Beyond the standard model with the LHC

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Whether or not the Large Hadron Collider reveals the long-awaited Higgs particle, it is likely to lead to discoveries that add to, or challenge, the standard model of particle physics. Data produced will be pored over for any evidence of supersymmetric partners for the existing denizens of the particle 'zoo' and for the curled-up extra dimensions demanded by string theory. There might also be clues as to why matter dominates over antimatter in the Universe, and as to the nature of the Universe's dark matter.

The unparalleled high energy of the Large Hadron Collider (LHC), with its 7 TeV per beam and its enormously high collision rate that should reach a billion collisions per second, makes it a microscope able to explore the inner structure of matter on a scale that is an order of magnitude smaller than previously achieved. Results at the energies and distances explored so far led physicists to successfully describe matter using the standard model of particle physics[1–3]. But this description is incomplete, and the standard model raises, but leaves unanswered, many fundamental questions. Explanations are needed for the origin of particle masses and the small differences seen in the properties of matter and antimatter, as well as to establish whether fundamental interactions can be unified. Moreover, the standard model has no explanation for some of the basic puzzles of cosmology, such as the origin of matter and the nature of the Universe's dark matter and dark energy. There are high hopes that the LHC will help resolve at least some of these basic issues in cosmology and in physics beyond the standard model[4].

Theoretical calculations made using the standard model agree well with data collected at lower-energy accelerators, such as at CERN's Large Electron–Positron (LEP) accelerator in the 1990s and, more recently, at the Tevatron proton–antiproton collider at Fermilab (Batavia, Illinois)[5]. Data collected at LEP agreed with the standard model at the per-mille level, and recent measurements of the masses of the intermediate vector boson W (ref. 6) and the top quark[7] agree well with standard-model predictions. But the theoretical calculations are valid only with an ingredient that has not yet been observed — the notorious Higgs boson. Without this missing ingredient, the calculations yield incomprehensible, infinite results[8,9]. The agreement of the data with the calculations implies not only that the Higgs boson (or something equivalent) must exist, but also suggests that its mass should be well within the reach of the LHC[5].

In this review, I discuss the likelihood of finding the Higgs boson and what other physics beyond the standard model the accelerator might reveal.

Searching for symmetry breaking

Why should the Higgs boson exist, and are there any alternatives? In the underlying equations of the standard model, none of the elementary particles seems to have mass. In the real world, however, only the photon and gluon, the carriers of the electromagnetic and strong nuclear interactions, are massless. All the other elementary particles are massive, with the W and Z bosons, intermediaries of the weak nuclear interaction, and the top quark weighing as much as decent-sized nuclei. The underlying symmetry between the different particles of the standard model must be broken so that some may acquire masses.

There are two ways to break the symmetry of the standard model. The preferred way is to respect the symmetry of the underlying equations, in which the massless photon and the massive W and Z bosons appear in the same way, but look for an asymmetric solution, much as the reader and writer are lopsided solutions of the symmetric equations of electromagnetism. According to this approach to the standard model, symmetry is thought to be already broken in the lowest-energy state, the so-called vacuum. This 'spontaneous' symmetry breaking is ascribed to a field that permeates all space, taking a specific value that can be calculated from the underlying equations, but with a random orientation in the internal 'space' of particles that breaks the underlying symmetry. This mechanism, which was suggested by Peter Higgs[10] and independently by Robert Brout and François Englert[11], forces some particles, such as the photon, to remain massless, but gives masses to others in proportion to their coupling to this vacuum field (Fig. 1).

In the same way that the electromagnetic field has a quantum particle associated with it, the photon, this vacuum field would also have an associated quantum particle, the Higgs boson. Experiments at LEP seemed at one time to have found a hint of its existence[12]. In the end, however, these searches were unsuccessful and told us only that any Higgs boson must weigh at least 114 GeV (ref. 13). If its mass is less than about 200 GeV, researchers using the Tevatron may find some evidence for it before the LHC comes into operation[14].

