Update on NMSSM "Ideal Higgs" Scenarios

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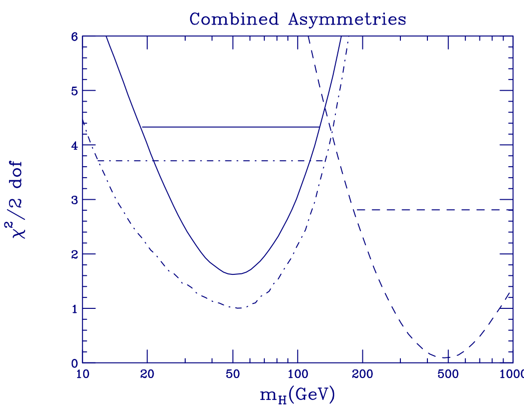
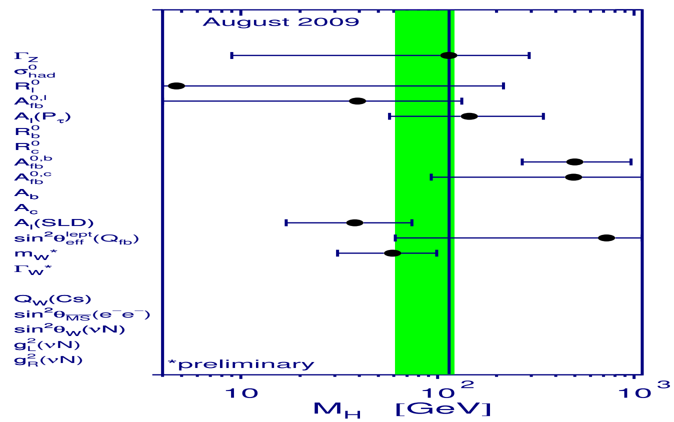
Definition of Ideal Model

1. **Excellent agreement with precision electroweak (PEW) data.**





Dropping hadronic asymmetries this $\Rightarrow m_h < 105~\text{GeV}$ if the h has SM-like WW, ZZ couplings, or more generally $m_{eff} < 105~\text{GeV}$ where

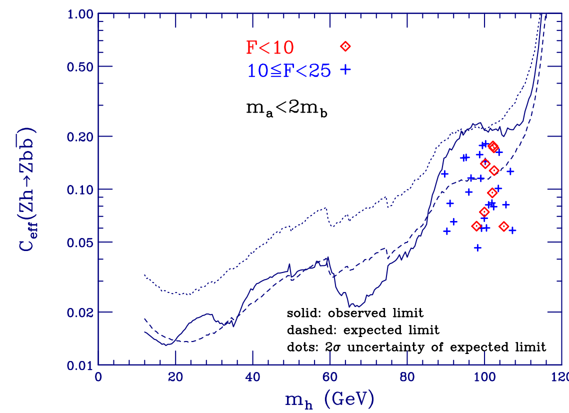
$$\ln m_{eff} \equiv [g_{ZZh_i}/g_{ZZh_{\rm SM}}]^2 \ln m_i \tag{1}$$

is the effective PEW mass for a collection of Higgs bosons with WW, ZZ couplings;

2. **Consistency with LEP limits.**

   $m_h > 114$ GeV **is required without unusual decays** $\Rightarrow$ **unusual decays must dominate in the ideal case of** $m_h < 105$ GeV.

3. **Consistency with** 98 GeV **LEP excess?**



4. **Low enough Higgs mass for electroweak baryogenesis independently** $\Rightarrow$ $m_h, m_{eff} \lesssim 105$ GeV **more or less.**

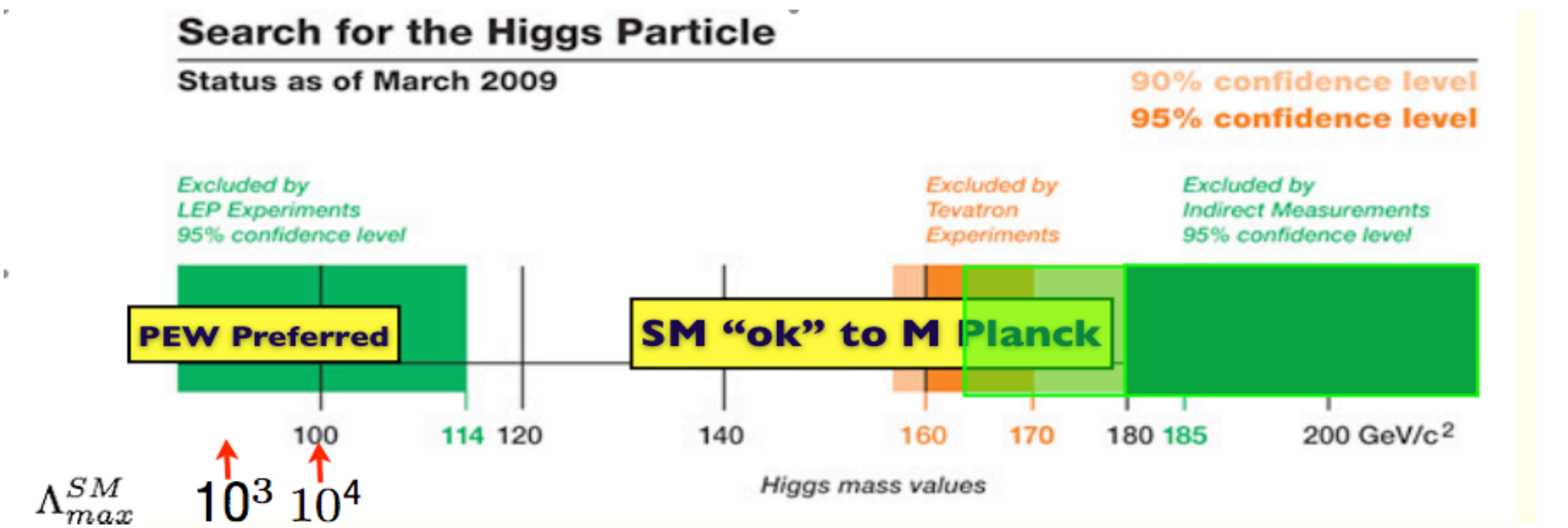
5. **No hierarchy problem;** *i.e.* **the quadratically divergent loop contributions to the Higgs mass should be cut off by new physics at a scale of** $\mathcal{O}(\text{ TeV})$.

6. **Coupling constant unification without adhoc tuning of matter content and/or Lagrangian parameters.**

7. **No electroweak finetuning; *i.e.* the value of m_Z is not simply input and/or is not strongly dependent on input global parameters at the GUT, or any other, scale.**

8. **Consistency with triviality and vacuum stability constraints.**

Various aspects of the situation are summarized by the plot below.



The NMSSM fills the bill Besides being a beautiful SUSY model with automatic solution to the μ problem, one finds:

- $h_1 \to a_1 a_1 \to 4\tau, 2\tau + 2j, 4j$ decays allow $m_{h_1} < 105~\mathrm{GeV}$, with $m_{h_1} \sim 100~\mathrm{GeV}$ certainly possible, while escaping LEP limits.

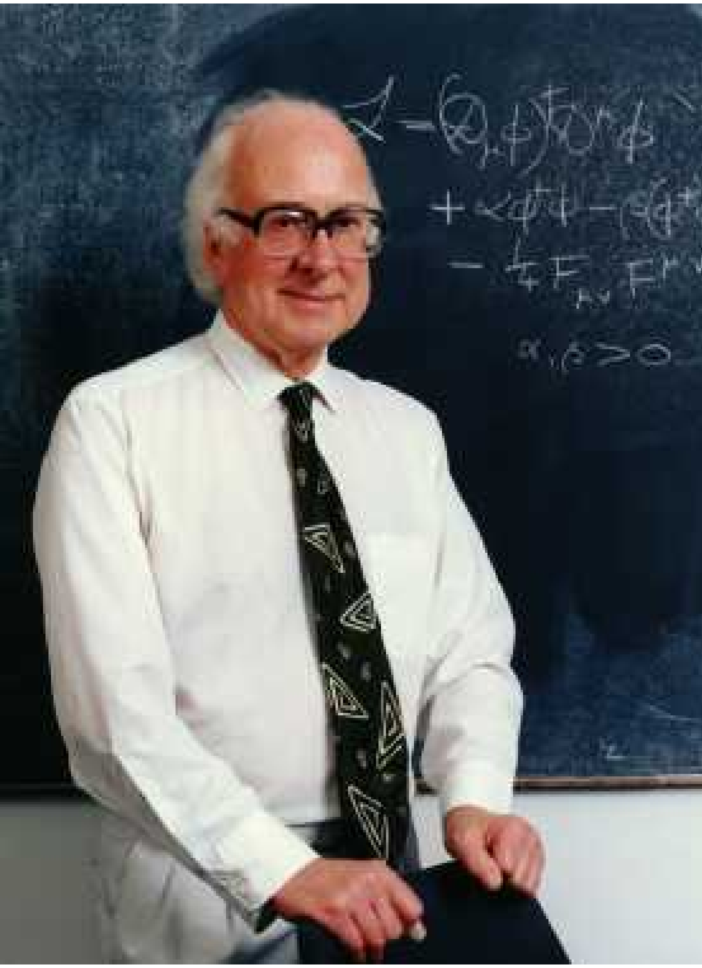
- low electroweak finetuning ($F < 10 - 20$) is automatic if stop masses are low (and gluino mass is not large), in which case $m_{h_1} < 105~\mathrm{GeV}$ is predicted in the NMSSM context.

- a small value of $m_{a_1} < 2m_B$ does not require A_λ-A_κ ($V \ni A_\lambda S H_u H_d + \frac{1}{3} A_\kappa S^3$) finetuning (i.e. $G < 20$ is very possible) and one finds $B(h_1 \to a_1 a_1) > 0.7$ so long as $\cos\theta_A$ does not fall below some minimum value — here, $\cos\theta_A$ is defined by
$$a_1 = \cos\theta_A a_{MSSM} + \sin\theta_A a_S\,. \tag{2}$$

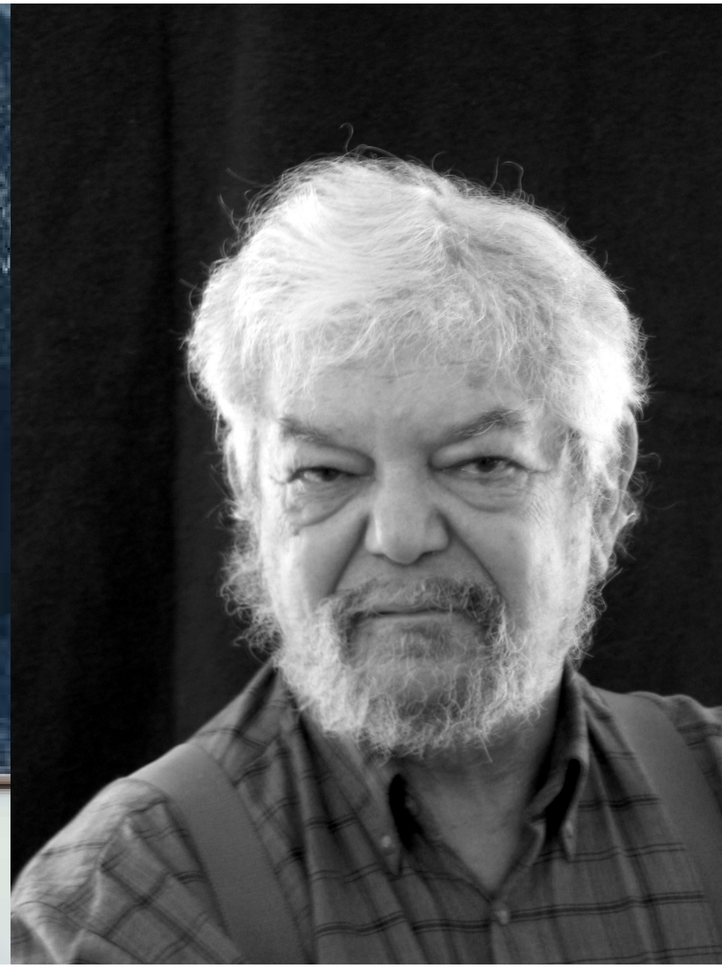
Of course, multi-singlet extensions of the NMSSM will expand the possibilities, and are typical of string models.

