Heretical Higgs Boson(s)

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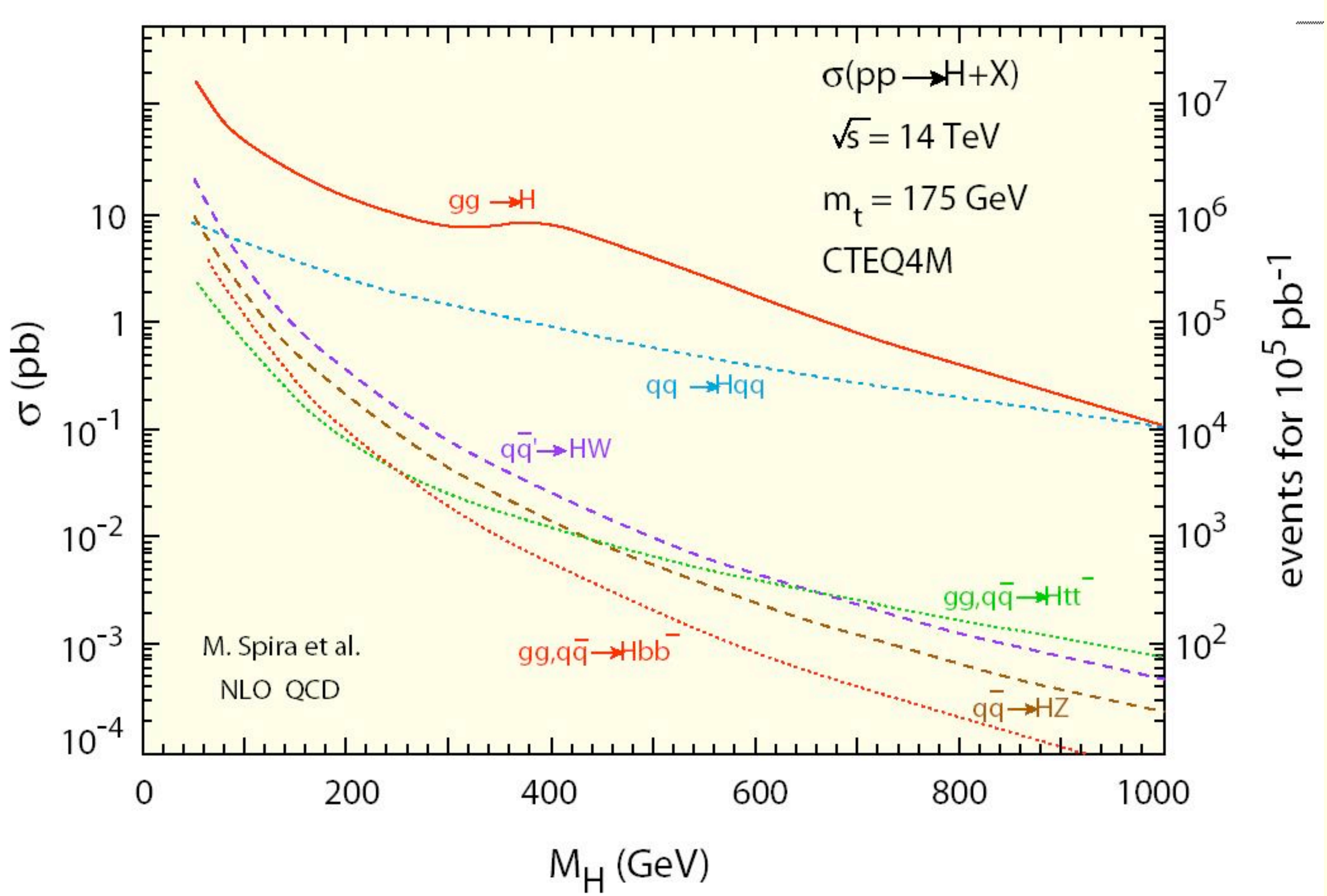
Workshop on Multi-Higgs Bosons, Lisbon, September 16, 2009

Synopsis/Outline

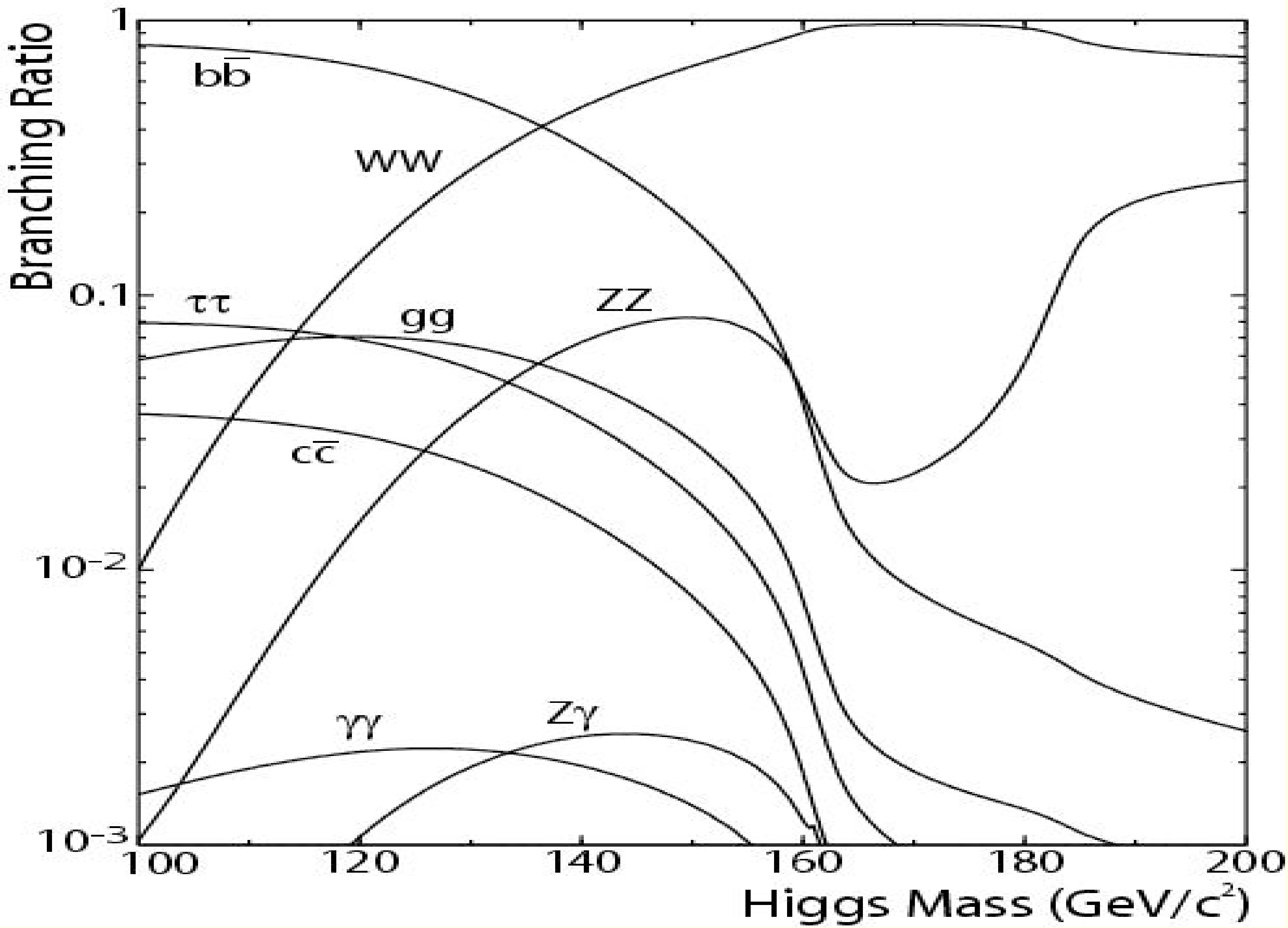
There are excellent motivations for the Higgs to have orthodox couplings to SM particles but heretical decays.

