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Chapter 27

Physics at Higher Energy at the Large Hadron Collider

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1. Introduction

The High Luminosity LHC programme will have reached its completion by around 2040, resulting in outstanding measurements of fundamental SM parameters and studies of the heavy-flavour sector, as well as extensive searches for new physics at the energy frontier. Even if not a discovery, the HL-LHC will have provided a unique understanding of the Higgs boson properties and their relation to the EWSB mechanism, the potential observation of the SM Higgs-pair production process, and the exploration of a variety of BSM scenarios, including new resonances, additional Higgs bosons, candidates for dark matter, feebly-interacting new particles arising in a hidden sector, and lepton flavour violation. The direct reach in mass and coupling for most new particles predicted by beyond SM theories will have increased by at least 20–50% thanks to the large *pp* datasets collected by ATLAS and CMS, and the LHCb programme will have enabled precision searches for BSM physics through loop processes at unprecedented level. High-density QCD studies with ion and proton beams will have allowed characterisation of quark-gluon plasma properties. Finally, a suite of non-collider experiments,[1,2] if realised, will have provided exciting opportunities to complement the LHC programme in searches for feebly-interacting particles and measurements of high-energy neutrinos produced at the LHC.

The possibility of increasing the centre-of-mass energy of the LHC machine, turning the current accelerator complex into a High Energy (HE) machine, is certainly an appealing option for a future hadron collider project at CERN after the end of the High Luminosity physics programme. A HE-LHC immediately following the HL phase would allow collection of large *pp* datasets at a centre-of-mass energy at least two times that of the HL-LHC for both *pp* ($\sqrt{s}$ = 27–30 TeV) and heavy-ion collisions (*PbPb*: $\sqrt{s_{NN}} = 10.6$ TeV; *pPb*: $\sqrt{s_{pN}} = 17$ TeV). This would lead to a substantial extension of the HL-LHC reach in direct searches for new physics, approximately doubling the reach in mass of potential new particles. Through energy recovery technologies, collisions of one of the proton or ion beam from the HE-LHC with an intense electron beam ($E_e = 60$ GeV) could allow concurrent electron-proton (HE-LHeC[3]) and proton-proton operations, extending the reach of deep-inelastic scattering to unprecedented high centre-of-mass energies (*ep*: $\sqrt{s} = 1.7$ TeV, *ePb*: $\sqrt{s} = 1.1$ TeV). Finally, the infrastructure, yet to be build, hosting forward-physics, non-collider experiments could be exploited further.

In this chapter, the physics reach of a possible upgrade of the LHC to high energies is presented, with emphasis given to its discovery potential and its perspective value for the future of particle physics. The studies mostly refer to those performed in preparation for the European Strategy for Particle Physics update (ESPPU) process[4,5] and during the Snowmass and Particle Physics Project Prioritization Panel (P5) process.[6]

2. The High Energy LHC Physics Potential: an overview

One of the primary objectives of a HE-LHC programme would be to establish the structure of the symmetry-breaking Higgs potential through measurements of the Higgs self-coupling, and improve the precision of the HL-LHC measurements on Higgs properties, EW and flavour sectors. Concurrent *ep* operations would complement the results of *pp* experiments, offering unique access to rare Higgs decay modes in a relatively clean environment, and providing precision measurements of fundamental EWK SM parameters and PDFs. The latter is particularly relevant for classification of the strong interactions dynamics, especially at high parton densities (low-x). In the context of new physics models, if tentative signs of discovery arise from the LHC experiments by the end of the HL programme, the HE-LHC could corroborate the signs of discovery, and allow exploration of their properties in greater detail. Much better sensitivity to dark matter and hidden sectors could be achieved depending on the models. In case new phenomena are revealed indirectly, i.e. through anomalies or deviations from SM predictions, or in other experiments (e.g. DM, neutrino or LFV experiments), the HE-LHC experiments could study and possibly identify their underlying origin — even more effectively by considering *pp* and *ep* collisions together. Finally, heavy-ion increased centre-of-mass collisions and *ePb* collisions would offer an excellent endeavor for the studies of denser and hotter strongly-interacting systems.

The physics potential of a HE-LHC facility is depicted through examples[7] of expected results for measurements of the Higgs boson properties,[8] searches for new physics,[9] including scenarios considered to quantify the HE-LHC's ability to characterise potential new physics, precision measurements[10,11] in the EW and flavour sectors, and heavy-ion physics measurements.[12] Rather than a direct comparison with the obviously more powerful and ambitious FCC-hh project, the expected benefits that a HE facility will bring after the HL-LHC has finished operation are emphasised.

