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 e^+e^- Collider Prospects**

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A 96 GeV Higgs Boson in the 2HDMS: e^+e^- collider prospects*

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Abstract

The CMS collaboration reported a $\sim 3\sigma$ (local) excess at 96 GeV in the search for light Higgs-boson decaying into two photons. This mass coincides with a $\sim 2\sigma$ (local) excess in the $b\bar{b}$ final state at LEP. We show an interpretation of these possible signals as the lightest Higgs boson in the 2 Higgs Doublet Model with an additional complex Higgs singlet (2HDMS). The interpretation is in agreement with all experimental and theoretical constraints. We concentrate on the 2HDMS type II, which resembles the Higgs and Yukawa structure of the Next-to Minimal Supersymmetric Standard Model. We discuss the experimental prospects for constraining our explanation at future e^+e^- colliders, with concrete analyses based on the ILC prospects.

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1 Introduction

The Higgs boson discovered in 2012 by ATLAS and CMS [1, 2] is so far consistent with the predictions of a Standard-Model (SM) Higgs boson [3] with a mass of ~ 125 GeV. However, the experimental and theoretical uncertainties of the Higgs-boson couplings are at the level of $\sim 10 - 20\%$, leaving ample room for Beyond Standard-Model (BSM) interpretations. Many theoretically well motivated extensions of the SM contain an extended Higgs-boson sector. The additional Higgs boson can have masses above, but also below 125 GeV.

Searches for Higgs bosons below 125 GeV have been performed at LEP, the Tevatron and the LHC. Two excesses have been seen at LEP and the LHC at roughly the same mass, suggesting a possible common origin of both excesses via a new scalar. LEP observed a 2.3σ local excess in the $e^+e^- \rightarrow Z(H \rightarrow b\bar{b})$ searches [4], at a mass scale of ~ 98 GeV. However, the mass resolution is rather imprecise due to the hadronic final state. The signal strength, i.e. the measured cross section normalized to the SM expectation assuming a SM Higgs-boson mass at the same mass, was extracted to be $\mu_{\text{LEP}} = 0.117 \pm 0.057$.

CMS searched for light Higgs bosons in the di-photon final state. The results from Run II [5] show a local excess of $\sim 3\sigma$ at ~ 96 GeV, and a similar excess of 2σ at about the same mass [6] in the Run I data. Assuming gluon fusion to be the dominant production mode the excess corresponds to $\mu_{\text{CMS}} = 0.6 \pm 0.2$. Results from Run II from ATLAS with 80 fb^{-1} in the di-photon final state turned out to be still weaker than the corresponding CMS results (see, e.g., Fig. 1 in [7]). Possibilities of how to simultaneously explain both excesses by a common origin are discussed in the literature.

In Ref. [8] (see also Refs. [9, 10]), it was analyzed that the Two Higgs doublet model (2HDM) extended by a real singlet (N2HDM) [11, 12] can perfectly describe both excesses, while being in agreement with all current theoretical and experimental constraints. It was shown that the N2HDM type II is best suited to explain the excesses. This points to further investigations into two directions. The Higgs sector of supersymmetric models are naturally of type II. Consequently, it is of interest to test how well the more rigid structure of SUSY Higgs sectors containing two doublets and (at least) one singlet can describe the excesses. It was shown that indeed such models can accommodate the LEP and the CMS excesses at the $1 - 1.5\sigma$ level, while being in agreement with all experimental data [13–18] (for reviews see Refs. [7, 19, 20]). On the other hand, the singlets contained in the SUSY Higgs sector contain, in contrast to the N2HDM, a complex singlet. Furthermore, an additional Z_2 symmetry implemented into the N2HDM [11, 12] is not present in SUSY models, which conversely obey an additional Z_3 symmetry. Consequently, it is of interest to analyze how well the 2HDM with an additional complex singlet and the Z_3 symmetry imposed (2HDMS) can describe the CMS and the LEP excess, while being in agreement with all current theoretical and experimental constraints.

Here we present a first step into this direction. We sample a relevant part of the 2HDMS parameter space, where it is found that the model can perfectly accommodate both excesses [21]. We focus on measurements of a future e^+e^- collider of the 125 GeV Higgs-boson couplings, and how they can reveal deviations from the SM. While such measurements can be performed at any planned future e^+e^- collider (ILC, CLIC, FCC-ee or CEPC), concretely we use analyses for the anticipated ILC precisions. A corresponding analysis for the N2HDM can be found in Ref. [10] (see Ref. [22] for the prospects at future LHC runs).

