The Elusive Higgs Boson(s)

Jack Gunion
U.C. Davis

Quantum Mechanics, Elementary Particles, Quantum Cosmology and Complexity ,
Feb. 24, 2010

To a large extent its all about Quantum Loops:

- Loop corrections to $m_W, \ldots$.
- Quadratically divergent loop corrections to the Higgs mass.
- Loop-derived Renormalization Group Evolution for parameters,
- .....

Introduction

- **Exposing the nature of electroweak symmetry breaking is goal #1 for the LHC.**

- **If we demand that the theory be "ideal" (as specified below), the possibilities are very limited and imply the existence of a Supersymmetric Higgs boson with SM-like $WW, ZZ, f\overline{f}$ couplings but with unusual decays.**

- **The definition of "ideal":**

  1. **Calculable unitarization of $WW \to WW$.**
  2. **Excellent agreement with precision electroweak (PEW) data.**
  3. **Consistency with LEP limits.**
  4. **No hierarchy problem ($i.e.$ cutoff of m_h quadratic divergence by $\mathcal{O}\left(\text{ TeV}\right)$).**
  5. **Coupling constant unification without adhoc tuning of matter content and/or Lagrangian parameters.**
  6. **No electroweak finetuning (i.e. the value of m_Z is not simply input and/or is not strongly dependent on input global parameters).**

Most important points/ingredients leading to Supersymmetry and, in particular, the Next-to-Minimal Supersymmetric Model.

- **Precision electroweak (PEW) data is beautifully consistent with a light Higgs boson with SM-like couplings to WW, ZZ.**

  The best, most 'ideal', PEW description is obtained if there is a Higgs that couples to WW, ZZ that has $m_h \lesssim 105\ \mathrm{GeV}$.

- **Supersymmetry with a supersymmetry breaking scale $\mathcal{O}(\ \mathrm{TeV})$ is a very beautiful approach to curing the hierarchy problem.** **And, spin-0 particles have a natural place in SUSY.**

- **A supersymmetric model with TeV scale for supersymmetry breaking and exactly two Higgs doublets gives "dynamical" ($i.e.$ RGE) gauge coupling unification.**

- **Minimizing electroweak finetuning (sensitivity of m_Z to high scale parameters) in Supersymmetric Models implies m_h (for the lightest CP-even SUSY Higgs) of order $100\ \mathrm{GeV}$.**

- **An h with SM-like WW, ZZ couplings and $m_h < 105$ GeV must have unusual/unexpected and maybe "elusive" decays.**

1. **LEP excludes a SM Higgs with $m_{h_{\rm SM}} < 114$ GeV using mainly the $e^+e^- \to Zh_{\rm SM} \to Z + 2b$ channel.**

2. **LEP excludes the Minimal Supersymmetric Model h^0 if $m_{h^0} < 114$ GeV since h^0 has SM-like couplings and decays.**

3. **LEP limits for alternative (more "elusive") h decay channels are weaker and allow $m_h < 105$ GeV. Particularly attractive are the final three modes below. But, there are many more with weak LEP m_h limits.**

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 $86 \to \sim 108$ [1] (1. new ALEPH)	any (e.g. $4j$) 82	$2f + \not{E}$ 90?			

4. Since $\Gamma(h \to b\bar{b})$ is so small, unusual decays are easily arranged and often very "natural" in extended models.

   Very generally, the Higgs provides a natural "portal" to new physics of many kinds that could lead to a weak m_h LEP limit.

5. The N. . . MSSM is the perfect model.

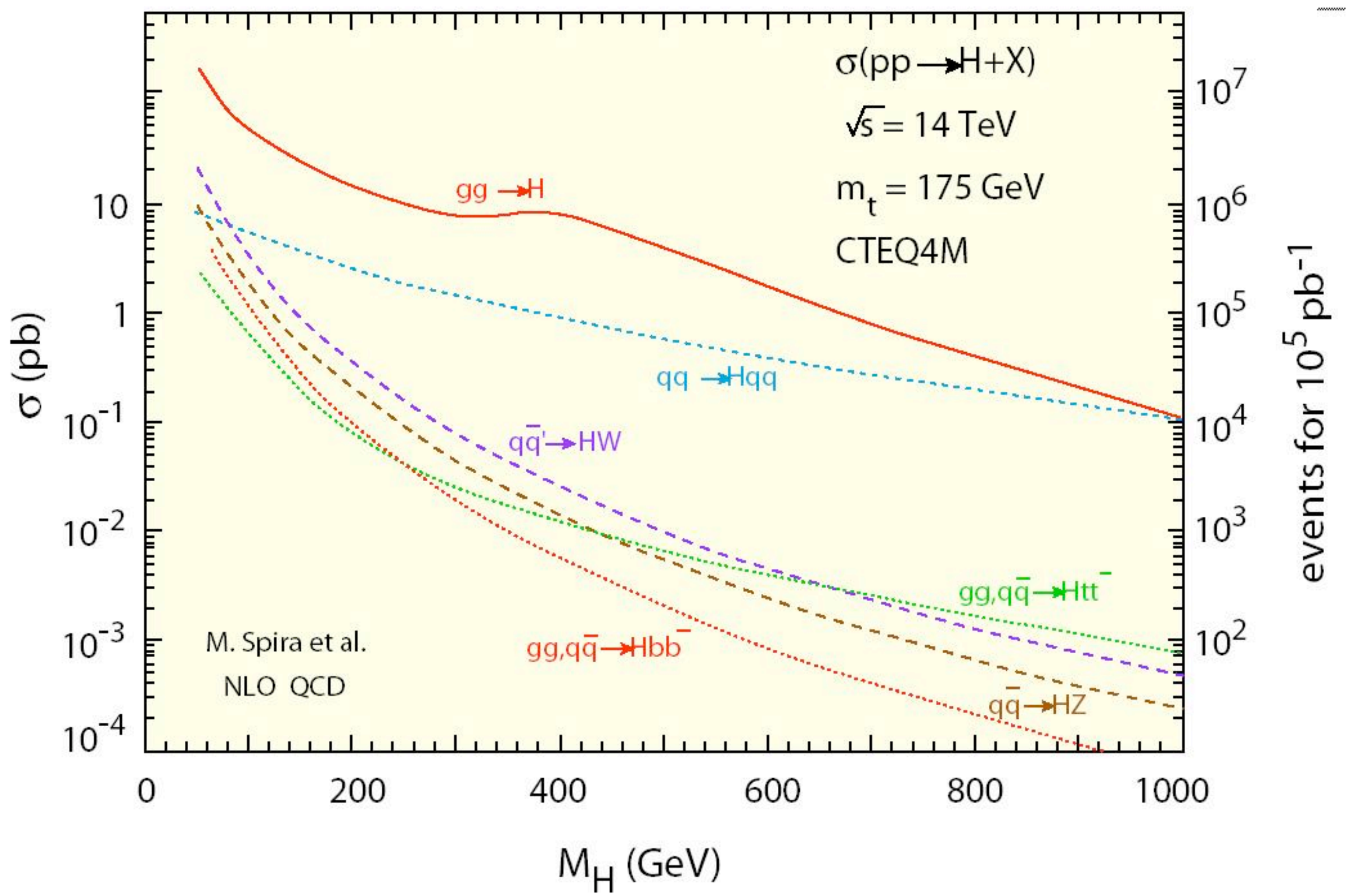
   (a) It is a beautiful model. (Higgs Bosons in a Nonminimal Supersymmetric Model. Ellis, Gunion, Haber, Roszkowski, Zwirner, Phys.Rev.D39:844,1989.).

   (b) A h with $m_h < 105~\mathrm{GeV}$ can escape LEP limits since $h \to aa \to 4\tau, 4j$ (with $m_a < 2m_B$) decays can naturally dominate. (see R. Dermisek and J. F. Gunion, "Escaping the large fine tuning and little hierarchy problems in the next to minimal supersymmetric model and $h \to aa$ decays," Phys. Rev. Lett. 95, 041801 (2005), ...)

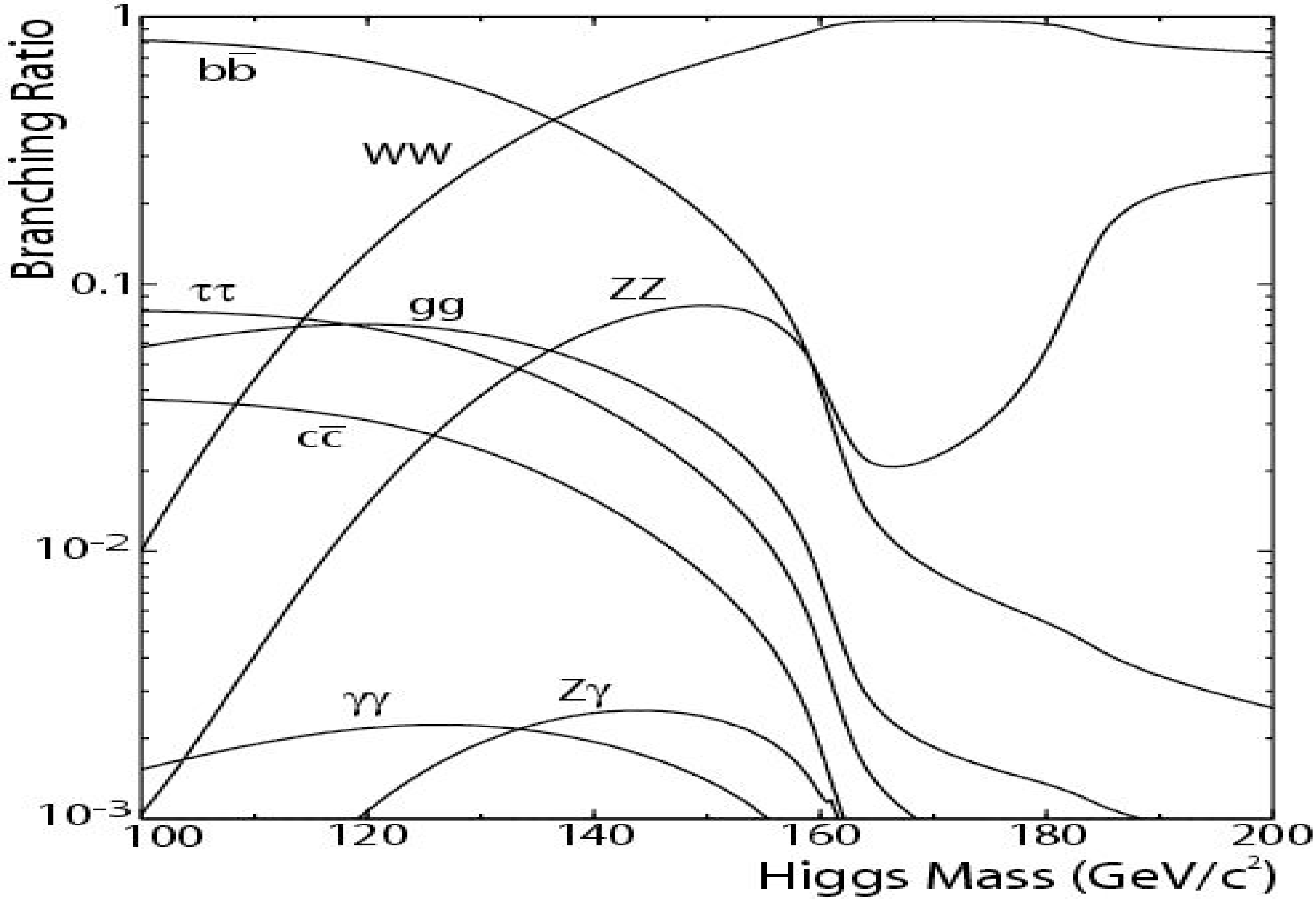
6. LHC strategies for Higgs searches will need to be expanded.

