https://doi.org/10.1142/9789811280184_0024

# Chapter 24

# Higgs and Beyond the Standard Model Physics

J. de Blas*, O. Fischer† and U. Klein‡

*CAFPE and Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada, Spain

†University of Liverpool, Department of Mathematics, Liverpool, United Kingdom

‡University of Liverpool, Department of Physics, Liverpool, United Kingdom

## 0. Introduction[a]

The discovery of the Higgs boson at the Large Hadron Collider by ATLAS[1] and CMS[2] collaborations opened a new chapter in particle physics. The Higgs Boson ($H$) is of fundamental importance for the future of particle physics and the LHC. It is related to the mechanism predicted by Refs. 3–5 in which the intermediate vector bosons of the spontaneously broken electroweak symmetry acquire masses[b] while the photon remains massless. Fermions obtain a mass via the Yukawa couplings with the Higgs field. Following the discovery of the Higgs boson, its physics has become a central theme of the experimental and theoretical programmes pursued with the LHC as well as for the high luminosity upgrade of the Large Hadron Collider, the HL-LHC, as described in this book.



[a]This section has been reproduced from [P. Agostini et al., 2021 J. Phys. G: Nucl. Part. Phys. 48 110501]. ©The Author(s). Published by IOP Publishing Ltd. CC BY 4.0.

[b]The mass of the $W$ boson, $M_W$, is generated through the vacuum expectation value, $v$, of the Higgs field ($\Phi$) and given by the simple relation $M_W = gv/\sqrt{2}$ where $g$ is the weak interaction coupling. Here $v = \sqrt{-\mu^2/2\lambda}$ with the two parameters of the Higgs potential that is predicted to be $V = -\mu^2\Phi^+\Phi - \lambda(\Phi^+\Phi)^2$. The Higgs mass is given as $M_H = 2v\sqrt{\lambda}$ while the mass of the $Z$ boson is related to $M_W$ with the electroweak mixing angle, $M_Z = M_W/\cos\Theta_W$.

Any new high-energy future collider project has placed its focus on the potential to precisely study the properties of the Higgs mechanism, to understand its characteristics and hopefully open a new window into physics extending beyond the Standard Model. The LHeC, as presented in detail in Ref. 6, provides a salient opportunity for exploring the physics of the Higgs boson in *ep* collisions due to the following features: i) the production through vector boson scattering in the t-channel has a cross section of order 200 fb, comparable to that of Higgs radiation from a $Z$ boson in the so-called $e^+e^-$ Higgs factories; ii) the theoretically well controlled neutral and charged current production processes uniquely distinguish the $HZZ$ and $HWW$ vertices; iii) the clean semi-leptonic final state which is free of multiple interactions (pile-up); iv) the empowerment of the Higgs measurement programme at the hadron collider, LHC, through the resolution of uncertainties related to the strong interactions (consult the chapter on hadron structure and QCD with the LHeC), such as the unknowns related to proton structure, the value of the strong coupling and the question of possible non-linear gluon dynamics at small Bjorken-$x$.

Like in the case of the $e^+e^-$ colliders, the LHeC provides high precision measurements of the characteristics of the seven most abundant Higgs decay channels, which comprise 99.9% of all SM decays. Owing to the high gluon-gluon fusion $gg \to H$ production cross section, only a hadron collider, such as the LHC, would be able to extend these explorations to the very rare decay channels. When the *ep* results will be combined with the anticipated HL-LHC measurements, the characteristics of the SM Higgs boson could be explored at per-cent level in numerous reactions. The first significant observation of the Higgs self-coupling is in reach, with a precision to be evaluated for a combined $pp - ep$ high luminosity data analysis. This high precision programme is expected to shed light on the question of whether the Higgs mechanism potentially leads beyond the Standard Model (BSM) or not.

Despite having too many free parameters, the Standard Model provides phenomenological explanations to the observed properties and kinds of elementary particles thus far. However, there remain several fundamental questions and tasks unresolved, such as the nature of lepton-quark and baryon-antibaryon asymmetries, the quest of a grand unification of forces, possibly resolving the distinction between fermions and bosons in a supersymmetric theory, or the origin of neutrino masses. Current experimental hints as to how this may be accomplished turned out to be scarce at the LHC, while scientists are still thinking of theoretical hints. The initial

LHC data have confirmed the Higgs boson's existence to be SM-like, without much experimental hints of physics beyond the Standard Model. A special, cosmological and particle physics question regards the nature of Dark Matter. The situation resembles the time prior to the advent of the SM. It motivates the search for the widest possible options and realisation of dedicated search experiments including high energy, high intensity colliders of different types in order to lead beyond the Standard Model. This is why the HL-LHC has its special importance and is perhaps the strongest reason as to why its combination with an intense electron accelerator has been seriously brought forward.

Several anomalies in experiments at all energy scales, which could be linked to open questions as mentioned above exist.[7] However, the absence of convincing BSM signals in the currently available LHC data may indicate that "new" physics could be inaccessible at the TeV scale. And yet, it could be a very rare phenomenon possibly still hidden in the backgrounds, requiring more data and refined analysis techniques. New theoretical developments consider that as a possibility and explore the complementarity of the different collider experiments. The LHeC is projected to operate concurrent with the LHC's high luminosity phase which it may extend in time, depending on CERN's future plans. Because of its clean experimental environment and different production mechanisms, the LHeC, and future, even higher energy *ep* colliders, such as the high energy (HE) version of the LHeC (for the HE-LHC see the subsequent part of the book), or the FCC-eh,[6,8] could indeed observe BSM physics near the TeV scale, including an extended scalar particle sector, sterile neutrinos, and other exotic particles. Following the brief description of Higgs physics in *ep*, example studies for this BSM potential are presented subsequently too.

