New Results for NMSSM Higgs and Dark Matter

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NMSSM Review

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

$$W = \lambda \, \widehat{S}\widehat{H}_u\widehat{H}_d + \frac{\kappa}{3} \, \widehat{S}^3 \tag{1}$$

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

$$\mu_{\rm eff} = \lambda \langle S \rangle \, . \tag{2}$$

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

- The extra singlet field $\widehat{S}$ implies: 5 neutralinos, $\widetilde{\chi}^0_{1-5}$ with $\widetilde{\chi}^0_1$ 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:

$$\lambda A_\lambda S H_u H_d + \frac{\kappa}{3} A_\kappa S^3 . \quad (3)$$

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 $A_\lambda \sim 100 \text{ GeV}$ and $A_\kappa \sim 1 - 20 \text{ GeV}$, 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 $\sqrt{m_{\widetilde{t}_1} m_{\widetilde{t}_2}} \sim 350-500~\mathrm{GeV}$, 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 $m_H \sim 90 - 110~\mathrm{GeV}$.

- 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 $m_H \sim 50~\mathrm{GeV}$ and with a 95% CL upper limit of $\sim 105~\mathrm{GeV}$ (Chanowitz, xarXiv:0806.0890).

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

- Largest LEP excess: Perhaps the Higgs should be such as to predict the

2.3σ excess at $M_{b\bar{b}} \sim 98~\mathrm{GeV}$ seen in the $Z + b\bar{b}$ final state.

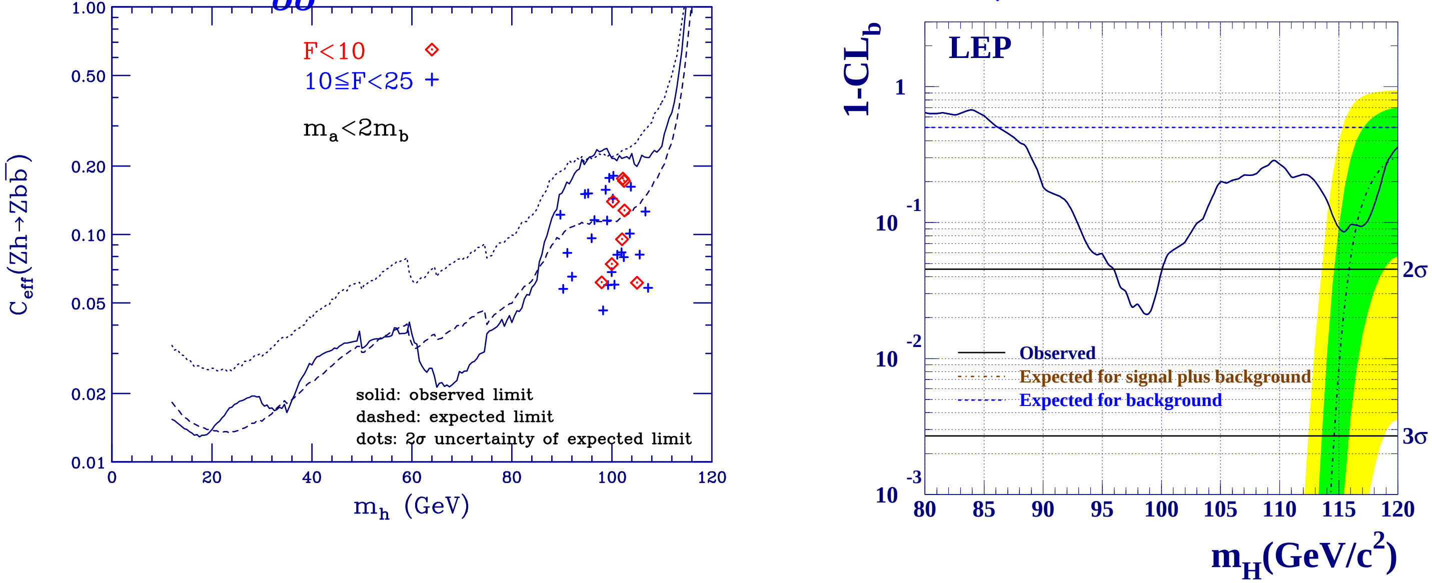


Figure 1: Plots for the $Zb\bar{b}$ final state. F is the m_Z-fine-tuning measure for the NMSSM.

- The simplest possibility for the excess is to have $m_H \sim 100~\mathrm{GeV}$ 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 $H \to a_1 a_1$ 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 $H \to a_1 a_1 \to 4\tau$ tend to force one to the region of $10~\mathrm{GeV} \lesssim m_{a_1}$ when $m_H < 110~\mathrm{GeV}$.

  This is also the region where BaBar limits from Υ_{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_λ and A_κ need not be chosen very precisely — 20% or so is ok — to get large $B(h_1 \to a_1 a_1)$ 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 $m_{h_2} \lesssim 105 - 110~\mathrm{GeV}$ 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

$$\ln m_{eff} = \sum_i C_V^2(i) \ln m_{h_i} \,, \quad (4)$$

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

- 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 ($m_{\widetilde{\chi}_1^0} < 10~\mathrm{GeV}$) dark matter with correct relic density.

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

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

- Other points consistent with Cogent σ_{SI} with $110~\mathrm{GeV} \lesssim m_{h_2} \lesssim 115~\mathrm{GeV}$ (and $C_V(2) \sim 1$) are less attractive from the EWSB finetuning point of view but can have any m_{a_1} because $B(h_2 \to a_1 a_1 \to 4b) \sim 1$ is allowed in $e^+e^- \to Zh_2$ in this mass range.

- $\Omega h^2 \sim 0.1$ and large σ_{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 $b\overline{b}$ coupling and for detection of the h^+ at the LHC.

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

Reminders about the NMSSM a_1

- Define a generic coupling to fermions by

$$\mathcal{L}_{af\bar{f}} \equiv iC_{af\bar{f}} \frac{ig_2 m_f}{2m_W} \bar{f} \gamma_5 f a \,, \tag{5}$$

In the NMSSM, at tree level

$$C_{a_1 b\bar{b}} = \tan\beta \cos\theta_A \,, \tag{6}$$

where

$$a_1 = \cos\theta_A a_{MSSM} + \sin\theta_A a_S \,. \tag{7}$$

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

- Limits on $C_{ab\bar{b}}$ 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.

