PHYSICS FROM TEVATRON TO LHC AND ILC

M.L. Mangano, PH-TH, CERN, Geneva, Switzerland

Abstract

This talk reviews, for an audience of accelerator physicists, the main physics motivations of and expectations for the current high-enegy physics programme, as well as the ambitions for future progress.

INTRODUCTION

By 1973, the theoretical foundations of the Standard Model (SM) of particle physics were fully established. This included the overall mathematical framework, the idea of spontaneous symmetry breaking as the mechanism responsible for the mass of the electroweak (EW) gauge bosons and of the fermions, and the Kobayashi–Maskawa (KM) proposal for the mechanism of CP violation, based on the existence of three families of leptons and quarks. After 1973, followed over 30 years of validation and 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 radiative corrections in the sectors of strong and EW interactions, and, last but not least, 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).

Accelerator physics played a primary and essential role in this enterprise, and should proudly share the glory of a monumental scientific achievement, which parallels in importance the discovery of the theory of electromagnetism, of special and general relativity, and of quantum mechanics.

Just one piece is still missing from the picture: the direct observation of the Higgs boson, and the verification of whether the EW symmetry breaking (EWSB) mechanism is as predicted by the SM, or follows a different scheme. This is no minor detail. EWSB represents possibly the most puzzling feature of the SM and, even though the Higgs mechanism built into the SM provides a working "mechanical" explanation of it, it comes short of providing a theoretically satisfying scheme. In addition to this, a few experimental facts point unambigously to phenomena not predicted by the SM: the SM, in fact, cannot quantitatively explain neither the existence of Dark Matter, nor the amount of the baryon asymmetry of the Universe (BAU). Furthermore, although neutrino masses could be incorporated with a minimal and trivial adjustment of the SM spectrum and lagrangian, the only compelling explanations of how neutrinos acquire such a small mass rely on the existence of new phenomena at a scale of the order of the Grand Unification (GUT). And, finally, there are several questions that within the SM cannot even be quantitatively formulated, but which could acquire a dynamical content if the SM were embedded in a broader framework. As examples, we can take the issue of what is the origin of the three generations and of the diverse mass patterns between and within them. Since the EWSB is ultimately responsible for the generation of masses, with the differentiation between flavours and the consequent appearance of mixing angles and CP violation, speculating a relation between EWSB and the flavour structure of the fundamental particles is unavoidable. This relation is trivial in the context of the SM, where the flavour structure is determined by the values of the quark mixing angles, which enter as given parameters. In most models beyond the Standard Model (BSM), viceversa, the low-energy flavour structure is the result of specific dynamics, and relations between masses and mixings of different particles become in principle calculable.

EWSB therefore brings together the two main elements of the SM, the gauge and the flavour structure. Both elements have so far survived the most stringent experimental tests: LEP and the Tevatron data do not leave much room for new phenomena in the EW sector, and no departure from the CKM picture has been observed by the B factories. But both components are vulnerable, liable to crack under the weight of new data, and this crack will hopefully lead us to a new level of understanding of Nature.

The observation of the Higgs boson, and the clarification of the EWSB mechanism, are therefore the most pressing issues facing particle physics today.

STATUS OF AND PROSPECTS FOR HIGGS DISCOVERY

The combined results of LEP, SLD, LEP2 and the Tevatron put very strong constraints on the mass range allowed for a SM Higgs boson. LEP2 sets a direct lower limit at about 114 GeV. EW fits [1], which include the latest Tevatron determinations of the W and top mass, predict a central value of 76 GeV, in the LEP2 excluded region. The 95%CL upper limit is $m_H < 144$ GeV (182 GeV including the direct LEP2 limit at 114 GeV). The tension between the direct limit and the EW fits is shown in fig. 1, where the

