News from The NMSSM and Beyond

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News from the NMSSM and Beyond

- General Conditions for CP Violation in 2HDM
- NMSSM Naturalness Issues
- NMSSM Baryogenesis
- NMHDECAY
- NMSSM LHC and LC Phenomenology
- Models with extra $U(1)$

MSSM problems:

- The MSSM is being pushed into parameter regions characterized by substantial fine tuning and a "little" hierarchy problem (i.e. large stop masses) in order to have a heavy enough Higgs boson for consistency with LEP limits.

- A strong phase transition for baryogenesis is hard to arrange when the Higgs is heavy and the stops are heavy.

- No really attractive explanation for the μ parameter has emerged.

One can marginally escape all but the last of these problems if significant Higgs sector CP violation is introduced through SUSY loops. However, I will propose that it is time to adopt the NMSSM [18] as the baseline supersymmetric model.

The NMSSM phenomenology is considerably richer than that of the MSSM in many important ways. The focus here is on Higgs physics.

However, I will begin with a brief discussion of 2HDM CP violation.

References

[1] G.C. Branco, L. Lavoura and J.P. Silva, *CP Violation* (Oxford University Press, Oxford, England, 1999), chapters 22 and 23.

[2] L. Lavoura and J.P. Silva, Phys. Rev. D50, 4619 (1994); F.J. Botella and J.P. Silva, Phys. Rev. D51, 3870 (1995).

[3] I. F. Ginzburg and M. Krawczyk, arXiv:hep-ph/0408011.

[4] H. P. Nilles, M. Srednicki and D. Wyler, Phys. Lett. B 120 (1983) 346.
J. M. Frere, D. R. T. Jones and S. Raby, Nucl. Phys. B 222 (1983) 11.

J. P. Derendinger and C. A. Savoy, Nucl. Phys. B 237 (1984) 307.

J. R. Ellis, J. F. Gunion, H. E. Haber, L. Roszkowski and F. Zwirner, Phys. Rev. D 39 (1989) 844.

M. Drees, Int. J. Mod. Phys. A 4 (1989) 3635.

U. Ellwanger, M. Rausch de Traubenberg and C. A. Savoy, Phys. Lett. B 315 (1993) 331 [arXiv:hep-ph/9307322], and Nucl. Phys. B 492 (1997) 21 [arXiv:hep-ph/9611251],

S. F. King and P. L. White, Phys. Rev. D 52 (1995) 4183 [arXiv:hep-ph/9505326].

F. Franke and H. Fraas, Int. J. Mod. Phys. A 12 (1997) 479 [arXiv:hep-ph/9512366].

[5] M. Bastero-Gil, C. Hugonie, S. F. King, D. P. Roy and S. Vempati, Phys. Lett. B 489 (2000) 359 [arXiv:hep-ph/0006198].

[6] S. F. King and P. L. White, Phys. Rev. D 52, 4183 (1995) [arXiv:hep-ph/9505326].

[7] S. A. Abel, S. Sarkar and P. L. White, Nucl. Phys. B 454 (1995) 663 [arXiv:hep-ph/9506359].

[8] S. A. Abel, Nucl. Phys. B 480 (1996) 55 [arXiv:hep-ph/9609323],

C. Panagiotakopoulos and K. Tamvakis, Phys. Lett. B 446 (1999) 224 [arXiv:hep-ph/9809475].

[9] H. P. Nilles, M. Srednicki and D. Wyler, Phys. Lett. B 124 (1983) 337,

U. Ellwanger, Phys. Lett. B 133 (1983) 187,

J. Bagger and E. Poppitz, Phys. Rev. Lett. 71 (1993) 2380 [arXiv:hep-ph/9307317],

J. Bagger, E. Poppitz and L. Randall, Nucl. Phys. B 455 (1995) 59 [arXiv:hep-ph/9505244].

[10] U. Ellwanger, Phys. Lett. B 303 (1993) 271 [arXiv:hep-ph/9302224].

[11] P. N. Pandita, Phys. Lett. B 318 (1993) 338,
T. Elliott, S. F. King and P. L. White, Phys. Rev. D 49 (1994) 2435 [arXiv:hep-ph/9308309],

[12] J. i. Kamoshita, Y. Okada and M. Tanaka, Phys. Lett. B 328 (1994) 67 [arXiv:hep-ph/9402278],
U. Ellwanger, M. Rausch de Traubenberg and C. A. Savoy, Z. Phys. C 67 (1995) 665 [arXiv:hep-ph/9502206],
S. F. King and P. L. White, Phys. Rev. D 53 (1996) 4049 [arXiv:hep-ph/9508346],
S. W. Ham, S. K. Oh and B. R. Kim, J. Phys. G 22 (1996) 1575 [arXiv:hep-ph/9604243],
D. J. Miller, R. Nevzorov and P. M. Zerwas, Nucl. Phys. B 681 (2004) 3 [arXiv:hep-ph/0304049],
G. Hiller, arXiv:hep-ph/0404220.

[13] U. Ellwanger, J. F. Gunion, C. Hugonie and S. Moretti, "NMSSM Higgs discovery at the LHC," arXiv:hep-ph/0401228, and "Towards a no-lose theorem for NMSSM Higgs discovery at the LHC," arXiv:hep-ph/0305109.

[14] D. J. Miller and S. Moretti, "An interesting NMSSM scenario at the LHC and LC," arXiv:hep-ph/0403137.

[15] G. K. Yeghian, "Upper bound on the lightest Higgs mass in supersymmetric theories," arXiv:hep-ph/9904488.

[16] U. Ellwanger and C. Hugonie, Eur. Phys. J. C 25 (2002) 297 [arXiv:hep-ph/9909260].

[17] U. Ellwanger, J. F. Gunion and C. Hugonie, arXiv:hep-ph/0406215.

[18] J. R. Ellis, J. F. Gunion, H. E. Haber, L. Roszkowski and F. Zwirner, Phys. Rev. D 39, 844 (1989).

[19] G.L. Kane and S.F. King, Phys. Lett. B451 (1999) 113.
See also: S. Dimopoulos and G.F. Giudice, Phys. Lett. B357 (1995) 573; P.H. Chankowski, J. Ellis, S. Pokorski, Phys. Lett. B423 (1998) 327; P.H. Chankowski, J. Ellis, M. Olechowski, S. Pokorski, Nucl. Phys. B544 (1999) 39.

[20] A. Menon, D. E. Morrissey and C. E. M. Wagner, Phys. Rev. D 70, 035005 (2004) [arXiv:hep-ph/0404184].

[21] S. J. Huber and M. G. Schmidt, Nucl. Phys. B 606, 183 (2001) [arXiv:hep-ph/0003122].

[22] J. F. Gunion, H. E. Haber and T. Moroi, arXiv:hep-ph/9610337.

[23] J. Dai, J. F. Gunion and R. Vega, Phys. Rev. Lett. 71, 2699 (1993) [arXiv:hep-ph/9306271].

[24] J. Dai, J. F. Gunion and R. Vega, Phys. Lett. B 345, 29 (1995) [arXiv:hep-ph/9403362].

[25] D. L. Rainwater and D. Zeppenfeld, Phys. Rev. D 60, 113004 (1999) [Erratum-ibid. D 61, 099901 (2000)] [arXiv:hep-ph/9906218].

[26] T. Plehn, D. L. Rainwater and D. Zeppenfeld, Phys. Lett. B 454, 297 (1999) [arXiv:hep-ph/9902434].

[27] D. L. Rainwater, D. Zeppenfeld and K. Hagiwara, Phys. Rev. D 59, 014037 (1999) [arXiv:hep-ph/9808468].

[28] B. A. Dobrescu, G. Landsberg and K. T. Matchev, Phys. Rev. D 63, 075003 (2001) [arXiv:hep-ph/0005308].

[29] U. Ellwanger, J. F. Gunion and C. Hugonie, arXiv:hep-ph/0111179.

[30] U. Ellwanger, J. F. Gunion, C. Hugonie and S. Moretti, arXiv:hep-ph/0305109.

[31] J. F. Gunion and M. Szleper, arXiv:hep-ph/0409208.

2HDM CP Violation

with H. Haber

Consider the most general two-Higgs doublet extension of the Standard Model (2HDM). Let Φ_1 and Φ_2 denote two complex $Y = 1$, SU(2)$_L$ doublet scalar fields. The most general SU(2)$_L\times$U(1)$_Y$ invariant scalar potential is given by

$$\begin{aligned}
\mathcal{V} &= m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - [m_{12}^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}] \\
&\quad +\frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\
&\quad +\left\{\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \left[\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)\right]\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}\right\} ,
\end{aligned} \tag{1}$$

where m_{11}^2, m_{22}^2, and $\lambda_1, \cdots, \lambda_4$ are real parameters and m_{12}^2, λ_5, λ_6 and λ_7 are potentially complex parameters. We assume that the parameters of the scalar potential are chosen such that the minimum of the scalar potential respects the U(1)$_{\mathrm{EM}}$ gauge symmetry. Then, the scalar field vacuum expectations values are of the form

$$\langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \qquad \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2\, e^{i\xi} \end{pmatrix}, \tag{2}$$

where v_1 and v_2 are real and non-negative, $0 \leq |\xi| \leq \pi$, and

$$v^2 \equiv v_1^2 + v_2^2 = \frac{4m_W^2}{g^2} = (246 \text{ GeV})^2 \,. \tag{3}$$

In writing eq. (2), we have used a global U(1)$_Y$ hypercharge rotation to eliminate the phase of v_1.

We consider the necessary and sufficient conditions for explicit CP-invariance of the 2HDM scalar potential given in eq. (1).

These conditions correspond to the requirement that there exists a basis choice for the scalar fields for which all the parameters of the scalar potential are simultaneously real. In our approach to this issue we have been influenced by the work of refs. [1] and [2].

One procedure for determining if such a basis exists is to look at all new bases obtained from the original one by rotating the fields according to $\Phi'_a = U_{a\bar{b}}\Phi_b$, where U is a U(2) matrix:

$$U = e^{i\psi} \begin{pmatrix} \cos\theta & e^{-i\xi}\sin\theta \\ -e^{i\chi}\sin\theta & e^{i(\chi-\xi)}\cos\theta \end{pmatrix} , \tag{4}$$

and the indices a and b can take on two possible values (1 and 2). (Such transformations and their uses have been independently introduced recently in [3].) With respect to this new basis, the scalar potential takes on the same form given in eq. (1) but with new coefficients m'^2_{ij} and λ'_j. If there exists a U(2) matrix such that the m'^2_{ij} and λ'_j are all real, then the scalar potential is explicitly CP-conserving. (Spontaneous CP violation could still occur.) In general, to find if such a rotation exists is an extremely arduous task.

We write the scalar Higgs potential of the 2HDM in a manner that explicitly reflects these possible rotations.

$$\mathcal{V} = Y_{a\bar{b}}\Phi^\dagger_{\bar{a}}\Phi_b + \frac{1}{2}Z_{a\bar{b}c\bar{d}}(\Phi^\dagger_{\bar{a}}\Phi_b)(\Phi^\dagger_{\bar{c}}\Phi_d)\,, \tag{5}$$

where the indices a, $\bar{b}$, c and $\bar{d}$ run over the two-dimensional Higgs flavor space and

$$Z_{a\bar{b}c\bar{d}} = Z_{c\bar{d}a\bar{b}}\,. \tag{6}$$

Hermiticity of V implies that

$$Y_{a\bar{b}} = (Y_{b\bar{a}})^*\,, \qquad Z_{a\bar{b}c\bar{d}} = (Z_{b\bar{a}d\bar{c}})^*\,. \tag{7}$$

Under a U(2) transformation $\Phi_a \to U_{a\bar{b}}\Phi_b$ (and $\Phi^\dagger_{\bar{a}} \to \Phi^\dagger_{\bar{b}}U^\dagger_{b\bar{a}}$), where $U^\dagger_{b\bar{a}}U_{a\bar{c}} = \delta_{b\bar{c}}$, and the tensors Y and Z transform covariantly: $Y_{a\bar{b}} \to$

$U_{a\bar{c}}Y_{c\bar{d}}U^\dagger_{d\bar{b}}$ and $Z_{a\bar{b}c\bar{d}} \rightarrow U_{a\bar{e}}U^\dagger_{f\bar{b}}U_{c\bar{g}}U^\dagger_{h\bar{d}}Z_{e\bar{f}g\bar{h}}$. The use of barred indices is convenient for keeping track of which indices transform with U and which transform with $U^\dagger$. We also introduce the U(2)-invariant tensor $\delta_{a\bar{b}}$, which can be used to contract indices. In this notation, one can only contract an unbarred index against a barred index. For example,

$$Z^{(1)}_{a\bar{d}} \equiv \delta_{b\bar{c}}Z_{a\bar{b}c\bar{d}} = Z_{a\bar{b}b\bar{d}}\,, \qquad Z^{(2)}_{c\bar{d}} \equiv \delta_{b\bar{a}}Z_{a\bar{b}c\bar{d}} = Z_{a\bar{a}c\bar{d}}\,. \tag{8}$$

With respect to the basis of the unprimed scalar fields, we have:

$$\begin{aligned} Y_{11} &= m^2_{11}\,, & Y_{12} &= -m^2_{12}\,, \\ Y_{21} &= -(m^2_{12})^*\,, & Y_{22} &= m^2_{22}\,, \end{aligned} \tag{9}$$

and

$$\begin{aligned}
&Z_{1111} = \lambda_1\,, && Z_{2222} = \lambda_2\,, \\
&Z_{1122} = Z_{2211} = \lambda_3\,, && Z_{1221} = Z_{2112} = \lambda_4\,, \\
&Z_{1212} = \lambda_5\,, && Z_{2121} = \lambda_5^*\,, \\
&Z_{1112} = Z_{1211} = \lambda_6\,, && Z_{1121} = Z_{2111} = \lambda_6^*\,, \\
&Z_{2212} = Z_{1222} = \lambda_7\,, && Z_{2221} = Z_{2122} = \lambda_7^*\,.
\end{aligned} \tag{10}$$

For ease of notation, we have omitted the bars from the barred indices in eqs. (9) and (10).