The large experiments, ATLAS[15] and CMS[16], at the LHC will be looking for the Higgs boson in several ways (Fig. 2). The Higgs boson is predicted to be unstable and decay into other particles, such as photons, bottom quarks, tau leptons, W or Z bosons. It may well be necessary to combine several different decay modes to uncover a convincing signal. The LHC experiments should be able to find the Higgs boson even if it weighs as much as 1 TeV, and there are high expectations that it could be found during the first couple of years of LHC operation. Its discovery would set the seal on the success of the standard model.

Higgs or bust?

With the impending confirmation or refutation of the Higgs hypothesis, many theorists are getting cold feet. Some are beginning to support alternative scenarios that go beyond the standard model[17]. One popular suggestion is that the Higgs boson might not be an 'elementary' particle in the same sense as the quarks, leptons and the photon, but instead might be composed of simpler constituents[18]. This model would be analogous to the Bardeen–Cooper–Schrieffer (BCS) theory of superconductivity, in which a photon acquires an effective mass by interacting with 'Cooper pairs' of electrons. In this analogy, the W and Z bosons would 'eat' tightly bound pairs of novel strongly interacting fermions

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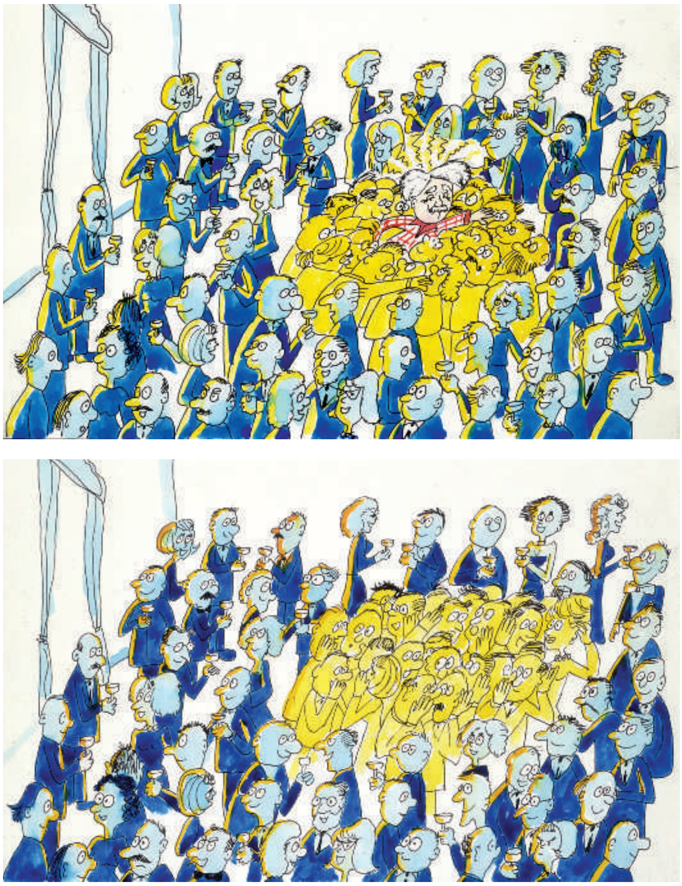


Figure 1 | Picturing the Higgs field. The behaviour of physicists in a crowded social event at a conference is an analogy for the Higgs mechanism, as proposed by David Miller (University College London). The physicists represent a non-trivial medium permeating space. In the upper panel, the physicists cluster around a famous scientist who enters the room, slowing the scientist's progress. In much the same way, a particle passing through the Higgs–Brout–Englert field slows down and acquires a mass. In the lower panel, a rumour propagates. This is an excitation of the medium — the group of physicists — itself, forming a body with a large mass; this is analogous to the formation of a Higgs boson. Figure reproduced with permission from CERN.

rather than an elementary Higgs field. It seems rather difficult to reconcile this composite alternative with the accurate low-energy data from LEP[5], but some enthusiasts are still pursuing this possibility. Alternatively, it has been suggested that the Higgs boson is indeed elementary, but is supplemented by some additional physics — for example, being supersymmetric (discussed later).

The most radical alternative to the Higgs hypothesis exploits the second way of breaking the standard model's symmetry. It postulates that, although the underlying equations are symmetric, their solution is subject to boundary conditions that break that symmetry. What boundary would that be, given that space is apparently infinite (or at least very large compared to the scale of particle physics)? The answer is that there might be additional, very small dimensions of space with edges where the symmetry may be broken[19]. Such models would have no Higgs boson, and are difficult to reconcile with the data already acquired that seem to require a relatively light Higgs boson.