2 The 2HDMS

The Two-Higgs-Doublet Model with complex singlet (2HDMS) is an extension of Two-Higgs-Doublets Model (2HDM) by an additional complex singlet field. The field content of the Higgs sector can be described as follows. Φ_1 and Φ_2 are the $SU(2)$ doublets, and S is the complex gauge singlet. Imposing the \mathbb{Z}_2 Symmetry for two doublets can suppress the tree-level flavour-changing neutral currents (FCNC):

$$\Phi_1 \rightarrow \Phi_1, \quad \Phi_2 \rightarrow -\Phi_2, \quad S \rightarrow S \quad (1)$$

Furthermore, one can assume that the Higgs structure of 2HDMS is NMSSM-like, corresponding to an additional \mathbb{Z}_3 Symmetry being imposed on the Higgs potential. For this \mathbb{Z}_3 Symmetry, the Higgs potential stays invariant under the transformation:

$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \\ S \end{pmatrix} \rightarrow \begin{pmatrix} 1 & & \\ & e^{i2\pi/3} & \\ & & e^{-i2\pi/3} \end{pmatrix} \begin{pmatrix} \Phi_1 \\ \Phi_2 \\ S \end{pmatrix} \quad (2)$$

The scalar potential is then given by

$$\begin{aligned} V = & m_{11}^2(\Phi_1^\dagger\Phi_1) + m_{22}^2(\Phi_2^\dagger\Phi_2) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) \\ & + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + m_S^2(S^\dagger S) + \lambda'_1(S^\dagger S)(\Phi_1^\dagger\Phi_1) + \lambda'_2(S^\dagger S)(\Phi_2^\dagger\Phi_2) \\ & + \frac{\lambda''_3}{4}(S^\dagger S)^2 + \left(-m_{12}^2\Phi_1^\dagger\Phi_2 + \frac{\mu_{S1}}{6}S^3 + \mu_{12}S\Phi_1^\dagger\Phi_2 + \text{h.c.} \right) \end{aligned} \quad (3)$$

After electroweak symmetry breaking, the scalar component of Φ_1 , Φ_2 and S acquire the non trivial vacuum expectation values (vevs). Thus the fields can be expanded around vevs and have the following expressions:

$$\begin{aligned} \Phi_1 = \begin{pmatrix} \chi_1^+ \\ \phi_1 \end{pmatrix} &= \begin{pmatrix} \chi_1^+ \\ v_1 + \frac{\rho_1 + i\eta_1}{\sqrt{2}} \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \chi_2^+ \\ \phi_2 \end{pmatrix} = \begin{pmatrix} \chi_2^+ \\ v_2 + \frac{\rho_2 + i\eta_2}{\sqrt{2}} \end{pmatrix}, \\ S &= v_S + \frac{\rho_S + i\eta_S}{\sqrt{2}} \end{aligned} \quad (4)$$

One can define $\tan \beta = v_2/v_1$ as in the 2HDM. The ‘‘SM vev’’ is then given by $v = \sqrt{v_1^2 + v_2^2} \approx 174$ GeV.

The charged Higgs sector of 2HDMS has the identical structure as the charged Higgs sector of 2HDM. However, the additional singlet enter the neutral Higgs sector and mix with two doublets for both CP-even sector and CP-odd sector. Therefore, we have 3 scalar Higgs bosons h_1, h_2, h_3 , 2 pseudo-scalar Higgs bosons a_1, a_2 , and the charged Higgs boson H^\pm . We use the conventions of $m_{h_1} < m_{h_2} < m_{h_3}$ and $m_{a_1} < m_{a_2}$.

