CERN-TH/99-365

THE CRUCIAL PROBLEM: THE ELECTROWEAK SYMMETRY BREAKING

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Talk given at the XIth Rencontres de Blois
Frontiers of Matter
Blois, Loire Valley, France, 27 June – 3 July 1999

CERN-TH/99-365
November 1999

1 Why we do Believe in the SM: Precision Tests

In recent years new powerful tests of the Standard Model (SM) have been performed mainly at LEP but also at SLC and at the Tevatron. The running of LEP1 was terminated in 1995 and close-to-final results of the data analysis are now available [1, 2]. The experiments at the Z resonance have enormously improved the accuracy of the data in the electroweak neutral current sector. The LEP2 programme is in progress and will continue till the end of 2000. The top quark has been at last found at the Tevatron and the mass determined with few percent accuracy. The errors on m_Z and $\sin^2\theta_{eff}$ went down by two and one orders of magnitude respectively since the start of LEP in 1989. Similar drastic progress has been made on α_s, m_W and the Higgs search. The validity of the SM has been confirmed to a level that we can say was unexpected. In the present data there is no significant evidence for departures from the SM, no convincing hint of new physics. The impressive success of the SM poses strong limitations on the possible forms of new physics. Favoured are models of the Higgs sector and of new physics that preserve the SM structure and only very delicately improve it, as is the case for fundamental Higgs(es) and Supersymmetry. Disfavoured are models with a nearby strong non perturbative regime that almost inevitably would affect the radiative corrections, as for composite Higgs(es) or technicolour and its variants.

The main lesson of the precision tests [3] of the standard electroweak theory can be summarised as follows. It has been checked that the couplings of quark and leptons to the weak gauge bosons $W^{\pm}$ and Z are indeed precisely those prescribed by the gauge symmetry. The accuracy of a few 0.1% for these tests implies that, not only the tree level, but also the structure of quantum corrections has been verified. To a lesser accuracy the triple gauge vertices γW^+W^- and ZW^+W^- have also been found in agreement with the specific prediction, at the tree level, of the $SU(2)\bigotimes U(1)$ gauge theory. This means that it has been verified that the gauge symmetry is indeed unbroken in the vertices of the theory: the currents are indeed conserved. Yet there is obvious evidence that the symmetry is otherwise badly broken in the masses. In fact the $SU(2)\bigotimes U(1)$ gauge symmetry forbids masses for all the particles that have been sofar observed: quarks, leptons and gauge bosons. But of all these particles only the photon is massless (and the gluons protected by the $SU(3)$ colour gauge symmetry), all other are massive (probably also the neutrinos). Thus the currents are conserved but the spectrum of particle states is not symmetric. This is the definition of spontaneous symmetry breaking. The practical implementation of spontaneous symmetry breaking in a gauge theory is via the Higgs mechanism. In the minimal SM one single fundamental scalar Higgs isospin doublet is introduced and its vacuum expectation value v breaks the symmetry. All masses are proportional to v, although the Yukawa couplings that multiply v in the expression for the masses of quarks and leptons are distributed over a wide range. The Higgs sector is still very much untested. The Higgs particle has not been found [4] but its mass can well be heavier than the present direct lower limit $m_H \gtrsim 106$ GeV from LEP2 [5] [1]. One knew from the beginning that the Higgs search is difficult: being coupled in proportion to masses one has first to produce heavy particles and then try to detect the Higgs (itself heavy) in their couplings. What has been

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[1] In writing these Proceedings, I include all information available in November 1999.

tested is the relation $m_W^2 = m_Z^2 \cos^2\theta_W$, modified by computable radiative corrections. This relation means that the effective Higgs (be it fundamental or composite) transforms indeed as a weak isospin doublet.

