NMSSM Higgs at the HPS: update

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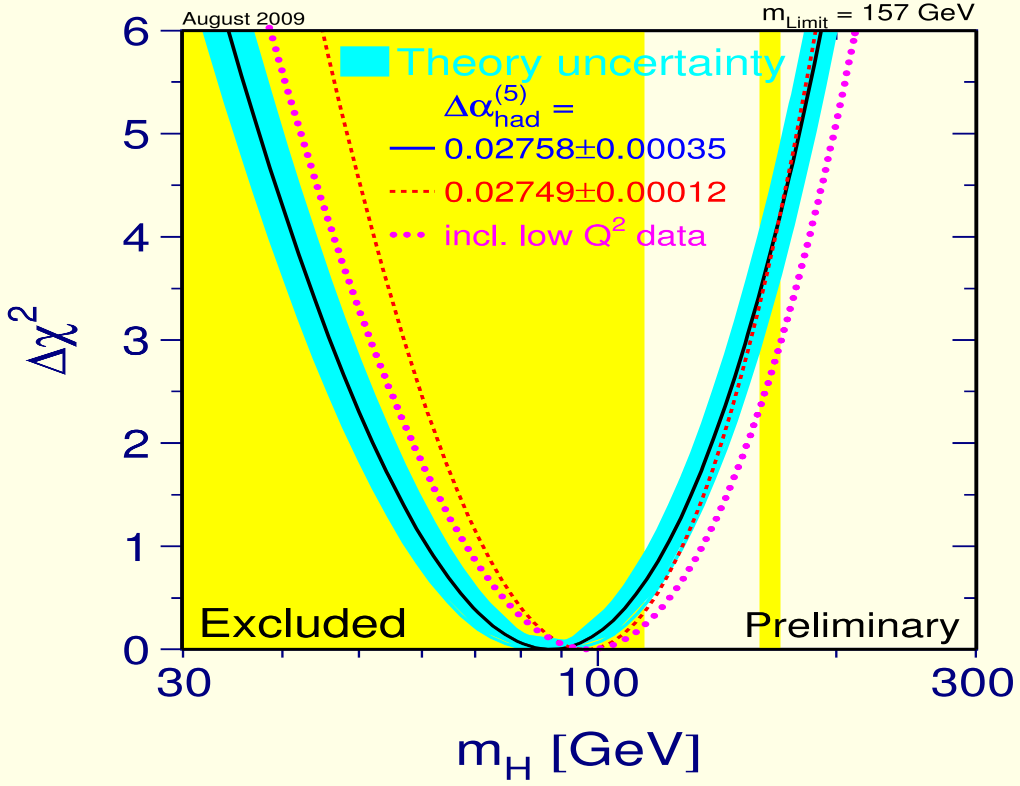
Synopsis/Outline

There are excellent motivations for the Higgs to have orthodox couplings to SM particles but heretical 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.**
- **Orthodox 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.**
- **Some slightly heretical SUSY models, including the NMSSM (which preserves all good MSSM features and solves the μ problem) give very heretical decay scenarios not ruled out by LEP for lighter Higgs mass.**
- **LHC strategies for Higgs searches will need to be unorthodox.**

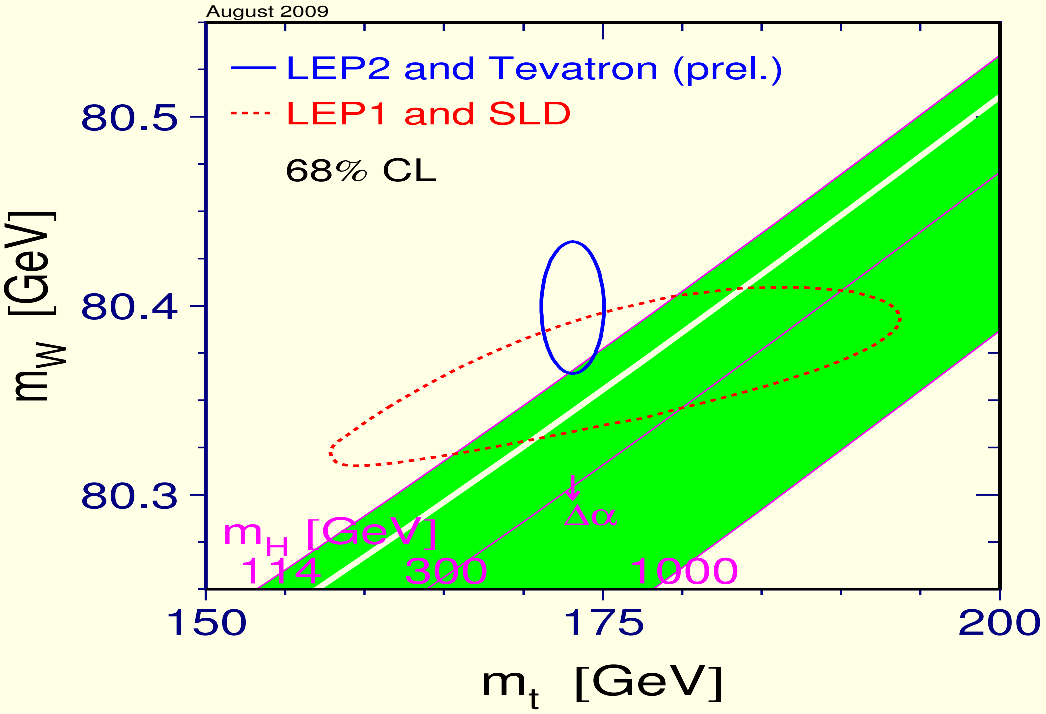
Motivation for Non-Standard Decays — single H

- 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 $m_{h_{\rm SM}} \sim 100~{\rm GeV}$.



However, 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).

