Updates on Higgs and Dark Matter in the NMSSM

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Outline

1. **Brief Review of NMSSM**
2. **Higgs in the NMSSM, new LEP limits and low fine-tuning**
3. **Implications for Dark Matter of a light CP-odd Higgs**

Brief NMSSM Review

- The LEP limits on Higgs bosons have pushed the MSSM into an awkward corner of parameter space characterized by very high fine-tuning, lack of electroweak baryogenesis, ...

  At a more fundamental level, a satisfactory explanation of the μ term in the MSSM superpotential, $\mu \widehat{H}_u \widehat{H}_d$, remains elusive.

  The NMSSM introduces an extra singlet superfield, with superpotential $\lambda \widehat{S} \widehat{H}_u \widehat{H}_d$. The μ parameter is then automatically generated by $\langle S \rangle$ leading to $\mu_{eff} \widehat{H}_u \widehat{H}_d$ with $\mu_{eff} = \lambda \langle S \rangle$.

  Another substantial motivation for something like the NMSSM is that extra singlet fields are common in string models.

  The single extra singlet superfield of the NMSSM contains an extra neutral gaugino (the singlino) ($\Rightarrow \widetilde{\chi}^0_{1,2,3,4,5}$), an extra CP-even Higgs boson ($\Rightarrow h_{1,2,3}$) and an extra CP-odd Higgs boson ($\Rightarrow a_{1,2}$).

  The result is that the NMSSM is much less constrained than the MSSM, and does not require awkward parameter choices in general. In my opinion, the NMSSM should be adopted as the more likely benchmark minimal

SUSY model and it should be explored in detail. There is much to do even after a number of years of working on this.

- To further this study, Ellwanger, Hugonie and I constructed NMHDECAY

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

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

  It computes all aspects of the Higgs sector and checks against LEP limits and various other constraints.

- We also developed a program to examine the LHC observability of Higgs signals in the NMSSM.

  A significant hole in the LHC no-lose theorem emerges: only if we avoid that part of parameter space for which $h \to aa$ and similar decays are present is there a guarantee for find a Higgs boson at the LHC in one of the nine "standard" channels (e.g. $h \to \gamma\gamma$, $t\bar{t}h, a \to t\bar{t}b\bar{b}$, $b\bar{b}h, a \to b\bar{b}\tau^+\tau^-$, $WW \to h \to \tau^+\tau^-$, to name the most important ones).

- The portion of parameter space with $h \to aa, \ldots$ is small $\Rightarrow$ one is tempted to ignore it were it not for the fact that it is where fine-tuning can be absent (small sensitivity to GUT scale SUSY boundary conditions).

Fine-Tuning and new LEP limits

with R. Dermisek

- Dermisek and I have shown that fine-tuning is absent in the NMSSM for precisely those parameter choices for which $h_1 \to a_1 a_1$ decays are present.

  In particular, the weaker LEP limits on such decays in the Zh production state allow a smaller value of m_h, which already goes a long way towards giving small fine-tuning.

  In addition, the NMSSM gives a natural algebraic reduction of fine-tuning when the lightest CP-odd Higgs boson has modest mass.

  After incorporating the latest LEP limits (to be discussed), we find the results shown in the following figure after doing a large scan. The $+$ points have $m_{h_1} < 114~\mathrm{GeV}$ and the $\times$ points have $m_{h_1} \geq 114~\mathrm{GeV}$.

  For $m_{h_1} < 114~\mathrm{GeV}$, one can achieve very low F values.

