Constraints on and Direct Discovery Prospects for the Light CP-odd Higgs Boson of NMSSM Ideal Higgs Scenarios

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This talk is largely based on the following papers with R. Dermisek:

- **New constraints on a light CP-odd Higgs boson and related NMSSM Ideal Higgs Scenarios. Published in Phys.Rev.D81:075003,2010, arXiv:1002.1971**
- **Direct production of a light CP-odd Higgs boson at the Tevatron and LHC. Published in Phys.Rev.D81:055001,2010, arXiv:0911.2460**

Motivations for light CP-odd Higgs search

1. Lots of models, especially string models and extended SUSY models, have light CP-odd Higgs bosons.

2. There is particularly strong motivation in the context of Ideal NMSSM Higgs Scenarios, as reviewed by Radovan.

3. Generically, a light h can escape LEP limits if $B(h \to aa)$ (a is a light CP-odd Higgs) is large and $a \to \tau^+\tau^-$ or $a \to 2j$ ($a \to b\bar{b}$ does not allow $m_h < 105~\mathrm{GeV}$ [as preferred by: low finetuning; precision electroweak; baryogenesis; and $100~\mathrm{GeV}$ LEP excess] to escape LEP limits).

   Thus, one must have $m_a < 2m_B$.

4. In the NMSSM, the light a is typically a mixture of the MSSM doublet-like Higgs and the CP-odd singlet Higgs coming from the complex S field:

$$a_1 = \cos\theta_A a_{MSSM} + \sin\theta_A a_S\,. \tag{1}$$

The tuning required to get $m_{a_1} < 2m_B$ and $B(h_1 \to a_1 a_1) > 0.7$ is called "light-a_1" finetuning — associated measure is G.

Really small G typically yields a preference for rather well defined values of $\cos\theta_A$ when $\tan\beta$ is large.

5. The problem is that Higgs detection in $h_1 \to a_1 a_1 \to 4\tau, 2\tau, 4j$ modes is quite difficult, especially at low $\tan\beta$ where $4j$ becomes dominant.

Thus, the Higgs could be "buried" under backgrounds at the LHC.

It then becomes particularly relevant to search directly for the light a_1.

Predictions regarding a light a and the NMSSM a_1

What limits on the a can be obtained from existing data?

- Define a generic coupling to fermions by

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

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 $C_{a\tau^-\tau^+}$. Will ignore.

- To extract limits from the data on $C_{ab\bar{b}}$, we need to make some assumptions. Here, we presume a 2HDM(II) model as appropriate to the NMSSM and SUSY in general.

  Then, we can predict the branching ratios of the a. First $a \to \mu^+\mu^-$.

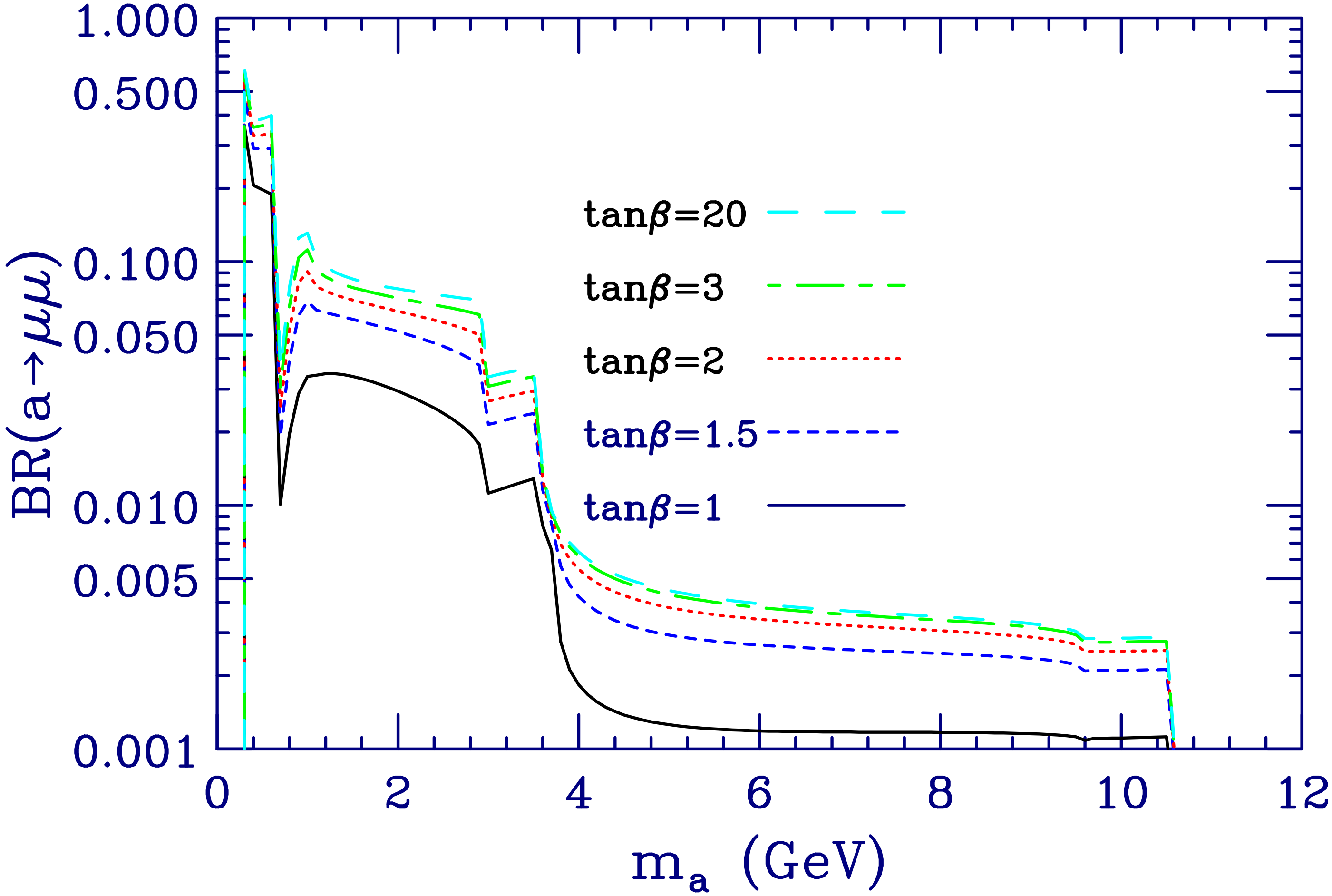


Figure 1: $B(a \to \mu^+\mu^-)$ **for various** $\tan\beta$ **values. Note decline once** $\tan\beta < 1.5$.

- **It will also become important to know about $B(a \to \tau^+\tau^-)$. Note values at high $\tan\beta$ of ~ 0.75 (*i.e.* below max of ~ 0.89) for $m_a \gtrsim 10$ GeV.**

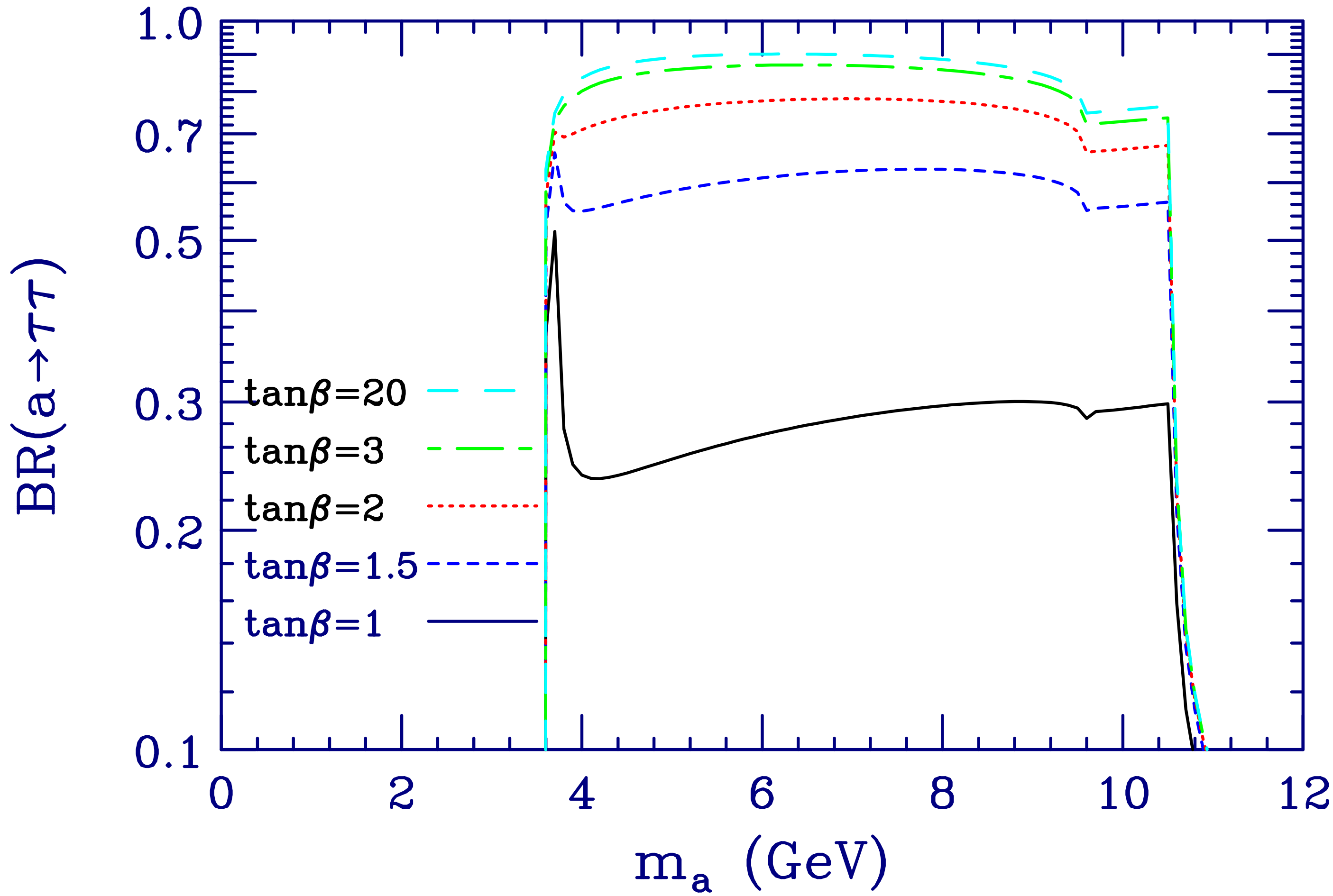


Figure 2: $B(a \to \tau^+\tau^-)$ **for various** $\tan\beta$ **values.**

- **Both are influenced by the structures in $B(a \to gg)$, which in particular gets substantial at high m_a where the b-quarks of the internal b-quark loop can be approximately on-shell.**

