backgrounds, although much lower probability, is $H^0 \rightarrow \gamma\gamma$. Both decays have played important roles in the LHC experiments.

The first collisions took place at the LHC in March 2010 between beams of protons, each with an energy of 3.5 TeV, increased to 4 TeV in 2012. Experiments were conducted until early in 2013, when the machine was shut down for a major upgrade to 6.5 TeV per beam, with reopening scheduled for early 2015. During this three-year period, the LHC generated about 6 million billion proton-proton collisions, of which the ATLAS and CMS (Compact Muon Solenoid) experiments each recorded around 5 billion collisions of interest. Of these, a mere 400 or so produced results compatible with a Higgs-like particle, but enough for its discovery to be tentatively announced in March 2012, and confirmed in July 2013 as more data were accumulated. The mass obtained from both experiments agree and are compatible with a value of 126 GeV/c^2, with an uncertainty of less than 1 GeV/c^2. Statistically, scientists say it is a '5 sigma result' which means they are 99.999% sure they have found the Higgs particle. Data from the two decay modes $H^0 \rightarrow Z^0Z^0$ and $H^0 \rightarrow \gamma\gamma$ also show that the spin and parity of the Higgs is $J^P = 0^+$, in agreement with the standard model, and for the determined mass, so are the couplings governing the decays.

These experiments have stunningly confirmed the predictions of the standard model, and when the LHC re-opens in 2015, much effort will be devoted to studying the detailed properties of the Higgs boson, in particular probing whether there are any small deviations from the predications of the standard model. Whatever the results, interesting times lie ahead.

10
Beyond the standard model

Particle physics is still a relatively young branch of physics, even if you date its birth to the discovery of the electron in 1896. Yet it has a comprehensive theory, the standard model, the success of which is already spurring physicists to construct larger unifying theories to incorporate the strong interaction – even gravity in some cases – to understand why particle masses and forces have the values they do, why there are three generations of elementary particles and why gauge invariance holds such a special place in nature.

Grand unified theories

One area where particle physicists are extending the standard model involves attempts to include the strong interaction in a unification scheme with the electroweak interaction. These are the *grand unified theories* (GUTs).

Unification of the weak and electromagnetic interactions is not manifest until energies of the order of the W and Z masses, approximately 90 GeV/c^2. To get some idea of the energy scale involved in a grand unified theory, we can use the fact that the weak and strong couplings in the standard model are running coupling constants, that is, they vary with energy. When their predicted energy dependences are used to extrapolate the couplings to higher energies, the three curves fail to meet at a point. Nevertheless, this suggests that the interactions are approximately equal at an enormous *unification mass* (M_U) of about 10^{15} GeV/c^2. At the equivalent energy the theory has a single GUT coupling (α_U), with a value of approximately $\frac{1}{42}$.

There are many competing grand unified theories but the simplest incorporates the known quarks and leptons into common families. In a way this is natural, since the fact that the proton and electron have electric charges of the same magnitude hints at a deep relationship between quarks and leptons. In this version of a GUT, one family consists of the three coloured d quarks and a pair of leptons: $(d_r, d_b, d_g, e^+, \bar{\nu}_e)$. Transitions between quarks and leptons are made possible by introducing two new gauge particles, denoted X and Y, with electric charges $-\frac{4}{3}e$ and $-\frac{1}{3}e$, where e is the magnitude of the electron charge. Their masses would necessarily be roughly equal to the unification mass.

This simple model has a number of attractive features. For example, the sum of the electric charges of all the particles in a given family is zero. So, using the multiplet $(d_r, d_b, d_g, e^+, \bar{\nu}_e)$, it follows that $3q_d + e = 0$, where q_d is the charge of the down quark. Thus $q_d = -\frac{1}{3}e$ and the fractional charges of the quarks can be seen to originate from their three colour states. By a similar argument, the charge of the up quark can be found to be $q_u = \frac{2}{3}e$. With the usual quark assignment ($p = uud$), the proton charge can be obtained from $q_p = 2q_u + q_d = e$. So, this GUT gives an explanation for the long-standing puzzle of why the proton and positron have precisely the same electric charge.

All grand unified theories, including this one, make a number of predictions that can currently be tested. If the three couplings of the weak and strong interactions really did meet at a point when extrapolated to high energies, then the three low-energy couplings of the standard model would be expressible in terms of the GUT coupling and the unification mass. This approach can be used to calculate either α_U or M_U, or equivalently the weak mixing angle θ_W. The results are close to the measured value

of θ_W but not exactly equal to it. To date, only θ_W has actually been measured.

