https://doi.org/10.1142/9789811278952_0002

Chapter 2

The Physics Landscape of the High Luminosity LHC

M. Mangano

CERN, TH Department, Genève 23, CH-1211, Switzerland

This contribution reviews the physics potential of the HL-LHC experimental programme. The first 10 years of the LHC has demonstrated the vast open range of opportunities for measurements and discoveries of new phenomena. Starting from the results of the first two runs of the LHC, extensive experimental and theoretical studies have now defined a broad set of goals for the future high-luminosity phase of the project, reviewed here. The precision measurement of the Higgs boson properties, which has greatly expanded our knowledge today, represents the primary guaranteed deliverable. This target is complemented by a vast array of additional measurements, ranging from the continued search for phenomena beyond the Standard Model, to the study of the Standard Model dynamics and parameters, flavour phenomena, and the study of matter at high density and temperature.

1. Introduction

The first 10 years of data collection and analysis by the LHC experiments delivered three key takeaways: (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 corroboration between the data and the theoretical modeling of proton-proton (pp) collisions at center of mass energies ranging between $\sqrt{S} = 2.76$ and 13 TeV. Each of these points contributes to sharpening the definition of the landscape for the future of the LHC programme.

The prospects for LHC physics with a dataset of 3000 fb^{-1} had been outlined in the early 2000's, in a series of studies collected in Ref. [9]. The abundance of physics results obtained during the first two LHC runs, the experience gained by the experiments with the operation and the performance of their detectors, and the immense work done to characterize the features of their future high-luminosity upgrades, contributed to a recent thorough assessmemt of the HL-LHC physics potential.[10] The five Working Group reports contained in that document cover all areas of LHC research, from the SM[11] and the Higgs,[12] to searches for new physics beyond the SM[13] (BSM), flavour,[14] and studies of QCD matter at high densities and temperature.[15] These documents provide the most comprehensive and up-to-date overview of the key role to be played by the HL-LHC in shaping the future progress of high-energy physics, which we will briefly summarize here.

The observation of the Higgs boson provides a compelling and concrete case to define and quantify the goals and targets of the long-term LHC exploration. 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 BSM physics. 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 to benchmark the performance of the future detector and accelerator improvements against.

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, as well as on 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 runs of the LHC does not dampen that expectation. It just constrains the set of suitable BSM models, possibly reducing the appeal of some frameworks, as they would now require a finer tuning of their parameters to remain viable. The search for BSM signals therefore remains 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 13 to 14 TeV will mildly extend the LHC search potential at high mass, but the higher statistics will push it towards the kinematic limit, and, perhaps more importantly, will allow to pursue the more *stealthy* manifestations of new physics. High luminosity will also allow to exploit the potential for very precise measurements, building on the great progress that has taken place over the last 10 years.

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 surpasses, the expectations. This is particularly true of the ability to operate in a regime of very high pile-up, a critical test for effective data taking in the environment expected with the HL-LHC. On the other, the theoretical modelling of the properties of pp collisions at these energies has proven very accurate. Dedicated precise measurements of SM processes and cross sections have shown that data and theory agree over a broad dynamical range of phenomena, including the very complex final states with mixtures of gauge bosons, heavy quarks, and multijets, which characterize BSM processes. Where the theoretical predictions are limited in precision by the lack of higher-order calculations or by uncertainties in the knowledge of the quark and gluon content of the proton (the so-called parton distribution functions, PDFs), great progress is taking place to match the precision needs, by improving the calculations, and by using the LHC data themselves, to validate the theoretical progress and to refine the knowledge of PDFs. This progress will continue with more data and more powerful theoretical tools. For the specific case of PDFs, further insight could also arise from a programme of ep collisions, as proposed by the LHeC project.[16] Its results would surely fulfill, and even exceed, the precision requirements of the HL-LHC.