- 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.

- **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 $WW \to h$.**



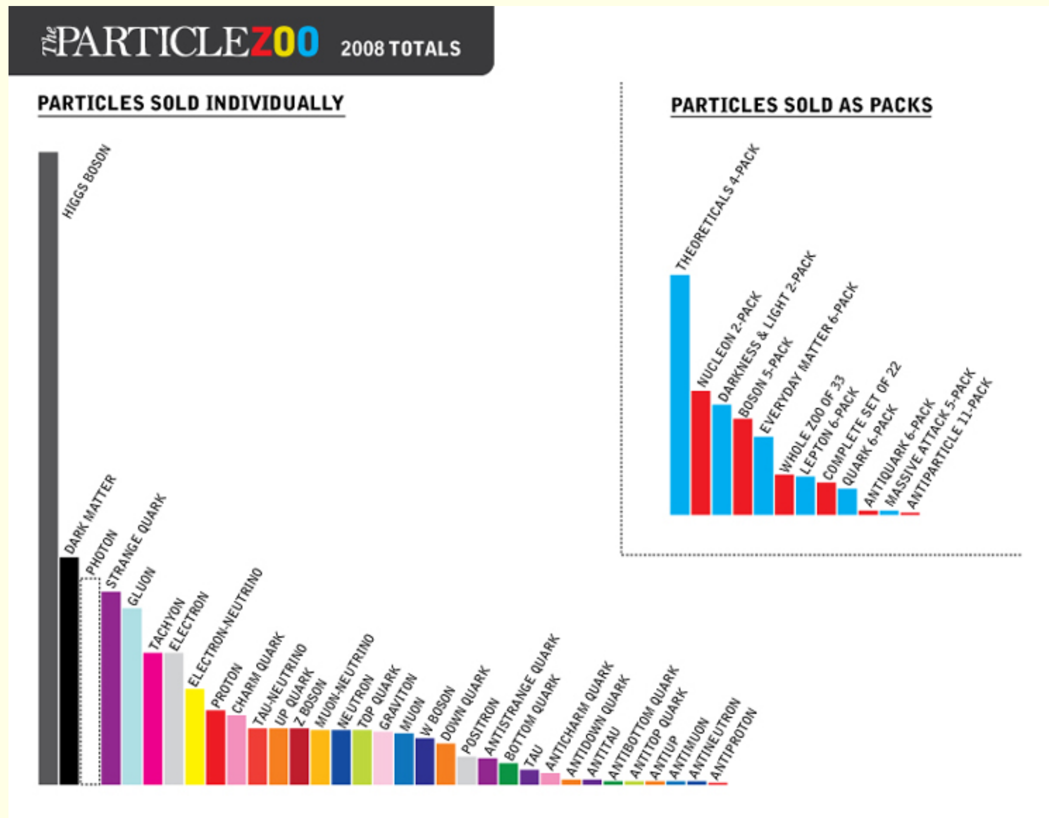
- **In the absence of new physics, Higgs decays are also determined by these same couplings.**



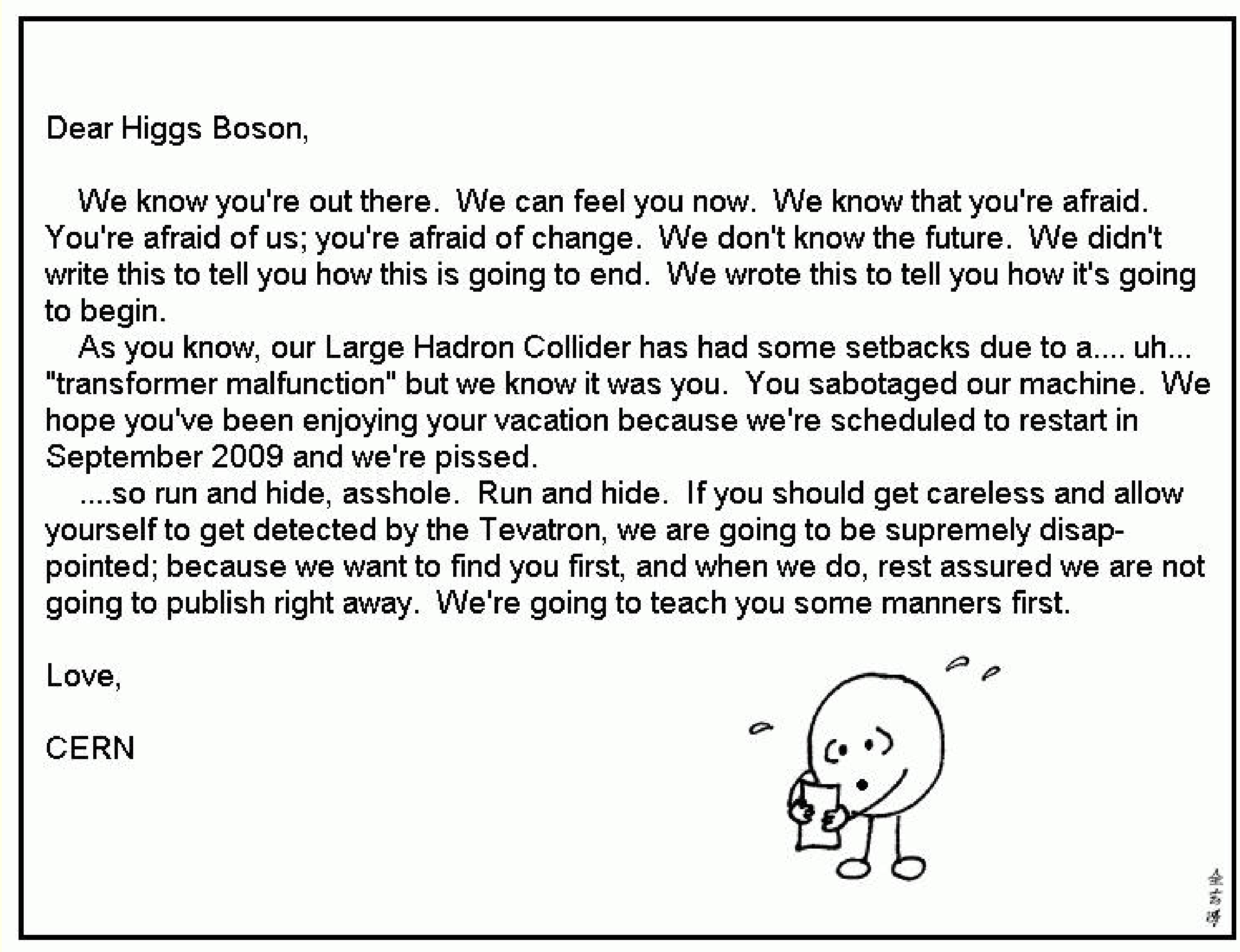
- **However, Beyond the SM physics could completely alter the Higgs decay patterns.**

