The Quest for the Infinitesimally Small

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Abstract

This is a review of the present status of particle physics and of our main scientific goals in our "Quest for the Infinitely Small". Based on an extraordinarily successful Standard Model, our field is on the verge of answering the fundamental questions such as the nature of mass and the unification scheme which only a few decades ago seemed to belong mostly to the realm of dreams. The next major step forward is based on an ambitious experimental challenge, which the LHC is crystallising at CERN in a spirit of total international collaboration.

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1 Introduction

Ask any particle physicist what is happening in the field and there is little doubt that the answer will be "The Standard Model is working too well". This is indeed the summary of this talk. However it is my hope to convince you also that the Standard Model is a thriving frontier in physics, with lots of exciting happenings and lots of challenging questions but at the same time with a clear indication of how to find the answers.

2 Particle physics, goals and tools

2.1 The present framework: quarks, leptons and basic interactions.

The purpose of particle physics is to explore and understand the deep structure of matter. At any given time, particle physicists are seeking the deepest layer in the succession of structures which can be unravelled in the objects around us. Thus, they deal with the basic constituents of Nature, as we know them today, thanks to the resolution available with our instruments.

Today, even though we have already reached a very good understanding of physics at the level of 10^{-18} metre we can barely probe the structure of matter down to 10^{-19} metre. At our present level of scrutiny the fundamental constituents of matter are the quarks and the leptons (Figure 1).

There are six quarks, set up in three families, each one grouping two quarks differing by one unit of charge. In parallel with these three quark families, we have three families of leptons containing each a negatively charged particle and a neutrino. Each quark exists under three varieties of "colour", which we can dub as "red", "green" and "blue", whereas the leptons have no "colour". This altogether represents 24 fundamental particles, to which one associates as many antiparticles, with the same masses but the opposite charges and "colours".

This is a lot of fundamental particles ! However, we have long realised that, at this level of exploration, unity and simplicity should not be looked for in a very small number of fundamental fields. Indeed, in the framework of superstring theory, which we think would reveal itself openly at the level of 10^{-35} metre, all these fields appear as the many lowest excitation modes of a superstring, which we can visualise as a tiny loop closed upon itself at the level of 10^{-35} metre, and probably in more space dimensions than our usual three dimensions, [the other ones being compactified at the level of 10^{-35} metre]. Much unity and simplicity is found, however, but it is in the form which all interactions take at the quark and lepton level. Unity and simplicity are thus found in the scripts which the actors follow far more than in the numerous cast of actors.

All interactions can indeed be described in terms of a unique gauge principle. The deep origin of all the basic interactions is found in invariance properties, or symmetries, which the laws of physics should show with respect to

some interchanges of the properties which we attach to the quarks and leptons, thus defining their different and specific characters. The universal validity of these symmetries calls for a gauge formulation and the gauge properties imply the existence of forces and specify their properties.

It is well known that Quantum Electrodynamics (QED) is a gauge theory and that its form is actually determined by Lorentz invariance and by the gauge invariance property attached to the phase of the charged fields. Similarly the strong interaction corresponds to a gauge theory where the gauged quantity is the "colour" of the quarks. This is Quantum Chromodynamics (QCD). The formulation of a gauge theory of the weak interaction, the only interaction which can change the nature of a quark or of a lepton, requires its combination with electromagnetism into a unique gauge theory covering both. This is the electroweak interaction.

Lorentz invariance and specific gauge symmetries thus specify the nature and structure of all these interactions. The basic processes all correspond to the exchange of a quantum of the gauge field (Figure 2) and the number of gauge fields is specified in each case by the gauge symmetry group. For the electroweak interaction it is $SU(2) \times U(1)$. There are therefore four gauge fields and the basic physical processes correspond to the exchange of a photon (electromagnetic coupling), the exchange of a charged W (standard weak coupling) and to the exchange of a neutral Z (neutral current weak coupling). For the strong interaction the gauge group is $SU(3)$. One has therefore eight gluons each carrying "colour".

All the gauge fields correspond to vector particles of spin 1. There is therefore a great unity and a great simplicity at the level of the basic interactions ! The possible existence of such a general and simple principle at the origin of all forces was realised twenty years ago. Since then we have found the experimental proofs that Nature does behave that way. We have reached a good understanding of the deep origin and of the nature of forces.

2.2 The complicated vacuum

Yet, as many of you know, there are some twists to this simple picture. In a gauge theory, the gauge fields should all have a zero mass. This is the case for the photon and for the gluons but the W and the Z are very massive, with masses close to a hundred times that of the proton. The strict invariance property used also seems to require all quarks and leptons to be massless, which is obviously not the case. The answer to this problem is however provided by the Higgs mechanism. It allows a breaking of the primordial symmetry, providing masses to the particles but keeping enough relations untouched so that the theory remains renormalizable.

The blame for the apparent lack of symmetry is thus put on the vacuum. The vacuum, which corresponds by definition to the lowest energy state, contains a field with a non-zero expectation value, the Higgs field. Fluctuation quanta from this non-zero expectation value should correspond to the presence of a neutral spin zero particle, the Higgs meson, but its mass remains an open parameter in the theory. As

a consequence of the presence of the Higgs field, the vacuum behaves like a medium with properties which are very similar to those of a superconductor. Indeed, one may say that the W and the Z appear with important masses in the vacuum in much the same way as a photon acquires a mass inside a superconductor.

There is yet another twist. Whereas the gluon has a zero mass and should, as the photon does, give rise to an interaction of infinite range, the strong interaction has, as is well known, a finite range. This is now due to the fact that the gluon carries "colour" and that the vacuum is opaque to "colour", with a penetration length of the order of one fermi. It is this penetration length which specifies the finite range of the strong interaction. One may say that the vacuum behaves again like a superconducting medium with respect to "colour".

These peculiar properties of the vacuum represent one of the great challenges of particle physics today. We have a beautiful and simple formulation for all the forces but it operates in a complicated vacuum. One may say that with the Glashow-Salam-Weinberg (G-S-W) electroweak theory we are at the level of the Landau-Ginsburg theory of superconductivity. The G-S-W theory is of course relativistic and non Abelian, but the basic idea is similar. We have to realise that we have not yet reached the Bardeen-Cooper-Schrieffer level, with an understanding of the dynamics behind symmetry breaking. We do not know yet what the nature of the Higgs field is. Is it an elementary field? Is it a bound state of hitherto unknown fermions? This is one of the key questions today and it should bring us to the fundamental origin of mass. We can estimate the critical temperature at which the vacuum would return to normal and the masses of the W and of the Z would disappear. It is of the order of 200 GeV. The phase transition should therefore have occurred when our universe was about 10^{-11} second old. We are led to expect dramatic new features as we reach collision energies of the order of 1 TeV and beyond, that is at collision energies neatly above that corresponding to the critical electroweak temperature. This is the energy scale which defines the next big step, corresponding to the LHC in Europe. SSC, the other similar project in Texas, has recently been cancelled by the United States Congress.

