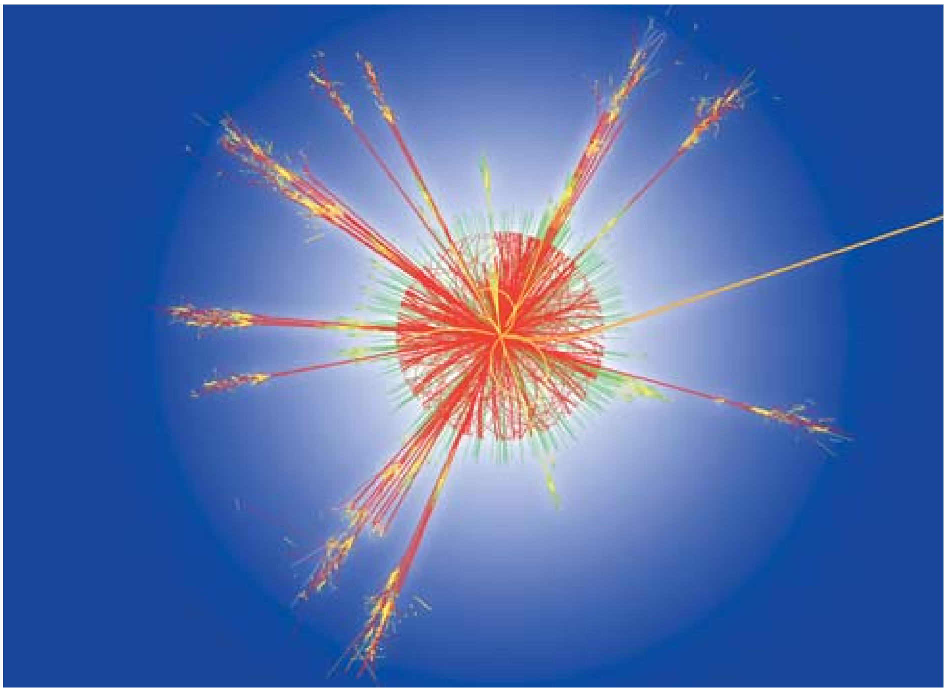
The **electroweak interaction** from one **accelerator** to the next:
The **LHC** roadmap and the yardstick of **LEP** measurements

Preparations for the experiments, crucial for the future of particle physics, that are to begin in 2007 at LHC will be greatly indebted to the precision of the measurements carried out at the facility's forebear, LEP. Far from being an end in itself, such precision was indispensable if the quantum electroweak theory was to be validated. A look back at findings – some of which were only finalized over the past few months – that will long remain authoritative.



Simulation of a proton–proton collision in the beam axis of the Large Hadron Collider. The colors of the trajectories correspond to the various types of particles generated in the event. Initial collisions at LHC are scheduled for November 2007.

At the end of 2000, LEP (Large Electron–Positron), the great electron–positron collider at CERN, the European particle physics laboratory, delivered its final collisions. This marked the conclusion of a decade-long experimental program that proved outstandingly fruitful, the key result being the validation of the quantum electroweak theory (see Box B, *Fundamental interactions and elementary particles*).

The electroweak interaction on the LEP testbench

LEP ranked, in the 1990s, as CERN's largest particle accelerator. Sited in a near-circular underground tunnel, 27 km in circumference, this accelerator made it possible to set up high-energy frontal collisions between electrons and positrons, the electrons' antiparticles. The end-products yielded by the collisions were recorded by four detectors. LEP went through two stages: from 1989 to 1995 (LEP 1), collision energy stood at 91 GeV, this subsequently, from 1995 to 2000 (LEP 2), being raised gradually from 130 GeV to 209 GeV.

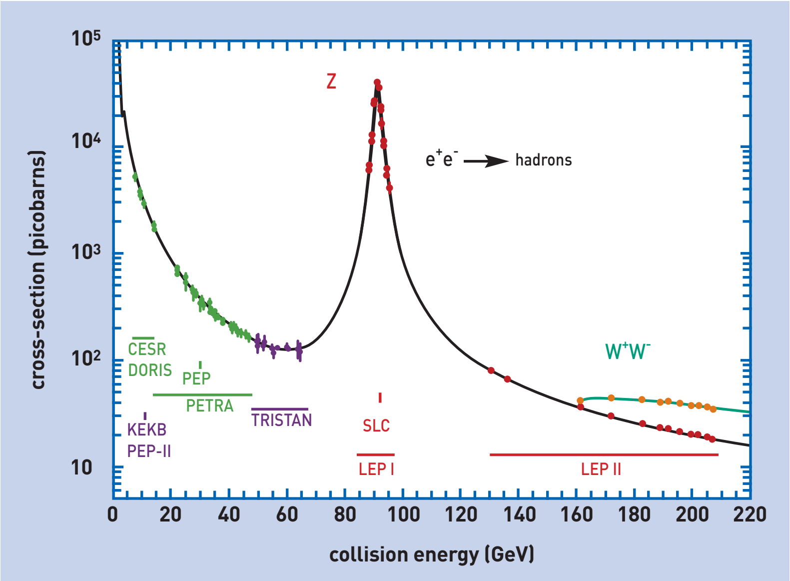
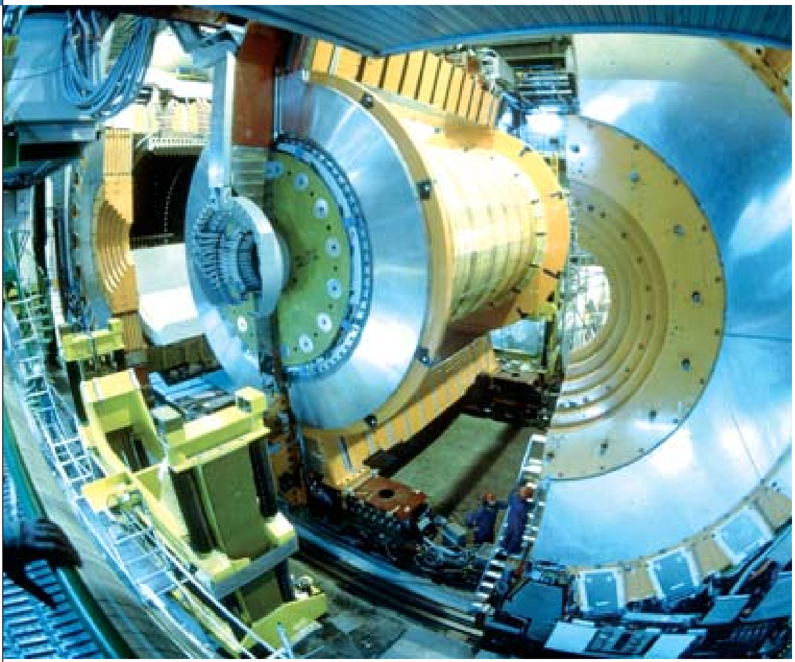


