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The future of particle physics ⋆

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Abstract

I review the prospects for future progress in accelerator-based particle physics

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1 Introduction

To discuss the future it is useful to review the past first. By 1973 the theoretical foundations of the Standard Model (SM) were fully established, the last ones being the proof of renormalizability and unitarity of the $SU(2) \times U(1)$ Yang-Mills Lagrangian with the Higgs mechanism of EW symmetry breaking (EWSB), the discovery of asymptotic freedom and the ensuing proposal of QCD as the gauge theory of strong interactions, and, finally, the Kobayashi-Maskawa (KM) description of CP violation with a fermionic 3-family structure. After 1973 followed over 30 years of consolidation, whose main ingredients are summarized as follows: (i) theoretical technical advances (development of techniques for more and more accurate calculations, and lattice gauge theories to deal with the non-perturbative aspects of strong interactions); (ii) experimental verification of the SM spectrum, with the discovery of the new fermions (charm, plus all members of the third generation) and of the predicted gauge bosons (the gluon, W and Z); and (iii) experimental verification of the SM dynamics, with the measurement and test of EW radiative corrections, of the running of $\alpha_s(Q)$, and, finally, the confirmation of the KM model of quark mixings and CP violation (the measurement of direct CP violation in K decays, and the recent successful tests for the third generation performed at LEP/SLC, the Tevatron and, most compelling, at the B-factories).

Those who claim that nothing interesting has happened in particle physics in the past 30 years should think twice. The formulation and consolidation of the SM is a monumental scientific achievement, with

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parallels only in the discovery of Maxwell's theory of electromagnetism, of special and general relativity, and of quantum mechanics. These past 30 years will be recorded in history as a milestone in the development of our understanding of Nature.

After 1973, theoretical progress has been mostly driven by theory itself, rather than by data. The push came from the need of a better understanding of several issues left open by the SM: (i) identifying the deep origin of EWSB, (ii) of the gauge structure, (iii) of the family structure and, last but not least, (iv) the understanding of quantum gravity and of the vanishing of the cosmological constant (which, most recently, turned out to be true only approximately, making the puzzle even more challenging). The milestones that emerged from these speculations include:

- GUTs (grand unified theories, 1974), to extend Maxwell's unification to all gauge interactions;
- Supersymmetry (SUSY, 1974), to complete the set of mathematically allowed symmetries of space-time;
- The see-saw mechanism (1977), to provide a dynamical explanation of the smallness of neutrino masses;
- Technicolour (1979), to provide a dynamical framework for EWSB and the Higgs mechanism;
- Inflation (1980), to explain the flatness of the Universe;
- Superstrings (1984), to provide a consistent theory of quantum gravity and a possible Theory of Everything;
- Large-scale extra dimensions, to provide a natural explanation of the large difference between the strength of gauge and gravitational interactions.

In addition to the above, theoretical physics has witnessed the establishment and consolidation of a Standard Model of cosmology, based on general relativity, particle physics, and inflation, capable of explaining, among others, properties of the Universe as diverse as the nuclear abundances, the fine structure of the microwave background radiation, and the formation of large-scale structures.

Since 1973, experimental particle physics has been mostly occupied with verifying the SM, as mentioned above, and attempting to find traces of the new theoretical ideas that were being put forward: proton decay or neutron oscillations in the case of GUTs; signatures of sparticles in the case of SUSY; neutrino masses or mixings; signatures of extra-dimensions (deviations from Newton's law or graviton emission in hard collisions); and more. With the exception of the discovery of neutrino oscillations, nothing compelling has unfortunately emerged as yet. This resembles the most frustrating among the scenarios envisaged by Glashow in a seminar with a title similar to mine given almost 30 years ago [1]. Are we therefore destined to be stuck forever with the SM? Why should we expect that something new and exciting will happen soon, with the accelerator and experiments that are operating or about to start?

The are two sets of reasons that justify the expectation that something new and exciting is just about to happen: the first set relies on theoretical prejudice, the second on experimental facts. We shall now examine these two complementary viewpoints.