No detailed design for a HE-LHC detector is currently available. The experimental environment in terms of radiation flux, track densities and event pile-up is expected to be more challenging than the one at the HL-LHC, but less demanding than the one at the FCC-hh. Hence, while upgrades of the detector designs and novel technologies may be needed — especially for the innermost tracking systems, it is not inconceivable that currently available or in-development approaches can be adopted, *i.e.* for outer trackers, calorimeter systems and muon detectors. At this stage, physics studies assume the typical performances of the ATLAS and CMS HL-LHC detectors for *pp* collisions, modelled by a simplified simulation software, and neglecting the impact of the expected higher pile-up. For an electron-proton(ion) experiment, the detector dimensions and acceptances scale with the logarithm of the proton energy, such that the same technologies and very similar resolution assumptions can be made for a HL and a HE *ep* detector. It should also be noted that in some cases, the physics studies are simply of a phenomenological nature, or extrapolated from (HL-)LHC (prospective) current results. The integrated luminosity benchmark is set at 15 ab^{-1} for *pp* and 1 ab^{-1} for *ep*, to be compared with 3–4 ab^{-1} at HL-LHC and 0.001 ab^{-1} delivered at the first *ep* collider HERA. This is consistent with the accelerator projections and with the possibility to combine the results of two experiments for *pp* and one experiment for *ep*, respectively.

3. Higgs properties and EW symmetry breaking

The study of the Higgs boson properties and their connection to EW symmetry breaking will remain one of the most important targets of particle physics well beyond the HL-LHC. At the HE-LHC, the reach of the Higgs physics programme will be substantially extended; the number of collected Higgs events will increase by a factor between 10 and 25 (depending on the production process), with the largest increases occurring for the production of a Higgs boson in association to top-quark pairs, and for Higgs boson pair production.

3.1. *Higgs boson couplings to bosons and fermions*

Measurements of Higgs boson couplings to photons, gluons, W, Z, taus, and b-quarks at HE-LHC will reach a percent-level precision by virtue of the increase in Higgs boson production rates. Higher yields will lead to an overall reduction in the statistical uncertainties of Higgs boson properties measurements by factors of 3 to 5, with the biggest improvements occurring for the $t\bar{t}H$ channel where the HL-LHC is statistically limited. Couplings to top quarks through the study of $t\bar{t}H$ processes could be measured with a 3% precision, which could be further reduced to 1–2% measuring ratios of couplings (e.g. $t\bar{t}H$ to $t\bar{t}Z$ ratio). The overall precision in Higgs boson couplings to bosons and fermions at HE-LHC will be limited by the theoretical uncertainty on the signal predictions, hence significant improvements in the precision of theoretical calculations will be required. In this respect, the concurrent operations of a HE-LHeC, for example, would lead to substantially improved PDFs and α_S measurements that can, in turn, provide a significant boost to the achievable precision of Higgs boson properties. Standalone measurements of the Higgs boson coupling to b-quarks at the HE-LHeC would also allow the $H \to b\bar{b}$ signal strength to be constrained to less than 1%.

The available HE-LHC statistics will also considerably improve the sensitivity to elusive or rare decays (i.e. Higgs boson decay into second generation quark or lepton pairs, or into a Z-boson and a photon), and to hypothetical invisible decays (i.e. Higgs boson decay into a pair of dark matter candidates). For rare processes, such as the decay into a muon pair, a precision of approximately 2% on the coupling could be achievable, whilst for Higgs boson decaying into a charm-quark pair, inclusive searches similar to the ones carried out at the LHC could offer good sensitivity since the signal to SM background ratio is improved at HE-LHC. The HE-LHeC would measure the Higgs to charm quarks decay to 4%, giving the possibility of setting sensible constraints on the Higgs interactions with charm quarks.[3]

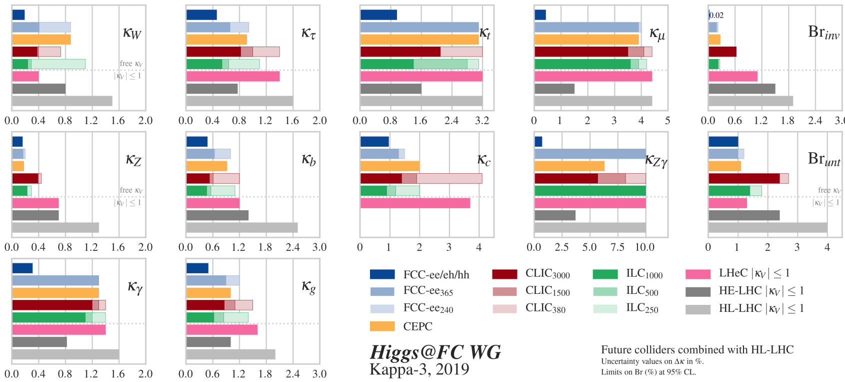

Fig. 1. Expected relative precision of the κ parameters and 95% CL upper limits on the branching ratios to bosons, fermions, and invisible and untagged particles for various colliders. The HE-LHC prospect results are depicted in dark gray. All future colliders are combined with HL-LHC. From Ref. 13.

