

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

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**Abstract.** 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 patterns. Presented in this contribution are results from the ongoing studies on prospects of direct light scalar observation at future Higgs factory experiments in different decay channels.

## 1 Motivation

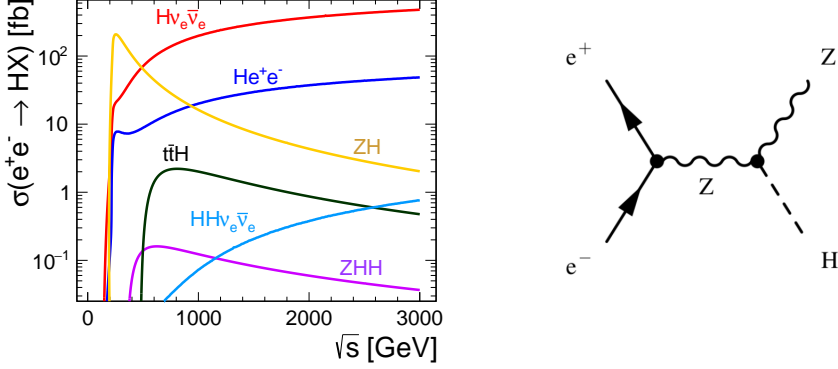
In recent years, a general consensus was reached in the particle physics community about the need for the next-generation large infrastructure to be an electron-positron Higgs factory. It was indicated as the highest-priority next collider in the 2020 Update of the European Strategy for Particle Physics [1]. While full exploitation of the Higgs boson physics requires running at collision energies up to the TeV range, see figure 1 (left), most of the precision measurements will be carried out at the collision energy of 240–250 GeV, maximizing the cross section for the Higgs boson production in the so called Higgsstrahlung process, see figure 1 (right). However, existence of additional light scalar particles, with masses of the order of or below the mass of the 125 GeV state observed at the LHC, is by far not excluded experimentally and also well motivated theoretically [3–5]. Higgs factories should be sensitive to exotic scalar production even for very light scalars and small couplings, thanks to clean environment, precision and hermeticity of the detectors. Still, prospects for light scalar measurements at the  $e^+e^-$  Higgs factory were hardly studied in the past. That is why this subject was included as one of the so called focus topics of the ECFA  $e^+e^-$  Higgs/EW/top factory study [6]. Two theoretical and phenomenological targets were defined: associated production of the new scalar with the Z boson,  $e^+e^- \rightarrow Z S$  (scalar-strahlung process) and light scalar pair-production in 125 GeV Higgs boson decays,  $H \rightarrow S S$ .

## 2 Decay mode independent search

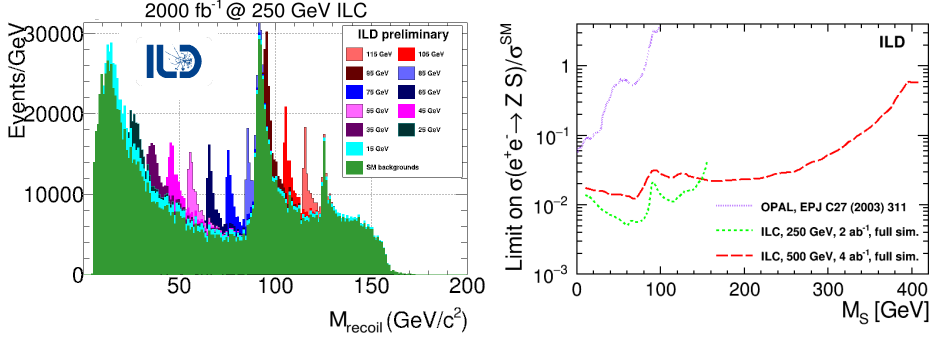
As for the SM Higgs boson, the production of new scalars in the scalar-strahlung process can be tagged, independent of their decay, based on the recoil mass technique [7]. For best

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**Figure 1.** Left: cross section as a function of centre-of-mass energy for the main Higgs production processes at an  $e^+e^-$  collider. Right: the leading-order Feynman diagram for the Higgsstrahlung process. Figures taken from [2].

