Will at least one of the Higgs bosons of the next-to-minimal supersymmetric extension of the Standard Model be observable at LEP2 or the LHC?

John F. Gunion

Collaborators: Ellwanger + Hugonie

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THE MODEL

- MSSM + single field N.
- Superpotential contains usual except that $\mu \widehat{H}_1 \widehat{H}_2$ is replaced by $\lambda \widehat{N} \widehat{H}_1 \widehat{H}_2$.
- Perturbative limits on λ are crucial: $\lambda < .7$

Snowmass 96 report reviewed problem covering all of NMSSM
Detection modes considered there:

- 1) $Z^\star \to Zh$ at LEP2;
- 2) $Z^\star \to ha$ at LEP2;
- 3) $gg \to h \to \gamma\gamma$ at LHC;
- 4) $gg \to h \to ZZ^\star$ or $ZZ \to 4\ell$ at LHC;
- 5) $t \to H^+ b$ at LHC;
- 6) $gg \to b\bar{b}h, b\bar{b}a \to b\bar{b}\tau^+\tau^-$ at LHC;
- 7) $gg \to h, a \to \tau^+\tau^-$ at LHC.
- a) $a \to Zh$;
- b) $h \to aa$;
- c) $h_j \to h_i h_i$;

- d) $a, h \to t\bar{t}$.

Because of the more complicated Higgs self interactions, b) and c) cannot be reliably computed in the NMSSM without additional assumptions. The Higgs mass values for which mode a) is kinematically allowed can be quite different than those relevant to the MSSM and thus there are uncertainties in translating ATLAS and CMS results for the MSSM into the present more general context. Finally, mode d) might turn out to be either more effective or less effective than current estimates. Thus, to be conservative, we excluded from our considerations any choice of NMSSM parameters for which the modes a)-d) might be relevant.

1 Parameters and Scanning Procedure

In order to specify a point in NMSSM parameter space, we have adopted the following procedure.

- Employ a basis in which only the first neutral Higgs field has a vev: $\langle \phi_1 \rangle = v = 246\,\mathrm{GeV}$. In this basis, the $(11, 12, 21, 22)$ elements of the Higgs mass-squared matrix (denoted $\mathcal{M}^2$ below) take the simple form

$$\begin{pmatrix} m_Z^2 + m_{Z\lambda}^2 s_{2\beta}^2 + \delta_{11} & m_{Z\lambda}^2 s_{2\beta} c_{2\beta} + \delta_{12} \\ m_{Z\lambda}^2 s_{2\beta} c_{2\beta} + \delta_{12} & m_{PP}^2 - m_{Z\lambda}^2 s_{2\beta}^2 + \delta_{22} \end{pmatrix} \tag{1}$$

  where λ appears in the superpotential in the term $W \ni \lambda \hat{H}_1 \hat{H}_2 \hat{N}$, $m_{Z\lambda}^2 \equiv \frac{1}{2}\lambda^2 v^2 - m_Z^2$, and $\delta_{11,12,22}$ are the radiative corrections[1] (which are independent of λ and m_{PP}, but depend on $\tan\beta$ and m_t — we take $m_t = 175\,\mathrm{GeV}$). We note that there are enough parameters in the NMSSM model superpotential and soft-supersymmetry-breaking terms that the $\mathcal{M}^2_{13,23,33}$ entries can have arbitrary values. (Specific Planck scale boundary conditions could restrict these latter $\mathcal{M}^2$ entries and thereby impose restrictions on the allowed parameter space beyond those described below; such boundary conditions will not be imposed here.)

[1] These have been computed following the two-loop procedures of Haber etal.

- Pick a value for $\tan\beta$ and a value for $m_{h_1} \leq m_{h_1}^{\rm max}$, where $m_{h_1}^{\rm max} = \mathcal{M}_{11}(\lambda = \lambda_{\rm max})$. The crucial ingredient in limiting the scan is the upper limit of $\lambda_{\rm max} = 0.7$, obtained by requiring that λ remain perturbative during evolution from scale m_Z to the Planck scale.