Figure 1.
Electron–positron collision cross-section as a function of collision energy for processes yielding hadrons, or a W pair. The points mark experimental measurements, including LEP measurements at the higher energies. The curves correspond to theoretical predictions, vertical segments to measurements at a definite energy (e.g. 91.2 GeV at SLC), the horizontal segments to measurements over a broader range of energies (e.g. at 88.2–94.2 GeV at LEP 1).

The experimental environment at LEP may be seen from Figure 1, showing collision cross-section (related to interaction probability) as a function of collision energy. At high energies, contrary to what happens in the classical case, collision processes most commonly result in final states that are different from the initial state. Two of the possible final states are shown in the figure, with the first one corresponding to production of hadrons. The cross-section exhibits a characteristic resonance-curve shape, with the maxi-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"Exploded" view of the OPAL detector at LEP, as it was being assembled in 1989. The core is flanked by the two half hulls that will enclose it. The technicians provide a scale check.

mum showing up at LEP 1 energies. Such a shape is a telltale indicator of the collision process, taking place as it does by way of annihilation of the initial electron–positron pair to form a **Z boson**, a characteristic particle for the **weak interaction**, having a mass close to 91 GeV. After an extremely short interval ($2.6 \cdot 10^{-25}$ seconds), the Z decays, and it is the **decay** products that are reconstructed in the apparatus, in this instance hadrons, materializing a **quark**–antiquark pair. Translating cross-section into number of collisions, this process will have yielded 17 million final states from Z decay, recorded by the four LEP 1 detectors.

The second cross-section curve starts off at LEP 2 energies, rising, then plateauing. This corresponds to production of a **W^+–W^- boson** pair, these, just as the Z, being particles that are characteristic of the weak interaction, with masses close to 80 GeV. 50,000 W^+–W^- pairs were recorded by the four LEP 2 detectors. The numbers of collisions collected at LEP are large, owing to the multiplicity of final states that have to be investigated, and the measurement precision being sought, entailing that measurements be repeated a large number of times.

Figure 1 further shows the theoretical predictions from the **standard model of particle physics**. Arrived at in the 1960s, on the basis of all of the experimental evidence accumulated by that time, this model is a true theory, with strong predictive content. Its ingredients include, first of all, the **elementary** – i.e., not liable to be split further – constituents of matter (see Box B, ***Fundamental interactions and elementary particles***). The correct description of experimental findings calls for twelve constituents, all of them **fermions**, subsumed into three families. Each family holds one charged **lepton**, one light **neutrino**, and two **quarks**. The first family allows the atoms of normal matter to be reconstructed, and an understanding to be gained of the decay modes of **radioactive nuclei**. The constituents in the two remaining families are heavier. The standard model does not predict the precise values for some of the characteristics of these constituents, such as electric charge or mass, for which values must be determined experimentally. The same holds of possible further families, not adumbrated by the model.

The second ingredient in the standard model is the description of the three fundamental interactions that prevail at the microscopic level: **electromagnetism**, and the **strong** and **weak interactions**. By positing invariance properties for these interactions, subject to certain transformation laws, the standard model arrives at a description in terms of interactions propagated by way of bosons, of **spin** 1: the **photon** (γ), for the electromagnetic interaction; the W^+, W^- and Z for the weak interaction; and eight **gluons** for the strong interaction. Figure 2 illustrates this description, with a collision process at LEP.

Taking a look back at the Universe's past

The standard model, however, goes further. It assumes the electromagnetic and weak interactions are not distinguishable at high energies, in other words in the past state of the Universe. At a given point in the evolution of the latter, this electroweak symmetry was broken, yielding the two individual interactions, exhibiting distinct properties at low energies, i.e. at the energies accessible to experiment. Such **symmetry breaking** is responsible for generating the mass exhibited by particles, whether constituents of matter or mediators of interactions. Thus, the photon remains with zero mass, accounting for the infinite range of the electromagnetic interaction. The W and Z bosons are endowed with mass, which agrees with the finite range of the weak interaction. Contrary to what is the case for particles of matter, the standard model does predict the values of these masses, to wit 91 GeV for the Z, and 80 GeV for the two W bosons. By way of comparison, the mass of a proton is equivalent to an energy of 1 GeV. These values, along with the actual existence of the Z and W bosons, were experimentally corroborated, in signal fashion, at CERN in the early 1980s.