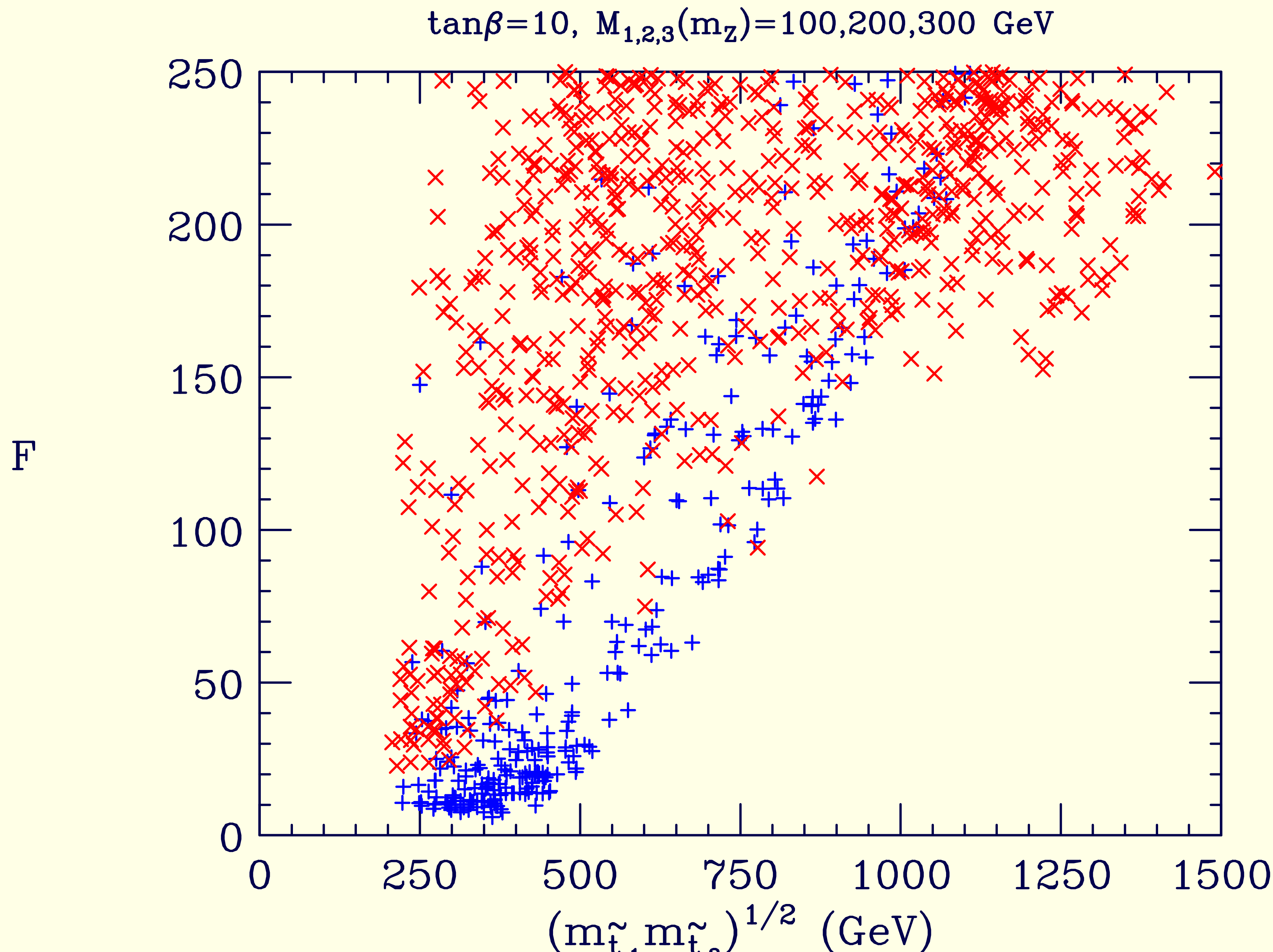

Figure 1: *F* as a function of root mean stop mass after latest LEP limits.

- **It is interesting to compare the new LEP limits for $Zh \to Zaa \to Z4b$ production to the old limits: Fig. 2.**

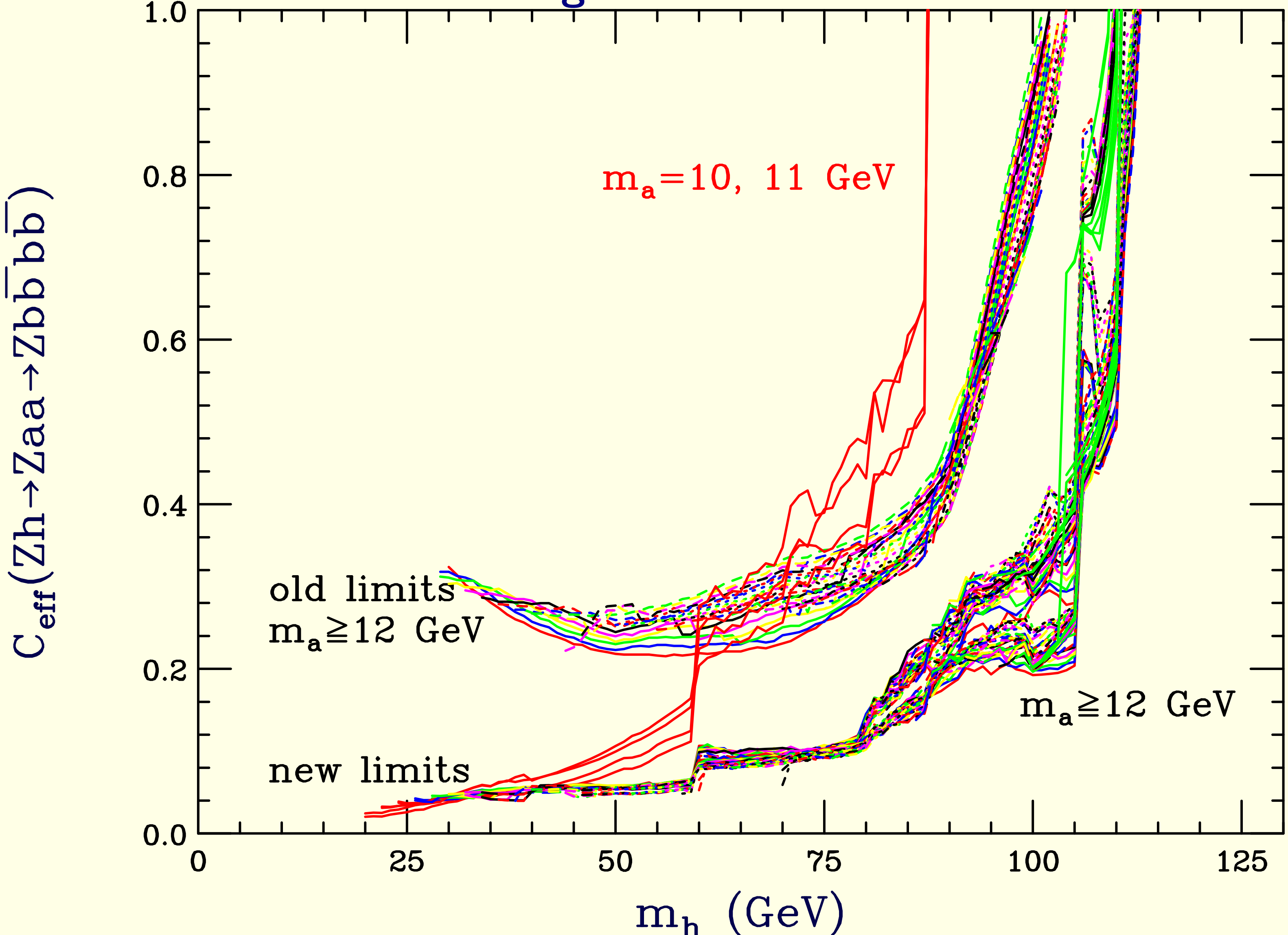

Figure 2: LEP limits on $C_{eff} = [g^2_{ZZh}/g_{ZZh^2_{SM}}]B(h_1 \to a_1a_1)[B(a_1 \to b\bar{b})]^2$, old and new. New are stronger but small F still possible.