- Pick values for the angles $-\pi/2 \leq \alpha_1 \leq +\pi/2$, $0 \leq \alpha_2 \leq 2\pi$, and $0 \leq \alpha_3 \leq \pi/2$ that appear in the matrix V which diagonalizes the CP-even Higgs mass-squared matrix via $V^\dagger \mathcal{M}^2 V = {\rm diag}(m_{h_1}^2, m_{h_2}^2, m_{h_3}^2)$:

$$V = \begin{pmatrix} c_1 & -s_1 c_3 & -s_1 s_3 \\ s_1 c_2 & c_1 c_2 c_3 - s_2 s_3 & c_1 c_2 s_3 + s_2 c_3 \\ s_1 s_2 & c_1 s_2 c_3 + c_2 s_3 & c_1 s_2 s_3 - c_2 c_3 \end{pmatrix} \tag{2}$$

where $c_1 = \cos\alpha_1$, and so forth. It is useful to note that

$$m_{h_2}^2 \leq \frac{[m_{h_1}^{\rm max}]^2 - V_{11}^2 m_{h_1}^2}{1 - V_{11}^2} \tag{3}$$

$$m_{h_3}^2 \leq \frac{[m_{h_1}^{\rm max}]^2 - V_{11}^2 m_{h_1}^2 - V_{12}^2 m_{h_2}^2}{1 - V_{11}^2 - V_{12}^2} . \tag{4}$$

- Pick a value $\lambda_{\rm min} \leq \lambda \leq \lambda_{\rm max}$, and compute

$$\begin{aligned} m_{h_2}^2 &= \frac{V_{13}\mathcal{M}_{12}^2 - V_{23}\mathcal{M}_{11}^2 - m_{h_1}^2 V_{11}(V_{21}V_{13} - V_{23}V_{11})}{V_{12}(V_{22}V_{13} - V_{23}V_{12})} , \\ m_{h_3}^2 &= \frac{V_{12}\mathcal{M}_{12}^2 - V_{22}\mathcal{M}_{11}^2 - m_{h_1}^2 V_{11}(V_{21}V_{12} - V_{22}V_{11})}{V_{13}(V_{23}V_{12} - V_{22}V_{13})} , \\ m_{PP}^2 &= \Sigma_{i=1,2,3} V_{2i}^2 m_{h_i}^2 + m_{Z\lambda}^2 s_{2\beta}^2 - \delta_{22} , \\ m_{H^+}^2 &= m_{PP}^2 - m_{Z\lambda}^2 . \end{aligned}$$

The lower limit on λ is given by

$$\lambda_{\rm min}^2 v^2 = 2\left[\frac{m_{h_1}^2 - \delta_{11} - m_Z^2}{s_{2\beta}} + m_Z^2\right] , \tag{5}$$

which is obtained by noting that $m_{h_1}^2 \leq \mathcal{M}_{11}^2$. If $\lambda_{\rm min}^2 < 0$ then use $\lambda_{\rm min} = 0$. It is consistent to consider only those α_i, λ values such that $m_{h_3}^2 \geq m_{h_2}^2 \geq m_{h_1}^2$. Further restrictions are imposed on the $m_{h_i}^2$ as follows.

– First, we require that $m_{h_3} \leq 2m_{h_1}$, in which case the decays $h_2 \to h_1h_1$, $h_3 \to h_1h_1$ and $h_3 \to h_2h_2$ are all kinematically disallowed. (If kinematically allowed, such decays are model dependent and could be dominant; their experimental accessibility would have to be evaluated.)

– Second, we require that $m_{h_3} \leq 2m_t$ so that the decays $h_{1,2,3} \to t\bar{t}$ are forbidden.

- The CP-odd mass-squared matrix takes the form

$$\mathcal{N}^2 = \begin{pmatrix} m_{PP}^2 & \cdot \\ \cdot & \cdot \end{pmatrix}, \tag{6}$$

where the unspecified entries may take on any value given the parameter freedom of the model. For simplicity, we assume that only one CP-odd scalar, the a (which must have $m_a^2 \leq m_{PP}^2$), is possibly light and that the other is heavy and, therefore, unobservable. In principle, we could scan $0 \leq m_a \leq m_{PP}$. However, we impose three additional restrictions on m_a as follows.

– In order to avoid the presence of the model-dependent, possibly dominant $h_{1,2,3} \to aa$ decays, we restrict the scan to $m_a \geq m_{h_3}/2$. In particular, this implies that no m_a scan is possible if $m_{PP} \leq m_{h_3}/2$.