Quantum corrections to the electroweak precision tests depend on the masses and the couplings in the theory. For example they depend on the top mass m_t, the Higgs mass m_H, the strong coupling $\alpha_s(m_Z)$, the QED coupling $\alpha(m_Z)$ (these are running couplings at the Z mass) and other parameters which are better known. In particular quantum corrections depend quadratically on m_t and only logaritmically on m_H. From the observed radiative corrections one obtains a value of m_t in fair agreement with the observed value from the Tevatron. For the Higgs mass one finds a quantitative indication of the mass range [1]: $\log_{10} m_H(\mathrm{GeV}) = 1.88^{+0.28}_{-0.30}$ (or $m_H = 77^{+69}_{-39}$). This result on the Higgs mass is particularly remarkable. The value of $\log_{10} m_H(\mathrm{GeV})$ is right on top of the small window between ~ 2 and ~ 3 which is allowed by the direct limit, on the one side, and the theoretical upper limit on the Higgs mass in the minimal SM (see later), $m_H \lesssim 600-800$ GeV, on the other side. If one had found a central value like $\gtrsim 4$ the model would have been directly discarded. Thus the whole picture of a perturbative theory with a fundamental Higgs is well supported by the data on radiative corrections. It is important that there is a clear indication for a particularly light Higgs. This is quite encouraging for the ongoing search for the Higgs particle. More in general, if the Higgs couplings are removed from the lagrangian the resulting theory is non renormalisable. A cutoff Λ must be introduced. In the quantum corrections $\log m_H$ is then replaced by $\log\Lambda$ plus a constant. The precise determination of the associated finite terms would be lost (that is, the value of the mass in the denominator in the argument of the logarithm). Thus the fact that, from experiment, one finds $\log m_H \sim 2$ is a strong argument in favour of the specific form of the Higgs mechanism as in the SM. A heavy Higgs would need some unfortunate conspiracy [6]: the finite terms should accidentally compensate for the heavy Higgs in the few key parameters of the radiative corrections (e.g the ϵ parameters [3]) [7]. Or additional new physics, for example in the form of effective contact terms added to the minimal SM lagrangian, should accidentally do the compensation [8], which again needs some sort of conspiracy [9].

2 Why we do not Believe in the SM

2.1 Conceptual Problems

Given the striking success of the SM why are we not satisfied with that theory? Why not just find the Higgs particle, for completeness, and declare that particle physics is closed? The main reason is that there are strong conceptual indications for physics beyond the SM.

It is considered highly unplausible that the origin of the electro-weak symmetry breaking can be explained by the standard Higgs mechanism, without accompanying new phenomena. New physics should be manifest at energies in the TeV domain. This conclusion follows from an extrapolation of the SM at very high energies. The computed behaviour of the $SU(3)\otimes SU(2)\otimes U(1)$ couplings with energy clearly points towards the unification of the electro-weak and strong forces (Grand Unified Theories: GUT's) at scales of energy $M_{\rm GUT} \sim 10^{14} - 10^{16}$ GeV [10] which are close to the scale of quantum gravity, $M_{\rm Pl} \sim 10^{19}$ GeV. One can also imagine a unified theory of all interactions also including gravity (at present superstrings [11] provide the best attempt at such a theory). Thus GUT's and the realm of quantum gravity set a very distant energy horizon that modern particle theory cannot anymore ignore. Can the SM without new physics be valid up to such large energies? This appears unlikely because the structure of the SM could not naturally explain the relative smallness of the weak scale of mass, set by the Higgs mechanism at $\mu \sim 1/\sqrt{G_F} \sim 250$ GeV with G_F being the Fermi coupling constant. This so-called hierarchy problem [12] is related to the presence of fundamental scalar fields in the theory with quadratic mass divergences and no protective extra symmetry at $\mu = 0$. For fermions, first, the divergences are logaritmic and, second, at $m = 0$ an additional symmetry, i.e. chiral symmetry, is restored. Here, when talking of divergences we are not worried of actual infinities. The theory is renormalisable and finite once the dependence on the cut off is absorbed in a redefinition of masses and couplings. Rather the hierarchy problem is one of naturalness. If we consider the cut off as a manifestation of new physics that will modify the theory at large energy scales, then it is relevant to look at the dependence of physical quantities on the cut off and to demand that no unexplained enormously accurate cancellations arise.

According to the above argument the observed value of $\mu \sim 250$ GeV is indicative of the existence of new physics nearby. There are two main possibilities. Either there exist fundamental scalar Higgses but the theory is stabilised by supersymmetry, the boson-fermion symmetry, that would downgrade the degree of divergence from quadratic to logarithmic. For approximate supersymmetry the cut off is replaced by the splitting between the normal particles and their supersymmetric partners. Then naturalness demands that this splitting (times the size of the weak gauge coupling) is of the order of the weak scale of mass, i.e. the separation within supermultiplets should be of the order of no more than a few TeV. In this case the masses of most supersymmetric partners of the known particles, a very large managerie of states, would fall, at least in part, in the discovery reach of the LHC. There are consistent, fully formulated field theories constructed on the basis of this idea, the simplest one being the MSSM [13]. As already mentioned, all normal observed states are those whose masses are forbidden in the limit of exact $SU(2) \otimes U(1)$. Instead for all SUSY partners the masses are allowed in that limit. Thus when supersymmetry is broken in the TeV range but $SU(2) \otimes U(1)$ is intact only s-partners take mass while all normal particles remain massless. Only at the lower weak scale the masses of ordinary particles are generated. Thus a simple criterium exists to understand the difference between particles and s-particles.