1.1. *Status and prospects of Higgs studies*

Since the discovery of the Higgs in July 2012, it has since been studied in greater detail, using the additional statistics of Run 2, and continuously refining the 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, leading to a total of three neutral and one charged scalar particles. Other extensions include the possibility of further doublets, or of different $SU(2)$ representations, including singlets, or vectors, in which case doubly-charged Higgs fields could 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 review see e.g. Ref. [19]). 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.

The dominant production and decay channels of the Higgs have all been observed with a significance exceeding 5 standard deviations.[20,21] These measurements lead to a quantitative agreement with the SM predictions at level of

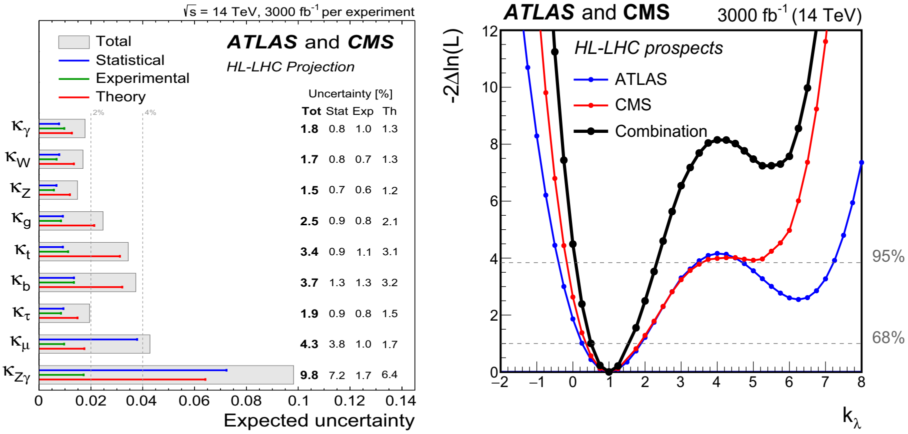

Fig. 1. HL-LHC projections for the precision of the Higgs couplings measurements (left) and for the significance of the Higgs self-coupling extraction (right) (for details see Ref. [12]).

$\sim 10\%$, which can still be greatly improved with additional statistics, leaving plenty of room for possible surprises. The latest HL-LHC projections for the main Higgs couplings, documented in the recent report,[12] are summarized in the left plot of Figure 1. The κ_X quantities represent the ratios of the measured and the SM values of the Higgs coupling to the particle X. For example, κ_Z refers to the coupling of the Higgs to the Z boson, which determines the decay $H \to ZZ \to 4$ leptons; κ_t refers to the couling with the top quark, which can be measured in the process $pp \to t\bar{t}H$, where the Higgs boson is emitted from the top or antitop quarks. Deviations from the SM behaviour would be signalled by $\kappa_X \neq 1$, and the horizontal bars in the plot show the precision with which the various κ will be measured, including the three shources of systematics: purely experimental, statistical, and the systematics arising from the uncertainties in the theoretical prediction of the various production rates, due to higher-order corrections or PDF uncertainties. The expected precision, e.g. better than 2% for the couplings to the EW gauge bosons, exceeds all earlier estimates, reflecting the fantastic performance of the experiments and the experience gained in operations with a high pile-up environment. For most cases, theoretical uncertainties dominate the systematics, a limitation that will likely be overcome with the hard work of the theoretical community. The projected experimental systematics shown in Figure 1 are never a dominating factor, indicating that each additional ab^{-1} of statistics is well justified and highly desirable. As shown in the figure, this is particularly true of the rare Higgs final states that have not been seen so far, such as $\mu^+\mu^-$ and $Z\gamma$, which will likely be discovered only during the HL-LHC phase. The HL-LHC statistics, furthermore, will bring us closer to a measurement of the extremely challenging $H \to c\bar{c}$ decay, and will push the sensitivity to possible flavour-changing couplings of the Higgs (e.g. $H \to e\mu$, $H \to \tau\mu$, $t \to Hc$), whose detection would signal new physics. A large number of even more exotic Higgs decays, which are signatures of BSM phenomena, has been proposed for exploration.[22]

One of the key properties of the Higgs boson, which still needs experimental validation, is its self-coupling. Its strength, uniquely specified within the SM, probes the global shape of the Higgs potential, and could expose the existence of BSM Higgs interactions. In turn, these could shed light on the nature of the cosmological phase transition, which took place as the universe's temperature cooled down below the EW scale, settling the Higgs field in the ground state that we have today. The existence of a strong first order phase transition (SFOPT), instead of the mild cross-over predicted by the SM, could leave imprints in a stochastic gravitational wave background, within the reach of a next generation of space-based interferometers.