2 The theoretical wisdom

2.1 Electroweak symmetry breaking

The required step towards future progress in particle physics is today the observation of the Higgs boson, which should lead to the beginning of a clarification of the EWSB mechanism. From the theoretical point of view, Higgs boson searches at the LHC will provide non trivial information regardless of the outcome. If the SM description of EWSB is correct (and if the LHC and the experiments perform as expected, something we'll give for granted), the observation of the Higgs is guaranteed. The SM fits of the current EW data firmly predict at 95%CL that $m_H \lesssim 200$ GeV; the direct LEP limit, valid within the SM, says that $m_H \gtrsim 114$ GeV. In the mass range $114 < m_H(\text{GeV}) < 200$, ATLAS and CMS promise a discovery with an integrated luminosity between 1 and 10 fb^{-1}. If this does not happen, the SM is in trouble. Whether the Higgs is not seen because it decays to final states with small detection efficiency, or because the production rates are much smaller than predicted, in all cases this would point to physics BSM, since production rates and decay modes and BRs are uniquely predicted with good accuracy by the SM. A SM-like Higgs with a mass of several hundred GeV, visible at the LHC for masses up to about one TeV, would also create problems to the SM, since such a large mass would conflict with the EW measurements. Complete lack of a Higgs resonance below the TeV, finally, would also be a clear indication of new physics, because of a violation of perturbative unitarity in WW scattering at high energy. In the context of standard 4-dimensional field theories this could only be circumvented by the appearance of resonances in gauge boson scattering around the TeV, yet another interesting new phenomenon.

Contrary to previous accelerators, like LEP2 or the Tevatron, the LHC will therefore be able to conclusively answer the question of whether or not nature is consistent with the SM description of EWSB. Regardless of the outcome, one of the most long-awaited questions in particle physics will soon be answered. Even if the Higgs will appear to behave like in the SM (i.e. its mass will be consistent with the current bounds and its production and decay properties will match those predicted by the SM), there is no guarantee that no other underlying phenomena are at work, and therefore in all cases a more complete exploration of the EWSB dynamics will need to be carried out. In particular, EWSB as described in the SM opens a major theoretical puzzle, discussed in the next section, which strongly calls for physics BSM.

2.2 The hierarchy problem

Radiative corrections induced by the coupling with the top quark generate a shift of the Higgs mass squared:

$$\Delta m_H^2 = \frac{6G_F}{\sqrt{2}\pi^2}\, m_t^2 \Lambda^2 \,, \tag{1}$$

where Λ is the upper limit of the momentum in the loop-integration. This correction diverges quadratically as Λ is sent to infinity. The renormalizability of the theory allows with a single subtraction to relate, via a finite relation, the Higgs mass parameter calculated at different scales:

$$m_H^2(Q) = m_H^2(Q_0) + \frac{6G_F m_t^2}{\sqrt{2}\pi^2}\,(Q_0^2 - Q^2) \,. \tag{2}$$

We say that the quadratic divergence is reabsorbed into the bare Higgs mass parameter defined at the scale Q_0, $m_H(Q_0)$. This relation implies that the combination

$$m_H^2(Q_0) + \frac{6G_F m_t^2}{\sqrt{2}\pi^2} Q_0^2 \tag{3}$$

is a constant, independent of Q_0 for all values of Q_0 at which the theory is represented by the SM.

