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DOSSIER

AVANCÉES EN PHYSIQUE DES PARTICULES : LA CONTRIBUTION DU LEP
ADVANCES IN PARTICLE PHYSICS: THE LEP CONTRIBUTION

Foreword

1. The pre-LEP era in particle physics

The goals of particle physics is the identification of the basic constituents of matter and the study of the fundamental interactions between them. As such, advances in particle physics result from a subtle, but powerful, interplay between experimental and theoretical works. One of the major successes during the LEP [1] era has been the strengthening of this interplay, leading to very fundamental results which could not have been produced from theory or experiment alone. Before discussing the broad pattern of the physics produced in the nearly 12 years of LEP operation, it is instructive to be briefly reminded of the progress in particle physics before LEP came into operation.

In the 1960s, particle physics was lacking a sound theoretical framework in order to describe particle interactions at a fundamental level, except for electromagnetic interactions of charged leptons and photons with quantum electrodynamics. The major progress in connection with experiment was the identification of internal degrees of freedom for the hadrons (strongly interacting particles) corresponding to global symmetries. Thus the spectroscopy of hadrons led to the concept of quarks as possible fundamental building blocks inside the composite hadrons. The real turning point occurred in 1969–70 with the experimental discovery of point-like charged constituents inside protons and neutrons. The renewed experimentation in the 1970s focussed on this aspect and the properties found for these constituents soon matched the expectations from the spectroscopy-inferred quarks. With the discovery of a fourth type of quark – the heavy 'charmed' quark c – in 1975–77, the quark level of hadronic matter was firmly established. And to make things even more clear, a third charged lepton (τ) and a fifth quark (b) were discovered in 1976–77, conforting the new idea of lepton-quark symmetry.

It also turned out that, for the first time, the two aspects of particle physics became intimately linked, as this fourth quark had been predicted from theories concerned rather with the structure of the fundamental interactions. In fact, the seventies were marked by the advent of quantum gauge theories, where interactions are generated from invariance under geometrical transformations. The so-called Standard Model of particle physics describes, on the one hand, electromagnetism and the weak interactions in a unified way by a gauge theory based on the group $SU(2) \times U(1)$ and, on the other hand, the strong interactions among quarks by another gauge theory, soon called quantum chromodynamics, based on the group $SU(3)$. The discovery of neutral currents in the interactions of neutrinos at CERN in 1973, implying the exchange of a neutral weak boson (Z^0) was a dramatic confirmation of the electroweak model.

The highlights of the 1980s have been the discovery at DESY of the gluon, the spin-1 photon-like carrier of the strong force between quarks and the confirmation of the unified electroweak model. First, the expected photon–Z^0 interference was demonstrated in electron–nucleon interactions, through parity violation in scattering experiments at SLAC and also in atomic transitions (ENS-Paris), then for all leptons in e^+e^- annihilation at DESY and SLAC. Finally, the long-awaited heavy weak bosons were discovered at CERN in a heroic effort to transform the large synchrotron SPS into a proton–antiproton storage ring: the charged bosons, $W^\pm$, in 1983, then the neutral one, Z^0, a year later. The stage was set for precise studies of the gauge interactions for which the LEP accelerator was designed and uniquely suited.

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2. The LEP project

The principle of a large electron–positron storage ring with energies in the centre-of-mass E_{cm} close to the Z mass ($\sim$90 GeV) was first proposed by B. Richter. The idea is simple: electromagnetic cross sections decrease with E_{cm}, while weak cross sections have the opposite behaviour in the local limit; hence they are expected to cross over, and this crossing should occur close to the electroweak unification scale. If unification is indeed achieved, a huge resonance peak should be seen at the Z mass close to the unification scale, preventing the weak amplitude from continuing its growth as the interaction would no longer be local.

The construction of the LEP machine was a formidable challenge. Its large size – 27 km circumference – was dictated by the need to keep the synchrotron radiation at a reasonable level as the radiated energy has to be restored to the beam in radiofrequency (RF) accelerating cavities. At the same time the orbits of the stored particles had to be kept very precise, requiring the development and the operation of numerous beam-position monitors. Although LEP was unusually large, the basic principles for such an instrument had been established through pionneering projects in Frascati, Orsay and Novosibirsk. In fact, the functional elements to be found around the LEP circumference – bending magnets, focussing quadrupoles, RF cavities, intersection regions – can be easily seen on the small ACO machine in Orsay, now a registered historical landmark. A LEP prototype, at the 1% scale! The LEP machine was designed for 200 GeV in the centre-of-mass in order to permit the production of W^+W^- pairs. The project was led and brought to completion by E. Picasso.

