The Higgs Connexion

M. Aguilar-Benitez[1] and Maria J. Herrero, Madrid[2]

([1]Particle Physics Div., CIEMAT and [2]Universidad Autónoma de Madrid)

The scenario emerging from research over the past years is that matter is made of fundamental fermions (quarks and leptons, all of spin 1/2) and forces are mediated by gauge bosons (particles of integer spin). The most elementary fermions appear in three generations, each generation composed of a doublet of quarks and leptons. The first generation, which is the one relevant to our familiar universe in its present state, contains the up and down quarks, the electron and the associated electron neutrino. The so called second and third generations are made of charm and strange and top and bottom quarks, the muon and the muon neutrino, and the tau and tau neutrino respectively. All these matter particles, with the disturbing exception of the top quark, have been experimentally identified. A summary of their properties is listed in Table 1. It is interesting to note that elementary quarks have fractional electric charges and have not been isolated in the laboratory (they remain confined in hadrons like the proton and neutron, less fundamental matter entities which are constructed of at least three quarks or a quark and an antiquark pair).

Four fundamental forces among matter particles are distinguished:

1) the gravitational force through which massive macroscopic objects (stars, galaxies,...) interact,

2) the electromagnetic force accounting for atomic and molecular binding and permanently present in every day phenomena,

3) the weak force responsible for beta decay-like processes, radioactivity, and neutrino interactions with matter, and

4) the strong force which holds quarks together and gives consistency to nuclear matter. In field theory language, the concept of force is intimately tied to the concept of a field, the field manifesting itself by means of the exchange of intermediate boson particles. It has long been known or assumed that: a) the electromagnetic force is mediated by the photon, b) the weak force is felt by the exchange of the recently discovered W^+, W^- and Z° vector bosons, c) the strong force is transmitted by the exchange of eight massless vector gluons, and d) the as yet undetected graviton is the carrier of the gravitational force.

In Table 2 we give some of the properties of the forces and force particles. Notice the widely different mass values of the force carriers, which reflect the very distinct ranges of the forces. The gravitational and electromagnetic forces with massless mediators, the graviton and the photon respectively, have infinite range, whereas the very short range of the weak force is associated with the massive nature of the $W^\pm$ and Z° vector bosons. The short range of the strong force is, however, explained in terms of the strengthening of this interaction with distance, which is believed to result in quark confinement at a distance scale of 10^{-13} cm. It is also worthy of note that, for the mass scales relevant to high energy physics, the strength of the gravitational force is negligible in comparison with the other fundamental interactions. Quantum gravitational effects only become significant for systems with a gravitational energy comparable to their total mass. This situation occurs for a mass value of 10^{19} times the mass of the proton, the so called Planck mass scale, which is larger by a factor of 10^{17} than the mass of any fundamental particle which has so far been detected, so that we can safely ignore gravitational effects in our discussion.

The scientific architecture supporting our present understanding of matter particles and matter forces sketched in the preceding paragraphs is the so called Standard Model. This fundamental theory of strong, electromagnetic and weak processes is constructed in quantum field theory from $SU(3)_C \times SU(2)_L \times U(1)$ gauge invariance, and incorporates all the well known symmetries and successful features of Quantum Chromodynamics (QCD), Quantum Electrodynamics (QED) and low energy weak interaction phenomenology.

Gauge Invariance

The idea of gauge invariance which plays a central role in the Standard Model had a distinguished predecessor in Maxwell's Theory of electrodynamics, where it is possible to construct many electromagnetic potentials, related by local and continuous transformations $A_\mu(x) \rightarrow A_\mu(x) + e^{-1}\partial_\mu \alpha(x)$, the so called gauge transformations, which satisfy Maxwell's equations. In other words, the laws of nature that are described in the theory of electrodynamics, are invariant under these specific continuous transformations.

