The LEP 200 programme at CERN is under way: electrons and positrons are colliding at a centre-of-mass energy which, having gradually increased every year, will this year approach 200 GeV, hence the name LEP 200

Daniel Treille, CERN

LEP in the year 2000

LEP came into operation in 1989 and has been run for seven years as a Z^0 factory; in 1995 a second phase started at higher energies. The goal of 'LEP 2000', as it is called, is simply to extend the running of LEP 200 into the year 2000. Exploiting LEP one more year may look like a step of secondary importance, ensuring simply a better exploitation of the programme. Actually, because of the increase of energy and luminosity, one still expects (*see box* 1) that this last year will represent the culmination of LEP physics potential and lead to a substantial increase in size of its window of discovery. This extra year devoted to LEP does not harm the planning of the LHC collider—which will later replace LEP in the same tunnel—and it will allow the registration of about 200 events per picobarn (200 pb^{-1}) at, or close to, the maximum energy. It will also reduce the unfortunate gap in physics output between the two machines.

Overview of LEP 1 results

In the first phase of LEP the four experiments registered a total number of ~ 20 million Z^0, the neutral vehicle of the weak interaction, under optimal experimental conditions. This led to a breakthrough in the quantitative tests of the Standard Model (SM), *see box* 2.

The Z^0 mass which finally, after an epic and most exciting experimental fight, has been measured to two parts in 10^5, has acquired a prestigious status by becoming one of the three basic inputs of the SM. This has been obtained through a clever exploitation of the transverse polarization of the particles in LEP and a close collaboration between the machine and the experiments.

The Z^0 resonance line shape has been determined with an extreme accuracy to: one in a thousand of its width, 1.5 in a thousand of its 'height', namely the production cross-section of the Z^0. An important quantity, derived from the line shape parameters, is the number of light neutrino species: $N_\nu = 2.994 \pm 0.011$.

Drawing the legitimate conclusion that there are three, one can deduce the amount of helium expected in primordial nucleo-synthesis: one expects ~ 24%, in fair agreement with astrophysical data.

The universality of the electroweak couplings of the three lepton species has been demonstrated at the 2.5 in a thousand level. The muon and tau thus appear more and more to be mere replications of the electron.

The flavour content of the Z^0 has been carefully measured: in particular the fraction of beauty-antibeauty in the hadronic final state, R_b—a potential carrier of information on phenomena beyond the SM—has been obtained with an accuracy of 4 in a thousand, less than one sigma away from its SM expectation.

From all LEP electroweak measurements, and adding the specific contribution of the SLAC collider in California (SLC), US, a value of $\sin^2 \theta_w = 0.23156 \pm 0.00019$ has been obtained for the electroweak mixing angle (*see box* 2). This result is 25 times more accurate than what was known before the LEP era, and it definitely excludes some theories, like the simplest grand-unified model, SU(5).

A fit to these results, in the frame of the SM, leads to the indirect measurement of the top quark mass through its contribution as a virtual particle in certain quantum fluctuations ("loop" diagrams) since LEP energy is too low to pair-produce it directly: $M_t = 160^{+13}_{-10}$ GeV.

Such a result, indicative of a heavy top quark, was available at LEP well before the direct observation of the top quark at the Fermilab Tevatron Collider (*see further reading:* TOP-ology). The present Tevatron direct mass measurement is: $M_t^{direct} = 173.8 \pm 5.0$ GeV.

Using this precise value as an input, one can focus on the next and last unknown of the SM, the Higgs boson (*see box* 3). Unfortunately, the effects of this particle as a virtual state give access only to the logarithm of its mass. Within the framework of the SM one finds:

$$\log_{10} (M_H \,[\mathrm{GeV}]) = 1.88^{+0.33}_{-0.41} \pm 0.05$$

in other numbers $M_H \leq 260$ GeV at 95% confidence level. (We will return to this upper bound later in the article.)

The set of LEP/SLC accurate electroweak measurements can also challenge expectations of models beyond the SM. Composite models, such as Technicolour which postulates the existence of new forces and new layers of constituents, are not, in their present versions, in agreement with experimental results. On the other hand supersymmetric models (*see box* 4), in which the effects of virtual new particles in loops are naturally well shielded, pass the exam as satisfactorily as the SM.

Another important set of results from LEP 1 improved our knowledge of the tau lepton and of heavy flavours of quarks: charm and especially beauty. The LEP 1 harvest has indeed provided huge samples of these particles in all kinds of species and in optimal experimental conditions. In particular they are produced in LEP with a strong Lorentz boost and the time dilation effect helps in determining their finite lifetimes, which are of the order of a picosecond. A key asset of these studies has been the impressive progress made in the field of microvertexing thanks to the development of elaborate microstrip silicon detectors, providing a spatial accuracy of ~ 10 micrometres. This is also now vital for searches during LEP 200.