Theorists are amusing themselves discussing which would be worse: to discover a Higgs boson with exactly the properties predicted in the standard model or to discover that there is no Higgs boson. The former would be a vindication of theory, but would teach us little new. The latter would upset the entire basis of the standard model. The absence of a Higgs boson would be exciting for particle physicists, but it might not be so funny to explain to the politicians who have funded the LHC mainly to discover this particle. Whichever option nature chooses, the good news is that the LHC will provide us with a clear-cut experimental answer and end the speculation.

The hierarchy problem

Resolving the Higgs question will set the seal on the standard model, but, as I mentioned at the beginning, there are plenty of reasons to expect other physics beyond the standard model to be discovered (Fig. 3). Specifically, there are good reasons to expect other discoveries at the TeV energy scale, within reach of experiments at the LHC. Many would consider this to be the primary motivation for the leap into the unknown that the LHC represents.

For example, it is generally thought that the elementary Higgs boson of the standard model cannot exist in isolation. Specifically, difficulties arise when one calculates quantum corrections to the mass of the Higgs boson owing to the exchanges of virtual particles (see, for example, ref. 20). Not only are these corrections infinite in the standard model, but, if the usual procedure of controlling them by cutting the theory off at some high energy or short distance is adopted, the net result depends on the square of the cut-off scale. This implies that, if the standard model were embedded in some more complete theory that kicks in at high energy — such as a grand unified theory of the particle interactions or a quantum theory of gravity — the mass of the Higgs boson would be sensitive to the details of this high-energy theory. This would make it difficult to understand why the Higgs boson has a (relatively) low mass. It would also, by extension, make it difficult to explain why the energy scale of the weak interactions — as reflected in the masses of the W and Z bosons — is so much smaller than that of unification or quantum gravity.

One might be tempted simply to wish away this 'hierarchy problem' by postulating that the underlying parameters of the theory are tuned finely, so that the net value of the Higgs boson mass obtained after adding in the quantum corrections is unnaturally small as the result of some sneaky cancellation. But it would surely be more satisfactory either to abolish the extreme sensitivity to the quantum corrections or to cancel them in a systematic manner. Indeed, this has been one of the reasons for believing that the Higgs boson is composite. If it is, the Higgs boson would have a finite size, which would cut the pesky quantum corrections off at some relatively low scale. In this case, the LHC might uncover a cornucopia of new particles with masses around this cut-off scale, which should be near 1 TeV. At the very least, the interactions of the W and Z vector bosons would be modified in an observable way.

The supersymmetric solution

An alternative way to get rid of these quantum corrections is provided by supersymmetry[21]. This is an elegant theory that would pair up fermions, such as the quarks and leptons that make up ordinary matter, with bosons, such as the photon, gluons, W and Z that carry forces between the matter particles or even the Higgs itself (Fig. 4). Supersymmetry also seems to be essential for making a consistent quantum theory of gravity based on string theory (of which more later). However, these elegant arguments give no clue as to what energies would be required to observe supersymmetry in nature.

The first argument that supersymmetry might appear near the TeV scale was provided by the hierarchy problem: in a supersymmetric theory, the quantum corrections owing to the pairs of virtual fermions and bosons cancel each other systematically[22], and a low-mass Higgs boson no longer seems unnatural[23]. The residual quantum corrections to the mass of the Higgs boson would be small if differences in mass between supersymmetric partner particles were less than about 1 TeV. Because the fermions and bosons of the standard model do not pair up with each other in a neat supersymmetric manner, this theory would require each of the standard-model particles to be accompanied by an as-yet unseen supersymmetric partner. It might seem profligate for there to be all these partners, but at least the hypothesis predicts a 'scornucopia' of supersymmetric particles that should weigh less than about 1 TeV and hence could be produced by the LHC[15,16].

In the wake of this hierarchy argument, at least three other reasons have surfaced for thinking that supersymmetric particles weigh about 1 TeV.