Net result: PEW and finetuning suggest that we really should not count on knowing what the Higgs "looks like". It could be ...

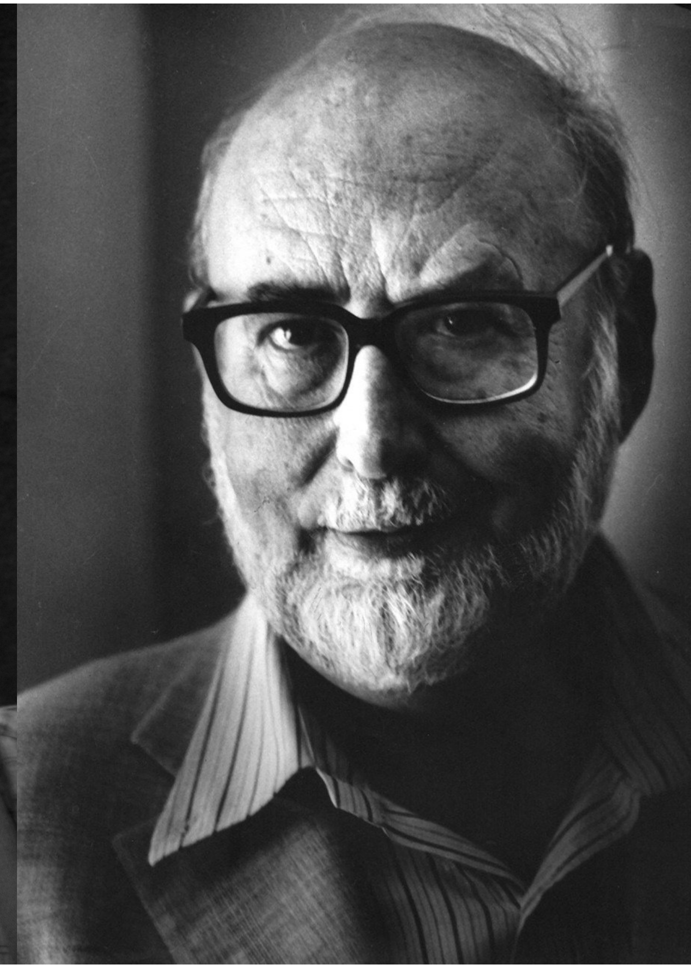
Priestly, highly orthodox **Less saintly, but still "standard"**



Higgs

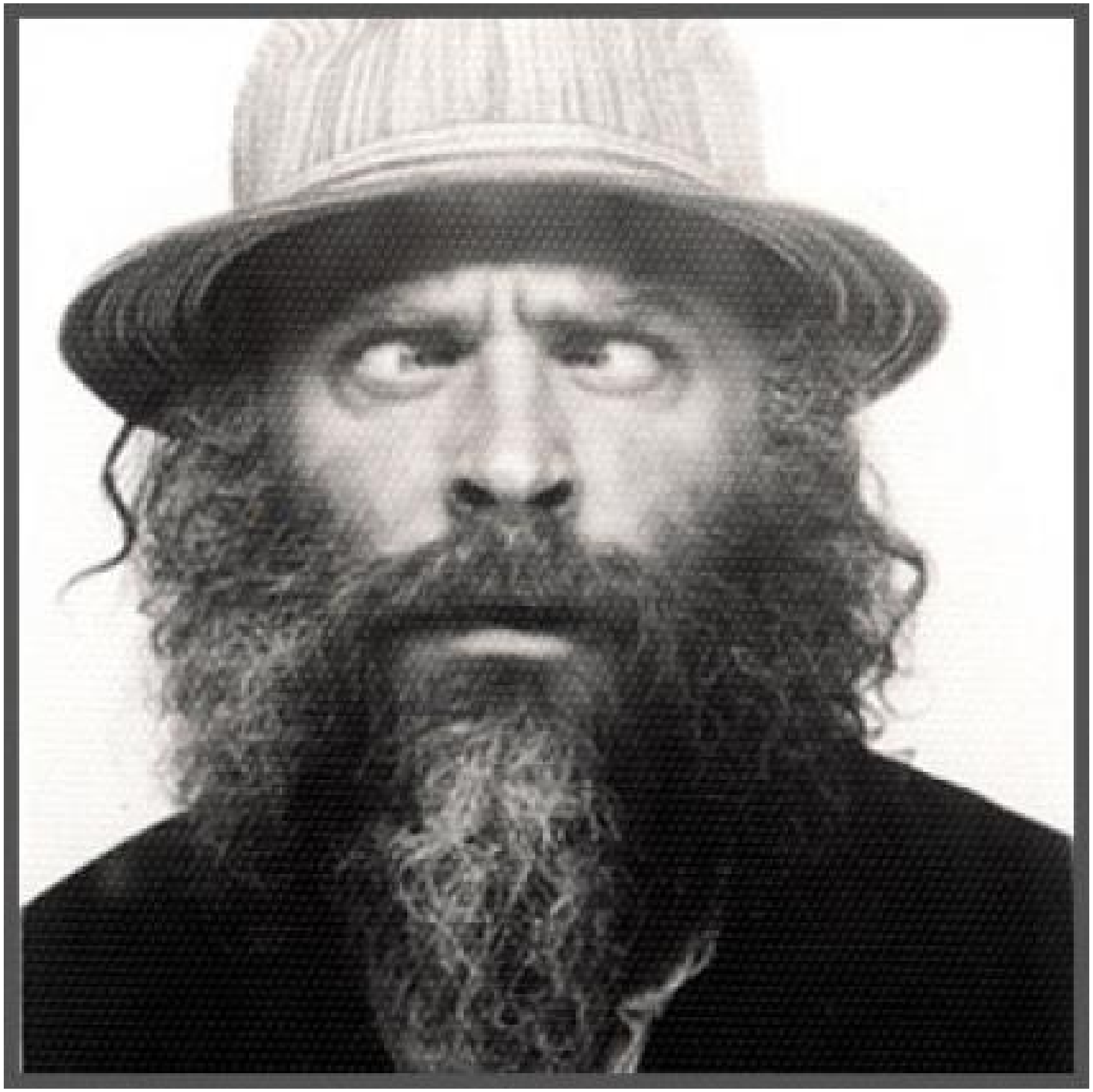


Brout



Englert

Ornery/ mean, highly heretical



singer Daniel Higgs

Beautiful/ephemeral but unorthodox

singer Rebekah Higgs

Or, will the LHC bury the Higgs?

In fact, at low $\tan\beta$ a PEW/finetuning-ideal NMSSM Higgs is largely "buried" since it decays mainly to 4 non-b jets.

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**

$$\mathcal{L}_{af\overline{f}} \equiv iC_{af\overline{f}} \frac{ig_2 m_f}{2m_W} \overline{f} \gamma_5 f a \,, \tag{3}$$

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 $a \to \mu^+\mu^-$.

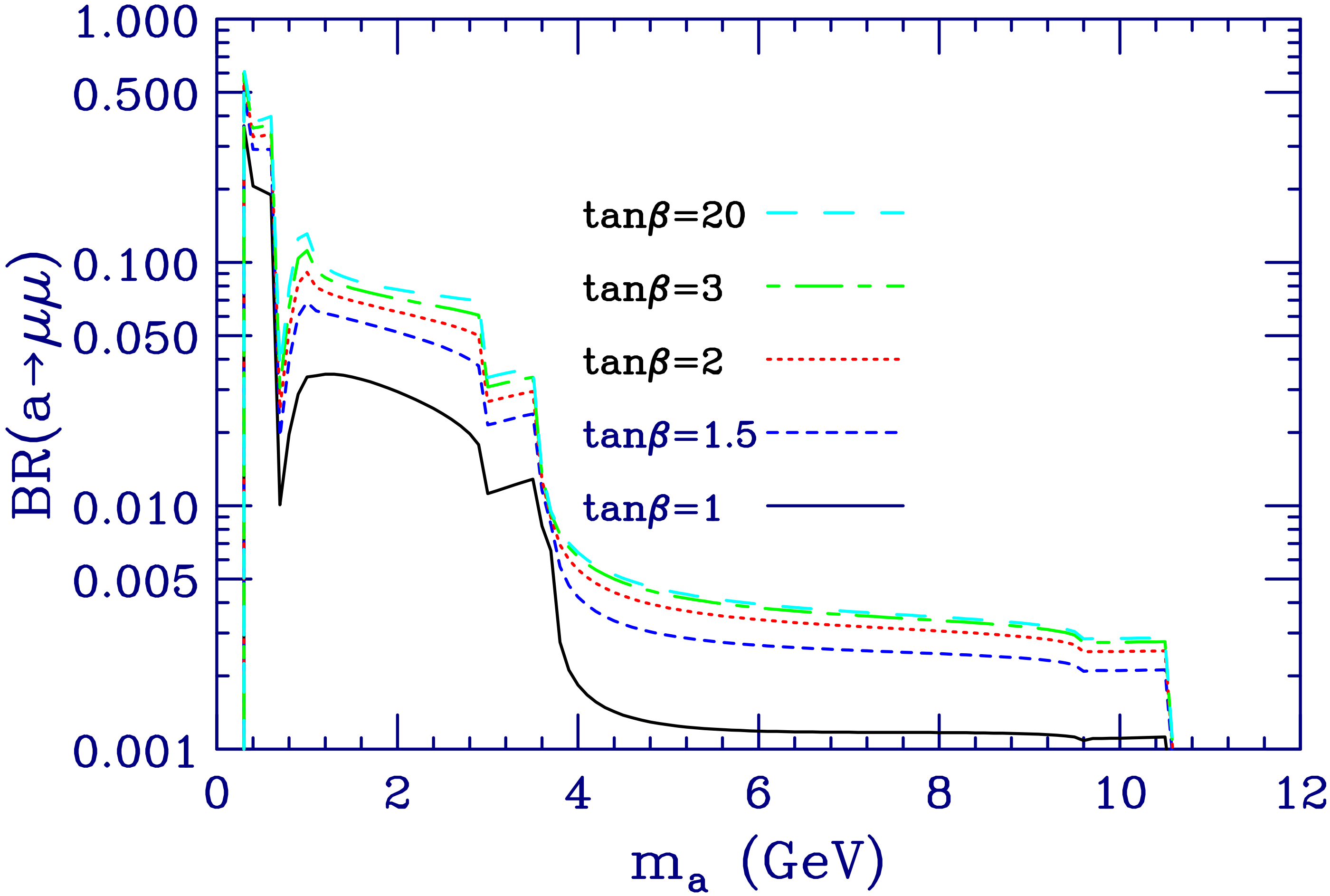


Figure 1: $B(a \to \mu^+\mu^-)$ **for various** $\tan\beta$ **values.**

- **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 $m_a \gtrsim 10$.

