Signatures of new scalar particles at future $e^+e^-$ colliders

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Research supported by

Preparatory Joint Sessions on ”Open questions and News Ideas” Snowmass 2021 Energy Frontier (EF)
Outline

1 Inert Doublet Model analysis
   - Benchmark points
   - Leptonic analysis
   - Semi-leptonic analysis

2 Search for invisible scalar production

3 Future plans

For more details:

Out of about 15’000 points consistent with all considered constraints, we chose **41 benchmark points (including 20 “high mass”)** for detailed studies:

The selection was arbitrary, but we tried to:
- cover wide range of scalar masses and the mass splittings
- get significant contribution to the relic density

See previous presentation by Tania Robens for more details
IDM production at $e^+e^-$ colliders

Production of IDM scalars at $e^+e^-$ colliders dominated by two processes:

\[ e^+e^- \rightarrow A \ H \quad e^+e^- \rightarrow H^+H^- \]

Leading-order cross sections for IDM scalar production at 500 GeV:

Production via EW couplings \Rightarrow week dependence on IDM couplings

Beam luminosity spectra not taken into account
**IDM scalars: leptonic analysis**

Same flavour lepton pair production can be considered a signature of the $AH$ production process followed by the $A$ decay:

$$e^+ e^- \rightarrow HA \rightarrow HHZ^{(*)} \rightarrow HH \mu^+ \mu^-$$

while the production of the different flavour lepton pair is the expected signature for $H^+ H^-$ production:

$$e^+ e^- \rightarrow H^+ H^- \rightarrow HHW^{+ (*)} W^{- (*)} \rightarrow HH \ell^+ \ell^- \nu \bar{\nu}$$
Neutral IDM scalar production

**Significance of observation**

Summary of results for multivariate analysis of $\mu^+\mu^-$ final state (generator level analysis, cuts reflecting detector acceptance)

High significance of observation for scenarios accessible at given energy

Significance mainly related to the $A_H$ production cross section $\Rightarrow$ scalar masses
Charged IDM scalar production

**Significance of observation**

Summary of results for multivariate analysis of $e^{\pm} \mu^{\mp}$ final state (generator level analysis, cuts reflecting detector acceptance)

Fewer scenarios can be observed, clear need for 500 GeV

Significance mainly related to the $H^+ H^-$ production cross section $\Rightarrow$ scalar mass

A.F. Żarnecki (University of Warsaw)

New scalars @ e^+e^- colliders

July 7, 2020
IDM scalars: semi-leptonic analysis

For high scalar masses leptonic channel sensitivity limited by cross section

Much higher significance can be expected for $H^+H^-$ production in the semi-leptonic final state (isolated lepton and two jets)

- energy and invariant mass reconstruction for one of $W$ bosons ⇒ better signal-background separation
- much larger branching fraction compared to $e\mu$: 2.25% ⇒ 28.6% ⇒ discovery reach should increase significantly
Results

Summary of results obtained for the semi-leptonic channel compared with leptonic channel results for high mass benchmarks @ CLIC

Huge increase of signal significance!
Discovery reach extended up to $m_{H^\pm} \sim 1$ TeV for CLIC @ 3 TeV
Motivation

In Higgs-portal models, new scalars fields $\phi$ coupling to dark matter particles can mix with the SM Higgs field $h$ resulting in two mass eigenstates:

$$
\begin{pmatrix}
  h_1 \\
  h_2
\end{pmatrix}
= 
\begin{pmatrix}
  \cos \alpha & \sin \alpha \\
  -\sin \alpha & \cos \alpha
\end{pmatrix}
\begin{pmatrix}
  h \\
  \phi
\end{pmatrix}
$$

If $\alpha \ll 1$, $h_1$ is SM-like (the observed 125 GeV state), but it can also decay invisibly via $\phi$ component ($\text{BR} \sim \sin^2 \alpha$)

If $h_2$ is also light, it can be produced in $e^+e^-$ collisions in the same way as the SM-like Higgs boson; invisible decays dominate.