## 1. Higgs physics at high energy ep colliders

### 1.1. *Technical aspects*

As part of the updated Conceptual Design, physics, and detector of the LHeC, the technical details and the prospects of Higgs physics at the LHeC have been described in a detailed study report,[6] as well as providing further detailed references. In deep inelastic electron-proton scattering (DIS), the SM-Higgs boson is predominantly produced through $WW$ fusion in charged current DIS (CC) scattering. The next large Higgs production mode in *ep* is $ZZ \to H$ fusion in neutral current DIS (NC) scattering. The NC reaction is even cleaner than the CC process as the scattered electron fixes the kinematics more accurately than the missing energy. While in *pp* the $WW$ and $ZZ$ Higgs boson generations are hardly distinguishable, in *ep* they are very distinguishable, providing particularly precise constraints on the $WWH$ and $ZZH$ couplings, which can be clearly identified via the detection of large missing energy or the selection of the final state electron respectively.

Kinematics reconstruction in DIS is very precise and in neutral currents redundant, leading to important tracking and calorimeter cross calibrations and significant reduction of systematic uncertainties. Electron-proton scattering is thus an outstanding environment for most accurate measurements of particle physics processes without the pile-up complications of the LHC analyses. The energies of the electron and proton beams are quite different, causing constraints on the design of the detector to provide the necessary angular acceptance for the scattered lepton, the Higgs decay particles and the final state emerging at the virtual $W/Z$-proton interaction vertex. Studies using the MadGraph program assured, even for the most asymmetric energy configuration of the FCC-eh, that the complete final state can be very well reconstructed, with emphasis on the very forward (i.e. proton beam) direction for the hadronic final state. The Higgs decay products are well confined in the apparatus, appearing near a pseudorapidity $\eta$ value of around 2 which corresponds to a polar angle of about $\theta = 15°$, where $\eta = -\ln\tan\theta/2$.

The scattering cross sections, including the decay of the Higgs boson into a pair of particles $A_i\bar{A}_i$, can be written as:

$$\sigma^i_{CC} = \sigma_{CC} \cdot \frac{\Gamma^i}{\Gamma_H} \quad \text{and} \quad \sigma^i_{NC} = \sigma_{NC} \cdot \frac{\Gamma^i}{\Gamma_H}. \tag{1}$$

Here, the ratio of the partial to the total Higgs decay width defines the branching ratio, $br_i$, for each decay into $A_i\bar{A}_i$. The size of the *ep* Higgs production cross section and about 1 $\text{ab}^{-1}$ luminosity prospect allows the seven most frequent SM Higgs decays to be considered, i.e. those into fermion ($b\bar{b}$, $c\bar{c}$, $\tau^+\tau^-$) and into gauge particle pairs ($WW$, $ZZ$, $gg$, $\gamma\gamma$) with high precision at the LHeC and its higher energy versions.[c]

Initially, detailed simulations and Higgs extraction studies for LHeC were made for the dominant $H \to b\bar{b}$ and the challenging $H \to c\bar{c}$ channels. These analyses were eventually updated, first using simple kinematic

[c]This paragraph has been reproduced from [P. Agostini et al., 2021 J. Phys. G: Nucl. Part. Phys. 48 110501]. 

requirements and later using advanced boosted decision tree techniques (BDT). The focus on the $H \to b\bar{b}$ decay has been strongly motivated by its dominating size and difficulty reconstructing it accurately at the LHC. For *ep*, it seemed natural to extend this to the $H \to c\bar{c}$, especially because it is currently considered not to be observable at the HL-LHC, due to permutation and large background reasons. A further detailed analysis was performed for the $H \to W^+W^-$ decay based on a complete signal and background simulation and eventual BDT analysis. For this channel, CC DIS cleanly determines the $HWW$ coupling to its fourth power assuming SM production and decay. Results on other channels were obtained using an acceptance, efficiency and signal-to-background scale factor approach[6] which was successfully benchmarked with the detailed simulations for heavy quark and $W$ decays.

### 1.2. *Results on ep Higgs physics prospects*

The sum of the branching ratios for the seven Higgs decay channels accessible to *ep* at the LHeC adds up to 99.87% of the total SM range. As discussed in Ref. 6, significant constraints of the $H \to invisible$ decay can be set with *ep* as well, albeit not being able to exclude exotic, unnoticed Higgs decays. The accurate reconstruction of all decays considered here will present a severe constraint on the total cross section and, with that, constraint of the total decay width of the Higgs boson in the SM. Evaluation of the cross section measurement prospects for a decay channel $i$ is based on the relative signal strengths $\mu^i(NC, CC)$ with respect to the SM cross section.[d] The results for the LHeC, the HE-LHeC and the FCC-eh are displayed in Fig. 1. They are the input to joint coupling constant analyses. These can be performed in the simplest, so-called $\kappa$ framework,[9] considered subsequently, or e.g. in formalisms embedded in effective field theories.

The $\kappa$ parameters are scaling factors to the various Higgs couplings. Higgs production cross section thus scale as $\sigma_{NC/CC} \propto \kappa^2_{Z/W}$ (equal to 1 in the SM), and the channel $i$ decay width $\Gamma^i \propto \kappa^2_i$. Assuming only SM Higgs boson decays, and therefore $\Gamma_H = \Sigma_j \kappa_j \Gamma^j$, this leads to the following

[d]Reproduced from [P. Agostini et al., 2021 J. Phys. G: Nucl. Part. Phys. 48 110501]. 

