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AVANCÉES EN PHYSIQUE DES PARTICULES :
LA CONTRIBUTION DU LEP

ADVANCES IN PARTICLE PHYSICS: THE LEP CONTRIBUTION

Conclusions and perspectives

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Abstract LEP1 precision measurements, combined with LEP2 searches for the Higgs boson, define the framework for future investigations in subatomic physics. In particular they define the energy and the luminosity which are needed at a future e^+e^- collider to settle the issue of the origin of mass and to complement the LHC on the various scenarios proposed beyond the Standard Model. ***To cite this article: F. Richard, P. Zerwas, C. R. Physique 3 (2002) 1245–1253.***

Standard Model / electroweak interaction / Higgs boson / supersymetry / extra dimensions / unification of forces / future colliders

Conclusions et perspectives

Résumé Les mesures de précision de LEP1, combinées aux recherches du boson de Higgs à LEP2, permettent de définir le cadre des futures recherches en physique subatomique. Elles définissent, en particulier, l'énergie et la luminosité d'un futur collisionneur e^+e^- qui permettrait de comprendre l'origine des masses et qui serait complémentaire du LHC pour l'analyse des différents scénarios qui vont au-delà du Modèle Standard. ***Pour citer cet article : F. Richard, P. Zerwas, C. R. Physique 3 (2002) 1245–1253.***

Modèle Standard / interaction électrofaible / boson de Higgs / supersymétrie / dimensions supplémentaires / unification des forces / futurs collisionneurs

1. Introduction

This last article is not an attempt to summarize LEP results but rather intends to focus on the issues opened by these results in our understanding of Nature and on the prospects that they offer for future high energy machines. After LEP, our confidence in what we call the Standard Model (SM) of subatomic particles and interactions, lies on very firm grounds, indicating no apparent flaw, while this model is presumably not viable in its present version and a dramatic revolution should take place with the next

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generation of colliders. The present introduction will try to explain why this is so, and in which way LEP has brought us in this tantalizing situation.

LEP has provided a very precise test of the SM, or to be more modest, of the SM framework since, within the present state of affairs, one needs more than 20 free parameters to describe the subatomic world. This may sound extravagant but one should not forget that this description has allowed a wide spectrum of relations and predictions which have been passed with an excellent precision.

A natural step to reduce this arbitrariness is to postulate the unification of the 3 fundamental forces, electromagnetic, weak and strong at some higher energy scale and LEP has allowed a crucial test of this idea. Since at the LEP energy scale the strong force is still much larger than the electromagnetic force and since the 3 couplings move slowly with energy, unification should occur at an enormous scale, 10^{16} GeV, only three orders of magnitude below the Planck scale, perhaps suggesting some possible unification also with gravity. This scale, called the GUT (Grand Unified Theory) scale, correlates quite well to the mass scale needed to explain the suppression of proton decay and to generate very light neutrinos. This line of thought, however, creates a formidable mass hierarchy between the weak scale and the unification scale which provokes severe problems in the Higgs sector.

The Higgs mechanism introduces, for the first time in particle physics, an elementary scalar field, and this provides an effective framework to generate masses for gauge bosons and fermions. LEP1 has tested to an incredible accuracy the fermionic sector, in particular for the heaviest fermions, the b quark and the τ lepton. The boson sector has also been tested very accurately through Z/W mass measurements and the triple boson coupling ZWW at LEP2. These results pass superbly the SM predictions. The most exciting and fruitful consequence of this success is that LEP precision is sufficient to test the SM at the quantum level. The benefit is that LEP could give information on particles which cannot be produced directly, in particular on the top quark and the Higgs boson.

It is fair to say that, in the SM, the Higgs mechanism appears somewhat arbitrary and suffers from severe ultra-violet divergences if one believes that no new physics can occur before the unification scale. These divergences can be tamed at the right level, that is at the level of the Z/W mass scales, if one assumes that a new symmetry appears below the TeV scale. This symmetry, called supersymmetry (SUSY), relates bosons and fermions and has to be broken since it predicts a new spectrum of particles which have not been observed so far. The virtue of SUSY is not only to tame divergences but also to satisfy unification with such good agreement with experiment [1] that may not be a mere accident, a primordial result of LEP. SUSY predicts a Higgs mass close to the Z mass and potentially within the reach of LEP2.