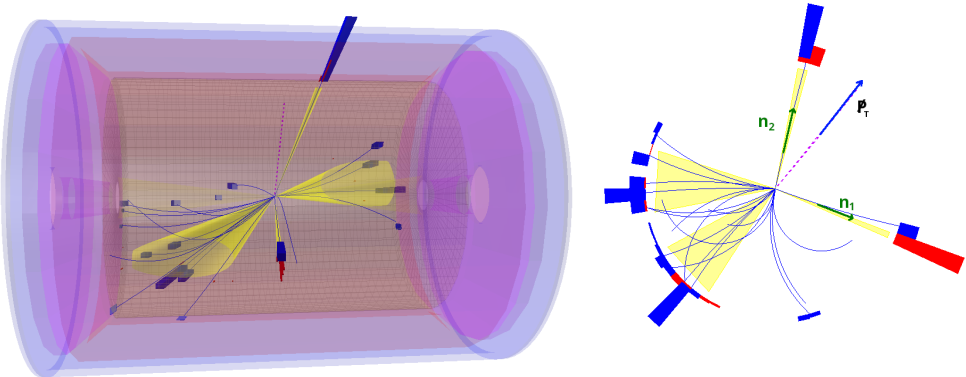


**Figure 2.** Left: the recoil mass distributions after the selection cuts for signal of light scalar production and SM background processes for ILC running at 250 GeV. Right: expected 95% C.L. limits on the scalar production cross section, relative to the SM scalar production cross section at given mass, for ILC running at 250 GeV and 500 GeV [8, 9].

35 recoil mass reconstruction  $Z$  decays to muon pair can be used, which were exploited in the  
 36 full simulation studies performed within ILD [8, 9]. Shown in figure 2 (left) is the recoil  
 37 mass distribution expected for SM background processed at 250 GeV ILC together with ex-  
 38 pectations for different signal hypothesis. Expected limits on the are the scalar production  
 39 cross section, relative to the SM scalar production cross section at given mass are compared  
 40 with LEP limits based on the similar approach in figure 2 (right). Expected sensitivity of the  
 41 experiment at future  $e^+e^-$  Higgs factory is an order of magnitude better than the existing LEP  
 42 limit and the mass range probed can be significantly extended as well.

### 43 3 Search for $S \rightarrow \tau^+\tau^-$

44 While limits resulting from the decay independent search based on the recoil mass distribu-  
 45 tion only are the most general ones, mostly model independent, significant improvement of  
 46 sensitivity is expected when particular decay channels of the new scalars are addressed. As



**Figure 3.** 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.

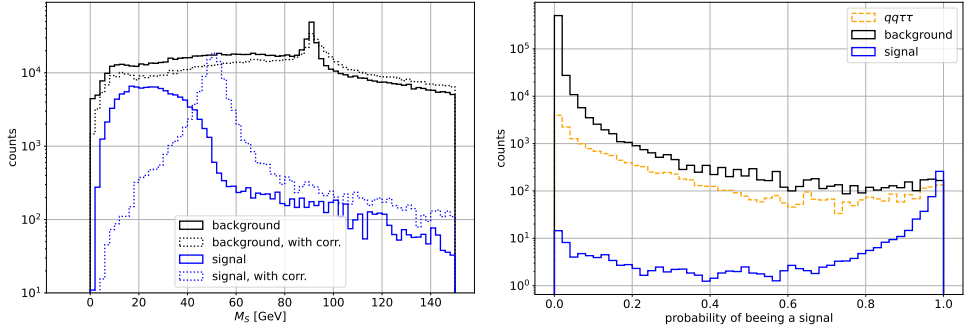
47 some of the discrepancies from SM predictions observed in LEP and LHC data suggested  
 48 possible existence of the new scalar with mass of about 95 GeV and enhanced branching  
 49 ratio to the  $\tau^+\tau^-$  final state [4], we decided to consider this decay channel as the possible dis-  
 50 covery scenario. Event samples used for the presented study were generated using WHIZARD  
 51 [10, 11] version 3.1.2. Both background (including 125 GeV Higgs boson production assum-  
 52 ing nominal couplings) and light scalar signal production were modeled using built-in  
 53 SM\_CKM model. For signal sample, Higgs boson with modified mass was forced to decay  
 54 to tau lepton pair. Total luminosity of  $2 \text{ ab}^{-1}$  was assumed for ILC running at 250 GeV, as  
 55 expected in the H-20 running scenario [12], with  $\pm 80\%$  and  $\pm 30\%$  polarisation for electron  
 56 and positron beams, respectively. The ILC beam energy profile was taken into account based  
 57 on CIRCE2 parametrization and hadronisation was simulated with the PYTHIA 6 [13]. The fast  
 58 detector simulation framework DELPHES [14] was used to simulate detector response, with  
 59 built-in cards for parametrisation of the ILC detector, delphes\_card\_ILCgen.tcl [15].  
 60 Example of signal event with hadronic final state, as simulated by DELPHES, is shown in fig-  
 61 ure 3 left.