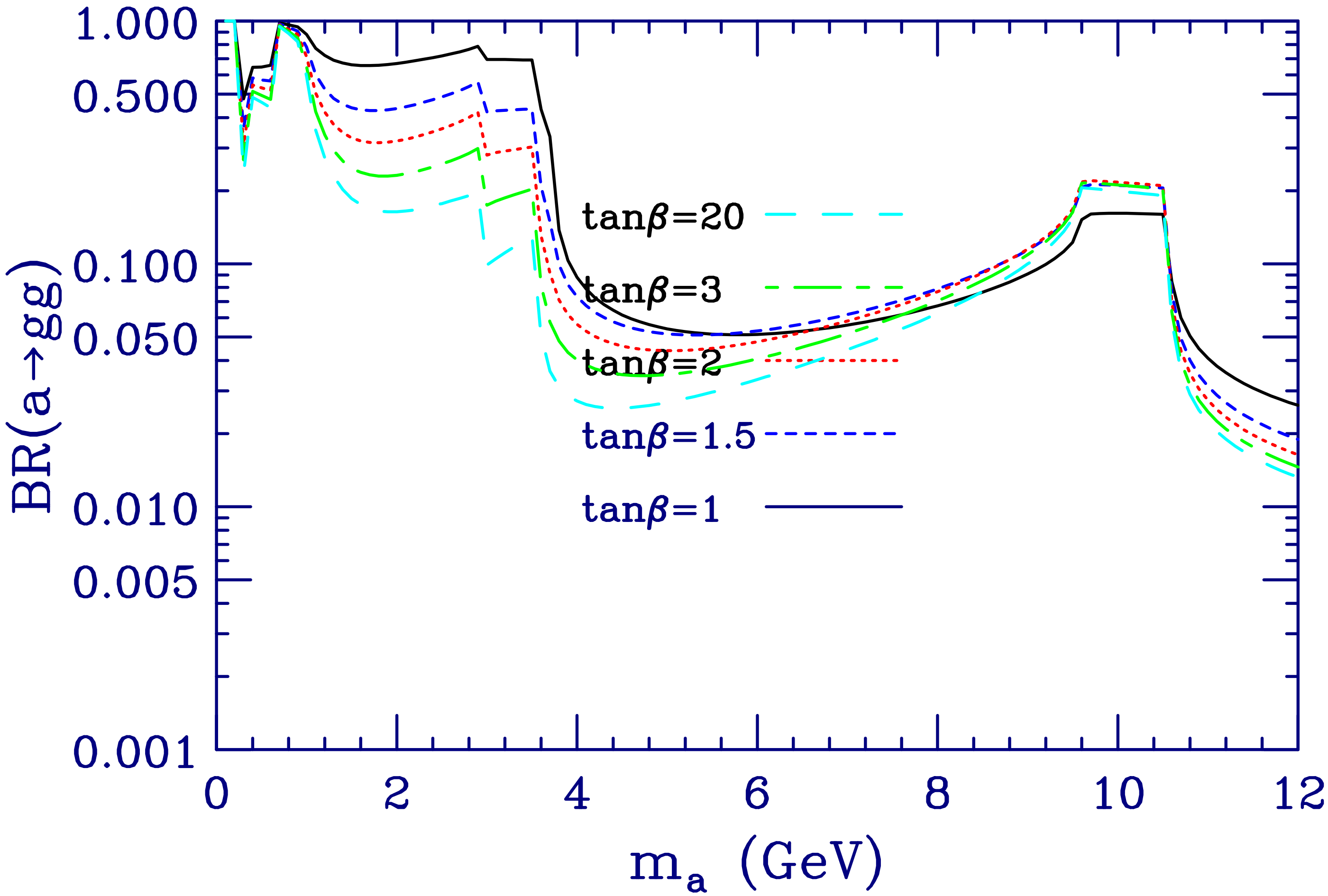


Figure 3: $B(a \to gg)$ **for various** $\tan\beta$ **values.**

- **The extracted $C_{ab\bar{b}}$ limits (JFG, arXiv:0808.2509 and JFG+Dermisek, arXiv:0911.2460; see also Ellwanger and Domingo, arXiv:0810.4736) appear in Fig. 4.**

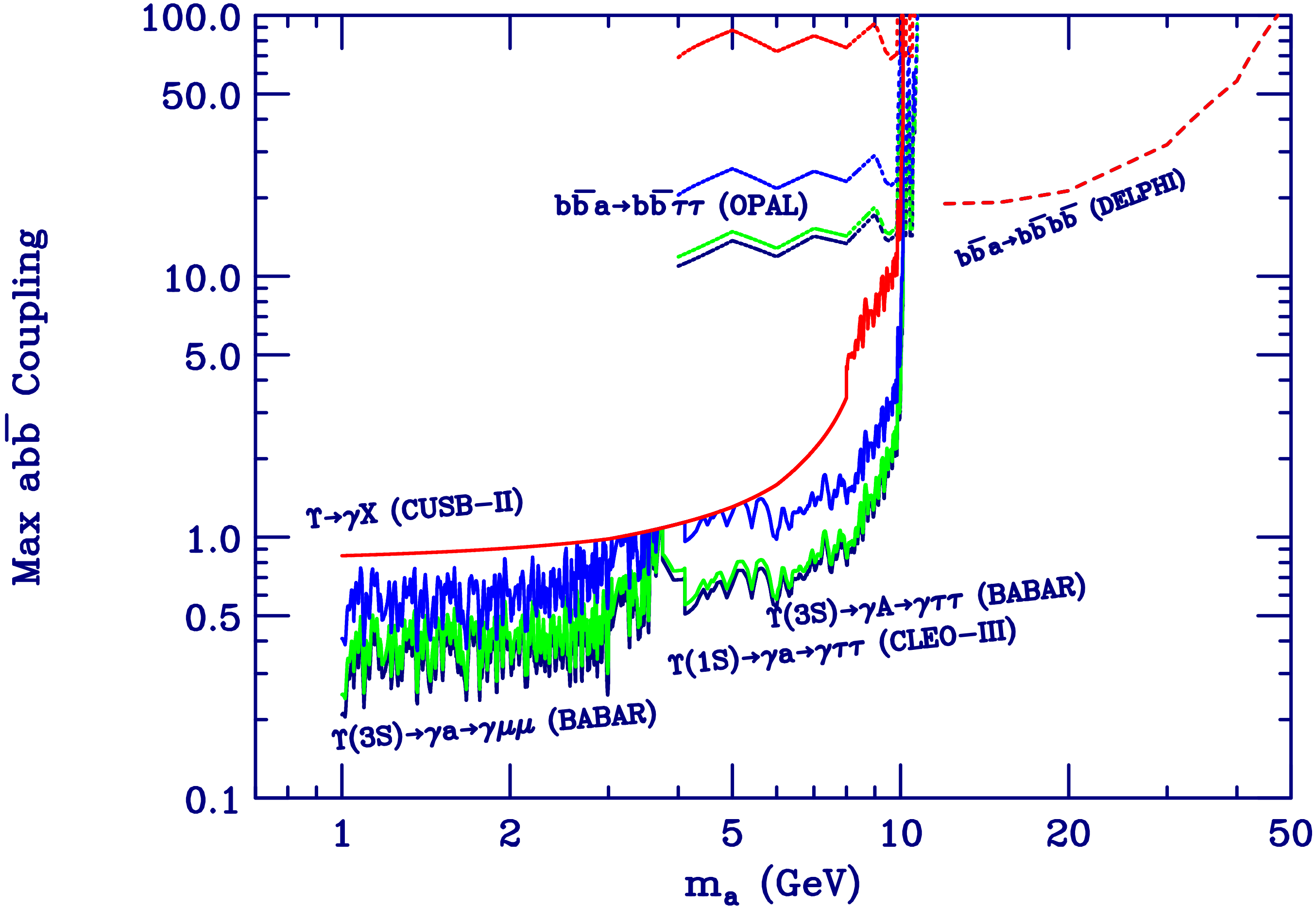


Figure 4: Limits on $C_{ab\bar{b}}$ from JFG, arXiv:0808.2509 and JFG+Dermisek, arXiv:0911.2460. These limits include recent BaBar $\Upsilon_{3S} \to \gamma\mu^+\mu^-$ and $\gamma\tau^+\tau^-$ limits. Color code: $\tan\beta = 0.5$; $\tan\beta = 1$; $\tan\beta = 2$; $\tan\beta \geq 3$. Keep an eye on $C_{ab\bar{b}} = 1$.

