Finding Heavy Scalar bosons at the LHeC

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Motivation

- Additional CP even scalars come with many theory extensions.
- Can be connected to neutrino mass physics, Dark Matter, vacuum stability ...
- There are hints in the LHC data for a $\sim$ 300 GeV scalar.
- This is difficult to detect and almost impossible to study at the LHC.

The Model

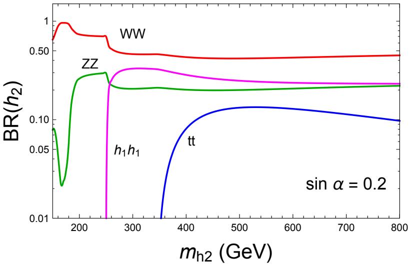
- SM extended with a complex neutral scalar boson S
- S is a singlet under the SM gauge group
- Most general renormalizable scalar potential:

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

- The scalar fields H, S develop vevs v, x.
- Mass matrix mixes the fields, mixing angle α
- The neutral mass eigenstates:

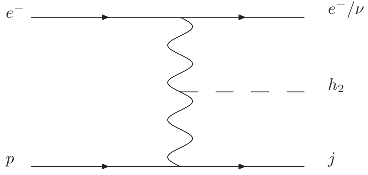
$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H \\ S \end{pmatrix}$$

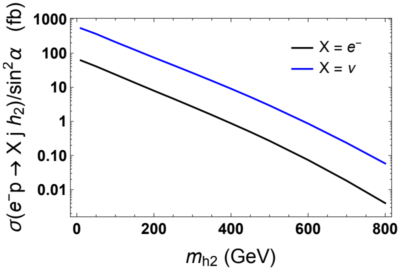
Physical scalars



- In the limit of $\alpha \to 0$ the SM Higgs boson is recovered.
- We define h_1 being "SM-like" Higgs, meaning:
  - $m_{h_1} = 125$ GeV
  - interaction strength $=$ SM$\times \cos^2 \alpha$
  - Limit from current LHC data: $\alpha < 0.3$.
- h_2 is a heavy Higgs-like scalar. We posit:
  - $m_{h_2} > m_{h_1}$
  - Interaction strength $=$ (SM Higgs with $m_h = m_{h_2}$) $\times \sin^2 \alpha$.
  - No other decay modes ($h_2 \to 2\, h_1$ possible above threshold)

Scalar production at the LHeC





- Production modes identical to SM Higgs boson.
- CC cross section is larger than NC one.

Considered signal modes

We focus on the leading decay modes, $h_2 \to VV$.
The three signal modes are:

1. $\mu^Z_{\ell\ell} := h_2 \to ZZ \to 4\ell$
2. $\mu^Z_{\ell q} := h_2 \to ZZ \to 2\ell 2q$
3. $\mu^W_{\ell q} := h_2 \to WW \to \nu\ell 2j$

Quote from the article:

> ... other interesting decay channels ... extremely useful to characterise ... the extra scalar, ... discriminate among different models, are the di-higgs and di-top decay modes [and the hadronic decays of the vector bosons].

Considered backgrounds

Nr.	final state	σ_{LHeC} [fb]
1	$e^- jWW$	23.0
2	$e^- jZW^+$	4.16
3	$e^- jZZ$	0.1
4	νjWW	10.4
5	νjZW^-	8.0
6	νjZZ	2.4

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

Sidenote on simulation

Cuts:

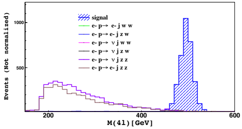
- All: $|\eta(j)| < 4.5$
- DIS jet: $P_T(j) > 10$ GeV
- Electrons and muons: $P_T(l) > 2$ GeV

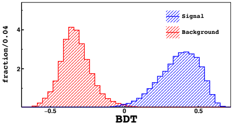
Simulation:

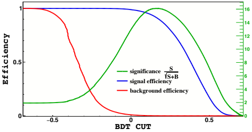
- Madgraph, Pythia6, Delphes
- We patched Pythia as prescribed by Uta
- We used a modified delphes card, including:
  - a muon module
  - adjusted eta acceptance
  - hadron tracking precision as in CDR

$\Rightarrow$ This needs to be made available publicly to support 'external' BSM studies.

Signal channel 1: 4 leptons





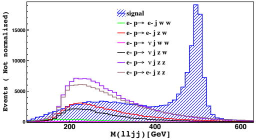


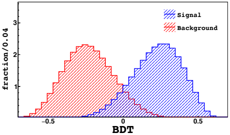
- $\ell_\alpha^+ \ell_\alpha^- \ell_\beta^+ \ell_\beta^-$ with flavours $\alpha, \beta \in \{e, \mu\}$.
- τ not considered; unsure about τ reconstruction@LHeC.
- Preselection collects same flavor $\ell^+\ell^-$ pairs with $M_{2\ell}$ closest to m_Z.
- Main backgrounds are νjZZ and $e^- jZZ$.
- MVA BDT with 42 kinematical observables.
- Most important observables are $M_{4\ell}$ and $M_{2\ell}$.

