THEORY SUMMARY TALK

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This is a short Summary of the theoretical presentations in the ElectroWeak session of the Moriond 2014 Conference.

1 Contents

I. What we have learned:

1. Heavy flavours
2. Neutrinos
3. Astrophysics and Cosmology
4. Standard Model Physics
5. Beyond the Standard Model

II. General Outlook

2 Introduction. General Outlook

In this Conference we had more than 40 theoretical talks, some reviewing a subject and some presenting original contributions. I cannot possibly do justice to all of them in such a short time and I will use them as guide in order to present my summary. The list of the subjects is given above and, as I go on, I will mention the particular contributions. I apologise for the numerous omissions.

Let me start with the second topic, namely the General Outlook which can be stated in just one sentence:

The Standard Model is complete!

In fact, we should not call it any more "The Standard Model", but **The Standard Theory**.

The Standard Theory has been enormously successful! It is a gauge theory of the group $SU(3) \times SU(2) \times U(1)$ spontaneously broken to $SU(3) \times U(1)_{em}$. It has four fundamental coupling constants, *i.e.* the three gauge couplings g, g' and g_3, as well as the scalar coupling constant λ, in addition to the Yukawa couplings of the scalar with the fermions which give rise to the fermion masses. All these parameters have now been measured experimentally, the last one being determined by the measurement of the scalar mass. Some are very small, ex. the electron Yukawa coupling constant[a], and others are quite appreciable, like the top-scalar coupling. It is remarkable however, that they are all smaller than one and perturbation theory seems to be applicable. We shall come back to this point presently.

Let us first ask the following question: are all these parameters truly independent, in other words, can we reduce their number by imposing some relation among them? An example of such a relation is $\lambda = F(g)$, the scalar coupling being a function of the gauge coupling constants. There have been very interesting attempts to impose such a relation of the form $m_Z^2/m_S^2 = (g^2 + g'^2)/8\lambda = C^2$ with C some fixed constant. This in turn implies a relation between the scalar and the gauge boson masses. The renormalisation group equations allow us to address this question. In the tree approximation we have:

$$C = \frac{m_Z}{m_\phi} = \frac{\sqrt{g_1^2 + g_2^2}}{\sqrt{8\lambda}} \tag{1}$$

So, the question is: is there any renormalisation scheme, no matter how complicated in practice, in which the relation (1) does not receive an infinite counterterm? Such a relation will correspond to a zero of the β-function for the combination of the coupling constants which appears at the r.h.s. of (1). The β-functions of the Standard Model, with or without fermions, have been computed at one and two loops. With three coupling constants we can form the two ratios:

$$\eta_1 = \frac{g_1^2}{\lambda} \quad ; \quad \eta_2 = \frac{g_2^2}{\lambda} \quad ; \quad z = \eta_1 + \eta_2 \quad ; \quad \rho = \frac{\eta_1}{\eta_2} \quad ; \quad w = \eta_1 \eta_2 \tag{2}$$

Notice that λ must be positive, otherwise the classical Higgs potential is unbounded from below. This implies that both η's are positive. If we leave out the fermions, the corresponding β-functions are given by:

$$\begin{aligned}
\beta_{\eta_1} &= \frac{1}{\lambda^2}(2g_1\lambda\beta_{g_1} - g_1^2\beta_\lambda) = \\
&= \frac{\lambda}{16\pi^2}\left(2\eta_1^2 - 12\eta_1 + 9\eta_1\eta_2 - \frac{27}{100}\eta_1^3 - \frac{9}{10}\eta_1^2\eta_2 - \frac{9}{4}\eta_1\eta_2^2\right) \\
\beta_{\eta_2} &= \frac{1}{\lambda^2}(2g_2\lambda\beta_{g_2} - g_2^2\beta_\lambda) = \\
&= -\frac{\lambda}{16\pi^2}\left(\frac{16}{3}\eta_2^2 + 12\eta_2 - \frac{9}{5}\eta_1\eta_2 + \frac{27}{100}\eta_1^2\eta_2 + \frac{9}{10}\eta_1\eta_2^2 + \frac{9}{4}\eta_2^3\right)
\end{aligned} \tag{3}$$