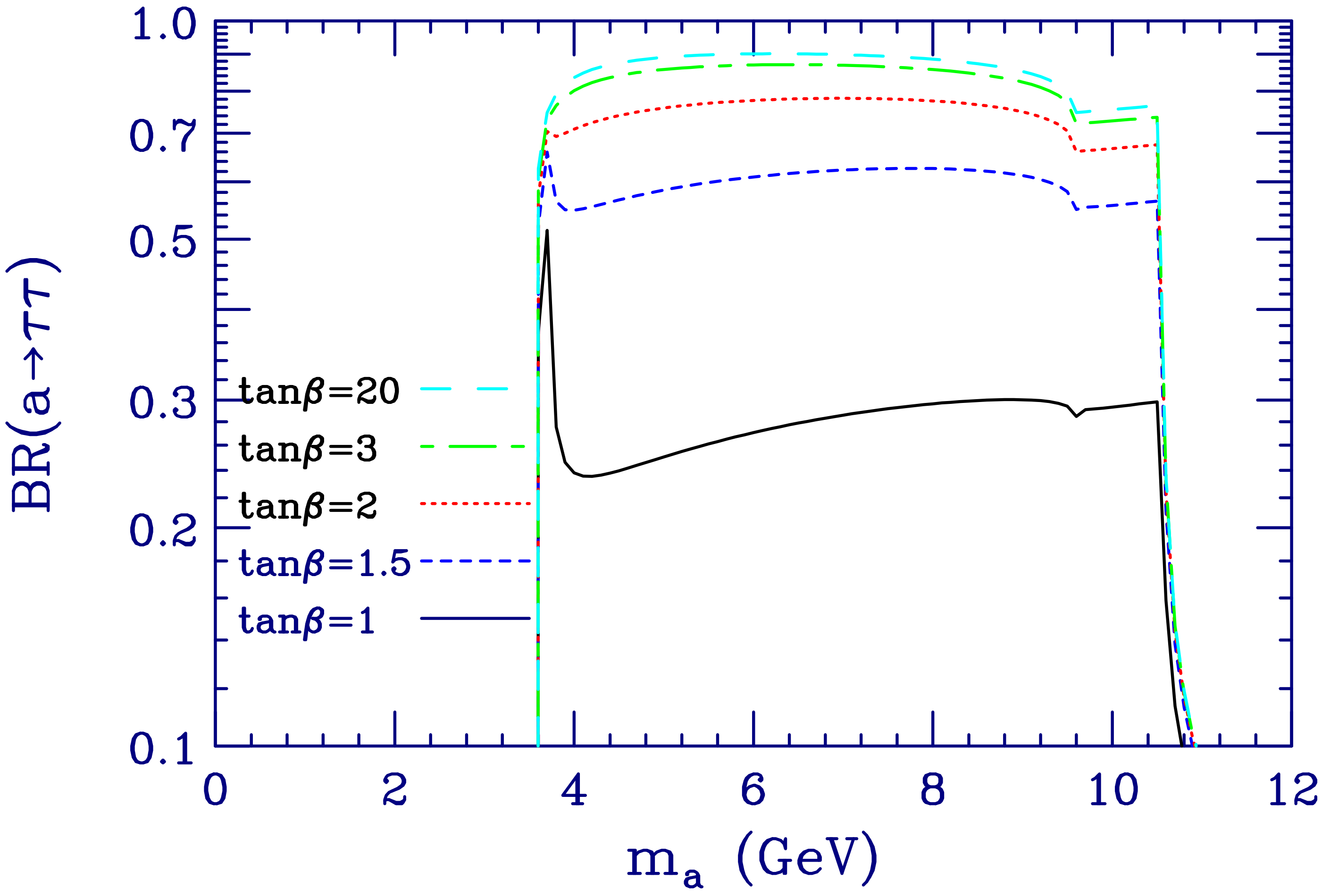


Figure 2: $B(a \to \tau^+\tau^-)$ for various $\tan\beta$ values.

- **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.**

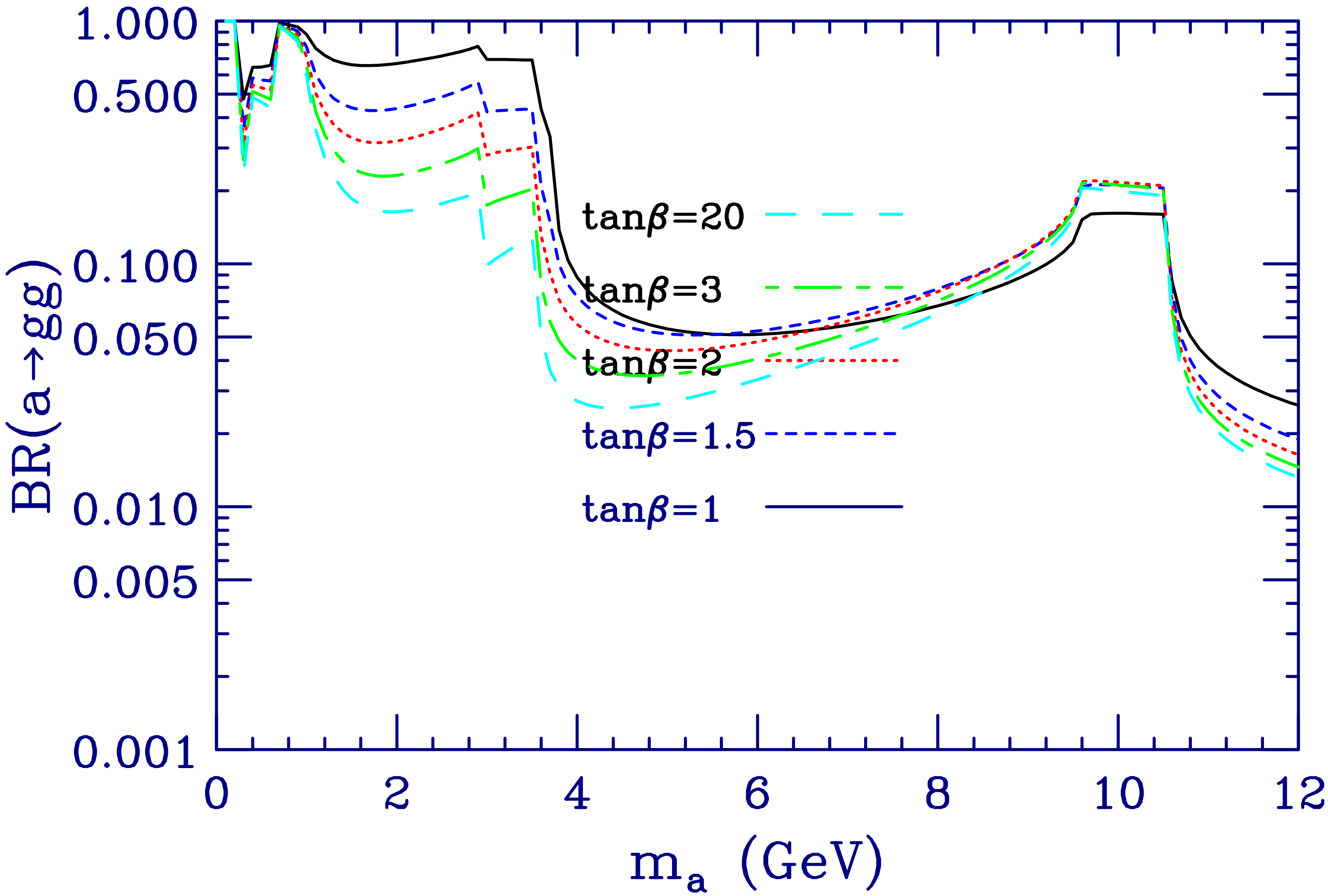


Figure 3: $B(a \to gg)$ **for various** $\tan\beta$ **values.**

- **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.**

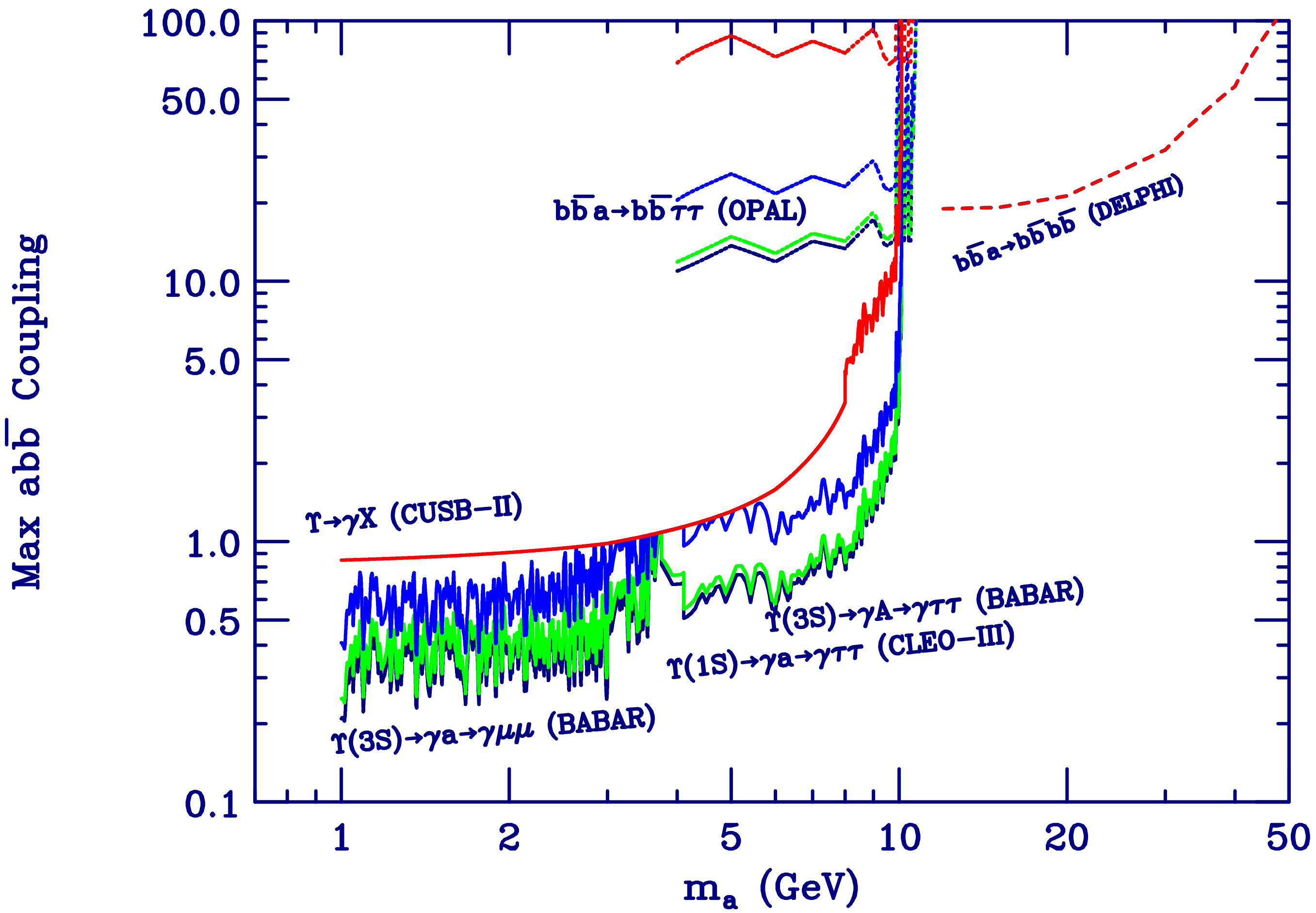


Figure 4: **Limits on $C_{ab\bar{b}}$ from JFG, arXiv:0808.2509 and JFG+Dermisek, arXiv:0911.2460. These limits include recent BaBar $\Upsilon_{3S} \to \gamma\mu^+\mu^-$ and $\gamma\tau^+\tau^-$ limits. Color code: $\tan\beta = 0.5$; $\tan\beta = 1$; $\tan\beta = 2$; $\tan\beta \geq 3$.**

