The physics potential of the LHC

Zoltan Kunszt

Institute of Theoretical Physics, ETH, Zürich, Switzerland.

Abstract. This talk is a short overview of the physics potential of the LHC with emphasis on Higgs search and SUSY search. First I review why LHC with the ATLAS and CMS detectors is expected to give a decisive test of the electroweak symmetry breaking mechanism of the Standard Model. Then I consider the Higgs sector of the Standard Model (SM). Finally the search for supersymmetry is discussed within the framework of various implementation of the Minimal Supersymmetric Standard Model (SM).

INTRODUCTION

Future progress concerning the physics beyond the Standard Model depends crucially from the successful experimental tests of the electroweak symmetry breaking mechanism. The Standard Model is an “almost good” effective field theory with many good and few bad properties [1]. According to the effective field theory concept the Lagrangian of a successful low energy theory is built

1) Talk given at the meeting Beyond The Standard Model V, Balholm, Norway April 29 – May 4, 1997; E-mail: kunszt@itp.phys.ethz.ch
from the known fundamental fields restricted by the symmetries of the theory. Renormalizability is not required, but it emerges as the consequence of the fact that the scale of new physics is high in comparison with the experimentally accessible energy range. The effective Lagrangian then can be classified into relevant, marginal and irrelevant terms

$$L_{\text{eff}} = L_{\text{relevant}} + L_{\text{marginal}} + L_{\text{irrelevant}}$$

or in terms of local operators

$$L_{\text{eff}} = \sum_{n,i} \frac{c^{(i)}_{n}}{\Lambda^{n-4}} \mathcal{O}_{i}, \quad \text{dim}_{\text{mass}} \mathcal{O}_{n} = n$$

The relevant, marginal and irrelevant terms are those with $n < 4$ (fermionic and bosonic mass terms), $n = 4$ (kinetic energy terms, gauge interactions, Yukawa interactions, Higgs bosons self interaction) and $n > 4$ (non-renormalizable interaction terms such as $(\bar{\psi} \psi)^2$). The contributions of irrelevant terms are negligible at low energies since they give negligible terms of order $\approx (E/\Lambda)^{n-4}$ inversely proportional to some positive power of the cut-off. In contrary, the relevant terms give rise to contributions proportional to the cut-off, and are unwanted since they can not hide efficiently the effects of the unknown physics of very high scales. Therefore a good low energy effective theory is a renormalizable theory with only marginal terms

$$L_{\text{eff}} = \sum \text{all marginal operators}$$

The Standard Model because of two (apparently minor) faults is NOT a good effective field theory. First, one relevant term is missing. According to the general rules of constructing good effective field theory in QCD we have to include CP violating the marginal term

$$L^{(\Theta)}_{\text{QCD}} \approx \Theta \epsilon_{\mu\nu\lambda\sigma} G_{\mu\nu} G_{\lambda\sigma}$$

where $G_{\mu\nu}$ denotes the gluon field tensor. The experimental limit on the coupling of this term, however, is extremely small $\Theta < 10^{-9}$. This is puzzling and lead to the suggestion of the existing of axions. The second fault is an unwanted relevant term. Although local gauge invariance forbids mass terms for vector particles and the requirement of chiral $SU(2)_L \times U(1)$ gauge symmetry for right handed fermion singlets and left handed fermion doublets forbids fermionic mass terms, a scalar mass term of the Higgs-boson, a relevant operator, is allowed. The presence of a relevant scalar mass term of the SM Lagrangian gives the most clear hint that its range of the validity can not extend to far above the scale of the electroweak symmetry breaking of $\approx 260\text{GeV}$. This qualitative argument is independent from the actual value of the Higgs mass and this difficulty (in slightly different context) is called the gauge
hierarchy problem. It may indicate that either the electroweak symmetry breaking mechanism is not given simply by elementary Higgs fields or that there is a new additional symmetry which renders the relevant operators of the scalar sector to marginal. Technicolour models give examples for the first possibility and supersymmetry with low supersymmetry breaking scale is the answer for the second possibility. For example, the Minimal Supersymmetric Standard Model is favored in comparison with the SM since it provides a good effective field theory.