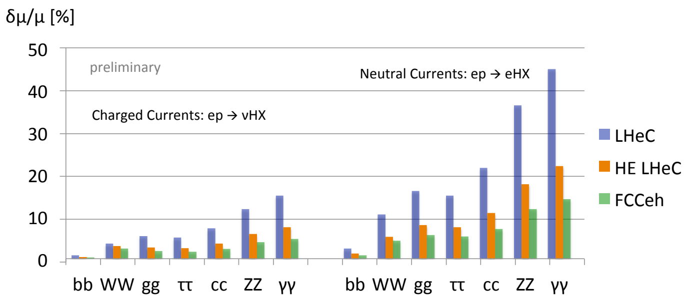


Fig. 1. Uncertainties of signal strength determinations in the seven most abundant SM Higgs decay channels for the FCC-eh (green, 2 ab$^{-1}$, $E_p = 50$ TeV), the HE LHeC (brown, 2 ab$^{-1}$, $E_p = 14$ TeV) and LHeC (blue, 1 ab$^{-1}$, $E_p = 7$ TeV), in charged and neutral current DIS production using a polarised electron beam ($P = -0.8$) of 60 GeV. From Ref. 6.

(Eq. (1)):

$$\begin{aligned} \sigma^i_{CC} &= \sigma^{SM}_{CC}\ br^{SM}_i \cdot \kappa^2_W \kappa^2_i \frac{1}{\sum_j \kappa^2_j br^{SM}_j} \quad \text{and} \\ \sigma^i_{NC} &= \sigma^{SM}_{NC}\ br^{SM}_i \cdot \kappa^2_Z \kappa^2_i \frac{1}{\sum_j \kappa^2_j br^{SM}_j}. \end{aligned} \tag{2}$$

Here the quantities $\sigma_{NC/CC}$ and $br_j$ are understood to be the SM values. Dividing these expressions by the SM cross section predictions, one obtains the variations of the relative signal strengths, $\mu^i$, for charged and neutral currents and their $\kappa$ dependence

$$\mu^i_{CC} = \kappa^2_W \kappa^2_i \frac{1}{\sum_j \kappa^2_j br^{SM}_j} \quad \text{and} \quad \mu^i_{NC} = \kappa^2_Z \kappa^2_i \frac{1}{\sum_j \kappa^2_j br^{SM}_j}. \tag{3}$$

With seven decay channels considered in CC and NC, one finds that for each of the *ep* collider configurations there exist eight constraints on $\kappa_W$ and $\kappa_Z$ and two on the other five $\kappa$ parameters. Using the signal strength uncertainties for both NC and CC reactions, illustrated in Fig. 1, fits to all seven channels are performed in a minimisation procedure to determine the resulting uncertainties for the $\kappa$ parameters. These are done separately for each of the three *ep* collider configurations.[e] The results, listed in Table 1, exhibit an amazing precision with small systematic or theoretical uncertainties as were considered in Ref. 6.

One observes that the naive expectation of $\delta\kappa \simeq \delta\mu/2$ holds approximately for the $gg$, $\tau\tau$, $c\bar{c}$, $\gamma\gamma$ channels. However, due to the dominance

[e]Reproduced from [P. Agostini et al., 2021 J. Phys. G: Nucl. Part. Phys. 48 110501]. 

Table 1. Summary of $\kappa$ uncertainty values as obtained from fits to the signal strength uncertainty estimates for the seven most abundant Higgs decay channels, in charged and neutral currents for the LHeC, the HE-LHeC and the FCC-eh.

| Setup | $\sqrt{s}$ | $L/ab^{-1}$ | $b\bar{b}$ | WW | gg | $\tau\tau$ | cc | ZZ | $\gamma\gamma$ |
|---|---|---|---|---|---|---|---|---|---|
| LHeC | 1.3 | 1 | 1.9 | 0.70 | 3.5 | 3.1 | 3.8 | 1.2 | 6.8 |
| HE-LHeC | 2.0 | 2 | 1.0 | 0.38 | 1.8 | 1.6 | 1.9 | 0.6 | 3.5 |
| FCC-eh | 3.5 | 2 | 0.60 | 0.22 | 1.1 | 0.93 | 1.2 | 0.35 | 2.1 |

of $H \to b\bar{b}$ in the total Higgs decay width and owing to the sensitivity to both the $WWH$ and $ZZH$ couplings in the initial state, there occurs a reshuffling of the precisions in the joint fit: $\kappa_b$ becomes even relatively less precise than $\mu_{bb}$ while both $\kappa_W$ and $\kappa_Z$ become more precise than naively estimated, especially when one takes into account that the $H \to WW$ decay in CC measures $\kappa_W^4$.

The potential of LHeC Higgs measurements can be compared and jointly interpreted with the anticipated results from the HL-LHC. The HL-LHC projections for the precision of the different $\kappa$ parameters from a global fit to the Higgs projected uncertainties are shown in Fig. 2[10,11] (from Ref. 6).