The exchange of the new gauge bosons would allow transitions between leptons and quarks and so neither baryon nor lepton numbers would be conserved. That would make the proton unstable and open the way for several possible final states, including a pion and a positron ($p \to \pi^0 + e^+$) and a pion and an anti-neutrino ($p \to \pi^+ + \bar{\nu}_e$). Examples of Feynman diagrams for the first of these decay modes are shown in Figure 10.1. Interestingly, we already know something about the lifetime of the proton from the existence of life itself. If the proton decayed, the resulting radiation from the material of our bodies could kill us depending, of course, on the rate of radiation produced. For that not to happen, the proton lifetime must be greater than about 10^{16} years, taking account of reasonable uncertainties in the values of α_U and M_U. Grand unified theories give much better bounds than this rough estimate. For the decay modes noted, the predicted value of the proton's lifetime is 10^{30} to 10^{31} years. For comparison, the age of the universe is believed to be about 10^{10} years. Experimenters have looked for proton decay via the two modes specifically mentioned above, for example in the Kamiokande experiment, but no events have yet been observed. This has left physicists to conclude that the proton lifetime is greater than about 10^{32} years, which rules out the simplest GUTs. Still, there are other, more complicated GUTs, that may yet be proven, some of which incorporate the idea of *supersymmetry*.

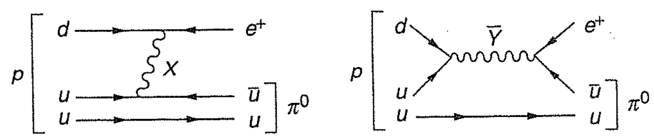

Figure 10.1 Feynman diagrams for the proton decay mode $p \to \pi^0 + e^+$

Supersymmetry

New particles in GUTs would have to be included as additional contributions in higher-order calculations in the electroweak theory, and would upset the delicate cancellations that ensure finite results throughout the standard model. To avoid this, some means of cancelling these contributions would need to be found: supersymmetry provides those means. Supersymmetry (SUSY) is the proposal that every elementary particle has a *superpartner*, which is identical to it except for its spin. Spin-$\frac{1}{2}$ particles have spin-0 superpartners and spin-1 particles have spin-$\frac{1}{2}$ superpartners. To distinguish between a spin-$\frac{1}{2}$ particle and its superpartner, an 's' is attached to the front of the superpartner's name. Thus, a spin-$\frac{1}{2}$ electron has a spin-0 selectron as its superpartner. The full set of elementary particles and their superpartners in a simple SUSY model is shown in Table 3. (This is itself a simplification, because even the simplest SUSY model requires both neutral and charged Higgs bosons.)

If supersymmetry were an exact symmetry, a particle and its superparticle would have identical masses. Such states have not been found so this is clearly not the case. At best, supersymmetry

Table 3 The particles of the standard model and their superpartners

Particle	Symbol	Spin	Superparticle	Symbol	Spin
Quark	q	$\frac{1}{2}$	Squark	$\tilde{q}$	0
Electron	e	$\frac{1}{2}$	Selectron	$\tilde{e}$	0
Muon	μ	$\frac{1}{2}$	Smuon	$\tilde{\mu}$	0
Tauon	τ	$\frac{1}{2}$	Stauon	$\tilde{\tau}$	0
W–boson	W	1	Wino	$\widetilde{W}$	$\frac{1}{2}$
Z–boson	Z	1	Zino	$\widetilde{Z}$	$\frac{1}{2}$
Photon	γ	1	Photino	$\tilde{\gamma}$	$\frac{1}{2}$
Gluon	g	1	Gluino	$\tilde{g}$	$\frac{1}{2}$
Higgs boson	H	0	Higgsino	$\widetilde{H}$	$\frac{1}{2}$

is an approximate symmetry of nature; nevertheless, even in an approximate symmetry the couplings of the two states are equal and opposite, ensuring cancellation, if their masses are not too large. In practice, GUTs that incorporate supersymmetry assume that the masses of the superparticles are roughly equal to the masses of the W and Z bosons. With the inclusion of superparticles, there is a slight change in the way the standard model's coupling constants vary with energy; when the constants are extrapolated to very high energies they now meet very close to a single point, and the unification mass is increased somewhat to about 10^{16} GeV/c^2. At the same time, the value of α_U remains roughly constant and the predicted lifetime of the proton is increased to about 10^{32} to 10^{33} years, just beyond the reach of today's experiments. Likewise, the value of the weak mixing angle is brought into almost exact agreement with the measured value. Whether all this is simply a coincidence is unclear.

