Accessing the LHC /LC Higgs Wedge.

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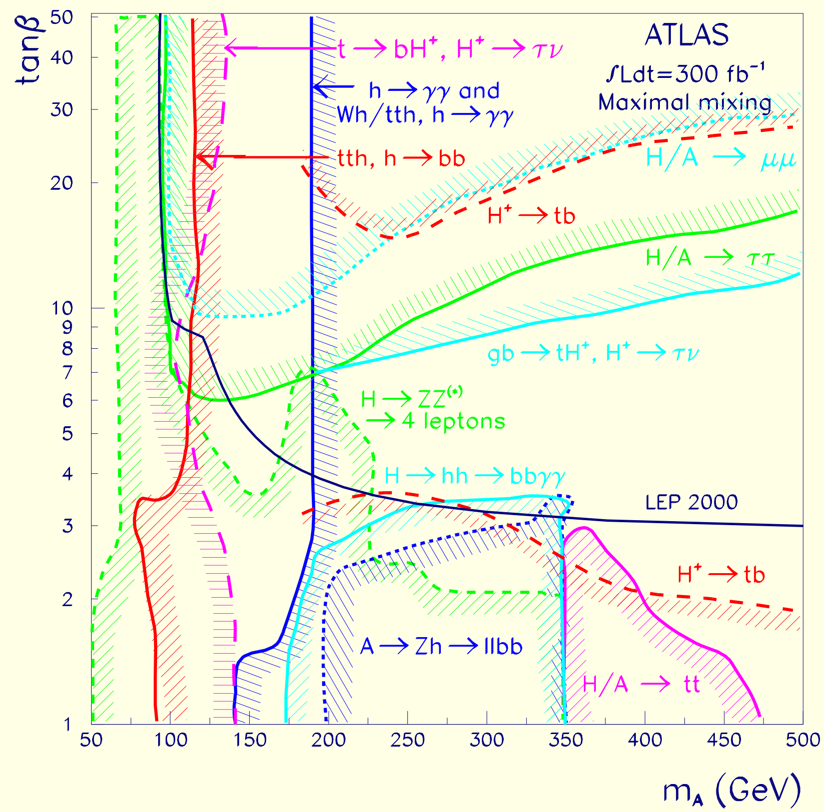
Motivations and Procedures

There is a region starting at $m_{A^0} \sim 200$ GeV at $\tan\beta \sim 6$, widening to $2.5 < \tan\beta < 15$ at $m_{A^0} = 500$ GeV for which the LHC cannot directly observe any of the heavy MSSM Higgs bosons.