The expected precision for each coupling, including that to invisible particles, can be expressed via the κ framework introduced in Chapter 15 about the Higgs Chapter. Figure 1 shows the relative precision of the κ parameters and 95% CL upper limits on the branching ratios to bosons, fermions, and invisible and untagged particles for various colliders. HE-LHC prospects, combined with HL-LHC results, are especially competitive for couplings involving top-quarks or rare decays. The figure also depicts prospects from the *ep* facility proposed for HL (LHeC) which are estimated to reach half of the HE-LHC uncertainty, as presented in Ref. 3.

The significantly larger dataset and the increase in centre-of-mass energy at the HE-LHC would allow measurement of differential Higgs boson production cross sections, which are sensitive probes for physics beyond the SM. Thus far, projections and results obtained depend on the assumed detector layout due to challenging pile-up conditions. However, it is unambiguous that sufficient statistics could be collected to perform searches for new physics through deviations from SM predictions of high-transverse momenta Higgs boson production, especially in the gluon-gluon fusion loop — the dominant Higgs boson production mechanism at *pp*.

3.2. *Higgs boson self-coupling and rare decays*

The statistics available for Higgs boson pair production (HH) process at the HE-LHC will be about 20 times higher than at the HL-LHC, allowing

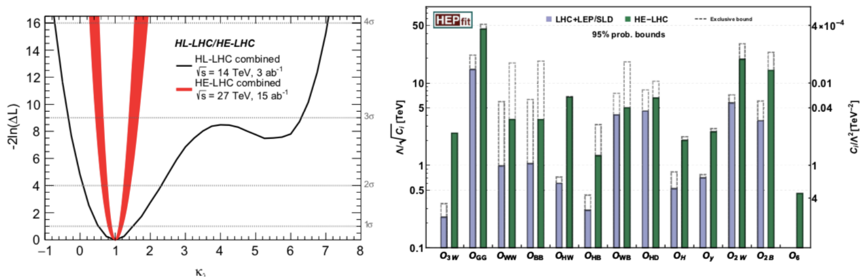

Fig. 2. Left: Projected precision for the measurement of the Higgs trilinear coupling through the measurement of Higgs pair production via gluon-gluon fusion at the HE-LHC. The HL-LHC is shown for comparison. Right: Summary of constraints on the EFT operators considered. The shaded bounds arise from a global fit of all operators, those assuming the existence of a single operator are labeled as "exclusive". From Ref. 5.

constraint and measurement of Higgs boson trilinear coupling, λ_{HHH}, with considerable precision. Sensitivity studies have been carried out on the basis of the methods and channels considered at the HL-LHC, in particular considering one Higgs boson decaying into a pair of b quarks and the other into a pair of photons or of tau leptons ($b\bar{b}\tau^+\tau^-$ and $b\bar{b}\gamma\gamma$ channels, respectively). The results are reported in Fig. 2(left). At the HE-LHC the HH signal would be observed unambiguously, leading to a precision in λ_{HHH} of 10–20% just by combining these two channels, assuming no BSM contributions. The second minimum of the likelihood distribution would be unambiguously excluded at the HE-LHC. Additional sensitivity to the Higgs self-coupling is expected when other channels are also considered, such as if both Higgs bosons decay into a b-quark pair, or if one decays into a pair of W-bosons, or considering rarer decays that could become relevant at the HE-LHC and when adding the sensitivity of ep-based studies. Therefore, the HE-LHC could be the most realistic option to access the Higgs potential without considering any future colliders.

Several BSM theories predict deviations from the SM Higgs couplings, which would be sizable at the HE-LHC. The Higgs boson could decay into invisible particles (DM candidates) or into particles decaying promptly or long-lived and belonging to a wider hidden sector, such as light scalars, dark photons or axion-like particles. Direct searches for these exotic rare Higgs decays would result in a substantially higher reach than at the HL-LHC, and branching ratios one or two order of magnitude smaller could be probed. Precision measurements of the Higgs properties can also help to constrain new physics models. Within the effective field theory (EFT) framework, where the SM Lagrangian is supplemented with higher dimension operators, BSM effects can be systematically parametrised and their deviations from SM processes, estimated. Figure 2(right) shows the summary of constraints on the EFT operators comparing LHC and HE-LHC reaches. Constraints on the operators can translate into sensitivity to new physics models: for example, at the HE-LHC a Higgs compositness scale below 2 TeV would be excluded, corresponding to a new physics mass scale of 25 TeV for an underlying strongly coupled theory.