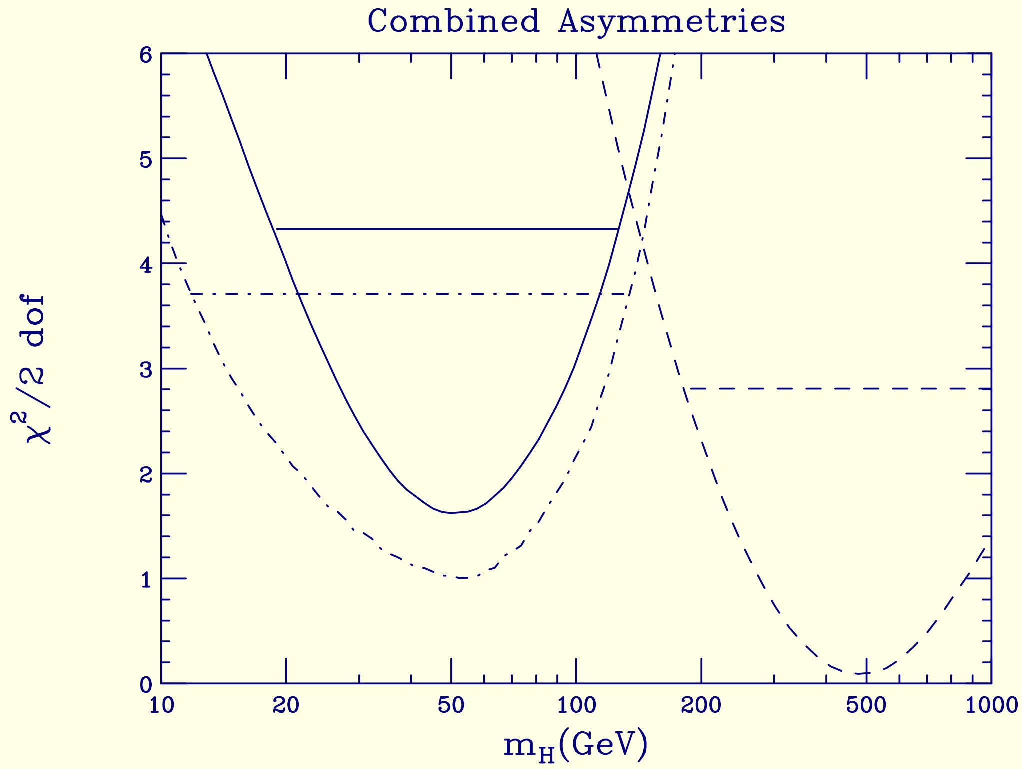


Figure 1: χ^2 distributions as a function of m_H from the combination of the three leptonic asymmetries A_{LR}, A^{ℓ}_{FB}, $A_{\ell}(P_{\tau})$ (solid line); the three hadronic asymmetries A^b_{FB}, A^c_{FB}, and Q_{FB} (dashed line); and the three m_H-sensitive, nonasymmetry measurements, m_W, Γ_Z, 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 $105~\mathrm{GeV}$.**

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

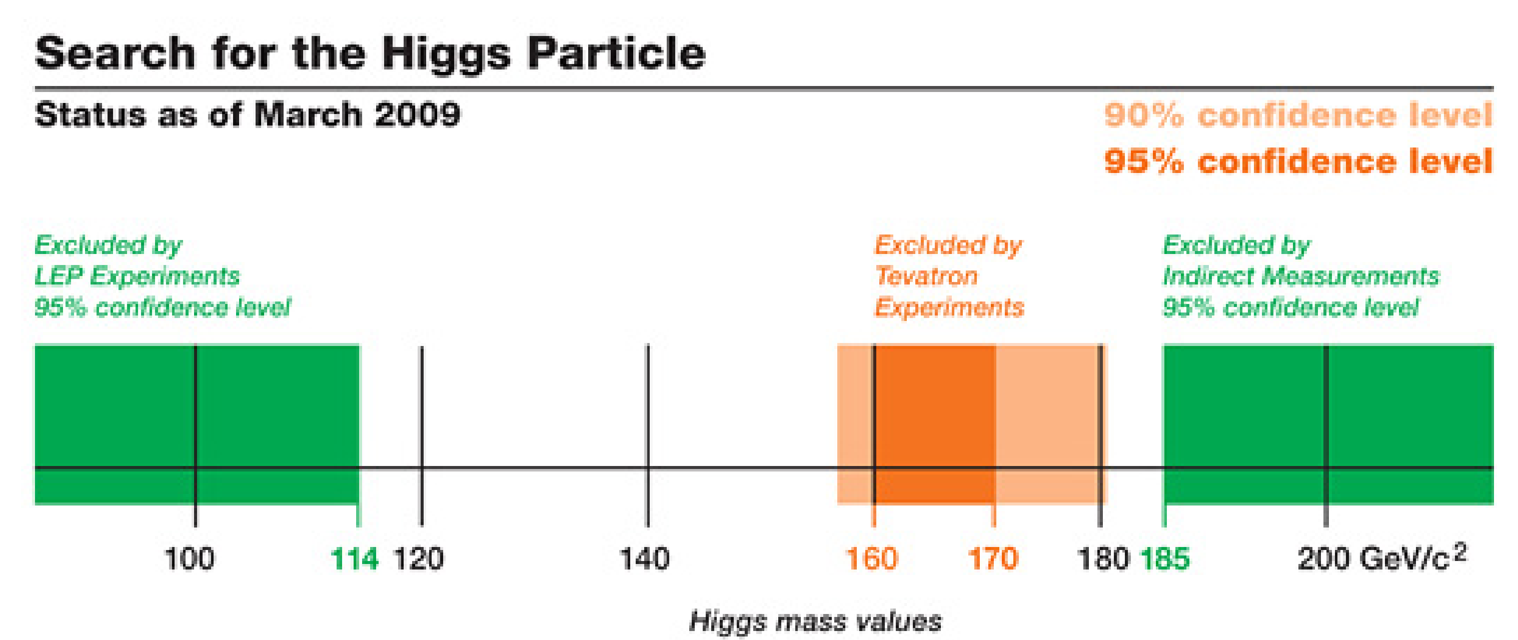


Table 1: LEP m_H Limits for a H with SM-like ZZ coupling, but varying decays. See (S. Chang, R. Dermisek, J. F. Gunion and N. Weiner, Ann. Rev. Nucl. Part. Sci. 58, 75 (2008) [arXiv:0801.4554 [hep-ph]]).

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

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

Sensitivity to these peculiar modes by typical LHC search techniques is quite uncertain.

$pp \rightarrow pph$ seems to be one of the more useful approaches.

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

  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.

- **This is precisely what emerges in the NMSSM after evolving down to m_Z**

from the $U(1)_R$ symmetry limit of $A_\lambda, A_\kappa \to 0$ at M_U.

- **And the NMSSM is an even more attractive SUSY model than the MSSM.**

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 $m_{h_1} \sim 90 - 100~{\rm GeV}$ is allowed because of $h_1 \to a_1a_1$ decays with $m_{a_1} < 2m_b$:

(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 ($\sim \mathbf{350}\ \mathrm{GeV}$ is just right) . Also need $m_{\widetilde{g}}$ not too far above $\mathbf{300}\ \mathrm{GeV}$.

(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_1 with large $B(h_1 \to a_1 a_1)$ and $m_{a_1} < 2m_b$ 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_1 properties. (R. Dermisek and J. F. Gunion, Phys. Rev. D 75, 075019 (2007) [arXiv:hep-ph/0611142].)

The a_1 is largely singlet ($e.g.$10% at amplitude level if $\tan\beta \sim 10$) and $\sim 7\ \mathrm{GeV} \lesssim m_{a_1}$ (but below $2m_b$) in the best cases.

Predictions regarding a light a and the NMSSM a_1

- **Define the mass eigenstate:** $a_1 = \cos\theta_A a_{MSSM} + \sin\theta_A a_S$.