The invariance of a law of nature under certain transformations implies the existence of a symmetry. Thus, the invariance of a ball under rotations reveals its spherical symmetry, and the invariance of the laws of nature under the space-time transformations, forming the Poincaré group, reveals the homogeneity and isotropy of our space-time world. In the case of Maxwell's Theory, the invariance under gauge transformations leads to a very important conservation law: the conservation of electric charge, in much the same way that invariance under the transformations of the Poincaré group leads to the conservation of momentum, energy, and angular momentum.

The strategy of considering local symmetries as the starting point and deriving gauge theories with associated conservation laws was essential for the construction of the Standard Model. The resulting gauge theory is based on a local symmetry group which encompasses the $SU(3)$ colour group, responsible for the strong interactions between quarks and gluons, and the $SU(2)_L \times U(1)$ group, which accounts for electroweak interactions and for the existence of four massless gauge bosons (W^+, W^-, Z° and the photon).

Symmetry Breaking

Unfortunately, this approach has shown some unappealing features. Perhaps the most important has to do with the fact that theories derived from a gauge symmetry principle lead to interactions in which the force particles have zero mass. This works for the photon and gluon case, but it is totally inadequate for the carriers of the weak force. Another complication arises from the fact that the derivation of gauge theories from symmetry principles is some-

Table 1 — Properties of the Matter Particles

LEPTONS

Particle Name	Symbol	Mass at Rest	Electric Charge	
Electron Electron neutrino	e^- ν_e	0.511 MeV <18 MeV (95% CL)	−1 0	1st Gen.
Muon Muon neutrino	μ^- ν_μ	105.658 MeV <0.25 MeV (90% CL)	−1 0	2nd Gen.
Tau Tau neutrino	τ ν_τ	1784.1 MeV <35 MeV (95% CL)	−1 0	3rd Gen.

QUARKS

Particle Name	Symbol	Mass at Rest (MeV)	Electric Charge	
UP DOWN	u D	About 4 (*) About 7 (*)	+2/3 −1/3	1st Gen.
CHARM STRANGE	c s	About 1300 About 150 (*)	+2/3 −1/3	2nd Gen.
TOP/TRUTH BOTTOM/ BEAUTY	t b	Larger than 50000 About 5500	+2/3 −1/3	3rd Gen.

(*) Current algebra masses.

how perturbed when the symmetry is only approximately satisfied by nature. In this case the fundamental lagrangian of those theories describing the physical world will exhibit an imperfect symmetry, or an explicitly broken symmetry. A more involved situation occurs when an exact symmetry of nature is masked and the vacuum state (given by certain configurations of the fields that define the ground state of the physical system) does not exhibit the expected symmetry properties. In lagrangian field theory language, this corresponds to a peculiar breaking of the symmetry in which the lagrangian has a certain symmetry, whereas stable physical states, described by the lagrangian (including the vacuum), do not have that symmetry. In this situation, the symmetric states are unstable and a "spontaneous" transition to non-symmetrical stable states occurs under the action of infinitesimal perturbations.

Table 2 — Properties of the Forces and Force Particles

Force	Range	Strength (1)	Carrier	Mass at Rest (GeV)	Spin	Electric Charge
Gravity	Infinite	10^{-38}	Graviton	0	2	0
Electro-magnet.	Infinite	10^{-2}	Photon	0	1	0
Weak	Less than 10^{-16}cm	10^{-13}	W^+ W^- Z^0	81.0 81.0 92.4	1 1 1	+1 −1 0
Strong	Less than 10^{-13}cm	1	Gluons	0	1	0

(1) Strength at 10^{-13} cm in comparison with the strong force.

In the case of a quantum field theory with a continuous internal symmetry, it turns out that a spontaneous breakdown of the symmetry generates unwanted (since they have not been experimentally detected) massless scalar particles, the so-called Goldstone bosons, in a number equal to the number of generators of the symmetry group which is not apparent in the ground state. Intuitively, it is easy to see the reason for its presence. For instance, in the case of a complex scalar field, with an invariant lagrangian under the continuous transformation $\varphi(x) \rightarrow (\exp i\alpha)\, \varphi(x)$, there is a whole circumference of minima, $<|\varphi(x)|> = v$, that can be connected in a continuous way without any cost of energy. Excitations about any of these minima, which are along the tangent direction to the circumference, represent the presence of a massless mode, the Goldstone boson. In the case of the infinitely extended ferromagnet, the Goldstone boson analogues are the long-range spin waves, which are oscillations of the spin alignment.