– We require $m_a \leq 2m_t$, so that $a \to t\bar{t}$ decays are forbidden;

– We require $m_a \leq m_Z + m_{h_1}$, which implies that the model-dependent decays $a \to Zh_{1,2,3}$ are absent.

We emphasize that there may be parameter choices, for which no Higgs bosons of the NMSSM are observable, that lie outside the restricted portion of parameter space that we search.

Couplings

In order to assess the observability of modes 1)-7) we need the couplings of the $h_{1,2,3}$ and a. Those required are:

$$ZZh_i, WWh_i : [\frac{gm_Z}{c_W}, gm_W]V_{1i} \tag{7}$$

$$Zh_ia : \frac{g}{2c_W}V_{2i} \tag{8}$$

$$t\bar{t}h_i : \frac{gm_t}{2m_W}(V_{1i} + V_{2i}\cot\beta) \tag{9}$$

$$b\bar{b}h_i : \frac{gm_b}{2m_W}(V_{1i} - V_{2i}\tan\beta) \tag{10}$$

$$t\bar{t}a, b\bar{b}a : \frac{gm_t}{2m_W}\cot\beta, \quad \frac{gm_b}{2m_W}\tan\beta \tag{11}$$

Procedures

- As already noted, we do not search parameter regions in which the very model-dependent Higgs self-couplings would be needed.
- For the LHC modes 3)-7), we require 5σ statistical significance for $L = 600\ \mathrm{fb}^{-1}$.
- We performed various rescalings etc. to go from SM and MSSM results of ATLAS and CMS to the NMSSM.
- If none of the Higgs bosons $h_{1,2,3}$, a or $H^\pm$ are observable as defined above we declare a parameter point in our search to be a "point of unobservability" or a "bad point".

RESULTS

- We found that if $\tan\beta \lesssim 1.5$ then all parameter points that are included in our search are observable for m_{h_1} values up to the maximum allowed ($m_{h_1}^{\max} \sim 137\,\mathrm{GeV}$ for $\lambda_{\max} = 0.7$, after including radiative corrections). For such low $\tan\beta$, the LHC $\gamma\gamma$ and 4ℓ modes allow detection if LEP2 does not.
- For high $\tan\beta \gtrsim 10$, the parameter regions where points of unobservability are found are also of very limited extent, disappearing as the $b\bar{b}h_{1,2,3}$ and/or $b\bar{b}a$ LHC modes allow detection where LEP2 does not.
- However, we found that significant portions of searched parameter space contained points of unobservability for moderate $\tan\beta$ values.

- That such $\tan\beta$ values should be the most 'dangerous' can be anticipated from the MSSM wedge where only the h^0 is detectable mainly using $\gamma\gamma$ decay mode.
- By choosing m_{h_1} and m_a in the NMSSM so that $m_{h_1}+m_Z$ and $m_{h_1}+m_a$ are close to or above the $\sqrt{s}$ of LEP2, then at moderate $\tan\beta$ we would need to rely on the $h_{1,2,3}\to\gamma\gamma$ modes.
- However, in the NMSSM, parameter choices are possible for which all the $WWh_{1,2,3}$ couplings are reduced relative to SM strength. This reduction will suppress the $\gamma\gamma$ couplings coming from the W-boson loop. All the $h_i\to\gamma\gamma$ widths can be sufficiently smaller than the somewhat enhanced $b\overline{b}$ widths so that the $\gamma\gamma$ branching ratios are *all* no longer of useful size.
- **Modes with $h_{1,2,3}\to b\overline{b}$ will be crucial** These were not available at Snowmass 96!

A typical result before doing so is the $\tan\beta=5$, $m_{h_1}=105\,\mathrm{GeV}$ plot shown below.