Another area where supersymmetry might be tested indirectly is the measurement of the *electric dipole moment* (EDM) of a particle, a quantity that determines how it interacts with an external electric field. EDMs are exactly zero unless parity and time-reversal are both violated. In principle, the violation of CP and T observed in the decay of some neutral mesons could generate a nonzero EDM, although in the standard model EDMs only appear in higher orders of perturbation theory and are extremely small. In the case of the electron, the calculated value from the standard model is vastly smaller than the upper bound found from experiment. Supersymmetric theories contain a host of new particles and couplings, and much larger symmetry-violating effects can be generated by these theories. Although no unique predictions have been made, a suitable choice of the parameters of supersymmetric theories leads to values for EDMs that might be measurable in the not-too-distant future.

To verify supersymmetry directly, it will be essential to detect superparticles in reactions. In the simplest SUSY theory, superparticles are produced in pairs; the decay of a superparticle must produce at least one superparticle in the final state, and the lightest such particle will necessarily be stable. Most versions of SUSY theories assume that the lightest particle is a *neutralino*, denoted $\tilde{\chi}_0$, which is the name given to a mixture of the photino, the neutral Higgsino and the zino. If this is the case, a possible reaction that could be studied is $e^+ + e^- \to \tilde{e}^+ + \tilde{e}^-$, followed by the decays $\tilde{e}^\pm + e^\pm \to \tilde{\chi}_0$, giving the overall reaction $e^+ + e^- \to e^+ + e^- + \tilde{\chi}_0 + \tilde{\chi}_0$. Neutralinos, like neutrinos, only have weak interactions, so they are practically undetectable. Any reactions would be characterized by e^+e^- pairs in the final state that carry only a fraction (typically 50%) of the initial energy. Also, because this is not a two-body reaction, these pairs would not be emitted back-to-back. This, and many other reactions involving hadrons, have been studied in experiments at LEP, CDF and the LHC, but no evidence for the existence of superparticles has been found, although the null results have enabled lower limits to be set on the masses of some superparticles.

A major indirect test of theories that go beyond the standard model, including supersymmetry, is to check the predictions of the standard model for rare reactions. An exacting example of this is the measurement of the lifetime of the extremely rare decay $B_s^0 \to \mu^+\mu^-$, where B_s^0 is a B meson with one strange quark. This has been done at the LHC by the ATLAS and CMS experiments. The results are in excellent agreement with the prediction of the standard model, without the need for any modifications. The search for evidence for any deviations from the standard model will be a major focus of experiments at the upgraded LHC accelerator, but the present absence of such evidence is causing many physicists to doubt the validity of supersymmetry.

String theories

Undeterred by the lack of immediate success with supersymmetry, many bold physicists are attempting to incorporate gravity into ever-grander unified schemes. The problems are mathematically formidable, not least because the infinities encountered are far more severe than those in either QCD or the electroweak theory. Furthermore, there is presently no successful stand-alone quantum theory of gravity analogous to the other two.

An unusual predicament in assessing such theories is the extreme difficulty they have in making unambiguous predictions that can some day be tested by experiment. The theories that have been proposed to include gravity invariably replace point-like elementary particles with tiny one-dimensional quantised *strings* and are formulated in many more dimensions – usually ten, including one dimension of time – than are observed in nature. Unlike the standard model, with its nineteen free parameters, which include the masses of quarks, coupling constants, mixing angles and so on, these theories have a single free parameter: the string tension. Because we live in a four-dimensional world (including time) the extra dimensions have to be *compactified*; that is, reduced to an unobservably small size. It was hoped that compactification would result in the emergence of the standard model as a unique theory, with its nineteen parameters explained in terms of string theory's string tension. This would be a major triumph. Unfortunately, the early optimism about this mathematical scheme has not been sustained. Despite these setbacks, string theory has provided some powerful theoretical tools that have contributed to a better understanding of gauge theories and their relation to gravity.

As we have seen, the standard model uses a conventional particle picture of interactions. Since the structures of the corresponding quantum field theories (such as QCD) are known, it is possible to make unique physical predictions using perturbation theory and the appropriate Feynman rules. In the string formulation, there are five sets of possible Feynman rules, each operating in a ten-dimensional space-time continuum. String theorists have discovered that this leads to a vast landscape of low-energy theories – possibly as many as 10^{500}! – that could result after compactification. Each of these theories would describe a distinct universe, with its own set of fundamental particles, interactions and parameters. Unless there is a method of choosing among the huge range of possibilities, string theories have little or no real predictive power. For this reason, a lively philosophical debate has arisen about whether they should even be considered as scientific theories, since acceptable theories must make unique, experimentally-testable predictions. However, their proponents counter that string theories are being judged by standards that, historically, have not been applied to other emerging theories.