- **It is particularly interesting to zero-in on the cases with the very lowest fine-tuning values: $F < 10$. The relevant plot appears in Fig. 3.**

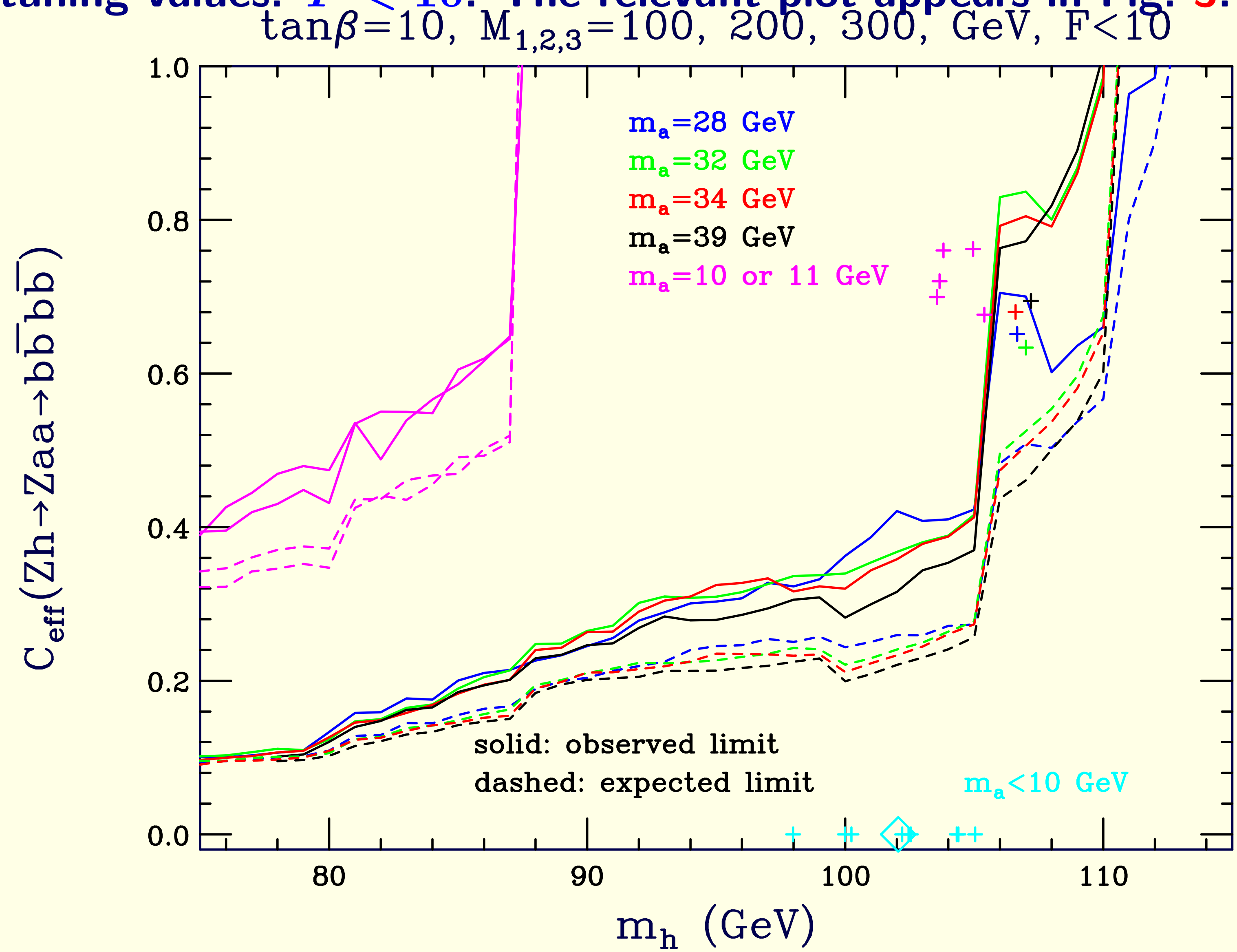

Figure 3: New LEP limits on C_{eff} and low-F points. Note the $m_{a_1} \sim 25-40$ points between expected and observed limits.

- Of course, we can also look at the $b\bar{b}$ final state which has some signal in it. The $F < 10$ points appear in Fig. 4.