Since the tensors $Y_{a\bar{b}}$ and $Z_{a\bar{b}c\bar{d}}$ exhibit tensorial properties with respect to global U(2) rotations in the Higgs flavor space, one can easily construct invariants with respect to the U(2) by forming U(2)-scalar quantities.

- The scalar potential is CP-conserving if and only if *all* possible U(2)-invariant scalars are manifestly real.

- Conversely, if the scalar potential explicitly violates CP, then there must exist at least one manifestly complex U(2)-scalar invariant.

- **We shall exhibit the simplest set of potentially complex U(2)-scalar invariants that can be employed to test for explicit CP-invariance or non-invariance of the scalar potential.**

- **As opposed to the work of refs. [1] and [2], our formalism avoids having to first figure out what the vacuum state is. One need only have in hand the potential parameters themselves, as presumably obtained in some particular model.**

Theorem: The necessary and sufficient conditions for an explicitly CP-conserving 2HDM scalar potential consist of the (simultaneous) vanishing of four potentially complex invariants:

$$I_{Y3Z} \equiv \mathrm{Im}(Z^{(1)}_{a\bar{c}} Z^{(1)}_{e\bar{b}} Z_{b\bar{e}c\bar{d}} Y_{d\bar{a}})\,, \tag{11}$$

$$I_{2Y2Z} \equiv \mathrm{Im}(Y_{a\bar{b}} Y_{c\bar{d}} Z_{b\bar{a}d\bar{f}} Z^{(1)}_{f\bar{c}})\,, \tag{12}$$

$$I_{6Z} \equiv \mathrm{Im}(Z_{a\bar{b}c\bar{d}} Z^{(1)}_{b\bar{f}} Z^{(1)}_{d\bar{h}} Z_{f\bar{a}j\bar{k}} Z_{k\bar{j}m\bar{n}} Z_{n\bar{m}h\bar{c}})\,, \tag{13}$$

$$I_{3Y3Z} \equiv \mathrm{Im}(Z_{a\bar{c}b\bar{d}} Z_{c\bar{e}d\bar{g}} Z_{e\bar{h}f\bar{q}} Y_{g\bar{a}} Y_{h\bar{b}} Y_{q\bar{f}})\,. \tag{14}$$

The proof of this theorem is fairly involved.

Explicit forms for these potentially non-zero imaginary parts of invariants in a general basis are as follows.

$$
\begin{aligned}
I_{Y3Z} &\equiv \mathrm{Im}(Z^{(1)}_{a\bar{c}} Z^{(1)}_{e\bar{b}} Z_{b\bar{e}c\bar{d}} Y_{d\bar{a}}) \\
&= 2(|\lambda_6|^2 - |\lambda_7|^2)\mathrm{Im}[Y_{12}(\lambda_6^* + \lambda_7^*)] + (\lambda_1 - \lambda_2)\big[\mathrm{Im}(Y_{12}\Lambda^*) - \mathrm{Im}[Y_{12}\lambda_5^*(\lambda_6 + \lambda_7)]\big] \\
&\quad +(Y_{11} - Y_{22})\big[\mathrm{Im}[\lambda_5^*(\lambda_6 + \lambda_7)^2] - (\lambda_1 - \lambda_2)\mathrm{Im}(\lambda_7^*\lambda_6)\big] \,, \qquad (15)
\end{aligned}
$$

where

$$
\Lambda \equiv (\lambda_2 - \lambda_3 - \lambda_4)\lambda_6 + (\lambda_1 - \lambda_3 - \lambda_4)\lambda_7 \,. \qquad (16)
$$

$$
\begin{aligned}
I_{2Y2Z} &\equiv \mathrm{Im}(Y_{a\bar{b}} Y_{c\bar{d}} Z_{b\bar{a}d\bar{f}} Z^{(1)}_{f\bar{c}}) \\
&= (\lambda_1 - \lambda_2)\mathrm{Im}(Y_{12}^2\lambda_5^*) - (Y_{11} - Y_{22})\Big[\mathrm{Im}(Y_{12}\Lambda^*) + \mathrm{Im}(Y_{12}\lambda_5^*(\lambda_6 + \lambda_7))\Big] \\
&\quad -\mathrm{Im}[(Y_{12}\lambda_6^*)^2] + \mathrm{Im}[(Y_{12}\lambda_7^*)^2] + \Big[(Y_{11} - Y_{22})^2 - 2|Y_{12}|^2\Big]\mathrm{Im}(\lambda_7^*\lambda_6) \,. \qquad (17)
\end{aligned}
$$

$$
\begin{aligned}
I_{6Z} \equiv\ & \mathrm{Im}(Z_{a\bar{b}c\bar{d}} Z^{(1)}_{b\bar{f}} Z^{(1)}_{d\bar{h}} Z_{f\bar{a}j\bar{k}} Z_{k\bar{j}m\bar{n}} Z_{n\bar{m}h\bar{c}}) \\
=\ & 2|\lambda_5|^2 \mathrm{Im}[(\lambda_7^*\lambda_6)^2] - \mathrm{Im}[\lambda_5^{*\,2}(\lambda_6-\lambda_7)(\lambda_6+\lambda_7)^3] + (\lambda_1-\lambda_2)|\lambda_5|^2\mathrm{Im}[\lambda_5^*(\lambda_6+\lambda_7)^2] \\
& +2\mathrm{Im}(\lambda_7^*\lambda_6)\Big[|\lambda_5|^2[|\lambda_6|^2+|\lambda_7|^2-(\lambda_1-\lambda_2)^2] - 2(|\lambda_6|^2-|\lambda_7|^2)^2\Big] \\
& -(\lambda_1-\lambda_2)\mathrm{Im}(\lambda_5^*\Lambda^2) - 2(|\lambda_6|^2-|\lambda_7|^2)\mathrm{Im}[\lambda_5^*\Lambda(\lambda_6+\lambda_7)] \\
& +(\lambda_1-\lambda_2)\Big[\mathrm{Im}\left[\Lambda(\lambda_7\lambda_6^{*\,2}+\lambda_6\lambda_7^{*\,2}-|\lambda_7|^2\lambda_6^*-|\lambda_6|^2\lambda_7^*)\right] \\
& \qquad +2\mathrm{Im}\left[\lambda_5\left((|\lambda_6|^2+|\lambda_7|^2)\lambda_6^*\lambda_7^*-\lambda_7\lambda_6^{*\,3}-\lambda_6\lambda_7^{*\,3}\right)\right]\Big]\,,
\end{aligned}
\tag{18}
$$

where Λ is defined in eq. (16).

$$
\begin{aligned}
I_{3Y3Z} &= \mathrm{Im}(Z_{a\bar{c}b\bar{d}}Z_{c\bar{e}d\bar{g}}Z_{e\bar{h}f\bar{q}}Y_{g\bar{a}}Y_{h\bar{b}}Y_{q\bar{f}}) \\
&= (Y_{11}-Y_{22})\left[(\lambda_1-\lambda_3-\lambda_4)(\lambda_2-\lambda_3-\lambda_4)-|\lambda_5|^2+|\lambda_6|^2+|\lambda_7|^2\right]\mathrm{Im}[Y_{12}^2\lambda_5^*] \\
&\quad +[(Y_{11}-Y_{22})^2-|Y_{12}|^2]\,|\lambda_5|^2\,\mathrm{Im}[Y_{12}(\lambda_7^*-\lambda_6^*)]-Y_{11}Y_{22}\,(\lambda_1-\lambda_2)\,\mathrm{Im}[Y_{12}\Lambda^*] \\
&\quad +2\,[(Y_{11}-Y_{22})^2+Y_{11}Y_{22}-|Y_{12}|^2]\left[|\lambda_7|^2\mathrm{Im}(Y_{12}\lambda_6^*)-|\lambda_6|^2\mathrm{Im}(Y_{12}\lambda_7^*)\right] \\
&\quad +2\,Y_{11}Y_{22}\left[|\lambda_7|^2\,\mathrm{Im}(Y_{12}\lambda_7^*)-|\lambda_6|^2\mathrm{Im}(Y_{12}\lambda_6^*)\right] \\
&\quad +(\lambda_1-\lambda_2)Y_{11}Y_{22}\mathrm{Im}[Y_{12}\lambda_5^*(\lambda_6+\lambda_7)]-[(Y_{11}-Y_{22})^2-|Y_{12}|^2]\mathrm{Im}(Y_{12}\lambda_5^*\widetilde{\Lambda}) \\
&\quad -(Y_{11}-Y_{22})\Big\{(Y_{11}Y_{22}+|Y_{12}|^2)[\mathrm{Im}[\lambda_5^*(\lambda_6^2+\lambda_7^2)]-(\lambda_1-\lambda_2)\mathrm{Im}(\lambda_6\lambda_7^*)] \\
&\qquad\quad +(Y_{11}^2+Y_{22}^2-4|Y_{12}|^2)\mathrm{Im}[\lambda_5^*\lambda_6\lambda_7]-(\lambda_1+\lambda_2-2\lambda_3-2\lambda_4)\mathrm{Im}[Y_{12}^2\lambda_6^*\lambda_7^*]\Big\} \\
&\quad +\mathrm{Im}[Y_{12}^3\lambda_5^*\widetilde{\Lambda}^*]+2\,\mathrm{Im}[Y_{12}^3\lambda_6^*\lambda_7^*(\lambda_6^*-\lambda_7^*)]+\mathrm{Im}[Y_{12}^3(\lambda_5^*)^2(\lambda_6-\lambda_7)]\,,
\end{aligned}
\tag{19}
$$

where Λ is defined in eq. (16) and

$$
\widetilde{\Lambda} \equiv (\lambda_2-\lambda_3-\lambda_4)\lambda_6-(\lambda_1-\lambda_3-\lambda_4)\lambda_7\,. \tag{20}
$$

Is this result useful?

Consider two special cases. In case (i),

$$
\lambda_1=\lambda_2\,,\quad \lambda_6=\lambda_7 \quad \text{and} \quad Y_{11}=Y_{22}\,, \tag{21}
$$

where Y_{12}, λ_5 and λ_6 have arbitrary phases. In case (ii),

$$\lambda_1 + \lambda_2 = 2(\lambda_3 + \lambda_4)\,, \quad \lambda_5 = 0 \quad \text{and} \quad \lambda_6 = \lambda_7\,, \tag{22}$$

where Y_{12} and λ_6 have arbitrary phases.

- In the both cases, we employ the corresponding expressions in a generic basis to conclude that $I_{Y3Z} = I_{2Y2Z} = I_{6Z} = I_{3Y3Z} = 0$.
- Thus both cases (i) and (ii) correspond to explicitly CP-conserving models.
- In a more conventional approach to this issue, this would be far from obvious. Typically, we would require the existence of a basis in which

$$\mathrm{Im}\,(Y_{12}^2\lambda_5^*) = \mathrm{Im}\,(Y_{12}\lambda_6^*) = \mathrm{Im}\,(Y_{12}\lambda_7^*) = \mathrm{Im}\,(\lambda_5^*\lambda_6^2) = \mathrm{Im}\,(\lambda_5^*\lambda_7^2) = \mathrm{Im}\,(\lambda_6^*\lambda_7) = 0\,. \tag{23}$$

That there are such bases in these two cases is far from obvious.