All LEP 1 results have been obtained with accuracies better, sometimes much better, than foreseen in the prospective studies made earlier.

Intermediate results of LEP 200

Collisions at higher energies in LEP still provide clear and clean events. However, the rates of interesting SM events has dropped by around three orders of magnitude, compared to those at the Z^0 resonance. And, at energies not far above this resonance a new class of events appear which, in a first approximation, are simply parasitic ones. By radiating one or more photons in the initial state, the colliding $e^\pm$ may 'return' to a reduced effective centre-of-mass energy equal to the Z^0 mass. This occurs with a small probability, but because of the huge cross-section at the resonance the rate of such 'radiative return' events actually dominates all other annihilation ones.

Photon radiation is mostly collinear to the $e^\pm$ and, in the plane normal to the beam direction, does not carry transverse momentum. There is, however, some probability that it does so. In principle the emitted photons would then be visible in the detector and it is crucial to detect them with maximum efficiency, in order not to fake missing transverse momentum events besides the unavoidable SM ones; one must therefore ensure the hermeticity of the detector.

As shown in *figure* 1 the most abundant new SM process, besides radiative return to the Z^0 and normal fermion pair production, is the production of pairs of $W^{\pm}$, the charged vehicle of the weak interaction. The first W pair was observed when LEP reached 161 GeV centre-of-mass energy in 1996. Since then the four LEP experiments have collected ~ 15 000 such pairs. The physical interest in this process is considerable. It represents a clean and relatively abundant source of W bosons and allows accurately measuring the W mass. It also allows performing an accurate check of a still poorly known aspect of the SM: the triple boson couplings. This opportunity stems from the fact that among the processes leading to W pair production one finds virtual Z^0 and photon exchange in which such triple boson couplings intervene.

The Tevatron Collider at Fermilab also has the potential to perform these measurements and the two machines are thus in competition.

For the M_W measurement the LEP energy does not matter a great deal once it is far enough above the threshold of the reaction. What counts is the total number of events registered, since statistics will be the ultimate limitation. For gauge coupling measurements the number of events, as well as the quantity of information one can exploit in each of them, are important, but there is also a rapid growth of sensitivity with energy: typically a gain of a factor two for an increase of 20 GeV centre-of-mass energy.

Presently, the LEP 2 accuracy on M_W is ± 90 MeV, quite similar to the one from hadron colliders. At LEP it should steadily improve with luminosity and, for the total foreseen, reach ~ 30 to 50 MeV depending on our ability to master the most tricky systematic uncertainties. These appear in the all-hadronic decay mode of the W pairs, which is also the most abundant one. These uncertainties concern the possible interconnection of the decay products of the two Ws and, besides their possible impact on M_W, such effects are quite interesting *per se*.

As for the triple boson couplings, LEP should ultimately set bounds on possible departures from the SM at the few per cent level. Is this sensitivity sufficient to reveal new physics effects, which are not yet excluded by the very accurate LEP 1 results? This has been the subject of hot discussion, with the conclusion that it is still possible.

The Tevatron, presently stopped for major improvements, will resume its data-taking in 2000 with an increased luminosity. As far as one can predict it should achieve in both sectors a performance quite comparable to LEP, but involving a very different set of systematic errors.

Whatever the interest is of these new electroweak measurements (*see box 1*), it is nonetheless clear that for LEP 200 the strong emphasis put on the last few GeV of its energy range finds its real justification when one considers the search potential of this machine for the Higgs sector, and to a lesser extent, for the particles predicted by supersymmetry.

The Higgs boson at LEP 200

To get a fair idea of the relevance of LEP 200 (and of its limitations) for Higgs boson search, one must consider some basic facts of Higgs phenomenology.

An important experimental result is, as we saw, the indication from electroweak measurements that within the SM frame the Higgs boson should be light. As mentioned in *box* 2, undetected particles can nonetheless intervene as virtual states to modify the expectations of electroweak observables. The best example is the top quark, whose effect, until recently, was masking any possible one from the Higgs boson. To follow an amusing image by G. Altarelli, it was as if a bush hunter by putting his ear to the ground wanted to hear the footsteps of a tiger (the Higgs boson) while an elephant (the top quark) was rampaging around. No way! But now that the top mass has been accurately measured at Fermilab

Box 1 Radiofrequency Cavities

In a circular electron machine like LEP the main problems and limitations come from synchrotron radiation. Electrons, because they are light, "do not like bends." They react to a transverse acceleration by emitting synchrotron radiation. While this radiation can be very useful—it is just so at the European Synchrotron Radiation Facility in Grenoble—at LEP it is a nuisance, corresponding to a loss of energy that has to be given back to the particles. This loss is proportional to the fourth power of the beam energy. This dramatic increase with energy explains the severity of the problem for LEP 200 in which particles lose as much as 2.5% of their energy per turn, and explains why LEP will be the last high-energy circular *electron-positron* collider.