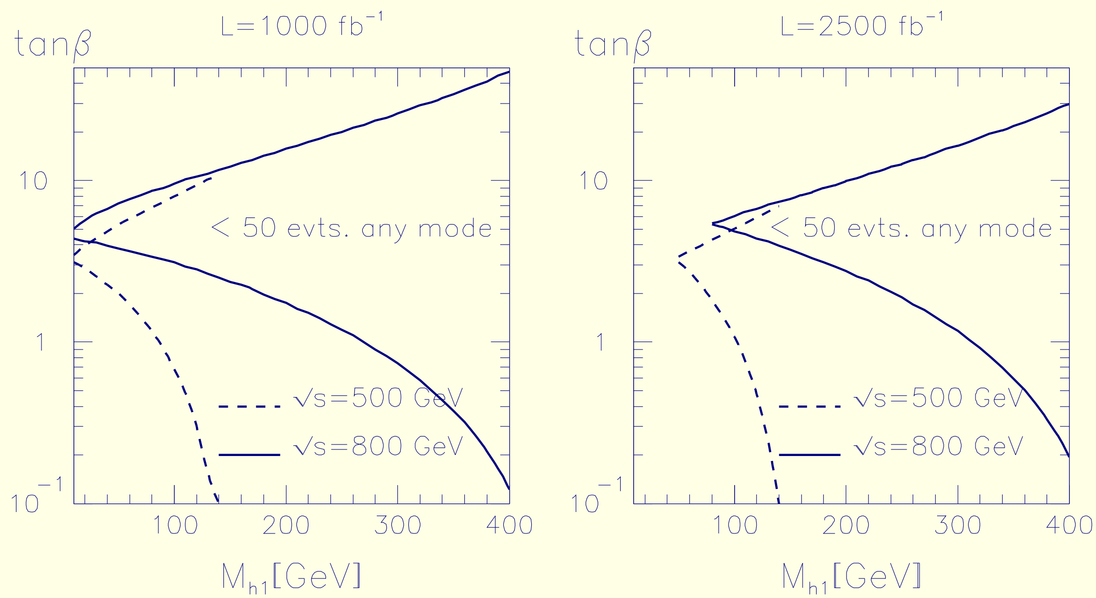


5σ discovery contours for MSSM Higgs boson detection in various channels are shown in the $[m_{A^0}, \tan\beta]$ parameter plane, assuming maximal mixing and an integrated luminosity of $L = 300\text{fb}^{-1}$ for the ATLAS detector. This figure is preliminary.

This wedge is not covered at the LC.

In fact, the LC wedge for $t\bar{t}+H^0, A^0$ and $b\bar{b}+H^0, A^0$ is even larger.

Further, $e^+e^- \to ZH^0H^0$ and $e^+e^- \to ZA^0A^0$ only cover up to $m_{A^0} = 150$ GeV ($m_{A^0} = 250$ GeV) at $\sqrt{s} = 500$ GeV ($\sqrt{s} = 800$ GeV) using 20 events in $L = 1$ ab^{-1}.



For $\sqrt{s} = 500$ GeV (dashes) and $\sqrt{s} = 800$ GeV (solid) the maximum and minimum $\tan\beta$ values between which $t\bar{t}h$ and $b\bar{b}h$ final states both have fewer than 50 events for decoupled h (a) $L = 1000\text{fb}^{-1}$ or (b) $L = 2500\text{fb}^{-1}$.

- In this region, the h^0 will be observed and its couplings measured to a certain level.of accuracy. (We will consider LHC only and LHC + LC.)

- **Will we be able to indirectly determine m_{A^0} from these precision measurements?**

- The issue: How much model dependence is there in the h^0 branching ratios, etc., that might prevent an interpretation in terms of m_{A^0} of the observations.

- Main difficulty: There are choices of parameters for which the h^0 has completely standard model couplings to gauge bosons and fermions **independent of m_{A^0}**.

- Main question: Can observations of other SUSY parameters guarantee that we are not in this situation?

Main Ingredient: Higgs Mass Matrix

$$\mathcal{M}^2 = \begin{pmatrix} \mathcal{M}^2_{11} & \mathcal{M}^2_{12} \\ \mathcal{M}^2_{12} & \mathcal{M}^2_{22} \end{pmatrix} = \begin{pmatrix} m^2_{A^0} s^2_\beta + m^2_Z c^2_\beta & -(m^2_{A^0} + m^2_Z) s_\beta c_\beta \\ -(m^2_{A^0} + m^2_Z) s_\beta c_\beta & m^2_{A^0} c^2_\beta + m^2_Z s^2_\beta \end{pmatrix} + \delta\mathcal{M}^2 \tag{1}$$

It is diagonalized by rotation angle α determined by

$$\sin 2\alpha = 2 c_\alpha s_\alpha = 2\frac{\mathcal{M}^2_{12}}{\sqrt{(\mathrm{Tr}\mathcal{M}^2)^2 - 4\mathrm{Det}\mathcal{M}^2}} \tag{2}$$

$$\cos 2\alpha = c^2_\alpha - s^2_\alpha = \frac{\mathcal{M}^2_{11} - \mathcal{M}^2_{22}}{\sqrt{(\mathrm{Tr}\mathcal{M}^2)^2 - 4\mathrm{Det}\mathcal{M}^2}} \tag{3}$$

where

$$\sqrt{(\mathrm{Tr}\mathcal{M}^2)^2 - 4\mathrm{Det}\mathcal{M}^2} = m^2_{H^0} - m^2_{h^0}\,. \tag{4}$$

Writing

$$\sin 2(\beta - \alpha) = 2\sin(\beta - \alpha)\cos(\beta - \alpha) = \sin 2\beta \cos 2\alpha - \cos 2\beta \sin 2\alpha \tag{5}$$

we obtain

$$\cos(\beta-\alpha) = \frac{(\mathcal{M}_{11}^2-\mathcal{M}_{22}^2)\sin 2\beta - 2\mathcal{M}_{12}^2\cos 2\beta}{2(m_{H^0}^2-m_{h^0}^2)\sin(\beta-\alpha)} \qquad (6)$$

$$= \frac{2m_Z^2\sin 2\beta\cos 2\beta + (\delta\mathcal{M}_{11}^2-\delta\mathcal{M}_{22}^2)\sin 2\beta - 2\delta\mathcal{M}_{12}^2\cos 2\beta}{2(m_{H^0}^2-m_{h^0}^2)\sin(\beta-\alpha)}. \qquad (7)$$