The CP-even sector is diagonalized as

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_S \end{pmatrix}, \quad \text{diag}\{m_{h_1}^2, m_{h_2}^2, m_{h_3}^2\} = R^T M_S^2 R, \quad (5)$$

where the symmetric M_S^2 is given by

$$\begin{aligned}
M_{S11}^2 &= 2\lambda_1 v^2 \cos^2 \beta + (m_{12}^2 - \mu_{12} v_S) \tan \beta, \\
M_{S12}^2 &= (\lambda_3 + \lambda_4) v^2 \sin 2\beta - (m_{12}^2 - \mu_{12} v_S), \\
M_{S13}^2 &= (2\lambda_1' v_S \cos \beta + \mu_{12} \sin \beta) v, \\
M_{S22}^2 &= 2\lambda_2 v^2 \sin^2 \beta + (m_{12}^2 - \mu_{12} v_S) \cot \beta, \\
M_{S23}^2 &= (2\lambda_2' v_S \sin \beta + \mu_{12} \cos \beta) v, \\
M_{S33}^2 &= \frac{\mu_{S1}}{2} v_S + \lambda_3'' v_S^2 - \mu_{12} \frac{v^2}{2v_S} \sin 2\beta
\end{aligned} \tag{6}$$

with

$$R = \begin{pmatrix} c_{\alpha_1} c_{\alpha_2} & s_{\alpha_1} c_{\alpha_2} & s_{\alpha_2} \\ -s_{\alpha_1} c_{\alpha_3} - c_{\alpha_1} s_{\alpha_2} s_{\alpha_3} & c_{\alpha_1} c_{\alpha_3} - s_{\alpha_1} s_{\alpha_2} s_{\alpha_3} & c_{\alpha_2} s_{\alpha_3} \\ s_{\alpha_1} s_{\alpha_3} - c_{\alpha_1} s_{\alpha_2} c_{\alpha_3} & -s_{\alpha_1} s_{\alpha_2} c_{\alpha_3} - c_{\alpha_1} s_{\alpha_3} & c_{\alpha_2} c_{\alpha_3} \end{pmatrix}, \tag{7}$$

where α_1 , α_2 and α_3 are the three mixing angles. Similarly, in the CP-odd sector the mixing angle α_4 enters in addition. The set of input parameters is:

$$\tan \beta, \quad \alpha_{1,2,3,4}, \quad m_{h_1}, \quad m_{h_2}, \quad m_{h_3}, \quad m_{a_1}, \quad m_{a_2}, \quad m_{H^\pm}, \quad v_S \tag{8}$$

In our analysis we interpret the experimental excess at ~ 96 GeV as the possible lightest scalar Higgs boson h_1 , and we identify the second lightest scalar Higgs h_2 as the SM-like Higgs at ~ 125 GeV.

The couplings of the Higgs bosons to the SM particles can be described as follows.

$$c_{h_i f f} = \frac{g_{h_i f f}}{g_{H_{\text{SM}} f f}}, \tag{9}$$

$$c_{h_i V V} = \frac{g_{h_i V V}}{g_{H_{\text{SM}} V V}}. \tag{10}$$

We focus here on the 2HDM type II (see Sect. 1). Thus the coupling modifiers for fermions are given by

$$\begin{aligned}
c_{h_i t t} &= R_{i2} / s_\beta, \\
c_{h_i b b} &= R_{i1} / c_\beta, \\
c_{h_i \tau \tau} &= R_{i1} / c_\beta.
\end{aligned} \tag{11}$$

Similarly, the coupling modifier for massive gauge bosons is given by

$$c_{h_i V V} = c_{h_i Z Z} = c_{h_i W W} = \cos \beta R_{i1} + \sin \beta R_{i2}. \tag{12}$$

3 Analysis details

In the following subsection we list the relevant details for our analysis: theoretical and experimental constraints, the χ^2 contribution from the two excesses as well as the scanned 2HDMS parameter space.

3.1 The constraints

In this section we give a brief description of the theoretical and experimental constraints applied in our analysis to the 2HDMS.

- **Tree-Level perturbative unitarity:**

Tree-Level perturbative unitarity conditions ensures perturbativity up to very high scales. This can be achieved by demanding the amplitudes of the scalar quartic interactions, which are given by the eigenvalues of the $2 \rightarrow 2$ scattering matrix, to be below a value of 8π . The calculation was carried out with a `Mathematica` package implemented in `ScannerS` [23] and by following the procedure of [24].

- **Boundedness from below:**

Boundedness from below conditions ensures that the potential remains positive when the field values approach infinity. The conditions can be found in [25] and were adapted for the 2HDMS.

- **Vacuum stability:**

An obvious condition is to require the EW vacuum to be the global minimum (*true vacuum*) of the scalar potential. In this case the EW is absolutely stable. If the EW vacuum is a local minimum (*false vacuum*) the corresponding parameter region can still be allowed if it is metastable. This is the case if the predicted life-time is longer than the current age of the universe. Any configuration with a life-time shorter than the age of the universe is considered unstable. For our study we used `Evade` [26–28].

