Implications of LHC Higgs results for supersymmetry

Sabine Kraml
Laboratoire de Physique Subatomique et de Cosmologie, UJF Grenoble 1, CNRS/IN2P3, INPG, 53 Avenue des Martyrs, F-38026 Grenoble, France
E-mail: sabine.kraml@lpsc.in2p3.fr

Abstract. The current LHC Higgs results may be used as a guide for where to look for SUSY. I discuss implications for the MSSM and NMSSM. Particularly interesting are NMSSM scenarios with large \( \lambda \) and small \( \tan \beta \); they are characterized by light stops and light higgsinos, and offer the intriguing possibility of observing more than one light Higgs at the LHC.

1. Introduction
The recent discovery \([1, 2]\) of a new particle with mass around 125 GeV and properties consistent with a Standard Model (SM) Higgs boson is a first triumph for the LHC physics program. However, while this discovery completes our picture of the SM, it still leaves many fundamental questions open. One of the most pressing issues is that the SM does not explain the value of the electroweak (EW) scale itself: Why is the Higgs boson so light when it is predicted to be driven to the scale of Grand Unified Theories (\( M_{\text{GUT}} \)), or even the Planck scale, by radiative corrections? Either new physics appears at the EW scale, or the Higgs mass-squared is fine tuned at the \( 10^{-32} \) level.

New particles that couple to the Higgs can however also modify the Higgs couplings, and thus the production and decay rates in various channels. So on the one hand we expect physics beyond the SM (BSM) to explain the Higgs mass, on the other hand the measured mass and signal strengths provide significant constraints on concrete BSM realizations, see \( e.g. \) \([3, 4]\). Moreover, while the SM provides a reasonably good fit to the current data, some new physics contributions to the Higgs couplings to gluons and photons are preferred, as shown in Fig. 1.1

![Figure 1. Global fit of additional loop contributions \( \Delta C_g \) and \( \Delta C_\gamma \) from new particles to the Higgs couplings to gluons and photons, assuming SM values for the couplings to \( W, Z \) and SM fermions. The fit includes all available Higgs signal strengths from ATLAS, CMS and the Tevatron experiments. The red, orange and yellow ellipses show the 68%, 95% and 99.7% CL regions, respectively. The white star marks the best-fit point \( \Delta C_g = -0.086, \Delta C_\gamma = 0.426 \). From [4].](figure1.png)

1 Based on the experimental results available at the end of 2012.
The arguably best motivated extension of the SM is weak-scale supersymmetry (SUSY), introducing a new symmetry between fermions and bosons. SUSY solves the hierarchy problem provided SUSY particles exist at or around the TeV energy scale. The (Next-to-) Minimal Supersymmetric Standard Model, (N)MSSM, moreover predicts a light, often SM-like, Higgs boson with mass below $\approx 135 \text{ (140)} \text{ GeV}$. This has always been regarded as an intriguing feature, and even more so with the actual observation of a Higgs-like state at 125 GeV. So far, however, SUSY searches at ATLAS and CMS show no signal whatsoever, and the mass limits in particular for squarks and gluinos have been pushed well into the TeV range [7, 8].

So the Higgs very likely has been found — but where is supersymmetry? In fact, the SUSY particles relevant for the Higgs sector and the hierarchy problem, stops and higgsinos, are much less constrained than light-flavor squarks and gluinos. “Natural” SUSY still lives on. In this talk I therefore discuss some implications of the LHC Higgs results for supersymmetric models.

2. Minimal Supersymmetric Standard Model

In the MSSM, $m_h^2 = m_Z^2 \cos^2 2\beta$ at tree level, where $\tan \beta = v_u / v_d$, $v = \sqrt{v_u^2 + v_d^2} = 174 \text{ GeV}$. This quickly saturates to $m_h^2 \lesssim m_Z^2$ for $\tan \beta \gtrsim 5$. To further lift $m_h^2$ from $m_Z^2 = (91 \text{ GeV})^2$ to around $(125 \text{ GeV})^2$, radiative corrections nearly as large as the tree-level value are required. The leading one-loop correction comes from the top–stop sector and is given by [5]

$$\Delta m_h^2 = \frac{3}{4\pi^2} m_t^4 \left( \log \frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2} \left( 1 - \frac{X_t^2}{12 M_S^2} \right) \right). \quad (1)$$

