

# Overview on low mass scalars at $e^+e^-$ facilities - theory

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## Abstract

I give a short summary of scenarios with new physics scalars that could be investigated at future  $e^+e^-$  colliders. I concentrate on cases where at least one of the additional scalar has a mass below 125 GeV, and discuss models where this could be realized. In general, there are quite a few additional new physics scenarios and signatures that are still allowed by current constraints and should be investigated in more detail at future  $e^+e^-$  machines. Most of the material presented here has already been discussed in [1], and I therefore try to focus on novel developments since then.

## I. INTRODUCTION

In the European Strategy report [2, 3], Higgs factories were identified as one of the high priority projects after the HL-LHC. At such machines, the properties of the Higgs particles should be measurable to utmost precision. Furthermore, new physics scalar states could also be produced in the mass range up to  $\sim 160$  GeV depending on the collider process.

In this short proceeding, I give a very brief overview on possible production channels and also give examples of models that can render low mass scalars. I here concentrate on novel developments since the LCWS 2023 proceedings [1]. Additional material is also available in [4]. Note that the material here is partly inspired by the discussion in the Focus Topics report of the ongoing ECFA study [5].

## II. PROCESSES AT HIGGS FACTORIES

At the center-of-mass (com) energies of Higgs factories, Higgs strahlung is the dominant production mode for single scalar production [6]. Leading-order predictions for  $Zh$  production at  $e^+e^-$  colliders for low mass scalars which are Standard Model (SM)-like, using Madgraph5 [7], are shown in figure 1 for a center-of-mass energy of 250 GeV. The  $e^+e^- \rightarrow h\nu_\ell\bar{\nu}_\ell$  process contains contributions from both scalar strahlung and VBF type topologies, so we also display the expected rates from the former for this final state using a factorized approach. It can be seen that for higher scalar masses the dominant contribution stems from  $Zh$  production.

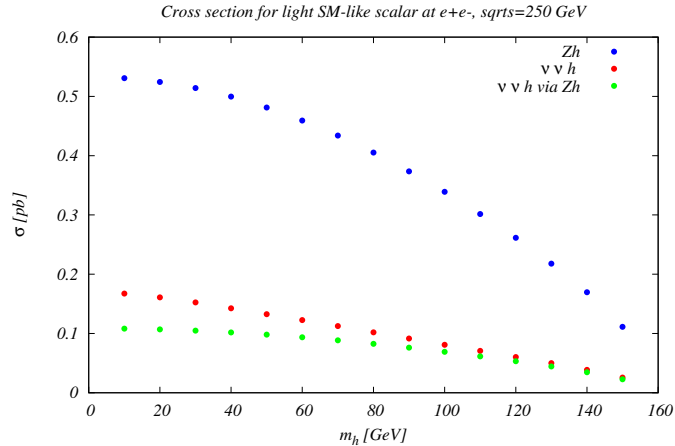


FIG. 1. Leading-order production cross sections for  $e^+e^- \rightarrow Zh$  (blue) and  $e^+e^- \rightarrow h\nu_\ell\bar{\nu}_\ell$  (red) production at an  $e^+e^-$  collider with a com energy of 250 GeV using Madgraph5 for an SM-like scalar  $h$ . We also display the contribution of  $Zh$  to  $\nu_\ell\bar{\nu}_\ell h$  using a factorized approach for the  $Z$  decay, generated via  $e^+e^- \rightarrow Zh \times \text{BR}(h \rightarrow \nu_\ell\bar{\nu}_\ell)$  (green). Update of plot in [1].

### III. PROJECTIONS FOR ADDITIONAL SEARCHES AND CONNECTIONS TO ELECTROWEAK PHASE TRANSITIONS

This section summarizes the findings already presented in [1]. We just list these here as we consider them to be fundamental for the past and current status regarding searches at Higgs factories as well as possible connections to electroweak phase transitions.

A standard reference regarding the production of lighter scalars in scalar strahlung is given in [8, 9]. In principle two different analysis methods exist, which either use the pure  $Z$  recoil ("recoil method") or take the light scalar decay into  $b\bar{b}$  into account. We display the reach of these two methods, derived via

$$S_{95} = \frac{\hat{\sigma}}{\sigma_{\text{ref}}} \quad (1)$$

that gives an upper limit  $\hat{\sigma}$  on a cross section compatible with the background only hypothesis at 95% confidence level [8]. The reference cross section  $\sigma_{\text{ref}}$  is given by the expected production cross section of a SM-like scalar at the respective mass. This quantity can directly be translated into an upper bound on rescaling, see figure 2<sup>1</sup>.