  This may make it hard to get our hands on the Higgs boson at the LHC.

If you are too impatient to wait to find a Higgs at the LHC, you can buy one online. Of all known and hypothesized particles the Higgs is the most popular.



Or, you could write a letter to the Higgs boson:



Dear Higgs Boson,

We know you're out there. We can feel you now. We know that you're afraid. You're afraid of us; you're afraid of change. We don't know the future. We didn't write this to tell you how this is going to end. We wrote this to tell you how it's going to begin.

As you know, our Large Hadron Collider has had some setbacks due to a.... uh... "transformer malfunction" but we know it was you. You sabotaged our machine. We hope you've been enjoying your vacation because we're scheduled to restart in September 2009 and we're pissed.

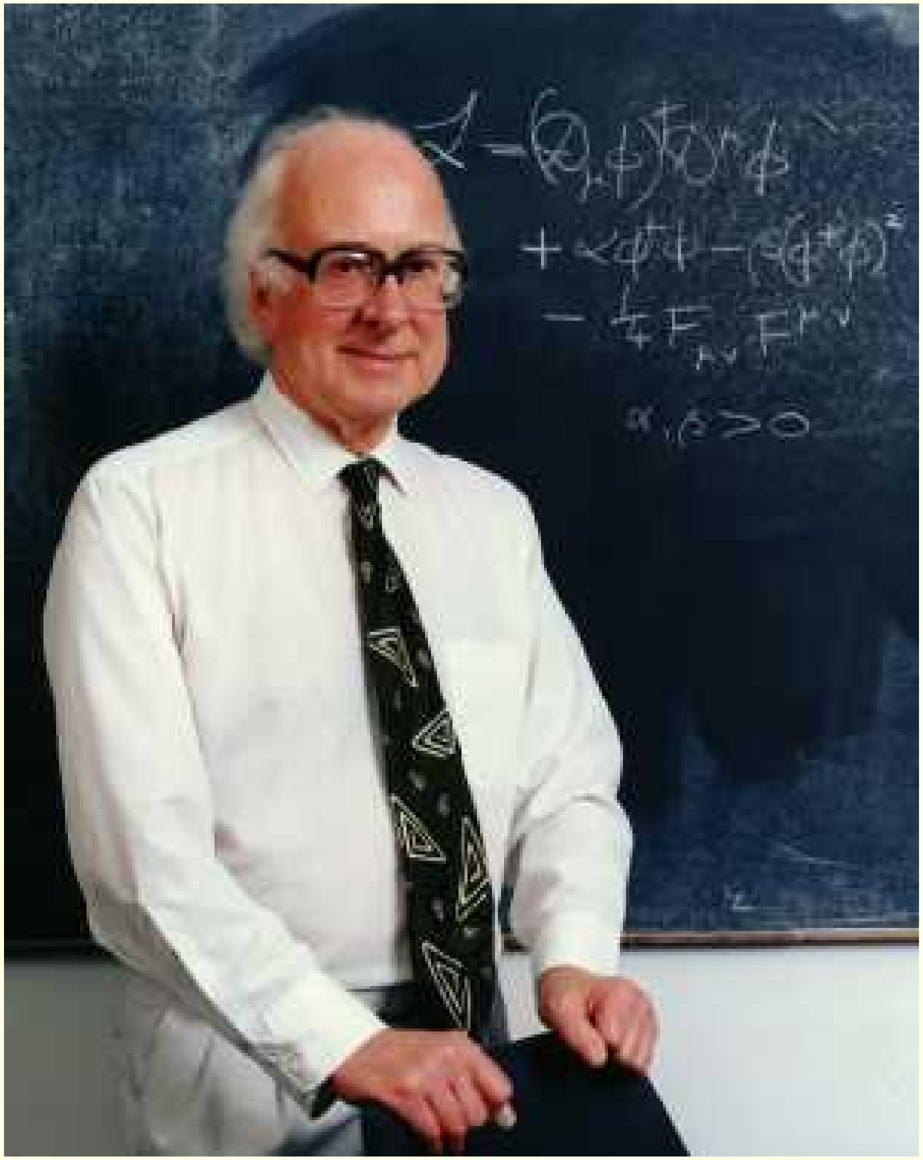
....so run and hide, asshole. Run and hide. If you should get careless and allow yourself to get detected by the Tevatron, we are going to be supremely disappointed; because we want to find you first, and when we do, rest assured we are not going to publish right away. We're going to teach you some manners first.

