Update on NMSSM "Ideal Higgs" Scenarios

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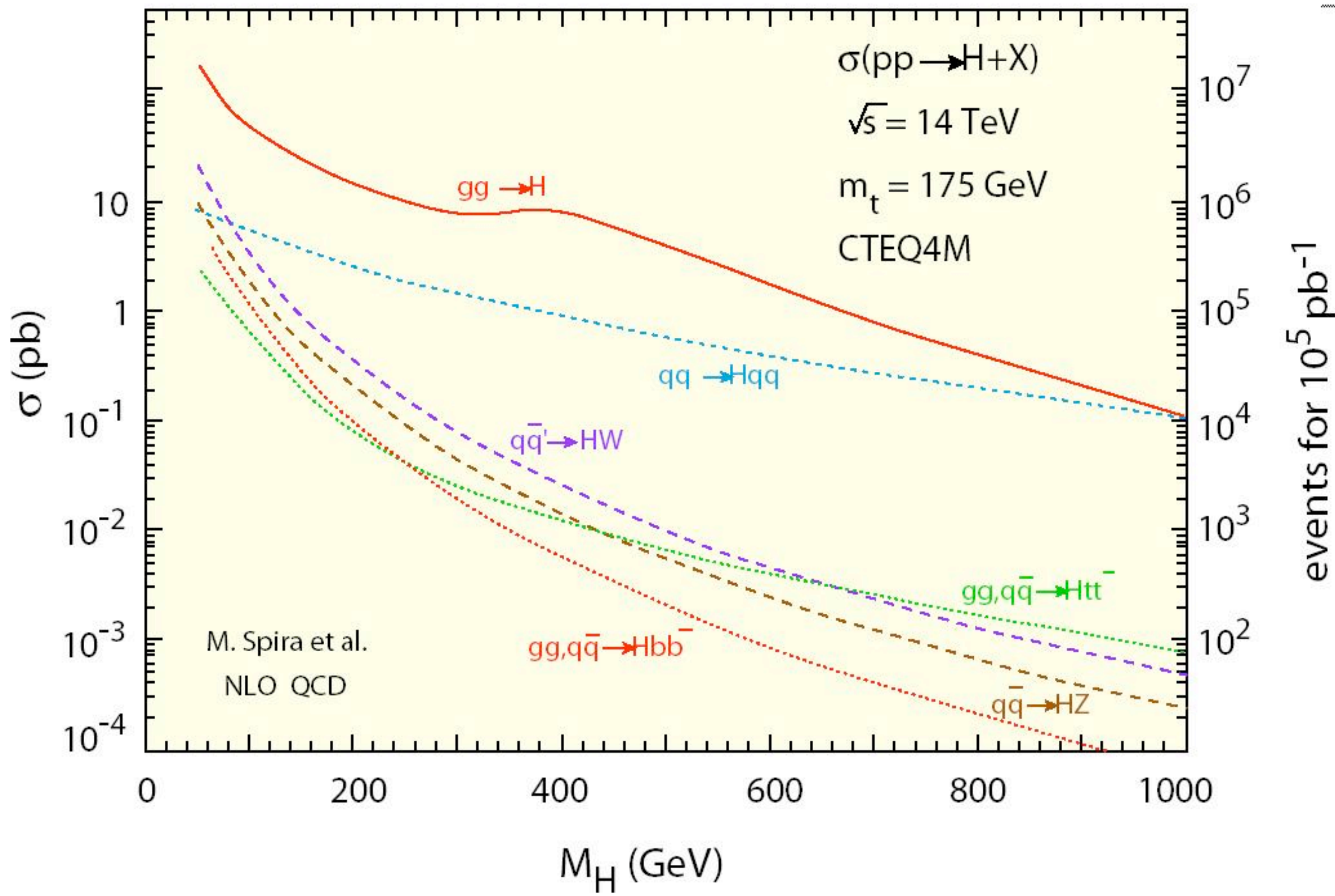
Synopsis/Outline

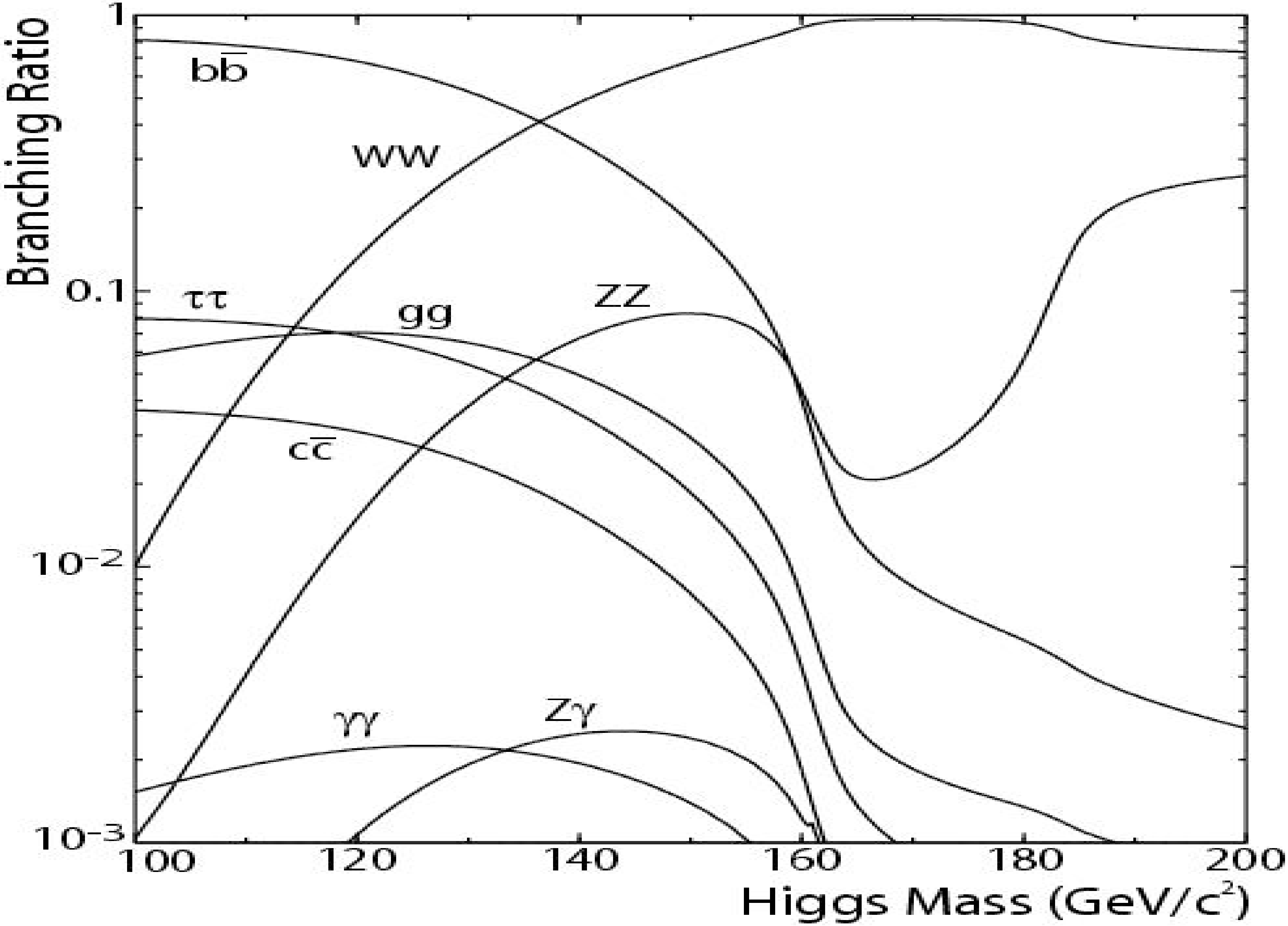
There are excellent motivations for an $m_h \lesssim 105~\mathrm{GeV}$ SUSY Higgs with SM-like couplings to SM particles but elusive decays.

- Precision Electroweak (PEW) data prefer a Higgs boson with SM-like $g_{WWh,ZZh}$ and $m_h \lesssim 105~\mathrm{GeV}$
- The simplest solution to the hierarchy problem is SUSY.
- Gauge coupling unification prefers something close to the MSSM.
- Absence of EWSB fine-tuning requires a light SUSY spectrum (in particular, a light $\widetilde{t}$) and a light $\widetilde{t}$ implies that the SM-like Higgs of SUSY is light.
- MSSM scenarios having a Higgs with SM-like properties that is light , i.e. $m_h \lesssim 105~\mathrm{GeV}$ (for PEW perfection) are excluded by LEP.
- Extended SUSY models, including the NMSSM (which preserves all good MSSM features and solves the μ problem) give elusive decay scenarios not ruled out by LEP for $m_h < 105~\mathrm{GeV}$.
- LHC strategies for Higgs searches will need to be expanded.

- **Higgs cross sections (initiated by SM particles with SM-like h couplings) are determined. Main processes are $gg \to h$ and $qq \to q'q'WW$ with $WW \to h$.**



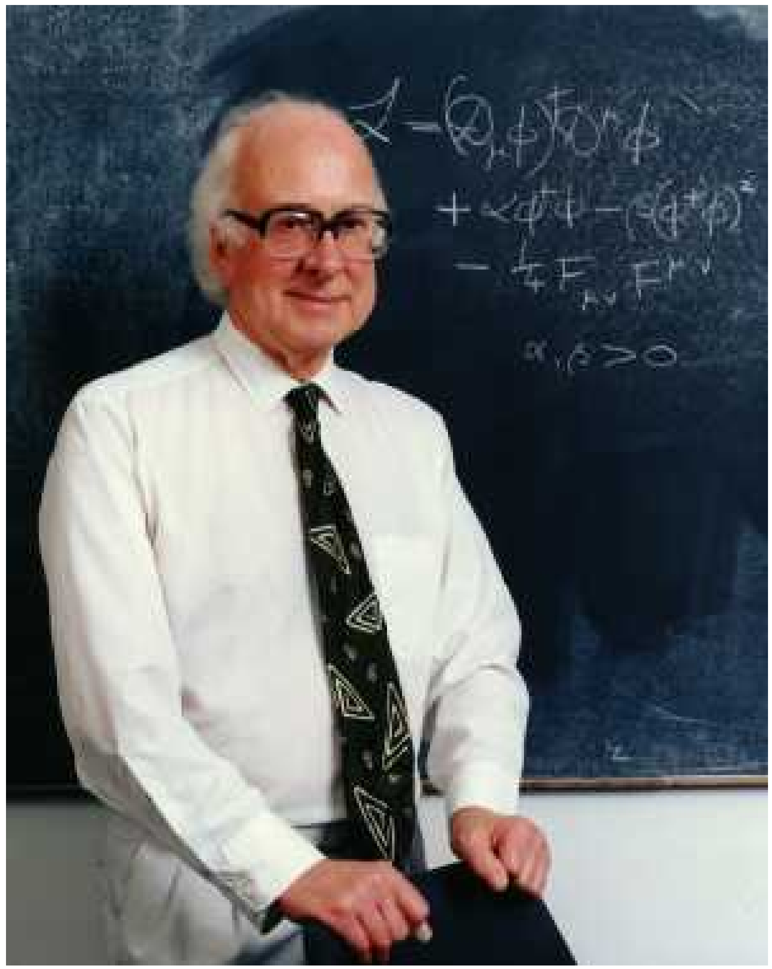
- **In the absence of new physics, Higgs decays are also determined by these same couplings.**



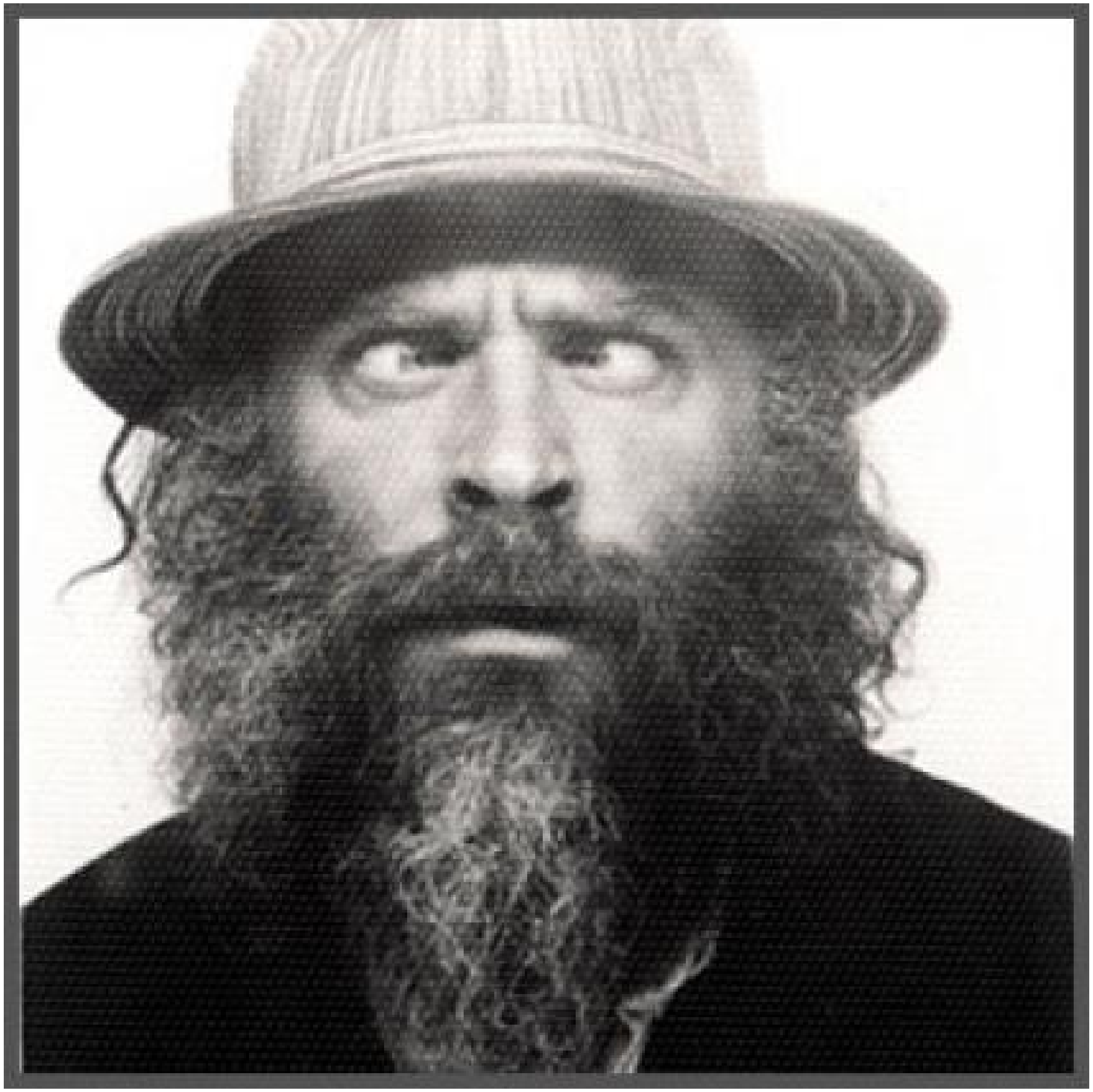
- **However, Beyond the SM physics could completely alter the Higgs decay patterns.**

  We really should not count on knowing what the Higgs "looks like". It could be ...

Priestly, highly orthodox



Ornery/ mean, highly heretical



singer Daniel Higgs

Beautiful but unorthodox

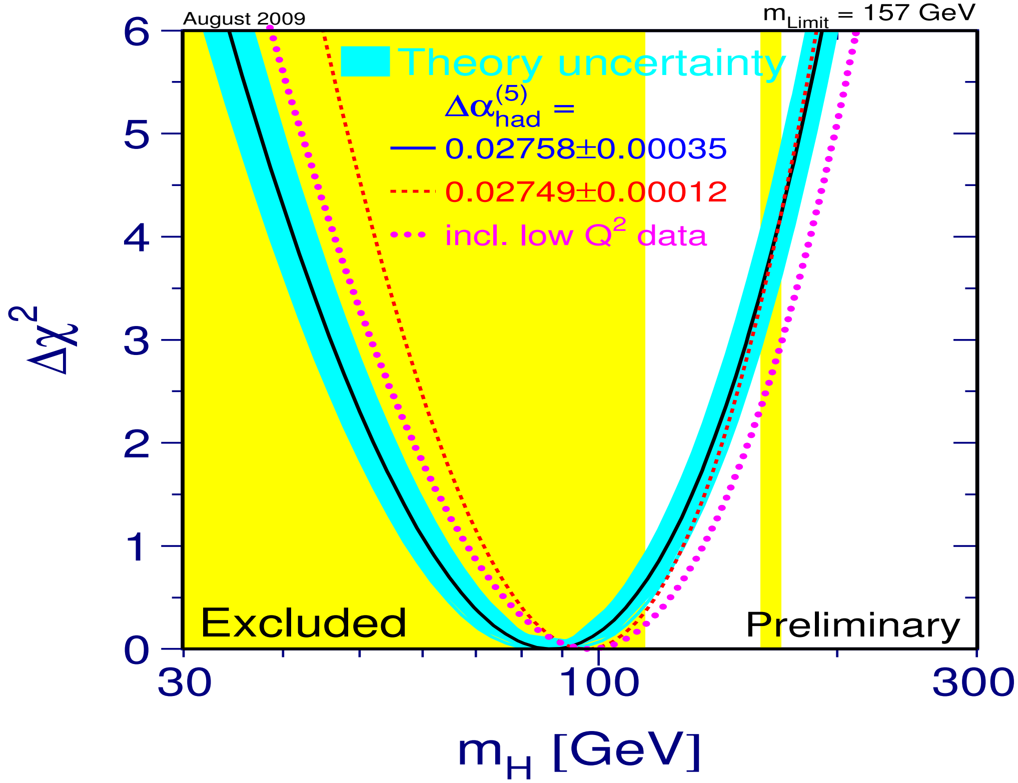
singer Rebekah Higgs

Or, will the LHC bury the Higgs?

In fact, there is even a "buried Higgs" model.

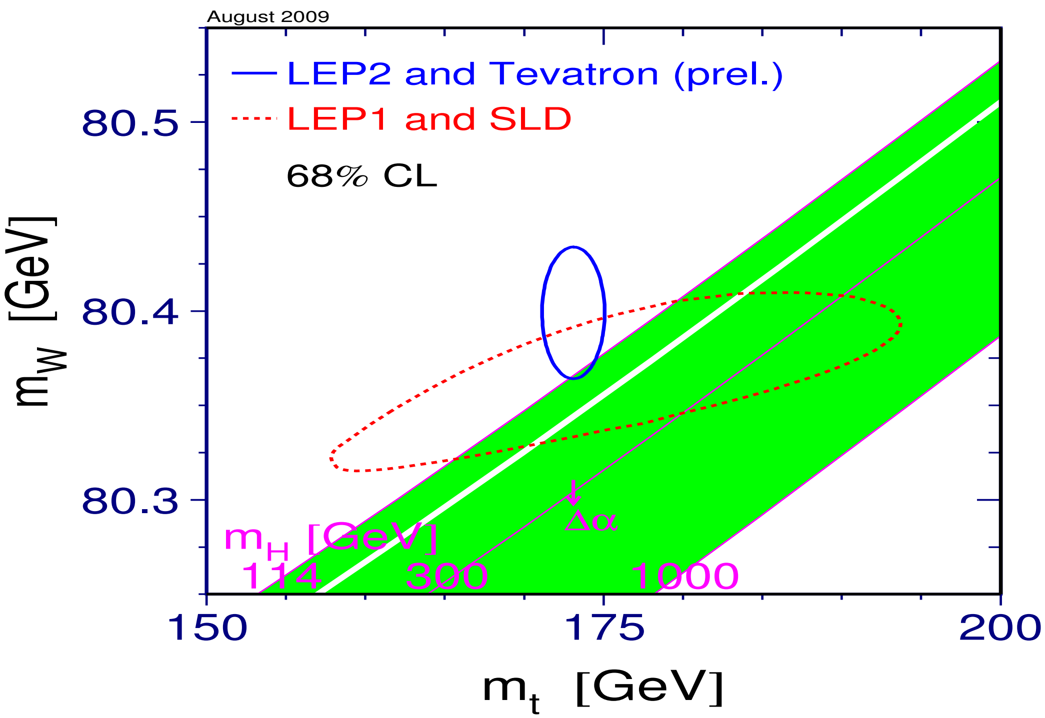
Motivation for Non-Standard Decays — single H

- A fairly recent plot of $\Delta\chi^2(PEW)$ vs. m_H is:



At 95% CL, $m_{h_{\rm SM}} < 157~{\rm GeV}$ and the $\Delta\chi^2$ minimum is near $85~{\rm GeV}$ when all data are included.

The latest m_W and m_t measurements also prefer $m_{h_{\rm SM}} \lesssim 100~{\rm GeV}$.



Further, the blue-band plot may be misleading due to the discrepancy between the "leptonic" and "hadronic" measurements of $\sin^2\theta_W^{eff}$, which yield $\sin^2\theta_W^{eff} = 0.23113(21)$ and $\sin^2\theta_W^{eff} = 0.23222(27)$, respectively. The SM has a CL of only 0.14 when all data are included.

If only the leptonic $\sin^2\theta_W^{eff}$ measurements are included, the SM gives a fit with CL near 0.78. However, the central value of $m_{h_{\rm SM}}$ is then near $50~{\rm GeV}$ with a 95% CL upper limit of $\sim 105~{\rm GeV}$ (Chanowitz, xarXiv:0806.0890).