- 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.**



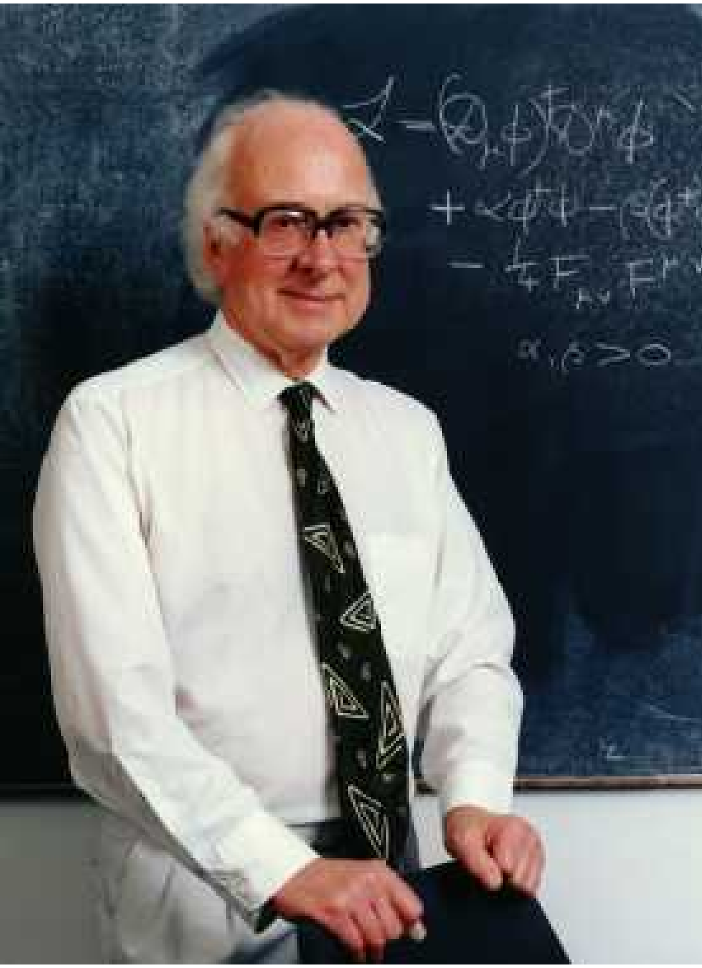
- **The strongest version of PEW constraints ⇒ These patterns must be altered by Beyond the SM (BSM) / Beyond the MSSM (BMSSM) physics.**

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

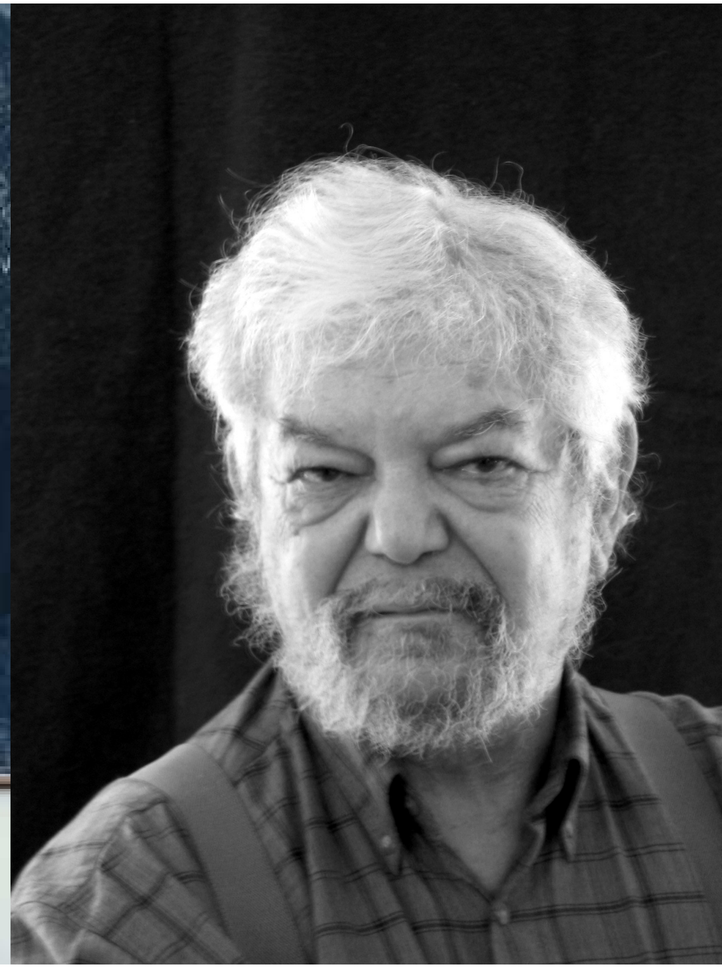
could be ...

Priestly, highly orthodox

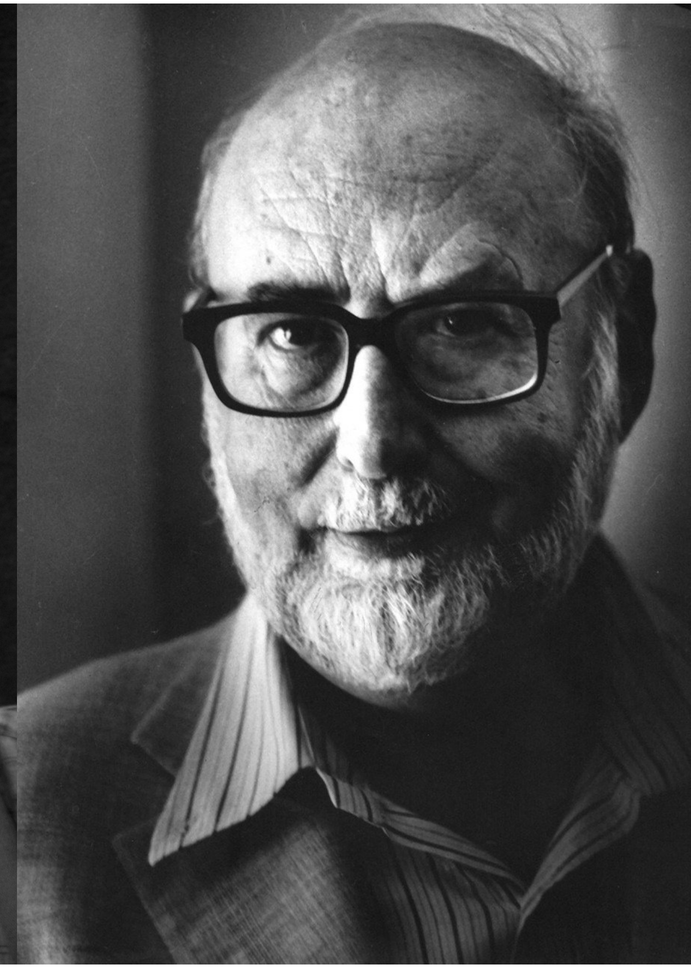
Less saintly, but still "standard"



Higgs

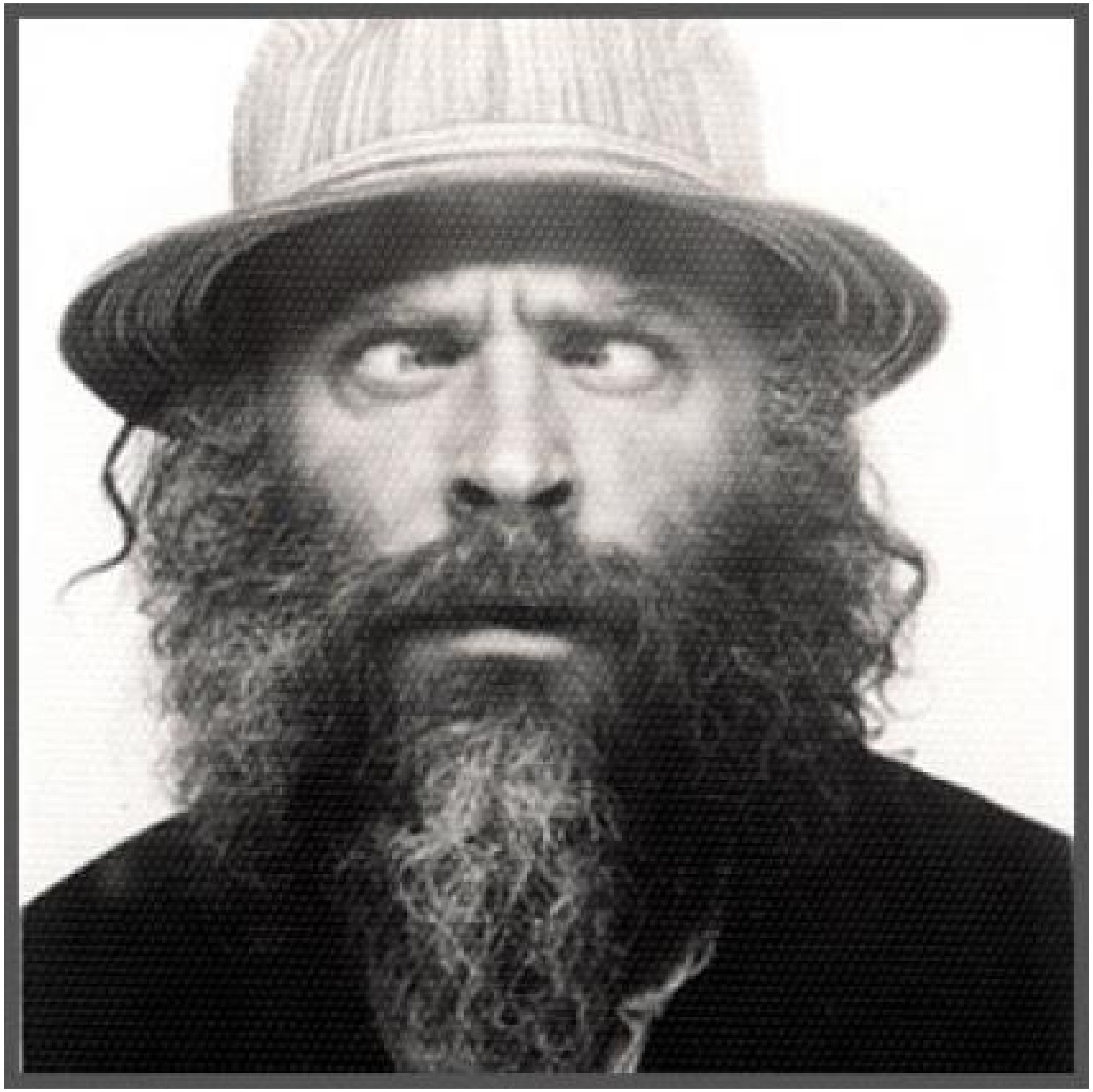


Brout



Englert

Ornery/ mean, highly heretical



singer Daniel Higgs

Beautiful but unorthodox

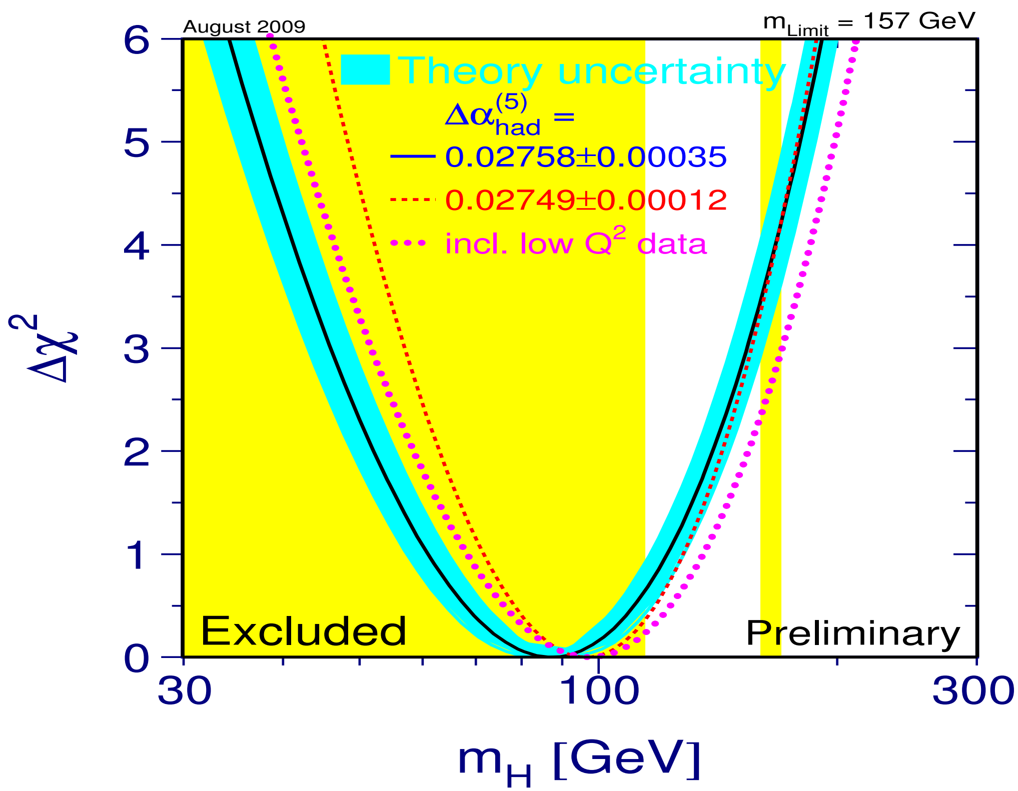
singer Rebekah Higgs

Or, will the LHC bury the Higgs?