The other main avenue is compositeness of some sort. The Higgs boson is not elementary but either a bound state of fermions or a condensate, due to a new strong force, much stronger than the usual strong interactions, responsible for the attraction. A plethora of new "hadrons", bound by the new strong force would exist in the LHC range. A serious problem for this idea is that nobody sofar has been able to build up a realistic model along these lines, but that could eventually be explained by a lack of ingenuity on the theorists side. The most appealing examples are technicolour theories [14, 15]. These models were inspired by the breaking of chiral symmetry in massless QCD induced by quark condensates. In the case of the electroweak breaking new heavy techniquarks must be introduced and the scale analogous to Λ_{QCD} must be about three orders of magnitude larger. The presence of such a large force relatively nearby has a strong tendency to clash with the results of the electroweak precision tests [16]. New versions have been developed [15] to overcome the negative response of the data, but models are far from offering a realistic picture.

Are there other ways to solve the hierarchy problem? Recently an exotic way was proposed [17, 18]. The idea is that perhaps the scale of gravity is only apparently so large. It has been shown that it is in principle possible to bring down the scale of gravity in the multi TeV energy range. This can happen if one assumes the existence of extra space dimensions with sufficiently large compactification radius, with the graviton propagating in all dimensions, while ordinary gauge interactions are trapped on a four dimensional wall. The corresponding modification of gravity at submillimetric distances is compatible with existing limits. The vicinity of the decompactification scale can manifest itself in high energy processes at e^+e^- and hadron colliders where gravitons can be produced and appear as missing energy. This very speculative scenario is certainly interesting especially as a stimulus to look for specific signals. But does not appear as particularly compelling because the reason why the decompactification scale should be $\simeq$ few TeV remains mysterious. In addition all the positive hints we have in favour of the ordinary picture of GUTs from coupling unification, neutrino masses, dark matter and so on would be emptied. Finally early time cosmology should be rewritten.

The hierarchy problem is certainly not the only conceptual problem of the SM. There are many more: the proliferation of parameters, the mysterious pattern of fermion masses and so on. But while most of these problems can be postponed to the final theory that will take over at very large energies, of order $M_{\rm GUT}$ or $M_{\rm Pl}$, the hierarchy problem arises from the unstability of the low energy theory and requires a solution at relatively low energies.

A supersymmetric extension of the SM provides a way out which is well defined, computable and that preserves all virtues of the SM. The necessary SUSY breaking [19] can be introduced through soft terms that do not spoil the good convergence properties of the theory. Precisely those terms arise from supergravity when it is spontaneoulsly broken in a hidden sector. This is the case in the Minimal Supersymmetric Standard Model (MSSM) [13]. In this most traditional approach SUSY is broken in a hidden sector [20] and the scale of SUSY breaking is very large of order $\Lambda \sim \sqrt{G_F^{-1/2} M_{\rm Pl}}$ where $M_{\rm Pl}$ is the Planck mass. But since the hidden sector only communicates with the visible sector through gravitational interactions the splitting of the SUSY multiplets is much smaller, in the TeV energy domain, and the Goldstino is practically decoupled. But alternative mechanisms of SUSY breaking are also being considered [18, 21, 22]. In one alternative scenario the (not so much) hidden sector is connected to the visible one by ordinary gauge interactions. As these are much stronger than the gravitational interactions, Λ can be much smaller, as low as 10-100 TeV. It follows that the Goldstino is very light in these models (with mass of order or below 1 eV typically) and is the lightest, stable SUSY particle, but its couplings are observably large. The radiative decay of the lightest neutralino into the Goldstino leads to detectable photons. The signature of photons comes out naturally in this SUSY breaking pattern: with respect to the MSSM, in the gauge mediated model there are typically more photons and less missing energy. The main appeal of gauge mediated models is a better protection against flavour changing neutral currents. In the gravitational version even if we accept that gravity leads to degenerate scalar masses at a scale near $M_{\rm Pl}$ the running of the masses down to the weak scale can generate mixing induced by the large masses of the third generation fermions [18]. More recently it has been pointed out [22] that there are pure gravity contributions to soft masses that arise from gravity theory anomalies. In the assumption that these terms are dominant the associated spectrum and phenomenology has been studied. In this case gaugino masses are proportional to gauge coupling beta functions, so that the gluino is much heavier than the electroweak gauginos, and the wino is most often the lightest SUSY particle.

The MSSM [13] is a completely specified, consistent and computable theory. There are too many parameters to attempt a direct fit of the data to the most general framework. But we can consider two significant limiting cases: the "heavy" and the "light" MSSM.