- Nevertheless, since for the above cases we have $I_{Y3Z} = I_{2Y2Z} = I_{6Z} = I_{3Y3Z} = 0$ one is assured of the existence of another basis choice in each case for which all Higgs potential parameters are real. In both cases, we have constructed the explicit $U(2)$ rotation that accomplishes this. The construction is messy.

The NMSSM

- **The Next to Minimal Supersymmetric Standard Model (NMSSM [4, 5, 6, 7, 8, 10, 11, 12, 13, 14, 15, 16]) provides a very elegant solution to the μ problem of the MSSM via the introduction of a singlet superfield $\widehat{S}$.**

  For the simplest possible scale invariant form of the superpotential, the scalar component of $\widehat{S}$ acquires naturally a vacuum expectation value of the order of the SUSY breaking scale, giving rise to a value of μ of order the electroweak scale.

  The NMSSM is actually the simplest supersymmetric extension of the standard model in which the electroweak scale originates from the SUSY breaking scale only.

- **In addition, the NMSSM renders the "little fine tuning problem" of the MSSM, originating from the non-observation of a neutral CP-even Higgs boson at LEP II, less severe [5]. Fine-tuning was also studied earlier in [6]. Our discussion here comes to rather different conclusions as compared to either reference.**

- A possible cosmological domain wall problem [7] can be avoided by introducing suitable non-renormalizable operators [8] that do not generate dangerously large singlet tadpole diagrams [9].

Hence, the phenomenology of the NMSSM deserves to be studied at least as fully and precisely as that of the MSSM.

Its particle content differs from the MSSM by the addition of one CP-even and one CP-odd state in the neutral Higgs sector (assuming CP conservation), and one additional neutralino. Thus, the physics of the Higgs bosons – masses, couplings and branching ratios [4, 10, 11, 12, 13, 14, 15, 16] can differ significantly from the MSSM.

I will be following the conventions of Ellwanger, Hugonie, JFG [17]. The NMSSM parameters are as follows.

a) Apart from the usual quark and lepton Yukawa couplings, the scale invariant superpotential is

$$\lambda\ \widehat{S}\widehat{H_u}\widehat{H_d} + \frac{\kappa}{3}\ \widehat{S}^3 \tag{24}$$

depending on two dimensionless couplings λ, κ beyond the MSSM. (Hatted capital letters denote superfields, and unhatted capital letters will denote their scalar components).

b) The associated trilinear soft terms are

$$\lambda A_\lambda S H_u H_d + \frac{\kappa}{3} A_\kappa S^3 \,. \tag{25}$$

c) The final two input parameters are

$$\tan\beta = \langle H_u \rangle / \langle H_d \rangle \ , \ \mu_{\rm eff} = \lambda \langle S \rangle \ . \tag{26}$$

These, along with M_Z, can be viewed as determining the three SUSY breaking masses squared for H_u, H_d and S through the three minimization equations of the scalar potential.

Thus, as compared to two independent parameters in the Higgs sector of the MSSM (often chosen as $\tan\beta$ and M_A), the Higgs sector of the NMSSM is described by the six parameters

$$\lambda \ , \ \kappa \ , \ A_\lambda \ , \ A_\kappa, \ \tan\beta \ , \ \mu_{\rm eff} \ . \tag{27}$$

We will choose sign conventions for the fields such that λ and $\tan\beta$ are positive, while κ, A_λ, A_κ and $\mu_{\rm eff}$ should be allowed to have either sign.

In addition, values for the gaugino masses and of the soft terms related to the squarks and sleptons that contribute to the radiative corrections in the Higgs sector and to the Higgs decay widths must be input.

Fine Tuning

w. Radovan Dermisek

The MSSM

Sample discussions of the issues appear in the papers cited in [19].

A typical and useful discussion for the MSSM is that given by Kane and King. They find that even at high $\tan\beta$ it is difficult to reduce fine tuning

$$F = \mathrm{Max}_a F_a \equiv \mathrm{Max}_a \left| \frac{d \log m_Z^2}{d \log a} \right| , \tag{28}$$

where the parameters a are the GUT scale soft-SUSY-breaking parameters and the μ parameter, below the level of about 50 for $M_3 = 200~\mathrm{GeV}$. A typical graph was that presented for $m_0 = 100~\mathrm{GeV}$ and $M_2 = M_1 = 200$, and $M_3 = 200$, 150 and $100~\mathrm{GeV}$. (All parameters given are GUT scale

values.)

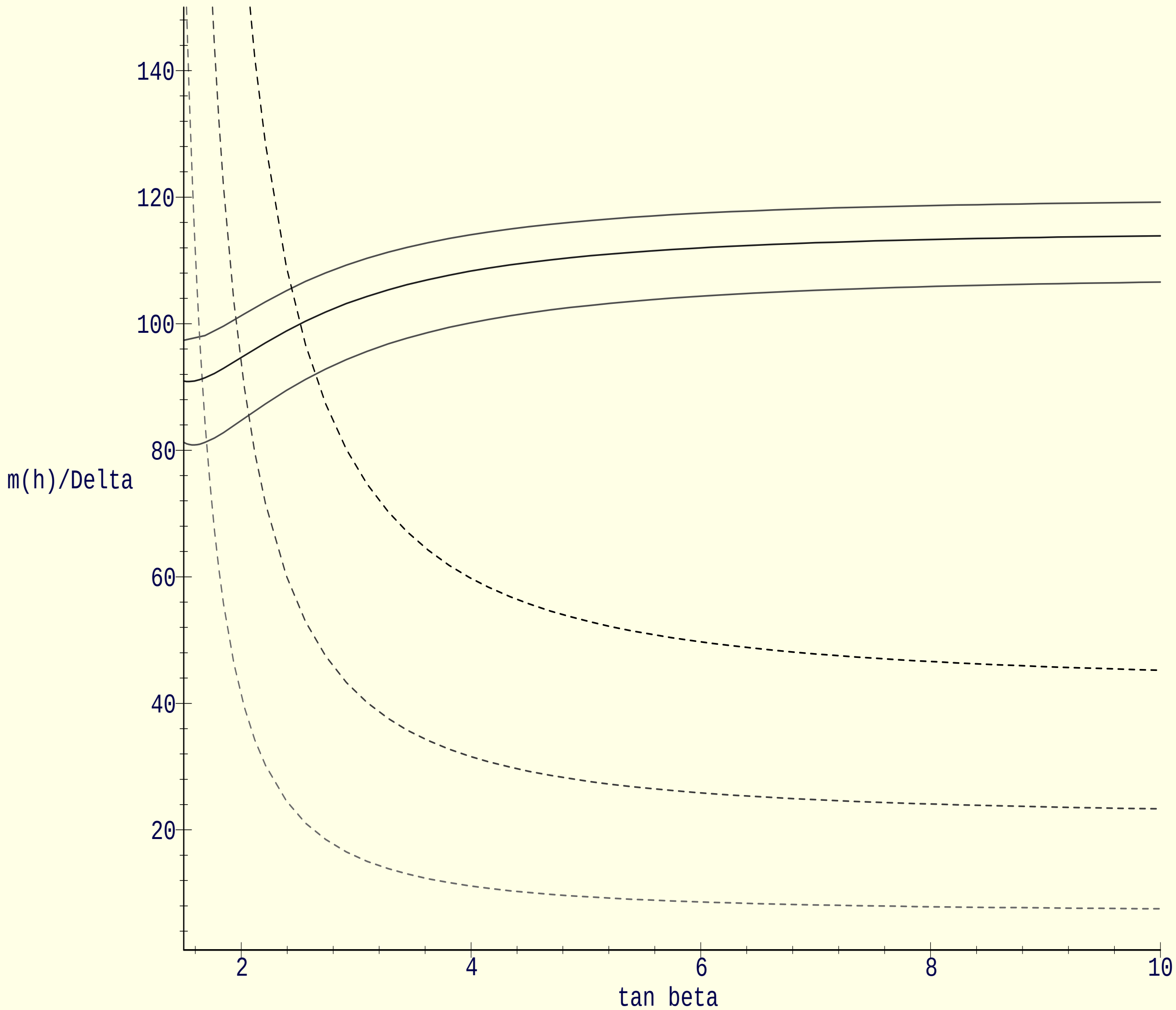


Figure 1: Higgs mass m_h and F_μ as functions of $\tan\beta$ for $m_0 = 100$ GeV, $M_{1,2} = 200$ GeV and $M_3 = 200$, 150 and 100 GeV.

One can write down formulae for m_Z^2 and F_μ. The procedure is to evolve GUT-scale parameters down to m_Z and then insert the evolution results into

$$\frac{1}{2}m_Z^2 = -\mu^2 + \frac{m_{H_d}^2 - t_\beta^2 m_{H_u}^2}{t_\beta^2 - 1}\,. \tag{29}$$

For example, at $\tan\beta = 2.5$ they find (GUT parameters again):

$$\begin{aligned} \frac{1}{2}m_Z^2 &= -0.87\mu^2 + 3.6M_3^2 - 0.12M_2^2 + 0.007M_1^2 - 0.71m_{H_u}^2 + 0.10m_{H_d}^2 \\ &\quad +0.48(m_Q^2 + m_U^2) - 0.34A_tM_3 + 0.25M_2M_3 + small\,. \end{aligned} \tag{30}$$

From this you already see the problem with large M_3^2. You must have carefully tuned cancellation to get m_Z^2 right now that experiment has forced M_3 to be sizable. However, one cannot rule out the possibility that such cancellation is natural in particular models.

Fine tuning provides a measure that goes beyond such cancellation. One computes how much m_Z changes if you change one GUT-scale parameter at a time, leaving the others fixed, but allowing $\tan\beta$ to readjust to the new minimum determined by evolving the GUT-scale parameter down to m_Z.

King and Kane give as a typical result the $\tan\beta = 2.5$ expression:

$$F_\mu = 5.1\tilde{\mu}^2 + 2.7\widetilde{M_3^2} - 0.6\widetilde{M_2^2} - 0.54\widetilde{m^2_{H_u}} - 0.91\widetilde{m^2_{H_d}}$$
$$0.36(\widetilde{m_Q^2} + \widetilde{m_U^2}) - 0.26\widetilde{A}_t\widetilde{M}_3 + \ldots \quad (31)$$

where the $\tilde{}$ indicates values scaled to m_Z. Substituting back in for μ^2 from the previous equation gives a term of $\sim 23.7\widetilde{M_3^2}$, implying that even for $M_3 \sim 200~\mathrm{GeV}$ one obtains $F_\mu \gtrsim 100$.

The NMSSM

We now contrast this to the NMSSM situation. Here, the computation of m_Z^2 is much more complicated. Some results on this have appeared in refs. [5] and [6], but I will claim they missed the most interesting part of parameter space with the smallest finetuning. We start with

$$V = \lambda^2(h_u^2 s^2 + h_d^2 s^2 + h_u^2 h_d^2) + \kappa^2 s^4 - 2\lambda\kappa h_u h_d s^2 - 2\lambda A_\lambda\, h_u h_d s$$
$$+\frac{2}{3}\kappa A_\kappa s^3 + m^2_{H_u} h_u^2 + m^2_{H_d} h_d^2 + m_S^2 s^2 + \frac{1}{4} g^2 (h_u^2 - h_d^2)^2 \,. \quad (32)$$

In the above, h_u and h_d are the vevs of the up and down type Higgs fields (without any $\sqrt{2}$) and s is the vev of the singlet Higgs field in the normalizations of NMHDECAY. (What I call g^2 is $g^2 \equiv \frac{1}{2}(g_2^2 + g'^{\,2})$ so that $m_Z^2 = g^2(h_u^2 + h_d^2)$.)