Using (3) we can investigate any ratio of the Higgs and the gauge boson masses. For the combination (1) we obtain:

$$\begin{aligned}
\beta_z &= \beta_{\eta_1} + \beta_{\eta_2} = \\
&= \frac{-\lambda w}{16\pi^2\rho z}\left[\left(\frac{27}{100}\rho^2 + \frac{9}{10}\rho + \frac{9}{4}\right)z^2 - \left(2\rho^2 + \frac{54}{5}\rho - \frac{16}{3}\right)z + 12(\rho+1)^2\right]
\end{aligned} \tag{4}$$

[a] If the neutrinos acquire their masses through the same Yukawa mechanism as the other fermions, the corresponding coupling constants must be really tiny. This point has been discussed in this Conference and we shall mention it later on.

It is easy to check that the quadratic form in the r.h.s. of (4) never vanishes for real and positive z and ρ. This implies that the relation (1) will be violated in one loop, no matter which renormalisation scheme one is using.

Similarly, we can check whether the ratio m_W/m_ϕ can provide a stable fixed point by looking for possible zeros of the β-function of η_2, eq. (3). The result is again negative. It is easy to show that adding the fermions does not produce any fixed points either and this applies to any other combination of the parameters of the theory. This allows us to conclude that:

The Standard Theory is irreducible under renormalisation!

It has all necessary coupling terms and nothing more. It is the extreme totalitarian system: everything which is not forbidden is compulsory.

2.1 The perturbation expansion.

The Standard Model is a renormalisable quantum field theory. Through the Feynman rules we obtain well defined expressions for any correlation function to any order of perturbation. Depending on the numerical value of the various coupling constants, we expect to find three different regimes: (i) the strong coupling regime, in which $g \geq 1$ for at least one coupling constant, (ii) the weak coupling regime, in which $g << 1$ for all coupling constants and (iii) a "gray area" in between. We expect perturbation theory to be reliable in (ii), we have developed a strong coupling approach based on lattice simulations for (i), and we are in the dark for (iii). In fact, at present energies the Standard Model appears to be in the gray area with some coupling constants rather large, although still smaller than one. Why does perturbation theory work so well? We can show the problem by a hand-waving argument. Let A_n be the nth order term in the perturbation expansion of some quantity A. We expect to have:

$$A_n \sim \alpha^n (2n-1)!! \tag{5}$$

where α is a typical coupling constant $\alpha = g^2/4\pi$ and the double factorial comes from the estimated number of diagrams at the $\alpha^n \sim g^{2n}$ order. In writing (5) we have made the following assumptions: (i) all diagrams at a given order give positive contributions and, (ii) the value of each diagram is roughly equal to one. Although neither one is correct for a general theory, we still expect the estimation to give the right order of magnitude. The perturbation theory breaks down when we have:

$$A_n \sim A_{n+1} \quad \Rightarrow \quad 2n+1 \sim \alpha^{-1} \tag{6}$$

This sounds fine for QED with $\alpha \sim 1/137$, but what about QCD at $Q^2 \sim 10 \mathrm{G}eV^2$? We have no rigorous answer to this question, but we believe we understand the structure of the theory and we have developed powerful techniques to perform calculations which, although still perturbative, go beyond the naïve Feynman diagram expansion. *(For the details, stay in Moriond next week.).* The conclusion is that the validity of (improved) perturbation theory seems to extend deep inside the gray area.

2.2 The strong coupling regime.

In the strong coupling regime we use a lattice approximation. It is a direct numerical computation of the functional integral and the formulation is interesting in its own right.

