Collider physics at the intensity and energy frontier – the HL-LHC and beyond

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Abstract. The LHC results have set the stage for the discussion of future high-energy physics facilities. The Higgs boson discovery, with the need of precise measurements of its properties, and the current absence of experimental evidence for new physics open a discussion on the best ways to move forward. This document summarises recent sensitivity studies for the HL-LHC physics programme and compares them with the opportunities offered by possible future circular collider facilities. The physics potential is highlighted through observation of new particles, new phenomena and precision measurements of Standard Model quantities.

1. Introduction
The discovery of the Higgs boson in 2012 opened up a wide range of possibilities to study the Standard Model (SM) electroweak (EW) sector and constrain, or possibly discover, an incredible variety of new physics (NP) scenarios. Such NP scenarios are motivated by longstanding problems such as EW naturalness, dark matter (DM), the flavour problem, neutrino masses, the strong CP problem, and baryogenesis. Many solutions to these outstanding issues predict the existence of new particles, which can be searched for at collider facilities.

The successful operation of the Large Hadron Collider (LHC) and the excellent performance of the ATLAS [1], CMS [2], LHCb [3] and ALICE [4] detectors were key in allowing a plethora of physics studies exploring the high-energy particle physics frontier. The LHC will undergo a major upgrade in the 2020s, the High-Luminosity LHC (HL-LHC), in order to collide protons against protons at 14 TeV centre-of-mass energy with an instantaneous luminosity a factor of five greater than the LHC. The HL-LHC is expected to deliver ten times more data than the LHC to the experiments, resulting in an integrated luminosity of \(3 \text{ ab}^{-1}\).

The absence of experimental evidence of the presence of NP opened, in the last few years, a discussion on the best ways to move forward with collider experiments beyond the HL-LHC. Several proposals and studies have been made, also aiming for the forthcoming update of the European Strategy for Particle Physics (ESPP) that will take place in 2019-2020. Various options for future colliders are being considered, such as:

- lepton colliders, either linear \(e^+e^-\) machines like ILC and CLIC, or circular \(e^+e^-\) like the FCC-ee;
- hadron \(pp\) colliders, e.g. a 27 TeV centre-of-mass upgraded HE-LHC, or a 100 TeV FCC-hh;
- lepton-hadron colliders, e.g. the LHeC or an analogous facility to be hosted at the FCC.
This document highlights some contributions prepared for the update of the ESPP, summarises the physics reach of the HL-LHC in the realms of precision SM measurements and direct NP searches, and provides some highlights of the potential of possible future collider facilities.

2. Precision measurements

The analysis of LHC data has confirmed the immense physics potential of the LHC to perform very precise and sensitive measurements, in spite of the highly challenging experimental environment. Some examples of this are provided by the progress made in the exploration of the Higgs sector, where the couplings to EW gauge bosons and to all charged third-generation fermions have been established with a statistical significance of more than five standard deviations. This remarkable result has been achieved through percent-level measurements of several SM cross sections and distributions, and by the precise determination of the top quark and W boson masses.

Precision measurements provide an important tool to search for NP associated to mass scales beyond the LHC direct reach. Collecting a dataset with large integrated luminosity will give access to the rarest phenomena, and will be critical to reduce systematic uncertainties or bypass their limitations with new analyses, leading to measurements of unanticipated precision. This section will present a few examples of how the HL-LHC dataset could be exploited to determine key quantities of the SM EW sector.

2.1. Measurement of electroweak bosons

The most precise measurements of the weak mixing angle $\sin^2 \theta_{\text{eff}}$ were performed by the LEP and SLD experiments. Those determinations, however, differ by over three standard deviations. A precision extraction using HL-LHC data can help settle this long-standing issue, giving insight into the source of tension between LEP and SLD, whether this is the result of systematics, or of new physics. The CMS Collaboration presented a prospect for this measurement [5] using a template fit of the forward-backward asymmetry $A_{\text{FB}}$ in Drell-Yan dimuon events as a function of the muon pair invariant mass and rapidity. The expected sensitivity from the CMS measurement is shown in Fig. 1. The statistical precision of $\sin^2 \theta_{\text{eff}}$ measurements with ATLAS, CMS and LHCb will be better than $5 \cdot 10^{-5}$. The overall uncertainty is expected to be dominated by the parton distribution functions (PDF), which can be reduced below $16 \cdot 10^{-5}$ using in-situ constraints, with an overall uncertainty below $18 \cdot 10^{-5}$. The PDF uncertainty on $\sin^2 \theta_{\text{eff}}$ can be reduced by 10% – 25% using the global fits to HL-LHC data. Data from the LHeC collider could strongly reduce the PDF uncertainties by an additional factor of 5.