Love,

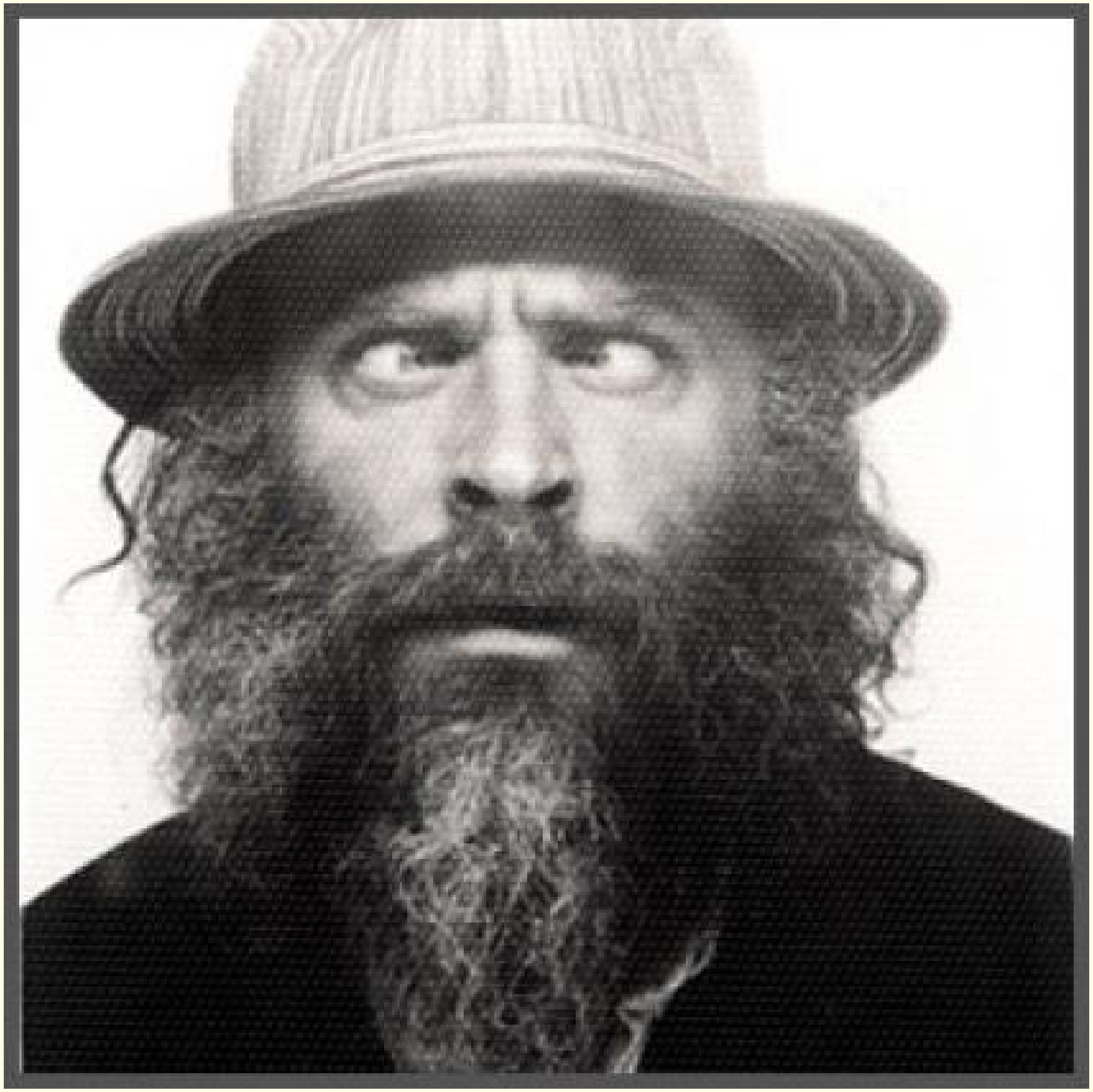
CERN

The problem is that we really should not count on knowing what the Higgs looks like. It could be ...

Priestly, highly orthodox



Ornery/ mean, highly heretical



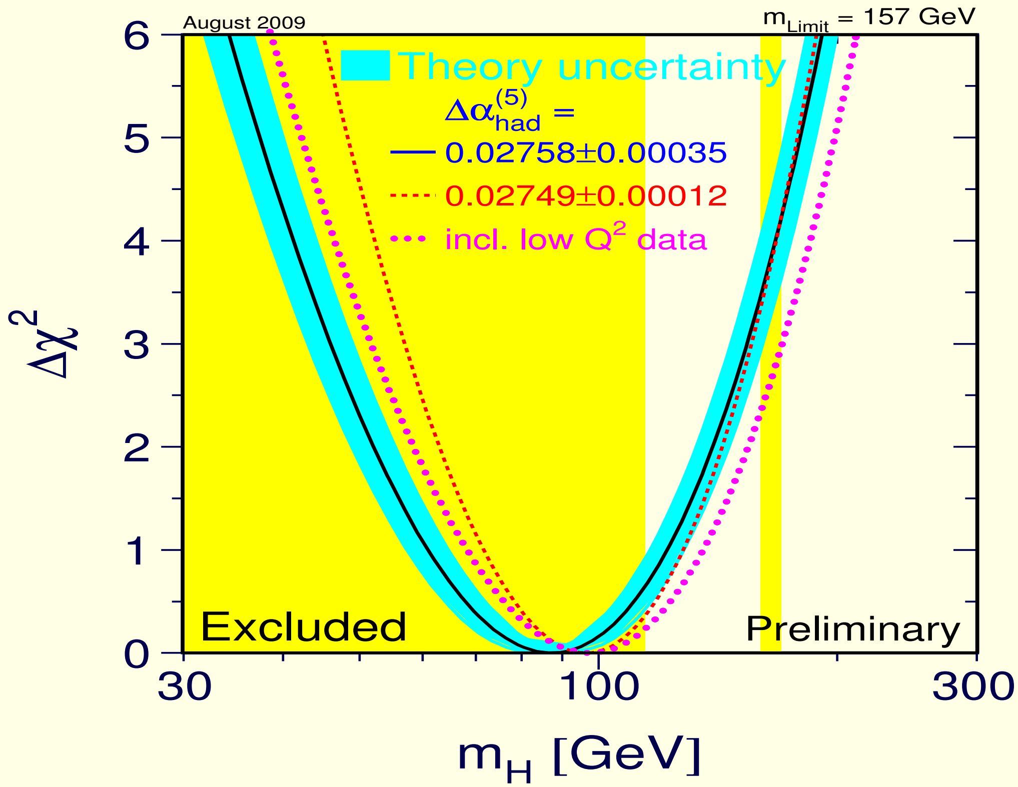
singer Daniel Higgs

Beautiful but unorthodox

Or, will the LHC bury the Higgs?

