Prospects for Heavy Scalar Searches at the LHeC

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Abstract

In this article we study the prospects of the proposed Large Hadron electron Collider (LHeC) in the search for heavy neutral scalar particles. We consider a minimal model with one additional complex scalar singlet that interacts with the Standard Model (SM) via mixing with the Higgs doublet, giving rise to a SM-like Higgs boson \( h_1 \) and a heavy scalar particle \( h_2 \). Both scalar particles are produced via vector boson fusion and can be tested via their decays into pairs of SM particles, analogously to the SM Higgs boson. Using multivariate techniques we show that the LHeC is sensitive to \( h_2 \) with masses between 200 and 800 GeV down to scalar mixing of \( \sin^2 \alpha \sim 10^{-3} \).

1 Introduction

One of the most important tasks of high-energy particle physics of our time is the detailed measurement of the couplings of the recently discovered Higgs boson. Thanks to the recent progress at the Large Hadron Collider (LHC) some of the Higgs boson properties are known with \( \sim 5\% \) precision. Unfortunately the foreseeable improvement of these measurements from the high-luminosity phase of the LHC is very limited due to the large systematic uncertainties. Since the Higgs boson provides a notorious portal to new physics, these measurements leave plenty of room for physics beyond the Standard Model (SM) in the scalar sector.

The dominant barriers for precision Higgs boson physics at the LHC stem from PDF measurements [1] which cannot be improved with the ambitious luminosity goals of the High-Luminosity LHC (HL-LHC). Moreover, its main decay mode into the \( b\bar{b} \) final state can only be accessed with poor precision due to the large backgrounds. A new generation of machines is presently discussed, which are to measure the Higgs boson properties with high precision. Among the others it is worth mentioning the so-called Higgs factories, the high-luminosity electron-positron colliders at 250 GeV [2–4].

It is possible, however, to improve the precision of many Higgs boson measurements at the LHC already, by colliding one of its proton beams with a new electron beam. The resulting facility is the Large Hadron electron Collider (LHeC) [5] which can run concurrently to the LHC at \( \sim 1.2 \) TeV centre-of-mass energy with a total integrated luminosity of \( 1 \) ab\(^{-1}\). One of its prime objectives is the improvement of the PDF sets [1] which would ameliorate many LHC studies, but it also has been proven to be more than competitive with Higgs boson measurements, cf. [6,7] and to bring unique opportunities with respect to Beyond the SM (BSM) physics, cf. e.g. [8–12].

Owing to the importance of measuring the Higgs sector, many LHC analyses are searching for additional neutral scalar bosons which can be produced and decay via their mixing with the SM Higgs boson. Like all BSM studies at the LHC, these searches have to deal with very high rates of SM backgrounds. These analyses can access the squared scalar mixing angle on the order of 10\% and are particularly sensitive to heavy scalars with masses above a few hundred GeV. It is interesting to note that there are some hints in the LHC data that can be interpreted as a 270 GeV neutral heavy scalar [13,14] which was referred to as the “Madala hypothesis” [15]. These observations, together with the background-related limitations of the LHC, represent our main motivation to study the prospects of searches for heavy neutral scalars at the LHeC. A similar study on a preparatory level, motivated by the “Madala hypothesis”, has been performed in [16].
In this paper we present a detailed study for searching a heavy Higgs-like at the LHeC via its dominant decays into SM gauge bosons, i.e., $WW$ or $ZZ$, which in turn give rise to the final states $4l$, $2l2j$ or $\nu l2j$, among others. Compared with existing analyses at LHC, (cf. [17]) we find plenty of room for a discovery.

2 The Model

Extended Higgs sectors are ubiquitous in many BSM scenarios and, as such, represent a very strong case for experimental searches. In particular, extra scalars that are singlets under the SM gauge group are envisaged in some of the most natural extensions of the SM, ranging from Supersymmetry to Composite Higgs models and to GUT extensions (in which the new scalar sector provides the mass to the extra massive gauge bosons). Moreover, in some scenarios the SM singlet scalars can act as a portal to SM neutral fields in dark sectors which otherwise would remain completely unobserved. Extra scalar singlets also play a major role in models of electroweak baryogenesis as they represent one of the most economical possibilities to realise a first-order electroweak phase transition.