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

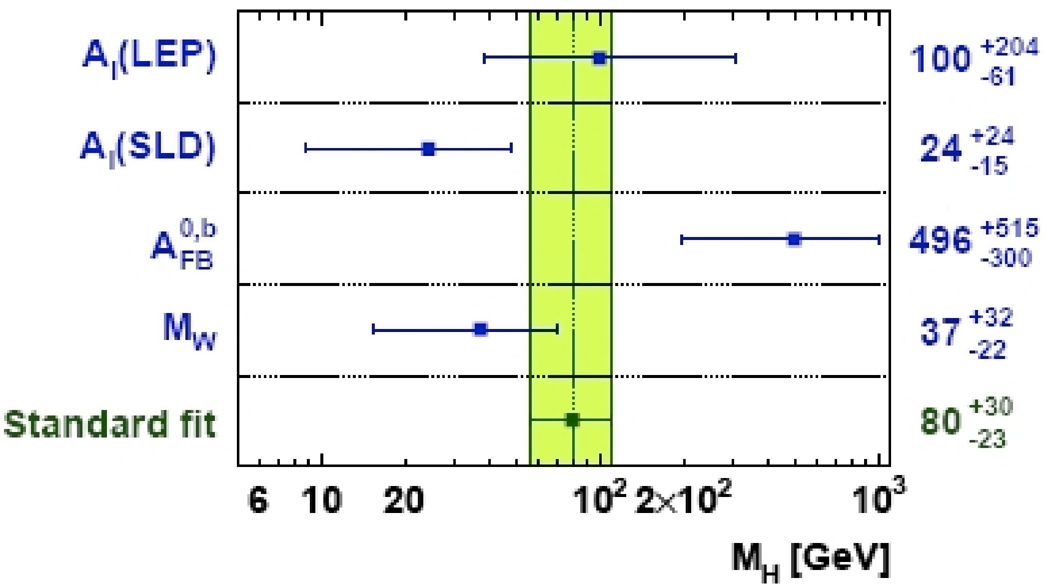
Motivations for Non-Standard Decays — single H

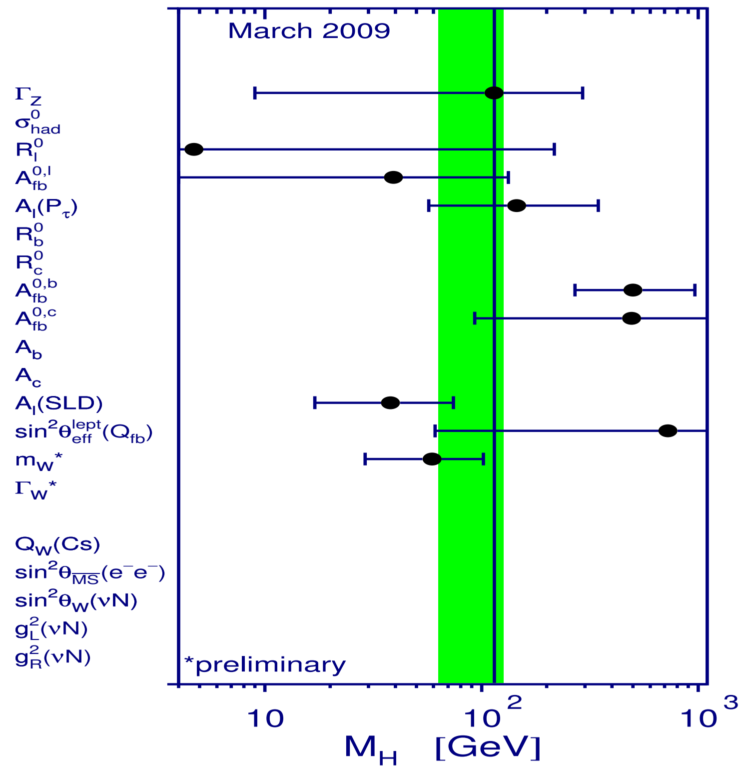
1. **Precision Electroweak data:** **A fairly recent plot of $\Delta\chi^2(PEW)$ vs. m_H is:**



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

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).

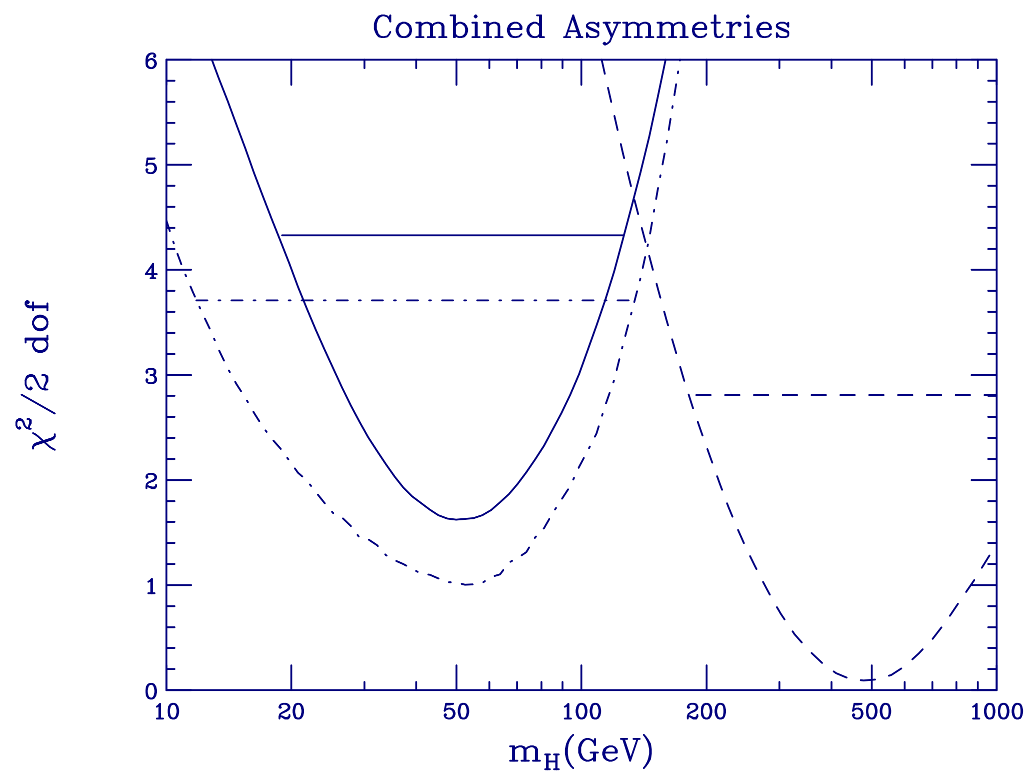
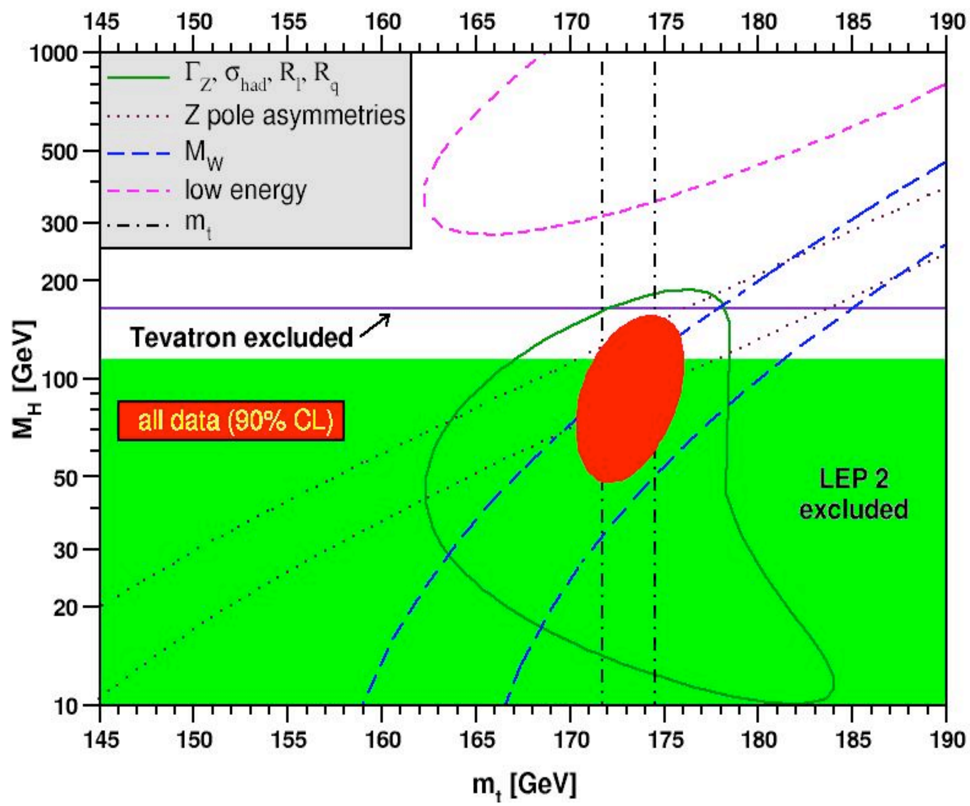


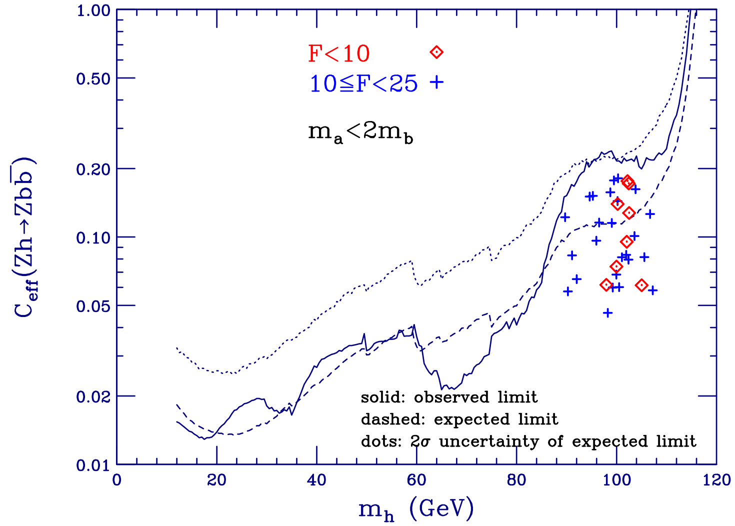
Figure 1: χ^2 **distributions as a function of** m_H **from the combination of the three leptonic asymmetries** A_{LR}**,** A^{ℓ}_{FB}**,** $A_{\ell}(P_{\tau})$ **(solid line); the three hadronic asymmetries** A^b_{FB}**,** A^c_{FB}**, and** Q_{FB} **(dashed line); and the three** m_H**-sensitive, non-asymmetry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

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



2. **Electroweak Baryogenesis: $m_h \lesssim 105~{\rm GeV}$ is needed for strong enough phase transition.**

3. **Largest LEP excess: Perhaps the ideal Higgs should be such as to predict the 2.3σ excess at $M_{b\bar b} \sim 98~{\rm GeV}$ seen in the $Z + b\bar b$ final state.**



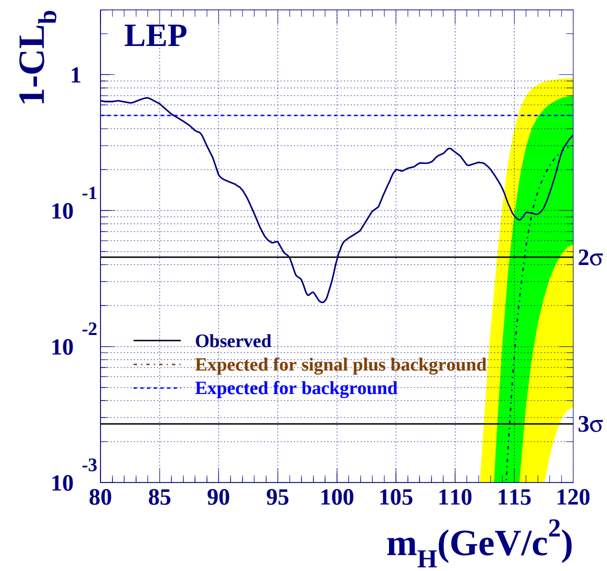


Figure 2: Plots for the $Zb\overline{b}$ final state. F is the m_Z-fine-tuning measure for the NMSSM.