Another key target of the LHC, investigated by the ATLAS Collaboration in Ref. [6], is to improve the knowledge of the W boson mass ($m_W$). Thanks to the foreseen detector upgrades, the HL-LHC will greatly reduce the systematic uncertainties, by limiting the PDF sensitivity via the extended lepton coverage of $|\eta| < 4$. PDF constraints coming from the HL-LHC data will also be crucial in reducing the uncertainties associated to this measurement. Dedicated low-pileup runs will provide the required conditions to optimize the reconstruction of the boson recoil system. Five to ten weeks of data taking in the course of the HL-LHC are expected to lead to a statistical precision of about 3 MeV. Experimental systematic uncertainties are largely of statistical nature, and with adequate efforts and exploiting the full available data sample, their impact can be maintained at a level similar to the statistical uncertainty. Assuming the extended lepton coverage allowed by the HL-LHC detectors, the impact of PDF uncertainties on the $m_W$ measurement would be in the range of 5-8 MeV. Similarly to the previous measurement, these uncertainties could be reduced to about 4 MeV when using the PDF global fits to HL-LHC data, leading to an overall HL-LHC target of $\Delta m_W = \pm 6$ MeV. LHeC measurements could further reduce the PDF systematics to 2 MeV.
Figure 1. From Ref. [5]: projected statistical, nominal PDF and constrained PDF uncertainties in $\sin^2 \theta_{\text{eff}}$ extracted by fitting $A_{FB}(m_{\mu\mu}, y_{\mu\mu})$ distributions at $\sqrt{s} = 14$ TeV with different values of integrated luminosities and for $|\eta| < 2.4$ and $|\eta| < 2.8$ acceptance selections for the muons.

The measurement of production of pairs or triplets of EW gauge boson will be of great importance to test the mechanism of EW symmetry breaking, since it can signal the presence of anomalous EW couplings, and of new physics at energy scales beyond the reach of direct resonance production. First observations of EW multiboson interactions have recently been achieved in vector boson scattering of $WW$ and $WZ$ and we expect a fuller picture to be accessible at the HL-LHC. The study of the scattering of a pair of $Z$ bosons was investigated by the ATLAS Collaboration in Ref. [7]. Under the assumption of the theoretical uncertainty being constrained at the 5% level for QCD-$ZZjj$ processes, the observation of the EW-$ZZjj$ process can be reached with a significance of 7 standard deviations. For the integrated cross-section measurements of EW-$ZZjj$ processes, the precision could reach a level of 20% with the assumption of 5% theoretical uncertainty on QCD-$ZZjj$ processes.

2.2. Higgs properties

The determination of Higgs boson properties is one of the primary targets of the HL-LHC physics programme. These will be measured considering five Higgs boson production modes (gluon fusion $ggF$, vector boson fusion VBF and associated productions $WH$, $ZH$ and $ttH$) and seven decay modes: $H \to \gamma\gamma$, $ZZ^\ast$, $WW^\ast$, $\tau^+\tau^-$, $bb$, $\mu^+\mu^-$ and $Z\gamma$. The latter two decay channels, as yet unobserved, should become visible, in the SM, during the next two LHC runs [8]. The rates measured for the various production and decay channels yield measurements of the Higgs couplings in the so-called “$\kappa$-framework”. This framework consists of a set of $\kappa$ factors that linearly modify the coupling of the Higgs boson to SM elementary particles, including the effective couplings to gluons and photons assuming no additional NP contribution to the Higgs total width.

Figure 2 shows the expected $\kappa_i$ measurement precision, as evaluated by the CMS Collaboration in Ref. [9]. The main Higgs boson couplings will be measured at HL-LHC with a precision around the percent level. Large statistics will particularly help the study of complex final states, such as those arising from $ttH$ production. The constraining power of the current
Figure 2. From Ref. [9]: summary plot showing the total expected ±1σ uncertainties in S1 (with Run-2 systematic uncertainties) and S2 (with Yellow Report 18 systematic uncertainties) on the coupling modifier parameters $\kappa_i$ for 3000 fb$^{-1}$. The statistical-only component of the uncertainty is also shown.

