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## In search of the origin of mass

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Particle physics explores the structure of matter by studying the behaviour of its most fundamental constituents. Despite the remarkable success of our theories, there remains much that is fundamental but unexplained. One of our most pressing questions concerns the origin of mass. Our favoured theoretical explanation for the existence of mass also predicts the existence of a particle that has never been seen—the Higgs boson. In this review, we survey our knowledge of the Higgs boson and explain why, if the theory is correct, we should expect to make our first observation of the elusive Higgs in the next few years, when a major new particle physics facility starts operating. This will be the most powerful particle accelerator in the world. Although searching for the Higgs boson will be challenging in this environment, we hope that our experimental results will allow us to finally understand the origin of mass and extend our knowledge of the Universe yet further.

**Keywords:** particle physics; Large Hadron Collider; Higgs

### 1. Introduction

The aim of particle physics is to uncover and understand the structure of matter. We think all matter in the Universe consists of the same fundamental constituents: 12 types of matter particles that interact via four fundamental forces. In order to observe these particles and study their behaviour, we must create the conditions necessary for their existence, a process which employs particle accelerators. Intense beams of particles travelling close to the speed of light are smashed together. The energy released in a particle beam collision, if large enough, can recreate conditions last seen, fractions of a second after the Big Bang when fundamental matter particles moved freely about the Universe. The more energetic the collision, the further back in time we can observe, the greater insight we gain into the true nature of matter.

In this paper, we will describe particle physics at the limit of our knowledge, at the high-energy frontier. This is a tremendously exciting time for particle physics. In 2007, our horizons will be extended by the operation of a new particle accelerator, which will produce the most energetic particle beams ever made. We hope that some of the outstanding questions of particle physics can be addressed here and finally understood. Thus, it is timely now to reflect on what particle physics can tell us about the Universe, what we do not yet understand, and what insights we hope to make at this future facility.

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One contribution of 23 to a Triennial Issue ‘Mathematics and physics’.

After reviewing the particles we believe to be fundamental, we describe how we study their behaviour and why we use large particle accelerators to perform our experiments. Section 2 describes today's most powerful facility and the future facility which will extend our high-energy frontier in 2007. We discuss our present theoretical understanding of particle physics and its strengths and weaknesses in §3. Of particular concern is our understanding of the origin of mass. The Higgs boson predicted by our theories has never been directly observed in our experiments. We review in §4 why we have not yet seen the Higgs boson, and why we must extend our high-energy frontier to do so. Finally, in §5, we give prospects for Higgs observation, and what the implications for particle physics might be if we do not see the Higgs boson at all.

(a) *What is fundamental in the Universe?*

Matter, although it looks quite diverse around us, seems very simple at the microscopic scale. At the turn of the twentieth century, it was believed that all matter was formed of atoms of a few (some 120, as it turned out) different types. Experiments by J. J. Thomson, E. Rutherford and J. Chadwick proved that atoms themselves consisted of nuclei containing protons and neutrons which were orbited by clouds of electrons (a type of matter particle called a lepton). Different atoms could be characterized simply by the different numbers of these particles that they possessed. Following experiments conducted in the late 1960s by Taylor, Kendall and Friedman (Miller *et al.* 1972), we now know that protons and neutrons themselves are made of smaller particles in turn called 'up'- and 'down'-type quarks. We also know that other types of quarks and leptons exist, if we have sufficient energy available to make them.

Having unravelled matter, we must understand how to put it back together. The fundamental particles are held together by four fundamental forces: the electromagnetic force, which affects all charged particles; the weak force, which is responsible for radioactive beta decay; the strong force, which is experienced only by quarks and which keeps positively charged protons from breaking nuclei apart; and the gravitational force, which acts on anything massive but which is so much weaker than the other forces that we ignore it. Each force is associated to a characteristic set of force-carrying particles (W and Z bosons for the weak, photons for the electromagnetic and gluons for the strong force), and force is transmitted to a matter particle when the two interact together. Our present knowledge of the fundamental building blocks of the Universe is summarized in figure 1.

(b) *Why is elementary particle physics also high-energy physics?*

It may seem paradoxical that the study of the smallest objects in the Universe requires the highest energies. Why is elementary particle physics also high-energy physics? There are two reasons.

Einstein's equation  $E=mc^2$ , which relates energy ( $E$ ) and mass ( $m$ ), gives us the first insight. Some elementary particles have very large masses. Other, as yet undiscovered, particles, which may signify new physics processes at work, are expected to have larger masses still. The equation  $E=mc^2$  implies that to create such massive particles in the laboratory, we need to supply correspondingly large energies to the colliding particles.