One must then solve the minimization equations

$$\frac{\partial V}{\partial h_u} = 0, \quad \frac{\partial V}{\partial h_d} = 0, \quad \frac{\partial V}{\partial s} = 0 \tag{33}$$

for the soft masses squared and explore combinations thereof for reexpressing the minimization conditions. One finds

$$m_{H_u}^2 = \frac{1}{2h_u}\left(g^2 h_d^2 h_u - g^2 h_u^3 - 2h_d^2 h_u \lambda^2 + 2A_\lambda h_d \lambda s + 2h_d \kappa \lambda s^2 - 2h_u \lambda^2 s^2\right) \tag{34}$$

$$m_{H_d}^2 = \frac{1}{2h_d}\left(g^2 h_d h_u^2 - g^2 h_d^3 - 2h_d h_u^2 \lambda^2 + 2A_\lambda h_u \lambda s + 2h_u \kappa \lambda s^2 - 2h_d \lambda^2 s^2\right) \tag{35}$$

$$m_S^2 = \frac{1}{s}\left(\lambda A_\lambda h_d h_u + 2h_d h_u \kappa \lambda s - h_d^2 \lambda^2 s - h_u^2 \lambda^2 s - \kappa A_\kappa s^2 - 2\kappa^2 s^3\right) \tag{36}$$

One then defines

$$\mu_{\rm eff} = \lambda s\,, \qquad \tan\beta \equiv \frac{h_u}{h_d}\,. \tag{37}$$

It is then easy to eliminate terms linear in s to find that

$$\frac{1}{2}m_Z^2 = -\mu_{\rm eff}^2 + \frac{m_{H_d}^2 - \tan^2\beta m_{H_u}^2}{\tan^2\beta - 1}\,. \tag{38}$$

However, $\mu_{\rm eff}$ is not a fundamental parameter in this case. Taking $(\kappa\lambda/\tan\beta - \lambda^2)$(35) $-(\kappa\lambda\tan\beta - \lambda^2)$ (34), we obtain a second equation

$$\begin{aligned}
&\kappa\lambda\left(\frac{1}{\tan\beta}m_{H_d}^2 - m_{H_u}^2\tan\beta\right) - \lambda^2\left(m_{H_d}^2 - m_{H_u}^2\right) \\
&= \frac{1}{2}m_Z^2\frac{\tan^2\beta - 1}{\tan^2\beta + 1}\left[\kappa\lambda\left(\frac{1}{\tan\beta} + \tan\beta\right) - 2\lambda^2 + \frac{2}{g^2}\lambda^4\right] \\
&\qquad + \mu_{eff}A_\lambda\lambda^2\left(\frac{1}{\tan\beta} - \tan\beta\right)
\end{aligned} \tag{39}$$

Let's make it simpler by defining

$$a = -\frac{1}{2}\frac{\tan^2\beta - 1}{\tan^2\beta + 1}\left[\kappa\lambda\left(\frac{1}{\tan\beta} + \tan\beta\right) - 2\lambda^2 + \frac{2}{g^2}\lambda^4\right] \qquad (40)$$

$$b = \frac{1}{\tan\beta}k\lambda\left(m_{Hd}^2 - m_{Hu}^2\tan^2\beta\right) - \lambda^2\left(m_{Hd}^2 - m_{Hu}^2\right) \qquad (41)$$

$$c = A_\lambda\lambda^2\left(\frac{1}{\tan\beta} - \tan\beta\right) \qquad (42)$$

so that it is simply

$$aM_Z^2 + b = c\mu_{eff}. \qquad (43)$$

Squaring this equation and plugging in μ_{eff} from Eq. (38) we can eliminate μ_{eff} completely, and we obtain a quadratic equation for M_Z^2 with coefficients given in terms of soft susy breaking parameters:

$$AM_Z^4 + BM_Z^2 + C = 0, \qquad (44)$$

where

$$
\begin{aligned}
A &= a^2 && (45)\\
B &= 2ab + c^2/2 && (46)\\
C &= b^2 + c^2 \frac{m_{Hd}^2 - m_{Hu}^2 \tan^2\beta}{1-\tan^2\beta}. && (47)
\end{aligned}
$$

This is the equivalent formula to that in the case of the MSSM. A, B, and C can be expressed in terms of SSB parameters at the GUT scale; the only difference is that it is a quadratic equation. Therefore there are two solutions:

$$
m_Z^2 = \frac{1}{2A}\left(-B \pm \sqrt{B^2 - 4AC}\right). \qquad (48)
$$

Only one applies for any given set of parameter choices.

To explore fine tuning, we begin at scale m_Z.

- We fix λ and κ, choose values for $\tan\beta$ and $\tan\gamma \equiv s/v$, and of course fix $h_u^2 + h_d^2 = v^2$. In the NMHDECAY conventions employed, $\lambda > 0$ and $\tan\beta > 0$, but κ can have either sign.

  We also find it easiest to fix the soft-SUSY-breaking parameters A_λ, A_κ, and $A_t = A_b$ at scale m_Z.

These we wish to preserve as fixed inputs.

- We also wish to fix the GUT scale values for

$$M_1, \quad M_2, \quad M_3, \quad m_Q^2, \quad m_U^2, \quad m_D^2, \quad m_L^2, \quad \text{and} \quad m_E^2\,. \tag{49}$$

These we will take to have respective universal values.

- We use the usual back and forth RGE iteration approach to determine the values of m_Q^2, m_U^2, m_D^2, m_L^2, and m_E^2 at scale m_Z that are consistent with these GUT scale values. These are then input into the Higgs multi-loop mass and analysis program.

  Once this is accomplished, we can determine $m_{H_u}^2$, $m_{H_d}^2$ and m_S^2 GUT scale values that are consistent with the choices determined by our m_Z scale inputs (which immediately fix the above quantities at scale m_Z).

- By making small perturbations at the GUT scale we may then determine how $m_{H_u}^2(m_Z)$, $m_{H_d}^2(m_Z)$, $m_S^2(m_Z)$, $A_\lambda(m_Z)$, and $A_\kappa(m_Z)$ depend upon the GUT scale parameters of Eq. (49).

- We then plug back into the expressions for a, b, and c (and, thence, A, B and C) and obtain a (messy) expression for m_Z^2 in terms of the parameters of Eq. (49).

Resulting observations

- It is usually the case that M_3^2 has a large coefficient in B, of magnitude similar to the MSSM coefficient given earlier.

  However, it can happen that $B^2 - 4AC$ and the appropriate sign in front of $\sqrt{B^2 - 4AC}$ are such that the growth with M_3^2 is automatically canceled.

  This shows the possibility of avoiding the usual increase in fine-tuning with increasing M_3.

- More generally, we can compute the F_a by perturbing the GUT scale input a a bit, recomputing the resulting $m_{H_u}^2(m_Z)$, $m_{H_d}^2(m_Z)$, $m_S^2(m_Z)$, $A_\lambda(m_Z)$ and $A_\kappa(m_Z)$ and then reminimizing the potential, which will yield new values of m_Z (and $\tan\beta$ and $\tan\gamma$).

  We use the shifted m_Z computed as above to compute F_a.

- One finds, depending upon input GUT scale parameters, that the largest of the F_a (F) can be quite modest in size even if the GUT scale parameters are quite large.

Of course, there are other choices that give large F.

An example of small F

- We consider Kane-King like choices: $\tan\beta = 3$, $M_1 = M_2 = M_3 = 300~\mathrm{GeV}$ (higher than their $200~\mathrm{GeV}$) and and a universal value for $m_0^2 = m_Q^2 = m_U^2 = m_D^2 = m_L^2 = m_E^2 = (400~\mathrm{GeV})^2$.

- We scan over various possible $A_t(m_Z)$, $A_\lambda(m_Z)$ and $A_\kappa(m_Z)$ values.

- We require the lightest Higgs boson to be heavier than $115~\mathrm{GeV}$ or that the lightest Higgs decay to two light pseudoscalars: $h_1 \to a_1 a_1$.

- We require $\mu_{\mathrm{eff}} > 100~\mathrm{GeV}$ and $M_2(m_Z) > 100~\mathrm{GeV}$ (to avoid a light chargino).

A typical small F case

```
F=9.3

H masses={361, 283, 72}  P masses= {355, 17}  H+ mass= 351

At low scale
l= 0.363 k= 0.214 tanb=3. s=665    M1= -126 M2=-248 M3=-888
mHu2u=-49708.3  mHd2u=52699.7  mS2u=043036.8
mQ2=448390. mu2=106338. md2=758901. mL2=241725. me2=102443.
Au=218.3 Al=11.53 Ak=0.462

At GUT scale
l=  0.4796  k= -0.2915    Ak=  -180.5   Al=  -1008.8   Au=  -2495.4
mHu2=  1065740  mHd2=  4936.6  mS2=  19770.1
```

Our scanning statistics are still low, but it can certainly be said that a very efficient means for selecting scenarios with small F is to focus on small A_κ, which generically leads to $h_1 \to a_1 a_1$ decays as being possible and not infrequently dominant, with the h_1 being quite SM-like.

Typical expressions for the things that enter into the calculation of a, b, and c and thence A, B and C are:

```
AlMZ= 0.760 AlG - 0.353 AuG  - 0.314 M2G + 0.699 M3G + small

AkMZ=0.867 AkG - 0.375 AlG + small
```

```
mHu2MZ=  0.151 M2G^2 + 0.281 AuG M3G - 0.189 M2G M3G - 3.1 M3G^2  + 0.523 mHu2G
       - 0.43 mQ2G - 0.33 mu2G

mHd2MZ= 0.446 M2G^2 + 0.899 mHd2G + small

mS2MZ= 0.742 mS2G + small
```

Clearly, the analysis of exactly why there is cancellation in the computation of F is somewhat complex, but we are working on it. What is clear is the general fact that there is a cancellation going on for all the small fine-tuning solutions. For example, in the above case, $B = 13210$ while $\sqrt{B^2 - 4AC} = 21556$ and $m_Z = (-B + \sqrt{B^2 - 4AC})/(2A)$. Thus, B is fairly dominant (often it is very dominant) and whatever dependence on some GUT parameter is present in B, it is also present with similar strength in $\sqrt{B^2 - 4AC}$.

Baryogenesis in the NMSSM

w. K. Kelley

The only work on this in the literature is that of ref. [5]. Others have focused on models with different or specialized superpotentials such as $W = \lambda\widehat{S}\widehat{H}_u\widehat{H}_d + \frac{m_{12}^2}{\lambda}\widehat{S}$ [20] or $W = \lambda\widehat{S}\widehat{H}_u\widehat{H}_d + \frac{\kappa}{3}\widehat{S}^3 + \mu\widehat{H}_u\widehat{H}_d + r\widehat{S}$ [21]. We are revisiting this to see to what extent the parameter regions with $h \to aa$ decays might be preferred over other regions.

We stick to the NMSSM as already defined. We employ the usual types of machinery to evaluate the strength of the phase transition prior to introducing CP violation into the Higgs sector (either through loops or explicitly). As usual, we employ the criterion of $\frac{v}{T_c} > 1$ as being required for a strong enough phase transition (as needed for the out-of-equilibrium condition for adequate baryogenesis). We have so far only looked at top and stop loop contributions. We are in the process of putting in contributions from the neutralino and chargino sectors, etc. The results are thus quite PRELIMINARY. As we expected, electroweak baryogenesis is more easily accommodated in the NMSSM than in the MSSM. The reasons are:

- The SM-like Higgs can be lighter and still escape detection via $h_1 \to a_1a_1$

dominance. (Recall that a light SM-like Higgs strengthens the phase transition.)

- If you require m_{h_1} to be up near the LEP limit because $h_1 \to a_1 a_1$ decays are absent, you can succeed with a lighter $\widetilde{t}$ than in the MSSM. This is because the h_1 mass gets an extra contribution at tree level:

$$m_{h_1}^2 \leq m_Z^2 \left(\cos^2 2\beta + \frac{2\lambda^2}{g_1^2 + g_2^2} \sin^2 2\beta \right) . \tag{50}$$

which can give substantial $m_{h_1}^2$ even at tree-level for moderate $\tan\beta$. For example, for small κ and $\widetilde{X_t} = \sqrt{6}$ (maximal mixing), $m_{h_1}^2$ is maximum for $\tan\beta \sim 3$ where, depending upon κ, λ can be big enough to give $m_{h_1} \sim 130$ GeV.

So far, we have kept $m_{\widetilde{t}_{1,2}} \sim 1$ TeV and explored parameter space in the region defined by:

$$\lambda \in [0.1, 0.65], \quad \kappa \in [0.1, 0.65], \quad \tan\beta \in [1.6, 3.0], \quad \mu_{\rm eff} = \lambda s \in [17.5, 350],$$
$$A_\lambda \in [-1000, 1000]~\mathrm{GeV}, \quad A_\kappa \in [-1000, 1000]~\mathrm{GeV}, \quad A_t = 1.5~\mathrm{TeV} \tag{51}$$

the latter being for roughly maximal mixing. A plot showing the v/T_c regions

from which an important conclusion is obvious is below.