- **What are the implications in the NMSSM context?**

$$C_{ab\bar{b}} = \cos\theta_A \tan\beta \quad (3)$$

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

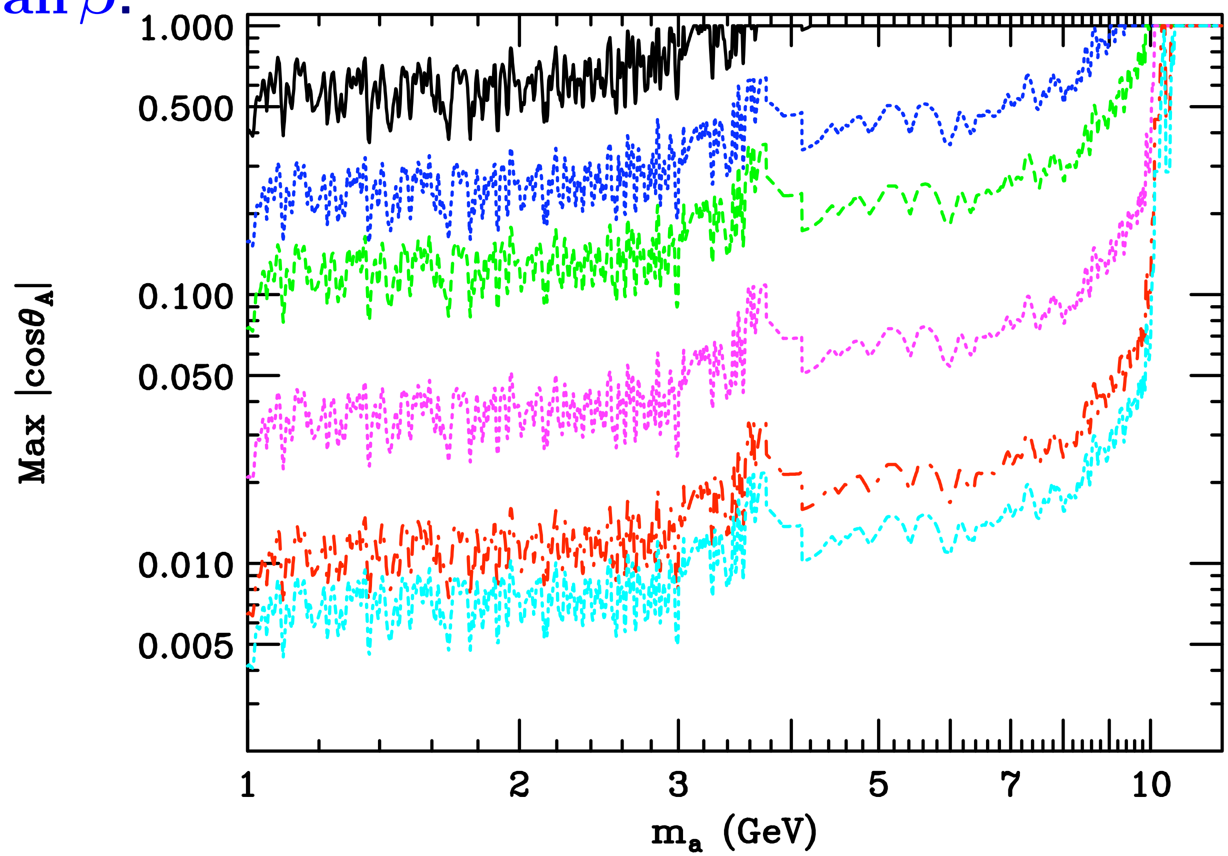


Figure 5: **Curves are for $\tan\beta = 1$ (upper curve), 1.7, 3, 10, 32 and 50 (lowest curve).**

What is the impact on "ideal" scenarios with low F. Examine the light-a finetuning measure G as a function of $\cos\theta_A$. Note that small G prefers "definite" $\cos\theta_A$ and large m_{a_1}.

- **To see more precisely the impact of the BaBar limits we can compare before and after.**

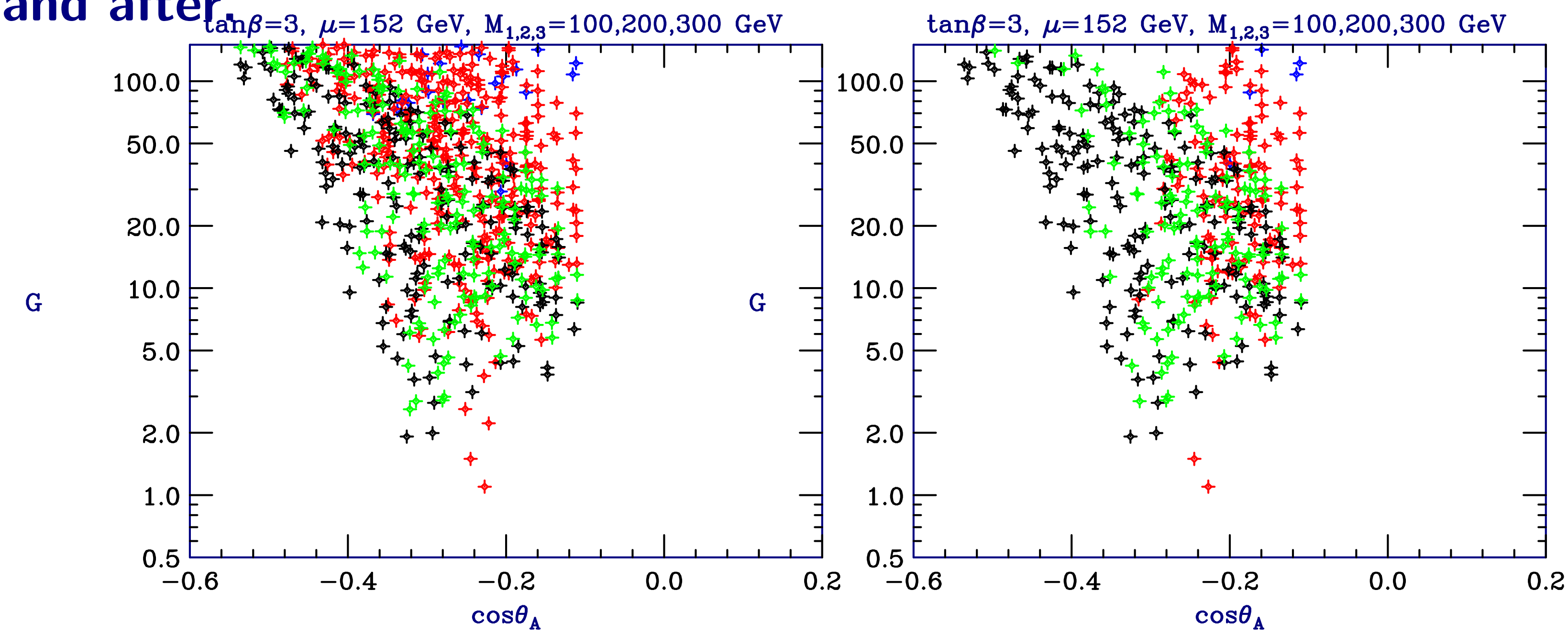


Figure 6: Light-a_1 finetuning measure G before and after imposing limits $|\cos\theta_A| \leq \cos\theta_A^{\max}$. Note that many points with low m_{a_1} and large $|\cos\theta_A|$ are eliminated by the $|\cos\theta_A| < \cos\theta_A^{\max}$ requirement, including almost all the $m_{a_1} < 2m_\tau$ (blue) points and a good fraction of the $2m_\tau < m_{a_1} < 7.5~\mathrm{GeV}$ (red) points.

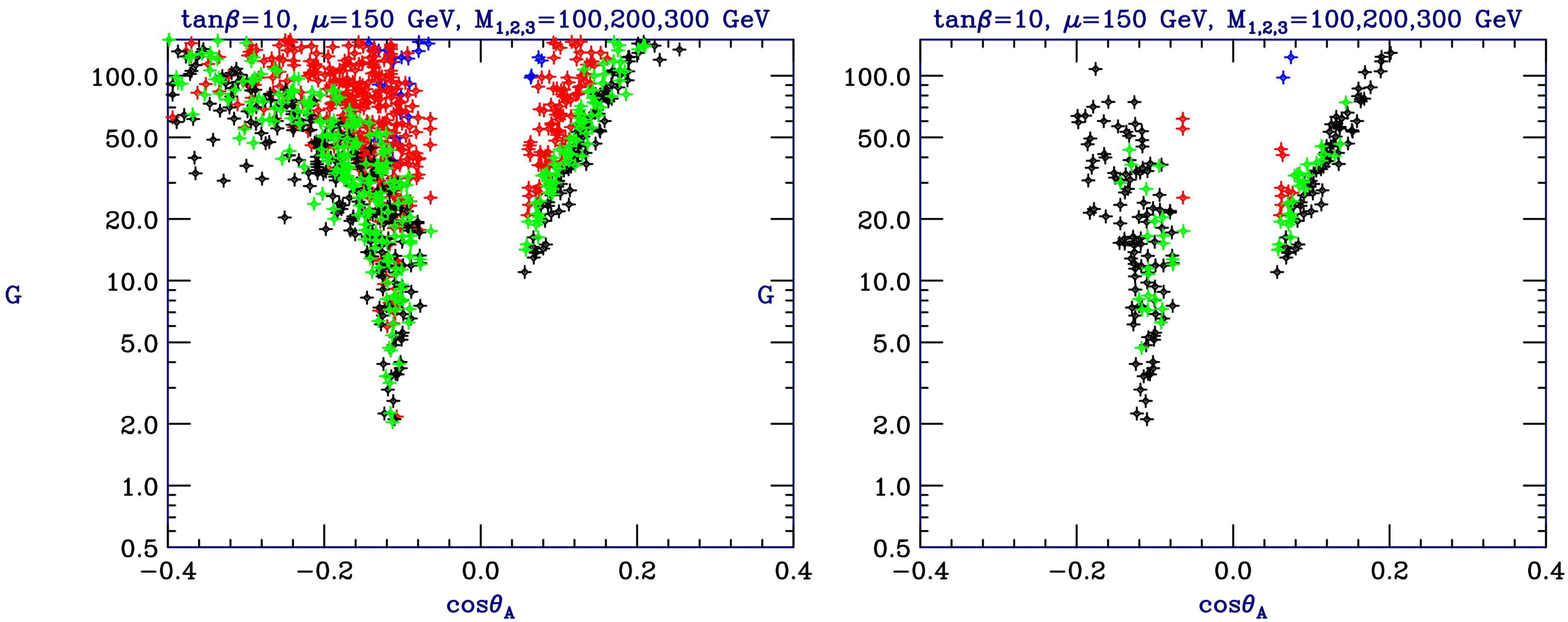


Figure 7: Results of $\mu = 150$ GeV and $\tan\beta = 10$ scan. Note that many points with low m_{a_1} and large $|\cos\theta_A|$ are eliminated, including almost all the $m_{a_1} < 2m_\tau$ points and most of the $2m_\tau < m_{a_1} < 7.5$ GeV points, leaving mainly $7.5~\mathrm{GeV} < m_{a_1} < 8.8~\mathrm{GeV}$ and $8.8~\mathrm{GeV} < m_{a_1} < 10~\mathrm{GeV}$ points.