Motivated by the aforementioned scenarios, we consider a simple extension of the SM with a complex neutral scalar boson $S$, singlet under the SM gauge group. The scalar sector is thus described by the potential

$$V(H,S) = m_1^2 H^\dagger H + m_2^2 S^\dagger S + \lambda_1 (H^\dagger H)^2 + \lambda_2 (S^\dagger S)^2 + \lambda_3 (H^\dagger H)(S^\dagger S),$$

which is the most general renormalizable scalar potential of the SM $SU(2)$ Higgs doublet $H$ and the complex scalar $S$. The mass eigenstates from the resulting mass matrix correspond to the physical fields $h_{1,2}$, which are given by

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} H \\ S \end{pmatrix},$$

where the scalar mixing angle $\alpha$ and the masses of the physical scalars are defined in terms of the original parameters of the potential as

$$\tan 2\alpha = \frac{\lambda_3 v x}{\lambda_1 v^2 - \lambda_2 x^2},$$

$$m_{h_{1,2}}^2 = \lambda_3 v^2 + \lambda_2 x^2 \mp \sqrt{\left(\lambda_1 v^2 - \lambda_2 x^2\right)^2 + \left(\lambda_3 v x\right)^2},$$

with $m_{h_2} > m_{h_1}$ and $h_1$ identified with the 125 GeV Higgs boson. In the previous equations, $v$ and $x$ are the vacuum expectation values of the $H$ and $S$ fields, respectively.

After mass mixing, the mass eigenstate $h_1$ corresponds to the SM-like Higgs, by which we mean that in the limit of the scalar mixing angle $\alpha \to 0$ we recover the Higgs boson with the interactions and properties as predicted by the SM. The scalar mixing yields couplings between the mass eigenstate $h_2$ and the SM fermions and gauge bosons proportional to those of a SM Higgs boson of the same mass, with a rescaling factor given by $\sin \alpha$. On top of the SM-like interactions, the last term in eq. (\ref{eq:potential}) proportional to $\lambda_3$ gives rise to a coupling between $h_1$ and $h_2$, which yields e.g. the additional decay channel $h_2 \to 2h_1$ if $m_{h_2} > 2m_{h_1}$. If no other decay modes are available for the $h_2$, as it is the case for our simple setup, the phenomenology of the $h_2$ below the $h_1h_1$ threshold is similar to that of the SM Higgs with $m_h = m_{h_2}$, with same the branching ratios and a total decay width simply rescaled by $\sin^2 \alpha$. Above the threshold, the branching ratios of $h_2$ into SM final states is given by

$$BR(h_2 \to SM) = BR_{SM}(h_2 \to SM)(1 - BR(h_2 \to h_1h_1))$$

with $BR_{SM}(h_2 \to SM)$ being the SM one. The branching ratio $BR(h_2 \to h_1h_1)$ is computed from the corresponding partial decay width which can be expressed explicitly as

$$\Gamma(h_2 \to h_1h_1) = \left(\frac{\sin 2\alpha}{v}(\cos \alpha + \frac{v}{x} \sin \alpha)(m_{h_2}^2 + m_{h_1}^2)\right)^2 \frac{1}{32\pi m_{h_2}} \left(1 - \frac{4m_{h_1}^2}{m_{h_2}^2}\right)^{1/2}.$$  

The main branching ratios of the heavy scalar $h_2$ are shown in fig. as a function of $m_{h_2}$ for a scalar mixing angle $\sin \alpha = 0.2$ and $x \gg v$. In BSM scenarios in which the SM gauge group is extended by extra abelian
3 Heavy Higgs search strategy

In the following we investigate the prospects of the LHeC in the search for a heavy Higgs $h_2$ in the mass region $m_{h_2} > m_{h_1}$ by focusing on its leading decay modes into SM weak gauge bosons, $WW$ and $ZZ$. It is worth mentioning that the other interesting decay channels which would be extremely useful to characterise the phenomenology of the extra scalar, and to eventually discriminate among different models, are the di-higgs and di-top decay modes. Nevertheless, here we consider only those search channels which will most likely represent the priorities of the research program for heavy scalars at the LHeC.