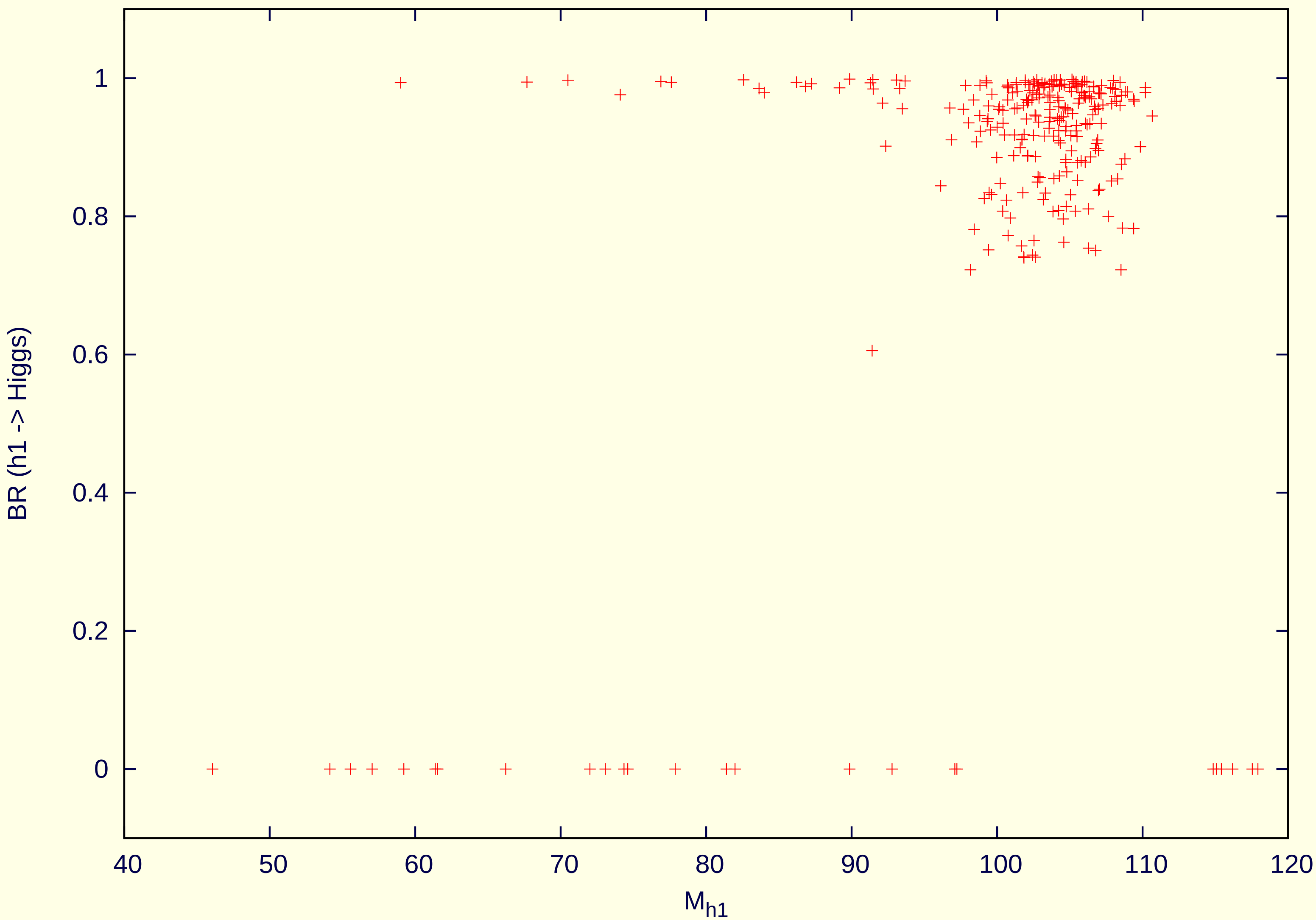


Figure 2: Scatter plot of $BR(h_1 \to a_1a_1)$ vs. m_{h_1} for points with $v/T_c > 1$.

Baryogenesis favors $h_1 \to a_1a_1$ scenarios!

NMHDECAY

We (Ellwanger, Hugonie, JFG [17]) have developed the NMSSM analogue of HDECAY. We provide two forms of the NMHDECAY program:

- NMHDECAY_SLHA.f — for study of one parameter point in the SLHA conventions for particle labeling etc. familiar to experimentalists;
- NMHDECAY_SCAN.f — designed for general phenomenological work including scanning over ranges of NMSSM parameters.

The programs, and associated data files, can be downloaded from the two web pages:

`http://www.th.u-psud.fr/NMHDECAY/nmhdecay.html`

`http://higgs.ucdavis.edu/nmhdecay/nmhdecay.html`

The web pages provide simplified descriptions of the programs and instructions on how to use them. The programs will be updated to include additional features and refinements in subsequent versions. We welcome comments with regard to improvements that users would find helpful.

Input files are `slhainp.dat` and `scaninp.dat`, respectively. They are simple!

```
#
#  Total number of points scanned
#
1000
#
#  Output format 0=short 1=long (not recommended for big scannings)
#
0
#
#  lambda
#
0.5
0.5
#
#  kappa
#
-0.15
-0.15
#
#  tan(beta)
#
3.5
3.5
#
#  mu
#
200.
200.
#
#  A_lambda
#
780.
780.
#
#  A_kappa
#
150.0
250.0
```

Table 1: Sample `scaninp.dat` file — 1st half for sample case #2.

```
#
#  Remaining soft terms (no scan)
#
mQ3=  1.D3
mU3=  1.D3
mD3=  1.D3
mL3=  1.D3
mE3=  1.D3
AU3=  1.5D3
AD3=  1.5D3
AE3=  1.5D3
mQ=   1.D3
mU=   1.D3
mD=   1.D3
mL=   1.D3
mE=   1.D3
M1=   5.D2
M2=   1.D3
M3=   3.D3
```

Table 2: The 2nd half of `scaninp.dat` file for sample case #2.

NMHDECAY performs the following tasks:

1. It computes the masses and couplings of all physical states in the Higgs, chargino and neutralino sectors.[1]

   Error messages are produced if a Higgs or squark mass squared is negative.

2. It computes the branching ratios into two particle final states (including charginos and neutralinos — decays to squarks and sleptons will be implemented in a later release) of all Higgs particles.

3. It checks whether the Higgs masses and couplings violate any bounds from negative Higgs searches at LEP, including many quite unconventional channels that are relevant for the NMSSM Higgs sector.

   It also checks the bound on the invisible Z width (possibly violated for light neutralinos).

[1] For the Higgses, we have included the leading two-loop effects, but neglected subleading two-loop contributions and subleading one-loop purely electroweak contributions. In MSSM limit, our Higgs masses agree to within a few GeV with HDECAY.

In addition, NMHDECAY checks the bounds on the lightest chargino and on neutralino pair production.

Corresponding warnings are produced in case any of these phenomenological constraints are violated.

4. It checks whether the running Yukawa couplings encounter a Landau singularity below the GUT scale.

   A warning is produced if this happens.

5. Finally, NMHDECAY checks whether the physical minimum (with all vevs non-zero) of the scalar potential is deeper than the local unphysical minima with vanishing $\langle H_u \rangle$ or $\langle H_d \rangle$.

   If this is not the case, a warning is produced.

- Below, I will discuss an example we employ to illustrate the use of these programs.

  It represents a scenario in which Higgs to Higgs decays make LHC Higgs detection very difficult.

  Other cases will be discussed.

Scenarios where LHC Higgs detection is hard

- **First, recall that normal MSSM Higgs detection at the LHC relies on:**

  1) $gg \to h/a \to \gamma\gamma$;
  2) associated Wh/a or $t\bar{t}h/a$ production with $\gamma\gamma\ell^{\pm}$ in the final state;
  3) associated $t\bar{t}h/a$ production with $h/a \to b\bar{b}$;
  4) associated $b\bar{b}h/a$ production with $h/a \to \tau^+\tau^-$;
  5) $gg \to h \to ZZ^{(*)} \to$ 4 leptons;
  6) $gg \to h \to WW^{(*)} \to \ell^+\ell^-\nu\bar{\nu}$;
  7) $WW \to h \to \tau^+\tau^-$;
  8) $WW \to h \to WW^{(*)}$.

  In supersymmetric models, it is also useful to include the mode

  9) $WW \to h \to invisible$.

  which, however, plays little role in the following. We also assume that $t \to H^{\pm}b$ will be observable for $m_{H^{\pm}} < 155~\mathrm{GeV}$ (could be raised).

- **We estimate the expected statistical significances at the LHC in all Higgs** boson detection modes 1) – 9) by rescaling results for the SM Higgs boson and/or the the MSSM h, H and/or A.

- **Scenarios for which LHC Higgs detection is "easy", for $L = 300\mathrm{fb}^{-1}$!**

If Higgs decays to Higgs and/or SUSY are forbidden, then [29]: We can always detect at least one of the NMSSM Higgs bosons.

This was not the case [22] until the $t\bar{t}h \to t\bar{t}b\bar{b}$ mode [23, 24] (We have had the experimentalists extrapolate this beyond the usual SM mass range of interest.) and the WW fusion modes [25, 26, 27] were brought into play.

The point yielding the very lowest LHC statistical significance in an extensive scan over 10^9 points in parameter space had the following parameters:

$$\lambda = 0.0535; \quad \kappa = 0.0259; \quad \tan\beta = 5.42; \quad \mu_{\mathrm{eff}} = 145; \quad A_\lambda = -46 \text{ GeV}; \quad A_\kappa = -141 \text{ GeV}. \tag{52}$$

Properties of the Higgs bosons for this point are listed in table 3.

Other points with relatively weak LHC signals are similar in that:

1. the Higgs masses are closely spaced and below or at least not far above the WW/ZZ decay thresholds,

2. the CP-even Higgs bosons tend to share the WW/ZZ coupling strength (indicated by R_i in the table),
3. couplings to $b\bar{b}$ of all Higgs bosons (the b_i or b_i' in the table) are not very enhanced,
4. and couplings to gg (the g_i or g_i' in the table) are suppressed relative to the SM Higgs comparison.

The most visible process for this point was the $WW \to h_3 \to \tau^+\tau^-$ channel, but many other (notably $t\bar{t}h \to t\bar{t}b\bar{b}$) channels are also visible.

Overall, we have a quite robust LHC no-lose theorem for NMSSM parameters such that LEP constraints are passed and Higgs-to-Higgs decays are not allowed once full LHC luminosity is achieved.

It would be a good idea for the LHC experimentalists to check that one really can see the Higgs signals at our estimated levels for this worst case no-Higgs-to-Higgs point.

Table 3: Properties of the neutral NMSSM Higgs bosons for the most difficult no-Higgs-to-Higgs-decays LHC point. In the table, $R_i = g_{h_iVV}/g_{h_{SM}VV}$, $t_i = g_{h_it\bar{t}}/g_{h_{SM}t\bar{t}}$, $b_i = g_{h_ib\bar{b}}/g_{h_{SM}b\bar{b}}$ and $g_i = g_{h_igg}/g_{h_{SM}gg}$ for $m_{h_{SM}} = m_{h_i}$. Similarly, t'_i and b'_i are the $i\gamma_5$ couplings of a_i to $t\bar{t}$ and $b\bar{b}$ normalized relative to the scalar $t\bar{t}$ and $b\bar{b}$ SM Higgs couplings and g'_i is the a_igg $\epsilon \times \epsilon'$ coupling relative to the $\epsilon \cdot \epsilon'$ coupling of the SM Higgs.

Higgs	h_1	h_2	h_3	a_1	a_2
Mass (GeV)	94	113	147	133	173
R_i	-0.440	-0.743	-0.505	0	0
t_i or t'_i	-0.421	-0.647	-0.662	-0.183	0.026
b_i or b'_i	-0.993	-3.55	4.10	-5.37	0.757
g_i or g'_i	0.470	0.554	0.435	0.139	0.021
$B(h_i\ or\ a_i \to b\bar{b})$	0.902	0.908	0.870	0.911	0.903
$B(h_i\ or\ a_i \to \tau^+\tau^-)$	0.081	0.085	0.086	0.088	0.095
Chan. 1) $S/\sqrt{B}$	0.00	0.20	0.26	0.00	0.00
Chan. 2) $S/\sqrt{B}$	0.83	0.76	0.22	0.00	0.00
Chan. 3) $S/\sqrt{B}$	3.03	6.28	5.64	5.64	0.00
Chan. 4) $S/\sqrt{B}$	0.00	0.88	3.24	3.24	0.04
Chan. 5) $S/\sqrt{B}$	0.00	0.12	1.59	—	—
Chan. 6) $S/\sqrt{B}$	0.00	0.00	1.26	—	—
Chan. 7) $S/\sqrt{B}$	0.00	6.88	6.96	—	—
Chan. 8) $S/\sqrt{B}$	0.00	0.17	0.44	—	—
All-channel $S/\sqrt{B}$	3.14	9.39	9.75	6.50	0.04

- **The difficult scenarios: Higgs to Higgs (or SUSY) decays**

The importance of Higgs to Higgs decays was first realized at Snowmass 1996 (JFG, Haber, Moroi [22]) and was later elaborated on in [28]. Detailed NMSSM scenarios were first studied in [29, 30].