Such corroboration, however, was but a first step. Indeed, discovery of the Z and W bosons stands as the equivalent, for the electroweak interaction, of the discovery of radio waves, for the electromagnetic interaction: there still remained to find evidence of fine-structure quantum effects, equivalent to those uncovered in the late 1950s for electromagnetism (the Lamb shift in the energy levels of the hydrogen atom, and the anomalous magnetic moment of the electron, both due to the quantization of electromagnetic radia-

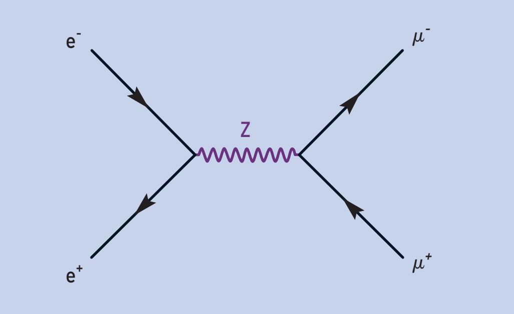


Figure 2.
Annihilation of an electron–positron pair yielding a muon–antimuon pair, via the most likely quantum-theoretical path (as given in lowest-order perturbation theory): the intermediate state is a Z.

tion). LEP was the major instrument that allowed that step to be made, thanks to the precise, and numerous, measurements carried out on the Z and W. In this, it was supported by two colliders located in the United States, Tevatron and SLC.

Finally, LEP also addressed the issue of the precise mechanism of electroweak symmetry breaking, which may be effected in many ways. The avenue singled out by the standard model comes down to linking particle masses to their coupling with a scalar boson, the so-called **Higgs boson**. This solution, which may be said to be minimal inasmuch as it adds but one particle to the already known set, allows the properties of that boson to be predicted, except for its mass, this being very weakly constrained by the theory, which yields, as possible interval, a window covering the 0–1,000 GeV range, or thereabouts! Exploring the entire window calls for very large-scale experimental resources, the first of which was provided by LEP.

The precision achieved for the measurements is one of the reasons for the advances LEP enabled. Measurement of the Z resonance curve (see Figure 3) is a good case in point. The findings were compared with the predictions yielded for three hypotheses as to the number of light neutrino species (i.e., neutrinos exhibiting a mass lower than half the Z mass), namely 2, 3, or 4. Each light neutrino species opens up a decay channel for the Z, thus altering its lifetime, and, consequently, the width and height of the resonance curve, this accounting for the notable differences between the three curves. The experiment's precision unambiguously allows the 2- and 4-light-neutrino hypotheses to be rejected. There are thus just three families of elementary constituents, each containing one light neutrino, strongly coupled with the Z. From this curve the value of the Z's mass may also be derived, to wit 91.187 5 ± 0.002 1 GeV. Such precision, reaching $2 \cdot 10^{-5}$, as compared to 1% prior to LEP, means the Z mass may rank as one of the fundamental constants of elementary particle physics.

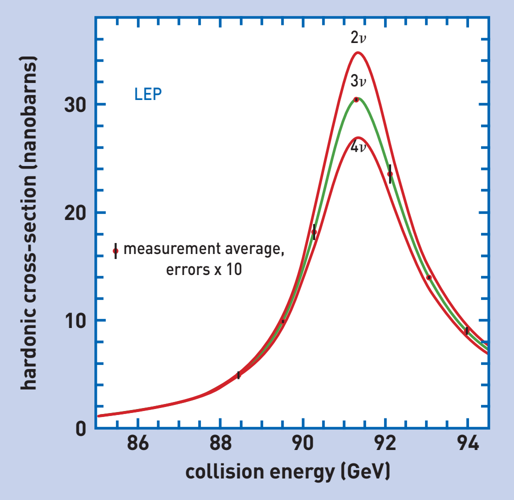


Figure 3.
Resonance curve for Z in the hadronic mode, as measured at LEP 1, compared with three theoretical predictions, corresponding to a number of light neutrino species equal to 2, 3, or 4.

Maximilien Brice/CERN

Transverse view of CMS (Compact Muon Solenoid), one of the four main experiments at LHC.
In December 2005, CMS first recorded cosmic rays in a complete sector, comprising the four muon measurement stations.