The LEP physics programme was planned and laid out very early. It is outlined in the 1976 Yellow Book [1] where most of the basic phenomenology can be found. The real starting point was a very successful workshop in Les Houches (1978): experimentalists and theorists met and discussed the physics goals and the means to best achieve them. Most of the physics results produced at LEP more than 10 years later can be traced back to these early studies of the required experimentation [2]. Several workshops were organized in the decade during which LEP was constructed. Thus the scientific community around LEP was progressively built up, attracting the best particle physicists in Europe and around the world. Four large detector projects were selected by CERN in 1982 among six proposals. By the time LEP was turned on in July 1989, they were all operational and ready to start a decade-long period of data taking.

The LEP exploitation was essentially done in two phases. From 1989 to 1995 LEP was operated at energies close to the Z resonance (LEP1), mostly on the peak to maximize the event rate, but also around in order to measure precisely the resonance shape. Starting in 1995, the energy was progressively raised, following the ongoing installation of superconducting RF cavities (LEP2). The highest energy of 209 GeV, dictated by the search for the Higgs boson, was reached in 2000.

The LEP machine was the ideal facility to study with unprecedented accuracy the predictions of the Standard Model of particle physics. The main contributions of the LEP experiments are now briefly examined.

3. LEP physics: the electroweak sector

At LEP1, 16-million Z decays have been reconstructed and identified. The mass and width of the Z resonance have been accurately determined. The obtained uncertainty on M_{Z} is 2.1 MeV, i.e., a relative precision of 2.3×10^{-5}. This impressive achievement opened a new way to test the Standard Model, because the Z mass could be used as input to calculate other observables that could be in turn accurately tested against the direct measurements. Since the Z boson decays into all fermion pairs, except the heavy top quark, it has been possible to measure all the fundamental electroweak couplings.

At LEP2, the main interest was the study of W pair production and the precise determination of its mass, thus offering another testing ground for the electroweak theory. Throughout LEP1 and LEP2 phases, a major effort was the search for the Higgs boson, the only remnant in the Standard Model of the scalar fields responsible for breaking the electroweak symmetry.

The important achievements in the electroweak sector can be summarized as follows.

- **The leptons and quarks are found to be universally coupled to the Z boson.** In the same way as the electric charge is a universal parameter, the weak couplings do not distinguish, to an accuracy of a few per mill, the different leptons or the different quarks of the same electric charge. Once the latter is specified, all couplings are defined by the electroweak unification at the level of each family of leptons and quarks. However, the fact that the theory applies universally to the different families has received so far no explanation: the electroweak theory is built at the level of the first family of leptons $(\mathrm{e}, \nu_{\mathrm{e}})$ and quarks (u, d) and the other families just look like replications of the first one with higher masses. Is a new symmetry responsible for this pattern?
- **The number of families is found to be equal to 3.** No new charged lepton beyond the first three and no new quark have been found up to masses of 45 GeV. In fact the internal consistency of the precision tests rules out the existence of new fermion families of the known type. The most powerful constraint on the family number comes from the direct determination of the number of light neutrino species, found to be equal to just three. Why three families? Again the standard theory does not provide any information on this, except for the fact that at least 3 families of quarks are needed to incorporate CP violation in the Standard Model. Indeed the unitary Cabibbo–Kobayashi–Maskawa (CKM) matrix, describing the weak charged couplings of quarks becomes complex when the number of quark doublets exceeds 2. Thus Nature seems to have chosen the minimum number of families consistent with CP violation.
- **The electroweak gauge theory is tested at the quantum level.** Higher order contributions in perturbation theory, occurring through fluctuations from pairs of virtual particles are indeed observed according to the theory. This effect is the quantum analogue of the polarization of a dielectric medium placed in an electric field. It is well known in electrodynamics, where the vacuum is polarized by virtual $\mathrm{e}^+\mathrm{e}^-$ pairs, and it should occur in any field theory such as the electroweak theory. The vacuum polarization leads to a modification of the interaction strength which depends on the energy scale of the studied process. Thus by performing accurate mesurements, it is possible to feel the effect of these higher order corrections and deduce from them the presence of as yet undiscovered particles. One of the most spectacular result of LEP has been *the indirect determination of the top quark mass from precision measurements of the couplings*. The LEP value turned out to be in excellent agreement with the direct measurement performed later at FNAL in Chicago, profiting from the much higher energy of their proton–antiproton collider.
- **Likewise, the mass of the Higgs boson can be indirectly determined from the precision measurements.** The precision obtained is still limited, but enough to constrain the mass to be around 100 GeV, in any case less than 200 GeV. LEP also proved to be the ideal tool to directly search for Higgs bosons – a completely new field of investigation. In fact, the Higgs search became the point of focus until the end of the LEP program. Ingenious ways to raise the beam energy had been devised, providing for a dramatic last year of operation. Conservatively, *the Higgs mass had to be heavier than* 114 GeV; however, convincing indications for a signal at a mass of 115 GeV were presented. The particle physics community was torn between extending LEP running in order to turn the evidence into a discovery and not delaying the construction of the upcoming Large Hadron Collider (LHC). Issuing from a heated debate, the decision of the CERN Direction was to stop LEP forever and to reset the Higgs agenda for 2006.[2] In retrospect, it would have been wiser to secure more energy reserve for LEP, since there were some strong indication from supersymmetric theories that the lightest Higgs boson had to be below 130 GeV, within the reach of an RF-cavity-boosted LEP.
- **The charged weak couplings of fermions to the** W **boson are also universal.** Precise studies with the τ lepton have provided universality tests at the few per mill level. In the quark sector, the measurements performed at LEP have covered a broad range of issues, most importantly for the heavy c and b quarks. The high quality achieved for this physics programme owes much to the performance of precision vertex detectors which allowed the selection of high-purity samples, exploiting the finite lifetime of the corresponding hadrons. The impact of these measurements on the phenomenology has largely