If we take Q_0 to be of the order of the EWSB scale, $v = 247$ GeV, and we use the range of m_H from the EW data, we obtain for this constant a number of the order of few ×100 GeV. If we allow Q_0 to become as large as the Planck mass $M_{Pl} \sim 10^{19}$ GeV, the region where the SM gets unavoidably modified by quantum gravity, $m_H^2(M_{Pl})$ must be fine tuned to the level of $(v/M_{pl})^2 \sim 10^{-33}$ in order for the cancellation between $M_{pl})^2$ and $m_H^2(M_{Pl})$ to result in a number of order v^2. This fine tuning, while formally legitimate, is considered theoretically to be extremely unnatural, and suggests to theorists that eq. 1 should receive additional contributions cancelling the quadratic term at energy scales of O(few $\times v \sim$TeV), thus removing the need for fine tuning. When theorists say that the SM is *incomplete*, they usually refer to this issue, called the “hierarchy problem”. Most of the theoretical work of the past 30 years has been devoted, directly or indirectly, to identifying solutions to this problem. Supersymmetry, technicolour, large extra-dimensions, are all different ways of addressing this issue. Their common approach is to tie the Higgs boson to some new symmetry, which protects its mass against the appearance of quadratic divergencies (see [2] for a more complete discussion and for references).

In supersymmetry this is achieved by introducing a fermionic partner. Since fermion masses only receive logarithmic corrections, the Higgs mass correction must be logarithmic as well. The way this happens in practice is through the addition of the stop quark $\tilde{t}$ (the supersymmetric partner of the top) contribution to the radiative corrections to ${m_H}^2$. The quadratic component of this contribution has the same size of the top one, but opposite sign due to Bose statistics, leading to a cancellation which leaves only a finite term, proportional to the logarithm of the ratio of stop and top masses.

In the so-called *little-Higgs* theories, which are a modern incarnation of technicolour, one introduces a global symmetry under shifts of the Higgs field, $H \to H + a$. In this way, the fundamental Lagrangian can only contain terms proportional to derivatives of the Higgs field, and no mass can be present. When this symmetry is broken, only small corrections to the Higgs mass can arise, and the radiative correction are protected against the appearance of logarithmic contributions. In these theories new particles are required to enforce this cancellation at the diagrammatic level. In the case of the simplest little-Higgs theories, these are new, heavier partners of the top quark, and new gauge bosons W' and Z', all with masses in the 1–few TeV range.

In theories with extra dimensions, the Higgs is a component of gauge fields along the extra dimensions, something that behaves as a scalar in 4 dimensions. The gauge symmetry that protects the mass of gauge bosons will then take care of eliminating the quadratic divergence, using once again the contributions to the Higgs mass loop corrections of the new particles appearing as Kaluza-Klein modes.

In all of these examples, care must be exercised to ensure that the impact of the new particles on the EW observables be compatible with the current precision measurements. This, together with the request that the reduction of the fine-tuning is not spoiled by the introduction of new very large mass scales, leads to the prediction of a rich phenomenology of new phenomena at scales potentially within the reach of the LHC.

3 The experimental hints for new physics

While the above ideas are considered as sufficiently compelling by most theorists to justify great optimism in the appearance of new phenomena at the LHC, it is encouraging that also more pragmatic, data-driven considerations, point in the same direction. There are in fact at least three compelling experimental observations that clearly demand new physics BSM: neutrino mixing, dark matter, and the baryon asymmetry of the Universe, namely the amount of baryons emerging from the early Universe. None of these observations can be accommodated within the SM, regardless of how much we allow ourselves to fiddle with possible uncertainties in the theoretical predictions. Independently of our personal level of pragmatism and indifference towards theoretical speculations such as those presented in the previous section, as scientists we therefore have to accept the existence of physics BSM.

In addition to those three clear cases, an increasing number of less significant, but nevertheless tantalizing, indications of possible discrepancies with the SM are emerging in various low-energy observables. The crucial issues for the future of our field are therefore the following. Is there a common thread among all deviations from the SM, pointing towards a new paradigm in particle physics? If so, how soon, and with which experimental tools, will it be possible to learn more about it? I personally feel that it is justified to answer positively to the first question, and to expect that the field is ready, with the forthcoming generation of experiments, to start unveiling and quantitatively exploring these new phenomena.

I will now elaborate a bit more on this by using the example of neutrino physics, and reviewing some of the weaker but nevertheless interesting anomalies alluded to above.