A measurement… involving no direct measurement

Measurement precision, far from being an end in itself, was indispensable if measurement was to be carried out of extremely small quantum effects, so-called *quantum corrections*. Figure 4 shows the first order of corrections to the process shown in Figure 2. Whereas the top quark has a mass that is too high for a Z to decay into a detectable top–antitop pair, quantum corrections do allow materialization, for a very short interval, of virtual top–antitop pairs (Figure 4: left), in the sense of pairs the constituents of which exhibit the same quantum numbers as a top, but much lower mass, thus complying with momentum and energy conser-

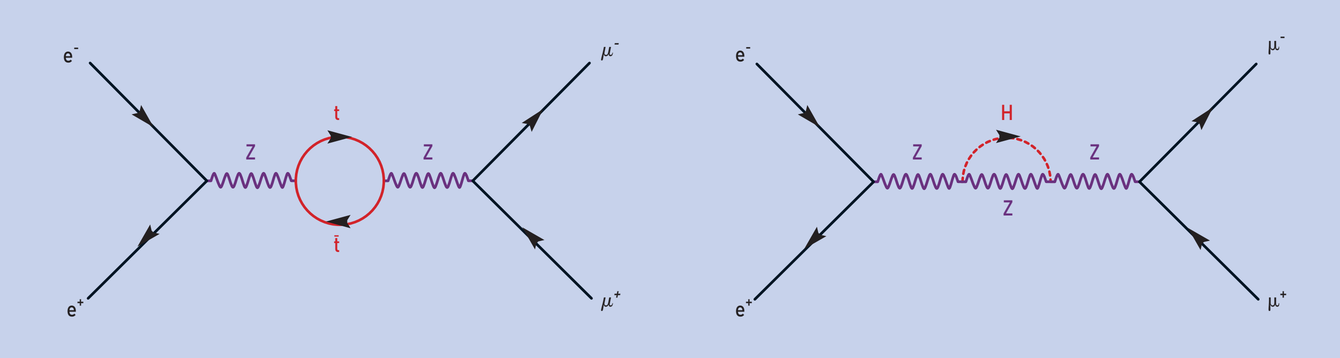
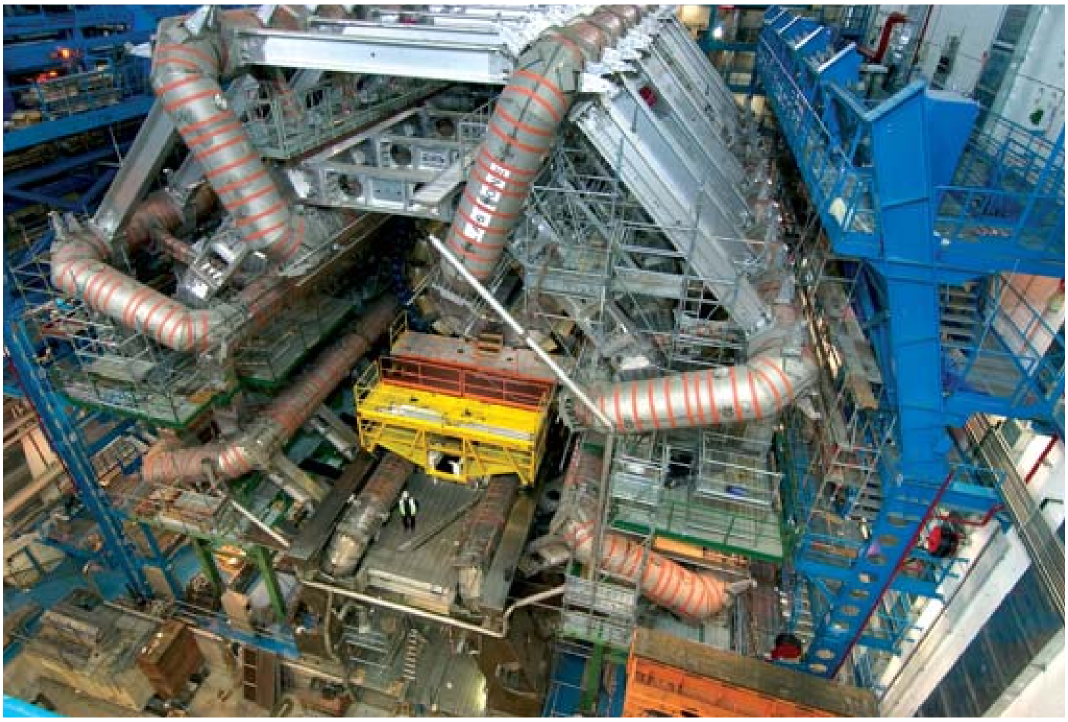


Figure 4.
Annihilation of an electron–positron pair yielding a muon–antimuon pair, via less likely quantum-theoretical paths (as given in first-order perturbation theory): at left, a Z materializes over a very short interval into a virtual top–antitop pair; right, a Z releases then reabsorbs a virtual Higgs boson.



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General view of the ATLAS (A Toroidal LHC ApparatuS) detector, with its eight toroidal magnets in place, in November 2005. After detecting its first cosmic rays *in situ*, in its hadronic calorimeter, ATLAS initiated operation of two of its tracking systems, in June 2006, to record such rays.

vation. However, the astonishing fact is that these corrections do depend on the actual mass of the top quark, M_{top}. Likewise, quantum corrections allow the materialization of a virtual Higgs boson, H, during the propagation of the Z intermediate boson (Figure 4: right). Their value, however, depends on the actual mass of the Higgs boson, M_H. The whole point of a precise measurement of quantum corrections is that this makes it possible to set experimental constraints for the key parameters of the standard model, such as the masses of the top quark and Higgs boson, *without measuring them directly*.

