SEARCHES AT LEP

INTRODUCTION

A writer in a hurry could conclude rapidly this chapter since the twelve years of LEP, although they have revolutionized the quantitative tests of the Standard Model (SM), in all its aspects (1,2,3) , did not reveal anything new, particle nor effect, even if a few points still need to be clarified in future programmes.

On the other hand a large number of limits were set on their existence, either by the negative result of direct searches, or indirectly, given the excellent numerical agreeement between measurement and prediction for all electroweak observables considered so far.

Furthermore many of these measurements, whose accuracy allowed to validate and exploit the theory at the quantum loop level, have delivered important messages. Indeed, in spite of its successes, the SM is considered as an effective theory which has to be superseeded, and these indices are precious guides to explore the unknown.

It is therefore judicious to ask the question in different terms. What is the impact of these limits on the possible physics beyond SM ? Which of them are the most powerful in constraining the different models and eventually falsifying them? The answer naturally depends on the nature of these models and on the accuracy of their predictions, since it is easier to shoot at a fixed target rather than a moving one. In particular the falsification of a model, while it can be sharp, may also rest on arguments of naturalness or fine tuning, which keep a subjective side.

Another question is whether one may have missed some unpredicted effect, a regrettable but not unprecedented occurence. In other terms, were LEP searches systematic enough ? Did we exploit at best the remarkable cleanliness of LEP physics (figure 1), allowing to explore quantitatively practicaly all topologies of the final state?

Finally, after celebrating the outstanding quality of the work accomplished, experimentally as well as theoretically, it will be profitable for the future to ask oneself what could have been done better.

INDIRECT AND DIRECT SEARCHES

Searching for new particles and phenomena beyond the Standard Model consists in revealing discrepancies between data and the SM expectations. To open with a truism, for the discrepancy to be genuine, both the data and the SM expectations must be correct.

We live in a quantum world. This means that, to generate such discrepancies, new particles do not need to be produced, but can act as virtual ones in the loops of higher order diagrams, like those of figure 2. Their existence modifies, generally slightly, the numerical values of observables. From a new effect one can expect a pattern of correlated deviations among various observables. Before trying to ″feel″ a new particle, one must be sure that the similar effect of SM heavy ones, like the top at LEP, is under control. Searches proceeding that way are called INDIRECT SEARCHES. Besides LEP, other programmes, in particular low energy ones, perform indirect searches.

However the best way to discover new particles is certainly to reveal their presence in the final state of the collisions under study. This implies that the available energy is sufficient to produce them. If all decay products of the particle are visible and measured, one can reconstruct its mass and exhibit a bump in the relevant distribution. Bump hunting stays as the golden search method. If the total energy and momentum of the final state are known, like in e^+e^- collisions (barring radiative phenomena that we will discuss later), one can also perform constraint analyses and reconstruct the mass of a system when part of the decay products is missing, and even in the case of a totally invisible decay mode. These are DIRECT SEARCHES.

Indirect searches call for measurement accuracy, which in turn requires high statistics. Therefore LEP1 data on the Z^0 (18 millions of events) weight a lot in the game, although LEP200 data, still reasonably abundant and offering a large lever arm in energy, have brought much information as well. Concerning direct searches, it is clear that the twice larger available energy of LEP200 make the difference : most searches performed on the Z^0 resonance were superseded by the second phase of LEP.

MESSAGES FROM LEP AND INDIRECT SEARCHES

As described in (1) the first message of LEP/SLC is the quality of the agreement of the SM with data. Any theory attempting to go beyond the SM (see below) must therefore mimic it closely and offer very similar predictions of the various EW observables. Most interestingly, because of the extreme accuracy of the measurements, the agreement has been demonstrated at the loop-level.

From the agreement of the Z lineshape with the SM expectations, one can already set quite decisive limits. For instance the number of light neutrino species is found to be 2.9841 ± 0.0083.The width left for non SM invisible final states in Z^0 decay is < 1.33 MeV at 95% CL. Similarly the width corresponding to new non SM hadronic modes is $<$ 3.9 MeV at 95% CL. We will see later that these limits lead to interesting exclusions.

In the SM the main items still missing at the beginning of LEP were the top quark and the Higgs boson. While the existence of the former was never in doubt, the latter is still elusive today. Given the heavy mass of the top, it was excluded to produce it directly at LEP. To use an image due to G.Altarelli, LEP physicists were in the situation of a bush hunter, his ear on the ground, who wanted to spot a tiger creeping stealthily - the Higgs boson – while an elephant – the top – was stamping his feet nearby.