One controversial approach has been to invoke the *anthropic principle*. Roughly speaking, this states that what we can expect to observe is restricted by the conditions necessary for our presence as observers. In other words, the universe is observed to be the way it is because that is the only way it could exist that would allow humans to be in it considering such questions. This somewhat circular-sounding principle has been used to explain the apparent improbable values of some cosmological constants, but is by no means generally accepted as a way forward for string theories. Other theorists believe that a physics-based method for choosing a unique theory will eventually be found. For instance, the internal consistency of string theories in ten dimensions has been shown to imply the existence of higher-dimensional mathematical objects, *branes* (short for membranes). It has been suggested that using branes will allow theorists to construct an even more fundamental theory, involving eleven dimensions, in which all five supersymmetric string theories are unified. This theory has a name – M-theory – although no one knows if the conjecture is true, let alone how to construct such a theory.

Leaving aside their formidable theoretical complexity, string theories are strictly applicable only at energies where gravitational effects become comparable to those of the gauge interactions. Since gravity is so weak, this does not happen until enormous energies are reached, at approximately $10^{19}\text{GeV}/c^2$, the *Planck energy*. By wave-particle duality, this means that strings have a size of around 10^{-35} m. The Plank energy is so large that it is difficult to imagine how string theories could be tested by experiments, although some physicists believe that information produced even at the (comparatively) low energies of the LHC, for example the discovery of superparticles, may help to prove them.

At present, the main appeal of string theories lies in their mathematical beauty and naturalness. Although mathematical beauty is a notoriously hard-to-define concept, string theorists have history on their side. A similar consideration of beauty inspired Dirac to persevere with his idea of anti-particles, despite the apparent absurdity of states with total negative energy, and the lack of any supporting evidence. The belief that correct theories are mathematically elegant was also cited by the pioneers of the quark model, pursued in the absence of free quarks, and by those developing the electroweak unification, despite the initial prediction of zero masses for the participating particles. Both were eventually accepted. On the other hand, many short-lived theories were doubtless also considered beautiful by their originators. Needless to say, experimenters will remain sceptical until definite experimental tests can be designed and made: a great challenge for the next generation of particle physicists.

The nature of the neutrino

The neutrino has always been a mystery particle, whose properties have been difficult to study experimentally because it only interacts via the weak interaction. It took about twenty-five years after Pauli postulated it for its existence to be confirmed and a further fifty years to show that its mass was non-zero. Another piece of the neutrino's history is the assumption that it is a *Dirac particle*, described by the Dirac equation. It might seem this has to be true because this equation formed the basis of Dirac's original description of spin-$\frac{1}{2}$ fermions. However, for neutral states, a particle and its anti-particle do not necessarily have to be distinct and this could be the case for neutrinos, as it is for photons. A neutrino that is identical to its anti-particle is called a *Majorana neutrino* and obeys a variation of the original Dirac equation.

The Majorana neutrino may help physicists understand why quarks and leptons have the masses they do. The three known neutrino masses so far observed in experiments have much smaller masses than the other fundamental fermions. A possible explanation has been suggested in the context of extensions of the standard model, in which it is possible for both types of neutrino – the standard Dirac type and the Majorana type – to co-exist. The observed neutrinos, with their very small masses, emerge naturally as a mixture of the two types. However, there is always a price to pay: in this case, it is the prediction that the 'other' combination corresponds to a very heavy neutrino, yet to be discovered.

How might the puzzle of the nature of the neutrino be resolved? The most direct method is to look for reactions that can only occur if the neutrino is its own anti-particle. The most promising of these reactions is neutrinoless double beta decay. In Chapter 1, beta decay was introduced as the most common way that radioactive nuclei decay. This is a weak interaction in which a charged lepton (either an electron or a positron) is emitted together with a single neutrino (or anti-neutrino, as appropriate). In a very small number of nuclei, a second possibility is allowed, whereby two nucleons decay simultaneously, so that two charged leptons and their associated neutrinos are emitted. Because two neutrinos are emitted, double beta decay is a

second-order reaction in the weak interaction and so is very rare, with predicted lifetimes for the particles of around 10^{18} to 10^{24} years, depending on the nucleus concerned. Double beta decay can only be observed if the single beta decay process is forbidden by energy conservation and the parent nucleus is stable against decay by emission of alpha particles or photons. In other words, double beta decay is only observable when it is the only allowed decay mode. The decay mechanism is illustrated in the Feynman diagram of Figure 10.2a. Such decays were first directly observed in 1987 and have since been established for ten nuclei.