For "colour" we expect the vacuum to turn from superconducting to normal and become transparent to "colour" when the temperature reaches a level of the order of 200 MeV. This transition should have occurred when the Universe was a little over 10 microseconds old. This is what we are trying to reach at CERN, the European laboratory for particle physics (Figure 3), with relativistic heavy ion collisions, a programme which will benefit from a lead source next year and would cover a tremendous step forward with the LHC.

Granting the existence of these challenging complications associated with the structure of our too cold vacuum (much cooler than the critical temperature just mentioned above), physics at the quark and lepton level is particularly simple. This is the Standard Model of fundamental particles and fundamental interactions

which provides our understanding of the dynamics at the deepest accessible level today.

2.3 The Standard Model, a first look

Twenty years ago the Standard Model appeared as an interesting possibility but it did not have only supporters. Its renormalizability and its "asymptotic freedom" have long fuelled the enthusiasm of the theorists and, over the past twenty years, many striking experimental results have beautifully vindicated it. The two key ones came from CERN, namely the discovery of the "neutral current" interaction in 1973 [1], and the discovery of the W [2] and Z [3] in 1983. At the same time the $p\bar{p}$ collider and now LEP have allowed us to obtain many important results on jets which are the way quarks and gluons manifest themselves most openly in a vacuum opaque to "colour".

A gauge theory specifies the form of the coupling but not the value of the coupling constant. There are two independent couplings for the electroweak theory since the gauge group is $SU(2)\times U(1)$. There is only one for the strong force, which is based on the $SU(3)$ gauge group. They vary in a predictable way with the momentum transfer squared at which the process occurs or, more generally, with the scale at which a process is analysed. The coupling constants "run". This has also been verified.

The close similarities between the electroweak and strong couplings, together with the fact that the three couplings approach one another with increasing energy to eventually meet for a value which the LEP results now lead us to expect to be around 10^{16} GeV [4], strongly suggests a Grand Unified Theory where quarks and leptons would appear as different manifestations of the same field. A Grand Unified Theory mixes quarks and leptons and this implies proton decay, a process which we should be very much concerned with. We do not know yet the form which such a Grand Unified Theory takes. This is also one of the great questions today. Superstrings have been a guide line in our thinking in that direction for almost a decade. They however refer to the Planck scale, 10^{19} GeV, where gravity fully comes into the picture. We have not yet succeeded, however, in extracting from such a "Theory of Everything" compelling constraints which would apply to our present level of experimental investigation in the 100 GeV domain.

Following this bird's eye view of our theoretical framework, a few words about the experimental tools are in order.

2.4 Tools in high energy physics

It is well known that quantum physics implies that the price to pay for high resolution is a high colliding energy. For instance, with a collision energy of 100 GeV one can "see" clearly at the level of 10^{-18} metre. From what has been said, this is a particularly interesting energy for the electroweak theory. LEP, which now operates close to 100 GeV, or to be more precise at the Z mass of 91 GeV, and which will be upgraded in 1995 to close to 200 GeV, in order to allow for W pair formation,

was actually designed as the ideal machine to test the Standard Model. This it has done in a particularly impressive way already.

The operation of LEP illustrates very well the working of the CERN accelerator complex, where previous machines are used as injectors for the newest one. LEP is presently the largest machine in the world with a circumference of 27 Km. Electrons and positrons collide head on in four interaction zones where four large detectors have been installed. Electrons and positrons are accelerated in the PS and then in the SPS before being further accelerated and held coasting in LEP. The machine operates perfectly: record luminosity levels are broken each year and the energy precision is such that small shifts in energy can even be used to measure the sun and moon tidal forces on the earth's crust, a 10^{-8} effect (Figure 4).

The operation of each of the four LEP detectors requires collaborations of several hundreds of physicists (Figure 5). I know that many of you are still very much attached to "small science" as opposed to "big science". Let me stress that the very large collaborations, which are a fact of life in particle physics, leave much room for individual initiative. A collaboration is comparable to what a full laboratory used to be with a broad distribution of tasks and know-how. It is easy to realise who has been doing what for each major finding reported by a large collaboration. This is a cardinal condition for the continuation of the thriving research adventure provided by the field.

Whereas LEP is at present the flagship of CERN, the Laboratory has always operated over a large experimental range to serve its many users. The CERN machine complex (Figure 6) serves several types of experiments at the same time from very low energy to the highest energy. The complexity of the system can be illustrated by the supercycles (Figure 7) of the former giants now used as injectors. Electrons and positrons but also protons, antiprotons and ions can be accelerated.

2.5 The Standard Model, a second look

The Standard Model has so far successfully passed all tests with flying colours. It works so well that one has become impatient to find some deviations heralding new physics but nothing has appeared so far. Concluding his rapporteur talk on "Precision tests of the Standard Model" at the recent Europhysics Conference in Marseille, Jacques Lefrançois said "Will one of the future electroweak rapporteurs finally have the pleasure of announcing a deviation from the Standard Model? I wish this pleasure to my successors."

The success of the Standard Model can be illustrated by many results. Let us look at but a few.

As we have mentioned already the electroweak theory has two couplings. One can be chosen as the electromagnetic coupling. The coupling constant α at LEP is not the standard fine structure constant α , which is defined at zero momentum transfer and takes the well known value of $1/137.0459895(61)$. It should be an α "having run" to the mass of the Z. One finds indeed $1/128.87(12)$ [5]. The

strength of the coupling has increased as it should have done. The other coupling can be conveniently defined in terms of the Weinberg angle θ_W , and the quantity $\sin^2\theta_W$ specifies, for instance, how the neutral current coupling (Z exchange) relates to the standard charged one (W exchange) in the Born approximation. The same value of this parameter should be extracted from many different independent results if, as the electroweak theory claims, it is enough to specify all these processes. This turns out to be the case (Figure 8).

To illustrate the universality of the weak coupling one can also compare the vector and axial couplings measured at LEP [6] (that is in the time-like region with lepton-antilepton annihilation) with their values extracted from a recent experiment on neutrino-electron scattering [7] (that is in the space-like region with lepton-lepton scattering) (Figure 9).

Turning now to strong interactions, we can for instance look at the beautiful jet events observed at LEP. The simplest process consists of the formation, in an electron-positron collision, of a Z which annihilates into a quark-antiquark pair (Figure 10). The quarks carry "colour" and cannot penetrate the vacuum. Their energy and momentum turn into that of jets of hadrons (mainly π mesons) which leave little doubt as to their origin. Part of the time the production of the quark-antiquark pair is accompanied by the radiation of an energetic gluon. This gives a third jet (Figure 11). Quarks and gluons are thus almost directly "seen".