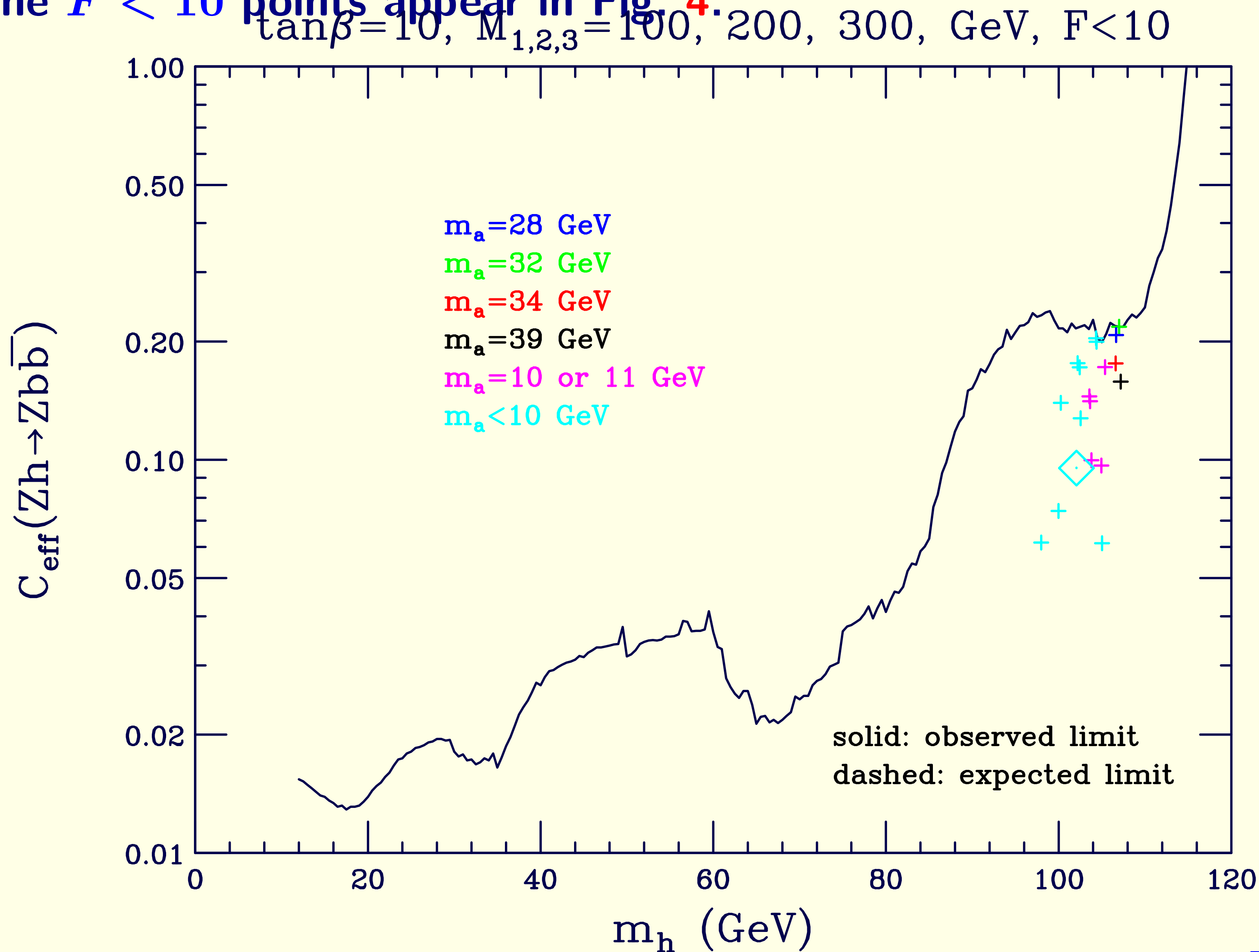

Figure 4: Observed LEP limits on $C_{eff} = [g^2_{ZZh}/g^2_{ZZh_{\rm SM}}]B(h \to b\bar{b})$ for the low-F points.

- **The observed 95% CL limit is shown in Fig. 4. Our points fit right below the observed limit but above the expected limits shown in Fig. 5.**

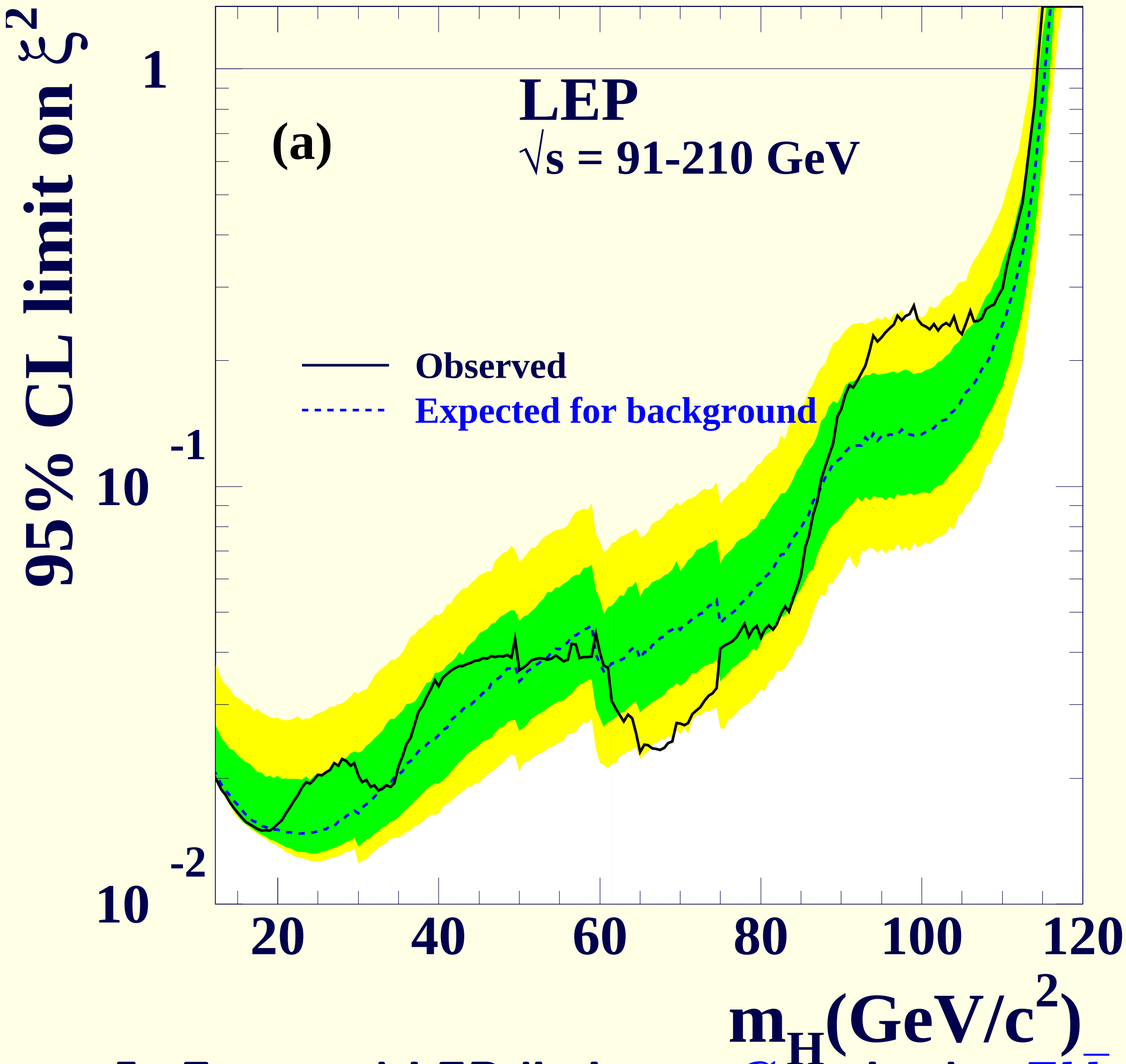

Figure 5: Expected LEP limits on C_{eff} in the $Zb\bar{b}$ final state.