The Higgs Mechanism

A major step in the formulation of the Standard Model was to realize that for the special class of theories constructed from a gauge symmetry principle, the *a priori* disturbing phenomenon of spontaneous symmetry breakdown, when referred to a gauge symmetry, simultaneously resulted in the generation of masses for the force carriers and the disappearance of the Goldstone scalar bosons. In other words, through this intriguing artifact, the so-called Higgs mechanism, the unwanted massless Goldstone bosons combine with the massless intermediate vector bosons to form physical massive vector bosons, whose masses turn out to be proportional to the coupling strength of the external scalar field to the vector boson fields and to the constant value of the scalar field into the vacuum.

The simplest realization of the Higgs mechanism in the Electroweak Theory is based on the assumption that the breaking of the $SU(2)_L \times U(1)$ symmetry down to $U(1)_{EM}$ takes place spontaneously from a non-linear self-interacting doublet of complex scalar fields (four real scalar fields as a whole). Counting the degrees of freedom is as follows: the "would be" three emerging Goldstone bosons are "swallowed" by three massless gauge bosons giving rise to the $W^\pm$ and Z^0 vector bosons with the correct masses, keeping the fourth gauge boson, the photon, massless. The remaining scalar degree of freedom unavoidably introduces an extra scalar mode in the theory, which turns out to be massive, the so-called Higgs particle. It is a primary characteristic of the Higgs mechanism. that all the physical particles, not just the force carriers but also fermions and the Higgs particle itself acquire their masses by interacting with the non-zero external scalar field, in such a way that the stronger that interaction is, the larger is the generated mass. It is clear that the identification of the Higgs boson, or for that matter the unique external agent that remains after the spontaneous symmetry breaking of the $SU(2)_L \times U(1)$ symmetry, is an issue of paramount importance in particle physics.

The strongest feature in favour of the simplest scenario, with just one scalar doublet, is that it is the best defined model of electroweak symmetry breaking with only one unknown parameter, the mass of the Higgs particle. Within this basic model, once a Higgs mass value is assumed, it is possible reliably to predict all other properties, and thus, it is possible to analyze experiments and design future searches. In what follows, we summarize some of these properties:

1 - The Higgs boson must be a scalar particle. Otherwise the mass of a particle would depend on the particle orientation with respect to the Higgs field.

2 - The Higgs boson has to be electrically neutral. Otherwise its coupling to the photon would generate a non zero mass for the carrier of the electromagnetic force.

3 - The mass of the Higgs boson is given, in a first approximation, by the relation $m_H = 2\sqrt{\lambda}v$, where λ is the unknown scalar self coupling, and, $v = 246$ GeV is the scalar field vacuum expectation value, which is uniquely determined from the experimental value of the Fermi coupling constant. In the absence of any reliable information on the size of λ, the value of v simply gives a feeling for the energy scale related to the symmetry breaking onset. We shall review later the bounds derived theoretically for the mass of the Higgs boson.

4 - The dimensionless coupling of the Higgs boson to a pair of fermions or bosons XX is proportional to the mass of the particle X:

$$g_{HXX} \cong m_X/v$$

In Table 3 we list some relevant coupling strengths normalised to the coupling to the Z. The observation of this table yields some interesting conclusions:

i - The Higgs boson will have the largest branching ratio to the heaviest possible pair of particles.