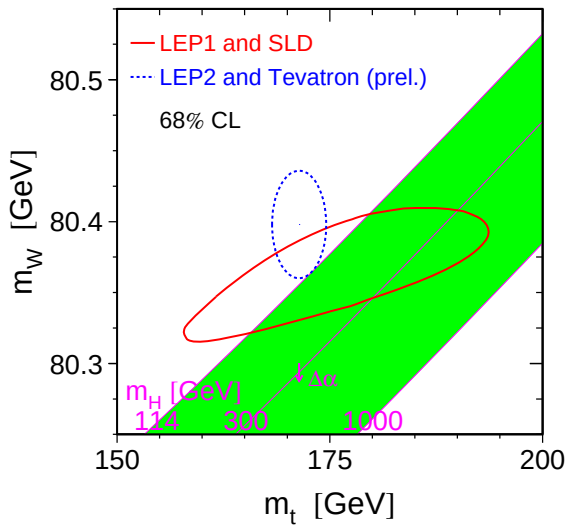

Figure 1: Tevatron+LEP2 combined constrains on the SM Higgs mass.

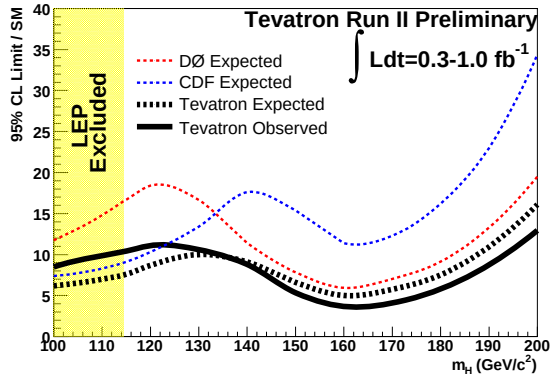

Figure 2: CDF+D0 combined limit on SM Higgs production rate at the Tevatron.

1-σ region defined by the current values of m_{top} and m_W just touches the allowed domain. In this range of m_H, the Tevatron has a great opportunity to strike a major result. Figure 2 shows the current Tevatron limit on the SM Higgs production rate, obtained by combining several measurements from both CDF and D0 [2]. These analyses exploit so far only a fraction of the available luminosity, and the results provide sensitivity only to production rates varying between a factor of 4 and 10 larger than the SM rate. The fact that the sensitivity is better at 160 GeV than at 120 indicates that in this mass range luminosity, rather than energy, is the asset. Higgs bosons below 200 GeV are light enough for the Tevatron, and are copiously produced, but the signal suffers from large backgrounds and great statistics are required. In view of the excellent current performance of both the accelerator and the experiments, there is plenty of room for the Tevatron to either detect a first indication of a signal, or to exclude an important range of the SM-allowed m_H values.

While the Tevatron may not guarantee a complete coverage of the Higgs mass spectrum, the LHC will answer in a conclusive way the question: "Does a SM-like Higgs boson exist?". Its discovery or exclusion potential are shown in fig. 3. The expectation of the two experiments [3, 4] are combined, and reported in terms of the integrated luminosity required to achieve a combined 5σ discovery, or 95%CL exclusion, as a function of the Higgs mass. Just 1 fb^{-1} is sufficient for the discovery over the range $\sim$ 140—500 GeV, and to exclude a SM Higgs over the full range from the LEP2 limit up to 1 TeV. About 5 fb^{-1} are required to guarantee the discovery over the full range. Notice furthermore that only few hundred pb^{-1} are enough to cover, with comparable sensitivity, the region most easily accessible at the Tevatron. This is clearly setting the stage for a truly exciting challenge for the first 2 years of operation of the LHC [5]!

From the theoretical point of view, Higgs boson searches at the LHC will provide non-trivial information regardless of the outcome. As we just saw, 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. If this does not happen, something beyond the SM must be in action! 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.