- **The observed vs. expected discrepancy yields bad consistency with pure background and a preferred h mass just a bit below our NMSSM low-F values.**

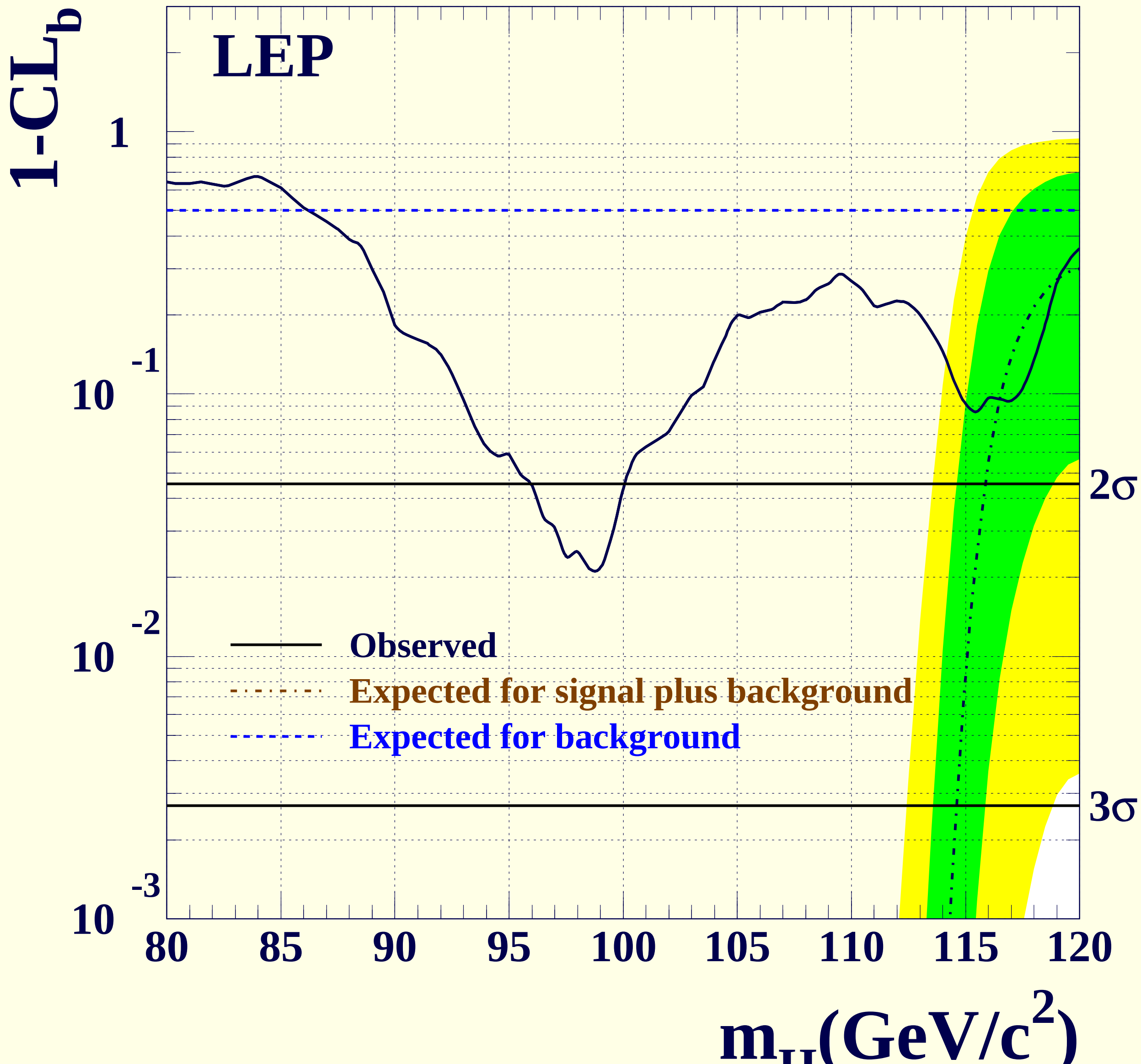

Figure 6: Plot of $1 - CL_b$ for the $Zb\bar{b}$ final state.

- We observe that about 1/3 of the points with the lowest F values would cause an excess in precisely the m_{a_1}, m_{h_1} bins of the $Z4b$ plot for which there is some excess beyond the LEP prediction.

- Precisely these same points predict a $Zb\overline{b}$ excess consistent in magnitude and location in $b\overline{b}$ mass range with that present in the LEP data.

- The very lowest F point, however, is one with $m_{a_1} < 2m_b$ (see the large cyan colored diamond in the earlier plots). For this type of parameter point, the $4b$ and $2b$ final states are not relevant.

- As shown in Fig. 7, the statistical significance of the best "standard" LHC signal (including those for the a_1 and a_2) for any of these points is below 5 (assuming full $L = 300~\mathrm{fb}^{-1}$) and is typically more like 1.5 to 4.

  Of course, the larger the C_{eff} for the "undesirable" $4b$ type of final state, the smaller the maximum LHC significance.