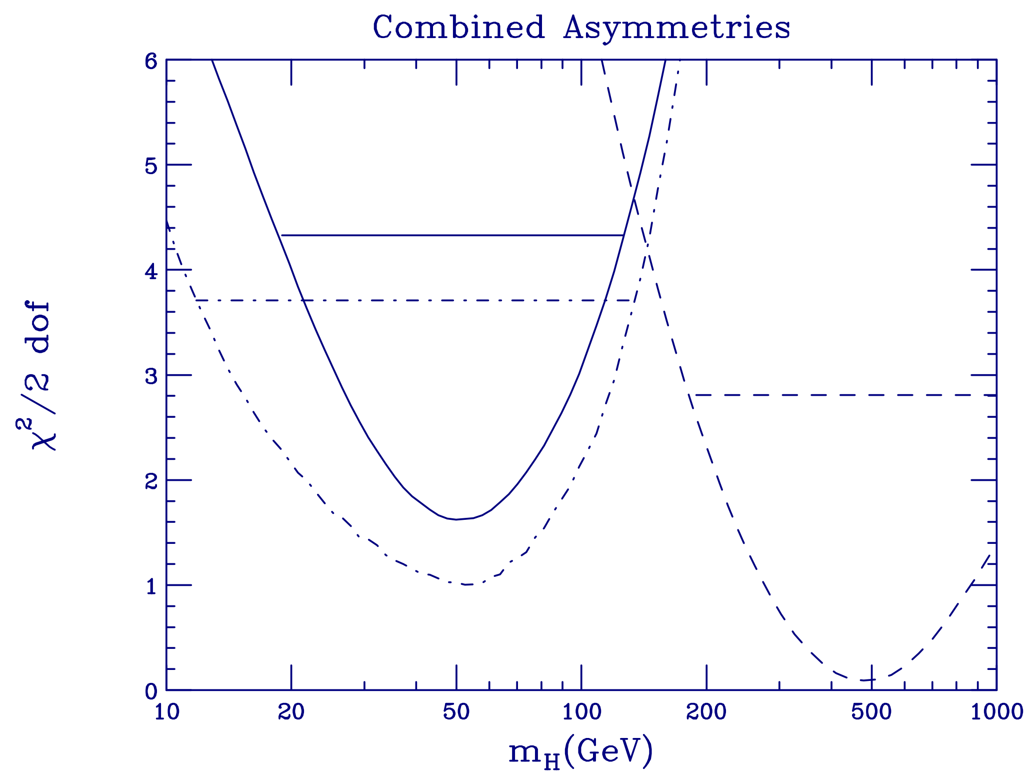


Figure 1: χ^2 distributions as a function of m_H from the combination of the three leptonic asymmetries A_{LR}, A^{ℓ}_{FB}, $A_{\ell}(P_{\tau})$ (solid line); the three hadronic asymmetries A^b_{FB}, A^c_{FB}, and Q_{FB} (dashed line); and the three m_H-sensitive, non-asymmetry measurements, m_W, Γ_Z, and R_l (dot-dashed line). The horizontal lines indicate the respective 90% symmetric confidence intervals.

- Thus, in an ideal model, a Higgs with SM-like ZZ coupling should have mass no larger than 105 GeV.

But, at the same time, the H must escape LEP and CDF/D0 limits on m_H. In the case of a completely SM-like Higgs they are summarized as

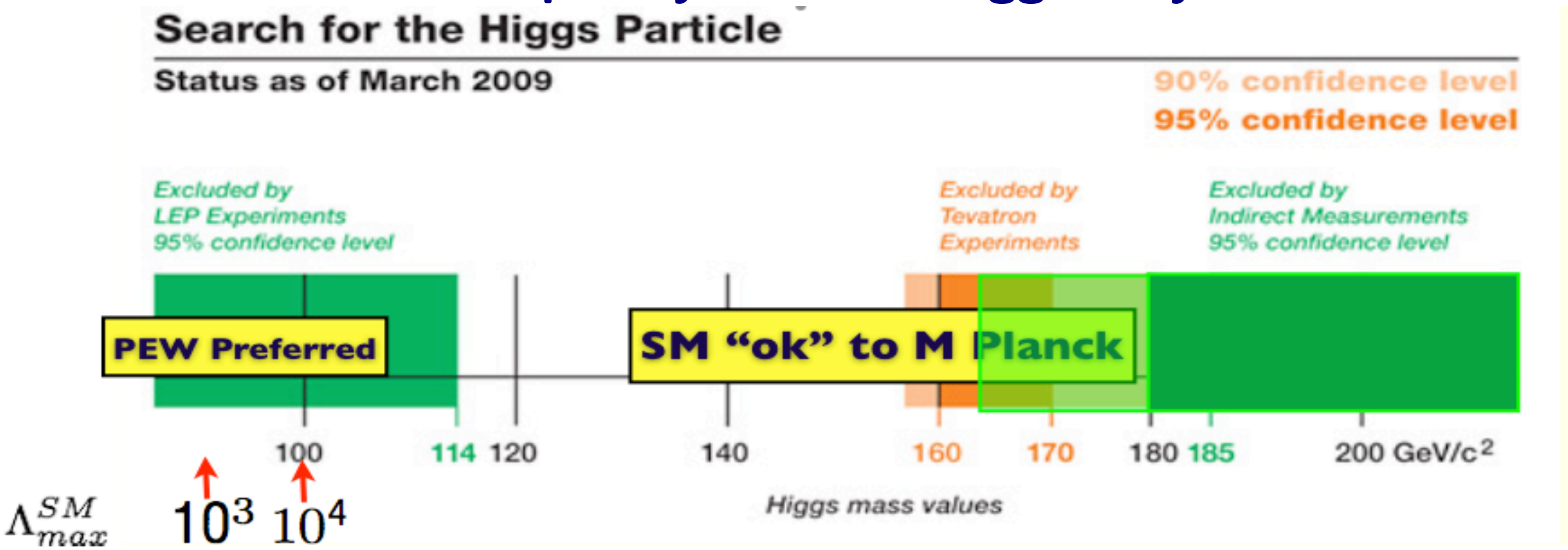


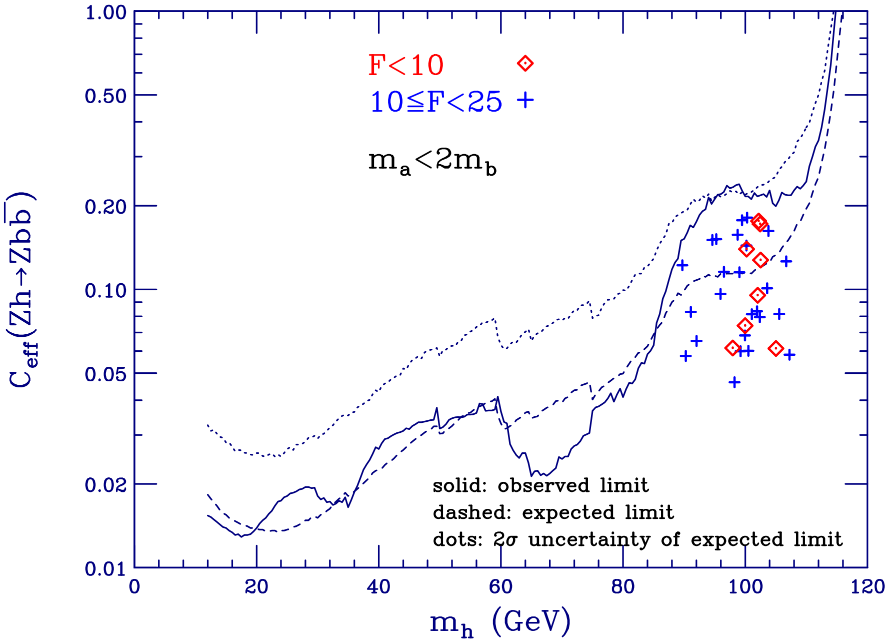
Table 1: LEP m_H Limits for a H with SM-like ZZ coupling, but varying decays. See (S. Chang, R. Dermisek, J. F. Gunion and N. Weiner, Ann. Rev. Nucl. Part. Sci. 58, 75 (2008) [arXiv:0801.4554 [hep-ph]]).

Mode Limit (GeV)	SM modes 114.4	2τ or $2b$ *only* 115	$2j$ 113	$WW^* + ZZ^*$ 100.7	$\gamma\gamma$ 117	$\not{E}$ 114	$4e, 4\mu, 4\gamma$ 114?
Mode Limit (GeV)	$4b$ 110	pure 4τ $86 \rightarrow \sim 108?$[1]	any (e.g. $4j$) 82	$2f + \not{E}$ 90?			

1. Latest ALEPH result.

To have $m_H \leq 105\ \mathrm{GeV}$ requires one of the final three modes.

- **Perhaps the ideal 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.**



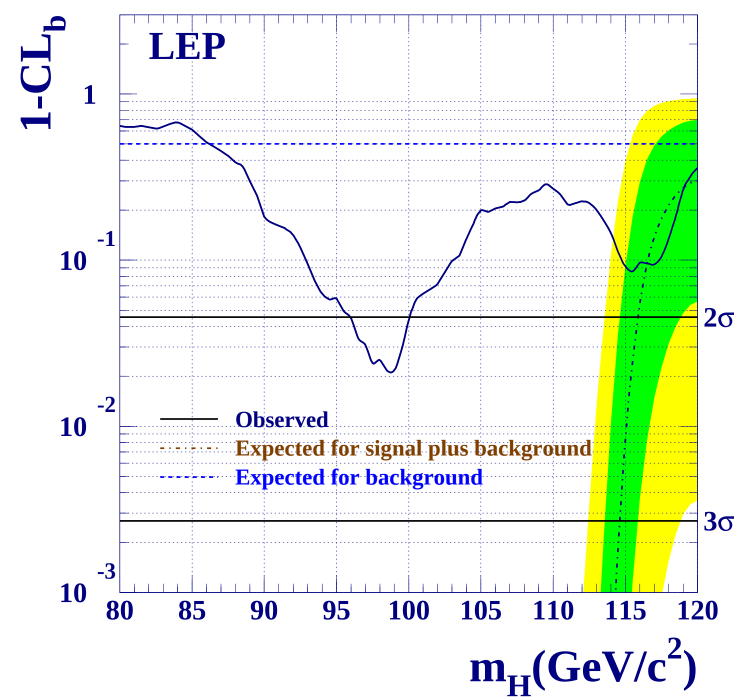


Figure 2: **Plots for the $Zb\bar{b}$ final state. F is the m_Z-fine-tuning measure for the NMSSM.**

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 poorly constrained channels.

- One generic way of having a low LEP limit on m_H is to suppress the $H \to b\bar{b}$ branching ratio by having a light a (or h) with $B(H \to aa) > 0.7$ and $m_a < 2m_b$ (to avoid LEP $Z + 4b$ limit at $110~\mathrm{GeV}$, i.e. above ideal). For $2m_\tau < m_a < 2m_b$, $a \to \tau^+\tau^-$. For $m_a < 2m_\tau$, $a \to jj$.

  See: (R. Dermisek and J. F. Gunion, Phys. Rev. Lett. 95, 041801 (2005) [arXiv:hep-ph/0502105]; R. Dermisek and J. F. Gunion, Phys. Rev. D 73, 111701 (2006) [arXiv:hep-ph/0510322])

- Since the $Hb\bar{b}$ coupling is so small, very modest Haa coupling suffices.

  Higgs pair modes can easily dominate until we pass above the WW threshold.

- So, let us suppose that we want $m_H < 105~\mathrm{GeV}$. We should then recall the triviality and global minimum constraints on the scale Λ of new physics.

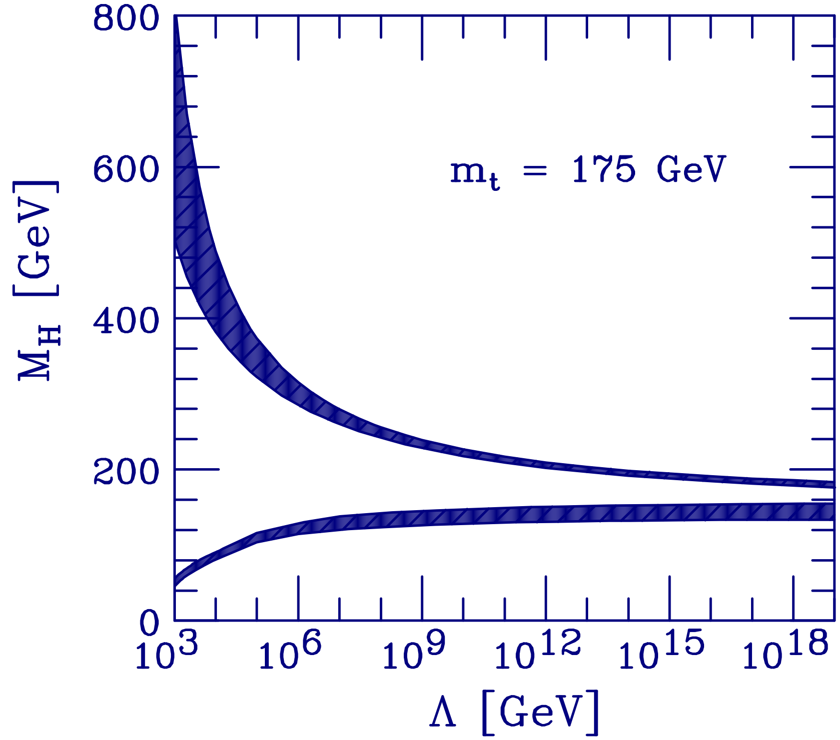


Figure 3: Triviality and global minimum constraints on $m_{h_{\rm SM}}$ vs. Λ.

The implication is that some new physics should arise for $\Lambda < 10^4 (10^3)$ GeV if $m_h \sim 100$ GeV (~ 50 GeV). A wonderful choice would be SUSY.

- **SUSY does many wonderful things. In particular, SUSY cures the naturalness / hierarchy problem.**

- **Indeed, the MSSM comes close to being very nice.**

  If we assume that all sparticles reside at the $\mathcal{O}(1\ \mathrm{TeV})$ scale and that μ is also $\mathcal{O}(1\ \mathrm{TeV})$, then, the MSSM has two particularly wonderful properties.

1. Gauge Coupling Unification

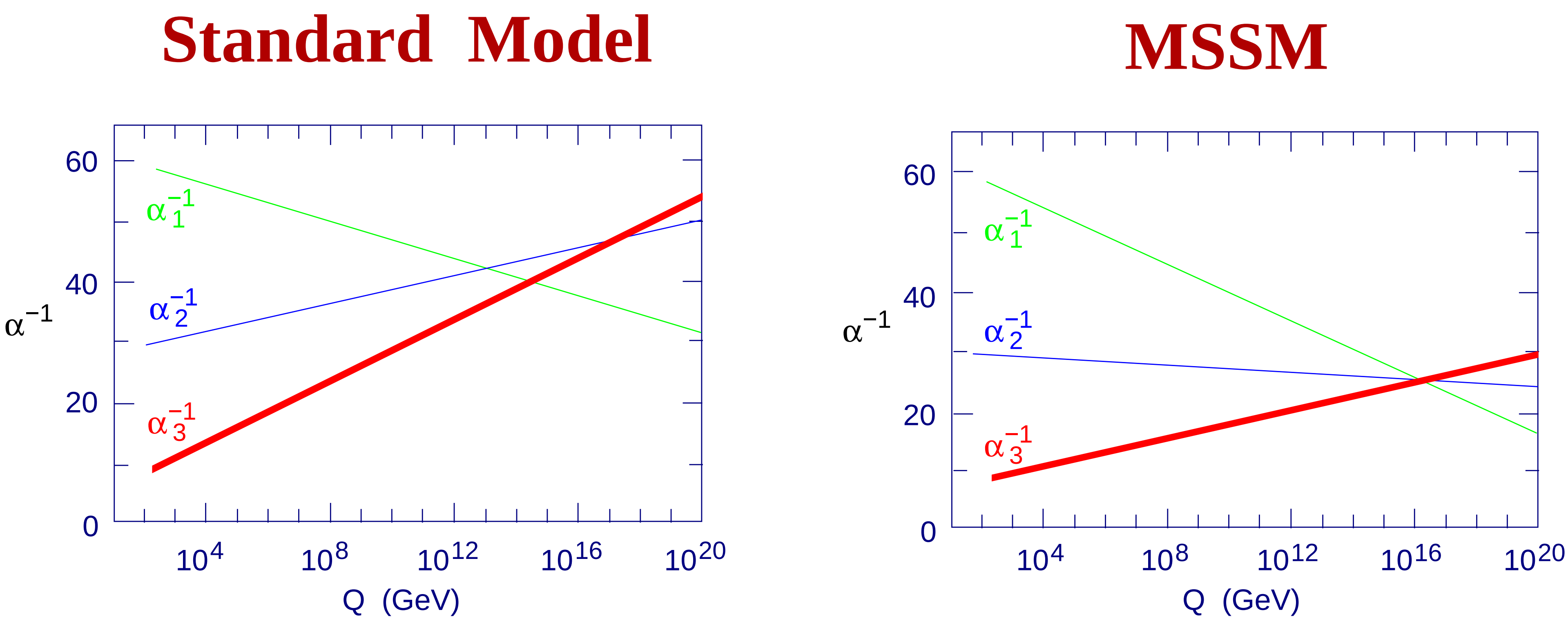


Figure 4: **Unification of couplings constants ($\alpha_i = g_i^2/(4\pi)$) in the minimal supersymmetric model (MSSM) as compared to failure without supersymmetry.**

2. **RGE EWSB**

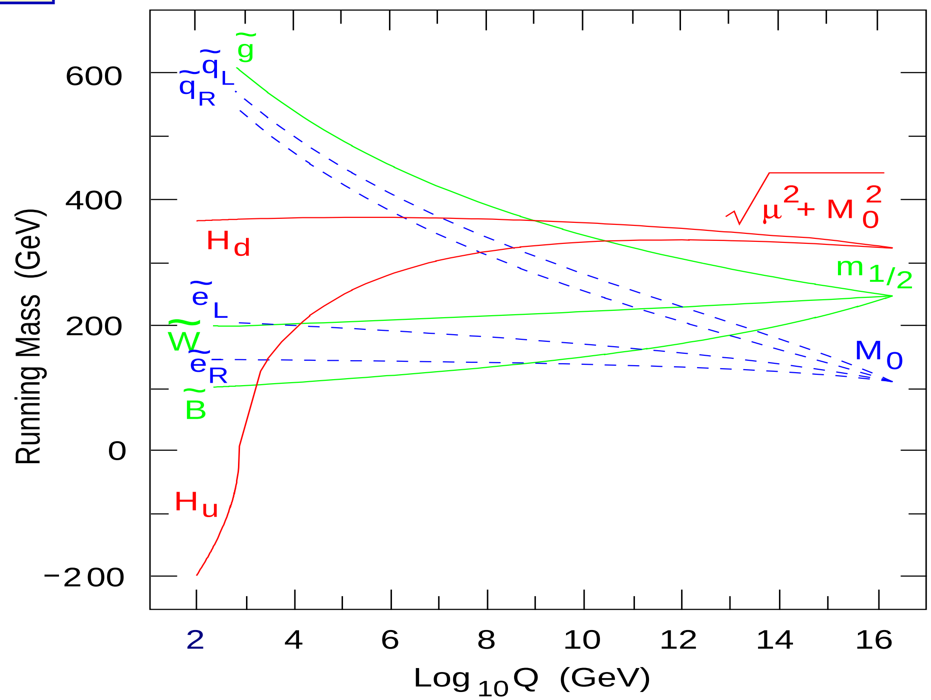


Figure 5: **Evolution of the (soft) SUSY-breaking masses or masses-squared, showing how $m^2_{H_u}$ is driven < 0 at low $Q \sim \mathcal{O}(m_Z)$.**

But, must one fine-tune the GUT scale parameters to get correct Z mass?

F measures the degree to which GUT parameters must be tuned. Want $F < 10$. This requires $m_{\tilde t} \lesssim 400~\mathrm{GeV}$ and a relatively light gluino.

For such $m_{\tilde t}$ SUSY predicts $m_h < 110~\mathrm{GeV}$. This is a problem for

the MSSM for which the h is typically SM-like in its decays. To get $m_h > 114~\mathrm{GeV}$ requires $m_{\widetilde t} > 800~\mathrm{GeV}$ and then $F > 50$.

- What is needed is a SUSY model for which the stop mass can be low but for which the resulting light $\lesssim 105~\mathrm{GeV}$ Higgs is not excluded by LEP.

  LEP exclusion can be avoided by having unusual decays as seen earlier.

- The NMSSM is perfect

  It is the h_1 that is light and SM-like and the a_1 is mainly singlet and has a small mass that is protected by a $U(1)_R$ symmetry. Large $B(h_1 \to a_1 a_1)$ is easy to achieve. We will simplify and denote for the most part $h_1 \to h$ and $a_1 \to a$.

The many attractive features of the NMSSM are well known:

1. Solves μ problem: $W \ni \lambda \widehat{S}\widehat{H}_u\widehat{H}_d \Rightarrow \mu_{\rm eff} = \lambda\langle S\rangle$.
2. Preserves MSSM gauge coupling unification.

3. **Preserves radiative EWSB.**

4. **Preserves dark matter (assuming R-parity is preserved).**

5. **Like any SUSY model, solves quadratic divergence hierarchy problem.**

6. **Has additional attractive features when $m_h \sim 90 - 105$ GeV is allowed because of $h \to aa$ decays with $m_a < 2m_b$:**

   (a) **Allows minimal fine-tuning for getting m_Z (i.e. v) correct after evolving from GUT scale M_U.** (R. Dermisek and J. F. Gunion, Phys. Rev. D 73, 111701 (2006) [arXiv:hep-ph/0510322])
   This is because $\widetilde{t}_1, \widetilde{t}_2$ can be light (~ 350 GeV is just right). Also need $m_{\widetilde{g}}$ not too far above 300 GeV.
   (In MSSM, such low stop masses are not acceptable since m_{h^0} would be below LEP limits; large $m_{\widetilde{t}} \Rightarrow m_Z$ fine tuning would be large, especially if m_h is SM-like.)

   (b) **An a with large $B(h \to aa)$ and $m_a < 2m_b$ can be achieved without fine-tuning of the A_λ and A_κ soft-SUSY breaking parameters ($V \ni$**

$A_\lambda S H_u H_d + \frac{1}{3} A_\kappa S^3$) that control the a properties. (R. Dermisek and J. F. Gunion, Phys. Rev. D 75, 075019 (2007) [arXiv:hep-ph/0611142].)

The a is largely singlet ($e.g.$ 10% at amplitude level if $\tan\beta \sim 10$) and ~ 7.5 GeV $\lesssim m_a$ (but below $2m_b$) in the best cases.

7. Of course, multi-singlet extensions of the NMSSM will expand the possibilities.

   Indeed, typical string models predict a plethora of light a's, light h's and light $\widetilde\chi$'s .

Predictions regarding a light a and the NMSSM a

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

- Define a generic coupling to fermions by

$$\mathcal{L}_{af\overline{f}} \equiv iC_{af\overline{f}}\frac{ig_2 m_f}{2m_W}\overline{f}\gamma_5 f a\,, \tag{1}$$

  At large $\tan\beta$, SUSY corrections $C_{ab\overline{b}} = C_{ab\overline{b}}^{tree}[1/(1+\Delta_b^{SUSY})]$ can be large and either suppress or enhance $C_{ab\overline{b}}$ relative to $C_{a\tau^-\tau^+}$. Will ignore.

- To extract limits from the data on $C_{ab\overline{b}}$, 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 $a \to \mu^+\mu^-$.