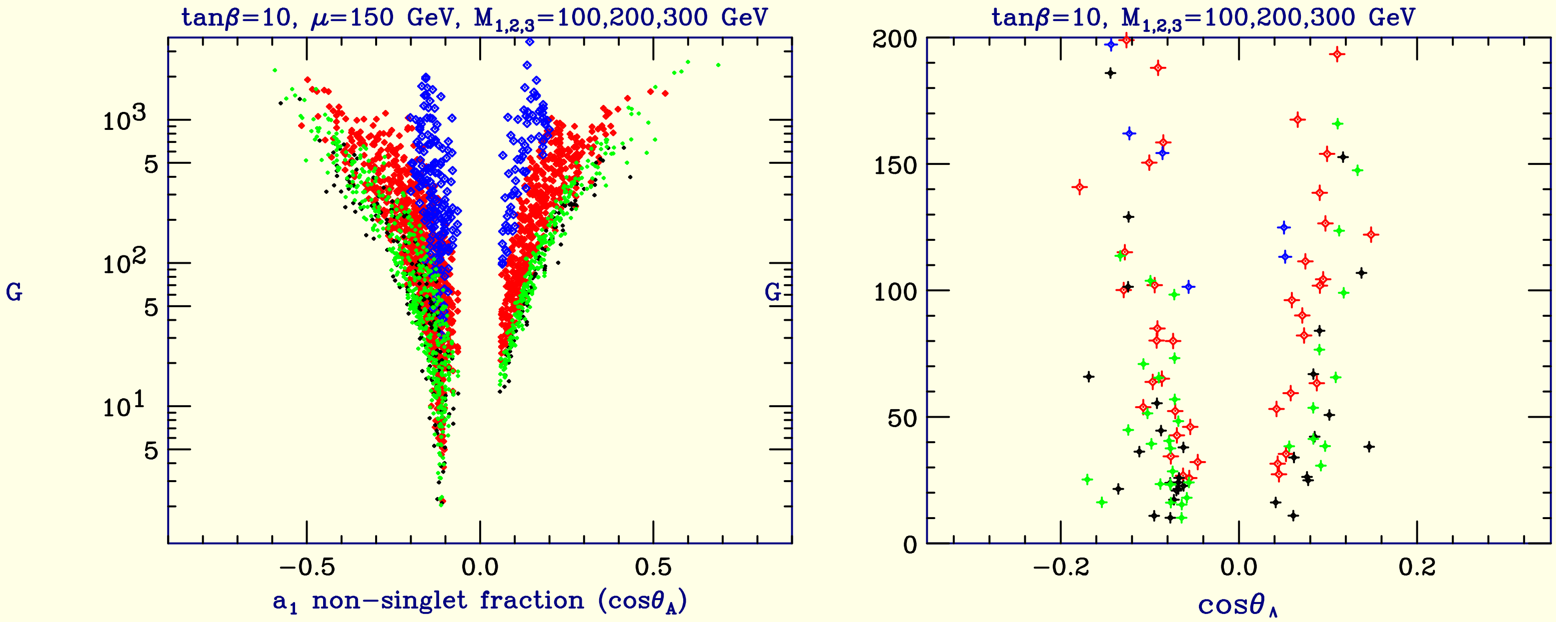


Figure 2: G vs. $\cos\theta_A$ for $M_{1,2,3} = 100, 200, 300~\mathrm{GeV}$ and $\tan\beta = 10$ from $\mu_{\rm eff} = 150~\mathrm{GeV}$ scan (left) and for points with $F < 15$ (right) having $m_{a_1} < 2m_b$ and large enough $B(h_1 \to a_1 a_1)$ to escape LEP limits. The color coding is: blue $= m_{a_1} < 2m_\tau$; red $= 2m_\tau < m_{a_1} < 7.5~\mathrm{GeV}$; green $= 7.5~\mathrm{GeV} < m_{a_1} < 8.8~\mathrm{GeV}$; and black $= 8.8~\mathrm{GeV} < m_{a_1} < 9.2~\mathrm{GeV}$.

- **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_1" fine tuning) in order to achieve required a_1 properties of $m_{a_1} < 2m_b$ *and* $B(h_1 \to a_1 a_1) > 0.7$. The plot of G vs. $\cos\theta_A$ shows a strong preference for $m_{a_1} > 7.5~\mathrm{GeV}$ and $\cos\theta_A \lesssim 0.1$ (for $\tan\beta = 10$). Note the strict lower bound on $\cos\theta_A$ needed for $B(h_1 \to a_1 a_1) > 0.7$.

- Define a generic coupling to fermions by

$$\mathcal{L}_{af\bar f} \equiv i C_{af\bar f} \frac{i g_2 m_f}{2 m_W} \bar f \gamma_5 f a\,, \quad \text{then} \quad C_{ab\bar b} = \cos\theta_A \tan\beta \qquad (1)$$

- The extracted $C_{ab\bar b}$ limits (JFG+Dermisek, in preparation; JFG, arXiv:0808.2509; see also Ellwanger and Domingo, arXiv:0810.4736) are quite $\tan\beta$-independent so long as $\cos\theta_A \lesssim 0.3$.

  However, they do not approach the $C_{ab\bar b} \lesssim .5$ region typical of the preferred Higgs scenarios.

  One needs to achieve limits of $C_{ab\bar b} < 0.3$ to rule out the a_1 of the $C_{ab\bar b} = \cos\theta_A \tan\beta \lesssim 1$ (a number which applies for $\tan\beta > 3$) scenarios preferred to achieve small light-a_1 finetuning.

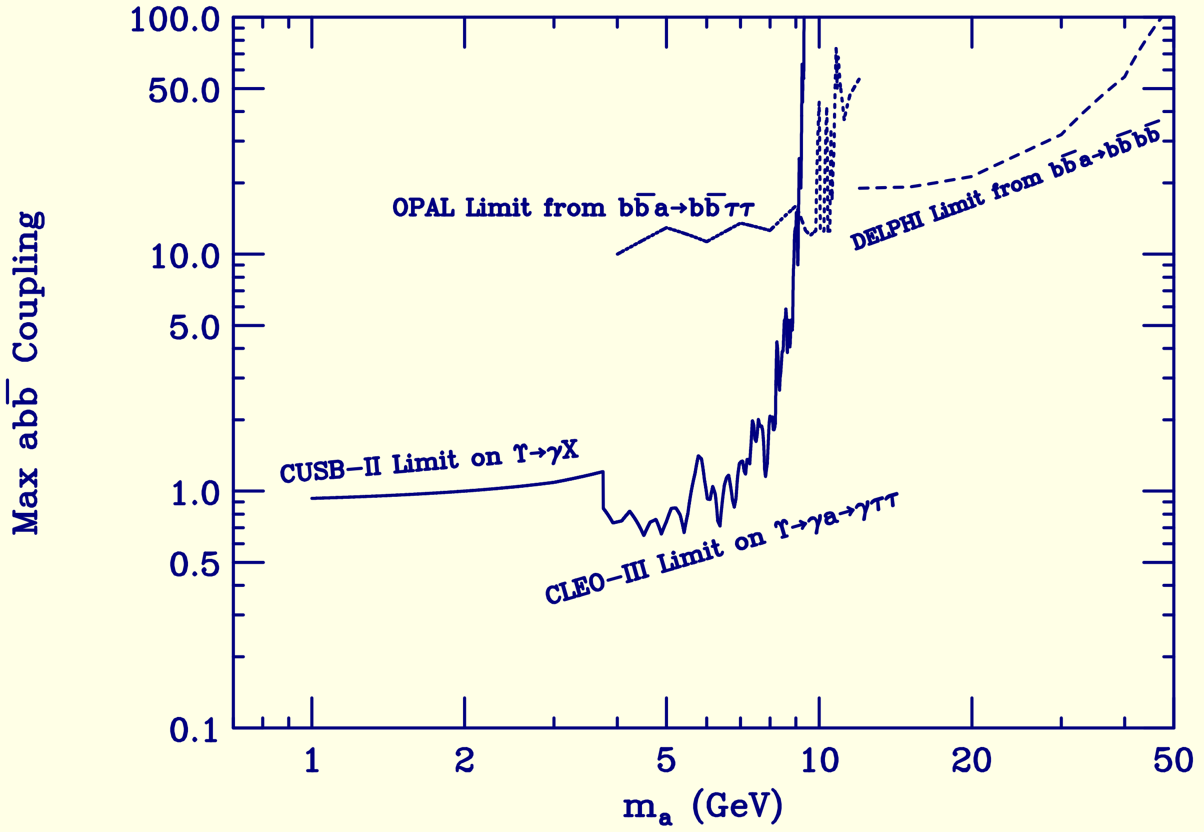


Figure 3: Limits on $C_{ab\bar{b}}$ from JFG, arXiv:0808.2509.