Even if the Higgs will appear to behave as 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 have to be carried out. The precise determination of the Higgs properties, its couplings to the EW gauge bosons, to the fermions, and its own selfinteractions, are the starting point of this second phase of the programme. The LHC, and its possible upgrades [6, 7], will measure the Higgs couplings to EW bosons and to the fermions of the third family with a precision not better than 10-20%, depending

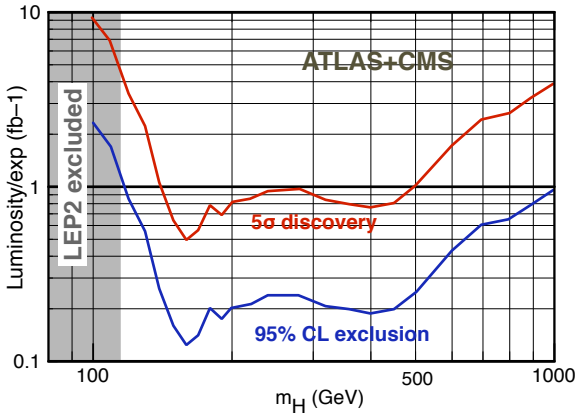

Figure 3: Combined ATLAS+CMS SM Higgs exclusion and discovery reach at the LHC.

on m_H and on the state. While this could be good enough for a first assessment, it is only with an e^+e^- linear collider that one will be able to push the accuracy down to the 1% level required for more compelling tests. An example of the expected accuracy at the ILC is given in Table 1. Such a precision could, for example, allow to exclude EWSB models in which the Higgs results from strong dynamics, setting a lower limit on the scale of such dynamics in the range of 30 TeV [8]. This sensitivity is well beyond anything that can be attained through direct searches at the LHC, and represents one of many examples of the beneficial synergy between the discovery power of the LHC and the precision of the linear collider, as documented in [9].

Table 1: Expected accuracy for Higgs coupling determinations at the ILC

Coupling	$m_H = 120$ GeV	$m_H = 140$ GeV
g_{HWW}	± 0.012	± 0.020
g_{HZZ}	± 0.012	± 0.013
g_{Htt}	± 0.030	± 0.061
g_{Hbb}	± 0.022	± 0.022
g_{Hcc}	± 0.037	± 0.102
$g_{H\tau\tau}$	± 0.033	± 0.048

THE HIGGS AND THE HIERARCHY PROBLEM

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

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

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 us, with a single subtraction, to relate, via a finite relation, the Higgs mass parameter calculated at different scales:

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

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

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

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 $\times 100$ GeV. If we allow Q_0 to become as large as the Planck mass $M_{\rm Pl} \sim 10^{19}$ GeV, the region where the SM gets unavoidably modified by quantum gravity, $m_H^2(M_{\rm Pl})$ must be fine tuned to the level of $(v/M_{\rm Pl})^2 \sim 10^{-33}$ in order for the cancellation between $M_{\rm Pl}^2$ and $m_H^2(M_{\rm Pl})$ 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". To help you sense how uncomfortable a theorist feels about the hierarchy problem, I'll propose a game as a trivial example. Ask 10 of your friends to give you an irrational number randomly taken within the range $[-1, 1]$. Then sum these 10 numbers, which your friends should have given to you without knowing about each others' choice. And suppose you find out that these 10 numbers sum up to something which is zero all the way up to the 32nd decimal place. What would you rather think: that this was just a bizarre coincidence, or that your friends played a trick on you? Theorists feel the same about the hierarchy problem and nature: they cannot accept that the fine tuning, while technically legitimate, is a pure accident, and prefer to assume that this is telling us something about a deeper structure. Most of the theoretical work in 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 divergences (see [10] 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 as the top one, but opposite sign owing 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, $H \rightarrow H + a$. 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 corrections 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. In teh specific case of Supersymmetry, the discovery reach as a function of integrated luminosity is shown in fig. 4.