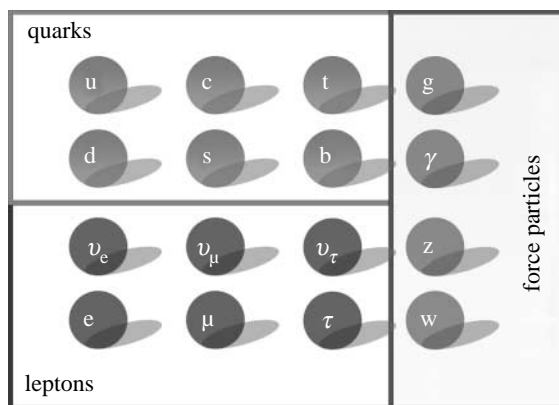


Figure 1. Fundamental particles that have been discovered to date. Quarks and leptons form matter, and are held together by the electromagnetic, weak and strong forces (which are mediated by the force-carrying particles). Note that gravity is not included in this figure.

Quantum mechanics gives us the second reason for going to ever-higher energies. Wave–particle duality, a fundamental tenet of quantum mechanics, dictates that all objects can display both particle properties (e.g. having a well-defined position) and wave properties (e.g. having a specific wavelength). At higher energies, the colliding particles have a smaller wavelength, which in turn enables finer structure to be resolved, in much the same way that electron microscopes allow smaller details to be discerned than simple optical microscopes. The limit of resolving power for colliders operating today is *ca*  $10^{-18}$  m, enabling us to confirm the basic point-like nature of electrons and quarks down to distance scales a thousand times smaller than the radius of a proton.

(c) *How do we accelerate particles to very high energies?*

In even the largest particle accelerator complexes, particle acceleration uses the same principle as an ordinary television cathode ray tube. As illustrated schematically in [figure 2](#), charged particles are accelerated when they pass through regions of high electric field strength. When a particle passes through an accelerating structure, the electric field is aligned such as to give the charged particles an additional ‘kick’ in their direction of motion. The highest accelerating gradient that can be achieved with these devices is roughly  $25 \text{ MeV m}^{-1}$  (1 eV is the energy gained by an electron when it passes through a potential difference of 1 V; 1 MeV (GeV, TeV) corresponds to a million ( $10^9$ ,  $10^{12}$ ) times this amount). This made it feasible to build a linear accelerator 2 miles long with energy of 50 GeV in the late 1980s, but it is clearly not feasible for reaching the TeV scale energy frontier, where we expect signs of new physics to lie.

Rather than build ever longer linear accelerators to reach high energies, physicists wrap linear accelerators around into circular ‘synchrotrons’. Particles can then be accelerated over many seconds or even minutes, with huge effective path lengths and correspondingly small accelerating gradients. Unfortunately, this process suffers from a couple of drawbacks: firstly, the particles must be bent into their circular trajectories by powerful magnets; secondly, owing to their circular orbits the particles lose a fraction of their energy through the emission of

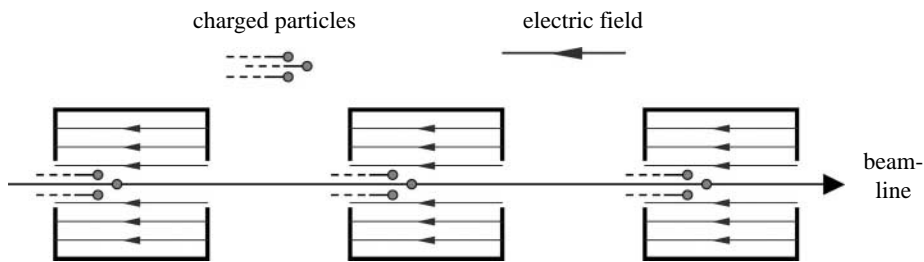


Figure 2. The accelerator schematic shows that charged particles travel through a series of accelerating chambers. Electric fields (either static or time-varying) give the particles a series of 'kicks' in their direction of motion.

Table 1. Synchrotron radiation losses for different particle types. (Note that a high-energy muon collider has yet to be realized.)

particle	mass	synchrotron energy losses (proton=1)
proton	938 MeV $c^{-2}$	1
electron	511 keV $c^{-2}$	$1 \times 10^{13}$
muon	106 MeV $c^{-2}$	6000

'synchrotron radiation', which grows with increasing particle energy and is larger for lighter particles. The energy lost by particles in emitting this radiation must be constantly replenished at various points around the accelerator. Table 1 shows the rate of this energy loss for different particle types. The overwhelming rate of energy loss for high-energy electrons means that it is only feasible to accelerate protons to reach the highest possible energies. An interesting proposal for the future is to accelerate beams of muons, the heavy partner of the electron, and to create a collider that combines many of the advantages of electron and proton colliders.