- Further $C_{ab\bar{b}}$ limits (JFG+Dermisek, in preparation) arise from CDF $L = 630~\mathrm{pb}^{-1}$ limits on $R \equiv \sigma(a)B(a \to \mu^+\mu^-)/\sigma(\Upsilon_{1S})B(\Upsilon_{1S} \to \mu^+\mu^-)$ for a narrow a in the $6~\mathrm{GeV} < m_a < 9~\mathrm{GeV}$ region and generically from looking for peaks in the $\mu^+\mu^-$ pair mass spectrum for higher masses..

These are actually the best limits for $m_a > M_\Upsilon$ and imply $C_{ab\bar{b}} \lesssim 2-5$ for $m_a < 12~\mathrm{GeV}$, but are not strong enough to impact the preferred NMSSM scenarios.

If CDF were to analyze $10~\mathrm{fb}^{-1}$ of data, these limits should further improve by a factor of about 2.

In general, searching for a light a is a natural spin-off the the Υ studies already planned for early running.

The LHC experiments should not miss this opportunity.

LHC will probably do better than the Tevatron using just $100~\mathrm{pb}^{-1}$ of data.

ALICE could conceivably do better for this study than either CMS or ATLAS.

- Back to what is directly relevant for the HPS

- $B(a_1 \to \mu^+\mu^-)$ is an interesting quantity. We plot it for $\cos\theta_A \sim 0.1$. Note that it is independent of $\tan\beta$ because all up-type couplings $\propto \cos\theta_A \cot\beta$ are strongly suppressed.

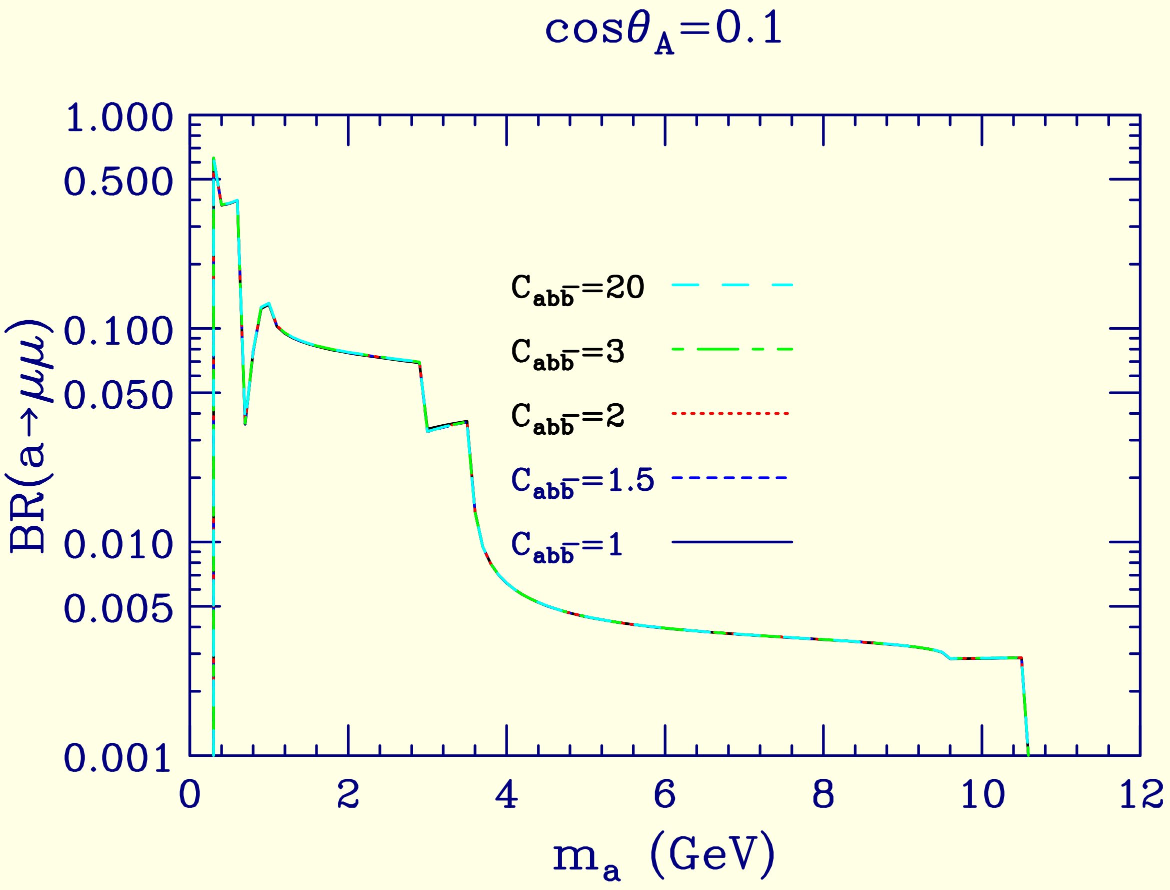


Figure 4: $B(a \to \mu^+\mu^-)$ for preferred $\cos\theta_A \lesssim 0.1$ scenarios.

- In fact, there are now strong BaBar limits on $B(\Upsilon_{3S} \to a\gamma)B(a \to \mu^+\mu^-)$

that become very constraining for $m_a < 2m_\tau$.