The way to give back the lost energy to the particles is to use, along their trajectory, radiofrequency (RF) cavities, in which a longitudinal oscillating electric field is present. Particles arriving with the correct phase are accelerated, the others are lost. RF cavities are fed by a klystron. They are characterized by the value of the accelerating field, E_{acc}, and by their quality factor, Q.

For LEP 1 it was possible to use conventional warm copper cavities working at a frequency of 350 MHz, and providing an accelerating field of typically 1 MV per meter. For LEP 200 these are insufficient, and we had to build a large set of superconducting cavities, working at the same frequency but with a much higher accelerating field, of the order of 6 to 7 MV per meter, and an excellent quality factor (proportional to the inverse of the surface resistance of the superconducting medium) of ~ 3×10^9.

The conception and development of these cavities—made of a copper core covered with a thin (~ 1 micron) layer of sputtered niobium—and their construction in European industry have been, for the last ten years, a most challenging enterprise, finally crowned with success. In 1999 the complete set of 288 such cavities will be operating at LEP. It has been partially demonstrated that the bulk of these, for which the design value of the accelerating field was 6 MV/m, can probably be run at values approaching 7 MV/m. Actually, given the number of cavities available, a mean value of 6.8 MV/m is what one needs to run LEP at 100 GeV per beam, keeping a reasonable safety margin. Hence the hope to exploit, sometime this year, a genuine LEP 200 machine. The required cooling power will be available, and later will be largely re-used for the superconducting magnets of the LHC.

Besides the RF system the success of LEP 200 rests on a clever choice of the optics of the machine, maximizing the luminosity, and on a good mastering of the backgrounds (synchrotron photons, which can reach one MeV, and lost particles) that it can generate for experiments. The last years, in particular 1998, have been extremely encouraging in these respects: last year LEP delivered to each of the experiments, under generally excellent conditions, ~ 200 pb^{-1} (events per picobarn), more than foreseen in the most optimistic scenarios, with a record of up to 3 pb^{-1} in 24 hours.

Box 2 The Standard Model

The Standard Model (SM) incorporates the electromagnetic and weak interactions in a single theoretical frame: in a lesser sense the strong interaction is also incorporated. The SM gives a classification of the basic constituents of matter, as well as a unified description of their interactions.

The basic constituents are fermions (spin 1/2)—the leptons, which are freely propagating particles, and the quarks, which are "confined" objects, always bound to other quarks or antiquarks. A quark is not directly detectable, but it may manifest itself as a jet of ordinary particles, like pions kaons... Leptons and quarks are grouped in families. Three such families are known. Measurements performed on the Z^o resonance show that there are three families and not more which contain a light neutrino. There is no explanation, for the time being, for this replication of families. The first one, with the electron, its neutrino and the up and down quarks, is sufficient to build the present universe, including ourselves. But the constituents of the other families are produced in high energy collisions in accelerators. And presumably this occurred also in the primitive universe.

With respect to the weak force, there exists a basic asymmetry between fermions of left and right handedness. The left-handed ones appear as doublets, the right-handed ones as singlets (it is the opposite for antifermions). Singlets and doublets can be considered as mathematical objects in an internal "spin" space called the weak isospin space.

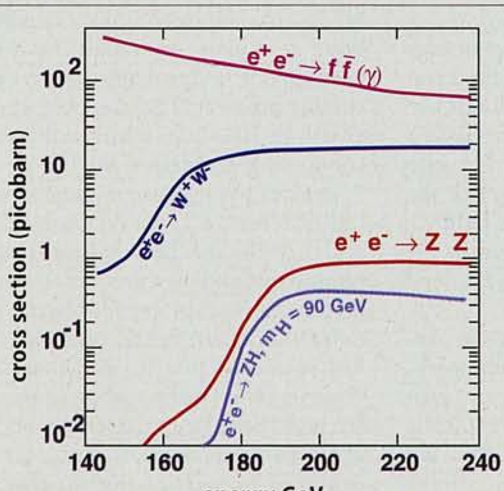
All fundamental forces are transmitted by the exchange of a vector boson (spin 1)—the photon for the electromagnetic interaction, the Z^o and $W^{\pm}$ for the weak interaction; the gluon (which, like the quark, is never found free) for the strong interaction. Each type of boson is coupled to a charge carried by the constituents—the photon to the electric charge, the Z^o and $W^{\pm}$ to the weak charge, the gluon to a charge called "colour" that, among the fermions, only the quarks possess. While the photon does not itself carry the electric charge, the weak bosons and the gluon carry the weak and the colour charge, respectively. The weak bosons can therefore interact among themselves and this new property is directly studied in LEP 200. The self-interaction of the gluons leads to the surprising and fundamental phenomenon of confinement.