The "heavy" limit corresponds to all s-particles being sufficiently massive, still within the limits of a natural explanation of the weak scale of mass. In this limit a very important result holds [23]: for what concerns the precision electroweak tests, the MSSM predictions tend to reproduce the results of the SM with a light Higgs, say $m_H \sim 100$ GeV. So if the masses of SUSY partners are pushed at sufficiently large values the same quality of fit as for the SM is guaranteed.

In the "light" MSSM option some of the superpartners have a relatively small mass, close to their experimental lower bounds. In this case the pattern of radiative corrections may sizeably deviate from that of the SM [24]. The potentially largest effects occur in vacuum polarisation amplitudes and/or the $Z \to b\bar{b}$ vertex. Since no sign of deviations from the SM is seen in the data and no light SUSY partners have been found at LEP2 or at the Tevatron, the "light" case can no more be that light.

According to the prevailing view at present, the large scale structure of particle physics consists of a unified theory at $M = M_{\rm GUT} - M_{\rm Pl}$ and a low energy effective theory valid at and above the weak scale of energy. The lagrangian density of the low energy effective theory, after integrating out all very heavy degrees of freedom, consists of a set of operators of dimension non larger than 4, that correspond to the renormalisable part, plus a set of higher dimension, non renormalisable, operators. Schematically, we have:

$$\mathcal{L} = \mu^2\phi^2 + m\bar{\psi}\psi + g\bar{\psi}i\not{D}\psi + \lambda\phi^4 + ... + \frac{\lambda_5}{M}\bar{\psi}\psi\phi\phi + \frac{\lambda_6}{M^2}\bar{\psi}\psi\bar{\psi}\psi + ... \tag{1}$$

Indicatively, we have shown a number of typical terms of dimension 2 (boson masses), 3 (fermion masses), 4 (renormalisable interactions) plus examples of operators of higher dimension, 5 and 6. Due to the very large scale of energy where the really fundamental theory applies, the conditions on the low energy effective theory are severe. First, the dimension ≤ 4 part must be renormalisable. This is a minimum requirement in order to have a closed, consistent and predictive description of the dynamics after the presence of the very high cut off has been hidden inside renormalised masses and couplings. But this is not enough because the dependence of masses and couplings from the cut off must be reasonable in order to avoid the necessity of immense fine tuning. For this to be true additional conditions must be satisfied. The coupling in front of each operator, in absence of specific reasons, should be proportional to the large cut off M raised to a power d fixed by dimensions. For example, μ^2 should be proportional to M^2. In the SM there is no symmetry reason why this should not be the case. So boson masses, like the W and Z masses, should be of order M. This the hierarchy problem [12] . In supersymmetric extensions of the SM μ^2 is instead of order the mass splittings of SUSY multiplets, because in the limit of exact SUSY symmetry there are no quadratic divergences (in presence of boson-fermion symmetry the stronger bosonic divergences must disappear, in order that bosonic and fermionic divergences can both be logaritmic). For fermions m is not of order M but of order $v \log M$ because the divergences in the fermionic sector are always at most logaritmic. Also, chiral symmetry ensures that if you start from zero masses the quantum corrections to m must vanish. Once supersymmetry or some other stabilising mechanism is introduced, the renormalisable part of the lagrangian is sufficiently insensitive to the presence of the very large cut off M. The additional non renormalisable terms are suppressed by powers of M. At energies of order v, the electro-weak scale, their effects are proportional to $(v/M)^d$, $d = 1, 2, ...$, hence very small.

2.2 Hints from Experiment

2.2.1 Unification of Couplings

At present the most direct phenomenological evidence in favour of supersymmetry is obtained from the unification of couplings in GUTs. Precise LEP data on $\alpha_s(m_Z)$ and $\sin^2\theta_W$ confirm what was already known with less accuracy: standard one-scale GUTs fail in predicting $\sin^2\theta_W$ given $\alpha_s(m_Z)$ (and $\alpha(m_Z)$) while SUSY GUTs [25] are in agreement with the present, very precise, experimental results. According to the analysis of ref. [26], if one starts from the known values of $\sin^2\theta_W$ and $\alpha(m_Z)$, one finds for $\alpha_s(m_Z)$ the results:

$$\begin{aligned} \alpha_s(m_Z) &= 0.073 \pm 0.002 \qquad \text{(Standard GUTs)} \\ \alpha_s(m_Z) &= 0.129 \pm 0.010 \qquad \text{(SUSY GUTs)} \end{aligned} \tag{2}$$

to be compared with the world average experimental value $\alpha_s(m_Z)$ =0.119(4).

