PERSPECTIVES IN HIGH ENERGY PARTICLE PHYSICS

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SUMMARY

1. Introduction: a Fermi legacy

In January 1954, E. Fermi gave a talk entitled ‘What Can We Learn With High Energy Accelerators?’ at the American Physical Society. He was then leaving the APS Chair, which he had taken during 1953. The University of Chicago Library has short personal notes that Fermi wrote for the talk as well as the slides of the figures.

It was indeed a crucial moment in particle physics. The discovery of many new particles in cosmic rays had had opened a new world and stimulated the development of particle accelerators. Big projects were starting in the US, the URSS and Europe, where CERN was being created just for this purpose.

At that time, Fermi was fully engaged in particle physics[1]. On the experimental side, he was studying the π-N cross sections at the Chicago Synchrocyclotron, finding the first hints of the 3/2-3/2 resonance and the confirmation of the isotopic spin symmetry in π-N

[1] See M. Jacob and L. Maiani XXXX

interactions. On the theoretical side, Fermi was impressed by the wealth of new particles that were being discovered in the high-energy cosmic ray interactions. Not all these particles could really be elementary! Together with C. N. Yang, he had developed, in 1949, a model of the π mesons as bound states of a nucleon-antinucleon pair, the precursor of the quark model of mesons and baryons, which was going to be discovered by Gell-Mann and Zweig some twelve years later.

What to do with high-energy accelerators? Fermi underlines the difficulty of looking into a "very, very cloudy crystal ball". He mentions the observation of antinucleons, the puzzle of the long lifetime of strange particles (high angular momentum barrier, or associated production, which he qualifies as "at present more probable"), the need for precision measurements. But also the possibility of "a lucky break, or theoretical leap, or more probably a combination of hard work, ingenuity and a little bit of good luck". All that and much more did in fact happen from the 1950s until now in High-Energy Particle Physics. Progress is exemplified in Fig. 1, by the chart of what are now considered to be the elementary constituents of matter, the three generations of quarks and leptons.

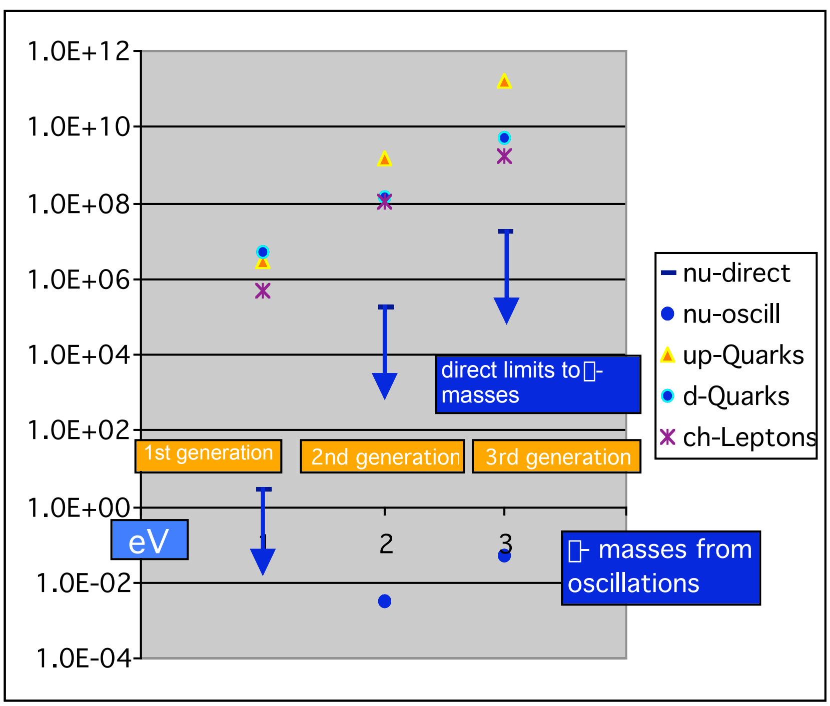

Fig. 1. The mass spectrum of quarks and leptons (ascending powers of eV). Upper bounds to neutrino masses are taken from beta decay spectra; estimates of ν_μ and ν_τ masses are from solar and atmospheric neutrino oscillations.

The forces acting on quarks and leptons are described by a coherent theoretical framework, usually referred to as the Standard Theory (see box). They encompass the familiar electromagnetic forces acting between charged particles, the weak forces responsible, among other processes, of the beta decay of nuclei, and the strong forces that bind quarks into nucleons (proton and neutron) and nucleons into nuclei. To those forces, one has to add those associated with the, still hypothetical, Higgs field, which are responsible for the arising of particle masses, as discussed below.

1. Normal Matter (Galaxies, stars, us,…)

QUARKS LEPTONS

(M. Gell-Mann, G. Zweig, 1962)

$\begin{pmatrix} u \\ d \end{pmatrix}$ $\begin{pmatrix} \nu_e \\ e \end{pmatrix}$

2. Analogous structures at higher energy

$\begin{pmatrix} c\,(1974) \\ s \end{pmatrix}$ $\begin{pmatrix} \nu_\mu\,(1962) \\ \mu \end{pmatrix}$

$\begin{pmatrix} t\,(1994) \\ b\,(1977) \end{pmatrix}$ $\begin{pmatrix} \nu_\tau\,(2000) \\ \tau\,(1976) \end{pmatrix}$

3. Forces

Electromagnetic

Mass Generation

Box: Particles of the Standard Theory. The year of the first experimental observation is indicated next to each particle, but for the "classical" ones (the electron, the muon, the nuclear beta decay neutrino and the three quarks of Gell-Mann and Zweig).

In the Standard Theory, the Electromagnetic and weak forces are unified in a simple scheme and all the three forces are determined by the same principle: the invariance under transformations which may very arbitrarily from point to point (in jargon, a gauge symmetry). This similarity is a strong hint that it may be possible to discover a more unified scheme which encompasses all forces, including the Higgs and, most important, the gravitational forces. New dynamical concepts and new symmetries will be certainly required to accomplish this very ambitious further step in our knowledge of Nature.

2. Colliders

To illustrate the potential of particle accelerators, Fermi considered in his seminar a proton accelerator running on a maximum circle around the Earth. With a magnetic field of 2 Tesla, this gives an energy $E_{Max} = 5 \cdot 10^{15}$ eV. It is the energy of the cosmic rays around the 'knee', the most energetic cosmic rays that can be accelerated by the galactic magnetic clouds, according to Fermi's ideas developed in the very same years.

By extrapolating from the plots of energy or cost vs. time of the nuclear installations of the time, Fermi concluded that this energy could be reached in the year 1994, at a cost of about 170 billion US dollars.