3.1 Signatures and analysis

In particular, the following signatures will be studied:

1. $\mu^Z_{4\ell} := h_2 \rightarrow ZZ \rightarrow 4\ell$
2. $\mu_{e q}^Z := h_2 \rightarrow ZZ \rightarrow 2\ell 2q$

3. $\mu_{e q}^W := h_2 \rightarrow WW \rightarrow \nu\ell 2j$

As already stated above, further channels exist, which are not expected to add significantly to the final sensitivity of the LHeC to heavy Higgses but are also very interesting in their own right. Examples for these channels are the boosted mono-$Z$ ($h_2 \rightarrow Z q q_{inv}$), di-top ($h_2 \rightarrow t\bar{t}$) and di-Higgses ($h_2 \rightarrow 2 h_1$).

Since the signal channels studied here all consist of two vector bosons of high invariant mass, we consider diboson processes in the SM as our primary background. We neglect the small QCD and QED contributions which typically carry smaller momenta in particular in the transverse direction. The background processes considered here and the corresponding cross sections are listed in tab. 1. For such backgrounds we use a systematic uncertainty of 2% [5].

The centre-of-mass at the LHeC is boosted with respect to the laboratory system due to the asymmetric beam energies which pushes the final states towards positive $\eta$ values. Accordingly, for heavy $h_2$, which requires larger parton energies, the decay products are strongly forward boosted with large (positive) $\eta$ values. This provides a good handle to separate signal from background events. For $h_2$ masses that become comparable to the centre-of-mass energy of $\sim 1.2$ TeV this good separability is countered by the reduction of the total cross section due to the restricted phase space.

For the reconstruction of the signal we require that the beam-remnant jet from the deep inelastic scattering (DIS) off the proton has a transverse momentum of $P_T(j) > 10$ GeV and a pseudo rapidity of $|\eta(j)| < 4.5$ for geometric acceptance, while for leptons we require $P_T(l) > 2$ GeV and $|\eta(l)| < 4.5$, with $l$ accounts for electrons and muons.

For the simulation of the signal and background event samples, the Monte Carlo event generator MadGraph5 version 2.4.3 [18] is employed. As usual, parton shower and hadronisation is taken care of by Pythia6 [19] while the fast detector simulation is carried out by Delphes [20]. We use the Delphes detector card from the LHeC collaboration. We note that Pythia needs to be patched [21] in order to achieve a reasonable event generation efficiency and that it is crucial that the first (second) beam, as inputted in the MadGraph run card, corresponds to the proton (electron) to correctly match the asymmetric detector setup implemented in the Delphes card. We use an electron beam of 60 GeV with 80% polarisation, the proton beam with energy of 7 TeV and we consider to the proton (electron) to correctly match the asymmetric detector setup implemented in the Delphes card. We use a total integrated luminosity of $1/ab$. It is important to notice, that a smaller electron beam energy would result in a smaller production cross section of the $h_2$ and it would also reduce the LHeC reach with respect to the heavy Higgs mass due to the more restricted phase space.

We perform the analysis for five benchmark masses $m_{h_2}$ from 200 GeV to 800 GeV and, for illustrative purposes, we present detailed results for a specific benchmark point, allowed by current LHC searches [24], defined by $m_{h_2} = 500$ GeV and $\sin \alpha = 0.2$. For larger heavy Higgs masses, the number of events drops significantly and, consequently, the error bands highly enlarge over the expected median preventing us from reaching a reasonable statistical conclusion. All the backgrounds from tab. 1 with all possible decay channels were included for each of the three signal channels, $4\ell$, $2\ell + 2j$, $\ell + 2j + E_T$. A total of $10^7$ events for each signal and background sample was simulated.

From the available visible final states, a number of observables are constructed that are then input into the TMVA package [22] which handles a Multi-Variate Analysis (MVA). Among the different analysis techniques, we employed the Boosted Decision Tree (BDT) which is largely used by the LHC experimental collaborations.

