An overview on low mass scalars at future lepton colliders

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based on Universe 8 (2022) 286

Higgs 2022
10. November ’22
new scalars ⇒ models with scalar extensions
many possibilites: introduce new $SU(2) \times U(1)$ singlets, doublets, triplets, ...
unitarity ⇒ important sum rule*

\[
\sum_i g_i^2 (h_i) = g_{SM}^2
\]

for coupling $g$ to vector bosons
many scenarios ⇒ signal strength poses strong constraints

* modified in presence e.g. of doubly charged scalars, see Gunion, Haber, Wudka, PRD 43 (1991) 904-912.
Possible production modes and rates

$$e^+ e^- \rightarrow Z^* \rightarrow Zh, \quad e^+ e^- \rightarrow \nu \bar{\nu} h (VBF)$$

Cross section for light SM-like scalar at $e^+ e^-$, $\sqrt{s}=250$ GeV

[cross sections for $e^+ e^-$ at $\sqrt{s} = 250$ GeV using Madgraph5;

LO analytic expressions e.g. in Kilian ea, Phys.Lett.B 373 (1996) 135-140]

- rule of thumb: rescaling $\lesssim 0.1$
- $\Rightarrow$ maximal production cross sections around 50 fb
- $\sim 10^5$ events using full luminosity
Models

typical content:
singlet extensions $\Rightarrow$ additional CP-even/odd mass eigenstates
2HDMs, 3HDMs: add additional charged scalars

- e.g. 2 real scalars $\Rightarrow$ 3 CP-even neutral scalars
- 2HDM $\rightarrow$ 2 CP-even, one CP odd neutral scalar, and charged scalars
- ...

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Typical processes at Higgs factories

various production modes possible

1) **easiest example:** $e^+ e^- \rightarrow Z h_1$, onshell production interesting up to $m_1 \sim 160 \text{ GeV}$

2) in **models with various scalars:** e.g. also $e^+ e^- \rightarrow h_1 h_2$ (e.g. from 2HDMs); example processes and bounds from LEP in Eur.Phys.J.C 47 (2006) 547-587
   again: for onshell production, $\sum_i m_i \leq 250 \text{ GeV}$

3) another (final) option: **look at** $e^+ e^- \rightarrow h_i Z$, $h_i \rightarrow h_j h_k$

already quite a few studies for 1), 3) available
Projections for additional scalar searches

[P. Drechsel, G. Moortgat-Pick, G. Weiglein, Eur.Phys.J.C 80 (2020) 10, 922]

estimate of ILC sensitivity based on validation using LEP results

ILC: $\sqrt{s} = 250$ GeV, $\int \mathcal{L} = 2 \text{ab}^{-1}$; S95: rescaling limit
Projections for additional scalar searches

[Y. Wang, M. Berggren, J. List, arXiv:2005.06265]

additional scalar, \( \sin \theta \) rescaling wrt SM prediction,
comparison of different detector models
recoil method

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The 96 GeV LEP resonance

[S. Heinemeyer, C. Li, F. Lika, G. Moortgat-Pick, S. Paasch, Phys.Rev.D 106 (2022) 7, 075003]

[see also T. Biekoetter, M. Chakraborti, S. Heinemeyer, Eur.Phys.J.C 80 (2020) 1, 2]

Various BSM models, rates using $\int \mathcal{L} = 2 \text{ ab}^{-1}$

N2HDM/ 2HDMS: 2HDM extended by real (complex) singlet, various symmetries imposed, fit to LEP/ CMS data [within/ outside 1 $\sigma$]

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Current constraints for the $h_{125} \rightarrow s s$ searches at LHC

[M. Cepeda, S. Gori, V. Martinez Outschoorn, J. Shelton, arXiv:2111.12751]

bound on decays into lighter scalars from current searches

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low mass region allowed; however, $HZZ$ typically suppressed by $\cos(\beta - \alpha) \lesssim 0.25$

[aligned flavour structure: $Y_{d,\ell} = \varsigma_{d,\ell} M_{d,\ell}$, $Y_u = \varsigma_u^* M_u$]
... and in terms of mixing angle... [Thanks to V. Miralles]
Singlet extensions [TR, arXiv:2203.08210 and Universe 8 (2022) 286]