The key to high energy and relatively low cost (very low indeed, compared to Fermi's extrapolation) has been, of course, technological innovation, above all the invention of "colliders", structures which are capable to accelerate and store two beams of particles, then made to collide head-on at a few, fixed points. The discovery has made possible a gigantic leap forward in the energy available for the collision, the energy in the center of mass, which in turns determines the discovery potential of the machine[2].

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[2] For relativistic particles, the c.o.m. energy in the fixed target mode is $\sqrt{2E_{beam}M_{target}}$, while for two symmetrically colliding beams is $\sqrt{4E_{beam}^{(1)}E_{beam}^{(2)}} \simeq 2E_{beam}$. Thus the available energy increases much faster with E_{beam} in the second case. Colliders, on the other hand, pose enormous technological challenges to achieve sufficiently high density of beam packets and to store them for enough time, so as to have an appreciable number of collisions.

The first electron–positron collider was realized in Italy, at the Frascati National Laboratories (AdA, 1962) by Bruno Touschek and collaborators. Proton–proton (ISR, CERN, 1971), proton–antiproton ($Sp\bar{p}S$, CERN, 1981) and electron-proton (HERA, DESY, 1992) colliders followed.

Transforming back to the fixed-target energy, the Tevatron (proton-antiproton collider, 2 TeV in the c.o.m.) reached 2 10^{15} eV in 1987. LEP (electron-positron, 200 GeV in the c.o.m.) and HERA (electron-proton, 300 GeV in the c.o.m.) have explored about the same energy range with probes unthinkable at Fermi's time. The Large Hadron Collider (LHC, proton-proton collider with 14 TeV in the c.o.m.) will reach 1 10^{17} eV in 2006, 20 times E_{Max}, at an all-out cost of about $5 billion.

If the VLHC which is being considered today at FermiLab or the Eloisatron proposed by INFN will be realized, with a center-of-mass energy of 200 TeV and a corresponding to fixed-target energy around 2 _ 10^{19} eV, mankind will have been able to produce collisions at an energy equivalent to that of the highest-energy cosmic rays that can originate from nearby galaxies[3].

3. Symmetry in Particle Physics

On the theoretical side, *symmetry* has been a crucial concept to investigate the role of the new particles.

In plain language, symmetry implies well-balanced proportions (from the Greek words *sym*, 'with', and *metros*, 'measure'). Symmetric objects have grace and beauty. The most beautiful vistas, whether faces or buildings, are the most symmetric, the most perfect. What is more important for us, the natural balance of symmetry leads to *predictability*. We can guess a hidden part of a figure, if we know the symmetry, which supervises its design.

[3] i.e. those below the GZK cut-off due to the onset of □-meson production in the scattering of cosmic ray protons off the microwave cosmic background photons.

Symmetry is demanding. The slightest fault, and the symmetry is no longer faithful. The picture in Fig.2 (Pala della Misericordia) looks left right symmetric at first sight, but this is not exact. The Madonna has an asymmetric belt's knot; the praying figures are not symmetrical. Most important, the figure is illuminated from one side. The fully

Fig. 2. Pala della Misericordia. The real picture is shown (left) together with the artificially

reconstructed picture "predicted" by left-right symmetry, from the right half of the figure.

Fig. 3. La Madonna del Parto. The angels are left-right symmetric to great extent, except for the colours of their dresses, but the Madonna breaks the symmetry quite dramatically.

symmetric picture looks more flat, static and hieratic, the real Madonna is human and closer to us.

In the Madonna del Parto (Fig. 3), the angels are almost left right symmetric, but the different colours of their dresses give movement to the whole picture. And, of course, the Madonna in the centre is now "breaking the symmetry", with the wonderful curve associated to her maternity.

We still do not know why symmetry is relevant to physics, but predictability is the key of its success. To describe fully the complexity of the world, however, some of the most beautiful symmetries have to be broken. Fig.4 shows with a few examples the power of symmetry and the need for symmetry to be broken.

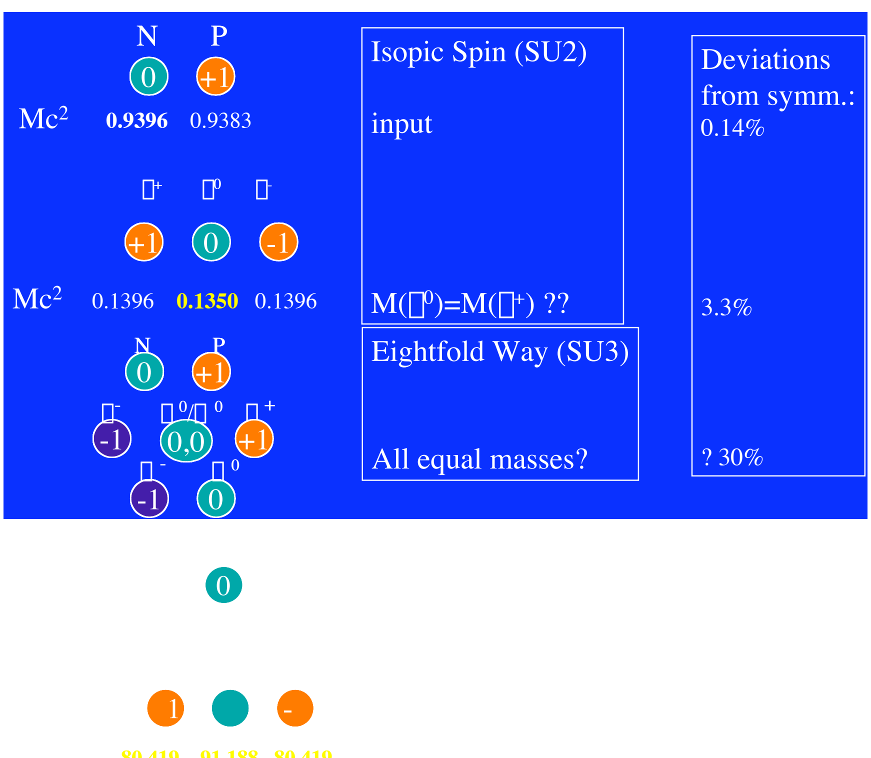
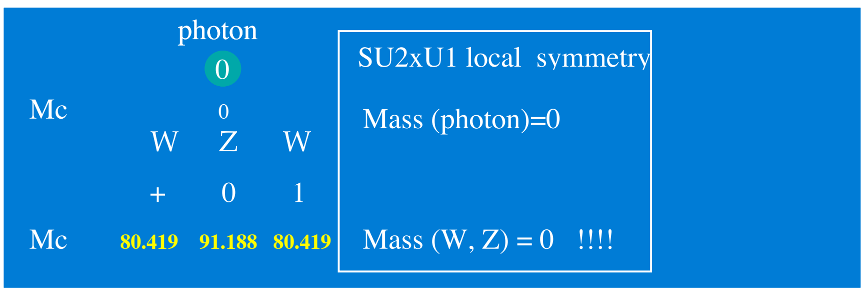


Fig. 4. Symmetry in particle physics: predictions vs. reality. Top: predictions of the approximate global symmetries in Particle Physics. Bottom: local symmetry predicts equal masses for the photon and for the intermediate bosons, in flagrant contradiction with reality.