Exact decoupling corresponds to $\cos(\beta-\alpha)=0$, which is obtained by zeroing the numerator, equivalent (assuming $\tan\beta\neq 1$) to requiring

$$2m_Z^2\sin 2\beta + (\delta\mathcal{M}_{11}^2-\delta\mathcal{M}_{22}^2)\tan 2\beta - 2\delta\mathcal{M}_{12}^2 = 0\,. \qquad (8)$$

To evaluate where exact decoupling occurs and how rapidly one moves away from exact decoupling as SUSY parameters change, one needs the best available expressions for the $\delta\mathcal{M}_{ij}^2$'s. We have used those employed in hep-ph/0106116 (Carena, Haber, Logan, Mrenna).

One finds many decoupling solutions at all $\tan\beta$ values in the wedge region, although the difficulty of finding solutions consistent with $m_{h^0}\gtrsim 113$ GeV (the LEP limit for an exactly SM-like coupled h^0) increases at lower $\tan\beta$ values.

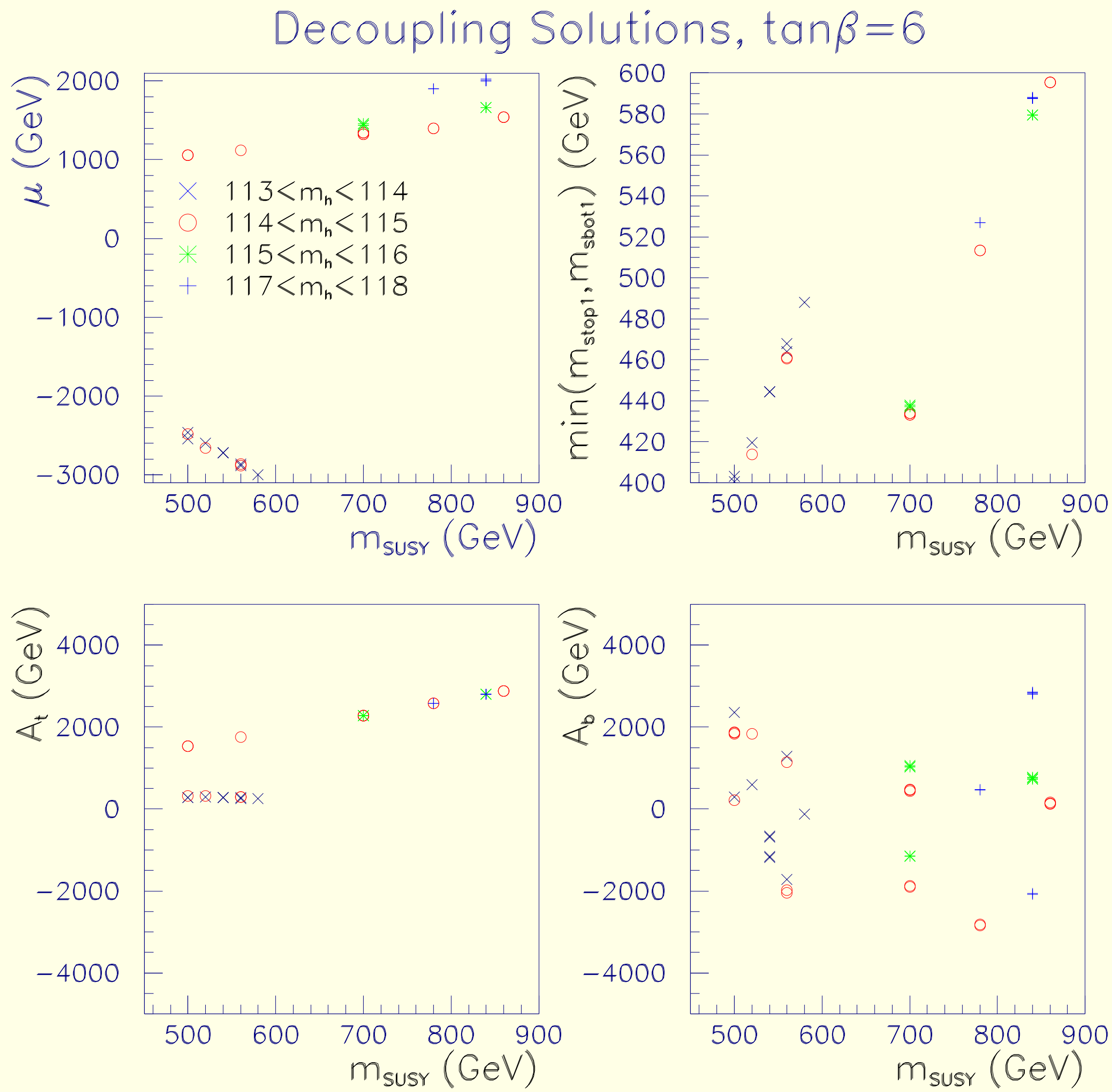
Important parameters for our scanning:

- m_{SUSY}
- $\tan\beta$
- μ, A_t, A_b
- Note: at the decoupling limit, there is no dependence on m_{A^0}.

Outputs

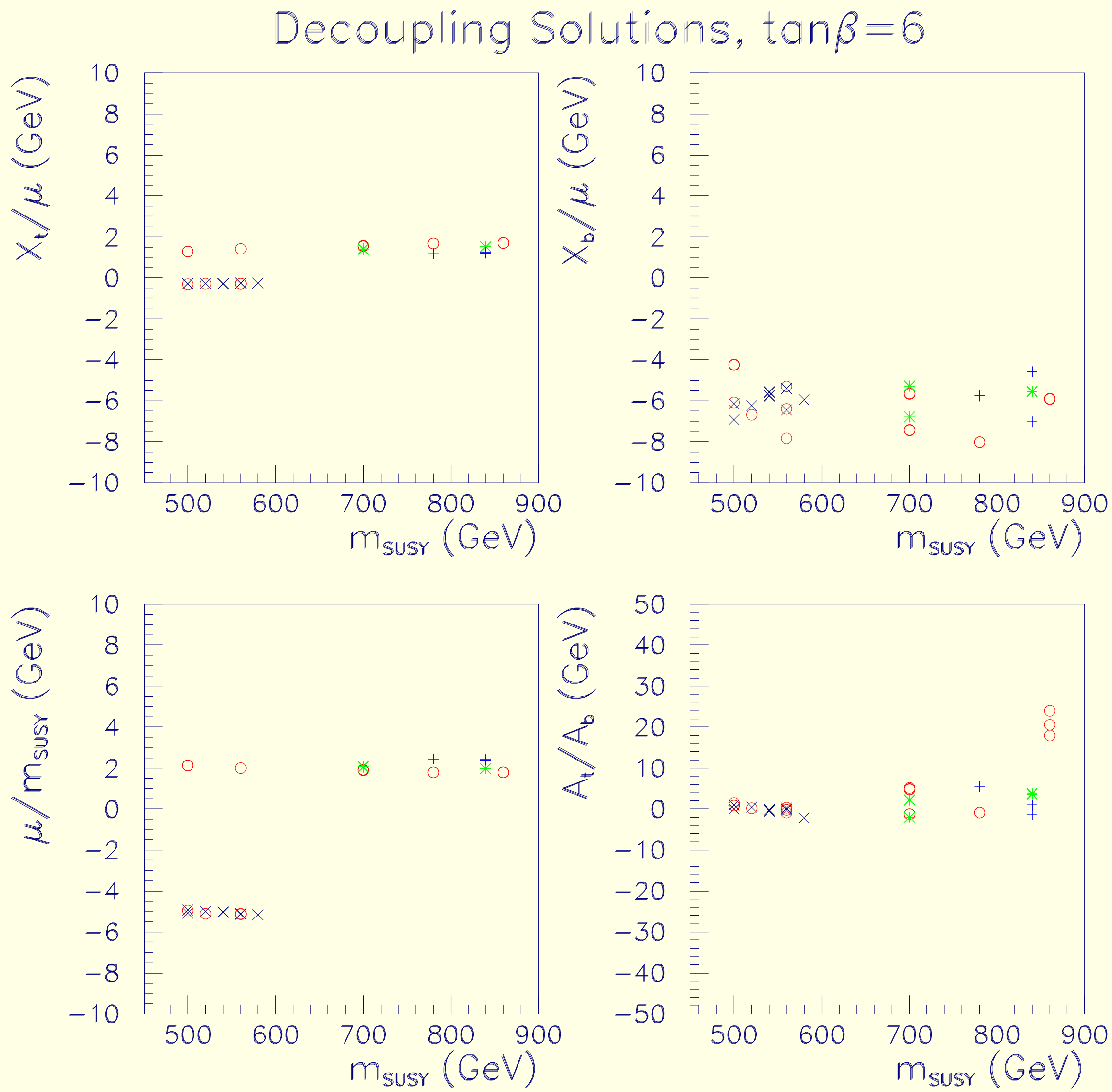
- Stop and sbottom masses
- Light Higgs boson mass
- Note: even if A_t and A_b are large, what is important is whether the output stop and sbottom masses are reasonable enough that the approximations being employed are acceptable.