It is well known that Z^0 physics at LEP gave rapidly a rather accurate “indirect” estimate of the top quark mass in fair agreement with the value that later the Tevatron measured “directly” by producing the top (4) (figure 3a). Once the “large” effect of the top on the relevant electroweak observables was well under control, one could search for the tiny one expected from the Higgs boson.

One could thus deduce, in the strict frame of the SM, the preferred mass region for the Higgs boson (remembering that the information concerns the logarithm of its mass):

$m_h = 113^{+62}_{-42}$ GeV, and $m_h < 237$ GeV at 95% CL (figure 3b).

The other key message of LEP/SLC is thus the indication of a light Higgs boson (see however (1) for some warning). Is this the truth, or could it be an illusion? Clearly if one quits the frame of the SM by introducing new physics, it is quite possible to invent “conspiracies”, by which a heavy Higgs boson has its effect on electroweak observables compensated by something else (5), like new particles or extradimensions of space. However, these solutions are more or less artificial: it is thus reasonable to focus on the simplest scenario and to test in priority the assumption of a light boson by obtaining direct evidence for it.

Another important result derived from the LEP data is the quasi-perfect convergence near 10^{16} GeV of the electromagnetic, weak and strong coupling “constants” in the frame of SUSY, the so-called Supersymmetric Grand Unification (SGU) (figure 4). This “running” of coupling constants with the energy scale is another consequence of the quantum nature of the theory: it is due to the effect of virtual particles appearing in the loop diagrams. The presence of superpartners explains why the “running speed” is different in SUSY and in the SM.

As described in (1), besides LEP/SLC other sectors of physics have brought indirect information on the validity of the SM and set limits on new physics. Improvements will bring further constraints or may reveal discrepancies.

Let me quote here the famous and beautiful programme concerning the muon g factor, differing from the simple prediction of 2 by about one part in 800. The measurement of this spin anomaly, termed g-2, was started at CERN 47 years ago. It led to successive experiments which paved the way to the present and most accurate one, performed in Brookhaven and resulting in a 0.5 part per million measurement. However the theoretical estimate of g-2 asks for subsidiary data: unfortunately the two methods which were used give slightly different results and the comparison to the SM is still inconclusive.

THE SCENE FOR DIRECT SEARCHES

A first important factor explaining the success of the LEP programme was the wonderful cleanliness of the machine itself. The collision scheme was easy to deal with: a crossing every 10 μs, usually empty of any hard process, a Z^0 every 3s at the peak of LEP1 luminosity. The selection of potentially interesting events was relatively straightforward and allowed to keep the trigger wide open and even redundant. Neither the irradiation of the detectors, nor their occupancy was a problem. Thanks to the LEP design (in particular its large size), to the outstanding quality of its vacuum (due to the use of getter pumping) and to its most careful collimation and shielding schemes, the machine backgrounds (particle loss, synchrotron radiation,..) were never a severe matter.

It is notorious that e^+e^- interactions in general and LEP in particular offer physics of great clarity (figure 1). The colliding leptons being elementary, the full center of mass energy is available to produce new particles. The final state has zero total momentum, a powerful constraint. The most frequent annihilation final states consist of two back-to-back fermions, leptons or quarks. In the latter case one deals with two ideally separated jets. If the quark is a heavy flavoured one, like beauty, the heavy flavoured particles are strongly boosted, a most favourable situation to ensure their tagging.

The only effects which limit this simplicity are radiative phenomena, in particular in the initial state, and photon-photon collisions, interesting by themselves, but a background for many e^+e^- processes. However the resulting events are dominantly coplanar, i.e. they conserve momentum in the transverse plane.

A few major instrumental breakthroughs occured during LEP times. In particular the decade saw decisive progress concerning microvertex detectors which opened the era of highly efficient and pure heavy flavour tagging, key of many searches.

Another major asset of LEP was the existence of four experiments, all of a multipurpose type but nevertheless quite different. This allowed to cross-check results, and once the systematics, common and specific, were understood, to combine the results of the four experiments (the ADLO collaboration) under the guidance of common LEP Physics Groups.

Last but not least an unprecedented collaboration between theorists and experimentalists was pursued during many years. Several EW global variables, summarizing the impact of the EW measurements and allowing to discriminate between various types of potential deviations from the SM, were invented (1). The calculations of the SM expectations were performed to the required level of perturbation and implemented in programs like ZFITTER and TOPAZ0 which became basic tools in the extraction of the EW parameters from global fits to the data. The evaluation of small angle Bhabha scattering, required for the cross section normalization, reached an accuracy of 0.5%, matching well the performance of the luminometers. Concerning direct searches for Supersymmetry, new elaborate simulation programs like SUSYGEN were implemented.