During the first year LHC will operate as proton-proton collider at center-of-mass energy of \( \sqrt{s} = 14 \text{ TeV} \) with low luminosity \( \mathcal{L} = 10^{33} \text{ cm}^{-2} \text{ sec}^{-1} \) which subsequently will be increased to the design value of \( \mathcal{L} = 10^{34} \text{ cm}^{-2} \text{ sec}^{-1} \). With the universal ATLAS [2] and CMS [3] detectors in its proton-proton collider mode LHC will provide us the possibility to test the Standard Model well above the scale of the electroweak symmetry breaking [4]. It will be possible to test the validity of the one-doublet Higgs sector of the SM as well its possible supersymmetric extensions. One can decisively test the MSSM standard model and get direct evidence for the existence of the supersymmetric partners of the known particles. If elementary Higgs boson does not exist the ATLAS and CMS collaborations will be able to provide the first experimental hint for the presence of new type interactions between longitudinal W-bosons. Beyond these fundamental physics tests, new quarks or leptons, new electroweak gauge bosons or leptoquarks could be discovered or the decay mode of the top quarks could be quantitatively tested. LHC will also be able to accelerate heavy ions and for example by observing \( Pb-Pb \) collisions at 1150 TeV center of mass energy at luminosity of \( 10^{27} \text{ cm}^{-2} \text{ sec}^{-1} \) with the ALICE detector it will be possible to obtain decisive experimental test on the physics of strongly interacting matter at extreme energy densities. In particular it will be possible to test the formation of quark-gluon plasma, a new phase of matter. Finally, special purpose detector will be installed to perform high precision experiment on B-physics, with emphasis on CP-violation.

The full use of the physics potential requires extreme effort in the performance of the machine and the detectors. In order to illustrate the new technical complications at LHC I recall that in the pp collider mode as a result of the very large non-diffractive inelastic cross-section of about 70 mb on average 18 minimum bias interactions are expected per beam crossing in 25 ns time intervals. The interesting weak physics signals of short distance physics are buried in this enormously noisy background. The weak signatures of new physics can show up in a number of (sometimes complex) final states of leptons, jets and missing energy. This puts extreme requirement on the performance of the detectors: they must have good particle identification, good energy, momentum and angle resolutions for charged leptons, jets, photons and missing transverse energy. ATLAS and CMS are designed to meet these constraints.
SEARCH FOR THE HIGGS BOSON OF THE STANDARD MODEL

The search method for the SM Higgs boson depends crucially on the actual value of its mass $m_H$ [5], therefore, constraints restricting the allowed values of $m_H$ have great significance. The latest analysis of the LEP experiments [6] gives experimental lower bound $m_H > 77$ GeV at 95% confidence level as a result of direct search. The final analysis at the end of the LEP200 program is expected to give a lower limit of about $95 - 100$ GeV. The high precision data are consistent with the theoretical predictions (which depend on $m_H$ via higher order radiative corrections) if $m_H < 430$ GeV at 95% confidence level.

There are, however, also important theoretical constraints. The triviality problem constraints the range of validity of the field theoretical treatment of the scalar sector characterized by a cut-off scale. This cut-off scale can be considered as the upper limit on the scale of new physics. It is, however, correlated to the value of the Higgs mass. In perturbation theory, in leading order, the running coupling of the quartic scalar self-interaction $\lambda(\mu)$ has a Landau pole at $\Lambda_c$

$$\lambda(\mu) = \frac{\lambda(m_H)}{1 - 12\frac{\lambda(m_H)}{16\pi^2} \ln \frac{\mu^2}{m_H^2}}, \quad \Lambda_c = \frac{m_H e^{\frac{2\pi^2}{16\pi^2} - \frac{312\lambda^2}{16\pi^2} \ln \frac{\mu^2}{m_H^2}}}{5} \tag{5}$$