## 2. The high-energy frontier: today and in 2007

### (a) *The Tevatron proton-antiproton collider*

The Tevatron particle accelerator, located at the Fermi National Accelerator Laboratory some 40 miles outside Chicago, collides beams of protons and their antimatter partners, antiprotons, with a combined energy of 1.96 TeV. It is the highest energy collider in the world today, famous for the discovery of the top quark in 1994, and is where the best chance for new particle discovery presently lies. A panorama of the accelerator complex is shown in figure 3 and its basic operating parameters are listed in table 2. Using protons and antiprotons enables the same apparatus to carry counter-circulating beams of positively and negatively charged particles. However, the production of antiprotons is a complicated and costly process, which is the bottleneck limiting the overall number of collisions that can be delivered to the experiments located at the Tevatron.



Figure 3. Aerial view of the Fermilab accelerator complex. The initial proton acceleration and antiproton production takes place at the top left of the picture. Different accelerators in the near ring cool the antiprotons and ramp both proton and antiproton beams to 150 GeV prior to Tevatron insertion. The ring in the distance is the 6.28 km circumference Tevatron collider. The 980 GeV beams are brought together to collide at two points where experiments are sited (photograph courtesy of Fermilab VisualMedia Services).

Table 2. Parameters of the Tevatron collider, the world's highest energy particle accelerator and the Large Hadron Collider (LHC), presently under construction.

accelerator parameter	Tevatron	LHC
accelerator circumference	6.28 km	27 km
number of bending magnets	716	1232
bending magnet field strength	4.4 T	8.3 T
insertion beam energy	150 GeV	450 GeV
final beam energy	980 GeV	7 TeV
beam radius	30 $\mu\text{m}$	16 $\mu\text{m}$
protons/beam	$1000 \times 10^{10}$ (150 mA)	$10^{14}$ – $10^{15}$ (0.5 A)
antiprotons/beam	$100 \times 10^{10}$ (15 mA)	—
collision rate per detector	5 million per second	billion per second

Particle acceleration starts with  $\text{H}^-$  ions (which consist of a proton and two electrons), accelerated to energy of 400 MeV in a succession of electrostatic and linear accelerators. The electrons are then stripped off and the bare protons are boosted to energy of 8 GeV. One more intermediate synchrotron raises the proton energy to 150 GeV before injection into the Tevatron, where a final acceleration to reach 980 GeV is performed. However, the great majority of protons are diverted at 120 GeV and slammed into a metal target to form

antiprotons. The process is quite inefficient—*ca* 200 000 protons are required to create and successfully capture a single antiproton. Peak production of antiprotons at Fermilab, the world's largest antimatter factory, is at the rate of approximately 15 ng per year; miniscule amounts, but sufficient to furnish physicists with the yields they need to explore the high-energy frontier.

After a number of upgrades to the accelerator complex completed around the turn of the millennium, the Tevatron is now performing better than ever. The proton and antiproton beams collide at two points around the ring and an experiment straddles each crossing point to record any particles produced. Collisions are provided to the two experiments at unprecedented rates, at times providing data at a higher rate than can be handled. The amount of collision data collected is now more than 10 times greater than that used originally to discover the top quark, and this gives the experiments their first realistic chance of detecting the existence of rare new particle species.

### *(b) The Large Hadron Collider*

Towards the end of the decade, the baton of discovery will pass from the Tevatron to the Large Hadron Collider (LHC), a machine at the European Centre for Nuclear Research (CERN) situated near Geneva, Switzerland, that is presently under construction. The collision energy of 14 TeV will represent a sevenfold increase over that available at the Tevatron. Physicists believe that there is a very good chance that a whole array of new particles will be discovered at the LHC, which would revolutionize our understanding of elementary particle physics.

The LHC takes advantage of much existing infrastructure, in particular the 27 km circumference underground tunnel that previously housed the large electron positron collider (LEP). [Figure 4](#) shows a schematic view of the collider together with experiments presently under construction at four points around the ring. Two of these, ATLAS and CMS, are general-purpose detectors designed to search for as wide a variety of particle interactions as possible. The others, LHCb and ALICE, specialize in measurements of particles containing b quarks and heavy ion collisions, respectively.

Accelerator design parameters for the LHC are given in [table 2](#). At the LHC, unlike the Tevatron, two beams of protons will collide together; there is no need to use antiprotons at these energies since enough of the proton fragments are already comprised of antimatter—a great advantage as antiprotons are so resource intensive to produce. Consequently, the accelerator is arranged differently to the Tevatron; the LHC will use two separate high-vacuum rings to carry the counter-circulating proton beams, both embedded in the same cleverly designed dipole magnet enclosures. In fact, each of the thousand or so magnets around the ring is a complex and high-precision piece of equipment, the production and installation of which represent a large fraction of the 1.3 billion pound sterling overall cost of the LHC project.