Let us consider, for simplicity, a lattice with hypercubic symmetry. The space-time point x_μ is replaced by:

$$x_\mu \to n_\mu a \tag{7}$$

where a is a constant length, (the lattice spacing), and n_μ is a d-dimensional vector with components $n_\mu = (n_1, n_2, ..., n_d)$ which take integer values $0 \leq n_\mu \leq N_\mu$. N_μ is the number of points of our lattice in the direction μ. The total number of points, *i.e.* the volume of the system, is given by $V \sim \prod_{\mu=1}^{d} N_\mu$. The presence of a introduces an ultraviolet, or short distance, cut-off because all momenta are bounded from above by $2\pi/a$. The presence of N_μ introduces an infrared, or large distance cut-off because the momenta are also bounded from below by $2\pi/Na$, where N is the maximum of N_μ. The infinite volume continuum space is recovered at the double limit $a \to 0$ and $N_\mu \to \infty$.

The dictionary between quantities defined in the continuum and the corresponding ones on the lattice is easy to establish (we take the lattice spacing a equal to one):

1. A field $\Psi(x) \quad \Rightarrow \quad \Psi_n$
2. A local term such as $\bar{\Psi}(x)\Psi(x) \quad \Rightarrow \quad \bar{\Psi}_n\Psi_n$
3. A derivative $\partial_\mu\Psi(x) \quad \Rightarrow \quad (\Psi_n - \Psi_{n+\mu})$

   where $n + \mu$ should be understood as a unit vector joining the point n with its nearest neighbour in the direction μ.
4. The kinetic energy term[b] $\bar{\Psi}(x)\partial_\mu\Psi(x) \quad \Rightarrow \quad \bar{\Psi}_n\Psi_n - \bar{\Psi}_n\Psi_{n+\mu}$
5. A gauge transformation $\Psi(x) \to e^{i\Theta(x)}\Psi(x) \quad \Rightarrow \quad \Psi_n \to e^{i\Theta_n}\Psi_n$

   All local terms of the form $\bar{\Psi}_n\Psi_n$ remain invariant but the part of the kinetic energy which couples fields at neighbouring points does not.
6. The kinetic energy $\bar{\Psi}_n\Psi_{n+\mu} \to \bar{\Psi}_n e^{-i\Theta_n} e^{i\Theta_{n+\mu}}\Psi_{n+\mu}$

which shows that we recover the problem we had with the derivative operator in the continuum. In order to restore invariance we must introduce a new field which has indices n and $n + \mu$. We denote it by $U_{n,n+\mu}$ and we shall impose on it the constraint $U_{n,n+\mu} = U^{-1}_{n+\mu,n}$. Under a gauge transformation, U transforms as:

$$U_{n,n+\mu} \quad \to \quad e^{i\Theta_n} U_{n,n+\mu} e^{-i\Theta_{n+\mu}} \tag{8}$$

With the help of this gauge field we write the kinetic energy term with the covariant derivative on the lattice as:

$$\bar{\Psi}_n \; U_{n,n+\mu} \; \Psi_{n+\mu} \tag{9}$$

which is invariant under gauge transformations.

U is an element of the gauge group but we can show that, at the continuum limit and for an infinitesimal transformation, it reproduces correctly A_μ, which belongs to the Lie algebra of the group. Notice that, contrary to the field Ψ, U does not live on a single lattice point, but it has two indices, n and $n+\mu$, in other words it lives on the oriented link joining the two neighbouring points. We see here that the mathematicians are right when they do not call the gauge field "a field" but "a connection".

In order to finish the story we want to obtain an expression for the kinetic energy of the gauge field, the analogue of $Tr\mathcal{G}_{\mu\nu}(x)\mathcal{G}^{\mu\nu}(x)$, on the lattice. As for the continuum, the guiding principle is gauge invariance. Let us consider two points on the lattice n and m. We shall call a path $p_{n,m}$ on the lattice a sequence of oriented links which join continuously the two points. Consider next the product of the gauge fields U along all the links of the path $p_{n,m}$:

$$P^{(p)}(n,m) = \prod_p U_{n,n+\mu} ... U_{m-\nu,m} \tag{10}$$

[b]We write here the expression for spinor fields which contain only first order derivatives in the kinetic energy. The extension to scalar fields with second order derivatives is obvious.