One can predict the observed jet pattern in LEP events and many other processes in terms of the unique strong coupling, α_s . It "runs" and one can convert all results to a scale corresponding to the Z mass. The same value is found as required (Figure 12). One can now quote a value of $\alpha_s(M_Z)$ of 0.118 with an error of 0.006 [8]. Measuring it at different energy scales, one has clear evidence for its "running" (Figure 12), even within the LEP experiments alone, since they obtained data at the tau lepton mass scale [9] in addition to the Z mass scale.

This overview of the Standard Model and of some of its great successes may lead us to expect that particle physics is almost "finished", or rather almost completed. One may be tempted to think that we now have a theory which beautifully describes all the experimental results which we can obtain whilst having predicted most of them in the first place. One may think that all there is to do is to increase the precision with which we know the parameters. This has, however, already been heard in physics in the last century and, for the very same reasons, it does not apply to particle physics today ! The field is very much alive with new results and burning questions. During the summer there have been two major conferences on the subject. One in Marseille, the Europhysics conference, organised every other year in Europe, and one in Cornell, which stood as the continuation of the "Lepton-Photon" series organised by the International Union of Pure and Applied Physics (IUPAP), and which is also held every other year. The highlights of these two conferences, which were actually very close in time, can be used to

illustrate the recent results and to present the challenging questions which we have in front of us.

3 *Questions with the Standard Model*

Despite its great success, or rather because of it, the Standard Model raises challenging questions which are at present the object of a thriving experimental and theoretical activity. Let us consider some of them.

3.1 *The top quark*

First the actors. We mentioned that there are 6 quarks. One of them is however still missing. It is the top quark. It has to exist as a partner to the b quark since the quark-lepton doublet symmetry is of cardinal importance in our present understanding. Its heavy mass has, however, protected it from our curiosity so far. At present its non observation implies a mass higher than 108 GeV (Fermilab) [10]. With the instruments now available in the world the only place where one can find it soon is indeed at Fermilab with its 2 TeV $p\bar{p}$ collider. The top quark can be produced only together with an antitop quark and the pair represent a very high excitation energy. Such a very high mass implies a very small cross-section, hard to find with the available luminosity. The top quark being heavier than the W decays immediately and evidence for its formation has to be found among the W produced by its decay. Evidence for such top-W's has to be obtained out of a relatively large background. Picking up W's through their clear leptonic decays only reduces greatly the number of events; and including the dominant hadronic jet decay of the W makes them hard to extract out of the background. One expects the top quark to decay predominantly into a b quark and a W. Tagging the b quark is a great help but it requires instrumentation which is still being developed. It is therefore quite difficult to see the top quark but its existence is a very important question.

At present Fermilab reports "a few interesting events", but nothing definite can be concluded yet. If most of these events turn out to be top quarks, their production rate would imply a mass of the order of 160 GeV but with still a very large uncertainty. We can believe that the top quark is now "around the corner", since such a mass value matches the one that can now be extracted from the LEP results (Figure 14a) [11]. We hope that our Fermilab colleagues will quickly succeed in obtaining compelling evidence.

The electroweak theory is indeed a renormalizable theory with which one can calculate radiative corrections beyond the simple tree-graph values. These radiative corrections are sensitive to all known fields appearing in loops but also to the hitherto unknown ones and in particular to the Higgs and the top quark. It turns out that unfortunately the sensitivity to the Higgs is rather weak whereas that on the top quark is far more important. The LEP results are now so precise that one can extract the value of these radiative corrections, compare them to theoretical expectations, and extract a mass for the top quark. One comes up with the

conclusion that the top-quark mass should be 160 GeV with an uncertainty of 16 GeV. This certainly encourages us in our hope that the top quark is just "around the corner" but we still have to find it. This assumes a Higgs mass of 300 GeV. Letting the Higgs mass vary over a wide range (60 – 1000 GeV) adds a further error of ± 20 GeV. One can however try to constrain both the top and Higgs masses through a confidence plot (Figure 14b) [12].

3.2 The electroweak interaction

It is clear from these graphs that one cannot fully dissociate the top mass determination from that of the Higgs but nothing as precise occurs for the Higgs. As previously said, we cannot predict the mass of the Higgs. Because of its special role in the Standard Model it has the interesting property to couple to particles more strongly the more massive they are. The abundant production of Z at LEP (several millions already) makes LEP a particularly favourable hunting ground, but the production rate falls rapidly with the Higgs mass and there may not be enough energy. Extensive searches have been unsuccessful so far. At present we may only say that the Higgs mass is greater than 63 GeV [13].

There is something remarkable about the electroweak corrections at the Z mass where we now operate at LEP. We should definitely include them in the running of the electromagnetic coupling which we should take at the Z mass and not at zero momentum transfer. We already mentioned the change which that implies. Let us do it. One then finds that all the other corrections appear to cancel against one another, at least within our present experimental accuracy. All results agree with a tree-graph approximation, once α has been evaluated at the proper value. This conspiracy is of course not for free since radiative effects are there! It implies a top quark with a mass of the order of 160 GeV.

This has been emphasised by Lev Okun in his summary talk at the Marseille conference. A table which he presented (Table 1) gives the experimental values of 9 different quantities measured at LEP and the results of their electroweak calculation in the tree-graph approximation. There is a remarkable agreement !

Table 1: Comparison between tree-graph calculation and experimental value for various Standard Model quantities. The first value is experimental and the second one corresponds to the tree-graph calculation.

	Exp.	Tree-level Theory		Exp.	Tree-level Theory
M_W/M_Z	0.8798(29)	0.8768(2)	g_a	- 0.5008(8)	- 0.5000
g_v/g_a	0.0712(28)	0.0753(12)	Γ_e (MeV)	83.79(28)	83.57(2)
Γ_h (MeV)	1740(6)	1741(5)	Γ_Z (MeV)	2489(7)	2490(5)
σ_h (nb)	41.55(14)	41.44(5)	R_e	20.77(5)	20.84(6)
R_b	0.2191(27)	0.2197(1)			

This means that, when we take the top quark into account, there is very little room for extra radiative effects which could reveal new physics through the virtual effects in which that new physics would be implied. One can regroup such effects into parameters which are rightfully labelled as "epsilons" by G. Altarelli et al. [14]. At present their experimental values are all compatible with zero but there is no reason to leave them there, despite difficulties in improving the results. It is also tantalising to find the top quark in the restricted mass range in which we should now have it cornered.

Okun et al. [15] introduce a particularly useful set of parameters which makes use of the fact that three quantities are already very well known, namely the electroweak coupling $\alpha(M_Z)$, the Fermi coupling G_F and the Z mass. Experimental quantities such as the W to Z mass ratio, the axial coupling and the ratio between the vector and axial couplings of the Z, can then be expressed in terms of their Born approximation values and correction terms, all proportional to α and asymptotically proportional to $(M_{\text{top}}/M_Z)^2$. The top contribution is clearly separated and could be readily introduced when the top mass is known, the remainder offering a test for new physics. One can illustrate with one of them, V_R , corresponding to the correction to the vector-axial ratio, the respective contributions of the top and of the Higgs as a function of their mass (Figure 15). The present experimental value of V_R is compatible with zero, namely -0.5 with an error of 1.9 . This implies, of course, a top quark in the already given mass range.