The most 'dangerous' region is $\alpha_3\sim 0$ and $\alpha_1\neq 0,\pm\pi/2$, for which $m_{h_2}\sim m_{h_1}$ so that both h_2 and h_1 would have to be found in the $\gamma\gamma$ If the value of α_2 is such that neither s_2 nor c_2 is small, then both V_{21} and V_{22} can be substantial, and the $\gamma\gamma$ mode can be suppressed for both $h=h_1$ and $h=h_2$ by a combination of WWh coupling suppression, $t\bar{t}h$ coupling suppression (to diminish $gg\to h$ production) and $b\bar{b}h$ coupling enhancement (as natural for moderate or large $\tan\beta$). The latter enhances the $b\overline{b}$ partial width and diminishes the $h\to\gamma\gamma$ branching ratio. The moderate $\tan\beta\sim 5$ value makes it possible to have the required $b\bar{b}h$ coupling enhancement without it being so large as to make the $h\to\tau^+\tau^-$ mode observable in $b\bar{b}h$ production.

A Sample Point

For $\tan\beta=5$ and $m_{h_1}=105\,\mathrm{GeV}$, no Higgs boson can be observed for $m_a=103\,\mathrm{GeV}$ if $\alpha_1=-0.479$, $\alpha_2=0.911$, $\alpha_3=0.165$, and $\lambda=0.294$. At this point:

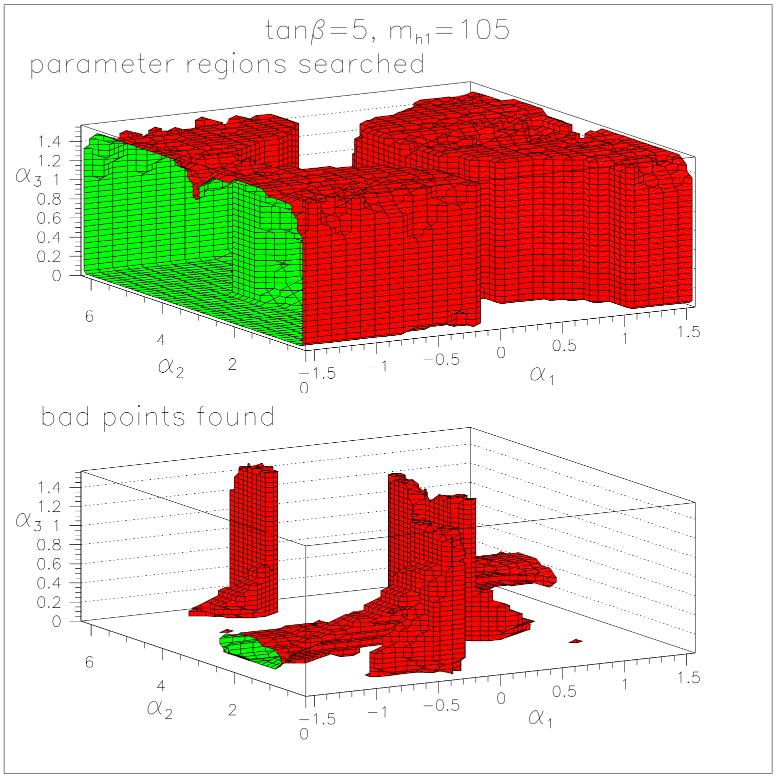

Figure 1: For $\tan\beta = 5$ and $m_{h_1} = 105\,\mathrm{GeV}$, we display in three dimensional $(\alpha_1, \alpha_2, \alpha_3)$ parameter space the parameter regions searched (which lie within the surfaces shown), and the regions therein for which the remaining model parameters can be chosen so that no Higgs boson is observable (interior to the surfaces shown).

- $m_{h_2} = 124\,\mathrm{GeV}$,
- $m_{h_3} = 206\,\mathrm{GeV}$,
- $m_{H^+} = 201\,\mathrm{GeV}$.

The corresponding V matrix entries are:

$$V = \begin{pmatrix} 0.887 & 0.455 & 0.0757 \\ -0.283 & 0.407 & 0.869 \\ -0.364 & 0.792 & -0.490 \end{pmatrix}. \qquad (12)$$

From the V_{ij}, and the value of $\tan\beta$, we compute (relative to the SM values)

$$\begin{array}{ccc} (VVh_1)^2 = 0.79 & (VVh_2)^2 = 0.21 & (VVh_3)^2 = 0.006 \\ (b\bar{b}h_1)^2 = 5.3 & (b\bar{b}h_2)^2 = 2.5 & (b\bar{b}h_3)^2 = 18 \\ (t\bar{t}h_1)^2 = 0.69 & (t\bar{t}h_2)^2 = 0.29 & (t\bar{t}h_3)^2 = 0.062 \end{array}$$

where $V = W$ or Z. Note that h_3 has very small couplings to VV. The manner in which this point escapes discovery is now apparent.