3.1 Neutrinos

Neutrino masses themselves do not provide a new theory, and can be incorporated within a trivial extension of the SM. What is exciting is that once we look beyond this trivial realization in terms of sterile right handed neutrinos, we find an amazingly fertile terrain for interesting speculations: the connection with GUT-scale physics, via the see-saw mechanism, is as strong as, if not stronger than, the unification of the gauge couplings. The coincidence between these two totally independent hints at grand unification certainly adds to their individual strength! The failure of the SM to accommodate the baryon asymmetry of the Universe makes leptogenesis (the lepton-driven B asymmetry of the Universe) a very exciting possibility. The connection with GUT, and the fact that SUSY quantitatively accommodates gauge coupling unification much better than any non-SUSY GUT, strengthens the case for SUSY itself. Willing to explore the broad consequences of neutrino masses and to anticipate possible experimental needs to analyze them, it is mandatory to explore the joint implications of SUSY and neutrino masses and mixings. As briefly summarized here, these are manifold and far reaching [3].

The form of the most general terms leading to neutrinos masses is given by:

$$L_m \propto y_\ell \, H_\ell \, L_i \, L_i^c \\ + y_\nu^{ij} \, H_\nu \, L_i \, N_j \; + \; M_N^{ij} \, N_i \, N_j \quad (4)$$

If $M_N = 0$, and the Higgs field coupled to N is the conjugate of the SM Higgs field, then we have a trivial extension of the SM, and the smallness of the neutrino masses is driven by the (*unnatural?*) smallness of the Yukawa couplings y_ν. In this scheme neutrino masses and mixings are given parameters, without any dynamical content. Neutrino mixings will lead to FCNC processes in the charged lepton sector. Their rates will be proportional to the probability that a neutrino can oscillate and change flavour during the time allowed to the virtual transition $\ell \to \nu_\ell W \to \ell$, leading to invisibly small effects. The presence of the additional Majorana mass term enables the see-saw mechanism: a large value of M_N leads to the following solution for the light eigenvalues of the (ν, N) mass matrix:

$$M_\nu = -y_\nu \, M_N^{-1} \, y_\nu^T \; \langle H_\nu \rangle^2 \qquad (5)$$

Assuming that the expectation value of the Higgs field coupling to neutrinos is of the same order of magnitude as that of the SM Higgs, one can generate masses in the range given by data provided M_N is of order 10^{15}

GeV. In the presence of Supersymmetry, H_ν is not an arbitrary new Higgs field, but is the Higgs giving mass to the up-type quarks. Taking seriously the connection with the GUT scale suggested by the see-saw mechanism, enforcing the GUT symmetry on the high-energy lagrangian leads to an even more direct relation between up-type quark and neutrino masses. For example, in the simplest case of a $SO(10)$ theory we would have:

$$\begin{aligned} L_m \propto\ & y^{d,\ell}_{i,j}\, \mathbf{16}_i \mathbf{16}_j H^{10}_d \\ & + y^{u,\nu}_{i,j}\, \mathbf{16}_i \mathbf{16}_j H^{10}_u \ + \ y^{R}_{i,j}\, \mathbf{16}_i \mathbf{16}_j H^{126}_{R} \end{aligned} \qquad (6)$$

where the Higgs fields coupling to up and down-type quarks H_u and H_d lie in different 10-dimensional representations of $SO(10)$, and

$$\mathbf{16} = (u_L, d_L, u^c, e^c)_{10} + (d^c, L)_{\bar{5}} + N^c \qquad (7)$$

is the $SU(5)$ decomposition of the representation containing all SM fermion fields plus the left-handed anti-neutrino N^c. The first consequence of these relations is that at least one entry in the neutrino mass matrix is of the order of the top Yukawa coupling, and

$$m(N) \sim m^2_{top}/m_\nu \qquad (8)$$

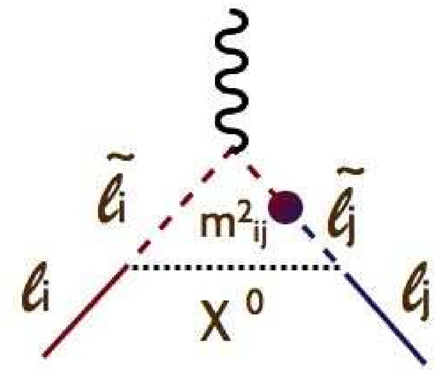

Fig. 1. $\ell_i \to \ell_j \gamma$ decay induced by the mixing of charged sleptons.