Using the transformation rule (8), we see that $P^{(p)}(n,m)$ transforms as:

$$P^{(p)}(n,m) \to e^{i\Theta_n} P^{(p)}(n,m) e^{-i\Theta_m} \tag{11}$$

It follows that if we consider a closed path $c = p_{n,n}$ the quantity $\mathrm{Tr}P^{(c)}$ is gauge invariant. The simplest closed path for a hypercubic lattice has four links and it is called *plaquette.* The correct form of the Yang-Mills action on the lattice can be written in terms of the sum of $\mathrm{Tr}P^{(c)}$ over all plaquettes.

On the lattice the functional integral becomes an ordinary multiple integral, in principle computable numerically. However, there are still several problems which should be addressed, both conceptual and technical:

1. Fermions. We just saw that the lattice provides for a cut-off which removes all divergences and respects gauge invariance. Therefore, it must violate chiral symmetry, otherwise we would have obtained a regularised theory with no axial anomaly. This is an old problem known as the *Nielsen-Ninomiya theorem.* There are several ways to bypass it, the most common one, introduced already by Ken Wilson, consisting of doubling all fermion species on the lattice. One can show that it is possible to recover the usual theory with the physical fermion content in the continuum limit. Alternative formulations, such as starting from a five dimensional theory, also exist.

2. Computers do not know how to handle anti-commuting variables, so, integrating over fermion fields is not straightforward. Fortunately, we never have to do it, because all terms in the Standard Model Lagrangian are at most quadratic in the fermion fields. So, the integration can be done analytically and we recover a determinant which depends on the gauge fields.

3. Computing the determinant for every gauge field configuration is a time-consuming operation. For this reason most early lattice calculations assumed non-dynamical fermions, the so-called *quenched* approximation. It is only recently, with the last generation of powerful computing systems, that real dynamical fermions can be included.

4. Even today a realistic computation covering the entire energy scale of interest in QCD, from the spontaneous breaking of chiral symmetry with real pions all the way to match perturbative calculations, is beyond our reach. These phenomena can be studied only by extrapolations. However, with the projected increase in computing power, such "dream" calculations can be expected for the next decade.

5. At present we have a good fit of hadron spectra with the exception of the very light pseudo scalars which are sensitive to the spontaneous breaking of chiral symmetry. In addition, the matrix elements describing the weak decays of heavy quarks are also quite reliably estimated (*see the talk by F. SanFilippo*).

2.3 New Physics.

We have been told repeatedly that New Physics is around the corner.....but, for the moment, we see no corner! There exist, however, good reasons to believe that new physics is indeed there, except that the corner may be a bit further than what we thought.

The ST is a renormalisable Quantum Field Theory. As such, it gives perfectly well-defined answers for every correlation function at any order in perturbation theory. Remember, however, that parameters such as masses and coupling constants are not calculable. They are taken by experiment. From the mathematical point of view any number is as good as any other but this leaves some conceptual questions unanswered.

1. *Hierarchy:* Why all dimensionless numbers are not of order one. In particular, why there seem to be widely separated mass scales. The problem is physical, not mathematical.

2. *Naturalness, or Fine tuning:* Why some choice of parameters may require fine tuning in perturbation.

Both problems are aesthetic. If you are happy with very small, or very large, numbers, you do not have to worry about them. We can show the problem using Wilson's effective theory approach.