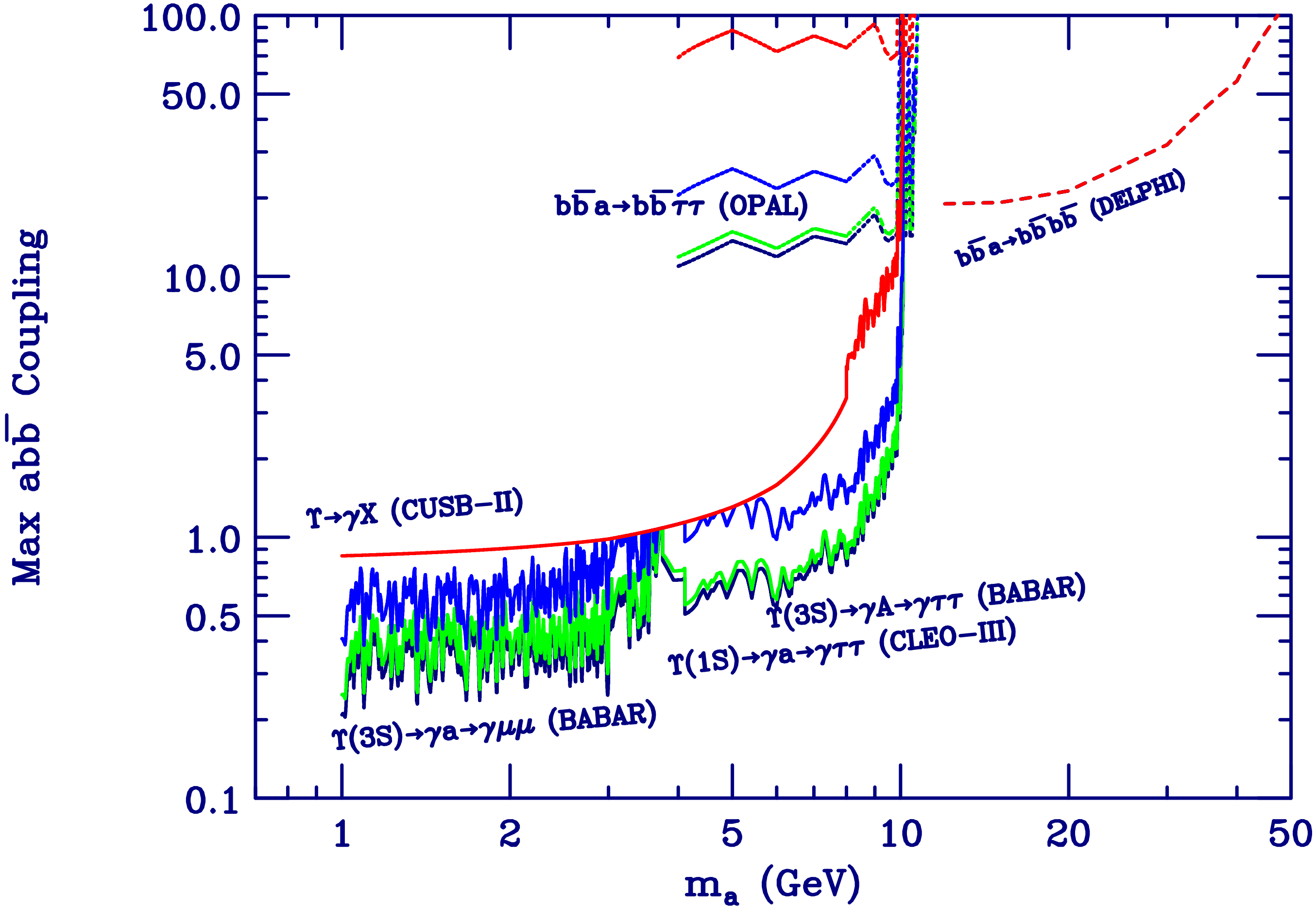


Figure 2: Limits on $C_{ab\bar{b}}$ from JFG, arXiv:0808.2509 and JFG+Dermisek, arXiv:0911.2460. These limits include recent BaBar $\Upsilon_{3S} \to \gamma\mu^+\mu^-$ and $\gamma\tau^+\tau^-$ limits. Color code: $\tan\beta = 0.5$; $\tan\beta = 1$; $\tan\beta = 2$; $\tan\beta \geq 3$. Keep an eye on $C_{ab\bar{b}} = 1$.

- **In the NMSSM, the limits on $C_{ab\bar{b}}$ imply limits on $\cos\theta_A$ for any given choice of $\tan\beta$.**

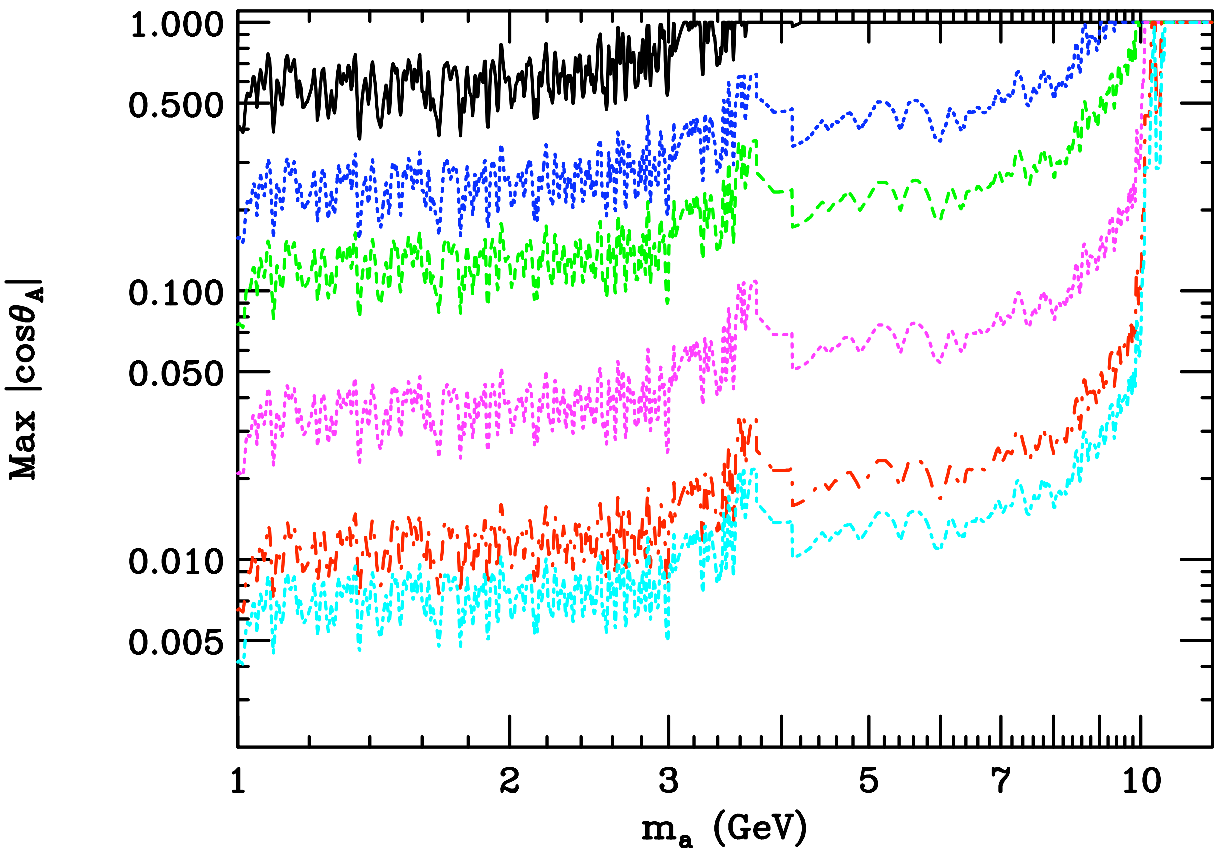


Figure 3: **Curves are for $\tan\beta = 1$ (upper curve), 1.7, 3, 10, 32 and 50 (lowest curve).**

- 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 $gg \to a \to \mu^+\mu^-$ 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 $\Rightarrow \sigma(gg \to a) \propto C^2_{ab\bar{b}}$.

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

- So long as $m_a < 2m_B$, $B(a \to \mu^+\mu^-) \sim 0.002 - 0.003$ is normal in SUSY models at large $\tan\beta$, and rates for $gg \to a \to \mu^+\mu^-$ are generically 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 (fb^{-1}) needed for 5σ if $\tan\beta = 10$ and $\cos\theta_A = 0.1$.

Case	$m_a = 8$ GeV	$m_a = M_{\Upsilon_{1S}}$	$m_a \lesssim 2m_B$
ATLAS LHC7	17	63	9
ATLAS LHC10	13	48	7
ATLAS LHC14	10	37	5.4

Current projections of CMS working group are still more favorable.