4. Can we break a local symmetry?

Piero della Francesca could introduce variations at will in his symmetry pattern. But, is this possible in Nature? Is it possible at all to violate the symmetry? And if so, are there limitations?



There is only a numerable infinity of discrete symmetries (the "crystallographic groups"). Similarly, we can classify by numerable series the continuous groups. It would be relatively easy for God to assign a symmetry to the world! Symmetry breaking, instead, belongs to the realm of unpredictability, fantasy and chaos (is this why the Madonnas and angels of Piero are so fascinating?). In mathematical terms, symmetry can be broken in infinitely many continuous ways.

Seen in this context, the issue belongs to the wider philosophical question of the uniqueness of the fundamental laws of physics. Is there only one consistent set of laws and therefore only one consistent Universe? Or can we put arbitrary parameters in the basic laws such that there may exist, or at least we can "imagine", different, equally consistent Universes, distinguished by the actual values of these parameters (masses, electric charges, Newton constant)? We have made limited but interesting progress on these fascinating questions.

First, we have to distinguish between symmetries where the same transformation (say, a rotation) is applied at all points of space and time, the so-called "global symmetries", and symmetries where laws are invariant under transformations, which can be chosen differently from point to point in space and time. The latter are called ”local”, or “gauge”, symmetries.

There is essentially no restriction to violate any global symmetry. However, more important is the second case, which includes the Einstein Theory of gravity and the theories introduced by Yang and Mills in 1954 (the so-called "gauge theories"), known today to accurately describe the interactions of fundamental particles.

In these cases, introducing symmetry violations in the basic laws (technically, adding non-symmetric terms in the Action) leads to *mathematically inconsistencies*.

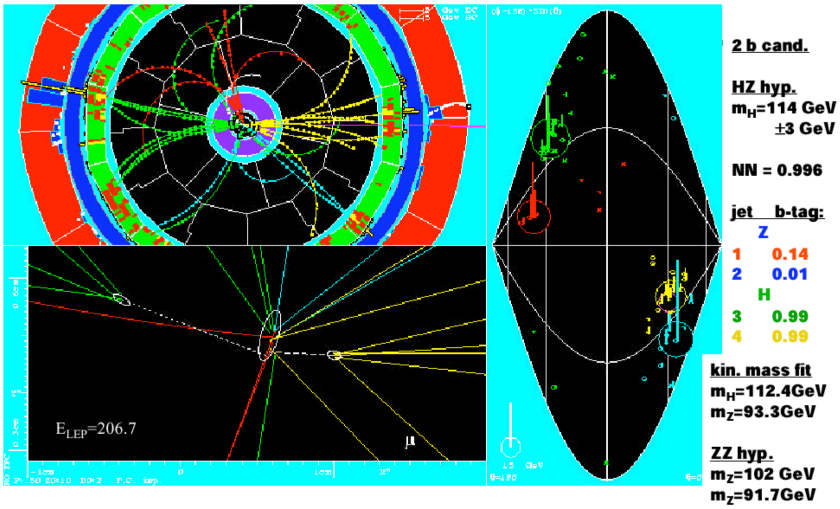
There are quite a number of qualifications to append to this very blunt statement, but I think my theoretical colleagues would agree that it describes correctly the situation: no Piero della Francesca has the freedom to "deform" even slightly the Yang Mills or Einstein basic laws.

But then, how are we going to account for the asymmetries observed in Nature, namely the unequal masses of photons, W and Z particles, or the masses of quarks and leptons, which also should vanish in the symmetric world? The solution is simple and fascinating.

A field pervades all space and affects the way particles move. Whilst the basic laws are exactly symmetric, the very presence of this field violates the symmetry, in that the field itself “distinguishes” different particles related by symmetry. By their interaction with this background field, W and Z acquire a mass but the photon remains mass less, leptons and quarks acquire different masses.

In this picture, the "vacuum", the state where “there is nothing”, is not empty at all. Rather, it is like the surface of a perfectly calm lake: there seems to be nothing because it is everywhere equal to itself. In collisions, waves can be produced on the surface of the lake, some of which correspond to a new particle: the Higgs boson. The Higgs boson is needed for the mathematical structure of the theory to agree with what we see in Nature, but the whole picture gives a description of vacuum which may lead us to a new vision of the Universe, in particular of the primordial Universe (inflation, chaotic Universe).

5. Higgs Hunting



I would not go so far as to call the Higgs Boson the "God particle"[4], but it is clear that the observation of this particle is crucial, to give solid foundation to our theory of Elementary Particles and to validate the more advanced views on the primordial Universe. This justifies the excitement that has pervaded the world of physics (not only!) when some tantalizing evidence of a Higgs boson was seen, last summer, in the ALEPH experiment at CERN.

Fig. 5. ALEPH: candidate event for $e^+ + e^- \to Z + H$, followed by $Z \to hadrons$ (jets 1 and 2) and $H \to b + \bar{b}$ (the dotted lines indicate the path of neutral unstable particles which decay in jets 3 and 4 and are identified as beauty particles); the decay into a beauty particle pair is the theoretically preferred decay mode of the Higgs boson and is used to select events which should contain this particle with higher probability.

The definitive analysis of the LEP data still shows some evidence of a Higgs boson, but the degree of confidence that the events seen are not due to a statistical fluctuation is smaller than what was indicated by the preliminary analyses made at the end of the year 2000. This dry scientific statement has recently given rise to a curious debate on a scientific journal, following a rather unrefined interpretation of the LEP data analysis given by its scientific editor, which reads[5]: " No sign of the Higgs boson. The legendary particle that physicists thought explained why matter has mass probably does not exist. So say researchers who have spent a year analysing data from LEP accelerator at the CERN nuclear physics lab near Geneva." The ensuing discussion has made it clear[6] the

[4] L. Lederman with D. Teresi, "The God particle", Dell Publishing, New York, 1993.
[5] New Scientist, 5 Dec. 2001.
[6] Edward Witten, Princeton New Jersey: "One question is whether the Higgs boson exists; the answer is almost certainly yes…" Michael Chanowitz Lawrence Berkeley National Laboratory: "I would argue even

importance of continuing the search with the TeVatron, at FERMI Lab in the US, and later with the LHC[7]. In one year running, the LHC will be able to clarify definitely the issue of the Higgs boson, not only the energy range indicated by the LEP events but also in all the wider energy range compatible with the present theory of particle interactions.