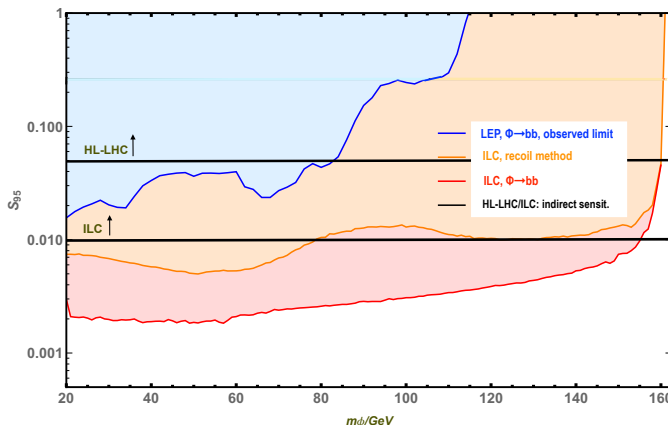


FIG. 2. Sensitivity predictions for an ILC with a com energy of 250 GeV from [8], as a function of the new scalars mass. The quantity  $S_{95}$  is defined via Eqn. (1). See text for further details.

Another important topic is the connection of models with extended scalar sectors with different scenarios of electroweak phase transitions. In particular, for scenarios where the second scalar is lighter than a SM like candidate, such states can be investigated in Higgs-strahlung. A tell-tale signature in this case is the associated decay of  $h \rightarrow h_i h_i$ . The clean

<sup>1</sup> Note that this figure was derived recasting results from LEP [10–12]. Therefore, only the contribution from the  $Z$  peak has been taken into account in the analysis. We refer the reader to the above references for a more detailed discussion regarding the treatment of these contributions.

environment of a lepton collider typically allows to test the respective parameter space into regions that provide a priori relatively low rates. There has been a lot of recent activity in this field; in figure 3, we here exemplarily show results from [13]. This study assumes a simple singlet extension where the SM scalar sector is augmented by an additional scalar. The mixing between gauge and mass eigenstates of the SM-like doublet and the singlet is denoted by  $\cos \theta$ , where  $\cos \theta = 0$  denotes the SM decoupling scenario of no mixing. Several collider sensitivity projections are shown, including generic bounds for various discalar decay modes that have originally been derived in [14]. Shown is also the region where strong first order electroweak phase transitions are possible following the analysis in [13] (*light blue band*), as well as a lower bound on the respective normalized cross sections guaranteeing a successful completion of the phase transition, denoted by  $\Delta R = 0.7^2$ . It is evident that  $e^+e^-$  Higgs factories would be an ideal environment to confirm or rule out such scenarios.

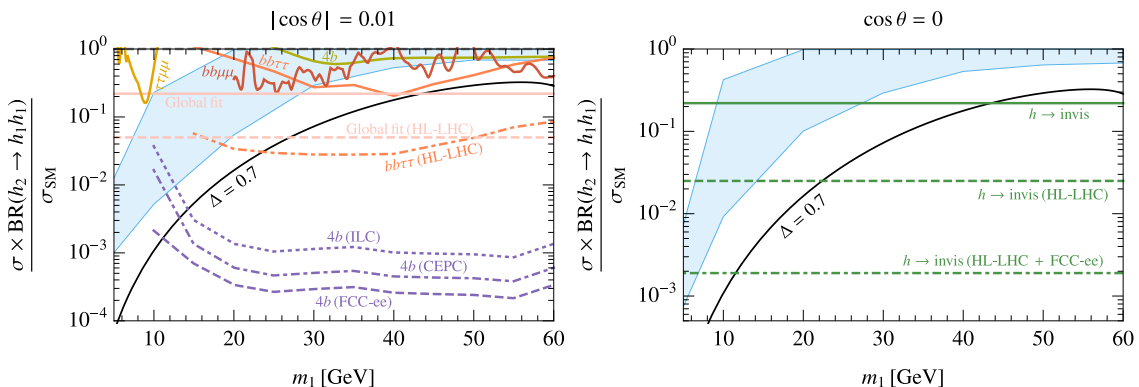


FIG. 3. Expected bounds on Higgs production via Higgs strahlung and subsequent decay into two light scalars, in the singlet extension scenario discussed in [13, 15]. For  $\cos \theta = 0$  the constraints mainly stem from  $h_{125} \rightarrow$  invisible searches. The blue shaded area corresponds to the region that allows for a strong first order electroweak phase transition in agreement with the scans performed in [13].  $\Delta R$  is a measure of the relative difference of realized singlet vacua to the true vacuum over the difference of the maximal barrier field configuration again with respect to the true vacuum (see text for details). Depending on  $m_1$  this scenario can be tested at current or future collider experiments.