Results for $\tan\beta = 6$



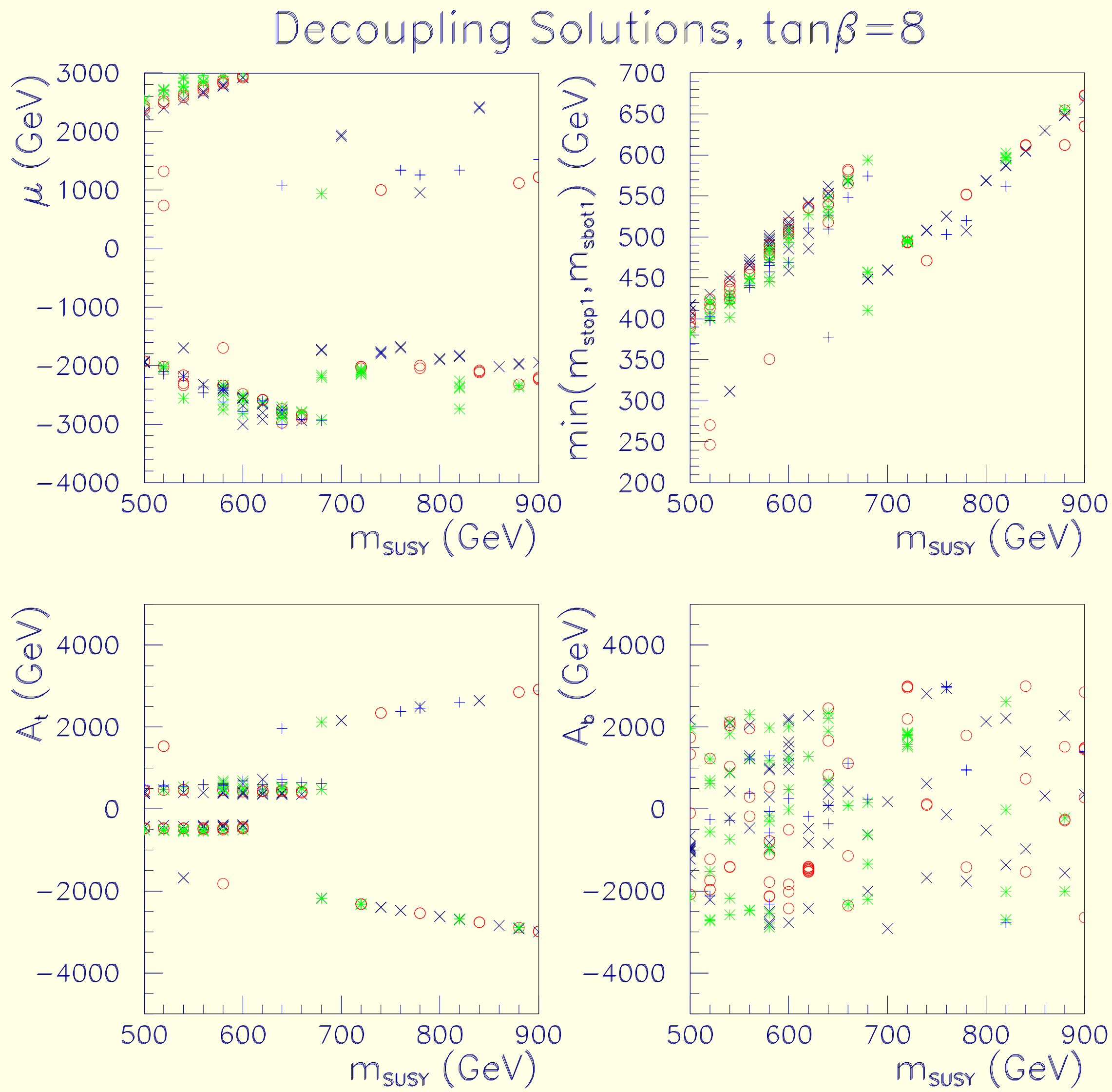
For $\tan\beta = 6$, we plot μ, $\min(m_{\tilde{b}_1}, m_{\tilde{t}_1})$, A_t and A_b as a function of m_{SUSY} for various small bands of m_{h^0}.