Why is there such a conspiracy which makes radiative corrections globally cancel whereas each one of them is sizeable? Why is the top quark mass of the same order as the energy scale proper to the electroweak theory? These may be deep questions loaded with meaning but we cannot yet grasp their significance.

With the top quark we would complete the three families of quarks and leptons which are the actors of the Standard Model. We do not know yet why there should be three families. However each family has a massless neutrino and one of the first experiments at LEP counted the number of apparently massless neutrino species and hence the number of families with which we should deal at the present stage. Three were found. The present number of massless neutrino species can now be given as 2.98 with an uncertainty of 0.027 [16]. The shape of the Z excitation curve in electron-positron annihilation, as seen in any visible mode, is indeed sensitive to the number of neutrino species. One can then count the neutrinos produced in Z decay despite the fact that they escape the detectors.

The Standard Model is great but we feel uneasy with it because it has too many free parameters (close to 30). There are the three couplings which we mentioned. This is fine but there are also all the masses. They correspond to the different couplings of the particles to the Higgs field but these many Yukawa-type couplings are also free parameters.

There is also the fact that the electroweak interaction mixes quarks of different families together, thus allowing the heavy quarks to decay into the lightest ones. This is parametrized in the form of a 3×3 matrix connecting the lower ($-1/3$) charge members (d, s, b) to the mixed states (u', c', t') relevant for the weak interaction, which is known as the CKM matrix. The constraints on this matrix allow for the existence of a small CP violation which may come for free once one has at least three families of quarks. This is great since we badly need CP violation to build an excess of particles over antiparticles in the exploding early universe. However is it the only way through which CP violation actually occurs? It implies a non-vanishing value for a very small parameter measured in neutral K decay where CP violation has only been seen so far. Present results are not yet fully conclusive. We are dealing here with a still challenging experimental question worth much effort.

It is necessary to proceed with the measurement of the mixing parameters which are the elements of the CKM matrix. This is all the more difficult since some of them, those which mix across different families, are small.

Progress is slow but steady. At the summer conferences one thus heard for the first time about the $b \rightarrow s$ transition seen dramatically in $B \rightarrow K^* \gamma$ decay (CLEO) [17]. This is a particularly interesting process, of the so called "penguin" type (Figure 16) with for one of the terms both a $b \rightarrow t$ and a $t \rightarrow s$ weak transition. The top quark is very much needed there!

One also heard about B decays "jumping" over the dominant charm-type decay with direct production of π and K mesons [18].

In neutral K decay there is the famous oscillation between the K^0 and the anti- K^0 , which corresponds to a doubly weak process. A $d\bar{s}$ system is thus turned into a $\bar{d}s$ one and vice versa. This phenomenon has been known to exist also in the neutral B case but one can now observe the oscillation as a function of time (Figure 17) [19]. The neutral B system is thus turning into a beautiful experimental tool.

There is the hope that the neutral B system will eventually offer another window to study CP violation. One however needs a lot of B mesons produced under well-controlled conditions. This is fuelling the motivation to build a B factory as an electron-positron collider in the 10 GeV range with a very high luminosity. It is also fuelling much interest to find ways to use the numerous b 's produced but not yet tapped on present machines, and of course at the LHC.

The lepton families also offer interesting challenges. Isn't it remarkable that the tree charged leptons (Figure 1) turn out to have the very same properties once their big differences in mass are taken into account? This intriguing similarity has to be probed with great accuracy. There has recently been some excitement at the news that the tau lepton was not behaving exactly as it should, as a "heavy electron". The summer conferences have however brought everything back in line. It is interesting to note that an important element in resolving the discrepancy came from a more precise measurement of the tau lepton mass made by the Beijing electron-

positron machine (BEPC) [20]. The tau lepton is sufficiently massive that it has abundant semi leptonic decays. Everything is found in good agreement with QCD predictions.

3.3 *The neutrinos*

The most exciting sector of the lepton world is perhaps that of the neutrinos. In the Standard Model neutrinos are introduced as massless. They are left handed and cannot mix among themselves. However this could be only an approximation even though it would be an excellent one. We cannot avoid thinking about a Grand Unified Theory, possibly in the framework of superstrings where the energy scale proper to such grand unifications is tremendous as compared to our modest 100 GeV. One is indeed talking about 10^{16} GeV for GUT's and 10^{19} GeV for superstrings. With such energy scales in mind all known particle masses are practically zero. The neutrinos, with their zero mass within experimental errors, do not distinguish themselves from the other particles, as they clearly appear to do when their vanishing mass is compared directly to the other masses in the same family of the Standard Model. The left handedness of our apparently massless neutrinos may be an asymmetry which would vanish at extremely high energy, well above the masses of hitherto unknown right handed neutrinos.

What are the present limits for the neutrino masses? The values reported at the summer conferences were respectively less than 7.2 eV [21] for the electron neutrino, less than 270 KeV [22] for the muon neutrino and less than 31 MeV [23] for the tau neutrino. Except for the electron neutrino the limits are not very binding, but they are already very much smaller than the lepton and quark masses in the same family. One may remark that with a neutrino mass of 10 to 50 eV one would have enough energy density to make the universe critical. One of the neutrinos could still well be responsible for that, or part of it, as Martin Rees [24] and John Ellis [25] will tell us. If neutrinos have masses there is also no reason why they should not mix, a neutrino of one species turning into another and vice versa. This can be parametrized in terms of two parameters: one is the difference of masses squared (Δm^2) and the other one, ($\sin^2(2\theta)$), is a function of the neutrino mixing angle.

There has been a recent debate about the mass of the tau neutrino. Some β -decay experiments have reported a mixing of the electron neutrino with the tau neutrino with a mass of 17 KeV. Others did not find anything of the sort. The issue was finally settled at the summer conferences. The 17 KeV neutrino hypothesis was wrong [26]. Everything fell back to normality ! This is however worth mentioning since this was the first case where a question raised in particle physics brought a serious question in particle physics through a cosmological argument. As we saw, a 17 KeV neutrino is massive enough to close the Universe and even so heavy that the Universe does not have the time to expand, allowing for galaxy formation, before it re-contracts again. One has therefore to make these neutrinos decay quickly enough into lighter objects but there is no interaction to do the job in the Standard Model !

We do not have to worry about this any more. The Standard Model is again enough, until the next problem comes up.

There are models to provide the neutrinos with masses. They of course require actors which are not in the Standard Model. However, the so-called "seesaw" models [27] seem to provide a natural extension of the present Standard Model. Neutrinos then get a mass through their coupling to a (very heavy) neutral particle of mass M with therefore right handed and left handed components. There are good reasons to expect that the off diagonal terms of the mixing mass matrix are of the order of the charged lepton mass m_l , or perhaps of the charge $2/3$ quarks m_q . The eigenstate appearing with the neutrino mass is then found to have a mass of the order of m^2/M . Since M is assumed to be very large, all such masses are very small. Yet, they are not vanishing but are in the ratio of the squares of the charged lepton or quark masses.

