Chapter 2

The Physics Landscape of the High Luminosity LHC

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We review the status of HEP after the first run of the LHC and discuss the opportunities offered by the HL-LHC, in light of the needs for future progress that are emerging from the data. The HL-LHC will push to the systematic limit the precision of most measurements of the Higgs boson, and will be necessary to firmly establish some of the more rare decays foreseen by the Standard Model, such as the decays to dimuons and to a Z + photon pair. The HL-LHC luminosity will provide additional statistics required by the quantitative study of any discovery the LHC may achieve during the first 300 inverse femtobarn, and will further extend the discovery potential of the LHC, particularly for rare, elusive or low-sensitivity processes.

1. Introduction

The first run of the LHC, during the period 2009–2012, delivered three key messages: (i) the discovery [1, 2] of the Higgs boson [3–5], (ii) the lack of evidence for particles and interactions beyond those described by the Standard Model (SM) [6–8] and (iii) the excellent agreement between the data and the theoretical modeling of proton–proton (pp) collisions at a center-of-mass energy $\sqrt{s} = 7$ and 8 TeV. Each of these points contributes to sharpening the definition of the landscape for the future of the LHC programme, as we briefly summarize here, and elaborate in more detail in the rest of this Section.

The prospects for LHC physics with a dataset of 3000 fb^{-1} had been outlined already more than ten years ago, in a series of studies collected in [9]. Work has taken place within the experiments over the last couple of years [10, 11], to update these studies using the more realistic simulation tools certified by data, and to adapt them to the overall post-Run-1 physics scenario. The recent Snowmass process in the US has also contributed to further understand the physics case of future LHC operations [12, 13]. More progress, and further refinement of the goals and ambitions, will be possible after the analysis of the 14 TeV data.

To start with, the observation of a Higgs boson gives a compelling and concrete case to define, quantify and justify the goals of the long-term LHC exploration.

Table 1. SM branching ratios, in %, for various Higgs decay channels and at $m_H = 125.5$ GeV (see [14] for details).

$b\bar{b}$	$\tau^+\tau^-$	$\mu^+\mu^-$	$c\bar{c}$	gg	$\gamma\gamma$	$Z\gamma$	WW^*	ZZ^*
56.9	6.2	0.02	2.9	8.5	0.2	0.16	22.3	2.8

Within the SM, the value of the Higgs mass allows to predict uniquely its production and decay properties. A large number of decay final states is accessible for exploration at the LHC, each of them sensitive, in different ways, to the possible effects of physics beyond the SM (BSM). The relevant decay branching ratios, for a SM Higgs of mass $m_H = 125.5$ GeV, are collected in Table 1. One of the primary goals of the future LHC programme is therefore to greatly extend the range and precision of Higgs studies, improving the accuracy of the measurements, searching for yet unobserved decay modes, and probing in more detail the mechanism of electroweak symmetry breaking (EWSB). Precision targets in the range of few percent provide a concrete reference against which to benchmark the performance of the plans for future detector and accelerator improvements.

The expectation that the LHC should find evidence for BSM phenomena is justified by decades of theoretical work on the foundations of the SM and its conceptual shortcomings, and on the possible interpretations of experimental facts that cannot be explained within the SM, such as dark matter (DM), the baryon asymmetry of the universe and neutrino masses. The lack of BSM signals from the first run of the LHC does not spoil this expectation. It just constrains the set of suitable BSM models, possibly reducing the appeal of some frameworks, which would now require a finer tuning of their parameters to remain viable. The search for BSM signals remains therefore a top priority for the LHC. Two directions emerge: searching for particles of higher mass, and searching for final states that are harder to distinguish from the SM backgrounds. The increase in energy from 8 to 14 TeV will greatly extend the LHC search potential at high mass: within few months the discovery reach of Run 1 will be matched and surpassed. Higher statistics will however be crucial to push it towards the kinematic limit, and to pursue the more *stealthy* manifestations of new physics. High luminosity will also be needed in case of an early discovery: the constraints on new physics already established during the first LHC run are such that, if discovered, new physics will appear as a rare phenomenon even at 14 TeV. A detailed study of its properties, therefore, will demand extraordinary amounts of luminosity.

