New Results for NMSSM Higgs and Dark Matter

Jack Gunion
U.C. Davis

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• The NMSSM is defined by adding a single SM-singlet superfield $\hat{S}$ to the MSSM and imposing a $Z_3$ symmetry on the superpotential, implying

$$ W = \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{\kappa}{3} \hat{S}^3 $$  \hspace{1cm} (1)

The reason for imposing the $Z_3$ symmetry is that then only dimensionless couplings $\lambda$, $\kappa$ enter. All dimensionful parameters will then be determined by the soft-SUSY-breaking parameters. In particular, the $\mu$ problem is solved via

$$ \mu_{\text{eff}} = \lambda \langle S \rangle. $$ \hspace{1cm} (2)

$\mu$ is automatically of order a TeV (as required) since $\langle S \rangle$ is of order the SUSY-breaking scale, which will be below a TeV.

• The extra singlet field $\hat{S}$ implies: 5 neutralinos, $\tilde{\chi}_{1-5}^0$ with $\tilde{\chi}_1^0$ being either singlet or bino, depending on $M_1$; 3 CP-even Higgs bosons, $h_1, h_2, h_3$; and
2 CP-odd Higgs bosons, $a_1, a_2$. Their effects/implications will be the focus of this talk.

- The soft-SUSY-breaking terms corresponding to the terms in $W$ are:

$$\lambda A_\lambda SH_uH_d + \frac{\kappa}{3} A_\kappa S^3.$$ (3)

When $A_\lambda, A_\kappa \to 0$, the NMSSM has an additional $U(1)_R$ symmetry, in which limit the $a_1$ is pure singlet and $m_{a_1} = 0$.

If, $A_\lambda, A_\kappa = 0$ at $M_U$, RGE’s give $A_\lambda \sim 100$ GeV and $A_\kappa \sim 1 - 20$ GeV, resulting in $m_{a_1} < 2m_B$ (see later) being quite natural and not fine-tuned.

- The NMSSM maintains all the attractive features (GUT unification, RGE EWSB) of the MSSM while avoiding important MSSM problems.

- In particular, there are very attractive scenarios in the NMSSM with no EWSB fine-tuning.
To avoid EWSB fine-tuning (the sensitivity of $m_Z$ or $v$ to GUT-scale parameters), sparticles must be light, especially the stops; the optimal is $\sqrt{m_{\tilde{t}_1}m_{\tilde{t}_2}} \sim 350-500$ GeV, somewhat above Tevatron limits but accessible at the LHC. (Also, the gluino should be light.)

As for the MSSM, for such stop masses, the Higgs that couples to $WW, ZZ$ is predicted to have mass $m_H \sim 90 - 110$ GeV.

- This is perfect for precision electroweak.

Indeed, if only the leptonic $\sin^2 \theta_W^{eff}$ measurements are included, the SM gives a fit with CL near 0.78 with $m_H \sim 50$ GeV and with a 95% CL upper limit of $\sim 105$ GeV (Chanowitz, xarXiv:0806.0890).

- Electroweak Baryogenesis: $m_H \lesssim 105$ GeV is needed for strong enough phase transition.

- Largest LEP excess: Perhaps the Higgs should be such as to predict the
2.3σ excess at $M_{b\bar{b}} \sim 98$ GeV seen in the $Z + b\bar{b}$ final state.

Figure 1: Plots for the $Zb\bar{b}$ final state. $F$ is the $m_Z$-fine-tuning measure for the NMSSM.

- The simplest possibility for the excess is to have $m_H \sim 100$ GeV and $B(H \to b\bar{b}) \sim (0.1 - 0.2) \times B(H \to b\bar{b})_{SM}$ (assuming $H$ has SM $ZZ$ coupling as desired for precision electroweak) with the remaining $H$ decays being to one or more of the $Z + X$ channels that are poorly constrained at LEP.