Nature may proceed differently. More generally one may say that the question of the neutrino mass is tantalising because any non zero mass would indicate a departure from the Standard Model.

There are two main ways to address the problem. One way is to use intense but distant sources and in particular the sun. The fusion processes at work in the sun are abundant sources of electron neutrinos. The Standard Solar Model makes definite predictions about the rate and energy spectrum of the neutrinos produced (Figure 18). Here the situation is still unsettled. It is not yet clear whether the electron neutrinos produced at the centre of the sun reach the earth detectors in a sufficiently large number as detectable electron neutrinos. Pioneering experiments such as Homestake, a radiochemical detector using the absorption of ν_e on ^{37}Cl producing ^{37}Ar as a signal, found a surprisingly low rate : 2.2 ± 0.2 SNU [28] to be compared to theoretical predictions of 8.0 ± 3.0 in J. Bahcall's model [29] and 6.4 ± 1.4 SNU in Turk-Chièze's model [30]. The deficit was later confirmed by Kamiokande, a large water Cerenkov detector in Japan which obtained a very clear neutrino signal in the direction of the sun (Figure 19), but again with a rate somewhat low compared to the prediction of current models : $\text{Data/Theory} = 0.55 \pm 0.07 \pm 0.06$ [31]. The main question is whether we are dealing with a solar model problem as some believe or with a phenomenon due to peculiar neutrino properties.

New data [32] on the subject came from the SAGE experiment under Mount Andyrchi in Russia and most recently from the GALLEX experiment at the Gran Sasso Laboratory. They are sensitive mainly to the p-p component of the solar neutrino spectrum. After the summer conferences, and in particular with the latest results of GALLEX, the solar neutrino problem seems to be shifting to the astrophysicists and to the nuclear physicists who provide them with input data. There seems indeed to be enough neutrinos seen to take into account all that is expected from the dominant p-p reaction in the sun (Table 2). The presently reported discrepancy appears to be more significant with higher energy neutrinos, far more easily detected, but which correspond to minority reactions in the sun

power production. Calculating their production requires many input data for which error assessment call for further scrutiny. Nevertheless if everything is taken at face value, one would conclude that neutrino oscillations exist. A very elegant mechanism known as the Mikheyev–Smirnov–Wolfenstein (MSW) mechanism [33] predicts that if neutrinos have mass, the oscillation from one species to the other could be enhanced in a dramatic way by the presence of electron rich matter. This is one of the possibilities put forward as an explanation to the solar neutrino problem. Within this hypothesis, two small regions of the $\Delta m^2, \sin^2(2\theta)$ plane are consistent with all experimental results (Figure 20). It is unlikely that present experiments will resolve the puzzle since none of them individually can distinguish effects due to the nature of neutrinos from effects due to the neutrino production mechanism inside the sun. A new generation of experiments (Superkamiokande [34], ICARUS [35], SNO [36], HELLAZ [37], BOREXINO [38] and other projects at Baksan in Russia) is therefore needed to tell us which, if any, of the various possible existing solutions shown in figure 21 corresponds to Nature's choice. This topical and very important question will be covered in more details by E. Fiorini in his talk on "Solar Neutrinos".

Table 2 : GALLEX results [32] and comparison with solar models.

GALLEX I	May 91 – May 92	$81 \pm_{-17}^{+18} \pm_{-9}^{+7}$
GALLEX II	Sept. 92 – Jan 93	$97 \pm 23 \pm 7$
GALLEX I + II	May 91 – Jan 93	$87 \pm 14 \pm 7$
Bahcall et al.	–	$127 \pm_{-16}^{+20} (3 \sigma)$
Turk-Chièze	–	$123 \pm 7 (1 \sigma)$

The other possibility is to look for oscillations between different species of neutrinos produced by intense terrestrial sources, nuclear reactors and accelerators. Much effort has been expended along this line in particular at CERN where two major new experiments are in preparation: CHORUS [39] and NOMAD [40]. They will be searching for tau neutrinos which would have been produced, by oscillations, in a pure beam of muon neutrinos. These experiments are scheduled to start taking data in 1994.

As previously mentioned, there are two parameters in the prediction of oscillations between neutrino species: Δm^2 and $\sin^2(2\theta)$. A negative result excludes therefore a region of the corresponding two-variable plane. Accelerators produce large quantities of high energy muon neutrinos. It is interesting to see, for instance, where we are with respect to a possible oscillation between the muon and tau

neutrinos and the new ground which will be covered by the CHORUS and NOMAD experiments at CERN (Figure 22).

Long baseline neutrino oscillation experiments are under discussion for the longer term future. The main projects under review are: a CERN neutrino beam aimed at the Gran Sasso laboratory in Italy (730 km), with ICARUS as the main detector for this type of physics; a FERMILAB neutrino beam aimed at the Soudan detector (730 km); a Serpukhov neutrino beam aimed also at the Gran Sasso Laboratory (2200 km). These projects have the potential of increasing in a spectacular way our knowledge of mixing between neutrino families.

Many cosmologists believe that our universe must be closed, which means that more than 90 to 95 % of the matter in the universe is dark, non luminous and of yet unknown nature. Recent observation on both the large scale and the small scale structure of the early universe suggest that both "hot" and "cold" components of the dark matter must be present (Figure 23) [41]. In that case neutrinos are the most natural candidates for "hot" dark matter; and a tau neutrino mass of 3 to 40 eV, precisely in the range of the CHORUS and NOMAD experiments, would fit perfectly both the present cosmological scenarios as well as some of the most natural see-saw mechanism where neutrino mixing would emulate quark mixing.

Neutrino astrophysics is a budding new field with the promise of a prominent extension. Beside the solar neutrino question, there is that of atmospheric neutrinos which provide an already important base line for possible oscillations between production and observation. There is supernova collapse, for which one hopes to repeat soon with better means the observations of SN87A. There is also the fascinating question of possible surprises in reactions induced by extremely energetic cosmic neutrinos leading us beyond energies accessible with accelerators for some time to come.

3.4 Proton decay and other rare decays

Some of the very large detectors needed for cosmic neutrinos are also great tools searching for proton decay. The present limit of 10^{32} years applies only to one particular decay mode, namely $\pi^0 e^+$. It is very important to push the limit further in that mode and even more to look for other modes which call for more sophisticated detectors. As previously said it is a cardinal question since it is the only experimental proof which we can find for a Grand Unified Theory. One should note that the present data [42] from Kamiokande and IMB on the apparent deficit of muon neutrinos in the atmospheric neutrino flux has been interpreted by others as, on the contrary, an excess of electron neutrinos coming from proton decay (Figure 24) [43]. The impossibility to either confirm or disprove such an hypothesis illustrates the need for better detectors. Superkamiokande [34], in preparation in Japan, will offer the same water Cerenkov technique but an improvement of the fiducial mass by a factor of 30; while ICARUS [35], with its large liquid argon detector, should allow proton decay searches in many exclusive channels with

bubble chamber quality data. Figure 25 shows that the next generation of proton decay experiments will reach proton lifetimes up to 10^{34} years, and cover many interesting scenarios, in particular in the framework of supersymmetry.