such that $\lambda(\Lambda_c) = \infty$, where in leading order $\lambda(m_H) = \frac{m_H^2}{2v^2}$ and $v = 10^{19}$ GeV and it decreases exponentially with increasing Higgs mass. By demanding the cut-off scale to be larger than the Higgs mass we get an upper bound on $m_H$. This perturbative result are further substantiated by non-perturbative treatment. Lüscher and Weiss [7] found that at the scale where the sensitivity to the cut-off becomes non-negligible the value of the Higgs mass is about 650 GeV, moreover, the value of $\lambda(2M_H)$ is about 3.5 well within the perturbative regime. It has recently been shown [8] that this result is consistent with perturbation theory if higher order perturbative corrections (at least two loop order) are taken into account. The two loop beta function

$$\beta_\lambda = 24 \frac{\lambda^2}{(16\pi^2)^2} - 312 \frac{\lambda^3}{(16\pi^2)^3} \tag{6}$$

develops a metastable fixed point at $\lambda_{FP} \approx 12.1$. A typical cut-off scale can be defined by requiring $\lambda(\Lambda_c) \approx \lambda_{FP}/2$. The upper limit obtained from such an analysis is consistent with the lattice values, furthermore one also finds that $W_LW_L$ scattering is well described by improved NLO perturbation theory up
TABLE 1. Upper and lower limits on the SM Higgs mass at typical values of the cut-off.

| cut-off in (GeV) | upper limit (GeV) | lower limit (GeV) |
|-----------------|------------------|------------------|
| $10^7$          | $650 \pm 150$    | $47 \pm 4$       |
| $10^6$          | $300 \pm 20$     | $120 \pm 8$      |
| $10^{15}$       | $195 \pm 5$      | $140 \pm 10$     |
| $10^{19}$       | $180 \pm 4$      | $147 \pm 12$     |

to $\sqrt{s} = 2$ TeV collision energies. This result means that in the SM we can describe $W_L W_L$ scattering at LHC and NLC precisely.

For quantitative studies, in the the evolution of $\lambda(\mu)$ the large Yukawa coupling of the top quark has to be taken into account.

$$\beta_\lambda = \frac{24 \lambda^2 + 12 \lambda g_t^2 - 6 g_t^4}{(16 \pi^2)^2} + \text{gauge and higher order terms} \quad (7)$$

where in leading order $g_t^2(m_t) = \sqrt{2} m_t / v$. Since the top quark is heavy $m_t = 175$ GeV these new terms can drive $\lambda(\mu)$ to negative values at small scales. By demanding the stability of the vacuum ($\lambda > 0$) we get a lower limit on the Higgs mass. In recent two loop calculations [9] (when the QCD corrections are non-negligible) the lower bounds have been evaluated with $m_t = 175 \pm 5$ GeV and $\alpha_S = 0.118 \pm .003$. In Table 1 we summarized the upper and lower bounds for a few typical value of the cut-off [10]. The LEP limits on $m_H$ quoted above are completely consistent with the theoretically allowed range, in particular, the values $m_H \approx 170$ GeV allow a valid field theoretical treatment of the SM model up to the Planck scale. In this case the bound following from triviality alone is much higher than the scale of new physics suggested by the gauge hierarchy problem. These considerations as well as the first indirect experimental hints indicate that the mass of the Higgs boson is likely in the mass range of $m_H = 95 - 400$ GeV. Particularly difficult of the detection of the Higgs boson in the low mass range $m_H = 95 - 140$ GeV. The signal to background ratio plotted in fig. 1 [11] clearly shows that the full coverage of this range requires a run at high luminosity, the combination of the signals of several decay modes ($h \to b\bar{b}$ and $h \to \gamma\gamma$) and detector performances as designed or better. In the the intermediate range $m_H = 140 - 180$ GeV the detectable signals are provided by the four lepton decay modes of gauge boson pair ($ZZ^*$ and $WW^*$) production. Recently Dittmar and Dreiner [12] have shown that the polarization properties of the $WW$-pairs if come from Higgs decay are very different from the ones of those $WW$-pairs which are produced by the standard QCD quark-antiquark annihilation mechanism. Therefore, in the range $m_H = 155 - 180 \text{GeV}$ even with two undetectable neutrinos in the final state the $WW^*$ pair production and its subsequent decay into $l^+l^-\nu\bar{\nu}$ gives improved signal together with the mode $H \to Z^0 Z^{0*} \to l^+l^-l^+l^-$. Finally in the upper range $m_H = 180 - 700$ GeV the gold plated mode $H \to Z^0 Z^0 \to l^+l^-l^+l^-$ gives clear signal. Updated branch-
SEARCH FOR SUPERSYMMETRY

