrino) is in itself of fundamental interest. Not only would neutrinoless double-β decay imply lepton number violation by 2 units; Majorana-type neutrinos also have implications for the question of CP violation in the lepton sector of the Standard Model and, as a consequence, for leptogenesis.

Strong evidence for non-zero neutrino masses and some information about the mass hierarchy of neutrinos has been obtained from neutrino oscillation observations. In 1998, following results from for example IMB and Kamiokande, the Super-Kamiokande experiment reported on the observation of discrepancies between data and predictions for atmospheric neutrino fluxes. The collaboration investigated the zenith-angle distribution of the ratio of muons to electrons from atmospheric neutrino interactions in the low-energy (few GeV) regime and found a value significantly smaller than two that would be expected from pion and muon decay. This pointed to a lower-than-expected ratio of atmospheric muon to electron neutrinos, $(\nu_\mu + \overline{\nu}_\mu)/(\nu_e + \overline{\nu}_e)$, for neutrinos which travelled a long distance after their production (large zenith angles). The findings were confirmed by other experiments like Soudan 2 and MACRO. Clear evidence for muon neutrino disappearance has now also been seen in accelerator-based experiments like K2K and MINOS.

1) Further developments in this direction will be made by the MARE, MIBETA and MANU experiments.
2) In the future also GERDA, CUORE, NEMO-3, SNO+ and COBRA will play a role.

In parallel, the Super-Kamiokande collaboration discovered a deficit (with respect to the Standard Solar Model prediction)[3)] of charged-current reactions induced by solar electron neutrinos, which was confirmed by SNO. On the other hand, using neutral-current interactions SNO could show that the *total* neutrino flux is according to expectations.

Quickly oscillations between different neutrino flavour eigenstates composed of mixtures of mass eigenstates (which propagate with different velocities) were suggested as a possible explanation, requiring the neutrinos to have non-zero masses. In the case of disappearing atmospheric muon neutrinos the transition from muon to tau neutrinos, $\nu_\mu \rightarrow \nu_\tau$, was held to be mainly responsible[4)]. For the solar ν_e disappearance, oscillations $\nu_e \rightarrow \nu_{\mu,\tau}$ were assumed. At reactor-based experiments like KAMLAND also the behaviour of anti-electron neutrinos is investigated (KAMLAND has reported a significant disappearance signal).

Considering transitions between all three lepton generations (electron, muon, tau), the oscillation scenario has room for five mixing parameters – namely the three mixing angles θ_{ij} $(i, j = 1, 2, 3)$ and two independent squared mass differences between the three mass eigenstates, Δm^2_{ij}. Different experiments have different sensitivities to these quantities, and numerous measurements have been performed. Here only a few main results are summarised:

- Together, atmospheric and accelerator neutrino experiments (Super-Kamiokande, Soudan, MACRO, K2K, Minos) suggest almost pure $\nu_\mu \rightarrow \nu_\tau$ oscillations with large mixing angle θ_{23} of about 45°.
- Solar neutrino experiments provide, via electron–neutrino disappearance, the highest sensitivity to the mixing angle θ_{12}, the best values[5)] currently being of the order of 33°; in addition, they provide access to the sign of the squared mass difference Δm^2_{12}.
- In addition to the neutrino mass results mentioned above, the Super-Kamiokande results are suggestive of a minimum neutrino mass of the order of 0.05 eV.
- The highest precision for $|\Delta m^2_{13}|$ $(|\Delta m^2_{12}|)$ is achieved by the K2K and MINOS accelerator experiments (KAMLAND reactor-based experiment). The currently quoted best-fit values (assuming $|\Delta m^2_{13}| \cong |\Delta m^2_{23}|$) are $|\Delta m^2_{13}| = 2.40 \times 10^{-3}\,\mathrm{eV}^2$ and $|\Delta m^2_{12}| = 7.65 \times 10^{-5}\,\mathrm{eV}^2$.

3) Historically, the Homestake experiment was the first to report on a neutrino deficit; it was later followed by a number of other radio-chemical experiments like GALLEX, GNO and SAGE which made use mainly of gallium and chlorine.

4) Recently, the OPERA collaboration reported on the first observation of tau neutrinos from oscillations $\nu_\mu \rightarrow \nu_\tau$ – before that, only ν_μ disappearance had been observed by atmospheric and accelerator neutrino experiments.