- **The simplest possibility for the excess is to have $m_H \sim 100~\mathrm{GeV}$ and $B(H \to b\overline{b}) \sim (0.1 - 0.2) \times B(H \to b\overline{b})_{SM}$ (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.**

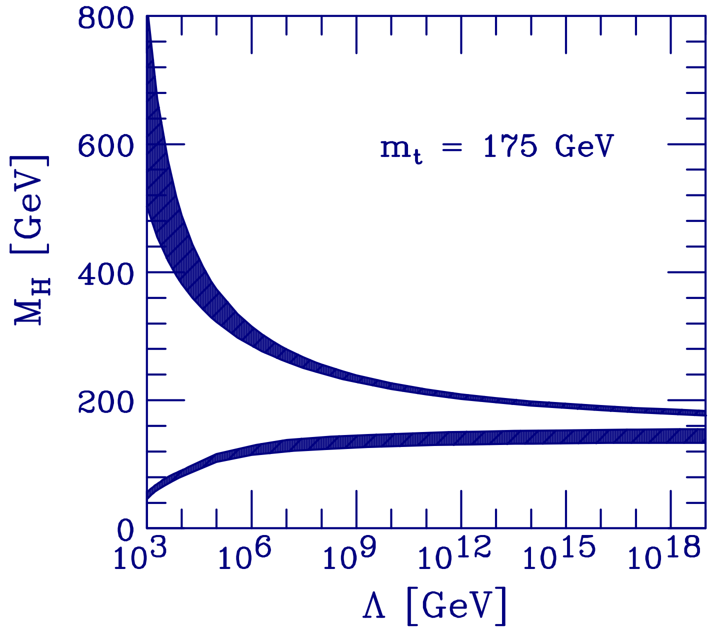
- **One generic way of having a low LEP limit on m_H is to suppress the $H \to b\overline{b}$ branching ratio by having a light a (or h) with $B(H \to aa) > 0.7$ and $m_a < 2m_b$ (to avoid LEP $Z + 4b$ limit at $110~\mathrm{GeV}$, i.e. above ideal). For $2m_\tau < m_a < 2m_b$, $a \to \tau^+\tau^-$. For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

See: (R. Dermisek and J. F. Gunion, Phys. Rev. Lett. 95, 041801 (2005); Phys. Rev. D 73, 111701 (2006))

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

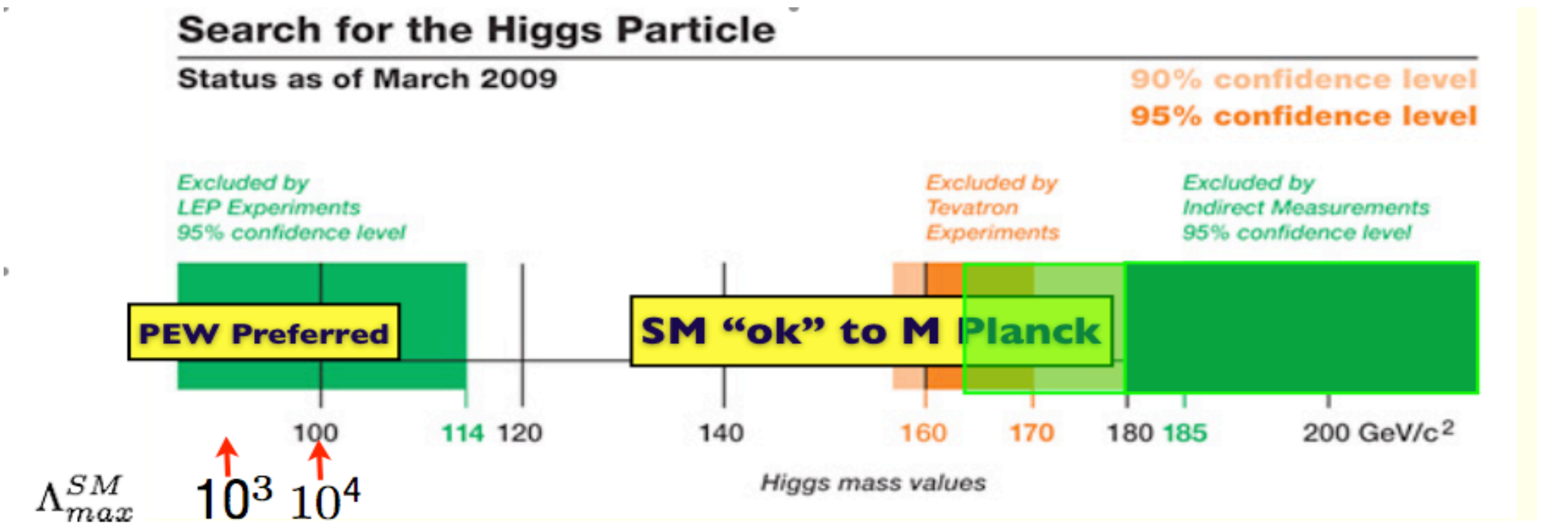
Higgs pair modes can easily dominate below WW threshold.

- Thus, in an ideal model, a Higgs with SM-like ZZ coupling should have mass no larger than $105~\mathrm{GeV}$. But, then we should recall the triviality and global minimum constraints on the scale Λ of new physics.



New physics needed by $\Lambda < 10^4 (10^3)~\mathrm{GeV}$ if $m_h \sim 100~\mathrm{GeV}$ ($\sim 50~\mathrm{GeV}$).

- **The situation can be sketched as below:**



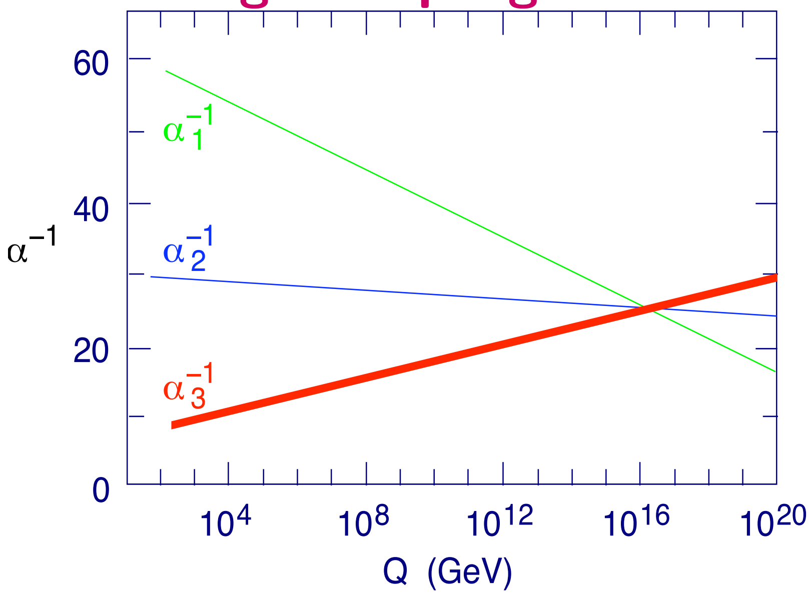
with LEP excess also preferring $m_h \sim 90 - 105$ GeV and Baryogenesis preferring $m_h < 105$ GeV.

- **Final note: Somewhat light SUSY (as needed for no Electroweak finetuning) coupled with $m_h \sim 90 - 105$ GeV can give "apparent" m_h for PEW fits well below actual m_h.**

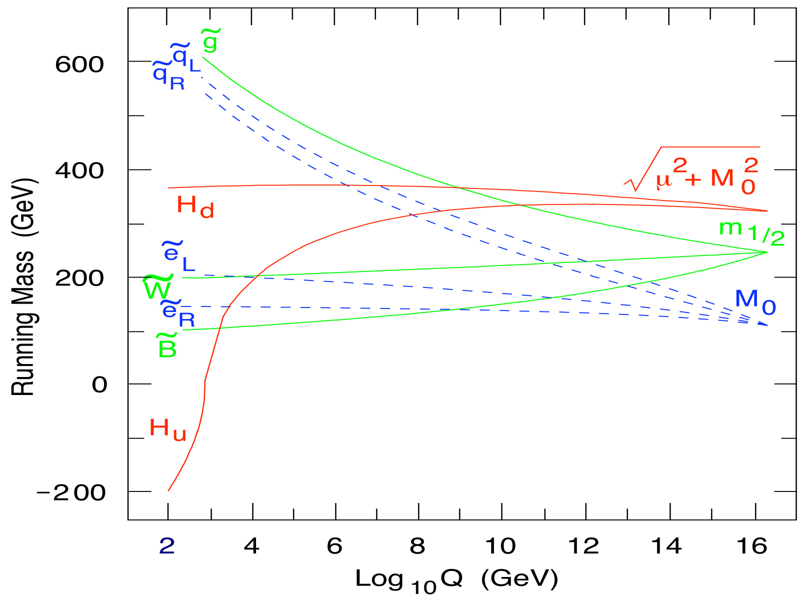
Why SUSY, in particular the NMSSM

- **SUSY cures the naturalness / hierarchy problem.**
- **SUSY + R-parity $\Rightarrow$ dark matter candidate.**
- **In the MSSM, 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 we get:**

Gauge Coupling Unification



RGE EWSB



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

  $F \equiv \mathrm{Max}_i \frac{\partial \log m_Z}{\partial \log p_i}$ (p_i = GUT-scale parameter) measures the degree to which GUT parameters must be tuned. Want $F < 10 - 20$. In the MSSM context, this requires $m_{\widetilde t} \lesssim 400~\mathrm{GeV}$ and a relatively light gluino.

  For such $m_{\widetilde t}$ 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).

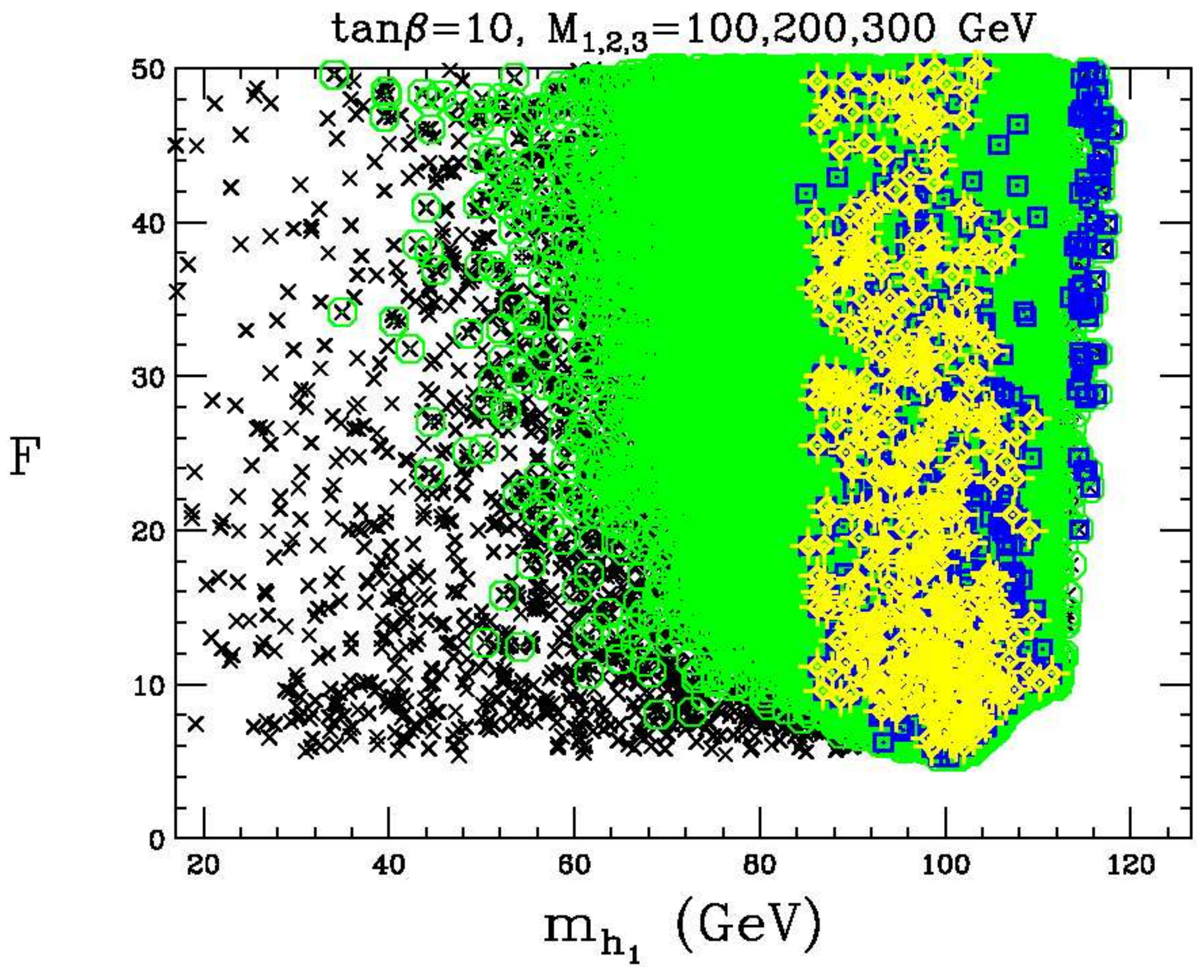
5. Like any SUSY model, solves quadratic divergence hierarchy problem.

