PROCEEDINGS OF SCIENCE

Prospects for exotic light scalar measurements at the e^+e^- Higgs factory

Aleksander Filip Żarnecki[a,*]

[a] *Faculty of Physics, University of Warsaw*
Pasteura 5, 02-093 Warsaw, Poland

E-mail: filip.zarnecki@fuw.edu.pl

The physics program of the Higgs factory will focus on measurements of the 125 GeV Higgs boson, with the Higgs-strahlung process being the dominant production channel at 250 GeV. However, production of extra light scalars is still not excluded by the existing experimental data, provided their coupling to the gauge bosons is sufficiently suppressed. Fermion couplings of such a scalar could also be very different from the SM predictions leading to non-standard decay paterns. Considered in the presented study is the sensitivity of future Higgs factory experiments to direct observation of the new light scalar production for the scalar mass range from 50 GeV to 120 GeV.

The European Physical Society Conference on High Energy Physics (EPS-HEP2023)
21-25 August 2023
Hamburg, Germany

*Speaker

PoS(EPS-HEP2023)459

1. Motivation

While the existence of the Standard Model like Higgs boson with mass of 125 GeV has been firmly established, experimental results obtained so far still leave room for additional light scalar states [1]. Some deviations observed in the LHC Run 1 and Run 2 have been interpreted as a possible existence of the new scalar with the mass of around 96 GeV [2–4]. Considered in the presented study are prospects for observing the new scalar produced in the scalar-strahlung process, $e^+e^- \rightarrow Z\ \phi$, at the International Linear Collider (ILC) running at 250 GeV. Previous studies focused on establishing the decay independent limits [5] or on the $\phi \rightarrow b\bar{b}$ decay channel [6], which is expected to be dominant in most scenarios. In the presented study, light scalar decay to tau lepton pair is considered, which is expected to be the dominant decay channel in some theoretical scenarios [4]. This seems to be an interesting and challenging benchmark scenario for the light scalar searches at future Higgs factories.

2. Analysis setup

The production of light scalar is considered in scalar-strahlung process, $e^+e^- \rightarrow Z\ S$, with subsequent hadronic Z decay (for higher statistics) and scalar decay to tau lepton pairs: $Z \rightarrow q\,\bar{q}$ and $S \rightarrow \tau^+\tau^-$. Event samples used for the presented study were generated using Whizard [7, 8] version 3.1.2. Signal samples were generated with the Whizard built-in SM_CKM model, by varying the Higgs boson mass in the 15 – 140 GeV range and setting its tau branching ratio to 100%. While the dominant background contribution is expected to come from the SM process with the same final state, $e^+e^- \rightarrow q\bar{q}\tau\tau$, other four-fermion final states were also considered as possible background sources. Contribution from two-fermion and six-fermion processes was found to be small. Total lumionsity of 2 ab^{-1} was assumed for ILC running at 250 GeV, as expected in the H-20 running scenario [9], with ±80% and ±30% polarisation for electron and positron beams, respectively. The ILC beam energy profile was taken into account based on Circe2 parametrization and hadronisation was simulated with the Pythia 6 [10]. The fast detector simulation framework Delphes [11] was used to simulate detector response, with built-in cards for parametrisation of the ILC detector, `delphes_card_ILCgen.tcl` [12].

3. Tau reconstruction

Depending on the decays of the two tau leptons, three decay channels can be considered for the signal events: hadronic (with both taus decaying hadronicly), semi-leptonic (with one leptonic tau decay) and leptonic (with leptonic decays of both taus). Example of signal event with hadronic final state is shown in Fig. 1.

Depending on the scalar decay channel, zero, one or two isolated leptons are expected in the final state. Each isolated lepton (electron or muon) is considered as a tau candidate. The remaining final state particles are clustered into four, three or two jets, depending on the number of leptons. Jets are selected as coming from tau decays based on the tau tagging result. For "tight selection" we require two tau candidates in an event. As the tau tagging efficiency is only at the level of 50–70%, we also consider "loose selection", when we also accept events with one tau candidate (isolated