Here $m_t$ is the running top-quark mass at the scale $m_t$, $M_S^2 = M_{1/2}^2 / 2$ with $M_{1/2}$ the stop masses, and $X_t$ is the stop mixing parameter, $X_t = A_t - \mu \cot \beta$, at the scale $M_S$. The contribution from the logarithmic term in Eq. (1) can be increased by simply raising $M_S$, but naturalness demands that the SUSY scale should be not too far above the EW scale. The $X_t$ contribution is maximized at $|X_t/M_S| \simeq \sqrt{6} = 2.45$; this is called the maximal-mixing scenario. So $m_h \simeq 125 \text{ GeV}$ requires either (unnaturally) heavy stops, or maximal mixing. This is illustrated in Fig. 2 for a semi-constrained version of the MSSM with universal gaugino mass $M_{1/2}$, scalar mass $m_0$ and trilinear coupling $A_0$ all defined at $M_{\text{GUT}}$, but non-universal Higgs mass parameters (NUHM model). As can be seen, a 125 GeV Higgs together with stops in the 0.5–1 TeV mass range indeed requires maximal mixing, i.e. very large $|A_t|$ (left plot).
1st/2nd generation squarks turn out to be heavy, with masses above 1–2 TeV (right plot), thus automatically avoiding the current LHC limits. The Higgs signal strengths in the $\gamma\gamma$ and $ZZ$ channels are however $R \lesssim 1$ in this case, see [6].

3. Next-to-Minimal Supersymmetric Standard Model

The NMSSM differs from the MSSM by to the presence of the gauge singlet superfield $\hat{S}$ [9]. In the simplest $Z_3$ invariant realization of the NMSSM, the Higgs mass term $\mu \hat{H}_u \hat{H}_d$ in the superpotential $W_{\text{MSSM}}$ of the MSSM is replaced by the coupling $\lambda$ of $\hat{S}$ to $\hat{H}_u$ and $\hat{H}_d$ and a self-coupling $\kappa S^3$. The superpotential $W_{\text{NMSSM}}$ is given by:

$$W_{\text{NMSSM}} = \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} \hat{S}^3 + \ldots,$$

where hatted letters denote superfields, and the dots denote the MSSM-like Yukawa couplings of $\hat{H}_u$ and $\hat{H}_d$ to the quark and lepton superfields. Once the real scalar component of $\hat{S}$ develops a vev $\langle S \rangle$, the first term in $W_{\text{NMSSM}}$ generates an effective $\mu$-term, $\mu_{\text{eff}} = \lambda \langle S \rangle$.

As compared to two independent parameters in the Higgs sector of the MSSM at tree level, often chosen as $\tan \beta$ and $M_A$, the Higgs sector is now described by

$$\lambda, \kappa, A_\lambda, A_\kappa, \text{tan } \beta = v_u/v_d, \mu_{\text{eff}}.$$  

(3)

The neutral Higgs sector of this model consists of three CP-even $(h_1, h_2, h_3)$ and two CP-odd $(a_1, a_2)$ states. The CP-even mass eigenstates are superpositions of the neutral CP-even components of $H_u, H_d$ and $S$:

$$h_1 = S_{1,d} H_d + S_{1,u} H_u + S_{1,s} S, \quad h_2 = S_{2,d} H_d + S_{2,u} H_u + S_{2,s} S, \quad h_3 = S_{3,d} H_d + S_{3,u} H_u + S_{3,s} S,$$

(4)

with the couplings to gauge bosons and fermions determined by the $3 \times 3$ mixing matrix $S$, e.g. $g_{h_i VV}/g_{H_{\text{MSSM}}VV} = \cos \beta S_{i,d} + \sin \beta S_{i,u}$.

An interesting feature is that the coupling $\lambda S \hat{H}_u \hat{H}_d$ in the superpotential leads to an extra tree-level contribution to the SM-like Higgs mass $m_h^2 = m_\phi^2 \cos^2 2\beta + \lambda^2 \sin^2 2\beta + \Delta m_h^2$. It is thus much easier to obtain $m_h \simeq 125$ GeV in constrained versions of the NMSSM then in their MSSM equivalents [10]. Moreover, as pointed out by Ellwanger [11, 12], for large $\lambda$ (and small $\tan \beta$) doublet–singlet mixing can reduce the $hbb$ coupling, thus enhancing the di-photon signal at the LHC. This works in fact for both, the lightest and the second-lightest scalar, $h_1$ and $h_2$, and either of them could be the observed state at 125 GeV [12, 10, 13].