The LHC construction is well underway. [Figure 5](#) shows the first magnet being installed in early 2005 and the first proton–proton collisions are expected to be delivered in 2007. While the commissioning of the largest scientific instrument ever built will not be easy, the turn-on of the LHC will represent the most significant milestone in the field for decades.



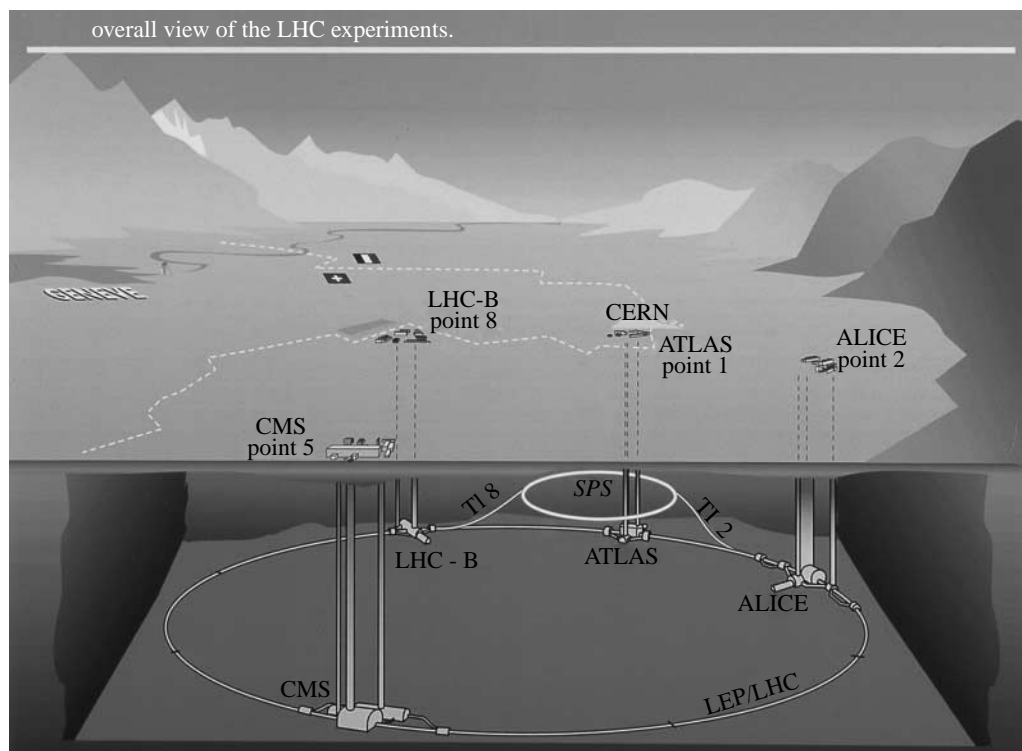


Figure 4. Schematic view of the Large Hadron Collider tunnel, 27 km in circumference and *ca* 100 m underground, which straddles the French–Swiss border close to Geneva. The positions of the four major experiments that will operate at the LHC (photograph copyright of CERN) are also indicated.



Figure 5. The first superconducting magnet for the LHC is carefully installed in the tunnel in March 2005 (photograph copyright of CERN).



### 3. The Standard Model of particle physics

The behaviour of all the fundamental particles is expressed mathematically in a theory known as the Standard Model (further details may be found in the references of [Glashow \(1961\)](#), [Weinberg \(1967\)](#), [Salam \(1968\)](#), [Glashow \*et al.\* \(1970\)](#), [Ellis \*et al.\* \(1996\)](#) and [Eidelmann \*et al.\* \(2004\)](#)). The Standard Model describes the interactions a particular particle will undergo, and how likely it is to do so. It allows us to predict the type of interactions that will occur inside our experiments at particle accelerators and the frequency with which they will occur. It even predicts properties for phenomena that are theoretically expected, but have not yet been observed. This theory is the bedrock underlying particle physics research today and is remarkably successful. Nobel prizes have been awarded to several of the theorists who developed it, notably [Glashow \*et al.\* in 1979](#), [t'Hooft and Veltmann in 1999](#) and [Gross \*et al.\* in 2004](#).

Despite this success, particle physicists have tried for years to find a crack in the Standard Model that would allow an underlying theory of matter to surface. The reason for this discontent is that although the Standard Model successfully describes so many phenomena, it does not explain their origin. There are 26 parameters in the Standard Model, which describe the strength of forces, particle masses, CP violation, and so on, whose values are not predicted. Each of these must be measured experimentally and then added to the theory. As the Standard Model does not predict values for these properties, we cannot use it to understand the mechanisms which give rise to them. For example, we do not know how and why particles possess particular values of mass, or why these masses span many orders of magnitude in scale.