4. Searches for new physics

The HE-LHC is expected to double the mass reach for the discovery of new particles, when compared to the HL-LHC. In several interesting new physics scenarios this is sufficient to cover a large fraction of the relevant parameter space. This covers SUSY models based on the principle of naturalness, extended Higgs sector models and DM models predicting the presence of mediator particles. Direct searches for heavy new particles can be complemented by precision studies of SM observables, and deviations from predictions can provide evidence of new physics. The copious amount of HE-LHC datasets would enable these studies such that, in the possible absence of direct observation of new physics, the EFT formalism could provide a framework to study BSM physics that is realized at a scale Λ much larger than the collider $\sqrt{s}$. In the following, a few examples of direct searches for new physics possible at HE-LHC are given, focusing on new heavy resonances, supersymmetric particles and dark matter candidates. In the case of heavy resonances, a brief description of how possible future discoveries at the LHC could be further scrutinised at the HE-LHC is also given.

4.1. *New resonances*

Several BSM theories, ranging from new models of EWSB to extensions of the SM gauge group, predict multi-TeV resonances to exist. Typical scenarios include singly-produced resonances with integer spin, or pair-produced heavy resonances. Since direct access requires the centre-of-mass energy of the collider to be large enough to produce them, searches of this kind greatly benefit from the increased energy of the HE-LHC. A qualitative estimate of the improved sensitivity with respect to the expected HL-LHC reach can be obtained by extrapolating the partonic luminosities that are

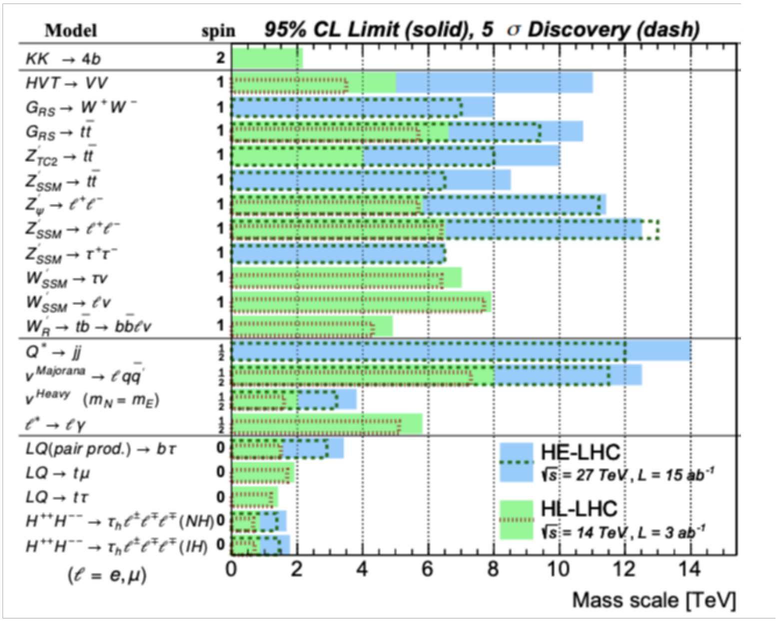

Fig. 3. Summary of the expected mass reach for 5 σ discovery and 95% C.L. exclusion at the HE-LHC (blue) as a result of feasibility studies carried out on a variety of models predicting new resonances. Results for HL-LHC are also depicted in green. From Ref. 9.

relevant for the production of various final states. In general, for a system mass that can be probed in searches for new particles at HE-LHC and given an established reach at HL-LHC, an approximate factor of two increase in mass reach is expected.

Dedicated studies for specific new physics models verify (if not exceed in reach) qualitative results obtained via extrapolation. Figure 3(right) shows a summary of the expected mass reach for 5σ discovery and 95% CL exclusion at the HE-LHC as a result of feasibility studies carried out on a variety of models predicting new resonances and documented extensively in Ref. 9. The HL-LHC projections are also shown. One of the most widely used benchmark scenarios predicts a new high-mass vector (spin-1) boson, the Z', whose couplings to SM quarks and leptons are assumed either as in the SM (SSM) or modified (ψ, TC2). Di-leptonic and di-top-quark final state events are searched for resonances and results are interpreted depending on the couplings, with the best discovery reach (13 TeV) achieved for a SSM Z' in the dilepton (e^+e^-, $\mu^+\mu^-$) channel. In the di-tau channel, where hadronic τ reconstruction is more challenging, the discovery reach is about 6 TeV. In the di-top channel, a Z' decaying into a top-quark pair could be discovered up to 6 TeV and excluded up to 8 TeV. The same search interpreted in terms of Randall–Sundrum Kaluza–Klein heavy particles lead to a sensitivity up to 10.7 TeV. This is a 4 TeV extension with respect to HL-LHC and discovery of masses up to around 10 TeV would be possible. The HE-LHC would approximately double the HL-LHC mass reach for dijet resonances. For instance, the reach for an excited quark Q^* decaying to two jets will be improved to 14 TeV, with discovery potential up to 12 TeV. Expected sensitivity on the production and decay of spin-0 and -2 particles decaying into several different SM final states are also studied. Models considered include, among others, resonant double-Higgs production and heavy scalar singlets that could mix with the Higgs boson. Leptoquark (LQ) models, that can give rise to lepton universality violating decays of heavy mesons at tree level, are also studied for couplings to b-quark and τ or μ leptons. Masses up to about 3 TeV can be reached at the HE-LHC for τ final states, while reinterpretations of Z' searches in LQ models in $b\mu$ final state events indicate that masses up to about 4 TeV can be excluded, depending on the coupling's strength (2 TeV at HL-LHC).