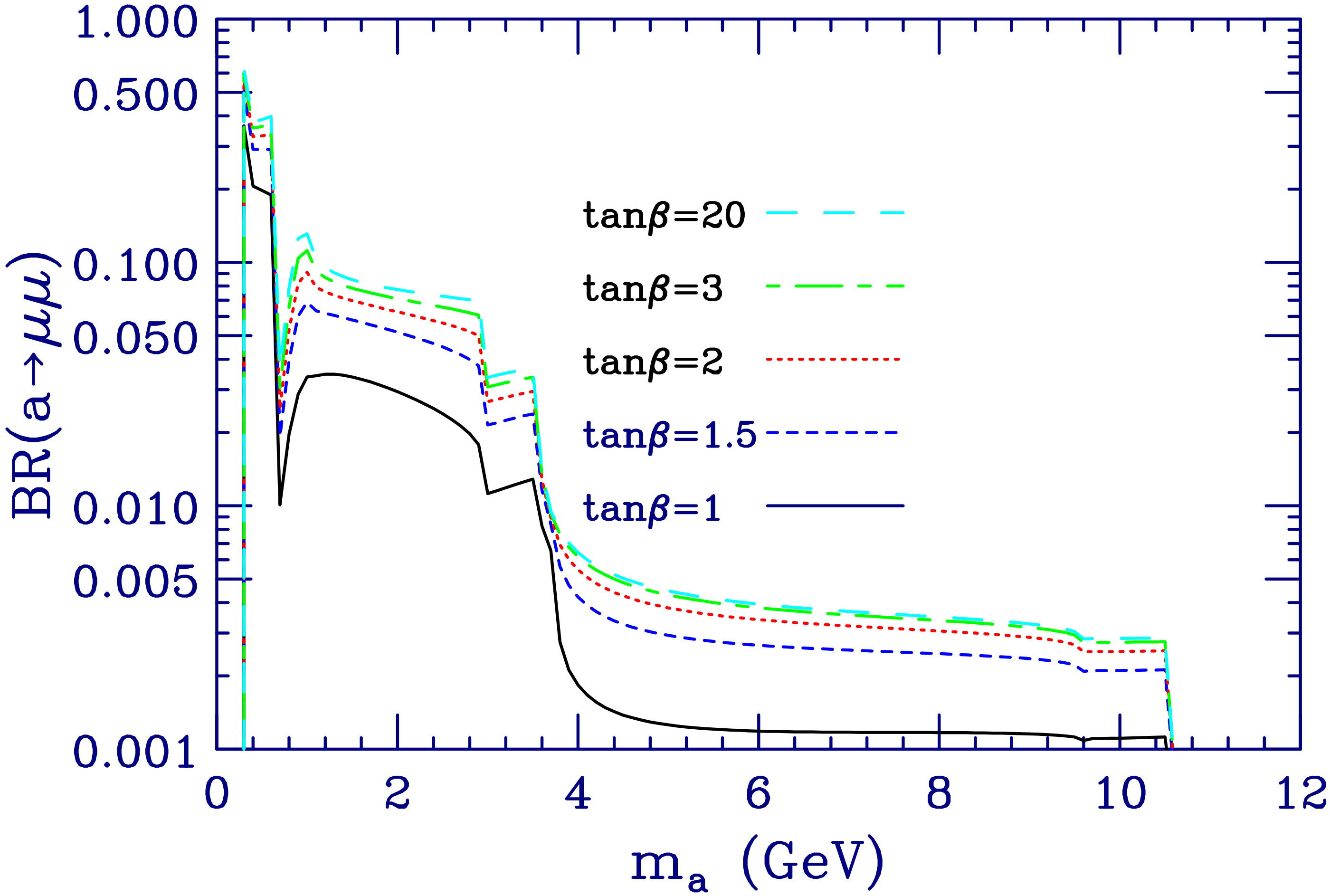


Figure 6: $B(a \to \mu^+\mu^-)$ **for various** $\tan\beta$ **values.**

- **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 $m_a \gtrsim 10$.

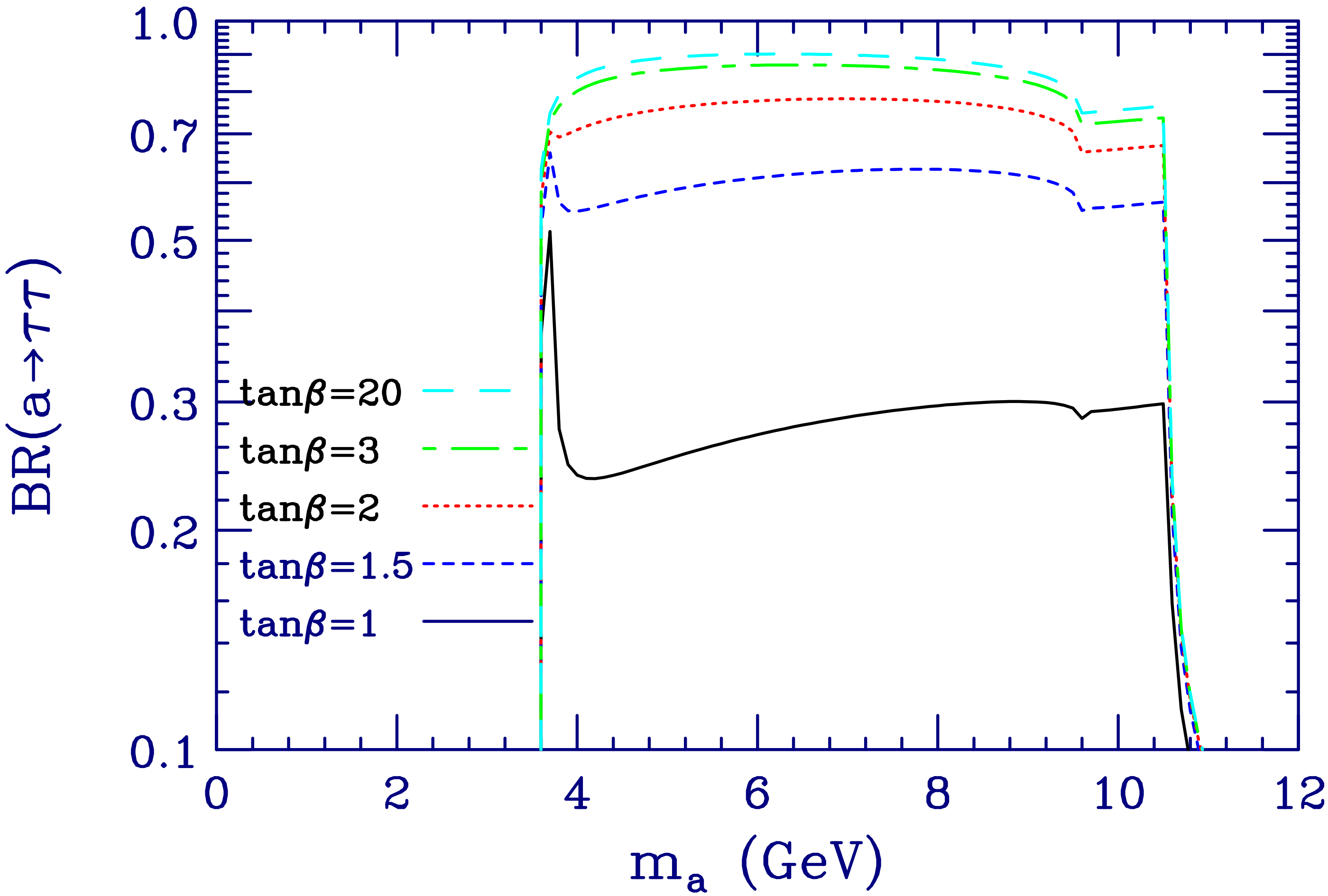


Figure 7: $B(a \to \tau^+\tau^-)$ for various $\tan\beta$ values.

- **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.**

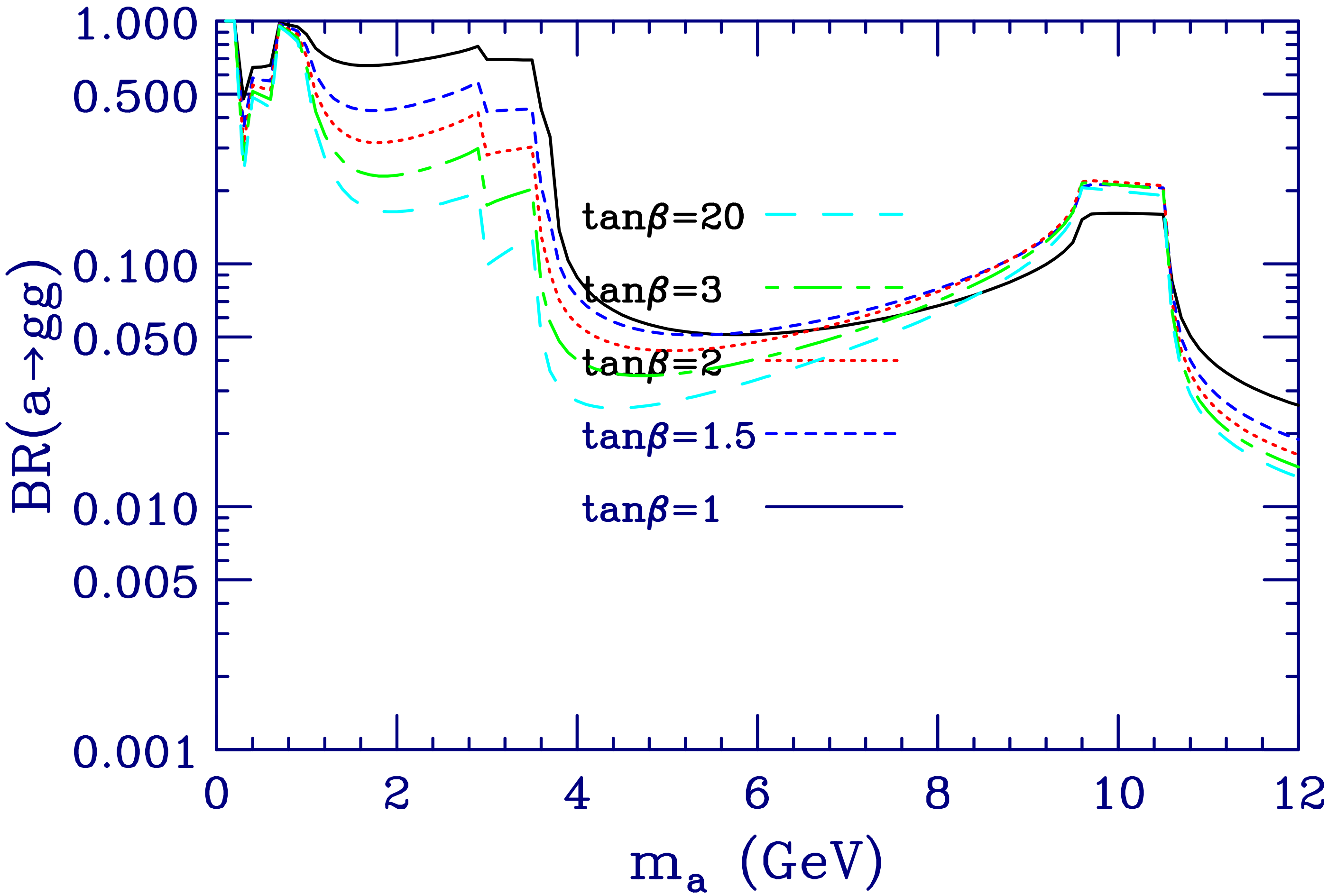


Figure 8: $B(a \to gg)$ **for various** $\tan\beta$ **values.**

- **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. 9.**

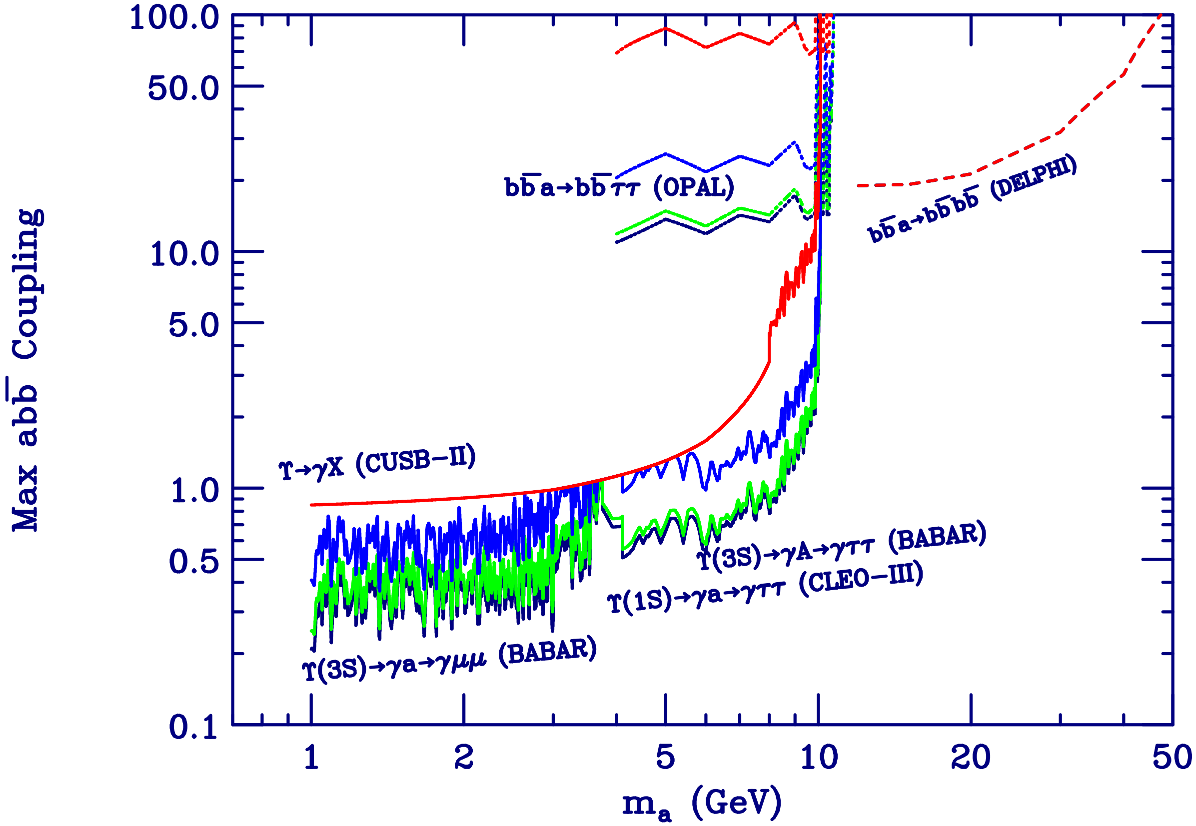


Figure 9: Limits on $C_{ab\bar{b}}$ from JFG, arXiv:0808.2509 and JFG+Dermisek, arXiv:0911.2460. These limits include recent BaBar $\Upsilon_{3S} \to \gamma\mu^+\mu^-$ and $\gamma\tau^+\tau^-$ limits. Color code: $\tan\beta = 0.5$; $\tan\beta = 1$; $\tan\beta = 2$; $\tan\beta \geq 3$.

- **The most unconstrained region is that with $m_a > 8$ GeV, especially $9\ \mathrm{GeV} < m_a < 12\ \mathrm{GeV}$.**

- In the $\sim 10 \lesssim m_a \lesssim 12$ GeV region only the OPAL limits are relevant.

  Those presented depend upon how the $a \leftrightarrow \eta_b$ states mixing is modeled. A particular model (Drees+Hikasa: Phys.Rev.D41:1547,1990) is employed. Now that the first η_b state has been observed, perhaps this region can be better pinned down, see Domingo, Ellwanger and Lozano (arXiv:0810.4736).

- Given $C_{ab\bar{b}}$ limits, an interesting question is whether there is any possibility that a light a could be responsible for the observed a_μ discrepancy which is of order $\Delta a_\mu \sim 30 \times 10^{-10}$. For this, large $C_{ab\bar{b}} \sim 30$ is needed.

  The plotted $C_{ab\bar{b}}$ limits suggest that it is generically possible if $m_a > 9$ GeV.

- What are the implications in the NMSSM context?

  Define the mass eigenstate: $a = \cos\theta_A a_{MSSM} + \sin\theta_A a_S$.

  Then,

$$C_{ab\bar{b}} = \cos\theta_A \tan\beta \quad (2)$$

  Where in $\cos\theta_A$ do the NMSSM Ideal Higgs Scenario type points lie?

To begin, ignore new BaBar limits. The old situation was:

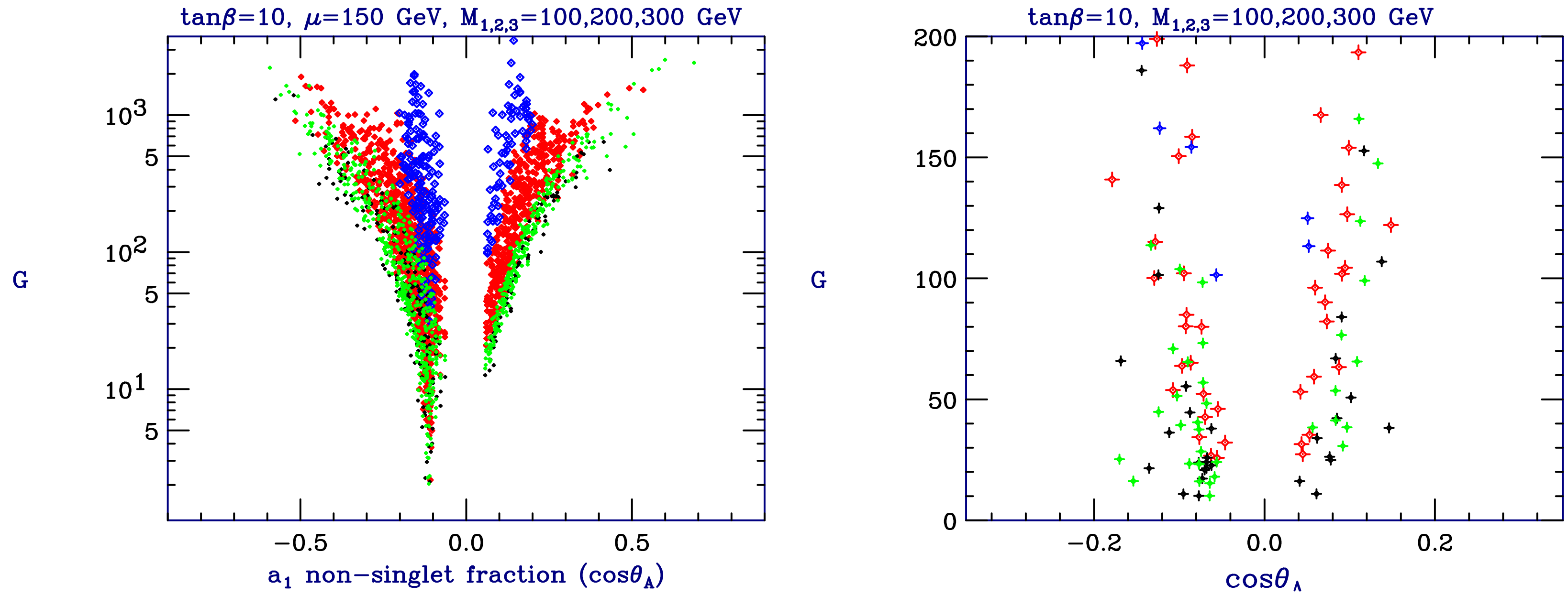


Figure 10: G vs. $\cos\theta_A$ for $M_{1,2,3} = 100, 200, 300$ GeV and $\tan\beta = 10$ from $\mu_{\rm eff} = 150$ GeV scan (left) and for points with $F < 15$ (right) having $m_a < 2m_b$ and large enough $B(h \to aa)$ to escape LEP limits. The color coding is: blue $= m_a < 2m_\tau$; red $= 2m_\tau < m_a < 7.5$ GeV; green $= 7.5$ GeV $< m_a < 8.8$ GeV; and black $= 8.8$ GeV $< m_a < 9.2$ GeV.

- In the figure, G is a measure (Dermisek+JFG: hep-ph/0611142) of the degree to which A_λ and A_κ have to be fine tuned ("light-a" fine tuning) in order to achieve required a properties of $m_a < 2m_b$ *and* $B(h \to aa) > 0.7$.

- Note the strict lower bound on $\cos\theta_A$ needed for $B(h \to aa) > 0.7$.

  If one could achieve limits of $|C_{ab\bar b}| \lesssim 0.2$ (a number which applies for $\tan\beta > 3$) this kind of scenario could be ruled out.

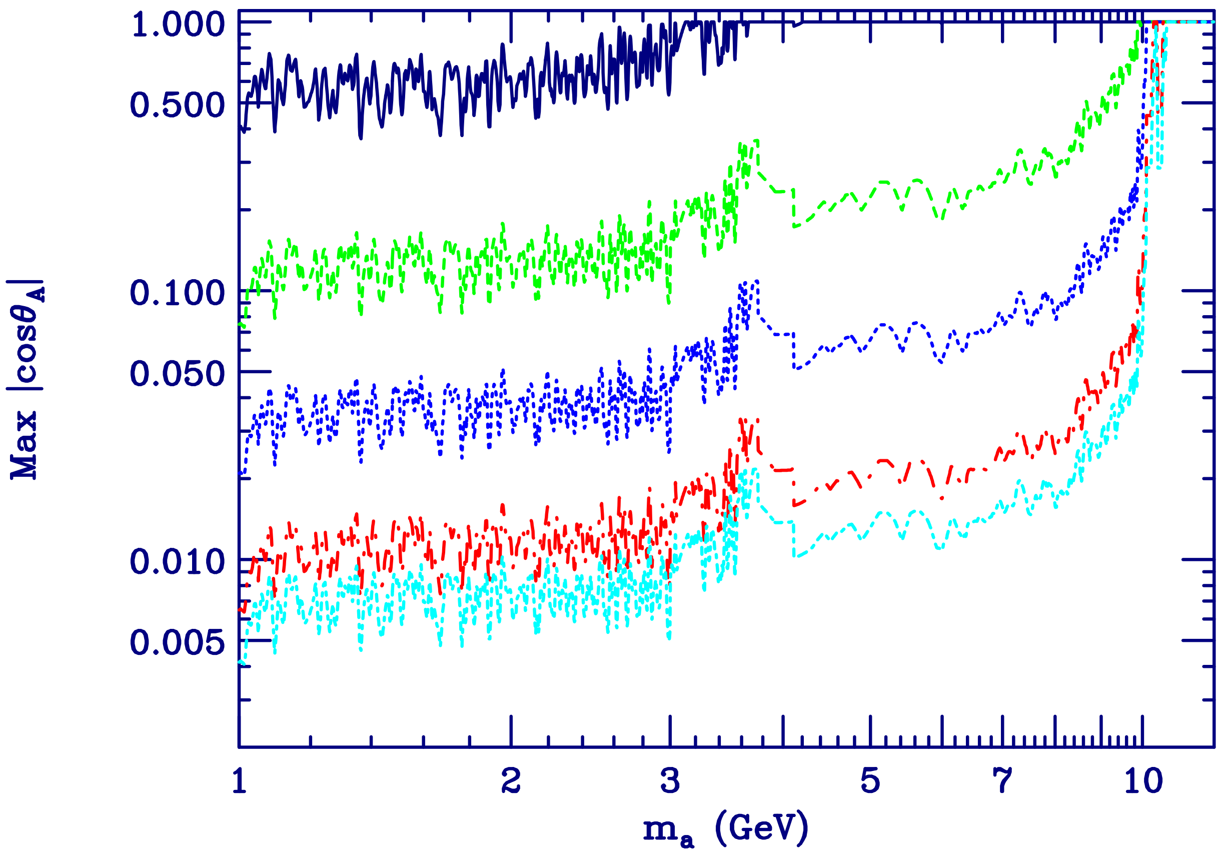
- The plot of G vs. $\cos\theta_A$ shows a strong preference for $m_a > 7.5~\mathrm{GeV}$ and $\cos\theta_A \lesssim 0.1$ (for $\tan\beta = 10$).