for the third-generation neutrinos. Assuming that $m(N)$ should not exceed the GUT scale, there is a lower limit on the mass of the light 3^{rd}-generation neutrino. The second consequence is that quark mixings lead to charged slepton mixing via renormalization group evolution from M_{GUT} to m_N. In the case of supersymmetry breaking induced by common soft scalar masses m_0 at the GUT scale, one for example obtains:

$$(m^2_{\tilde{L}})_{ij} \ \sim\ -\frac{3m_0^2 + A_0^2}{8\pi^2}\, y_t^2\, O_{ij}\ \log\frac{M_{GUT}}{M_{N_R}};\,, \qquad (9)$$

where

$$y_t^2\, O_{ij} = \sum_k\ y^\nu_{ik}\, y^{\nu *}_{kj} \qquad (10)$$

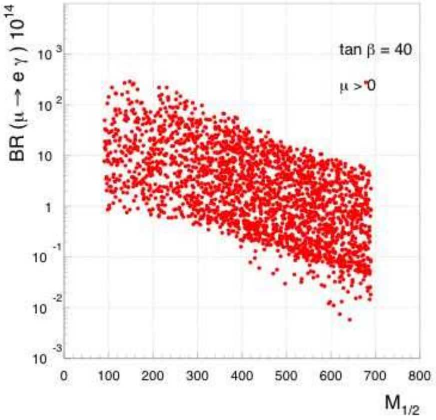

Fig. 2. $\mu \to e\gamma$ decay rates in the CKM case.

The diagrams in fig. 1 will then induce transitions such as $\mu \to e\gamma$ or $\tau \to \mu\gamma$. The quantitative prediction for the branching ratios depends on the specific values of the entries of the mass matrix O_{ij}, something that the available data cannot allow

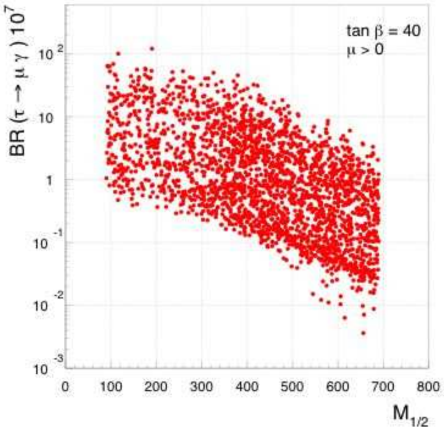

Fig. 3. $\tau \rightarrow \mu\gamma$ decay rates in the PMNS case.

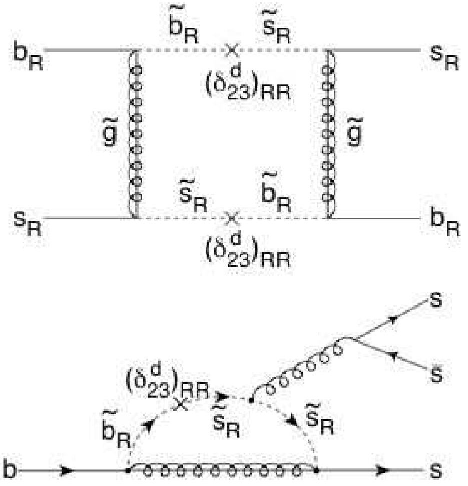

Fig. 4. Possible contributions to B_s mixing and CP violation in $B \rightarrow \psi\phi$ and $B \rightarrow \phi K_s$, induced by mixing among "right-handed" b and s squarks.

