Although the basic building blocks of matter and their interactions have been placed on a firm theoretical footing, many fundamental questions remain unanswered and await the experiments of the future.

Particle physics: the next generation

John Ellis

Particle physics was born in 1897 with the discovery of the electron by J.J. Thomson, and many experimental and conceptual strides have been made in the century or so since this discovery. Several layers of the cosmic onion have been peeled away, and our current understanding of the subject is summarized in the so-called Standard Model, which has been tested with high precision at particle-physics laboratories around the world. There is no confirmed measurement from any laboratory experiment that contradicts the Standard Model. However, we particle physicists find it very unsatisfactory because its very successes raise many fundamental questions that cry out for answers.

Our challenge in the next millennium will be to transcend the Standard Model and reach a new level in the description of the constituents of matter and their interactions. It is very likely that this new understanding will make the Standard Model appear as primitive and incomplete as we now find the atomic model that described physics and chemistry at the end of the last century. Nevertheless, even atoms still have some relevance and utility, as do Maxwell’s equations and Newtonian gravity. Therefore, we may expect that any new theory developed in the next millennium will have the Standard Model embedded within it. So, let us first recapitulate the essential features of the Standard Model, before musing on its open problems and how to resolve them.

Triumphant discovery

The discovery of the massive top quark at Fermilab in 1994 spectacularly confirmed the predictions of the Standard Model. The discovery of such a massive new particle is a triumph for our understanding of the fundamental forces of nature. It is a significant step forward in our quest to understand the structure of the universe.

The triumph of the Standard Model

The fundamental particle interactions described by the Standard Model are the electromagnetic, weak and strong nuclear forces. It has been known from the early days of quantum physics that the electromagnetic forces between charged particle and another are mediated by the exchange of the massless photon. Electromagnetic interactions are well described by the long-established quantum theory of electrodynamics, called QED. Meanwhile, the strong nuclear interactions are described by quantum chromodynamics (QCD), and are mediated by massless bosons, called gluons. These were discovered at the DESY laboratory in Germany in 1979.

According to the unified theory of the weak and electromagnetic interactions developed by Sheldon Glashow, Steven Weinberg and Abdus Salam in the 1960s, weak nuclear interactions such as beta decay should similarly be mediated by the exchange of charged (W⁺ and W⁻) and neutral (Z⁰) massive intermediate bosons. These were only discovered at CERN, the European laboratory for particle physics near Geneva, in 1983 and weigh about 80 and 91 GeV c⁻², respectively. Thus all the fundamental interactions have very similar structures, but the question of why only the weak bosons are massive is a puzzle to which we will return.

As already mentioned, the first elementary matter particle to be identified was the electron, which weighs about 0.5 MeV c⁻² and has an intrinsic spin of ½. This was followed by the discoveries of other particles, called leptons, that do not feel the strong nuclear interactions: the unstable muon in 1936 (weighing about 100 MeV c⁻²) and the tau in 1975 (about 1800 MeV c⁻²). Each of these charged leptons has its own associated uncharged neutrino, and experiments at the Large Electron-Positron (LEP) accelerator at CERN have shown that there can be no more similar neutrinos. Accelerator data have also established upper limits on the possible masses of the neutrinos, which are much less than those of
Precise predictions

Over 20 million Z° bosons have been produced in electron–positron collisions at the LEP and SLC accelerators, making this one of the most studied particles in high-energy physics. The number of Z° bosons produced as a function of centre-of-mass energy is sensitive to the number of types of neutrino. Early measurements at the LEP experiments (black points) confirmed that there are precisely three types of neutrino.

the corresponding charged leptons.

The precision of strongly interacting particles, known as hadrons, that have been discovered since the 1940s are known to be composite bound states of more elementary entities called quarks. We now know that there are six different types of quark, and that their masses range from a few MeV to several GeV, for the up and down quarks that make up conventional nuclear matter, to about 5 GeV for the bottom quark discovered in 1977. Meanwhile the top quark, which was discovered in 1994 during proton–antiproton collisions at Fermilab near Chicago, weighs in at around 170 GeV (figure 1).

Although the strong nuclear forces are—rather weak—strong, it is known that they get weaker at high energies, which corresponds to short distances. This property of "asymptotic freedom" is a central prediction of QCD. Like the other elementary-particle interactions, QCD is what we call a "gauge theory".