Discussing questions in the Standard Model we touched on experimental approaches which could lead us beyond it. We shall come back to that in connection with future collider physics and in particular physics at the LHC. However one should stress at this stage that there are two ways to probe higher energies and therefore smaller scales. The first is the direct way, increasing the power of our accelerators. The next major step should lead us beyond 1 TeV at the quark and lepton level. The second is to analyse with great scrutiny very rare processes which imply jumping over very large energy barriers, thus probing much smaller scales through virtual interactions. Proton decay is a clear example.

One can also illustrate such high precision measurements with recent results on double β -decay. This process has been used for years as a possible test of the nature of the neutrino. It can proceed in a standard way with two standard decays producing two neutrinos. However it could also proceed in a direct way, with no neutrino produced, only if the neutrino is identical to its antiparticle. A virtual neutrino thus induces a reaction which we would normally associate with an incoming antineutrino. In that case, the neutrino would have to be a Majorana particle and not a standard Fermi particle. One should however keep in mind, in the latter case, that the process could also happen through a violation of the number of neutrinos mediated by a Majoron. Present experiments are reaching a very high level of precision with the standard process clearly seen and nothing peculiar to report in addition (Figure 26) [44]. Yet this type of experiment illustrates the precision which has been achieved with such a very rare process. One can expect further improvements.

Neutrinos will remain a fascinating domain for years to come. We shall, however, now turn to hadron structure with, in particular, the research domain opened by the newest European machine, namely HERA at DESY.

4 The hadron structure

We have no doubt that QCD is the correct theory of strong interactions. However we are far from being able to reproduce all the experimental results on hadron properties and hadronic interactions which have been obtained and are being collected. QCD has asymptotic freedom. The coupling constant α_s "runs", it decreases as the energy scale increases. We can therefore easily use the theory in a perturbative way at large momentum transfers, or at small distances (less than about 10^{-17} metre to be on the safe side) but using it in a fully satisfactory way at larger distances, where quarks get confined into hadrons, is still beyond the available computer power, despite recent impressive progress. One may say that when we can apply QCD perturbatively we have great success, as already illustrated by some examples from LEP. In the other cases, when perturbative calculations do not apply,

we are still left with only qualitative, or at best semi-quantitative, agreement. Progress, so far, has been slow but steady and we can be hopeful.

4.1 Deep inelastic scattering and recent HERA results

Deep inelastic lepton scattering has been the object of extensive studies over more than twenty years and it offers a great testing ground for hadron structure as described by QCD. One cannot predict how quarks and gluons are distributed in the proton but, once this is measured at a sufficiently large momentum transfer squared, one can predict how these distributions vary with increasing transfers, that is as one probes the proton structure with more scrutiny.

The distributions are described in terms of structure functions which involve two variables, the momentum transfer squared Q^2 , and a dimensionless variable x which, we may say, corresponds to the fraction of the proton momentum taken by the constituent which is observed.

The HERA machine [45] at DESY (Figure 27), the first electron-proton collider ever built, is providing a new boost to the field of deep inelastic scattering. Electrons of 27 GeV are colliding with 820 GeV protons. The centre-of-mass energy is of the order of 300 GeV. There are two large detectors, ZEUS and H1 operating at the intersection regions.

Experimentation at HERA will tremendously increase the range of Q^2 and x values over which one can probe the structure of the proton. Whereas we have been so far limited to values of Q^2 which were less than 300 GeV² and values of x which were greater than 10^{-2} , we should now be able to reach up to 3×10^4 GeV² in Q^2 , and down to 10^{-4} in x , hence a gain by two orders of magnitude in both variables. The machine started operating in 1992. The luminosity has been climbing with time but it is still much below the design value (Figure 28). Only a very limited amount of the eventual potential of the machine could thus be exploited so far, but hopes are great.

The results for the structure functions as a function of Q^2 , for different values of x , (Figure 29) [46] are in good agreement with presently known values but not yet as precise. However one should note that they have been obtained with only 1/4000 of the design luminosity per year! A new detailed look at the proton structure is thus "around the corner". Also worth mentioning is the entirely new look at the proton structure function down to very low x values, where it shows a sharp rise (Figure 30) [47].

This rise at low x , by typically a factor 2, is of great interest to theorists. It results from quarks and gluons branching into many quarks, antiquarks and gluons as we observe with more scrutiny. What is at stake at very low x and high Q^2 , is the screening which these many constituents will eventually have on one another as they become more numerous. There are very interesting theoretical questions attached to this low x behaviour. HERA is not only a great "high Q^2 machine" but it is also a great "large $\ln(1/x)$ machine" !

An interesting finding has been that of a diffractive type of events where the proton recoils quasi-elastically while the particle production in deep inelastic scattering is associated with the fragmentation of the virtual photon being exchanged. The observation of Pomeron exchange in deep inelastic scattering is new. It corresponds to about 6% of the events.

HERA should also soon be able to study deep inelastic scattering with weak interactions. Here the key question is luminosity. Only four charged current events have been seen so far!

It is for large cross-sections, like that for photoproduction, that HERA could already obtain highly significant results. The total photoproduction cross-section could be measured at 210 GeV when nothing much was known beyond 20 GeV. The value obtained agrees with Regge predictions. The photoproduction events at such an energy show the emergence of energetic jets, as those seen in hadronic reactions.

HERA also opens an interesting hunting ground for hitherto unknown objects which could more easily be produced in lepton-hadron interactions, such as lepto-quarks or excited leptons. This would readily take us away from the Standard Model.

With polarised lepton probes and polarised hadron targets, one can measure the spin dependent structure functions. This has been the object of extensive research at CERN (muon beam) and at SLAC (electron beam). One can extract the neutron structure function from scattering off polarised deuterium or polarised helium 3. The value of the structure function translates the mean polarisation of a quark for any fractional momentum x . Direct contact with specific theoretical predictions is however possible through sum rules which correspond to the integrals over x of the difference between the proton and neutron structure functions (Bjorken) or, with extra assumptions, to the separate integrals made for the proton and the neutron (Ellis-Jaffe).

A violation of the Ellis-Jaffe sum rule, as it could be inferred from the CERN EMC results of 5 years ago, has created much turmoil. To put it in a nutshell, it was as if the quarks were on the average not carrying the nucleon spin, with a strong negative polarisation attached to the $s-\bar{s}$ pairs! A new result from SLAC [48] reported at Marseille shows, however, that the sum rule holds with the quarks carrying on the average half of the nucleon polarisation (the gluons have to take a share !) and with no appreciable polarisation for the $s-\bar{s}$ pairs. We may again be back to normality ! However, the discrepancy between the SLAC and CERN results should first be clarified experimentally. The truth may be half way in between.