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

$$C_{ab\bar{b}} = \cos\theta_A \tan\beta \quad (4)$$

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

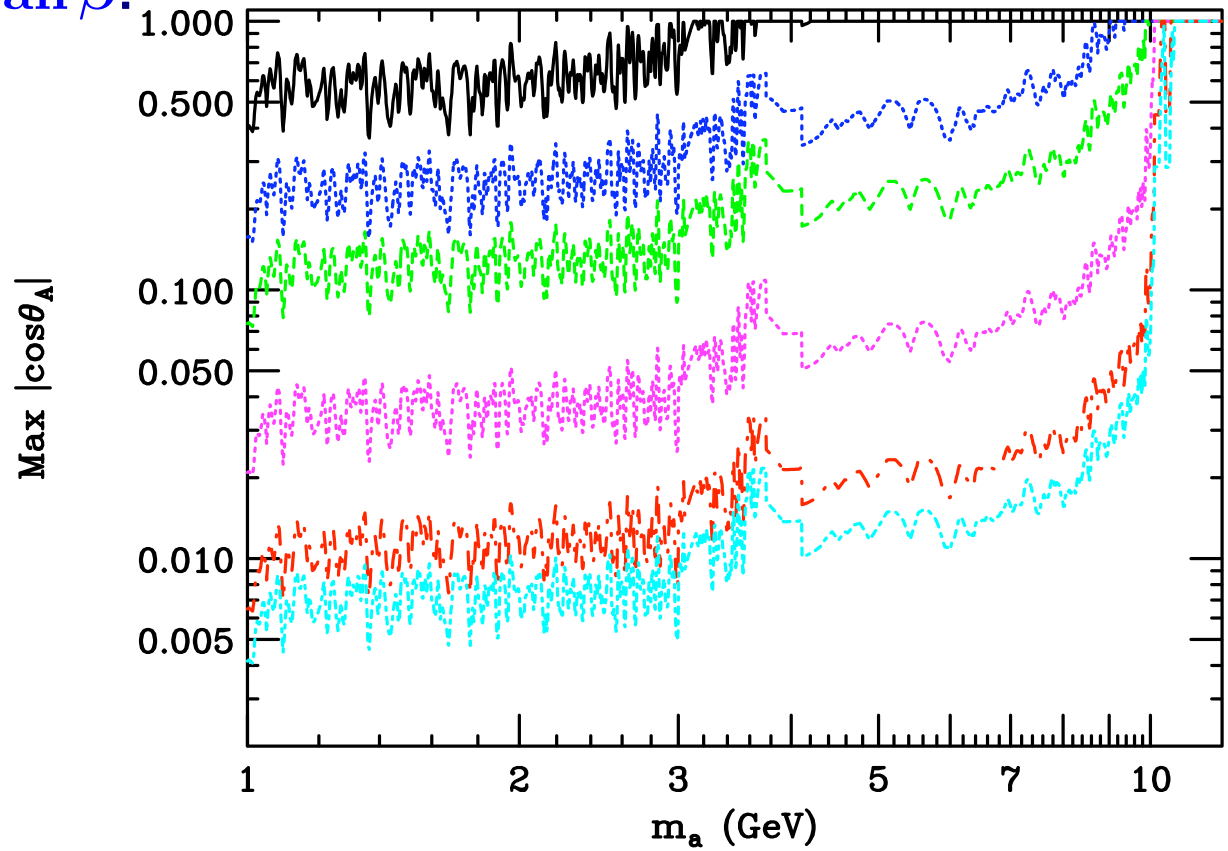


Figure 5: **Curves are for $\tan\beta = 1$ (upper curve), 1.7, 3, 10, 32 and 50 (lowest curve).**

What is the impact on "ideal" scenarios with low F. Examine the light-a finetuning measure G as a function of $\cos\theta_A$.

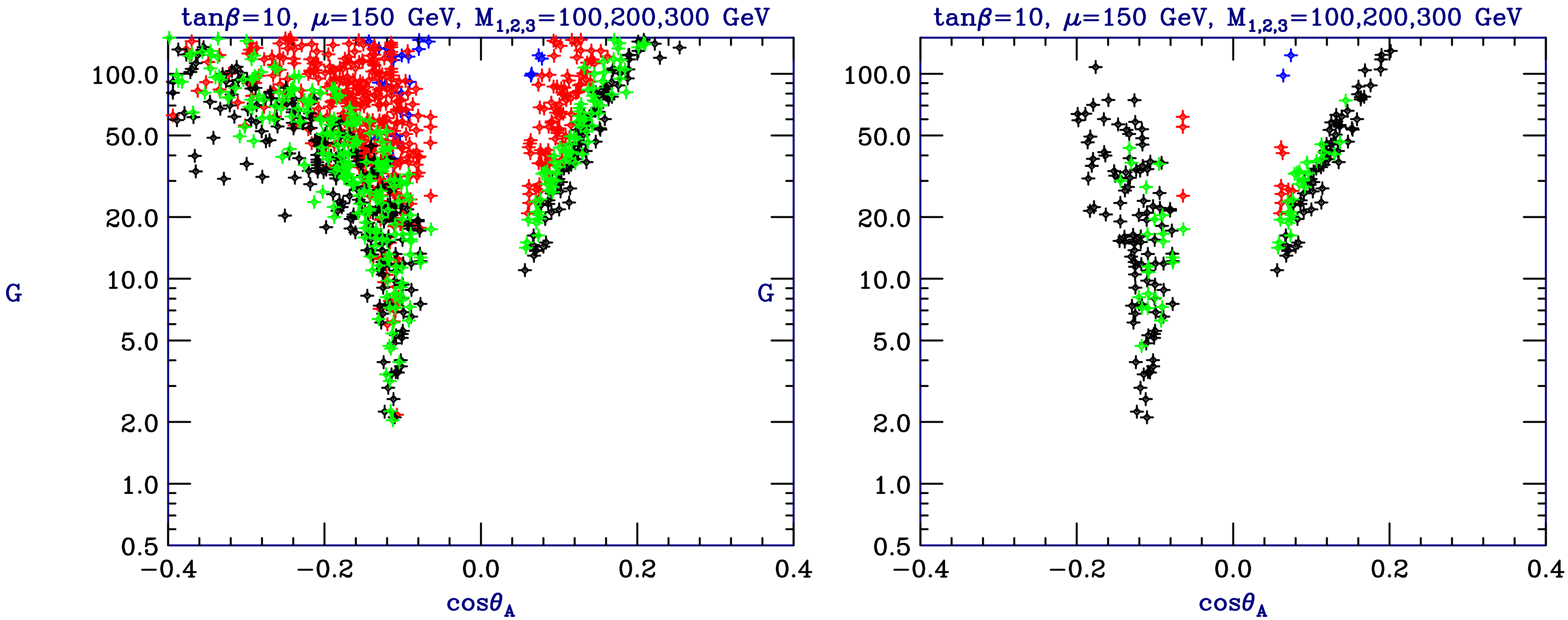


Figure 6: **Results of $\mu = 150$ GeV and $\tan\beta = 10$ scan. Note that many points with low m_{a_1} and large $|\cos\theta_A|$ are eliminated, including almost all the $m_{a_1} < 2m_\tau$ points and most of the $2m_\tau < m_{a_1} < 7.5$ GeV points, leaving mainly 7.5 GeV $< m_{a_1} < 8.8$ GeV and 8.8 GeV $< m_{a_1} < 10$ 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 $\Upsilon_{3S} \to \gamma\mu^+\mu^-$ limits single out the $m_a > 7.5$ 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 $2m_\tau < m_a < 2m_B$.

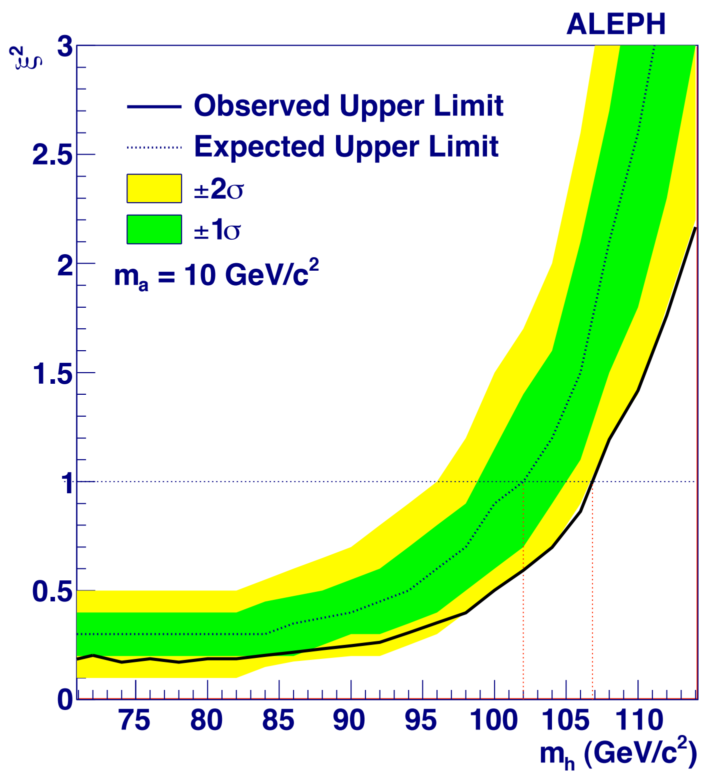
Of course, the Tevatron and LHC *can* probe $m_a < 2m_\tau$:

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.**

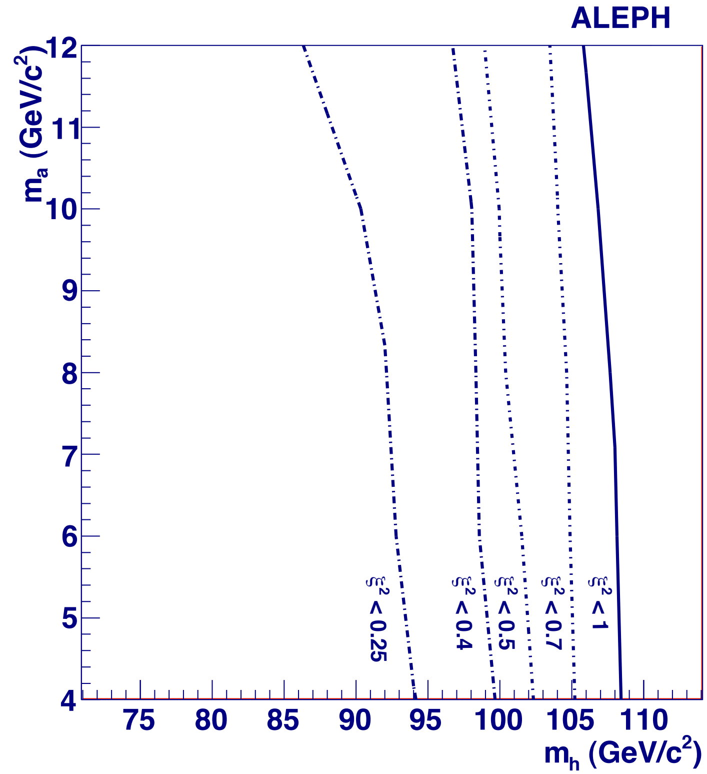
Studies of $m_a < 2m_\tau$ cases at hadron colliders are worth pursuing since they might completely eliminate all such NMSSM ideal Higgs scenarios, irrespective of G.

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

- **In fact, results from ALEPH further shift the focus to high m_a in the NMSSM context.**



(a)



(b)

But, notice the huge difference between expected and observed limits.

- **Comparison to NMSSM ideal scenarios:**

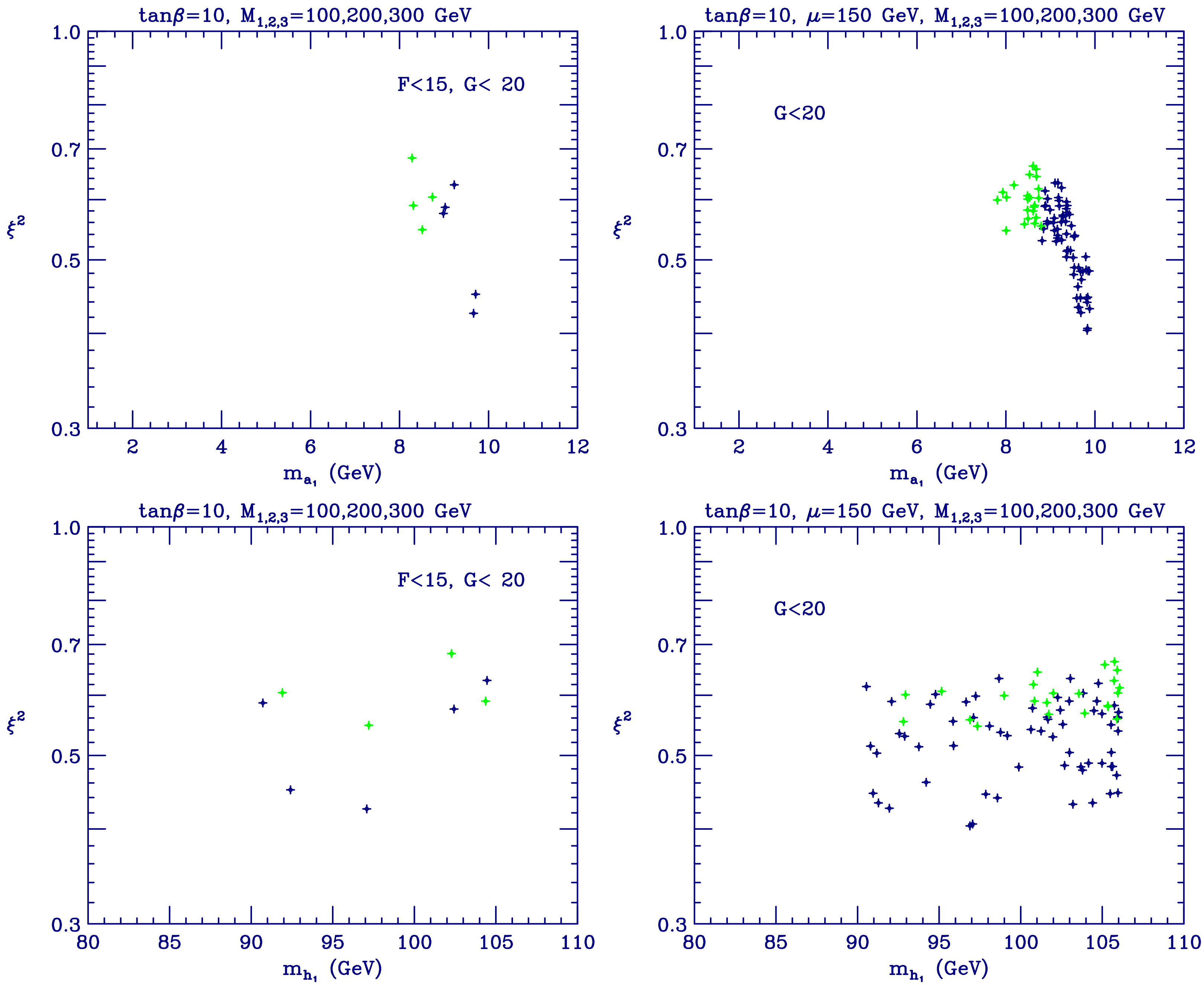


Figure 7: ξ^2 vs. m_{a_1} and m_{h_1} for $\tan\beta = 10$; $|\cos\theta_A| < \cos\theta_A^{\max}$; general scan and fixed μ scan.

What actually survives ALEPH limits?

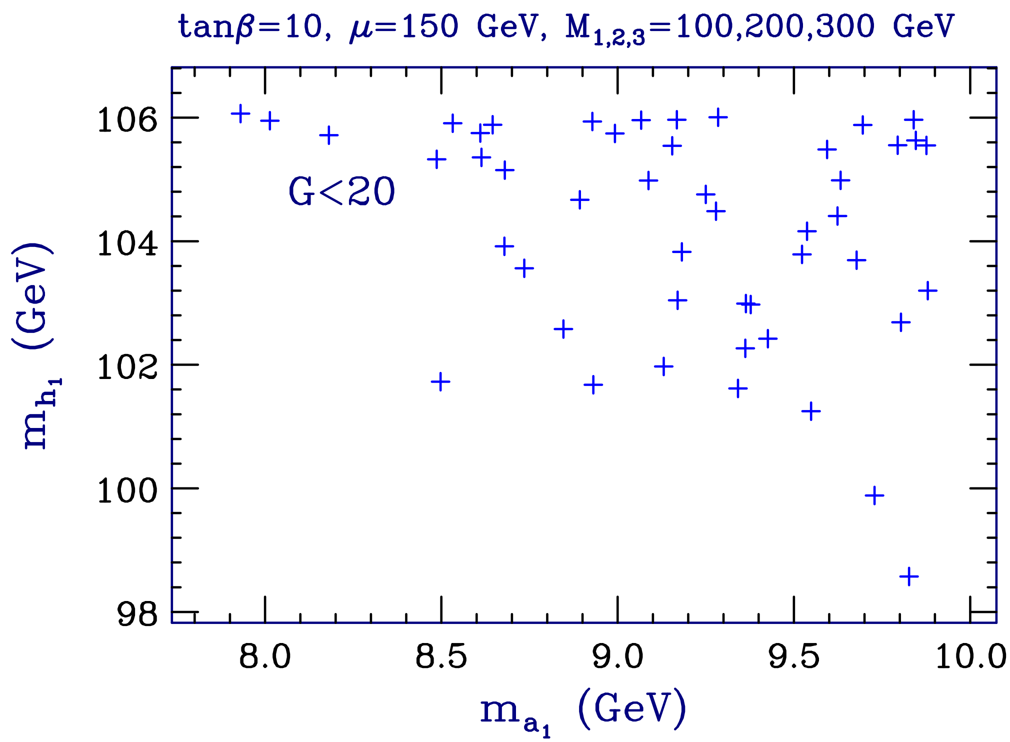


Figure 8: Points with $G < 20$ at $\tan\beta = 10$ that survive $|\cos\theta_A|$ and ALEPH limits.

- For $\tan\beta = 3$, no scan points survive the ALEPH limits. m_{h_1} is typically $\lesssim 95$ GeV, for which ALEPH limits are strong.

- For $\tan\beta \leq 2$ one finds that ξ^2 declines significantly, and will escape ALEPH limits more easily.