Numerically, the LHeC Higgs physics programme improves the precision of several HL-LHC projections. This is apparent from the same figure, where the $\kappa$ interpretation for the LHeC is displayed, both as a stand-alone prospect result and in combination with the HL-LHC. The lower panel of the same figure illustrates the improvements in these two scenarios with respect to the HL-LHC alone. Improvements are most notable for the Higgs couplings to the $W$, $Z$ bosons and to the $b$ quark, $\kappa_{W/Z}$ and $\kappa_b$, respectively, as expected from Table 1. The complementarity between the two Higgs physics programmes is indeed remarkable: the LHeC, with its clean environment, adds precision and the possibility of measuring the charm coupling, $\kappa_c$, while the HL-LHC, owing to its high luminosity and large Higgs production cross sections, leads to the rare and very rare decays, such as $H \to \mu^+\mu^-$ and $H \to Z\gamma$.

The verification of such precise results at per cent level requires very careful checks of the experimental methods and the consistency of the applied theoretical frameworks. Hence it will be of utmost importance to test the Higgs mechanism in the $pp$, $ep$ and $e^+e^-$ environments with different production modes and detectors, thereby fully exploring the synergies of the diverse physics programmes. This includes: i) very rare Higgs boson decays are accessible only with $pp$; ii) a unique virtue of $ep$ is the accurate resolution of strong interaction uncertainties related to the proton substructure and

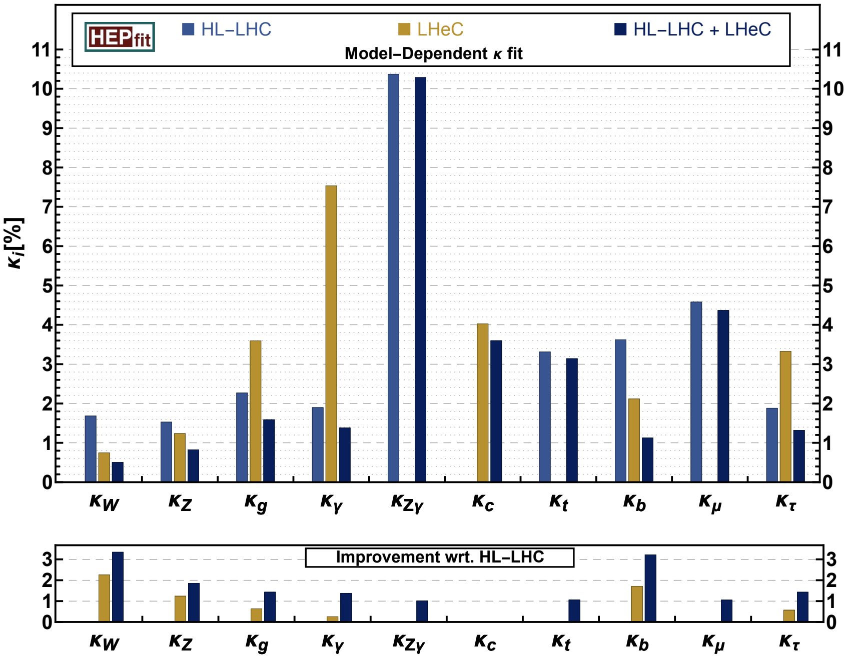


Fig. 2. Projected uncertainty (in percent) in the determination of the modified Higgs couplings in terms of the scaling parameters $\kappa_i$ at the HL-LHC (blue), LHeC (gold) and the combination HL-LHC with the LHeC (dark blue), see text. The bottom panel shows the improvement in the determination of the $\kappa$ parameters with respect to the HL-LHC prospects by adding LHeC prospected measurements. From Ref. 6.

parton dynamics as is required for precision *pp* measurements; iii) a unique result in $e^+e^-$ will be the model independent measurement of the Higgs decay width owing to the constrained initial and final state kinematics of Higgs radiation from the $Z$ boson. All these programmes require decades of preparation, operation and innovative analyses, and as such constitute a salient part of the future of particle physics and the LHC in particular. There is a host of questions on the Higgs phenomenon which extend beyond the mere verification of the Higgs boson decays. In fact, owing to the unique features of the Higgs particle, one may hope it would open a window to BSM physics. Some examples are briefly presented below, with more details in the updated CDR of the LHeC.[6]

### 1.3. *Exotic Higgs decays*

A detailed experimental characterisation of the Higgs boson includes an exhaustive study of its decay modes, which may include modes beyond the ones predicted by the SM. One of these modes is given by invisible final states, which could indicate, for example, dark matter particles. In the SM, invisible decays stem from $H \to ZZ^* \to 4\nu$ and have a tiny branching ratio of 0.1%. The latest upper bound from the ATLAS collaboration in this channel is 14.5%.[12] Invisible decays of the Higgs boson can be tested in $ep$ collisions in the NC channel, where the unambiguous signal of missing energy may stem from invisible decays and allows branching ratios as small $\sim 6\%$ to be accessed at the LHeC, as shown in initial studies.

The Higgs boson may also decay into pairs of non-SM particles, for instance into a pair of light scalar bosons which in turn decay into the $4b$ final state. This signature is very difficult to test at the LHC, even if the branching ratio were to be sizeable. At the LHeC on the other hand, this process can test models with scalar masses of $\mathcal{O}(10$ GeV$)$ and couplings to SM particles at the per-mille level. Moreover, when the scalars have macroscopic lifetimes with $\mu$m displacements in the detector, their detection prospects will improve. Scalar mixing angles as small as $\sin^2\alpha \sim 10^{-7}$ can be tested at the LHeC for scalar masses between 5 and 15 GeV.[13,14]