6. And, assuming $m_h \lesssim 105~\mathrm{GeV}$ is allowed because of $h \to aa$ decays with $m_a < 2m_b$, the NMSSM

   (a) Yields excellent agreement with PEW constraints.

   (b) Allows minimal finetuning 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)

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.



To repeat, in the 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 h^0 is SM-like.

Note: 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].)

When $A_\lambda, A_\kappa \to 0$, the NMSSM has an additional $U(1)_R$ symmetry, in which limit the a is pure singlet and $m_a = 0$. If $U(1)_R$ is exact at M_U, then a mainly singlet a with small m_a is natural result of RGE equations.

We will be examining a measure called G of the A_λ and A_κ tuning needed to achieve $m_a < 2m_B$ *and* $B(h \to aa) > 0.7$.

In order to achieve small G, one must be near the $U(1)_R$ symmetry limit, implying that the a is largely singlet ($e.g.$ $\sim 10\%$ at amplitude level if $\tan\beta \sim 10$) and $\sim 7.5~\mathrm{GeV} \lesssim m_a$ (but below $2m_b$) in the best cases.

- 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

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

(Will ignore possible large $\tan\beta$ SUSY corrections.)

- In the NMSSM context (more generally, in 2HDM(II) models), we can predict the branching ratios of the a. Especially important, $a \to \mu^+\mu^-$ and $a \to \tau^+\tau^-$.

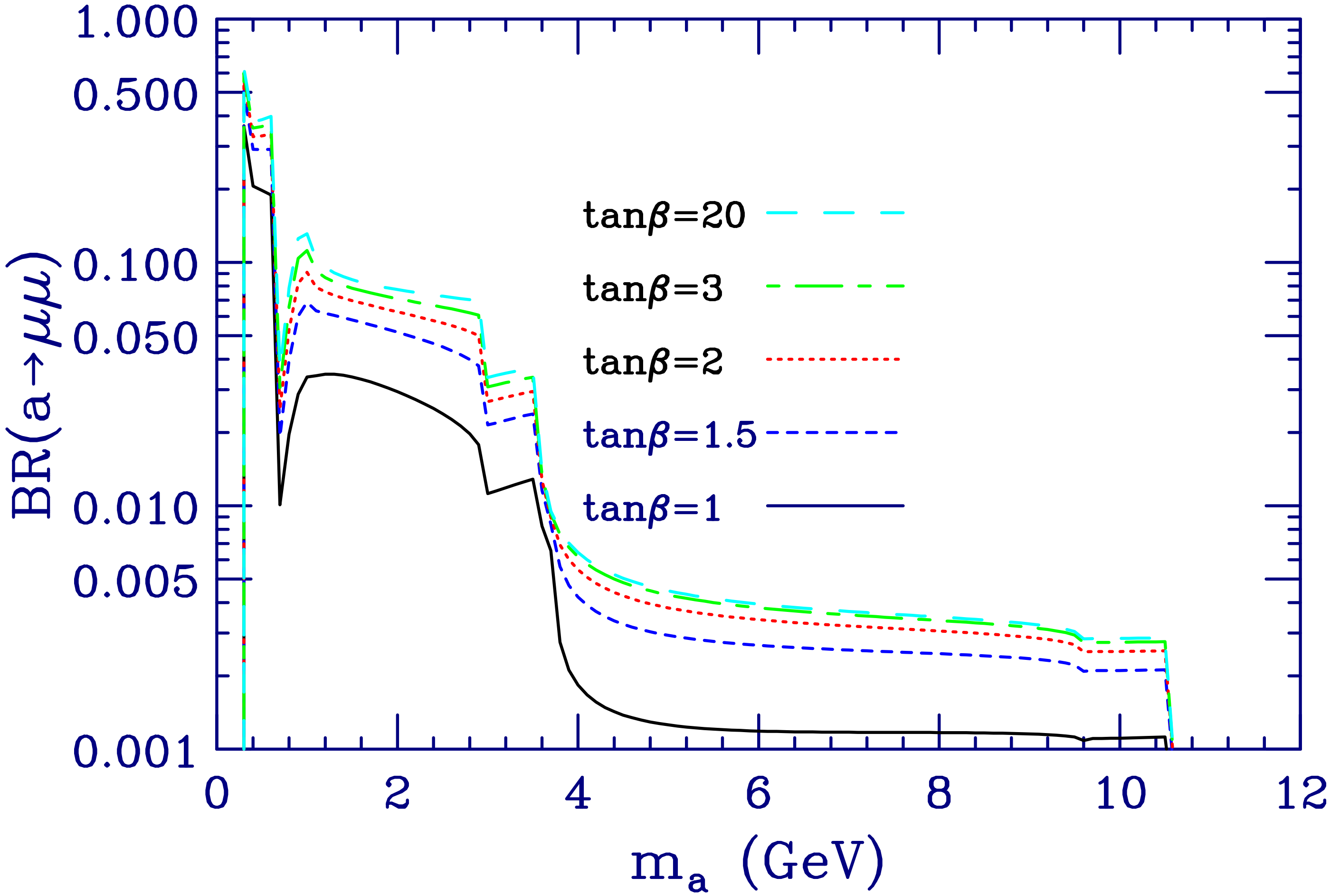


Figure 3: $B(a \to \mu^+\mu^-)$ for various $\tan\beta$ values.

Note: for $m_a \lesssim 2m_B$ $B(a \to \mu^+\mu^-) \sim \mathbf{0.002 - 0.003}$ for $\tan\beta > 1.5$.

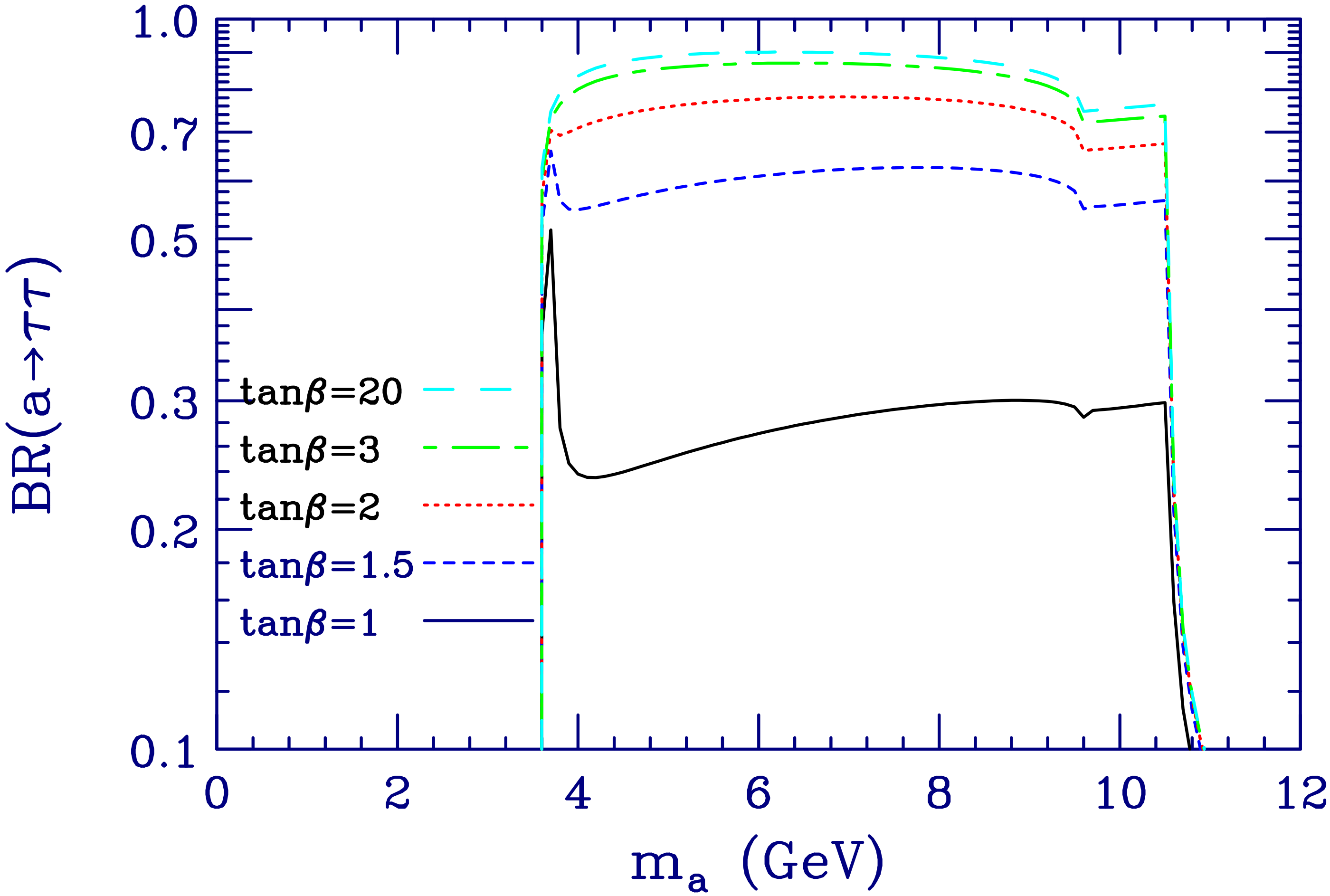


Figure 4: $B(a \to \tau^+\tau^-)$ **for various** $\tan\beta$ **values.**

Note: values at high $\tan\beta$ **are** $\sim \mathbf{0.75}$ **(***i.e.* **below max of** $\sim \mathbf{0.89}$**) for** $\mathbf{10}\ \mathrm{GeV} \lesssim m_a \lesssim 2m_B$**.**

- **The strongest $|C_{ab\bar{b}}|$ limits derive from BaBar and CLEO data on $\Upsilon(nS) \to \gamma a$; they appear in Fig. 5 along with some old LEP limits.**

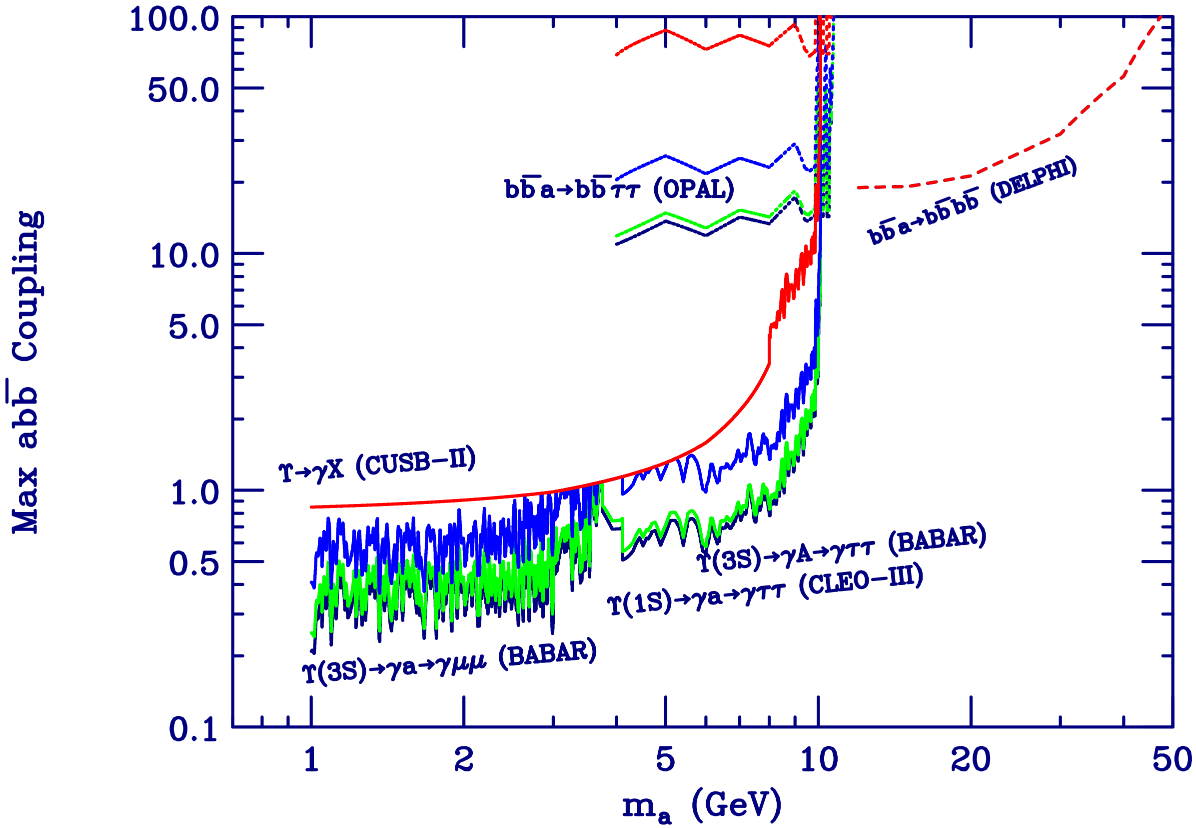


Figure 5: **Limits on $C_{ab\bar{b}}$ from JFG, arXiv:0808.2509 and JFG+Dermisek, arXiv:0911.2460. These limits include recent BaBar $\Upsilon_{3S} \to \gamma\mu^+\mu^-$ and $\gamma\tau^+\tau^-$ limits. Color code: $\tan\beta = 0.5$; $\tan\beta = 1$; $\tan\beta = 2$; $\tan\beta \geq 3$.**

The most unconstrained region is that with $m_a > 8$ GeV, especially 9 GeV $< m_a < 12$ GeV.