Table 3 — Comparison of coupling strengths of Higgs boson normalised to the value for $Z^\circ Z^\circ H^\circ$ coupling

Coupling	m_x (GeV/c^2)	g_{XXH°
$Z^\circ Z^\circ H^\circ$	~ 92.4	1.00
$W^+W^-H^\circ$	~ 81.0	~ 0.877
$t\bar{t}H^\circ$	~ 44	~ 0.476
$b\bar{b}H^\circ$	~ 5.5	~ 0.059
$p\bar{p}H^\circ$	~ 0.938	~ 0.010
$\tau^+\tau^-H^\circ$	~ 1.784	~ 0.019
$\mu^+\mu^-H^\circ$	~ 0.106	~ 1.1×10^{-3}
$e^+e^-H^\circ$	~ 0.0005	~ 5.5×10^{-6}

ii - Owing to the small coupling of the Higgs to the e^+e^- and proton-antiproton pairs, the production cross-sections of the Higgs in e^+e^- and $p\bar{p}$ annihilations will be small.

iii - The massless nature of the photon and the gluon prevents the Higgs boson from coupling to the $\gamma\gamma$ and gluonium systems.

iv - The width of the Higgs boson depends on the number of kinematically available decay channels. In general, for $m_H < m_Z$, the Higgs particle should show up in an effective mass distribution as a fairly narrow resonance. On the contrary, for very large values of the Higgs boson mass (say 800 GeV), the coupling to its decay products becomes so strong, it cannot be any longer identified by a resonance lineshape.

The outcome of this discussion is that, in view of the small couplings of the Higgs boson to the standard initial states available in lepton or hadron colliders, the very many possible open decay channels leading to high multiplicity final states, and the ignorance of the Higgs mass value, its discovery appears as a rather formidable enterprise.

Remembering that the reason for postulating the Higgs boson was to make the Standard Model mathematically consistent, attempts have been made to put restraints on the Higgs mass on theoretical grounds. However, space does not permit us to go into these in any detail and we can only note that the models have not proved to be very illuminating.

Experimental Search

We shall concentrate therefore on the evidence that is available from the different experimental searches for theHiggs boson that have been undertaken.

i - Direct searches for Higgs emitted in nuclear decay exclude the mass range from 3-14 MeV.

ii - From a study of K decays, a limit on the mass of a light Higgs emitted in the process $K \rightarrow \pi H$ can be obtained. Although some theoretical uncertainties are inherent to the extraction of the mass using this decay and some caution must be exercised, the mass region 50–221 MeV can be tentatively ruled out.

iii - The process $B \rightarrow KH$ can also give information on the Higgs mass, although there are also theoretical uncertainties. Assuming that the top quark mass is larger than 43 GeV, one experiment claims to exclude the ranges 0.3 GeV $< M_H <$ 3.0 GeV and 3.2 GeV $< M_H <$ 3.6 GeV.

iv - One group has used the process $\gamma \rightarrow H\gamma$ to exclude the range 600 MeV $< M_H <$ 3.2 GeV, although the calculation of the rate is not yet free from theoretical uncertainties.

From this limited available experimental information very little can be said about the allowed range of the Higgs. The lower mass limit can be safety set to 14 MeV. A combination of theoretical arguments and bounds from B, γ and K decays probably excludes the range below 4 GeV. More meaningful constraints from the above processes, requiring better limits on the branching rations and a measurement of the top quark mass, should become available in the near future.

In the past few years, considerable literature has been accumulated on the various strategies that have been worked out to uncover the Higgs in electron-positron machines. There is rather overwhelming information on many possible Higgs production processes with detailed accounts of rates and background shapes and sizes. In the following we summarize some of the *a priori* more rewarding avenues leading to the isolation of the Higgs particle.

1) Toponium decay $V_t \rightarrow H^\circ + \gamma$. This process involves the so far undetected top quark, but benefits from the fact that the H° coupling to heavier quarks is large. It has an experimentally appealing monochromatic photon signature, but its discovery potential is limited to a Higgs mass smaller than the toponium mass. Another mechanism, which involves toponium production, is $e^+e^- \rightarrow V_t + H^\circ$, although the rate for this process is small and, at least in the first LEP and SLC phases, will allow only the low mass range (say below 10 GeV) of the Higgs to be explored.

2) Z° decay $Z^\circ \rightarrow H^\circ + \gamma$. Although this process has a small rate, the large number of Z° expected at LEP and the monochromatic photon signature argue in favour of this channel. Some possible complications may even decrease the expected rate and there are background problems, radiative corrections to fermion pair production, which will have to be overcome in a most cautious way.