We have shown that (for relatively heavy squarks and gauginos) all scenarios of this type for which discovery is not possible in modes 1) – 9) are such that there is a SM-like Higgs h_H which decays to a pair of lighter Higgs, $h_L h_L$.

In general, the h_L decays to $b\bar{b}$ and $\tau^+\tau^-$ (if $m_{h_L} > 2m_b$) or to jj and $\tau^+\tau^-$ (if $2m_\tau < m_{h_L} < 2m_b$) or, as unfortunately still possible, to jj if $m_{h_L} < 2m_\tau$.

In the first two cases, a possibly viable LHC signal then comes [29, 30] from $WW \to h_H \to h_L h_L \to jj\tau^+\tau^-$ in the form of a bump in the $M_{jj\tau^+\tau^-}$ reconstructed mass distribution. It is not a wonderful signal, but it is a signal.

A number of detailed benchmark points will appear in a forthcoming paper (JFG, Ellwanger, Hugonie, Moretti).

For most such cases, h_L is actually the lightest CP-odd scalar a_1 and h_H is the lightest or 2nd lightest CP-even scalar, h_1 or h_2.

Experimentalists should work hard to see if our crude estimates that there would be an observable signal will survive reality.

Ground rules:

- Take a h with 0.8 to 1 coupling to WW (relative to SM) and assume $BR(h \to aa) \in [0.8, 1]$.
- Allow $m_h \in [50, 120]$ GeV.
- Allow any $m_a \leq \frac{m_h}{2}$.
- Take a deep breath and have lots of coffee on hand.
- Assemble a group of students and postdocs to do all the hard work.
- Don't get discouraged – after all, you have brought to light many previously crazy signals that I and collaborators have brought to your attention.

  But, I have to admit, this is certainly the worst.

- As regards the cases where $m_{a_1} < 2m_\tau \Rightarrow a_1 \to c\bar{c}, s\bar{s}, gg$, these are not excluded by LEP (but we are pushing the LEP people for improvements).

  We believe it will be very difficult to find techniques that will allow extraction of a signal in these cases where neither b nor τ tagging is relevant. The only hope would be jet counting, but QCD backgrounds are probably enormous.

Since the $b\bar{b}$ coupling of these very light a_1's is not enhanced significantly (typically), there are no reliable exclusions coming from Υ or $B_{s,d}$ decays. We believe there is simply too much model dependence in the theory for such decays, although we would be happy to be persuaded otherwise.

- Incidentally, the MNMSSM ($\kappa = 0$ and $A_\kappa = 0$) also has this kind of case where LHC discovery is not possible. (I did not have time to review the Pilaftsis etal papers, but I suspect that Higgs-to-Higgs decays must have been left out to arrive at the opposite conclusion.)

- There are also cases in which $h_H = h_2$ and $h_L = h_1$, $m_{h_1} > 2m_b$, but yet $h_1 \to c\bar{c}, gg$ decays are completely dominant — parameters are chosen near a special region where the h_1 decouples from leptons and down-type quarks.

  Again, it is very hard to imagine a technique for extracting a signal at the LHC.

  One such case is illustrated below.

Sample case: no LHC signal

- For figs. 3–4, we take $\lambda = 0.5$, $\kappa = -0.15$, $\tan\beta = 3.5$, $\mu_{\rm eff} = 200~{\rm GeV}$, $A_\lambda = 780~{\rm GeV}$ and $A_\kappa \in [150~{\rm GeV}, 250~{\rm GeV}]$.

  The `scaninp.dat` file for this case was given in Table 1.

- For much of this parameter range, neither the h_1 nor the h_2 would have been observable at LEP.

  In particular, fig. 3–left shows that $m_{h_2} \gtrsim 120~{\rm GeV}$ implying that the h_2 is beyond the LEP kinematical reach.

  The h_1 is lighter, but $m_{h_1} > 2m_b$. However, this light Higgs is not excluded by LEP over most of the above A_κ range since: a) its reduced coupling to gauge bosons is small; and b) $h_1 \to b\overline{b}$ is suppressed so that $h_1 \to jj$ decays are dominant (see fig. 4–left).

  In fig. 3–right, we plot $\xi^2 = C_V(h_1)^2 \times BR(h_1 \to jj)$ for our selected points as well as the region excluded by LEP searches in this channel.

  We see that only if $m_{h_1} \lesssim 53~{\rm GeV}$, which corresponds to $A_\kappa \gtrsim 235~{\rm GeV}$, would the h_1 be excluded by LEP data.

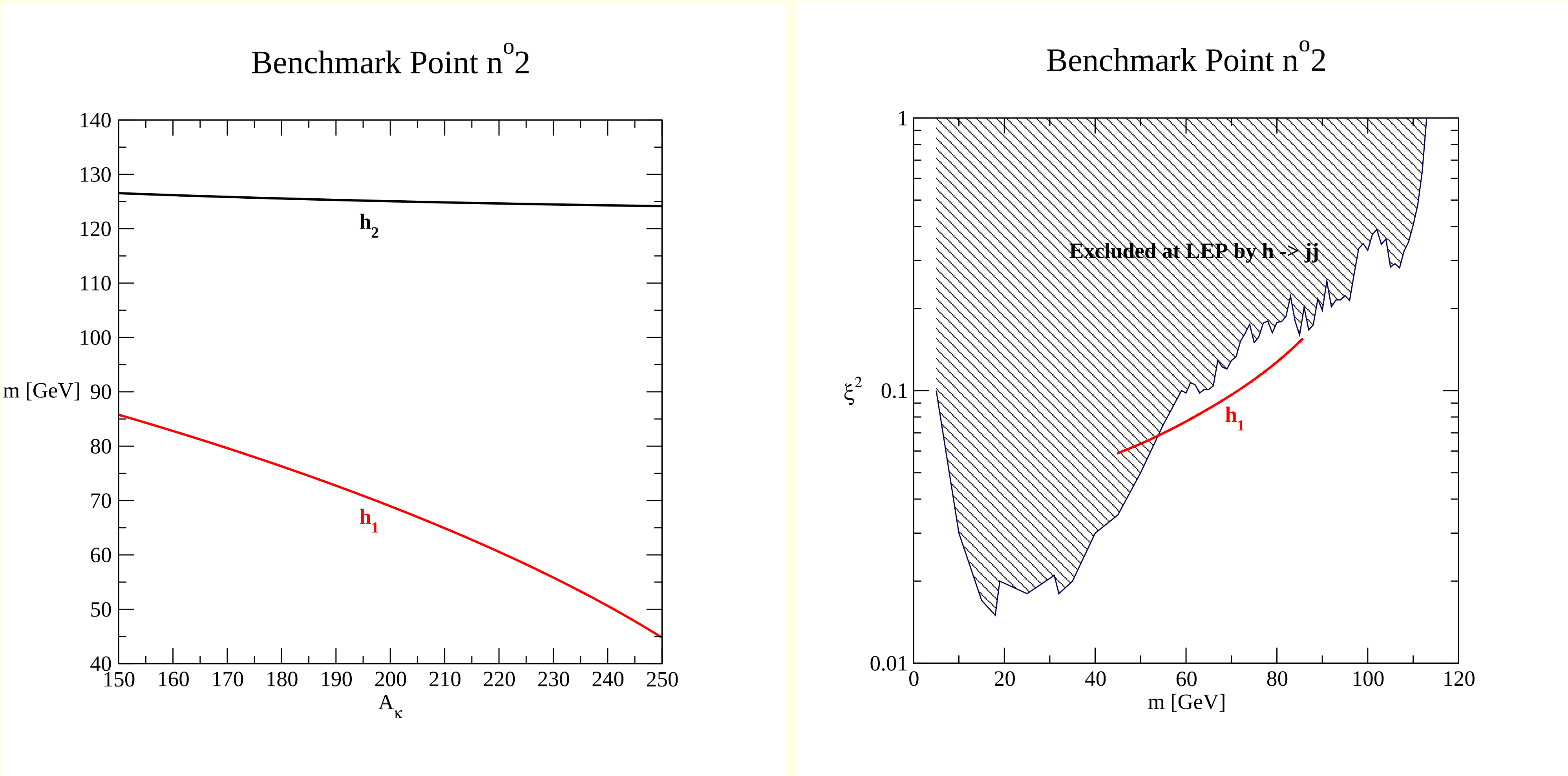


Figure 3: Left: m_{h_1} and m_{a_1} as a function of A_κ for the same parameters as in fig. 4. Right: LEP constraints in comparison to predictions for h_1 for these parameters. Note the correlation of $m = m_{h_1}$ with A_κ given in left-hand graph. New LEPHIGGS results may lower LEP exclusion curve in jj channel and make finding this kind of point more difficult.

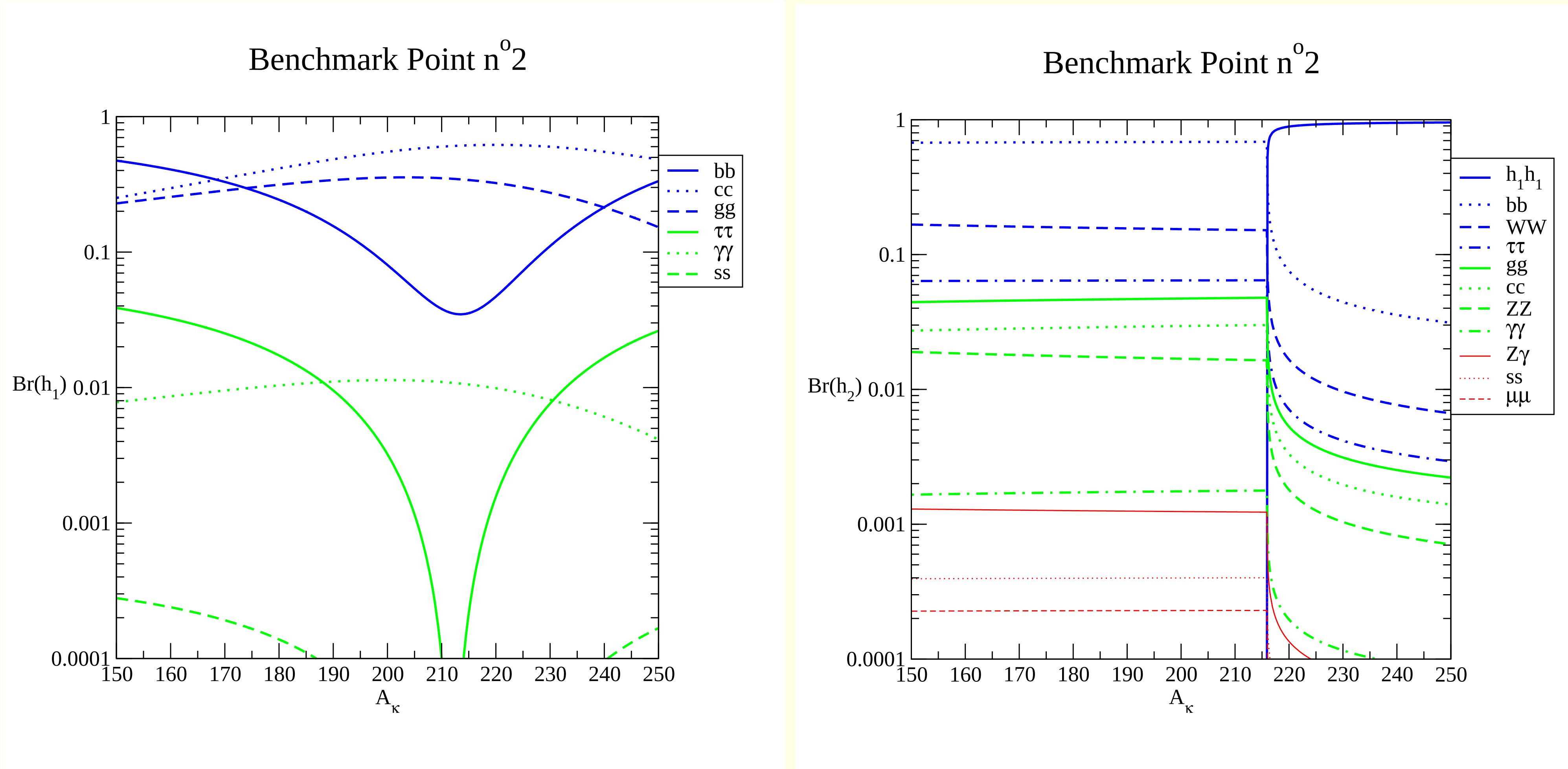


Figure 4: Left: Branching ratios of h_1 as a function of A_κ for $\lambda = 0.3$, $\kappa = -0.15$, $\tan\beta$ = 3.5, $\mu_{\rm eff}$ = 200 GeV, $A_\lambda = 780$ GeV, $m_{\rm squark} = 1$ TeV, and $A_t = 1.5$ TeV. Right: Branching ratios of h_2 as a function of A_κ for the same parameter choices.