Results for $\tan\beta = 6$. Note how the decoupling solutions tend to lie in fixed bands of X_t/μ, X_b/μ and $\mu/m_{\rm SUSY}$.



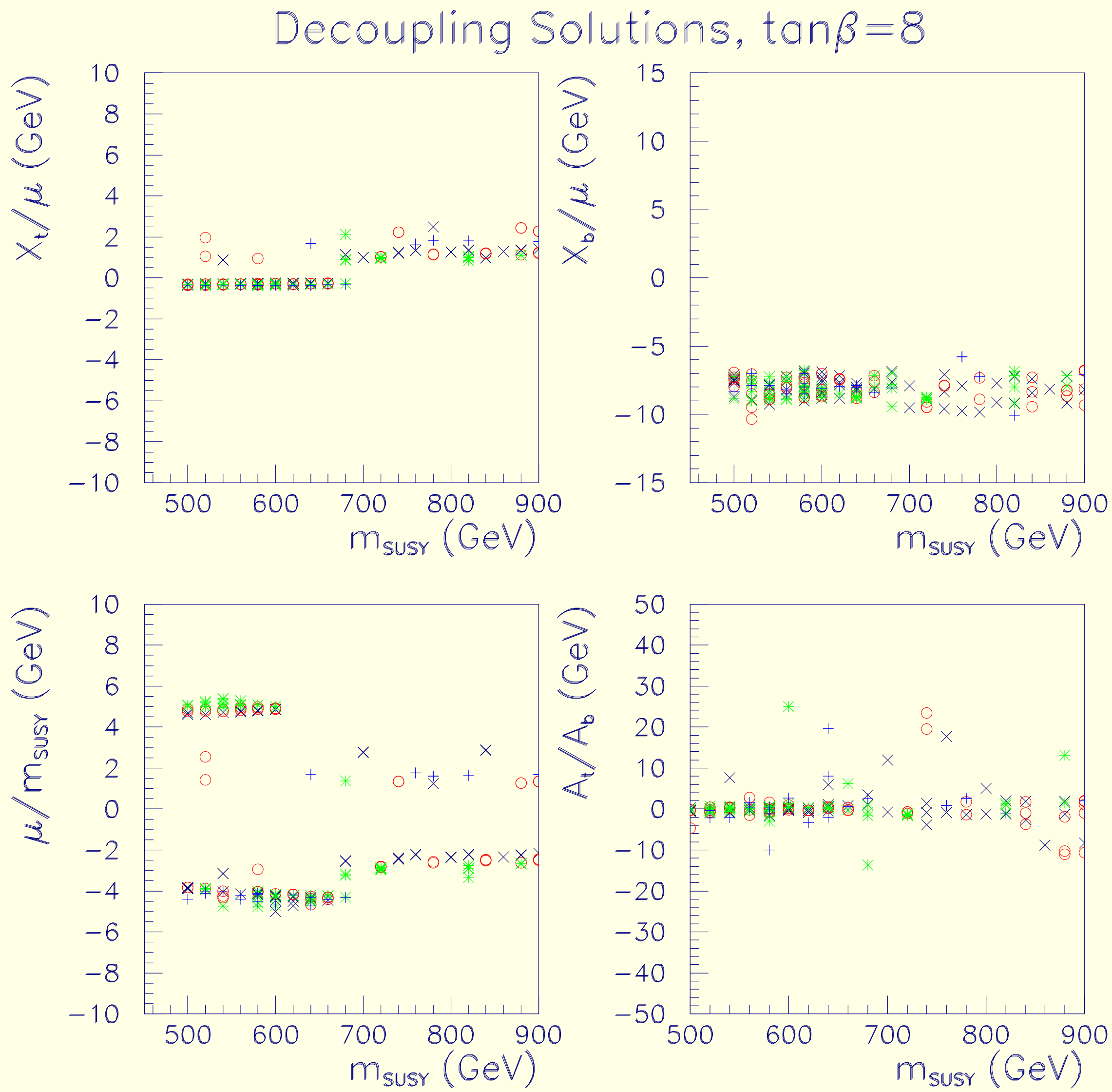
For $\tan\beta = 6$, we plot X_t/μ, X_b/μ, μ/m_{SUSY} and A_t/A_b as a function of $m_{\rm SUSY}$ for various small bands of m_{h^0}.