The fully leptonic final state, $\mu_{e q}^Z$: This signal channel consists of two lepton pairs $\ell_\alpha^+ \ell_\alpha^- \ell_\beta^+ \ell_\beta^-$ with the lepton flavours $\alpha, \beta \in \{e, \mu\}$. Conservatively, we considered here only electrons and muons but, in principle, reconstructing tau leptons is also possible and may enhance the significance of this channel. We observed that the final state events are characterised by a highly boosted beam-remnant jet with large positive $\eta$ values.

The mass of $h_2$ in the range investigated here is always larger than $2m_Z$, thus we can require the two $Z$ bosons to be produced on shell and to decay leptonically. From the possible combinations of same flavour and opposite sign leptons, one should recover the invariant masses of both pairs compatibly with $m_Z$. Nevertheless, for our pre-selection before the actual MVA, we do not explicitly require the lepton pairs to reconstruct the $Z$ boson peaks within a given mass window but simply collect, among all possible leptons in the events, the electron or muon pairs that are closest to the $Z$ rest mass. Final state leptons are thus grouped into three categories:
Figure 3: The most relevant observables as ranked by the BDT analysis for the three signal channels $\mu^Z_{\ell\ell}$ (left), $\mu^Z_{\ell q}$ (middle) and $\mu^W_{\ell q}$ (right) with a signal benchmark point defined by $m_{h_2} = 500$ GeV and $\sin \alpha = 0.2$. The variable in the left plot is the invariant mass of four final state leptons. The variable in the middle plot is the invariant mass of two final state jets and two final state leptons. The variable in the right plot is the transverse mass of the lepton and the two jets in the final state.

Figure 4: The BDT distributions for the three signal channels $\mu^Z_{\ell\ell}$ (left), $\mu^Z_{\ell q}$ (middle), and $\mu^W_{\ell q}$ (right) with $m_{h_2} = 500$ GeV and $\sin \alpha = 0.2$.

Figure 5: Cut efficiency and the relevant significance distributions for the three signal channels $\mu^Z_{\ell\ell}$ (left), $\mu^Z_{\ell q}$ (middle), and $\mu^W_{\ell q}$ (right) with $m_{h_2} = 500$ GeV and $\sin \alpha = 0.2$. 

Table 1: The SM background processes considered in this analysis. The samples have been produced with the following cuts: \( p_T(j) > 20 \text{ GeV}, p_T(l) > 2 \text{ GeV} \) and \(|\eta(j/l)| < 6 \).

4\(\mu\), 2e2\(\mu\) or 4e. The main source of irreducible backgrounds in this case is given by \( \nu j ZZ \) and \( e^- j ZZ \), while the other backgrounds that contain \( W \) bosons are suppressed during the MVA process by exploiting the different positions of the peaks in the invariant mass distributions of the lepton pairs.

We take advantage of the full power of BDT algorithm in distinguishing between signal and background events, feeding it with 42 kinematical observables. The most relevant observables according to the BDT ranking are, as expected, the invariant mass of \( h_2 \) from 4\(\mu\), 2e2\(\mu\) and 4e respectively, as well the reconstructed invariant mass of \( Z \) boson. As an example, the four-lepton invariant mass distribution for the signal and the background samples is shown in fig. 3 for the benchmark point defined by \( m_{h_2} = 500 \text{ GeV} \) and \( \sin \alpha = 0.2 \).

The semileptonic final state, \( \mu W \ell q \): This signal channel is much more difficult to reconstruct compared to the first two due to the final state neutrino which escapes from the detector and makes it impossible to fully reconstruct the \( h_2 \) system.

For our pre-selection we select in each event, among all jets with highest momentum, the two jets with the reconstructed invariant mass that is closest to the \( W \) boson mass, and, among all possible leptons, that with the highest momentum that together with the missing energy reconstructs more closely the transverse mass of the second \( W \). The main discriminating variable here is the transverse mass of \( h_2 \) which is peaked around the rest mass of \( h_2 \) and has a flat tail, due to the missing energy contribution. This distribution is shown in fig. 3 for a particular benchmark point. Further relevant observables are the invariant mass of the \((W + l)\) system, the \( \eta(W, l) \) and \( \eta(l) \) distributions.

Here the usage of MVA, and especially the BDT, is found to be extremely useful, with respect to standard cut-based analysis, in exploiting the differences between signal and background distributions.