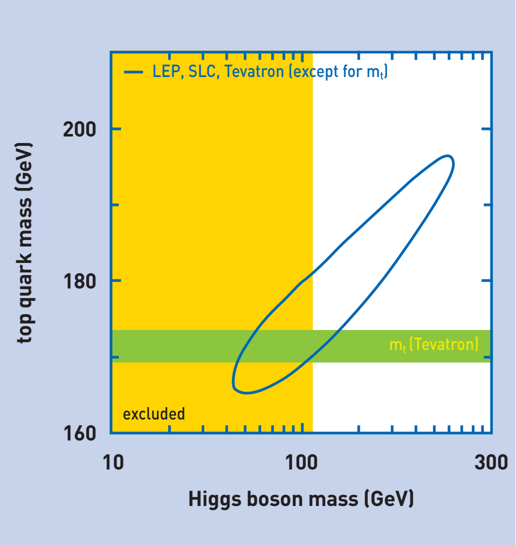

Figure 5.
Comparison of experimental measurements with theoretical predictions, given as a function of the masses of the Higgs boson (M_H) and of the top quark (M_{top}). In the (M_H, M_{top}) plane, the outline yielded by the precision measurements (excluding the direct measurement of M_{top}), taking into account experimental uncertainties (ellipse), is compared with the direct measurement of M_{top} (horizontal band). The two regions overlap for values of M_H lying between 50 GeV and 200 GeV or so. The vertical band indicates the region excluded in direct searches for the Higgs boson.

Advancing the quest for the "Higgs"

In concrete terms, this involves comparing, for one and the same set of observables, experimental measurements with the theoretical predictions arrived at as functions of M_{top} and M_H, to derive the most probable values for these parameters, namely those resulting in the best agreement between the data and predictions. Experimental precision will be directly reflected in the uncertainty attaching to such derived results. Thus, by combining all of the precision measurements, except for the direct measurement of M_{top} effected at Tevatron, the top's mass could be predicted as standing at 177.6 GeV, to within some 10 GeV or so, showing excellent agreement with the direct measurement of M_{top}, 171.4 ± 2.1 GeV, achieved at Tevatron, the only facility having the energy required to produce top quarks in the final states from collisions.

Figure 5 sets out this comparison. The agreement between theory and experiment validates the standard model, right down to its description of the finer quantum effects for the electroweak interaction. Just as for M_{top}, precision measurements make it possible to set constraints on the mass of the Higgs boson. This adjustment, however, is less precise than that for Mtop, since the quantum corrections only depend on the logarithm of M_H. For that reason, the finding is converted into an upper limit to be set for the Higgs boson mass, $M_H < 166$ GeV. This is a definite advance over the theoretical constraint – the only one available prior to LEP – $M_H < 1{,}000$ GeV.

LEP, however, did tell us more about the Higgs boson.

Indeed, the energy at the facility was sufficient to have achieved direct production of a light Higgs boson, typically with a mass up to 120 GeV. Such a particle would have yielded easily identifiable final states, among the millions of final states recorded. Searching for such states in the accumulated data, the LEP experiments could show no sign of a Higgs boson, up to a mass of 114.4 GeV (see Figure 5). Here again, this means a notable advance, considering the experimental constraint, prior to LEP, stood at $M_H > 100$ MeV.

However, in the final data, LEP did detect a handful of final states compatible with direct production of a Higgs boson having a mass greater than 114 GeV. One if these is shown in Figure 6. The combined findings from four experiments thus showed up a number of final states compatible with the hypothesis of a mass signal standing at 115–118 GeV. Research workers evaluated at 15% the compatibility of any one of these states with the hypothesis of a 115-GeV Higgs boson, and at 9% their compatibility with the hypothesis of background fluctuation in the standard processes. LEP's answer, as to the existence of a Higgs boson, thus remains ambiguous, and may only be refined with the help of experiments carried out with the hadron colliders that are taking over from LEP, namely the Tevatron, and subsequently the LHC (Large Hadron Collider), due to come on stream in 2007 at CERN.

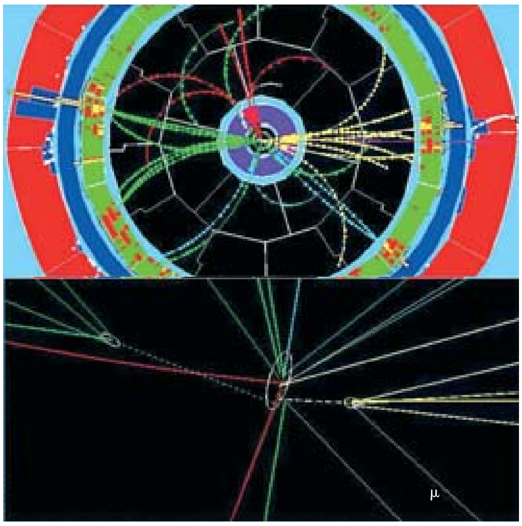

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Figure 6.
Graphical reconstruction of a collision final state compatible with the production of an H–Z pair. At top, transverse section showing four particle jets; bottom, close-up view of the interaction region, showing the emission of two neutral particles, which decayed some way away from the collision point, as expected for particles forming from *b* quark jets. This final state thus includes two jets emanating from b quarks, and two other jets, this being the most likely configuration for the production of an H–Z pair.