to uniquely fix. One could envisage two cases as representing the possible range:

$$O_{ij} \propto \sum_k V^{CKM}_{ik} V^{CKM*}_{kj} , \tag{11}$$

(the CKM case) where V^{CKM} is the CKM matrix, and

$$O_{ij} \propto \sum_k U_{ik} U^*_{kj} , \tag{12}$$

(the PMNS case) where U is the neutrino mixing matrix. In the CKM case the transitions $\mu \rightarrow e\gamma$ or $\tau \rightarrow \mu\gamma$ are proportional to $|V_{ts}V^*_{td}|^2$ and $|V_{tb}V^*_{ts}|^2$, respectively. One therefore expects the $\tau \rightarrow \mu$ decay to have a BR a couple of orders of magnitude larger than $\mu \rightarrow e$. In spite of the smallness of the CKM matrix elements, rates for $\mu \rightarrow e\gamma$ can still be large enough to be within the reach of the forthcoming experiments for a large fraction of the model parameters space, as is shown by the scatter plot in fig. 2. In the PMNS case, the rates can be significantly larger, given the larger size of the neutrino mixing matrix elements. In the particular case of $\tau \rightarrow \mu$ transitions, the rate is proportional to $U_{\mu 3}U_{\tau 3}$, which is known and large. A large fraction of parameter space would already be excluded by the current limits [4], in the range of $BR(\tau \rightarrow \mu\gamma) < 10^{-7}$, as shown in fig. 3. The $\mu \rightarrow e$ transition depends on U_{e3}, which is yet unknown and could be very small.

There is another important by-product of SUSY-GUT frameworks for neutrino masses, which leads to possible manifestations in the quark sector: since the neutrinos sit in the same $SU(5)$ multiplet as down-type antiquarks (or right-handed quarks), the large mixing between μ and τ neutrinos leads to a large mixing between right-handed quarks. This has no impact on phenomenology, since right-handed quarks do not couple to weak interactions. However it feeds via Supersymmetry into a large mixing between the scalar partners of R-handed squarks, and to interactions like the ones shown in fig. 4.

The first contribute to B_s mixing and possibly CP violation in $B \to \phi\psi$ decays (which is approximately 0 in the SM). The second lead to an extraction of $\sin 2\beta$ from $B \to \phi K_S$ decays which is different from what obtained in $B \to \psi K_S$.

3.2 Clues from flavour physics

We tend to associate today the origin of the SM with the gauge principle and the consolidation of Yang-Mills interactions as unitary and renormalizable quantum field theories. We often forget that flavour phenomena have contributed as much as the gauge principle, if not more, in shaping the overall structure of the SM. It is the existence of flavours (both in the lepton and quark sector) which gives the SM its family and generation structure. The idea of assembling quarks in EW doublets was guided by the suppression of FCNCs, which led to the GIM mechanism and to the prediction of the charm quark. Kaon decays led to the observation of CP violation, and to the CKM model. B_d mixing, similarly to the role played by $K^0 - \bar{K}^0$ mixing in getting the mass range for charm, was the first experimental phenomenon that correctly anticipated the large value of the top quark mass. And, last but not least, the observation of neutrino masses provides today the first concrete and uncontroversial evidence that the SM is incomplete: most modestly, we need to introduce degrees of freedom for sterile right-handed neutrinos; more ambitiously, neutrino masses are a window on physics at the grand unification scale!

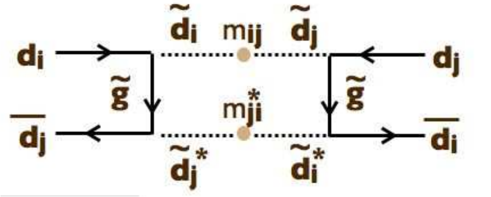

Fig. 5. Contribution to $Q - \bar{Q}$ mixing ($Q = K, B$) from gluino and squark exchange in Supersymmetry.