The prospects for the Higgs self-coupling measurement at the HL-LHC are discussed in Ref. [12], and summarized in the right plot of Figure 1. As before, κ_λ is the ratio of the measured value of the self-coupling, relative to its SM expectation. The y-axis shows the number of standard deviations with which a given value of κ_λ can be excluded (expressed in terms of confidence levels at the 68% and 95% points on the right side of the plot). The minimum at $\kappa_\lambda \sim 5$ reflects a negative interference among different contributions to the Higgs-pair production cross section, which reduce the rate and the statistical power of the measurement. The black line represents the combination of the individual ATLAS and CMS projections. The significant improvement arising from the combination confirms the crucial role played for this fundamental measurement by the integrated luminosity. The precision around the SM value $\kappa_\lambda = 1$, at the 68% of confidence level (CL), is about ±50%, a significant improvement over earlier estimates. This will give sensitivity to a large fraction of the parameter space characteristic of BSM models with a SFOPT, complementing possible evidence emerging from the direct creation of the new scalar particles present in those theories.[12]

1.2. *Prospects for 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 extremely unnatural fine tuning of the Higgs bare mass, necessary to justify the smallness of the Higgs mass with respect to the Planck scale. The LHC experiments have found no evidence so far for such new phenomena, setting limits that often well exceed the TeV scale. But the search for hints of new phenomena remains one of the top priorities of the future HL-LHC programme, and an extensive study of prospects is documented in Ref. [13]. Following are some indicative examples.

The HL-LHC statistics will benefit BSM searches in at least three different ways. Firstly, as already discussed above, more precise measurements of the Higgs boson and SM processes will increase the sensitivity to possible small deviations. Secondly, the increase in energy from 13 to 14 TeV will complement the increase in luminosity, pushing to the upper edge the mass reach for new very heavy particles. Finally, greater statistics will allow to probe the existence of new phenomena that, while being easily accessible in terms of available energy, tend to be very elusive, either because of very small couplings (low production rates or small decay branching ratios), or because of features that make them hard to single out from the large backgrounds.

These features are shown by the examples of Figure 2. The left plot shows the HL-LHC sensitivity to a new W' gauge boson decaying to electrons or

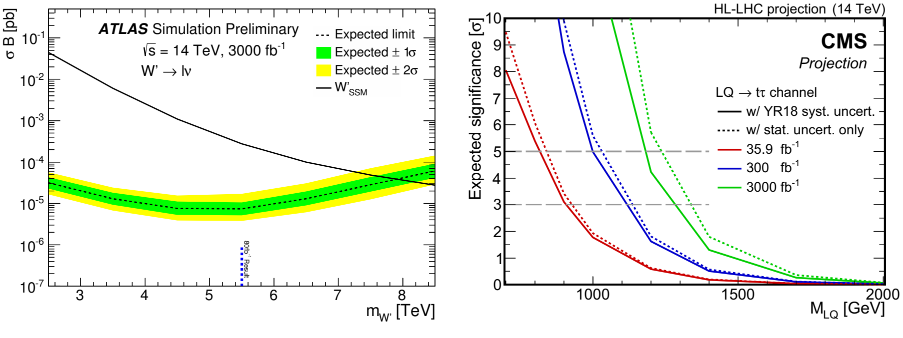

Fig. 2. Left: 95% CL upper limit on the production times decay rate of new W' gauge bosons decaying to $\ell\nu$ ($\ell = e, \mu$). The blue marker shows the current mass limit from 80 fb^{-1} of Run 2 data. Right: signal significance for the observation of a possible leptoquark (LQ), decaying to top quarks and tau leptons. From Ref. [13].