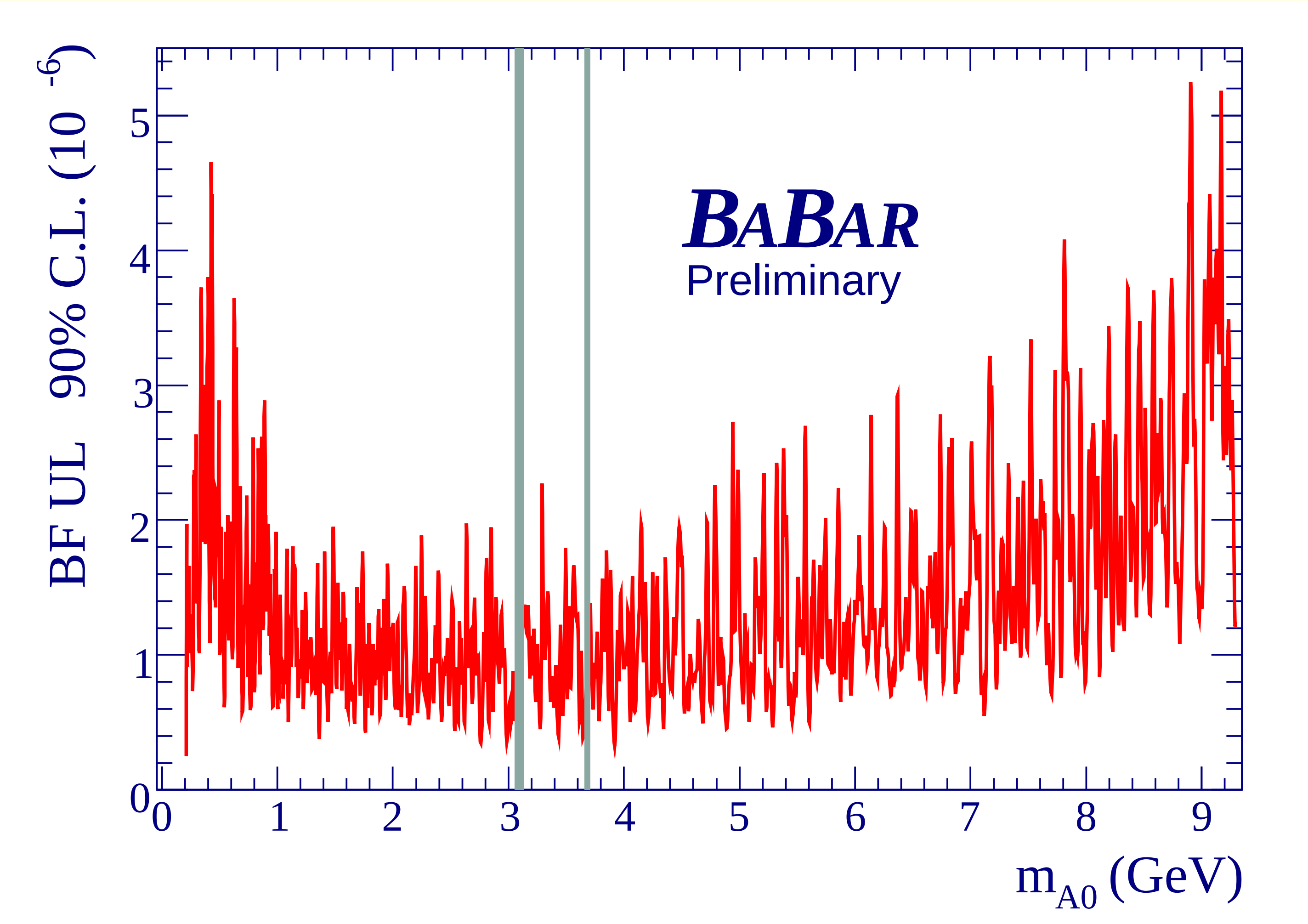


Figure 5: BaBar limits on $B(\Upsilon_{3S} \to \gamma a) B(a \to \mu^+\mu^-)$.

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

A comparison to NMSSM predictions shows that most $m_{a_1} < 2m_\tau$ NMSSM scenarios with $B(h_1 \to a_1 a_1) > 0.7$ are eliminated; only a few at $\tan\beta \lesssim 3$ survive.

In the following plots, we show $B(\Upsilon_{3S} \to \gamma a_1) \times B(a_1 \to \mu^+\mu^-)$ for NMSSM scenarios with various ranges for m_{a_1}: blue = $m_{a_1} < 2m_\tau$; red = $2m_\tau < m_{a_1} < 7.5~\mathrm{GeV}$; light grey (green) = $7.5~\mathrm{GeV} < m_{a_1} < 8.8~\mathrm{GeV}$; and black = $8.8~\mathrm{GeV} < m_{a_1} < 2m_B~\mathrm{GeV}$.

It is the blue points we wish to focus on.

In each case, the left plot comes from an A_λ, A_κ scan holding $\mu_{eff}(m_Z) = 150~\mathrm{GeV}$ ($= 152~\mathrm{GeV}$ for $\tan\beta = 3$) fixed.

The right plot shows results for $F < 15$ scenarios with $m_{a_1} < 2m_B$.

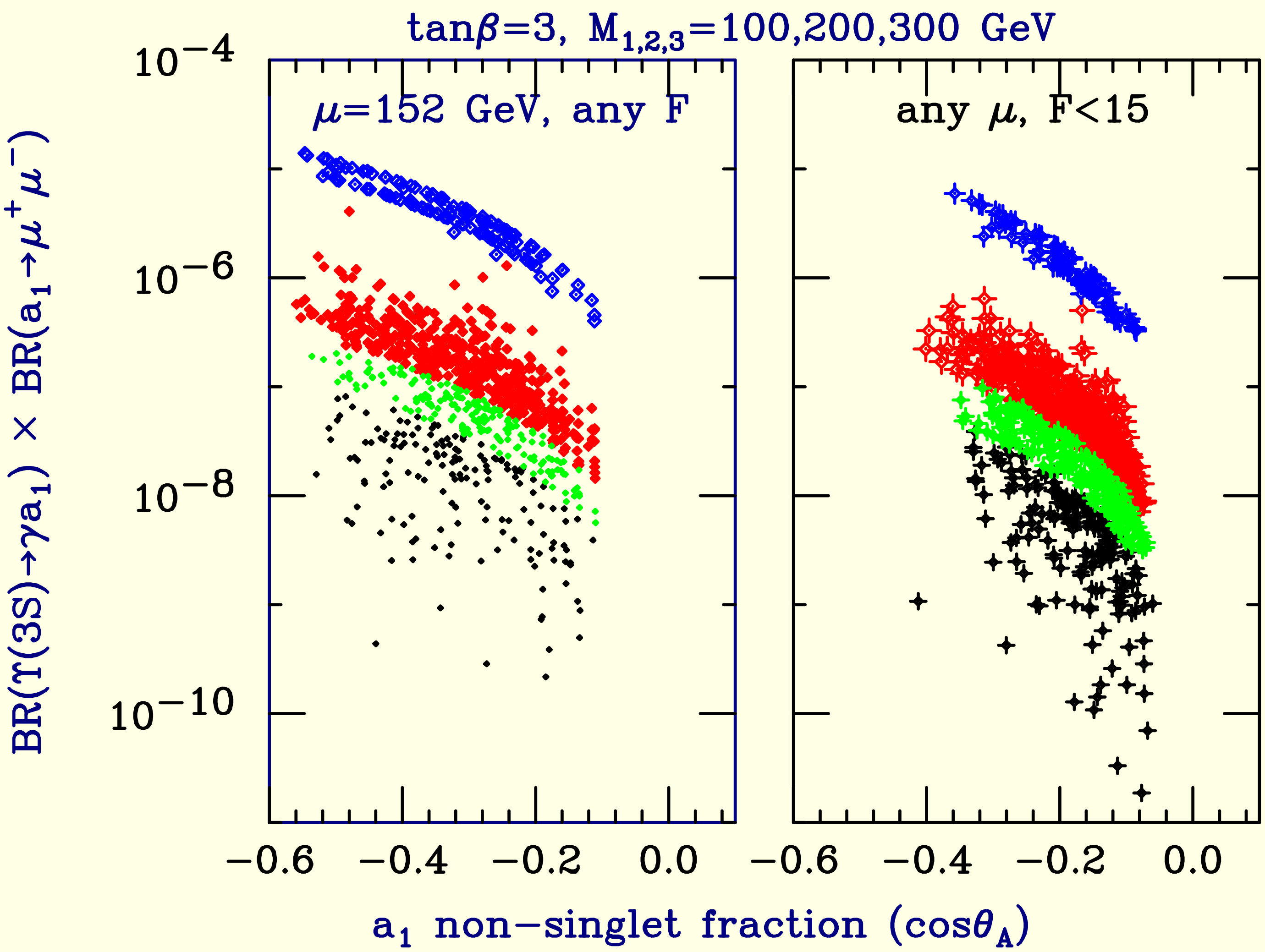


Figure 6: Results for $\tan\beta = 3$.