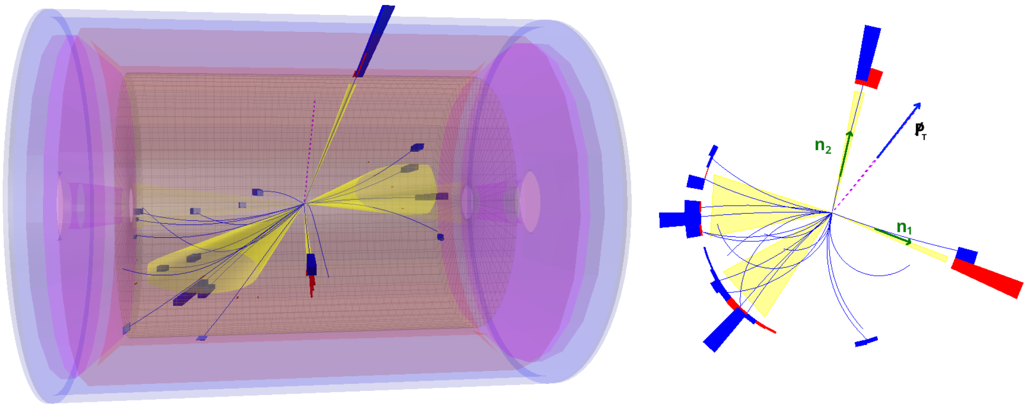

Figure 1: Left: example signal event, with hadronic decays of the two tau leptons produced in the light scalar decay. Right: same event in the transverse plane, missing transverse momentum $\vec{p}\!\!/_T$ and two unit vectors along tau jet directions ($\vec{n}_1$ and $\vec{n}_2$) are indicated.

lepton or tagged jet) and take the untagged jet with the lowest invariant mass as the second tau candidate.

One of the challenges in the presented study is to correct the invariant mass of the two tau candidates, which can be significantly underestimated due to the escaping neutrinos. To correct for the neutrino energy, we use the so called collinear approximation [13]. For high energy tau leptons, decay products are highly boosted in the initial lepton direction. One can therefore assume that the initial tau lepton, escaping neutrino and the observed tau candidate are collinear. Neutrino energies can be found from transverse momentum balance:

$$\vec{p}\!\!/_T \quad = \quad E_{\nu_1} \cdot \vec{n}_1 + E_{\nu_2} \cdot \vec{n}_2$$

where $\vec{n}_1$ and $\vec{n}_2$ are directions of the two tau candidates in the transverse plane (see right plot in Fig. 1). While this is the simplest possible method to correct for the missing neutrino energy, its clear advantage is that the solution is unique.

Compared in Fig. 2 are the raw (before correction) and corrected invariant mass distributions of the tau candidate pairs in signal events. It turns out that the collinear correction allows to reconstruct the scalar mass with about 5 GeV precision not only for hadronic events (left plot) but also for semi-leptonic (right plot) and leptonic events. This is because the invariant mass of the two neutrinos emitted in the leptonic tau decay has to be small (below tau mass), so neglecting it does not bias the estimate of the escaping energy significantly. Distributions of the reconstructed Z boson and scalar masses are shown in Fig. 3 for the signal events corresponding to the scalar mass of 80 GeV and for the combined SM background.

4. Results

Final selection of signal events for each considered scalar mass is based on the BDT classifier trained with ten input variables: measured Z (di-jet) mass, raw and corrected scalar (di-tau) mass, recoil mass calculated from the Z boson four-momentum, total event energy, jet clustering parameter y_{34}, polar angle of the Z boson emission, two scalar decay angles in the scalar rest frame and the

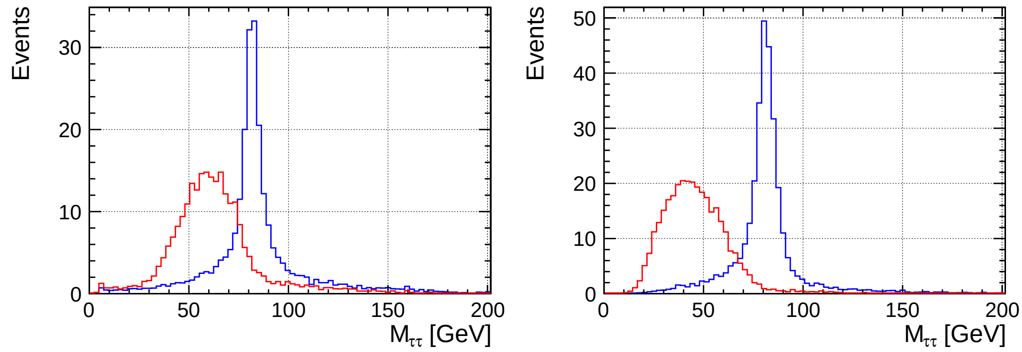

Figure 2: Reconstructed invariant mass of the two tau candidates, before (red) and after (blue) the collinear energy correction. Distributions are shown for signal of light scalar production with mass of 80 GeV, for hadronic (left) and semi-leptonic (right) event selection.