Note the lower limit on $|\cos\theta_A|$ which results from the requirement $B(h_1 \to a_1 a_1) > 0.7$ for evading $e^+e^- \to Zh_1 \to Z + b's$ LEP limits.

- Thus, we have a convergence whereby low "light-a" fine tuning in the

NMSSM and direct $\Upsilon_{3S} \to \gamma\mu^+\mu^-$ and $\Upsilon_{3S} \to \gamma\tau^+\tau^-$ limits single out the $m_a > 7.5~\mathrm{GeV}$ part of parameter space.

In this talk, I will focus on Tevatron and LHC probes of a light a with $2m_\tau < m_a < 2m_B$.

Of course, the Tevatron and LHC *can* probe $m_a < 2m_\tau$:

1. $B(a \to \mu^+\mu^-)$ is much larger. BUT
2. Acceptance is presumably smaller because of p_T distributions for the μ's shifting down.
3. Backgrounds are presumably larger.

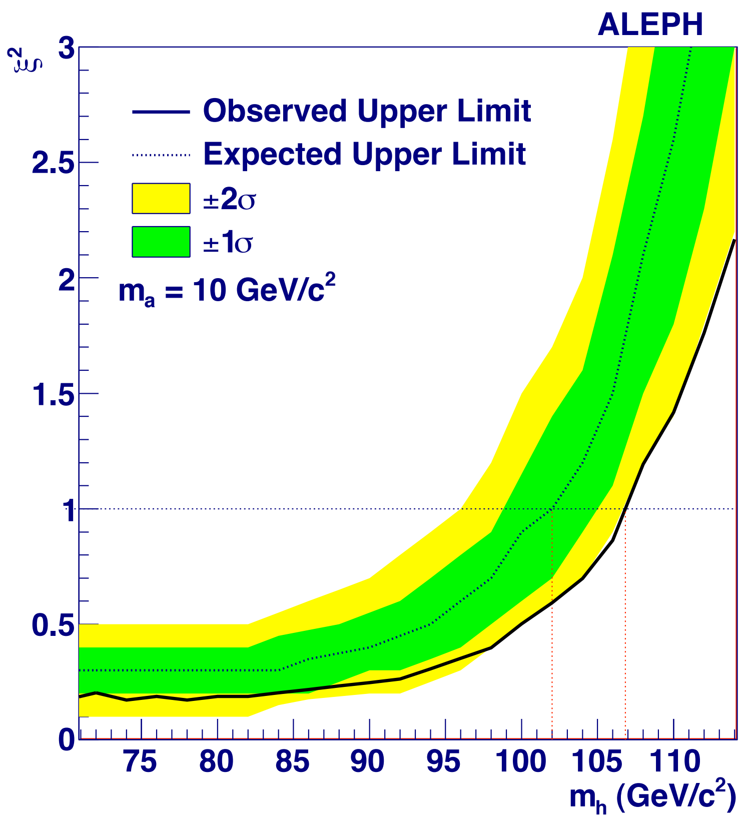
Studies of $m_a < 2m_\tau$ cases at hadron colliders are worth pursuing since they might completely eliminate all such NMSSM ideal Higgs scenarios, irrespective of G.

Here we will focus on $m_a > 2m_\tau$.

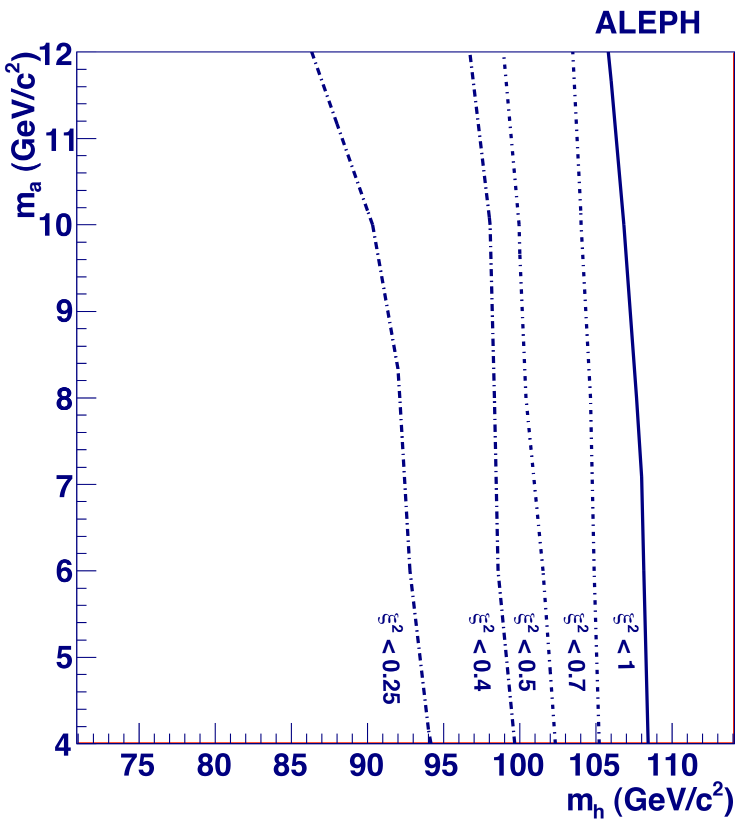
- Of course, as you saw from Radovan's talk, results from ALEPH further shift the focus to high m_a in the NMSSM context. A quick reminder.

ALEPH places limits on

$$\xi^2 = \frac{\sigma(e^+e^- \to Zh)}{\sigma(e^+e^- \to Zh_{\rm SM})} B(h \to aa)[B(a \to \tau^+\tau^-)]^2 , \qquad (4)$$



(a)



(b)

(Notice the huge difference between expected and observed limits.)

- **Comparison to NMSSM ideal scenarios:**

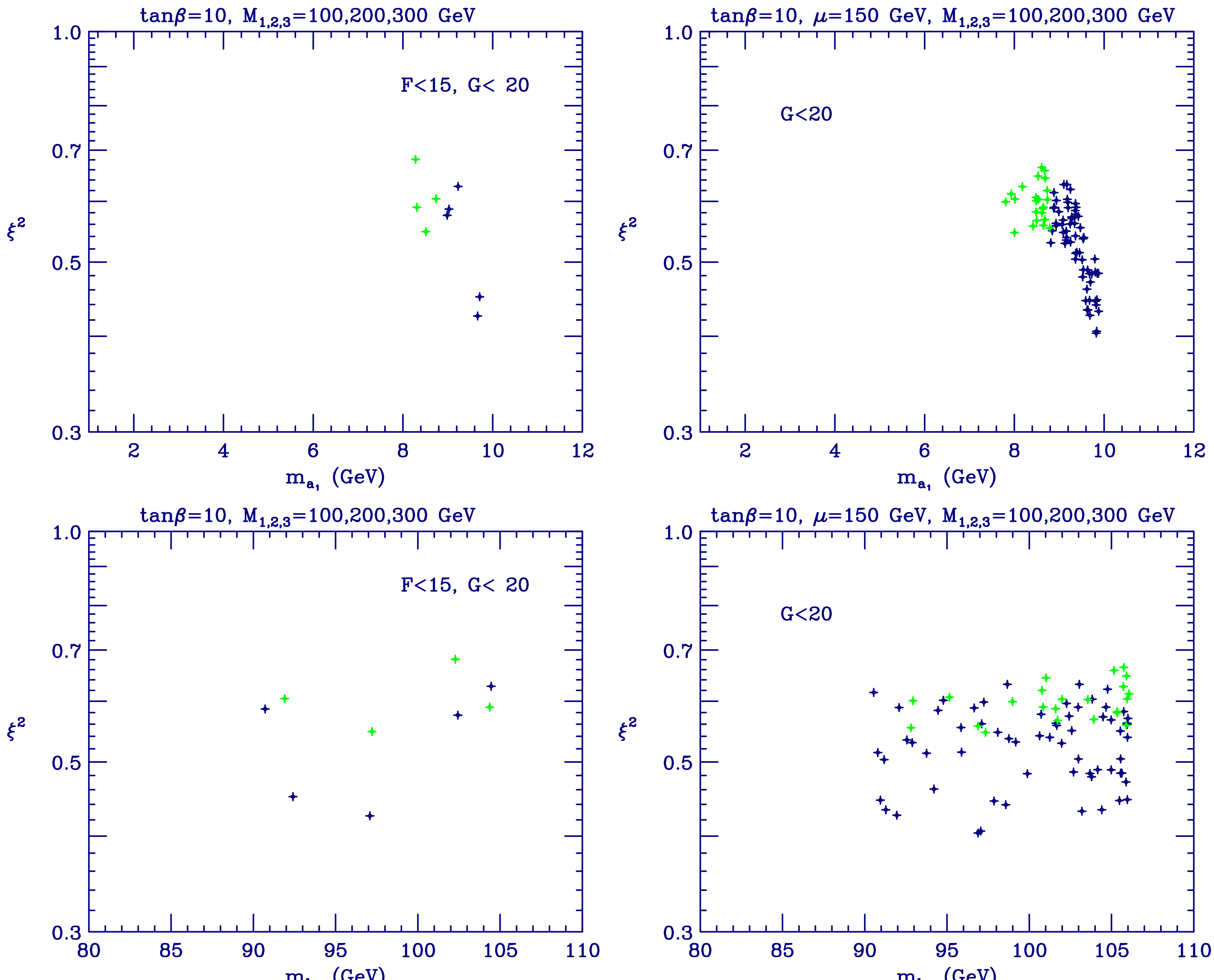


Figure 8: ξ^2 vs. m_{a_1} and m_{h_1} for $\tan\beta = 10$; $|\cos\theta_A| < \cos\theta_A^{\max}$; general scan and fixed μ scan.