In the SM, all electroweak observables can be calculated from a basic tree level diagram (excluding radiative corrections) using three basic parameters. These are the gauge couplings g and g' of the $SU(2)_L$ and $U(1)$ groups, and the vacuum expectation value v of the Higgs field (*see box* 3). Actually one replaces them by three well measured quantities. For these, given the accuracy with which they are known, one chooses the electromagnetic constant α, the weak constant G_μ and, since LEP 1 results are available, the Z^o mass, M_{Z^o}. The least well known is α, needed here at the scale M_Z, and much effort, experimental and theoretical, is under way to improve the situation.

An important but derived quantity in the SM is the weak mixing angle θ_ω. It is the angle of the rotation which relates the two neutral orthogonal states of the electroweak theory to the neutral physical states, the photon and the Z^o. This angle, or rather $\sin^2\theta_w$, appears in the expression of most observables of the SM and can be extracted from their measurement. Checking the SM means checking that all values of $\sin^2\theta_w$, extracted from the various observables, are compatible within errors. The uncertainty on $\sin^2\theta_w$ can be considered as a measure of the quality or sensitivity of the observable.

A major contribution of LEP/SLC was the accurate measurement of the couplings of the electromagnetic, weak and strong interactions at the 100 GeV energy scale. We recall that these are "running" quantities, whose values depend on the resolution power, *ie* the energy scale considered. Within a given model, namely for a given population of the virtual particles entering loops and responsible for the running, evolution with energy is predicted. In the SM the three couplings, evolved from their accurate LEP values, converge together, but fail to unify by many standard deviations. supersymmetry, on the other hand, provides such a triple unification.

The SM does not provide quantities like the masses of the fermions, which may originate from the Higgs mechanism (*see box* 3), but must nevertheless be counted as free parameters of the model. Overall the SM has 19 such parameters.



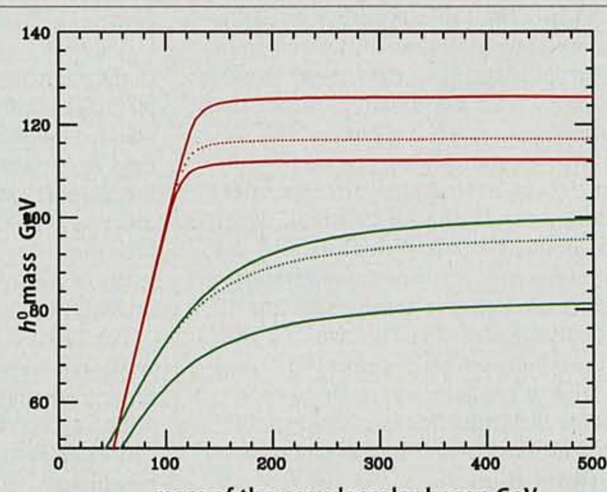


Fig 1 The cross sections of the four main processes of particle transformation of LEP 200 • Fig 2 The h^0 mass in minimal supersymmetry against M_A, the mass of the pseudoscalar boson; the lower curves refer to small $tg\beta$, the higher ones to large $tg\beta$. In each family the three curves refer to different versions of the stop (the superpartner of the top quark *see box 4*) sector. The values are given for a top mass of 175 GeV. The highest possible mass is thus ~ 125 GeV

(the elephant has become still) one can attempt to locate the Higgs boson. The result, within the SM frame, is as we saw that this boson must be lighter than ~ 260 GeV at the 95% confidence level. The more accurate the Fermilab M_t measurement will be—and the better one will control the next limiting factor, the uncertainty on $\alpha(M_z)$, *see box* 2—the sharper will be this upper bound on the SM Higgs mass.

Let us now turn to theoretical considerations. In the SM the Higgs mass is not predicted. This reflects our ignorance of the magnitude of the Higgs self-coupling (*see box* 3). However, reasonable additional constraints allow us to reduce the possible domain. If one requires that the Higgs sector should stay perturbative up to a high energy scale—a condition which is mandatory if one wants to deal with a computable theory—one can set an upper limit on the boson mass as a function of that scale. By requiring that the Higgs potential should stay bounded from below, a quite legitimate condition indeed, if the vacuum is to remain stable, one can set a lower limit on the mass of the boson, depending on the same scale, and also very strongly on the top mass. If one defines the SM as a theory which should stay valid up to a very high energy scale—this is in a sense a tautological statement since the SM *stricto sensu* does not contain any new ingredient, neither force nor constituent, until the Planck scale—the Higgs boson should then be found in the 130-180 GeV mass range. This will certainly be a privileged region for the LHC, but it is out of reach for LEP 200.