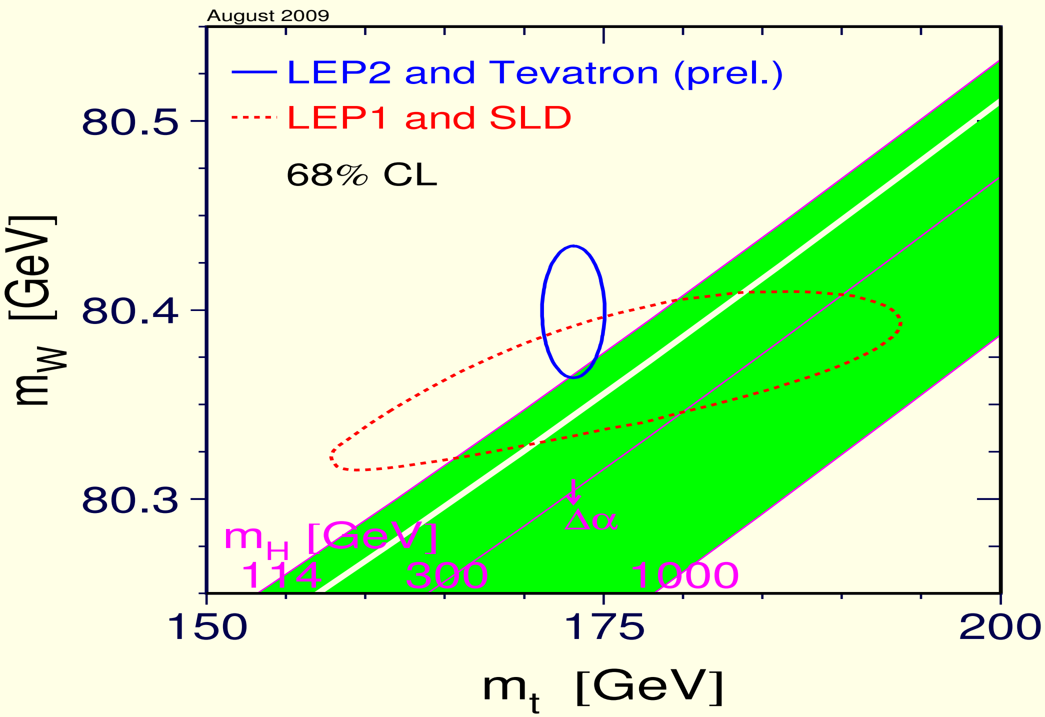
Motivation for Non-Standard Decays — single H

- 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 $m_{h_{\rm SM}} \sim 100$ 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 GeV with a 95% CL upper limit of ~ 105 GeV (Chanowitz, xarXiv:0806.0890).

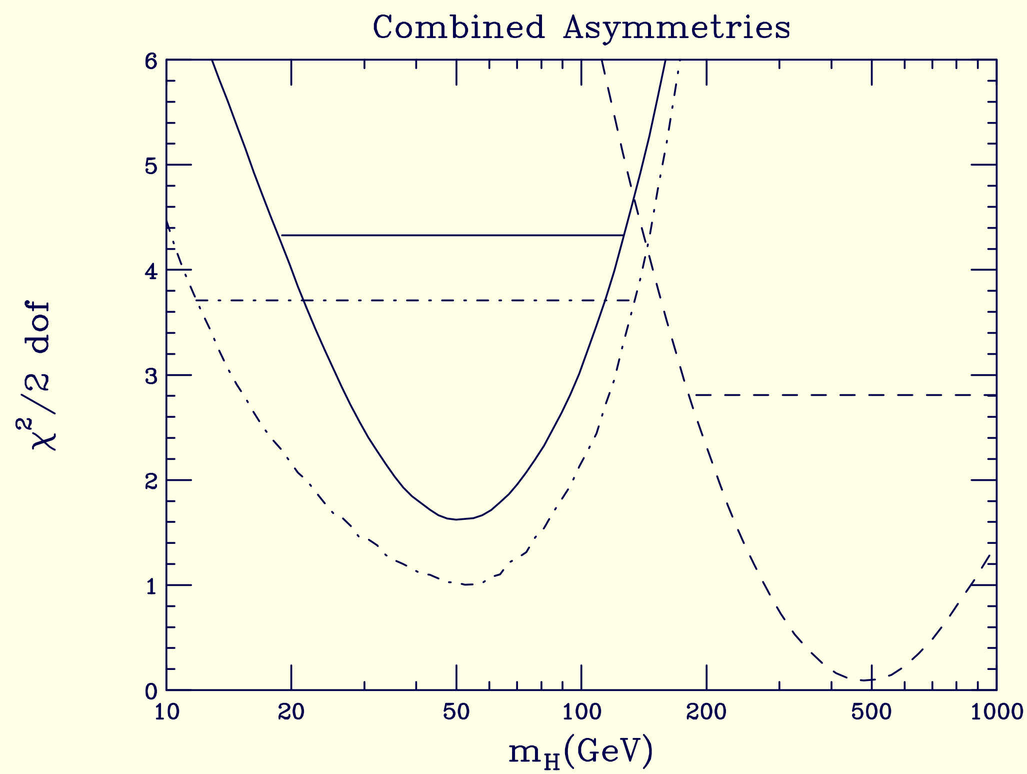


Figure 1: χ^2 **distributions as a function of** m_H **from the combination of the three leptonic asymmetries** A_{LR}, A^{ℓ}_{FB}, $A_{\ell}(P_{\tau})$ **(solid line); the three hadronic asymmetries** A^b_{FB}, A^c_{FB}, **and** Q_{FB} **(dashed line); and the three** m_H**-sensitive, nonasymmetry measurements,**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