Most particle theories have symmetries under which the properties of a particle, such as its charge and spatial coordinates, can be changed without changing the predictions of the theory. The special feature of a gauge theory is that these transformations can be made independently at each point in space and time. This is possible if the exchange particles that mediate the interactions have integer spin; in other words, if they are bosons. In QED, the prototype gauge theory, the photon has a spin of 1. Gauge theories provide the only consistent description of the interactions of such particles. General relativity has a very similar structure to QED but with the role of the mediating boson being played by the elusive graviton, which has a spin of 2 and has yet to be detected.

Particle physics has been dominated in recent years by a series of precision tests of the Standard Model, including both its strong and electroweak sectors. The asymptotic freedom of the strong interactions has been confirmed in a large number of experiments with energies ranging from 1 GeV to about 200 GeV. Tests of the electroweak sector have been dominated by high-energy collisions between electrons and positrons at LEP, and at the Stanford Linear Collider (SLC) in California.

For the first few years of its operation, the beams at LEP were tuned so that their energies corresponded to the mass of the Z° particle. At these specific energies, the rate at which the electron–positron interactions occur is enhanced, and a plot of the interaction rate versus energy shows a "resonance peak" (figure 2). A crucial role has been played by measurements at this Z° resonance peak, which must be one of the most carefully studied resonances in particle physics, since 20 million measured Z° bosons have contributed to it. The height and width of the peak depend on the number of ways that the short-lived Z° particles decay. It also includes decay modes that cannot be detected directly, such as those into a pair of neutrinos. The LEP measurements tell us that there are precisely three neutrino species, no more and no less.

In addition to measuring the total interaction rates, LEP and the SLC have provided many other precision measurements, including the relative probabilities for the Z° particle to decay into different heavy quarks, the angular distributions for particle production, and their dependencyps on the particle spins.

Many of these measurements are accurate to one part in a thousand, and none differs significantly from the Standard Model prediction. These predictions require calculations of the small quantum corrections due to "virtual" particles that are emitted by a particle and exist briefly before being reabsorbed. These corrections can be calculated reliably within the electroweak theory. In many quantum theories, these calculations are infinite, and it is not possible to make reliable predictions. It is one of the miracles of gauge theories that these infinities can be removed, allowing finite predictions for physical quantities to be made. This was first done for QED in the 1940s. In the early 1970s Gerard 't Hooft and Martinus Veltman proved that it could also be done for the electroweak theory—an achievement that has won them the 1999 Nobel Prize for Physics.

These so-called "loop calculations" are sensitive to the masses of the virtual particles that are too heavy to be produced directly at LEP or the SLC. In particular, the various measurements from the Z° decays are quite sensitive to the mass of the top quark. Particle physicists were therefore able to successfully predict the mass of the top quark before it was discovered by confronting the Standard Model with all the measurements and determining which mass fitted best.

The LEP beam energies have now been raised well above the threshold for Z° production so that pairs of W bosons can be created and studied in detail. According to the Standard Model, the W pairs can be produced if the electron and positron first create a photon or Z° boson, or exchange a neutrino. All three contributions are required to explain the LEP data, and the measurements are in good agreement with theoretical predictions. Thus the Standard Model remains triumphant!

Standard Model shortfalls

There are still some key features of the theory that have not yet been tested. One of these is the origin of the particle masses. According to the Standard Model, the underlying...
field theory may be formulated in terms of massless particles, in a very symmetric way. However, the electroweak vacuum is believed to break this symmetry, and give different masses to different particles. The culprit for this spontaneous symmetry breakdown is believed to be a scalar field, which has an associated particle called the Higgs boson. The precision electroweak data described earlier are sensitive to the mass of this particle, and currently indicate that it weighs around 100 GeV/c², with an uncertainty of a factor of about 2.

The search for the Higgs boson has been one of the continuing objectives of the LEP experimental programme (figure 3). These searches have so far been unsuccessful, and have established that its mass must exceed about 102 GeV/c². The LEP experiments should be able to extend the search to around 110 GeV/c². However, if the Higgs boson is heavier, its discovery may have to await future experiments at Fermilab in the US or at the Large Hadron Collider (LHC) at CERN.