#### IV. PARAMETER SPACE FOR SOME SAMPLE MODELS

After briefly discussing new physics signatures, we now turn to models that still allow for such low mass scalars. This is obviously only a brief overview, and more models might

<sup>2</sup> The quantity  $\Delta R = \frac{V(\phi_s, T^*) - V(\phi_h, T^*)}{V(\phi_b, T^*) - V(\phi_h, T^*)}$  is taken as a measure of the so-called thin-wall limit [13], where it was numerically found that  $\Delta R \geq 0.7$  seems to provide a sufficient condition to evade this region. Here,  $T^*$  denotes the temperature at which the transition is completed, and  $\phi_s$ ,  $\phi_h$ , and  $\phi_b$  denote the singlet, broken phase, and location of barrier peak along the tunneling trajectory, respectively.

exist allong for low mass scalars accessible at Higgs factories; see e.g. [4] for more details.

The first model we discuss is a model that extends the scalar sector of the SM by two additional fields that transform as singlets under the electroweak gauge group, the Two Real Singlet Model (TRSM) [16, 17]. This model contains three CP-even neutral scalars that relate the gauge and mass eigenstates  $h_{1,2,3}$  via mixing. One of the scalars necessarily needs to comply with current LHC findings for the SM-like 125 GeV resonance. However, the other two can in principle take any mass values, as long as all current theoretical and experimental constraints are fulfilled. A detailed discussion including all constraints can be found in [16, 17], with recent updates on benchmark planes also presented in [18]. In figure 4, two cases are shown where either one (high-low) or two (low-low) scalar masses are smaller than 125 GeV. On the y-axis, the respective mixing angle is shown. Decoupling here corresponds to  $\sin \alpha = 0$ . The parameter space is basically identical to the one discussed in [1]. We use the scan discussed in [16, 17], making use of the ScannerS framework [19, 20]. Direct search constraint are implemented via HiggsTools [21] using the most up to date publicly available version. This codes includes HiggsBounds [22–25] and HiggsSignals [26–28] for testing direct searches and Higgs signal strength constraints, respectively.

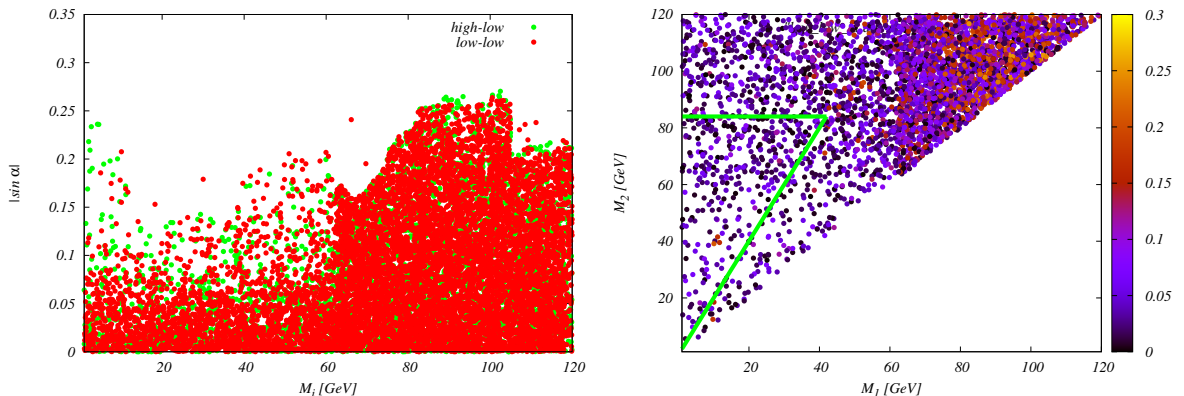


FIG. 4. Available parameter space in the TRSM, with one (high-low) or two (low-low) masses lighter than 125 GeV. *Left*: light scalar mass and mixing angle, with  $\sin \alpha = 0$  corresponding to complete decoupling. *Right*: available parameter space in the  $(m_{h_1}, m_{h_2})$  plane, with color coding denoting the rescaling parameter  $\sin \alpha$  for the lighter scalar  $h_1$ . Within the green triangle,  $h_{125} \rightarrow h_2 h_1 \rightarrow h_1 h_1 h_1$  decays are kinematically allowed. Taken from [4].