exceeded the expectations. Unique results have been obtained, such as the first observation of the time-dependent $B^0\overline{B}^0$ oscillations. Such measurements are playing a crucial role in the context of the CP violation problem.

4. LEP physics: the strong sector

Although it was not its primary physics target, it turned out that LEP was the perfect machine to make some decisive measurements and many investigations for quantum chromodynamics (QCD).

- **Precise tests show that QCD is a perturbative gauge theory.** The strength of e^+e^- annihilation into hadrons is that the primary process is quark-antiquark production from the vacuum as far as QCD is concerned (no strongly interacting particles in the initial state). The quarks can then radiate gluons, like charged particles emit photons when they are accelerated. At the large LEP energies, the memory from the primary quarks and gluons is kept as they hadronize in jets of hadrons which are accurately correlated to the quark/gluon initial direction. By observing two-, three-, four-jet production, it is possible to have direct access to the order of the QCD process involved, thus observing perturbation theory at work. A beautiful confirmation of the SU(3) gauge structure has been achieved.
- **QCD has been tested at the quantum level by observing the change of the interaction strength on the energy scale.** This so-called running of the strong coupling 'constant' has been established at an unforeseen precision level. This is due to the fact that QCD could be investigated both in e^+e^- annihilation at the highest energies and in τ decays where perturbative QCD was shown to accurately describe the data on hadronic decays. A solid prediction of the SU(3) gauge theory is that, unlike quantum electrodynamics, the effective coupling decreases with energy because gluons carry strong charges: LEP made a splendid determination of this effect for energies from 1 to 200 GeV, where the strength of the strong interaction decreases by a factor of 5. Thus QCD becomes almost a free-field theory at short distances, a feature anticipated by Feynman in his initial parton theory.

5. LEP physics: beyond the Standard Model

Since the production processes are so clean in e^+e^- annihilation, it provides the most suitable environment to look for new phenomena. Moreover, the standard physics being well understood, it becomes much easier to detect non-standard effects, such as the production of particles of a new type. The strong hope that LEP would permit the discovery of 'something' beyond the Standard Model was not to be fulfilled, despite years of intense and ingenious searches. In fact, no other facility could have with equal certainty ruled out such new phenomena in the large energy range explored.