This is natural in the NMSSM by virtue of $H \to a_1a_1$ decays, where $m_{a_1} < 2m_B$ so that $a_1 \to \tau^+\tau^-$ or $jj$ (so as to escape LEP limits in the $Z + b's$ channel).
In the case of large $\tan \beta$ where $a_1 \to \tau^+\tau^-$ is big, new ALEPH (LEP) limits on $e^+e^- \to ZH$ with $H \to a_1a_1 \to 4\tau$ tend to force one to the region of $10 \text{ GeV} \lesssim m_{a_1}$ when $m_H < 110 \text{ GeV}$.

This is also the region where BaBar limits from $\Upsilon_{3S}$ decays run out.

Dermisek and I showed in earlier work that this is also precisely the region with least "light-$a_1$" finetuning (i.e. $A_\lambda$ and $A_\kappa$ need not be chosen very precisely — 20% or so is ok — to get large $B(h_1 \to a_1a_1)$ and $m_{a_1} < 2m_B$).

- In the simplest "ideal" Higgs scenarios, it will be the $h_1$ of the NMSSM that has strong $WW, ZZ$ couplings.

But, in some other scenarios related to dark matter, it might be the $h_2$ that couples to $WW, ZZ$ and $m_{h_2}$ will be in the $m_{h_2} \lesssim 105 - 110 \text{ GeV}$ range.

In some cases, $h_1$ and $h_2$ will share the $WW, ZZ$ coupling.
What is important for precision electroweak is $m_{eff}$ defined by

$$\ln m_{eff} = \sum_i C_V^2(i) \ln m_{h_i} ,$$  

(4)

where $C_V(i) = g_{ZZh_i}/g_{ZZh_{SM}}$. We want $m_{eff} \lesssim 105 - 110$ GeV.

- Important bottom lines for the “ideal” NMSSM Higgs scenarios are:
  
  (i) the Higgs could be “buried” under backgrounds;

(ii) and searching directly for the light $a_1$ could be especially relevant.
Dark Matter and the NMSSM Warm-Up

- It has long been known (Gunion, McElrath, and Hooper, hep-ph/0509024) that the NMSSM can accommodate light ($m_{\tilde{\chi}_1^0} < 10$ GeV) dark matter with correct relic density.

- But, can the NMSSM light dark matter have $\sigma_{SI}$ as large as suggested by COGENT data, $\sigma_{SI} \sim 10^{-4}$ pb?

- We will find that a large fraction of the interesting points from the dark matter perspective have $m_{h_1}$ somewhat below 100 GeV and $m_{h_2}$ slightly above 100 GeV with $|C_V(h_2)| > |C_V(h_1)|$ and will escape LEP limits because of $h_2 \rightarrow a_1 a_1 \rightarrow 4\tau$ for $10$ GeV $\lesssim m_{a_1} \lesssim 2m_B$.

- Other points consistent with Cogent $\sigma_{SI}$ with 110 GeV $\lesssim m_{h_2} \lesssim 115$ GeV (and $C_V(2) \sim 1$) are less attractive from the EWSB finetuning point of view but can have any $m_{a_1}$ because $B(h_2 \rightarrow a_1 a_1 \rightarrow 4b) \sim 1$ is allowed in $e^+e^- \rightarrow Zh_2$ in this mass range.
• $\Omega h^2 \sim 0.1$ and large $\sigma_{SI}$ increase the likelihood that the CP-even Higgs with large $WW, ZZ$ coupling will be very hard to detect at the LHC, but increase possibilities for detection of a neutral Higgs with enhanced $b\bar{b}$ coupling and for detection of the $h^+$ at the LHC.