We also know that the Standard Model only describes a very small fraction of the Universe. Results from the WMAP experiment ([Spergel \*et al.\* 2003](#)), among others, indicate that the fundamental particles we have identified make up only 4% of the observed energy density in the Universe. Of the rest, 23% is attributed to dark matter and 73% to dark energy. The Standard Model cannot explain dark energy or dark matter. Neither can it explain how a Universe, which was created as equal amounts of matter and antimatter in the Big Bang, can evolve into the matter-dominated Universe we see around us today. There is clearly more to the Universe than our theory describes.

#### (a) *The problem of mass and the elusive Higgs*

Particle masses cover a surprisingly large range. Neutrinos are almost massless, whereas the top quark is as massive as an atom of gold. Some force-carrying particles are massive (W and Z bosons) and others (gluons, photons) appear to be massless. The mass of certain mesons and baryons can be predicted very accurately by calculating the binding energy of their quark and gluon constituents, but there is no corresponding theory which predicts the mass of the fundamental particles themselves. Understanding the origin of mass is rather problematic.

The presently favoured theory to explain mass was first put forward in 1963 by Peter Higgs (see [Higgs 1964, 1966](#)), among others (see [Englert & Brout 1964](#); [Guralnik \*et al.\* 1964](#) for more details), and predicts the existence of a new

particle—the Higgs boson. The theory hypothesizes the existence of a field (the Higgs field) which permeates the entire Universe. The Higgs bosons themselves are excitations of the Higgs field, in the same sense that photons are excitations of an electromagnetic field, and couple to all matter in the Universe. Within the theory, the strength of coupling of a particle to a Higgs boson determines the mass conferred to the particle. The interaction of particles with the Higgs field is somewhat analogous to motion through a fluid. A body moving in water experiences less resistance than the one moving through treacle—its effective mass is greater in treacle than in water. Some particles behave as if they were moving in water and some as if they were moving in treacle when they move through the Higgs field. The degree of interaction they experience determines the mass conferred to them.

The Higgs also causes a process known as electroweak symmetry breaking to occur. When it couples to the carriers of the weak forces, it not only confers mass to them, but also causes the observable photon and Z bosons to become quantum mechanical mixtures of the original, massless weak and electromagnetic force carriers (photons remain massless in this process). Hence, besides explaining the origin of mass, the Higgs mechanism also suggests that two of the fundamental forces in nature are intimately related at a very deep level. This makes the theory very compelling—the only snag is that the Higgs boson has not yet been discovered in any experiment (see [Eidelmann \*et al.\* 2004](#) for a survey of experimental searches).

#### 4. What do we know about the Higgs?

Many experiments have looked for evidence of Higgs production without success. The most stringent direct bounds on Higgs production come from the ALEPH, DELPHI, L3 and OPAL experiments at LEP ([Rolandi 2003](#)) which ruled out the existence of the Higgs bosons with a mass less than  $114.4 \text{ GeV } c^{-2}$ , with a confidence level of 95%.

At the high-energy frontier, the two Tevatron experiments continue to search for evidence of Higgs production. If the Standard Model is correct, then proton–antiproton collisions at the Tevatron are energetic enough to produce the Higgs. In fact, if the theory and the current experimental constraints on the Higgs mass are correct, then between a few hundred and a thousand Higgs bosons should have already been produced inside each experiment. Detecting these particles is another matter altogether. We infer the presence of a Higgs by reconstructing its decay products, which can vary depending on the Higgs mass. The most commonly predicted outcome of Higgs decay (for the Higgs mass most consistent with our experimental measurements) is a pair of b quarks. Approximately, a million events containing b quarks produced by strong force interactions appear for every one Higgs; thus backgrounds overwhelm the signal. Detecting the Higgs is immensely challenging and neither experiment has discovered any significant evidence for Higgs production yet. The best contribution the Tevatron experiments have made to the Higgs search is indirect, by making a precise measurement of the top quark mass (which is sensitive to the Higgs mass), as we will see in §4a.

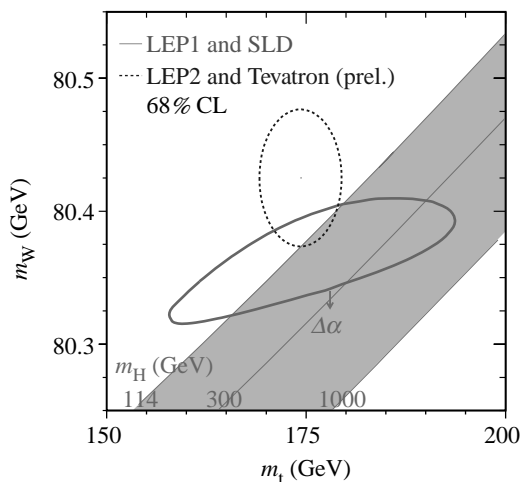


Figure 6. Experimental bounds on the mass of the W boson and top quark, shown by the blue and red circles. Possible values for the Higgs mass are shown by the green band; the most likely value for the Higgs mass occurs where the band and circles overlap each other.