Consider any 4-dim renormalisable theory. Integrate over all modes of the fields with energy above a given scale M. M does not have to correspond to a physical scale. You obtain an effective theory in terms of the light , *i.e.* lighter that M, modes. The general form of this theory will be an infinite sum of terms of the form:

$$\mathcal{L}_{eff} = \sum_i C_i(g, M)\mathcal{O}_i \tag{12}$$

where $\mathcal{O}_i$ form an infinite set of *all* local operators which are consistent with the symmetries of the initial theory and C_i are c-number functions of the coupling constants and the scale M. If the initial theory is renormalisable, the coefficient functions C_i can be computed in perturbation. Notice that this expansion is valid irrespectively of whether the initial theory was "fundamental" or "effective". The dependence of the C_i's on M can be deduced by dimensional analysis. If d_i is the dimension of the operator $\mathcal{O}_i$, the corresponding coefficient is proportional to M to the power $(4-d_i)$. We see that we obtain three kinds of terms. (i) Those with $d_i > 4$ have a negative power of M and they become *irrelevant* for large M. (ii) Those with $d_i = 4$ are *marginal* operators and their coefficients are M-independent[c]. Since the Standard Model is irreducible, all these terms appear already in the original Lagrangian. (iii) Finally we have terms with $d_i < 4$ whose coefficients have positive powers of M and become *dominant* for large M. *The only dominant operator in the Standard Model is the scalar mass term:* $m_S^2\phi_S^2$. It will grow as M^2, *unless, for some reason, its coefficient vanishes.* This will require the introduction of new physics and we heard in this Conference several ways such a thing could happen.

3 What we have learned

I shall follow the topics, as they were presented in the Conference.

3.1 Heavy flavours

Many contributions by W. Altmannshofer, Ch. Bobeth, S. Descotes-Genon, M. Gorbahn, F. Sala, F. SanFilippo, A. Tayduganov.

Heavy flavors present a rich and exciting phenomenology, but we have to admit that we do not understand the underlying physics. It was I. Rabi who, after the identification of the muon, almost seventy years ago, asked the question: "who ordered that?" The question is still with us extended to all quark and lepton flavours beyond the first family. Even if we forget about neutrinos, their masses are spread over a wide range of more than five orders of magnitude and this creates a naturalness problem which we do not understand. We try to turn it into a blessing. For example, b-quarks present an interesting new source of CP violation and they are the subject of both experimental and theoretical investigation. Rare decays may reveal the presence of new physics.

[c] We ignore in this discussion any logarithmic dependance on M.

3.2 Neutrinos

We had many reviews and contributions: R. Alonso, G. Altarelli (general review), F. Capozzi, P. Coloma, M. Drewes, A. Kartavtsev, F. Lyonnet, M. Maltoni (on sterile neutrinos), P. Schwaller, Y. Wong

Neutrinos have provided the only experimental results which, quite probably, point already to physics beyond the Standard Model. It is a data driven subject in which, for a change, the theorists did not play the major role. There have been very few new ideas and most of them provide an independent indication for the possible existence of a GUT-like scale.

A point which was emphasised in this Conference is that the presence of sterile neutrinos will not help in the effort to remove the discrepancies and fit all the experimental results. Unless something totally unexpected happens, some measurements should be revised.

From G. Altarelli's review: So far no real illumination came from leptons to be combined with the quark sector for a more complete theory of flavour

3.3 Astrophysics and Cosmology

We were presented with great new results in astrophysics and cosmology. Since they were essentially experimental, I will mostly mention them very briefly

1. Planck: Beautiful measurements of CMB anisotropies in temperature and polarisation.

   (See the theory talk by J. Hamann.)

2. Ice Cube: We enter the era of High Energy Neutrino Astronomy.

   (See the theory talks by I. Saba, G. Sigl and I. Tamborra.)

3. BICEP2: First evidence for the B-mode in polarisation. The trace of primordial gravitational waves?

   Let me remind you here the well known fact that scattering on free electrons can produce linearly polarised light. Let us choose the rest frame of the target electron and consider a beam of photons incident along the z axis. The initial polarisation vectors $\vec{\epsilon}_i$ lie on the $x-y$ plane. If we look at a scattered photon at large angles, say along the x axis, its polarisation vector $\vec{\epsilon}_f$ will lie on the $y-z$ plane. Thompson's classical formula tells us that only the y component survives, *i.e.*, even if the incident beam was unpolarised, the scattered photon will be linearly polarised.