On the other hand the scenario offered by supersymmetry is radically different. We will not describe here the motivations which lead particle physics to go beyond the SM: they are mainly considerations of internal coherence of the model and, as stated in *box* 4, the desire to eliminate offending divergences, starting with the one of the Higgs boson mass in the presence of physics at a very high mass scale, like the Planck scale. The hint that neutrinos could have a non-zero mass, as recently reported, would be another strong incentive since nothing exists in the SM which could be at the origin of such a situation.

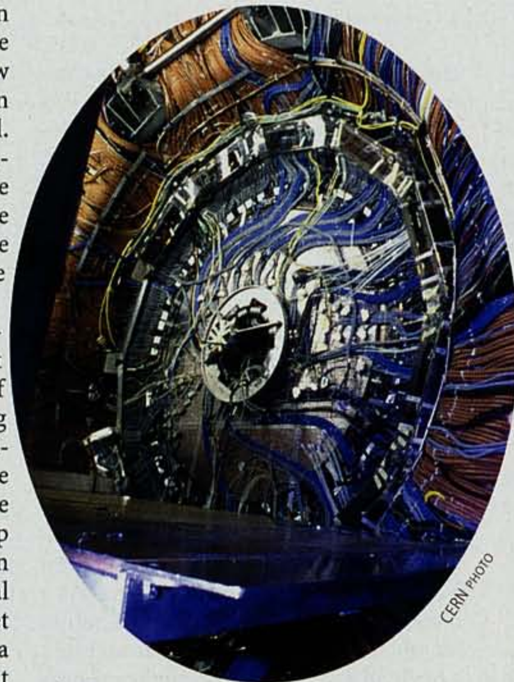
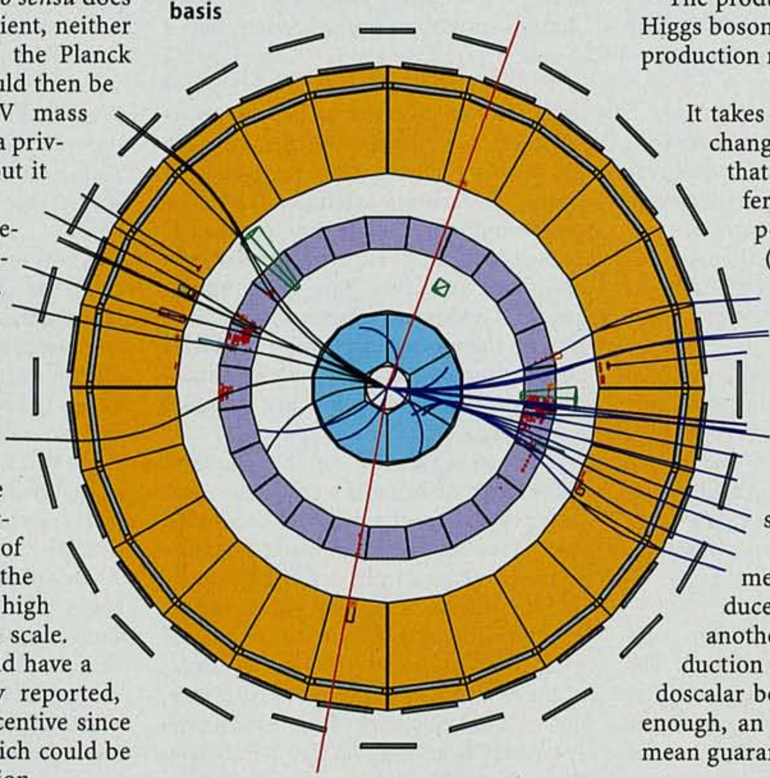


Fig 3
Above The Delphi detector
Below A Z^0Z^0 event registered by the Delphi detector, with a boson decaying into two muons, the other into two quarks. The production of a ~ 90 GeV Higgs boson would look the same, with two b-quarks. Such a Higgs boson has already been excluded on a statistical basis



The two main avenues beyond the SM, as stated before, are theories connected either to one of the composite scenarios, like Technicolor, which in their simplest versions do not seem to be compatible with the electroweak measurements, or with supersymmetry (*see box* 4) which in all its incarnations accommodates them very well.