- Some DM scenarios with large σ_{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 $B(a_1 \to \mu^+\mu^-)$.

  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 ($\lesssim 10$ GeV) and have large σ_{SI}.

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

- Sufficiently small Ωh^2 is typically achieved via $\widetilde{\chi}_1^0\widetilde{\chi}_1^0 \to a_1^* \to X$ annihilation.

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

  In such cases, the a_1 must be fairly singlet.

- There is a fairly clear strategy for maximising σ_{SI}.

The largest elastic scattering cross sections arise in the case of large $\tan\beta$, significant N_{13} (the Higgsino component of the $\widetilde\chi_1^0$), and relatively light m_{H_d}, where H_d is the Higgs with enhanced coupling to down quarks, $C_{H_d d\bar d} \sim \tan\beta$. In this limit, the relevant scattering amplitude is

$$\frac{a_d}{m_d} \approx \frac{-g_2 g_1 N_{13} N_{11} \tan\beta}{4 m_W m_{H_d}^2}, \tag{8}$$

which in turn yields

$$\begin{aligned} \sigma_{\widetilde\chi_1^0 p,n} &\approx \frac{g_2^2\, g_1^2\, N_{13}^2 N_{11}^2\, \tan^2\beta\, m^2_{\widetilde\chi_1^0}\, m^4_{p,n}}{4\pi\, m_W^2 m_{H_d}^4\, (m_{\widetilde\chi_1^0} + m_{p,n})^2} \left[f_{T_s}^{(p,n)} + \frac{2}{27} f_{TG}^{(p,n)} \right]^2 \\ &\approx 1.1 \times 10^{-41} \mathrm{cm}^2 \left(\frac{N_{13}^2}{0.10} \right) \left(\frac{\tan\beta}{50} \right)^2 \left(\frac{100\mathrm{GeV}}{m_{H_d}} \right)^4 . \end{aligned} \tag{9}$$

The higgsino content of the lightest neutralino is constrained by the invisible width of the Z as measured at LEP, $\Gamma_{\rm inv}^{\rm LEP} = 499 \pm 1.5$ MeV. In contrast, the standard model prediction for this quantity is slightly (1.4σ) higher,

$\Gamma_{\rm inv}^{\rm SM} = 501.3 \pm 0.6$ MeV. Combining the measured and predicted values, we find a 2σ upper limit of $\Gamma_{Z\to\widetilde\chi_1^0\widetilde\chi_1^0} < 1.9$ MeV.

As $\Gamma_{Z\to\widetilde\chi_1^0\widetilde\chi_1^0}$ 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 $e^+e^- \to \widetilde\chi_1^0\widetilde\chi_i^0$ 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 σ_{SI}) has enhanced $C_{h_2 d\bar d}$ (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 $C_{h_1 d\bar{d}}$ while the h_2 is SM-like.

   We find that this configuration gives the largest σ_{SI} values: a factor of 10 larger σ_{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 $m_{\rm SUSY}$ and this keeps m_{h_2} low.

   In these cases the h_2 can be in the "ideal" zone and escapes LEP detection via $h_2 \to a_1 a_1$ 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 $h_1 a_1$ and $h_1 a_2$.

   The $h_1 a_1$ cross section is $\propto maximal \times (\cos\theta_A)^2$. Thus, small $\cos\theta_A$ is desirable, which fits with the need for not having strong $\widetilde\chi_1^0 \widetilde\chi_1^0 \to a_1^* \to X$ annihilations, so as to achieve adequate Ωh^2.

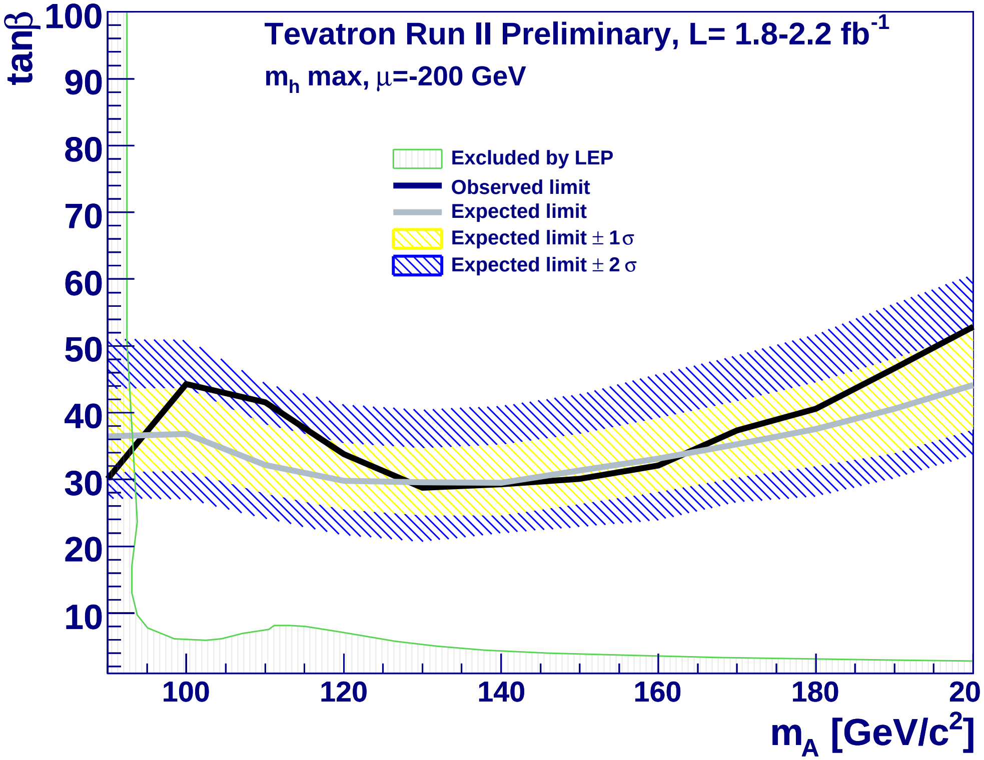
3. Tevatron limits.

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

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

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

   We will (at most) accept any parameter choices that yield less than a 2σ excess from the current limits in these two cases, but will also summarize how keeping only points with at most 1σ excess affects results.