THE EVOLUTION OF THEORETICAL IDEAS

In spite of its success, the motivations pushing to go beyond the SM are more compelling than ever. The main one is the Hierarchy Problem (the Big one, we will allude later to the Small one) which is stated as follows. Gravity exists and defines a very high energy scale, the Planck scale (~10^{19} GeV) at which the gravitational force becomes as strong as the others. In the SM all other masses, in particular the Higgs mass, should be irredeemably pulled towards this high scale. Something more is needed to guarantee the stability of low mass scales.

Traditionally the routes leading beyond the SM either call for new levels of structure and/or new forces, as Technicolour (TC) (6) does, or involve more symmetry among the players of the theory, as in the case of Supersymmetry (SUSY) (7), in which SM particles and their "superpartners", i.e. the new particles of opposite spin-statistics that SUSY introduces, conspire to solve the hierarchy problem.

TC breaks the EW symmetry in an appealing way, very reminiscent of the way the electromagnetic one is broken by supraconductivity (which, crudely speaking, gives a mass to the photon). However TC meets serious problems in passing the tests of electroweak measurements, because it harms too much the predictions.

On the other hand SUSY, which has a more discrete effect in this respect, keeps its eminent merits and remains the most frequented and even crowded route. SUSY is certainly a broken symmetry as no partner of known particles exists with the same mass. These partners are assumed to be heavy, but not too much (few hundred GeV to few TeV) as otherwise SUSY would no longer cure the hierarchy problem. Furthermore the convergence of couplings quoted above requires that the superpartners appear at relatively low mass. In SUSY the masses of superpartners evolve between their values at very high mass scale and the EW scale: a most remarkable feature is that this leads naturally to EW symmetry breaking.

With the diversity of its possible breaking mechanisms (SBM), SUSY presents a complex phenomenology with many different possible mass spectra for the supersymmetric particles. Its minimal version however offers a golden test: it predicts a very light Higgs boson, i.e. less than about 135 GeV (for m_{top}=178 GeV and in reasonably general conditions), and less than 130 GeV in the usual breaking schemes, in particular in all versions of Supergravity (see below) presently considered as the reference points for future searches (8). By considering a non minimal scenario (NMSSM), one can somewhat evade such a sharp constraint, although the lightest boson stays below 190 GeV or so.

Besides these two leading scenarii, quite interesting new roads appeared in the recent years. But they had no or little impact on LEP physics and we postpone their description to the end of this review.

MORE ON SUSY PHENOMENOLOGY AND PROMISES

Unbroken SUSY doubles the number of states without introducing new parameters. The couplings involving SUSY partners are known, within possible mixing effects. Unfortunately SUSY is a broken theory and the breaking mechanism is unknown. Not to reintroduce quadratic divergences the breaking must be ″soft″, i.e. obey certain rules. The phenomenology of soft breaking which is not more than a "parameterization of our ignorance" introduces many new parameters, up to 105 new ones. Basic requirements restrain the range of possibilities. However it is necessary to make further assumptions to reduce the number of free parameters and their range in order to get a tractable situation.

Apart from the clear prediction concerning the lightest Higgs state, dwelling into broken SUSY phenomenologies is entering a jungle. SUSY can be minimal or not. Minimality means one superpartner only per SM particle, a minimal Higgs system made of two complex doublets (a single one is not sufficient, the ratio of their two vacuum expectation values called tg□ is one of the important parameters), and therefore five bosons, and a further symmetry called R-parity. Conserving R-parity implies that superpartners (SP) are produced in pairs and have always another SP in their decay, which means that the lighest of them, the Lightest SuperPartner (LSP), is stable. If neutral, this LSP provides a source of missing energy in the final state of a reaction. It is also an excellent candidate for the cold dark matter (CDM) of the Universe. On the other hand, in R-breaking theories, SP can be produced singly and the LSP decays: the missing energy signature and the CDM candidate are lost.

Considering SUSY breaking, the lore is that it occurs in a Hidden Sector which does not communicate directly with the known particles, but does it through a Messenger Sector. Three main possibilities are considered. In Supergravity (SUGRA) the messenger is gravity. In gauge-mediated SUSY breaking (GMSB) the messengers are particles which couple to the observable ones by usual gauge interactions. Anomaly-mediated SUSY breaking (AMSB) is actually a variant of SUGRA. In SUGRA, for instance, one usually assumes the universality of the parameters and deals with 5 of them. Besides tg□, let us simply quote m_0, the common mass of all scalars at very high mass scale, and $m_{1/2}$, the same for spin 1/2 particles. We will describe later the main features of the various phenomenologies and the searches performed at LEP.

But let us emphasize first one of the most interesting promises of SUSY because of its deep implication in cosmology.