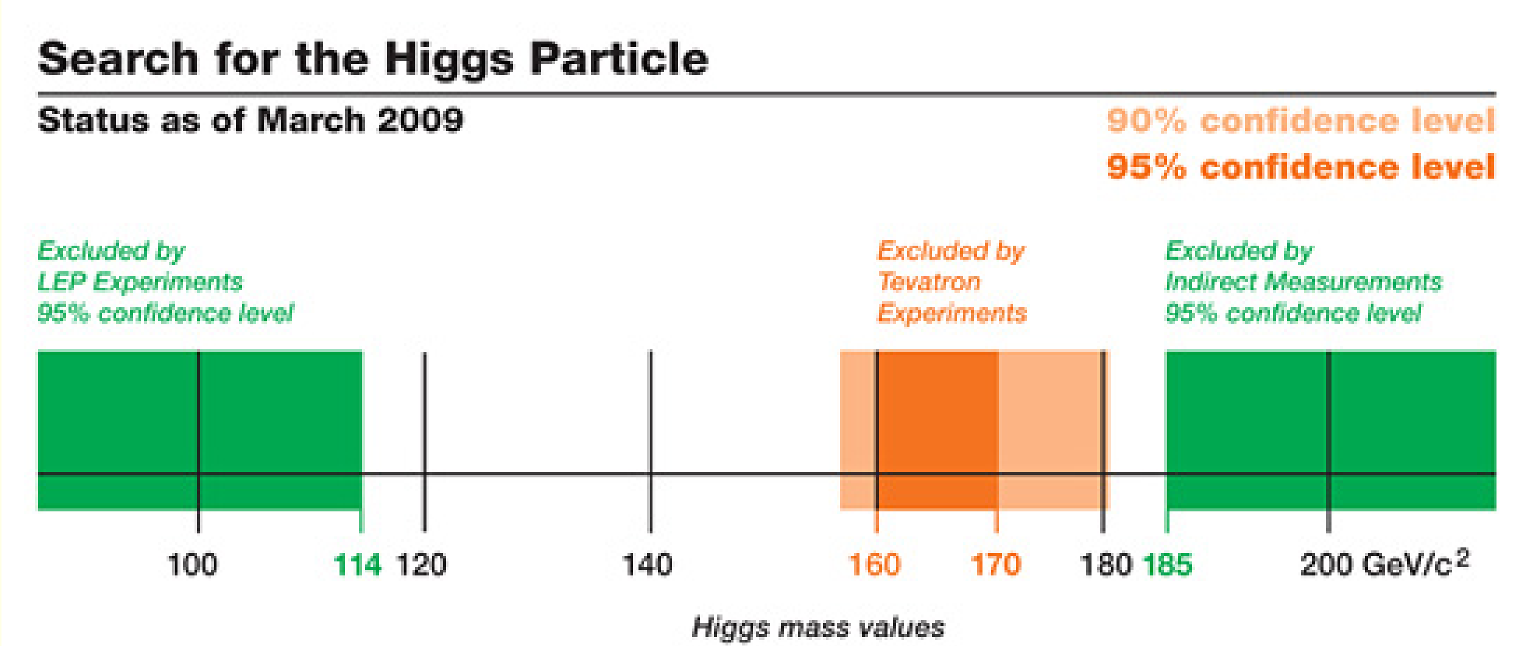
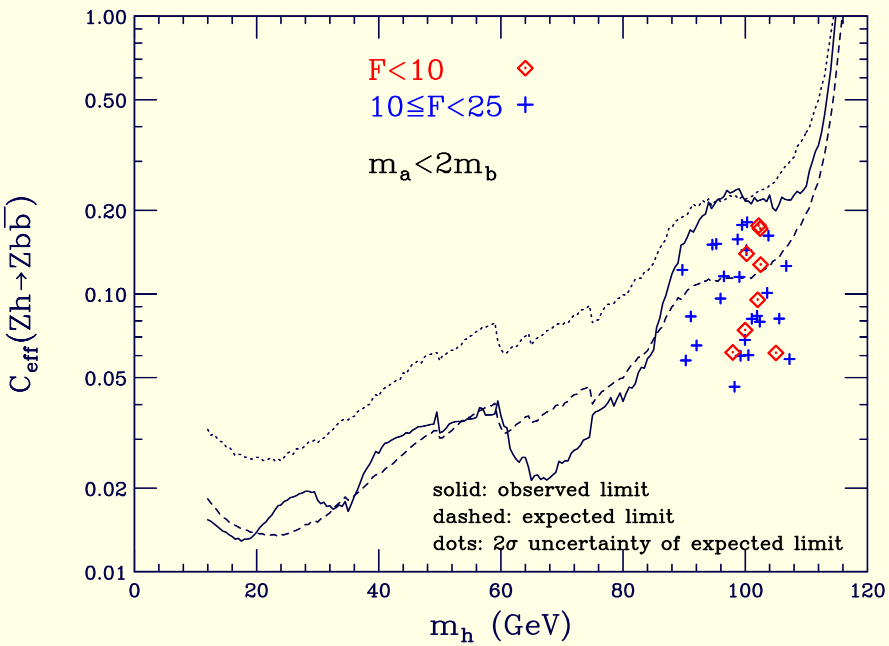


Table 1: LEP m_H Limits for a H with SM-like ZZ coupling, but varying decays. See (S. Chang, R. Dermisek, J. F. Gunion and N. Weiner, Ann. Rev. Nucl. Part. Sci. 58, 75 (2008) [arXiv:0801.4554 [hep-ph]]).

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 $m_H \leq 105$ 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.**



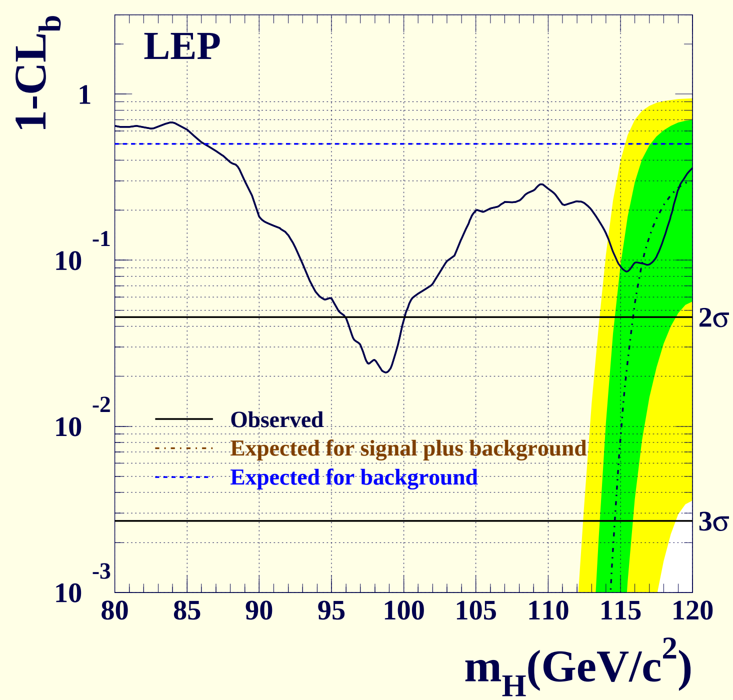


Figure 2: Plots for the $Zb\bar{b}$ final state. F is the m_Z-fine-tuning measure for the NMSSM.

The simplest possibility for the excess is to have $m_H \sim 100~\mathrm{GeV}$ and $B(H \to b\bar{b}) \sim 0.1 B(H \to b\bar{b})_{SM}$ (assuming H has SM ZZ coupling as desired for precision electroweak) with the remaining H decays being to one 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.