(a) *Where is the Higgs?*

The Standard Model cannot predict the mass of the Higgs boson. However, it is possible to constrain the Higgs mass by experimentally measuring the W boson mass and top quark mass. Our current direct measurements of the W boson (from the LEP and Tevatron experiments) and top quark (from the Tevatron experiments) masses are shown in figure 6 as a blue circle, together with other indirect measurements made at LEP and SLD (a similar accelerator in California) which are shown as a red circle. Allowed Higgs masses are shown by the green band. The most likely value for the Higgs mass is found where this band overlaps the blue and red circles and is  $91^{+45}_{-32} \text{ GeV c}^{-2}$  (LEP Electroweak working group 2005). The Higgs mass must be less than  $195 \text{ GeV c}^{-2}$  if the Standard Model is valid, and we know it must also be greater than  $114.4 \text{ GeV c}^{-2}$ , otherwise we would have already observed it. In other words, the range of allowed Higgs masses is actually quite small.

The Standard Model can predict how often the Higgs bosons should be produced at particle accelerators and what they should decay to, in terms of the Higgs mass. Figure 7a shows the relative probabilities for Higgs to be produced singly or in conjunction with particles, such as W or Z bosons, at the LHC (Spira & Zerwas 1998). The Higgs bosons produced in the latter fashion (where backgrounds are thought to be smaller) occur 10 times less often than the former, for the masses the Higgs are believed to have. Figure 7b shows many ways in which a Higgs particle can decay. If the Higgs mass is lighter than *ca*  $140 \text{ GeV c}^{-2}$ , we would expect it to decay predominately to a pair of b quarks. If greater, the Higgs should decay most often to pairs of W bosons. Our W boson and top quark mass measurements suggest that the Higgs is most likely to decay to b quarks, because it is most likely to have a mass near our experimental limit.

With the benefit of hindsight, it is easy to see why we have not been able to observe the Higgs boson to date. Many previous accelerators were simply unable to reach the high energies needed to allow the Higgs boson to appear. Only the

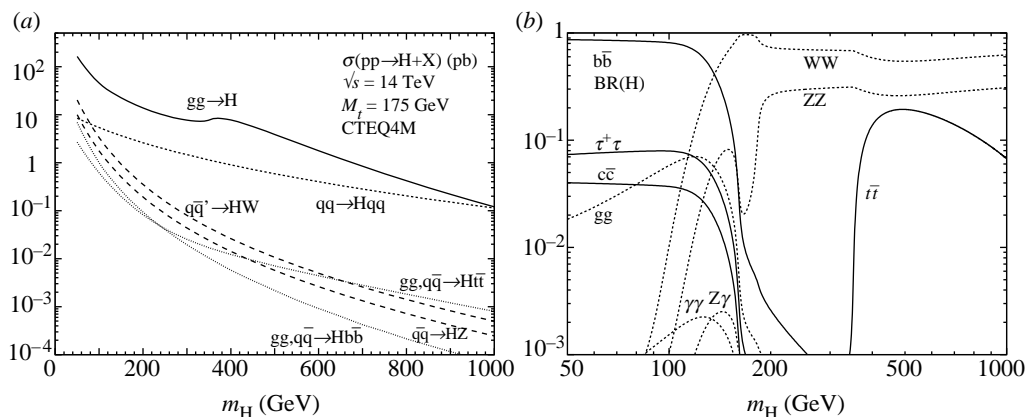


Figure 7. (a) Different modes of Higgs production, where the production cross-section is shown as a function of the Higgs mass; (b) favoured Higgs decay signatures, shown by probability and as a function of the Higgs mass. The calculations by Spira & Zerwas (1998) are relevant for the LHC accelerator.

Tevatron facility has sufficient energy to generate the Higgs bosons. However, detection here is hampered by the enormous backgrounds which mask the signs of Higgs decay. In order to reduce the effect of these backgrounds, it is necessary to look for the Higgs bosons produced in conjunction with easily identifiable W or Z bosons—and this just does not happen very often. Looking for the Higgs here means playing a very long waiting game, which so far has not yielded any results. Therefore, it is important to have a particle accelerator that is not only powerful, but also has a much higher rate of particle interactions, if we are going to find and understand the nature of the Higgs boson. It is for this reason that we need to push our frontier further out to the LHC to observe the Higgs, if it exists.

## 5. Finding the Higgs at the Large Hadron Collider

### (a) The Large Hadron Collider experiments

The four LHC experiments (ALICE 1995; ATLAS 1994; CMS 1994; LHCb 1998) are extremely large and technologically very complex. More than 6000 particle physicists from all over the world are members of one or other of these large experimental collaborations. The experiments represent the cutting edge of detector technology and their construction is proceeding apace. When completed, they will be the windows through which we can glimpse the high-energy frontier.