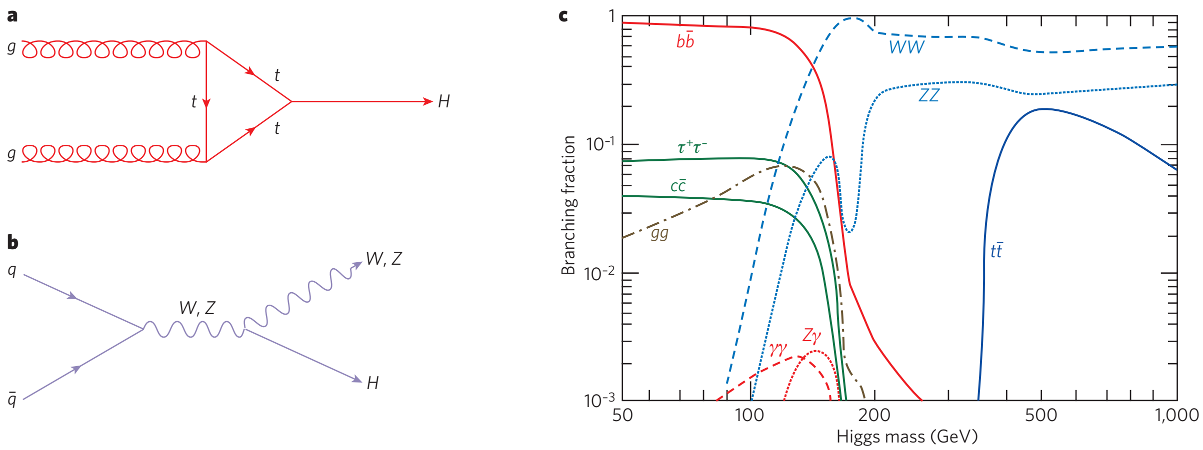


Figure 2 | The Higgs boson at the LHC. A Higgs (*H*) boson may be produced by a range of interactions, two examples of which are shown here. The first, **a**, is through fusion of gluons (*g*) from the protons in the LHC beams, through a top (*t*) quark loop; and the second, **b**, is through a *bremsstrahlung* process, in which a quark (*q*) and antiquark ($\bar{q}$) annihilate to create a *W* or *Z* boson, which may then radiate a Higgs. **c**, The Higgs itself then decays, and it is these decay products that will be caught in a detector. The 'branching fraction' or probability of decay to certain products depends on the (as-yet unknown) mass of the Higgs particle, which is dominated by decay to a bottom–antibottom quark pair at low mass, but by decay to pairs of *W* bosons at high mass.

The first is that these particles would facilitate the unification of the strong, weak and electromagnetic forces into a simple grand unified theory[24]. Another argument is that a theory with low-energy supersymmetry would predict that the Higgs boson weighs less than about 150 GeV (ref. 25), which is precisely the range favoured indirectly by the present data. The final one is that, in many models, the lightest supersymmetric particle (LSP) is an ideal candidate for the dark matter advocated by astrophysicists and cosmologists.

The LSP is ideal because it is stable when a suitable combination of baryon and lepton numbers is conserved[26], as happens in the minimal supersymmetric extension of the standard model, as well as in simple models of grand unification and neutrino masses. In this case, LSPs would be left over as relics from early in the Big Bang, and calculations of their abundance yield a density of dark matter in the range favoured by astrophysics and cosmology if the LSP weighs at most a few hundred GeV, probably putting it within reach of the LHC[27].

Supersymmetry could be a bonanza for the LHC, with many types of supersymmetric particle being discovered. In many models, the LHC would produce pairs of gluinos (the supersymmetric partners of the gluons) or squarks (the supersymmetric partners of the quarks) that would subsequently decay through various intermediate supersymmetric particles. Finally, each of these pairs of particles would yield a pair of LSPs that interact only weakly and hence carry energy away invisibly. In favourable cases, the masses of several intermediate particles could be reconstructed this way. It might even be possible to use these measurements to calculate what the supersymmetric dark-matter density should be, so as to compare the result with the astrophysical estimates[28].

Into extra dimensions?