### 1.4. *Higgs pair production and the self-coupling*

The verification of the Higgs potential, specifically the measurement of the Higgs self-coupling via the $HHH$-vertex, is a prime target of the HL-LHC and future Higgs physics experiments. At a high-energy $ep$ collider, charged current DIS di-Higgs production involves in the SM only three Higgs vertices in vector-boson fusion, i.e. $HHH$, $WWH$, and $WWHH$ (see Ref. 15), and is therefore not hampered by other di-Higgs production modes which occur at hadron colliders. It is worthwhile to point out that the $WWH$ coupling will be tested extensively at the HL-LHC and may also be very well explored at LHeC. An initial study of di-Higgs production at the FCC-eh, albeit using only the 4b decay[15] and simple kinematic requirements, indicates the important potential of $ep$ colliders to disentangle the Higgs trilinear coupling, $\kappa_\lambda$, as well as to identify potential BSM contributions in the $HH$-related vertices. A recent study[16] considered modifications of the Higgs self-coupling and the $WWHH$ coupling in non-resonant $HH$ production, using also the 4b decay only and simple cuts. It suggests that the LHeC constraining power on $\kappa_\lambda$ would be weaker than the HL-LHC expectations, while being complementary in probing the $WWHH$ vertex. A more detailed analysis of the very promising, joint LHeC and HL-LHC sensitivity to the Higgs self-coupling calls for applying state-of-the-art neural network analysis techniques and incorporating all possible Higgs decay channels.

## 2. Beyond the Standard Model in ep at high energies

The physics beyond the Standard Model which can be probed with the LHeC (and at higher ep energies) has been studied for about a decade and recently been presented with the comprehensive report on the LHeC.[6] It comprises a broad spectrum of hypotheses and questions, such as supersymmetry, with prompt and long lived particle signatures, in R-parity conserving or violating models, feebly interacting particles such as heavy neutrinos or fermion triplets, dark photons or axion-like particles. It extends to anomalous gauge couplings, heavy resonances such as leptoquarks or extra $Z$ bosons, vector-like quarks, excited or colour octet leptons, quark substructure and contact interactions, etc. It so includes a very large variety of BSM physics questions which can be explored in energy frontier $ep$ and $eA$ collisions. It shall be noted that owing to the intense hadron beams and the energy recovery type of electron accelerator, the anticipated luminosity values exceed those of HERA by 2–3 orders of magnitude. Subsequently, a few illustrative examples are given while an interested reader is directed to Ref. 6 and the literature cited there. These studies, also as theory and LHC analyses proceed and the LHeC design progresses, will be further deepened and new ideas be incorporated. It has been recognised for quite some time, especially at the LHC, that many results may be anticipated but real data usually led to results exceeding the scope of even detailed simulations.

### 2.1. *Unique setting for BSM searches*

The unique advantages of the LHeC in the search for BSM physics are: i) the absence of towering backgrounds; ii) the absence of pile-up and complicated triggering; iii) the excellent angular acceptance and resolution of the detector to find displaced vertices for heavy flavour tagging. These properties are ideal to discover BSM that is characterised by the presence of non-prompt, long-lived particles. They are also ideal for BSM physics where the final states can be numerous and have low momenta, and which would be rejected as hadronic noise at the LHC. This renders the LHeC's discovery potential complementary to the one at the LHC and *pp* collisions in general.

Additionally, from the LHeC's very controlled asymmetric initial state, most BSM physics is created via vector-boson fusion, which suppresses the production cross section for new particles that are heavier than the weak bosons, but renders their signatures very separable from the background processes. This is particularly relevant for extensions of the SM scalar sector and neutrino mass physics, which can be well tested in this environment. An increase in the centre-of-mass energy as high as the one foreseen possibly with the HE-LHC and at the FCC would naturally boost the reach in most scenarios considerably.

### 2.2. *Extensions of the scalar sector*

The question of whether the scalar sector contains degrees of freedom beyond the Higgs boson still remains. In this regard, there are several hints in LHC data that could indicate a non-trivial scalar sector with at least two additional neutral fields.[21,22]

Several scalar extensions with interesting phenomenology have been proposed that can be studied at the LHeC, for example: i) CP violating top-Higgs interactions; ii) flavor changing neutral currents, to be tested via decays of the top quark into a charm quark and a Higgs boson; iii) doubly charged scalar bosons from the Georgi-Machacek model, produced via $W^-W^-$ fusion.

In many extensions of the SM, a number of neutral scalars are introduced, which often mix with the SM Higgs doublet. In these scenarios, additional Higgs-like resonances with reduced interaction strength are predicted, which are well testable at the LHC for masses around and above the TeV scale. Testing scalar resonances with masses at the electroweak scale is easier at the LHeC, as shown in Fig. 3.

### 2.3. *Searches for long-lived particles*

One can loosely define long-lived particles (LLP) via their lifetime, which allows them to travel measurable distances before they decay. Many BSM theories predict the existence of LLP with all kinds of spin or quantum numbers. At the LHC, these are often difficult to detect or study, for instance because of pile-up and hadronic background noise.[23] A prime example for such new particles comes from supersymmetric scenarios with compressed