The smallness of FCNC and of CP violation are not an outcome of the SM: they have been built into its structure from the outset. In the quark sector, they are guaranteed by the unitarity of the CKM mixing matrix and by the small mixing between heavy and light generations. The transition $d_i\bar{d}_j \to X$, where d_i are down-type quarks, $i \neq j$ and $X = \ell^+\ell^-$ or $d_j\bar{d}_i$, is proportional to

$$\begin{aligned}\Delta_{ij} &\sim \sum_{k=u,c,t} V_{ki}\, V^*_{kj}\, f(m_k/m_W) \\ &\sim \sum_{k=c,t} V_{ki}\, V^*_{kj}\, m_k^2/m_W^2 \,, \qquad (13)\end{aligned}$$

where V_{ij} are the elements of the CKM mixing matrix. As a result of the unitarity of V_{ij}, the leading contributions to this expression are given by

$$V_{ci}\, V^*_{cj}\, \frac{m_c^2}{m_W^2} + V_{ti}\, V^*_{tj} \,. \qquad (14)$$

The first term is strongly suppressed by the charm mass (GIM), the second by the smallness of the mixing of the third generation with the first two. In the lepton sector, it is the smallness of the neutrino masses that suppresses possible evidence for mixings and CP violation for charged leptons. There is absolutely no guarantee that the above properties survive in extensions of the SM [5]. A typical example of what may happen is given in fig. 5: if the squark mixing matrix is not aligned with CKM, the squark mass eigenstates can mix and lead to potentially large contributions to $K\bar{K}$ or $B\bar{B}$ mixing. In a model where squark flavours are maximally mixed, squark and gluino masses should be larger than several TeV in order to sufficiently suppress these contributions and not clash with the data on mixing or CP violation in the K sector! As long as no evidence is brought forward for the existence of supersymmetry, this is not an issue. The day that supersymmetry (or other forms of new physics) should be discovered at mass scales below or around the TeV, say at the LHC, understanding how this problem is bypassed will become one of the the most exciting issues in our field!

3.3 Hints of more to come

Before that day arrives, new very accurate data from flavour physics start providing interesting and tantalizing clues for the existence of small deviations. While still not significant from the statistical/systematic viewpoint, these deviations are enoguh to keep our expectations high.

In addition to the well known discrepancy [6] in the anomalous magnetic moment of the muon, $a_\mu = (g-2)_\mu$:

$$a_\mu^{SM} - a_\mu^{exp} = (2 \pm 1) \times 10^{-9} \ , \qquad (15)$$

two recent long-awaited measurements have appeared, both indicating a deviation from the SM at the level of $\sim\ 2\sigma$ [7]. The first is the determination of the B_s oscillation frequency by CDF [8]:

$$\Delta M_{B_s}(\mathrm{ps}^{-1}) = \left(17.31 \begin{array}{l} +0.33 \\ -0.18_{stat} \end{array} \pm 0.07_{syst}\right) , \qquad (16)$$

which is slightly smaller than the SM expectation:

$$\frac{\Delta M_{B_s}^{exp}}{\Delta M_{B_s}^{SM}} = 0.80 \pm 0.12 \, . \qquad (17)$$

The second is the detection by Belle of the $B \to \tau\nu$ decay [9] [1], with a branching ratio $B_\tau = B(B^- \to \tau^-\nu)$ measured as:

$$10^4 \times B_\tau = \left(1.06 \begin{array}{l} +0.34 \\ -0.28_{stat} \end{array} \begin{array}{l} +0.18 \\ -0.16_{syst} \end{array}\right) \qquad (18)$$

again slightly lower compared to the SM prediction (normalized here to the B_s mixing rate, to reduce the theoretical systematics [11]):

$$\frac{B_\tau^{exp}/\Delta M_{B_s}^{exp}}{B_\tau^{SM}/\Delta M_{B_s}^{SM}} = 0.67 \qquad (19)$$
$$\begin{array}{l} +0.27 \\ -0.22_{exp} \end{array} \pm 0.06_{\hat{B}_{B_d}} \pm 0.07_{|V_{ub}/V_{td}|} \, .$$

These deviations have been found by several authors (see e.g. [11,12,13]) to be consistent with a SUSY extension of the SM, with a large value of the Higgs mixing angle $\tan\beta$ and with charged Higgs bosons with mass in

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[1] A measurement by BaBar recently appeared as well [10], $B_\tau = (0.88^{+0.68}_{-0.67}(stat.) \pm 0.11(syst.)) \times 10^{-4}$.

the range of few hundred GeV. Such scenarios will be well explored by the LHC and the ILC by directly producing and observing the new states required.