  This is the m_a region, especially $9~\mathrm{GeV} < m_a < 2m_B$, where $C_{ab\bar b}$ is least constrained.

  A limit of $|C_{ab\bar b}| < 0.3$ would rule out most small G scenarios.

  Such a limit is not far from being realized for lower m_a values, but Upsilon decays are limited in m_a reach.

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



The different curves correspond to $\tan\beta = 1$ (upper curve), 3, 10, 32 and 50 (lowest curve).

- More on the strong BaBar limits on $B(\Upsilon_{3S} \to a\gamma)B(a \to \mu^+\mu^-)$ that become very constraining for $m_a < 2m_\tau$.

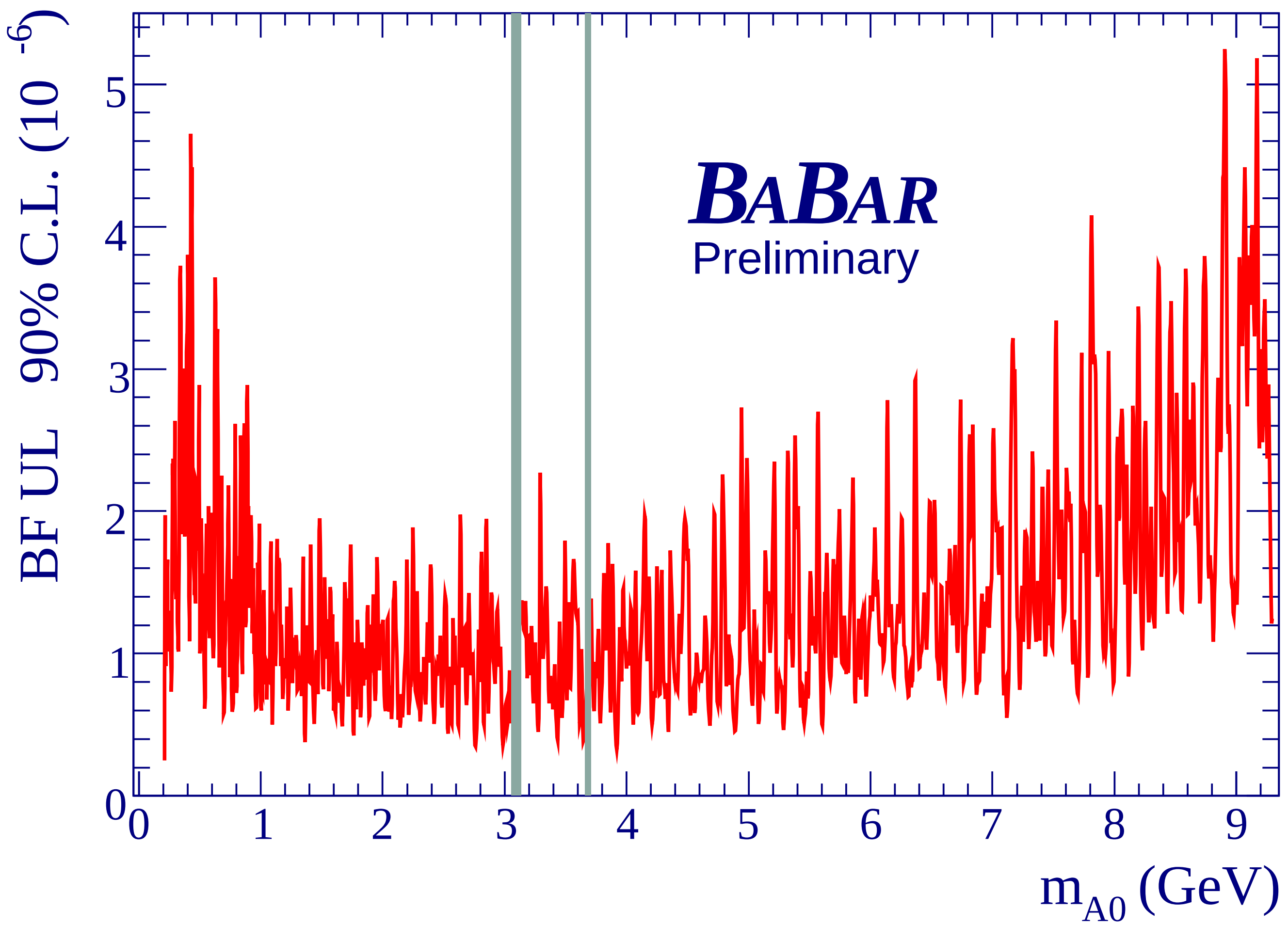


Figure 11: **BaBar limits on $B(\Upsilon_{3S} \rightarrow \gamma a)B(a \rightarrow \mu^+\mu^-)$.**

For $m_a < 2m_\tau$, the limits are below 2×10^{-6} except for very low m_a.

A comparison to NMSSM predictions $\Rightarrow$ most NMSSM scenarios with

$B(h \to aa) > 0.7$ and $m_a < 2m_\tau$ are eliminated; only a few at $\tan\beta \lesssim 3$ survive.

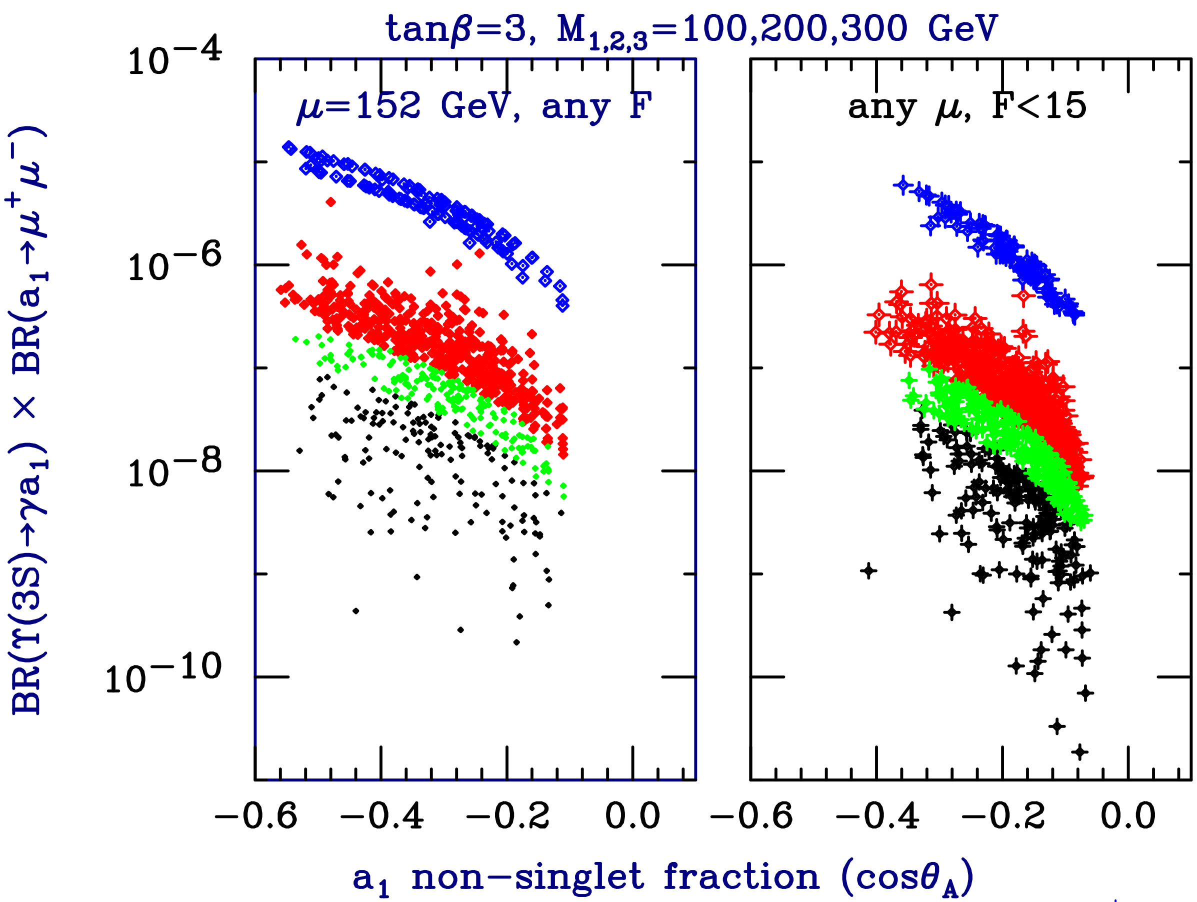


Figure 12: **For $\tan\beta = 3$, we plot $B(\Upsilon_{3S} \to \gamma a) \times B(a \to \mu^+\mu^-)$ for NMSSM scenarios with various ranges for m_a. Color code: $m_a < 2m_\tau$; $2m_\tau < m_a < 7.5$ GeV; 7.5 GeV $< m_a < 8.8$ GeV; 8.8 GeV $< m_a < 2m_B$ GeV. The left plot comes from an A_λ, A_κ scan holding $\mu_{eff}(m_Z) = 152$ GeV fixed. The right plot shows results for $F < 15$ scenarios with $m_a < 2m_B$.**

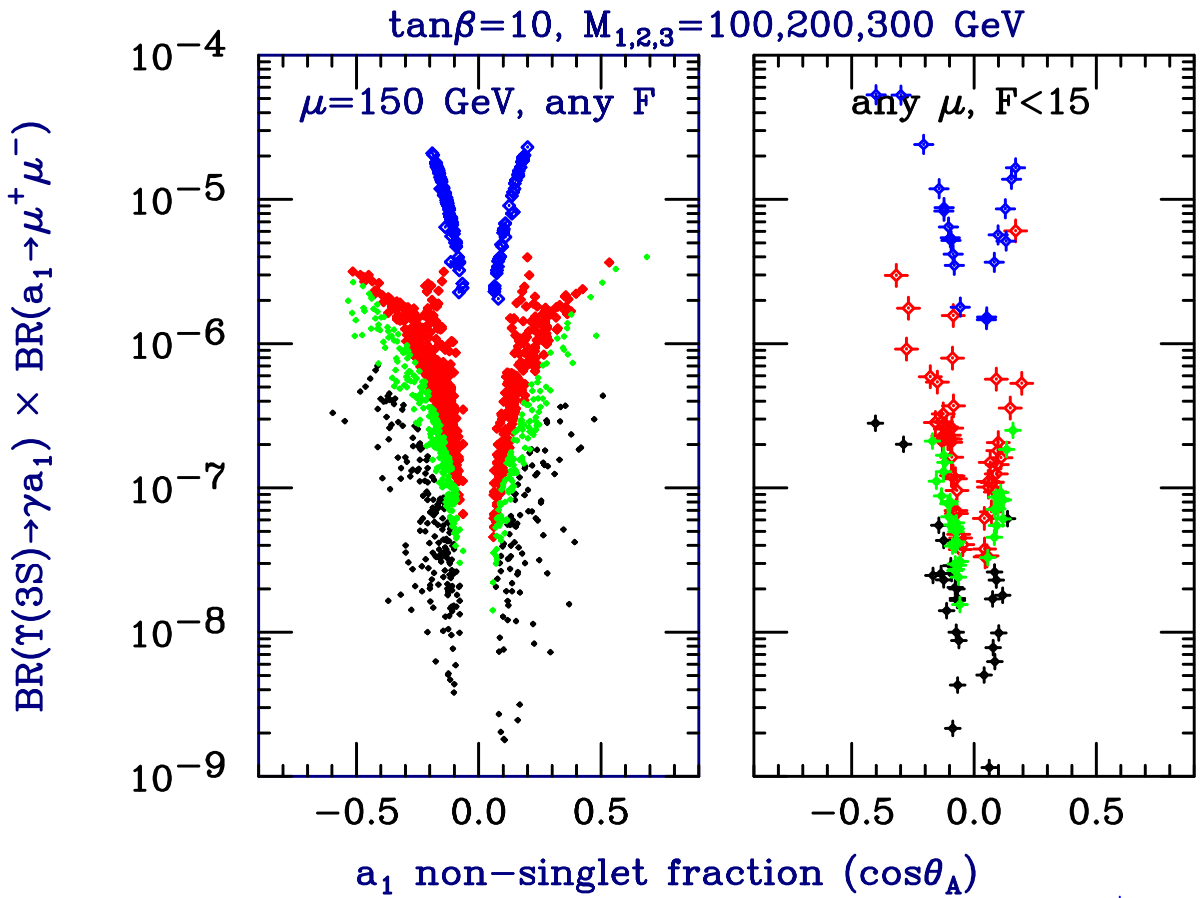


Figure 13: For $\tan\beta = 10$ we plot $B(\Upsilon_{3S} \to \gamma a) \times B(a \to \mu^+\mu^-)$ for NMSSM scenarios with various ranges for m_a. Color code: $m_a < 2m_\tau$; $2m_\tau < m_a < 7.5$ GeV; 7.5 GeV $< m_a < 8.8$ GeV; 8.8 GeV $< m_a < 2m_B$ GeV. The left plot comes from an A_λ, A_κ scan holding $\mu_{eff}(m_Z) = 150$ GeV fixed. The right plot shows results for $F < 15$ scenarios with $m_a < 2m_B$.

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

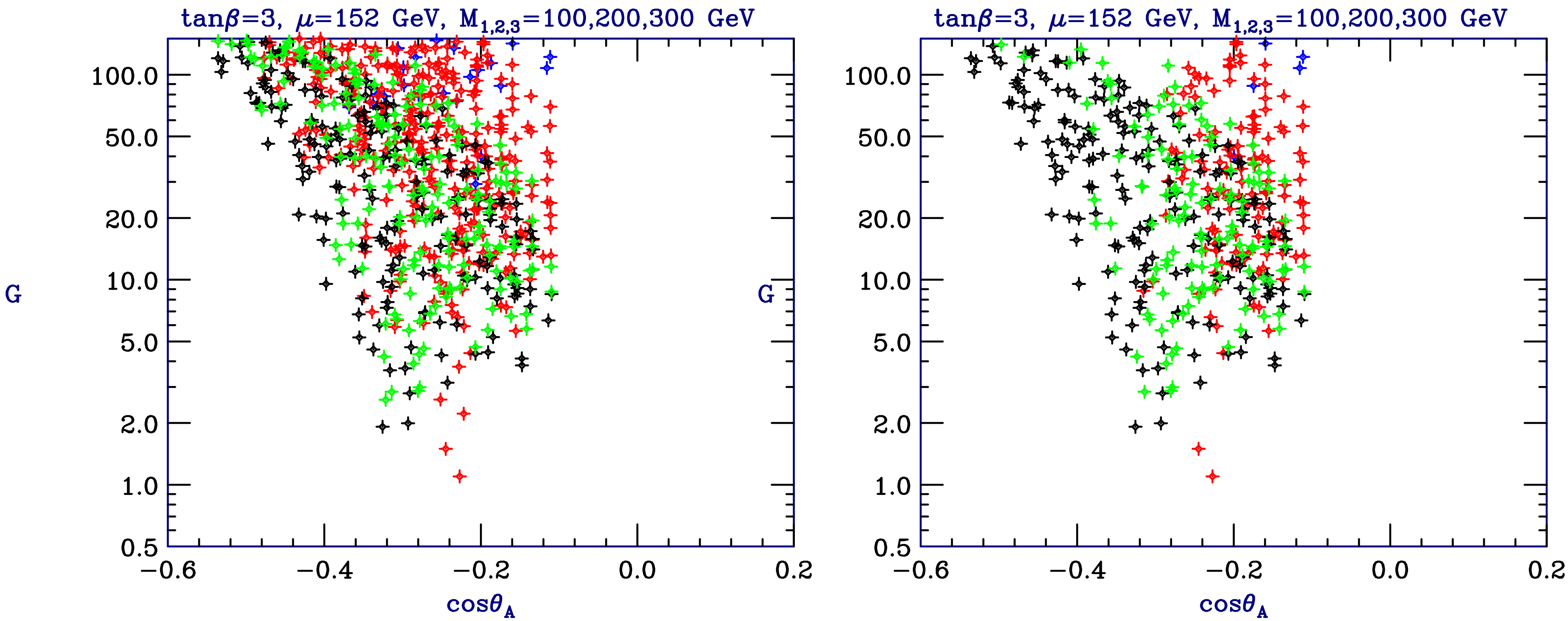


Figure 14: **Light-a_1 finetuning measure G before and after imposing limits $|\cos\theta_A| \leq \cos\theta_A^{\rm max}$. Note that many points with low m_{a_1} and large $|\cos\theta_A|$ are eliminated by the $|\cos\theta_A| < \cos\theta_A^{\rm max}$ requirement, including almost all the $m_{a_1} < 2m_\tau$ (blue) points and a good fraction of the $2m_\tau < m_{a_1} < 7.5~{\rm GeV}$ (red) points.**

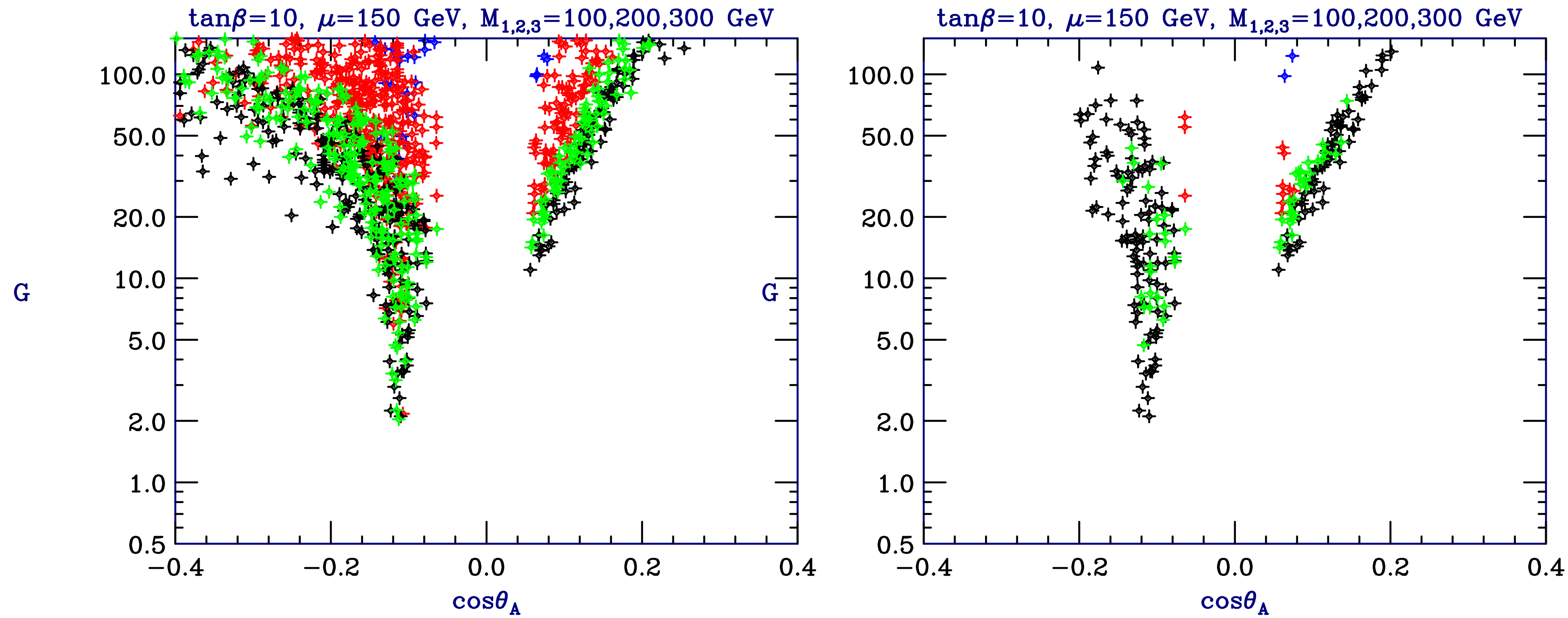


Figure 15: **As in Fig. 14, but for $\mu = 150\ \mathrm{GeV}$ and $\tan\beta = 10$. Note that many points with low m_{a_1} and large $|\cos\theta_A|$ are eliminated, including almost all the $m_{a_1} < 2m_\tau$ (blue) points and $2m_\tau < m_{a_1} < 7.5\ \mathrm{GeV}$ (red) points.**

- Thus, we have a convergence whereby low "light-a" fine tuning in the NMSSM and direct $\Upsilon_{3S} \to \gamma\mu^+\mu^-$ limits single out the $m_a > 7.5~\mathrm{GeV}$ part of parameter space.

  LHC studies of light h NMSSM scenarios should (and have) focused on this case.

  With regard to the a itself, we should 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 $m_a > 2m_\tau$.