   According to the Standard Cosmological Model, the Universe started very hot and dense and it cools down as it expands. During this process it went through several phase transitions. When the temperature was above a few keV, matter consisted of a hot plasma made out of electrons and protons with some light nuclei, mainly helium. Photons were trapped in the plasma and were not free. As the temperature dropped electrons and nuclei combined to form the first atoms. Matter became neutral and photons could travel freely through space and can be observed today. They carry precious information regarding the conditions that prevailed when they last interacted with free electrons, *i.e.* the moment of recombination. According to the model, this happened at a time around 380000 years after the big bang. Because of the expansion, the photon wave length has since been redshifted and today it is observed as a cosmic microwave background (CMB) radiation. It is remarkably homogeneous and isotropic and this fact is best understood in the framework of the so-called *inflation* model which postulates that, at very early times, of the order of 10^{-33} seconds after the big bang, the Universe went through a state of exponentially fast expansion. Thus, the present visible Universe results from a very small region of the early Universe and the study of the CMB radiation brings to us the earliest information of the world history. This information is of two kinds. First, we observe density and temperature fluctuations of the order 10^{-5}. They are at the origine of the formation of the large structures we observe today. A second kind of information concerns the polarisation of the CMB photons. As we noticed already, scattering at 90 degrees of unpolarised photons produces linear polarisation. However, if, in the electron rest frame, the incident radiations along the z and the y axis have the same intensity, the polarisation of the photons scattered in the x direction, cancels. It follows that a net polarisation will reveal the presence of anisotropies along perpendicular directions, *i.e. quadrupole anisotropies*, at the moments just before the last scattering. It is assumed that inflation has washed out any large anisotropies, so the polarisation is expected to be small. We can treat these anisotropies as perturbations and make a multipole expansion in scalar, vector, tensor etc. We can imagine various sources of such perturbations. In the inflation model scalar perturbations come from density anisotropies, vector perturbations from the presence of magnetic vortices in the plasma and tensor perturbations from the presence of gravitational waves created during the set up of inflation. These perturbations are expected to leave their imprint in the polarisation pattern of CMB radiation.

Like any vector field, a polarisation $\vec{\epsilon}(\vec{x})$ of the CMB radiation can be decomposed into a pure gradient part and a pure curl part. They have different transformation properties under parity: the first, called *the E-mode*, is a pure vector and the second, *the B-mode*, a pseudo-vector. The scalar perturbations will contribute only to the E-mode because we cannot make a pseudo-vector out of the derivatives of a scalar. The E-mode polarisation has been measured already and it is well correlated with the observed temperature fluctuations. A B-mode can come only from vector or tensor perturbations. The first are expected to be very small because inflation has presumably diluted any primordial vortices in the plasma, so we are left with gravitational waves as the principal source of a B-mode. Furthermore, their presence is a generic prediction of all inflation models. Therefore, it is easy to understand the excitement caused by the BICEP2 results which were shown in this Conference. They have the magnitude and the properties expected from inflation models. At this moment this observation is still preliminary but, if it is confirmed by independent measurements and if all other sources of contamination are eliminated, it will be the first, albeit indirect, observation of gravitational waves.

4. Limits on Dark Matter searches were presented together with planned new experiments. Several theoretical talks addressed the question in the framework of specific models. I will mention them mostly in the section "Beyond the Standard Model". More specifically, see the contributions of *J.Heisig and T. Scarna.*

3.4 Standard Model Physics

Several subjects have been discussed. I will present my conclusions.

1. The Standard Model and scale invariance.

   We had a good discussion on this subject (*see talks by M. Raidal, K. Kannike, M. Schmaltz*). The conclusion is that the Standard Model is not scale invariant. This result does not depend on the particular regularisation scheme one uses to perform the renormalisation.