6. More symmetry at High Energy

The fundamental particles that we see in Nature feature different values of their intrinsic angular momentum, spin. Quarks and leptons, the constituents of matter, carry _ unit of spin, the Higgs boson and the particles that mediate the different forces carry integer values of the spin. Spin equal to zero for the Higgs boson, spin equal to one for the intermediaries of the strong, electromagnetic and weak forces, and spin two for the elementary quantum of gravity, the graviton.

In a truly unified scheme, all these particles should be related to each other by some symmetry, which then has necessarily to transform into one another particles with different spin, unlikely any other of the known symmetry transformations.

For some time it was believed that such a symmetry would be so restrictive that it would not be compatible with any possible interaction among particles, a clear absurdity. In the 70s, in Russia and at CERN[8] a completely new kind of symmetry, able to transform particles with spin differing by _ unit[9] was discovered and shown to be compatible with the usual laws of Quantum Theory and Relativity. The new concept was so remarkable that it was dubbed Supersymmetry (later SUSY for brevity), to distinguish

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more strongly that the precision data does not support the standard model prediction of the mass of the Higgs boson, based on my recent analysis of the data (*Physics Review Letters, vol* 87,p 23802). The standard model may well be "dead" but the Higgs boson can survive, accompanied by other--as yet unknown--new physics. Until the nature of this new physics is known, we cannot predict the mass of the Higgs boson". John Ellis, CERN: "Those measurements suggest strongly that the particle weighs less than about 200 gigaelectronvolts (GeV). Direct searches for the Higgs boson at LEP tell us that it must weigh more than about 114 GeV, leaving plenty of space for it to exist… You quote John Swain as being prepared to bet large amounts of money that the Higgs boson will not be found: many of us particle physicists are each prepared to bet £100 against him. Let us see how much money he is prepared to put where his mouth is!"

[7] See finally the article by G. Kane and E. Witten, New Scientist, 30 March 2002.

[8] by XX. Volkov and XX. Akulov and by J. Wess and B. Zumino, respectively.

[9] As a consequence, the generators of Supersymmetry obey anti-commutation relations, unlike the generators of a usual symmetry; it is precisely this anti-commuting property that allows super symmetry to escape the no-go theorem alluded to before (due to S. Coleman and J. Mandula theorem) and permits relativistic, supersymmetric field theories with non vanishing interaction.

it from normal symmetries, and the properties of quantum field theories enjoying such a symmetry have been systematically studied since then. It was also found that theories with local SuperSymmetry must necessarily encompass gravity, which shows that this concept provides the natural bridge between particle forces and gravity.

Two new aspects have been brought into this matter during the 80's. The first one is a stability condition on the Higgs boson mass that requires that the supersymmetry partners of the known particles have to appear in a mass range of the order of 1 TeV (1TeV=1000GeV). This is very attractive indeed. While there is little doubt that Supersymmetry must apply in the real world, because of unification with gravity, the particles characteristic of this symmetry could be so heavy as to escape being produced at the energies reachable with particle accelerators.

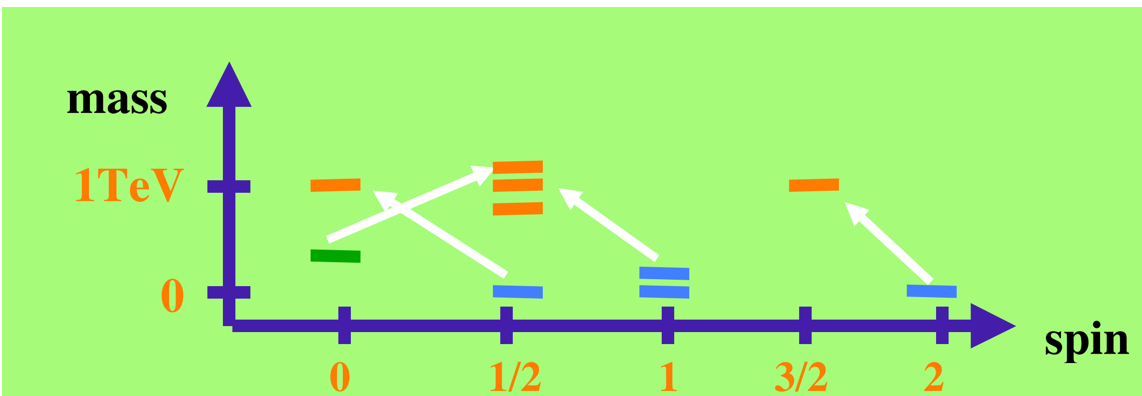

Fig. 6. The spectrum of particles of different spin in SUSY theories. The lowest level is filled by the particles of the Standard Theory (Higgs boson, quarks and leptons, vector bosons and the gravitons, with spin 0, 1/2, 1 and 2, respectively). Each of these particles has a SUSY partner with a spin differing by _ unit and a mass of the order of 1 TeV. At present, we have only experimental lower limits to the masses of SUSY partners, of the order of some 100 GeV, obtained from the non-observation of any such particle at LEP, the Tevatron and Hera.

The second element has been the observation of large quantities of non-radiating (dark) matter in the Universe. The dark matter makes large massive halos around Galaxies and it accounts for the largest fraction of the matter in the Universe. The dark matter is "seen" by its gravitational effects, but it seems very unlikely that it is made by usual atoms, nuclei etc. Rather, it could be made by heavy, electrically neutral particles, which have only a very weak interaction with the normal matter or with the electromagnetic field and that are remnants of the Big Bang. The SUSY partners of the Higgs boson or of the vector bosons could be ideal candidates as constituents of the dark matter, and again a mass scale of 1 TeV would be consistent with the dark matter cosmological properties and distribution.

The arguments just mentioned indicate that SUSY particles may form most of the Universe's mass and appear in a range accessible to the accelerators of the next generation. In particular, the LHC should cover most of the energy range where such particles are predicted to appear. The search for signals associated with the SUSY partners of quarks, leptons and gluons is an essential part of today's high-energy frontier.