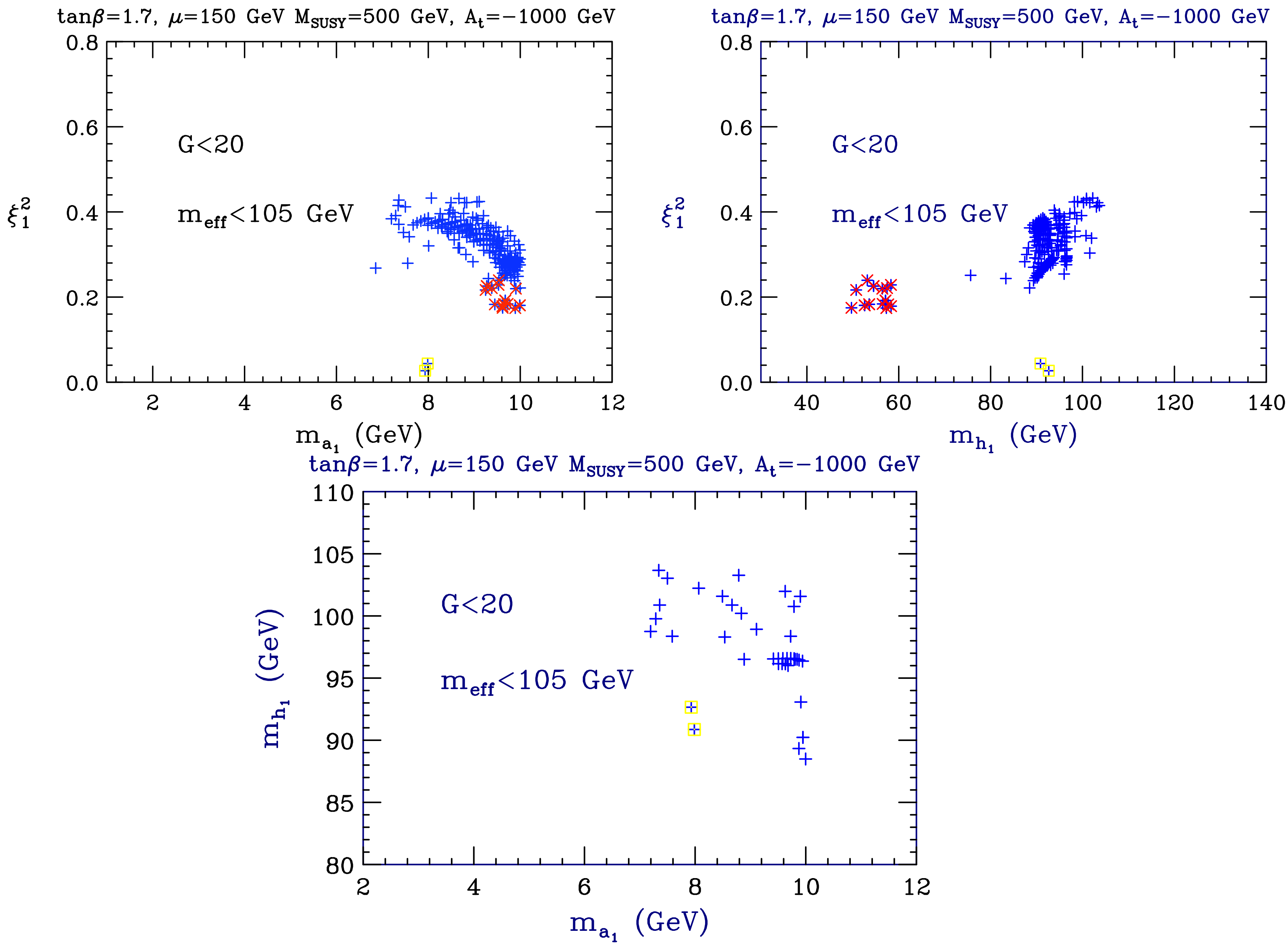


Figure 9: ξ^2 vs. m_{a_1} and m_{h_1} for $\tan\beta = 1.7$; $|\cos\theta_A| < \cos\theta_A^{\max}$, $m_{eff} < 105\,\mathrm{GeV}$. Yellow squares have $B(h_1 \to a_1 a_1) < 0.7$ but still escape usual LEP limits. Also shown are the points that survive the ALEPH limits.

Probing the a at the Tevatron and LHC

- As we have seen, the Upsilon constraints on a light a run out for $m_a > M_{\Upsilon_{3S}} - \delta$. 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 $6.3 < m_\epsilon < 9~\mathrm{GeV}$. The latest CDF limits from $L = 630~\mathrm{pb}^{-1}$ 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 $m_\epsilon = 7.2~\mathrm{GeV}$ 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 $gg \rightarrow ag$) are, however, very significant.

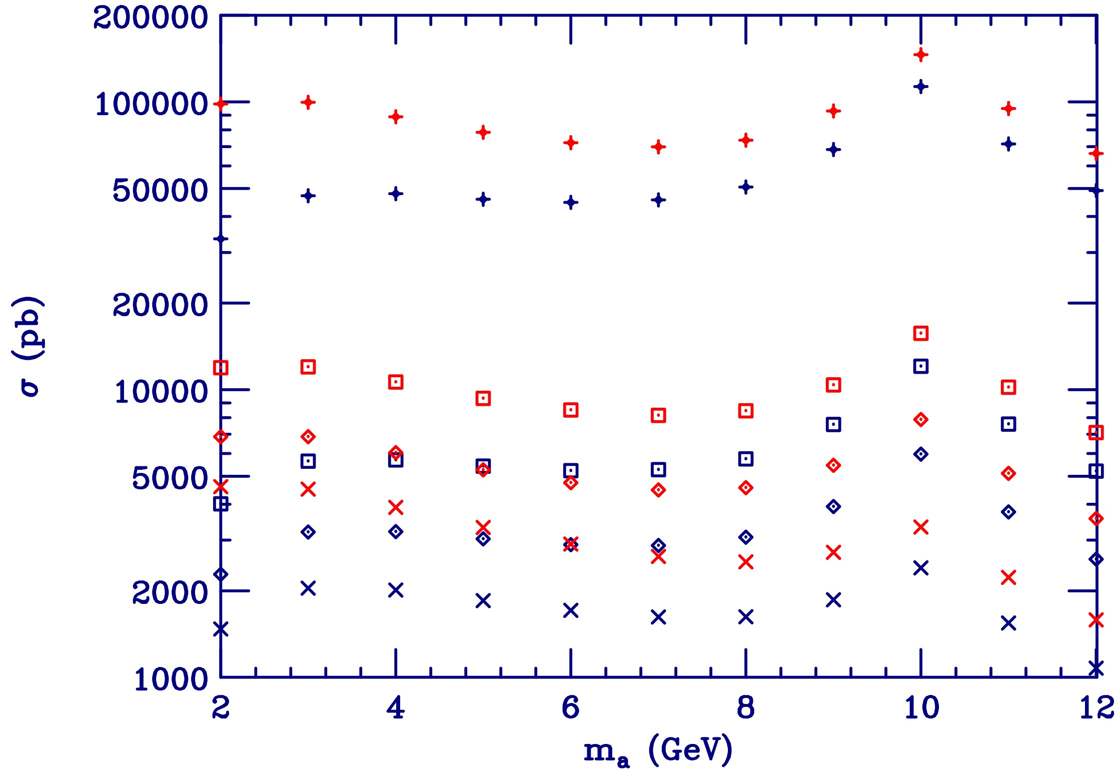


Figure 10: Tevatron cross sections for $\tan\beta = 1, 2, 3, 10$ (lowest to highest point sets). For each m_a and $\tan\beta$ value, the lower (higher) point is the cross section without (with) resolvable parton final state contributions.

  - We then include: $B(a \rightarrow \mu^+\mu^-) \sim 0.002 - 0.003$; efficiencies after imposing μ isolation cuts needed to reduce the heavy flavor background (Drell-Yan background is much smaller).

Putting it all together gives:

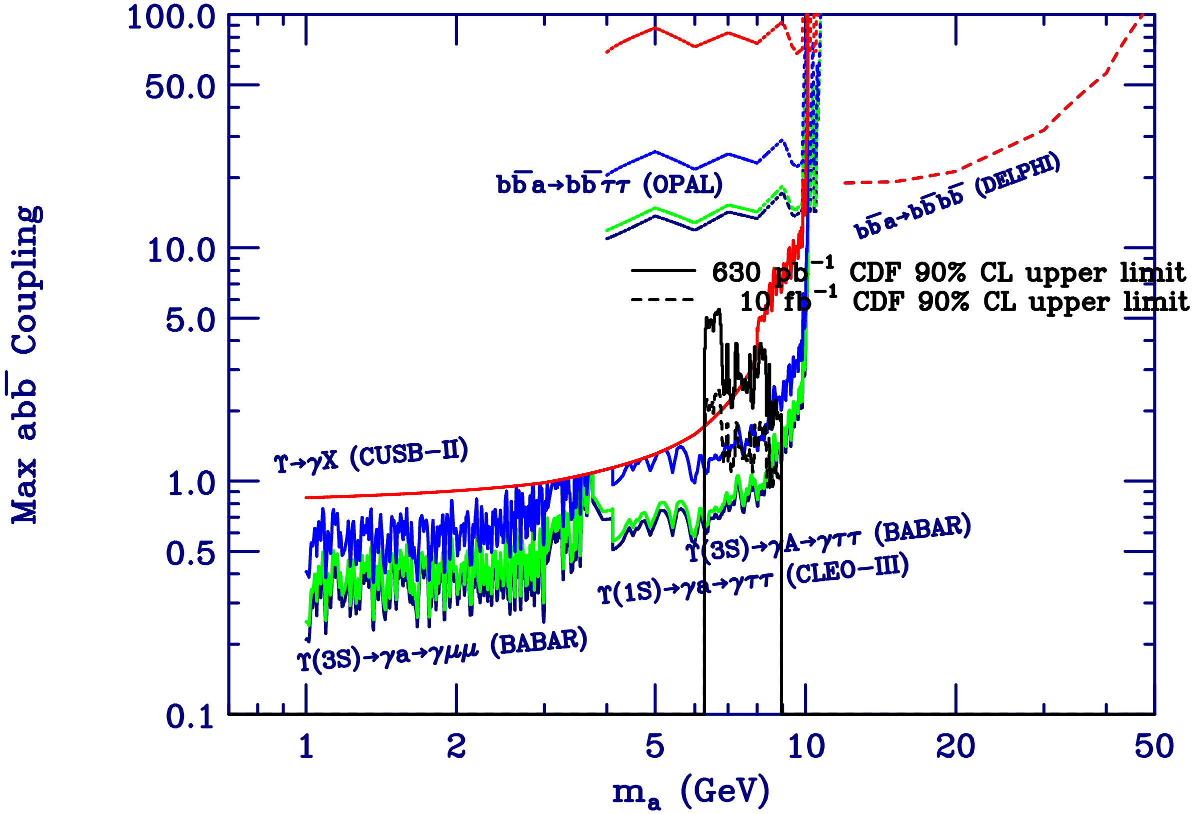


Figure 11: Tevatron limits (roughly $\tan\beta$-independent for $\tan\beta > 2$) compared to previous plot limits for $\tan\beta = 0.5$, 1, 2, ≥ 3.

For $M_{\mu^+\mu^-} > 9$ 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.

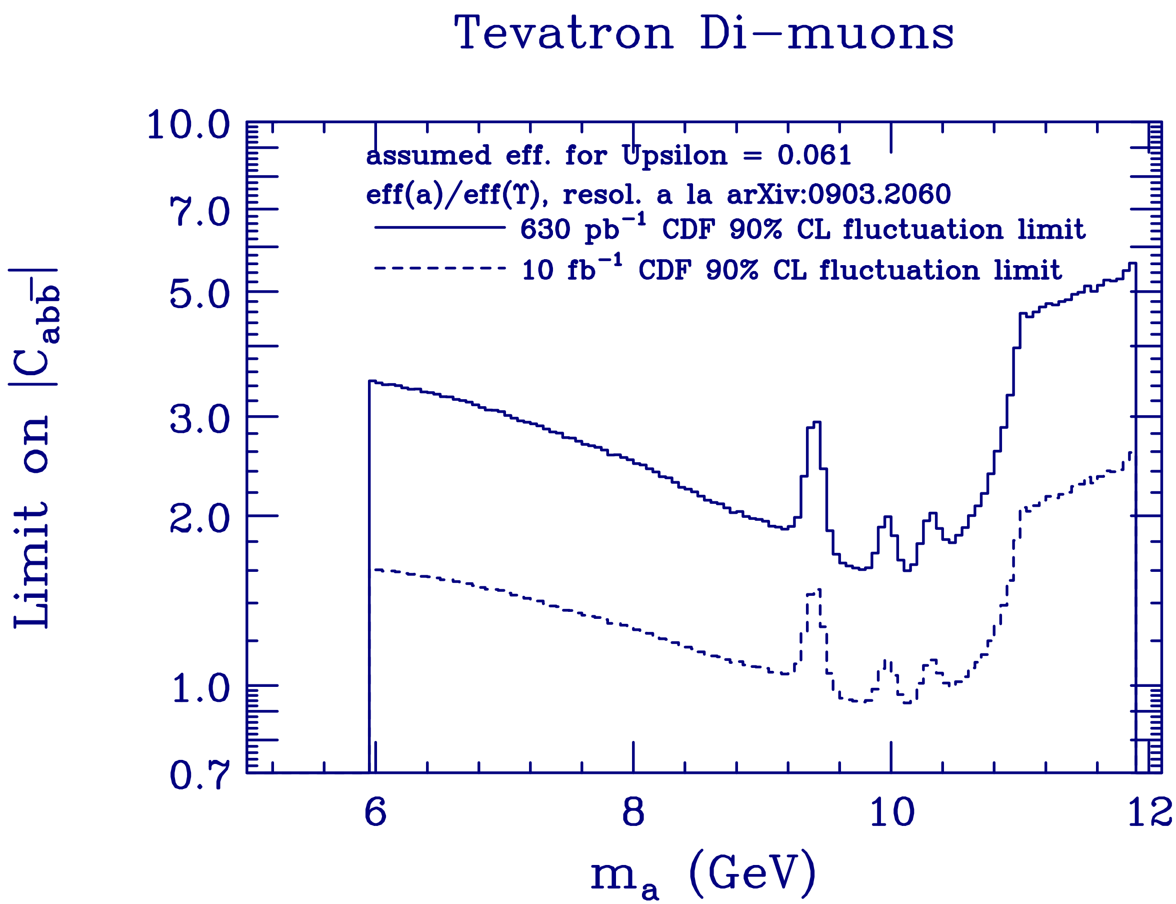


Figure 12: $L = 630\ \mathrm{pb}^{-1}$ and $10\ \mathrm{fb}^{-1}$ limits based on no 1.686σ excess in optimal interval. They are $\tan\beta$-independent for $\tan\beta > 2$.