Another missing element in tests of the Standard Model is its mechanism for preferring matter over antimatter. This subject is potentially important for the history of the universe, which does not appear to contain any substantial amount of antimatter despite the natural expectation that it would initially have contained equal amounts of both matter and antimatter. In 1957 weak interactions were shown to violate not only parity (or mirror) symmetry, but also charge conjugation in which particles are replaced by their antiparticles. This means that, in general, particles spinning in one particular direction behave differently from particles spinning in the opposite direction. It also means that particles and antiparticles spinning in the same direction behave differently.

At first, it was thought that the combination of parity inversion and charge conjugation, known as CP, might be a “good” symmetry. In other words particles spinning in one direction would behave the same as antiparticles spinning in the opposite direction. However, an experiment in 1964 discovered that CP was also violated in the weak decays of neutral K mesons (which contain “strange” quarks). This means that matter does not behave in exactly the same way as antimatter, even if one reflects the experiment in a mirror in an attempt to recover the symmetry.

In 1973 Makoto Kobayashi and Toshikide Maskawa realized that this matter–antimatter asymmetry could be accumulated within the Standard Model if there were at least six quark species. Subsequently, much theoretical effort has been devoted to evaluating the Standard Model predictions for matter–antimatter asymmetries in different processes, and there is an extensive experimental programme to test these predictions. Follow-up experiments are consistent with the Standard Model, confirming recently that CP symmetry is violated directly in the decay of neutral K mesons (see Quinn and Hewett in further reading). However, experiments have not yet verified the characteristic predictions of the Standard Model for CP violation in other particle decays. There is currently great interest in the search for CP violation in decays of B mesons, which contain the bottom quark. Large numbers of B mesons will be produced in new accelerators called B factories, which began running this year at the Stanford Linear Accelerator Center (SLAC) in the US and the KEK laboratory in Japan.

Although the Standard Model of particle physics is very successful, with no confirmed accelerator data that contradict it, there are many theoretical reasons to consider it unsatisfactory and to expect some physics beyond the Standard Model. For example, even if one accepts the charges and spins of the quarks and leptons, the Standard Model contains 19 free parameters that are obtained from experiment. Having so many parameters is surely unacceptable for any candidate for a “theory of everything”. Attempts to go beyond the Standard Model typically try to simplify at least one of its aspects.

Towards grand unification

In a so-called grand unification theory one regards the strong, weak and electromagnetic interactions as different aspects of a single force, with a universal “coupling strength” that describes the probabilities of all the different types of particle interaction. This is made possible by the fact that the strengths of the different interactions vary with energy, as exemplified by the asymptotic freedom of the strong interactions. Calculations indicate that the coupling strengths may become equal at an energy around 10¹⁵ to 10¹⁷ GeV, relatively close to the so-called Planck energy scale of about 10¹⁸ GeV, where gravity becomes a strong force.

Many grand unified theories predict the appearance of novel interactions that may cause the proton to decay and/or give neutrinos mass. There have been many unsuccessful searches for proton decay, and its lifetime must be at least 10²⁵ years. However, recent studies of solar and atmospheric
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The experimental calendar