Unification of forces means that quarks and leptons belong to a common representation of a symmetry group. The simplest group is SU(5) which breaks naturally into the SM non-unified groups, SU(3) for the strong interaction and SU(2)$\otimes$U(1) for electroweak (EW) interactions. There are however several other possibilities [2], one of which being E_6, an exceptional group, which occurs naturally in the ultimate extension of the theory, the superstring theory. This group, contrary to SU(5), has the virtue of predicting right-handed neutrinos, providing, if heavy, a possible explanation for neutrino masses which are much smaller than for standard fermions. It also predicts a heavier Z resonance, called Z', which could appear at the TeV scale. It is noticeable that the search for a Z' has been able to reach a sensitivity on the Z' mass well beyond the maximum energy of LEP2.

Alternative approaches have been proposed to solve the hierarchy problem. Assuming that there are more than 3 space dimensions, one can suppress the hierarchy problem since in these theories the effective Planck scale may become as small as a few TeV.

Still viable, but not without unresolved theoretical problems, is the idea that the Higgs boson is not an elementary field but a bound state of new fermions at the TeV scale, therefore avoiding the ultra-violet divergences coming from an elementary scalar field.

LEP has been able to provide very constraining results on these ideas which will be described in the next section.

Finally, with the proliferation of fermions, in analogy with the proliferation of baryons and mesons, one could postulate that these fermions are composite objects, made out of some elementary partons which would become manifest at very small scale. LEP tells us that the new scale falls below 10^{-17} cm.

After discussing, in a first part, precision measurements (PM) and their consequences, a second part will review direct searches for new particles at LEP, mainly for Higgs boson(s) and SUSY.

The last part will describe our expectations from LEP for present and future colliders and how they could provide the necessary improvements on LEP PM and allow to understand the mass generation mechanism.

2. Precision measurements

The following discussion will illustrate the power of the precision achieved at LEP [3] in constraining the theoretical ideas and in predicting what one can expect to observe, and not to observe, from future machines.

Let us first recall the rule of the game for PM. All LEP1 measurable quantities depend on 3 parameters, and the more precisely known are the Z mass M_Z, the Fermi constant G_F and $\alpha(M_Z)$ known to an accuracy of, respectively, 23 ppm, 9 ppm and 150 ppm. All other quantities, in particular $\sin^2\theta_W$ and M_W, can simply be derived from them. These relations are however affected by quantum effects, e.g., virtual fluctuations of gauge bosons into fermions pairs or boson pairs, with subsequent recombination. A photon will fluctuate into a pair of quarks or a pair of leptons and this effect will modify the photon coupling α. This modification of α with the energy scale depends on physics essentially occurring below $\sqrt{s}$. The precision of this quantity was a limiting factor which has been considerably reduced using τ decays plus some safe theoretical inputs. At present [4] $\Delta\alpha/\alpha \sim 0.015\%$, which matches the precision achieved at LEP on $\sin^2\theta_W$ (see Table 1).

W or Z bosons are massive particles and therefore the electroweak symmetry is broken. The quantum fluctuations provide, contrary to electromagnetism, a very good sensitivity to the top quark which cannot be produced at LEP. One can simply parameterise the virtual fluctuations of Z and W in terms of two parameters called T and S. T is primarily affected by the weak isospin symmetry violation, while S carries mostly the residual information on the Higgs mass and the heavy degenerate new fermions. The most precise experimental input comes from $\sin^2\theta_W$. Table 1 shows the dramatic improvement brought by LEP not only on this parameter but also on some of the fundamental quantities which provide critical information.In the following subsections the usefulness of these measurements will be illustrated by showing how they provide important answers on very basic questions.

2.1. The top mass prediction

A major outcome of LEP1 precision measurement has been the prediction of the top quark mass [5]:

$$m_t^{\text{indirect}} = (178 \pm 11 \pm 19)\ \text{GeV}$$

which fits very well with the direct measurement:

$$m_t^{\text{direct}} = (174 \pm 5)\ \text{GeV}.$$

Table 1. Improved accuracies after LEP1 on the Z and W masses, $\sin^2\theta_W$, the strong coupling constant at the Z energy scale $\alpha_s(M_Z^2)$, the τ leptonic branching ratios and the τ lifetime.