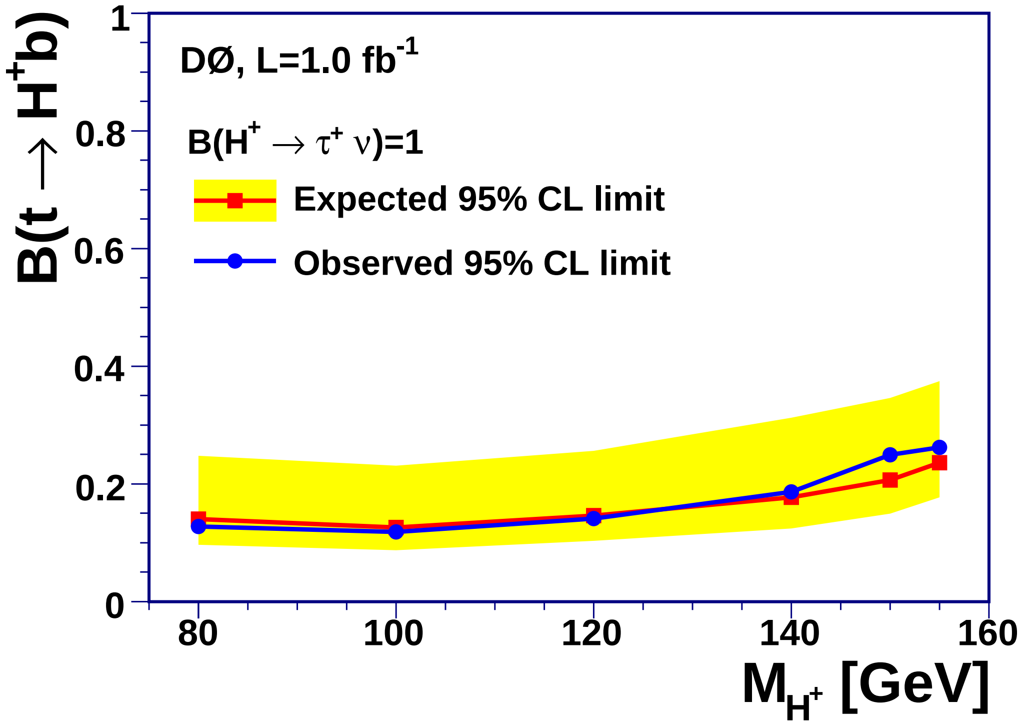


Figure 4: In left plot, must correct for fact that these curves assume $m_{H^0} \sim m_{A^0}$ which does not normally apply in our case.

4. B-physics constraints.
   (a) The most restricting constraint arises from the very strong limit on $B(B_s \to \mu^+\mu^-)$.
   Achieving a small enough value fixes A_t as a function of $m_{\rm SUSY}$.
   (b) $b \to s\gamma$.

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

(c) $B^+ \to \tau^+ \nu_\tau$.

- The $\mu > 0$ scenarios are mostly within the 2σ experimental window.
- The $\mu < 0$ scenarios with largest σ_{SI} typically have $1-2\sigma$ deviations from the experimental 2σ window.

5. $(g-2)_\mu$.

This is possibly crucial.

- For $\mu < 0$, the largest σ_{SI} values are achieved when $(g-2)_\mu$ is a few sigma outside the 2σ limits including theoretical uncertainties.

  If $(g-2)_\mu$ is strictly enforced, then it is not possible to get σ_{SI} as large as that suggested by the COGENT data.
- For $\mu > 0$, the largest σ_{SI} (so far) yield $(g-2)_\mu$ within the 2σ exp.+theor. window, but (again, so far) after including all other constraints the σ_{SI} values for $\mu > 0$ are not as large as those found with $\mu < 0$.

Results

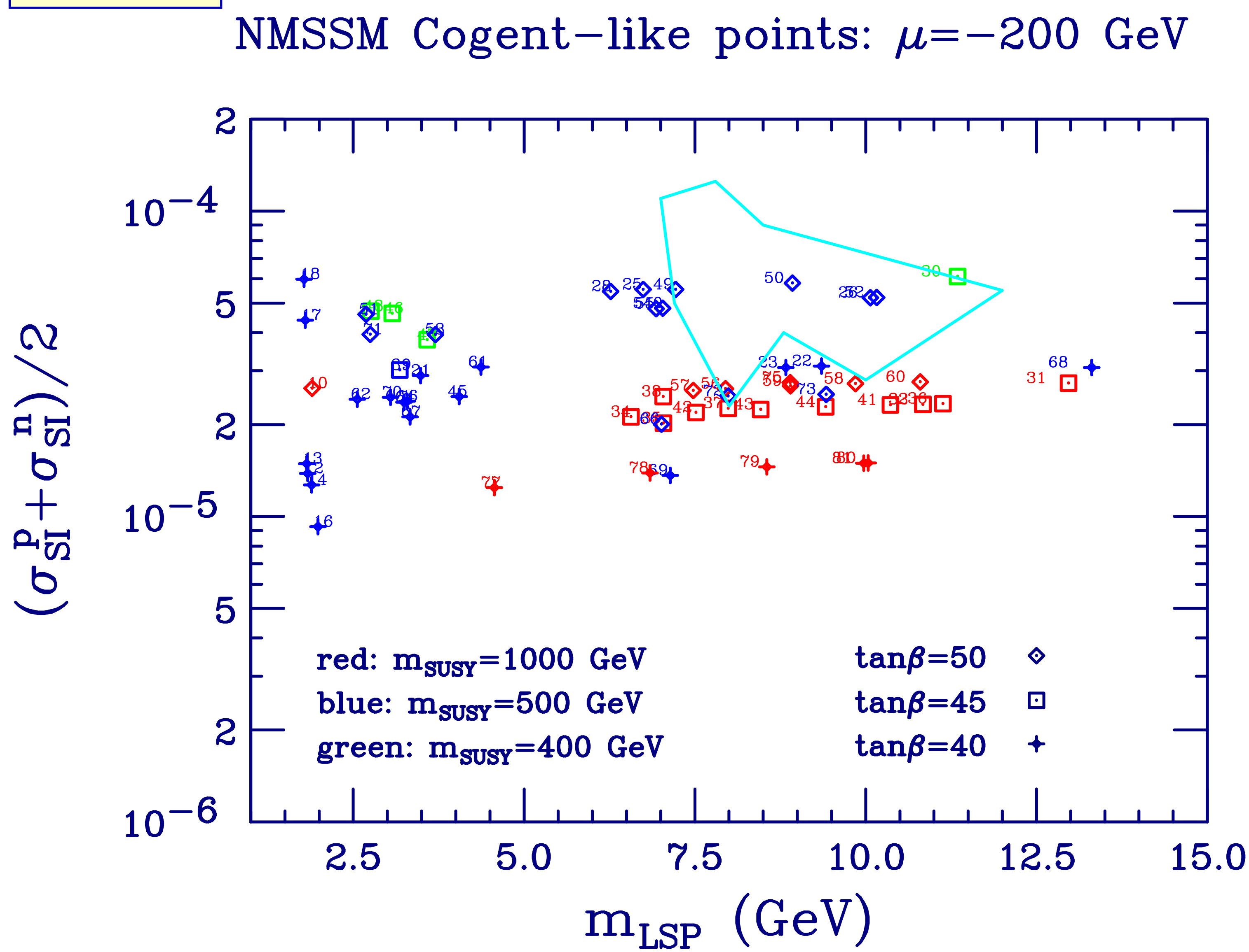


Figure 5: $\mu < 0$: all points. Almost all these points have $m_{eff} < 115$ GeV.