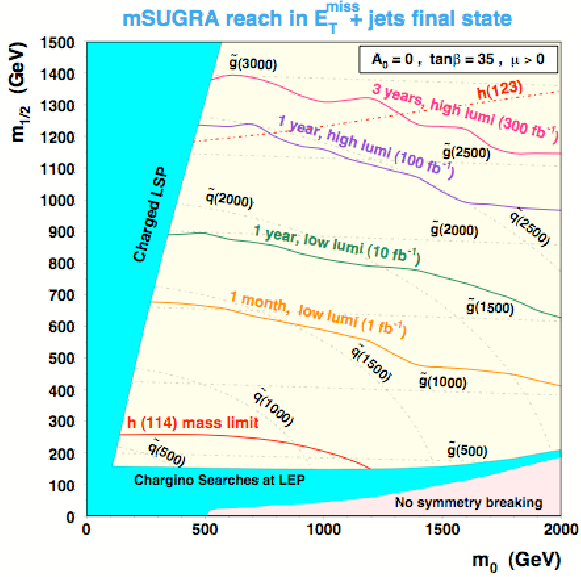

Figure 4: Discovery potential for Supersymmetry at the LHC.

DARK MATTER AND EWSB AT LHC/ILC

The evidence for the existence of dark matter is very strong today, with the new recent findings from studies of structure formation and CMB fluctuations. It is important to realize that, whatever its origin, the existence and properties of DM must be encoded somewhere in the Lagrangian of HEP. So it is "our" problem to find out what it is, and not the astrophysicists' problem. From our point of view, the main ingredients of DM are: a stable weakly interacting particle, with mass vs annihilation rates such as to decouple during the Big Bang from the other states at the appropriate time and with the appropriate density. It so happens that the required numerics works out to match the expected cross section of particles with mass O(100 GeV) and weak coupling:

$$\sigma \sim \frac{\alpha_W^2}{M_W^2} \,. \qquad (4)$$

It is unavoidable to speculate that the origin of DM is directly linked to the phenomena responsible for EWSB. It is therefore not surprising that most alternative approaches to EWSB (little Higgs, extra-dimensions, Higgsless theories) provide a possible DM candidate. The mass vs coupling relations are inherited by the link to EWSB and the stability is associated to discrete symmetries (like SUSY's R parity). In the case of extra-dimensions, for example, DM could originate from the first photon or neutrino Kaluza-Klein mode. In most of these models, the predictions are that the DM particle should have a mass in the range of 1-200 GeV, and therefore within the reach of the first phase of the ILC.

The direct observation at the LHC of final states with unexpected amounts of missing energy, will provide a strong indication that the particle responsible for DM is being produced. Whether this comes from Supersymmetry or something else, is something that only more accurate studies will reveal. As in the case of the Higgs, only a very accurate study of this weakly interacting particle can prove that its properties are consistent with those of DM. This may prove a long process, starting from the first observation at the LHC, through the build up of qualitative evidence for the identification of the specific model in action (spectrum, spin and quantum numbers of the new particles), ending with the accurate measurement of the new couplings at the linear collider. A thorough review of the potential of the LHC and ILC to pin down the DM candidate can be found in ref. [11].

NEUTRINOS

Neutrino experiments of the future generations have a well defined programme: to determine as accurately as

1-4244-0917-9/07/$25.00

possible the parameters of the neutrino mass spectrum and mixing. To connect these findings with the grand picture of particle physics, will however require extra inputs. Are neutrino masses the result of a see-saw mechanism, pointing to the existence of some new dynamics at scales of the order of 10^{15} GeV? Is CP violation in the decay of the superheavy neutrinos required by the see-saw mechanism responsible for the BAU? Can neutrino mixings feed into flavour-changing processes among charged leptons? Hints at the answer to these questions can come from the LHC and the ILC, as well as from other laboratory-based accelerator experiments. Evidence for Supersymmetry at the LHC would add extra support to the idea of GUT, thus favouring the see-saw mechanism. Furthermore, the mixing of neutrinos in GUT supersymmetric theories feeds a potentially large mixing among the scalar partners of the charged leptons, thus driving processes like $\mu \to e\gamma$ and $\tau \to \mu\gamma$, which are otherwise suppressed in the SM. The observation of these decays, together with the discovery of Supersymmetry and of scalar electrons and muons at the ILC, could give quantitative evidence of GUT-scale processes.