Item	ΔM_Z	ΔM_W	$\Delta\sin^2\theta_W$	$\Delta\alpha_s$	$\Delta BR_l(\tau)$	$\Delta\tau_\tau$
Pre-LEP	350 MeV	400 MeV	2.5%	15%	2%	2.5%
Post-LEP	2 MeV	39 MeV	0.06%	2.3%	0.3%	0.38%

The effect on T, for a top-bottom doublet, goes like $m_t^2 - m_b^2$ and therefore benefits from a strong isospin violation. This impressive result serves as a basis for our confidence in the predictions provided by PM.

2.2. Do we expect more families?

After measuring the top mass directly, one can deduce useful bounds on new families of fermions. These families are necessarily heavy since LEP1 only allows 3 light neutrinos (light meaning with mass below $M_Z/2$). There is of course some uncertainty due to the Higgs mass on T and S but, as recalled in 2.3, this effect is weak.

One can easily exclude from T new families of fermions which are not degenerate in mass but S also allows one to exclude the presence of new degenerate families, replica of the first 3. These measurements leave the possibility of extra fermions which couple symmetrically left–right (in contrast with standard fermions) as expected in some extended groups.

New heavy fermions could mix with standard fermions, most likely with the third family. Mixing effects with ν_τ, τ, b could appear and alter universality. No significant effect has been observed in the b sector except on the forward–backward asymmetry A_{FB}^b at a 3 s.d. level. Note that since A_{FB}^b factorises into the left–right asymmetries $\mathcal{A}_b\mathcal{A}_e$, one can expect that $\mathcal{A}_b$ is responsible for this deviation. $\mathcal{A}_b$ has been measured with a polarized beam at the Stanford Linear Collider but with insufficient precision to confirm or reject the LEP result. The same is true for the beauty cross-section measured at LEP which shows no effect but could have less sensitivity to new physics. This deviation is therefore inconclusive and requires a better measurement.

In the ν sector, there is room for some effect, although weakly significant, since the measured number of light neutrinos, $N_\nu = 2.9841 \pm 0.0083$, deviates from 3 by about 2 standard deviations.

In the τ sector there is beautiful agreement. As an example (see Table 1) combining the measured lifetime τ_τ and the leptonic branching ratio $BR_l(\tau)$ one can derive the leptonic width of the τ which shows perfect agreement with the prediction from the muon width, showing that there is leptonic universality.

Technicolor, which assumes extra fermionic doublets and no elementary Higgs boson, seems excluded in its minimal version by the S measurement. However in extended versions, this theory becomes non-perturbative and S can no longer be computed [6].

2.3. Is there a light Higgs?

Precision measurements give access to the logarithm of the Higgs mass, meaning that they are weakly affected by the uncertainty on this parameter. Fixing the top mass one finds:

$$\log_{10} M_H^{\mathrm{GeV}} = 1.94^{+0.21}_{-0.22}, \quad M_H = 88^{+53}_{-35}\ \mathrm{GeV}.$$

The SM interpretation (including the direct search) gives, at 95% C.L.:

$$114 < M_H < 195\ \mathrm{GeV}$$

while the central value, ∼100 GeV, is consistent with the minimal SUSY prediction (MSSM): $M_h <$ 125 GeV. This result is probably the most important one from PM:

– it is clearly compatible with a SUSY scenario with light Higgs;
– it sets the energy scale for present and future Higgs searches.

How solid is this important conclusion? As stated previously, the Higgs term provides a small contribution and therefore can be easily affected by some parasitic effects either experimental or theoretical. Ignoring the second aspect and assuming that there is only the SM, an appropriate question is how consistent are the various measurements which matter: $\sin^2\theta_W$, M_W, m_t? The overall SM fit on PM gives a χ^2 of 23 for 15 degrees of freedom which corresponds to less than 2 standard deviations discrepancy between the data and the SM predictions. The highest contribution to this χ^2 comes from the b forward–backward asymmetry already mentioned but, given the limited discrepancy, it seems artificial and biasing to withdraw this measurement from the fit arguing that there could be either an underestimated experimental error or some new contribution beyond the SM. If one does so nevertheless, the mass determination of the Higgs boson becomes inconsistent with the limit given by direct searches [7]. The main conclusion that the Higgs boson mass limit cannot be large, remains unchanged and even becomes stronger if one ignores the b asymmetry measurement.