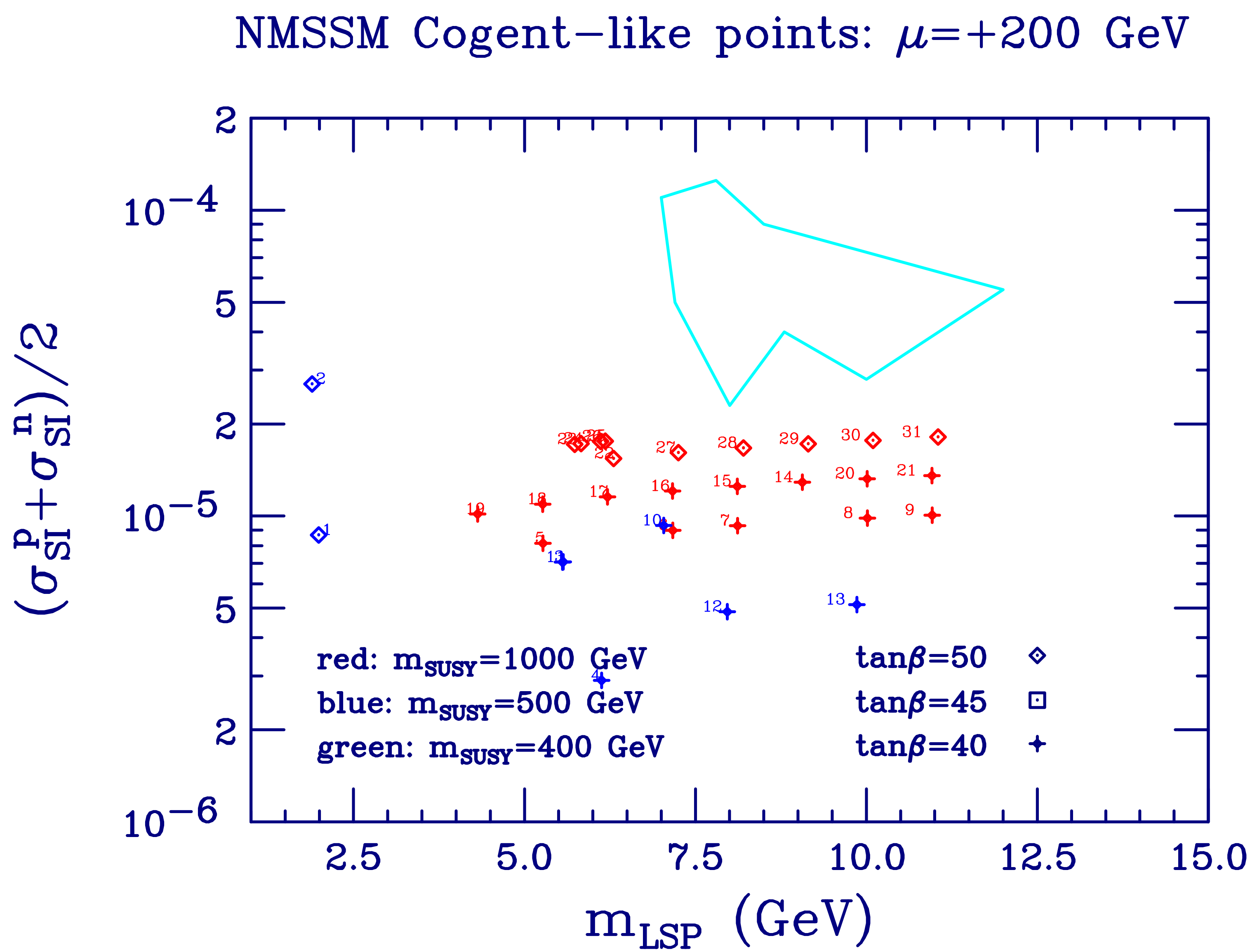


Figure 6: $\mu > 0$: all points (so far). Observe that the $m_{\rm SUSY} = 1000~{\rm GeV}$ points are a factor of about 2 lower than equivalent $\mu < 0$ points. No low-$m_{\rm SUSY}$ points with large σ_{SI} have emerged so far after imposing Higgs sector restrictions including LEP constraints.

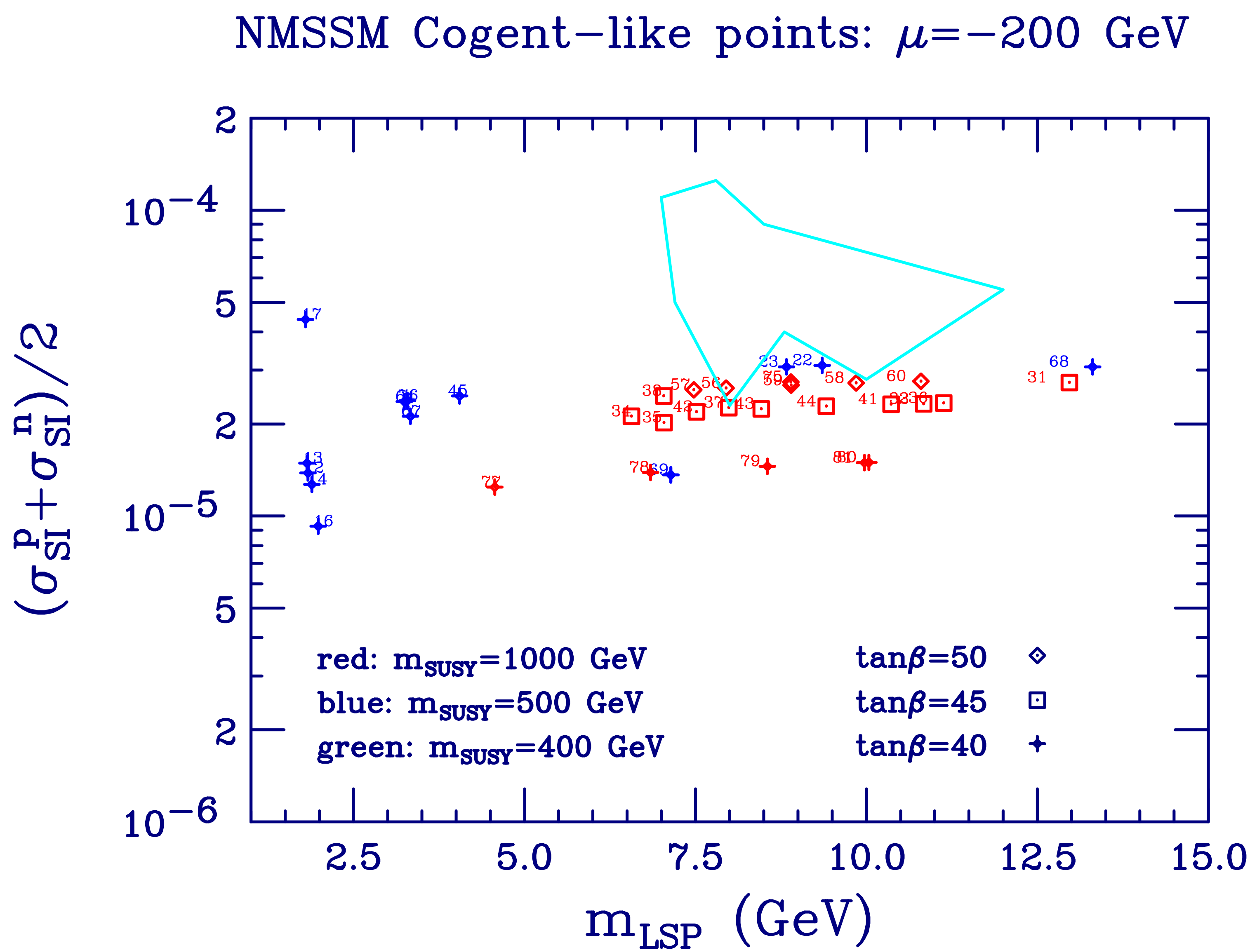


Figure 7: $\mu < 0$: **all points with no more than** 1σ **discrepancy with** $h_1(\to \tau^+\tau^-)b\overline{b}$ **and/or** $t \to h^+(\to \tau^+\nu)b$ **Tevatron bounds. Note that highest-**σ_{SI} **large-**$\tan\beta$ **points have disappeared.**