3) Z° decay $Z^\circ \rightarrow H^\circ$ + lepton pair. Since many Z° events (of the order of one per second) are expected at LEP, decay into a Higgs lighter than 55 GeV and a pair of leptons may be observable.

4) e^+e^- annihilation, *via* off shell Z° ("Z°"), into a H° boson and an onshell Z° which decays into e^+e^-, $\mu^+\mu^-$, $\nu\bar{\nu}$ and jets. This reaction has been extensively Monte Carlo studied. At a centre of mass energy of 160 GeV and for a Higgs mass of 50 GeV it looks particularly promising. The reconstruction of the Z° from e^+e^-, $\mu^+\mu^-$ pairs and missing energy is fairly advantageous and essentially background free. Higgs signals may emerge when measuring the recoiling missing mass distribution or the effective mass distribution of the hadronic system recoiling against the reconstructed Z° peak.

One Experiment

As an illustration of how, experimentally, the search for the Higgs boson will be performed in the near future, we shall describe one possible specific approach to the Higgs quest. For biased (one of the authors of this paper being involved in the experiment), although perfectly justifiable reasons, we have selected the L3 detector, which is being assembled for the LEP machine and more precisely the isolation of the Higgs particle produced together with a Z, whose $\mu^+\mu^-$ decay is identified and accurately measured by the central muon detector.

The L3 detector has been constructed over a period of six years by a large international collaboration made by more than 460 physicists and 400 engineers and technicians from 36 research institutions in 13 countries. It will enable us to measure with unprecedent precision and resolution the electrons, photons and muons which are emitted from the electron-positron collisions.

The L3 detector, sketched in Fig. 1, consists of an assembly of subdetectors immersed in a large volume (1300 m^3) low field (0.5 T) provided by an octagonal shaped solenoid magnet of approximate dimensions 12 m by 12 m by 12 m. The yoke consists of 6400 tons of low carbon steel and the coil is made of 1100 tons of aluminium. The axis of the octagonal prism runs along the electron-positron colliding beam axis.

The large volume of the detector allows a high precision muon momentum measurement, performed by three sets of drift chambers with multiple measurement of the co-ordinate in the bend plane. Going radially inwards, the combined hadron calorimeter and muon absorber consists of around 8000 wire chambers operating in the proportional mode, sandwiched with Cu or U-plates as energy converter (approximate weight is 300 tons). A subdivision into 3000 space elements covering the full solid angle (except the beam pipe) allows localization and determination of the hadronic energy flow with around 45% energy resolution. The electromagnetic energy flow will be determined by approximately 11000 crystals of BGO ($Bi_4Ge_3O_{12}$), a transparent scintillator with 1.1 cm radiation length (total weight is 12 tons). Full electromagnetic shower containment near 4π solid angle coverage is foreseen. An energy resolution smaller than 1.2% and a spatial resolution better than 2 mm will be obtained for gamma energies larger than 1 GeV with a rejection against hadrons of better than 1000. Surrounding the beam pipe a high precision drift chamber operating in the time expansion mode acts as a charged particle vertex detector. One can expect a resolution down to $\sigma = 30\ \mu m$. Specifically this chamber allows an electron/photon separation and a high precision on the muon vertex, as well as making possible a direct measurement of the lifetime of the long-lived particles.

The central precision muon detector will provide a mass resolution *(ΔM)* of the dimuon system $\Delta M/M = 1.4\%$. Its total volume is 1000 m^3, total weight 190 tons and the area of the chambers reaches 900 m^2. The total number of wires in the 80 chambers is 250000. The sagitta of a 45 GeV muon in the bending plane of the L3 detector is approximately 3.7 mm. High resolution implies very good precision in the measurement of this quantity. That is achieved by maximizing the analyzing power: increasing the lever arm over which muons are measured (2.9 m), optimizing the chambers to give a resolution better than 280 μm/wire and reducing the systematic errors on the sagitta to less than 30 μm by very advanced construction and most precise opto-mechanical alignment devices.