The most solid and dramatic prediction of supersymmetry models concerns the Higgs sector. Supersymmetry, in its minimal version, requires the existence of two Higgs doublets in weak isospace (*box* 2), *ie* 8 real quantities; once the three vector bosons have acquired mass, five bosons are left. The most interesting object for LEP 200 is the lightest of the two scalar bosons predicted, called h^o, because supersymmetry in its minimal version gives a sharp *upper* limit to its mass: $M_{h^o} \leq 125$ GeV (*see further reading:* M. Carena).

This striking difference with the SM case is due to the fact that in supersymmetry the Higgs self-coupling is now perfectly known, in terms of the gauge couplings g and g'. Actually the h^o boson can be even lighter *as shown in figure* 2. Once the top mass is fixed the value of the h^o mass is governed essentially by the value of the $tg\beta$ parameter, the ratio of the vacuum expectation values of the two doublets (*see box* 4), which is *a priori* unknown. An additional dependence stems from the value of the masses of the top superpartners and the amount of mixing in their sector. The hope for LEP 200 is thus that $tg\beta$ is small. Some theoretical considerations prefer such a scenario, although none is compelling.

The production mechanism of the SM Higgs boson at LEP 200 is the associated production mechanism:

$$e^+e^- \to H^o{}_{SM}Z^o$$

It takes place through virtual Z^o exchange, and reflects the basic fact, that the Higgs boson coupling to fermions (bosons) being proportional to the mass (squared) of the partner, it likes to couple to the heaviest possible ones. This also explains why in the mass range considered the $H^o{}_{SM}$ boson decays mostly into beauty-antibeauty, since a beauty quark is the heaviest fermion kinematically accessible.

The lightest supersymmetry Higgs boson, h^o, is produced by the same process; but another possibility exists: its production in association with the pseudoscalar boson, A^o, if the latter is light enough, an occurrence which is by no mean guaranteed:

$$e^+e^- \to h^oA^o$$

The two bosons decay mostly into $b\bar{b}$ for the reason quoted, and the final state of the second process is thus four *b*-jets. The first one leads to Z^o $b\bar{b}$ and the Z^o is

Box 3 The Higgs boson

While the photon and the Z^0 are, algebraically, close relatives in the Standard Model (SM), they appear as radically different particles. The former is massless, the latter weighs nearly as much as 100 protons. This is a manifestation of the spontaneous breaking of the electroweak symmetry. The Higgs mechanism is, for the time being, the most satisfactory explanation, or at least description, of this breaking. It bears a strong analogy with the well-known phenomenon of superconductivity.

Consider an electron moving in space-time; its wave function has a phase. Is the physicist free to choose this phase arbitrarily at each point in space-time? Yes, the physicist has this freedom, provided he or she introduces a new boson, the photon: it is in fact the emission/absorption of the photon which will change the phase.

We saw, in *box* 2, that the fermions of the SM, besides being spinors, a variety of state vector, in space-time, exist as well in the "abstract" space of the weak isospin, where they appear as singlets or doublets. By performing a "rotation" in that space one can, for instance, transform a charged lepton into its neutrino species, or change an up quark into a down quark. Is the physicist free to choose arbitrarily at each point the nature of a fermion, namely to call it a charged lepton or a neutrino? Yes, provided he or she introduces new bosons, the electroweak bosons Z^0 and $W^{\pm}$. The emission/absorption of a W, for instance, will turn a charged lepton into a neutrino.

This freedom exists as long as nothing in nature opposes it. However, in a superconducting medium, there exist Cooper pairs, which are overlapping macroscopic objects. Their effect is actually to lock the phase of an electron wave function, and the freedom quoted above does not exist anymore. One consequence is the well-known Meissner effect: in a superconducting medium, an electromagnetic field cannot penetrate a distance larger than λ, the penetration length. It is as if the photon had acquired a mass, $m \sim \lambda^{-1}$, which is actually proportional to the square root of the density of Cooper pairs: $m \sim \sqrt{n}$.

The Higgs mechanism is analogous, but acts in a different space. The assumption is that there exists a field, the spin 0 Higgs field, which is a doublet in the weak isospin space. Like the field of Cooper pairs, the Higgs field fixes a preferred orientation in the weak isospace, and the freedom quoted above, for instance to rotate a charged lepton into a neutrino, is lost. This Higgs mechanism has a similar effect on the electroweak bosons: while the photon remains massless, the Z^0 and $W^{\pm}$ acquire a mass. For instance: $M_{W^{\pm}} = (g/2)v$, where g is the gauge coupling of *box* 2, while v, reminiscent of the density of Cooper pairs, is the vacuum expectation value of the Higgs field. However, the limits of this analogy between superconductivity and the relativistic Higgs effect should be noticed.

The SM Higgs field is a doublet in weak isospace, *ie* represents four real quantities. Once the three vector bosons have acquired their mass, one is left, which, in the SM, corresponds to a scalar particle, the Higgs boson.