- **In fact, results from ALEPH that (Kyle Cranmer, Nov. 3 seminar) further shift the focus to high m_a in the NMSSM context.**

Expected limits @ m_a = 4,10 GeV

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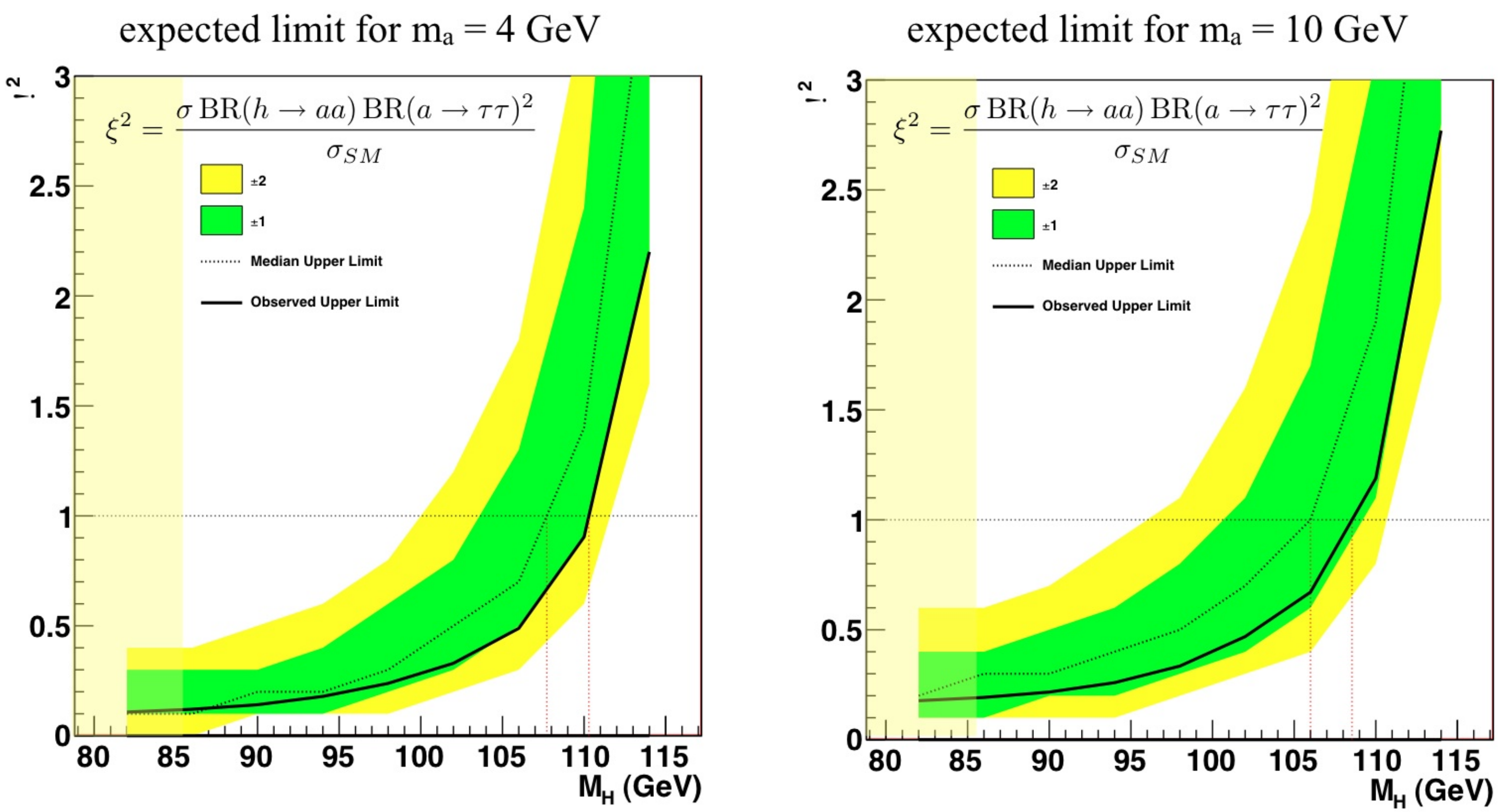
Seeing no sign of excess, we proceed to set limits

! Here, we make reference to background acceptance uncertainties in MSSM Higgs analysis. (Statistical errors dominate, systematics make little di! erence in result)



$\Rightarrow \xi^2 < 0.3$ **(0.4)** if $m_h = 100$ GeV and $m_a = 4$ GeV **(10** GeV**)**.

- **Comparison to NMSSM ideal scenarios:**

  1. $m_h \sim 95$ GeV $- 103$ GeV to minimize electroweak m_Z finetuning.
  2. Large enough $B(h \to b\bar{b}) \sim 0.15 - 0.2$ to explain 2.3σ LEP excess.
  3. $9 \lesssim m_a \lesssim 2m_B$ to fully minimize light-a finetuning.

  In this case, we typically have:

  1. $\sigma(h)/\sigma(h_{\rm SM}) \sim 0.92 - 1.0$
  2. $B(h \to aa) \sim 0.8 - 0.85$
  3. $B(a \to 2\tau) \sim 0.75 - 0.8$ at high $\tan\beta$, lower at low $\tan\beta$.

  Together, these yield ξ^2 as low as $\xi^2 \sim 0.43, 0.4, 0.2, 0.1$ at $\tan\beta = 10, 3, 1.7, 1.2$, respectively (see plots below) — the minimum is always at highest m_a, $m_a \sim 10$ GeV, we scanned to.

- Thus, for $\tan\beta \geq 3$, it is only the higher m_a part of model space, i.e. that which has minimal light-a finetuning, that could still escape ALEPH, but $m_h \gtrsim 105$ GeV is required.

  Of course ALEPH limits are stronger than expected $=$? statistical downward fluctuation.

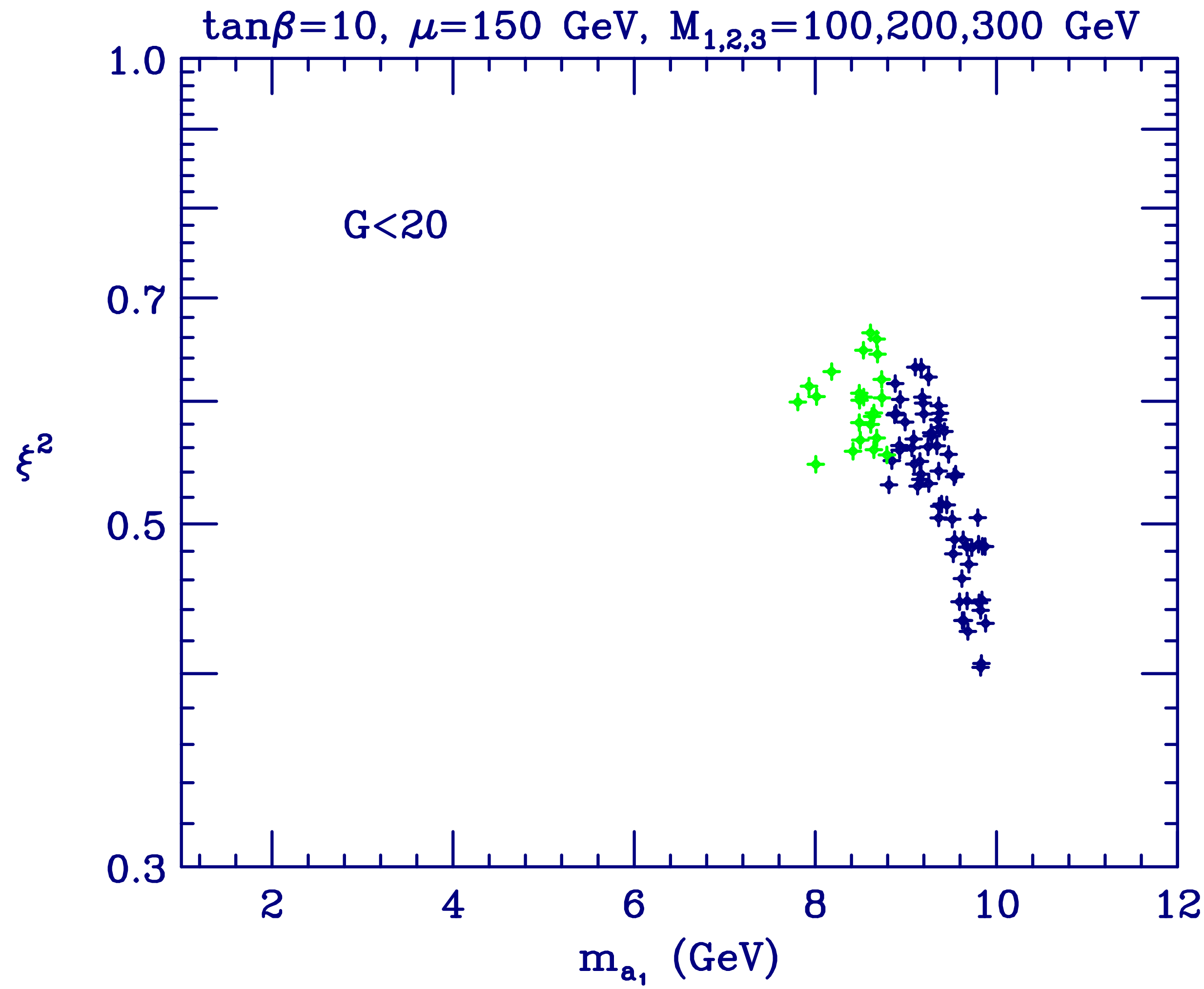


Figure 16: ξ^2 vs. m_{a_1} for $\tan\beta = 10$; $|\cos\theta_A| < \cos\theta_A^{\rm max}$; fixed μ scan.

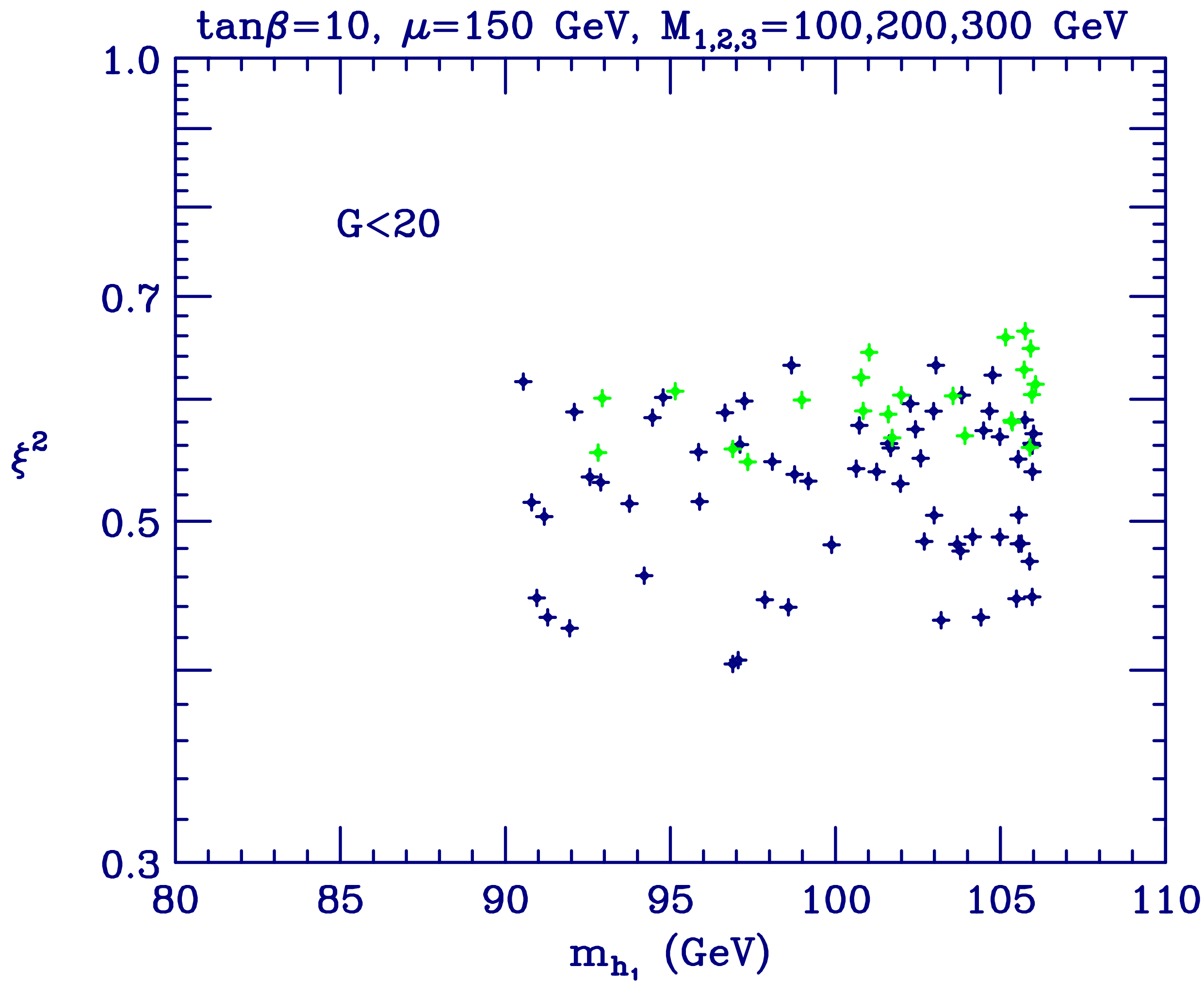


Figure 17: ξ^2 vs. m_{h_1} for $\tan\beta = 10$; $|\cos\theta_A| < \cos\theta_A^{\rm max}$, fixed μ scan.

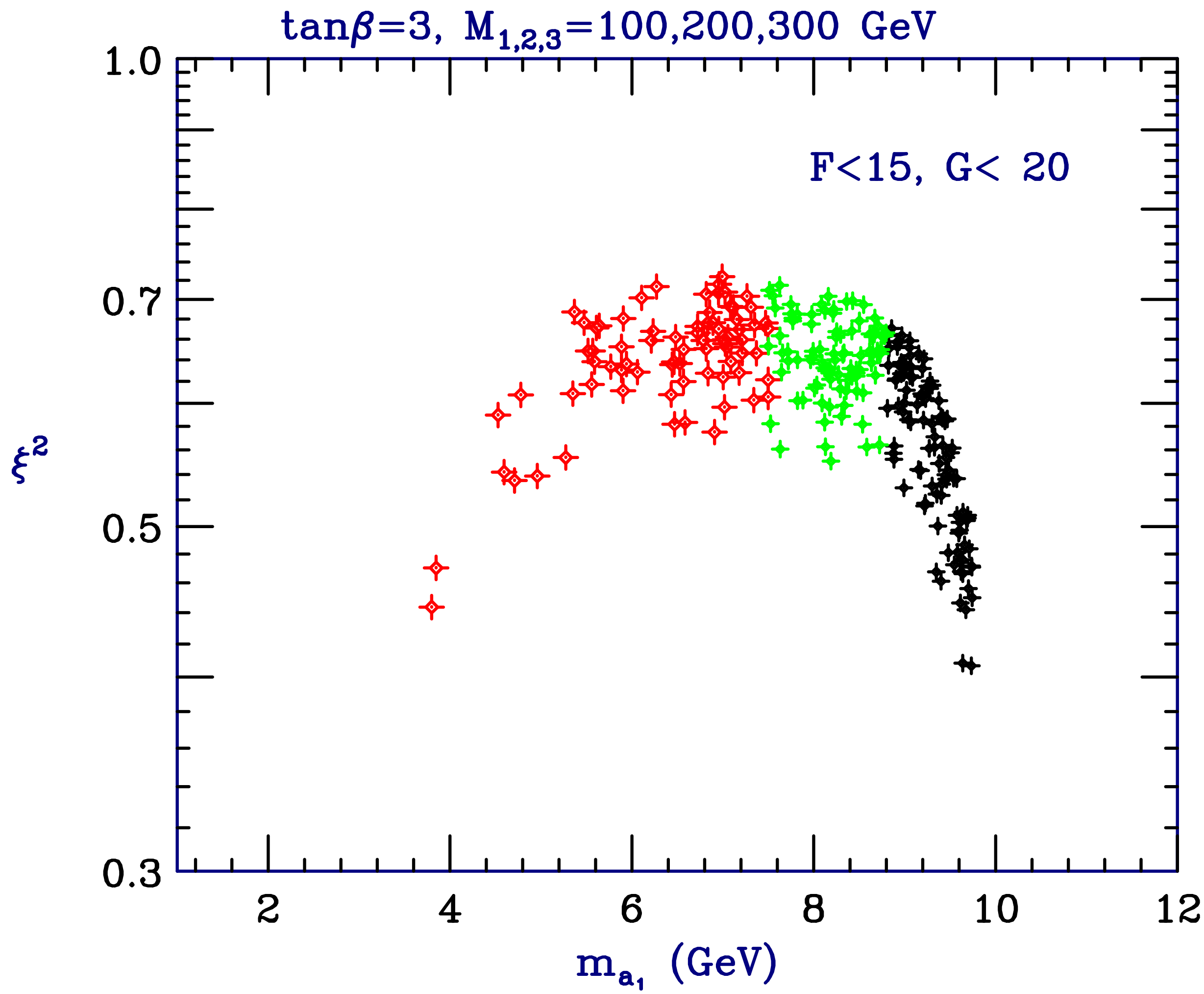


Figure 18: ξ^2 vs. m_{a_1} for $\tan\beta = 3$; $|\cos\theta_A| < \cos\theta_A^{\max}$, full scan.

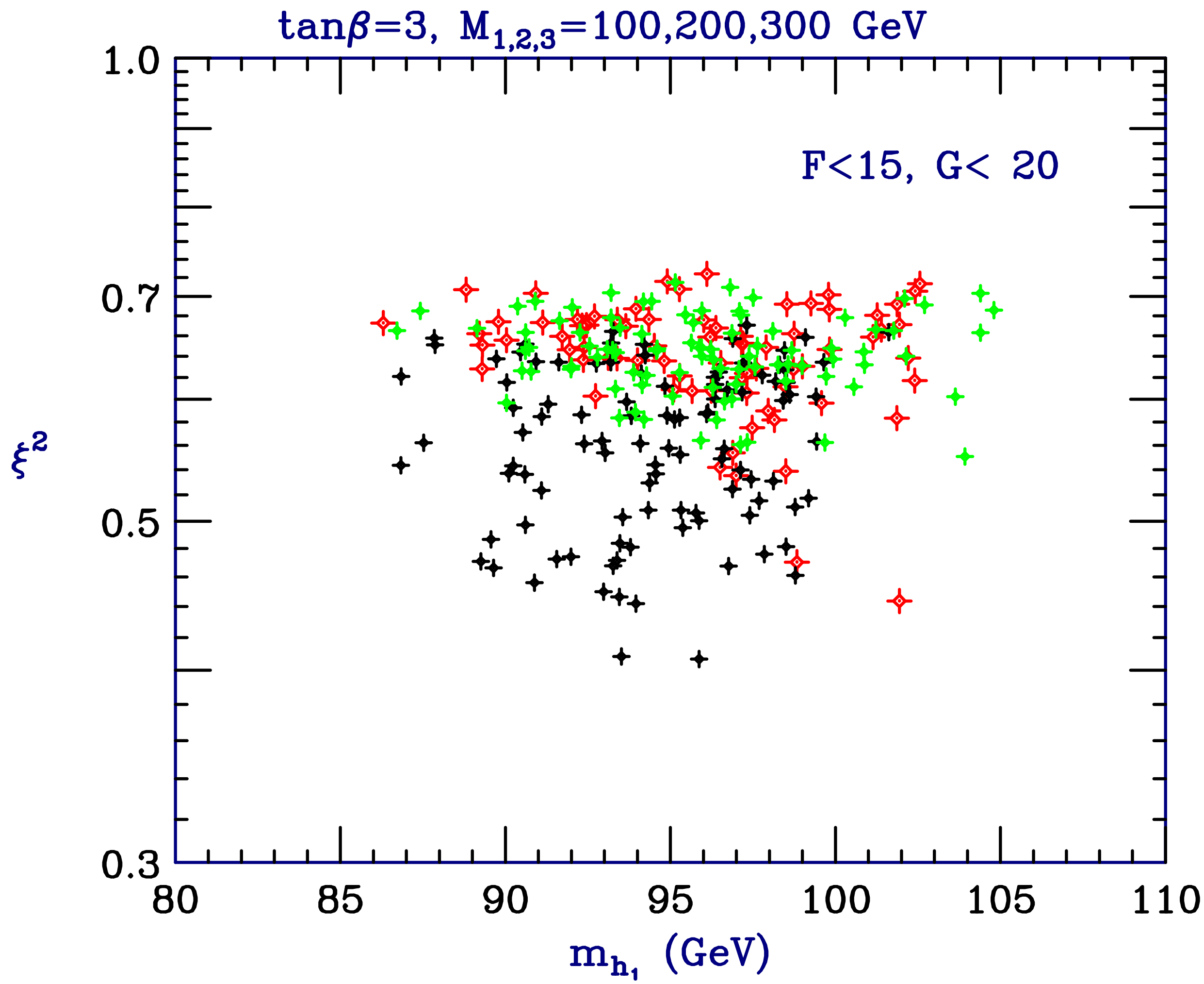


Figure 19: ξ^2 **vs.** m_{h_1} **for** $\tan\beta = 3$; $|\cos\theta_A| < \cos\theta_A^{\max}$**, full scan.**

- **For lower** $\tan\beta$ **it becomes progressively easier to escape these new ALEPH limits.**

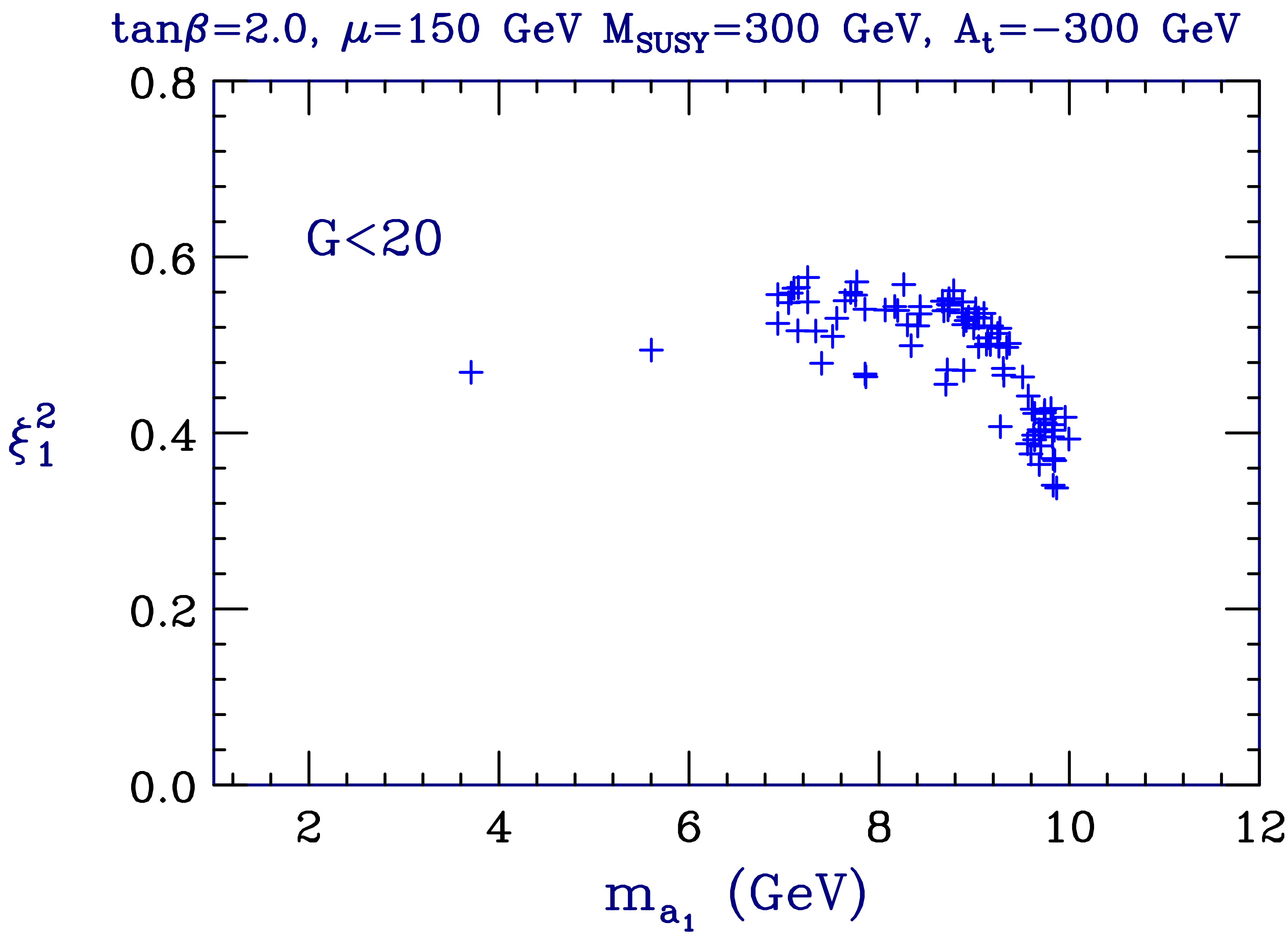


Figure 20: ξ^2 **vs.** m_{a_1} **for** $\tan\beta = 2$; $|\cos\theta_A| < \cos\theta_A^{\rm max}$. **In this and next figures, we are no longer color coding different** m_{a_1}. **Need to use colors differently as we will see.**