Another interesting scenario is given by two Higgs doublet models, where the SM scalar sector is augmented by a second doublet. Such models have been studied by many authors, see e.g. [29] for an overview on the associated phenomenology. We here focus on the available parameter space in 2HDMs of type I, where all leptons couple to one doublet only. In such models, flavour constraints that are severely constraining the parameter space for other Yukawa structures (see e.g. [30] for a discussion in type II models) are leviated.

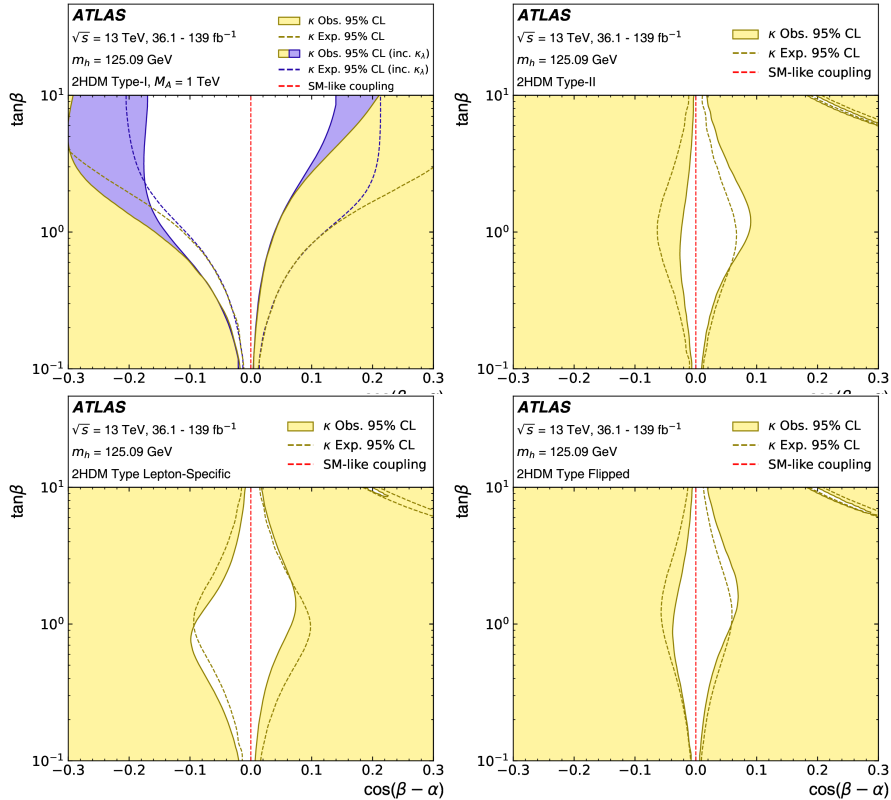


FIG. 5. Allowed and excluded regions in the  $(\cos(\beta - \alpha), \tan\beta)$  parameter space from Higgs signal strength from the ATLAS collaboration [32], for various Yukawa structures.

Apart from the masses of the additional particles, important parameters in 2HDMs are given by a combination of the different mixing angles from gauge to mass eigenstates,  $\cos(\beta - \alpha)$ , as well as  $\tan\beta$  that describes the ratio of the vacuum expectation values in a certain basis<sup>3</sup>. In general, if the lighter neutral CP-even scalar  $h$  is identified with the 125 GeV resonance, the decoupling limit  $\cos(\beta - \alpha) = 0$  denotes the configuration where the couplings to vector boson become SM-like. The Higgs signal strength poses important constraints on this quantity. In figure 5, we display the current constraints from the ATLAS collaboration using the 125 GeV scalar signal strength for various types of Yukawa structures [32].

Another question of interest is which parameter space is still allowed in such models after all possible other theoretical and experimental constraints are taken into account. For this, we make use of the publicly available tool `thdmTools` [33], that allows for efficient scans of the 2HDM parameter space and contains an internal interface to `HiggsTools` for comparison with null-results from collider searches.

<sup>3</sup> See e.g. [31] for a discussion of the meaning of physical parameters in a basis independent way.