- **Will these Higgs bosons be observable at the LHC?**

  In this regard, it is important to note from fig. 4–right that when $A_\kappa \gtrsim 215~\mathrm{GeV}$, $h_2 \to h_1 h_1$ decays are dominant. This occurs because m_{h_1} decreases with A_κ, see fig. 3–left.

  Meanwhile, fig. 4–left shows that $BR(h_1 \to b\bar{b})$ and $BR(h_1 \to \tau^+\tau^-)$ are both small when $A_\kappa \in [205~\mathrm{GeV}, 220~\mathrm{GeV}]$; in this region of parameter space, the h_1 decays mainly to $c\bar{c}$ or gg.

  Thus, for $A_\kappa \sim 215 - 220~\mathrm{GeV}$:

  - **The h_1 has a mass that lies below the mass range currently studied for Higgs detection at the LHC.**
    Further, the h_1 will be so weakly produced at the LHC (since $\xi^2 \lesssim 0.1$) that extensions to lower Higgs masses of the current LHC studies would probably conclude it was undetectable.
  - **Simultaneously, the strongly produced h_2 has decays dominated by $h_2 \to h_1 h_1$ with $h_1 \to c\bar{c}, gg$ (but not $b\bar{b}$ or $\tau^+\tau^-$).**
    As a result, the techniques for $h \to aa$ (which require a significant $a \to \tau^+\tau^-$ branching ratio) do not apply, and the h_2 would also appear to be very difficult to observe at the LHC.

How common are points that require the $aa \to jj\tau^+\tau^-$ mode at the LHC?

1. We scanned randomly over 10^8 points in the ranges:

$$10^{-4} \leq \lambda \leq 0.75; \quad -0.65 \leq \kappa \leq 0.65; \quad 1.6 \leq \tan\beta \leq 54;$$
$$-1 \text{ TeV} \leq \mu_{\rm eff}, A_\lambda, A_\kappa \leq +1 \text{ TeV} . \qquad (53)$$

2. Of the 10^8 points, 86818793 yielded negative $m^2_{h_1}$, $m^2_{a_1}$ or $m^2_{H^\pm}$, implying that $\sim 13\%$ survive the basic requirements for a local minimum of the Higgs potential.

3. All points for which all Higgs masses-squared were positive also had positive $m^2_{\widetilde t_1}$ and $m^2_{\widetilde b_1}$.

4. Of the $\sim 1.32 \times 10^7$ remaining points, 1407077 would have resulted in an observable LEP signal as defined in NMHDECAY.

5. Of the remainder, 41306 are eliminated by the requirement of no $t \to H^\pm b$ decays and 576 are eliminated since there were no Higgs-to-Higgs decays.

   (Note how small the no-Higgs-to-Higgs fraction is.)

6. **Of the remaining $\mathbf{11732824}$ points, $\mathbf{11726304}$ would yield $\mathbf{5\sigma}$ signals in channels 1) – 9) and are not considered further.**

7. **This leaves $\mathbf{6520}$ points.**

   Of these, $\mathbf{2198}$ have a Landau pole below M_U and $\mathbf{266}$ have an unphysical global minimum.

8. **The result is $\mathbf{3480}$ points for which Higgs-to-Higgs decays are present, no Higgs would have been observed at LEP and no Higgs would be observable at the LHC in modes 1) – 9).**

   This represents $\sim \mathbf{0.026\%}$ of the $\mathbf{13181207}$ points that have a proper local minimum.

   Thus, the standard LHC detection modes 1) – 9) suffice $\mathbf{99.974\%}$ of the time, for $\boldsymbol{L} = \mathbf{300}\mathrm{fb}^{-1}$.

   Still, the parameter ranges associated with these points for which all NMSSM Higgs bosons escape LEP detection and LHC detection in modes 1) – 9) are broad:

$$\mathbf{0.0623} \leq \boldsymbol{\lambda} \leq \mathbf{0.7235}; \quad -\mathbf{0.6230} \leq \boldsymbol{\kappa} \leq \mathbf{0.6331}; \quad \mathbf{1.65} \leq \tan\boldsymbol{\beta} \leq \mathbf{53.13};$$
$$-\mathbf{1}\ \mathrm{TeV} \leq \boldsymbol{\mu}_{\mathrm{eff}}, \boldsymbol{A_\lambda} \leq \mathbf{1}\ \mathrm{TeV}; \quad -\mathbf{715}\ \mathrm{GeV} \leq \boldsymbol{A_\kappa} \leq \mathbf{502}\ \mathrm{GeV}\,. \tag{54}$$

9. **And, there is significant fine-tuning and baryogenesis motivation for these special points.**

10. **The $jj\tau^+\tau^-$ detection has some hope of working for all but 26 of the 3480 points.**

    For some of the 26 points, $h_{1,2} \to a_1 a_1$ decays are prominent but $m_{a_1} \leq 2m_\tau$.

    For the remainder the a_1 or h_1 in the $a_1 a_1$ or $h_1 h_1$ pair final state simply has suppressed couplings to $b\overline{b}$ and $\tau^+\tau^-$. We saw an example of this earlier.

    In either case, τ triggering does not work and NMSSM Higgs detection at the LHC would probably be impossible.

    The following table illustrates 5 parameter space points having one or the other of the above characteristics.

11. **We note that for all these 3480 points, the h_3 or a_2 will only be detectable if a super high energy LC is eventually built so that $e^+e^- \to Z \to h_3 a_2$ is possible.**

Point Number	10	11	12	13	14
Bare Parameters					
λ	0.390	0.500	0.270	0.373	0.411
κ	0.183	$-.152$	0.147	0.243	$-.184$
$\tan\beta$	3.50	3.50	2.86	3.36	2.42
$\mu_{\rm eff}$	-245.0	200.0	-753.0	-315.0	184.0
A_λ	-230.0	780.0	312.0	171.0	626.0
A_κ	-5.0	230.0	8.4	52.1	32.8
CP-even Higgs Boson Masses and Couplings					
m_{h_1} (GeV)	94.1	57.3	95.4	88.0	113.8
R_1	0.945	-0.278	0.997	0.980	-0.992
t_1	0.949	-0.301	0.991	0.966	-0.989
b_1	0.890	0.015	1.047	1.135	-1.011
g_1	0.952	0.326	0.988	0.957	0.988
$B(h_1 \to b\overline{b})$	0.047	0.055	0.003	0.001	0.007
$B(h_1 \to \tau^+\tau^-)$	0.004	0.003	0.000	0.000	0.001
$B(h_1 \to c\overline{c} + s\overline{s} + gg)$	0.005	0.933	0.000	0.000	0.001
$B(h_1 \to a_1 a_1)$	0.943	0.000	0.996	0.999	0.991
m_{h_2} (GeV)	239.5	124.7	483.1	198.5	168.9
R_2	-0.327	-0.961	-0.014	-0.026	-0.122
t_2	-0.299	-0.952	-0.364	-0.321	-0.085
b_2	-0.669	-1.066	2.843	3.314	-0.339
g_2	0.295	0.948	0.366	0.384	0.080
$B(h_2 \to b\overline{b})$	0.002	0.048	0.020	0.060	0.004
$B(h_2 \to \tau^+\tau^-)$	0.000	0.004	0.002	0.007	0.000
$B(h_2 \to W^+W^- + ZZ)$	0.437	0.012	0.003	0.001	0.050
$B(h_2 \to a_1 a_1)$	0.246	0.000	0.002	0.079	0.944
$B(h_2 \to h_1 h_1)$	0.314	0.930	0.010	0.007	0.000
$B(h_2 \to a_1 Z)$	0.000	0.000	0.485	0.845	0.002
$B(h_2 \to \widetilde\chi_1^0 \widetilde\chi_1^0)$	0.000	0.000	0.000	0.000	0.000
$B(h_2 \to \chi_i^0 \widetilde\chi_j^0 + \widetilde\chi_i^+ \widetilde\chi_j^-)$	0.000	0.000	0.000	0.000	0.000

Table 4: Properties of points for which the $WW \to h_H \to h_L h_L \to jj\tau^+\tau^-$ modes don't work.

Point Number	10	11	12	13	14
m_{h_3} (GeV)	561.7	731.1	820.8	406.2	529.8
R_3	-0.017	-0.006	-0.079	-0.199	-0.019
t_3	-0.301	-0.290	-0.093	-0.228	-0.430
b_3	3.466	3.481	0.031	0.138	2.391
g_3	0.302	0.288	0.093	0.229	0.431
$B(h_3 \to b\bar{b})$	0.045	0.015	0.000	0.000	0.008
$B(h_3 \to \tau^+\tau^-)$	0.006	0.002	0.000	0.000	0.001
$B(h_3 \to t\bar{t})$	0.674	0.278	0.099	0.088	0.457
$B(h_3 \to W^+W^- + ZZ)$	0.009	0.001	0.500	0.365	0.003
$B(h_3 \to Higgses)$	0.127	0.360	0.401	0.546	0.318
$B(h_3 \to \chi_i^0\widetilde{\chi}_j^0 + \widetilde{\chi}_i^+\widetilde{\chi}_j^-)$	0.138	0.344	0.000	0.000	0.212
CP-odd Higgs Boson Masses and Couplings					
m_{a_1} (GeV)	40.0	188.2	1.3	3.4	1.9
t_1'	0.000	0.044	0.076	0.204	0.081
b_1'	0.000	0.534	0.624	2.303	0.473
g_1'	0.000	0.038	0.363	1.003	0.197
$B(a_1 \to b\bar{b})$	0.015	0.007	0.000	0.000	0.000
$B(a_1 \to \tau^+\tau^-)$	0.001	0.001	0.000	0.000	0.000
$B(a_1 \to c\bar{c} + s\bar{s} + gg)$	0.000	0.000	0.948	0.938	0.936
$B(a_1 \to \gamma\gamma)$	0.983	0.000	0.000	0.000	0.000
$B(a_1 \to \widetilde{\chi}_1^0\widetilde{\chi}_1^0)$	0.000	0.992	0.000	0.000	0.000
m_{a_2} (GeV)	557.9	735.5	492.7	270.6	535.1
$m_{h^\pm}$ (GeV)	559.6	726.9	485.1	202.7	526.1
Most Visible of the LHC Processes 1)-9)	5 (h_2)	2 (h_2)	5 (h_3)	5 (h_3)	2 (h_1)
$N_{SD} = S/\sqrt{B}$ of this process at L =300 fb^{-1}	1.5	1.3	0.1	0.9	0.2

Table 5: Properties (continued) of selected scenarios for which LHC Higgs detection would not even be possible in the $WW \to h_H \to h_L h_L \to jj\tau^+\tau^-$ modes.

Difficult scenarios at the LC

- Whether or not we have a good LHC signal if nature chooses a difficult point, ultimately, a means of confirmation and further study will be critical.

  Thus, it is important to summarize the prospects at the LC.

- For difficult scenarios, we always find that the h_H ($h_H = h_1$ or h_2) has reasonable WW, ZZ coupling and mass at most $\sim 150~\mathrm{GeV}$ (but possibly much lower).

  Discovery of the h_H will be very straightforward via $e^+e^- \to Zh_H$ using the $e^+e^- \to ZX$ reconstructed M_X technique which is independent of the "unexpected" complexity of the h_H decay to h_Lh_L ($h_L = a_1$, or h_1 for $h_H = h_2$).

  This will immediately provide a direct measurement of the ZZh_H coupling with very small error.

- The LC will find it quite easy to look for even a rather light h_H decaying to h_Lh_L in the ZX channel.

- Once it is found, then, look for different final states and check for Higgs-like coupling of the h_L to various final state fermions.

Perhaps one will find one of the special cases with h_L decoupled from $b\overline{b}$ and $\tau^+\tau^-$.