- **Higgs-boson rate measurements:**

We use the public code `HiggsSignals v.2.5.1` [29–31] to verify that all generated points agree with currently available measurements of the SM Higgs-boson. `HiggsSignals` uses a statistical χ^2 analysis of the SM-like Higgs-boson of a given model and compares it to the measurements of the Higgs-boson signal rates and masses at Tevatron and LHC.

- **BSM Higgs-boson searches:**

The public code `HiggsBounds v.5.9.0` [32–36] provides 95% confidence level exclusion limits of all important direct searches for charged Higgs bosons and additional neutral Higgs-bosons.

- **Flavor physics observables:**

The charged Higgs sector of the 2HDMS is unaltered with respect to the general 2HDM, and we can take over the corresponding constraints from flavor physics. The most important bounds, see Ref. [37], come from $\text{BR}(B_s \rightarrow X_s \gamma)$, constraints on ΔM_{B_s} from neutral B-meson mixing and $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$. These give a lower limit for the charged Higgs mass $m_{H^\pm} \geq 650 \text{ GeV}$ [38].

- **Electroweak precision observables:**

Constraints from electroweak precision observables (EWPO) can be expressed in terms of the parameters S , T and U [39, 40]. If BSM physics enters mainly through gauge boson self-energies, as it is the case for the extended Higgs sector of the 2HDMS, these

parameters can give a good approximation to capture the constraints from EWPO. In the 2HDMS the parameter T is the most sensitive and has a strong correlation to U . Contributions to U can therefore be dropped [41,42]. For our scan we require the prediction of the S and T parameters to be within the 95% confidence level interval, corresponding to $\chi^2 = 5.99$ for two degrees of freedom. The calculations were carried out by `SPheno-4.0.4` [43,44].

3.2 The experimental excesses

The experimental excesses at both LEP and CMS could be translated to the following signal strengths:

$$\mu_{\text{LEP}}^{\text{exp}} = \frac{\sigma(e^+e^- \rightarrow Z\phi \rightarrow Zb\bar{b})}{\sigma(e^+e^- \rightarrow ZH_{\text{SM}}^0 \rightarrow Zb\bar{b})} = 0.117 \pm 0.05, \quad (13)$$

$$\mu_{\text{CMS}}^{\text{exp}} = \frac{\sigma(pp \rightarrow \phi \rightarrow \gamma\gamma)}{\sigma(pp \rightarrow H_{\text{SM}}^0 \rightarrow \gamma\gamma)} = 0.6 \pm 0.2, \quad (14)$$

where the H_{SM}^0 is the SM Higgs-boson with the rescaled mass at the same range as the new scalar particle ϕ at ~ 96 GeV.

We interpreted the new scalar ϕ as the lightest CP-even Higgs-boson h_1 of the 2HDMS. Its signal strengths can be calculated by the following expressions in the narrow width approximation:

$$\mu_{\text{LEP}}^{\text{theo}} = \frac{\sigma_{2\text{HDMS}}(e^+e^- \rightarrow Zh_1)}{\sigma_{\text{SM}}(e^+e^- \rightarrow ZH_{\text{SM}}^0)} \times \frac{\text{BR}_{2\text{HDMS}}(h_1 \rightarrow b\bar{b})}{\text{BR}_{\text{SM}}(H_{\text{SM}}^0 \rightarrow b\bar{b})} = |c_{h_1VV}|^2 \frac{\text{BR}_{2\text{HDMS}}(h_1 \rightarrow b\bar{b})}{\text{BR}_{\text{SM}}(H_{\text{SM}}^0 \rightarrow b\bar{b})} \quad (15)$$

$$\mu_{\text{CMS}}^{\text{theo}} = \frac{\sigma_{2\text{HDMS}}(gg \rightarrow h_1)}{\sigma_{\text{SM}}(gg \rightarrow H_{\text{SM}}^0)} \times \frac{\text{BR}_{2\text{HDMS}}(h_1 \rightarrow \gamma\gamma)}{\text{BR}_{\text{SM}}(H_{\text{SM}}^0 \rightarrow \gamma\gamma)} = |c_{h_1tt}|^2 \frac{\text{BR}_{2\text{HDMS}}(h_1 \rightarrow \gamma\gamma)}{\text{BR}_{\text{SM}}(H_{\text{SM}}^0 \rightarrow \gamma\gamma)} \quad (16)$$

The effective couplings of c_{h_1VV} and c_{h_1tt} in Eqs. (12) and (11). The corresponding BRs are evaluated with `SPheno-4.0.4` [43] [44].