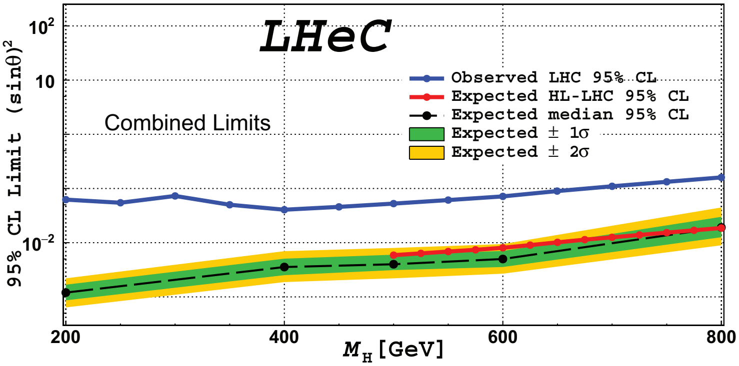


Fig. 3. Expected exclusion limits on the scalar mixing angle $\theta$ for a heavy scalar search at the LHeC[18] considering 1 $ab^{-1}$. The blue and red line denotes the LHC limit[19] and the forecast of the HL-LHC sensitivity,[20] respectively.

mass spectra, where the next-to-lightest supersymmetric particle (NLSP) is long lived because of phase space limitations. At the LHC, these are impossible to detect, due to the low amount of visible energy from the NLSP decay. At the LHeC these signatures, e.g. single pions with transverse momenta below a few GeV, can be tested.[13]

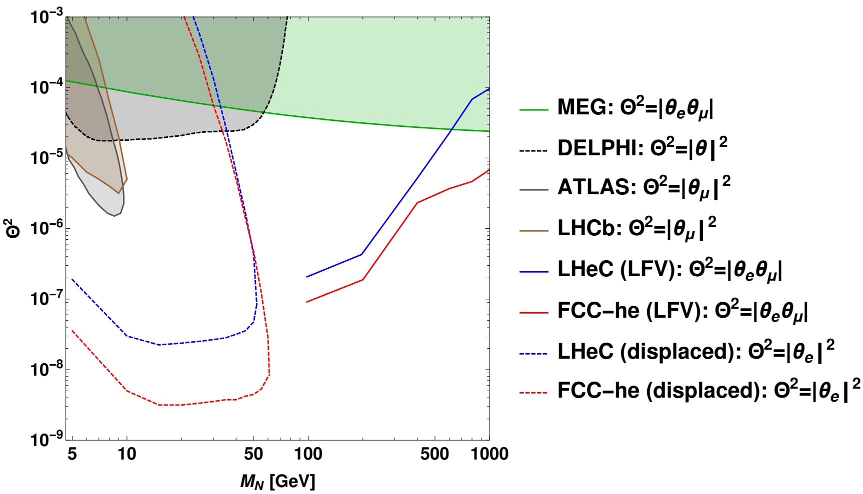


Fig. 4. Overview on prospected sterile neutrino searches. For a detailed discussion see Refs. 24 and 6.

A well-motivated class of BSM models predicting LLP are right-handed neutrinos, which address the big open question of the origin of neutrino masses. An overview of collider searches for right-handed neutrinos[24] shows a comparison of current limits and future LHeC and FCC-eh searches in Fig. 4. In these models the particles are LLP for masses below $M_W$, which makes displaced vertices the most promising way to detect and study them. Extensions with fermion triplets address the neutrino oscillations, and for very small Yukawa couplings their lifetimes can be sizeable and lead to interesting LLP signatures.

LLP also arise naturally in many theories that extend the SM with additional gauge sectors, in particular with the most common abelian $U(1)$ one. Such gauge extensions can be connected to a dark sector and imply a dark charge and a dark gauge boson. More importantly, the dark gauge boson can mix with the neutral gauge bosons of the SM and inherit interactions with charged SM particles that are scaled with the small mixing parameter $\epsilon$. A new heavy gauge boson, often called a dark photon, emerges which has lifetimes that are macroscopic for masses below the GeV scale. At the LHeC, these dark photons are produced via radiation from the electron and be searched for via an appearing vertex of two charged SM particles.[25]

### 2.4. *Leptoquarks*

Leptoquarks (LQ) were introduced in the Pati and Salam SU(4) model, where the lepton number was considered to be the fourth colour.[27] They can be scalar or vector particles with Yukawa couplings to leptons and quarks. These interactions allow, in principle, for the violation of lepton flavour at the tree level, which is why LQs provide feasible solutions to the so-called flavour anomalies[28] in the decays of heavy mesons.

One example of such scalar leptoquarks is a color triplet and electroweak doublet of hypercharge 7/6, denoted $R_2$, which dominantly couples to third generation fermions and can address the $R_{D^{(*)}}$ anomaly with the combination of coupling and mass parameters, see Fig. 5. Limits and future projections of LHC searches for $R_2$ are also shown in Fig. 5. This demonstrates that $R_2$ with $\mathcal{O}(1$ TeV$)$ mass is not excluded at the LHC and could be studied at the LHeC, where it is produced via its small Yukawa couplings to first generation fermions and can be tested via, for example, the $b\tau$ final states.[26]

At the LHC, LQ are pair produced via the strong interaction. The current limits assume LQ with 100% branching ratios into SM fermions, and

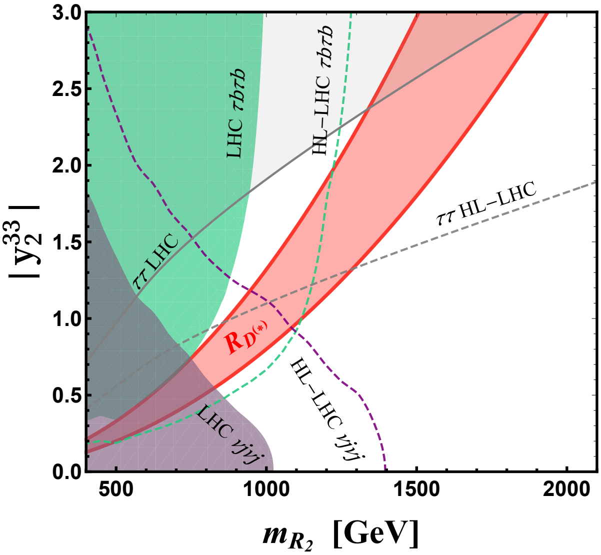


Fig. 5. Existing and projected LHC constraints at the 95% confidence level on the $y_2^{33}$ Yukawa coupling and mass of the $R_2$ leptoquark. Two other non-zero Yukawa couplings are $y_1^{23} = 1$ and $y_2^{11} \ll 1$. The red area denotes parameter combinations where $R_{D^{(*)}}$ can be explained. From Ref. 26.