7. How many dimensions?

In the '30s, P. Kaluza and O. Klein, in an attempt to write a unified theory of electromagnetism and gravity, made the hypothesis that our physical space has one more additional dimension. If the subspace corresponding to the additional dimension is "curved" upon itself, with radius R, waves of wavelength larger than $2\pi R$ could not be fitted into it, therefore ordinary light would not propagate in the additional dimension and we would not perceive it. Similarly, if R were much smaller than the typical wavelengths of our electrons and nuclei, according to the wave mechanics of De Broglie and Schrödinger, normal matter would be prevented to move into the new dimension. Only very energetic particles, with momentum $p >> h/(2\pi R)$, with h the Planck constant, would be able to "feel" a space with more than 3 dimensions.

For a long time, the Kaluza Klein (KK) idea has remained an intriguing but unwarranted hypothesis. The situation changed when it was found that the "string theories", the best available candidate theory for unifying gravity with quantum mechanics, do require a high dimensional space to be mathematically consistent. All of a sudden, we learn that the KK idea is not only possible, but it is in fact required.

Only waves of wavelength such that $\lambda = (2\pi R)/n$, with integer n, can propagate in the additional dimension, corresponding to a momentum[10] $p_5 = n\, h/(2\pi R)$. A mass-less

[10] We consider a space-time with one time-like and four space-like dimensions; the additional curved dimension is labelled as the fifth dimension.

particle in the full 5-dimensional space-time would have a momentum, which satisfies the Einstein null condition ($\vec{p}$ represents the usual three-dimensional momentum):

$$E^2 - (\vec{p})^2 - (p_5)^2 = E^2 - (\vec{p})^2 - (n\frac{h}{2\pi R})^2 = 0$$

that is:

$$E^2 - (\vec{p})^2 = (n\frac{h}{2\pi R})^2 \equiv (M_n)^2$$

This result means that each mass less particle in normal space, like the photon, the graviton, etc, is accompanied by a “KK tower” of massive companions, with mass M_n (n=1, 2 etc.) which are called its KK excitations. KK particles are stable if the extra component of momentum is conserved (as it happens for the usual momentum). These particles must be rather heavy on particle mass scale (say more than a few hundred GeV) and therefore R must be rather small, since otherwise we would have seen their effects, in particular there would be a lot of such particles as remnants of the Big Bang.

In high-energy collisions, if energy were enough, we would start producing the low-lying excitations. As energy, and n, increases we would be sending wave packets of smaller and smaller wavelength in the new dimension, and we would explore it with finer and finer resolution. While particles are turning around the curved dimension, our macroscopic detectors would see energy and electric charge disappearing into nothing and coming back (periodically) from nothing. Together with the observation of the typical spectrum of KK excitations of mass M_n, the lack of energy and charge conservation in our three-dimensional space would be a most unique sign of the existence of new dimensions.

Recently, the issue of additional dimensions has taken a dramatic turn with the realisation that in most string theories, particles associated with normal matter (electrons, quarks, photons, gluons, etc.) are confined to a three-dimensional surface in multidimensional space, called a p-brane. In the simplest version of such theories[11] gravity only can extend to the full space. In this case, there is no need for a microscopic radius of curvature to avoid us going in the new dimensions, confinement to the p-brane assures it. The only limit to the radius arises from the fact that the Newton law we

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[11] N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Lett. B 429, 263 (1998).

observe with macroscopic bodies (force inversely proportional to the square of the distance) is itself indicative of a three-dimensional space. But we have checked Newton's law only down to distances of millimetres or, more recently, microns[12]. This leaves open the issue of a macroscopic KK radius R!! Gravity in the full multidimensional space would be still characterized by a constant of the dimension of a mass, but if the radius is large, this constant could be of the order of 1 TeV, thus eliminating the disparity of scale between the W mass (about 0.1 TeV) and the mass which characterizes gravity in three dimensions, the so-called Planck mass of order 10^{16} TeV.

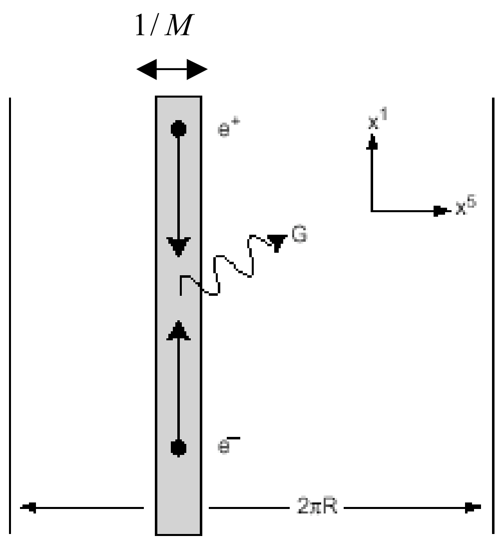


Fig. 7. In certain string theories, normal particles are dynamically confined to a p-brane (represented as a grey slab in the figure[13]) while gravity can propagate in the full space. The extra dimension could even be macroscopically large. Deviations from the Newton's law, the gravitational pull between two bodies at distance r decreases proportionally to $1/r^2$, are expected for values of r of the order of or smaller than the radius of the extra dimension, R. The present experimental tests of the Newton's law leave do not exclude this possibility for R of the order of a micron, or smaller.

[12] C. D. Hoyle et al., Feb. 2001.
[13] L. Hall, ICHEP2000, Osaka.

If this picture were true, the mass of KK excitations of the graviton would be way smaller than in the other case. Also they would not be stable, since the d-brane can absorb any momentum in the additional dimensions. In fact, one could ask if reactions like:

$$e^+ + e^- \rightarrow \gamma + (KK\ tower\ of\ gravitons)$$

are already occurring at LEP. If one can produce excitations of the graviton up to very high order, a large cross-section would result. This process would then produce a typical distortion at low energy of the photon spectrum in the reaction:

$$e^+ + e^- \rightarrow \gamma + (unobserved\ particles)$$

with respect to what predicted by the Standard Theory. No distortions have been observed so far at LEP.

The LHC would push further the limit on the additional dimension (or observe it!) with the study of reactions like:

$$P + P \rightarrow gluon + (unobserved\ particles)$$

8. The Large Hadron Collider

Started in 1996, the construction of the Large Hadron Collider proceeds at full speed at CERN. The LHC is a proton-proton or ion-ion collider to be housed in the 27 km underground circular tunnel nearby Geneva, where the LEP collider has been operating until the end of the year 2000. The design energy of each proton beam is 7 TeV, corresponding to the design magnetic field of 8.1 Tesla in the super-conducting dipoles that keep the protons in circular orbits inside the tunnel. Oppositely circulating beams cross in eight fixed points around the circumference, four of which are reserved for the experiments. Protons are packed in very dense bunches which are stacked in the orbit at intervals of about 7.5m in space (25ns in time) from each other. Very high design luminosity is foreseen, of $10^{34}cm^{-2}sec^{-1}$. At this luminosity, there are about 30 elementary proton-proton collisions at each bunch crossing and correspondingly a very high flux of secondary particles bunched with a 40 MHz frequency.