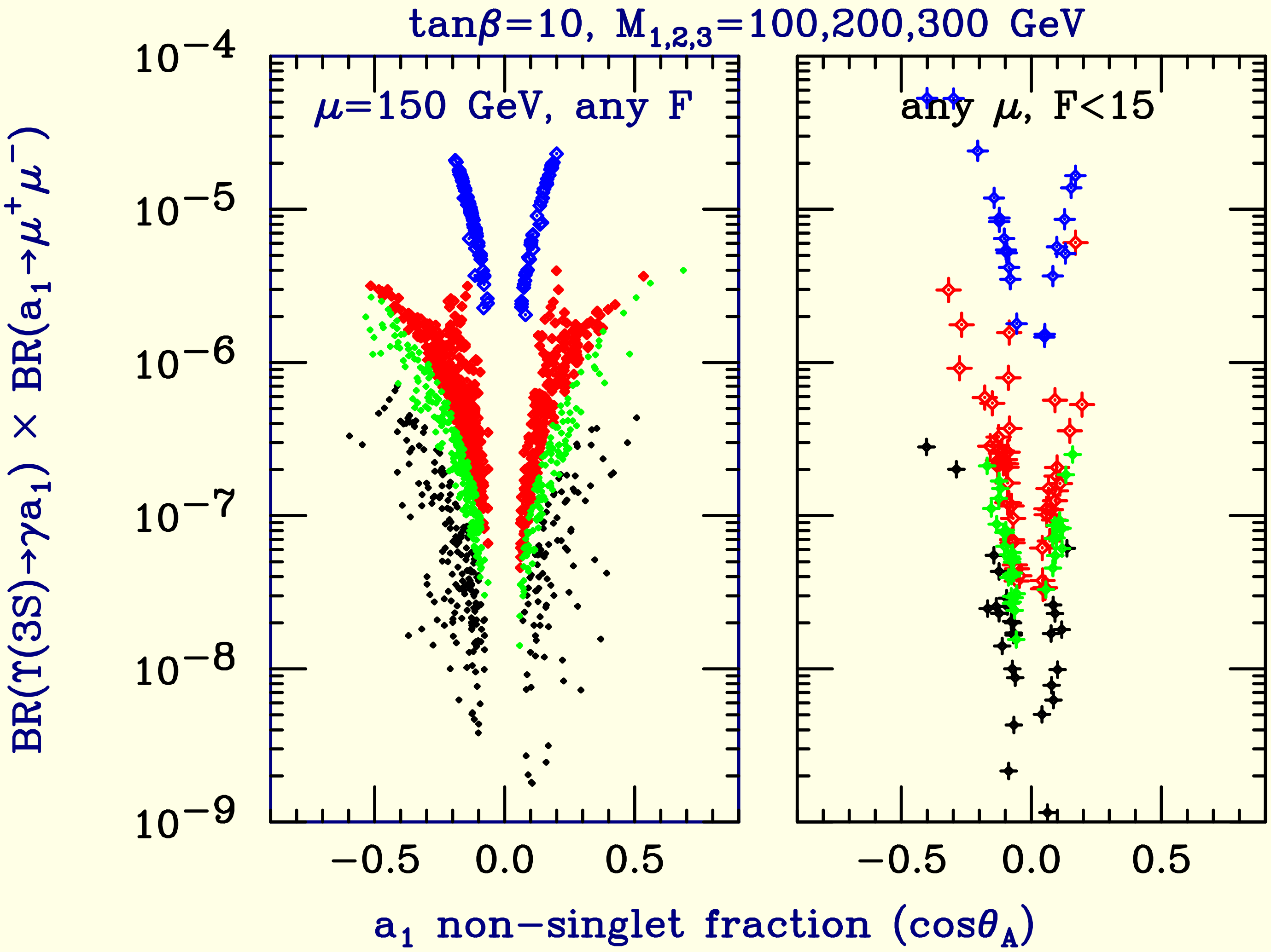


Figure 7: Results for $\tan\beta = 10$.

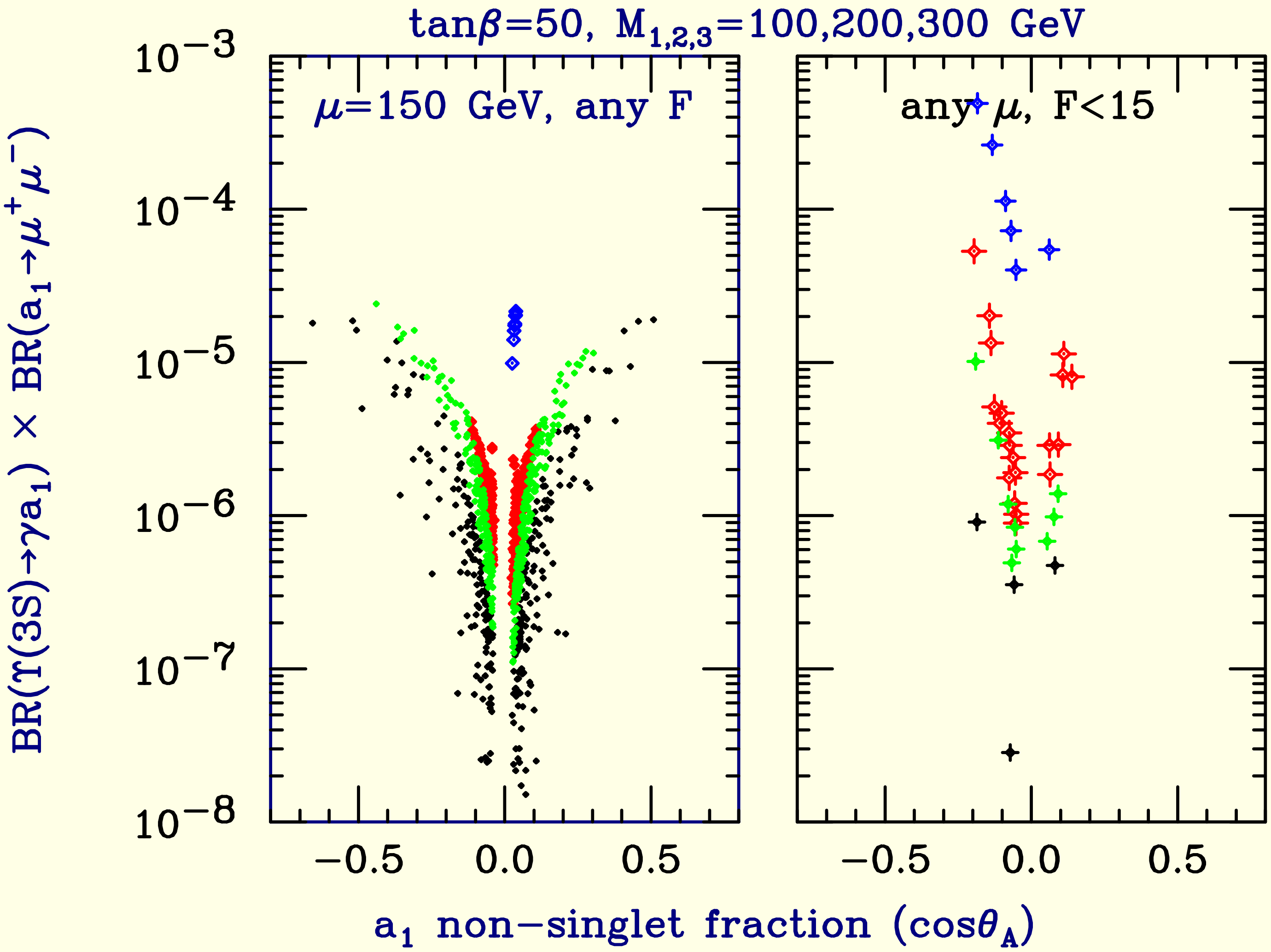


Figure 8: Results for $\tan\beta = 50$.