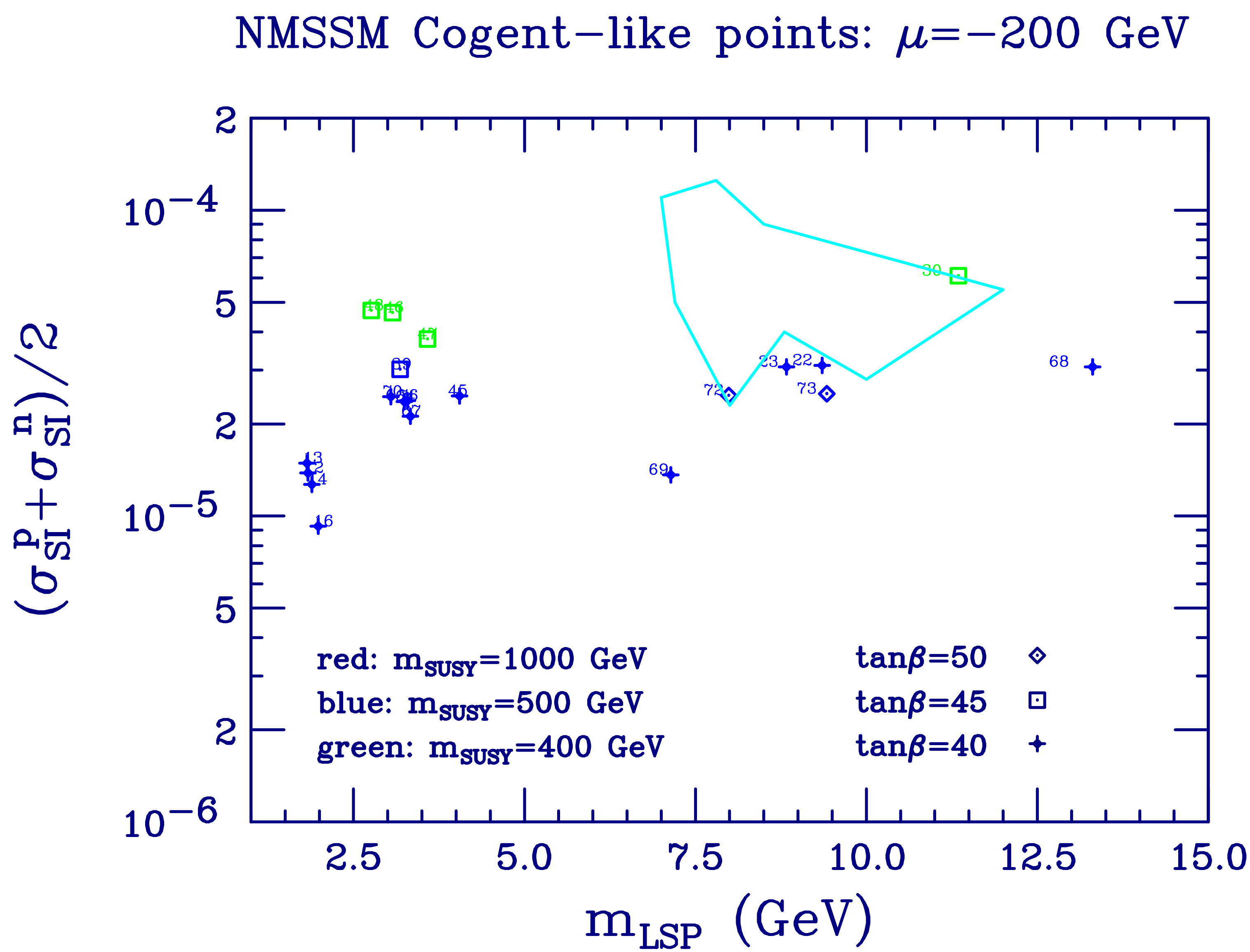


Figure 8: $\mu < 0$: **all points with** $m_{eff} < 110$ GeV. **Note that** $m_{\rm SUSY} = 1000$ GeV **points have disappeared, but there are still some low-**$m_{\rm SUSY}$ **points on Cogent region border.**

Note: points 22 and 23 are common to this and previous figure.

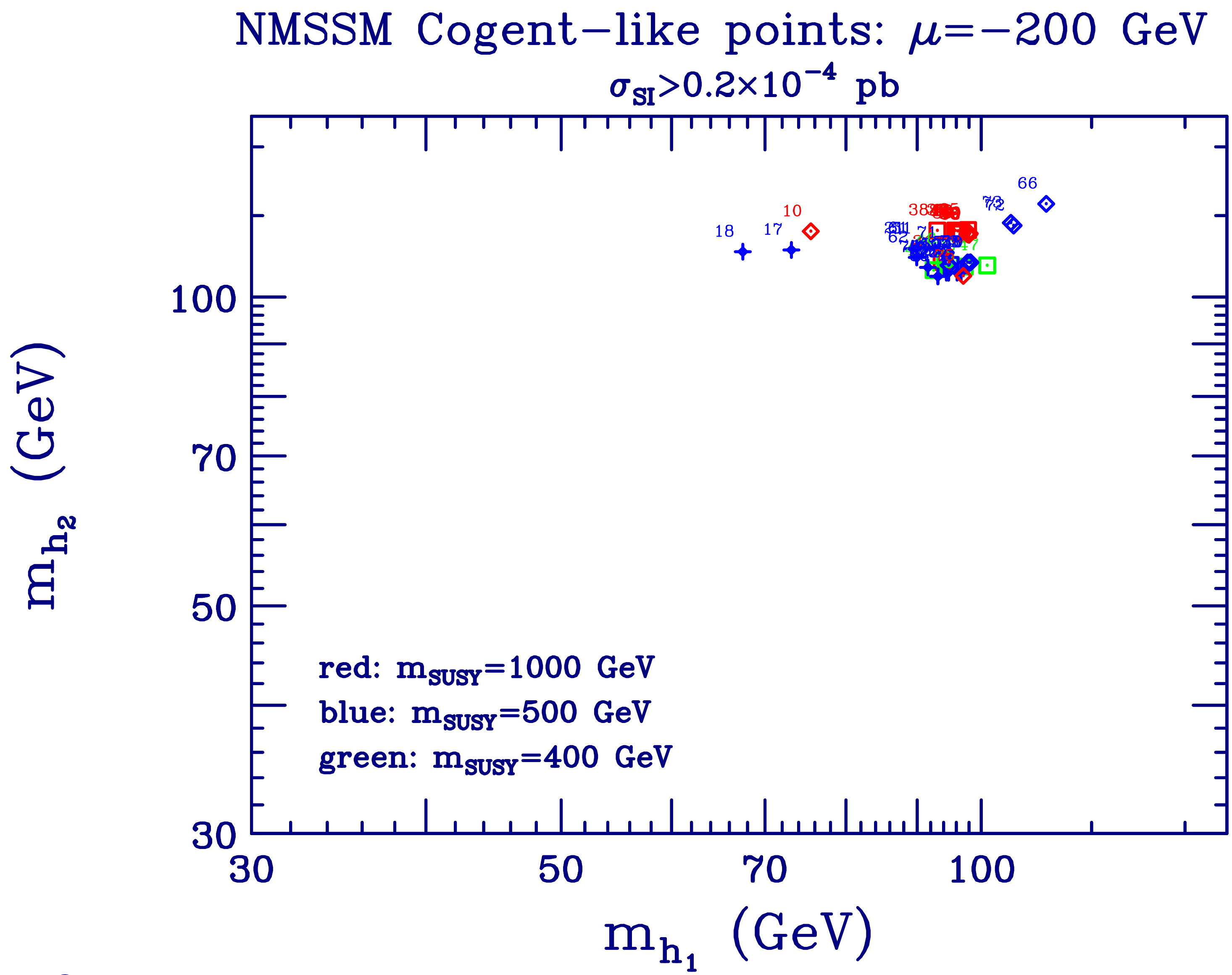


Figure 9: $\mu < 0$: all points. Note that both m_{h_2} and m_{h_1} are below or not far above $110~\mathrm{GeV}$.