5) The preferred solution to the solar/reactor neutrino disappearance is the so-called LMA-MSW interpretation, with a large mixing angle $\theta_\odot$ and taking into account matter effects in the sun (the "Mikheyev–Smirnov–Wolfenstein" effect). It is considered a striking feature of neutrino physics that both the atmospheric and the solar mixing angles are large, in contrast to the quark mixing in the CKM matrix (see Chapter 8).

- The quantities describing the 1–3 mixing are under intense investigation: as of now, the mixing angle θ_{13} seems to prefer low values – the question is how low a value is realised, and whether or not it is compatible with zero. First limits were derived by the CHOOZ experiment, and future reactor and accelerator experiments will further investigate this via anti-electron neutrino disappearance[6] and the appearance of electron neutrinos in a muon-neutrino beam[7].

Future emphasis will be on determining in more detail the masses of the eigenstates, the mass hierarchy (or equivalently the sign of the squared mass difference Δm^2_{23}), and on determining the as of now only weakly constrained mixing angle θ_{13}. Furthermore, the question is still open whether CP violation in the neutrino sector exists or not.
All in all, neutrino physics is an extremely active field with many ongoing and planned facilities, and very promising prospects for the coming years.

1.3.2
Astroparticle Physics

Astroparticle physics aims at measuring elementary particles of astronomical origin, and at understanding their origin, production, and acceleration mechanism. In doing so, astronomical and cosmological questions can be addressed. Various different elementary particles are used for astroparticle studies, and the relevant experiments are well adapted to the instrumental challenges (here only a small fraction of all experiments and results can be mentioned).

Neutrinos of all energies (from a few keV to the highest measured energies) are used for astroparticle physics studies. The existence of neutrinos of the highest energies (several TeV and above) is a sign of hadronic acceleration processes in the universe. Because of their low reaction cross sections, neutrinos allow cosmic sources to be observed which otherwise would remain hidden by dense matter distributions or at large distances. The small cross section, on the other hand, makes them hard to detect. Sources that are held responsible for neutrino production in the universe are both galactic (supernova remnants, pulsars, nebulae, binary systems) and extra-galactic (active galactic nuclei, other point sources on the diffuse neutrino background). First-generation high energy neutrino telescopes showed that large-scale facilities may be used to measure neutrinos via the Cerenkov light emitted by reaction products in clean water (Lake Baikal, Antares) or ice (AMANDA) using a lattice of photomultiplier tubes. Currently, kilometre-scale experiments (for example IceCube at the geographic south pole, km3net, ...) are being constructed or designed that will significantly increase the sensitivity.

Medium-energy neutrinos (typical energies of 1–1000 GeV) are mainly interesting for atmospheric neutrino oscillation studies and as backgrounds to low-background experiments (like, for example, the search for proton decay). Low-energy

6) DoubleCHOOZ, Daya Bay, RENO.
7) MINOS, T2K, planned: NOVA.

neutrinos mostly have solar or supernova origins. Besides their use for neutrino studies (mass, oscillation, etc. – see Section 1.3.1), solar neutrinos allow the solar core region, the processes taking place there and the related neutrino fluxes to be studied (test of the Standard Solar Model).

Like neutrinos (and unlike charged particles), photons traverse the universe undeflected and point back to their production origin, thus allowing the identification of point sources in the sky. Very high or ultra high energy (VHE/UHE) photons with energies of several TeV are assumed to stem from even more energetic primary particles that are probably accelerated via diffuse shock acceleration in the expanding blast waves of supernova remnants. They therefore open a window on the "accelerator sky". There are numerous gamma-ray observatories, typically based on imaging air Cerenkov telescopes, which have in the past decade identified a rich and diverse collection of VHE sources. Examples are H.E.S.S., MAGIC, and VERITAS. Their main observation is a photon energy spectrum that falls with a power of the energy.

Figure 1.3 shows the energy spectrum of cosmic rays (mostly protons) as measured by numerous experiments. The figure shows only the high energy part of the cosmic ray spectrum above 10^{13} eV, scaled by $E^{2.7}$. The plot shows that cosmic rays with energies of more than 10^{20} eV have been observed. Three distinct regimes are visible in Figure 1.3: up to about 3×10^{15} eV (where the so-called "knee" is located), particles are assumed to be accelerated via the above-mentioned shock acceleration mechanism in our galaxy. Between the "knee" and the "ankle" at about 10^{18}–