- **Several considered extensions of the Standard Model have been unambiguously ruled out.** This is the case, for example, for the simplest theories where electroweak symmetry breaking is achieved dynamically by introducing a new strong sector (technicolour). Also, no indication for the compositeness of fermions or bosons could be found, although this was considered a possible, yet not attractive, solution to the fermion multiplicity.
- **Supersymmetry was not discovered, but not ruled out either.** This area was the subject of an all-out search for the many particles predicted by this most convincing extension of the standard theory. A lot of progress was achieved in the understanding of how supersymmetry could be realized and broken, and strong constraints are now placed as a result of the thorough LEP searches.

6. Contributions versus expectations

It is amazing to compare the physics output of LEP to the planned physics programme defined in 1976–78. All the important measurements have been successfully performed and published. However, the quality of the results is, in general, far in excess of expectation and, as a consequence, the physics reach has been significantly stronger than foreseen. Several reasons can be invoked:

– The LEP accelerator system, although very complex, performed extremely well. The duty cycle was high and the achieved luminosity[3] fulfilled the goals. Energies in excess of the design could be reached through agressive developments on the technology of superconducting cavities.
– The accuracy achieved on the absolute energy calibration of LEP exceeded by a factor of 20 the foreseen limit. This was made possible by polarizing the beams – a task considered difficult by the experts, given the size and the expected imperfections of the machine – and then using resonant depolarization. This major technical achievement led to a significant improvement in the physics output.
– The four detectors performed very well and reliably over 12 years. The breadth of the LEP physics programme profited from their complementarity, but the most important aspect was the possibility of cross checking, thus greatly improving the quality and the reliability of the results. Moreover, the competition created by the simultaneous operation of the different detectors resulted in a very stimulating and lively confrontation of the data and the various analyses. Finally the major measurements by the four collaborations could be combined in order to maximize the power of the physics results.
– The need for high precision tracking detectors placed near the LEP beam pipe was not fully appreciated in the planning phase. It became obvious very soon that such devices could greatly enhance the physics possibilities, so they were built and incorporated rather early. They proved to be a big asset for τ and heavy quark physics as decay paths in the range of a few millimeters could be accurately measured, extrapolating the precisely measured tracks from outside the beam pipe, with a precision better than 10 μm.
– The combination of a background-free environment and the good performance of the detectors, in particular the high granularity planned for some of the calorimeters was the key in many physics areas. This is certainly the case for the physics of the τ lepton, which was not anticipated to play such an important role.

7. The dialogue between theory and experiment

It was clear from the start that LEP was highly desired not only by the experimental community, but also by the particle physics theorists. The prospects of a direct and unambiguous confrontation between experiment and the Standard Model acted as a strong stimulant. The dialogue was immediately fruitful and it is still going on.

An excellent collaboration spirit set in very early and one can say beyond doubt that the success of LEP in most areas has been considerably enhanced from it. Cross sections for relevant processes were calculated and, most of all, the electromagnetic radiative corrections and the higher order electroweak contributions were computed and reliably checked. New results fostered new ideas for theoretical improvement, and vice versa, leading to a fruitful exchange and a general optimization of the physics output. This process was probably less fruitful in France than in other European countries, such as Germany, Italy or United Kingdom, as French particle theorists became no longer interested in phenomenology, except for a few active groups. However, thanks to the LEP results, some hopeful signs indicating a reversal of this trend have become apparent in the last years.

It is clear that the nature of the confrontation based on precision measurements on one side and accurate calculations on the other, required a timely and constructive collaboration. The indirect determination of the top quark and the Higgs boson masses is a tribute to this excellent working spirit. Other fields, such as supersymmetry searches, also benefited greatly from this interaction. It was even enhanced in this particular case, perhaps because of the more speculative and open nature of the problem.

8. Sociological aspects

The LEP era in particle physics marked a qualitative transition. The exploration of the high-energy frontier necessitates large accelerator facilities which are located at a few sites around the world. Basically, 2 in Europe (CERN and DESY), 2 in the United States (FNAL and SLAC) and 1 in Japan (KEK). Also experiments are now designed around multipurpose detectors which enable a large field of investigations. They have to be designed, built, installed and operated in a common way, through an international collaboration structure. Thus the balance between activities in home laboratories and the centre hosting the accelerator and the detector significantly changed over the years. The fact that a particle physicist has a dual affiliation to his institute and to his collaboration has profound sociological effects, of which the feeling of being part of a truly worldwide community is one of the most important aspects.

With the LEP programme, CERN became the leading centre for particle physics in the world. The four LEP experiments were run by large international collaborations with many groups from non-CERN member states (in particular from United States, Canada, Japan and China). Many groups or individuals from developing countries were also able to participate.