The χ^2 contribution from these two excesses can then be calculated as

$$\chi_{\text{CMS-LEP}}^2 = \left(\frac{\mu_{\text{LEP}}^{\text{theo}} - 0.117}{0.057} \right)^2 + \left(\frac{\mu_{\text{CMS}}^{\text{theo}} - 0.6}{0.2} \right)^2 \quad (17)$$

The SM, in which no scalar at ~ 96 GeV is present thus receives a χ^2 penalty of ~ 13.2 . In our analysis we will only consider points in the 2HDMS which are in agreement with the two excesses at the 1σ level, i.e. with $\chi_{\text{CMS-LEP}}^2 \leq 2.3$.

3.3 Parameter scan

Following the N2HDM interpretation [42], we focus on the type-II Yukawa structure and the low $\tan\beta$ region.

As discussed before, in our analysis we interpret the experimental excess at ~ 96 GeV as the possible lightest scalar Higgs boson h_1 , and we identify the second lightest scalar Higgs h_2 as the SM-like Higgs at ~ 125 GeV. We furthermore made the pedagogical guess

that the lightest CP-odd Higgs a_1 is singlet dominant, which corresponds to the condition of $\sin^2 \alpha_4 > \frac{1}{2}$. To avoid decay $h_2 \rightarrow a_1 a_1$ we explore an m_{a_1} range of 200 GeV to 500 GeV. Following the preferred ranges in the N2HDM [42], we scan the following parameter space:

$$\begin{aligned}
m_{h_1} &\in \{80, 93\} \text{ GeV}, & m_{h_2} &\in \{110, 126\} \text{ GeV}, & m_{h_3} &\in \{650, 1000\} \text{ GeV}, \\
m_{a_1} &\in \{200, 500\} \text{ GeV}, & m_{a_2} &\in \{650, 1000\} \text{ GeV}, & m_{H^\pm} &\in \{650, 1000\} \text{ GeV}, \\
\tan \beta &\in \{1, 6\}, & \alpha_4 &\in \{1.25, \frac{\pi}{2}\}, & v_S &\in \{100, 2000\} \text{ GeV} \\
\frac{\tan \beta}{\tan \alpha_1} &\in \{0, 1\}, & \alpha_2 &\in \pm\{0.95, 1.3\}, & |\sin(\beta - \alpha_1 - |\alpha_3|)| &\in \{0.98, 1\} \quad (18)
\end{aligned}$$

4 Results: prospects for e^+e^- colliders

The results of our parameter scans in the type II of the 2HDMS [21], indicate that this model configuration can accommodate both excesses simultaneously, while being in agreement with all considered constraints described above. This was to be expected because of the similarity of the 2HDMS and the N2HDM, where the latter was shown to perfectly fit the excesses previously [8–10, 22].

The particle h_1 is dominantly singlet-like, and acquires its coupling to the SM particles via the mixing with the SM Higgs boson h_2 . Thus, the presented scenario will be experimentally accessible in two complementary ways. Firstly, the new particle h_1 can be produced directly in collider experiments (see, e.g., Ref. [45]), an avenue we will not pursue here. Secondly, deviations of the couplings of 125 GeV Higgs boson h_2 from the SM predictions are present. Currently, the uncertainties of the measurement of the coupling strengths of the SM-like Higgs boson at the LHC are still large [3, 46, 47]. In the future, even tighter constraints are expected from the HL-LHC with 3000 fb^{-1} integrated luminosity [48]. Finally, a future linear e^+e^- collider, for instance the ILC, could improve the precision measurements of the Higgs boson couplings with unprecedented precision (see, e.g., Ref. [49]).¹ We compare our scan points to the expected precisions of the LHC and the ILC as they are reported in Refs. [49, 50], neglecting possible correlations of the coupling modifiers.