The Z' has been used as reference to evaluate the capability at HE-LHC to determine the nature and properties of a new hypothetical di-leptonic resonance if discovered at the HL-LHC in the e^+e^- or $\mu^+\mu^-$ channels. This is because, as opposed to supporting evidence or claiming a discovery, the complete identification of the properties of a new particle requires large datasets and possibly higher centre-of-mass energy. Results show that high statistics HE-LHC samples are sufficient to study angular and rapidity distributions and discriminate different models of Z' by exploiting forward-backward asymmetry and other observables.

4.2. *Supersymmetry*

Despite the excellent sensitivity of searches in the strong and electro-weak sectors, supersymmetry might remain elusive at the HL-LHC. As one of the most plausible beyond the SM scenarios, providing the only known dynamical solution to the Higgs naturalness problem that can be extrapolated up to very high energies, a potential DM candidate, and the possible reconciliation of gravity and other forces, supersymmetry will certainly be at the core of the HE-LHC programme. Similarly to many scenarios of new physics, SUSY presents a spectrum of multiple states distributed over a broad mass range such that, in case a deviation from SM predictions is found at HL-LHC, the doubling of the LHC energy will be crucial to complement a discovery.

The increase in centre-of-mass energy leads to a large increase in the production cross section of heavy coloured states, such that a 3.5 TeV gluino has a nearly 400-fold increase in production cross section. For supersymmetric spectra without compression, the HE-LHC has 95% CL sensitivity to gluinos up to masses of 6 TeV and a discovery potential up to 5.5 TeV. If the coloured states are close in mass to the lightest supersymmetric particle (LSP), the amount of missing transverse momentum is decreased. Prospect studies in such a compressed scenario show that if, for example, the gluino-LSP mass splitting is assumed to be 10 GeV, gluino masses can be excluded up to 2.6 TeV exploiting the so-called monojet searches. Exclusion and discovery reaches for top squarks are up to 3.5 TeV and 3 TeV, respectively. If the top-squark and the LSP masses are close, final states include very off-shell W and b-jets, and masses up to about 1 TeV could be excluded, extending the HL-LHC reach by about a factor of two. Results of this kind would certainly shed light on "natural" supersymmetric models, and potentially discover or exclude them conclusively.

The SUSY electroweak sector presents a considerable challenge for any proton-proton collider, due to the chargino and neutralino (collectively called ewkinos) cross sections depending on the mixing parameters and typically much smaller than those of coloured SUSY particles. If the LSP is a pure higgsino or wino, a very small neutralino-chargino mass splitting is expected (340 MeV or 160 MeV, respectively) and the chargino has a correspondingly long lifetime ($c\tau \simeq 5$ or 1 cm, respectively). The value of the missing transverse momentum is small unless the produced electroweakinos recoil against an ISR jet. A search for monojet signature would give a sensitivity for exclusion (discovery) of winos up to about 600 GeV (300 GeV) and of higgsinos up to about 400 GeV (150 GeV). Taking advantage of the long lifetime of the charginos, searches for disappearing charged tracks can also be performed. Considering a detector similar to the ones available for HL-LHC, winos below 1.8 TeV (1.5 TeV) can be excluded (discovered), while the equivalent masses for higgsinos are 500 (450) GeV (see Fig. 4). Sensitivity to disappearing track signatures relevant for SUSY models at intermediate or shorter lifetime can be complemented by HE-LHeC searches, thanks to the absence of pile-up and the low levels of backgrounds. Feasibility studies[3] have been carried out for LHC- and FCC-like proton beam

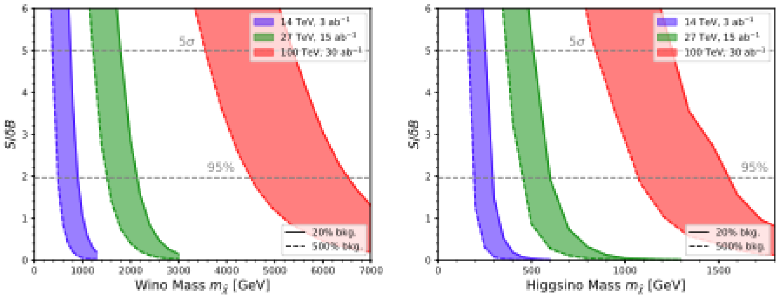

Fig. 4. The reach of HE-LHC in the search for a wino (left) or higgsino (right) DM WIMP candidate, using a disappearing charged track signature.[9] The bands limited by the solid and dashed lines show the range obtained by modifying the central value of the background estimate by a factor of five. The results are compared to the reach of HL-LHC and FCC-hh.

energies. While these results do not reach the mass values required for electroweakinos to be a thermal relic and account for all of DM, the mass range accessible to HE-LHC greatly extends the HL-LHC potential and can be complementary to the indirect detection probes, e.g. using gamma rays from dwarf-spheroidal galaxies.