Many such scenarios also suggest that $a_1$ detection in $gg \rightarrow a_1 \rightarrow \mu^+\mu^-$ at the LHC will be possible.
Reminders about the NMSSM $a_1$

- Define a generic coupling to fermions by

$$\mathcal{L}_{a_{\bar{f}f}} \equiv i C_{a_{\bar{f}f}} g_2 m_f \frac{f}{2m_W} f \gamma_5 f a,$$  \hspace{1cm} (5)

In the NMSSM, at tree level

$$C_{a_1 b\bar{b}} = \tan \beta \cos \theta_A,$$  \hspace{1cm} (6)

where

$$a_1 = \cos \theta_A a_{\text{MSSM}} + \sin \theta_A a_S.$$  \hspace{1cm} (7)

At large $\tan \beta$, SUSY corrections $C_{a_{\bar{b}b}} = C_{a_{\bar{b}b}}^{\text{tree}} [1/(1 + \Delta_b^{\text{SUSY}})]$ can be large and either suppress or enhance $C_{a_{\bar{b}b}}$ relative to $C_{a_{\tau-\tau+}}$. These are not included in next two plots, but are incorporated in final results.

- Limits on $C_{a_{\bar{b}b}}$ derive primarily from recent BaBar data (JFG, arXiv:0808.2509 and JFG+Dermisek, arXiv:0911.2460; see also Ellwanger and Domingo, arXiv:0810.4736) and appear in Fig. 2.
Figure 2: Limits on $C_{ab\bar{b}}$ from JFG, arXiv:0808.2509 and JFG+Dermisek, arXiv:0911.2460. These limits include recent BaBar $\Upsilon_{3S} \rightarrow \gamma\mu^+\mu^-$ and $\gamma\tau^+\tau^-$ limits. Color code: $\tan \beta = 0.5$; $\tan \beta = 1$; $\tan \beta = 2$; $\tan \beta \geq 3$. Keep an eye on $C_{ab\bar{b}} = 1$. 
In the NMSSM, the limits on $C_{ab\bar{b}}$ imply limits on $\cos \theta_A$ for any given choice of $\tan \beta$.

Figure 3: Curves are for $\tan \beta = 1$ (upper curve), 1.7, 3, 10, 32 and 50 (lowest curve).
As we have seen, the Upsilon constraints on a light $a$ run out for $m_a > M_{\Upsilon_{3S}}$. Tevatron data provides some constraints in this region.

The LHC will do much better.

At a hadron collider, one studies $gg \rightarrow a \rightarrow \mu^+\mu^-$ and reduces the heavy flavor background by isolation cuts on the muons.

At lowest order, the $gga$ coupling is induced by quark loops, esp. $b$ loops $\Rightarrow \sigma(gg \rightarrow a) \propto C^2_{a bb}$.

Higher order corrections, both virtual and real (e.g. for the latter $gg \rightarrow ag$) are, however, very significant.

So long as $m_a < 2m_B$, $B(a \rightarrow \mu^+\mu^-) \sim 0.002 - 0.003$ is normal in SUSY models at large $\tan \beta$, and rates for $gg \rightarrow a \rightarrow \mu^+\mu^-$ are generically very very large if the $a$ is mainly doublet.

However, for a fairly singlet $a \sim a_1$, these rates are reduced by $(\cos \theta_A)^2$ and, while still sizable, are often smaller than backgrounds and will be hard to dig out.
Table 1: Luminosities ($\text{fb}^{-1}$) needed for $5\sigma$ if $\tan \beta = 10$ and $\cos \theta_A = 0.1$.

<table>
<thead>
<tr>
<th>Case</th>
<th>$m_a = 8$ GeV</th>
<th>$m_a = M_{\Upsilon_1}^{S}$</th>
<th>$m_a \lesssim 2m_B$</th>
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<tr>
<td>ATLAS LHC7</td>
<td>17</td>
<td>63</td>
<td>9</td>
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<tr>
<td>ATLAS LHC10</td>
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<td>48</td>
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<tr>
<td>ATLAS LHC14</td>
<td>10</td>
<td>37</td>
<td>5.4</td>
</tr>
</tbody>
</table>

Current projections of CMS working group are still more favorable.

