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 paterns. 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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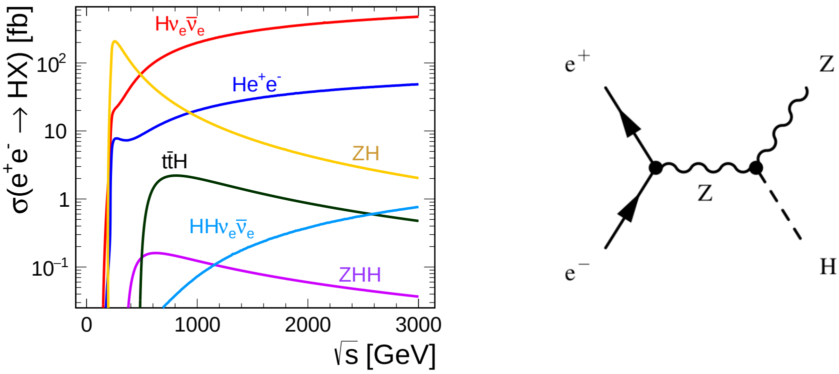

Figure 1. Left: cross section as a function of centre-of-mass energy for the main Higgs production processes at an e^+e^- collider. Right: the leading-order Feynman diagram for the Higgsstrahlung process. Figures taken from [2].

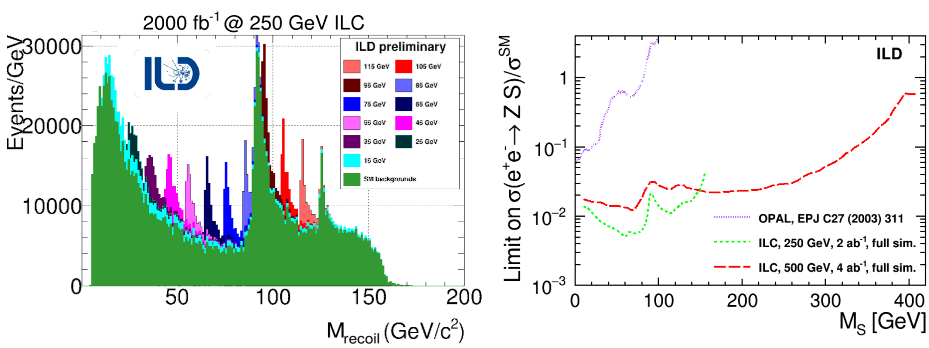

Figure 2. Left: the recoil mass distributions after the selection cuts for signal of light scalar production and SM backgrounds processes for ILC running at 250 GeV. Right: expected 95% C.L. limits on the scalar production cross section, relative to the SM scalar production cross section at given mass,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

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

3 Search for S $\to \tau^+\tau^-$

While limits resulting from the decay independent search based on the recoil mass distribution only are the most general ones, significant improvement of sensitivity is expected when

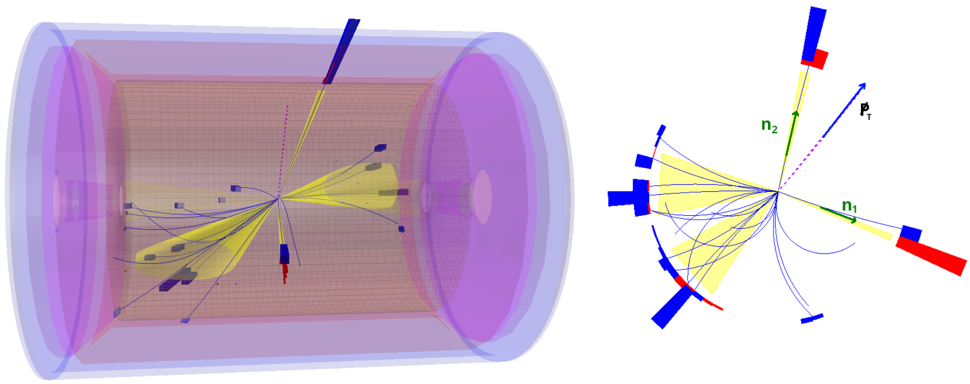

Figure 3. Left: example signal event, with hadronic decays of the two tau leptons produced in the light scalar decay. Right: same event in the transverse plane, missing transverse momentum $\vec{\not{p}}_T$ and two unit vectors along tau jet directions ($\vec{n}_1$ and $\vec{n}_2$) are indicated.