Postulating a composite Higgs boson or supersymmetry are not the only strategies that have been proposed for dealing with the hierarchy problem. Another suggestion is that there are additional dimensions of space[29]. Clearly, space is three-dimensional on the scales that we know so far, but the idea that there are additional dimensions curled up so small that they are invisible has been in the air since it was first proposed by Kaluza and Klein over 80 years ago. This idea has gained ground in recent years with the realization that string theory predicts the existence of extra dimensions of space[30].

According to string theory, elementary particles are not idealized points of euclidean geometry, but are objects extended along one dimension (a string) or are membranes with more dimensions[31]. For the quantum theory of strings to be consistent, particles have to move in a space with more than the usual three dimensions. Initially, it was thought that these extra dimensions would be curled up on scales that might be as small as the Planck length of around 10^{-33} cm. But more recently, it was realized that at least some of these new dimensions might be much larger and possibly have consequences observable at the LHC.

One of the possibilities offered by these speculations is that gravity is strong when these extra dimensions appear, possibly at energies close to 1 TeV. Under this condition, according to some variants of string theory, microscopic black holes might be produced by the LHC[32]. These would be short-lived, decaying rapidly through thermal (Hawking) radiation. Measurements of this radiation would offer a unique laboratory window on the mysteries of quantum gravity. The microscopic black holes would emit energetic photons, leptons, quarks and neutrinos, providing distinctive experimental signatures. In particular, the neutrinos they emit would carry away more invisible energy than LSPs would in the supersymmetric models discussed previously[33].

Although microscopic black holes would be the most dramatic sign of large extra dimensions, they are not the only sign of such theories that might be visible at the LHC. If the extra dimensions are curled up on a sufficiently large scale, the ATLAS and CMS projects might be able to see Kaluza–Klein excitations of standard-model particles, or even of the graviton, the mediator particle of gravity. Indeed, the spectroscopy of some extra-dimensional theories might be as rich as that of supersymmetry[34]. If so, how do we tell which cornucopia the LHC is uncovering? There are significant differences in the relationship between, for example, the masses of the partners of quarks and leptons in supersymmetric theories and in theories with large extra dimensions. Moreover, the spins of the Kaluza–Klein excitations would be the same as those of their standard-model progenitors, whereas the spins of the supersymmetric partners

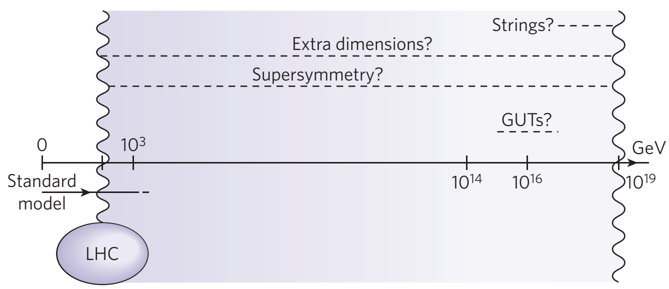


Figure 3 | Physics beyond the TeV scale. The standard model has been well tested up to around the 100-GeV mass scale. The LHC will test beyond this, to the crucial 1,000-GeV level, the TeV scale, at which hints of new physics, such as supersymmetry and extra dimensions, may emerge. String theory or grand unified theories (GUTs) inhabit much higher energy scales, approaching 10^{19} GeV, which is called the Planck scale.

	Known particles of the standard model	Postulated supersymmetric partners or 'sparticles'	
Half-integer spin	Electron	Selectron	Integer spin
	Neutrino	Sneutrino	
	Top quark	Stop	
Integer spin	Gluon	Gluino	Half-integer spin
	Photon	Photino	

Figure 4 | Examples of supersymmetric partners. Supersymmetry is a symmetry drawn between fermions (with half-integer spin) and bosons (with integer spin). It postulates that, for each fermion, there exists a bosonic partner — such as the supersymmetric electron, or 'selectron', which partners the electron. Similarly, each boson is thought to have a fermionic superpartner, which for the gluon is the 'gluino'.

would be different. These underlying differences translate into characteristic differences in the spectra of decay products in the two classes of model and into distinctive correlations between them[35].

It is amusing that, in some theories with extra dimensions, the lightest Kaluza–Klein particle (LKP) might be stable[36], rather like the LSP in supersymmetric models. In this case, the LKP would be another candidate for astrophysical dark matter. Thus, there is more than one way in which LHC physics beyond the standard model might explain the origin of dark matter: fortunately, the tools seem to be available for distinguishing between them.