In Fig. 1 we plot the coupling modifier of the SM-like Higgs boson h_2 to τ -leptons, $c_{h_2\tau\tau}$ on the horizontal axis against the coupling coefficient to b -quarks, $c_{h_2b\bar{b}}$ (top), to t -quarks, $c_{h_2t\bar{t}}$ (middle) and to the massive SM gauge bosons, c_{h_2VV} (bottom). These points passed all the experimental and theoretical constraints and have $\chi_{\text{CMS-LEP}}^2 \leq 2.3$. We include several future precisions for the coupling measurements. It should be noted that they are centered around the SM predictions to show the potential to discriminate the SM from the 2HDMS. The magenta ellipse in each plot shows the expected precision of the measurement of the coupling coefficients at the 1σ -level at the HL-LHC from Ref. [50]. The current uncertainties and the HL-LHC analysis are based on the coupling modifier, or κ -framework. These modifiers are then constrained using a global fit to projected HL-LHC data assuming no deviation from the SM prediction will be found. We use the uncertainties given under the assumptions that no decay of the SM-like Higgs boson to BSM particles is present, and that current systematic

¹Similar results can be obtained for CLIC, FCC-ee and CEPC. We will focus on the ILC prospects here following Ref. [8].

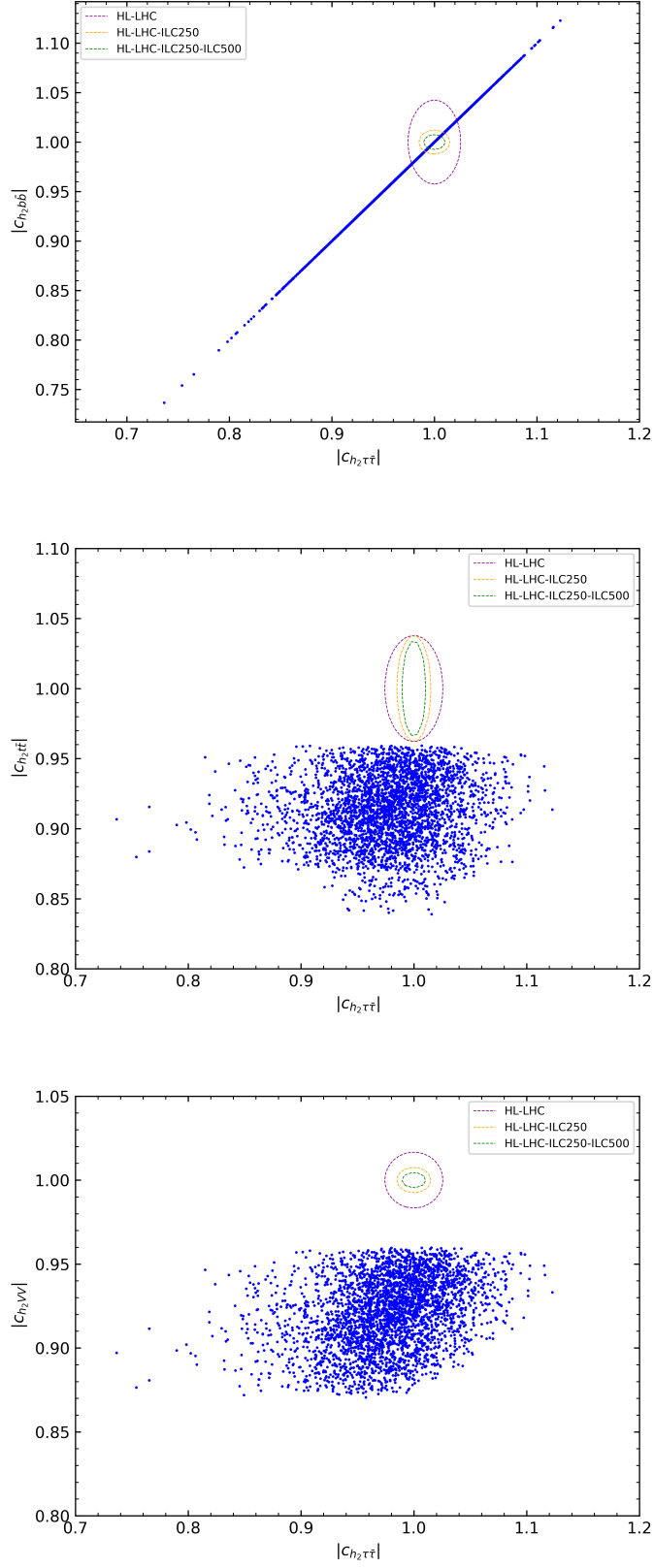


Figure 1: Prospects for the Higgs coupling measurements at the HL-LHC and the ILC (see text). The upper, middle and lower plot show the planes of $|c_{h_2 \tau \tau}| - |c_{h_2 t \bar{t}}|$, $|c_{h_2 \tau \tau}| - |c_{h_2 b \bar{b}}|$, $|c_{h_2 \tau \tau}| - |c_{h_2 V V}|$