For illustration, Fig. 3 shows the result of a scan of the “semi-constrained” NMSSM with universal $m_0$, $M_{1/2}$ and $A_0$ at the GUT scale, but the NMSSM-specific parameters of Eq. (3) treated as free parameters at the EW scale. The scan was performed with NMSSTools [14]; all points have a neutralino as the lightest SUSY particle (LSP) and obey the current mass limits as well as the constraints on $\text{BR}(B_s \to X_s \gamma)$, $\Delta M_s$, $\Delta M_d$, $\text{BR}(B_s \to \mu^+ \mu^-)$, $\text{BR}(B^+ \to \tau^+ \nu_\tau)$ and $\text{BR}(B \to X_s \mu^+ \mu^-)$ at $2\sigma$. The light, medium and dark blue points have $\Omega h^2 \lesssim 0.136$ and obey the bounds on the spin-independent LSP–proton scattering cross section from XENON100. Light and medium red points have $0.094 \lesssim \Omega h^2 \lesssim 0.136$ and of course also pass the XENON100 bounds. (The shades of blue and red just help indicate the level of enhancement or suppression of the $\gamma\gamma$ signal.) The green points have $\Omega h^2 \leq 0.136$ and in addition explain $\Delta a_\mu$ within $2\sigma$. 


Figure 3. Signal strength (relative to SM) in the $h_i \rightarrow \gamma\gamma$ channel as function of $\lambda$ from a scan over the semi-constrained NMSSM, on the left for the $h_1$ lying in the 123 – 128 GeV mass range, on the right for the $h_2$ lying in the 123 – 128 GeV range. See text for color code.

4. Two Higgs bosons at 98 and 125 GeV

If the $h_2$ of the NMSSM is responsible for the signal at 125 GeV, a particularly interesting question [15] is whether one could simultaneously explain the LHC signal and the small ($\sim 2\sigma$) LEP excess in $e^+e^- \rightarrow Zb\bar{b}$ in the vicinity of $M_{Z2} \sim 98$ GeV. We recall that the LEP excess is clearly inconsistent with a SM-like Higgs boson at this mass, being only about $10-20\%$ of the rate predicted for the $H_{SM}$. Consistency with such a result for the $h_1$ is natural if the $h_1$ is primarily $ZZ$ coupling, as required by the observed LHC signals.

As above, we perform a scan over the semi-constrained NMSSM. We compute the ratio of the $gg$ or vector-boson fusion (VBF) induced Higgs cross section times the Higgs branching ratio to a given final state $X$, relative to the corresponding value for the SM Higgs boson, as

$$R_{gg}^{h_i}(X) \equiv \frac{\Gamma(h_i \rightarrow gg) \text{BR}(h_i \rightarrow X)}{\Gamma(H_{SM} \rightarrow gg) \text{BR}(H_{SM} \rightarrow X)}, \quad R_{VBF}^{h_i}(X) \equiv \frac{\Gamma(h_i \rightarrow WW) \text{BR}(h_i \rightarrow X)}{\Gamma(H_{SM} \rightarrow WW) \text{BR}(H_{SM} \rightarrow X)}.$$  

(5)

where $h_i$ is the $i^{th}$ NMSSM scalar Higgs, and $H_{SM}$ is the SM Higgs boson, taking $m_{H_{SM}} = m_{h_i}$.

To describe the LEP and LHC data the $h_1$ and $h_2$ must have $m_{h_1} \sim 98$ GeV and $m_{h_2} \sim 125$ GeV, respectively, with the $h_1$ being largely singlet and the $h_2$ being primarily doublet. Figure 4 shows $R_{VBF}^{h_1}(b\bar{b})$ versus $R_{gg}^{h_2}(\gamma\gamma)$ for the scan points that pass LEP, B-physics and dark matter constrains as above and have in addition $m_{h_1} \in [96, 100]$ GeV and $m_{h_2} \in [123, 128]$ GeV. (These ranges take into account a 2–3 GeV theoretical error in the computation of the Higgs masses.) The points with $0.1 \leq R_{VBF}^{h_1}(b\bar{b}) \leq 0.25$ would provide the best fit to the LEP excess. As can be seen, a large portion of these points have $R_{gg}^{h_2}(\gamma\gamma) > 1$ as preferred by LHC data.

