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A THEORIST'S PERSPECTIVE*

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The present turning point in particle physics is briefly discussed.

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The purpose of physics of elementary interactions has always been to understand the structure of matter at shorter and shorter distances. The challenges of this fundamental goal have been changing with time, with spin-off of the whole new branches of physics such as condense matter physics, atomic physics and nuclear physics. We are now in a turning point of the physics of elementary interactions. The chapter opened by the discovery of radioactivity at the end of the XIX century is (almost) closed. We have the theory of strong, electromagnetic and weak interactions, known as the Standard Model, and we understand the structure of matter down to 10^{-18} m. Although the Higgs particle has not been discovered yet, there is little doubt that the electroweak theory based on the spontaneously broken SU(2)×U(1) gauge symmetry is the correct effective theory up to the energies $\mathcal{O}(100)$ GeV. It is likely that the ultimate discovery of the Higgs particle, or some other effective mechanism of the spontaneous breakdown of the electroweak symmetry, will tell us more about the physics beyond the Standard Model than about the Standard Model itself.

Contrary to certain continuity of research problems that led to the formulation of the Standard Model, the turning point means that, except for the expected Higgs particle, we simply do not know what is the physics beyond the Standard Model. For many decades, the situation in particle physics has not been as intriguing as now, with totally unpredictable outcome of the LHC experiments. Surely, there are many theoretical speculations but …

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Nevertheless, it may be interesting to review model independent arguments in favour of *some* physics beyond the Standard Model, hints to a new mass scale within the reach of the LHC and the present experimental constraints on the existence of such a scale.

On the theoretical side, for many years a guiding principle for going beyond the Standard Model has been the desire to better understand the Fermi scale, known also as the hierarchy problem of the Standard Model. The effective Higgs potential of the Standard Model

$$V = m_H^2 HH^\dagger + \left(\frac{\lambda}{2}\right)(HH^\dagger)^2 \,, \tag{1}$$

has two free parameters, which determine the Fermi scale and the Higgs boson mass. With $v = 240$ GeV and for m_h in the range 100 GeV–1 TeV, the Higgs potential mass parameter m_H^2 must be in the range $(10^{-2}$–$3 \times 10^{-1})$ TeV^2. In general

$$m_H^2 = m_0^2 + \delta m^2 \,, \tag{2}$$

where m_0^2 is the tree level value and δm^2 are quantum corrections. The question is what physics determines the scale m_0^2 and how to protect δm^2 against very high energy effects (*e.g.* the Planck scale). The latter question is particularly difficult in a theory with an elementary scalar. Clearly, this line of thinking suggests to us that there exists a deeper theory, with a characteristic mass scale M close to the Fermi scale. It is striking that this theoretical argument is supported by an empirical one, coming from cosmology. Strong evidence for dark matter in the universe calls for a particle candidate for dark matter. It has been checked by many calculations that for a weakly interacting dark matter candidate, its mass should be $\mathcal{O}(1)$ TeV!

A discovery of a new mass scale M requires either the energy $E \sim M$ or a precision $\mathcal{O}(E/M)$. For $M \sim \mathcal{O}(1)$ TeV, the energies to be available at the LHC are very promising for a direct discovery. However, the LEP precision data provide already now strong constraints on new physics at $M \sim 1$ TeV. It is well known that fits in the Standard Model to the electroweak observables, assuming no physics beyond it, are consistent with the precision LEP data only for a light Higgs boson ($m_h < 250$ GeV at 95 per cent C.L.). However, one can change the logic and fit the data in an effective theory defined by the Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \text{corrections} \,, \tag{3}$$

where corrections are given by all higher dimension operators that are SU(2)×U(1) gauge invariant, suppressed by appropriate powers of a new mass scale(s) M. This is a model independent way to include in the fits potential effects of the physics beyond the Standard Model with a characteristic mass scale(s) M, with the Standard Model being only the effective theory at $E < M$. In such fits, both m_h and M are free parameters and it is interesting to see what kind of physics is acceptable as a function of m_h. One should remember, however, that the electroweak observables depend only logarithmically on the Higgs boson mass, so the room for new physics from rising the m_h up to $\mathcal{O}(1)$ TeV (the unitarity bound) cannot be very large. The success of the Standard Model puts very strong constraints on the physics beyond it. Qualitatively speaking, the results of those fits tell us that, for any Higgs boson mass consistent with the unitarity bound, a tree level modification of the Standard Model and/or some new strong interactions as a cut-off to the Standard Model are acceptable only if their characteristic mass scale M is above 4–5 TeV. Secondly, if the Higgs boson mass is larger than $\mathcal{O}(400)$ GeV new tree-level or non-perturbative effects are actually needed for good fits, with however a mass scale $M \sim (10–30)$ TeV. Thus, taking seriously the discussed here hints for a new mass scale around 1 TeV, we expect it to be linked to some physics which is perturbative and contributes to the electroweak observables only at loop level.

Among the higher dimension operators in Eq. (3) there are some that contribute to the electroweak observables and some that violate the accidental global symmetries of the Standard Model, *e.g.* the lepton or baryon number conservation. The limits on the suppression scale M and/or the hints for its existence may, of course, depend on the nature of the operator. In fact, it is very likely that neutrino masses and mixing suggest new, but very high, mass scale $M > 10^{10}$ GeV related to the see-saw mechanism. Proton decay, if eventually discovered, would provide even more dramatic evidence for new physics at very high energies.

Here we focus on the chances to discover new mass scale at the LHC. The theoretical and empirical hints for physics beyond the Standard Model at $M \sim \mathcal{O}(1)$ TeV and, on the other hand, the contraints for such physics from precision electroweak data confront us with a very challanging situation.

Many exciting ideas have been proposed as an extension of the Standard Model, to cure the hierachy problem. Among others, there is technicolour, Higgs doublet as a (pseudo)-Nambu–Goldstone boson, extra spacial dimensions and, first of all, supersymmetry. Neither scenario is theoretically fully satisfactory and there is often present some tension with experimental data. Among the proposed frameworks, low energy supersymmetry is by far the most complete one. In particular, the minimal supersymmetric extension of the Standard Model has several important virtues: no new tree level effects, perturbative physics, neutralino as a good dark matter candidate, electroweak symmetry breaking triggered dynamically by the top quark Yukawa coupling and the gauge coupling unification. Unfortunately, it is also not free of some tension in the Higgs potential, the problem of flavour changing neutral currents has no natural solution and, on the theoretical side, the origin of soft supersymmetry breaking is a very difficult question. Clearly, there is now time for experiment to confirm one of the proposed theoretical ideas or to suggest a new direction.

In the cyclic process of moving from a dicovery accelerator to a precision data machine and *vice versa*, the results of the LHC experiments will have the leading impact on the developement of particle physics and on the choice between precison or again dicovery for after the LHC experimental tools. In parallel, neutrino experiments, experiments on rare leptonic decays, dedicated experiments searching for dark matter and the new generation of cosmological experiments are a very important potential source of complementary information on the physics beyond the Standard Model.