particular decay channels of the new scalars are addressed, at the price of some model dependence. As some of the discrepancies from SM predictions observed in LEP and LHC data suggested possible existence of the new scalar with mass of about 95 GeV and enhanced branching ratio to the $\tau^+\tau^-$ final state [4], we decided to consider this decay channel as the possible discovery scenario. Event samples used for the presented study were generated using Whizard [10, 11] version 3.1.2. Both background (including 125 GeV Higgs boson production assuming nominal couplings) and light scalar signal production were modeled using the built-in `SM_CKM` model. As signal samples we generated Higgs boson production with subsequent decays to tau lepton pair, for sets of modified Higgs masses. Total lumionsity of 2 ab^{-1} was assumed for ILC running at 250 GeV, as expected in the H-20 running scenario [12], with ±80% and ±30% polarisation for electron and positron beams, respectively. The ILC beam energy profile, as simulated with GuineaPig [13], was taken into account based on Circe2 parametrisation and hadronisation was simulated with the Pythia 6 [14]. The fast detector simulation framework Delphes [15] was used to simulate detector response, with built-in cards for parametrisation of the ILC detector, `delphes_card_ILCgen.tcl` [16]. Example of signal event with hadronic final state, as simulated by Delphes, is shown in figure 3 left.

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

One of the challenges in the search for scalar decays into tau leptons is to properly reconstruct the invariant mass of the produced scalar, which can be significantly underestimated due to the escaping neutrinos. To correct for the neutrino energy, we use the so called collinear approximation [17]. For high energy tau leptons, decay products are highly boosted in the ini-

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 τ-tag	4 jets, 1 with τ-tag
semi-leptonic	one	3 jets, 1 with τ-tag	3 jets with no τ-tag
leptonic	two	two jets without τ-tag	

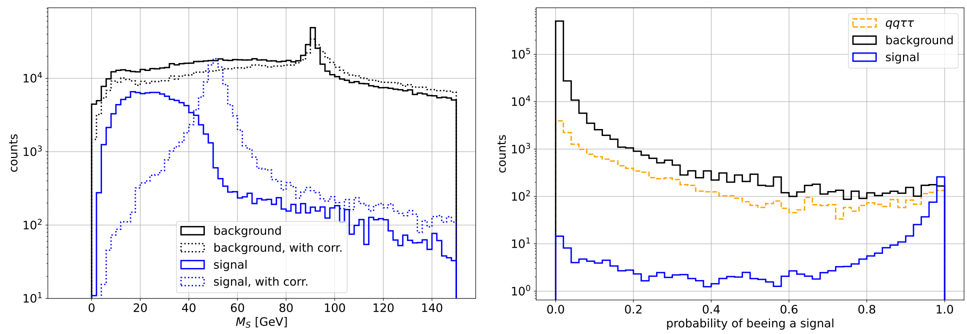

Figure 4. Left: reconstructed invariant mass of the two tau candidates after tight selection for SM background (black) and signal of 50 GeV scalar production (blue) before (solid) and after (dashed) collinear correction. Right: example of the BDT response distribution for 50 GeV scalar signal (blue) and SM background (black) events, for tight semi-leptonic event selection and ILC running with $e^-_L e^+_R$ polarisation 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, $e^+e^- \to qq\tau\tau$.

tial lepton direction and 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:

$$\vec{p}\!\!/_T \;=\; E_{\nu_1} \cdot \vec{n_1} + E_{\nu_2} \cdot \vec{n_2} \tag{1}$$

where $\vec{n_1}$ and $\vec{n_2}$ are directions of the two tau candidates in the transverse plane (see the right plot in figure 3). While more advanced reconstruction methods exist, based on the reconstruction of secondary decay vertex position, the advantage of this method is that it can be applied to all events and the solution is unique.

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

For best event classification, we consider each event category (see table 1) and each beam polarisation combination separately, resulting in 20 independent BDTs trained for event classification, for each scalar mass considered. Example of BDT response distribution is presented in figure 4.