Understanding the precise mechanism of symmetry breaking

Thanks to LEP, significant advances have been achieved, as regards our understanding of the microscopic world. The quantum theory of electroweak interaction is now validated once and for all: the weak and electromagnetic interactions are propagated by vector bosons, they were unified in the distant past of the Universe, and their symmetry, breaking as the latter cooled down, set off the generation of masses for all particles! The precise mechanism of such breaking does still remain to be understood: a 115-GeV Higgs boson, possibly seen at LEP, or some other mechanism, involving more massive particles? It now behoves to LEP's successors to provide the answer…

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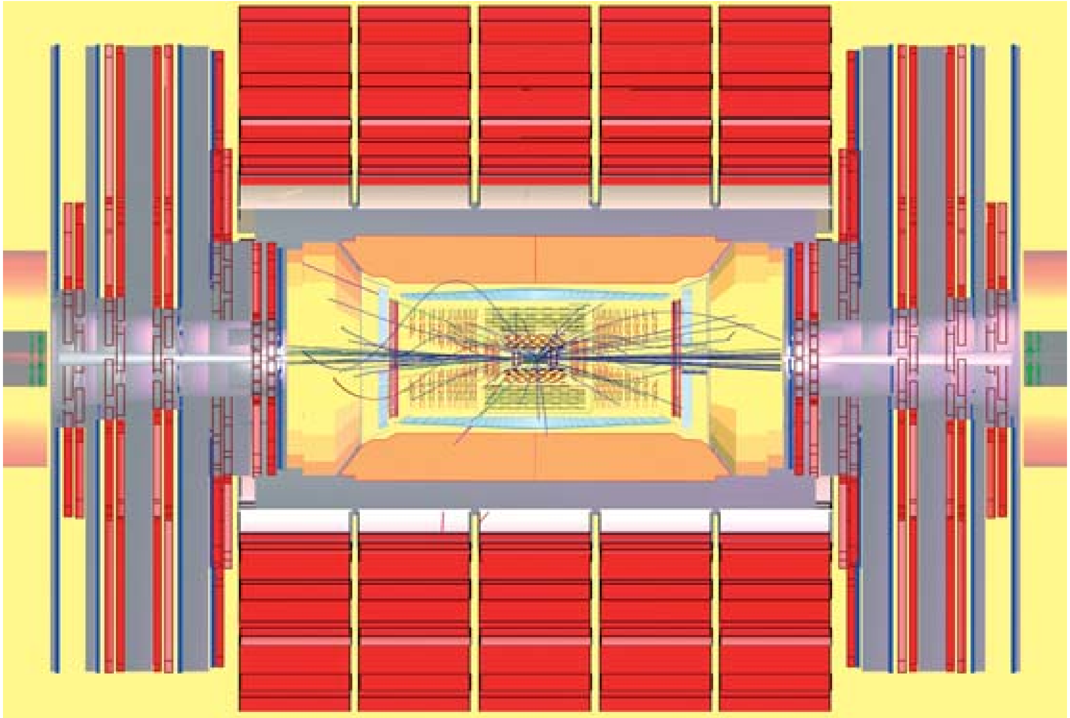

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Simulation of a detection showing the "signature" of the presence of the Higgs boson in the CMS experiment.

B Fundamental interactions and elementary particles

The **standard model** of particle physics is the reference theoretical framework describing all known **elementary particles** (see Table 1) and the fundamental **interactions** these particles are involved in (see Table 2). The basic constituents of matter, known as **fermions**, are partitioned into two main categories, as determined by their participation in the fundamental interactions, or forces (the **gravitational**, **electromagnetic**, **weak**, and **strong** forces), which are mediated by **vector bosons**, the fundamental particles which carry out the transmission of the forces of nature[1] (see Table 2). Whether a particle belongs to the category of fermions, or to that of bosons depends on its **spin** (i.e. its intrinsic angular moment, or internal rotation moment), depending on whether it exhibits half-integer spin (fermions) or integer spin (**bosons**).

At the same time, to every constituent of matter is associated its **antiparticle**, a particle having the same *mass*, but the opposite *charge*. The **positron** is thus the positively charged antiparticle of the **electron**, which exhibits a negative charge.

Leptons and quarks

Fermions include, on the one hand, **leptons**, which may travel freely and do not participate in the *strong interaction*, which ensures the cohesion of atomic **nuclei** (it is consequently termed a *nuclear* interaction), and, on the other hand, **quarks**, which participate in all interactions but are not individually observed, enmeshed and confined as they are within **hadrons**, the particles susceptible to strong interaction, of which they are the constituents.[2]

In the lepton category, **charged leptons** participate in the *electromagnetic interaction* (which ensures the cohesion of **atoms** and **molecules**, and in the *weak interaction* (which underlies **decay** processes, in particular **β radioactivity**). Neutral leptons, or neutrinos, for their part, participate in the weak interaction only. Exhibiting very low mass, there is one type of neutrino for each type of charged lepton.

Independently from their involvement in interactions, the basic constituents of matter are classified into three *generations*, or *families*, of particles. From one family to the next, quarks and leptons having the same charges only differ by their mass, each family being heavier than the preceding one.

The **electron**, up quark (symbolized *u*) and down quark (symbol *d*), which belong to the first generation, are the lightest massive particles, and are stable. These are the sole constituents of **normal matter**, so-called **baryonic** matter (a baryon is an assembly of quarks), which is made up of **protons** and **neutrons**, this however only accounting for 4% of the Universe's energy content!

Particles in the other two families are heavier, and are unstable, except for neutrinos, which on the other hand exhibit non-zero mass, but are stable.

These latter particles may only be observed or detected in the final states resulting from collisions effected in **accelerators**, or in **cosmic radiation**, and rapidly decay into stable first-generation particles. This is why all the stable matter in the Universe is made up from constituents from the first family.