62 Depending on the decays of the two tau leptons, three decay channels can be considered  
 63 for the signal events: hadronic (with both taus decaying hadronically), semi-leptonic (with  
 64 one leptonic tau decay) and leptonic (with leptonic decays of both taus). For tight selection,  
 65 we require each tau lepton to be identified either as an isolated lepton (and missing  $p_T$ ) or  
 66 hadronic jet with  $\tau$ -tag. In addition to two tau candidates from scalar decay, we also require  
 67 reconstruction of two (untagged) hadronic jets from hadronic Z boson event. However, as  
 68 the efficiency of tau jet tagging implemented in DELPHES is relatively poor (at most 70%),  
 69 we also consider loose event selection, when we require only one identified tau candidate  
 70 (isolated lepton or  $\tau$ -tagged jet) and three untagged hadronic jets, and take the jet with smaller  
 71 invariant mass as the second tau candidate. At the pre-selection stage we thus select five event  
 72 categories, as summarized in table 1.

73 One of the challenges in the search for scalar decays into tau leptons is to properly recon-  
 74 struct the invariant mass of the produced scalar, which can be significantly underestimated  
 75 due to the escaping neutrinos. To correct for the neutrino energy, we use the so called collinear  
 76 approximation [16]. For high energy tau leptons, decay products are highly boosted in the initial  
 77 lepton direction and one can therefore assume that the initial tau lepton, escaping neutrino

**Table 1.** Event categories considered in the search for light scalar production with scalar decay to tau lepton pair.

Event category	Isolated leptons	Selection requirements	
		tight selection	loose selection
hadronic	zero	4 jets, 2 with $\tau$ -tag	4 jets, 1 with $\tau$ -tag
semi-leptonic	one	3 jets, 1 with $\tau$ -tag	3 jets with no $\tau$ -tag
leptonic	two	two jets without $\tau$ -tag	



**Figure 4.** Left: reconstructed invariant mass of the two tau candidates after tight selection for SM background (black) and signal of 50 GeV scalar production (blue) before (solid) and after (dashed) collinear correction. Right: example of the BDT response distribution for 50 GeV scalar signal (blue) and SM background (black) events, for tight semi-leptonic event selection and ILC running with  $e_L^- e_R^+$  polarization combination. The signal cross section is normalized to 1% of the SM Higgs boson production cross section at given scalar mass. Orange dashed lines indicated the contribution of the leading background process,  $e^+ e^- \rightarrow qq\tau\tau$ .

78 and the observed tau candidate are collinear. Neutrino energies can be found from transverse  
79 momentum balance:

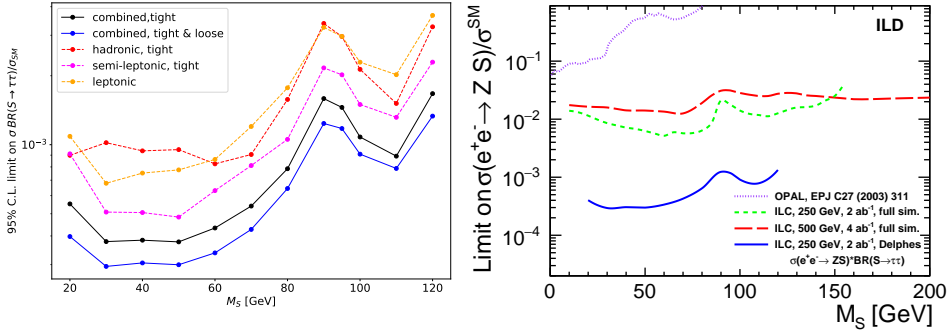
$$80 \quad \vec{p}_\tau = \nu_1 \cdot \vec{n}_1 + E_{\nu_2} \cdot \vec{n}_2 \quad (1)$$

81 where  $\vec{n}_1$  and  $\vec{n}_2$  are directions of the two tau candidates in the transverse plane (see right plot  
82 in figure 3). While more advanced reconstruction methods exist, based on the reconstruction  
83 of secondary decay vertex position, the advantage of this method is that it can be applied to  
84 all events and the solution is unique.

85 Shown in figure 4 (left) are the mass distributions of the tau candidate pairs in signal and  
86 background events, before (solid) and after (dashed) collinear correction. After the correction,  
87 the scalar mass can be reconstructed with about 5 GeV precision, also for semi-leptonic  
88 and leptonic events.

89 For best event classification, we consider each event category (see table 1 and each beam  
90 polarization combination separately, resulting in 20 independent BDTs trained for event clas-  
91 sification, for each scalar mass considered. Example of BDT response distribution is pre-  
92 sented in figure 4.