muons. The dotted line gives the 95% CL limit that can be set on the total production rate (cross sections (σ) times branching ratio (B) for the decay to leptons), as a function of the new W' mass. The green and yellow bands represent the uncertainty in this projection, based on statistical and systematic effects, at a CL of 1 and 2 sigma (68 and 95%), respectively. The interpretation of these limits in terms of models of new physics depends on the specific prediction for $\sigma \times B$ arising in a specific BSM theory. As an example, the black line gives the $\sigma \times B$ rate of a W' coupled with the same strength as the SM W boson. The mass exclusion increases from today's ~5.5 TeV (the blue marker) to almost 8 TeV, a 50% increase. A similar relative increase is foreseen in the search for leptoquarks (LQs) decaying with branching ratio $B = 1$ to a τ lepton and a top quark, as shown by the right plot in Figure 2. Here the production proceeds via the strong interaction, and different models are only characterized by the different LQ mass. The three sets of lines correspond to the number of standard deviations that could arise, for a given M_{LQ}, with different amounts of integrated luminosities. Solid (dotted) lines refer to the consideration of the full set (statistical only) of uncertainties.

If we focus instead on the increase in sensitivity at a fixed mass value, e.g. for a possible W' at 5.5 TeV, the left plot shows that the HL-LHC could probe a W' with a production rate about 50 times smaller than today's reach. As far as theory is concerned, the search for very weakly coupled particles is as significant as that of very heavy ones, and, for this, the increase in luminosity is typically more effective than the increase in beam energy!

Examples of elusive signatures that could be exposed by the HL-LHC are given in Figure 3. On the left, we show the prospects for the search of the supersymmetric partners of the Higgs and weak gauge bosons (generically labeled as gauginos, $\tilde{\chi}$), in regions of parameter space where the small mass differences lead to difficult signatures. The study considers associated production of pairs of the lightest ($\tilde{\chi}_1^0$) and next-to-lightest ($\tilde{\chi}_2^0$) neutral gauginos, and of the lightest charged gauginos ($\tilde{\chi}_1^\pm$). For mass differences $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ and $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ above few hundred MeV, the decays considered include, for example, $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \ell^\pm \nu$ and $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^-$. These lead to leptons with small momentum ("soft leptons"). For smaller mass splittings, down to the pion mass, the searches use $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \pi^\pm$ decays, where the charged tracks left by the long-lived $\tilde{\chi}_1^\pm$ crossese only the first tracking layers, before its decay to the undetectable $\tilde{\chi}_1^0$ and soft pion ("disappearing tracks"). The corresponding

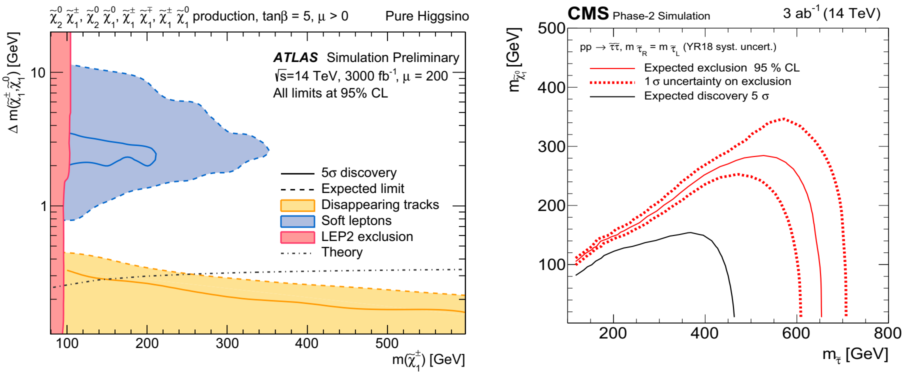

Fig. 3. Exclusion and discovery reach for elusive, weakly interacting supersymmetric particles. Left: the fermionic partners of gauge and Higgs bosons, in the region of parameters with O(GeV) mass differences. Right: the partner of the tau lepton ($\tilde{\tau}$). From Ref. [13].