It is presently admitted that a substantial part of the matter of the Universe is “dark”, i.e. invisible and felt only through its gravitational effect. Moreover most of it must be “cold”, i.e, non relativistic at the time relevant for galaxy formation. The cold dark matter contribution to the content of the universe has been accurately determined by WMAP (29 ± 4%, of which only 4.4 ± 0.4 % is baryonic). For non baryonic dark matter, the neutralino, as lighest supersymmetric particle (LSP), is the main suspect. Neutralinos and more generally WIMPS, fossile weakly interacting particles, can be produced at colliders if they are light enough, and we will describe below what LEP has achieved and what may come next concerning them.

THE HIGGS BOSON SEARCH :

Among the five Higgs bosons of the MSSM, the lightest one, h^0, was the most relevant for LEP and, apart under special and unlikely conditions, is SM-like. Therefore in this chapter we will not distinguish between the SM and SUSY Higgs searches. The other MSSM Higgs bosons, a scalar H^0, a pseudoscalar A^0 and two charged bosons, are likely to be heavy, at a common mass M_A. In the mass range considered the light boson decays mostly into beauty-antibeauty.

Let us start with a quick historical account.

At the time of the Aachen 1986 LEP200 Workshop (9) it was still considered as impossible, for experimental reasons, to explore the domain of Higgs mass in the vicinity of the W mass, and a fortiori of the Z mass.

In 1989 however it started to be realized that with a good b-tag one would probably be able to ″break the Z^0 wall″. On the basis of simple estimates, the rule of thumb for a reach of $M_H \sim \sqrt{s} - 100$ GeV was proposed, with the meaning of a discovery potential per experiment.

In 1991 appeared the preliminary computations of the radiative corrections to the mass of the lightest MSSM Higgs boson h^0 (10), showing that they could be large and that the exact value of the top mass was a critical ingredient since it enters there to the 4th power.

In 1992 a first LEP2 LEPC Workshop was held at Cern, from which stemmed the familiar discovery and exclusion L_{min} - M_H plots.

By the end of 1994 everything needed to predict the upper limit of M_h in the MSSM was known: the top mass, as shown by figure 3a, and the theoretical computation of the radiative correction to the required order, giving a figure of ≈126 GeV for this upper limit for M_{top}=175 GeV. The energy needed to give a meaningful answer, yes or no, about the MSSM was then well defined.

In 1994 the LHC was approved. The foreseen date for its startup was then the end of 2002. 1995 saw the start of the energy rise at LEP. 1996 was the year of the important LEP2 workshop, which led to the Yellow Book, Bible of the LEP200 era (11) . By that time, improvements of the simulation and of the statistical methods were such that the crude thumb rule mass reach had become $\sqrt{s} - M_Z$ for exclusion by the four experiment added together, with typically 200 pb^{-1} per experiment, and 2 GeV less for discovery.

The W pair threshold was crossed in 1996. Around the same time, the production of SC cavities was discontinued. After that the story is well known, dominated by the constant and most successful progress of the machine in energy, within the allocated park of supraconducting RF cavities, as well as in luminosity, by the obtention of one extra year of running in 2000, and the difficult and painful decision to be taken at the end of 2000.

Let us turn now to a brief description of the search itself. This has been done elsewhere in such detail (12) that we will only focus on the highest accessible mass region and summarize the final situation.

A SM or SM-like boson is produced in association with a Z^0 by the Higgsstrahlung (HS) process (figure 5, left). The HS hits a kinematical barrier when $\sqrt{s} = M_Z + M_H$: tails beyond this barrier reflect the tail of the Z^0 Breit-Wigner. At and beyond the kinenatic limit, the fusion process and its interference with HS can be used in the H□□ channel, but the cross-section is tiny. So LEP was a threshold machine and the goal was to run at the highest possible energy to maximize the chances of discovery. An increase of energy pushes up the kinematic limit. For a given Higgs mass it allows the Higgs production cross-section to approach it maximal value. In case of a possible signal, it gives a chance to check its stability and therefore its reality.

Given the three generic channels of Z^0 decay, the Higgs boson was searched for in all-hadronic mode (4 jets, two from beauty), missing-energy mode (the Z^0 into neutrinos) and dilepton-dijet (the jets being b-jets from the Higgs boson).

The last one is the cleanest, but has the smallest branching ratio.

The $H\nu\nu$ channel considers events with two beauty jets and missing energy. Even close to the Higgsstrahlung kinematical limit, these two jets are still notably acolinear and acoplanar. The main weapon against background is therefore to reject coplanar and a fortiori colinear due to radiative return or large missing energy normal 2-jet events.

In the four jet channel, WW, ZZ and QCD all contribute to the SM background, up to the highest masses that even WW and ZZ can populate through mis-pairing of jets. A very strong rejection of WW is obtained through b-tagging, the limit coming in particular from the unability to distinguish totally c from b jets, and from some tiny content of beauty in WW events. As one can expect, the ZZ background is the most resistant.