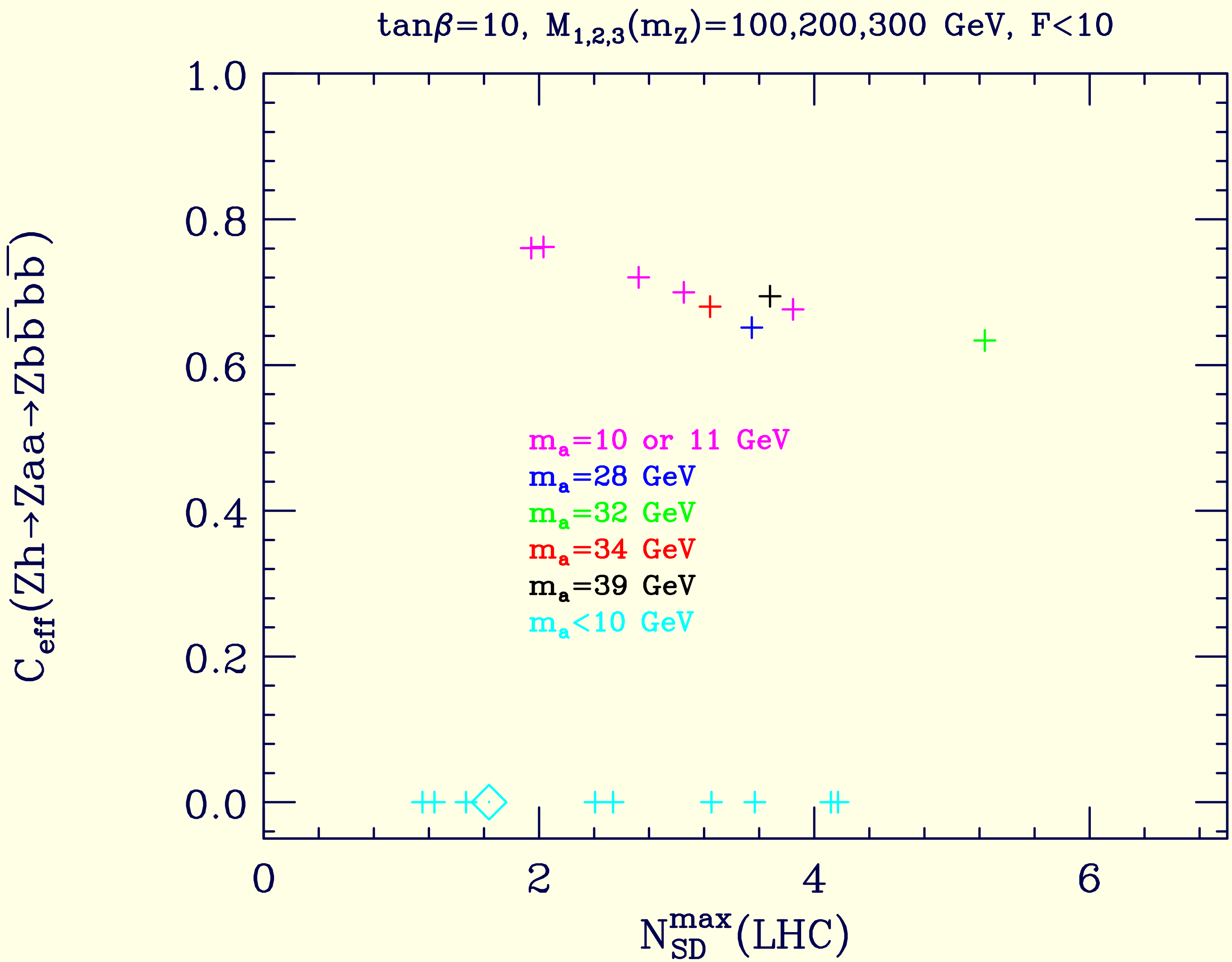

Figure 7: Correlation between $C_{eff}(Z4b)$ and maximum LHC statistical significance in "standard" channels.

- The ILC will be required in order to see a clear Higgs signal. The $e^+e^- \to ZX$ M_X bump will be easily seen independently of h_1 decays. The h_2 and h_3 might also be visible.

- The LHC can "only" see supersymmetry (which should be relatively low-scale for low F) and check that the $WW \to WW$ scattering is perturbative.

  The h_1 is hidden as already discussed and the a_1 is also hidden in so far as current studies are concerned. (Note that the a_1 coupling to $b\bar{b}$ is never more than very modestly enhanced relative to a "$\tan\beta = 1$" type strength.)

- It seems quite important to explore hadron collider sensitivity to the $h \to aa \to 4b$ or 4τ final states.

  It is not impossible that the Tevatron could have some sensitivity given that the Higgs for the low-F scenarios has a very modest mass and has SM-like couplings to fermions and gauge bosons.

  Exploring the possibilities could teach us new techniques that would help at the LHC.

- **At the LHC, the modes that seem to hold some promise are:**

1. $WW \to h_1 \to a_1 a_1 \to b\bar{b}\tau^+\tau^-$.
   Our (JFG, Ellwanger, Hugonie, Moretti) work suggested some hope. Experimentalists (esp. D. Zerwas) are working on a fully realistic evalutaion but are not that optimistic.
2. Gluino cascades containing $\widetilde{\chi}_2^0 \to h_1 \widetilde{\chi}_1^0$.
   It is known that the h_1 can be discovered in such cascades if the production rate for gluinos is large and $h_1 \to b\bar{b}$ is the primary decay. The case of $h_1 \to 4b$ will be harder since the jets are softer, but maybe some signal will survive.
3. Doubly diffractive $pp \to pph_1$ followed by $h_1 \to a_1 a_1 \to 4b$ or $2b2\tau$.
   A group of us (JFG, V. Khoze, A. deRoeck, ...) are looking into this.
   The claim is that the M_X in $pp \to ppX$ can be reconstructed from the tagged protons with a resolution of a few GeV and that proper restrictions on the event structure can give reasonable signal efficiency while removing most backgrounds.
   This would then be analogous to the ILC ZX approach in its independence of Higgs decays.
   The key issue may turn out to be whether triggering efficiency for the $4b$ final state is adequate.

- **At the Tevatron, perhaps the lack of overlapping events and lower background rates might allow some sign of a signal in modes such as Wh_1 and Zh_1 production with $h_1 \to a_1 a_1 \to 4b$ or $2b2\tau$.**

New Dark Matter Scenarios

with McElrath and Hooper

- The typical low-F scenario has a light a_1 and a $\widetilde{\chi}_1^0$ that is mainly bino.
- The mass of the $\widetilde{\chi}_1^0$ can be easily adjusted by varying the bino SUSY breaking mass M_1 (with negligible effect on the fine-tuning measure).

  $\Rightarrow$ new dark matter scenarios.
- In particular, if there is a light, somewhat non-singlet a_1 as in the low-F scenarios described, then one could also have a light $\widetilde{\chi}_1^0$ without having too much relic density.

  The reason is that the $\widetilde{\chi}_1^0\widetilde{\chi}_1^0 \to a_1 \to X$ annihilation channels can be sufficiently strong to reduce the relic density to the observable $\Omega h^2 \sim 0.1$ (WMAP, ...).
- This is not possible in the MSSM unless $\tan\beta$ is very large and other parameters are carefully adjusted.