- Some DM scenarios with large $\sigma_{SI}$ have $|C_{ab\bar{b}}| \sim 1$ as presumed for Table 1; others have $|C_{ab\bar{b}}| \sim 5 - 25$, but with larger $m_{a_1}$ and therefore reduced $B(a_1 \rightarrow \mu^+\mu^-)$.

There are no current estimates as to ability of LHC to see such $a_1$. 
Dark Matter

(collaborators: D. Hooper and A. Belikov)

- There are now significant hints that the dark matter particle could be quite light ($\lesssim 10 \text{ GeV}$) and have large $\sigma_{SI}$.

- In the NMSSM, large $\sigma_{SI}$ from the $\tilde{\chi}_1^0$ is typically achieved for a fairly bino-like $\tilde{\chi}_1^0$ (with some higgsino/wino content).

- Sufficiently small $\Omega h^2$ is typically achieved via $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow a_1^* \rightarrow X$ annihilation.

- However, when $m_{\tilde{\chi}_1^0} \sim 5 - 10 \text{ GeV}$ the annihilation can easily be too strong if the Higgs sector forces $m_{a_1} \sim 10 \text{ GeV}$ (as is often the case).

  In such cases, the $a_1$ must be fairly singlet.

- There is a fairly clear strategy for maximising $\sigma_{SI}$. 
The largest elastic scattering cross sections arise in the case of large $\tan \beta$, significant $N_{13}$ (the Higgsino component of the $\tilde{\chi}_1^0$), and relatively light $m_{H_d}$, where $H_d$ is the Higgs with enhanced coupling to down quarks, $C_{H_d\bar{d}\bar{d}} \sim \tan \beta$. In this limit, the relevant scattering amplitude is

$$\frac{a_d}{m_d} \approx -\frac{g_2 g_1 N_{13} N_{11} \tan \beta}{4 m_W m_{H_d}^2},$$

(8)

which in turn yields

$$\sigma_{\tilde{\chi}_1^0 p,n} \approx \frac{g_2^2 g_1^2 N_{13}^2 N_{11}^2 \tan^2 \beta m_{\tilde{\chi}_1^0}^2 m_{p,n}^4}{4 \pi m_W^2 m_{H_d}^4 (m_{\tilde{\chi}_1^0} + m_{p,n})^2} \left[ f^{(p,n)}_{Ts} + \frac{2}{27} f^{(p,n)}_{TG} \right]^2$$

$$\approx 1.1 \times 10^{-41} \text{cm}^2 \left( \frac{N_{13}^2}{0.10} \right) \left( \frac{\tan \beta}{50} \right)^2 \left( \frac{100 \text{GeV}}{m_{H_d}} \right)^4. \quad (9)$$

The higgsino content of the lightest neutralino is constrained by the invisible width of the $Z$ as measured at LEP, $\Gamma_{\text{inv}}^{\text{LEP}} = 499 \pm 1.5$ MeV. In contrast, the standard model prediction for this quantity is slightly (1.4$\sigma$) higher,
\[ \Gamma_{\text{SM inv}} = 501.3 \pm 0.6 \text{ MeV}. \] Combining the measured and predicted values, we find a 2\(\sigma\) upper limit of \(\Gamma_{Z \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0} < 1.9 \text{ MeV.}\)

As \(\Gamma_{Z \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0}\) scales with \([N_{13}^2 - N_{14}^2]^2\), we can translate this result to a limit of \(|N_{13}^2 - N_{14}^2| < 0.103\). For moderate or large values of \(\tan \beta\), the two higgsino terms do not efficiently cancel, leading us to conclude that \(|N_{13}^2| < 0.103\).

There are also important constraints arising from \(e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_i^0\) for the relevant parameter regions.

- In the MSSM, it is only the heavier of the two CP-even Higgs bosons, the \(H^0\), that can have enhanced down-type coupling in the region allowed by LEP Higgs constraints, while it is the lighter \(h^0\) that will play the role of the SM-like Higgs.