This conclusion is also being questioned by several authors for theoretical reasons. If there is physics beyond the SM or MSSM scheme, for instance a Z′ with mass of order a few TeV, with some small mixing with Z, this new effect can contribute to the S parameter and it can mask to some extent the $\log \mathrm{M}_H$ term coming from a heavy Higgs [8]. This means that the present result is limited by our ignorance of the full theory but also implies that, if a Higgs with mass above 200 GeV is found at future colliders, one expects a rich and complex scenario with signals of new physics observable in PM.

2.4. Could there be a Z′?

LEP1 results show that the Z–Z′ mixing angle is below a few 10^{-3}. At LEP2, the reaction $e^+e^- \to f\bar{f}$ should receive contribution from a Z′ term which would interfere with the Z/γ part. There are several schemes predicting a Z′ with different fermionic couplings: limits from LEP2 are all above 400 GeV and in case there is a simple replication of a Z, almost up to 2000 GeV, which illustrates the power of precise measurements with an e^+e^- machine. It is fair to say that atomic-parity violation [9] is reaching a comparable sensitivity on a Z′ contribution with some complementarities. Direct searches at the Tevatron are giving comparable bounds but they are more model-dependent since one has to assume that the Z′ has a standard total width, that is, it only decays into standard particles.

2.5. Could there be more than 3 dimensions in nature?

Based on superstring theory, there has been a vigorous revival of the old Kaluza–Klein theory which unifies EM-gravity assuming 1 extra dimension in Nature. These extra dimensions were first supposed to compactify at the Planck scale but recent ideas [10] show that compactification can occur at the TeV scale, leading to possible modifications of Newton's law at a fraction of a mm scale. In the latter scheme, gravity propagates freely in the new dimension. In both models the Planck scale reduces to a TeV, which has the virtue of eliminating the hierarchy problem. These models are already testable at LEP2, which has provided limits on the new scale of order 1 TeV in analyses similar to those used for Z′. The size of the new dimension depends on the number of new dimensions. In some scenarios, one extra dimension is excluded by cosmology, two extra dimension are compatible with deviations with respect to standard gravity below 1 mm, not in contradiction with Cavendish experiments. LEP2 sets a limit at ∼0.3 mm.

2.6. Is there indirect evidence for SUSY?

Very weak effects are expected on S and T from virtual SUSY contributions.

Unification of couplings can be used to derive α_s from $\sin^2\theta_W$ with the result, $\alpha_s = 0.130 \pm 0.001$, while the present experimental value is $\alpha_s = 0.118 \pm 0.003$. Theoretical uncertainties, of order 0.01, are due to our ignorance on the masses at the GUT scale, in particular the mass of the heavy coloured Higgs bosons which occur in SU(5). It seems that taking into account the limit on proton life-time, which depends on the same parameter, this discrepancy cannot be fixed in a satisfactory way.

Minimal SUSY SU(5) is thus excluded [11]. One may therefore take two attitudes: ignore the problem as too speculative, or introduce new particles, therefore extending the MSSM, to be compatible with PM. This illustrates how PM can be affected by phenomena occurring at the GUT scale, inaccessible to any foreseeable accelerator.

2.7. CP violation for b quarks

As pointed out in the contribution by Kluit and Stocchi [12], LEP1 has provided very precise results on the weak decays of B hadrons. Significant progress of the theory has allowed us to extract from these data unique and very valuable input for our knowledge of the CKM matrix. The most spectacular outcome of this work has been to provide a fairly precise prediction for the CP violation in the B mesons. This opportunity follows from the unitary nature of the CKM matrix, as overconstrained measurements of the moduli of the matrix elements (CP-conserving observables) do yield information on the CP-violating phase. Ongoing experiments at 'Beauty factories' in Stanford and Tsukuba have recently given a splendid confirmation of these predictions.

In the next few years these measurements will be improved and new experiments are planned for hadrons colliders, first in Chicago and then at CERN on the LHC. Although the understanding of electroweak CP violation is well underway, the elucidation of its role (or its interplay with other mechanisms) in order to explain the disappearance of antimatter in the early universe remains a very challenging problem.