The Higgs potential of the SM can be written as

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

The key aspect of this potential is that, for μ^2 positive, it takes its minimum value for a non-zero value of the Higgs field ϕ, $v = \sqrt{(\mu^2/\lambda)}$. λ is the unknown Higgs self-coupling, while the Higgs mass

$$M_H = \mu\sqrt{2} = v\sqrt{\lambda}\sqrt{2}$$

is therefore unknown as well.

Through its coupling to fermions (called a Yukawa coupling) the Higgs field is also responsible for their mass generation. The Higgs coupling to fermions (bosons) is proportional to their

Box 4 Supersymmetry

As one can see from *box* 2 there is in the Standar Model (SM) a complete asymmetry between the constituents of matter, which are fermions, and the carriers of the forces between them, which are bosons. Many reasons encourage us to restore the symmetry between these two classes.

A basic one is that such a symmetrization is possible. One can show that operators Q can be defined, which turn a fermion into a boson and *vice versa*. They carry the spin quantum number 1/2 and have spin character. Thus they carry a four-index and satisfy anticommutation rules:

$$\{ Q_\alpha, Q_\beta \} = 2\, \gamma^\mu{}_{\alpha,\beta}\, p_\mu$$

Moreover, they commute with the components of the quadrimomentum. The anticommutation formula is sometimes boldly summarized by telling that the operator of supersymmetry is the square root of a space-time translation operator.

Phenomenologically, this leads to the invention of a new population of particles that mirror the existing one. In the most economic version of supersymmetry, there is one superpartner for each SM particle, more exactly for each spin degree of freedom. Attempts to be even more economical, by trying to consider known particles as superpartners of other known particles, have been unsuccessful. Obviously, supersymmetry is a broken theory because known particles have no superpartner of the same mass. These must be heavier, and are therefore yet undiscovered.

This symmetrization has several virtues. We mentioned in the main text the existence, in the SM, of divergences, for instance of the Higgs boson mass due to the presence of physics at high scale, like the Planck scale. These divergences disappear in supersymmetry, because of a cancellation between the virtual effects of the two mirror populations. However, not to spoil this cancellation by supersymmetry breaking, the way it is broken must obey strict rules, which dictate the mathematical structure of the terms responsible for the breaking, and the superpartners cannot be much heavier than the known particles. Supersymmetry would lose its virtues if their mass scale was above a TeV or so, and some species are even expected to be much lighter.

Another hint that supersymmetry could be the right path is that, while grand unification of the gauge couplings (*see box* 2) fails in the SM frame, excluding for instance the simple SU(5) scenario, it seems that in supersymmetry the three coupling constants, well measured at LEP energies, when extrapolated upward in energy in the supersymmetry scenario, converge accurately together at $\sim 10^{16}$ GeV.

An appealing aspect of supersymmetry is that it predicts couplings for the superpartners which, within details, are the same as the SM ones. In a sense, the only unknowns are the masses.

However, in the process of supersymmetry breaking, a potentially large number of unknown parameters enter the game. By assuming their universality at very high scale, it is usual, but not mandatory, to reduce them to five new mass (mass squared), and this is the main message of its phenomenology, governing both its production mechanism and its decay modes. For instance, in the mass range of LEP 200 it will preferentially decay into beauty—antibeauty, since the b-quark is the heaviest fermion kinematically accessible.

In supersymmetry (*box* 4) the Higgs sector is more complicated: two doublets, at least, are needed, and, after electroweak symmetry breaking, at least five bosons are left. Each doublet has a vacuum expectation value, and their ratio, called $tg\beta$, is an important unknown parameter of this sector. The other one can be chosen as the mass of the pseudoscalar Higgs boson, m_A. As soon as m_A is large (above 100 GeV or so, a condition which is likely to be satisfied) the h^0 boson is SM-like.

The association of a physical scalar boson to the Higgs mechanism is a natural assumption, but is not mandatory. Schemes of dynamical symmetry breaking exist, where condensates of fermions play the role of the Higgs boson, and which do not lead to the existence of such a physical particle. Such scenarios will be studied with the LHC, but are likely to be inaccessible to LEP 200, due to a lack of centre-of-mass energy, unless the new scale is very low.

ones, compared to the 19 parameters already existing in the SM.

It is commonly admitted that the partners of the leptons, the sleptons, and those of the gauge and Higgs bosons, the charginos and neutralinos, are the supersymmetry particles which are expected to have the lowest masses. If they exist, they must be pair-produced in e^+e^- collisions and are actively searched for at LEP 200, the mass limit set being generally close to the kinematical limit. However, no very strong argument guarantees that they should be accessible at LEP 200. Their search will also be one of the leading activities of the LHC and, later, of an e^+e^- linear collider or a muon collider.