4.3. *Dark matter and dark sector searches*

Generic weakly interactive dark matter candidates are predicted by several DM models beyond compressed SUSY scenarios. All of those could be targeted at the HE-LHC utilising monojet signatures,[4] as this channel is a useful probe for DM production through the exchange of a neutral mediator that couples to the SM, or for a dark sector that contains heavy coloured particles nearly degenerate with the DM and decaying to DM and SM coloured particles. The reach to these kinds of models is strongly dependent on the choice of couplings. Should an excess be observed, the identification of the spin and colour representation of the mediator sector will require high-order precision for the predictions of the SM backgrounds. Analyses of double-ratios of cross sections at varying transverse momenta of the jet could be utilized to partially cancel uncertainties, benefiting from the large HE-LHC datasets. Similarly, searches for monophoton and vector-boson-fusion production can be used, with the latter potentially being more dependent on the robustness of the selection against pile-up, the optimisation of the analysis, and the capability to reduce theoretical uncertainties.

Models characterized by the presence of an extended Higgs sector, with Higgs doublets mixing with an additional scalar or pseudo-scalar mediator that couples to DM, can be searched for in more complex signatures involving heavy-flavour quarks. Prospect searches for associate production of DM with a pair of top quarks show that HE-LHC is expected to be able to significantly improve upon the HL-LHC reach, in particular for spin-0 DM model realisations that predict small signal cross sections. Assuming the DM is lighter than half the mediator mass, a scalar or pseudoscalar mediator can be ruled out at 95% CL up to 900 GeV, a factor of two higher in mass compared to the HL-LHC bounds.

Finally, there is a vast landscape of theoretical models, motivated by DM, for which particles responsible for the still unexplained phenomena are below the EW scale and interact very weakly with SM particles. These particles would belong to a new hidden (or dark) sector where thermal DM is coupled to mediators through portal operators and often have long lifetimes. Prospect searches at future hadron colliders,[4] including the HE-LHC and HE-LHeC, have been carried out for dark photons, dark higgses, axion-like particles and heavy neutral lepton models, exploiting unconventional signatures such as reconstructed leptons, jets, tracks or vertices displaced from the primary interaction point. While it is difficult to firmly conclude on the sensitivity for each specific model, it is expected that a higher centre-of-mass energy and the exploitation of new technologies for the detectors would significantly extend upon the HL reach.

5. QCD and EW processes at the highest energies

The increase in energy and integrated luminosity at the HE-LHC will allow us to probe QCD at the highest values of Q^2 and search for potential deviations induced by new physics at energy scales well beyond the reach of the HL-LHC. The impact of precise PDFs measured at the HE-LHeC, especially at high x, would radically increase the potential of these searches.

In terms of strong interactions, the HE-LHC kinematic reach would extend up to 10 TeV in the jet transverse momentum, p_T (see Fig. 5(left)), and up to about 20 TeV in the di-jet invariant mass, m_{jj}. The inclusive production of isolated-photons and jets will reach up to 5 TeV in the photon transverse energy and jet p_T, respectively, and up to 12 TeV in the photon-jet invariant mass.

Among the EWK processes that can be studied at unprecedented energies is the scattering of two massive vector bosons $V = W, Z$ (vector boson

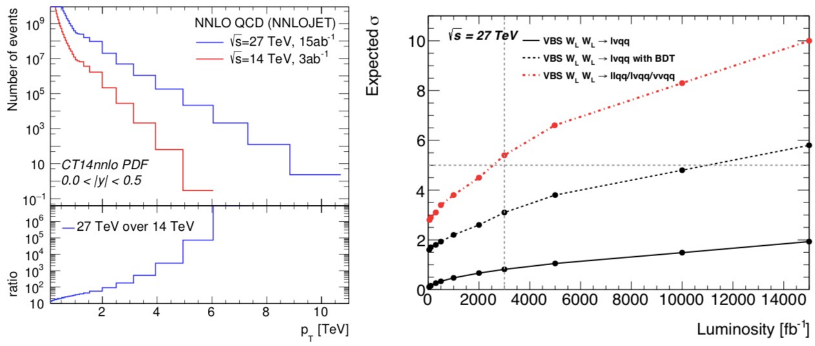

Fig. 5. Left: Predicted number of inclusive jet events as a function of the jet p_T. Right: Observed significance as a function of the luminosity and expected uncertainty for the EW $W_L W_L$ signal assuming a 10% fraction predicted from MC. One line shows the results obtained by fitting a single variable, the total invariant mass of the system and the other one shows the expected significance using the BDT. The third line shows the expected significance assuming the combination of all three semi-leptonic channels with the same sensitivity. From Ref. 10.