The principle of detector operation is simple. When protons from the separate beams collide together, a wealth of new particles is produced from interactions between the energetic proton constituents. These particles fly outwards, decaying and producing new particles in their wake. It is the job of the experimental detectors to record as much information about these particle trajectories and energies as possible. Silicon detectors surround the interaction point, which are capable of measuring the position of any charged particle passing through them to a 10th of a hair's thickness. Layers of gaseous wire chambers surround these, usually in a magnetic field so that a measurement of momentum can be obtained from the curved

particle trajectories. Calorimeters yield an estimate of particle energy. On the outer shell of the experiment, wire chambers detect any charged particle (usually only weakly interacting muons) that has survived passage through the calorimeters. We infer what happened in the initial proton collision by applying sophisticated pattern recognition strategies to detector signals and attempting to identify and reconstruct individual particles. Having made our interaction in the accelerator, we reconstruct it with the aid of the detector, and by comparing our results with hypotheses of Standard Model behaviour determine if anything unusual has happened.

The reality of detector operation will be harsh and challenging. An experiment such as ATLAS is tremendously complicated. Once constructed it will be the size of a cathedral and its constituent detectors will output some 100 million electronic channels of information that must be extracted, collated and analysed if an interaction is to be fully described. Inside the experiment, some 25 proton–proton collisions occur 40 million times each second during normal operation. Only a fraction of interactions can physically be recorded. As any of these interactions could potentially contain processes like Higgs production, they must be evaluated incredibly quickly to determine if they are of sufficient interest to retain. Event reduction is achieved in real time by a mixture of custom-made electronics in the detectors and software algorithms which run in dedicated computing farms connected to the experiment. These progressively select features of interactions which signal the presence of interesting physics processes and are designed to do so with high efficiency.

The enormity of the challenge facing us to find the Higgs, even with such sophisticated equipment, is striking. ATLAS can record the outcome of not more than 200 proton–proton collisions per second. Depending on its mass, the Standard Model predicts that a Higgs boson will be produced in proton–proton collisions inside ATLAS every 1–2 h. Our problem is not simply that we want to find a needle in a haystack, but it is that we want to find one needle in 20 million haystacks. Taking advantage of our window on the high-energy frontier demands that we are able to manipulate and filter a vast amount of data efficiently and with the minimum loss of interesting physics.

### *(b) The Grid*

It has been estimated that the total amount of information recorded at the LHC experiments each year will be a million times greater than that corresponding to the world annual book production. The [LHC Computing Grid \(LCG\) project \(2006\)](#) estimates that analysing this much data demands the exclusive use of one hundred thousand computers—a tall order for any physicist and yet, owing to its rarity, a necessity for finding the Higgs. To overcome this hurdle, physicists have developed a new distributed computing paradigm—the Grid.

The Grid is similar to the World Wide Web in concept. Anyone with a networked computer can access information distributed around the world, provided that they use a piece of software, called a web browser, to connect to it. The Grid shares not just information, but computing processors and data storage too. Computers with Grid software installed appear to the user to form part of a huge computing resource, regardless of geographical location, which achieves the goal of harnessing sufficient computing power.

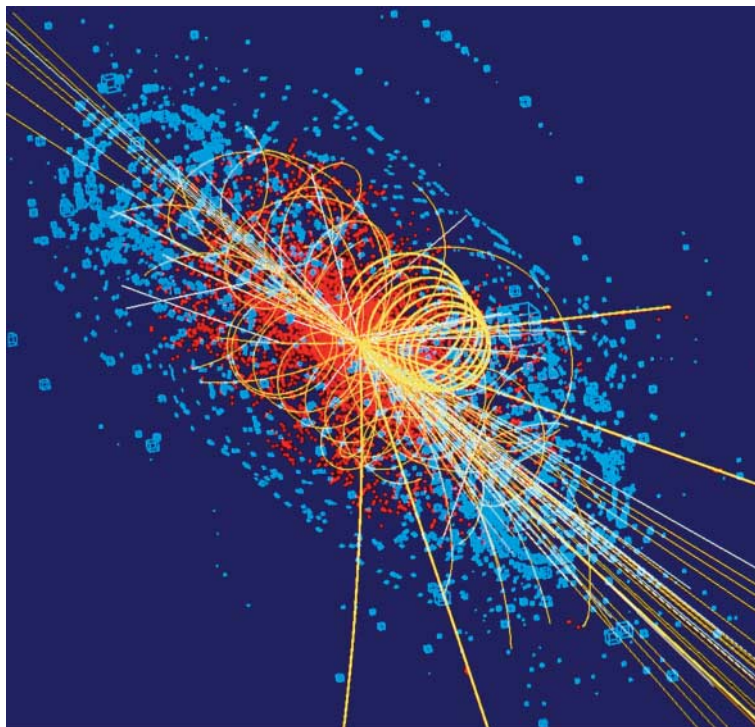


Figure 8. Simulation of Higgs decay to four isolated muons in the CMS experiment at the Large Hadron Collider at CERN. The lines denote particles produced from the collision of a pair of ultra-high-energy protons. Energy deposits of the particles in the detector are shown in blue (photograph copyright of CERN).