Expected exclusion limits, assuming no deviation from SM predictions are observed, are calculated from the Hessian matrix of the template fit to the BDT response distributions. Final results of the study are presented in figure 5. As expected, the semi-leptonic event se-

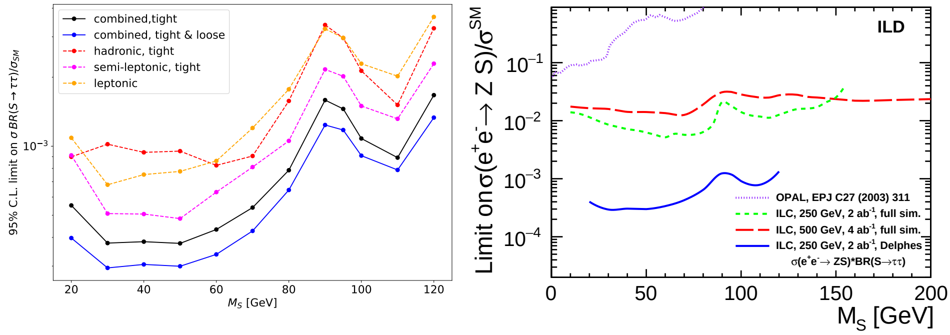

Figure 5. Expected 95% C.L. cross section limits on the light scalar production cross section times di-tau branching ration for ILC running at 250 GeV. Left: comparison of combined limits with limits obtained for different event categories. Right: combined limits compared with limits resulting from decay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

lection results in the strongest limits, combining high event statistics (about 47% of decays) with background lower than for the hadronic channel. Including loose selection categories improves the expected limits by 20-30% for the whole considered mass range. When comparing to the decay independent limits, we can state that the targeted analysis results in over order of magnitude increase in sensitivity. However, as the limit includes the branching ratio, we can conclude that the di-tau channel is more sensitive only if the branching ratio is of the order of 10% or above.

4 Search for $S \to b\bar{b}$

If the structure of new light scalar couplings to SM particles is similar to that of the SM Higgs boson then the decay to $b\bar{b}$ is expected to dominate down to the masses of the order of 10 GeV. As huge hadronic background is expected from pair production of W bosons, we focus on leptonic Z boson decays in this search channel. Again, invariant mass of the new scalar, as reconstructed directly from the two b-quark jets, is poorly measured due to neutrinos escaping in semi-leptonic heavy meson decays. However, as leptons from Z decays can be very precisely measured, we can use conservation of transverse momentum to reconstruct jet energies from leptonic final state and jet angles. This approach was first proposed for Higgs mass measurement at the ILC [18], but we verified that it works very well also for light scalar production. This is shown in figure 6, where reconstructed di-jet mass distributions are compared before and after correction for 125 GeV Higgs boson and new scalar of 50 GeV. Mass reconstructed with the recoil method (based on the Z decay measurement only) is also included for comparison. One can clearly see that jet energy correction based on the transverse momentum conservation significantly improves scalar mass measurement and allows to obtain precision much better than with uncorrected jet energies or the recoil method. The study of light scalar production in $b\bar{b}$ decay channel is ongoing and the expected exclusion limits will be presented at the 3rd ECFA workshop in Paris.

5 Conclusions

BSM scenarios involving light scalars, with masses accessible e^+e^- Higgs factories, are still not excluded by existing data. Sizable production cross sections for new scalars can also

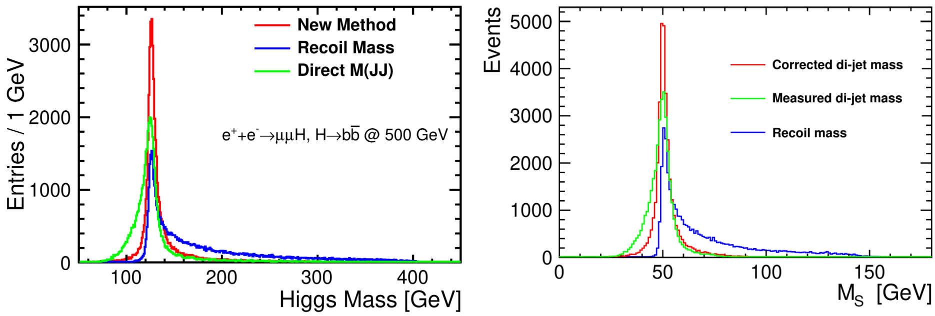

Figure 6. Invariant mass of two jets reconstructed using raw jet energies, corrected jet energies and recoil method. Left: full simulation results for the 125 GeV Higgs boson production at 500 GeV ILC [18]. Right: Delphes simulation results for the signal of 50 GeV scalar production at 250 GeV ILC.

coincide with non-standard decay patterns, so different decay channels should be considered. Strong limits are already expected from decay independent searches, based on recoil mass reconstruction. These are expected to be improved further with new analysis methods and the corresponding study is ongoing. Compared to the decay independent search, more than an order of magnitude limit improvement in search sensitivity is expected for light scalar decays to tau pairs, if this is a dominant decay channel. Studies of other decay channels are ongoing and the results are being prepared for the ECFA study report.

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