   In fact, the only generic 4-dim, non-trivial, scale invariant, quantum field theory is the N=4 supersymmetric theory with an $SU(k)$ gauge symmetry. The beta-function vanishes and the coupling constant does not run. This theory has remarkable properties which may lead to complete integrability and are the subject of intense scrutiny during the last years with very exciting perspectives.

2. Possible new particles without new physics.

We had the example of axions. They are part of QCD with massive quarks, so they do not imply necessarily "new physics", although, in practice, all proposed models have some features beyond the Standard Model. Their detailed properties are model-dependent. (*See review by A. Ringwald*).

Let me remind you that taking into account in the QCD functional integral gauge field configurations with non-trivial boundary conditions, amounts into adding to the effective Lagrangian a term proportional to $\epsilon_{\mu\nu\rho\sigma}F^{\mu\nu}F^{\rho\sigma} = F\tilde{F}$ and work with an effective action:

$$S_{eff} = S_{YM} + \frac{i\theta}{32\pi^2}\int d^4x F\tilde{F} \tag{13}$$

with S_{YM} the usual Yang-Mills term and θ an arbitrary constant. Our old perturbation theory corresponds to the particular value $\theta = 0$. In other words, a Yang-Mills theory has a more complex structure than naïvely anticipated, namely it contains a second "hidden" coupling constant, the parameter θ. It is easy to show that this new term is equal to the integral over all space of a four-divergence, however it would be a mistake to ignore it because the assumption that all fields always vanish at infinity is not correct for a gauge theory.

$$\partial^\mu G_\mu = \mathrm{Tr}\tilde{F}_{\mu\nu}F^{\mu\nu} \tag{14}$$

with

$$G_\mu = 2\epsilon_{\mu\nu\rho\sigma}\mathrm{Tr}\left(A^\nu\partial^\rho A^\sigma + \frac{2}{3}A^\nu A^\rho A^\sigma\right) \tag{15}$$

G_μ is not gauge invariant but, as shown in (14), its divergence is.

$F\tilde{F}$ is a pseudoscalar, therefore for $\theta \neq 0$ this term violates parity. Since it conserves charge conjugation, it violates CP and, consequently, time-reversal invariance. This is also obvious from the presence of the i-factor. If there were no other sources of CP violation in the theory, we could set $\theta = 0$, but we know that weak interactions will induce a non-zero θ term. Since strong interactions are known to conserve CP and T, it means that experiments should put severe bounds on the allowed values of θ for QCD. It turns out that the strongest constraint comes from the absence of a neutron electric dipole moment. It can be translated as an upper bound for θ of the order $\theta < 10^{-9}$, several orders of magnitude smaller than what we could naïvely expect from the electroweak radiative corrections. This is known as *the strong CP problem* and a deeper explanation is clearly needed.

The simplest and most elegant solution is to assume that at least one quark species is massless. The best candidate is the u quark. Then a chiral transformation on the quark fields will produce, through the axial anomaly, an $F\tilde{F}$ term which could absorb whichever θ term we had put in. The trouble is that $m_u = 0$ does not seem to be compatible with the results of chiral perturbation theory, so we must look for a different explanation.

Roberto Peccei and Helen Quinn proposed to enlarge the model in such a way as to restore a $U(1)$ axial symmetry, even in the presence of massive quarks. For the Standard Model a simple way to achieve this goal is to consider two BEH doublets, one which is coupled only to up-type quarks and a second one for the down-type. Now we have an extra freedom, namely to perform phase changes of the scalar fields. It is easy to check that the θ-term can be absorbed and no CP violation is induced. However, as Steven Weinberg and Franck Wilczek have observed, this $U(1)_{PQ}$ is spontaneously broken at the classical level, since both BEH doublets acquire a non-zero vacuum expectation value. The resulting Goldstone boson does not remain massless, because of the instanton effects. It follows that such a theory contains a pseudo-scalar pseudo-Goldstone boson which is called *an axion*. Its detailed properties, mass and couplings, depend on the particular model. The simplest two doublet model is already ruled out by experiment, but other models are not. An active experimental programme is being currently pursued aiming to the discovery and, possibly the study, of axions.