The matter–antimatter conundrum

Will the LHC explain the origin of conventional matter? As was first pointed out by the Russian physicist Andrei Sakharov[37], particle physics can explain the origin of matter in the Universe in terms of small differences in the properties of matter and antimatter, such as those discovered in the decays of *K* and *B* mesons. Present experimental data accord well with the matter–antimatter differences allowed by the standard model. However, by themselves, these differences in the properties of matter and antimatter would be insufficient to generate the matter seen in the Universe. It is possible that the deficit will be explained by new physics at the TeV scale revealed by the LHC. For example, supersymmetry allows many more possibilities for differences between the properties of matter and antimatter than are possible in the standard model[38]; some of these differences might explain the amount of matter in the Universe.

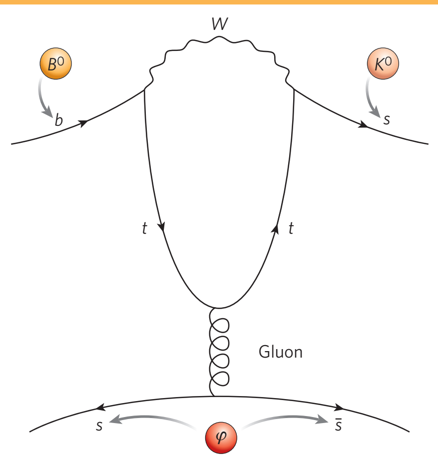
This provides one of the motivations for the LHCb experiment[39], which is dedicated to probing the differences between matter and antimatter, notably looking for discrepancies with the standard model (Box 1). In particular, LHCb has unique capabilities for probing the decays of mesons containing both bottom and strange quarks, the constituents of the *B* and *K* mesons probed in other experiments investigating matter–antimatter differences. There are many other ways to explore the physics of matter and antimatter, and the ATLAS and CMS experiments will also contribute to them, in particular by searching for rare decays of mesons containing bottom quarks.

If these experiments detect any new particles beyond the standard model at the TeV scale, questions will immediately arise as to whether this new physics distinguishes between matter and antimatter, and whether or not this new physics explains the origin of matter in the Universe. For example, if the Higgs boson is discovered at the LHC, are its couplings to matter and antimatter the same? If supersymmetry is discovered at the LHC, do supersymmetric 'sparticles' and 'antisparticles' behave in the same way? There are many models in which matter–antimatter differences in the Higgs or sparticle sector are responsible for the origin of the matter in the Universe.

Into the future

According to present plans, the first full-energy collisions of the LHC will take place in 2008, although it will take some time for the accelerator to build up to its designed nominal collision rate. There are hopes, however, that in its first couple of years of operation, it will already start to provide crucial information on physics beyond the standard model, for example by discovering the Higgs boson — or other new particles such as those

Box 1 | Penguin hunting at LHCb



Why does matter dominate over antimatter in the Universe, considering that both were thought to be created in equal quantities in the Big Bang? Part of the explanation is that some interactions between particles take place at different rates when two fundamental symmetries of the quantum field theory that underlie them are simultaneously reversed. There are two symmetries involved: charge conjugation, C; and parity symmetry, P. Charge conjugation turns particles into their antiparticles by reversing internal properties such as electric charge. By contrast, parity symmetry flips external particle properties such as spin, similar to looking at an interaction in a mirror.

CP violation was first discovered experimentally[45] in decays of *K* mesons, which contain a strange quark in addition to an up or down quark. Later theoretical work showed[46] that CP violation would occur naturally in interactions mediated by the weak nuclear force in the standard model with three quark generations. (At the time, particles from only two were known.) The degree of violation is, however, insufficient to explain the Universe's matter–antimatter imbalance.

The subsequent discovery of the third quark generation, formed of the bottom (*b*) and top (*t*) quarks, vindicated the model. A plethora of experiments has since confirmed CP violation, indirectly and directly, in decay channels of *B* mesons (those containing bottom quarks), where the effect is expected to be particularly large. These experiments notably include two specially constructed '*B* factories', the Belle detector at KEK in Japan, and BaBar at the Stanford Linear Accelerator Center (SLAC), in California, which have delivered a series of more precise values for the parameters of CP violation since 2001.