The new CERN EMC/SMC results and the SLAC results are in agreement with the Bjorken sum rule (Figure 31) [49]. However one needs more precise results.

4.2 Hadronic physics

Much activity is continuing along this more traditional line. As previously said, we are indeed far from fully understanding hadron structure from QCD. Progress is however difficult and slow. On the theoretical side calculations on the lattice are progressing but at the price of tremendous computer power largely provided by dedicated parallel computers. There is also much effort devoted to the understanding of the dynamics of the heavy quarks. On the experimental side, one tries to find interesting clues for confinement. The spectroscopy work is continuing in particular at LEAR, the CERN Low Energy Antiproton Ring. The hope is to collect evidence for states which would not be of the usual type, namely 3 quarks for a baryon and a quark-antiquark pair for a meson. Glueballs have long been on the hunting list!

One should mention also the heavy ion programmes at CERN and at Brookhaven. The goal there is to find evidence for the quark-gluon plasma which should exist at high enough temperature and/or quark density. "Colour" should be deconfined in such a new state of matter. One already has good evidence that relativistic heavy ion collisions do not proceed as a mere superposition of nucleon-nucleon collisions. There are specific effects such as J/Ψ suppression and strangeness enhancement which give a factor of two departure from that expected for nucleon-nucleon collisions. Such effects were predicted features of plasma formation but the present results are still not binding enough for a conclusion in that sense. This field of research will receive a big boost from the CERN lead source at the SPS, the advent of RHIC at Brookhaven and with the LHC.

In connection with hadron physics there is an important sociological feature worth reporting here. This type of physics is now pursued by a wide community of physicists which originates equally from particle physics and from nuclear physics. For instance, the CERN LEAR programme, the CERN heavy ion programme but also the CERN muon programme (deep inelastic scattering) now include altogether more than 500 nuclear physicists. An important and new fraction of nuclear physicists in Europe is now using the CERN facilities for their research. This of course has applied and still applies for the traditional nuclear physics research done at CERN, now centred on the new ISOLDE facility (on line study of radioactive nuclei).

5 The next large step forward in particle physics

5.1 The new energy range

The Standard Model is working too well but we cannot be fully satisfied with it. We have to understand the nature of the symmetry breaking which has to be introduced and, in doing so, we would like to be able to predict or relate some of its many parameters. We also want to know how it is eventually included into some Grand Unified Theory.

Using our superconductor analogy, we have to experiment at energies well above that corresponding to the critical temperature of the electroweak interaction which is of the order of 200 GeV. With our present understanding we think that we have to reach the TeV range in order to be certain to collect prominent clues. This we can think of doing with electron-positron collisions. The relevant collision energy is then that provided by the machine. Cross-sections are low but each event is *a priori* interesting. We can also do it with proton-proton collisions. The relevant energy is then of the order of one tenth of the nominal machine energy since what matters are collisions at the quark or gluon level when quarks and gluons each carry only a fraction of the momentum of the proton to which they belong (typically one tenth at the type of momentum transfers of interest). This is the reason why the SSC was designed as a 40 TeV machine and the LHC as a 14 TeV one. With the cancellation of the SSC programme, LHC is now a unique machine, the only one sure to reach beyond one TeV at the quark-gluon level. Cross-sections are large but most of them correspond to already well known processes. Interesting events of a new type have therefore to be extracted from a huge background.

From what has just been said one could be tempted to conclude that the preference should go to electron-positron colliders. However, at present, we would not know how to build such linear colliders reaching beyond the TeV with large enough luminosities (of the order of $10^{33} \text{ cm}^{-2}\text{s}^{-1}$). There is an important world-wide effort toward the design of such a type of machine but construction would still raise insurmountable problems.

We do know, however, how to build proton-proton colliders with the required energy and luminosity; and this is the reason why projects for the near future have been heading that way. The challenge is then with the detectors. They will have to extract information out of an imposing background, with events collected at a very high rate, but present techniques and ingenuity appears to be a good match for that. Proton machines also have the advantage to allow one to study many things at the same time since the observed collisions at the quark and gluon level cover a very large energy range for a given machine energy. Many cross-sections for peculiar new events also benefit from the relatively strong coupling of QCD. This is why both in the United States (SSC) and in Europe (LHC) there were hopes to have such instruments by the beginning of the next decade. The LHC [50] is planned to be installed alongside LEP in the LEP tunnel (Figure 32). It will therefore benefit from all the infrastructure at CERN and in particular from the existing machines serving as injectors. The LHC will accelerate protons but also heavy ions provided by the lead source now under completion at CERN. The high design luminosity LHC will initially focus on relatively rare events where quarks or gluons take a large fraction of the proton momentum. Later on the LHC beam and the LEP beam could be arranged to collide. The range now covered by HERA would then be extended up to 10^5 in Q^2 and down to 10^{-5} in x . Europe should therefore consider with optimism its LHC project.

There is a big difference between LEP and also the recent and present $p\text{-}\bar{p}$ colliders, and the future CERN proton-proton collider. The former can be somehow considered as "theorist machines". What is meant by that is that they were designed and constructed with a specific and precise shopping list in mind. The goal was to check well formulated predictions of the Standard Model. This they did beautifully. As usual, one hoped for interesting surprises. However, the only one so far was the clarity of the event structure which helped greatly in obtaining rapidly so many important results. With the new proton colliders the shopping list is also long but it is rather vague. One is certain that new prominent features have to show up as one reaches the TeV scale and beyond, but we have too many so called "possibilities" in mind and none of them can be precisely formulated. To that extent the LHC is clearly an "experimentalist machine" with the challenging goal of finding new things without knowing *a priori* what they should be and look like. This is even more interesting.

5.2 Search for the symmetry breaking mechanism

As repeatedly emphasised the key question is to understand the deep nature of symmetry breaking in the Standard Model. The Higgs may be found at LEP-200 but for that its mass should be less than 90 GeV [51]. The production cross-section would otherwise be too small. The Higgs could be more massive and its observation would then require a much higher collision energy.

We would however not like to have it too massive since the applicability of perturbation theory, which is a great asset of the Standard Model, would then break down. For instance if the Higgs mass is 500 GeV, perturbation theory would already break down at 1 TeV. The lower the mass the further perturbation theory can go. Let us, however, keep an open mind. If perturbation theory no longer holds at high energy, there would be strong interaction effects seen in WW or ZZ scattering as we reach beyond 1 TeV. They would be within the range covered by the new machines.

Talking about a very heavy Higgs, one is greatly worried that, in the framework of a Grand Unified Theory, nothing *a priori* prevents the Higgs mass from being driven up to the GUT energy scale through radiative corrections. Keeping the Higgs mass at a reasonable value would require incredibly fine tuning in the parameters. One is therefore led to expect something far more drastic and this motivates our urge to go and look.