**TRSM: 2 real singlets** [TR, T. Stefaniak, J. Wittbrodt, Eur.Phys.J.C 80 (2020) 2, 151]

- **low-low:** both additional scalars below 125 GeV; **high-low:** one new scalar above 125 GeV
N2HDM example

[H. Abouabid, A. Arhrib, D. Azevedo, J. El Falaki, P. M. Ferreira, M. Muehlleitner, R. Santos, JHEP 09 (2022) 011]

N2HDM: 2HDM+ real singlet
Conclusions

- Many new physics models predict one/ several scalars below 125 GeV.
- Typical decays into $b\bar{b}$, $\tau^+\tau^-$.
- Cross sections could reach up to 50 fb from $Zh$ production.
- Decays of $h_{125} \rightarrow ss$ also within reach.
- Important connection to EWSB/ EW phase transitions.

Still space for more studies!
Appendix
Decays of light SM-like scalars

![Graph showing BR(hSM→XX) as a function of M_h (GeV) for different decay modes.]

- $b\bar{b}$
- $c\bar{c}$
- $\tau\bar{\tau}$
- $g\bar{g}$
- $W^+ W^-$
- $ZZ$

[from YREP 4/ HDecay]

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Lepton-specific IDM

[X.-F. Han, T. Li, H.-X. Wang, L. Wang, Y. Zhang, Phys.Rev.D 104 (2021) 11, 115001]

Inert Doublet Model, with $\mathbb{Z}_2$ breaking terms coupling to leptons

various constraints (including agreement with $g_\mu - 2$);
squares: allowed, bullets: forbidden
Scalar triplet model

[P.M. Ferreira, B.L. Gonçalves, F.R. Joaquim, JHEP 05 (2022) 105]

5 neutral, 3 singly charged, 2 doubly charged scalars
Singlet extension, with connection to strong first-order electroweak phase transition

[J. Kozaczuk, M. Ramsey-Musolf, J. Shelton, Phys.Rev.D 101 (2020) 11, 115035]

blue band = strong first-order electroweak phase transition

comment: current constraints lead to prediction $\lesssim 10^{-1}$

[invisible BR, signal strength, assumes SM-like decay to $bs$]
[projections taken from Z. Liu, L.-T. Wang, and H. Zhang, Chin. Phys. C 41, 063102 (2017)]

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Higgs 2022, 10.11.’22
Singlet extension, spontaneous $Z_2$ breaking, with connection to strong first-order electroweak phase transition

[M. Carena, Z. Liu, Y. Wang, JHEP 08 (2020) 107]
$h \rightarrow 4j/4b/4c$ final states

[Z. Liu, L.-T. Wang, H. Zhang, Chin.Phys.C 41 (2017) 6, 063102]

Branching ratio vs $m_X$ (GeV)

$95\% \text{ CL bounds}, \sqrt{s} = 240 \text{ GeV}, \int \mathcal{L} = 5 \text{ ab}^{-1}$
Exotic decays - $h \rightarrow ss \rightarrow 4\tau$

[J. Shelton, D. Xu, arXiv:2110.13225]

$[m_s = 7.5 \text{ GeV}; \text{ background mainly from } h \rightarrow jj]$

$\varepsilon_{tk}$: tracking efficiency

95% C.L. limit on the Higgs exotic branching fraction

$\sigma \times BR(h \rightarrow ss + 4\tau) / \sigma(e^+e^- \rightarrow Z)$

$\sqrt{s} = 240 \text{ GeV @ 5 ab}^{-1}$

comment: **current constraints lead to prediction $\lesssim 10^{-3}$**

[invisible BR, signal strength, assumes SM-like decay to $\tau s$]
Type X 2HDM, $4 \tau$ final state via $\tau\tau A$ production

[E. J. Chun, T. Mondal, Phys. Lett. B 802 (2020) 135190]

one doublet couples to quarks, other to fermions; CP violation

Searches for light A in 2HDMX at ILC250

- The channel $Z \rightarrow h_{SM} A$ is not possible since the relevant coupling is proportional to $\cos(\beta - \alpha)$.
- At ILC250, $Z \rightarrow HA$ may not be feasible when $H$ is heavier than 200 GeV.
- Possible option: $Z \rightarrow \tau\tau \rightarrow \tau\tau A \rightarrow 4\tau$. So called Yukawa production.