- Currently operating at CERN is the LEP electron–positron collider, which this year has been teased up to, and even slightly beyond, its design energy of 200 GeV in the centre of mass. The LEP beams may even be cooled to slightly higher energies next year, the collider’s final year of operation.
- Several new accelerators started to take data this year. These include the DAFNE ion factory at Frascati in Italy, the B-meson factories at SLAC in the US and the KEK laboratory in Japan, and the Relativistic Heavy Ion Collider at the Brookhaven National Laboratory in the US.
- Next year will see the return of the Fermilab Tevatron proton–antiproton collider, which will have a centre-of-mass energy of 2 TeV. The Tevatron will remain the world’s highest energy machine until the start-up of the LHC at CERN, scheduled for 2005. The LHC will provide proton–proton collisions at 14 TeV in the centre of mass, and heavy-ion collisions above 1000 TeV in the centre of mass.
- Among the non-accelerator facilities, several underground experiments are looking for evidence of dark matter, and the immensely successful Super Kamiokande detector will continue to operate for the foreseeable future. It has recently complemented its studies of atmospheric neutrinos by starting to look at a beam of neutrinos directed from the KEK laboratory 250 km away. This long distance could be sufficient for the neutrinos to change from one flavour into another, if the previous atmospheric neutrino data are interpreted correctly. This so-called K2K project will be joined in 2001 in the same mine by the KamLAND detector, which is designed to be sensitive to neutrinos emitted by Japanese nuclear power reactors.
- In Canada, the SNO solar neutrino experiment has started to take data now, and other solar neutrino experiments, such as Borexino, are scheduled to come on-line within the next few years. In 2003 the Fermilab accelerator laboratory will start sending a neutrino beam to the MINOS detector in the Soudan mine 730 km away. It is also hoped that in 2005 CERN will start sending a neutrino beam over a similar distance to the Gran Sasso laboratory in Italy. Both of these projects will be seeking to confirm the oscillation interpretation of the atmospheric-neutrino data.
- Underwater, meanwhile, a detector has been taking data in Lake Baikal in Siberia for some time, and two more experiments – ANTARES and NESTOR – are planned in the Mediterranean. In ice, AMANDA is already taking data in Antarctica, and may be followed by the larger ICECUBE detector. Meanwhile, the first part of the Auger experiment to detect ultrahigh energy cosmic rays is currently under construction in Argentina, and new gamma-ray telescopes are planned, including GLAST which is due to be launched in 2005.

but bound states of even more fundamental constituents. So far, no compelling model of this type has emerged, so it will not be discussed further here. The stakes are high in constructing a theory of flavour and CP violation, since it may be a crucial ingredient in attempts to understand the asymmetry between matter and antimatter observed in the universe. (An example of a flavour-violating interaction would be if a muon and an electron were created in an electron positron collision, rather than a muon and antimuon.)

A third set of proposed extensions to the Standard Model attempts to understand better the observed magnitudes of particle masses. The principal problem here is that the virtual particles in the new theory have very large effects on the mass of the Higgs boson. In principle, these effects could be cancelled by bizarre initial values of the parameters in the theory, so as to obtain acceptable physical values, but this is an unsatisfactory situation to be in.

One way to avoid this delicate fine-tuning of parameters is to postulate that the particles of the Standard Model are accompanied by partners with identical charges (and hence interactions), but with spins differing by half a unit. These "supersymmetric" particles therefore have opposite statistics from the particles in the Standard Model – fermions are accompanied by bosons, and vice versa. The corresponding virtual-particle effects have opposite signs and cancel automatically, so that the fine-tuning problem is avoided if the supersymmetric partners of the particles weigh less than about 1000 GeV/c² (see Ellis in further reading).

One of the most intriguing aspects of many supersymmetric theories is that the lightest supersymmetric particle should be stable. It might therefore still be around in the universe today as a relic from the big bang, and might constitute much of the "cold" dark matter advocated by many astrophYSicists and cosmologists. So far we have no direct evidence for supersymmetric particles, but we believe that pairs of them could be created in collisions just like any other particle, provided the energy is high enough.

Finally, many theorists believe that the underlying theory of everything that resolves all the open problems of the Standard Model will be provided by some incarnation of string theory. This is an apparently consistent quantum theory of gravity that requires supersymmetry and is rich enough to accommodate a grand unified theory. String theory embodies a very high degree of symmetry that extends and generalizes both the symmetry of the Standard Model and the general coordinate invariance of general relativity. It is a mesmerizingly beautiful theory that has already provided us with many elegant mathematical insights, and promises to revolutionize our vision of the geometry of space–time (see “The new universe around the next corner” by Lee Smolin on page 79).

The next step

When and how might these ideas for possible physics beyond the Standard Model be tested? The calendar is largely determined by the opening of experimental opportunities at new accelerators. Non-accelerator facilities – experiments underground, underwater, in ice and in space – also have a role to play (see box). How can these experiments address the important open issues in particle physics?

First and foremost is the discovery of the Higgs boson. It may be found at LEP next year if it weighs less than about 110 GeV/c². This is not unlikely, in view of the precision
Standard Model measurements, and also in the light of supersymmetry, which predicts that at least one Higgs boson should weigh less than about 150 GeV. We wait for rumors with bated breath.

If LEP is lucky, the Tevatron collider has the next opportunity; it may have a chance if the Higgs mass is below about 70 GeV, but this will depend how long and how well the accelerator runs. If the Higgs boson has not been found by 2005, as is perhaps most likely, it will surely be found by experiments at the LHC, although this may take several years.