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 $m_a = 10$ GeV and $\tan\beta = 10$, one finds $\sigma_{NLO}(1.96, 7, 10, 14\ \mathrm{TeV}) \sim 1.5\times10^5, 5\times10^5, 7\times10^5, 9\times10^5$ pb.

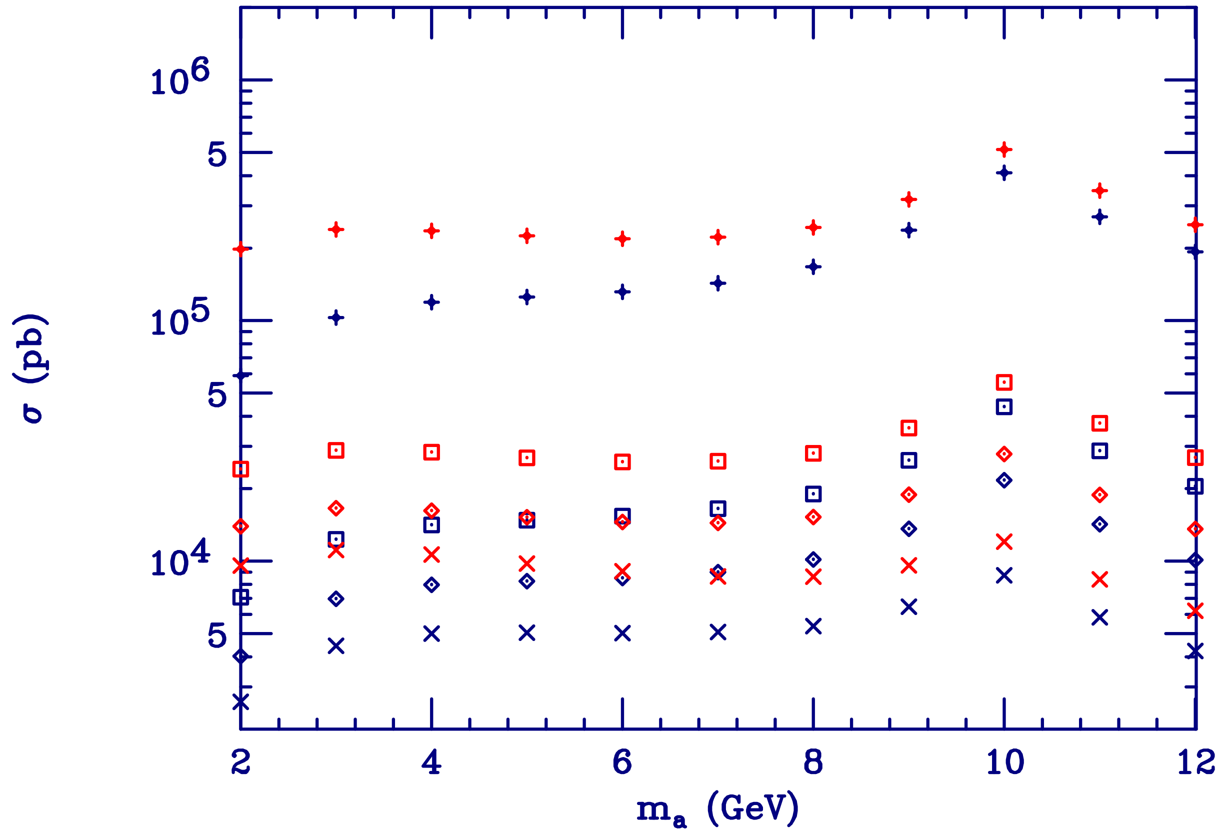


Figure 13: LHC, $\sqrt{s} = 7$ TeV cross sections for $\tan\beta = 1, 2, 3, 10$ (lowest to highest point sets). Factor of about $3\times$Tevatron at higher m_a.

There have been studies of the Upsilon and backgrounds by CMS and ATLAS, but only ATLAS has presented public results — see Fig. 14.

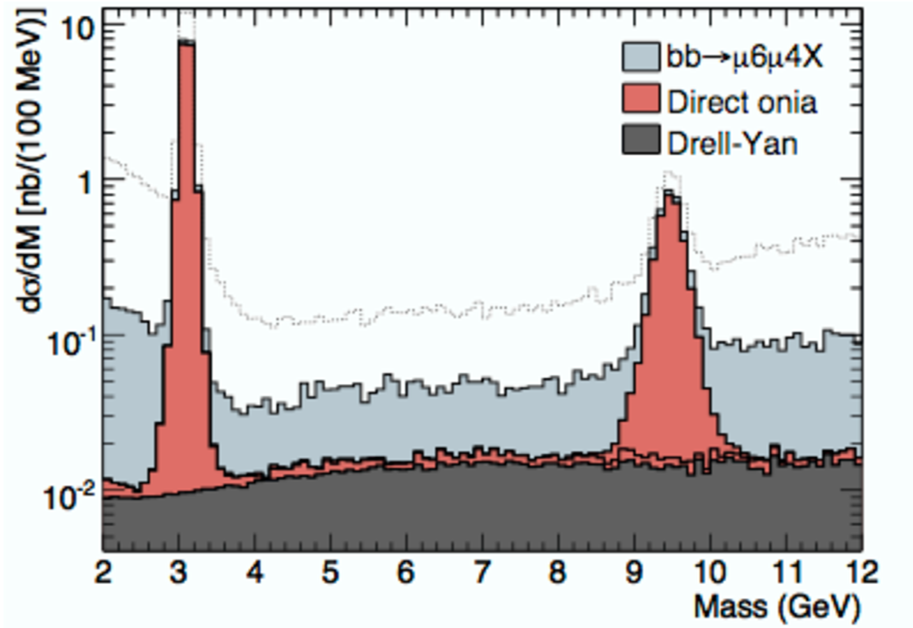


Figure 14: ATLAS dimuon spectrum prediction after corrections for acceptance and efficiencies (D. D. Price, arXiv:0808.3367 [hep-ex].).

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. 14 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. 14 we need to know 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. 14. We term this efficiency ϵ_{ATLAS}. An ATLAS MC gives $\epsilon_{ATLAS} = 0.1$. We write

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

- Also, Fig. 14 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 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 events in an interval of total width $\Delta M_{\mu^+\mu^-} = 2\sqrt{2}\sigma_r$ (the interval that maximizes $S/\sqrt{B}$).

- 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).

  Including ϵ_{ATLAS}, the bin acceptance factor of $Erf(1) = 0.8427$ for the ideal interval being employed, and multiplying by $(\cos\theta_A)^2$ we obtain the following results.

Table 1: Luminosities (fb^{-1}) needed for 5σ if $\tan\beta = 10$ and $\cos\theta_A = 0.1$.

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

The required L's away from the Upsilon resonance may be achieved after a year or two of LHC operation. Can r be improved?

CMS?

- Working subgroup: chiara mariotti, max chertok, maria assunta borgia, pietro govoni, leonard di matteo, mario pelliccioni and me.
- I cannot give details (except to CMS members) but I will summarize the basic conclusions.
- At higher $\tan\beta \geq 2$, $L = 10~\mathrm{fb}^{-1}$ may be sufficient to cover all the NMSSM points.
- 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.

Another way of thinking about what the LHC will achieve is in terms of the $|\cos\theta_A|$ limits as discussed earlier.

One finds that the LHC wins over BaBar starting with $m_a \gtrsim 8~\mathrm{GeV}$.

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** $B(h \to aa)$.

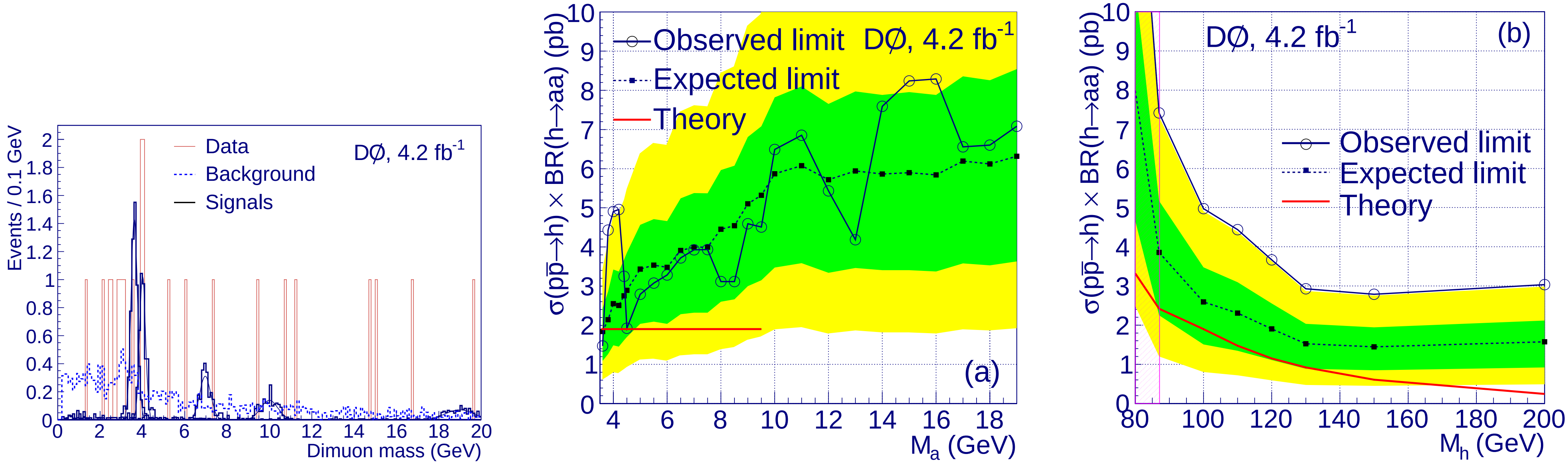
The possible new LHC channels include:

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:**

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

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

$$\sigma(gg \to h)B(h \to aa)[B(a \to \mu^+\mu^-]^2\epsilon > (153 \text{ fb}) \times \epsilon\,. \tag{7}$$

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. 15 for a variety of luminosity and triggering assumptions.