According to **quantum mechanics**, for an interaction to take place between particles of normal matter, at least one elementary particle, a boson, must be emitted, absorbed, or exchanged. The **photon** is the **intermediate** (or **vector**) boson for the electromagnetic interaction, the **W^+**, **W^-** and **Z** are the intermediate bosons for the weak interaction, and **gluons** are those of the strong interaction, acting at quark level.

As to the **graviton**, the putative vector for the gravitational interaction, it has not so far been empirically discovered. The **gravitational force**, which acts on all fermions in proportion to their mass, is not included in the standard model, due in particular to the fact that quantum field theory, when applied to gravitation, does not yield a viable scheme, as it stands. While gravitational effects are negligible in particle physics measurements, they become predominant on astronomical scales.

Interaction ranges

Quarks and charged leptons exchange photons. The photon having no electric charge, these particles conserve their electric charge after the exchange. Since the photon's mass is zero, the electromagnetic interaction has an infinite range. Having no electric charge, neutrinos are the only elementary fermions that are not subject to electromagnetic interaction.

In the electroweak theory (a unification of the weak and electromagnetic interactions), the weak interaction has two aspects: **charged-current weak interaction**, for which the interaction vectors are the W^+ and W^-; and **neutral-current weak interaction**, for which the mediator is Z^0. These two forms of weak interaction are active between all elementary fermions (quarks, charged leptons and neutrinos). The mass of these bosons being very large (about 80 GeV/c^2 for $W^\pm$, 91 GeV/c^2 for Z^0), the range of the weak interaction is tiny – of the order of 10^{-18} m. Since $W^\pm$ bosons have a non-zero electric charge, fermions exchanging such bosons undergo a change in electric charge, as of nature (*flavor*). Conversely, since the Z^0 boson has no electric charge, fermions exchanging one undergo no change in nature. In effect, neutral-current weak interaction is somewhat akin to exchanging a photon. As a general rule, if two fermions are able to exchange a photon, they can also exchange a Z^0. On the other hand, a neutrino has the ability to exchange a Z^0 with another particle, though not a photon.

Only those quarks that have a color charge[1] exchange gluons, these in turn being bearers of a color charge. Thus,

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(1) The participation of basic constituents in fundamental interactions is governed by their *interaction charges* (electric charge, color charge), or "conserved quantum numbers." *Color charge*, a quantum number that determines participation in strong interactions, may take one of three values: "red," "green," or "blue" (these colors bearing no relation to visible colors). Every quark bears one of these color charges, every antiquark one of the three anticolor charges. Gluons are endowed with double color–anticolor charges (eight combinations being possible).

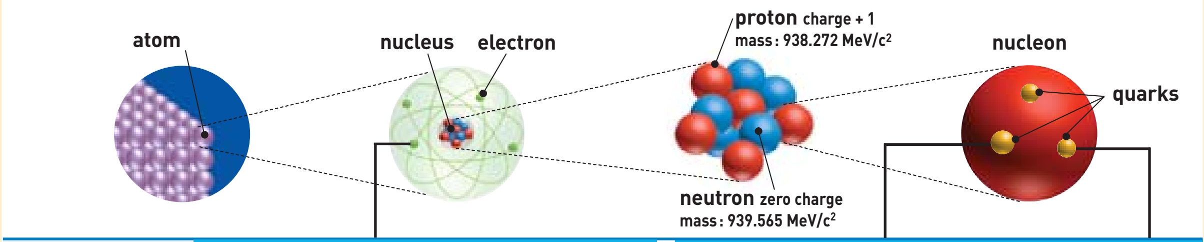
(2) To take e.g. **nucleons**: the proton holds two up quarks and one down quark, the neutron two down quarks and one up quark. A **meson** is made up of just two quarks (one quark and one antiquark).

B (cont'd)

when a gluon exchange takes place between quarks, the latter exchange their respective colors. Gluons have zero mass, however, since they do bear a color charge, they are able to interact together, which greatly complicates theoretical treatment of this interaction. The range of the strong interaction is consequently very restricted – of the order of 10^{-15} m.

The quest for unification

The theoretical framework for the standard model is quantum field theory, which allows a quantitative description to be made of the fundamental interac-



		leptons able to move freely		**quarks** assembled into triplets, or quark–antiquark pairs, to form the many subatomic particles	
Fermions Normal matter is made up of particles from this group.	First family	**electron** (e) responsible for electricity and chemical reactions charge:- 1 mass : 0.511 MeV/c^2	**electron neutrino** (ν_e) has no electric charge, and interacts very seldom with the ambient medium.	**down** (*d*) electric charge: - 1/3 the proton holds one, the neutron two mass : 4 – 8 MeV/c^2	**up** (*u*) electric charge: + 2/3 the proton holds two, the neutron one mass : 1.5 – 4 MeV/c^2
Most of these particles were around just after the Big Bang. Presently only to be found in cosmic rays, and around accelerators.	Second family	**muon** (μ) a more massive companion to the electron. mass : 105.658 MeV/c^2	**muon neutrino** (ν_μ) properties similar to those of the electron neutrino.	**strange** (*s*) a heavier companion to "up" mass : 80 – 130 MeV/c^2	**charmé** (*c*) a heavier companion to "down" mass : 1.15 – 1.35 GeV/c^2
	Third family	**tau particle** (τ) heavier still. masse : 1,776.99 ± 0.29 MeV/c^2	**tau neutrino** (ν_τ) properties similar to those of the electron neutrino.	**beauty** (*b*) tau particle. mass : 4.1 – 4.4 GeV/c^2	**top** (*t*) heaviest in the family (observed in 1995) mass : 171.4 ± 2.1 GeV/c^2
Vector bosons Fundamental particles carrying out transmission of natural forces.		**photon** elementary grain of light, vector for the electromagnetic force	**gluon** bearer of the strong force between quarks	**W$^{\pm}$, Z^0** bearers of the weak force, responsible for some forms of radioactive decay	
Higgs boson?		responsible for "electroweak symmetry breaking"			