In addition to the Higgs discovery, and to the tighter constraints on the existence of BSM phenomena, the first years of LHC physics have proven two facts, which corroborate the reliability of the projections for the physics potential of the HL-LHC phase. On one side, the performance of the detectors matches, and often

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experimental analyses. There is no reasonable doubt by now that this particle is a scalar [17, 18], consistent with being an excitation of the Higgs field, responsible for the breaking of the $SU(2) \times U(1)$ electroweak (EW) symmetry, and for the masses of the W and Z bosons, as well as of the known quarks and leptons. While the simplest theoretical model describing the Higgs boson is what is built into the SM itself, it is well known that there are several alternative “Higgs mechanisms”. A Higgs mechanism is defined by the spectrum of the Higgs states, and by the dynamics that leads the Higgs field to acquire a non-zero vacuum expectation value, resulting in the EWSB. In the SM version of the Higgs mechanism [7], there is a single complex $SU(2)$ doublet, corresponding to four real degrees of freedom. The symmetry breaking is driven by the minimization of the mexican-hat-shaped potential, described by two parameters associated to the mass of the Higgs boson and its expectation value. Three of the four degrees of freedom become the longitudinal modes of the W^+ , W^- and Z^0 massive vector bosons, and the fourth is left as *the* SM Higgs boson.

Alternatives to the SM Higgs mechanism include theories with a more extended spectrum and/or with a different EWSB dynamics. For example, several theories, most notably supersymmetric models, have two doublets, instead of one. One doublet is used to give mass to the up-type quarks, the other doublet is used to give mass to the down-type quarks and to the charged leptons. In these models, there is a total of five Higgs particles (the 2×4 states of 2 complex $SU(2)$ doublets, minus the 3 states absorbed by $W^\pm$ and Z^0), three of them neutral (typically labeled h^0 , H^0 , A^0), the other 2 being the opposite-charge states of a charged $H^\pm$ Higgs.

Other SM extensions include the possibility of further doublets, or of different $SU(2)$ representations, including singlets, or vectors, in which case doubly-charged Higgs fields would also appear. In other scenarios, EWSB may arise from an underlying strong dynamics, the Higgs field emerging as a composite particle, a bound state of elementary fermions confined together (for a recent review see e.g. [28]). In some theories with extra space dimensions, the Higgs scalar could be a component of vector fields living in higher dimensions.

In the SM, the production and decay properties of the Higgs boson are completely determined by its mass and by the masses of the SM particles. In BSM theories such as those described above, those properties can change, whether because of a richer Higgs spectrum, or of a different EWSB dynamics, or because the other new BSM particles can influence the Higgs couplings: additional decay channels can be open, or new intermediate virtual states can modify the loop-mediated Higgs effective couplings, such as those to gluons and photons.

While the available experimental information is sufficient to claim with complete confidence that the discovered particle is a Higgs boson, the quantitative determination of its consistency with the SM predictions is limited by the statistical

and systematics accuracy of the measurements. The Higgs has been searched, and detected, in a combination of different production and decay modes. The dominant production channels are: gluon fusion ($gg \rightarrow H$), vector-boson fusion ($qq \rightarrow qqH$, via intermediate $W^+W^- \rightarrow H$ or $ZZ \rightarrow H$), associated production with a gauge boson ($pp \rightarrow W/Z + H$) and with top quarks ($pp \rightarrow t\bar{t}H$). The decay modes that have been positively identified so far, including evidence from the Tevatron experiments [19], cover both decays to gauge boson pairs [20, 21] ($\gamma\gamma$, $ZZ^* \rightarrow 4$ leptons, $WW^* \rightarrow 2$ leptons + 2 neutrinos) and to fermion pairs ($\tau^+\tau^-$ [22, 23], and $b\bar{b}$ [25, 26]).

For both ATLAS and CMS, the measurement of production rates times branching fractions, averaged over all channels, agrees with the SM expectations to within 15–20%, consistent with the current statistical and systematic uncertainty. All the individual channels are also consistent with the SM prediction, with varying degrees of significance. Higgs decays to the $\mu^+\mu^-$ and $Z\gamma$ final states have been searched, but no signal was found, as expected from the very small branching ratios predicted by the SM. Likewise, there are no signals of decays that are forbidden in the SM, such as $H \rightarrow \mu^\pm e^\mp$, or indications of BSM Higgs-like states, over a mass range extending up to several hundreds GeV. Therefore, today's LHC data support the case of a SM Higgs mechanism.