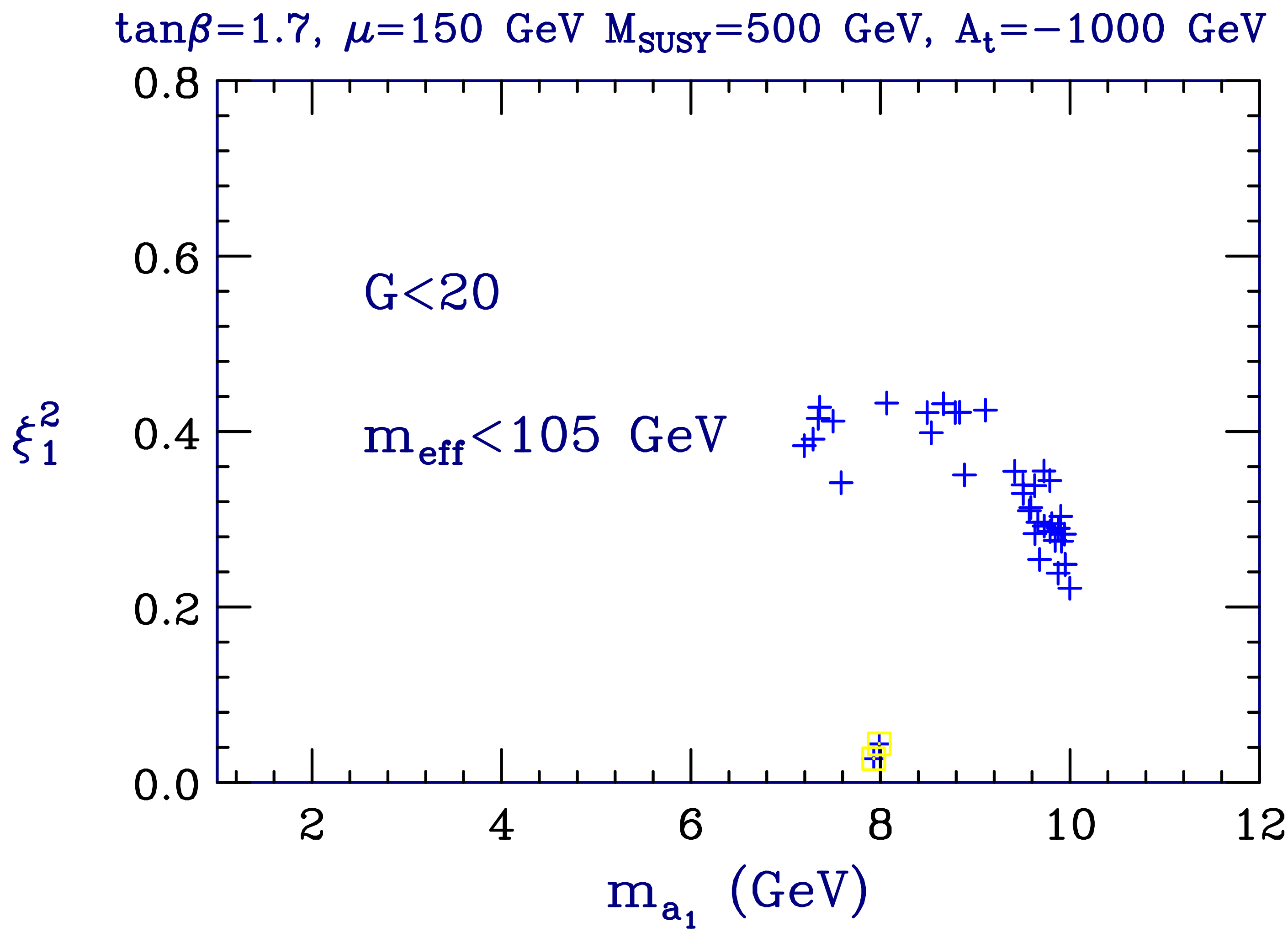


Figure 21: ξ_1^2 vs. m_{a_1} for $\tan\beta = 1.7$; $|\cos\theta_A| < \cos\theta_A^{\rm max}$, $m_{eff} < 105$ GeV. Yellow squares have $B(h_1 \to a_1 a_1) < 0.7$ but still escape usual LEP limits. Red crosses have $m_{h_1} < 65$ GeV. m_{eff} is the effective precision electroweak mass: $\log(m_{eff}) = CV_1^2 \log(m_{h_1}) + CV_2^2 \log(m_{h_2}) + CV_3^2 \log(m_{h_3})$, where $CV_i = g_{ZZh_i}/g_{ZZh_{\rm SM}}$.

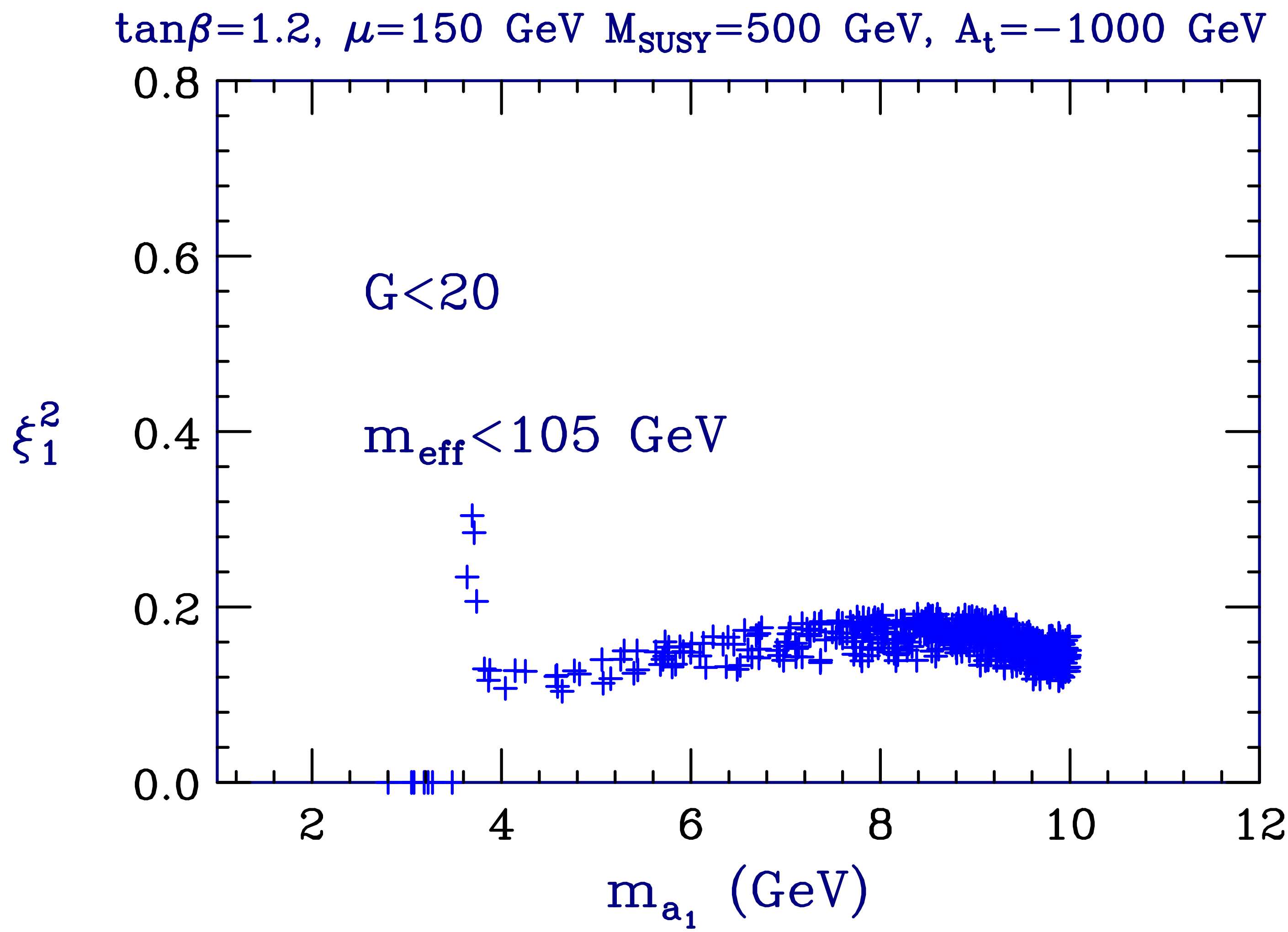


Figure 22: ξ_1^2 vs. m_{a_1} for $\tan\beta = 1.2$; $|\cos\theta_A| < \cos\theta_A^{\rm max}$, $m_{eff} < 105~\mathrm{GeV}$. **Note that at low $\tan\beta$, the Higgs is starting to be "buried" by having $h_1 \to a_1 a_1 \to 4j$ decays dominate.**

Hadron collider constraints on a light a

- As we have seen, the Upsilon constraints on a light a run out for $m_a > M_{\Upsilon_{3S}} - \delta$. This leaves open the possibility that Δa_μ could be explained by a light a if $C_{ab\bar{b}}$ is big in this region. Remarkably, existing Tevatron data rule out this possibility (JFG+Dermisek, arXiv:0911.2460). And LHC constraints on the a are likely to be even stronger.

- At a hadron collider, one studies $\mu^+\mu^-$ pair production and tries to reduce the heavy flavor background by isolation cuts on the muons. Various studies of Υ production have been performed and CDF has even done an analysis in which they look for a very narrow ϵ (a hypothesized particle of a non-SUSY model) over the region $6.3 < m_\epsilon < 9$ GeV. The latest CDF limits from $L = 630~\text{pb}^{-1}$ of data on $R \equiv \sigma(\epsilon)B(\epsilon \to \mu^+\mu^-)/\sigma(\Upsilon_{1S})B(\Upsilon_{1S} \to \mu^+\mu^-)$ rule out the old peak at $m_\epsilon = 7.2$ GeV and can be adopted to limit this same ratio for a general a or the NMSSM a.

- **Ingredients:**
  - First, we need the cross sections. These are basically from gg fusion with gga coupling induced by quark loops. Higher order corrections, both virtual and real ($e.g.$ for the latter $gg \to ag$) are, however, quite significant.

    Main points are:

    1. Isolation cuts on μ's do not seem to exclude NLO real radiation diagrams (based on CDF, ATLAS, CMS Υ efficiencies and fact that $\sigma(\Upsilon)$ has many components involving one or more extra final state g or q).
    2. Slow energy variation. At $m_a = 10~\mathrm{GeV}$ and $\tan\beta = 10$, one finds $\sigma_{NLO}(1.96, 7, 10, 14~\mathrm{TeV}) \sim 1.5 \times 10^5, 5 \times 10^5, 7 \times 10^5, 9 \times 10^5~\mathrm{pb}$.
    3. For NMSSM, multiply by $(\cos\theta_A)^2$.
  - Then, we must know $B(a \to \mu^+\mu^-)$, which we plotted earlier, a rough value being 0.003 for $m_a > 2m_\tau$ and $\tan\beta > 2$.
  - We need efficiencies for detecting the μ^+ and μ^- at given m_a.
  - We must know the background, which mainly derives from heavy flavor production, especially $b\bar{b}$ where the b's decay semi-leptonically.

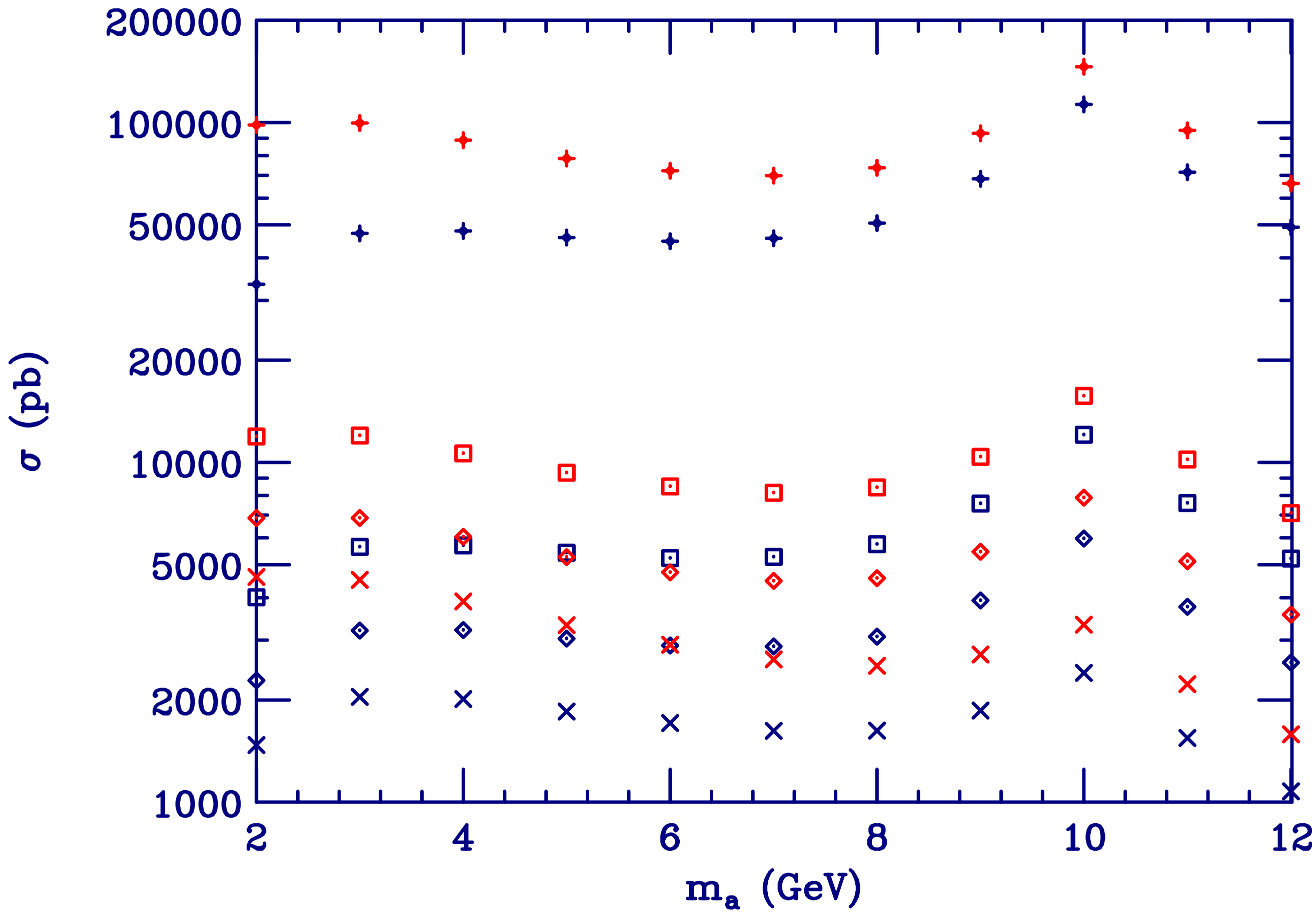


Figure 23: Tevatron cross sections for $\tan\beta = 1, 2, 3, 10$ (lowest to highest point sets). For each m_a and $\tan\beta$ value, the lower (higher) point is the cross section without (with) resolvable parton final state contributions.

For later reference when we discuss LHC:

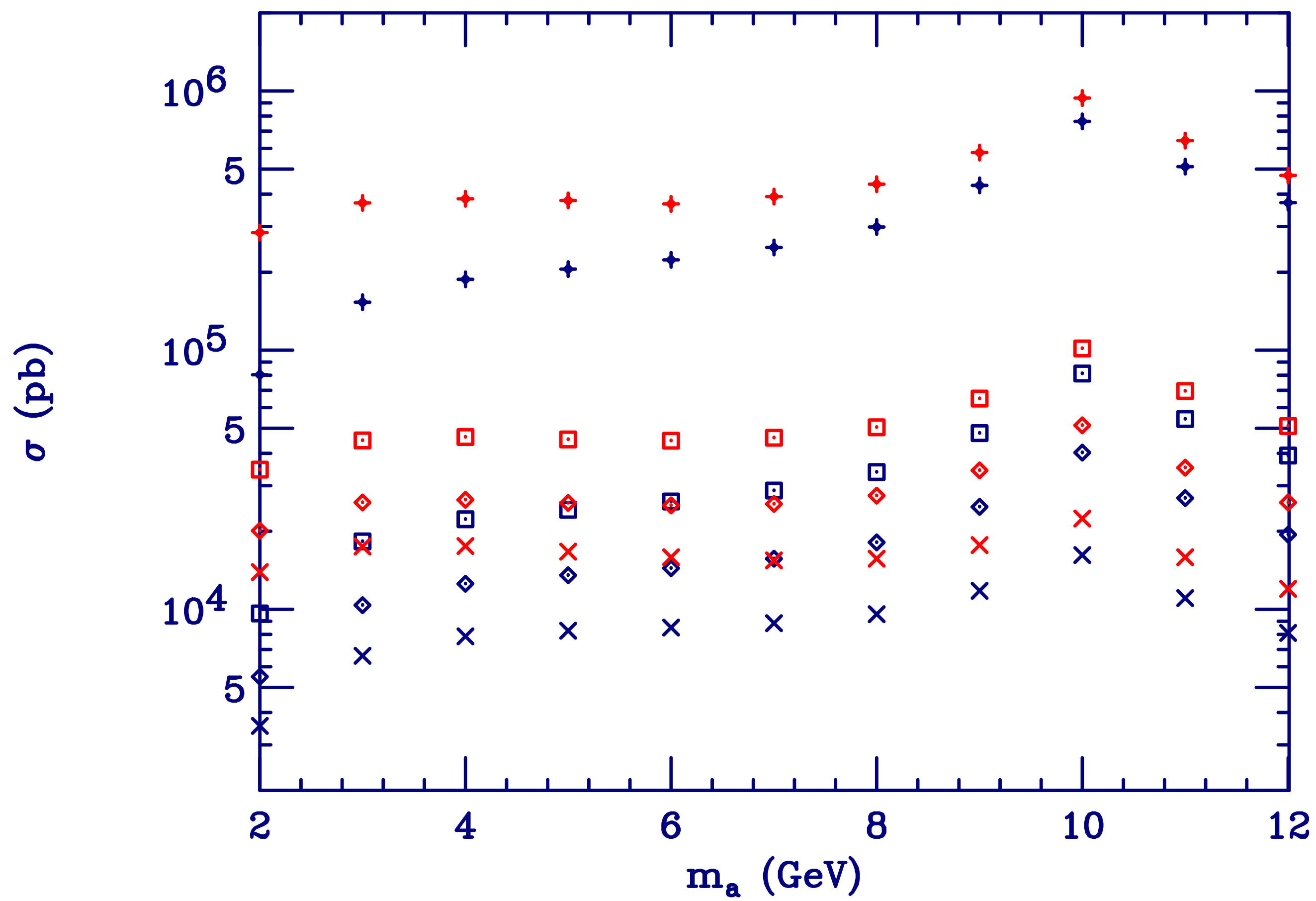


Figure 24: **LHC, $\sqrt{s} = 14~\mathrm{TeV}$ cross sections for $\tan\beta = 1, 2, 3, 10$ (lowest to highest point sets). Factor of about $7\times$Tevatron at higher m_a.**

Putting it all together gives:

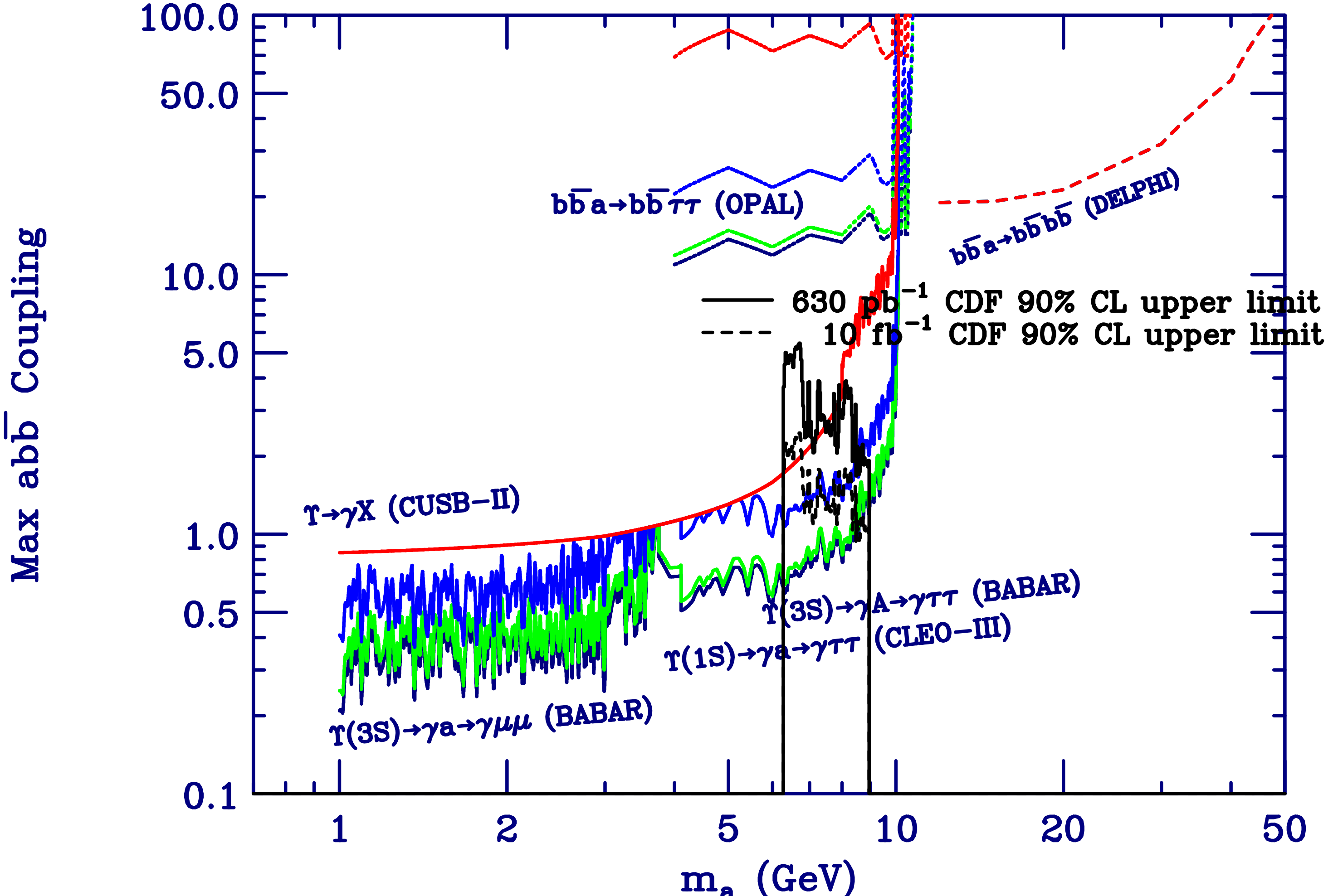


Figure 25: Tevatron limits compared to previous plot limits for $\tan\beta =$0.5, 1, 2, ≥ 3.