The limited transverse size of the tunnel and the need of very high magnetic field have required an innovative and compact design for the accelerator.

Each dipole has two parallel apertures, which house the vacuum pipes. Coils are designed so that the magnetic field is oriented in opposite directions in the two apertures. Therefore, two independent proton beams can run in opposite directions inside the same dipoles.

A current of 12 kA is circulating in super-conducting cables, kept at 1.8 ^{0}K by super-fluid Helium. Cables are made of Ti-Nb filaments, imbedded into a copper matrix.

In turn, the super-fluid Helium is distributed by a cryogenic line, which runs in parallel to the dipoles.

One problem of high-energy, high-field cryogenic machines is synchrotron radiation. Increasing with the fourth power of energy, synchrotron radiation in the LHC deposits about 0.2 W/m. In cryogenic machines, this power is expensive to carry away, due to the low temperature of the walls where it is to be dissipated (thermal capacity goes like the fourth power of the absolute temperature). For this reason, in the LHC, there is an inner beam screen kept at about 19 K (gaseous helium cooling), considerably higher than the 1.8 K temperature of the cold mass of the dipoles.

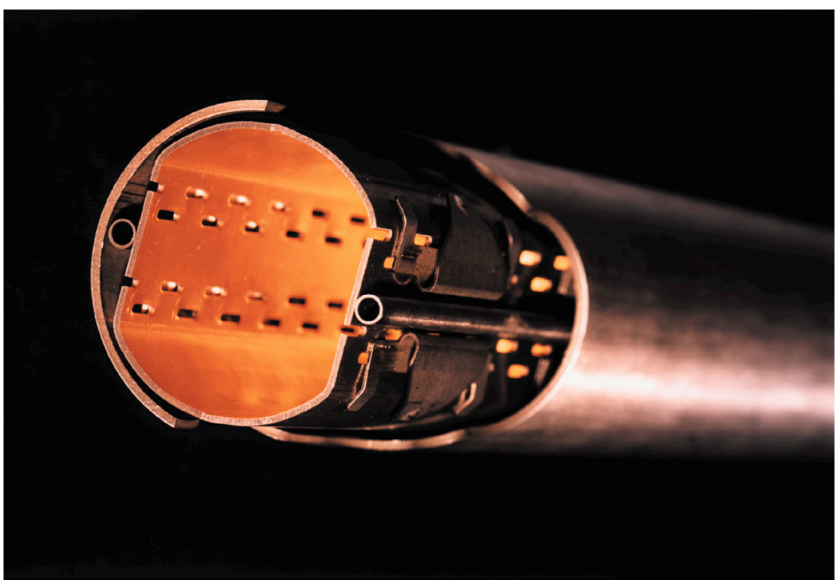


Fig. 8. In high-energy cryogenic proton machines, the power deposited by synchrotron radiation is difficult to remove because of the low temperature of the dipoles, 1.8^{0}K. In the LHC the heat is deposited on the an inner tube, which is kept at 19^{0}K by gaseous helium coolant circulating in the small tubes visible on both sides of the inner tube.

There are in all 1236 dipoles. Alternating with the dipoles, the super-conducting quadrupoles complete the main magnetic structure of the LHC. The basic cell of the structure is 120m long (with 6 dipoles and 2 quadrupoles). Fig. 9 shows an artist's view of the LHC.

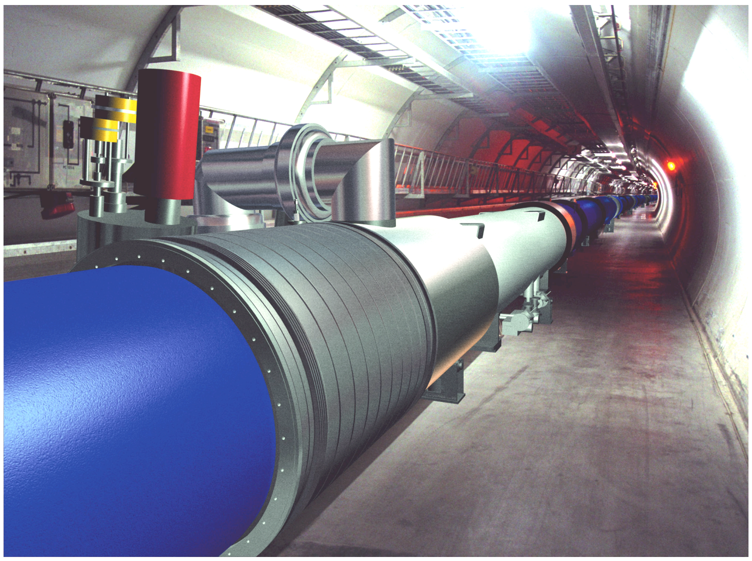


Fig. 9. Artist's view of the LHC. Dipoles in blue, quadrupoles in white. The cryoline is not visible, except for the grey tube shaped at right angles, which feeds the super fluid He in the cryostats of the magnets.

A half-cell of the LHC (called String2) is at present operating at CERN, with dipoles and

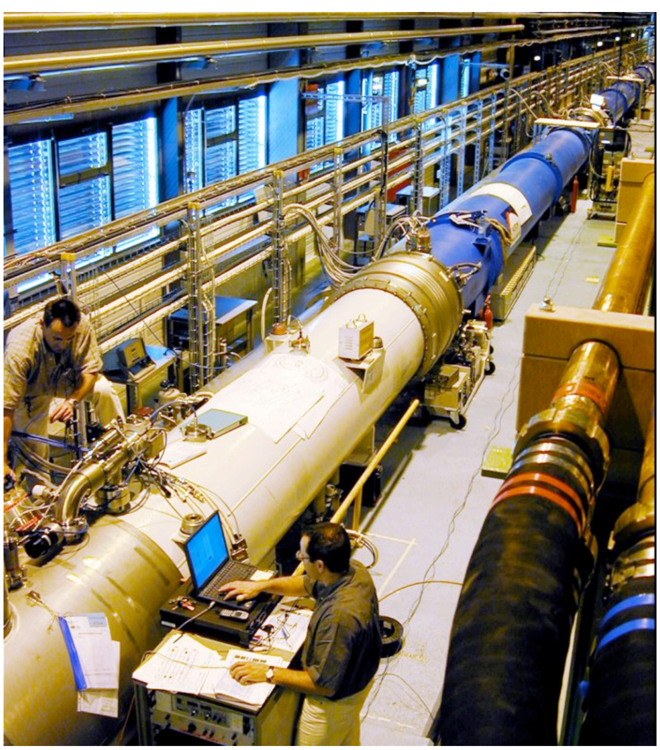


Fig. 10. A view of String2 in the SM18 Hall of CERN (September 2001).

quadrupoles of the final design, to test the properties of the very complex magnetic system. Fig. 10 shows a picture of String 2 at the end of 2001. String2 has been operated for the first time on Sept. 27, 2001, when it has reached successfully the 12 kA current, corresponding to the nominal magnetic field (and energy) of the LHC.