All countries involved in the LHC donate computing and data storage resources to the Grid. Experimental software is written to be Grid aware, and each experiment takes part in ‘data challenges’ each year where the Grid is used to simulate and reconstruct proton–proton collisions for a sustained period of time. These dry runs demonstrate that, so far, Grid construction and software development is proceeding to schedule and that we should be on course to meet our computing needs once the LHC starts.

(c) *Finding the Higgs at the Large Hadron Collider*

Owing to the immense challenge of finding the Higgs, much work has already gone into evaluating how best to observe it at LHC. Physicists have used simulations of experimental response, tied to Standard Model predictions of particle production, to study what a Higgs would look like inside an experiment and the best strategies to disentangle it from the many backgrounds. Figure 8 shows an example of a Higgs particle decaying inside the CMS experiment. In this case, the Higgs particle has decayed to four energetic muons (shown by the straight lines at large angles), which are hidden among the other particles rushing out from the proton–proton interaction in the centre of the detector. Identifying the Higgs within such a complex environment requires sophisticated pattern recognition techniques. The challenge is exacerbated by the high levels of background which look similar to



the Higgs inside the detector—particularly, as the expected ratio of Higgs to background events varies strongly with the Higgs mass. We need to isolate enough Higgs events to be sure that we have observed a signal.

Studies have been performed by [Asai \*et al.\* \(2004\)](#) for the ATLAS experiment and by [Abdullin \*et al.\* \(2003\)](#) for the CMS experiment, which examine many possible decay modes of the Higgs. Their results imply that after the first few years of LHC operation, sufficient data should be available to observe Higgs production over a wide range of masses, provided that the individual studies can be combined successfully.

Based on these studies, it looks like the elusive Higgs is at last within reach. However, it should be remembered that the studies are preliminary and rely on having an advanced understanding of detector response, backgrounds and optimized selection software. It is likely to take some time to make sure we understand each of these.

(d) *What if we do not find the Higgs?*

Section 5c demonstrated that, provided our experimental equipment works as expected, a Standard Model Higgs should be discovered at the LHC. But what if there is not a Standard Model Higgs? What if the Higgs field is more complicated than this, or simply just does not exist? It is worth considering what the implications of a Standard Model Higgs non-discovery would be.

The Higgs predictions we discussed previously are valid only if the Standard Model calculation is correct. It is possible to accommodate a more massive Higgs in the Standard Model if new and as yet undiscovered heavy quarks and leptons also exist. If this were true, we would not necessarily directly observe the Higgs or these heavy particles at the LHC. Without direct evidence for the Higgs, or having discovered new particles, it would be very difficult to establish that the Standard Model was still correct.

It is also possible that the Standard Model is not correct, and that a new theory of matter which underlies and extends it could become apparent at the LHC. One example of such a theory is Supersymmetry (see [Eidelmann \*et al.\* 2004](#) for a review). Supersymmetry partners each matter- and force-carrying particle in [figure 1](#) with a new supersymmetric particle partner and would result in a flurry of particle discoveries at the LHC. It is an attractive theory for among this superworld of new particles is a candidate for the composition of dark matter. Supersymmetry predicts not one but five Higgs bosons whose masses, rate of production and favoured decay modes may be quite different to those of the Standard Model Higgs. In this case, data taken at the LHC, even if it does not contain the Higgs we expect, will have extended our understanding of particle physics in a dramatic way.

## 6. Conclusions

Particle physics explores the structure of matter by studying the behaviour of its most fundamental constituents. Despite the remarkable success of our theories, explanations for many fundamental properties of matter are lacking. Of particular concern is the origin of particle mass, whose theoretical explanation predicts the existence of the Higgs boson. Although we have never observed the Higgs boson, experiments at the Tevatron, our current high-energy frontier,



provide us with valuable information about where we might find it in the future. If our theories are correct, we expect to finally observe the Higgs boson at the LHC, which takes over the mantle of the most powerful particle accelerator in the world when it starts operating in 2007. It is also possible that our theories of particle physics could be incomplete, in which case a variant of the Higgs boson, modified by an alternative description of matter, could be discovered. Whatever the outcome, data taken at the LHC would have provided us with the means to extend our knowledge of the Universe further than ever before.

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