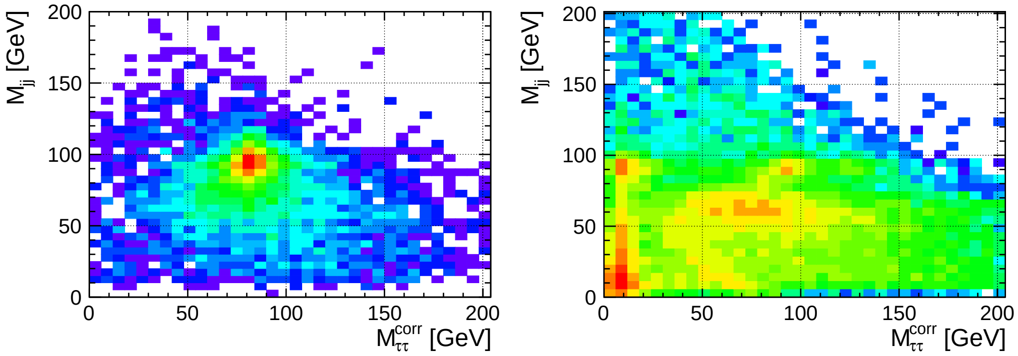

Figure 3: Reconstructed mass of Z boson decay, m_{jj}, as a function of the corrected invariant mass of the two tau candidates, $m_{\tau\tau}$. Compared are expected distributions for signal of light scalar production with mass of 80 GeV (left) and the combined SM background (right) after tight event selection. See text for details.

azimuthal distance between two tau candidates. Example of the BDT response distributions for the hadronic and semi-leptonic channels, for scalar mass of 80 GeV, is shown in Fig. 4.

For the preliminary limits presented here, common BDT classification was always applied to all considered data samples, combining all decay channels and data collected with different beam polarisation combinations. Limits shown were obtained with loose event selection, as it turned out to result in slightly higher sensitivity. For each scalar mass considered, the cut on the BDT classifier response was optimized for signal significance assuming the scalar production cross section corresponding to 1% of the SM Higgs boson production cross section at given mass. Then, with the fixed BDT response cut, the 95% CL limit on the scalar production cross section was calculated as the signal cross section corresponding to the significance of 1.64.

Expected cross section limits for ILC running at 250 GeV, resulting from the procedure described above, are presented in Fig. 5. For low scalar masses, up to about 80 GeV, semi-leptonic event selection results in highest significance to the scalar tau decays, see Fig. 5 (left). For higher masses, semi-leptonic and hadronic events equally contribute to the combined limit. As shown in Fig. 5 (right), targeted analysis, focused on the scalar decay to tau lepton pair, results in about an order of magnitude increase in sensitivity, compared to decay independent limits [5]. However, one

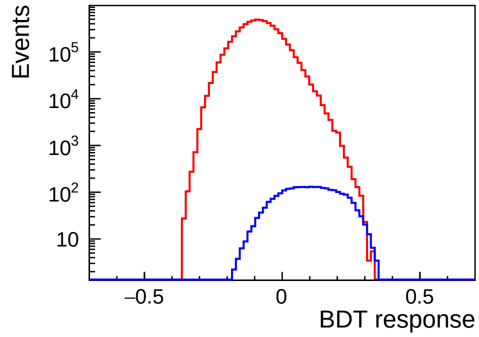

Figure 4: Example of the BDT response distribution for signal (blue) and background (red) events, for new scalar mass of 80 GeV. The signal cross section is set to 1% of the SM Higgs boson production cross section at given scalar mass. The BDT classification was applied to the combined data set, including all beam polarisation combinations, for the loose event selection.