3. Direct searches

At LEP2, the major effort has been on Higgs and SUSY searches. These searches have been energy limited since the high luminosity collected and the combination of experiments have allowed us to reach the kinematical limit. Rigorous statistical methods have been developed for an optimal choice of selection against background and for a meaningful interpretation of these results.

From SUSY and from PM it is clear that the Higgs sector provides a well motivated search at LEP2. To cover the MSSM scenario would have required reaching a total energy of about 10 GeV above the energy realized at LEP2. Given the electric fields achieved by the SC cavities, 50% above the design value, it would have been possible, by increasing the number of cavities by a quarter, to cover completely the MSSM scenario. This has not happened for several reasons: conservative estimates of the maximum field, insufficient pressure of the community and, most important, financial limitations.

3.1. Higgs search

One experiment has claimed some evidence for a signal at a mass $\sim$115 GeV, while the overall combination [13] shows that the observed effect has a 3.4% probability to come from background. This indication certainly requires confirmation.

The LEP experiments provide very robust results which can accommodate various non-standard scenarios:

- the mass limits reached are almost the same for an invisibly decaying Higgs [14], for a Higgs decaying into light quarks [15] or for a Higgs boson decaying into two photons [16];
- for a standard decay into a pair of beauty particles, this search can cover to a large extent non-minimal schemes, with the presence of several doublets and singlets of Higgs boson and a substantial decrease in the production cross-section of the lightest Higgs. For instance, if the cross section gets reduced by a factor 10, the LEP2 mass limit only decreases to 85 GeV.

In MSSM there are two Higgs doublets and therefore five physical particles, two scalars h and H, one pseudoscalar A and two charged Higgs $H^{\pm}$. If A is heavy, that is heavier than 100 GeV, the limit from SM applies on h. If not, the limit on h can become smaller and, due to background from the ZZ channel, limited to M_Z. In practice LEP2 has set a limit [17] on M_h at 91 GeV and on M_A at 91.9 GeV. The limit on $H^{\pm}$ is at 78.6 GeV due to the W^+W^- background [18].

3.2. SUSY searches

There are no definite predictions on the SUSY mass spectrum given that no symmetry breaking scheme has clearly emerged. As for the Higgs sector, LEP2 has provided robust limits covering all known scenarios up to the kinematical limit. It is important to notice that the Higgs search has a high reach on SUSY parameters. This feature can be simply understood by recalling that, within SUSY, the Higgs mass is of order M_Z up to some radiative corrections which depend on the logarithm of the top squark mass. This means that by reaching a mass limit of 114 GeV, well above M_Z, LEP2 shows that radiative corrections are large, implying that squarks should be heavier than several hundred GeV. In most schemes, the same should be true for the gluino mass. While these limits are somewhat model dependent, they illustrate the general argument.

An other important result of LEP2 on SUSY concerns the limit on the lightest neutral SUSY particle, assumed stable, which could provide the right candidate for 'dark matter' of our universe. LEP has reached a mass lower limit of 45 GeV on this particle [19] in some SUSY scenarios, an important mark nevertheless for the non-accelerator searches for these objects.

4. Future prospects

The search for the SM/MSSM Higgs boson will be carried on at the Tevatron, a proton anti-proton collider operating at Chicago, until LHC starts, presumably in 2007. A Higgs boson at 115 GeV is not easy to observe at hadron colliders. While the Tevatron can exclude it by 2005, it is not certain that it could confirm its presence before LHC. One year of data taking, with well understood detectors, will be necessary to confirm at LHC the indication from LEP2. LHC gives a full coverage of the SM and MSSM scenarios, for the latter in regard of the lightest Higgs and a substantial coverage for the heavier Higgs bosons.

The discovery of a Higgs boson will be a major step, but equally important will be the need to study in detail the properties of this entirely new sector of the SM. As already mentioned, a non-standard behaviour is not excluded and it could manifest itself at a crude level, detectable at LHC, but more likely it will require the precision given by an e^+e^- machine for full comprehension. This reminds us of the roadmap followed to study the Z/W bosons for which only limited information has been obtained before LEP. One would accordingly like to produce a large sample of Higgs events in an e^+e^- machine. A total energy of 350 GeV is needed to cover the Higgs mass domain predicted by LEP, giving access to PM for top quarks at the same time.