uncertainties will be reduced in addition to the reduction of statistical uncertainties due to the increased statistics. The green and the orange ellipses show the corresponding expected uncertainties when the HL-LHC results are combined with projected data from the ILC after the 250 GeV phase and the 500 GeV phase, respectively, taken from Ref. [49]. Their analysis is based on a pure effective field theory calculation, supplemented by further assumptions to facilitate the combination with the HL-LHC projections in the κ -framework. In particular, in the effective field theory approach the vector boson couplings can be modified beyond a simple rescaling. This possibility was excluded by recasting the fit setting two parameters related to the couplings to the Z -boson and the W -boson to zero (details can be found in Ref. [49]).

The future precision in the Higgs coupling measurement to quarks can be summarized as follows. The uncertainty of the coupling to b -quarks will shrink below 4% at the HL-LHC and below 1% at the ILC. The coupling to τ -leptons an uncertainty at the level of 2% is expected at the HL-LHC. Here, the ILC could reduce this uncertainty to below 1%. The coupling to t -quarks are expected to reduce the uncertainty by roughly a factor of three at the HL-LHC, employing, however, theoretical assumptions. At the ILC the accuracy of these couplings can be substantially improved to be model-independent.

In the top plot the 2HDMS points lie on a diagonal line, because in type II models the coupling to leptons and to down-type quarks scale identically. This diagonal goes through the SM prediction ($c_{h_2\tau\tau} = c_{h_2bb} = 1$). While current constraints on the SM-like Higgs-boson properties allow for large deviations of the couplings of up to 40%, the parameter space of our scans that is still allowed will be significantly reduced by the expected measurements at the HL-LHC and the ILC.² The couplings of the 125 GeV Higgs boson to t quarks, shown in the middle plot of Fig. 1, on the other hand show a deviation from the SM prediction for all points. The deviation ranges from $\sim 1.5\sigma$ to about $\sim 4\sigma$.

Finally, in the lower plot of Fig. 1, where we show the absolute value of the coupling modifier of the SM-like Higgs boson w.r.t. the vector boson couplings $|c_{h_2VV}|$, the parameter points of the 2HDMS show a deviation from the SM prediction substantially larger than the projected experimental uncertainty at HL-LHC and ILC. A $2 - 3\sigma$ deviation from the SM prediction is expected with HL-LHC accuracy. At the ILC a deviation of more than 5σ would be visible. Consequently, the 2HDMS explaining the two excesses in the low-mass Higgs boson searches at LEP and CMS at ~ 96 GeV, can be distinguished from the SM by the measurements of the 125 GeV Higgs-boson couplings at the ILC.

5 Conclusions

The possibility of the 2HDMS explaining both the CMS and the LEP excesses at ~ 96 GeV simultaneously offers interesting prospects to be probed experimentally. Here we have focused on the possibilities to measure the properties of the 125 GeV Higgs boson at future e^+e^- colliders. Concretely, we used the projected accuracies of the ILC running at $\sqrt{s} = 250$ GeV and 500 GeV, similar results are expected for CLIC, FCC-ee or CEPC. We analyzed such points that are in agreement with all experimental and theoretical constraints and have $\chi_{\text{CMS-LEP}}^2 \leq 2.3$ (i.e. they accomodate the two excesses at the 1σ level). These points show a

²Here one should keep in mind the theory input required in the (HL-)LHC analysis.

deviation from the prediction of the SM Higgs boson that can clearly be detected by the ILC coupling measurements. While part of the 2HDMS spectrum reproduces the SM coupling to b quarks, the coupling to t quarks deviates between ~ 1.5 and $\sim 4\sigma$ from the SM prediction. By measuring the coupling to the massive SM gauge bosons, a deviation of more than 5σ is expected. Thus, the 2HDMS explaining the excesses in the Higgs boson searches at LEP and CMS at ~ 96 GeV, can clearly be distinguished from the SM at the ILC.

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