In the following we thus require $m_{h_1} \in [96, 100]$ GeV with $0.1 \leq R_{VBF}^{h_1}(b\bar{b}) \leq 0.25$, and $m_{h_2} \in [123, 128]$ GeV with $R_{gg}^{h_2}(\gamma\gamma) > 1$. We refer to this as the “98 + 125 GeV Higgs scenario”. Points with $\Omega h^2 < 0.094$ are represented by blue circles and points with $\Omega h^2 \in [0.094, 0.136]$ (the “WMAP window”) are represented by red/orange diamonds.

Two distinct WMAP-window regions appear. The red region has $R_{gg}^{h_2}(\gamma\gamma) \sim 1.6$ and corresponds $\mu_{\text{eff}} \sim 120$ GeV and $\tan\beta \sim 2$; as can be seen in Fig. 5, it features a partly light spectrum with $m_{\tilde{t}_1} \sim 70 – 80$ GeV, $m_{\tilde{\chi}_1^0} \sim 105 – 110$ GeV and $m_{\tilde{l}_1} \sim 0.2 – 1$ TeV, while

2 Note that $R_{VBF}^{h_1}(b\bar{b})$ is equivalent to $R_{VBF}^{h_1}(b\bar{b})$ as relevant for LEP.
Figure 4. Signal strengths (relative to SM) $R_{VBF}^{h_1}(\bar{b}b)$ versus $R_{gg}^{h_2}(\gamma\gamma)$ for $m_{h_1} \in [96, 100]$ GeV and $m_{h_2} \in [123, 128]$ GeV in the semi-constrained NMSSM. Blue points have $\Omega h^2 < 0.094$ while red and orange points have $\Omega h^2 \in [0.094, 0.136]$. From [15].

Figure 5. Expectations for sparticle and Higgs masses in the 98 + 125 GeV Higgs scenario. Blue points have $\Omega h^2 < 0.094$ while red and orange points have $\Omega h^2 \in [0.094, 0.136]$. From [15].

$m_{\tilde{g}} \gtrsim 1$ TeV and $m_{\tilde{q}} \gtrsim 2$ TeV. Again, LHC SUSY limits are automatically avoided by the Higgs-sector requirements! Moreover, the other Higgses are light, too, $m_{a_2} \sim 150$ GeV and $m_{h_3} \simeq m_{H^\pm} \simeq m_{a_2} \sim 300 - 400$ GeV. The orange region is quite different. It appears at $\mu_{\text{eff}} \sim 200$ GeV and $\tan \beta \sim 5 - 8$ and has $R_{gg}^{h_2}(\gamma\gamma) \sim 1.1$. The overall mass scale is much heavier: $m_{n_1} \sim 90 - 150$ GeV and $m_{\tilde{t}} > 1.8$ TeV, see Fig. 5. Squarks and gluinos lie in the 3 - 5 TeV mass range, above the reach of the 14 TeV LHC. The heavy Higgses also have masses above 1 TeV, only the $a_1$ is still light with $m_{a_1} \lesssim 250$ GeV.

The LSP decomposition and its expected spin-independent scattering cross section off protons are shown in Fig. 6. The prospects to test the 98 + 125 GeV Higgs scenario at the LHC and a future ILC are discussed in detail in [15].
Figure 6. LSP higgsino component (left) and spin-independent scattering cross section (right) as function of the LSP mass for the 98 + 125 GeV Higgs scenarios. From [15].

5. Degenerate case: two Higgses hiding in the 125 GeV signal?
As mentioned, enhanced rates in the $\gamma\gamma$ channel arise in the NMSSM with large $\lambda$ when the $h_1$ and $h_2$ are sufficiently close in mass that one Higgs, $h_i$, “steals” (through mixing) some of the $b\bar{b}$ width of the other Higgs, $h_j$. The state with the enhanced $\gamma\gamma$ signal and mass near 125 GeV can be either the $h_1$ or the $h_2$. It is however also possible that $h_1$ and $h_2$ both lie in the 123–128 GeV mass window [16]. In this case, a second mechanism for large $\gamma\gamma$ rates emerges — namely both $h_1$ and $h_2$ contribute significantly and their summed rate is enhanced even though their individual rates are more or less at, or even somewhat below, the SM level.