As was mentioned in the introduction supersymmetry offers a solution to the gauge hierarchy problem. With direct supersymmetrization of the SM we get a better effective field theory provided the scale of supersymmetry breaking is naturally low (around 1 TeV). Supersymmetry is a theoretically attractive concept since it gives a generalization of Poincare invariance and it emerges naturally in string theories.

MSSM with SUGRA universal soft breaking terms

The MSSM is defined by minimal direct supersymmetrization of the Standard Model with supersymmetric GUT and with some simple boundary condition at the GUT scale. It has four basic properties. (1) it has minimal gauge group: $SU(3)_{C} \times SU(2)_{L} \times U(1)_{Y}$, (2) it has minimal particle content: three generation of quarks and leptons and their super partners, and two Higgs doublets plus superpartners; (3) it has an exact discrete $R$-parity, with $R = +1$ for SM particles and Higgs-bosons and $R = -1$ for the superpartners; (4) its couplings are constrained by SU(5) GUT with universal soft breaking terms.
at the GUT scale. Contrary to the SM, the SU(5) GUT MSSM is consistent with limit on the proton decay.

The assumption of SU(5) GUT unification with universal soft breaking allows to reduce the huge number of soft breaking terms. This universality is motivated by a universal supergravity Higgs mechanism in a hidden sector. Aside from the SM parameters, the model is completely specified by five SUSY breaking parameters: $m_0$ (universal scalar mass), $m_{1/2}$ (universal gaugino mass), bilinear and trilinear scalar couplings $\mu, A_0, B_0$. A very nice feature of the model is that it gives rise to radiative electroweak symmetry breaking in a wide range of parameters. Because of R-parity, the lightest SUSY particle (LSP) is stable which leads to the important missing transverse energy signal. The phenomenology of the SUGRA MSSM is well known with experimentally allowed constraints on its parameters. At the LHC the full range of possible supersymmetric particle masses can be explored. Extensive studies determined the regions of parameter space for direct discovery. The typical physics signals are i) $l^\pm + \text{jets} + \text{missing } E_T$ for gluino and squark pair production up to mass values of 3.6 TeV ii) $l^\pm l^\pm + \text{jets} + \text{missing } E_T$ for $gg, gg, q\bar{q}$ production. iii) $l^\pm l^\pm l^\mp$ + missing $E_T$ for $\chi_1^0 \chi_1^\pm$ production and iv) $l^\pm l^\mp$ + missing $E_T$ for slepton pair production up to 300 GeV sleptons. If the superpartners will be found their parameters can be measured by good precision. SUGRA MSSM gives a good strategy for searching for certain type of signals of supersymmetry, however, it has several specific features which are strongly depend on its untested technical simplifying assumptions. Therefore it is important to consider some other viable MSSM models with different soft breaking terms giving different supersymmetric particle spectrum and so different physics signals. It is also interesting to study R-parity violating schemes in which case the production of supersymmetric particles in general will not give the celebrated missing $E_T$ signals.