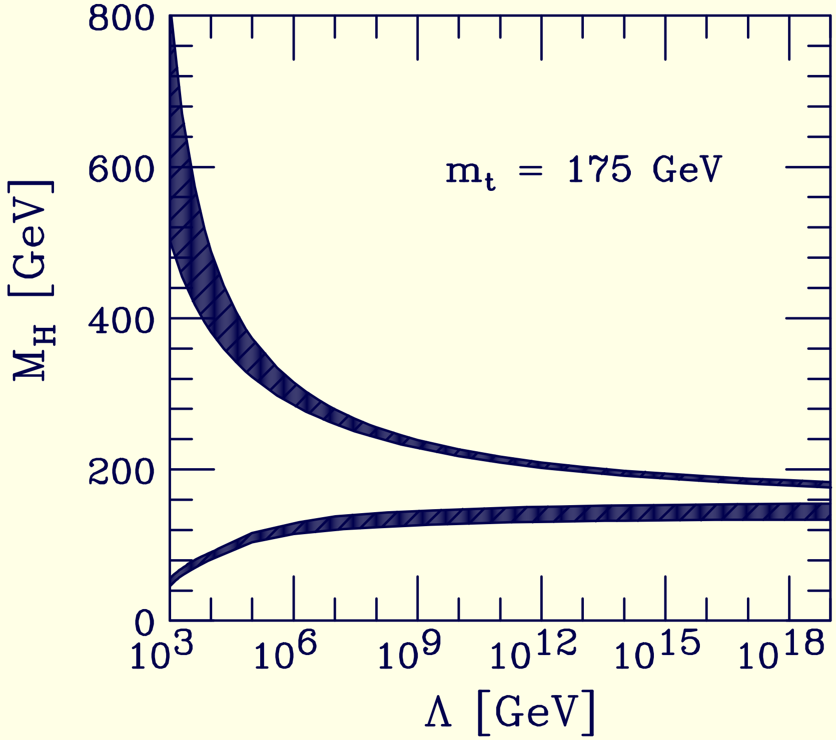


Figure 3: Triviality and global minimum constraints on $m_{h_{\rm SM}}$ vs. Λ.

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

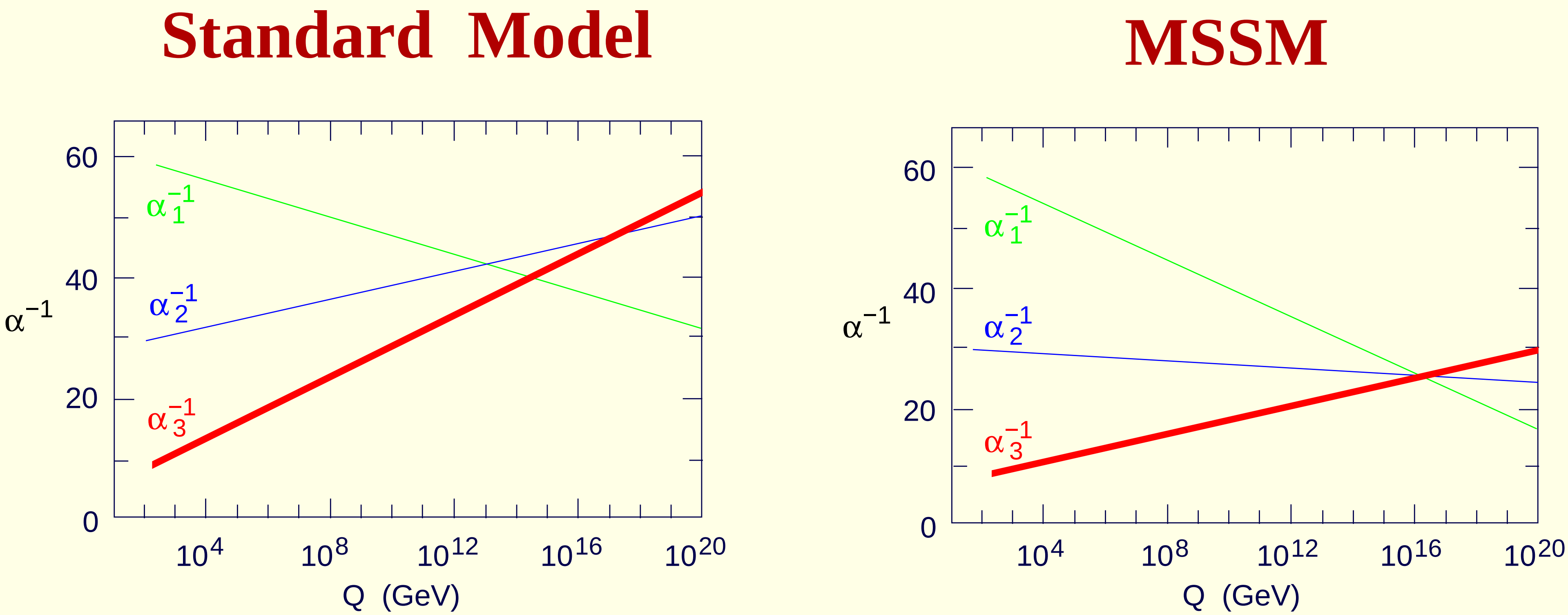


Figure 4: **Unification of couplings constants ($\alpha_i = g_i^2/(4\pi)$) in the minimal supersymmetric model (MSSM) as compared to failure without supersymmetry.**

2. RGE EWSB

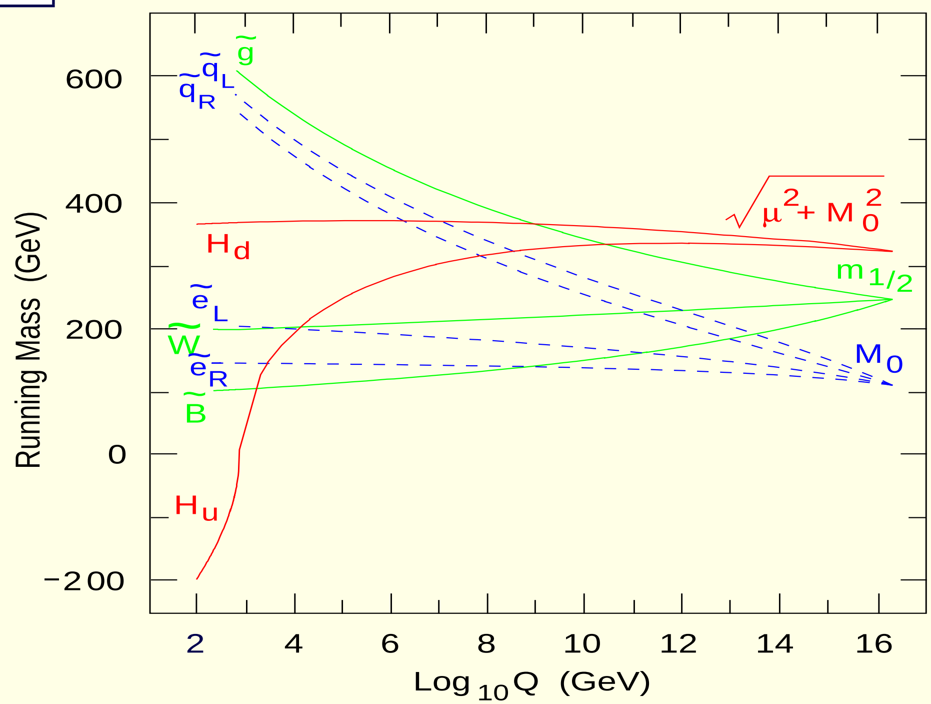


Figure 5: **Evolution of the (soft) SUSY-breaking masses or masses-squared, showing how $m^2_{H_u}$ is driven < 0 at low $Q \sim \mathcal{O}(m_Z)$.**

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 $< 100~\mathrm{GeV}$ 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.