Having excluded lower masses, up to 112.3 GeV, in summer 2000 the LEP search in the few last months of running focused on the highest accessible mass, at the kinematical limit of the Higgsstrahlung process, namely 115 GeV for an ultimate CM energy of 206 GeV. Under such conditions, for a mass of 115 GeV, the total Higgs cross-section is 50 fb only, compared to 1 picobarn for ZZ.

The final mass spectrum obtained at LEP is shown in figure 5, right. Some candidate events appearing around 115 Gev generated a lot of excitment. However, no appreciable gain in energy was foreseable and the decision to stop LEP by the end of 2000 was maintained.

More than two years after the end of LEP, the situation can be summarized as follows (13). In brief, most of the effect comes from the fact that one experiment (ALEPH) sees an excess in one channel (the four-jets, largely through three notorious events). ALEPH quotes $2.4\ 10^{-3}$ as the probability to be more signal-like in the absence of a real signal. Combining all four experiments, this becomes 9.9% (a 1.7 σ efect). The future will tell whether this indication is a true effect or not. The final LEP limit on a SM-like neutral boson is 114.4 GeV. This is also the limit for the MSSM h_0 in the (likely) case where $m_A > 100$ GeV.

NON SM LIKE HIGGSES

The canonical MSSM higgs search exploits both the HS mode and the associated production mode $e^+e^- \to h^0A^0$. The situation is governed by the mixing in the stop sector, which can range from maximal, the most conservative case, to the case of no mixing. The no mixing scenario is almost completely ruled out. In the maximal mixing scenario, the lower limits for m_h and m_A are 91 and 91.9 GeV, respectively, and the range

0.5<tg□<2.4 is excluded (for m_{top} = 174.3 GeV). The final truth will actually depend on the exact m_{top} value.

Among many searches for non-conventional Higgs bosons (14), let us quote first the invisible one. There may be several theoretical reasons why it could be so. For LEP, detecting such a boson is not much of a problem, since the bilan of energy-momentum can still be properly done. The main background is ZZ, with one Z decaying in neutrinos, and the possibility to reduce it through b-tagging is lost. The ADLO lower mass limit is presently 114.4 GeV, assuming that the boson is produced at the SM rate and decays exclusively into invisible final states.

For what concerns the flavour-blind search for a Higgs boson which would not decay specifically into beauty, as some alternative scenarios announce, the combined LEP lower mass limit is 112.5 GeV.

EPILOGUE ON THE HIGGS SEARCH AT LEP

In the frame of the SM, the non-observation of a Higgs boson up to 114 GeV does not contradict the indirect information of figure 3. Futhermore, in the SM, the theoretically preferred mass region, admittedly at the expense of an embarrassing fine tuning, is somewhat higher (130 to 180 GeV).

Concerning the MSSM h^0, about 15 GeV more in centre of mass energy (i.e.1.33 times the number of RF cavities, meaning 380 instead of 285, a number which would have fit in the equipped straight sections (15)) would have been needed to get a meaningful answer about its existence, if the top mass is not far from its present measured value. The non-observation of h_0 up to the present limit has been analyzed in terms of the degree of fine tuning required among the SUSY parameters and some authors concluded that the MSSM was in some trouble. This is however somewhat subjective, and the faith in this model is still, rightly or not, guiding most of the prospective studies for future programmes.

SEARCHES FOR SUSY PARTNERS

In R-parity conserving models, the missing energy signature, due to the non-observability of the LSP, played a crucial role. This led to focus in particular on the two-fermion acoplanar topologies. To cover GMSB and AMSB models several specific and striking features were searched for. Parity-breaking scenarios, generally lacking the missing energy signature, required the systematic exploration of a large variety of topologies. Some of the mass limits which resulted from the negative results of these searches can be found in Table 1. Such limits are mostly relevant for those particles which had a priori a chance to be within reach, namely some of the fermions and gauginos.

SUPERPARTNERS OF THE SM FERMIONS

In brief the partners of fermions, called sleptons and squarks, have been excluded at LEP up to masses which, for the first two generations, are close to the maximum beam energy. Sleptons, especially the partner of the right-handed (RH) fermion, may have been light and the corresponding limits have some impact in bounding the parameter space of SUSY.

In the sfermion sector a special role is played by the spartners of the third family, because of the potential existence of strong mixing effects. The lightest mass eigenstate, for instance of the stop, can be quite light and special searches at LEP and Tevatron were devoted to it. The results (16) show the complementarity of the two machines.