- First, the minimum values required for the $(b\bar{b}h_i)^2$ values for h_i observability in the $\tau^+\tau^-$ mode are: 53 ($i = 1$); 32 ($i = 2$); 35 ($i = 3$). The actual values all lie below those required.
- Observation of the a at $m_a = 103\,\mathrm{GeV}$ (without adding in the much smaller overlapping h_1 signal) would require $\tan\beta = 8$.
- h_1 and h_2 are both in the mass range for which the $\gamma\gamma$ mode is potentially viable and the h_3 is potentially detectable in the $ZZ \to 4\ell$ channel.

  However, the suppressed $t\bar{t}h_{1,2,3}$ couplings imply smallish gg production rates for $h_{1,2,3}$. Relative to a SM Higgs of the same mass we have:

$$\frac{(ggh_i)^2}{(ggh_{SM})^2} = 0.58\ (i = 1); \quad 0.43\ (i = 2); \quad 0.15\ (i = 3)\,. \qquad (13)$$

  (Note that these strengths are not simply the $(t\bar{t}h_i)^2$ magnitudes due to enhanced b-quark loop contributions which interfere with the t-quark loop contributions at amplitude level.)

  Further, the enhanced Higgs decay rate to $b\bar{b}$ and the reduced W-loop contributions to the $\gamma\gamma$ coupling suppress the $\gamma\gamma$ branching ratios of h_1 and h_2 relative to SM expectations. We find:

$$\frac{B(h_i \to \gamma\gamma)}{B(h_{SM} \to \gamma\gamma)} = 0.18\ (i = 1)\,; \quad 0.097\ (i = 2)\,; \qquad (14)$$

  i.e. suppression sufficient to make h_1 and h_2 invisible in the $\gamma\gamma$ mode. The suppressed ZZh_3 coupling and the enhanced $h_3 \to b\bar{b}$ decays are sufficient to suppress $B(h_3 \to ZZ)$ much below SM expectations:

$$\frac{B(h_3 \to ZZ)}{B(h_{SM} \to ZZ)} = 0.11\,, \qquad (15)$$

  i.e. such that the 4ℓ signal has a significance of only 1.5σ, even though a SM Higgs of this mass would yield a $\sim 37\sigma$ signal.

In short, there is enough flexibility due to the addition of the singlet Higgs field (which has no couplings to SM fermions and vector bosons!) for *all* the Higgs bosons to escape the non $b\overline{b}$ final state decay channels for certain choices of model parameters, provided $\tan\beta$ is moderate in size.
Moderate $\tan\beta$ implies that $h \to \gamma\gamma$ decays for light Higgs are suppressed, while at the same time $b\overline{b}h$ production is not adequately enhanced for detection of the $h \to \tau^+\tau^-$ mode.

Adding in the $t\bar{t}h \to t\bar{t}b\bar{b}$ channel: Sapinski ATLAS analysis

In detail the $S/\sqrt{B}$ values for various channels for the above point are (for h_1, h_2, h_2 in order):

- $\gamma\gamma$ inclusive: 1.649; 0.85; 0.
- $ZZ^\star \to 4\ell$: 0.; 0.825; 1.547.
- $\gamma\gamma$ + jet: 0.99; 0.26; 0.
- $WW^\star \to$ various: 0.: 1.26; 0.905.
- $t\bar{t}b\bar{b}$: **10.86**; 2.81; 0.

The $t\bar{t}b\bar{b}$ mode saves the day!!!!!
I did full scan last night for $\tan\beta = 5$ and $m_{h_1} = 105$ and found no points and parameter choices for which no Higgs would be discovered at the LHC with $L = 600$ fb^{-1}.

FINAL REMARK

SUSY decay modes of the Higgs bosons were neglected. If these decays are important, the regions of unobservability found without using the SUSY final states will increase in size. However, Higgs masses in the regions of unobservability are typically modest in size ($100 - 200\,\mathrm{GeV}$), and as SUSY mass limits increase this additional concern will become less relevant. Of course, if SUSY decays are significant, detection of the Higgs bosons in the SUSY modes might be possible, in which case the regions of unobservability might decrease in size.