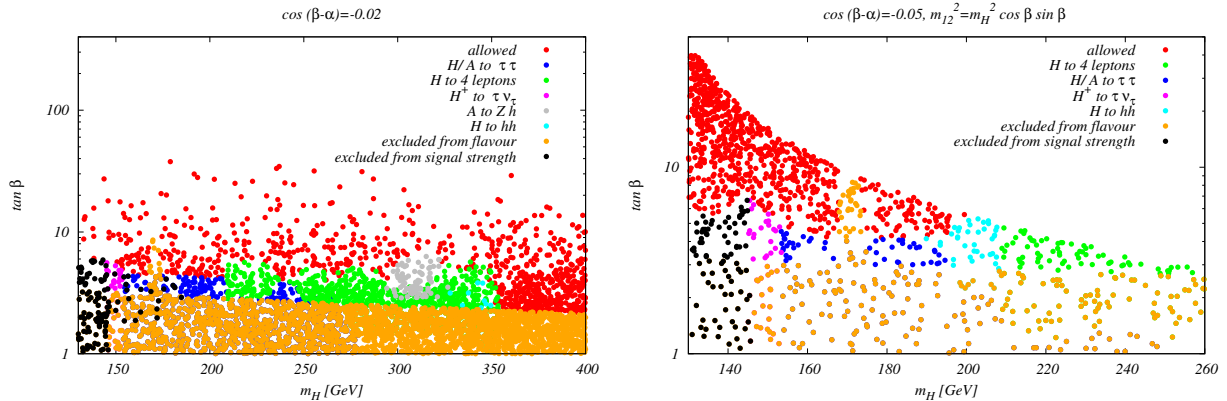


FIG. 6. Allowed regions in the  $(m_H, \tan\beta)$  plane after various constraints have been taken into account, including experimental searches at the LHC as currently available using thdmTools. *Left:* Here,  $\cos(\beta - \alpha) = -0.02$ , and  $m_{12}^2$  is floating freely. *Right:* We here fixed  $\cos(\beta - \alpha) = -0.05$ ,  $m_{12}^2 = m_H^2 \sin\beta \cos\beta$ . See text for further details.

As the minimal version of the 2HDM contains in total 6 free parameters after one of the CP even neutral scalar masses has been fixed to guarantee agreement with current LHC findings, it is customary to reduce the number of these parameters in typical scan plots to 2 dimensional planes. In such scenarios, care must be taken to not misinterpret the results; often, limits can change significantly once these underlying assumptions about parameter relations are altered.

We here exemplarily show the parameter space for a type I 2HDM, where we fixed all additional scalar masses to the same value  $m_H = m_A = m_{H^\pm}$  and additionally set  $\cos(\beta - \alpha)$  to a certain value. In one of the two scenarios shown here, we additionally fixed the additional potential parameter  $m_{12}^2 = m_H^2 \sin\beta \cos\beta$ .

We show the corresponding parameter space in figure 6. Note that we chose to require a set of initial conditions, such as vacuum stability, perturbative unitarity, and agreement with electroweak precision data to be fulfilled. Shown are then the exclusion bounds from flavour physics (via an internal interface to SuperIso [34, 35]), Higgs signal strength, as well as currently implemented collider searches. The relevant searches in this case are searches looking for a heavy resonance decaying into 4 lepton final states via electroweak gauge bosons [36], heavy resonances decaying into di-tau final states [37], searches for charged scalars into leptonic decay modes [38], resonance-enhanced discalar searches [39], and the process  $A \rightarrow hZ$  [40].

In general, for the two scenarios shown here, the available parameter space is already severely constrained from current searches at the LHC. For the scenario where  $\cos(\beta - \alpha) = -0.02$ , current searches cease to be sensitive for masses  $\gtrsim 400$  GeV, but we can find allowed parameter points in the whole mass range, where a lower scale for  $\tan\beta$  is set by flavour

constraints. On the other hand, if we additionally fix the potential parameter  $m_{12}^2$ , we see that there is also an upper limit on  $\tan\beta$  from the remaining constraints, basically leading to a maximal mass scale of around 200 GeV for the heavy scalars. Note that these bounds only apply when the other free parameters are fixed as discussed.

## V. CONCLUSIONS

I very briefly discussed some aspects of searches for low mass scalars at Higgs factories, including models that allow for such low mass states, and provided references for further reading. In particular, novel studies exceeding the ones presented here are highly encouraged and could be included as an input for e.g. the next European Strategy update.

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