discovery ranges (exclusion limits) are shown by the blue and yellow regions delimited by the solid (dashed) lines. The line labeled as "theory" reflects the mass difference expected in a class of models with small mass splittings. On the right, we show the sensitivity to the discovery (black solid line) or to the exclusion (red solid line, with $\pm 1\sigma$ uncertainty shown by the dashed lines) of the supersymmetric partners of the tau leptons ($\tilde{\tau}$). The results are presented in the plane of the $\tilde{\tau}$ mass vs the mass of the lightest gaugino, assuming the decay $\tilde{\tau} \to \tilde{\chi}_1^0 \tau$. No limit is available today from the LHC. All these exotic searches will be possible thanks to the large statistics, and to the improved performance of the upgraded detectors.

A further class of hard-to-detect signatures of new physics has recently gained great attention,[23] namely long-lived particles (LLPs). Particles with macroscopic lifetimes, in the range of several cm up to hundreds of meters, could be present in several BSM theories. Their detection challenges the standard triggers and reconstruction techniques, but new strategies, together with new features of the HL-LHC upgraded detectors (e.g. timing resolutions of $\mathcal{O}$(few tens) picoseconds), open new and exciting prospects. Dedicated detectors for HL-LHC are also being proposed for such searches. The HL-LHC datasets will allow to explore otherwise untestable scenarios.

1.3. *Final remarks*

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, were already seen, prior to their discovery, as 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 40 years were built to discover and study, in detail, these 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, today there is 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 3 of the LHC, or even in the subsequent phases of its upgrade. The programme of precision Higgs physics and continued exploration of EWSB is therefore the most concrete and robust deliverable that the LHC upgrade can promise, and whose future returns can be anticipated today.

The potential achievements of the HL-LHC programme presented in Ref. [10] will greatly enrich our knowledge of particle physics, even in absence of BSM discoveries, and by themselves motivate the upgrade effort. Alongside the few goals summarized here, a large set of ancillary measurements will take place, 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 observables and parameters of the SM. Among these, we mention the measurement of the top quark and W boson masses, and of the weak mixing angle $\sin^2\theta_W$.

The study of flavour physics, and of the properties of QCD matter at high-density, have also proven to be an essential complement to the Higgs and BSM physics studies, taking full benefit of the versatility of the beam configurations provided by the LHC. Flavour studies, and heavy ion collisions, do not rely directly on the highest possible pp luminosity. But recent studies have shown very clearly that these components of the LHC physics programme have a lot to gain from continued operations during the HL-LHC era. New targets for integrated luminosity have been set for the programme of flavour physics of the LHCb experiment,[14,24] and a strong physics case has been presented[15] to justify the extension of heavy ion collisions, including runs with lighter beam types. These demands pose new challenges to the HL-LHC project, but they underscore the great expectations built by the physics community as a result of the extreme success of LHC's operations to date.

The longevity of a hadron collider is a great asset, as the Tevatron, for example, has well illustrated. Following the discovery of the top quark, several of the Tevatron's most impressive legacy results, 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 all achieved within 20 years after the first collisions. The delivery of a slightly larger integrated luminosity, could have also enabled the Tevatron to discover the Higgs boson by the end of its Run 2. These examples underscore the potential of a hadron collider to deliver surprises over a very long life span, provided a sufficiently rapid luminosity doubling time is attainable. The HL-LHC project[25] will guarantee this longevity to the LHC programme.