Tevatron at $L = 10~\mathrm{fb}^{-1}$ competes with BaBar for $m_{a_1} \sim 9~\mathrm{GeV}$ even at high $\tan\beta$ and would win for $m_{a_1} > 9~\mathrm{GeV}$. Indeed, The $L = 10~\mathrm{fb}^{-1}$ statistically extrapolated limits are approaching the $C_{ab\bar{b}} = \tan\beta\cos\theta_A \sim 1$ level that impacts the most preferred NMSSM scenarios.

For $M_{\mu^+\mu^-} > 9\ \mathrm{GeV}$, CDF did not perform the R analysis. Instead, we use the event number plots that extend to larger $M_{\mu^+\mu^-}$. We ask for the $|C_{ab\bar{b}}|$ limits assuming no 90% CL (1.686σ) fluctuation in $S/\sqrt{B}$-optimized m_a interval of $2\sqrt{2}\sigma_r$, where σ_r is the $M_{\mu^+\mu^-}$ resolution.

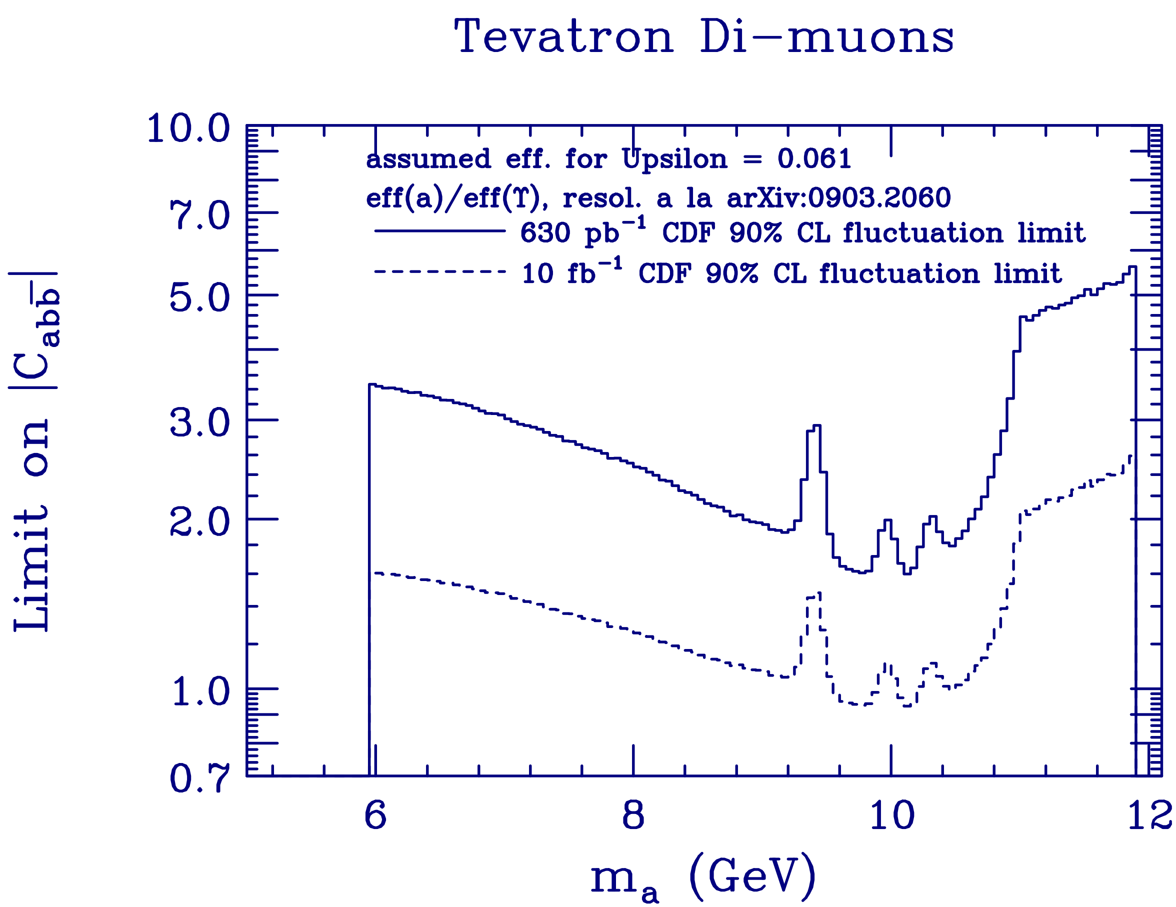


Figure 26: $L = 630\ \mathrm{pb}^{-1}$ and $10\ \mathrm{fb}^{-1}$ limits based on no 1.686σ excess in optimal interval.

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?

There have been studies of the Upsilon and backgrounds by CMS and ATLAS, but only ATLAS has presented public results — see Fig. 27.

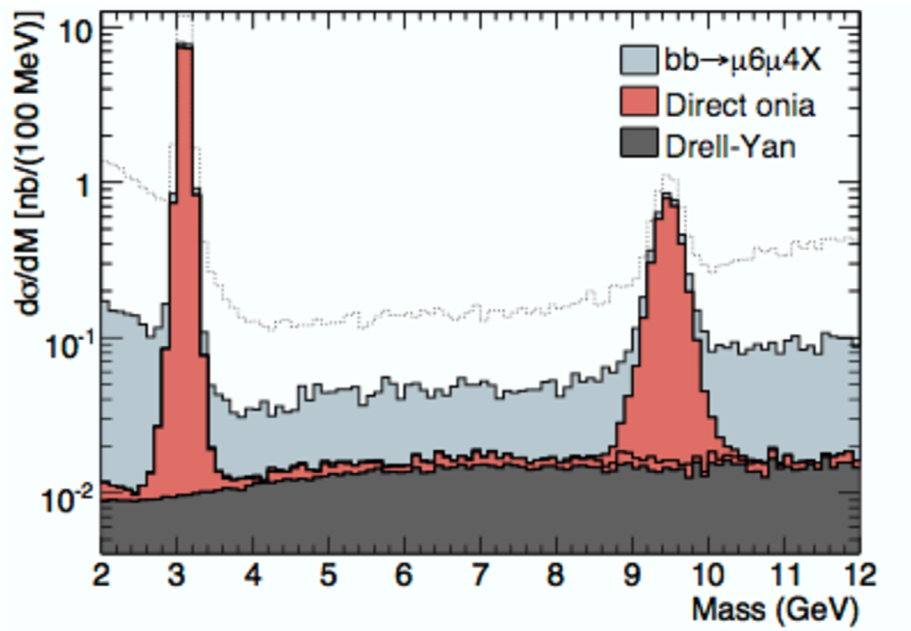


Figure 27: ATLAS dimuon spectrum prediction after corrections for acceptance and efficiencies (D. D. Price, arXiv:0808.3367 [hep-ex].).

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

- **An important point:** Events were generated for the above plot using monte carlo cuts that focused on getting muons with sufficiently high p_T that they passed trigger requirements. $\Rightarrow$ the events appearing in Fig. 27 are only a fraction of the total number of inclusive events for each of the processes.

  To make projections for the CP-odd Higgs, a, signal relative to the $b\bar{b}$ and Υ_{1S} events shown in Fig. 27 we made a guess for the fraction of a events that will be retained after p_T cuts are imposed on the muon (including those associated with triggering), after muon isolation requirements are imposed and after including all tracking and triggering efficiencies.

  The efficiencies for all the above are already built into the $b\bar{b}$ and Υ_{1S} contributions of Fig. 27. We term this efficiency ϵ_{ATLAS}.

  After some discussion with Price and others, we believe it is likely that $0.15 \leq \epsilon_{ATLAS} \leq 0.3$. (CMS claims 0.30 for the net efficiency at the moment.) **LAST MINUTE UPDATE:** $\epsilon_{ATLAS} \sim 0.1$

Without knowing this precise value we wrote

$$\epsilon_{ATLAS} = 0.15r \tag{3}$$

where $r = 2/3$ is the new result (could optimized procedures improve r?).

- Also, Fig. 27 only includes the $b\bar{b}$ heavy flavor background. Price says the full background, including $c\bar{c}, \ldots$ is at most double that shown.

- After accounting for the need to double plotted continuum background and the resolutions $\sigma_r(M_{\mu^+\mu^-})$ ($54~\mathrm{MeV}$ at J/ψ and $170~\mathrm{MeV}$ at Υ_{1S}), we compute the number, $N_{\Delta M_{\mu^+\mu^-}}$, of 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 $m_a = 8~\mathrm{GeV}$, 50968 at $m_a = M_{\Upsilon_{1S}}$ and 9620 at $m_a = 10.5~\mathrm{GeV}$. We take the square root to determine the 1σ fluctuation level.

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

  Consider $\tan\beta = 10$ and $\cos\theta_A = 0.1$ (middle range of most preferred NMSSM models).

  From Fig. 24, we see that at $\tan\beta = 10$ the total a cross section ranges from about 4.2×10^5 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 $4200 - 8500$ 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 $\epsilon_{ATLAS} = 0.15 \times r$.

  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 $L = 10$ pb^{-1} (as employed above in computing the number of background events), we obtain a event numbers of $15 \times r$, $28 \times r$ and $32 \times r$ at $m_a = 8$ GeV, $M_{\Upsilon_{1S}}$ and 10.5 GeV, respectively. Note small S/B.

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

- The statistical significances of the a peaks for $L = 10~\mathrm{pb}^{-1}$ are tabulated below.

Table 2: Comparison of statistical significances for $C_{ab\bar{b}} = \cos\theta_A \tan\beta = 1$

Case	$m_a = 8~\mathrm{GeV}$	$m_a = M_{\Upsilon_{1S}}$	$m_a \lesssim 2m_B$
Tevatron, $L = 10~\mathrm{fb}^{-1}$	0.9	0.7	1.7
ATLAS LHC7, $L = 10~\mathrm{pb}^{-1}$	$0.18r$	$0.094r$	$0.25r$
ATLAS LHC10, $L = 10~\mathrm{pb}^{-1}$	$0.21r$	$0.11r$	$0.28r$
ATLAS LHC14, $L = 10~\mathrm{pb}^{-1}$	$0.24r$	$0.12r$	$0.32r$

Table 3: Luminosities (fb^{-1}) needed for 5σ if $C_{ab\bar{b}} = \cos\theta_A \tan\beta = 1$

Case	$m_a = 8~\mathrm{GeV}$	$m_a = M_{\Upsilon_{1S}}$	$m_a \lesssim 2m_B$
ATLAS LHC7	$7.5/r^2$	$28/r^2$	$4.1/r^2$
ATLAS LHC10	$5.7/r^2$	$21/r^2$	$3.1/r^2$
ATLAS LHC14	$4.4/r^2$	$17/r^2$	$2.4/r^2$

For $r^2 = 4/9$, the required L's away from the Upsilon resonance may be achieved after a year or two of LHC operation.

The sensitivity of the required luminosities to r shows that there is an urgent need to firmly establish the expected $\mu^+\mu^-$ background level for the LHC experiments and optimize the efficiency for the signal..

- **Note:** To probe $C_{ab\bar b} \sim 0.2$, the minimum value at $\tan\beta = 10$ for which $B(h \to aa) > 0.7$ for LEP escape, requires $[(1/0.2)^2]^2 \sim 625 \times$ more L to reach same levels.

Back to the low-$\tan\beta$ NMSSM models in which several, perhaps many, Higgses carry the ZZ coupling

These arise for $\tan\beta < 3$. (R. Dermisek and J. F. Gunion, arXiv:0811.3537 [hep-ph].)

- It is possible to have h_1, h_2, h^+ all light but escaping LEP and Tevatron detection by virtue of decays to a with $m_a < 2m_b$.

  It is even possible to have $m_{h^+} \lesssim 100~\mathrm{GeV}$, but such scenarios have rather large light-a_1 fine tuning measure G. They do not arise if we require $G < 20$ for example. (See later plots.)

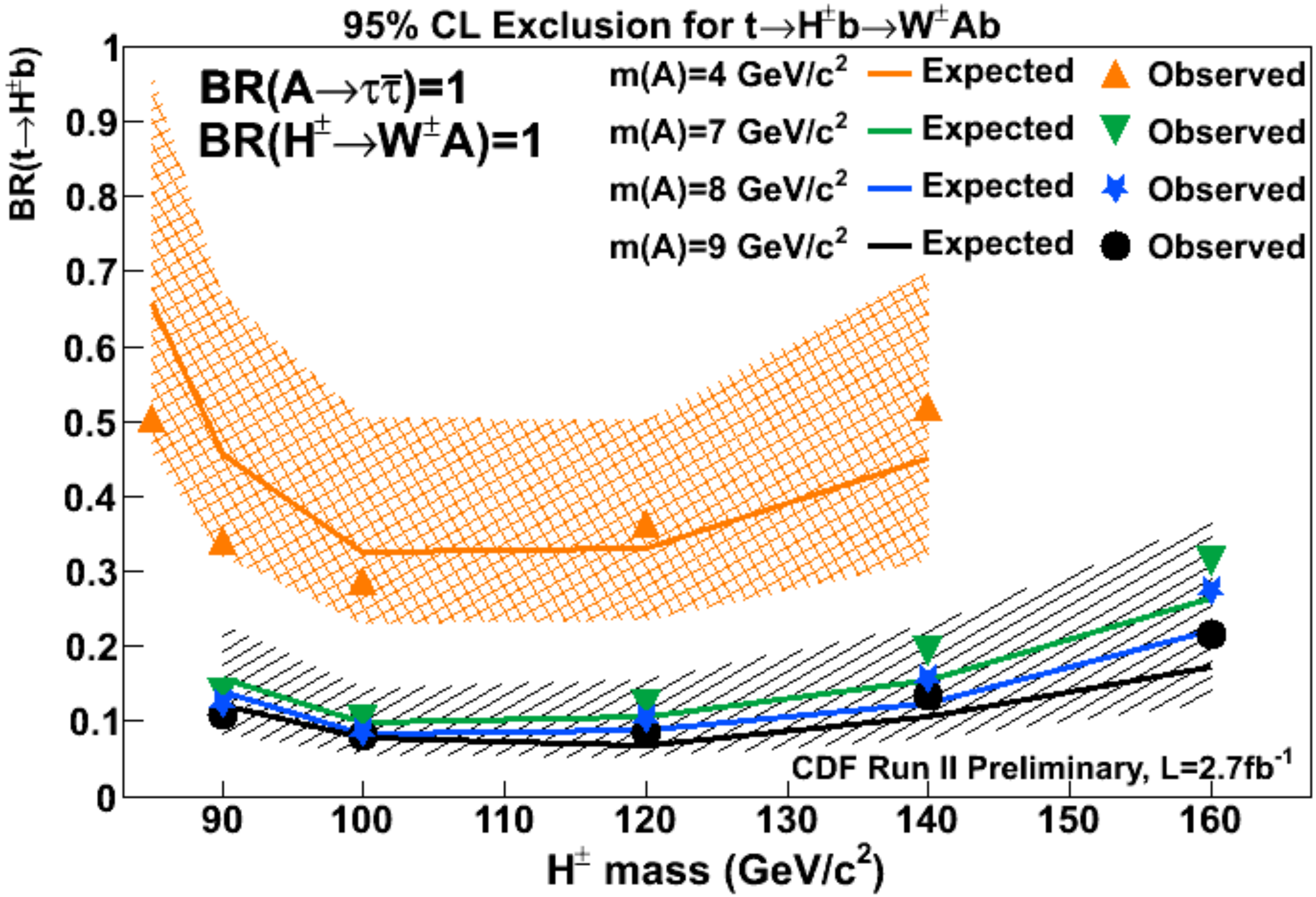
- h_1 need not be exactly SM-like — h_2 can be light enough ($\sim 100~\mathrm{GeV}$) for precision electroweak when $g^2_{h_2WW}$ is substantial.

- Relevant scenarios often arise for $C_{ab\bar b} \gtrsim 1$, especially if $\tan\beta = 2$. Current limits imply that $m_a \gtrsim 10~\mathrm{GeV}$ is needed for $C_{ab\bar b} \sim 2$ to be ok. However, low $\tan\beta$ scenarios also arise for very small $C_{ab\bar b} \sim 0.2$, for which exclusion via direct a searches is very hard.

- **The multiple LEP (and Tevatron) escapes:**

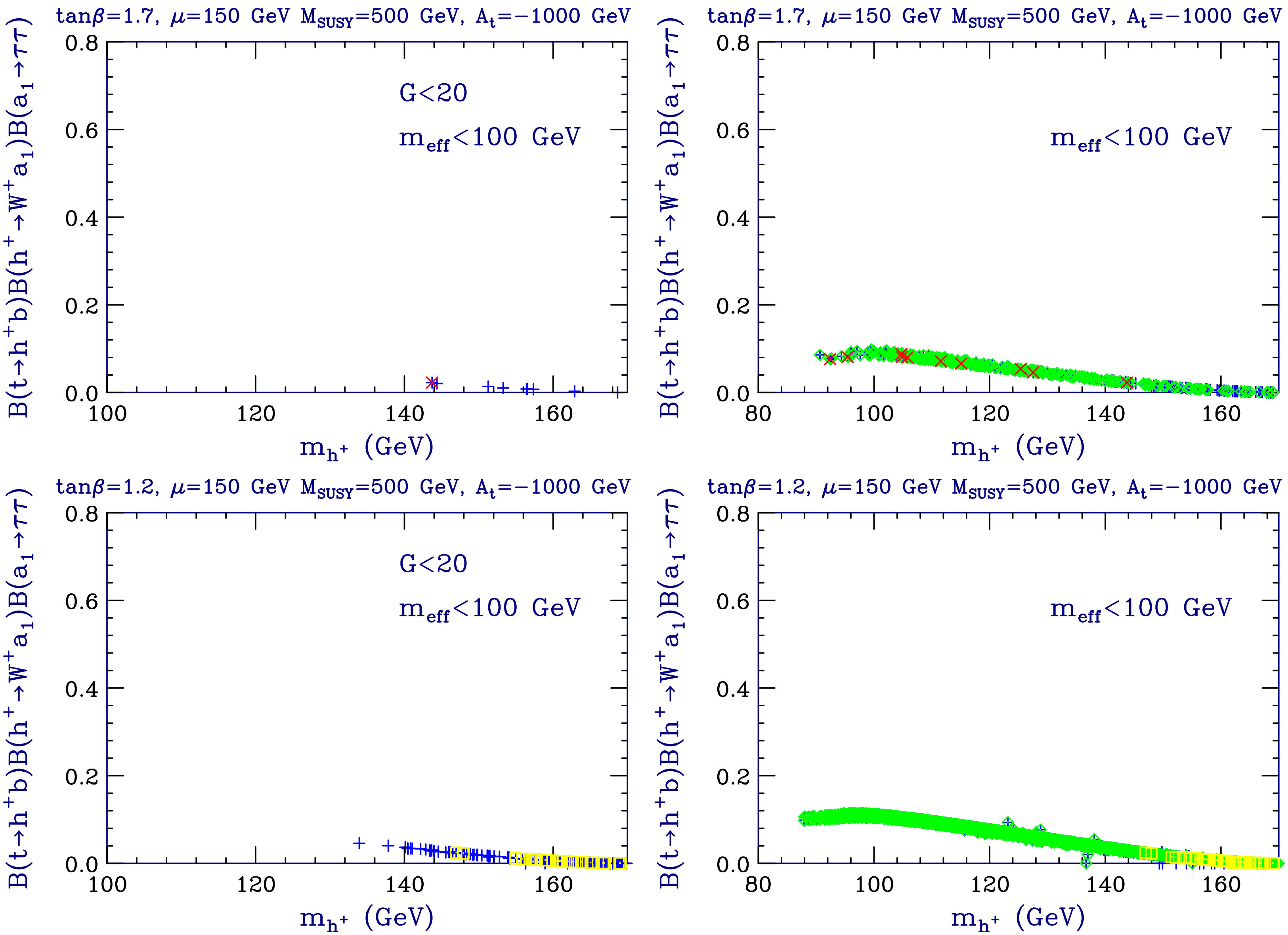
1. ξ^2 for $e^+e^- \to Zh_1 \to Zaa \to Z4\tau$ was discussed earlier.
2. $B(h^+ \to W^+a)$ is often large, and $e^+e^- \to h^+h^- \to W^+W^-aa$ with $a \to 2\tau$ was not directly searched for.
3. $B(h^+ \to \tau^+\nu)$ is often significant (but never dominant) and for cases with $m_{h^\pm}$ close to m_W, $e^+e^- \to h^+h^- \to \tau^+\tau^-2\nu_\tau$ could explain the 2.8σ deviation from lepton universality in W decays measured at LEP.
4. $B(h_2 \to aa)$ and/or $B(h_2 \to Za)$ are large.
   Thus, even if $e^+e^- \to Zh_2$ has large σ (which is often the case since m_{h_2} is not large), would not have seen it since the $h_2 \to Za$ decay was never looked for and an incomplete job was done on $h_2 \to aa \to 4\tau$.
5. For $\tan\beta = 1.7$ it is easy to find cases where $e^+e^- \to Zh_1 \to Zb\bar{b}$ *and* $e^+e^- \to Zh_2 \to Zb\bar{b}$ would yield a substantial contribution to the LEP $(0.1 - 0.2) \times SM$ excess near $m_{b\bar{b}} \sim 98~\mathrm{GeV}$.
6. To observe or constrain the a for larger (light-a finetuning preferred) $m_a \lesssim 2m_B$, will require Tevatron high luminosity data or LHC. **Still lots of models, even if not all, can be probed in this way.**
7. A just available analysis by CDF has placed direct limits on $t \to h^+b$

with $h^+ \to W^+ a$ where $a \to \tau^+\tau^-$.