93 Expected exclusion limits, assuming no deviation from SM predictions are observed, are  
94 calculated from the Hessian matrix of the template fit to the BDT response distributions.  
95 Final results of the study are presented in figure 5. As expected, semi-leptonic event selec-  
96 tion results in the strongest limits, combining high event statistics (about 47% of decays)



**Figure 5.** Expected 95% C.L. cross section limits on the light scalar production cross section times di-tau branching ratio for ILC running at 250 GeV. Left: comparison of combined limits with limits obtained for different event categories. Right: combined limits compared with limits resulting from decay independent study.

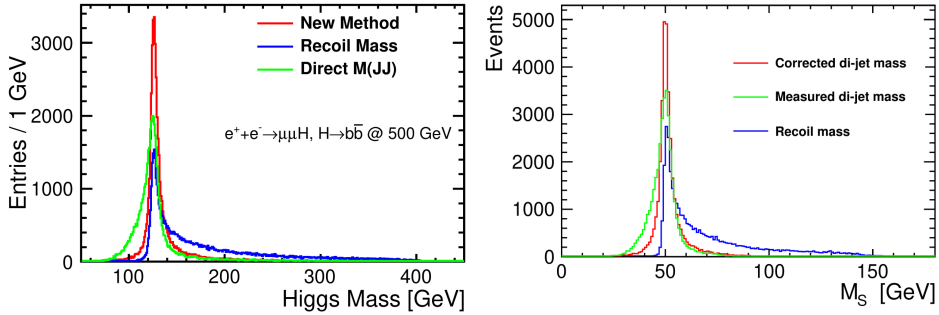
97 with background lower than for the hadronic channel. Including loose selection categories  
 98 improves the expected limits by 20-30% for the whole considered mass range. When compar-  
 99 ing to the decay independent limits we can state that the targeted analysis results in over  
 100 order of magnitude increase in sensitivity. However, as the limit includes the branching ratio,  
 101 we can conclude that the di-tau channel is more sensitive only if the branching ratio is of the  
 102 order of 10% or above.

## 103 4 Search for $S \rightarrow b\bar{b}$

104 If the structure of new light scalar couplings to SM particles is similar to that of the SM  
 105 Higgs boson then the decay to  $b\bar{b}$  is expected to dominate down to the masses of the order  
 106 of 10 GeV. As huge hadronic background is expected from pair production of W bosons, we  
 107 focus on leptonic Z boson decays in this search channel. Again, invariant mass of the new  
 108 scalar, as reconstructed directly from the two b-quark jets, is poorly measured due to neutri-  
 109 nos escaping in semi-leptonic heavy meson decays. However, as leptons from Z decays can  
 110 be very precisely measured, we can use conservation of transverse momentum to reconstruct  
 111 jet energies from leptonic final state and jet angles. This approach was first proposed for  
 112 Higgs mass measurement at the ILC [17], but we verified that it works very well also for light  
 113 scalar production. This is shown in figure 6, where reconstructed di-jet mass distributions are  
 114 compared before and after correction for 125 GeV Higgs boson and new scalar of 50 GeV.  
 115 Mass reconstructed with the recoil method (based on the Z decay measurement only) is also  
 116 included for comparison. One can clearly see that jet energy correction based on the trans-  
 117 verse momentum conservation significantly improves scalar mass measurement and allows to  
 118 obtain precision much better than with uncorrected jet energies or recoil method. The study  
 119 of light scalar production in  $b\bar{b}$  decay channel is ongoing and the expected exclusion limits  
 120 will be presented at the 3rd ECFA workshop in Paris.

## 121 5 Conclusions

122 BSM scenarios involving light scalars, with masses accessible  $e^+e^-$  Higgs factories, are still  
 123 not excluded by existing data. Sizable production cross sections for new scalars can also  
 124 coincide with non-standard decay patterns, so different decay channels should be considered.



**Figure 6.** Invariant mass of two jets reconstructed using raw jet energies, corrected jet energies and recoil method. Left: full simulation results for the 125 GeV Higgs boson production at 500 GeV ILC [17]. Right: DELPHES simulation results for the signal of 50 GeV scalar production at 250 GeV ILC.

125 Strong limits are already expected from decay independent search, based on recoil mass  
 126 reconstruction. These are expected to be improved further with new analysis methods and  
 127 the corresponding study is ongoing. Compared to decay independent search, over order of  
 128 magnitude limit improvement in search sensitivity is expected for light scalar decays to tau  
 129 pairs, if this is a dominant decay channel. Studies of other decay channels are ongoing and  
 130 the results are being prepared for the ECFA study report.

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

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