Let us consider electron positron annihilations at a total centre of mass energy of 160 GeV (second phase of LEP) and restrict our attention to those in which the muon spectrometer has registered the passage of two energetic particles with opposite charge. Having measured, very precisely, the effective mass of this two particle system, we may observe, by inspecting the resulting distribution, a clean Z^0 signal. From the measured Z^0 energy momentum four vector and the knowledge of the total centre of mass energy we could calculate the recoiling missing mass or, in other words, the mass of the system being produced along the Z^0. If, to be optimistic, the mass of the Higgs is 50 GeV and the total integrated luminosity is 400 inverse picobarns (of the order of 280 days of running at the nominal luminosity of $1.7 \times 10^{31}\ cm^{-2}\ s^{-1}$) a fairly narrow signal of approximately 20 events, centred at 50 GeV, will be seen in the missing mass distribution, see Fig. 2, provided that the dimuon system has been measured with the $\Delta M/M = 1.4\%$ resolution. More information on this Higgs candidate signal will be obtained by careful examination of the compounds of the missing mass system in the various parts of the detector.

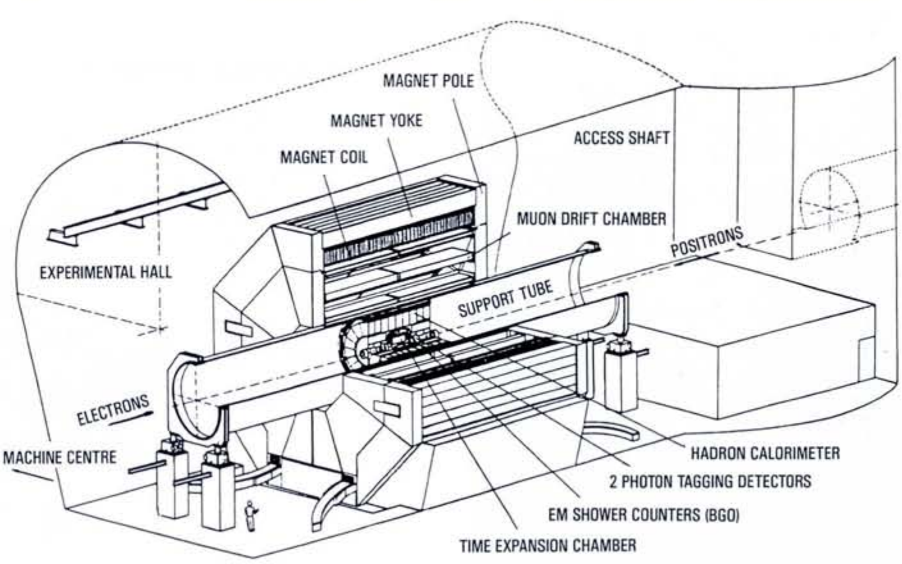


Fig. 1 — The L3 Detector.

BIBLIOGRAPHY

1. Cahn R.N., *Reports on Progress in Physics* (1989).
2. Chanowitz M.S., *Ann. Rev. Nucl. Part. Sci.* **38** (1988) 323.
3. Quigg C., 'Gauge Theories of the Strong, Weak, and Electromagnetic Interactions', *Frontiers in Physics* (The Benjamin/Cummings Publishing Company, Inc.) 1983.
4. Lecoq P. *et al.*, 'Big Detectors of BGO', *Europhys. News* **16** (1985) 2, 8.
5. Maiani L., 'Standard Theory of Particle Interactions', *Europhys. News* **18** (1987) 2.
6. Veltman M.J.G., Sci. Am. **255** (1986) 5.
7. *Physics at LEP*, Eds. by J. Ellis and R. Peccei, CERN 86-02.
8. 'Review of Particle Properties', *Phys. Lett.* **B204** (1988).