This energy cannot be achieved with a circular machine like LEP, since it would require an unrealistic size, given the synchrotron radiation losses. To solve this problem, the technology for a linear collider, LC, has been developed for more than a decade. In particular large experience has been gained by operating at Stanford LC at the Z peak. Three projects, mainly developed at SLAC, DESY and KEK, could be ready for a construction in 2005 [20]. They would reach 500 GeV in a first stage and deliver more than two orders of magnitude more luminosity than LEP2. This would allow to produce a sample of more than 10^5 Higgs bosons sufficient for PM. A second-generation facility such as CLIC, a project developed at CERN and designed to operate at multi-TeV energies, could later give access to the heaviest of the MSSM Higgs bosons.

Either one finds the light Higgs or nature has designed a more tricky scenario with a heavy Higgs, or even without a Higgs boson observable at LHC. This kind of scenario, clearly not the most likely one, can be deciphered if other new signals are observed at LHC but there could be a situation in which only subtle deviations are present. It will then take the full precision of a LC to solve the enigma. Significant effects will necessarily appear which should allow to identify the underlying pattern. If there is no observable Higgs at LHC, a LC which has a much more margin in accommodating non-minimal scenarios, will definitely exclude the presence of this particle. If there is no observable Higgs at LHC/LC one expects, on very general grounds, significant deviations from the SM predictions in WW pairs, which can be seen by a LC operating up to 1 TeV. The need to cover the worst scenario for electroweak symmetry breaking, sets the motivation to achieve this energy. The technology of the future LC should therefore allow to reach about 1 TeV in a second stage of these projects.

Table 2. Improved accuracies at a future Linear Collider (LC).

Item	ΔM_W	$\Delta \sin^2\theta_W$	$\Delta\alpha(M_Z)$	$\Delta m_t^{\mathrm{direct}}$	$\Delta M_H^{\mathrm{indirect}}$
LEP-Tevatron	39 MeV	0.06%	0.015%	5 GeV	50 GeV
LC	6 MeV	0.006%	0.005%	100 MeV	5 GeV

An increase of energy of the LC above 500 GeV is also necessary, even in a purely standard scenario, for measuring the top-Higgs coupling in the channel $t\bar{t}$H channel or the Higgs self-coupling in the ZHH channel.

While one cannot tell for sure the energy scale of physics beyond the SM, an important lesson from LEP is that precision can be used to test the theory well beyond the kinematically accessible scale. If, as expected, SUSY is discovered at LHC, a very precise determination of the SUSY spectrum will be needed to understand the origin of the symmetry breaking which probably occurs at energy scales inaccessible to accelerators. In particular this precision will be needed for extrapolations at the GUT scale in order to test, for instance, the hypothesis of a gravity mediated symmetry breaking scenario.

In some alternative scenario, for instance with more than 3 space dimensions, a different situation can occur without SUSY and even with a Higgs boson heavier than expected from PM. In this case one would like to revisit the PM with superior accuracy, to understand the compensation between the Higgs contribution and the contribution coming from extra dimensions. This can be done at a LC with the benefit of higher luminosity and longitudinal polarization. For instance $\sin^2\theta_W$ could be measured with 10 times more accuracy than at LEP1. The measurement of the top mass should also be improved and the measurement of $\alpha(M_Z)$ will need an accuracy 3 times better, which seems feasible. Table 2 shows what one can expect in a foreseeable future [21].

As a final illustration of the importance of a LC overlapping with LHC, let us assume that a mass peak has been discovered at LHC in lepton pairs at a few TeV. Clearly a LC operating below 1 TeV will not produce directly this resonance but, as for LEP2, PM can detect its effect and, knowing the mass from LHC, can determine the vector and axial couplings revealing its origin. Without this information, the origin is likely to be quite ambiguous: new symmetry group (which one?) or Kaluza–Klein excitation of a Z or a photon? This puzzle can be solved with a LC. It turns out that with higher luminosity and polarized beams the mass range can extend up to 10 TeV, beyond LHC reach.