Several aspects need to be mentioned:

– The building and running of these complex detectors, as well as their data analysis, require an efficient organization able to federate the efforts, taking into account the respective strength of each contributing group, the need for visibility and yet the strong constraints imposed by the scale of the project. These problems are dealt with collaboration structures, such as an elected spokesman, a steering committee with representatives from all participating groups, a technical coordinator, and many specialized responsible people, and committees. Frequent one-week-long collaboration meetings are held where progress and topical problems are openly and thoroughly discussed at all levels of the collaboration. Decision-making is a delicate balance between democracy and leadership. The success of the LEP detectors and of their exploitation validates the particle physics collaboration model.
– This worldwide organization can only work with good communication tools. Thus it is no surprize that the World Wide Web was invented by CERN and the particle physics community to serve its basic needs of exchanging information, documents, and software in an efficient way.
– The LEP collaborations provided an excellent training ground for students, both at the undergraduate and graduate level. One often hears from other branches of physics the criticism that those large collaborations are not fit for academic work. In fact each collaboration works like a large laboratory. Many physics subjects are studied, each one of them usually by a small group of physicists, often from different institutes. These small units are well matched to academic research and they can profit in addition from the stimulation of a large collaboration where many exchanges are possible, often between the students themselves, coming from different countries and systems.

9. Outreach

Although LEP was dedicated to research and progress in particle physics, its impact in other fields has been very significant. At the fundamental level, the connection of particle physics with cosmology was strengthened, as LEP experiments could produce results of immediate interest. The determination of the number of neutrino species has profound consequences on the standard model for primordial nucleosynthesis which received a strong confirmation. Supersymmetry searches at LEP place constraining lower limits on the mass of heavy weakly-interacting particles, which have been proposed to solve the long-standing problem of the missing matter in the universe. The absence of antibaryonic matter in the universe is another puzzling question which requires the understanding of the sources of CP violation: as electroweak CP violation is now understood, it remains to be seen whether other mechanisms are necessary in order to explain the cosmological baryon assymmetry.

The construction of LEP and its detectors have given a boost to many technological fields. They include novel developments in high-gradient superconducting RF cavities, distributed pumping for ultra-vacuum, microstrip and pixel precision detectors, detector techniques such as ring-imaging Cerenkov devices and calorimeter crystals, communication and data exchange tools (WWW), integrated environment for analysis of large data sample (PAW), and many others.

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10. Organization of the review

The major physics achievements made possible by LEP are described in the different contributions to this volume. They have been compiled and presented by world experts on the various subjects from the French particle physics community, in collaboration with colleagues from many countries. Only the most significant topics have been covered, but I believe they give an accurate, yet condensed, picture of the quality and the relevance of the LEP physics. In a field with so many outstanding contributions, some choices had to be made, as it was not possible to give credit to all of them. The important goal was to provide a digestable survey of the important results which could be useful both to the newcomers in the field and to interested physicists at large.

I want to express my appreciation to the authors for keeping this goal, and to the many colleagues – in Europe and around the world, experimentalists and theorists – who made this project one of the greatest scientific endeavours.

[1] A list of acronyms is given in this introduction.

[2] It turned out later that the start of LHC had anyway to be postponed until 2007 or later.

[3] The luminosity L of a collider, measured in $\text{cm}^{-2}\cdot\text{s}^{-1}$, is related to the event rate per second N of a given process with a cross section σ by $N = L\sigma$. The luminosity depends on the particle density in the colliding bunches.

Acronyms

ACO Anneau de Collisions d'Orsay
BNL Brookhaven National Laboratory, USA
CERN Centre Européen de Recherches Nucléaires, Genève
CKM Cabibbo–Kobayashi–Maskawa, matrice de
DESY Deutsches Elektronen-Synchrotron Laboratory, Hamburg
FNAL Fermi National Accelerator Laboratory, USA
KEK Koh-Enerugii Kasokuki Kenkyu Kikou, High Energy Accelerator Research Organization, Japan
LEP Large Electron–Positron project, CERN, Genève
LHC Large Hadron Collider, CERN, Genève
PAW Physics Analysis Workstation (CERN)
QED Quantum ElectroDynamics
QCD Quantum ChromoDynamics
SLAC Stanford Linear Accelerator Center, USA

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