2.2.2 Dark Matter

There is solid astrophysical and cosmological evidence [27, 28] that most of the matter in the universe does not emit electromagnetic radiation, hence is ”dark”. Some of the dark matter must be baryonic but most of it must be non baryonic. Non baryonic dark matter can be cold or hot. Cold means non relativistic at freeze out, while hot is relativistic. There is general consensus that most of the non baryonic dark matter must be cold dark matter. A couple of years ago the most likely composition was quoted to be around 80% cold and 20% hot. At present it appears that the need of a sizeable hot dark matter component is more uncertain. In fact, recent experiments have indicated the presence of a previously disfavoured cosmological constant component in $\Omega = \Omega_m + \Omega_\Lambda$ [27]. Here Ω is the total matter-energy density in units of the critical density, Ω_m is the matter component (dominated by cold dark matter) and Ω_Λ is the cosmological component. Inflationary theories strongly favour $\Omega = 1$ which is consistent with present data. At present, still within large uncertainties, the approximate composition is indicated to be $\Omega_m \sim 0.4$ and $\Omega_\Lambda \sim 0.6$ (baryonic dark matter gives $\Omega_b \sim 0.05$).

The implications for particle physics is that certainly there must exist a source of cold dark matter. By far the most appealing candidate is the neutralino, the lowest supersymmetric particle, in general a superposition of photino, Z-ino and higgsinos. This is stable in supersymmetric models with R parity conservation, which are the most standard variety for this class of models (including the MSSM). A neutralino with mass of order 100 GeV would fit perfectly as a cold dark matter candidate. Another common candidate for cold dark matter is the axion, the elusive particle associated to a possible solution of the strong CP problem along the line of a spontaneously broken Peccei-Quinn symmetry. To my knowledge and taste this option is less plausible than the neutralino. One favours supersymmetry for very diverse conceptual and phenomenological reasons, as described in the previous sections, so that neutralinos are sort of standard by now. For hot dark matter, the self imposing candidates are neutrinos. If we demand a density fraction $\Omega_\nu \sim 0.1$ from neutrinos, then it turns out that the sum of stable neutrino masses should be around 5 eV [27].

2.2.3 Neutrino Masses

Recent data from Superkamiokande [29, 30] have provided a more solid experimental basis for neutrino oscillations as an explanation of the atmospheric neutrino anomaly. In addition the solar neutrino deficit [31], observed by several experiments, is also probably an indication of a different sort of neutrino oscillations. Results from the laboratory experiment by the LSND collaboration [32, 33] can also be considered as a possible indication of yet another type of neutrino oscillation. Neutrino oscillations imply neutrino masses. The extreme smallness of neutrino masses in comparison with quark and charged lepton masses indicate a different nature of neutrino masses, linked to lepton number violation and the Majorana nature of neutrinos. Thus neutrino masses provide a window on the very large energy scale where lepton number is violated and on GUTs. The new experimental evidence on neutrino masses could also give an important feedback on the problem of quark and charged lepton masses, as all these masses are possibly related in GUTs. In particular the observation of a nearly maximal mixing angle for $\nu_\mu \rightarrow \nu_\tau$ is particularly interesting. Perhaps also solar neutrinos may occur with large mixing angle. At present solar neutrino mixings can be either large or very small, depending on which particular solution will eventually be established by the data. Large mixings are very interesting because a first guess was in favour of small mixings in the neutrino sector in analogy to what is observed for quarks. If confirmed, single or double maximal mixings can provide an important hint on the mechanisms that generate neutrino masses.

The experimental status of neutrino oscillations is still very preliminary . While the evidence for the existence of neutrino oscillations from solar and atmospheric neutrino data is rather convincing by now, the values of the mass squared differences Δm^2 and mixing angles are not firmly established. For solar neutrinos, for example, three possible solutions are still possible [34]. Two are based on the MSW mechanism [35], one with small (MSW-SA: $\sin^2 2\theta_{sun} \sim 5.5\ 10^{-3}$) and one with large mixing angle (MSW-LA: $\sin^2 2\theta_{sun} \gtrsim 0.2$), and one in terms of vacuum oscillations (VO) with large mixing angle (VO: $\sin^2 2\theta_{sun} \sim 0.75$). For atmospheric neutrinos the preferred value of Δm^2 is affected by large uncertainties and could still sizeably drift in one sense or the other, but the fact that the mixing angle is large appears established ($\sin^2 2\theta_{atm} \gtrsim 0.9$ at 90% C.L.) [36, 37, 30]. Another issue which is still open is the claim by the LSND collaboration of an additional signal of neutrino oscillations in a reactor experiment [32]. This claim was not so-far supported by a second recent experiment, Karmen [38], but the issue is far from being closed. Given the present experimental uncertainties the theorist has to make some assumptions on how the data will finally look like in the future. Here we tentatively assume that the LSND evidence will disappear. If so then we only have two oscillations frequencies, which can be given in terms of the three known species of light neutrinos without additional sterile kinds (i.e. without weak interactions, so that they are not excluded by LEP). We then take for granted that the frequency of atmospheric neutrino oscillations will remain well separated from the solar neutrino frequency, even for the MSW solutions. The present best values are [34, 36, 37, 30] $(\Delta m^2)_{atm} \sim 3.5\ 10^{-3}$ eV^2 and $(\Delta m^2)_{MSW-SA} \sim 5\ 10^{-6}$ eV^2 or $(\Delta m^2)_{VO} \sim 10^{-10}$ eV^2. We also assume that the electron neutrino does not participate in the atmospheric oscillations, which (in absence of sterile neutrinos) are interpreted as nearly maximal $\nu_\mu \rightarrow \nu_\tau$ oscillations as indicated by the Superkamiokande [29, 30] and Chooz [39] data. However the data do not exclude a non-vanishing U_{e3} element. In the Superkamiokande allowed region the bound by Chooz [39] amounts to $|U_{e3}| \lesssim 0.2$ [36, 37].