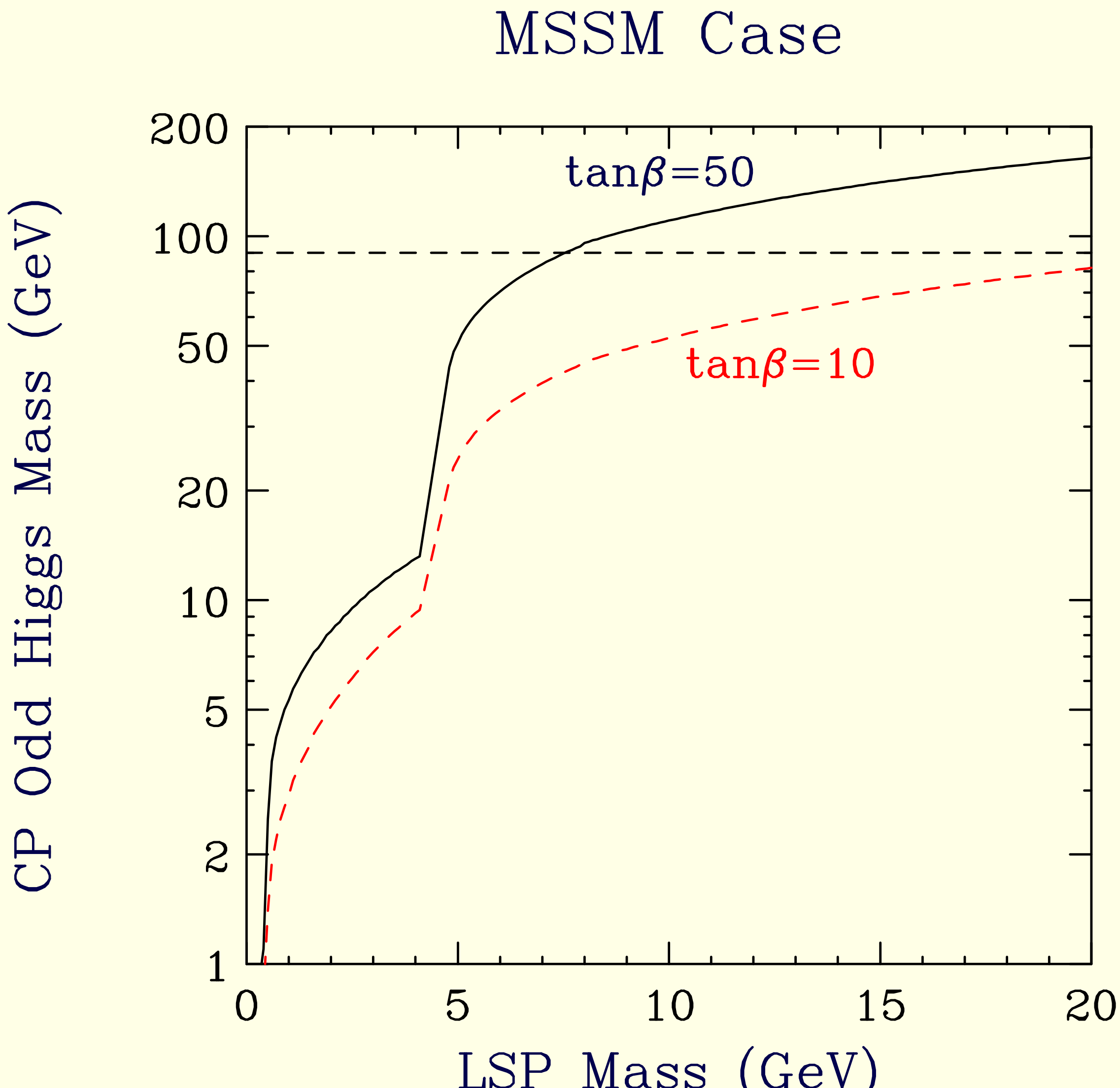

Figure 8: MSSM constraints on light dark matter. Models above the curves produce more dark matter than is observed. These results are for the case of a bino-like neutralino. Results for $\tan\beta = 10$ and 50 are shown. The horizontal dashed line is the lower limit on the CP-odd Higgs mass in the MSSM from collider constraints. To avoid overproducing dark matter, the neutralino must be heavier than about 8 (22) GeV for $\tan\beta = 50$ (10).

- In contrast, a light $\widetilde{\chi}_1^0$ is easily consistent with the NMSSM provided the a_1 has mass m_{a_1} that is an appropriate distance from $2m_{\widetilde{\chi}_1^0}$.

  To illustrate, we show contours of $\Omega h^2 = 0.1$ in Fig. 9 in the $[m_{\widetilde{\chi}_1^0}, m_{a_1}]$ mass plane. Values of $\tan\beta = 3$, 15 and 50 are considered.

  Note that unless $m_{\widetilde{\chi}_1^0}$ is below $2m_b$, the a_1 mass should not be too close to $2m_{\widetilde{\chi}_1^0}$ (so as to avoid too much annihilation).

  The results shown are for a bino-like neutralino with a small higgsino admixture ($\epsilon_B^2 = 0.94$, $\epsilon_u^2 = 0.06$). Here,

$$\widetilde{\chi}_1^0 = \epsilon_u \tilde{H}_u^0 + \epsilon_d \tilde{H}_d^0 + \epsilon_W \tilde{W}^0 + \epsilon_B \tilde{B} + \epsilon_s \tilde{S}. \quad (1)$$

  where ϵ_u, ϵ_d are the up-type and down-type higgsino components, ϵ_W, ϵ_B are the wino and bino components and ϵ_s is the singlet component of the lightest neutralino.

  We have also taken $\cos^2\theta_{a_1} = 0.6$, a typical value. Here, $\cos\theta_{a_1}$ is the amount of non-singlet content of the a_1:

$$a_1 = \cos\theta_{a_1} A_{\rm MSSM} + \sin\theta_A A_s, \quad (2)$$

  where A_s is the singlet CP-odd Higgs.