$ttH$ analyses has been limited to plausible improvements in the theory predictions, in particular in the $H \to bb$ channel. The 3.4% precision on $\kappa_t$ thus obtained is mostly due to the other direct $ttH$ measurement channels.

The full characterisation of the shape of the Higgs potential in the SM Lagrangian will only be achieved with the measurement of the triple- and quartic-Higgs boson couplings, which are related to the Higgs boson mass and vacuum expectation value. The observation of Higgs boson pair production is key to measure the Higgs boson self-coupling. The Run-2 experience in searches for Higgs pair production led to a reappraisal of the HL-LHC sensitivity, including several channels, some of which were not considered in previous projections: 2$b\gamma$, 2$b\tau$, 4$b$, 2$bWW$, 2$bZZ$. ATLAS and CMS project a relatively limited sensitivity to the $HH$ signal of approximately 3 standard deviations per experiment [10]. The results on $HH$ production studies are statistics limited, therefore a dataset of at least 6 ab$^{-1}$ (ATLAS and CMS combined) is essential to achieve this objective. Future collider facilities like for example the FCC-hh will be able to measure the Higgs boson self-coupling at the level of 3% [11].

3. Beyond Standard Model Searches
The lack of evidence for the presence of NP in the current data implies that either NP is not where we expect it, or that it is more subtle. NP may be hiding at a slightly higher mass scale or behind a lower interaction strength than we expected or, perhaps, in more experimentally
involved signatures, making it extremely difficult to observe. All these cases could lead to a
discovery happening at the edge of the LHC potential, with little space left for identifying and
studying the new particles.

The HL-LHC and future collider facilities will offer new possibilities to test many NP
scenarios. This section will present a few examples considering both supersymmetric (SUSY)
simplified models, resonances and additional results on dark matter and dark sectors.

3.1. Supersymmetry

The extension of the kinematic reach for SUSY searches at the HL-LHC is expected foremost in
the sensitivity to EW states. Studies under various hypothesis have been performed, including
prompt and long-lived SUSY particle decays. Compressed SUSY spectra are theoretically well
motivated but are among the most challenging scenarios experimentally, and are barely covered
by the Run-2 analyses. In Ref. [12], the ATLAS Collaboration investigated the sensitivity of
HL-LHC searches to pairs of higgsino-like electroweakinos exploiting low momentum leptons or
long-lived charginos that can decay after the inner layers of the tracking detectors. The resulting
expected sensitivity is shown in Fig. 3.

\[ \Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0), \Delta m(\tilde{\chi}_2^\pm, \tilde{\chi}_2^0) \text{ production, } \tan\beta = 5, \mu > 0 \]

Pure Higgsino discovery

\[ \sigma_5 \text{ Expected limit} \]

Disappearing tracks

Soft leptons

LEP2 exclusion

Theory

**Figure 3.** From Ref. [12]: expected exclusion reach at the 95% CL in higgsino models in the
\( \Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0), \Delta m(\tilde{\chi}_2^\pm, \tilde{\chi}_2^0) \) mass plane. The blue curve presents the exclusion limits from a search for
low momentum lepton pairs. The yellow contour presents the exclusion limit from a search for
disappearing inner detector tracks. The figure also presents the limits on chargino production
from LEP [13]. The relationship between the masses of the chargino and the two lightest
neutralinos in this scenario is \( m(\tilde{\chi}_1^\pm) = 1/2(m(\tilde{\chi}_1^0) + m(\tilde{\chi}_2^0)) \). The theory curve is a prediction
from a pure higgsino scenario taken from Ref. [14].

In the strong SUSY sector, HL-LHC will probe gluino masses up to 3.2 TeV, with discovery
reach around 3 TeV, in R-parity conserving scenarios and under a variety of assumptions on
the gluino prompt decay mode. Future colliders exploiting larger centre-of-mass energies will
be able to extend the reach at high masses up to about 5 TeV (HE-LHC) and about 10.5 TeV (FCC-hh) \[15\].