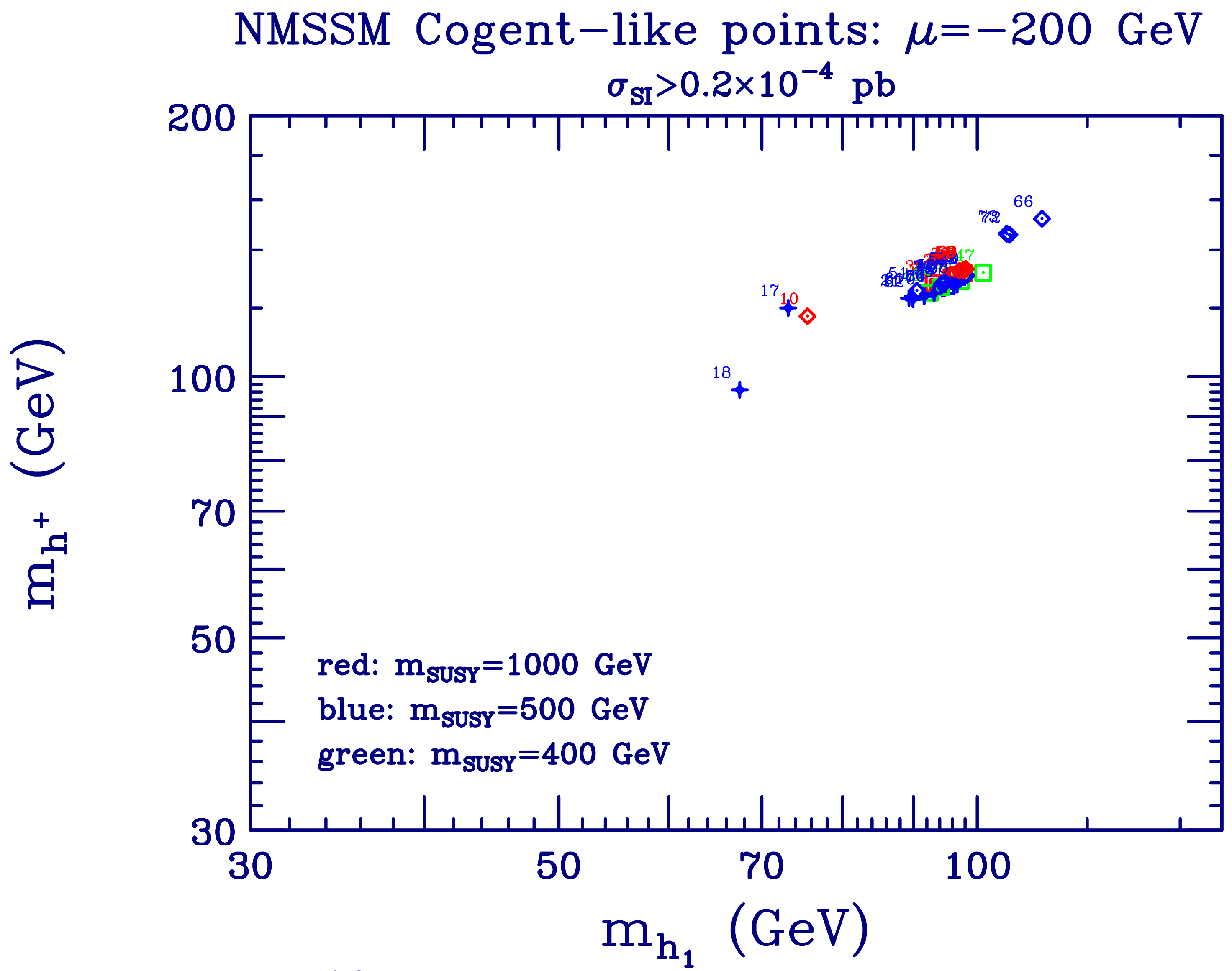


Figure 10: $\mu < 0$: all points. Note that m_{h^+} is also small.

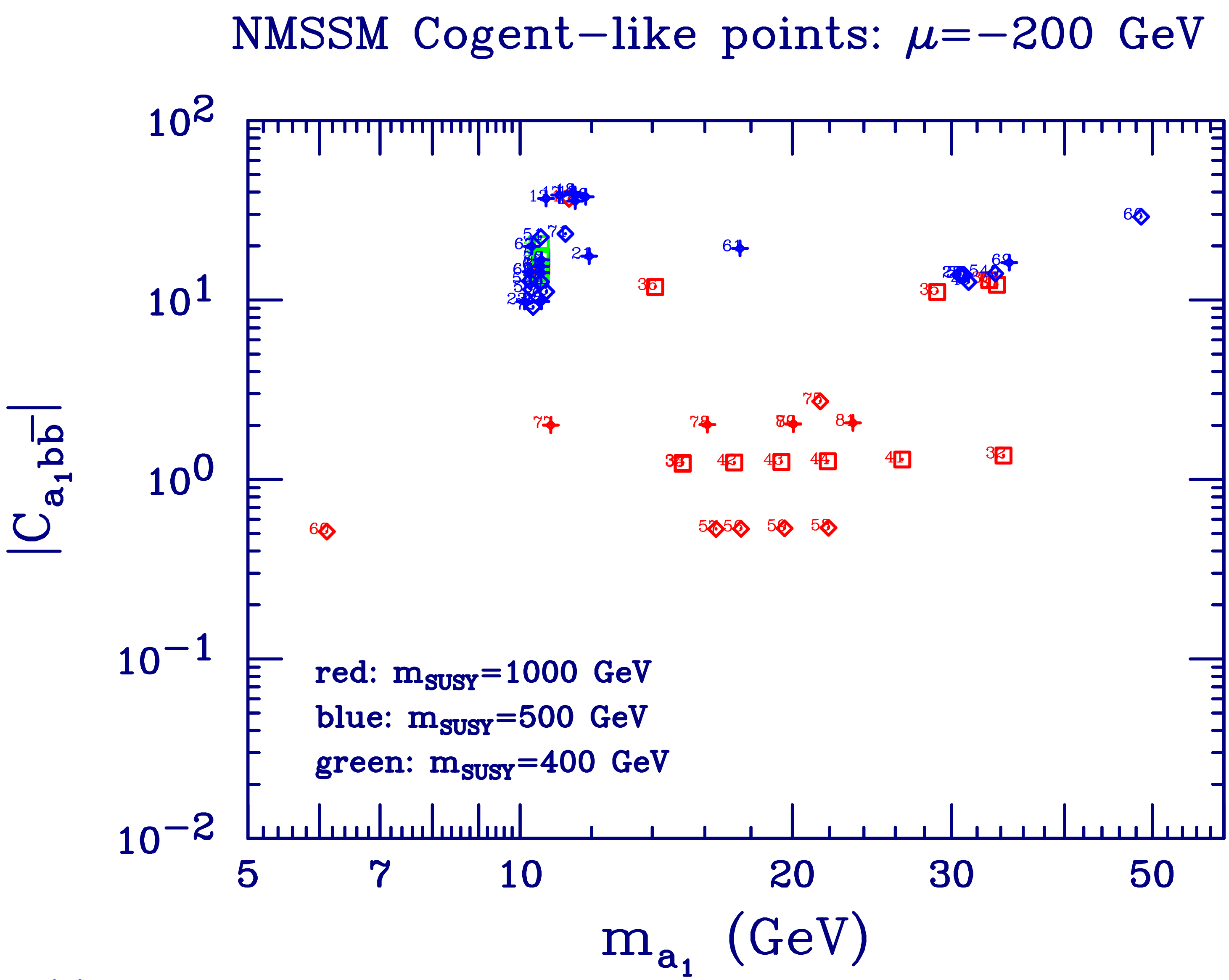


Figure 11: $\mu < 0$: all points. The cluster of (pretty good) blue points ($m_{\rm SUSY} = 500~{\rm GeV}$) near $m_{a_1} \sim 10~{\rm GeV}$ will have "significant" $B(a_1 \to \mu^+\mu^-)$ and should be readily observable at the LHC using $gg \to a_1 \to \mu^+\mu^-$. (Of course, they may be eliminated using first run data: c.f. Table 1 with $|C_{a_1 b\bar b}| \sim 1$.)