[png] [pdf] [gif]

Our prediction is ok, at least for small G scenarios. Large G scenarios (green points in plots below) with really light h^+ are borderline.


tanβ=1.7, μ=150 GeV M_SUSY=500 GeV, A_t=−1000 GeV
G<20
m_eff<100 GeV
B(t→h+b)B(h+→W+a1)B(a1→ττ)
m_h+ (GeV)
tanβ=1.7, μ=150 GeV M_SUSY=500 GeV, A_t=−1000 GeV
m_eff<100 GeV
tanβ=1.2, μ=150 GeV M_SUSY=500 GeV, A_t=−1000 GeV
G<20
m_eff<100 GeV
tanβ=1.2, μ=150 GeV M_SUSY=500 GeV, A_t=−1000 GeV
m_eff<100 GeV

Detecting the light h of the NMSSM

LHC assuming $\tan\beta \gtrsim 3$, *i.e.* large $B(a \to \tau^+\tau^-)$

All standard LHC channels fail: *e.g.* $B(h \to \gamma\gamma)$ is much too small because of large $B(h \to aa)$.

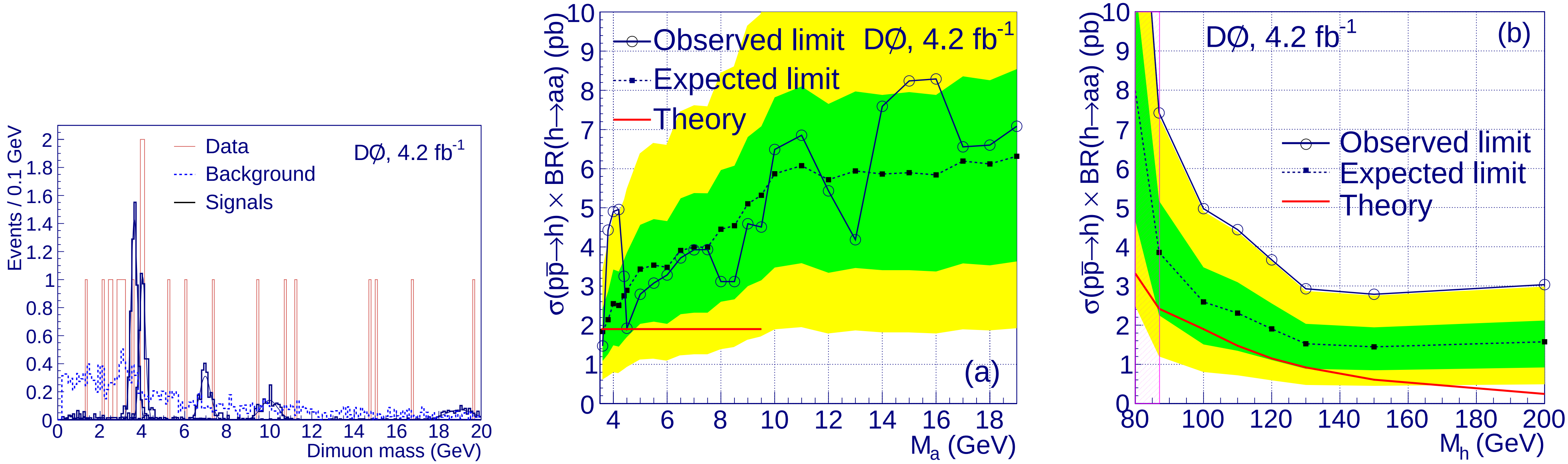
The possible new LHC channels include:

1. $gg \to h \to aa \to 4\tau$ and $2\tau + \mu^+\mu^-$

   Always use μ tag for accepted events. $2\tau + 2\mu$ is main signal source after cuts.

   There is an actual D0 analysis (A. Haas et. al.) of this mode using about $L \sim 4~\mathrm{fb}^{-1}$ of data. There are even small $\sim 1\sigma$ excesses for $m_a \sim 4$ and $10 - 11~\mathrm{GeV}$ consistent with predicted signal. About $L \sim 40~\mathrm{fb}^{-1}$ would

be needed for a 3σ signal.



From arXiv:0905.3381.

At the LHC? Studied by Wacker et al.

- $\sigma(gg \to h) \sim 50~\mathrm{pb}$ **for** $m_h \sim 100~\mathrm{GeV}$.
- $B(h \to aa) \sim 0.8 - 0.9$.
- $B(a \to \mu^+\mu^-) \sim 0.003 - 0.004$ **and** $B(a \to \tau^+\tau^-) \sim 0.75 - 0.9$
- **Useful branching ratio product is** $2 \times B(a \to \mu^+\mu^-) B(a \to \tau^+\tau^-) \sim .0075$.
- **Cut efficiencies** $\epsilon \sim 0.018$.

- **Net useful cross section:**

$$\sigma(gg \to h)B(h \to aa)[2B(a \to \mu^+\mu^-)B(a \to \tau^+\tau^-)]\epsilon \sim 3 - 6 \text{ fb}\,. \quad (4)$$

Backgrounds are small so perhaps $10 - 20$ events in a single $\mu^+\mu^-$ bin would be convincing $\Rightarrow$ need about $L = 4 \text{ fb}^{-1}$.

Note: If $m_a < 2m_\tau$, then $B(a \to \mu^+\mu^-) > 0.06$ and

$$\sigma(gg \to h)B(h \to aa)[B(a \to \mu^+\mu^-]^2\epsilon > (153 \text{ fb}) \times \epsilon\,. \quad (5)$$

If $\epsilon > 0.02$ (seems likely) then $\Rightarrow \sigma_{eff} > 3$ fb. This should be really background free and would eliminate $m_a < 2m_\tau$ once and for all.

2. $WW \to h \to aa \to \tau^+\tau^- + \tau^+\tau^-$.

Key will be to tag relevant events using spectator quarks and require very little activity in the central region by keeping only events with 4 or 6 tracks.

Looks moderately promising but far from definitive results at this time (see, A. Belyaev *et al.*, arXiv:0805.3505 [hep-ph] and our work, JFG+Tait+Z. Han, below). More shortly.

3. $t\bar{t}h \to t\bar{t}aa \to t\bar{t} + \tau^+\tau^- + \tau^+\tau^-$.

No study yet. Would isolated tracks/leptons from τ's make this easier than $t\bar{t}h \to t\bar{t}b\bar{b}$?

4. $W, Z + h \to W, Z + aa \to W, Z + \tau^+\tau^- + \tau^+\tau^-$.

Leptons from W, Z and isolated tracks/leptons from τ's would provide a clean signal. No study yet.

5. $\widetilde{\chi}_2^0 \to h\widetilde{\chi}_1^0$ with $h \to aa \to 4\tau$.

(Recall that the $\widetilde{\chi}_2^0 \to h\widetilde{\chi}_1^0$ channel provides a signal in the MSSM when $h \to b\bar{b}$ decays are dominant.)

6. Last, but definitely not least: diffractive production $pp \to pph \to ppX$.

The mass M_X can be reconstructed with roughly a $1-2~\mathrm{GeV}$ resolution, potentially revealing a Higgs peak, independent of the decay of the Higgs.

The event is quiet so that the tracks from the τ's appear in a relatively clean environment, allowing track counting and associated cuts.

Signal significances from JFG, Forshaw, Pilkington, Hodgkinson, Papaefstathiou: arXiv:0712.3510 are plotted in Fig. 28 for a variety of luminosity and triggering assumptions.

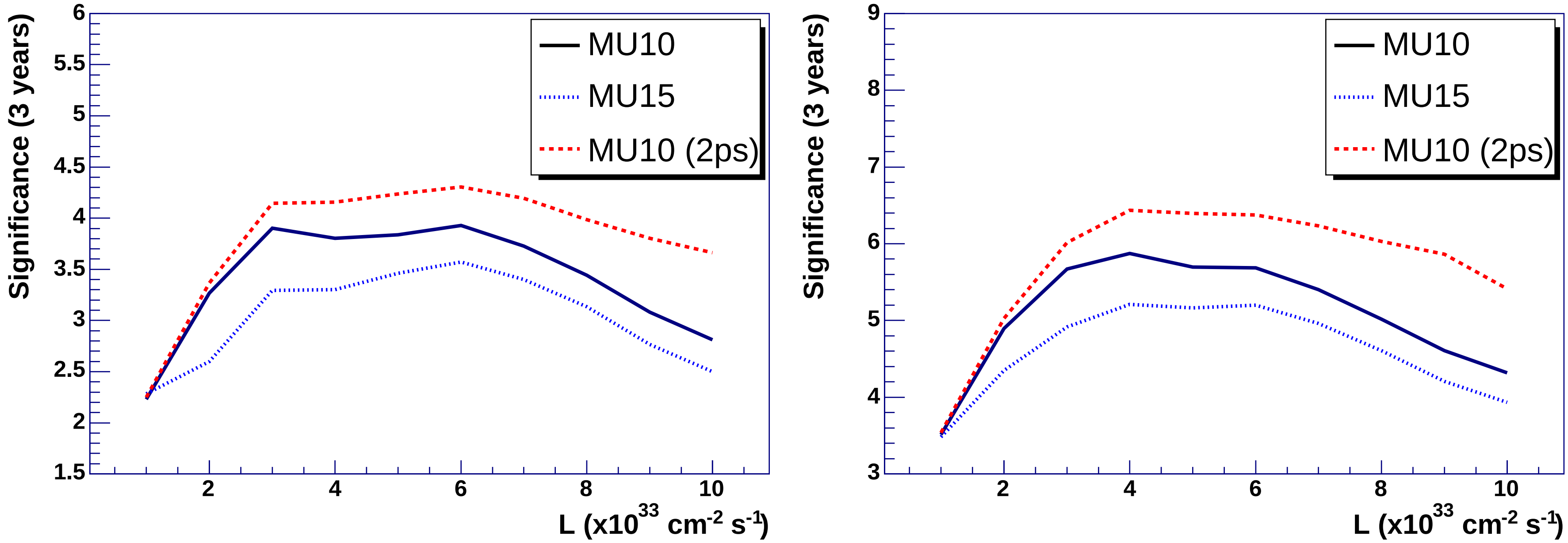


Figure 28: (a) The significance for three years of data acquisition at each luminosity. (b) Same as (a) but with twice the data. Different lines represent different μ trigger thresholds and different forward detector timing. Some experimentalists say more efficient triggering is possible, doubling the number of events at given luminosity.

CMS folk claim we can increase our rates by about a factor of 2 to 3 using additional triggering techniques.

The Collinearity Trick

- **Since $m_a \ll m_h$, the a's in $h \to aa$ are highly boosted.**

  $\Rightarrow$ the a decay products will travel along the direction of the source a.

  $\Rightarrow p_a \propto \sum$ visible 4-momentum of the charged tracks in its decay. Labeling the two a's with indices 1 and 2 we have

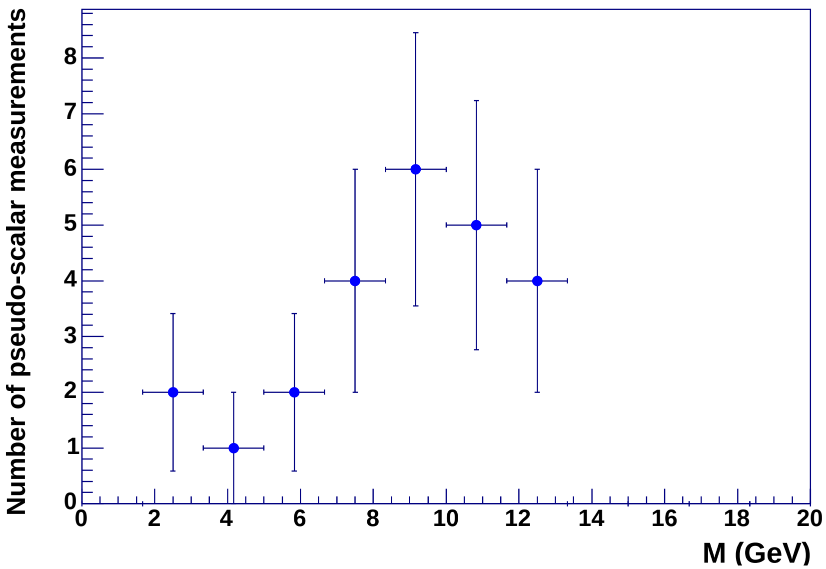
$$p_i^{vis} = f_i \, p_{a,i} \tag{6}$$

  where $1 - f_i$ is the fraction of the a momentum carried away by neutrals.

- **$pp \to pph$ case**

  The accuracy of this has now been tested in the $pp \to pph$ case, and gives an error for m_h of order $5~\mathrm{GeV}$, but this is less accurate than m_h determination from the tagged protons and so is not used.

  However, we are able to make *four* m_a determinations per event.



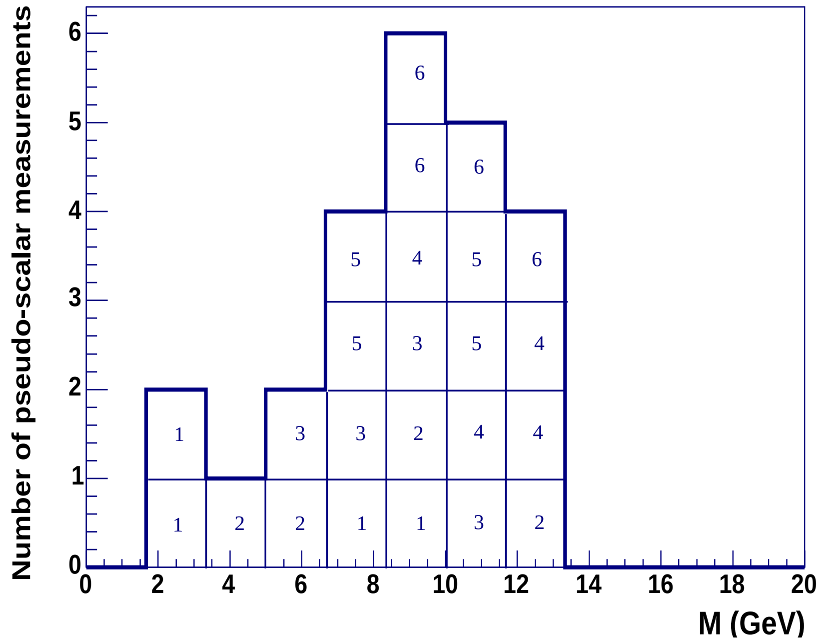


Figure 29: (a) A typical a mass measurement. (b) The same content as (a) but with the breakdown showing the 4 Higgs mass measurements for each of the 6 events, labeled $1 - 6$ in the histogram.

Figure 29 shows the distribution of masses obtained for $180\ \mathrm{fb}^{-1}$ of data collected at 3×10^{33} cm^{-2}s^{-1}, corresponding to about 6 Higgs events and therefore 24 m_a entries.

By considering many pseudo-data sets, we conclude that a typical experiment would yield $m_a = 9.3 \pm 2.3$ GeV, which is in reassuringly good agreement with the input value of 9.7 GeV.

- $\boxed{WW \to h}$

For $m_h = 100$ GeV and SM-like WWh coupling, $\sigma(WW \to h) \sim 7$ pb, implying 7×10^5 events before cuts for $L = 100$ fb^{-1}.

In this case, we do not know the longitudinal momentum of the h, but we should have a good measurement of its transverse momentum from the tagging jets and other recoil jets.

This gives two equations in the two unknown $f_{1,2}$ and allows us to solve

and construct mass peaks.

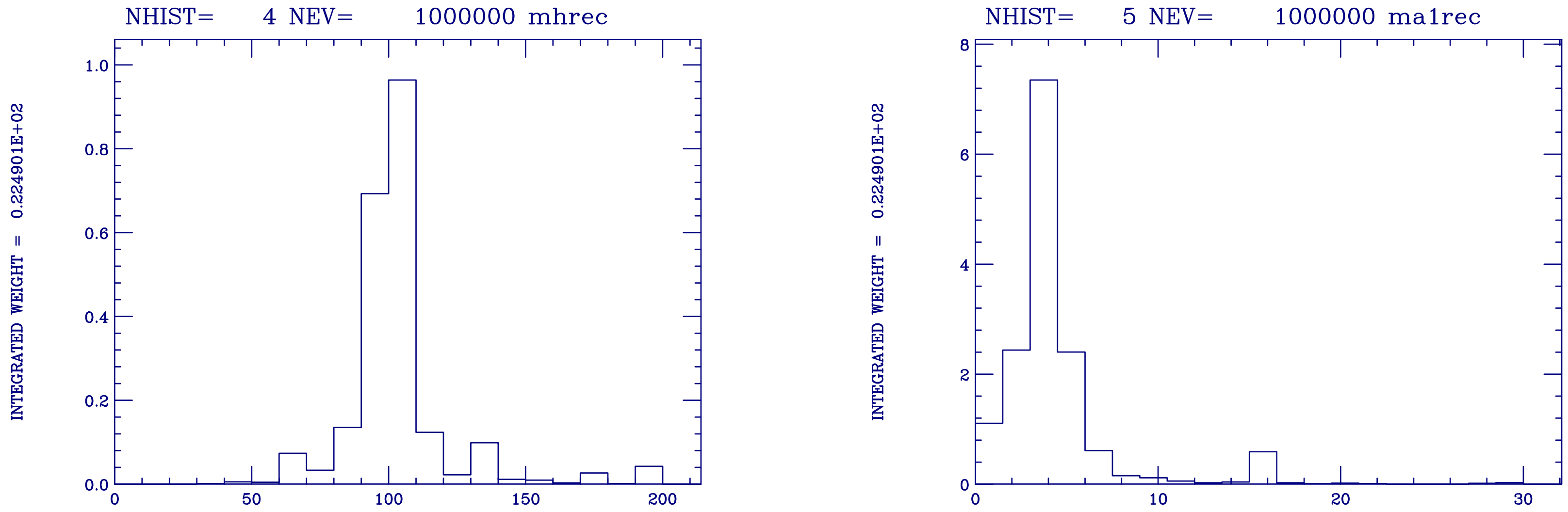


Figure 30: **(a) A typical h mass distribution. (b) A typical a mass distribution. No cuts imposed; signal only.**

LHC assuming $\tan\beta \lesssim 2$, *i.e.* mixed a decays

- **Much more difficult since $a \to 2j$ is much harder to pick out.**
- **Could perhaps consider $gg \to h \to aa \to \mu^+\mu^- X$.**

  (For $B(a \to \mu^+\mu^-) \lesssim 0.002$ could not require $X = \mu^+\mu^-$.)

  If a single a tag is ok then effective useful cross section is

$$\sigma(gg \to h)B(h \to aa)[2 \times B(a \to \mu^+\mu^-]\epsilon > (70 \text{ fb}) \times \epsilon \,. \qquad (7)$$

  for $B(a \to \mu^+\mu^-) > 0.001$ (as applies for $\tan\beta > 1$). If $\epsilon > 0.02$ (seems likely) then $\Rightarrow \sigma_{eff} > 1.4 \text{ fb}$.

  Probably some significant background, but maybe not too large after zeroing in on the a peak in the $\mu^+\mu^-$ channel.

  Perhaps 50 events would suffice? Would imply only $L = 30 \text{ fb}^{-1}$ would be needed.

  Should be pursued.

ILC

- **At the ILC, there is no problem: for planned $\sqrt{s}$ and L, $e^+e^- \to ZX$ is guaranteed to reveal the Higgs peak in M_X just as LEP might have.**

- **But the ILC is decades away.**

Other related scenarios

- **Low $\tan\beta$ NMSSM scenarios in which the first two CP-even Higgs bosons both have mass in the $\lesssim 100~\mathrm{GeV}$ region and decay so as to escape LEP (and Tevatron) limits. See earlier section. For $\tan\beta \leq 1.7$ the very difficult $h \to aa \to 4j$ channels partially 'bury' the Higgs.**

- **Drop dark matter requirement: $\Rightarrow$ huge plethora of possibilities in SUSY.**

  Includes "hidden valley" decays, R-parity violating decays, $\ldots$.

- **A string of Higgs, as possibly hinted at by the CDF multi-muon events.**

  The SM-like Higgs could then decay into a string of Higgs bosons: e.g. $h \to h_1 h_1 \to (h_2 h_2)(h_2 h_2) \to ((h_3 h_3)(h_3 h_3))((h_3 h_3)(h_3 h_3)) \to \ldots$. (Any of the h_i's could be a's and then $a_i \to a_j h_k$ would follow.)

  (Ellwanger et al have an NMSSM model that gives CDF multi-muon, but implications for unusual h decays are unclear.)

- **Many singlets, as generically possible in string models, could mix with the doublet Higgs and create a series of Higgs eigenstates (with mass weight in the < 100 GeV region for good PEW).**

  It can be arranged that these eigenstates decay in complex ways that would have escaped LEP limits.

  In fact, one can get really low "effective" Higgs mass from PEW point of view while fitting under LEP constraint curve.

  This is the "worst case" scenario envisioned long ago in JFG, Espinosa: hep-ph/9807275.

- **A true Higgs continuum as in the model of J. Van der Bij and collaborators and in the "unhiggs" models of Georgi and others.**

  These models rely on extra-dimensional concepts.

  The hierarchy problem remains unless the ultraviolet completion scale / extra-dimension cutoff scale is low.

There would be only one narrow Higgs-like resonance **and it would be impossible to see at the LHC** since it would have only 10% of the usual g^2_{ZZh} (to explain 2.3σ LEP excess near $98~\mathrm{GeV}$).

The many a_i or h_i of the preceding models would be replaced by a continuum and a search for narrow resonances as I have discussed would no longer work: $\Rightarrow$ **LHC won't be able to detect such a continuum.**

- Clearly an ILC/CLIC, e.g. with $\sqrt{s} = 250~\mathrm{GeV}$, would see a Higgs with unusual decays and/or weaker than SM ZZh coupling.

  At LEP or any e^+e^- collider the process $e^+e^- \to ZX$ will reveal a $M_X \sim m_h \sim 90 - 100~\mathrm{GeV}$ peak no matter how the h decays so long as $g^2_{ZZh} \gtrsim 0.05 g^2_{ZZh_{\mathrm{SM}}}$, *provided L is adequate*.

- In fact, for adequate L ILC/CLIC will make it possible to detect a series of Higgs bosons or even a continuum.

  Recall that precision electroweak favors placing all the excess below about $157~\mathrm{GeV}$ or perhaps even below $105~\mathrm{GeV}$ (in a g^2_{ZZh}-weighted sense) as I

have argued.

If there are many Higgs or even a continuum of Higgs, then the excesses in various bins of M_X will be apparent even if there is a broad sort of spectrum and X has a mixture of decays, provided the integrated L is large (JFG+Espinosa).

Conclusions

In case you hadn't noticed, 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".

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