Figure 7 shows the correlation of $gg \rightarrow (h_1, h_2) \rightarrow \gamma\gamma$ signal strengths in the semi-constrained NMSSM when both $h_1$ and $h_2$ lie in the 123–128 GeV mass range. We see that often one Higgs dominates the signal, but it is also possible that both have $R_{gg}(\gamma\gamma) \gtrsim 0.5$ thus giving a combined signal larger than 1.

To go a step further, we take the net signal in given production and decay channels $Y$ and $X$ to simply be $R_Y(X) = R_Y^{h_1}(X) + R_Y^{h_2}(X)$, and we define the resulting “effective” Higgs mass as

$$m_Y^X(X) = \frac{R_Y^{h_1}(X) m_{h_1} + R_Y^{h_2}(X) m_{h_2}}{R_Y^{h_1}(X) + R_Y^{h_2}(X)}.$$ (6)

Of course, the extent to which it is appropriate to combine the rates from the $h_1$ and $h_2$ depends upon the degree of degeneracy and the experimental resolution. It should be noted that the widths of the $h_1$ and $h_2$ are of the same order of magnitude as the width of a 125 GeV SM Higgs boson, i.e. they are very much smaller than this resolution.

In Fig. 8, we display in the left-hand plot the strong correlation between $R_{gg}^{h_1}(\gamma\gamma)$ and $R_{gg}^{h_2}(VV)$, $V = W, Z$. Note that if $R_{gg}^{h_i}(\gamma\gamma) \sim 1.5$, as suggested by current experimental results, then in this scenario $R_{gg}^{h_i}(VV) \gtrsim 1.2$.

The scenario again prefers small $\mu_{eff}$, which is very favorable in point of view of fine tuning, in particular if stops are also light. Indeed a good fraction of our points with degenerate $h_1, h_2$ and $R(\gamma\gamma) > 1$ features light stops with $m_{t_1} \in [300, 700]$ GeV and $M_{SUSY} = \sqrt{m_{t_1} m_{t_2}} \lesssim 1$ TeV. Because of the small $\mu_{eff}$, the LSP is dominantly a light higgsino. A relic density of $\Omega h^2 \simeq 0.1$ can be achieved for LSP masses just below 80 GeV, see the right-hand plot in Fig. 8. The LSP is 70–80% higgsino in this case, with order 20% singlino admixture. More details on the consequences for collider and dark matter phenomenology can be found in [16].
Figure 7. Correlation of $gg \rightarrow (h_1, h_2) \rightarrow \gamma \gamma$ signal strengths when both $h_1$ and $h_2$ lie in the 123–128 GeV mass range. Circular points have $\Omega h^2 < 0.094$, while diamond points have $0.094 \leq \Omega h^2 \leq 0.136$. Points are color coded according to $m_{h_2} - m_{h_1}$ as indicated on the figure. From [16].

Figure 8. Correlation between the $gg$ induced $\gamma \gamma$ and $VV$ signal strengths (left) and relic density $\Omega h^2$ versus LSP mass (right) for NMSSM points with quasi-degenerate $h_1$ and $h_2$ in the 123–128 GeV mass window. The green, blue and red points have $\Delta m = m_{h_2} - m_{h_1} = 2$–3 GeV, $\Delta m = 1$–2 GeV and $\Delta m \leq 1$ GeV, respectively. From [16].

6. Diagnosing degenerate Higgs bosons

Two or more degenerate Higgs bosons will in general have different relative production rates in the VBF and $gg$ fusion channels for one or more final states. In [17] we thus proposed double ratios of signal strengths as a useful diagnostic tool to reveal the existence of one or more quasi-degenerate (but non-interfering in the small width approximation) Higgs states. For models with Higgs doublets-singlets, the relevant double ratios are:

$$\text{I): } \frac{R^h_{VBF}(\gamma \gamma) / R^h_{gg}(\gamma \gamma)}{R^h_{VBF}(bb) / R^h_{gg}(bb)}, \quad \text{II): } \frac{R^h_{VBF}(\gamma \gamma) / R^h_{gg}(\gamma \gamma)}{R^h_{VBF}(WW) / R^h_{gg}(WW)}, \quad \text{III): } \frac{R^h_{VBF}(WW) / R^h_{gg}(WW)}{R^h_{VBF}(bb) / R^h_{gg}(bb)},$$

(7)

each of which should be unity if only a single Higgs boson is present but are generally expected to deviate from 1 if two (or more) Higgs bosons are contributing to the net Higgs signals. Values obtained in the semi-constrained NMSSM are shown in Fig. 9.