On the contrary, a very sharp prediction of supersymmetry, and the most important for LEP 200, concerns its Higgs sector. Shown in the main text is the following: the energy domain of LEP 200 is exactly the one where the lightest boson of SUSY is expected to be, if it exists, and the details of the search for it are described.

looked for in all its decay modes: $q\bar{q}$, $\nu\bar{\nu}$, l^+l^-. This leads to quite different final states, but which always contain two *b*-jets.

The main backgrounds, *ie* parasitic processes (*as shown by figure* 1), are the multijets originating from quark pair production, possibly accompanied by gluon radiation, the *W* pair final state and the Z^0 pair final state. The first two can be reduced or suppressed by requiring beauty in the final state. In particular we recall that *W* decay modes do not contain any appreciable amount of that flavour. On the other hand, the last one, when one Z^0 decays into $b\bar{b}$ for $M_h \sim M_Z$, is an irreducible background (*see figure* 3). But its cross-section is small enough to allow the detection of Higgs production with a signal/background ratio of ~ 1.

LEP 200, at the end of 1998 data-taking, has led to an exclusion limit of ~ 95 GeV per experiment. The combination of the results of the four experiments, still to be performed, should raise this limit by a few GeV. One sees that LEP has already entered well into the most interesting region.

With the extension foreseen, and 200 pb^{-1} registered per experiment at ~ 200 GeV centre-of-mass energy, the discovery potential of LEP, combining its four experiments, will reach ~ 107 GeV, while it will be able to exclude up to ~ 109 GeV. The old rule-of-thumb discovery limit of $M \sim E_{CM}$–100 GeV, conjectured long ago and understandable from the shape of the Higgs production cross—section of *figure* 1, was therefore slightly on the pessimistic side.

As one can see from *figure* 2, in the case of no observation the small $tg\beta$ region will be excluded. Following this exclusion some scenarios will be proven wrong. In particular, the interesting possibility that baryogenesis could have occurred at the weak scale, which requires a quite light Higgs boson, below ~ 105 GeV, will be discarded. Of course, there is the exciting alternative, namely the discovery of a light Higgs boson.

On the other hand there will be room left for the minimal supersymmetry model, if $tg\beta$ is large. This domain of mass will be explored at the LHC, in a decade or so, and before that by the Fermilab Tevatron Collider, if its ultimate luminosity upgrade, called TEV33, is achieved. For both machines the exploration of this mass range will be a challenge because of the huge background level.

One can ask oneself what would have been needed at LEP to give the best possible answer about minimal supersymmetry. As shown by *figure* 2, the heaviest h^0 boson to be considered has a mass of ~ 125 GeV. Scaling up the limit quoted for LEP 200, its exclusion would have required ~ 216 GeV of centre-of-mass energy, corresponding to an 8% increase relative to the presently foreseen value. Such an energy would have guaranteed a discovery, for a SM like boson, up to ~ 123 GeV. Because of the dependence of the synchrotron radiation loss on the fourth power of the beam energy, this would have required ~ 1.36 times more RF cavities, assuming the same accelerating field, namely ~ 385 cavities instead of the present ~ 288. Such a possibility, which uses all the room available in the four instrumented intersection regions of LEP, has been considered but not used for reasons of cost.

It is also fair to say that by leaving the frame of minimal supersymmetry, for instance by adding Higgs weak isospin scalars to the two doublets, it is possible to increase somewhat the upper bound on the lightest Higgs mass. Although there is some reluctance among theorists to complicate the simplest picture before it has been tested, one cannot exclude such a possibility.

It is still possible that the whole theory of supersymmetry is the wrong path. It is thus unfortunate that for the time being it is the only theory beyond the SM which, besides its own virtues in curing some of the SM's defects, leads to rather sharp predictions, and offers itself to the possibility of falsification.

It could also be that some scenario without an elementary Higgs boson is the correct one, implying that its present disagreement with electroweak measurements results from an inadequacy of the computational method. Unless the new scale is surprisingly low, LEP 200 will not be able to answer such a question, which will then be addressed later by the LHC.

Meanwhile, the main concern of the LEP community is to exploit optimally the luminosity that this splendid machine will offers, as well as its next increase in energy. The energy increase is at first sight modest, but it will take place in a potentially very hot domain for supersymmetry particles and in the most critical one for its Higgs sector. EN

The author is a research physicist at CERN near Geneva, and a former spokesman of the Delphi experiment

Further reading

TOP-ology by C. Quigg *Physics Today* **50** no. 5 • M. Carena et al *Phys. Lett. B* **355** 209 (1995)