exclude masses up to around 1 TeV where the limits are stronger (weaker) for the first (third) generation. Scenarios exist where LQ couple strongly to right-handed neutrinos, which in turn decay via a boosted topology that cannot easily be studied at the LHC. Such signatures can be addressed via displaced fat jets at the LHeC with great efficiency.[29]

### 2.5. *Further interesting subjects*

Many more enticing BSM theories have been studied over the years in the context of future *ep* colliders.[6] For example, couplings of gauge bosons and fermions may receive contributions from BSM at the loop level and deviate from the SM prediction. At the LHeC, one could study anomalous gauge couplings in interactions of $Wtb$, $t\bar{t}\gamma$ and $t\bar{t}Z$. Similarly, flavour changing neutral currents are strongly constrained from many experiments, but in interactions that involve top quarks the limits are not very strong, motivating studies of interactions like $tu\gamma$, $tuZ$ and $tHu$ via single top production. Also, anomalies in triple gauge boson vertices, $W^+W^-V$, $V = \gamma, Z$ can be tested at LHeC in great detail.

A unique opportunity comes with tests of charged lepton flavour violation in the tau sector at the LHeC. The BSM model under consideration could be a heavy $Z'$, scalar, or a generic contact interaction, and the tau lepton being correlated with the initial state electron makes this test more powerful than any other existing or proposed future experiment.[30,31]

Axion-like particles, motivated by the original idea of the QCD axion and dark matter candidates, are pseudoscalar particles assumed to be relatively light with QCD couplings. Interactions with other SM fields and mixing with the pion are possible, such that they can be produced via vector boson fusion processes, and improving on LHC results especially for masses below 100 GeV.[32]

It is not clear where new physics may appear. It ought to exist because the Standard Model, while being a phenomenologically successful gauge theory, it does not provide answers to a variety of fundamental questions as mentioned in the opening of this chapter and known to the field. It is very likely that the era of physics beyond the SM, wherever it commences, needs to be explored with different kinds of luminous colliders. Initial studies here sketched have illustrated the remarkable potential of high energy future *ep* colliders, of the LHeC, the HE-LHeC and later the FCC-eh, to find and understand new physics beyond their striking role for QCD, substructure, electroweak and Higgs physics. A next generation of colliders, much like LEP, HERA and the TeVatron, has crucial tasks ahead for a few decades hence. In the nearer future, the HL-LHC combined with its *ep* complement, the LHeC, provides a most attractive and affordable base for particle physics to be advanced, with surprises and possible discoveries that may change the route this science has hitherto taken.

## Acknowledgment

The work of J.B. has been supported by the FEDER/Junta de Andalucía project grant P18-FRJ-3735.

## References

1. G. Aad et al., Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC, *Phys. Lett. B.* **716**, 1–29 (2012). doi: 10.1016/j.physletb.2012.08.020.
2. S. Chatrchyan et al., Observation of a New Boson at a Mass of 125 GeV

with the CMS Experiment at the LHC, *Phys. Lett. B.* **716**, 30–61 (2012). doi: 10.1016/j.physletb.2012.08.021.