What actually survives ALEPH limits?

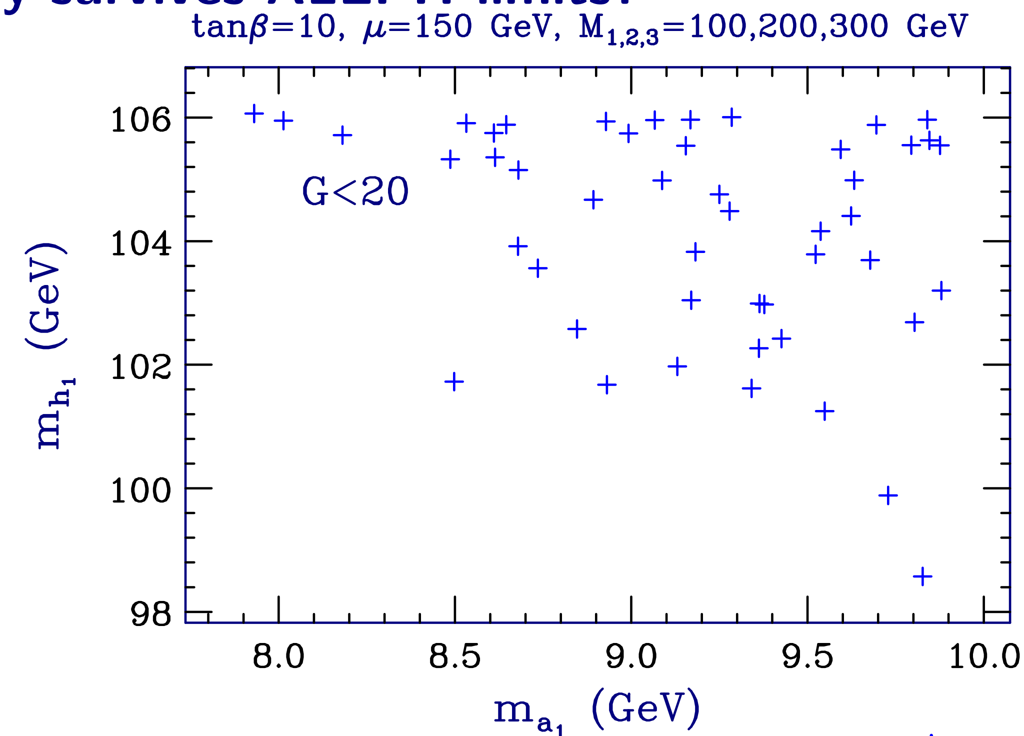


Figure 9: **Points with $G < 20$ at $\tan\beta = 10$ that survive $|\cos\theta_A|$ and ALEPH limits.**

- **For $\tan\beta = 3$, no points survive the ALEPH limits. ξ^2 is big even at large m_{a_1} and m_{h_1} is typically $\lesssim 95~\mathrm{GeV}$ where ALEPH limits are strong.**
- **For $\tan\beta = 2$, ξ_1^2 starts to decline at larger m_{a_1} sufficiently that some points survive.**
- **For $\tan\beta \lesssim 1.7$ one finds that ξ_1^2 declines significantly at larger m_{a_1} and most points escape ALEPH limits easily.**

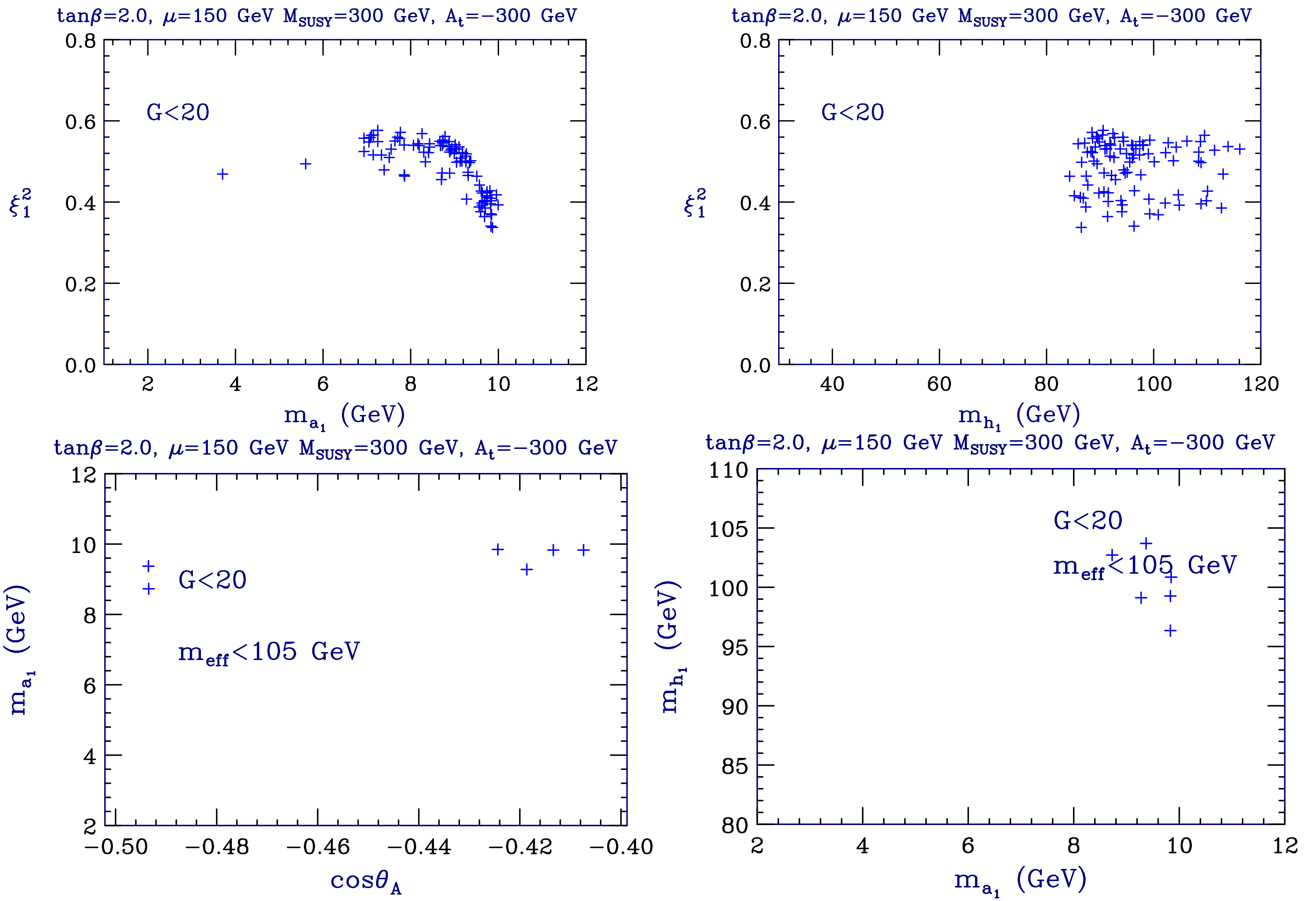


Figure 10: **Upper plots show ξ_1^2 vs. m_{a_1} and m_{h_1} for $\tan\beta = 2.0$; $|\cos\theta_A| < \cos\theta_A^{\max}$, $m_{eff} < 105$ GeV. Right-bottom plot shows the points that survive the ALEPH limits.**