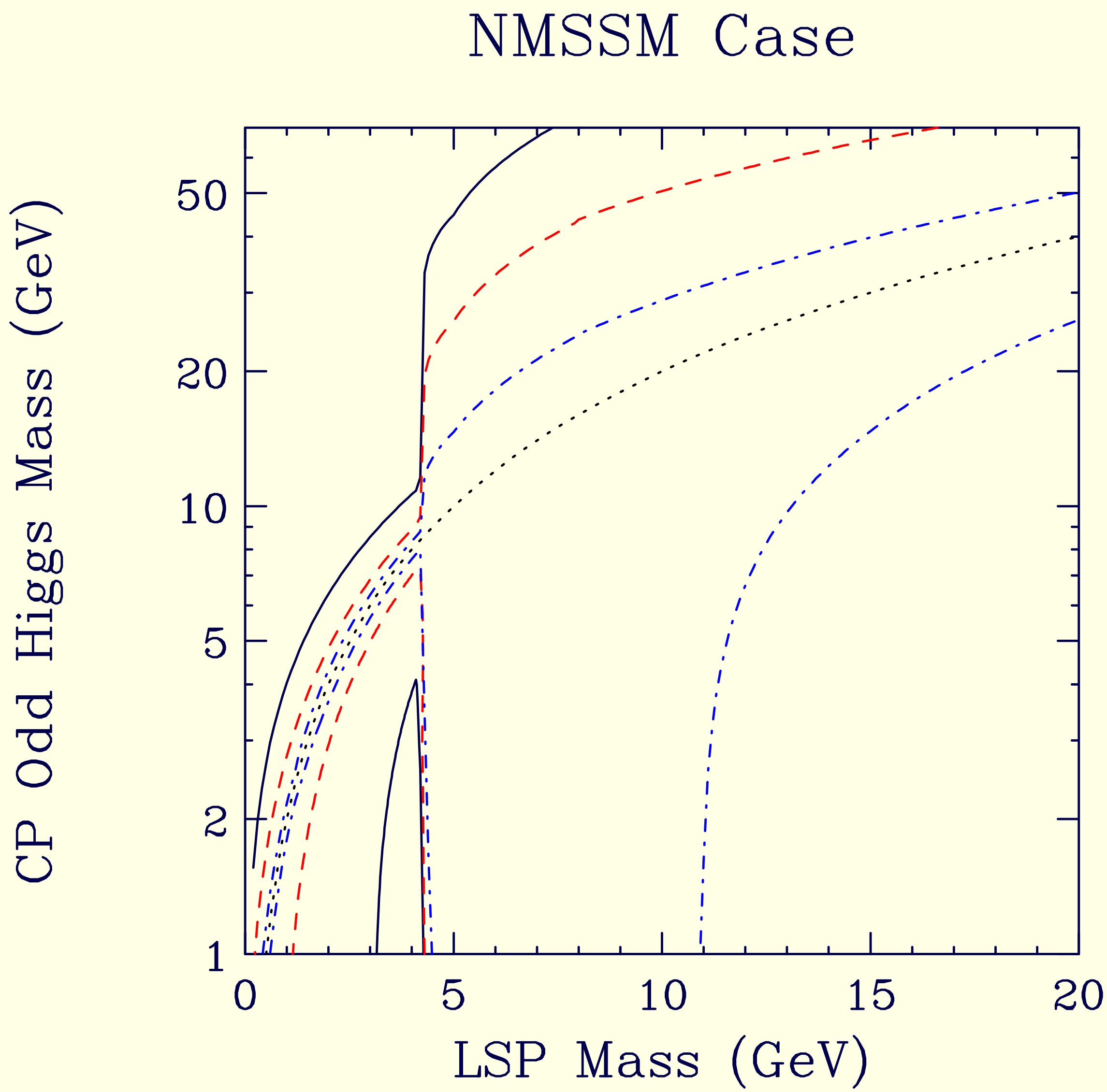

Figure 9: NMSSM scenarios for light dark matter. Contours of $\Omega h^2 = 0.1$ are shown for three values of $\tan\beta$ (50, 15 and 3, respectively). The dotted line is the contour corresponding to $2m_{\widetilde{\chi}_1^0} = m_A$. Between contours, $\Omega h^2 < 0.1$.

- **It is interesting to note that we have identified several promising models which could explain the SPI/INTEGRAL 511 keV photon anomaly and DAMA "evidence".**

- **McElrath has identified several ways to use existing b-factories BaBar and Belle to detect light dark matter in a model-independent fashion using invisible decays of quarkonium such as J/Ψ and Υ. This is sensitive to a dark matter particle (generically, ϕ) with mass $m_\phi < 5$ GeV, a region where direct detection experiments are extremely insensitive.**

- **Implications for verifying the dark matter picture**

  - **Hadron Collider:**
    The best that a hadron collider can do will probably be to set an upper limit on $m_{\widetilde\chi_1^0}$. Determining its composition is almost certain to be very difficult.
    Note that the $m_{\widetilde\chi_2^0} - m_{\widetilde\chi_1^0}$ mass difference should be large, implying adequate room for $\widetilde\chi_2^0 \to Z\widetilde\chi_1^0$ and a search for lepton kinematic edges and the like. (Of course, $\widetilde\chi_2^0 \to h_1\widetilde\chi_1^0$ will also probably be an allowed channel, with associated implications for h_1 detection in SUSY cascade decays.)

A light a_1 is probably very hard to see. Still, the $WW \to a_1 a_1$ rate is quite substantial and this should be studied. If the rate is measured, $\cos\theta_{a_1}$ would be determined.

– The ILC:

Precise measurement of the $\widetilde{\chi}_1^0$ mass and composition using the standard techniques should be straightforward.

$WW \to a_1 a_1$ and $Z^* \to Z a_1 a_1$ have very large rates at low m_{a_1}. I would think these processes could be studied with precision and $\cos\theta_{a_1}$ measured with high accuracy.

By combining the $\widetilde{\chi}_1^0$ and a_1 precision measurements, a precision determination of the $\widetilde{\chi}_1^0$ relic desnity should be possible. A study of precise errors in the dark matter density computation using the above measurements as compared to the expected experimental error for the Ωh^2 measurement is needed.

Conclusions

- The NMSSM allows an intriguing low fine tuning reinterpretation of existing LEP Higgs data in terms of a $m_{h_1} \gtrsim 100~\mathrm{GeV}$ Higgs boson decaying largely via $h_1 \to a_1 a_1$, leading to the observed excess in the $Z4b$ final state, while having exactly the right remnant in the $h_1 \to b\bar{b}$ mode to explain the long-present excess in the $Zh_1 \to Zb\bar{b}$ final state in the vicinity of $m_{h_1} \sim 100~\mathrm{GeV}$.

  We should work hard to see if we can observe or exclude such a Higgs scenario at the Tevatron and eventually the LHC.

- The naturally associated dark matter scenario would have an unexpectedly light $\widetilde{\chi}_1^0$. Its properties and those of the a_1 would need to be determined precisely to check consistency of the dark matter relic density with accelerator data.

  It seems quite certain that ILC precision data will be essential for this.