We consider Vector-fermion dark matter model (VFDM) for simulation: arXiv:1710.01853
Invisible scalar production

Same approach used as in the search for invisible SM Higgs boson decays. Search for the process:

\[ e^+ e^- \rightarrow Z S \rightarrow q \bar{q} + \not{E}_T \]

Expected distribution of the recoil mass for CLIC running at 380 GeV:
Cross section limits

Expected CLIC limits on the $h_2$ production cross section, relative to SM
for $1000 \text{ fb}^{-1}$ at 380 GeV and $2500 \text{ fb}^{-1}$ at 1500 GeV

assuming $\text{BR}(h_2 \rightarrow \text{inv}) \approx 100\%$
Invisible scalar production

Mixing angle limits

Corresponding CLIC limits on the sine of the mixing angle for \( 1000 \text{ fb}^{-1} \) at 380 GeV and \( 2500 \text{ fb}^{-1} \) at 1500 GeV

\[
\sin(\alpha) \quad \text{95\% CL limit on} \quad \sin(\alpha)
\]

\[
\begin{align*}
\text{380 GeV} & \quad \text{100\%} \\
\text{1500 GeV} & \quad \text{100\%}
\end{align*}
\]

assuming \( \text{BR}(h_2 \rightarrow \text{inv}) \approx 100\% \)
### Future plans

#### Experimental signatures

Covered in the presented studies (IDM and VFDM models)

<table>
<thead>
<tr>
<th>Final State</th>
<th>$\not{E}_T$ (1 particle)</th>
<th>$\not{E}_T$ (≥ 2 particles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z + \not{E}_T$</td>
<td>$e^+ e^- \rightarrow Z h_2$</td>
<td>$e^+ e^- \rightarrow A H \rightarrow Z H H$</td>
</tr>
<tr>
<td>$W^+ W^- + \not{E}_T$</td>
<td></td>
<td>$e^+ e^- \rightarrow H^+ H^-$</td>
</tr>
</tbody>
</table>
Future plans

Experimental signatures

Covered in the presented studies (IDM and VFDM models) and considered for new study (possible Snowmass contribution)

**Final state**

- $Z + \not{E}_T$
- $W^+ W^- + \not{E}_T$
- $h + \not{E}_T$
- $t\bar{t} + \not{E}_T$
- $b\bar{b} + \not{E}_T$

- $\not{E}_T : 1$ particle
  - $e^+ e^- \rightarrow Z h_2$
  - e.g. $e^+ e^- \rightarrow H a$

- $\not{E}_T : \geq 2$ particles
  - $e^+ e^- \rightarrow A H \rightarrow Z H H$
  - $e^+ e^- \rightarrow H^+ H^-$
  - in 2HDM+a
Signatures of new scalar production at future $e^+e^-$ colliders

Production of Inert Doublet Model scalars can be observed with high significance in the di-lepton channels already with 250 GeV $e^+e^-$ collider.

Discovery reach increases for higher $\sqrt{s}$. Semi-leptonic final state has to be considered for large masses!

Search for production and invisible decays of new scalars can give constraints complementary to precise 125 GeV Higgs boson measurements.

Experimentalist’s point of view:

Mono-Z and W-pair signatures considered so far.

Mono-h as well as $t\bar{t}$ and $b\bar{b}$ considered as next targets.

Focusing on cross-section limits rather than particular models...
Thank you!

Leptonic channel sensitivity for CLIC running scenarios:

\[1000 \text{ fb}^{-1} \text{ at } 380 \text{ GeV} \quad 2500 \text{ fb}^{-1} \text{ at } 1.5 \text{ TeV} \quad 5000 \text{ fb}^{-1} \text{ at } 3 \text{ TeV}\]

**AH signature** \((\mu^+\mu^-)\)

**\(H^+H^-\) signature** \((\mu^\pm e^{\mp})\)

Only moderate increase in discovery reach for 1.5 TeV:

- neutral scalar production: \(m_A + m_H < 450 \text{ GeV} \) (290 GeV @ 380 GeV)
- charged scalar production: \(m_{H^\pm} < 500 \text{ GeV} \) (150 GeV @ 380 GeV)

Production cross sections too low at 3 TeV...
**Analysis framework** for semi-leptonic and invisible scalar analysis

Event samples generated with Whizard 2.7.0

*based on the dedicated IDM and VFDM model implementations*

fragmentation and hadronisation is simulated using PYTHIA 6.4

CLIC beam energy spectra taken into account

*Consider running with ±80% electron beam polarisation,*

*with 2.5 ab$^{-1}$ collected at 1.5 TeV and 5 ab$^{-1}$ collected at 3 TeV*

Fast simulation of CLIC detector response with DELPHES

*dedicated CLICdet model cards*

beam related backgrounds taken into account

by additional jet energy-momentum smearing