3. The properties of the new scalar boson.

   (See contributions by K. Kannike, A. Pomarol, M. Raidal and C. Weiland)

   This is, obviously, a very important topic, although it is mostly the domain of experimentalists. We have to make sure that it is *the* boson of the Standard Model and, for that purpose, we must study and measure all its detailed properties.

   From the theoretical side people try to determine its general properties, as well as possible signals of new physics.

   Even if we have argued that new physics is expected at a nearby energy scale, it is still interesting to study the properties of the scalar potential as a function of the scale. Such studies had been done before the discovery, but now we have all the information. The intriguing result is that the measured value of the mass lies at the border of metastability: the scalar potential becomes metastable at very high energies. I confess I do not know whether this is an important result, or a mere numerical coincidence.

   Many contributions presented in this Conference aim at giving a precise picture of possible new physics via the study of the properties of the scalar boson. If any departure from the Standard Model values is detected, we shall know what kind of extensions we should consider.

4. The electric dipole moments as probes for new physics *(Review by J. Hisano)*.

   Non-zero electric dipole moments are only possible if time reversal invariance is violated. In the Standard Model these effects are suppressed, so the predicted values of EDM's are very small. This makes these quantities good probes for new physics, provided the latter offers the possibility of enhancing CP-violation effects. In this review we had a comprehensive picture of possible effects, but also the difficulties in interpreting whichever signals may occur.

3.5 Beyond the Standard Model

This has occupied a large part of the presentations. Even those which I have already mentioned previously, contain analysis for possible new physics. Specific contributions include: *M. Badziak, C. Biggio, M. Buchkremer, D. Buttazzo, O. Eberhardt, S. Fukasawa, M. Jung, D. Litim, F. Lyonnet, D. Marzocca, S. Najjari, Ch. Petersson, J. Quevillon.*

In a model independent way, we can use the analysis based on the Wilson expansion shown in equation (12). Here M represents the scale for new physics. Operators with dimensions $d_i > 4$, the ones we called "irrelevant operators", will give contributions suppressed by M^{4-d_i}. Since such operators may contribute to processes beyond the Standard Model, such as the EDM's we mentioned before, they provide sensitive tests of New Physics.

Supersymmetry is still the favourite model for both theorists and experimentalists. I am sure by now everybody has heard about supersymmetry more than he ever wished to know, so I will not present the details of any model. It is the most attractive and the most seminal theoretical idea of the last decades, but we have to admit that, if it is the way chosen by Nature, we do not know neither how, nor where it is broken. I was pleased to see that both theorists and experimentalists have escaped the unjustified tyranny of MSSM and the data are presented, as much as possible, in a model independent way. In the notation we used in equation (12), supersymmetry ensures that the coefficient C_S of the scalar mass term, which is proportional to M^2, vanishes and the fine tuning problem is eliminated. The second good thing about supersymmetry is that in order for this to happen, M cannot be arbitrarily large. We hope it will turn out to be within reach of improved LHC and we are looking forward to exciting discoveries.

4 Conclusions

• The field is active showing a good collaboration between theorists and experimentalists.

• More than 40 theoretical presentations, many coming from young researchers.

• We have the clear feeling of excitement, both from the long awaited confirmation of the Standard Theory, as well as from the expectation of New Physics.

I end with a story *(A. Pais, Inward Bound)*

A tourist was visiting Washington DC. Behind the National Archives he noticed a statue of a seated woman holding an open book on her lap. Underneath there was the inscription: *What is past is prologue.* What does it mean? he asked his guide. And the latter replied: *It means you ain't heard nothing yet.*