3.2. **Resonances**
Studies of resonance searches have been performed in a variety of final states. Notable examples, which are often used as standard benchmarks in studying the potential of future colliders, are heavy vector resonances. These are neutral $Z'$ and charged $W'$. The CMS Collaboration investigated the HL-LHC sensitivity to right-handed $W'$ bosons by looking for $W'_R \rightarrow t\bar{b}$ decays. The final-state signature consists of two $b$-quarks, one charged lepton and momentum imbalance from the presence of the neutrino. Assuming SM couplings, the existence of $W'_R$ can be excluded (discovered) for masses up to 4.9 (4.3) TeV.

3.3. **Dark Matter**
Compressed SUSY scenarios, as well as other DM models, can be targeted using signatures such as mono-jet, mono-photon and vector-boson-fusion production. Projections for searches for a mono-$Z$ signature, with $Z \rightarrow \ell^+\ell^-$ recoiling against missing momentum, have been interpreted in terms of models with two Higgs doublets and an additional pseudo-scalar mediator that couples to DM (2HDMa) by the CMS Collaboration \[16\]. The expected limits are shown in Fig. 4. The results are expected to be about a factor of three better than the 36 fb$^{-1}$ Run-2 constraints when considering mediator masses up to 1.5 TeV, and for DM and pseudo-scalar masses up to 600 GeV.

**Figure 4.** From Ref. \[16\]: expected 95\% CL exclusion limits on the signal strength of vector-mediated DM production in the plane of mediator and dark matter masses. The $m_{med} = 2 \times m_{DM}$ diagonal, which is the kinematic boundary for decay of an on-shell mediator to DM particles, is indicated as a grey line. The white line indicates parameter combinations for which the observed DM relic density in the universe can be reproduced.
The case of 2HDMa models is complemented by 4-top final states in a study performed by the ATLAS Collaboration [17], considering events with two same-charge leptons, or with at least three leptons. The HL-LHC dataset will allow to probe possible evidence of a signal with $\tan \beta = 1$, $m_H = 600$ GeV assuming $m_a$ masses between 400 GeV and 1 TeV, and will allow exclusion for all $200 \text{ GeV} < m_a < 1 \text{ TeV}$.

More generic simplified models which couple the dark and Standard Model sectors via the exchange of colour-neutral spin-0 mediators, assuming unitary couplings have also been considered [18]. Compared to a previous search conducted with 36.1 fb$^{-1}$ of data at $\sqrt{s} = 13$ TeV, the reach achievable for dark matter detection in events with top quarks extents by a factor of 5 when considering scalar mediators. For each dark matter and mediator mass pair, the exclusion limit on the production cross-section of colour-neutral scalar mediator particles can be converted into a limit on the spin-independent DM–nucleon scattering cross-section, highlighting a nice (although model-dependent) case of complementarity between collider and direct detection experiments. Figure 5 shows the resulting constraints in the plane defined by the dark-matter mass and the scattering cross-section, which are derived considering only models with scalar mediators.

Figure 5. Comparison of the 90% CL limits on the spin-independent DM-nucleon cross-section as a function of DM mass between these results and the direct-detection experiments, in the context of the colour-neutral simplified model with scalar mediator. The green contour indicates the 5$\sigma$ discovery potential at HL–LHC. The lower horizontal line of the DM–nucleon scattering cross-section for the red (green) contour corresponds to value of the cross section for $m(\phi) = 430$ GeV ($m(\phi) = 105$ GeV). The results are compared with limits from direct detection experiments and the exclusion derived from the observed limits for 36.1 fb$^{-1}$ at 13 TeV.
4. Conclusions

The excellent performance of the LHC has allowed to discover a new particle, the Higgs boson, and to start to measure its properties. In the data analysed so far there are no clear deviations from the predictions of the Standard Model. Nonetheless, it is possible that new physics could still emerge from the current LHC dataset, or that some of the existing small deviations could grow. It is also possible that the new physics has small production cross sections either because it is weakly coupled to the initial state at the LHC, or because it is heavy, or both.

Either way, a combined programme of precision measurements of Standard Model quantities and direct searches for new physics is the most promising way forward. Weakly coupled states within kinematic reach of the LHC may require increased data sets to uncover, such as the 3 ab\(^{-1}\) of the HL-LHC. Heavy states instead might require new collider facilities like the HE-LHC and FCC-hh that could provide both increased centre-of-mass energies and increased luminosity.

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