It must be said, however, that it would have been quite surprising to find deviations from the SM Higgs given the available statistics: precision EW measurements and direct BSM searches set indirect constraints on possible deviations of the Higgs properties from their SM expectations. Assuming new physics at a scale Λ to affect the Higgs properties, whether via modifications of Higgs dynamics due to the composite nature of the Higgs, or due to new particles affecting the Higgs interactions with SM particles, one expects the Higgs branching ratios to vary at the level of $\delta \times (1 \text{ TeV}/\Lambda)^2$, where $\delta \sim \mathcal{O}(1\text{--}10\%)$, depending on the model (for some explicit examples, see e.g. [12]).

The goal of the LHC is therefore to extend the measurements of the Higgs properties, and to reach a precision in the range of few percent, in order to match the sensitivity to direct manifestations of new physics appearing at the TeV scale. The prospects for such improvements, including estimates for the HL-LHC, have been studied by ATLAS [11] and CMS [10], and were summarized in the Snowmass study [12]. Those results are reproduced here in Table 2. The range in projections reflects two assumptions on the extrapolation of systematics uncertainties: the more conservative results assume uncertainties equal to those achieved today, while the more optimistic ones assume that experimental systematics scale with statistics like $1/\sqrt{\int \mathcal{L}}$ and theoretical systematics will be reduced by half.

Notice that only with the full statistics of the HL-LHC phase one can achieve a meaningful measurement of the important decay modes $H \rightarrow Z^0\gamma$ and $H \rightarrow \mu^+\mu^-$.

Table 2. Projected accuracy per experiment, in %, in the extraction of Higgs couplings, for 300 and 3000 fb⁻¹ of integrated luminosity at 14 TeV. The results are a fit to projected data of the parameters κ_X , representing the relative deviations from the SM of the Higgs couplings to the gauge bosons, $\kappa_{\gamma,g,W,Z}$, to the charm and top quarks, κ_u , to the bottom and strange quarks, κ_d , to the μ and τ leptons $\kappa_{\mu,\tau}$, and to the $Z\gamma$ final state, $\kappa_{Z\gamma}$. The last column gives the sensitivity to invisible Higgs decay modes. The ranges reflect different assumptions on the systematics uncertainties (see [12] for details).

L/fb ⁻¹	κ_γ	κ_g	$\kappa_{W,Z}$	κ_u	κ_d	κ_τ	$\kappa_{Z\gamma}$	κ_μ	BR _{BSM}
300	5–7	6–8	4–6	14–15	10–13	6–8	41	23	< 14–18%
3000	2–5	3–5	2–5	7–10	4–7	2–5	10–12	8	< 7–11%

The former has a sensitivity complementary to the $H \rightarrow \gamma\gamma$ decay to virtual particles propagating in the internal loop; the latter provides the most direct probe of an anomalous flavor pattern in the Higgs couplings to leptons. The HL-LHC statistics will also permit to increase the number of combinations of SM production and decays channels, enabling e.g. precise measurements of $pp \rightarrow t\bar{t}H$ and $pp \rightarrow W/ZH$ with $H \rightarrow \gamma\gamma$ [10, 11]. Access to multiple production and decay channels is crucial to reduce the systematics in the extraction of the Higgs couplings to individual particles, and to disentangle the origin of possible anomalies induced by BSM physics. The HL-LHC will furthermore extend the sensitivity to exotic or forbidden decays, such as $H \rightarrow \gamma J/\psi$ [29], $H \rightarrow \mu^\pm \tau^\mp, \mu^\pm e^\mp, t \rightarrow Hc$ and others [30].

To further probe the mechanism underlying the breaking of electroweak symmetry (EWSB), to prove that the observed Higgs is indeed responsible for it, and to determine whether it is a fundamental particle (as predicted by the SM and other theories), or whether it is a composite object (as predicted by others), other measurements, in addition to the determination of decay rates, will prove useful. These include the study of Higgs pair production and the measurement of WW scattering at high energy [9]. The production rate of Higgs pairs is sensitive to the Higgs selfcoupling, and thus to the form of the Higgs field potential. Its measurement is made difficult by the small cross-section and by the large backgrounds that affect the dominant decay modes, such as $HH \rightarrow b\bar{b}b\bar{b}$. Viability studies, using various decay modes, are in progress [12], and indicate that, while the study of Higgs pair production is likely beyond the reach of 300 fb⁻¹, a sensitivity at the level of $\pm 50\%$ becomes possible at the HL-LHC.