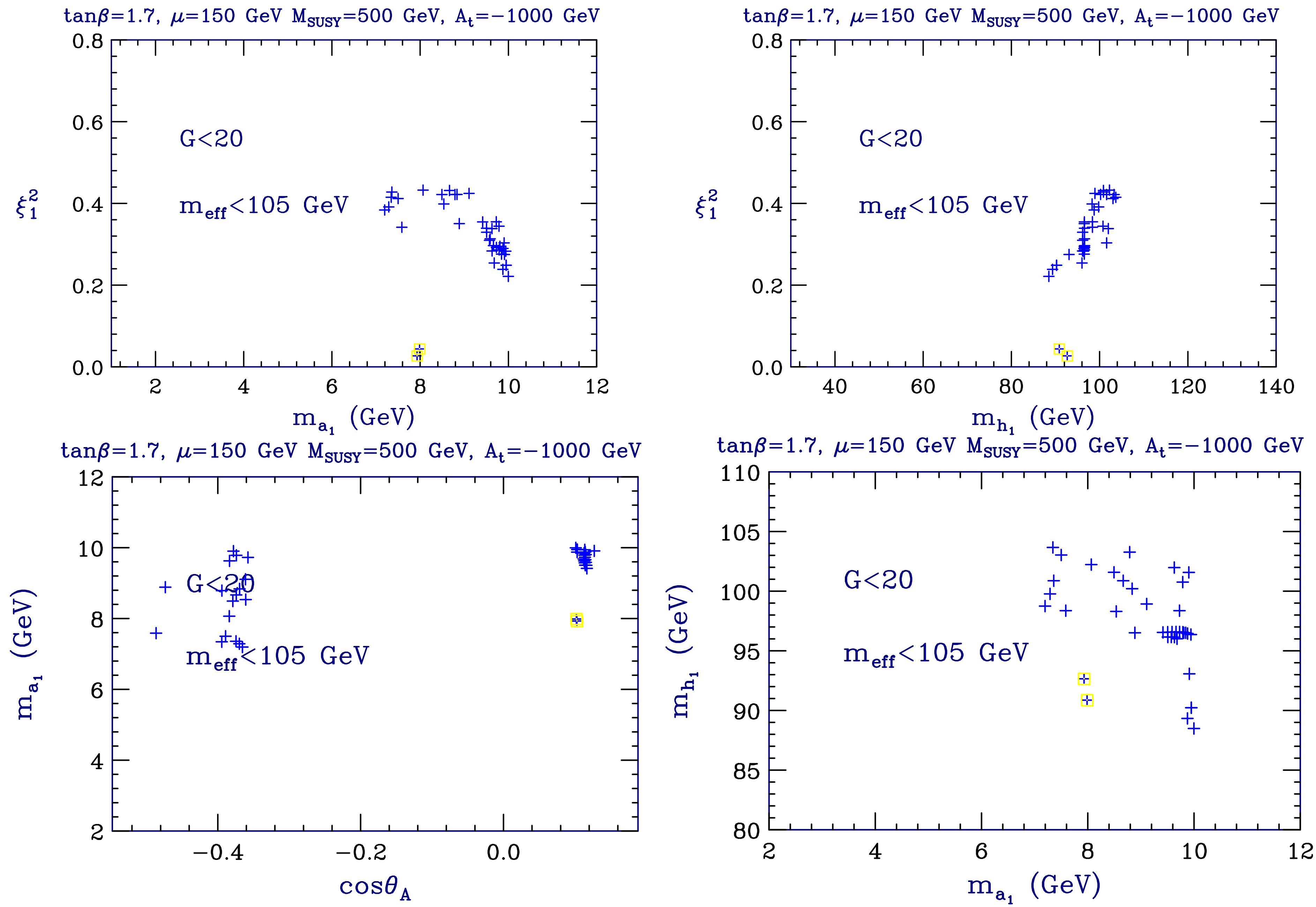


Figure 11: **Upper plots show ξ_1^2 vs. m_{a_1} and m_{h_1} for $\tan\beta = 1.7$; $|\cos\theta_A| < \cos\theta_A^{\max}$, $m_{eff} < 105$ GeV. Yellow squares have $B(h_1 \to a_1 a_1) < 0.7$ but still escape usual LEP limits. Right-bottom plot shows the points that survive the ALEPH limits.**

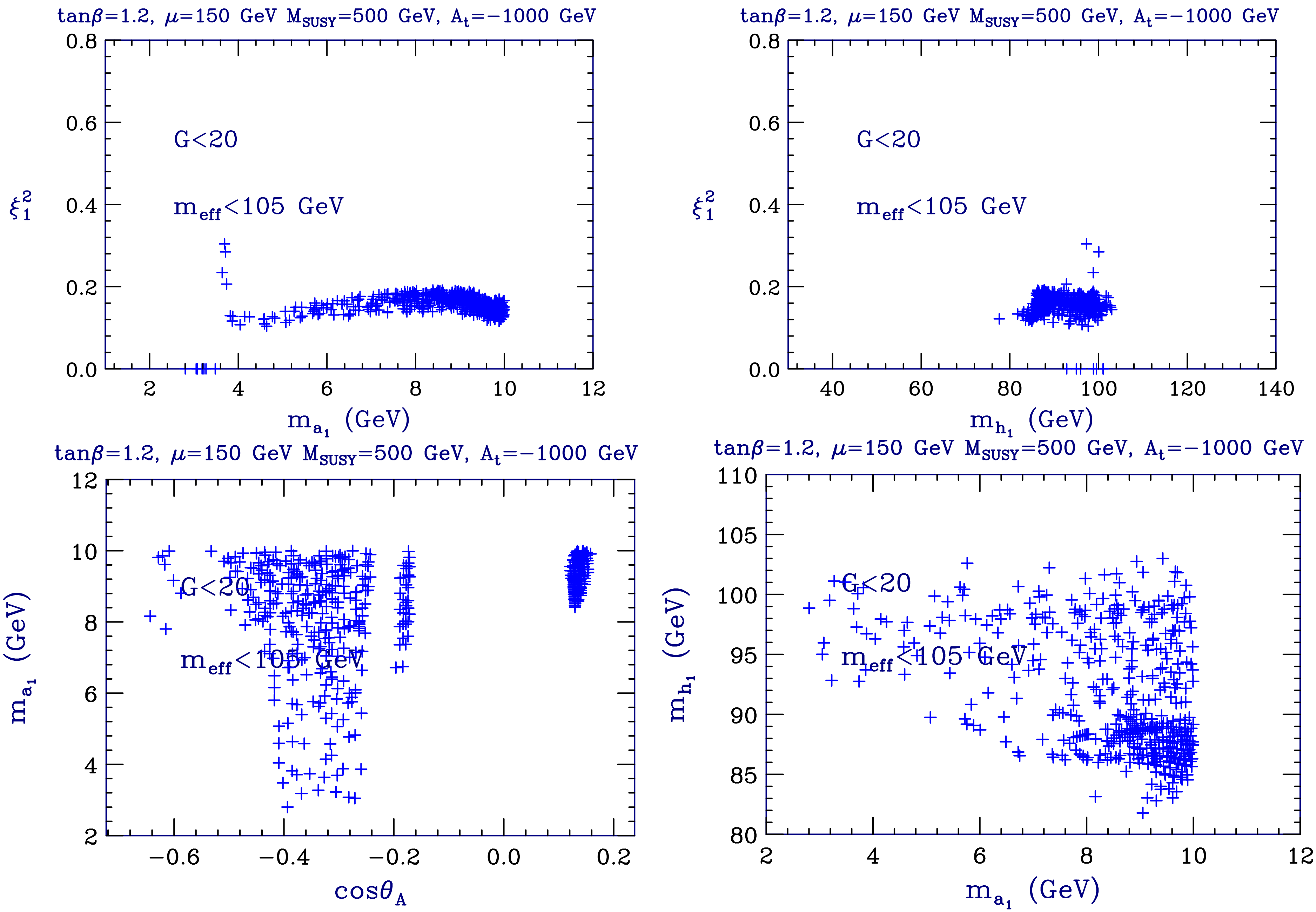


Figure 12: **Upper plots show ξ_1^2 vs. m_{a_1} and m_{h_1} for $\tan\beta = 1.2$; $|\cos\theta_A| < \cos\theta_A^{max}$, $m_{eff} < 105$ GeV. Bottom plot shows the points that survive the ALEPH limits. Note there are some $m_{a_1} < 2m_\tau$ points that survive.**

Table 1: Summary of $C_{ab\bar{b}} = \cos\theta_A \tan\beta$ ranges for points satisfying ALEPH ξ^2 limits, $|C_{ab\bar{b}}|$ limits, $G < 20$, and $B(h \to aa) > 0.7$.

$\tan\beta$	$C_{ab\bar{b}} < 0$ range	$C_{ab\bar{b}} > 0$ range
10	$[-2, -0.8]$	$[0.5, 1]$
3	N/A	N/A
2	$[-1, -0.8]$	none
1.7	$[-0.8, -0.6]$	~ 0.17
1.2	$[-0.72, -0.24]$	$[0.14, 0.2]$

- You see lots of possibilities for $|C_{ab\bar{b}}| \gtrsim 1$, but also many cases with $|C_{ab\bar{b}}|$ much < 1, particularly at low $\tan\beta$.
- Range of $|C_{ab\bar{b}}|$ expands substantially if $G < 20$ is relaxed.
- We will give some estimates relative to $|C_{ab\bar{b}}| = 1$, as achieved, for example, for $\tan\beta = 10$ and $\cos\theta_A = \pm 0.1$.

Probing the a at the Tevatron and LHC

- 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.

  (JFG+Dermisek, arXiv:0911.2460)

- 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.

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

- **The Tevatron**

  From a CDF analysis in the $6.3~\mathrm{GeV} - 9~\mathrm{GeV}$ mass window, one finds that the Tevatron will provide interesting constraints for $L = 10\ \mathrm{fb}^{-1}$.