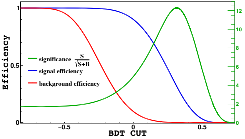
Analysis

- We created in total 42 observables from the visible final states.
- Made use of a Boosted Decision Tree and performed a multivariate analysis (with TMVA).
- Signal significances for each of the signal channels separately.
- Channels were combined with a statistical tool (Combined Higgs limits).

Signal channel 2: semileptonic without MET

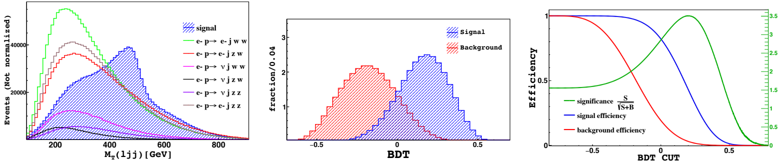






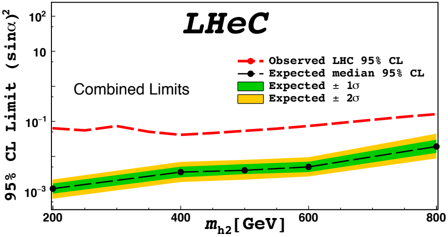
- Two leptons and two jets, each with M_{2f} close to m_Z.
- Main backgrounds are νjZZ and $e^- jZZ$, contributions from processes with at least one W boson
- Analysis strategy similar to the one for 4 leptons.
- Most important observables (BDT ranking):
  total invariant mass, $\eta(\ell)$, angular sep. between ℓ and Z.

Signal channel 2: semileptonic with MET



- One lepton, two jets with inv. mass $\sim m_W, m_Z$.
- Difficult to reconstruct because of escaping neutrino.
- Preselection collects among all jets the pair with invariant mass closest to m_Z.
- We reconstruct from lepton, MET, and W candidate the transverse mass of the second vectorboson.
- Most important observable is the total visible transverse mass.

Combination of signal modes and comparison to LHC



- Including a systematic uncertainty of 2% on the background.
- LHC results from 35.9/fb at 13 TeV, including $4\ell, 2\ell 2j$ and $2\ell 2\nu$.
- Extrapolations for HL-LHC, without new backgrounds, comparable to LHeC, better for larger masses.
- LHC analysis seems to struggle for masses $\sim 100 \div 300$ GeV.

Conclusions

- Present searches at the LHC are compatible with additional heavy scalar particles that mix on the percent level with the SM Higgs boson.
- Multivariate techniques: h_2 with mass $200\div 800$ GeV and mixings $> \sin^2\alpha \sim 10^{-3}$.
- Promising discovery prospects of heavy scalars at the LHeC
- Complementary to the searches at the LHC, especially wrt semileptonic final states.
- Many other interesting channels exist that could improve this sensitivity further.

$\Rightarrow$ We have a new working and efficient pipeline for BSM@ep studies at the reconstructed level!

4 Leptons

$$MET, P_T(j), \eta(j), P_T(l), \eta(l)$$
$$P_T(Z)_{ll}, \eta(Z)_{ll}, \Delta R(Z)_{ll}$$
$$P_T(h)_{llll}, \eta(h)_{llll}, \Delta R(h)_{llll}$$
$$P_T(h+j), \Delta R(h,j)_{llll}$$

With l = electron or muons

2l 2j

$$MET, P_T(j), \eta(j), P_T(l), \eta(l)$$
$$P_T(j)_{beam}, \eta(j)_{beam}, P_T(j_1), \eta(j_1), P_T(j_2), \eta(j_2)$$
$$P_T(l_1), \eta(l_1), P_T(l_2), \eta(l_2), P_T(Z)_{jj}, \eta(Z)_{jj}, M(Z)_{jj}$$
$$P_T(Z)_{ll}, \eta(Z)_{ll}, M(Z)_{ll}, P_T(h)_{jjll}, \eta(h)_{jjll}, M(h)_{jjll}$$
$$\Delta R(h)_{jjll}, \Delta R(Z_{ll}, Z_{jj}), \Delta R(h, j_{beam})$$

With l = electron or muons

vl 2j

$$MET, P_T(j)_{beam}, \eta(j)_{beam}, P_T(l), \eta(l)$$
$$P_T(j1)_W, \eta(j1)_W, P_T(j_2)_W, \eta(j_2)_W$$
$$P_T(W)_{jj}, \eta(W)_{jj}, M(W)_{jj},$$
$$P_T(W+l), \eta(W+l), M(W+l),$$
$$MT(W+l)$$

With l = electron or muons