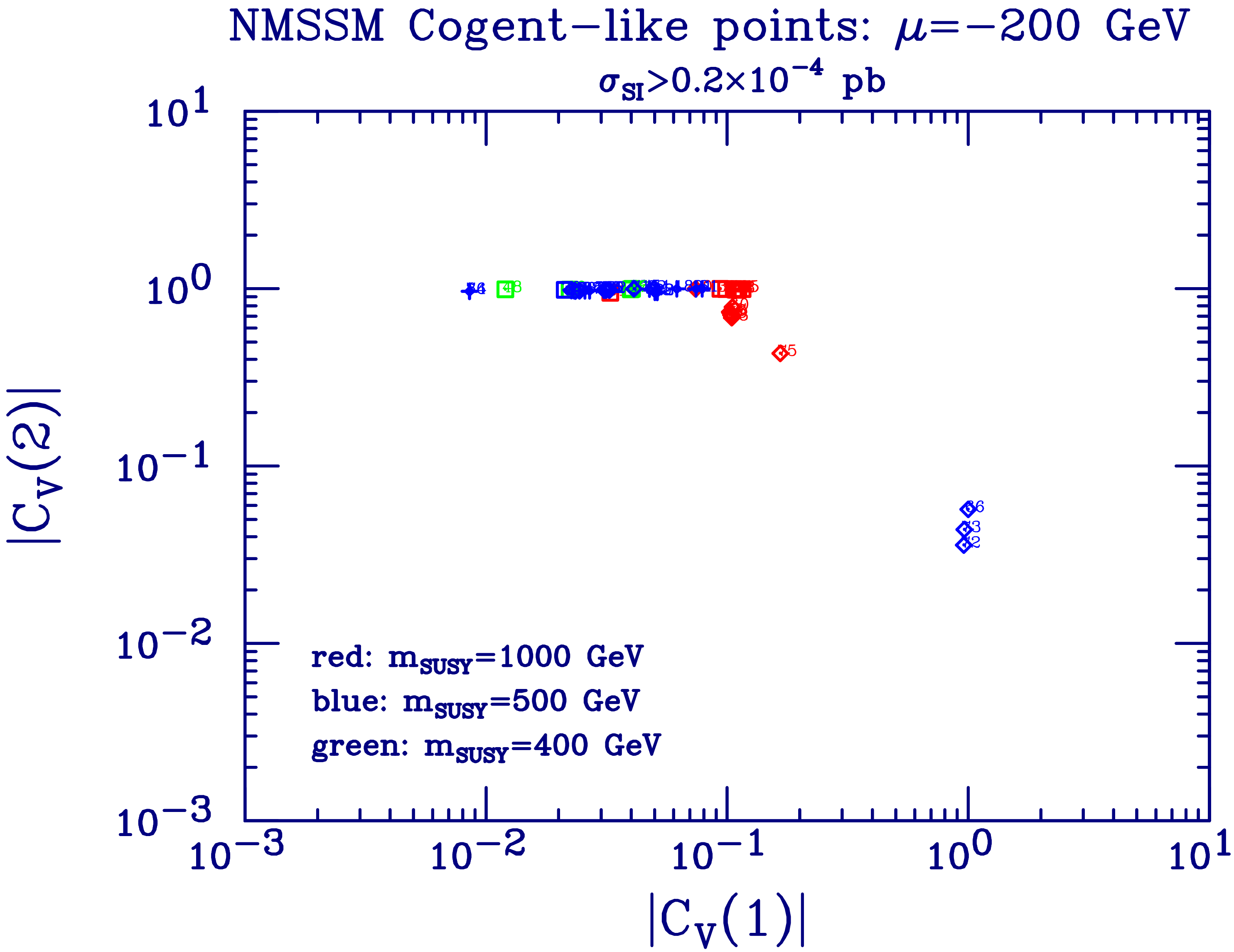


Figure 12: $\mu < 0$: all points. **Note:** one or the other of h_2 or h_1, and usually h_2, is SM-like.

- 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 σ_{SI} near 10^{-6} pb (without enhancing s content of nucleon).

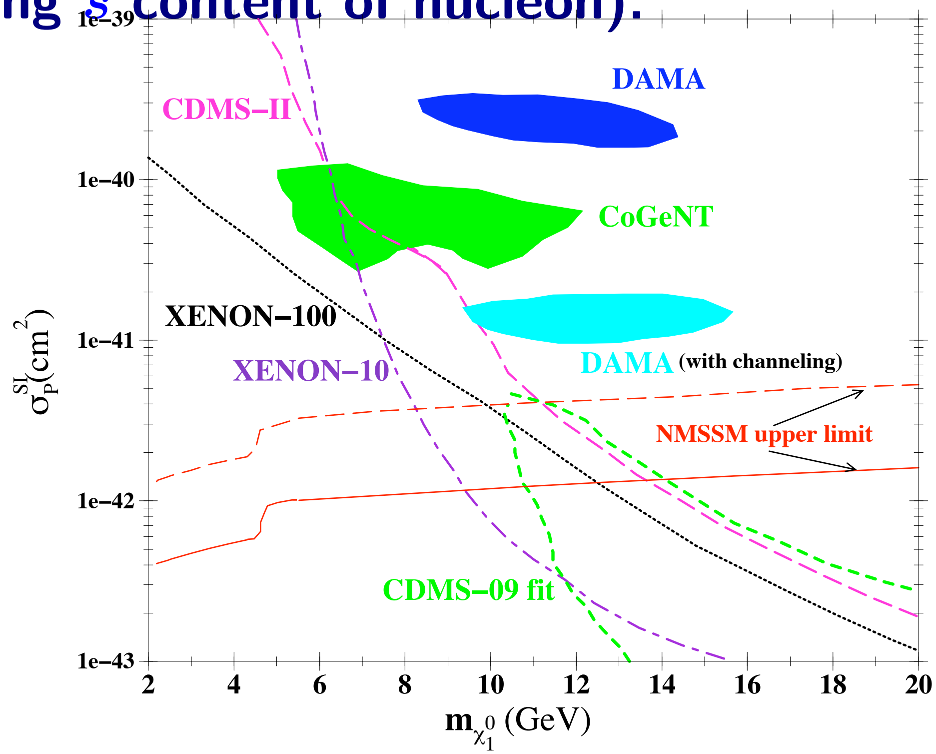


Figure 2: Upper bounds on the spin-independent cross section σ_p^{SI} in the NMSSM for default values of the strange quark content of nucleons as a full red line, and an enhanced strange quark content of nucleons as a dashed red line. Also shown are regions compatible with DAMA, CoGeNT and CDMS-II, and limits from Xenon10, Xenon100 and CDMS-II as explained in the text.

It may be that their smaller σ_{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 ~ 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 σ_{SI} can be Cogent-like.**

Front

Inside

- **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).