Potentially measurable effects could also emerge in a violation of universality [14] in

$$R_K = \Gamma(K \to e\nu)/\Gamma(K \to \mu\nu) \,. \tag{20}$$

Expressing any deviation from the SM as $R_{K,\pi} = R^{SM}_{K,\pi}(1 + \Delta r^{e-\mu}_{K,\pi\,NP})$ one has, for $\Delta^{31}_R \sim 5 \times 10^{-4}$ (the parameter proportional to the mixing between the 1^{st} and 3^{nd} generation sleptons), $\tan\beta = 40$ and $m_{H^\pm} = 500$ GeV [14]:

$$\begin{aligned} &\Delta r^{e-\mu}_{K,\pi\,NP} \sim \\ &\left(\frac{m_K^4}{m_{H^\pm}^4}\right)\left(\frac{m_\tau^2}{m_e^2}\right)|\Delta^{31}_R|^2 \tan\beta^6 \\ &\sim 10^{-2} \,. \end{aligned} \tag{21}$$

At this time, NA48/2 sets the bound [15]:

$$-0.063 < \Delta r^{e-\mu}_{K,\pi\,NP} < 0.017 \tag{22}$$

with a theoretical uncertainty at the per mille level. Future experiments should be planned to match this accuracy.

4 Conclusions

Progress in the field will be essentially driven by new and better experimental data. Theorists have pretty much exhausted their arsenal of weapons to make progress based on first principles only. Nevertheless, they have created scenarios for BSM physics that, in addition to addressing the most outstanding theoretical puzzles and the established deviations from the SM (DM, BAU, ν mixing), predict galore of new phenomena at energy scales and precision levels just behind the corner. If the only open questions required experiments at the GUT scale, HEP might be stuck for a long while. Fortunately, both theoretical and experimental issues point instead at the TeV scale. There is therefore a solid and justified expectation that progress will start emerging from the forthcoming generation of experiments, for which the detectors are being completed. This progress will bring a major revolution in HEP. It will not be a minor adjustment or incremental progress, like may have been the discovery of a 3^{rd} generation. We expect to uncover qualitatively new phenomena (e.g. SUSY), which will lead to a quantum leap in our understanding of the Universe, and will open new prospects for experimental research.

We have two main sets of laboratory tools available: the high-energy frontier (LHC, ILC, etc), which we anticipate will mostly address the problem of EWSB, and therefore “gauge-sector” issues; and the low-energy, high-intensity frontier, where experiments will probe mostly the “flavour sector” (flavour-changing transitions and CP violation phenomena with quarks, neutrinos and charged leptons). We still don’t know which of these two directions will provide more fruitful. Most likely, it will be the complementarity between these two experimental approaches that will give us most insights. Whether or not new physics is seen at the LHC, maintaining diversity in the experimental programme is therefore our best investment for HEP. If new physics (especially SUSY) is discovered at the LHC, a global flavour physics programme (LFV and CP/FCNC in the quark sector) is an essential component of the HEP research, required to explore the nature of the new BSM framework (e.g. to identify the SUSY breaking scenario). An ambitious and far-sighted ν programme is likewise a mandatory element of the HEP future, as this programme has concrete goals and benchmarks, and a direct impact on our ability to uncover new information about nature: GUT, CPV, BAU. Furthermore, as the indirect evidence for GUT grows, proton decay searches should continue.

The political feasibility of such a broad research programme was addressed at this meeting during the round table by the Directors of laboratories, funding agencies and the leaders of ongoing global projects. The experimental feasibility, in terms of suitable detectors, is what this conference is all about!

Exciting times are ahead of us, and the least we can do is to get ourselves ready on all fronts to face the challenge!

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