Acknowledgements

I wish to thank Genevieve Belanger, Beranger Dumont, Ulrich Ellwanger, John F. Gunion and Yun Jiang for a most fruitful and rewarding collaboration, and the organizers of KRUGER2012
Figure 9. Illustration of the double ratio I) of Eq. (7) for degenerate $h_1$ and $h_2$ in the 123–128 GeV mass range in the semi-constrained NMSSM. The green, blue and red points have $\Delta m = m_{h_2} - m_{h_1} = 2$–3 GeV, $\Delta m = 1$–2 GeV and $\Delta m \leq 1$ GeV, respectively. From [17].

for the invitation to this extraordinary conference. The work presented here was supported in part by IN2P3 under contract PICS FR–USA No. 5872 and by a PEPS-PTI grant “Physique Théorique et ses Interactions”.

References

[1] G. Aad et al. [ATLAS Collaboration], “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC,” Phys. Lett. B 716 (2012) 1 [arXiv:1207.7214 [hep-ex]].

[2] S. Chatrchyan et al. [CMS Collaboration], “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC,” Phys. Lett. B 716 (2012) 30 [arXiv:1207.7235 [hep-ex]].

[3] G. Cacciapaglia, A. Deandrea, G. D. La Rochelle and J. -B. Flament, “Higgs couplings beyond the Standard Model,” JHEP 1303 (2013) 102 [arXiv:1210.8120 [hep-ph]].

[4] G. Belanger, B. Dumont, U. Ellwanger, J. F. Gunion and S. Kraml, “Higgs Couplings at the End of 2012,” JHEP 1302 (2013) 053 [arXiv:1212.5244 [hep-ph]].

[5] A. Djouadi, “The Anatomy of electro-weak symmetry breaking. II. The Higgs bosons in the minimal supersymmetric model,” Phys. Rept. 459 (2008) 1 [hep-ph/0503173].

[6] F. Brummer, S. Kraml and S. Kulkarni, “Anatomy of maximal stop mixing in the MSSM,” JHEP 1208 (2012) 089 [arXiv:1204.5977 [hep-ph]].

[7] https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults.

[8] https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS.

[9] For a review, see e.g. U. Ellwanger, C. Hugonie and A. M. Teixeira, “The Next-to-Minimal Supersymmetric Standard Model,” Phys. Rept. 496 (2010) 1 [arXiv:0910.1785 [hep-ph]].

[10] J. F. Gunion, Y. Jiang and S. Kraml, “The Constrained NMSSM and Higgs near 125 GeV,” Phys. Lett. B 710 (2012) 454 [arXiv:1201.0982 [hep-ph]].

[11] U. Ellwanger, “Enhanced di-photon Higgs signal in the Next-to-Minimal Supersymmetric Standard Model,” Phys. Lett. B 698 (2011) 293 [arXiv:1012.1201 [hep-ph]].

[12] U. Ellwanger, “A Higgs boson near 125 GeV with enhanced di-photon signal in the NMSSM,” JHEP 1203 (2012) 044 [arXiv:1112.3548 [hep-ph]].

[13] U. Ellwanger and C. Hugonie, “Higgs bosons near 125 GeV in the NMSSM with constraints at the GUT scale,” Adv. High Energy Phys. 2012 (2012) 625389 [arXiv:1203.5048 [hep-ph]].

[14] http://www.th.u-psud.fr/HMDECYANMSSMROOTS.html.

[15] G. Belanger, U. Ellwanger, J. F. Gunion, Y. Jiang, S. Kraml and J. H. Schwarz, “Higgs Bosons at 98 and 125 GeV at LEP and the LHC,” JHEP 1301 (2013) 069 [arXiv:1210.1976 [hep-ph]].

[16] J. F. Gunion, Y. Jiang and S. Kraml, “Could two NMSSM Higgs bosons be present near 125 GeV?,” Phys. Rev. D 86 (2012) 071702 [arXiv:1207.1545 [hep-ph]].

[17] J. F. Gunion, Y. Jiang and S. Kraml, “Diagnosing Degenerate Higgs Bosons at 125 GeV,” Phys. Rev. Lett. 110 (2013) 051801 [arXiv:1208.1817 [hep-ph]].