There are three main lines of thought. Let us follow the first one – it is the more traditional one in which the Higgs is elementary – and search for it over a very wide mass range.

To that effect, one can see how any specific cross-sections vary with the machine energy (Figure 33) and assess the discovery potential for a given luminosity. One can get important hints from precision measurements but, most of the time, there is nothing like energy ! This certainly applies to the Higgs. As we

said, the mass should not be too high if the Standard Model is to keep its perturbative property. Within the framework of the Standard Model, the Higgs production mechanism and cross-section are entirely determined if its mass is known (Figure 34), and there is little doubt that if it exists it will be discovered.

However, we have also Grand Unification in mind and we cannot help keeping wondering how the Higgs mass could be kept low. This is where Supersymmetry (SUSY) comes into the picture in the most dramatic way. Supersymmetry is a symmetry between fermions and bosons, mixing geometrical and internal degrees of freedom. It has been with us for two decades already. It is very appealing theoretically but the main problem with it is that "sparticles", the supersymmetric partners of the existing particles, have been extensively looked for and not found so far [52]. The only thing which we can say from the LEP results is that their masses are all in excess of 50 GeV. However, this could well be the case if they exist, since supersymmetry is broken in the real world and they could be very massive. One should therefore keep trying with increasing energy.

The presence of supersymmetric partners to the existing particles is very welcome in the framework of our Higgs mass problem since radiative effects would then globally cancel themselves out. Not fully though and, if one wishes to keep the Higgs mass low, the supersymmetric partners could not be too massive. We are therefore led to focus on a mass range extending at most from a few to several hundreds of GeV. This is fine. The LHC would then have a great discovery potential.

If such particles exist, the running of the coupling constants is modified at energies beyond their production threshold. The precise LEP results indeed hint that this could be the case (Figure 35) [4]. This would be the way to reach a common GUT value assuming that there is nothing drastic happening for energies in between.

The lightest supersymmetric particle should be stable and very weakly interacting because its interactions require the exchange of a very massive supersymmetric particle. As will be discussed by Martin Rees [24] and John Ellis [25], it could then be an interesting candidate for cold dark matter.

Supersymmetric particles are of course a consequence of superstring theory but nothing can then be said about their masses which could be very heavy. On the other hand, observing them would be a strong experimental boost for superstrings which are still "stuck" at the Planck scale.

For all these reasons SUSY appears as an extremely interesting approach. There are many ways to introduce symmetry breaking in a SUSY theory but one is tempted to make sparticles play an important role at not too high an energy. One attaches, therefore, some particular interest in a Minimal Supersymmetric Standard Model, with a minimal number of extra parameters on which one can already put some constraints. The supersymmetric partners have their mass upper bounds lower than 1 TeV, and lower than 200 GeV for one of them! This, therefore, also puts them within the discovery range of the LHC. There are 5 Higgs particles in the model,

including 3 neutrals. This is then a strong encouragement in our search for the lightest Higgs, as a first wanted particle on the list.

In his concluding talk at Marseille, Lev Okun called such models with relatively light supersymmetric particles "une vraie bouillabaisse". He meant by that, something somewhat complicated to cook with odd-looking fish, but very tasty !

Another line of approach is more drastic and it does not make use of the appealing theoretical framework provided by supersymmetry. One assumes that the complications with a very high Higgs mass are actually not very relevant since the Higgs is a composite particle after all. It could be a bound state of hitherto unknown fermions and there are theoretical models along that line. The most popular one follows QCD calling for a "technicolour" interaction involving hitherto unknown massive "techni-particles". These models have had ups and downs in coping with existing data but they have remained alive for many years. If this is the way Nature works, thresholds could not be too high since the main goal is after all to keep the Higgs mass low. There is, therefore, a full new zoo of techni-particles which we could discover in the energy range offered by the LHC. This would reveal a further new layer in the structure of matter.

The third line of approach is to keep a far more open mind and be ready for something even more new and *a priori* more exotic. Again the energy range is appropriate for such surprises. To illustrate this, one may say that the successes met within gauge theories lead us to think that "all symmetries should be gauge symmetries unless they are accidental". One is then led to challenge even baryon and lepton conservation and could think of baryon number and lepton number violation already at the electroweak scale. This is the "sphaleron" approach. If the temperature can exceed the electroweak critical temperature in a very high energy collision, hosts of particles could be produced with violation of our standard conservation laws. In the early Universe this would lead to an erasure of the primordial production of quarks and leptons at the end of the GUT era. This is rather radical but we should be ready for surprises since we are seeking to understand a fundamental symmetry breaking mechanism through which particles acquire their masses.

Whatever line of thought is followed, one can say that probing physics in the TeV to a few TeV range and thus reaching an understanding of the structure of matter down to $10^{-19} \sim 10^{-20}$ metre, is an *a priori* very rich domain.

5.3 The experimental challenge

However, if we are certain that many new fundamental phenomena ought to appear in this new energy range, this survey clearly shows how vague our guidelines still are. We have to approach it in a full exploratory spirit. This puts a heavy demand on the detectors which should be able to cope with an intense production rate of mainly background events and still offer a detailed view of the collected events. It is a great experimental challenge but we think that we can tackle the issue. Two large detectors CMS (Figure 36) [53] and ATLAS (Figure 37) [54] have

been approved for the LHC proton-proton part of the programme. For those who are wondering about the spin-offs of particle physics, they can find there the assurance that the physical and technical ingenuity necessary for the design of such detectors will most certainly find many applications in other walks of life [55].

Much thought has already gone into the design of the detectors with which particle physicists want to approach this new and rich energy range at the LHC.

6 Conclusion

Particle physics is now faced with the success of the Standard Model. Forty years ago we could probe only down to 10^{-15} metre and the proton was still an elementary particle. We can now probe with accuracy down to 10^{-18} metre and we have discovered a whole new world inside the proton. We are sure to find completely new and spectacular things as we approach 10^{-20} metre. The present status of the Standard Model is not a completion point but the start of exciting new ventures. Research in particle physics is very much alive with a future loaded with fundamental questions which often jump from the deep structure of matter to the early Universe.

At this conference I would like to salute the spirit of EPS which has done so much to foster a good collaborative spirit between physicists from many nations and in particular between the eastern and western part of Europe at a time when it was very difficult.

Particle physics, with the large collaborations which it implies, has been spearheading this international approach to science. Many physicists of the former eastern bloc have long been closely associated with research at CERN and four countries from central Europe have recently joined the Organization as Member States. CERN is now serving half of the high energy physics community world-wide; and physicists from countries with only a budding scientific base can find in the large collaborations the help and support which they need in order to be active in front-line research at the world level, and with valid contributions of their own.

We love physics for its rational and rewarding approach to the mysteries of the world. We also love it as a bridge between people of different backgrounds and cultures.

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Figure captions

Figure 1: Table of Standard Model quarks and leptons including main properties.

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