The study of WW interactions at high invariant mass probes the unitarization of the scattering amplitude, to confirm the role of the Higgs boson, or to suggest the presence of a new strong dynamics underlying the EWSB mechanism and of a Higgs composite substructure. The nominal LHC luminosity is not sufficient to probe the relevant kinematical regions, where $m(WW) \gtrsim 1$ TeV. While the study of Higgs pair production and high-mass WW scattering would mostly benefit from

an increase in the LHC beam energy, the HL-LHC luminosities will be necessary to perform the first tests ever of these sensitive probes of EWSB and of the true nature of the Higgs boson.

1.2. Status and prospects of BSM searches

Physicists have long anticipated the existence of new phenomena at the TeV scale, in order to address issues like the existence of DM and the hierarchy problem, namely the fine tuning of the Higgs self-coupling, to one part in 10^{30} , necessary to justify the smallness of the Higgs mass with respect to the Planck scale. The LHC experiments have found no evidence, as yet, for such new phenomena, as exemplified in Fig. 2, which collects the exclusion limits obtained by ATLAS for a large number of (non-supersymmetric) BSM models. In most cases these limits already approach, or well exceed, the TeV scale. In the case of supersymmetry, partners of quarks and gluons are ruled out in the constrained minimal models, if their mass is below 1.5 TeV, and the partners of the top and bottom quarks have constraints reaching out to 500 GeV.

Fig. 2. Collection of mass limits for new particles of BSM models, as obtained by the ATLAS experiment [16]. Results from the 8 TeV run are highlighted in blue (thick lines).

Fig. 3. Projections for the search of a new Z' gauge boson. Left: 5σ discovery reach, in the dimuon channel [10], for different coupling scenarios (Z'_{SM} corresponds to SM-like couplings). Right: Exclusion limit, at 95%CL, in the case of SM-like couplings [11].

Fig. 4. Discovery/exclusion reach at high luminosity for squarks and gluinos (left panel) and for stop squarks (right panel) in some simplified supersymmetric scenarios [11, 31].

Needless to say, these results leave well open the possibility of discoveries at a higher mass, when the LHC reaches 14 TeV. Many examples have been studied in the past [9], and have recently been updated in view of the prospects for high luminosity [10, 11]. We collect here some indicative examples.

Figure 3 shows the increase in exploration reach of the HL-LHC for a new Z' gauge boson. The luminosity increase from 300 to 3000 fb^{-1} increases the discovery reach by 20%, up to ~ 6300 GeV, and increases the 95%CL limit up to ~ 7600 GeV. A similar reach improvement is observed for other searches, as shown in the case of squarks, gluinos and stops in Fig. 4.

In spite of the ample room for discoveries at 14 TeV, at these large masses the production rates will be small, and high-statistics precision measurements of their properties will call for a luminosity well beyond the nominal LHC phase. For

example, while new Z' gauge bosons, signaling the existence of new weak interactions, can be discovered with 300 fb^{-1} up to $\sim 5 \text{ TeV}$, the full HL-LHC luminosity will be needed to determine their properties if their mass is above 2.5 TeV . Since the available LHC data already constrain the existence of Z' bosons below 2.5 TeV (see e.g. Fig. 2), we can state already today that the clarification of any such discovery will need the luminosity upgrade.

1.3. Additional remarks

We conclude this Section with few independent remarks.