- In the NMSSM, there are actually two choices.
  1. The \(h_1\) is SM-like while the \(h_2\) (or \(h_3\) — not good for large \(\sigma_{SI}\)) has enhanced \(C_{h_2dd}\) (the generalized analogue of \(\tan \beta\)).
This configuration suffers from the fact that the $h_2$ is not as light as might be possible.

In fact, we find that the largest cross sections do not arise from this configuration.

**Corollary:** Cogent-like cross sections in the MSSM are not possible since it is always the case that it is the (at least moderately heavy) $H^0$ that is $\sim H_d$.

2. The $h_1$ has enhanced $C_{h_1d\bar{d}}$ while the $h_2$ is SM-like.

We find that this configuration gives the largest $\sigma_{SI}$ values: a factor of 10 larger $\sigma_{SI}$ is possible relative to the former configuration.

- Constraints on the 2nd configuration are significant!

1. **Constraints on the neutral Higgs sector from $Zh_2$ at LEP.**

   These are important since we can minimize $m_{h_1}$ for low $m_{SUSY}$ and this keeps $m_{h_2}$ low.

   In these cases the $h_2$ can be in the “ideal” zone and escapes LEP detection via $h_2 \rightarrow a_1a_1$ decays with $m_{a_1} < 2m_B$ (but very close to avoid BaBar limits).
Recall again that Dermisek and I have argued that the necessary “light-$a_1$” finetuning is not large due to the $U(1)_R$ symmetry limit of the NMSSM.

2. **LEP constraints on $h_1a_1$ and $h_1a_2$.**

The $h_1a_1$ cross section is $\propto \text{maximal} \times (\cos \theta_A)^2$. Thus, small $\cos \theta_A$ is desirable, which fits with the need for not having strong $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow a_1^* \rightarrow X$ annihilations, so as to achieve adequate $\Omega h^2$.

3. **Tevatron limits.**

There are two especially relevant limits given focus on large $\tan \beta$:

(a) $b\bar{b}h_1$ associated production, which scales as $C_{h_1b\bar{b}}^2$, the latter being something we want to maximize.

(b) And, since the $h^+$ tends to be quite light (e.g. $\sim 120 - 140$ GeV) when the $h_2$ is SM-like, it is quite critical to include constraints from Tevatron limits on $t \rightarrow h^+b$ with $h^+ \rightarrow \tau^+\nu_\tau$ (the dominant mode at large $\tan \beta$).

We will (at most) accept any parameter choices that yield less than a $2\sigma$ excess from the current limits in these two cases, but will also summarize how keeping only points with at most $1\sigma$ excess affects results.
Figure 4: In left plot, must correct for fact that these curves assume $m_{H^0} \sim m_{A^0}$ which does not normally apply in our case.

4. **$B$-physics constraints.**

(a) The most restricting constraint arises from the very strong limit on $B(B_s \rightarrow \mu^+\mu^-)$.

Achieving a small enough value fixes $A_t$ as a function of $m_{\text{SUSY}}$.

(b) $b \rightarrow s\gamma$. 
- The $\mu > 0$ scenarios have roughly $1\sigma$ discrepancy with the $2\sigma$ experimental window.
- The $\mu < 0$ scenarios only rarely have a $b \rightarrow s\gamma$ problem.

(c) $B^+ \rightarrow \tau^+\nu_{\tau}$.
- The $\mu > 0$ scenarios are mostly within the $2\sigma$ experimental window.
- The $\mu < 0$ scenarios with largest $\sigma_{SI}$ typically have $1-2\sigma$ deviations from the experimental $2\sigma$ window.