Tableau 1.
Table showing the twelve elementary constituents for which the standard model describes the interactions involved. The three charged leptons (electron e-, muon, μ^-, tau particle τ^-) are subject to electromagnetic and weak interactions, neutrinos (ν_e, ν_μ, ν_τ) are only affected by weak interaction, and the six quarks (up, charm, top – or *u*, *c*, *t* – bearing a charge of 2/3; and down, strange, bottom – *d*, *s*, *b* – bearing a charge of – 1/3) are subject to all three interactions. Every elementary constituent has its antiparticle, having the same mass, and algebraic quantum numbers (such as electric charge) of the opposite sign.

B (cont'd)

tions between elementary particles, while respecting the principles of *special relativity*, as those of quantum mechanics. According to the latter theory, if one seeks to observe a microscopic structure at high temporal and spatial resolution, this entails transferring to it an amount of energy–momentum, the greater, the higher the resolution being sought. However, according to the theory of relativity, such an energy–momentum transfer is liable to undergo transformation, yielding particles not present in the initial state: fermions may be generated, or annihilated, in particle–antiparticle pairs, while bosons may be so in any arbitrary number.

All processes involving one and the same fundamental interaction are interrelated. The quantum field theory approach, in which properties of **symmetry** play a fundamental part, seeks to describe all of the processes relating to each fundamental interaction, within overarching theoretical constructions.

The strong and electromagnetic interactions are formalized, respectively, in the theories of **quantum chromodynamics**, and **quantum electrodynamics**. The weak interaction, for its part, is not subject to a separate description, being described jointly with the electromagnetic interaction, in the unified formalism of **electroweak theory**. Theories of the *grand unification* of all fundamental interactions do exist, however they remain as yet lacking any experimental validation.

All the predictions of the standard model have been corroborated by experiment, except for just one, to wit, the existence of the **Higgs boson(s)**, which particle (particles?), it is hoped, will be discovered with LHC. The **Higgs mechanism** is thought to be responsible for the mass exhibited by elementary particles, the eponymous boson making it possible for zero-mass fermions interacting with it to be endowed with mass. This would allow the unification, at high energies, of the weak and electromagnetic interactions within the electroweak theory, while effectively accounting for the **breaking** of this **electroweak symmetry** at low energies, taking the form of two interactions, which may be seen as distinct at that energy level (see *The electroweak interaction from one accelerator to the next: the LHC roadmap and the yardstick of LEP measurements*, p. 23).

Going beyond, or completing the standard model?

The standard model features a set of parameters (such as the masses of elementary particles, or the intensities of fundamental forces) which are "anchored" in experimental findings. It is, in any event, a theory that is liable to be improved, or further elaborated, or even surpassed and left behind. It does not account in any way for the classification of the constituents of matter into three generations of particles, whereas it is precisely the existence of these three generations which makes it possible to account for **CP** (charge–parity) **invariance violation** (meaning that a physical process involving the weak interaction is not equivalent to its own mirror image), a violation that is in all likelihood the source of the matter–**antimatter** imbalance, running in favor of the former, in the primordial Universe. The model neither allows quantum treatment of gravitation, nor does it fully account for the fundamental property of *confinement*, which prevents quarks from propagating freely outside hadrons.

To go beyond, or to complete the standard model, research workers are mainly exploring two avenues:

– **supersymmetry** (widely known as SUSY) would associate, to every particle (whether a boson or a fermion) in the standard model, a partner from the other series, respectively a fermion or a boson. Supersymmetric partners would, at first blush, be highly massive, the lightest of them being a particle interacting very weakly only. This would be an ideal candidate to account for the **hidden matter** (or **dark matter**) in the Universe, accounting as it does for some 21% of the Universe's energy content, the remainder (close to 75%) consisting in a **dark energy**, the nature of which likewise remains to be determined. These WIMPs (acronym for "weakly interacting massive particles") are actively being sought (see *EDELWEISS II, the quest for dark matter particles*);

– the **substructure** path assumes there could be a new level of elementarity, underlying the particles in the standard model (or some of them). This would lead to a veritable blossoming of new, composite particles, analogous to hadrons, but exhibiting masses two to three thousand times heavier.

It should be noted that, whereas supersymmetry theories yield predictions that agree with the precision measurements carried out at LEP, the theories propounding substructures (or their simpler variants, at any rate) fail to do so. As for the more complex variants, these are encountering difficulties at the theoretical level.

fundamental interaction	associated particles (messengers)	actions
gravitation	graviton?	having an infinite range responsible for the mutual attraction of any two masses and for the law of falling bodies
electromagnetic interaction	photon	having an infinite range responsible for the attraction between electrons and atomic nuclei, hence for the cohesion of atoms and molecules
weak interaction	W^+, W^-, Z^0	responsible for β^- and β^+ radioactivity, reactions involving particles as neutrinos
strong interaction	gluons (there are 8 gluons)	ensures the cohesion of the atomic nucleus

Tableau 2.
Fundamental interactions, their vectors, and effects.