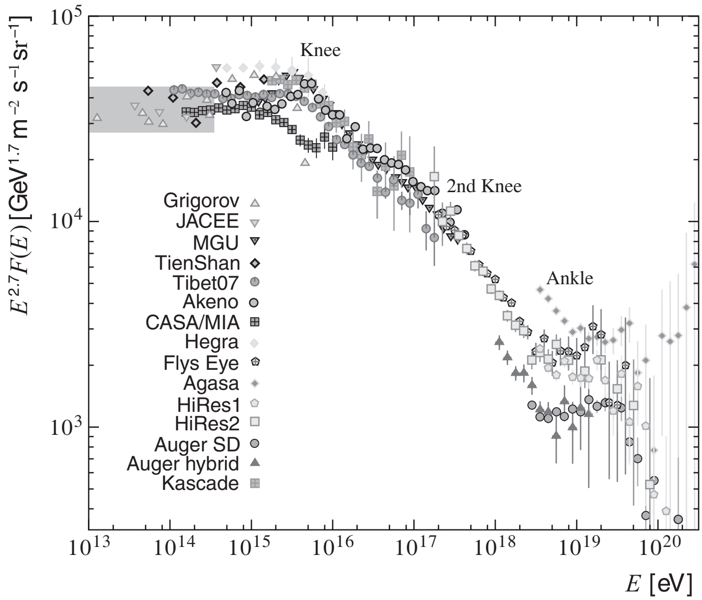

Figure 1.3 Overview of cosmic-ray energy measurements at high energies, including the "knee" and the "ankle" (Source: PDG 2008).

10^{19} eV, the particles are still assumed to be galactic in origin, although the acceleration mechanism is not understood. Beyond the "ankle", particles are assumed to be extra-galactic in origin, and extend in energy up to the so-called Greisen–Zatsepin–Kuzmin (GZK) cutoff at which they start to interact with the cosmic microwave background and thus lose energy. This prominent feature of the spectrum was quite recently observed by the HiRes and Pierre Auger experiments.

Cosmic ray experiments for the highest energy particles are typically based on the reconstruction of cascades of secondary particles produced when the primary impinges on the upper atmosphere. These cascades, or air showers, can be studied using either nitrogen fluorescence in the atmosphere or by sampling shower particles on the ground (or by combining the two methods like in the Pierre Auger Observatory which uses water Cerenkov detectors overlooked by fluorescence telescopes). The experiments are also able, by means of shower-shape analysis, to distinguish between various primary particles, for example proton-induced versus neutrino-induced events.

Astroparticle physics is a large and diverse field which employs numerous different methods and measurements. Only a "multi-messenger" approach, combining information from neutrinos, VHE gamma rays and cosmic rays of highest energies will, in the end, be able to give a full and detailed explanation of the sources of all cosmic particles and their acceleration mechanism. Through this, we will gain deeper insights into astrophysical and cosmological questions, like that of the dark matter in the universe.

A substantial fraction of the matter content of our universe is constituted from unknown particles ("dark matter", see Section 1.2). Weakly interacting massive particles (WIMPs) are a popular dark-matter candidate. These WIMPs are supposed to be located mainly in the galactic halo. One possibility is that they are then swept up by the sun as the solar system moves about, and will occasionally scatter elastically with nuclei in the sun, eventually becoming gravitationally bound. After sufficient time, an equilibrium between WIMP capture and annihilation (for example $\chi\chi \to W^+W^-$ or $\chi\chi \to b\overline{b}$ if the WIMP is a supersymmetric neutralino – see Chapter 7) in the sun might build up, allowing the annihilation products and their decay products (and here mainly neutrinos because of their small interaction cross section) to leave the sun and be detected on earth using high energy neutrino telescopes like IceCube. The corresponding signal can be easily predicted, given a certain WIMP mass, and measurements can thus be used to confirm or rule out models or regions in the supersymmetry parameter space; for certain regions the strongest limits presently come from data from the neutrino telescopes Super-Kamiokande, AMANDA, IceCube, and soon also from ANTARES.

Another approach is followed by experiments which try to detect the elastic collisions of the WIMPs in the galactic halo with a detector on earth, as the earth moves through the halo. The aim is to measure the nuclear recoil of the produced neutrinos (here a clear signature for WIMPs would be annual variations of the observed signal)[8]. It should be noted that these indirect searches for dark-matter candidates are complementary to direct, accelerator-based searches.

1.3.3 Heavy Ion Physics

The investigation of heavy ion collisions is a substantial part of the LHC programme, both in the dedicated ALICE experiment and in the omni-purpose experiments ATLAS and CMS. While the LHC prospects are not discussed in this book, some discussion is given here on the current status of the field.