CONCLUSIONS

After many years dedicated to the confirmation and consolidation of the SM, HEP is now on the verge of a phase transition [12]. The energy scale accessible at the LHC will allow to directly address the remaining issue of the SM, the EWSB mechanism, and there is great expectation that this will lead not just to a confirmation of the Higgs mechanism, but to a new realm of phenomena, directly related to some of the outstanding puzzles of the field: DM, neutrino masses, the hierarchy problem, etc.

Accelerator-based experiments are still the primary exploration tool for high-energy physics. The information collected using extraterrestrial sources of particles and radiation (from solar and atmospheric neutrinos, to cosmic rays, to the astronomical observations over the full spectrum) have dramatically enriched our picture of the Universe, and have led to remarkable progress (neutrino masses, DM, CMB, dark energy), rewarded with the latest series of experimental HEP Nobel prizes. But physicists are still looking at the forthcoming generation of laboratory-based experiments as the arenas within which the most outstanding questions about our Universe, including those which arise from the observation of the cosmos, can be tackled.

The emergence of new experimental handles to probe Nature's deepest secrets (CMB, supernovae, cosmic neutrinos, underground detectors for DM, neutrinos, proton decay, etc) should not be seen as a sign that accelerator physics is becoming obsolete. It simply provides physicists with alternative sensors, capable of detecting the warning signs of new exotic phenomena, deeply challenging our established theories into accounting for what is seen, and challenging accelerator science to provide more and more powerful tools to take a closer look at what is happening. Neutrinos masses and mixings have revived the interest in $\mu \to e\gamma$ decays, DM studies could ultimately be the primary research focus of the ILC, and table-top microgravity experiments suggesting the existence of extra dimensions could be the main driver for the push towards the 100 TeV scale, via muon colliders or VLHCs.

Higher and higher energy is not the only criterion for progress. While the LHC is the only tool today capable of pointing directly to the mass scale of new phenomena, and to determine at least qualitatively their properties, a complete picture will certainly demand the continued exploration also of the low-energy, high-intensity frontier. The great accuracy of the ILC can provide sensitivity to phenomena taking place at scales up to several 10s of TeV. A new generation of high-intensity flavour factories (for kaons, D and B mesons, muons, taus) can allow to determine the flavour properties of the new physics observed at the LHC, and could lead to discoveries (such as the decay $\mu \to e\gamma$) as profound as those accessible at the high-energy end.

Exciting times are ahead of us, and I expect a lot of hard work for your community to catch up with the ever-increasing ambitions of particle physicists!

REFERENCES

[1] http://lepewwg.web.cern.ch/LEPEWWG/

[2] B. Kilminster [on behalf of the CDF and D0 collaborations], arXiv:0705.3513 [hep-ex].

[3] ATLAS Collaboration, Detector and physics performance TDR, CERN/LHCC/99-15.

[4] CMS Collaboration, Physics Performance TDR, CERN/LHCC 2006-021.

[5] F. Gianotti and M. L. Mangano, arXiv:hep-ph/0504221.

[6] F. Gianotti *et al.*, Eur. Phys. J. C **39**, 293 (2005) [arXiv:hep-ph/0204087].

[7] A. Blondel et al., arXiv:hep-ph/0609102.

[8] G. F. Giudice, C. Grojean, A. Pomarol and R. Rattazzi, arXiv:hep-ph/0703164.

[9] G. Weiglein *et al.* [LHC/LC Study Group], Phys. Rept. **426**, 47 (2006) [arXiv:hep-ph/0410364].

[10] R. Rattazzi, PoS **HEP2005**, 399 (2006) hep-ph/0607058.

[11] E. A. Baltz, M. Battaglia, M. E. Peskin and T. Wizansky, Phys. Rev. D **74** (2006) 103521 [arXiv:hep-ph/0602187].

[12] T. Akesson *et al.*, arXiv:hep-ph/0609216.