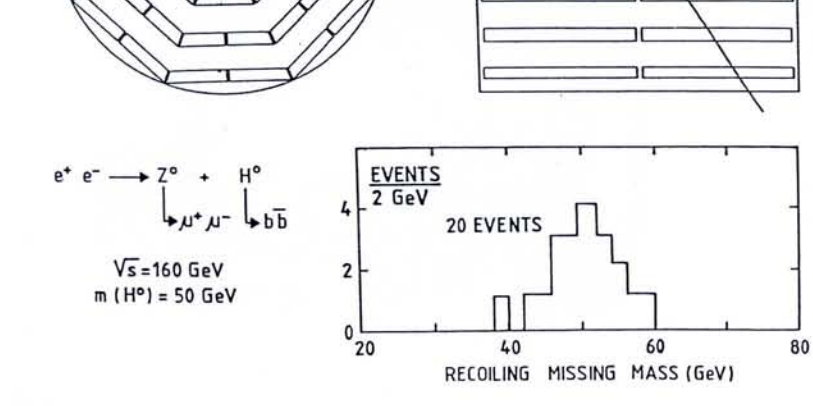
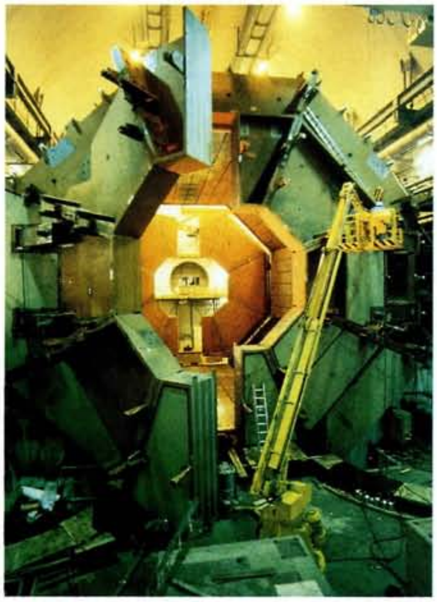
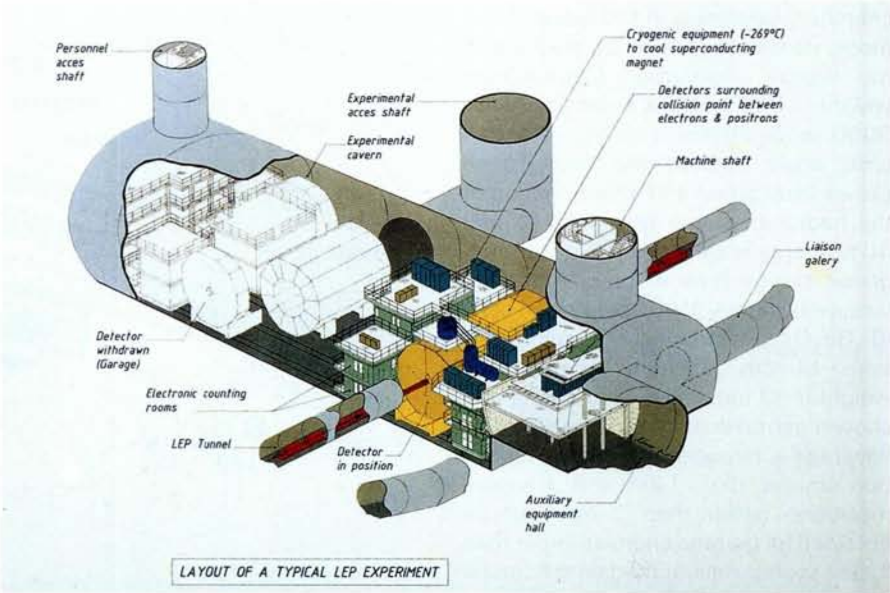