SUPERPARTNERS OF THE SM BOSONS

The gluino is the superpartner of the gluon. The two charginos and four neutralinos χ^0_i are linear mixtures of the spin 1/2 superpartners of the photon, Z and W gauge bosons and of Higgs bosons. Depending on the location in the parameter space, these particles, in particular the lighest neutralino χ^0_1, can be of different compositions and have therefore different patterns of interaction. In the case of a universal spin 1/2 $m_{1/2}$ mass at high scale, one foresees a mass hierarchy like: $M(\chi^0_1)$ / $M(\chi^0_2)$, $M(\chi^\pm_1)$ / M(gluino) ~ 1 / 2 / 7. The lightest neutralino is the LSP, generally dominantly partner of the Z^0 and the photon. However, dropping the mass universality could lead to quite different predictions.

The limits on charginos depend on their composition and on the mass difference between the chargino and the LSP into which it decays. In general mass values close to the kinematic limit are reached, but in some regions of the parameter space, namely a small m_0 i.e. light sleptons, the production rate and efficiency are lower and lead to a lower mass limit.

For neutralinos the reaction $e^+e^- \to \chi^0_1\chi^0_1$ is of no use in the MSSM since the LSP is invisible. Generally the production of higher masses neutralinos, like: $e^+e^- \to \chi^0_1\chi^0_2$, and of charginos help setting limits. But in the case just quoted these limits are weakened and one must get help from charged slepton searches

THE LSP AND COLD DARK MATTER

The exact limit set by LEP on the χ^0_1 LSP is thus model-dependent. In the MSUGRA framework the lower mass limit (at 95% CL) of the LSP, whatever be m_0, is about 50 GeV. In a general MSSM scenario this limit may go down to ~ 20 GeV or less (17).

The composition of the χ^0_1 LSP, as well as the exact features of the sparticle mass spectrum, are of great importance to determine the amount of relic cold dark matter in the Universe. Besides LEP limits, important constraints come from the information on CDM deduced from the Cosmic Microwave Background studies and presently dominated by the WMAP results. The figures of (18) shows which regions of the m_0 - $m_{1/2}$ plane of SUGRA are still admissible.

Before the LHC and LC bring more information on the LSP, what could one expect? Non-accelerator experiments can detect relic WIMPS, either directly by observing the recoil of nuclei they collide with or indirectly through the decay products of their mutual annihilation. Concerning these methods, that we will not describe here, the conclusion is that, even in a rather constrained case like SUGRA, such types of searches, although they can bring eventually a positive evidence, will be unable to falsify the theory.

R-PARITY BREAKING

The minimal version of SUSY is by definition R-parity conserving. On the other hand there is no good physical reason to impose a priori its conservation. R-violation is obtained by adding in the theory a large number of new couplings, some of which already bound by various low energy measurements, which lead to dramatic new effects. SUSY partners can be produced singly, for instance as a resonant state in the s-channel. An example would be the production in e^+e^- of a tau-sneutrino decaying into $\tau^+\tau^-$. The LSP neutralino is now unstable, for instance decaying into three leptons and it is therefore visible. The missing energy signature is lost and an extreme variety of final topologies can be obtained. R-parity breaking is thus an excellent motivation to study all final states one can get access to with enough purity and sensitivity: exactly what a search programme should be. The cleanliness of LEP physics allowed to meet or at least approach such a goal. No departure from the SM expectation was reported (19).

SOME SPECIAL SUSY SEARCHES

Final states with very low visible energy are the most difficult to select and measure properly. They occur in several scenarios which involve nearly mass degenerate SUSY particles since cascading from one to the other does not release much energy. Nevertheless LEP was able to achieve most performant searches in this respect. An example is the search for charginos, nearly degenerate with the lightest neutralino in the AMSB scenario, the trick being to use visible initial state photon radiation to tag the otherwise hardly visible final state.

The GMSB scenario as well calls for quite special studies. In GMSB the LSP is the gravitino, superpartner of the graviton, whose mass may range from 10^{-6} eV to the keV domain. This fact dominates the GMSB phenomenology. Its details depend then on the identity of the Next-to-LSP (NLSP) particle which can be either the lightest neutralino, decaying into photon-gravitino, or a slepton, most likely a stau.

Various striking signatures of a possibly long-lived NLSP (tracks with offsets, kinks, secondary vertices, non-pointing γ, heavy stable particles) were systematically looked for but not observed (20) .

Several other searches, like the one for charginos, in the GMSB scenario, are actually greatly facilitated by the request of prompt gammas in the final state and lead to limits even better than for SUGRA.

WHAT COULD WE HAVE MISSED ?