There is no doubt that, however welcome an increase in the LHC luminosity, the most effective way to push the discovery reach at large mass is to ultimately increase the beam energy. But it must be pointed out that the efforts to increase the LHC luminosity, and thus to develop the relevant technologies and experimental skills, will remain crucial even should the avenue of the energy increase be undertaken. While the hadronic cross section for the production of states of a given mass increases with the beam energy ($E_{\text{beam}} = 0.5\sqrt{S}$), the cross sections to produce states whose mass M is a fixed fraction of E_{beam} decreases as $1/S$. This is shown in practice in Fig. 5, which gives the cross-sections for production of pairs of heavy quarks with mass m_Q , plotted for $E_{\text{beam}} = 7$ and 50 TeV as a function of m_Q . For example, the event rate of $1/(1000 \text{ fb}^{-1})$ allows to reach $m_Q \sim 0.46 E_{\text{beam}}$ for $E_{\text{beam}} = 7 \text{ TeV}$, but only $m_Q \sim 0.31 E_{\text{beam}}$ at 50 TeV , with a loss of $1/3$ of the relative discovery reach.

Fig. 5. Cross-sections for the production of heavy quark pairs, as a function of m_Q/E_{beam} , for pp collisions at $E_{\text{beam}} = 7$ and 50 GeV .

To fully exploit the exploration power of a high energy hadron collider at the highest mass scales, its luminosity must therefore scale like S . In addition to challenging the accelerator, such high luminosities would greatly challenge the ability of the experiments to cope with very high levels of pile-up. On the other hand, pushing the high-mass frontier implies dealing with highly energetic final states, where pile-up will likely be a minor issue. For example, at 100 TeV the hardest jets will have energies about 7 times larger than at 14 TeV. One can thus probably tolerate a pile-up contribution to the energy of these jets at a level 7 times higher than at the HL-LHC. Since the energy deposit of a generic minimum bias event grows only logarithmically with energy, and so does not change much between 14 and 100 TeV, this means that one could tolerate a pile-up rate 7 times larger. This naive argument may fail for observables more sophisticated than jet energies (such as tracking efficiency, lepton or photon isolation, tagging of bottom hadrons, etc.), but overall it is not unreasonable that the detectors for a 100 TeV collider, 30 years from now, will be able to address the physics of the highest mass objects with several hundreds or perhaps 1000 pile-up events.

With the discovery of the Higgs boson, a long era of more or less guaranteed discoveries is over. The W and Z bosons, the top quark, and the Higgs, are the necessary components of an extremely compelling theoretical framework, the SM, whose predictions have steadily grown in reliability over the years. The high-energy accelerators of the last 30 years were built to discover and study in detail those particles, whose existence and whose properties were anticipated with great confidence. While there is similar confidence in the existence of new physics beyond the SM, there is nowadays no certainty as to precisely what this new physics should be, and where or how it will appear in accelerators. There is no guarantee that it will be discovered during the Run 2 of the LHC, or in the subsequent phases of its upgrade. The programme of precision Higgs physics and continued exploration of EWSB (including WW scattering and Higgs-pair production) is therefore the most concrete and robust deliverable that the LHC upgrade can promise, and whose future returns can be anticipated today.

The achievement of the HL-LHC programme as discussed above will greatly enrich our knowledge of particle physics, even in absence of BSM discoveries, and by itself it motivates the upgrade effort. In parallel with this programme, a large set of ancillary measurements are necessary, in order to improve the precision of the theoretical predictions, to reduce the experimental systematics, and to improve the knowledge of the complete set of parameters or observables defining the SM. Among these, we mention m_{top} , m_W , $\sin^2 \theta_W$, as well as the flavor observables associated to the quark-mixing phenomena. Furthermore, while the flavor programme carried out by LHCb, and the programme of heavy ion collisions engaging ALICE and the other general purpose detectors, will not be exposed to the highest lumi-

nosities afforded by the HL-LHC, they will nevertheless greatly benefit from the extended operation of the LHC.

The longevity of a hadron collider is a great asset, as the example of the Tevatron Run 2 shows very well. If the Higgs boson had had a mass of ~ 160 GeV, the Run 2 luminosity would have guaranteed its discovery, and an extension of the run by few more years would have guaranteed a full discovery even at the actual mass of 125 GeV. It is also remarkable that some of the most impressive results from Run 2, like the oscillations of B_s mesons, the observation of single top production, the precision measurement of the W and of the top quark masses, among others, were achieved after 20 years since the first Tevatron collider run. Tantalizing hints of new phenomena, like the production asymmetry of top quarks, have also emerged only after a major fraction of the ultimate luminosity sample was collected. This demonstrates the scientific longevity of a hadron collider, and its potential to deliver surprises over a very long life span, provided a sufficiently rapid luminosity doubling time is attainable.

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