The flavor and CP problems are the primary objectives of the K and B factories. Within the next few years, they should tell us whether CP violation is described approximately by the mechanism proposed by Kobayashi and Maskawa with the Standard Model. If so, there will follow a period of detailed studies to look for possible deviations that might be due to supersymmetry, for instance. Here there may be a good research opportunity for the dedicated B experiment at the LHC collider.

What about more direct searches for supersymmetry? Here again, LEP has a chance to discover it, as does the Tevatron collider. Once more, the LHC will surely discover it, if this has not happened previously, and will make detailed measurements. However, in this case there may be serious competition from non-accelerator experiments looking directly or indirectly for supersymmetric dark-matter particles that are relics from the big bang. One experiment at the Gran Sasso laboratory in Italy has already reported that it may be seeing a signal for the elastic scattering of supersymmetric cold dark-matter particles with heavy nuclei, and other underground experiments are poised to match or surpass its sensitivity.

Alternatively SuperKamiokande (figure 4) and the large underwater and ice experiments have a chance to see supersymmetric relics indirectly via their annihilation into neutrinos that yield detectable muons, while gamma-ray telescopes may be able to detect their annihilations into photons. These experiments have a window of opportunity until 2005, when the collider experiments at the LHC should settle the supersymmetric issue.

Grand unified theories (GUTs) are vulnerable on several fronts. The upcoming "long-baseline" neutrino experiments should establish whether one type of neutrino gradually transforms into another type as it travels over a long distance from source to detector. According to current atmospheric-neutrino data it is widely suspected that the muon neutrino transforms or "oscillates" into a tau neutrino. In parallel, the Kamiokande, Borexino and the Sudbury Neutrino Observatory (SNO) experiments should be able to pin down whether neutrino oscillations are responsible for the surprisingly small flux of solar neutrinos that has been detected so far. We should not forget the continuing search for proton decay. SuperKamiokande has not yet exhausted its sensitivity to the various possible decay modes.

A useful role may also be played by the future satellite measurements of the cosmic microwave background, NASA plan to launch the Microwave Anisotropy Probe in 2000, and the European Space Agency hopes to launch the Planck Surveyor in 2007. These will test models of fundamental cosmology, which postulate new physics that should be integrated into the overall framework of particle physics.

What are the prospects for testing fundamental string theory? Here the crystal ball is rather cloudy, but the subject is regularly shaken by conceptual revolutions, and there may be experimental opportunities to test it or alternative quantum theories of gravity. Any such theory could be expected to predict some small effects suppressed in strength by (at least) some power of the characteristic energy scale divided by the Planck energy scale. These new effects may respect the usual laws of quantum field theory, in which case they could be detectable if they yield novel phenomena such as proton decay or neutrino masses, as in conventional GUTs. Alternatively, they may predict supermassive relics from the big bang, the decays of which might be responsible for generating cosmic rays with inexplicably ultrahigh energies.

An even more speculative possibility is that quantum gravity breaks the usual laws of quantum field theory by upsetting, for example, our conventional ideas of locality, causality and Lorentz invariance. In this case, the signatures of quantum gravity might be more distinctive. My colleagues and I have not been afraid to stick our necks out and make some speculative suggestions along this line, which may be unpopular with our "stringy" colleagues but have the merit that they can be tested experimentally. One suggestion is that the normal Schrödinger equation may need to be modified to reflect the loss of quantum coherence. This would consequently violate the most sacred theorem of quantum field theory—the physics of a particle interaction remains the same when its charge, spatial coordinates and time are reversed. Neutral kaon decays provide the most sensitive microscopic laboratory for testing quantum mechanics, so here is a possible opportunity for the DAΦNE kaon factory in Frascati, Italy.

Another speculative suggestion is that the velocity of light in the vacuum may not be an absolute quantity, but may depend on the photon energy, through a refractive index induced by quantum gravity. Distant astrophysical sources, such as gamma-ray bursts, pulsars and active galactic nuclei, may provide the most sensitive probes of this crazy idea, and have already been used to show that any such effect must be suppressed by at least one factor of the energy divided by 10^{16}. Future gamma-ray telescopes such as

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**4 Neutrinos weigh in**

Results from SuperKamiokande in Japan suggest that neutrinos produced in cosmic rays transform from one type into another as they travel through space, something that can happen if neutrinos have mass.
A simulation of the particle tracks produced when a Higgs boson is created in proton–proton collisions at the LHC.