Could one have missed light new objects, not easy to distinguish from the bulk of normal SM processes ? For instance what about the pair production of a light gluino? Besides other negative indications, a decisive answer comes from the very sharp limit set at LEP1 on the extra width of the Z^0 due to new hadronic final states (<3.9 MeV, as said previously) : there is no room for a light gluino below 6.3 GeV. One reaches a similar conclusion about the pair production of an eventual very light sbottom quark : such a particle is excluded up to a similar value (21).

EPILOGUE

Another obvious question is whether, from the negative answers obtained and the lower limits set, SUSY, in its minimal low mass version, is already in trouble or not. The light Higgs window has not been closed, but the mass limit set calls for large tgβ versions of the MSSM or for non MSSM versions. Given the extreme variety of possible mass spectra, the non-observation of SUSY partners does not contrain much the theory. To judge their impact one must therefore resort to naturalness arguments i.e. evaluate the level of fine tuning needed between the SUSY parameters to satisfy the EW symmetry breaking without producing visible new states. One knows that such arguments are largely subjective.

Besides LEP limits, other informations allow to shape the future. Waiting for a stabilization of the situation concerning the g-2 factor of the muon and for more data on relevant rare decay modes of B mesons, the main ones come from CMB studies, as previously described.

OTHER SEARCHES

As we said, an alternative route beyond the SM is to invoke the existence of a new level of constituants and/or new forces. We will refer to it under the general label of Compositeness. We will also consider briefly the case of a possible recurrence of the Z^0 boson, as well as a scenario involving large extra-dimensions.

A/ COMPOSITENESS

Keeping in mind the caveat mentioned above concerning the EW tests, let us explore first the possible signals linked with composite scenarios (22) , namely at least one of the following effects :

1/ Technicolor particles

The idea is that a new level of constituants, Techniquarks, interact by mimicking (with however substantial differences) the strong interaction at much higher scale. After the Tevatron, LEP has performed a search for Technicolored vector bosons (TVB), ρ_T and ω_T, as predicted by the model of (6). These searches, actually quite similar to Higgs ones, were sensitive to TVB (Technipions) in the 200 (100) GeV region. They did not reveal any signal. The domain where one could expect such particles is however very model dependent and these first explorations (23) are just an appetizer for what more luminosity (at the Tevatron) and more energy (at LHC) will offer.

2/ Contact interactions

Crudely speaking, the idea is to search in various reactions for the manifestation of a form factor which would hint at a non point-like nature of the basic SM constituants : the limit is expressed as an energy □, inverse of a size. We recall that 1 fermi correspond to 200 MeV$^{\square 1}$. Neither LEP nor Hera or the Tevatron have seen any anomaly. They set on □ lower limits of several TeV, rather similar for the three machines, which reflects the fact that the energies and luminosities of their constituant collisions are comparable.

3/ Excited states of the known fermions

In brief, the Tevatron covers the field of excited quarks up to 700-800 GeV. For excited leptons, LEP and HERA compete well, the LEP limits on the coupling being stronger, while HERA has a higher mass reach. This is well illustrated in the case of radiatively decaying excited electrons (24).

4/ Leptoquarks (LQ)

These hypothetical objects carry the quantum numbers of a quark and a lepton. We will not enter here into their complicated phenomenology. At LEP LQ can be pair produced , but with obvious mass reach limitations. They can also be singly produced, by fusion of an $e^{\pm}$ with a quark of the hadronic content of a photon radiated by the partner e. Figure 6 (25) compares the LEP exclusion domain to those from other machines. Actually leptoquarks and squarks in R-parity breaking scenarios behave similarly and the results on the former can also be interpreted in terms of production of the latter.

The last two manifestations of composite scenarios (excited objects and leptoquarks) can also appear in fundamental theories with a gauge group larger than the SM one.

B/ NEW VECTOR BOSONS

The physical scenarios leading to consider new heavy vector bosons, in particular a neutral Z’, are numerous. A Z’ is expected whenever a new U(1) symmetry group appears in the breaking of a unification group larger than the SM one. This is the case in left-right (LR) models in which the LR symmetry is restored at high energy, or in E6 (one of the so-called Exceptional Groups) GUT models, labeled as □,

□, □ according to the value of an internal mixing angle. One can also consider a mere recurrence of the Z^0 with identical couplings, the Sequential SM (SSM). In general the Z' mixes with the Z^0, an effect parameterized by an angle $\square_{ZZ'}$. At the Z^0 pole, measured cross-sections and asymmetries are particularly sensitive to the mixing which modifies the coupling to fermions. At higher energies the interference between Z^0 and Z' is sensitive to the Z' mass. Indirect searches at LEP2 led to lower mass limits roughly equivalent to the direct Tevatron ones. Exact numbers depend on the scenarios considered. Let us also recall that the measurement of Atomic Parity Violation (APV) is quite competitive up to now with LEP and Tevatron for such an exclusion, as shown in (26). As an example, for a Z' of a Left□Right model, decoupled from the Z^0, the lower mass limits from APV, Tevatron and LEP are 665, 630 and 804 GeV, respectively.