5. Conclusions

With an outstanding metrology of the machine and of the experimental environment, LEP1 has tremendously improved our understanding of the EW theory. PM have been crucial in opening a new methodology for subatomic physics. The quest for precision has allowed us to 'see beyond the wall', a quantum concept which permits the sensing of particles not kinematically accessible. This wall should be broken with the advent of LHC which will be able to produce the Higgs boson and, most probably, other particles revealing what is hiding beyond the SM.

LEP2 has most probably come very near to discovering the light Higgs boson although with insufficient evidence. The beautiful achievements of LEP2 in energy and luminosity, a major success of the LEP team, tells us that it could have been technically feasible to cover the full MSSM scenario and, certainly, to confirm the 115 GeV evidence.

After LEP, the main task of subatomic physics will be to understand the origin of EW symmetry breaking and this will require an exploration up to the TeV mass scale. In a standard scenario LHC would find a light Higgs and SUSY, and a LC would provide the accuracy needed to measure the Higgs properties and to understand the origin of SUSY breaking.

The physics scenario encountered at LHC could be complex, e.g., a Higgs particle of say 300–400 GeV and nothing else, or even no Higgs observed at LHC, and one then has to decode the underlying mechanism using the full power of a LC. The Higgs visibility is guaranteed with a TeV collider, whatever the complexity, and if no Higgs boson is found, PM should give us critical information to understand the underlying mechanism. For instance, a future TeV LC should improve dramatically on LEP1 and LEP2 for PM and see 'far beyond the wall' by detecting new scales beyond the reach of LHC.

References

[1] U. Amaldi, et al., Phys. Lett. B 260 (1991) 447 and references therein.
[2] J.L. Hewett, T.G. Rizzo, Phys. Rep. 183 (1986) 193.
[3] LEP Electroweak Working Group and SLD Heavy Flavor and Electroweak Groups, D. Abbaneo, et al., LEPEWWG-2001-02, December 2001, 151 pp., hep-ex/0112021.
[4] M. Davier, A. Höcker, Phys. Lett. B 435 (1998) 427.
[5] A. Sirlin, Talk given at 19th International Symposium on Lepton and Photon Interactions at High-Energies, LP 99, Stanford, CA, 9–14 August 1999, Int. J. Mod. Phys. A 15S1 (2000) 398.
[6] K.D. Lane, BUHEP-00-15, Boston University, Lectures given at LNF, Rome, Italy, 15–20 May 2000, hep-ph/0007304.
[7] G. Altarelli, et al., JHEP 106 (2001) 018.
[8] M.E. Peskin, J.D. Wells, Phys. Rev. D 64 (2001) 093003.
[9] M.J. Ramsey-Musolf, Phys. Rev. C 60 (1999) 015501.
[10] I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos, G.R. Dvali, Phys. Lett. B 436 (1998) 257.
[11] H. Murayama, A. Pierce, Phys. Rev. D 65 (2002) 055009.
[12] P. Kluit, A. Stocchi, C. R. Physique 3 (2002) 1203.
[13] LEP Higgs Working Group, LHWG-NOTE-2001-03, July 2001, 27 pp., hep-ex/0107029.
[14] LEP Higgs Working for Higgs boson searches, LHWG-NOTE-2001-06, July 2001, 7 p., hep-ex/0107032.
[15] LEP Higgs Working Group, LHWG-2001-07, July 2001, 7 p., hep-ex/0107034.
[16] LEP Higgs Working Group, LHWG-NOTE-2001-08, July 2001, 7 p., hep-ex/0107035.
[17] LEP Higgs Working Group, LHWG-NOTE-2001-04, July 2001, 22 pp., hep-ex/0107030.
[18] LEP Higgs Working Group, LHWG-NOTE-2001-05, July 2001, 9 p., hep-ex/0107031.
[19] LEP2 SUSY Working Group, http://lepsusy.web.cern.ch/lepsusy.
[20] M. Tigner, in: High Energy Physics, Vol. 1, Osaka 2000, July 2000, World Scientific, Singapore, 2001, pp. 253–257.
[21] TESLA technical design report, Part 3, Physics at an e^+e^- linear collider, ECFA-2001-209, March 2001, 192 pp., hep-ph/0106315.