First indications for the creation of a so-called *quark–gluon plasma* (QGP) were obtained in the 1980s and 1990s at the CERN SPS, leading to the announcement of indirect evidence for a new state of matter by CERN in 2000. In recent years, heavy ion collisions using mainly gold and copper atoms have been investigated at the Brookhaven RHIC collider: here, four experiments have been or are still taking data: BRAHMS, PHOBOS, PHENIX, and STAR[9].

The physics questions investigated centre around the specific features of the high temperature/high energy environment. One topic is the behaviour of the gluon density in the nucleon in the limit of extremely small momentum fractions, x, where presumably perturbative QCD is not applicable and saturation effects might set in. The term *colour glass condensate* (CGC) has been created to describe the behaviour of gluons in this kinematic regime. The CGC is already relevant for proton–proton collisions but is still more important in collisions of nuclei, as here the projected area density of gluons should be higher and thus effects of gluon saturation should be stronger. In addition, the knowledge of the low-x gluon distribution determines the initial state of the created matter in heavy ion collisions. Therefore, knowledge about gluon saturation will be crucial for the interpretation of heavy ion data. However, the current data do not allow the details of the gluon density behaviour in this region to be pinned down (although RHIC data can be described using QCD predictions with some assumptions on the gluon at small x).

Arguably the most striking observation at RHIC is the observation of a strong global anisotropy of the azimuthal particle distributions, called elliptic flow. The creation of elliptic flow requires early equilibration of the produced matter, the absolute value points to an extremely low viscosity. Thus, the system produced at RHIC appears not at all as a weakly interacting plasma, but rather as a strongly coupled, close-to-perfect liquid. Detailed features of elliptic flow favour an evolution of the system undergoing a phase transition from the quark–gluon plasma, and the relevance of parton degrees of freedom is clearly visible in scaling properties of the data.

8) The DAMA collaboration, which performs dark-matter searches using scintillation techniques, has reported on a controversial 8.2σ signal for rather low mass dark-matter candidates with surprisingly high cross section.

9) The first two experiments finished data-taking in 2006; PHENIX and STAR are still taking data (or are being upgraded).

Another interesting question is that of the relative abundances of hadrons produced from the hot, dense system. It is found that the abundances can be described by a statistical model. In small systems (e. g. proton–proton collisions) such models are also applicable if one accounts for the fact that strangeness conservation provides a very strong constraint, leading to the so-called canonical suppression of strangeness. For large numbers, these constraints can be relaxed such that central heavy ion collisions should exhibit a strangeness enhancement compared to proton–proton collisions. This is indeed observed experimentally by CERN and RHIC experiments. Although the good agreement of the abundances with the statistical model does not prove thermal behaviour, it is striking that the temperature parameters extracted coincide with the predicted values of the transition temperature.

A further issue is the effect of the dense quark–gluon medium on final-state properties. The extended quark–gluon cloud will influence strongly interacting particles, and measurements of these influences will in turn allow conclusions on the properties of the medium. One effect observed by the RHIC experiments is that of a significant reduction of parton energies: in contrast to photons, which traverse the strongly interacting dense medium unaffected, quarks and gluon (and consequently also hadrons like protons or pions or even hadronic jets) lose a significant fraction of their energy in strong interactions before leaving the QGP (*jet quenching*). These effects are also observed in particle correlations: in hard collisions, a pair of back-to-back particles balanced in transverse momentum (quarks, gluons, or also photons) is typically created. Depending on the position of the hard interaction inside the QGP, one of the particles might have a longer path inside the plasma, allowing it to lose more of its energy and thus breaking the momentum balance. The use of different particles and particle correlations (single hadrons, hadron–hadron, photon–hadron, jet–jet, jet–photon) allows different aspects of the energy-loss process and the details of the QGP to be studied.

Concerning the future of heavy ion physics (beyond the LHC), it is very much open, and decisions about which direction to take (higher energy versus better detectors etc.) will only be possible in the light of the first LHC heavy ion data.

1.3.4
Spin Physics

It is common knowledge that the spin of the proton is 1/2, and for a long time this spin was assumed to be due to the spins of the (three) valence quarks in the nucleon which are also spin-1/2 particles. However, in 1988 the European Muon Collaboration (EMC) at CERN initiated the so-called *spin crisis* or *spin puzzle* when it discovered that the quark-spin contribution to the nucleon spin was far below 50%. Later experiments at CERN and SLAC confirmed these findings.