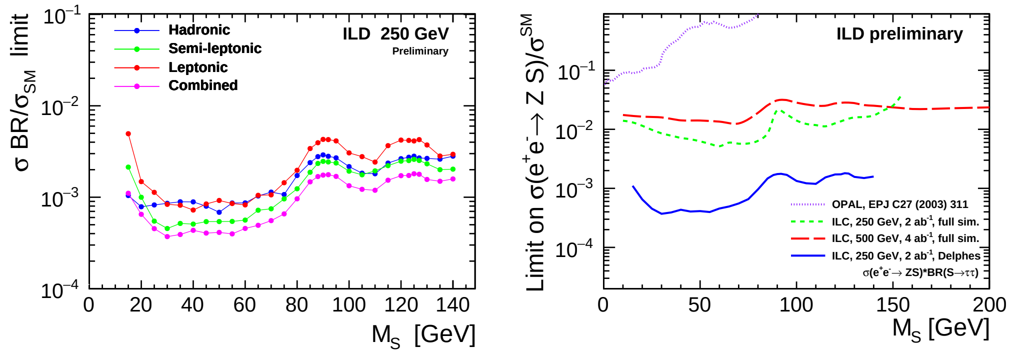

Figure 5: Cross section limits in di-tau channel expected for ILC running at 250 GeV, resulting form the selection based on the BDT response cut, as a function of the assumed scalar mass. Limits expected from the combined analysis of all data are compared with limit estimates for different signal channels (left) and with limits resulting from earlier, decay channel independent studies (right).

has to note that the limit considered in our case is the limit on the cross section times branching ratio. One can conclude that the scalar search in the di-tau final state is expected to result in more stringent limits than the decay independent search provided this branching ratio is of the order of 10% or above.

5. Conclusions

Beyond the SM scenarios with light scalars are still not excluded by the existing data. Sizable production cross sections for new scalars are still possible, if combined with non-standard decay patterns. Decays to tau pairs for new light scalars, with mass below 125 GeV, seems to be a challenging benchmark scenario and a good testing ground for detector concepts and analysis methods. Initial study performed for ILC running at 250 GeV indicates an order of magnitude limit improvement already with the very simple limit setting approach. Limits should improve further when properly combining results from different event samples (beam polarisations and decay channels). The study will continue to get better understanding of signal and background processes.

Acknowledgments

This work was carried out in the framework of the ILD concept group as a contribution to the ECFA e^+e^- Higgs/EW/top factory study. This work was partially supported by the National Science Centre, Poland, under the OPUS research project no. 2021/43/B/ST2/01778.

References

[1] T. Robens, *A Short Overview on Low Mass Scalars at Future Lepton Colliders*, *Universe* **8** (2022) 286 [2205.09687].

[2] T. Biekötter, M. Chakraborti and S. Heinemeyer, *A 96 GeV Higgs boson in the N2HDM*, *Eur. Phys. J. C* **80** (2020) 2 [1903.11661].

[3] S. Heinemeyer, C. Li, F. Lika, G. Moortgat-Pick and S. Paasch, *Phenomenology of a 96 GeV Higgs boson in the 2HDM with an additional singlet*, *Phys. Rev. D* **106** (2022) 075003 [2112.11958].

[4] T. Biekötter, S. Heinemeyer and G. Weiglein, *Mounting evidence for a 95 GeV Higgs boson*, *JHEP* **08** (2022) 201 [2203.13180].

[5] Y. Wang, M. Berggren and J. List, *ILD Benchmark: Search for Extra Scalars Produced in Association with a Z boson at* $\sqrt{s} = 500$ *GeV*, 2005.06265.

[6] P. Drechsel, G. Moortgat-Pick and G. Weiglein, *Prospects for direct searches for light Higgs bosons at the ILC with 250 GeV*, *Eur. Phys. J. C* **80** (2020) 922 [1801.09662].

[7] M. Moretti, T. Ohl and J. Reuter, *O'Mega: An Optimizing matrix element generator*, hep-ph/0102195.

[8] W. Kilian, T. Ohl and J. Reuter, *WHIZARD: Simulating Multi-Particle Processes at LHC and ILC*, *Eur. Phys. J.* **C71** (2011) 1742 [0708.4233].

[9] P. Bambade et al., *The International Linear Collider: A Global Project*, 1903.01629.

[10] T. Sjostrand, S. Mrenna and P.Z. Skands, *PYTHIA 6.4 Physics and Manual*, *JHEP* **05** (2006) 026 [hep-ph/0603175].

[11] J. de Favereau et al., *DELPHES 3, A modular framework for fast simulation of a generic collider experiment*, *JHEP* **02** (2014) 057 [1307.6346].

[12] A.F. Zarnecki. *The ILC DELPHES card* (IDT-WG3 Software Tutorial), https://agenda.linearcollider.org/event/9264/, 2021.

[13] S. Kawada, K. Fujii, T. Suehara, T. Takahashi and T. Tanabe, *A study of the measurement precision of the Higgs boson decaying into tau pairs at the ILC*, *Eur. Phys. J. C* **75** (2015) 617 [1509.01885].