Results for $\tan\beta = 8$



For $\tan\beta = 8$, we plot μ, $\min(m_{\tilde{b}_1}, m_{\tilde{t}_1})$, A_t and A_b as a function of m_{SUSY} for various small bands of m_{h^0}.

Results for $\tan\beta = 8$. Note how the decoupling solutions tend to lie in fixed bands of X_t/μ, X_b/μ and $\mu/m_{\rm SUSY}$.



For $\tan\beta = 8$, we plot X_t/μ, X_b/μ, μ/m_{SUSY} and A_t/A_b as a function of $m_{\rm SUSY}$ for various small bands of m_{h^0}.

Implications

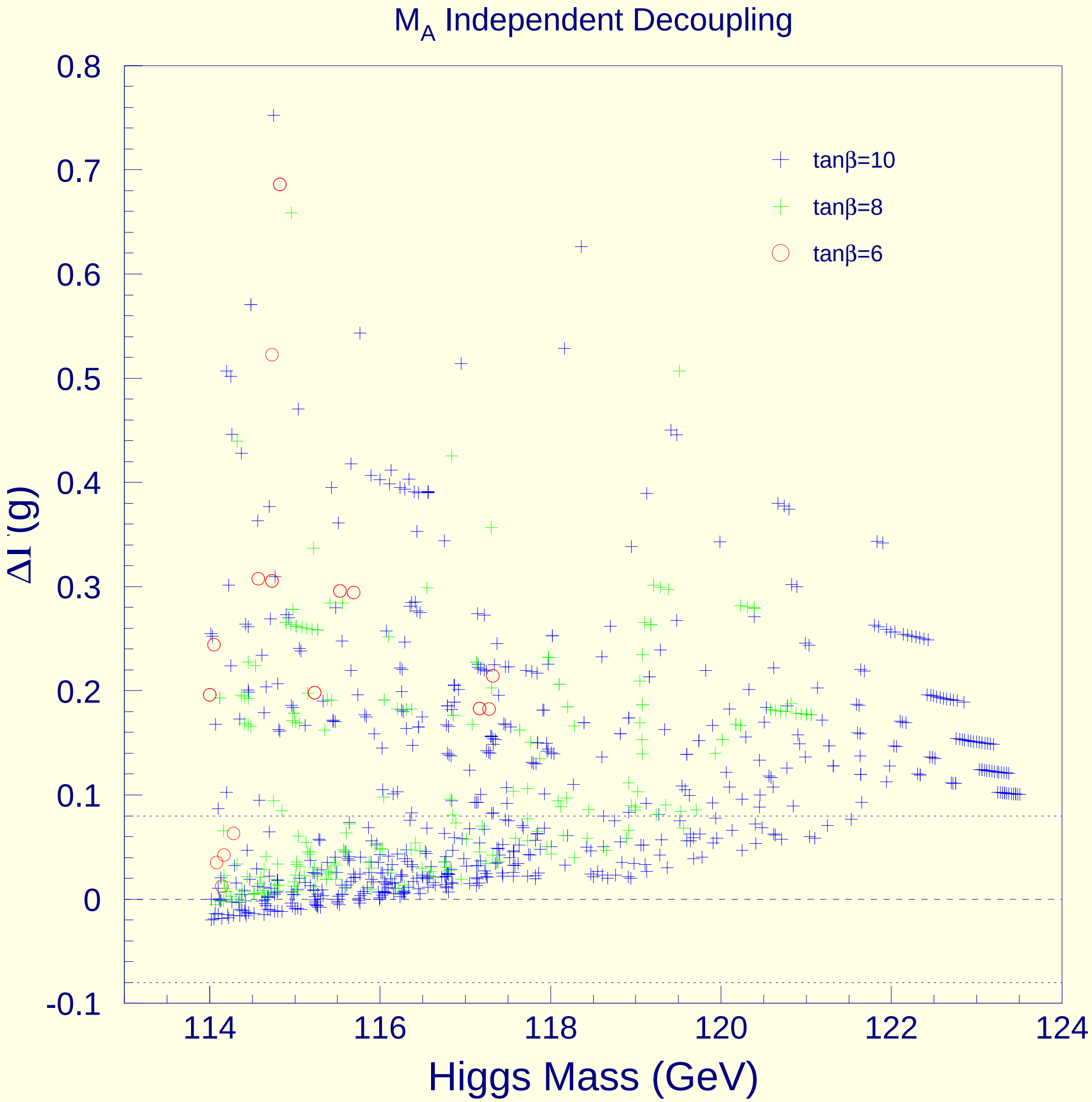
Even if we do not see the A^0 or H^0 (or $H^\pm$) at the LHC and LC, if we could approximately determine m_{A^0} this would:

- Allow us to know where to focus the $\gamma\gamma$ collider.
- Allow us to know where to focus the $\mu^+\mu^-$ collider.
- Allow us to know to what energy we must increase the LC $\sqrt{s}$.
- Give us important information regarding MSSM boundary conditions.

Our results show that if μ is large then there is a distinct possibility that the h^0 could be completely decoupled, implying independence of all its properties on the value of m_{A^0}.

Note: This does not mean that all of the h^0 properties will be the same as for the SM $h_{\rm SM}$. For example, stop and sbottom loops affect $\Gamma(h^0 \to gg)$ and $\Gamma(h^0 \to \gamma\gamma)$. However, the SUSY-loop correction, $\Delta\lambda_b$, vanishes in the exact decoupling limit.

Fractional deviations of the gg branching ratio for the decoupling scenarios. Note: The deviations are large enough to affect the branching ratios to the standard channels because of changes in the total h^0 width.



We present a scantter plot of the percentage deviations of $\Gamma(h^0 \to gg)$ in the exact decoupling scenarios.

CONCLUSIONS

- If, we observe that the h^0 has completely standard model *couplings* (*i.e.* not just branching ratios), then there are two possibilities:

  1. m_{A^0} is very large — $m_{A^0} \gtrsim 600~\mathrm{GeV}$ or so putting it outside the LC reach and outside the LHC reach unless $\tan\beta$ is large;
  2. we are close to one of the exact decoupling scenarios found here, in which case $\boldsymbol{m_{A^0}}$ **could be any value above** $\boldsymbol{\sim 150}~\mathrm{GeV}$.

- Obviously, it would be important to determine which of the above is correct, since the 2nd alternative would imply we should still search for the A^0 by raising the machine energy or using $\gamma\gamma$ or $\mu^+\mu^-$ collisions.

- To make this assesment we must have quite a bit of information about the overall SUSY scenario. It would appear that we need:

  – observations of the heavier charginos/neutralinos whose masses are of order μ (in many scenarios),

- observations of the 1st two generations of squarks (which more or less determine m_{SUSY}),
- observations of the lightest stop and sbottom squarks,
- information from, say, the chargino sector to determine $\tan\beta$.

Only with all this information would we have a good idea of whether or not we are in a decoupling scenario.

- These are a lot of if's.

- Further, even if we are only near the decoupling zone, the properties of the h^0 will have reduced sensitivity to m_{A^0}.

- We will study these scenarios further to see if we can find easier techniques for using other SUSY observations to allow us to know when decoupling is present.

- We will also study if some precision couplings might still reveal the mass of the $H^0, A^0, H^\pm$.

  The most obvious coupling of this type is $h^0 \to \gamma\gamma$ which has some sensitivity to the mass of the $H^\pm$ through the corresponding loop contribution. Probably, however, this is overwhelmed by the usual W-loop contribution (which is full SM strength in the decoupling scenarios).