The LHCb experiment is LHC's dedicated CP-violation detector. It is a 20-m-long spectrometer with a conical detection volume expanding in radius along the beam axis. It is attuned to detecting the distinctive signature of *B* decays — charged particles with high transverse momenta originating from a vertex significantly displaced from the interaction point of the proton beams.

To maximize the probability of only a single *B* interaction per beam crossing, the LHC beams are defocused slightly to a luminosity of around 2.5×10^{32} $cm^{-2}s^{-1}$, below the LHC's nominal value of 10^{34} $cm^{-2}s^{-1}$. The implied collision rates and the high energy of the LHC beams should allow CP-violation parameters to be more tightly constrained and perhaps also provide a glimpse of physics beyond the standard model.

Such physics could manifest itself, in particular, in 'penguin' processes such as $B^0 \rightarrow K^0 \varphi$ (see page 270) in which the decay of a highly energetic *B* meson takes place, legitimately according to the rules of the weak interaction, through an intermediate loop of massive particles such as a top quark and a *W* boson (see figure). Does the degree of CP violation in such a process differ significantly from that found, for example, in the decay $B^0 \rightarrow K^0 J/\Psi$, which does not include a penguin loop? If so, that could be an indication of new physics participating in the penguin loop — such as the involvement of supersymmetric particles.

predicted by supersymmetry, if they are not too heavy[40]. Continued running of the LHC at its nominal luminosity would enable many properties of the Higgs boson to be verified, for example by providing measurements of its couplings to some other particles and checking whether these are proportional to the particles' masses. This period should also enable the properties of any other newly discovered particles to be checked, such as establishing whether their spins are the same as those of their standard-model counterparts or are different.

What might be possible using the LHC after these planned phases of exploitation? One possibility is to add new components to the existing ATLAS and CMS detectors that would provide new ways to study the Higgs boson. For example, new components close to the beams several hundred metres from the interaction points might be able to detect rare proton–proton collisions that produce nothing except a single isolated Higgs boson[41]. Another possibility is that supersymmetric or other new particles might show up in unexpected ways. For example, in some supersymmetric scenarios there would be a metastable charged particle that would have quite distinctive experimental signatures[42], and it might be interesting to devise new detectors to explore this possibility.

It might also be possible to increase the LHC collision rate significantly beyond the nominal value. This possibility would be particularly interesting if, for example, the initial runs of the LHC discover new physics with a very low production rate, perhaps because it has a high energy threshold. Increasing the LHC collision rate might be possible by redesigning the collision points using new magnet technologies; it would also require replacing at least some of CERN's lower-energy accelerators, such as the low-energy linear proton accelerator and the Proton Synchrotron, so as to feed more intense beams into the LHC[43]. Technical options for increasing the LHC collision rate are now being evaluated, so that they can be considered when the first experimental results from the initial LHC runs become available, some time around 2010.

Exploitation of the LHC and the study of possible upgrade options are among the highest priorities for European particle physics and were decided upon at a special meeting of the CERN Council in Lisbon in July 2006 (ref. 44). Possible future accelerators were also considered, such as a linear electron–positron collider or a neutrino factory. The priorities for these options will surely depend on the nature and energy scale of whatever new physics beyond the standard model the LHC reveals, as well as on developments in other areas such as neutrino physics. A central element in the European strategy for particle physics is the need to review advances in particle physics in the coming years, and in particular to review the implications of any LHC discoveries at the end of this decade.

Particle physics stands on the brink of a new era. Research using the LHC will make the first exploration of physics in the TeV energy range. There are good reasons to hope that the LHC will find new physics beyond the standard model, but no guarantees. The most one can say for now is that the LHC has the potential to revolutionize particle physics, and that in a few years' time we should know what course this revolution will take. Will there be a Higgs boson, or not? Will space reveal new properties at small distances, such as extra dimensions or supersymmetry? Will experiments at the LHC cast light on some fundamental cosmological questions, such as the origin of matter or the nature of dark matter? Whatever the answers to these questions might be or whatever surprises the LHC might spring, it will surely set the agenda for the next steps in particle physics.■

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