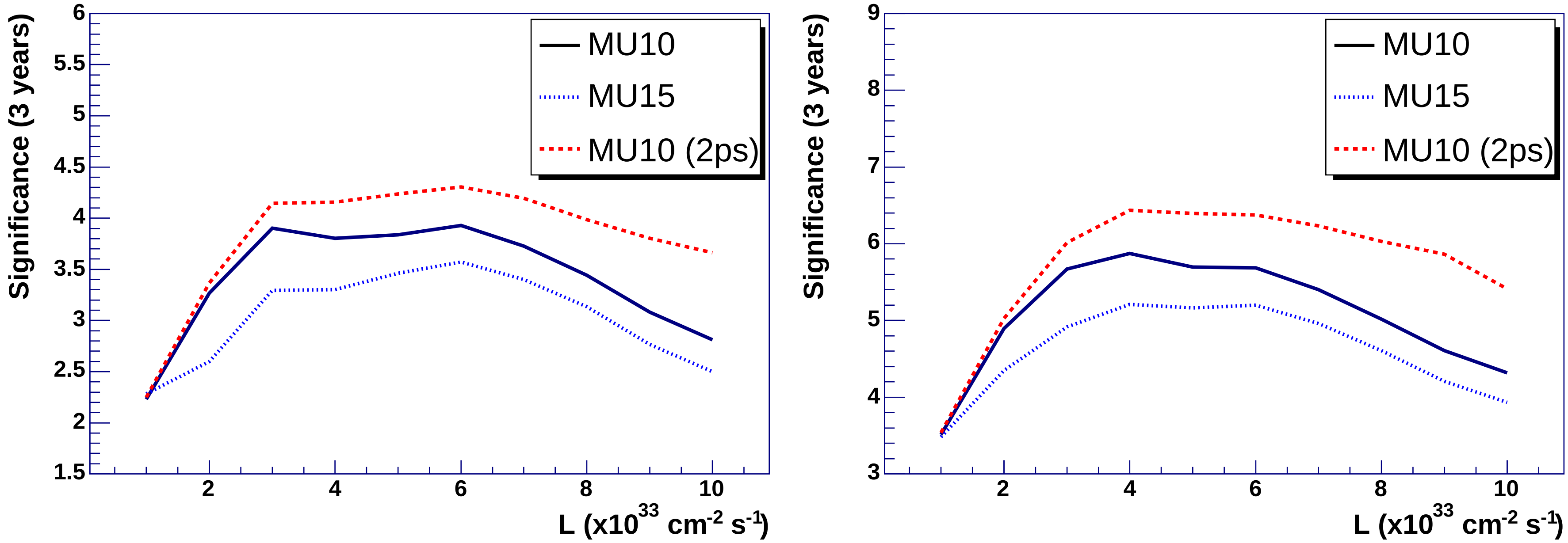


Figure 15: (a) The significance for three years of data acquisition at each luminosity. (b) Same as (a) but with twice the data. Different lines represent different μ trigger thresholds and different forward detector timing. Some experimentalists say more efficient triggering is possible, doubling the 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

$$p_i^{vis} = f_i\, p_{a,i} \quad (8)$$

where $1 - f_i$ is the fraction of the a momentum carried away by neutrals. In the $pp \to pph$ and $WW \to h$ cases there are enough equations to (oversolve in the pph case) for the f_i and determine the masses of both

the h and the a.

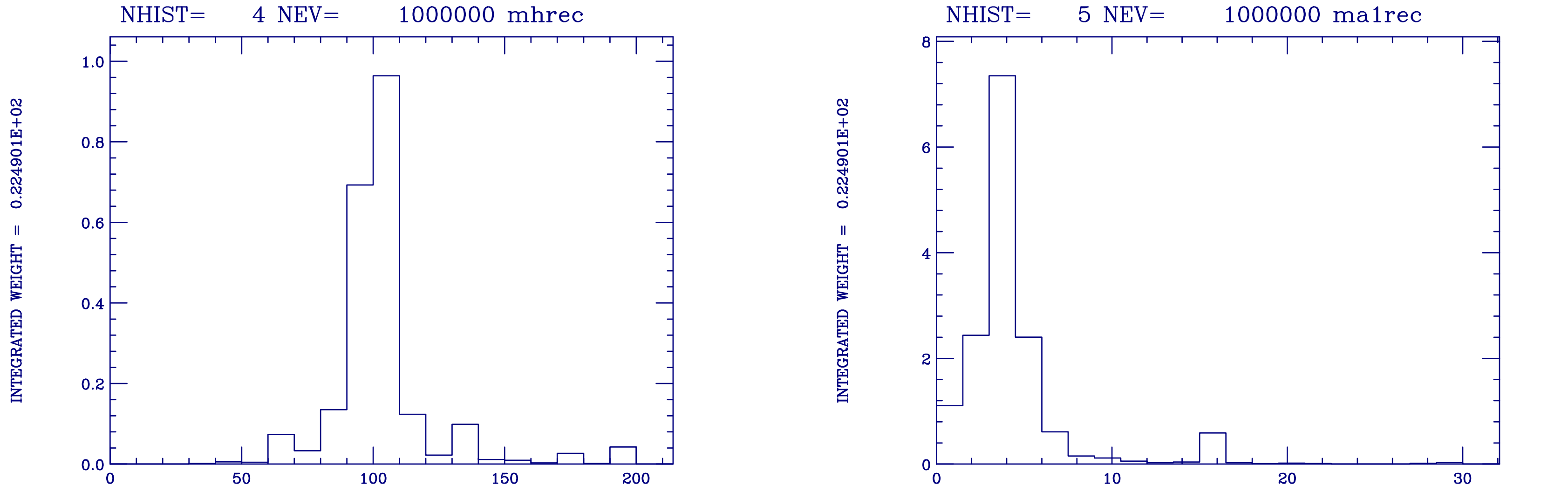


Figure 16: WW **fusion mass reconstruction: (a) A typical** h **mass distribution. (b) A typical** a **mass distribution. No cuts imposed; signal only.**

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

- Much more difficult since $a \to 2j$ is much harder to pick out.

  At low $\tan\beta$, the Higgs is starting to be "buried" by having $h_1 \to a_1 a_1 \to 4j$ decays dominate.

- 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

$$\sigma(gg \to h) B(h \to aa)[2 \times B(a \to \mu^+\mu^-]\epsilon > (70 \text{ fb}) \times \epsilon \,. \tag{9}$$

  for $B(a \to \mu^+\mu^-) > 0.001$ (as applies for $\tan\beta > 1$). If $\epsilon > 0.02$ (seems likely) then $\Rightarrow \sigma_{eff} > 1.4$ 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 $L = 30~\mathrm{fb}^{-1}$ would be needed.

Should be pursued.

- If the Higgs is really buried, then the LHC will still be able to check whether $W_L W_L$ scattering is perturbative or not, but very high L is required.

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

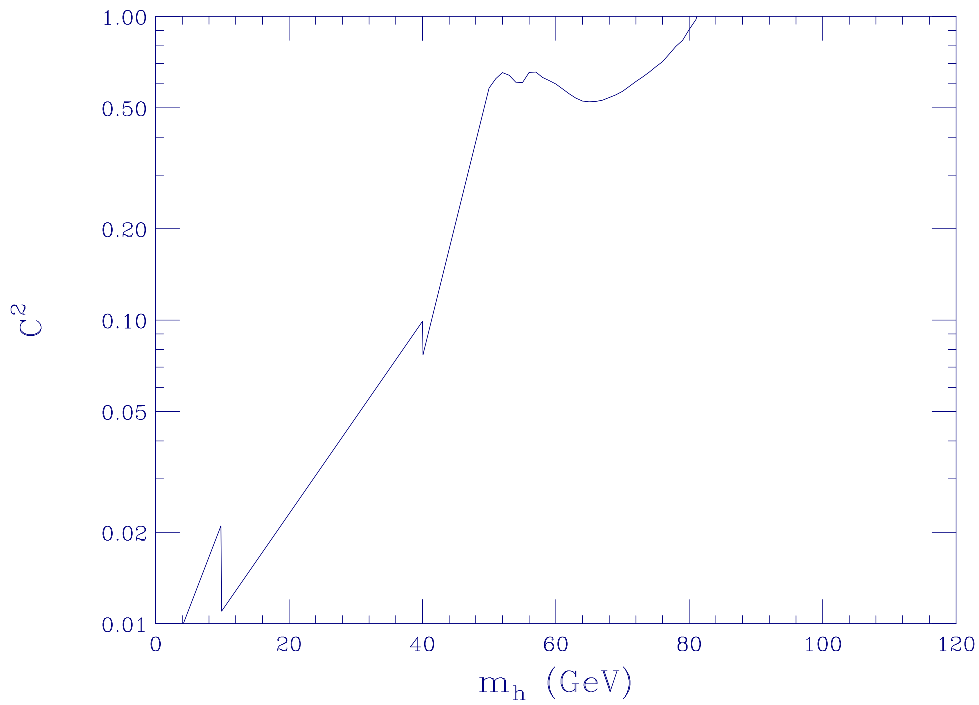
- A string of Higgs, as possibly hinted at by the CDF multi-muon events.

  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.)

- Many singlets, as generically possible in string models, could mix with the doublet Higgs resulting in a series of Higgs mass eigenstates, h_i with masses m_i.

  These states can be easily arranged to have $m_{eff} < 105~\mathrm{GeV}$ for PEW perfection and sufficiently complex decays that they would not have been observed at LEP.

  In fact, one can get really low "effective" Higgs mass, $m_{eff} \lesssim 50~\mathrm{GeV}$, while fitting under the LEP constraint curve for $e^+e^- \to Zh$ where $h \to visible$ ($m_h > 82~\mathrm{GeV}$ for a single h with SM ZZ coupling).



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

- **At any e^+e^- (or $\mu^+\mu^-$) collider with $\sqrt{s} > 250$ GeV the process $e^+e^- \to ZX$ will reveal a $M_X \sim m_h \sim 90-100$ GeV peak no matter how the h**

decays so long as $g^2_{ZZh} \gtrsim 0.05 g^2_{ZZh_{\rm SM}}$, assuming $L > 100~\mathrm{fb}^{-1}$.

- In fact, for adequate L and $\sqrt{s} \gtrsim 200~\mathrm{GeV}$ the ILC will make it possible to detect a series of Higgs bosons or even a continuum given that the PEW limit of $m_{eff} < 157~\mathrm{GeV}$ (or in ideal case, $< 105~\mathrm{GeV}$) restricts the mass range over which Higgs with ZZ coupling can be present.

  If the Higgs are discrete bumps then $L = 100~\mathrm{fb}^{-1}$ will reveal the various Higgs eigenstates.

  If the Higgs are sufficiently closely spaced to effectively (within resolution) form a continuum, then $L \gtrsim 500~\mathrm{fb}^{-1}$ will be needed to ascertain the presence of excesses in various bins of M_X, independent of the final states X in which the excesses are present. (JFG+Espinosa).

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".

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