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

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

$$C_{ab\bar b} = \cos\theta_A \tan\beta\,, \quad \text{where small} \quad \cos\theta_A \quad \text{is expected} \tag{2}$$

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

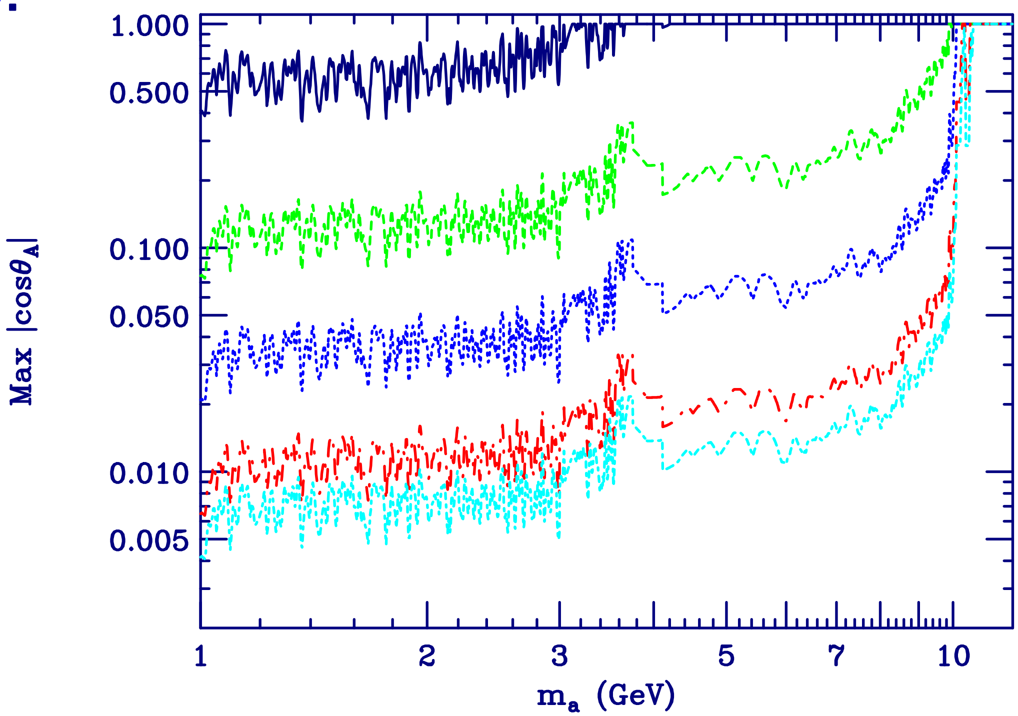


Figure 6: The curves are for $\tan\beta = 1$ **(upper),** 3**,** 10**,** 32 **and** 50 **(lower).**

- **To see the impact of these limits we can compare before and after.**

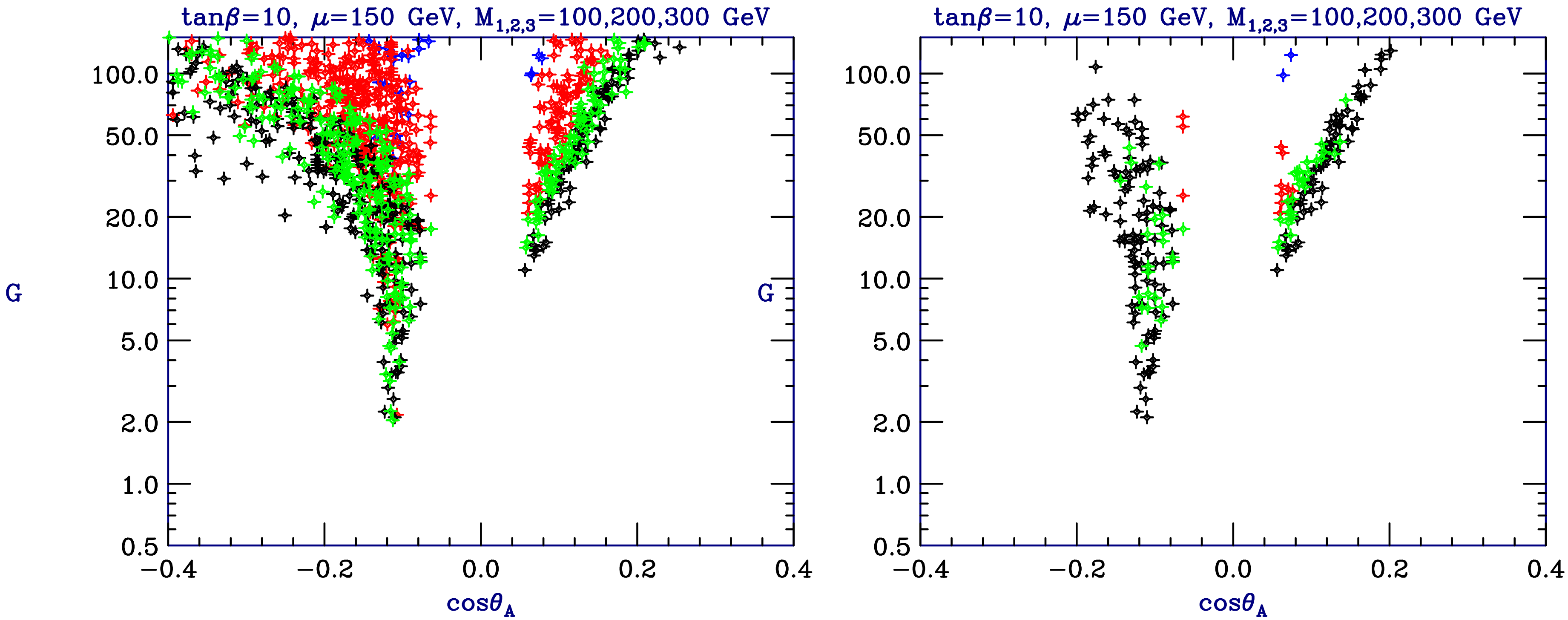


Figure 7: Light-a_1 finetuning measure G before and after imposing limits $|\cos\theta_A| \leq \cos\theta_A^{\max}$. Color code: $m_a < 2m_\tau$; $2m_\tau < m_a < 7.5~\mathrm{GeV}$; $7.5~\mathrm{GeV} < m_a < 8.8~\mathrm{GeV}$; $8.8~\mathrm{GeV} < m_a < 2m_B~\mathrm{GeV}$. Note that many points with low m_{a_1} and large $|\cos\theta_A|$ are eliminated by the $|\cos\theta_A| < \cos\theta_A^{\max}$ requirement, including almost all the $m_{a_1} < 2m_\tau$ (blue) points and a good fraction of the $2m_\tau < m_{a_1} < 7.5~\mathrm{GeV}$ (red) points.

- **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* $B(h \to aa) > 0.7$.**

- We have a convergence whereby low "light-a" finetuning in the NMSSM and direct $\Upsilon_{3S} \to \gamma\mu^+\mu^-$ limits *both* single out the small $|\cos\theta_A|$ and $m_a > 7.5~\mathrm{GeV}$ part of parameter space.

  LHC studies of the h and a should (and have) focused on this case.

- Note the strict lower bound on $\cos\theta_A$ needed for $B(h \to aa) > 0.7$. $\Rightarrow$ stronger limits could rule the scenario out.

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

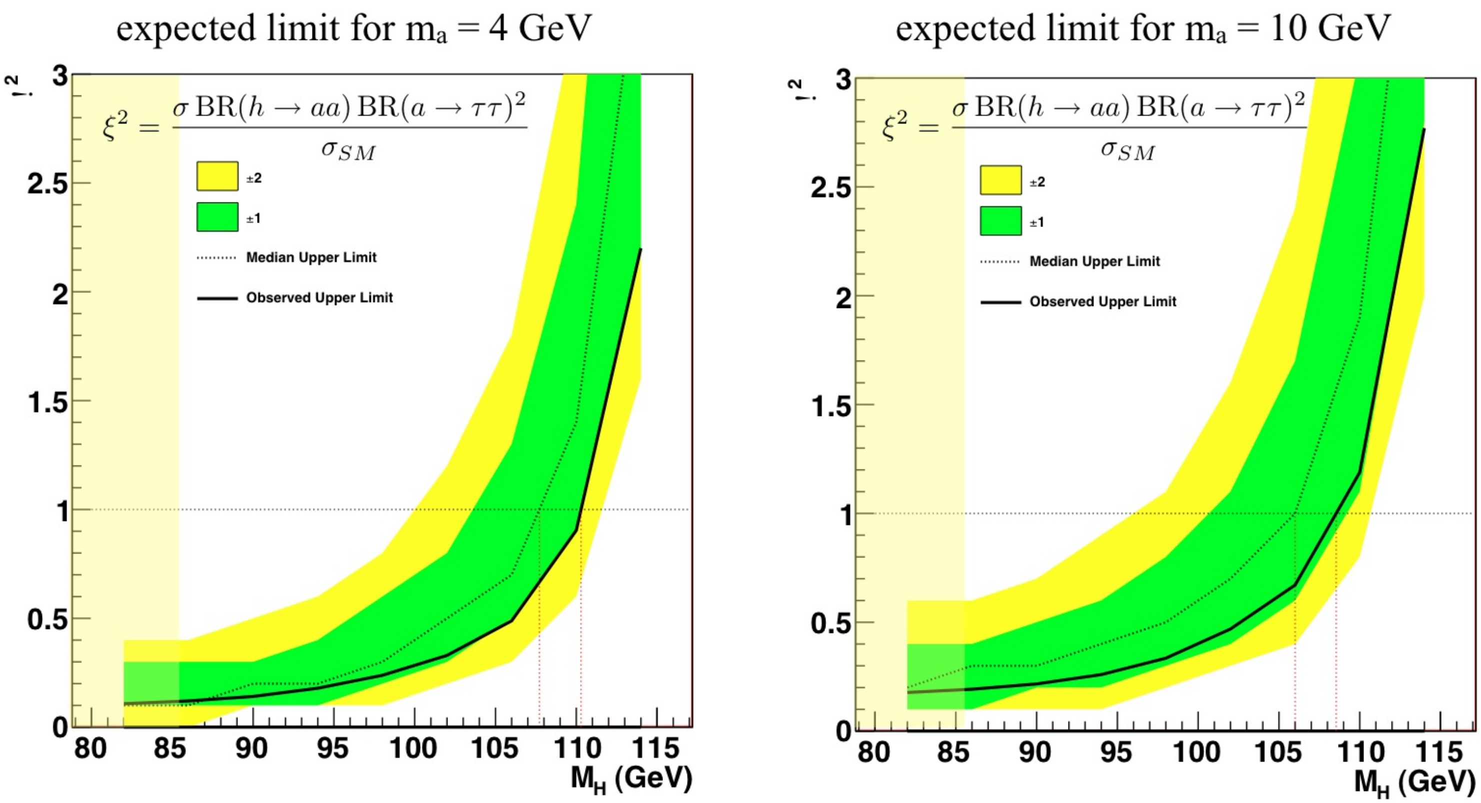
  They examine $e^+e^- \to Zh$ with $h \to aa$ and $a \to \tau^+\tau^-$ and place limits on

$$\xi^2 \equiv \frac{\sigma(Zh)}{\sigma(Zh_{\rm SM})} B(h \to aa) \left[B(a \to \tau^+\tau^-)\right]^2 . \tag{3}$$

Expected limits @ m_a = 4,10 GeV

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$)$, up to $\xi^2 < 0.63$ if $m_h = 105$ GeV (relevant for $\tan\beta = 10$) and $m_a = 10$ GeV.