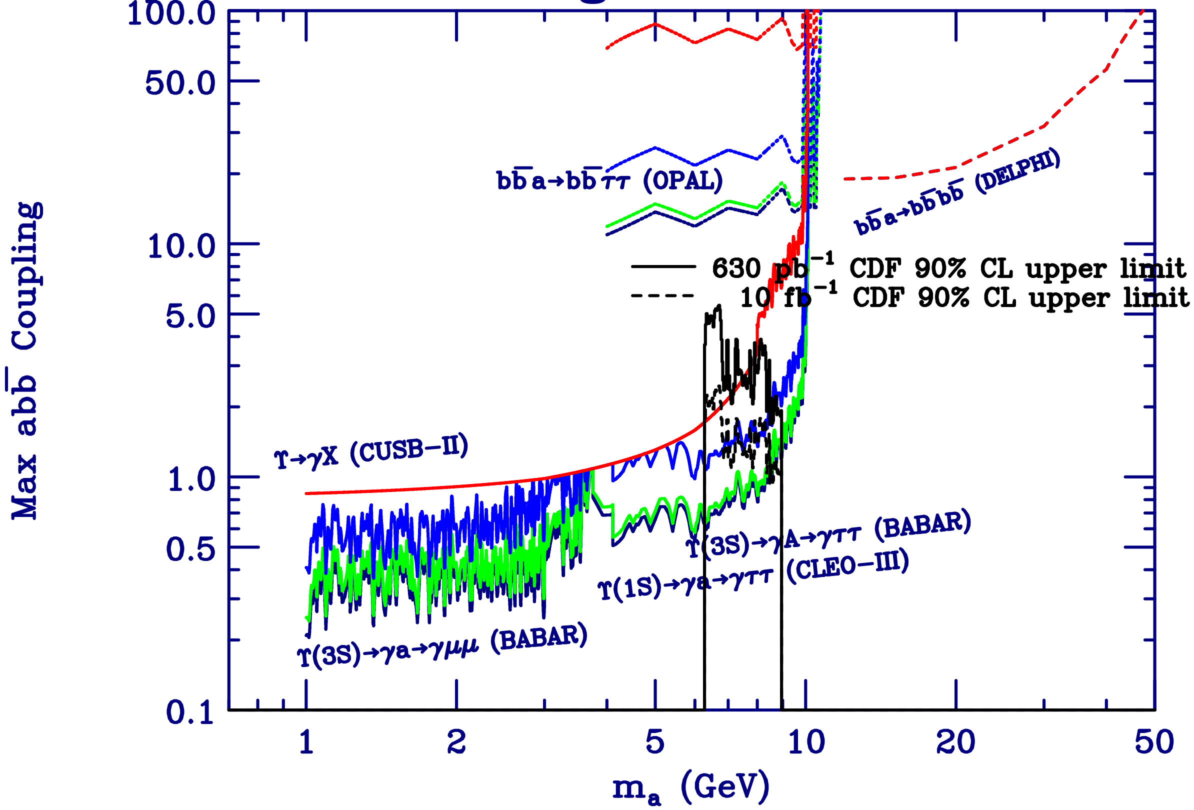


Figure 13: Tevatron limits (roughly $\tan\beta$-independent for $\tan\beta > 2$) compared to previous plot limits for $\tan\beta =$0.5, 1, 2, ≥ 3.

- CDF did not perform a detailed analysis outside $m_a \in [6.3\ \mathrm{GeV}, 9\ \mathrm{GeV}]$.
- We did our own estimate using the event number plots that extend to larger $M_{\mu^+\mu^-}$. We computed the $|C_{ab\bar{b}}|$ limits assuming no 90% CL (1.686σ) fluctuation in the $S/\sqrt{B}$-optimized m_a interval of $2\sqrt{2}\sigma_r$, where σ_r is the $M_{\mu^+\mu^-}$ resolution.

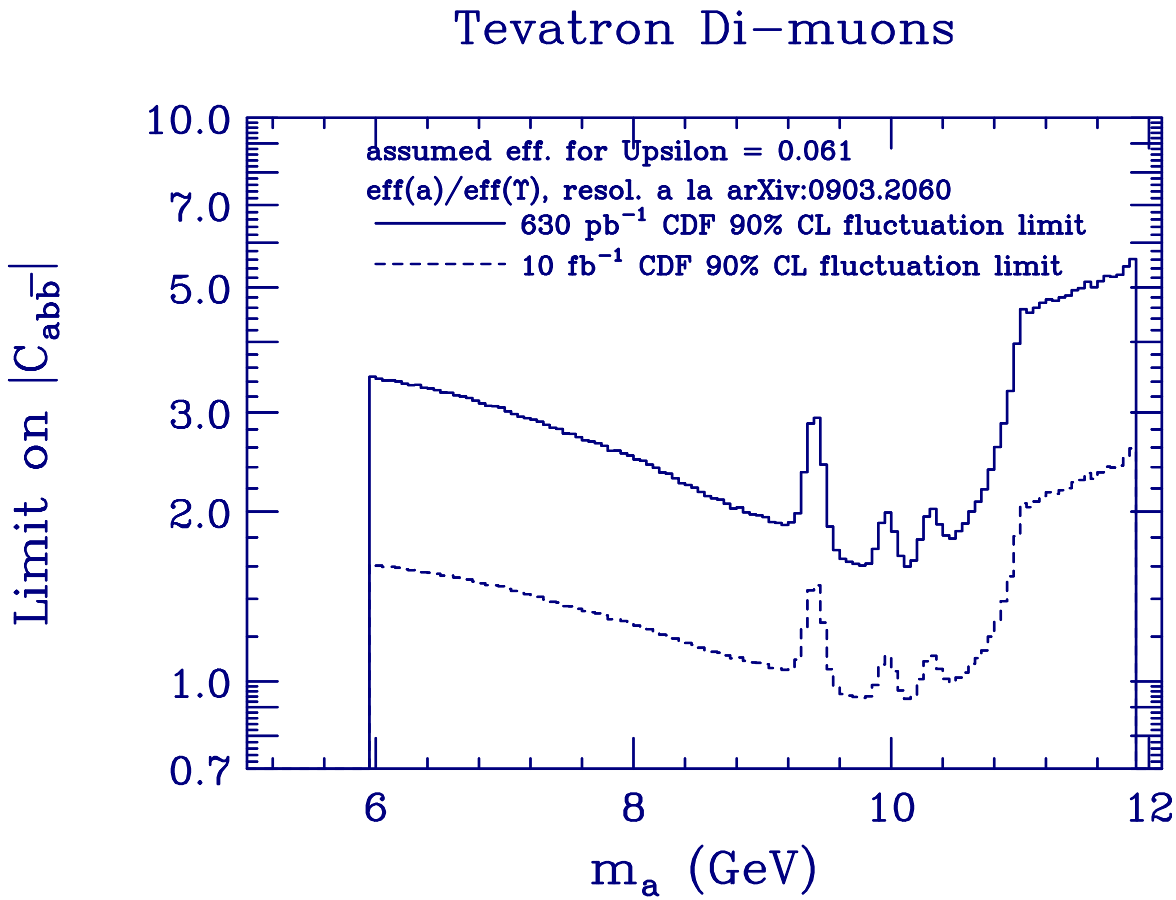


Figure 14: $L = 630~\mathrm{pb}^{-1}$ and $10~\mathrm{fb}^{-1}$ limits based on no 1.686σ excess in optimal interval. The limit as function of m_a is roughly $\tan\beta$-independent for $\tan\beta > 2$.

We see that in the region below $12~\mathrm{GeV}$ where a light a might have explained Δa_μ if $|C_{ab\bar{b}}| \gtrsim 32$, current Tevatron data forbids such a large $|C_{ab\bar{b}}|$. One can finally conclude that Δa_μ cannot be due to a light a.

- **What about the LHC?**

The cross sections vary slowly with $\sqrt{s}$. At $m_a = 10~\mathrm{GeV}$ and $\tan\beta = 10$, one finds (for $\cos\theta_A = 1$) $\sigma_{NLO}(1.96, 7, 10, 14~\mathrm{TeV}) \sim 1.5\times10^5, 5\times10^5, 7\times10^5, 9\times10^5~\mathrm{pb}$. Even after multiplying by $|\cos\theta_A|^2 \times B(a\to\mu^+\mu^-)$, the rates are substantial for $L = 1~\mathrm{fb}^{-1} = 1000~\mathrm{pb}^{-1}$!

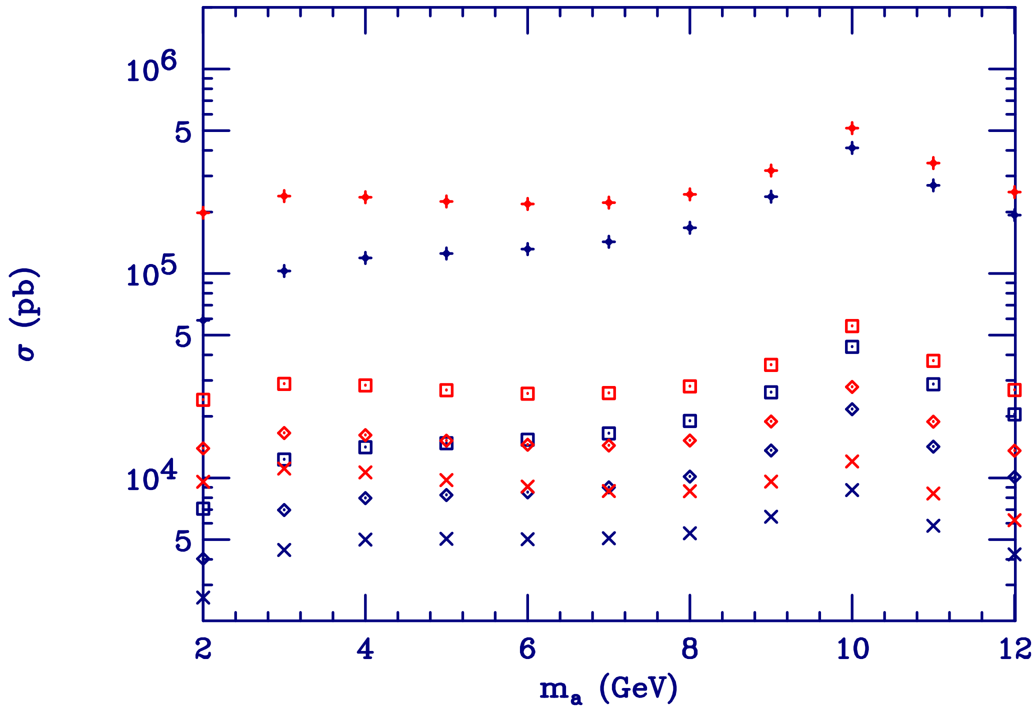


Figure 15: LHC, $\sqrt{s} = 7~\mathrm{TeV}$ cross sections for $\tan\beta = 1, 2, 3, 10$ (lowest to highest point sets). Factor of about $3\times$Tevatron at higher m_a.