5. $(g - 2)_\mu$.
This is possibly crucial.
- For $\mu < 0$, the largest $\sigma_{SI}$ values are achieved when $(g - 2)_\mu$ is a few sigma outside the $2\sigma$ limits including theoretical uncertainties.
  If $(g - 2)_\mu$ is strictly enforced, then it is not possible to get $\sigma_{SI}$ as large as that suggested by the COGENT data.
- For $\mu > 0$, the largest $\sigma_{SI}$ (so far) yield $(g - 2)_\mu$ within the $2\sigma$ exp. + theor. window, but (again, so far) after including all other constraints the $\sigma_{SI}$ values for $\mu > 0$ are not as large as those found with $\mu < 0$. 
Results

NMSSM Cogent–like points: $\mu = -200$ GeV

Figure 5: $\mu < 0$: all points. Almost all these points have $m_{eff} < 115$ GeV.
Figure 6: $\mu > 0$: all points (so far). Observe that the $m_{\text{SUSY}} = 1000$ GeV points are a factor of about 2 lower than equivalent $\mu < 0$ points. No low-$m_{\text{SUSY}}$ points with large $\sigma_{SI}$ have emerged so far after imposing Higgs sector restrictions including LEP constraints.
Figure 7: $\mu < 0$: all points with no more than 1\,$\sigma$ discrepancy with $h_1(\rightarrow \tau^+\tau^-)b\bar{b}$ and/or $t \rightarrow h^+ (\rightarrow \tau^+\nu)b$ Tevatron bounds. Note that highest-$\sigma_{SI}$ large-$\tan\beta$ points have disappeared.
Figure 8: \( \mu < 0 \): all points with \( m_{e,f} < 110 \) GeV. Note that \( m_{\text{SUSY}} = 1000 \) GeV points have disappeared, but there are still some low-\( m_{\text{SUSY}} \) points on Cogent region border. Note: points 22 and 23 are common to this and previous figure.
Figure 9: $\mu < 0$: all points. Note that both $m_{h_2}$ and $m_{h_1}$ are below or not far above 110 GeV.
Figure 10: $\mu < 0$: all points. Note that $m_{h^+}$ is also small.
Figure 11: $\mu < 0$: all points. The cluster of (pretty good) blue points ($m_{\text{SUSY}} = 500 \text{ GeV}$) near $m_{a_1} \sim 10 \text{ GeV}$ will have “significant” $B(a_1 \to \mu^+\mu^-)$ and should be readily observable at the LHC using $gg \to a_1 \to \mu^+\mu^-$. (Of course, they may be eliminated using first run data: c.f. Table 1 with $|C_{a_1bb}| \sim 1$.)
Figure 12: $\mu < 0$: all points. Note: one or the other of $h_2$ or $h_1$, and usually $h_2$, is SM-like.
In a very recent paper by Das and Ellwanger (arXiv:1007.1151), cross sections as large as those found here are not achieved. They have all $\sigma_{SI}$ near $10^{-6}$ pb (without enhancing $s$ content of nucleon).

It may be that their smaller $\sigma_{SI}$ is largely because they did not seek scenarios with $h_1 \sim H_d$. In addition, they did not take advantage of the $m_{a_1} \sim 10$ GeV possibilities (they regard these as too finetuned). Should we opt for enhanced-$s$ quark nucleon content, our cross sections would go up by about the same factor of $\sim 3$ as in their plot.
Conclusions

- If you are willing to relax a few $B$ physics bounds and/or $(g - 2)_\mu$ bounds, then the SM-like Higgs can be in the ideal mass range and $\sigma_{SI}$ can be Cogent-like.
• We theorists have been going a bit crazy waiting for THE Higgs and THE dark matter particle. There is a good chance that the Higgs sector and Dark Matter are strongly related.

• "Unfortunately", a lot of the theories developed make sense, but I remain enamored of the NMSSM scenarios and hope for eventual verification that nature has chosen "wisely".

• The first sign of the Higgs sector could be detection of a light $a$ and such
an *a* could play a crucial role in the case of light dark matter.

- Meanwhile, all I can do is watch and wait (but perhaps not from quite so close a viewpoint).