Perhaps the situation will be canonical with h_L having standard Higgs-like decays.

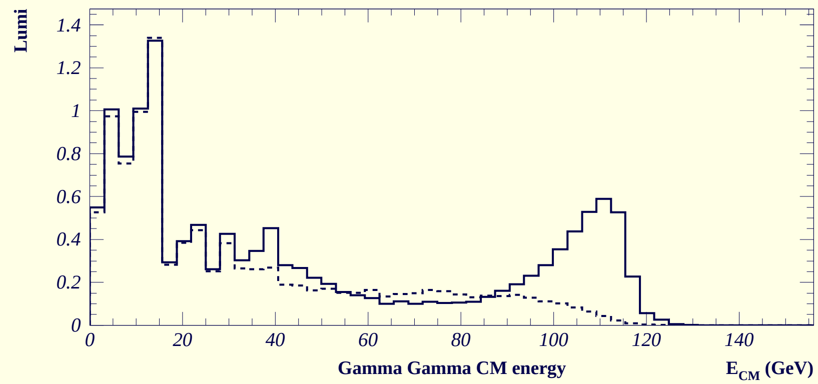
Either way, we will be able to pin down the nature of the Higgs sector and the parameters of the NMSSM.

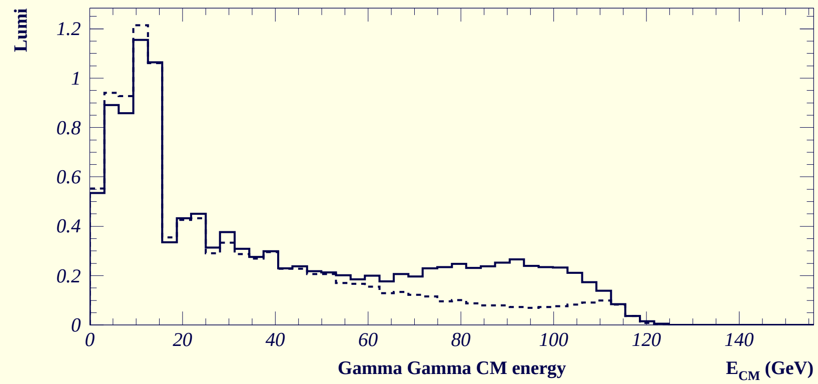
Difficult scenarios at a $\gamma\gamma$ collider of the CLICHE variety

- Mayda already showed some of the plots. We can get some really strong signals here (see [31] for full set of plots and details).

- **For the most general scan, it is best to use a broad spectrum.**

• Up to now: used CLIC 1 spectrum peaked at 115 GeV (top). Now: broad band spectrum (bottom), but $E_e = 75$ GeV $\rightarrow$ not practical for higher m_h.





• Total cross sections for $\gamma\gamma \rightarrow h_{SM}$ from Pythia: 31.8, 40.8, 40.4, 32.2 fb for m_h= 80, 90, 100, 110 GeV, respectively.

- Suppose $h \to aa$, with $a \to b\bar{b}$ allowed with $BR(a \to b\bar{b}) \sim \mathbf{0.9}$.

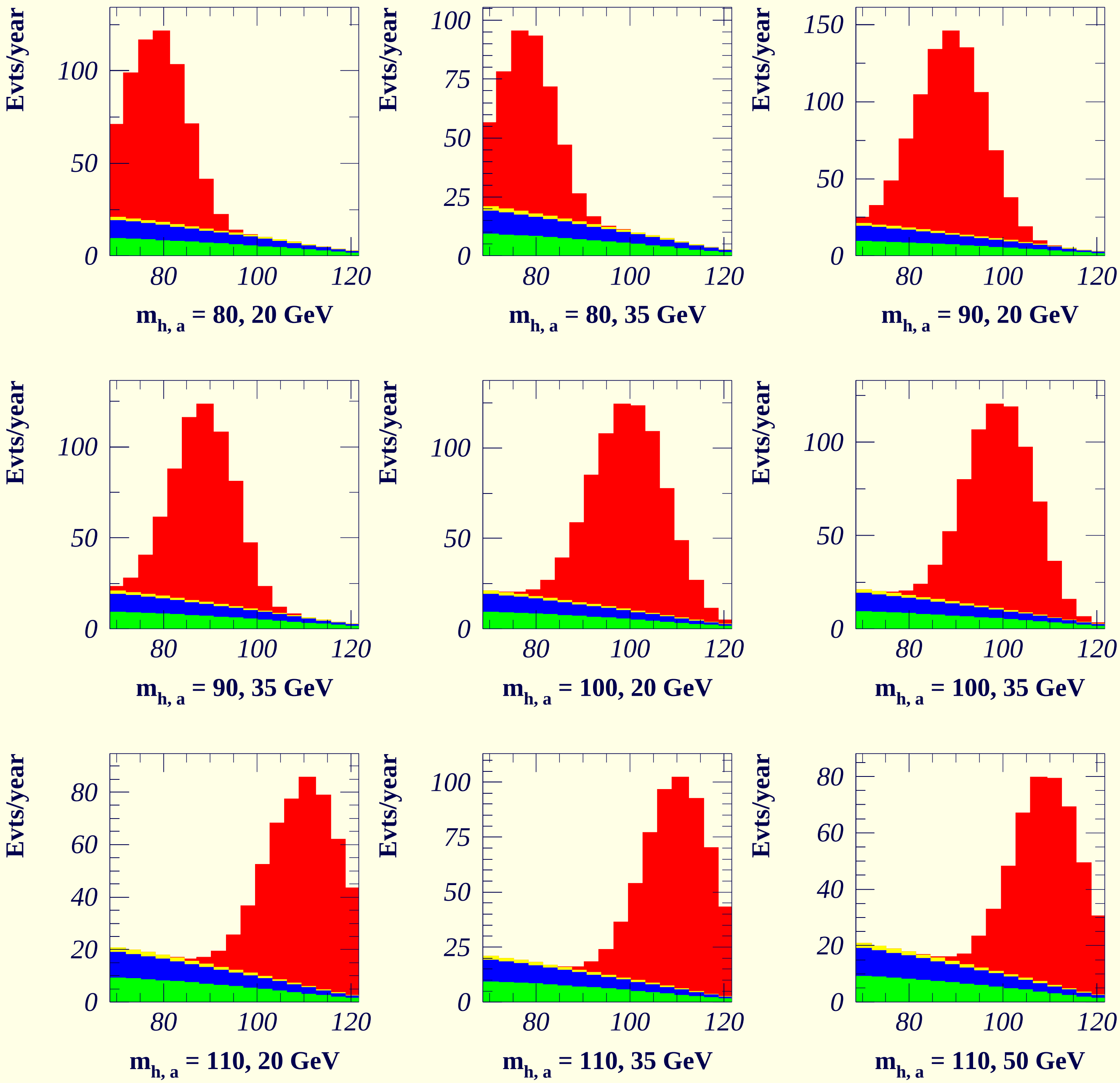
- Look at a grid of points: $m_h = \mathbf{80}$, $\mathbf{90}$, $\mathbf{100}$, $\mathbf{110}~\mathrm{GeV}$; $m_a = \mathbf{20}$, $\mathbf{35}$, $\mathbf{50}$. A total of 9 kinematically allowed possibilities.

- "Standard" cuts and tagging (mis-tagging) efficiencies.

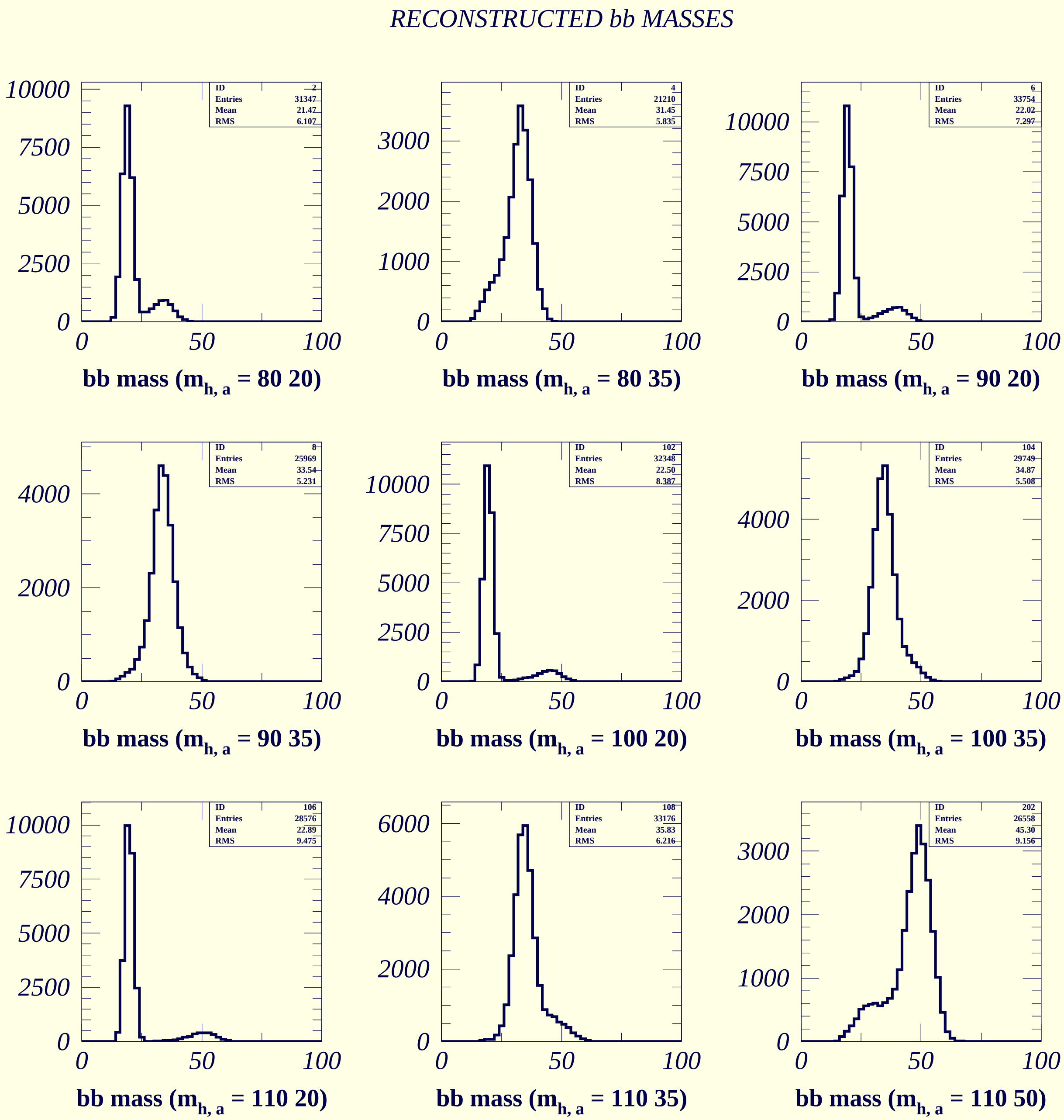
- Result is excellent signals and small backgrounds in all cases — see 1st figure.

- Excellent determination of m_a is possible — see 2nd figure.

4-JET INV. MASS - SIGNAL on top of BACKGROUND



How well can we determine the a mass?



NMSSM Summary

The LHC can detect at least one Higgs boson of the NMSSM for almost all of the model parameter space, assuming accumulated luminosity of $L = 300\mathrm{fb}^{-1}$.

However, there are residual corners of parameter space for which we would see supersymmetry (and see perturbative WW scattering), and yet have to wait until the LC to see a Higgs boson or (more optimistically) check that the observed $jj\tau^+\tau^-$ LHC signal was really a Higgs boson signal.

Once the LHC + LC really fix all 5 NMSSM parameters, we may find that $m_{h_3} + m_{a_2} > 1\ \mathrm{TeV}$ (quite common in our scans). In this case, LHC might be able to find the heavy Higgs signal since the approximate masses will be known. Sample channel: $gg \to h_3 \to t\bar{t}$ with $m_{h_3} \gtrsim 900\ \mathrm{GeV}$.

There are clearly enough NMSSM Higgs scenarios to keep simulators busy for years, probably more years than we have left before LHC turn-on.

It is very important for the Tevatron experimental groups to explore their sensitivity to the $h \to aa$ decays when m_h is relatively small (e.g. $\sim 50 - 70\ \mathrm{GeV}$) and $m_a < \frac{m_h}{2}$. For example, backgrounds might be smaller than at the LHC for such mass choices and it might happen that this mass range could only be covered at the Tevatron.