- **Thus, we have a convergence whereby low "light-a_1" fine tuning in the NMSSM and direct $\Upsilon_{3S} \to \gamma\mu^+\mu^-$ limits single out the $m_{a_1} > 2m_\tau$ part of parameter space.**

  LHC studies of light h_1 NMSSM scenarios should (and have) focused on this case.

Detecting the light h of the NMSSM

LHC

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

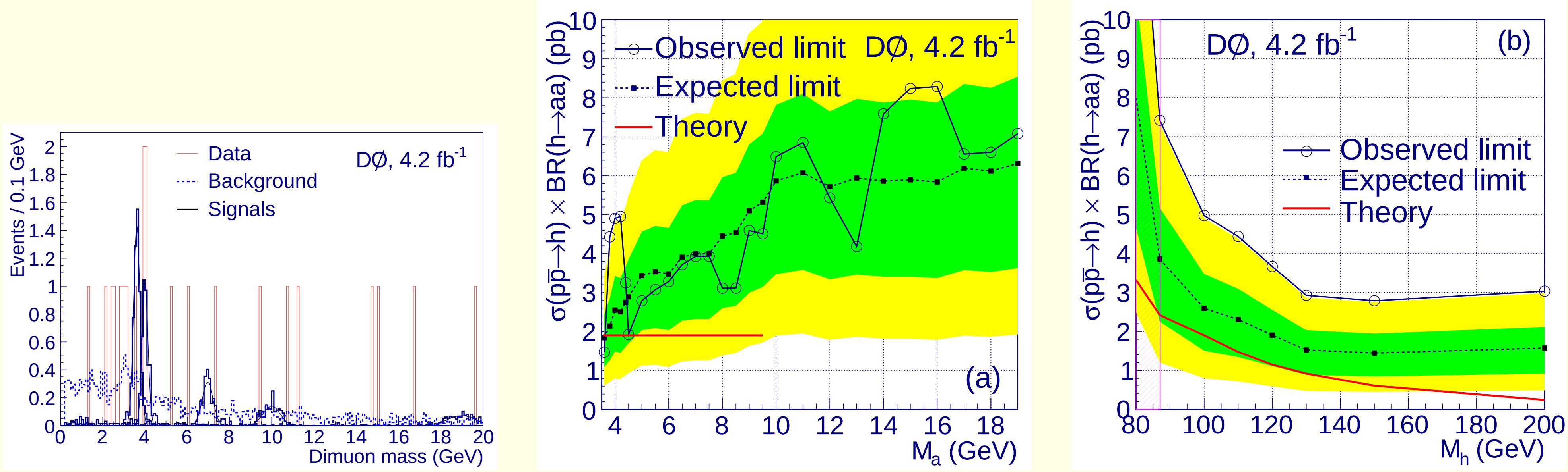
The possible new LHC channels include:

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 $m_h \sim 100~\mathrm{GeV}$.
- $B(h \to aa) \sim 0.8 - 0.9$.
- $B(a \to \mu^+\mu^-) \sim 0.0035 - 0.004$ and $B(a \to \tau^+\tau^-) \sim 0.95 - 0.98$
- 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:**

$$\sigma(gg \to h)B(h \to aa)[2B(a \to \mu^+\mu^-)B(a \to \tau^+\tau^-)]\epsilon \sim 4 - 7 \text{ fb}\,. \tag{2}$$

Backgrounds are small so perhaps 10 events in a single $\mu^+\mu^-$ bin would be convincing $\Rightarrow$ need about $L = 2 \text{ fb}^{-1}$.

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

$$\sigma(gg \to h)B(h \to aa)[B(a \to \mu^+\mu^-]^2\epsilon > (153 \text{ fb}) \times \epsilon\,. \tag{3}$$

If $\epsilon > 0.02$ (seems likely) then $\Rightarrow \sigma_{eff} > 3$ fb. This should be really background free and would close the $m_a < 2m_\tau$ "window of worry".

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. 9 for a variety of luminosity and triggering assumptions.

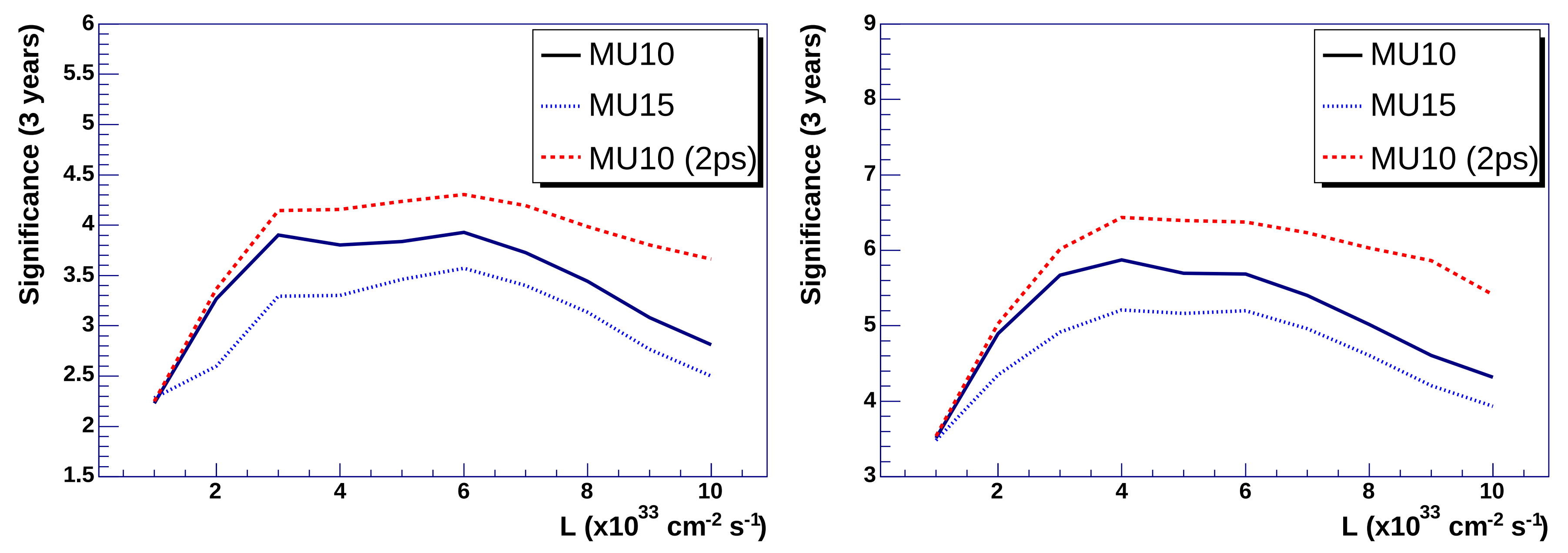


Figure 9: (a) The significance for three years of data acquisition at each luminosity. (b) Same as (a) but with twice the data. Different lines represent different μ trigger thresholds and different forward detector timing. Some experimentalists say more efficient triggering is possible, doubling the 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

$$p_i^{vis} = f_i \, p_{a,i} \tag{4}$$

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.