References

1. G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **716** (2012) 1 [arXiv:1207.7214 [hep-ex]].
2. S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **716** (2012) 30 [arXiv:1207.7235 [hep-ex]].
3. F. Englert and R. Brout, Phys. Rev. Lett. **13** (1964) 321.
4. P. W. Higgs, Phys. Rev. Lett. **13** (1964) 508.
5. G. S. Guralnik, C. R. Hagen and T. W. B. Kibble, Phys. Rev. Lett. **13** (1964) 585.
6. S. L. Glashow, Nucl. Phys. **22** (1961) 579.
7. S. Weinberg, Phys. Rev. Lett. **19** (1967) 1264.
8. A. Salam, Weak and electromagnetic interactions - in Elementary particle physics: relativistic groups and analyticity, N. Svartholm, ed p. 367. Almqvist & Wiskell, 1968. Proceedings of the eighth Nobel symposium. Conf. Proc. C **680519** (1968) 367.
9. F. Gianotti, M. L. Mangano, T. Virdee, S. Abdullin, G. Azuelos, A. Ball, D. Barberis and A. Belyaev *et al.*, Eur. Phys. J. C **39** (2005) 293 [hep-ph/0204087].
10. A. Dainese, M. Mangano, A. B. Meyer, A. Nisati, G. Salam and M. A. Vesterinen, "Report on the Physics at the HL-LHC,and Perspectives for the HE-LHC," CERN Yellow Rep. Monogr. **7** (2019), doi:10.23731/CYRM-2019-007.
11. P. Azzi *et al.*, CERN Yellow Rep. Monogr. **7** (2019) 1 doi:10.23731/CYRM-2019-007.1 [arXiv:1902.04070 [hep-ph]].
12. M. Cepeda *et al.*, CERN Yellow Rep. Monogr. **7** (2019) 221 doi:10.23731/CYRM-2019-007.221 [arXiv:1902.00134 [hep-ph]].
13. X. Cid Vidal *et al.*, CERN Yellow Rep. Monogr. **7** (2019) 585 doi:10.23731/CYRM-2019-

007.585 [arXiv:1812.07831 [hep-ph]].

14. A. Cerri *et al.*, CERN Yellow Rep. Monogr. **7** (2019) 867 doi:10.23731/CYRM-2019-007.867 [arXiv:1812.07638 [hep-ph]].
15. Z. Citron *et al.*, CERN Yellow Rep. Monogr. **7** (2019) 1159 doi:10.23731/CYRM-2019-007.1159 [arXiv:1812.06772 [hep-ph]].
16. J. L. Abelleira Fernandez *et al.* [LHeC Study Group], J. Phys. G **39** (2012) 075001 doi:10.1088/0954-3899/39/7/075001 [arXiv:1206.2913 [physics.acc-ph]].
17. S. Chatrchyan *et al.* [CMS Collaboration], Phys. Rev. Lett. **110** (2013) 081803 [arXiv:1212.6639 [hep-ex]].
18. G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **726** (2013) 120 [arXiv:1307.1432 [hep-ex]].
19. B. Bellazzini, C. Csáki and J. Serra, arXiv:1401.2457 [hep-ph].
20. G. Aad *et al.* [ATLAS Collaboration], Phys. Rev. D **101** (2020) no.1, 012002 doi: 10.1103/PhysRevD.101.012002 [arXiv:1909.02845 [hep-ex]].
21. A. M. Sirunyan *et al.* [CMS Collaboration], Eur. Phys. J. C **79** (2019) no.5, 421 doi: 10.1140/epjc/s10052-019-6909-y [arXiv:1809.10733 [hep-ex]].
22. D. Curtin, R. Essig, S. Gori, P. Jaiswal, A. Katz, T. Liu, Z. Liu and D. McKeen *et al.*, arXiv:1312.4992 [hep-ph].
23. J. Alimena *et al.*, arXiv:1903.04497 [hep-ex].
24. LHCb Collaboration, R. Aaij et al., Physics case for an LHCb Upgrade II - Opportunities in flavour physics, and beyond, in the HL-LHC era, arXiv:1808.08865.
25. Rossi, Lucio (ed.) (CERN); Brüning, Oliver (ed.) (CERN), “The High Luminosity Large Hadron Collider: the new machine for illuminating the mysteries of Universe”, World Scientific (2015) doi:10.1142/9581.