3. F. Englert and R. Brout, Broken Symmetry and the Mass of Gauge Vector Mesons, *Phys. Rev. Lett.* **13**, 321–323 (1964). doi: 10.1103/PhysRevLett.13.321.
4. P. W. Higgs, Broken Symmetries and the Masses of Gauge Bosons, *Phys. Rev. Lett.* **13**, 508–509 (1964). doi: 10.1103/PhysRevLett.13.508.
5. G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, Global Conservation Laws and Massless Particles, *Phys. Rev. Lett.* **13**, 585–587 (1964). doi: 10.1103/PhysRevLett.13.585.
6. P. Agostini et al., The Large Hadron-Electron Collider at the HL-LHC, *J. Phys. G.* **48** (11), 110501 (2021). doi: 10.1088/1361-6471/abf3ba.
7. O. Fischer et al., Unveiling hidden physics at the lhc, *Eur. Phys. J. C.* **82** (8), 665 (2022). doi: 10.1140/epjc/s10052-022-10541-4.
8. A. Abada et al., FCC Physics Opportunities: Future Circular Collider Conceptual Design Report Volume 1, *Eur. Phys. J. C.* **79** (6), 474 (2019). doi: 10.1140/epjc/s10052-019-6904-3.
9. A. David, A. Denner, M. Duehrssen, M. Grazzini, C. Grojean, G. Passarino, M. Schumacher, M. Spira, G. Weiglein, and M. Zanetti, LHC HXSWG interim recommendations to explore the coupling structure of a Higgs-like particle (9, 2012).
10. M. Cepeda et al., Report from Working Group 2: Higgs Physics at the HL-LHC and HE-LHC, *CERN Yellow Rep. Monogr.* **7**, 221–584 (2019). doi: 10.23731/CYRM-2019-007.221.
11. J. de Blas et al., Higgs Boson Studies at Future Particle Colliders, *JHEP.* **01**, 139 (2020). doi: 10.1007/JHEP01(2020)139.
12. G. Aad et al., Search for invisible Higgs-boson decays in events with vector-boson fusion signatures using 139 $\text{fb}^{-1}$ of proton-proton data recorded by the ATLAS experiment (2, 2022).
13. D. Curtin, K. Deshpande, O. Fischer, and J. Zurita, New Physics Opportunities for Long-Lived Particles at Electron-Proton Colliders, *JHEP.* **07**, 024 (2018). doi: 10.1007/JHEP07(2018)024.
14. K. Cheung, O. Fischer, Z. S. Wang, and J. Zurita, Exotic Higgs decays into displaced jets at the LHeC, *JHEP.* **02**, 161 (2021). doi: 10.1007/JHEP02(2021)161.
15. M. Kumar, X. Ruan, R. Islam, A. S. Cornell, M. Klein, U. Klein, and B. Mellado, Probing anomalous couplings using di-Higgs production in electron–proton collisions, *Phys. Lett. B.* **764**, 247–253 (2017). doi: 10.1016/j.physletb.2016.11.039.
16. A. Jueid, J. Kim, S. Lee, and J. Song, Studies of nonresonant Higgs pair production at electron-proton colliders, *Phys. Lett. B.* **819**, 136417 (2021). doi: 10.1016/j.physletb.2021.136417.
17. H. Hesari, H. Khanpour, and M. Mohammadi Najafabadi, Study of Higgs Effective Couplings at Electron-Proton Colliders, *Phys. Rev. D.* **97** (9), 095041 (2018). doi: 10.1103/PhysRevD.97.095041.
18. L. Delle Rose, O. Fischer, and A. Hammad, Prospects for Heavy Scalar

Searches at the LHeC, *Int. J. Mod. Phys. A*. **34** (23), 1950127 (2019). doi: 10.1142/S0217751X19501276.

19. A. M. Sirunyan et al., Search for a new scalar resonance decaying to a pair of Z bosons in proton-proton collisions at $\sqrt{s} = 13$ TeV, *JHEP*. **06**, 127 (2018). doi: 10.1007/JHEP06(2018)127. [Erratum: JHEP 03, 128 (2019)].
20. CMS, Search for a new scalar resonance decaying to a pair of Z bosons at the High-Luminosity LHC, CMS-PAS-FTR-18-040 (2019).
21. S. Buddenbrock, A. S. Cornell, Y. Fang, A. Fadol Mohammed, M. Kumar, B. Mellado, and K. G. Tomiwa, The emergence of multi-lepton anomalies at the LHC and their compatibility with new physics at the EW scale, *JHEP*. **10**, 157 (2019). doi: 10.1007/JHEP10(2019)157.
22. A. Crivellin, Y. Fang, O. Fischer, A. Kumar, M. Kumar, E. Malwa, B. Mellado, N. Rapheeha, X. Ruan, and Q. Sha, Accumulating Evidence for the Associate Production of a Neutral Scalar with Mass around 151 GeV (9, 2021).
23. J. Alimena et al., Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider, *J. Phys. G*. **47** (9), 090501 (2020). doi: 10.1088/1361-6471/ab4574.
24. S. Antusch, E. Cazzato, and O. Fischer, Sterile neutrino searches at future $e^-e^+$, $pp$, and $e^-p$ colliders, *Int. J. Mod. Phys. A*. **32** (14), 1750078 (2017). doi: 10.1142/S0217751X17500786.
25. M. D'Onofrio, O. Fischer, and Z. S. Wang, Searching for Dark Photons at the LHeC and FCC-he, *Phys. Rev. D*. **101** (1), 015020 (2020). doi: 10.1103/PhysRevD.101.015020.
26. G. Azuelos, O. Fischer, and S. Jana, Testing the $R_{D^{(*)}}$ anomaly at the LHeC, *Eur. Phys. J. C*. **81** (12), 1123 (2021). doi: 10.1140/epjc/s10052-021-09936-6.
27. J. C. Pati and A. Salam, Lepton Number as the Fourth Color, *Phys. Rev. D*. **10**, 275–289 (1974). doi: 10.1103/PhysRevD.10.275. [Erratum: Phys. Rev. D 11, 703–703 (1975)].
28. Y. S. Amhis et al., Averages of b-hadron, c-hadron, and $\tau$-lepton properties as of 2018, *Eur. Phys. J. C*. **81** (3), 226 (2021). doi: 10.1140/epjc/s10052-020-8156-7.
29. G. Cottin, O. Fischer, S. Mandal, M. Mitra, and R. Padhan, Displaced Neutrino Jets at the LHeC (4, 2021).
30. S. Antusch, A. Hammad, and A. Rashed, Probing $Z'$ mediated charged lepton flavor violation with taus at the LHeC, *Phys. Lett. B*. **810**, 135796 (2020). doi: 10.1016/j.physletb.2020.135796.
31. S. Antusch, A. Hammad, and A. Rashed, Searching for charged lepton flavor violation at *ep* colliders, *JHEP*. **03**, 230 (2021). doi: 10.1007/JHEP03(2021)230.
32. C.-X. Yue, M.-Z. Liu, and Y.-C. Guo, Searching for axionlike particles at future *ep* colliders, *Phys. Rev. D*. **100** (1), 015020 (2019). doi: 10.1103/PhysRevD.100.015020.