scattering, VBS), which provide a key opportunity to probe the nature of EWSB mechanism as well as BSM physics. At the HE-LHC, it will be possible to probe longitudinal VV scattering and verify whether the Higgs boson preserves unitarity at all energies. Figure 5(right) shows the significance as a function of the luminosity and expected uncertainty for the EW $W_L W_L$ signal assuming a 10% fraction predicted from MC. The different lines show the results using different analysis approaches and combining three channels exploiting semi-leptonic events. In the latter case, the HE-LHC will reach the 5 σ sensitivity with 3 ab^{-1}. The various VBS processes also provide excellent probes for the structure of gauge boson interactions, in particular for the quartic gauge couplings. Deviations from SM predictions can be parameterised by an effective Lagrangian, and operators of energy dimension-8, which do not give rise to anomalous trilinear couplings, can used for a parameterisation of anomalous quartic gauge couplings (aQGC). Using observables sensitive to high VV invariant-mass regions, 95% CL bounds on aQGC can be obtained: up to a factor of 10 reduction with respect to the expected HL-LHC bounds is found on all relevant coefficients of dimension-8 operators for HE-LHC.[10]

6. Top-quark sector and heavy flavour physics

The HE-LHC would significantly strengthen the role of high-p_T measurements in flavour physics. In the top-quark sector, the typical increase in event yields for inclusive $t\bar{t}$ pair production will be about a factor 15–20, and about a factor 500 if a selection for top-quark with $p_T > 2$ TeV is applied. The large data sets of top quarks will also improve the sensitivity to top-quark FCNC decays by one order of magnitude, relative to the HL-LHC. The production of four top-quark events will see an increase by about a factor 40, leading to an expected 1% statistical uncertainty in the cross section measurement. This process is particularly interesting as it provides direct ways to constrain the top quark Yukawa coupling as well as SM Effective Field Theory parameters sensitive to the quartic couplings between top quarks. The $t\bar{t}t\bar{t}$ signature also arises in models for dark matter involving a two-Higgs-doublet extended sector together with an additional pseudoscalar mediator to DM, and the HE-LHC could provide, if not a discovery, stringent constraints on these models.

It is expected that HE-LHC would be equipped with an upgraded LHCb-like detector fully dedicated to flavour physics studies. An integrated luminosity of about or exceeding 3 ab^{-1} could be collected during the HE LHC phase, hence guaranteeing a significant increase with respect to the HL-LHC, associated to the doubling of the b-quark production cross section as a result of the higher centre-of-mass energy. Processes such as rare kaon decays could also be exploited to find new sources of CP violation in the charm sector. Ratios of B_d and B_s process rates such as $\mathrm{BR}(B_d \to \mu^+\mu-)/\mathrm{BR}(B_s \to \mu^+\mu-)$ would be measured with precision at the percent level and would be a probe for new physics at very high energy (O(10–100) TeV). Finally, the CKM phase γ could be determined to $< 0.1^o$ using a variety of rare hadronic B decays, and the phase β could be extracted from several tree-level decays. Together, these measurements would result in uniquely stringent tests for CKM unitarity.

7. Heavy Ion physics

Heavy-ion collisions[12] would be possible at the HE-LHC with the same injected beams as the HL-LHC. Based on extrapolations of LHC performances, the increase in integrated luminosity per run with respect to the LHC is expected to be about a factor 2: about 6 nb^{-1} could be collected in a typical one-month run. A larger increase in terms of nucleon–nucleon luminosity could be achieved with collisions of nuclei lighter than Pb, such as Xe, which would retain production of Quark-Gluon Plasma (QGP) with a volume and energy density similar to those of *PbPb* at LHC energies.

An increased centre-of-mass energy in heavy-ion collisions lead to the creation of initially denser (a factor about 1.4 from LHC to HE-LHC) and hotter strongly-interacting systems that expand for a longer duration and over a larger volume, thereby developing stronger collective signals. The HE-LHC collision energies would be closer to the range of temperatures (T $\simeq$ 1 GeV) where charm quarks start to contribute as active thermal degrees of freedom in the QGP equation of state in addition to u, d, s, quarks, thus playing a novel role in QCD equilibration processes. High-energy partons produced in heavy-ion collisions also undergo jet quenching, a marked reduction of the energy of the emerging jets. Jet quenching measurements provide quantitative information on the transport properties of hot and dense QCD matter, hence they are a fundamental target of the heavy-ion programme at the highest possible energy.