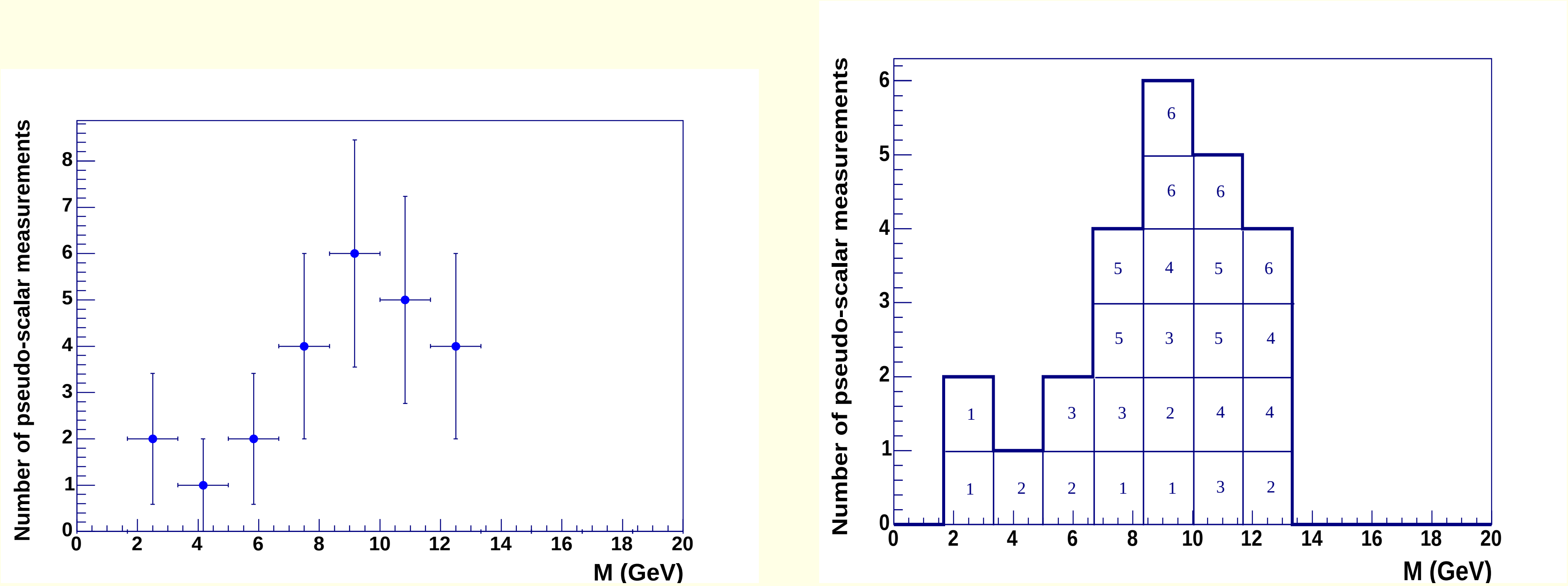


Figure 10: (a) A typical a mass measurement. (b) The same content as (a) but with the breakdown showing the 4 Higgs mass measurements for each of the 6 events, labeled $1-6$ in the histogram.

Figure 10 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 re-assuringly good agreement with the input value of $9.7~\mathrm{GeV}$.

- $\boxed{WW \to h}$

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

  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.

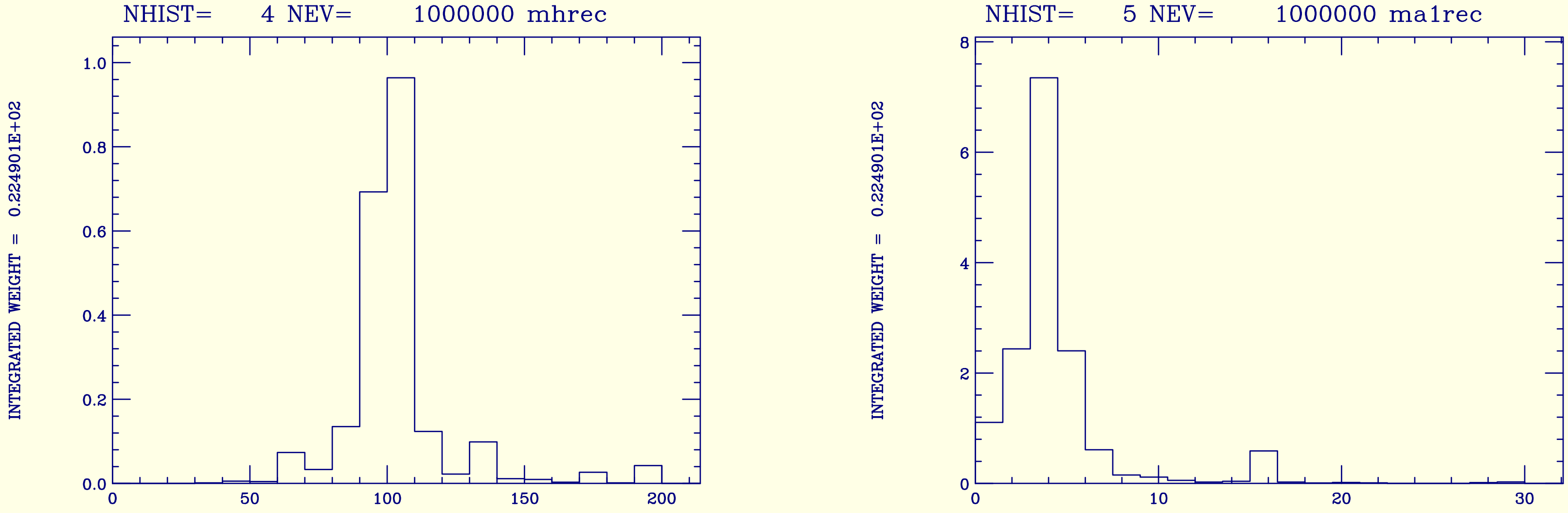


Figure 11: (a) A typical h mass distribution. (b) A typical a mass distribution. No cuts imposed; signal only.

Conclusions

- **The Higgs sector is very sensitive to new light states.**

  In the NMSSM case, Higgs decays expose the extended Higgs sector.

  In other cases, Higgs decays provide a very unique window on even more dramatic new physics.

  Probably, we have only touched the surface of the possibilities.

- **Only the $pp \to pph$ discovery mode is potentially insensitive to the way in which the h decays.**

  Of course, triggering will be decay-mode dependent. This is the weakness as compared to the ILC where one triggers on the Z in $e^+e^- \to ZX$ and looks for the M_X peak.

  Hopefully, μ's will always be present in the relevant h final states, but these might be quite complex as in the interpretation of the multi-muon CDF signal wherein the SM-like h decays sequentially to pairs of higgses.

- **Thus, we should work hard to improve triggering on various kinds of h final states.**

Very soon I will be watching and waiting (but perhaps not from quite so close a viewpoint) for the first Higgs signal.