### 3.2 Results

We employ the BDT method to perform the multivariate analysis. The discriminating power of the BDT relies on the fact that the signal and the background may be characterised by different features that can be entangled
has been investigated in the final state objects 4ℓ, Z of mass energy of 13 TeV and 35.9/ fb of integrated luminosity. In particular, the search has been performed for heavy scalars over the mass range of 130 GeV to 3 TeV at a centre of mass energy of 13 TeV and 35.9/ fb of integrated luminosity. In particular, the current LHC limit (red dashed line) at 95% CL has been extracted from [24],

Figure 4 shows the BDT distributions for the three channels µℓℓ (left), µℓq (middle), and µW (right) for the benchmark point given by mh2 = 500 GeV and sin α = 0.2. The BDT discriminator ranges from −1 to 1: the events with discriminant value near 1 are classified as signal-like events (blue distribution) and those near −1 are considered as background-like events (red distribution). The optimisation of the signal/background cut, as a function of the BDT variable, has been performed using the TMVA and expressed in terms of the significance σ = 0

Figure 5 shows the cut efficiency for the three channels µℓℓ (left), µℓq (middle), and µW (right) for mh2 = 500 GeV and sin α = 0.2. For µℓℓ channel, by requiring BDT > 0.163, we can reach significance σ = 0.313 with signal efficiency 0.91 and background rejection efficiency of 6.4 × 10−4, for the channel µℓq, with BDT > 0.163 we obtain a significance of 12.2σ with signal efficiency 0.4 and background efficiency 1.2 × 10−3. Finally, for the channel µW, with BDT > 0.23 one can get a significance of 3.5σ with signal efficiency 0.43 and background efficiency 0.034.

The combined sensitivity is derived from the BDT distributions of the above described analyses and for each benchmark mass. As stated above, we included a the systematic uncertainty on the background of 2% and we used the Higgs Analysis-Combined Limit tool [23]. To extract the limit we preformed a frequentist test which uses the profile likelihood as test statistics. In addition to the parameters of interest, such as the total cross section and the integrated luminosity, we include a nuisance parameter for background only of 2% as a logarithmic-normal distribution to account for the unknown systematic uncertainty of the future LHeC. In fig. 6 we show the 95% CL expected median limit on the square of the sine of the mixing angle, as well the error bands of 1 and 2 sigma. Due to the different efficiencies, branching fractions and the relevant backgrounds, each final state contributes differently depending on the mass of the heavy scalar. As an example, we find that the µℓℓ channel is the most sensitive one in the mass range 200 – 500 GeV, while the µℓq channel is sensitive in the higher mass regime. The current LHC limit (red dashed line) at 95% CL has been extracted from [24], where the search has been performed for heavy scalars over the mass range of 130 GeV to 3 TeV at a centre of mass energy of 13 TeV and 35.9/ fb of integrated luminosity. In particular, the Z boson pair decay channel has been investigated in the final state objects 4ℓ, 2ℓ2j and 2ℓ2ν. It is clear that the sensitivity of the LHeC is better than the current LHC one by about two orders of magnitude in the low mass regime up to one order of magnitude in the high mass region. As an example, the expected 2σ median sensitivity of the LHeC to sin^2α

![combined limits graph](image)
for the mass $m_{h^2} = 500$ GeV can be as small as $4 \times 10^{-3}$.

4 Conclusion

Precision measurements of the Higgs boson properties are very important due to its possible role as portal to BSM sectors. Present searches at the LHC are compatible with additional heavy scalar particles that mix on the percent level with the SM Higgs boson. We have shown that the prospects of discovering such heavy scalars at the LHeC are very promising and complementary to the searches at the LHC, where the notorious SM backgrounds and systematic uncertainties make discovery difficult. Using multivariate techniques and by exploiting three of the most promising decay channels of a heavy Higgs, we find that the LHeC can access heavy scalar bosons with masses between 200 and 800 GeV and scalar mixings as small as $\sin^2 \alpha \sim 10^{-3}$. We also pointed out that many other interesting channels exist that may allow to test the properties and the origin of the heavy Higgs boson. Among these, searches for (semi) invisible decays, di-higgs and the di-top final states may successfully exploit the cleaner environment offered by the future and promising LHeC machine.

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