- This is the equivalent to $ttH$ searches at LHC. Independent probe of Yukawa structure.
- At the ILC all the 4 $\tau$ s can be reconstructed using collinear approximation.
- This enables to measure mass of the light particle.
Type X 2HDM, 4 $\tau$ final state via $\tau \tau A$ production

[E. J. Chun, T. Mondal, Phys.Lett.B 802 (2020) 135190]
scNMSSM, $h \rightarrow s s \rightarrow$ various final states  
[sc=semi-constrained, aka NUHM]

[S. Ma, K. Wang, J. Zhu, Chin.Phys.C 45 (2021) 2, 023113]
Light charged scalars, 3HDM, $H^+ \rightarrow c\bar{b}$ final state

[A.G. Akeroyd, S. Moretti, M. Song, Phys. Rev. D 101 (2020) 3, 035021]

$BR(H^+ \rightarrow c\bar{b} = 0.05)$, $e_c$: charm tagging efficiency

$e^+ e^- \rightarrow H^+ H^-, \sqrt{s} = 240 \text{ GeV}$
Current constraints on alignment in 2HDMs

[ATLAS-CONF-2021-053]
2HDM parameter space

[F. Kling, S. Su, W. Su, JHEP 06 (2020) 163]
Another recent 2HDM study

[O. Atkinson, M. Black, C. Englert, A. Lenz, A. Rusov, J. Wynne, arXiv:2202.08807]

2HDM Type I, direct searches, signal strength, and flavour constraints
Models
ILC studies
Possible models
Appendix

scNMSSM parameter space

[K. Wang, J. Zhu, JHEP 06 (2020) 078]
Parameter space for light scalar

[S. Heinemeyer, talk at ILCX 2021 workshop]

4. Direct detection of "light" BSM Higgs bosons

Example for discovery potential for new light states:
Sensitivity at 250 GeV with 500 fb$^{-1}$ to a new light Higgs

\[
\left( \frac{g_{hZZ}}{g_{H^{SM}ZZ}} \right)^2
\]

Indirect LHC sensitivity from measurements of the Higgs at 125 GeV

Higgs factory sensitivity:
Recoil method

\[ M_h/\text{GeV} \]

Higgs factory at 250 GeV will explore a large untested region!

[Taken from G. Weiglein '18]
N2HDM (2HDM + singlet) type II, $h_1 \to b\bar{b}$

[S. Heinemeyer, talk at ILCX 2021 workshop]

ILC production of the light scalar in the N2HDM type II:

[T. Biekötter, S.H., G. Weiglein – PRELIMINARY]

$\Rightarrow$ new state easily in the reach of the ILC $\Rightarrow$ coupling measurements

Sven Heinemeyer, ILCX workshop, 28.10.2021
Type X 2HDM with vector-like leptons

[E. J. Chun, T. Mondal, JHEP 11 (2020) 077]

... including connection to $g_\mu - 2$
Scalar triplet model

[P.M. Ferreira, B.L. Gonçalves, F.R. Joaquim, arXiv:2109.13179]

| Mass spectrum  | CP-Conserving                      | CP-Violating          |
|----------------|-----------------------------------|-----------------------|
| Neutral        |                                   |                       |
| $h_0^0$        | Massless - Goldstone boson        |                       |
| $h_2^0$        | SM Higgs-like                     | Light                 |
| $h_3^0$        | Decoupled                         | SM Higgs-like         |
| $h_4^0$        |                                   |                       |
| $h_5^0$        | Decoupled                         | Decoupled             |
| $h_6^0$        |                                   |                       |
| Singly-charged |                                   |                       |
| $H_1^+$        | Massless - Goldstone boson        |                       |
| $H_2^+$        | Decoupled                         | Electroweak           |
| $H_3^+$        | Decoupled                         | Decoupled             |
| Doubly-charged |                                   |                       |
| $H_1^{++}$     | Decoupled                         | Electroweak           |
| $H_2^{++}$     | Decoupled                         | Decoupled             |