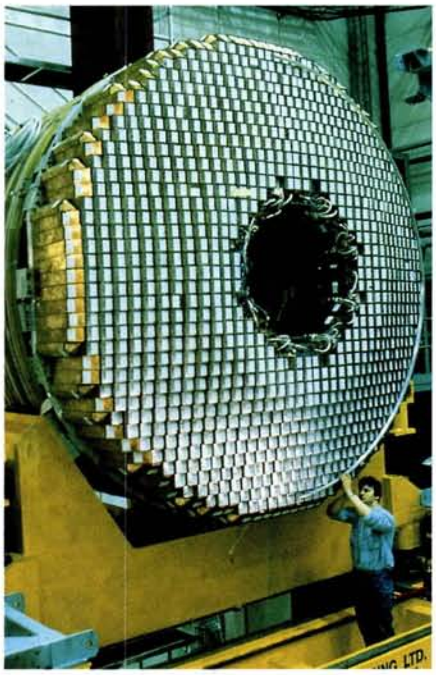
Fig. 2 — Display of a Monte Carlo generated event of the type $e^+e^- \to Z^0 + H^0$, with the Z^0 decaying into a $\mu^+\mu^-$ pair. The histogram shows the missing mass of the system recoiling against the reconstructed Z^0. 1 TEC; 2 BGO EM Calorimeter; 3 Hadron Calorimeter; 4 Muon Filter; 5 Muon Chambers.

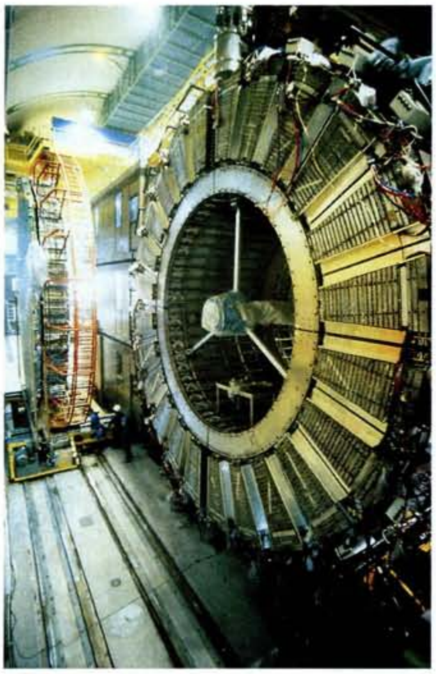




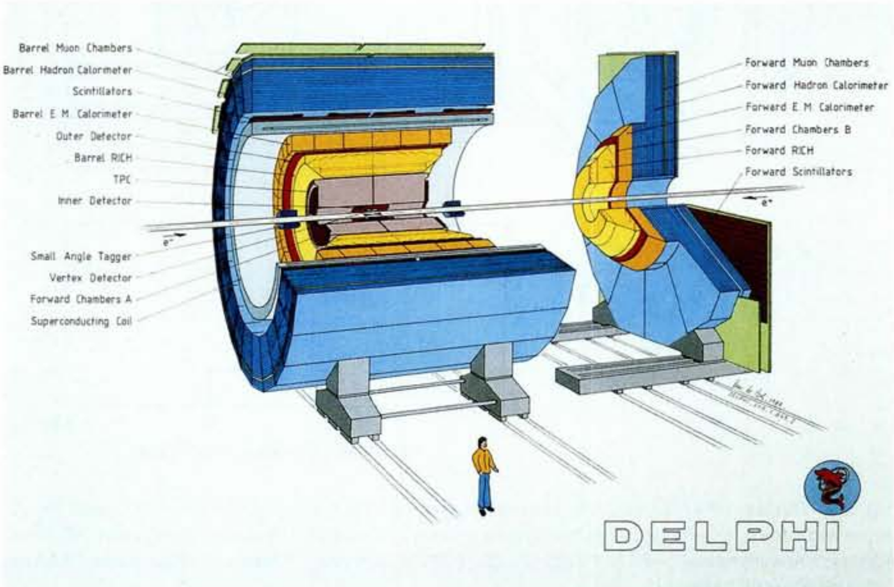
Above right — A typical experiment in its underground cavern.
Above — Doors of the pole pieces of the L3 ambient temperature magnet.

Far right — Barrel and cap of the ALEPH superconducting magnet.
Right — OPAL calorimeter containing 566 Cherenkov lead glass counters.





Below — Layout of the DELPHI experiment.



CERN is an Associate Member of the European Physical Society.