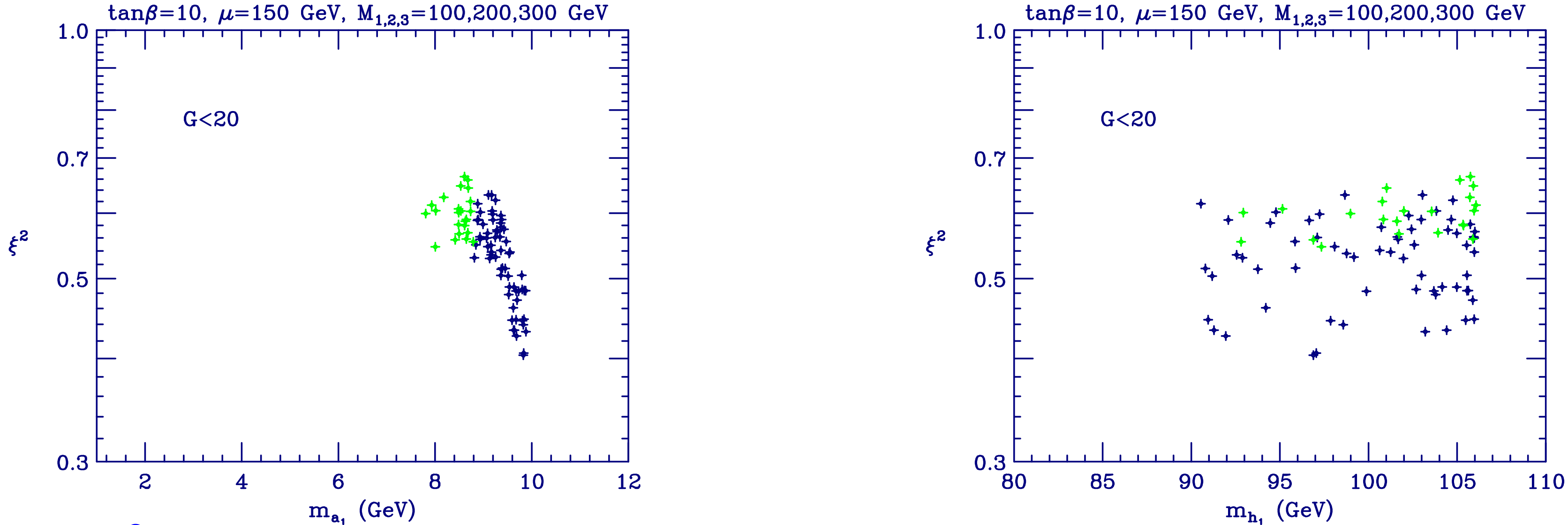


Figure 8: ξ^2 **vs.** m_{a_1} **and** m_{h_1} **for** $\tan\beta = 10$; $|\cos\theta_A| < \cos\theta_A^{\rm max}$; **fixed** μ **scan.**

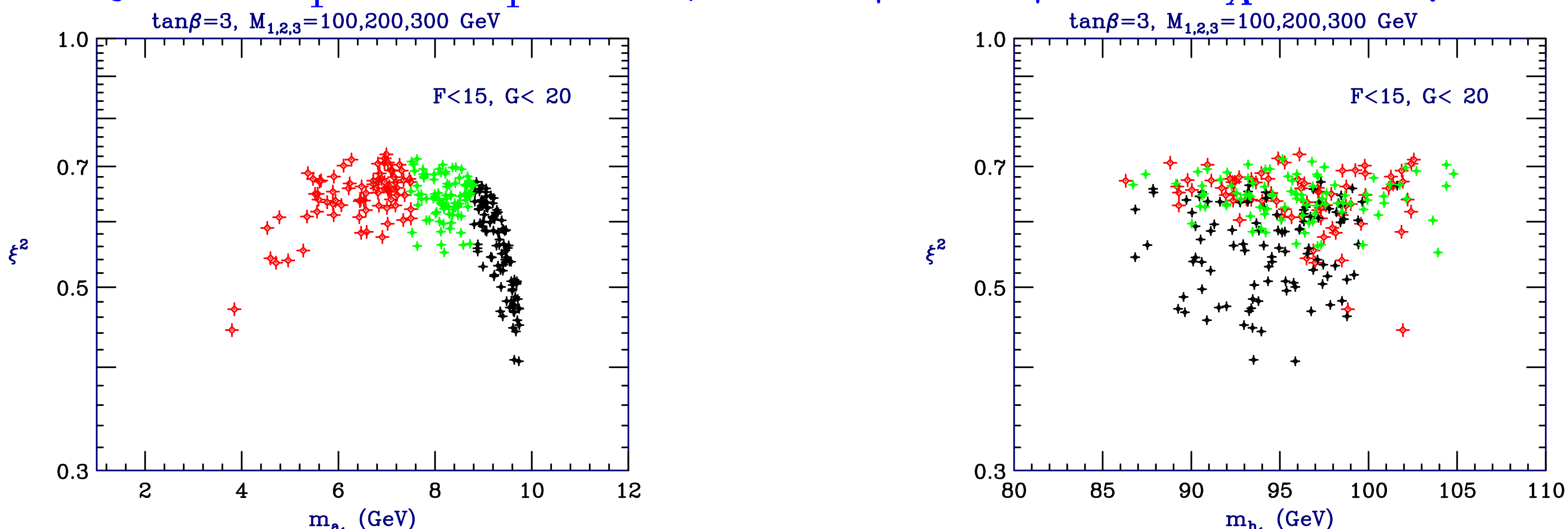


Figure 9: ξ^2 **vs.** m_{a_1} **and** m_{h_1} **for** $\tan\beta = 3$; $|\cos\theta_A| < \cos\theta_A^{\rm max}$, **full scan.**

- $\tan\beta \sim 3, 50$ **scenarios on verge of elimination.** $\tan\beta = 10$, $m_{h_1} \sim 105~{\rm GeV}$ **still ok.**

- **For lower $\tan\beta$ it quickly becomes easier to escape the ξ^2 limits.**

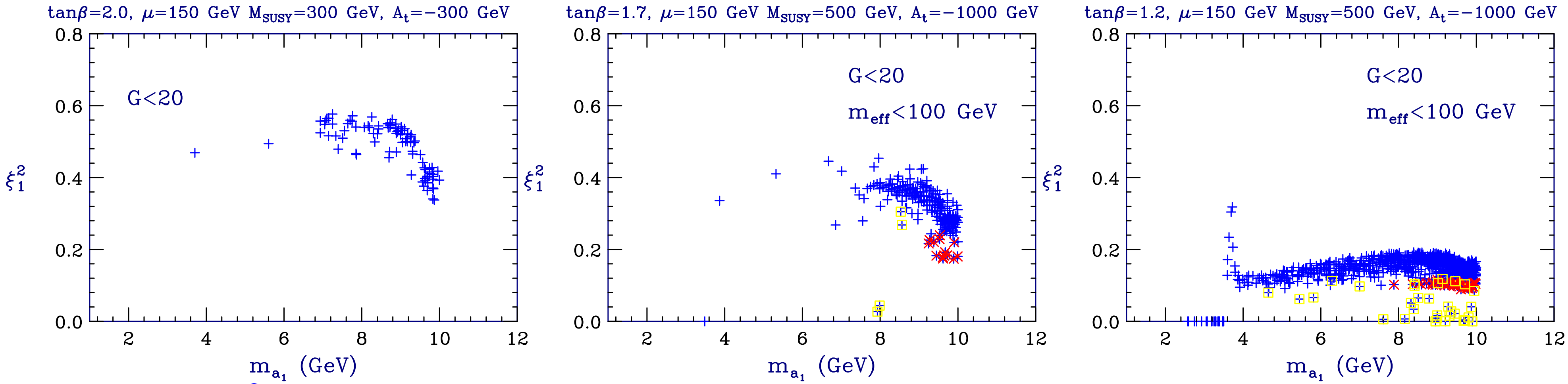


Figure 10: ξ_1^2 ($i.e.$ for h_1) vs. m_{a_1} for $|\cos\theta_A| < \cos\theta_A^{\max}$. **In this figure, we are no longer color coding different m_{a_1}. Yellow squares have $B(h_1 \to a_1a_1) < 0.7$ but still escape usual LEP limits. Red crosses have $m_{h_1} < 65~\mathrm{GeV}$. m_{eff} is the effective precision electroweak mass: $\log(m_{eff}) = CV_1^2\log(m_{h_1}) + CV_2^2\log(m_{h_2})$, neglecting CV_3^2, where $CV_i = g_{ZZh_i}/g_{ZZh_{\mathrm{SM}}}$.**

Note that at low $\tan\beta$, the Higgs is starting to be “buried” by having $h_1 \to a_1a_1 \to 4j$ decays dominate.

Could a Hadron collider discover or, at least, constrain the a directly?

- At a hadron collider, one studies $gg \to a \to \mu^+\mu^-$ and tries to reduce the heavy flavor background by isolation cuts on the muons.

  At the Tevatron, one finds (based on using related CDF search for narrow resonances)

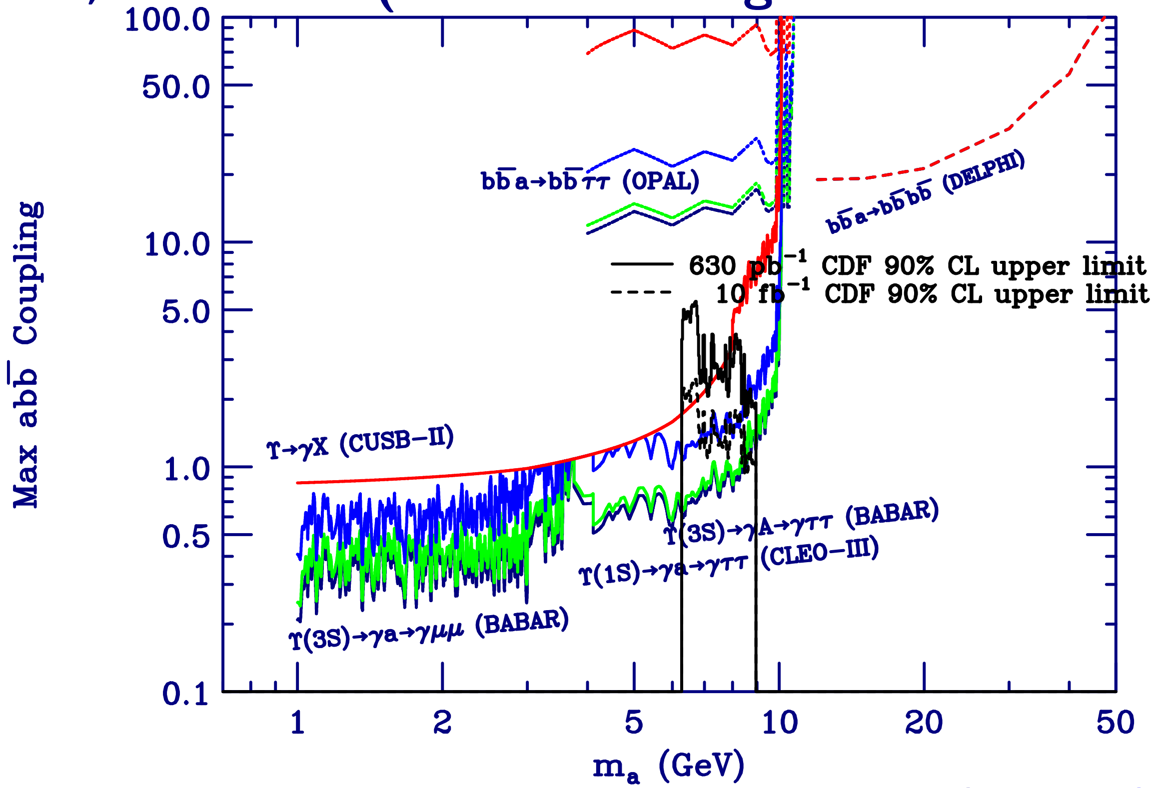


Figure 11: Tevatron limits compared to previous plot limits for $\tan\beta = 0.5$, 1, 2, ≥ 3.