Gamma Large Area Space Telescope (GLAST) may be able to test this speculation more thoroughly.

**Particle physics beyond 2010**

So far, so good, for the next decade, but what might be the questions still open after then, and how and when could we hope to address them? Here are just a few examples. I expect that even after the Higgs boson is discovered (figure 5), we will be clamouring to pin down its properties, to measure its decays and see whether it fits into a supersymmetric framework. We shall therefore need a Higgs “factory” to produce the Higgs boson in copious amounts, and to make more detailed studies of supersymmetry.

On the GUT front, even if neutrino oscillations are confirmed by long-baseline experiments, questions will remain, such as the overall scale of neutrino masses, lower-level oscillation effects, and the possible presence of CP violation in neutrino oscillations. We shall also want to push further the search for proton decay and supersymmetric relics, and will therefore need an underground detector that is even larger than the 50 000 tonne SuperKamiokande experiment. If the Auger observatory confirms the appearance of unexplained ultrahigh-energy cosmic rays, we shall want to explore this phenomenon further.

The next high-energy particle accelerator now being discussed actively is a linear electron–positron collider with an energy up to 1 TeV in the centre of mass. If approved early in the new millennium, it could come into operation a few years after the LHC. Such a linear collider would be complementary to the LHC, and could make many interesting Higgs and supersymmetry measurements, assuming these particles are light enough to be produced.

However, not all the Higgs questions might be answered, even by a linear collider. This has motivated some interest in a muon collider, which might be able to study the direct production of the Higgs boson and measure its line shape, much as LEP and the SLC did for the Z° boson. Going to higher energies would require another linear collider, or a muon collider, or a very large hadron collider. All these projects are technically very challenging, and much work is required to demonstrate the feasibility, in particular, of any muon collider.

A stepping stone on the route to a muon collider might be provided by a storage ring in which the muons are forced to collide, but simply allowed to circulate and decay into neutrinos that could then be used in future long-baseline neutrino experiments. The energy spectra, types and changes of neutrinos resulting from muon decays are known precisely. Such neutrino beams are so intense that one could even envisage a beam directed several thousand kilometres towards an experiment on the other side of the Earth. This may enable CP-violating effects to be seen in neutrino oscillations.

What might constitute a future generation of non-accelerator experiments? One suggestion is a water-filled Čerenkov detector that is an order of magnitude larger than the SuperKamiokande detector and sited, perhaps, in a natural cavern. Experimentalists are thinking of instrumenting a cubic kilometre of material underwater or in ice. In space, they are thinking of a satellite that can look down at ultrahigh-energy cosmic-ray collisions in the atmosphere, covering an area two orders of magnitude greater than the Auger project.

Another proposal is to have a proton-decay experiment on the Moon, where there is no atmospheric-neutrino background that could mask a true signal. Particle physicists have already accustomed themselves to using the most extreme environments on and below the Earth’s surface to perform their experiments. The next step would surely be to use the solar system as a laboratory. This has already been proposed for experiments such as the Laser Interferometer Space Antenna, a multi-satellite experiment to measure gravitational waves in the fabric of space–time caused by distant astrophysical cataclysms.

The globe and beyond

This brief survey shows that the past achievements of particle physics leave open a number of very definite and important questions. Several interesting projects capable of addressing these questions are either operational or under construction, and there are many intriguing suggestions for subsequent generations of experiments. The laws of physics are universal, and particle physicists learnt long ago to tackle them internationally. Current projects, such as the LHC, are already organized on a global basis, and this principle will be applied even more universally to future projects. Already the globe is used as a laboratory: next the universe?

**Further reading**

B Greene 1999 The Elegant Universe: Superstrings, Hidden Dimensions and the Quest for the Ultimate Theory (Jonathan Cape, London)
H Quinn and J Hewett 1999 CP and T Violations: new results leave open questions Physics World May pp37–42
For a general introduction to CERN and particle physics see http://www.cern.ch/Public
For the latest news of the search for the Higgs boson at LEP see http://www.cern.ch/LEPHIGGS

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