C/ LARGE EXTRA-DIMENSIONS

The other new route beyond SM postulates the existence, so far uncontradicted, of extra dimensions of space (ED), large enough to generate visible effects at future experiments. The general idea of an ED, due to Kaluza and Klein, is rather old (1919). The Superstring Theory requires EDs since it is consistent only in 9 or 10 spatial dimensions. For long, however, these EDs were thought to be “curled up” (compactified) at the Planck scale, until it was realized that things could be different. Several versions are presently put forward.

We will only quote one of them, the Arkani-Hamed, Dimopoulos, Dvali (ADD) scenario, which considers “big” dimensions (possibly up to 100 micron size), accessible only to gravity. Gravity then seems weak compared to the other forces because it is diluted in more dimensions, the effective Planck scale may be much lower than usually thought, possibly close at hand, and the hierarchy problem is thus eliminated or, rather, reformulated. The case of a large single ED is clearly excluded since the Newton law is valid at large scales. For 2 or 3 such ED astrophysics and cosmology give more powerful limits than the colliders. At colliders, the graviton can be directly produced and “disappear in extra dimensions”, giving a state with missing energy, or it can intervene as a virtual particle and change slightly the rate of some SM processes.

LEP looked for direct and indirect evidence of the role of the graviton (27). All missing energy modes, the simplest ones being the single gamma and the monojet final states were found to agree with the SM. Similarly two-body final states, like $e^+e^{\square}\square\ \square\square$ did not show any deviation up to the maximum energy. The former results give unambiguous limits on the effective Planck scale and the compactification radius : for the case of 4 extra-dimensions, as an example, these are about 1 Tev and $10^{\square 9}$ cm respectively. The interpretation of the latter is more subtle.

GENERAL OVERVIEW

THE LEP PARADOX?

At the end of LEP some authors consider that another problem has appeared, the Small Hierarchy one, namely the fact that LEP announces a light Higgs boson while it pushes beyond several TeV all new physics (except SUSY which can still be “behind the door”): again the Higgs mass should be pulled to this high scale and the fact that it is not calls for efficient cancellation mechanisms to be at work. The Little Higgs scenario (28) for instance was devised to solve this Small Hierarchy problem, leaving the Big one for later, without having recourse to SUSY. It requires several new particles and will be tested at LHC.

WHAT WE COULD HAVE MISSED

This was already discussed in the case of SUSY searches. Light objects can only be missed if they decouple from the Z^0.

LEP and previous searches have severely constrained the possibility that a light Higgs boson may have escaped detection (29). However here too, in case of strong decoupling from the Z^0, even a heavy one could be missed. This may be the case of the h^0 of a CP-violating SUSY Higgs sector, with some (unlikely) choice of parameters. A higher CM energy is then needed to observe instead its normaly coupled heavier partner.

Anyway nobody knows which new idea may come, calling for a reanalysis of some aspects of LEP data. It is therefore mandatory that they are kept in a safe repository, under a form such that they can be interrogated later if needed.

WHAT ELSE COULD HAVE BEEN DONE ?

Elaborate polarization studies, aiming at a program of longitudinal polarization, were performed (30) , but this difficult attempt was not pursued at LEP and left for SLC. However it led to a most accurate measurement of LEP energy by exploiting the transverse polarization. The prospect of an increased luminosity at LEP1 was also seriously considered, in particular through the study of the multibunch Brezel scheme (31). This study was quite useful, since it led to 4 and 8-bunch schemes. But the priority was correctly put on the energy increase and LEP, although its luminosity was substantially larger than anticipated, did not become a real Z factory. Several key measurements at LEP1 are still dominated by statistics. An interesting case concerns the B^0_S mixing parameter, whose measurement may have been nearly missed at LEP: it is potentially a powerful revelator of physics beyond SM, and one may have to wait still long before getting this answer from elsewhere.

It is clear that concerning the test of the validity of the MSSM in its usual scenarios an occasion has been lost. For 2-3% of the cost of the project the equipped straight sections of LEP could have been filled with about 100 more RF cavities, giving the CM energy needed to cover the Higgs mass window left open. The answer, in particular about the ”effect” at 115 GeV, will have been delayed by a decade. Meanwhile, prospective studies for LHC and LC are still largely dominated by the MSSM and SUGRA paradigms.

Nevertheless the twelve years of LEP physics have been a wonderful and most successful adventure, a period of great creativity and a model of an harmonious and fruitful collaboration between machine physicists, experimentalists and theorists.

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