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 $m_a > 9\ \mathrm{GeV}$ (above their narrow resonance analysis window) implicit limits are:

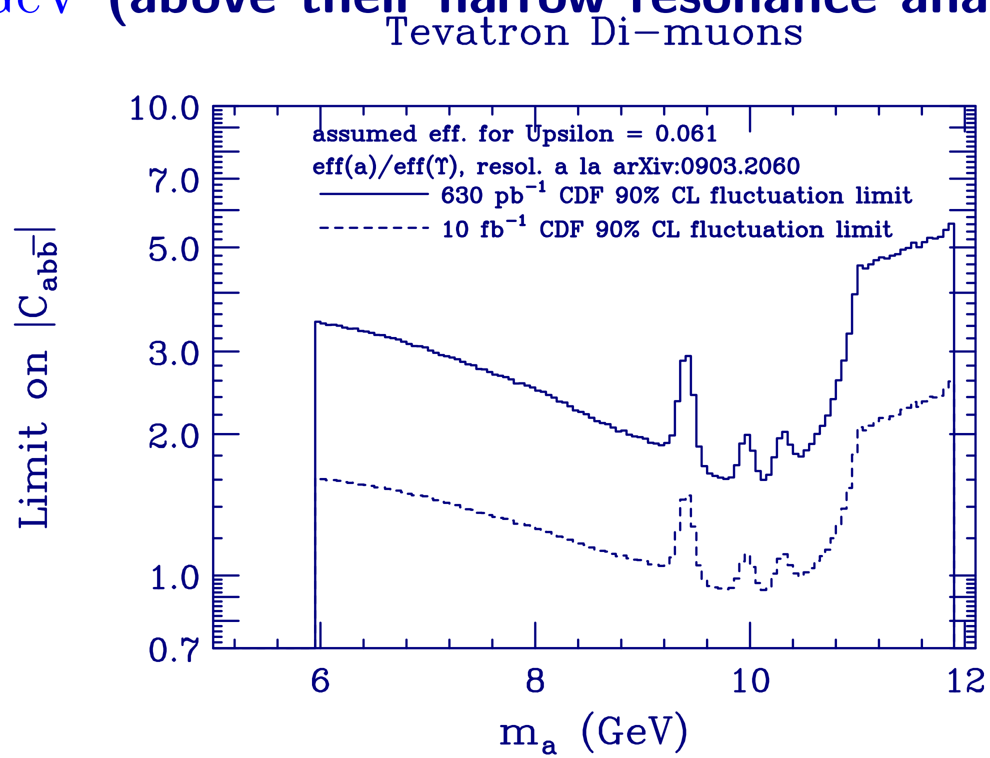


Figure 12: $L = 630\ \mathrm{pb}^{-1}$ **and** $10\ \mathrm{fb}^{-1}$ **limits based on no** 1.686σ **excess in optimal interval.**

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. 13.

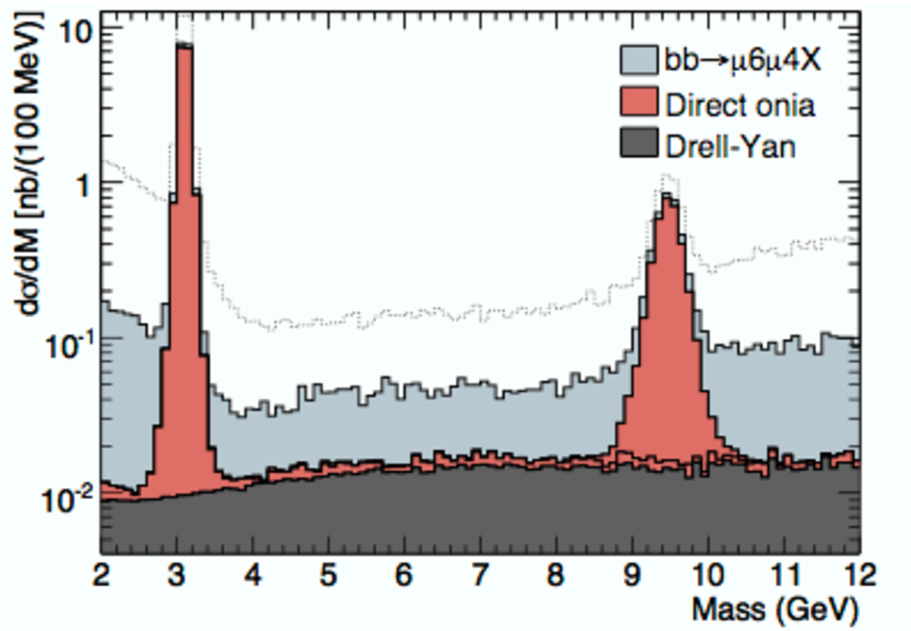


Figure 13: ATLAS dimuon spectrum prediction after corrections for acceptance and efficiencies (D. D. Price, arXiv:0808.3367 [hep-ex].).

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

What is the efficiency for a events relative to the plot. A recent Monte Carlo study gives $\epsilon_{ATLAS} = 0.1$. We write $\epsilon_{ATLAS} = 0.1r$. (CMS claims $r = 3$ is possible.)

- After accounting for resolutions, and taking $\tan\beta = 10$ and $\cos\theta_A = 0.1$ (middle range of most preferred NMSSM models), we obtain

Table 2: Luminosities (fb^{-1}) needed for 5σ if $C_{ab\bar{b}} = 0.1$ and $\tan\beta = 10$

Case	$m_a = 8~\mathrm{GeV}$	$m_a = M_{\Upsilon_{1S}}$	$m_a \lesssim 2m_B$
ATLAS LHC7	$17/r^2$	$63/r^2$	$9/r^2$
ATLAS LHC10	$13/r^2$	$47/r^2$	$7/r^2$
ATLAS LHC14	$10/r^2$	$38/r^2$	$5.4/r^2$

For $r = 1$, the required L's away from the Upsilon resonance may be achieved after a year or two of LHC operation.

Of course, smaller $\cos\theta_A$ values are possible in the context of this approach, in which case much larger L's would be needed for a discovery.

Detecting the light h of the NMSSM

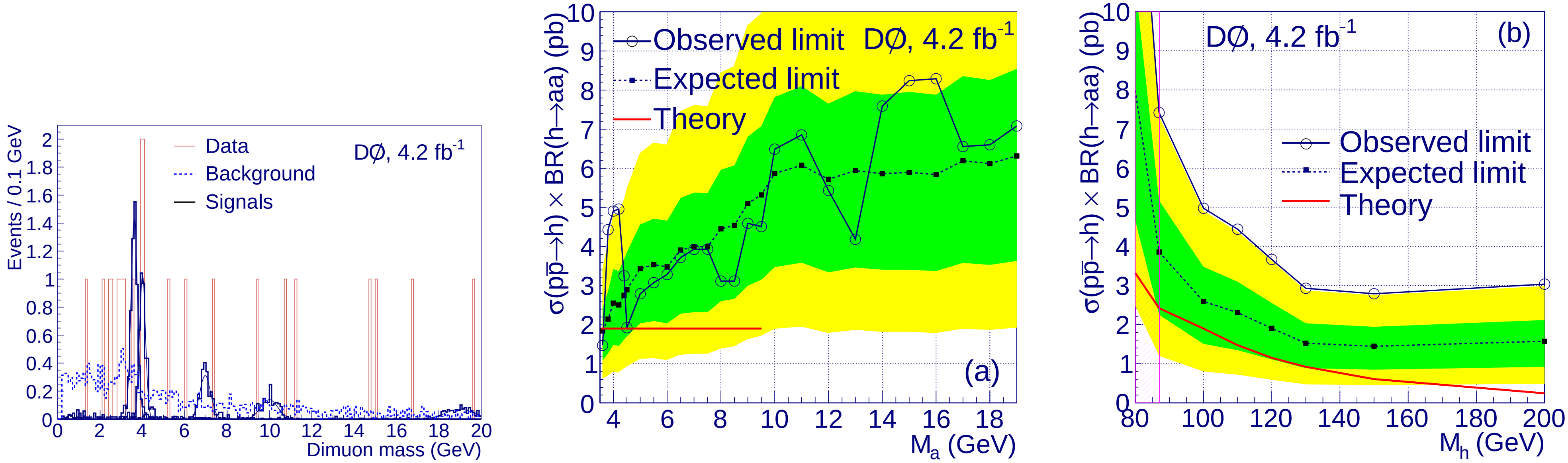
LHC assuming $\tan\beta \gtrsim 3$, *i.e.* large $B(a \to \tau^+\tau^-)$

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** $2\tau + \mu^+\mu^-$

   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.



At the LHC? Studied by Wacker et al.

- **Net useful cross section:**

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

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

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

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).

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

   (Recall that the $\widetilde{\chi}^0_2 \to h\widetilde{\chi}^0_1$ channel provides a signal in the MSSM when $h \to b\overline{b}$ 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. 14 for a variety of luminosity and triggering assumptions.

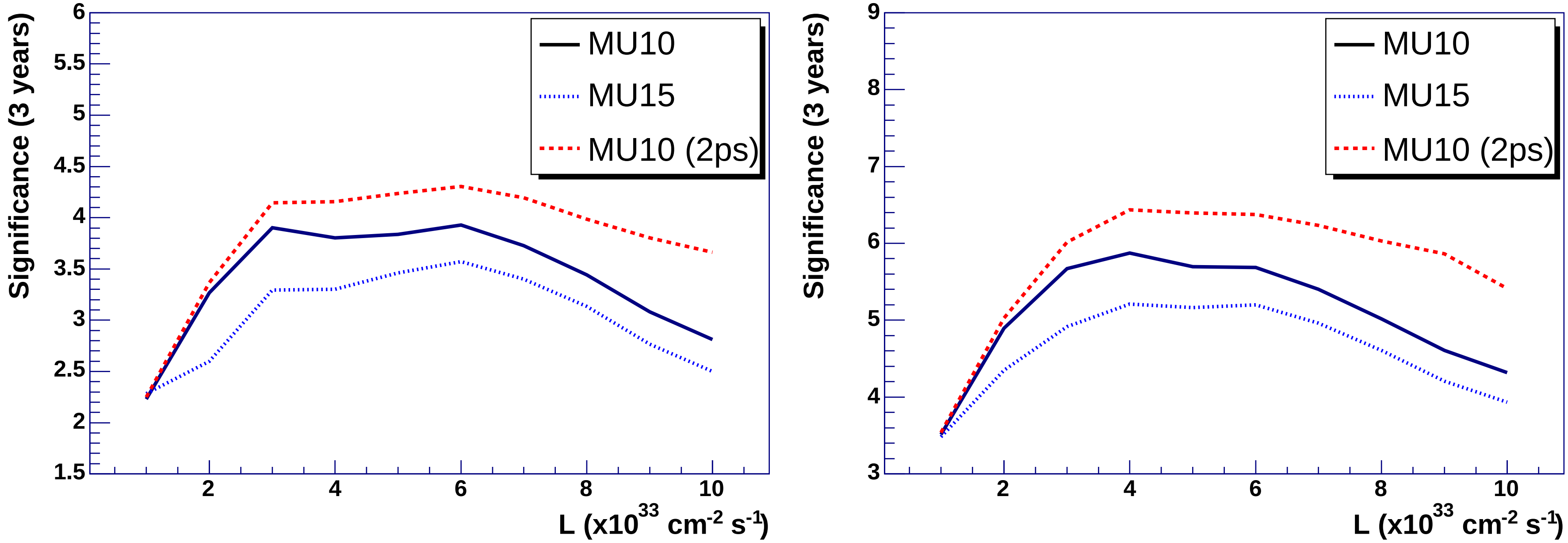


Figure 14: (a) The significance for three years of data acquisition at each luminosity. (b) Same as (a) but with twice the data. Different lines represent different μ trigger thresholds and different forward detector timing. Some experimentalists say more efficient triggering is possible, doubling the 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.

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

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

  Have we "buried" the Higgs under the background?

- Could perhaps consider $gg \to h \to aa \to \mu^+\mu^- X$.

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

$$\sigma(gg \to h)B(h \to aa)[2 \times B(a \to \mu^+\mu^-]\epsilon > (70 \text{ fb}) \times \epsilon \,. \tag{6}$$

  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 $L = 30 \text{ fb}^{-1}$ would be needed. This approach should be pursued.

- **Note:**

  Even if the light NMSSM h can't be found at the LHC, we can eventually check that $WW \to WW$ scattering is perturbative.

  And, if SUSY is sufficiently light to avoid electroweak finetuning then we will have a plethora of SUSY signals.

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 "nightmare" scenarios

- Introduce "hidden" sector of heavy Q's which induce large loop amplitude for $a \to gg$. Must then find $h \to aa \to (2g)(2g)$ at the LHC. Probably not possible.

  The Higgs is completely buried under the QCD background.

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

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

- 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 $< 100~\mathrm{GeV}$ 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.

See also related models of J. Van der Bij and collaborators and the "unhiggs" models of Georgi and others.

- At an ILC/CLIC, e.g. with $\sqrt{s} = 250~\mathrm{GeV}$, 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 $g^2_{ZZh} \gtrsim 0.05 g^2_{ZZh_{\rm SM}}$, *provided* L *is adequate*.

- In fact, for adequate L an ILC/CLIC can detect a series of *overlapping* Higgs bosons or even a continuum by simply looking for an excess in the M_X spectrum measured in $e^+e^- \to ZX$ (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).