Neutrinoless double beta decay involves a parent nucleus that decays by the emission of two electrons but no neutrinos. This is forbidden for a Dirac neutrino, because it violates electron lepton number but is allowed if the neutrino is its own anti-particle. The mechanism is shown in Figure 10.2b. Observation of neutrinoless double beta decay would be resounding evidence that the neutrino is its own anti-particle.

Neutrinoless double beta decay can in principle be distinguished from ordinary double beta decay by measuring the energies of the emitted electrons. In single beta decay, energy is carried away by the undetected neutrino, resulting in a continuous spectrum for the energy of the electron – which

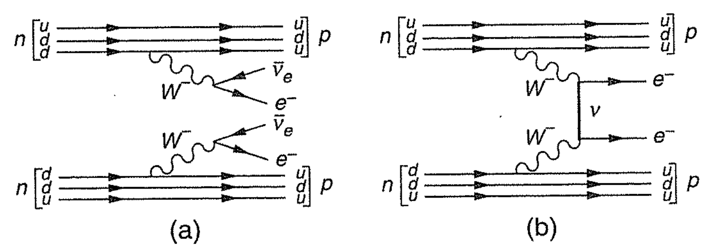

Figure 10.2 (a) Double β-decay, as allowed in the standard model (b) neutrinoless double β-decay, forbidden in the standard model

is why Pauli originally postulated that the neutrino existed. The same is true for the spectrum of the total energy of the two electrons in double beta decay. However, in the neutrinoless case, the electrons carry off all the available energy, which would be observable as a sharp peak in the electron's combined energy. The major problem with mounting an experiment is that the rate for neutrinoless double beta decay is expected to be much smaller even than that for normal double beta decay, perhaps one decay per year (or even fewer) per kilogram of unstable isotope, an incredibly low rate. Because of this, experiments to search for neutrinoless double decays are invariably located deep underground, to protect them from cosmic rays. They must also be shielded to eliminate spurious signals arising from ambient radiation. The sample of the decaying isotope must be extremely pure, because even a very small contamination of a beta-decaying impurity would swamp any signal from double beta decay. Since several kilograms of an isotope are needed to obtain a detectable counting rate, these are very exacting requirements.

One of the experiments currently underway is the NEMO3 detector, located in the Fréjus tunnel beneath Mont Blanc in the French Alps, shown in Figure 10.3. There, a decaying sample of 10 kg of double beta isotopes, in the form of thin sheets, is located in a central tower. The isotopes are surrounded by a detector that can observe and identify the electron tracks from the decays, as well as measure their energies. The detector consists of multi-wire drift chambers to record the electron tracks, electromagnetic calorimeters (plastic scintillator blocks coupled to low-radioactivity photomultiplier tubes) to measure their energy and a magnetic coil to provide a field for charge information. These in turn are surrounded by pure iron shielding, to eliminate gamma rays and wood and water shielding to eliminate neutrons. Overall, the structure is not unlike a conventional detector at a collider (but without the beams!).

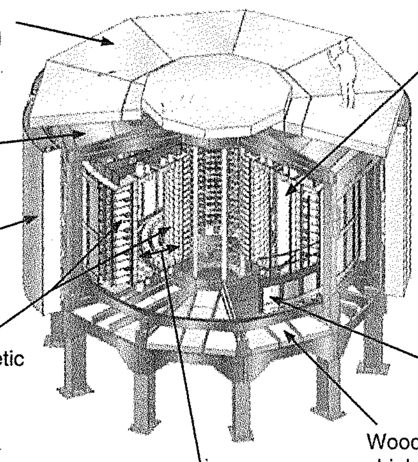

Figure 10.3 Schematic diagram of the NEMO3 detector (courtesy of the NEMO3 collaboration)

NEMO3 and other experiments are still in their early days and they have not yet provided evidence for neutrinoless double beta decay. The most recent results point to an upper limit of 0.5 eV/c^2 on the effective mass of a neutrino that is its own anti-particle. This is not very different to limits that exist for the masses of Dirac neutrinos.