**MSSM with gauge sector mediated SUSY breaking**

Recently, motivated by the anomalous CDF $ee\gamma\gamma$ event the phenomenology of the MSSM with gauge mediated SUSY breaking [16,17] also have been considered in great detail. In this case the lightest supersymmetric particle is the light gravitino therefore the lightest neutralino can decay as $\chi_1^0 \to \tilde{G} + \gamma$. Cosmological constraints give the upper limit $m_G < 1$ KeV. The parameter space of this model is strongly constrained by LEP200 where a large part of it can be excluded in the case of smaller values of the SUSY breaking scale when the next-to-lightest supersymmetric particle (NLP) can decay in the detector. Assuming higher SUSY breaking scale the NLP will decay outside the LHC detector which may require the building of dedicated detectors [18].
**MSSM with R-parity violation**

Recently, the ALEPH anomalous four jet events and the anomalous HERA events called great attention to the detailed phenomenology of MSSM models with $R$-parity violation [19]. $R$-parity conservation is not a unique mechanism to prevent fast proton decay. Two less constraining mechanisms are the so called baryon or lepton parities. The most general superpotential has both soft and hard $R$ parity violating terms

\[ -L_{\text{soft}}^R = \mu_i L_i H^1 \]

\[ L_{\text{hard}}^R = \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_l^c + \lambda''_{ijk} U_i Q_j D_l^c D_k^c \]

where $L$ denotes the chiral superfield of the lepton doublet, $U^c$ is the anti u-quark singlet and $Q$ is the quark doublet.

The first two terms give rise lepton number violating transitions $\Delta L = 1$ while the third term gives baryon number violating transitions $\Delta B = -1$. The transition amplitude of fast proton decay is proportional to the product $\lambda \lambda' \lambda''$. $R$-parity is a $Z_2$ symmetry which forbids all the three $R$-parity violating couplings. One can, however, impose weaker discrete $Z_3$ symmetries. In the the case of $Z_3$ baryon parity we get $\lambda'' = 0$ and in the case of $Z_3$ lepton parity one gets $\lambda = \lambda' = 0$. In both case fast proton decay is forbidden. Since we do not understand the origin of these discrete symmetries all the three options have to be considered. The unattractive feature of the $R$-parity violating options is that there are 45 additional couplings. Their values are only constrained by low energy data. The most important property of $R-$parity violation is that the celebrated missing energy signal got lost. For example, a selectron can decay with $R-$parity violating coupling into two jets or a stop quark can decay into a $d$-quark and a positron when the stop production would give signals similar to the production of a leptoquark. The phenomenology of the MSSM with $R$-parity violating terms is not yet worked out at the necessary details but work is in progress in this direction.

**Search for the MSSM Higgs Bosons**

The search for the Higgs bosons of the MSSM has particular significance in searching for supersymmetry since the Higgs sector of the MSSM is largely independent from the specific technical assumptions on the soft breaking terms and so from the properties of the supersymmetric particles.

The physical states of the MSSM Higgs sector are three neutral bosons (two CP-even, $h$ and $H$, and one CP-odd, $A$) and a charged Higgs boson $H^\pm$. In the Born-approximation the MSSM Higgs sector contains only two independent parameters. A usual choice for these parameters are $m_A$, the
FIGURE 2. Regions of the parameter space (\(\tan \beta - m_A\)) defined by 5\(\sigma\)-discovery contours for various MSSM signals at high integrated luminosity of \(3 \times 10^5\) \(\text{pb}^{-1}\).

The physical mass of the CP-odd neutral boson and \(\tan \beta = v_1/v_2\), where the vacuum expectation value \(v_1\) gives mass to the quarks of charge \(-1/3\) and to the leptons while \(v_2\) gives mass to the quarks of charge \(2/3\). The parameter \(m_A\) is essentially unconstrained, although naturalness arguments suggest that it should be smaller than \(\mathcal{O}(500\ \text{GeV})\) and \(1 < \tan \beta < m_t/m_b\). There are important inequalities. The most important one is on the mass of the light CP-even Higgs boson \(m_h < M_Z \cos 2\beta\). This leading order inequality is modified by radiative corrections allowing higher values up to 150 GeV, therefore if the Higgs boson will not be found at LEP200, the decisive test should come from the LHC. If \(M_A\) is large than 200 GeV or so the properties of the light Higgs boson \(h\) is very similar to the SM Higgs boson. At low values of \(\tan \beta\) the upper limit is smaller. At the LHC the Higgs searches are even more difficult than the search for the SM Higgs since the production rates are usually smaller. There is a variety of signatures in which MSSM Higgs bosons can be observed. Some of them similar to the SM case others concerns the production of decay of the heavy CP-even (H) and the CP-odd (A) and charged Higgs bosons. The search strategies and methods and the corresponding cross-section and branching ratio analysis have been carried out long time ago [20], a latest very detailed signal and background analysis can be found in ref. [11].