At the moment of writing (April 2002) the R&D and prototyping phase is definitely competed. The main industrial contracts (cables, dipole assembly, cryogenic line) have been adjudicated and signed; industrial production and installation have started. It will be quite a remarkable enterprise. The production of super conducting cable for the LHC amounts to little less than 30% of the world production.

The excavation of the two big halls for the general-purpose experiments, ATLAS and CMS, is well advanced, after several problems, in particular for the CMS cavern.

Fig. 11. The vault of the ATLAS cavern (September 2001). The concrete vault is suspended with cables, to allow for the excavation of the lower part of the cavern, down to some 30 m below the ground level shown in the picture. The ATLAS cavern is the biggest in the world to be excavated in the type of rock (molasse) present below CERN.

The caverns will be handed over to the experimental collaborations in April 2003 (ATLAS) and July 2004 (CMS).

A new schedule for the commissioning of the LHC has been recently defined, which foresees the super-conducting dipoles completed in mid 2006 and the first physics in 2007. The schedule is based on the contractual dates for the main items.

In 2001, the LHC has gone through a mid-project review of the cost to completion. The review indicates some 20% global extra cost for the machine hardware and installation and for the preparation of the experimental halls. A discussion is going on between Council and CERN Management to compensate for the extra costs, which envisages a plan for savings, the reduction of non-LHC activities and consequent budget reallocation to the LHC and the prolongation of the period of payments up to the year 2010.

9. Experiments at the LHC

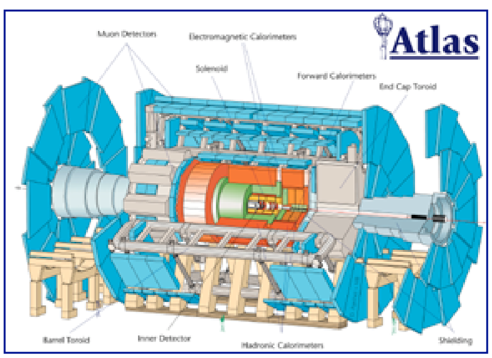
The effective energy in proton-proton collisions is directly related to the energy carried by the proton constituents, quarks and gluons. In turn, the constituent density decreases as its energy approaches the proton full energy. The collision probability itself, in addition, decreases with constituent energy. Thus the energy range that can be explored with a proton-proton collider is considerably limited with respect to the nominal beam energy. However, with a given beam energy and a given running time it is still possible to observe the interactions of the harder constituents, *provided* we have enough proton collisions per unit time, i.e. a sufficiently high luminosity. Luminosity can be traded for energy. At a given beam energy, as luminosity goes up the interactions of the harder constituents become more and more visible and the machine potential for discovery goes also up.

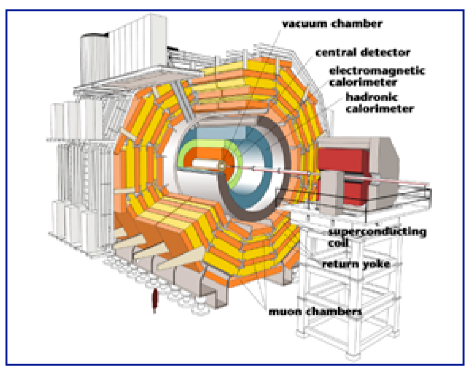
This concept is particularly important for the LHC, which had to fit in the existing LEP circular tunnel, of a radius of about 4 Km. With the magnetic field also limited by the available technology to 8-9 Tesla, the luminosity handle has been vital to extend the discovery potential of the machine well inside the TeV region, where signals of new physics are expected.

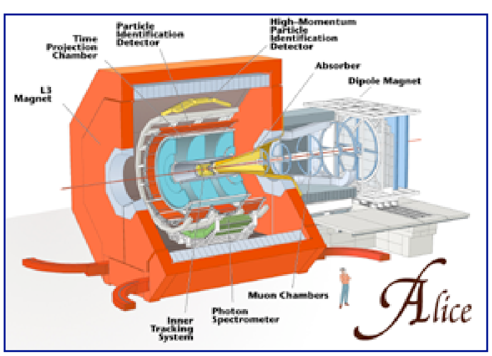
From the start, the LHC has aimed at values of luminosity one order of magnitude larger than what could be considered as "normal" for proton machines, and what detectors of the time could stand. To design detectors capable to face the luminosity challenge, a large R&D program and important conceptual developments have been required. Key issues have been radiation hardness and capability to handle the enormous flux of information, which goes through the detectors (the products of 30 high-energy collisions repeating at 40 MHz frequency). The programme has produced very innovative detectors, now in the phase of industrial production, and is essentially over.

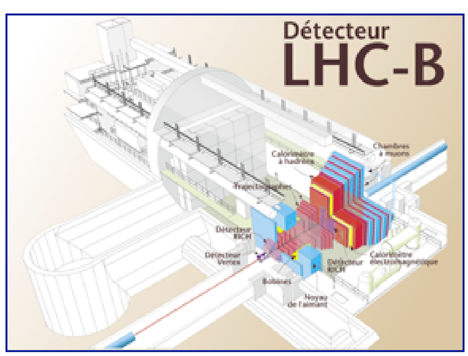
Four experiments are foreseen at the LHC. Two general-purpose detectors, ATLAS and CMS, to search for the Higgs boson, signals of super-symmetric particles and what ever else may be found at high energy.

A smaller size detector, ALICE, is designed to study the high-









energy heavy ion

Fig. 12. Artist's view of the four LHC detectors.