In summary, by now it is very unlikely that all this evidence for neutrino oscillations will disappear or be explained away by astrophysics or other solutions. The consequence is that we have a substantial evidence that neutrinos are massive. From a strict minimal standard model point of view neutrino masses could vanish if no right handed neutrinos existed (no Dirac mass) and lepton number was conserved (no Majorana mass). In GUTs both these assumptions are violated. The right handed neutrino is required in all unifying groups larger than SU(5). In SO(10) the 16 fermion fields in each family, including the right handed neutrino, exactly fit into the 16 dimensional representation of this group. This is really telling us that there is something in SO(10)! The SU(5) alternative in terms of $\bar{5} + 10$, without a right handed neutrino, is certainly less elegant. The breaking of $|B - L|$, B and L is also a generic feature of GUTs. In fact, the see-saw mechanism [40] explains the smallness of neutrino masses in terms of the large mass scale where $|B - L|$ and L are violated. Thus, neutrino masses, as would be proton decay, are important as a probe into the physics at the GUT scale.

Oscillations only determine squared mass differences and not masses. The case of three nearly degenerate neutrinos is the only one that could in principle accomodate neutrinos as hot dark matter together with solar and atmospheric neutrino oscillations. According to our previous discussion, the common mass should be around 1-3 eV. The solar frequency could be given by a small 1-2 splitting, while the atmospheric frequency could be given by a still small but much larger 1,2-3 splitting. A strong constraint arises in the degenerate case from neutrinoless double beta decay which requires that the ee entry of m_ν must obey $|(m_\nu)_{11}| \leq 0.2 - 0.5$ eV [41]. As observed in ref. [42], this bound can only be satisfied if double maximal mixing is realized, i.e. if also solar neutrino oscillations occur with nearly maximal mixing. We have mentioned that it is not at all clear at the moment that a hot dark matter component is really needed [27]. However the only reason to consider the fully degenerate solution is that it is compatible with hot dark matter. Note that for degenerate masses with $m \sim 1-3$ eV we need a relative splitting $\Delta m/m \sim \Delta m^2_{atm}/2m^2 \sim 10^{-3} - 10^{-4}$ and an even smaller one for solar neutrinos. It is not simple to imagine a natural mechanism compatible with unification and the see-saw mechanism to arrange such a precise near symmetry.

If neutrino masses are smaller than for cosmological relevance, we can have the hierarchies $|m_3| >> |m_{2,1}|$ or $|m_1| \sim |m_2| >> |m_3|$. Note that we are assuming only two frequencies, given by $\Delta_{sun} \propto m_2^2 - m_1^2$ and $\Delta_{atm} \propto m_3^2 - m_{1,2}^2$. We prefer the first case, because for quarks and leptons one mass eigenvalue, the third generation one, is largely dominant. Thus the dominance of m_3 for neutrinos corresponds to what we observe for the other fermions. In this case, m_3 is determined by the atmospheric neutrino oscillation frequency to be around $m_3 \sim 0.05$ eV. By the see-saw mechanism m_3 is related to some large mass M, by $m_3 \sim m^2/M$. If we identify m with either the Higgs vacuum expectation value or the top mass (which are of the same order), as suggested for third generation neutrinos by GUTs in simple SO(10) models, then M turns out to be around $M \sim 10^{15}$ GeV, which is consistent with the connection with GUTs. If solar neutrino oscillations are determined by vacuum oscillations, then $m_2 \sim 10^{-5}$ eV and we have that the ratio m_2/m_3 is well consistent with $(m_c/m_t)^2$.