ATLAS

ATLAS has presented public, but incomplete results at $\sqrt{s} = 14~\mathrm{TeV}$ — see Fig. 16.

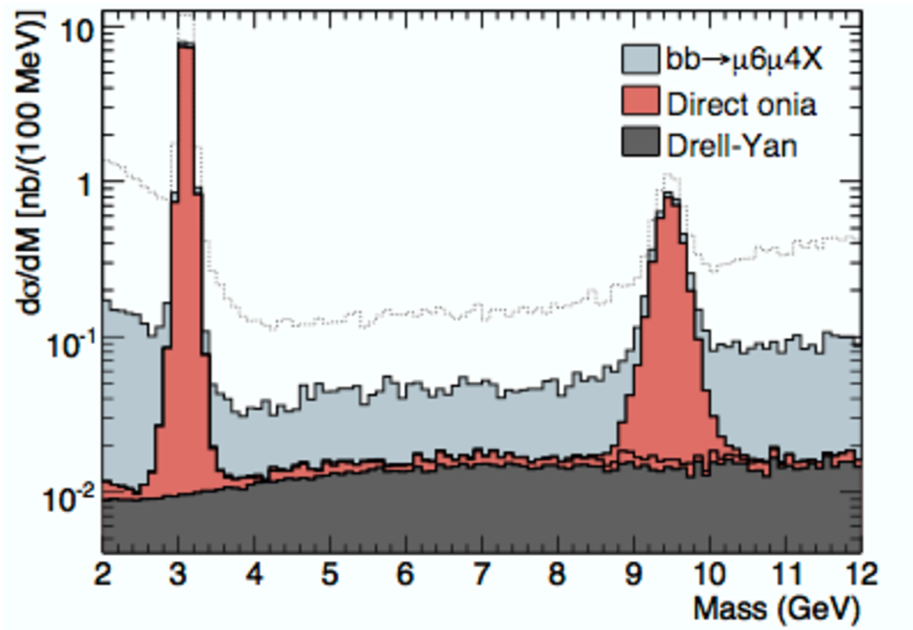


Figure 16: ATLAS dimuon spectrum prediction after corrections for acceptance and efficiencies (D. D. Price, arXiv:0808.3367 [hep-ex].).

In the above figure, the Drell-Yan background is much smaller than the heavy flavor background, even after muon isolation cuts.

The efficiencies for acceptance, reconstruction and isolation are already built into the $b\bar{b}$ and Υ_{1S} contributions of Fig. 16.

- After accounting for the need to double the plotted continuum background and the resolutions $\sigma_r(M_{\mu^+\mu^-})$ (54 MeV at J/ψ and 170 MeV at Υ_{1S}), we compute the number, $N_{\Delta M_{\mu^+\mu^-}}$, of background events in an interval of total width $\Delta M_{\mu^+\mu^-} = 2\sqrt{2}\sigma_r$ (the interval that maximizes $S/\sqrt{B}$).

  Assuming $L = 10\ \mathrm{pb}^{-1}$ of integrated luminosity, the background event numbers $N_{\Delta M_{\mu^+\mu^-}}$ in the intervals of size $\Delta M_{\mu^+\mu^-} = 2\sqrt{2}\sigma_r$ are 4055 at $m_a = 8$ GeV, 50968 at $m_a = M_{\Upsilon_{1S}}$ and 9620 at $m_a = 10.5$ GeV. We take the square root to determine the 1σ fluctuation level.

- We then consider the $a \to \mu^+\mu^-$ signal rates.

  An ATLAS Monte Carlo gives a net efficiency for the a of $\epsilon_{ATLAS} = 0.1$. In the hope that this can eventually be improved, we write

$$\epsilon_{ATLAS} = 0.1 r\,. \tag{5}$$

Consider $\tan\beta = 10$ and $|\cos\theta_A| = 0.1$ as reference case.

At $\sqrt{s} = 14$ TeV and $\tan\beta = 10$ the total a cross section ranges from about $4.2 \times 10^5\ \mathrm{pb}(\cos\theta_A)^2 \sim 4200$ pb at $m_a = 8$ GeV to ~ 8500 pb at $m_a \lesssim 2m_B$ for $\sqrt{s} = 14$ TeV.

The cross section for $a \to \mu^+\mu^-$ assuming $\tan\beta = 10$ and $\cos\theta_A = 0.1$ will then range from $4200 - 8500\ \mathrm{pb} \times (B(a \to \mu^+\mu^-) \sim 0.003) \sim 12 - 25$ pb.

As discussed above, we will write the total a efficiency in the form $\epsilon_{ATLAS} = 0.1 \times r$.

Multiplying the above cross section by ϵ_{ATLAS} and by the $Erf(1) = 0.8427$ acceptance factor for the ideal interval being employed and using $L = 10\ \mathrm{pb}^{-1}$ (as employed above in computing the number of background events), we obtain a event numbers of $10 \times r$, $19 \times r$ and $21 \times r$ at $m_a = 8$ GeV, $M_{\Upsilon_{1S}}$ and 10.5 GeV, respectively. Note small S/B.

We can repeat this analysis for lower $\sqrt{s}$.

Table 2: Luminosities (fb^{-1}) needed for 5σ if $\tan\beta = 10$ in terms of $R \equiv r\left(\frac{|C_{ab\bar b}|}{0.1}\right)$.

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

The L's that are needed according to the above analysis cannot be achieved in the first run, but may be achieved in the 2nd run.

Subjects of further study:

- **Can r be improved?**
- **Even more important, can be get better S/B without sacrificing $S/\sqrt{B}$ by finding better ways to reduce B.**
- **And, how do we deal with cases where m_a is degenerate with one of the Υ's?**

CMS?

- Working subgroup: Chiara Mariotti, Max Chertok, Maria Assunta Borgia, Pietro Govoni, Leonardo di Matteo, Mario Pelliccioni and JFG.

  Monte Carlos were run, acceptances and efficiencies for backgrounds and signal were evaluated and signal significances computed.

  For the signal, PYTHIA was employed for light A and then cross section was normalized to HIGLU predictions for integrated cross section. Gluon radiation in PYTHIA mimics that present in $gg \to a + NLO$. Signal width $=$ resolution dominated.

  For background, used ppMuX sample and $\Upsilon(nS)$ production ala PYTHIA.

  Very detailed reconstruction and isolation procedures were employed.

  Surviving background event rates are much below those of the ATLAS plot while net signal efficiencies are kept above 10%.

- A Survey of all NMSSM Ideal Higgs Models

- In the Upsilon peak regions the results are too naive since one must use some technique to normalize the Upsilon peaks themselves.
- We have plotted the $\sqrt{s} = 7~\mathrm{TeV}$ integrated L required to obtain a 3σ signal level above background.
- There is an obvious increase in the required L in the vicinity of the Υ resonances, especially the Υ_{1S}.
- At higher $\tan\beta \geq 2$, $L = 10~\mathrm{fb}^{-1}$ will yield a 3σ signal for all the NMSSM points, nominally even for $m_a \sim M_{\Upsilon_{1S},\Upsilon_{2S},\Upsilon_{3S}}$ if we can independently normalize the $\Upsilon(nS)$ cross sections accurately.
- But, for $\tan\beta \leq 1.7$, there is a large range of acceptable $\cos\theta_A$ values, some of which have small magnitude and therefore small LHC cross section. In addition, $B(a \to \mu^+\mu^-)$ declines at small $\tan\beta$. Lots of points will need to await higher energy and large $L > 10~\mathrm{fb}^{-1}$.

- Another way of viewing the results is in terms of the $|\cos\theta_A|$ limits as discussed earlier. For $1~\mathrm{fb}^{-1}$ of data at $7~\mathrm{TeV}$ CMS will definitely place significant limits on $|\cos\theta_A|$ throughout the $[8~\mathrm{GeV}, 12~\mathrm{GeV}]$ range, again ignoring the issue of exactly how to normalize the $\Upsilon(nS)$ backgrounds.

- **Main ideas for getting control in the $\Upsilon(nS)$ peak regions are based on assuming signal is present only in one peak region.**

  1. **Use theory to compute expected ratios for $1S : 2S : 3S$ and look for agreement in one ratio and disagreement in other ratios.**
     Proper understanding of $\Upsilon(nS)$ production, including p_T and η distributions at NLO, is needed to avoid too large systematic error.
  2. **Use $\Upsilon(nS) \to e^+e^-$ observations to normalize the peaks, assuming lepton universality for the $\Upsilon(nS)$ decays.**
     Of course electron efficiencies will be more poorly known than muon efficiencies and so we plan to explore using double ratios:

$$\frac{\left[\frac{\sigma(\Upsilon_{1S}\to\mu^+\mu^-)}{\sigma(\Upsilon_{2S}\to\mu^+\mu^-)}\right]}{\left[\frac{\sigma(\Upsilon_{1S}\to e^+e^-)}{\sigma(\Upsilon_{2S}\to e^+e^-)}\right]} \qquad \frac{\left[\frac{\sigma(\Upsilon_{2S}\to\mu^+\mu^-)}{\sigma(\Upsilon_{3S}\to\mu^+\mu^-)}\right]}{\left[\frac{\sigma(\Upsilon_{2S}\to e^+e^-)}{\sigma(\Upsilon_{3S}\to e^+e^-)}\right]} \tag{6}$$

for which some of the efficiency uncertainties should cancel.

Conclusions

In case you hadn't noticed, we theorists have been going a bit crazy waiting for THE Higgs.

"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.

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