The discovery potential of LHC is summarized in fig. 2 [11] in terms of 5\(\sigma\) discovery contours in (\(\tan \beta - M_A\)) parameter plane. The results are obtained
assuming no mixing in the third generation, $m_t = 175$ GeV and a SUSY mass scale of 1 TeV. Furthermore it was assumed that the decay modes of the Higgs bosons into supersymmetric particles are unimportant. With comparing the results summarized on fig. 1 and fig. 2 we can see that the search for the MSSM Higgs bosons at LHC is in general more difficult than the search for the SM Higgs boson and that the constraints provided by LEP200 are crucially important for a decisive test.

REFERENCES

1. H. Georgi, Weak Interactions and Modern Particle Phenomena; (Benjamin,1984); J. Polchinski, hep-th/9210046 (1992); F. Ravndal, this volume.
2. ATLAS Technical Proposal, CERN/LHC/94-43 LHCC/P2 (December 1994).
3. CMS Technical Proposal, CERN/LHC/94-43 LHCC/P1 (December 1994).
4. Proceedings of the “Large Hadron Collider Workshop”, Aachen, 4-9 October 1990, eds. G. Jarlskog and D. Rein, Report CERN 90-10, ECFA 90-133, Geneva, 1990;
5. J.F. Gunion, H.E. Haber, G.L. Kane and S. Dawson, “The Higgs Hunter Guide” (Addison-Wesley, Reading MA, 1990).
6. Joint LEP Working Group 1997, to be published.
7. M. Lüscher and P. Weiss, Nucl. Phys. B318 (1989) 705.
8. K. Riesselmann, in the Proceedings of the Ringberg Workhop “Higgs Hunting, 1996, ed. B. Kniehl, hep-ph/9708417 and references therein.
9. G. Altarelli and G. Isidori, Phys. Lett. B337 (1994) 141; J. A. Casas, J. R. Espinosa and M. Quirós, Phys. Lett. B342 (1996) 171; ibid B382 (1996) 374.
10. T. Hambye and K. Riesselmann, hep-ph/9708416.
11. E. Richter-Was et al.CERN-TH-96-111 (1996).
12. M. Dittmar and H. Dreiner, preprint RAL-96-049 (1996), hep-ph/9608317.
13. Z. Kunszt, S. Moretti and W.J. Stirling, Zeit. Phys. C (1997).
14. M. Spira, CERN-TH-97-068 (Apr 1997) 100p, hep-ph/9705337
15. J. F. Gunion, A. Stange (BNL) and S. Willenbrock (U. Ill., Urbana), hep-ph/9602238 (1996).
16. See, e.g.M. Dine and A. Nelson, Phys. Rev. D48 (1993) 1277, ibid d51 (1995) 1362, ibid D53 (1996) 2658. G. Dvali, G.F. Giudive and A Pomarol, Nucl. Phys. B478 (1996) 31, M Dine, Y. Nir and Y Shirman, Phys. Rev. D55 (1997) 1501
17. D. Pierce, this proceedings
18. S. Maki and S. Orito, Nucl. Phys. B365 (1991) 597; H. Dreiner, hep-ph/9706382
19. H. Dreiner, G.G. Ross, Nucl. Phys. B365 (1991) 597; H. Dreiner, hep-ph/9607261 (1997).
20. Z. Kunszt and F. Zwirner, Nucl. Phys. B385 (1992) 3; H. Baer, M. Bisset, C. Kao and X. Tata, Phys. Rev. D47 (1993) 1062; ibid D46 (1992) 1067; J. Gunion and L.Orr, Phys. Rev. D46 (1992) 2052; V. Barger, K. Cheung, R. Phillips and A. Stange, Phys. Rev. D46 (1992) 4914;