A lot of attention [43] is being devoted to the problem of a natural explanation of the observed nearly maximal mixing angle for atmospheric neutrino oscillations and possibly also for solar neutrino oscillations, if explained by vacuum oscillations. Large mixing angles are somewhat unexpected because the observed quark mixings are small and the quark, charged lepton and neutrino mass matrices are to some extent related in GUT's. There must be some special interplay between the neutrino Dirac and Majorana matrices in the see-saw mechanism in order to generate maximal mixing. It is hoped that looking for a natural explanation of large neutrino mixings can lead us to decripting some interesting message on the physics at the GUT scale.

2.2.4 Baryogenesis

Baryogenesis is interesting because it could occur at the weak scale [44] but not in the SM. For baryogenesis one needs the three famous Sakharov conditions [45]: B violation, CP violation and no termal equilibrium. In principle these conditions could be verified in the SM. B is violated by instantons when kT is of the order of the weak scale (but B-L is conserved). CP is violated by the CKM phase and out of equilibrium conditions could be verified during the electroweak phase transition. So the conditions for baryogenesis at the weak scale in the SM appear superficially to be present. However, a more quantitative analysis [46, 47] shows that baryogenesis is not possible in the SM because there is not enough CP violation and the phase transition is not sufficiently strong first order, unless $m_H < 80$ GeV, which is by now excluded by LEP. However, it is interesting that baryogenesis at the weak scale is not yet excluded in SUSY extensions of the SM [47]. In particular, in the MSSM there are additional sources of CP violations and the bound on m_H is modified by a sufficient amount by the presence of scalars with large couplings to the Higgs sector, typically the s-top. What is required is that $m_h \sim 80 - 110$ GeV, a s-top not heavier than the top quark and, preferentially, a small $\tan\beta$. This possibility is becoming more and more marginal with the progress of the LEP2 running and will be completely excluded if no signals are found in last phase of LEP2 operation.

If baryogenesis at the weak scale is excluded by the data it can occur at or just below the GUT scale, after inflation. But only that part with $|B - L| > 0$ would survive and not be erased at the weak scale by instanton effects. Thus baryogenesis at $kT \sim 10^{12} - 10^{15}$ GeV needs B-L violation at some stage like for m_ν, if neutrinos are Majorana particles. The two effects could be related if baryogenesis arises from leptogenesis [48] then converted into baryogenesis by instantons. Recent results on neutrino masses are compatible with this possibility [49]. Thus the possibility of baryogenesis at a large energy scale has been boosted by the recent results on neutrinos.

3 Status of the Search for the Higgs and for New Physics

The LEP2 programme has started in the second part of 1995. At first the energy was fixed at 161 GeV, which is the most favourable energy for the measurement of m_W from the cross-section for $e^+e^- \rightarrow W^+W^-$ at threshold. Then gradually the energy was brought up to 172, 183, 189 GeV. In ' 99 it was increased up to a maximum of 202 GeV with a record integrated luminosity in one year of $254 pb^{-1}$ [5]. LEP2 will resume the run in spring 2000, increasing the energy by a few more GeV, before its dismantlement at the end of 2000 for the installation of the LHC ring in the tunnel. The main goals of LEP2 are the search for the Higgs and for new particles, the measurement of m_W and the investigation of the triple gauge vertices WWZ and $WW\gamma$. A complete survey of the LEP2 physics is collected in the two volumes of ref. [50].

An important competitor of LEP2 is the Tevatron collider. In 2000-01 the Tevatron will start RunII with the purpose of collecting a few fb^{-1} of integrated luminosity at 2 TeV. The competition is especially on the search of new particles, but also on m_W and the triple gauge vertices. For example, for supersymmetry while the Tevatron is superior for gluinos and squarks, LEP2 is strong on Higgses, charginos, neutralinos and sleptons. There are plans for RunIII to start in $\gtrsim 2004$ with the purpose of collecting of the order 5 fb^{-1} of integrated luminosity per year. If so the Tevatron could also hope to find the Higgs before the LHC if the Higgs mass is close to the LEP2 range.

Concerning the Higgs, the present limits obtained by the LEP collaborations at the end of the '99 run and still preliminary and not combined, are, for the SM Higgs, $m_H \gtrsim 106$ GeV and for the lightest MSSM Higgs, $m_h \gtrsim 90$ GeV [5]. To understand the significance of these limits we recall the theoretical bounds on the Higgs mass.