The HE-LHC would provide much larger abundance of hard-scattering processes than the LHC, as well as novel probes such as boosted top quarks and, potentially, the Higgs boson. Figure 6(left) shows NNLO cross sections and event yields for various hard-scattering processes as a function of $\sqrt{s_{NN}}$. Photon–photon collisions can also arise: a higher centre-of-mass energy would allow the HE-LHC to reach higher diphoton masses and be sensitive to BSM physics through new heavy charged particles contributing to the virtual loop such as, e.g., from SUSY particles.

The higher centre-of-mass energy of HE-LHC gives access, in the initial state of heavy-ion collisions, to a wide, previously uncharted, kinematic range at low x and Q^2, where parton densities become very large and may reach the non-linear QCD regime known as “parton saturation”. Through the potentially available electron beam from the ERL, high energy, high luminosity deep inelastic electron-ion scattering physics could also be realised concurrently, giving new insight to the partonic substructure and dynamics inside nuclei. Figure 6(right) shows the kinematic regions in the $x-Q^2$ plane that could be explored by an electron beam colliding against a HL-LHC proton beam or a 20 TeV and 50 TeV beam. The HE line, not on this plot, would cover an area only slightly smaller than the 20 TeV case. With a kinematic reach at the TeV scale, the electron–nucleus option at the HE-LHC could provide conclusive evidence for the existence of a new non-linear regime of QCD, possibly uncovering the chromodynamic origin of the QGP. It would be clearly complementary with the *pPb* case, leading

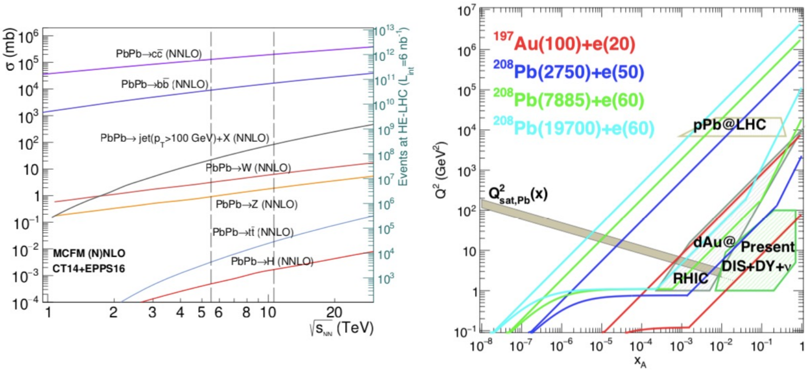

Fig. 6. Left: NNLO cross sections and event yield for various hard-scattering processes as a function of $\sqrt{s_{NN}}$, from Ref. 12. Right: Kinematic regions in the $x - Q^2$ plane explored by different data sets compared to the ones achievable at the EIC (red), the LHeC (ERL against the HL-LHC beams, dark blue) and two FCC-eh versions (with Pb beams corresponding to proton energies $E_p = 20$ TeV - green and $E_p = 50$ TeV - light blue). Details on assumptions in Ref. 3.

to a precise knowledge on the partonic structure of nucleons and nuclei and on the small-x dynamics.

8. Concluding remarks and summary

The possibility of utilising the LHC tunnel and accelerator complex for a higher energy proton-proton collider immediately after the completion of the HL-LHC programme has been historically one of the first (and most obvious) ideas for a future large-scale project at CERN. The physics potential of such HE-LHC has been briefly illustrated in this chapter, assuming a doubled proton-beam energy with respect to the LHC, and 20 years of operations delivering 10–15 ab^{-1} integrated luminosity to two general purpose detectors. The possibility of having a dedicated flavour physics experiment and a heavy-ion collisions programme are also factored in. Furthermore, the importance of a facility that allows concurrent electron-proton/ion collisions through the addition of a 60 GeV electron beam provided by an energy recovery linac has been illustrated.

It is clear that searches for new physics and precision measurements of Higgs properties, SM parameters and SM processes would greatly benefit from the increased partonic energy of a 27–41 TeV centre-of-mass energy machine. The 20-fold increase in statistics available for the Higgs boson pair production process with respect to the HL-LHC would allow constraint and measurement of the Higgs boson trilinear coupling with O(10%) precision. Heavy new particles up to masses around 10 TeV could be discovered i.e. if resulting in di-lepton or di-jet resonances, and several BSM models could be explored and uncovered.

The main technical challenges are posed by the need to replace the existing LHC dipole magnets with higher magnetic field dipole magnets, as described subsequently. Consequently, the HE-LHC would need civil engineering and technical infrastructure work, and substantial upgrades of the detectors to overcome the higher level of event pile-up, radiation flux, track densities, trigger and readout rates. Still, should the construction of a 100-km Future Circular Collider not be possible in the foreseeable future, the upgrade of the currently available and unique LHC facility to the highest energy possible can indeed be considered as one of the best routes to guarantee the future of collider particle physics.

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