For more than a decade, various experiments were performed to solve this puzzle and to measure precisely the various contributions to the nucleon spin, namely the contributions of the spins of the (valence and sea) quarks and the gluons, $\Delta\Sigma$ and ΔG, and the orbital angular momentum of these two contributions, L_q and L_g. Among these experiments are HERMES and COMPASS (polarised deep inelastic scattering), various experiments like CLAS at Jefferson Lab (JLab), and STAR, PHENIX and BRAHMS at the heavy ion collider RHIC (in the proton–proton mode). A distinguishing feature of all these spin experiments is that they require at least one polarised ingredient – beam or target. The most precisely measured value is $\Delta\Sigma$ for which HERMES has determined a value of 0.33 ± 0.011 (theo.) $\pm$ 0.025 (exp.) $\pm$ 0.028 (evol.). Numerous spin physics results have been obtained in recent years. Important examples are the determination of polarisation-dependent structure functions, the decomposition of the different quark flavour contributions using identified pions and kaons in polarised deep inelastic scattering, the confirmation of the opposite orientation of the up versus the down valence-quark spins, and determinations of the gluon-spin contribution ΔG (which turns out to be very small).

Figure 1.1 shows the proton parton distribution function measured by the HERA experiments H1 and ZEUS as a function of the longitudinal momentum fraction, x. In contrast to this *longitudinal* PDF, spin physics experiments have also determined the transverse structure of the nucleon. Transverse-momentum-dependent parton distribution functions are recognised as a tool to study spin–orbit correlations, hence providing experimental observables for studying orbital angular momentum via the measurement of certain azimuthal asymmetries.

Generalised parton distributions (GPDs) can be accessed via measurements of azimuthal spin or charge asymmetries in exclusive reactions for which the complete spectrum of produced particles is known. The GPDs give a three-dimensional representation of the nucleon which is often referred to as *nuclear tomography* (two spatial transverse dimensions and one longitudinal momentum dimension). With GPDs, it becomes possible to visualise the transverse position of quarks while scanning different longitudinal momentum slices. In addition, certain moments of the GPDs can in principle give constraints on the total angular momentum carried by quarks in the nucleon.

The future of spin physics offers a rich picture: in the near future, new polarised data will be taken with COMPASS and at JLab (CLAS and Hall A). After 2012, JLab will be upgraded. In the far future, an electron–ion collider (EIC) is foreseen in the US. There are two competing concepts – eRHIC at Brookhaven and eLIC at JLab. Probably at least one of these will be realised. There are also plans for an electron–nucleon collider (ENC) at GSI with $\sqrt{s} = 40\,\text{GeV}$ and also involving polarised beams. And finally, there are plans to provide polarised electrons also for the LHeC, the electron–proton machine foreseen for the LHC tunnel.

Further Reading

There are very many introductory particle physics books as well as ones on more specialised topics. The "best" book on a given topic is largely a matter of taste – we do not even agree on which book we like best. We list here a few introductory books as well as ones on those topics briefly discussed in this chapter, but otherwise not covered in this book.

Griffiths, D. (2008) *Introduction to Elementary Particles*, 2nd revised edn, Wiley-VCH Verlag GmbH.

Berger, C. (2007) *Elementarteilchenphysik – von den Grundlagen zu den modernen Experimenten*, Springer, Berlin.

Cahn, R. and Goldhaber, G. (2009) *The Experimental Foundations of Particle Physics*, 2nd edn, Cambridge University Press.

Particle Data Group, Amsler, C. *et al*. (2008) Review of Particle Physics, *Phys. Lett. B*, **667** 1, http://pdg.lbl.gov/ – contains a whole series of up-to-date articles on all aspects of particle physics as well as astroparticle physics.

Giunti, C. and Kim, C.W. (2007) *Fundamentals of Neutrino Physics and Astrophysics*, Oxford University Press.

Zuber, K. (2004) *Neutrino Physics*, IOP Publishing, Bristol.

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Perkins, D.H. (2003) *Particle Astrophysics*, 2nd edn, Oxford University Press.

Bartke, J. (2009) *Introduction to Relativistic Heavy Ion Physics*, World Scientific.

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Burkardt, M., Miller, C.A., and Nowak, W.-D. (2010) Spin-polarized high-energy scattering of charged leptons on nucleons, *Rep. Prog. Phys.*, **73**, 016201, http://arxiv.org/abs/0812.2208.