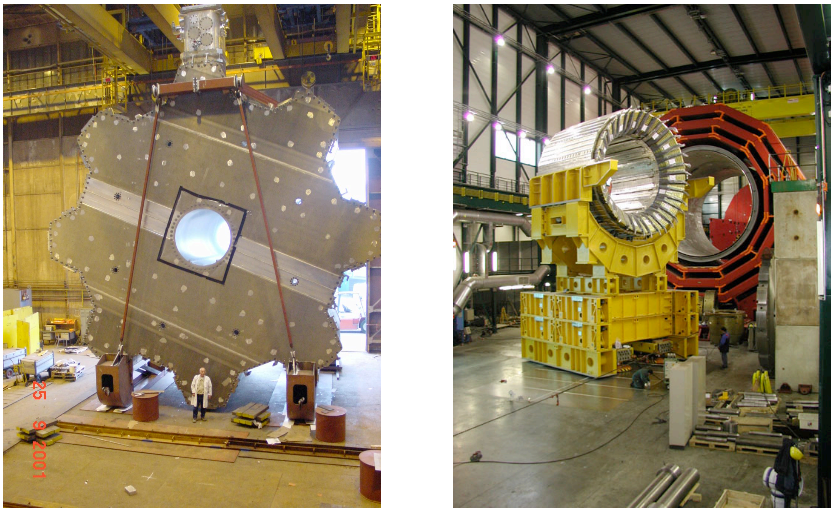
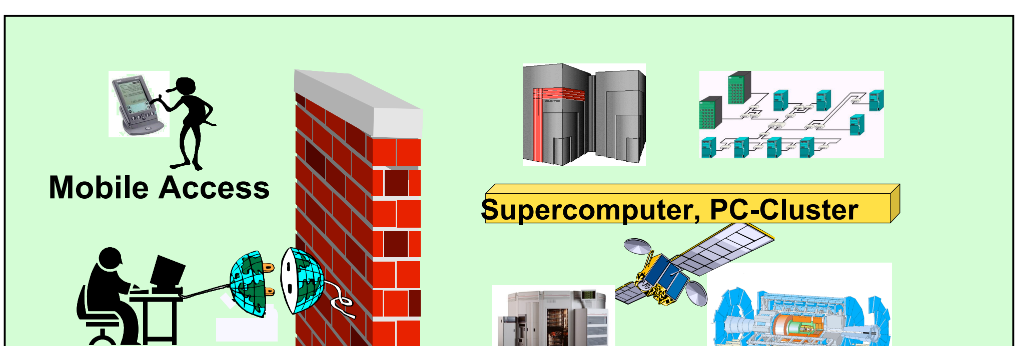


Fig. 13. Left: the ATLAS End-Cap cryostat during construction. Right: parts of the CMS detector being assembled at CERN.

collisions. At these energies, the collision is supposed to produce a new state of nuclear matter, the quark-gluon plasma, where quarks and gluons are not confined inside hadrons as it happens at low temperature. Hints of the new phase have been observed at CERN, with the SPS, and similar collisions, at higher energy with respect to the SPS but still lower than those of the LHC, are being studied at the Relativistic Heavy Ion Collider, RHIC, Brookhaven. Finally, a fourth detector, LHC-B, is optimised for the study of CP violation in decays of particles containing the b quark, extending and completing the studies which are being done at present with the so-called B-factories, in the US and in Japan.



10. Conclusions

Many of the problems that Fermi could enumerate in the fifties have been solved by the Standard Theory, notably the composite nature of the many hadronic particles (proton, mesons and so on) the common origin of the weak and electromagnetic forces. The next generation of accelerator should shed light on the new problems that the Standard Theory leaves unsolved.

There are many fascinating discoveries waiting for us in the High Energy Frontier. They range from what we could define as «*normal business*» - finding the Higgs boson or discovering low-energy SUSY - to «*new world*», like finding that there are extra dimensions in our space-time.

The High Energy frontier does not exhaust particle physics. We certainly need to understand the physics of flavour better, that is neutrinos and the origin of matter antimatter symmetry violation.

Developing new tools for particle acceleration is still the key to affordable high-energy. More than ever, we need to support research in the field of particle accelerators, in the big laboratories, like CERN, but also, and most importantly, in our Universities.

As for the strategy, a consensus is emerging on the roadmap to High-Energy Physics. First, and most important, the LHC has to be completed as soon as possible and exploited. The LHC is supposed to give us the much-needed indication of what is the solution to the problem of particle masses (the Higgs boson?) and of the hierarchy of mass scales (SUSY?). The complete exploration of the sub-TeV region, particularly in the lepton sector, requires in addition a high luminosity, e^+e^- Linear Collider in the class which is now arriving to technological maturity (either based on super-conducting cavities as in the TESLA project at DESY, Germany, or on warm cavity technology of the NLC at SLAC, US, and of the JLC at KEK, Japan).

The next step would be a Multi-TeV accelerator, something for which we do not have the appropriate technologies, yet. The most advanced study today refers to the two-beam accelerating principle for electrons developed at CERN (the Compact LInear Collider project, CLIC), capable to produce field gradients in excess of 150 MeV/m (i.e. 3 TeV over 10km!). A Very Large Hadron Collider, a proton-proton collider with 200 TeV c.o.m. energy has been considered in Europe (the Eloisatron project) and is studied at Fermi Lab, in the US. Proposals and studies of a $\square^+ \square^-$ collider are being entertained in US and, to a minor extent, in Europe but are still in their infancy.

On the flavour physics side, the violation of matter-antimatter symmetry, now studied with the so-called B factories at SLAC and KEK, will be continued with the LHC.

A long baseline neutrino beam exists in Japan (K2K, from KEK to the Kamioka underground laboratory) others are being built in CERN (from CERN to Gran Sasso, in Italy) and FermiLab (from FNAL to the Soudan mine). Studies for the production of very intense neutrino beams (Neutrino-factory) are carried on in the US and in Europe, to produce a new generation of long-baseline neutrino beams, such that could be detected in underground laboratory placed at distances of some thousand kilometres. Similar developments are considered in Japan, in connection with the construction of a very intense proton source, the Japan Hadron Facility.

Can we realise the ambitious plans I have just described, in a reasonable time, say 15 to 20 years? Can we afford? It is becoming more and more clear that new mechanisms for international collaboration are needed, carrying further what has been done for the LHC. Better efficiency is needed in decision-making, now leaved to separate negotiations inside each region (Europe, US, Japan) and to difficult approaches between different regions. Also, mechanisms must be found to follow the User distribution, in order to keep in the picture the young generations, which are formed in the Universities.

To realize the full programme, a transition to a new global organisation may be necessary, similar to the transition that Europe underwent, from National Laboratories to CERN. The wide discussion, which has started in these years, gives reasons to believe that a solution may be not too far.