It is well known [51]$^-$[54] that in the SM with only one Higgs doublet a lower limit on m_H can be derived from the requirement of vacuum stability. This criterium is equivalent to demand that the coupling λ of the quartic term $\lambda(\phi \dagger \phi)^2$ does not become negative while running from the weak scale up to the scale Λ. The initial value of λ at the weak scale increases with m_H^2, while the derivative, for m_H near the limit, is dominated by the top quark term which is large and negative. The value of the limit is a function of m_t and of the energy scale Λ where the model breaks down and new physics appears. If one requires that λ remains positive up to $\Lambda = 10^{15}$–10^{19} GeV, then the resulting bound on m_H in the SM with only one Higgs doublet is given by [52]:

$$m_H > 134 + 2.1\,[m_t - 173.8] - 4.5\,\frac{\alpha_s(m_Z) - 0.119}{0.006}\ . \tag{3}$$

We see that the discovery of a Higgs particle at LEP2, or $m_H \lesssim 110$ GeV, would imply that the SM breaks down at a scale Λ of the order of $\lesssim 100$ TeV. It can be shown [51] that the lower limit is not much relaxed even if strict vacuum stability is replaced by some sufficiently long metastability.

Similarly an upper bound on m_H (with mild dependence on m_t) is obtained [55] from the requirement that up to the scale Λ no Landau pole appears. The upper limit on the Higgs mass in the SM is important to guarantee the success of the LHC as an accelerator designed to solve the Higgs problem. In fact, for large Higgs masses, the initial value of λ is large and the derivative of λ is positive, because the positive λ term (the $\lambda\phi^4$ theory is not asymptotically free!) overwhelms the top Yukawa negative contribution. As a consequence the coupling λ tends to infinity (the Landau pole) at some finite scale. The upper limit on m_H has been recently reevaluated [56]. For $m_t \sim 175$ GeV one finds $m_H \lesssim 180$ GeV for $\Lambda \sim M_{GUT} - M_{Pl}$ and $m_H \lesssim 0.5 - 0.8$ TeV for $\Lambda \sim 1$ TeV. Actually, for $m_t \sim 174$ GeV, only a small range of values for m_H is allowed, $130 < m_H < \ \sim 200$ GeV, if the SM holds up to $\Lambda \sim M_{GUT}$ or $M_{\rm Pl}$ [56].

A particularly important example of theory where the above bounds do not apply and in particular the lower bound is violated, is the MSSM, which we now discuss. As is well known [13], in the MSSM there are two Higgs doublets, which implies three neutral physical Higgs particles and a pair of charged Higgses. The lightest neutral Higgs, called h, should be lighter than m_Z at tree-level approximation. However, radiative corrections [57] increase the h mass by a term proportional to m_t^4 and logaritmically dependent on the stop mass . Once the radiative corrections are taken into account the h mass still remains rather small: for $m_t = 174$ GeV one finds the limit $m_h \lesssim 130$ GeV (valid for all values of $tg\beta$ and saturated at large $tg\beta$) [58]. Actually one can well expect that m_h is sizeably below the bound if $tg\beta$ is small. LEP is now progressively eliminating the small $tg\beta$ region [5].

Another main goal of LEP2 is the search for direct signals of supersymmetry. By now most of the discovery potential of LEP2 for supersymmetry has been deployed. For example, the limit on the chargino mass was about $m_{\chi^+} \gtrsim 45$ GeV after LEP1 and is now about $m_{\chi^+} \gtrsim 100$ GeV, apart from exceptional regions of the MSSM parameter space. The lightest neutralino mass limit is around $m_{\chi^0} \gtrsim 36$ GeV [5]. The region of the MSSM parameter space that has been by now excluded by LEP is a very important one. The low $tg\beta$ solution was appealing in many respects. With no discovery of the Higgs and SUSY at LEP the case for the MSSM becomes less natural, and even less natural become the gauge mediated models , in the sense of, for example, refs. [59]. Similarly, some more constrained forms of the model, like the supergravity version, where degenerate scalar masses and gaugino masses are assumed at the GUT scale, are by now disfavoured becoming increasingly unnatural.But naturaleness is not a completely quantitative criterium so that the issue is open until the upper bound $m_H \lesssim 130$ GeV for the general MSSM is not disproven.

4 Conclusion

Today in particle physics we follow a double approach: from above and from below. From above there are, on the theory side, quantum gravity (that is superstrings), GUT theories and cosmological scenarios. On the experimental side there are underground experiments (e.g. searches for neutrino oscillations and proton decay), cosmic ray observations, satellite experiments (like COBE, IRAS etc) and so on. From below, the main objectives of theory and experiment are the search of the Higgs and of signals of particles beyond the Standard Model (typically supersymmetric particles). Another important direction of research is aimed at the exploration of the flavour problem: study of CP violation and rare decays. The general expectation is that new physics is close by and that should, be found very soon if not for the complexity of the necessary experimental technology that makes the involved time scale painfully long.

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