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 $m_{h_1} \sim 90 - 100~\mathrm{GeV}$ is allowed because of $h_1 \to a_1 a_1$ 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 ($\sim 350~\mathrm{GeV}$ is just right) . Also need $m_{\widetilde{g}}$ not too far above $300~\mathrm{GeV}$.
   (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.

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 .

8. Many other non-Higgs decay modes of the h or h_1 have been proposed. Even sticking to SUSY, we have lots.

   Models which preserve R-parity and thus dark matter possibility include:

   (a) $h \to \widetilde\chi_2^0 \widetilde\chi_1^0$ followed by $\widetilde\chi_2^0 \to \widetilde\chi_1^0 f \overline{f}$ (S. Chang and T. Gregoire, arXiv:09030403): Turns out to be hard to accommodate given LEP constraints.
   (b) $h \to \widetilde\chi_1^0 \widetilde\chi_1^0 \to \widetilde G \widetilde G \gamma\gamma \to \not{E}_T \gamma\gamma$: Can't recall others who have worked on this, but I consider it likely that LEP would have seen such decays for a light h in the mass range of interest for PEW perfection.

(c) $h \to \widetilde\chi_1^0 \widetilde\chi_1^0 \to \not{E}_T$: perfectly viable for non-unified gaugino masses, but LEP limit for invisibly decaying h is $114~\mathrm{GeV}$ which is too heavy for PEW perfection.

Many other models also have dominant invisible h decay, but all suffer from the $m_h > 114~\mathrm{GeV}$ LEP limit for this mode that is less than ideal for PEW.

Models which violate R parity (and therefore require an alternative DM candidate than the $\widetilde\chi_1^0$):

(a) There are too many to list systematically. A particularly nasty one is baryon-violating R-parity decays (L.M. Carpenter, D.E. Kaplan and E-J Rhee, arXiv:hep-ph/0607204) $h \to \widetilde\chi_1^0 \widetilde\chi_1^0 \to (3j)(3j)$.

Such a multi-jet mode is least constrained by LEP ($m_h > 82~\mathrm{GeV}$ is the limit) and the lighter the h the better the agreement with precision data (especially dropping hadronic asymmetries).

Predictions regarding a light a and the NMSSM a_1

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

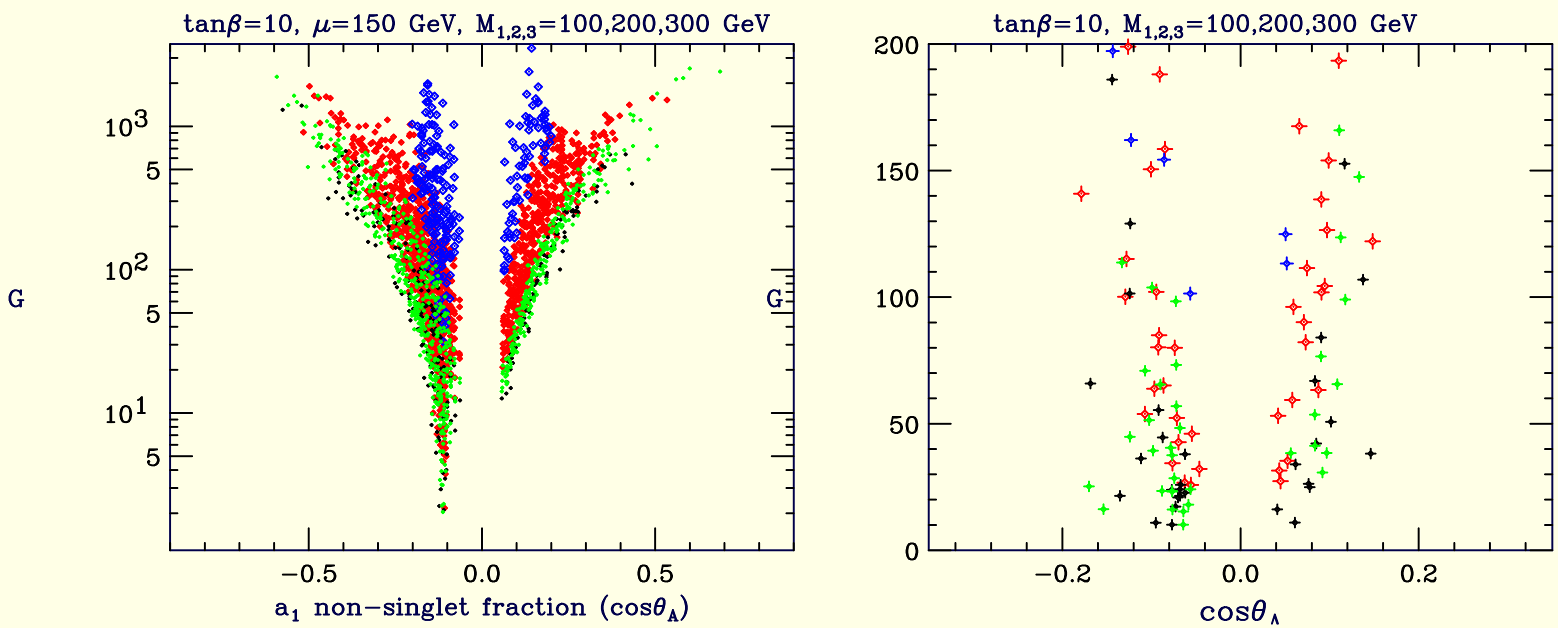


Figure 6: G vs. $\cos\theta_A$ for $M_{1,2,3} = 100, 200, 300$ GeV and $\tan\beta = 10$ from $\mu_{\rm eff} = 150$ GeV scan (left) and for points with $F < 15$ (right) having $m_{a_1} < 2m_b$ and large enough $B(h_1 \to a_1 a_1)$ to escape LEP limits. The color coding is: blue $= m_{a_1} < 2m_\tau$; red $= 2m_\tau < m_{a_1} < 7.5$ GeV; green $= 7.5$ GeV $< m_{a_1} < 8.8$ GeV; and black $= 8.8$ GeV $< m_{a_1} < 9.2$ 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_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 $m_a > 7.5~\mathrm{GeV}$ 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

$$\mathcal{L}_{af\overline{f}} \equiv iC_{af\overline{f}} \frac{ig_2 m_f}{2m_W} \overline{f} \gamma_5 f a\,, \quad \text{then} \quad C_{ab\overline{b}} = \cos\theta_A \tan\beta \qquad (1)$$

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

  The extracted limits on $C_{ab\overline{b}}$ appear in Fig. 7.

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

  This is the same as the region with least "light-a_1" fine-tuning in the NMSSM.

- **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.**

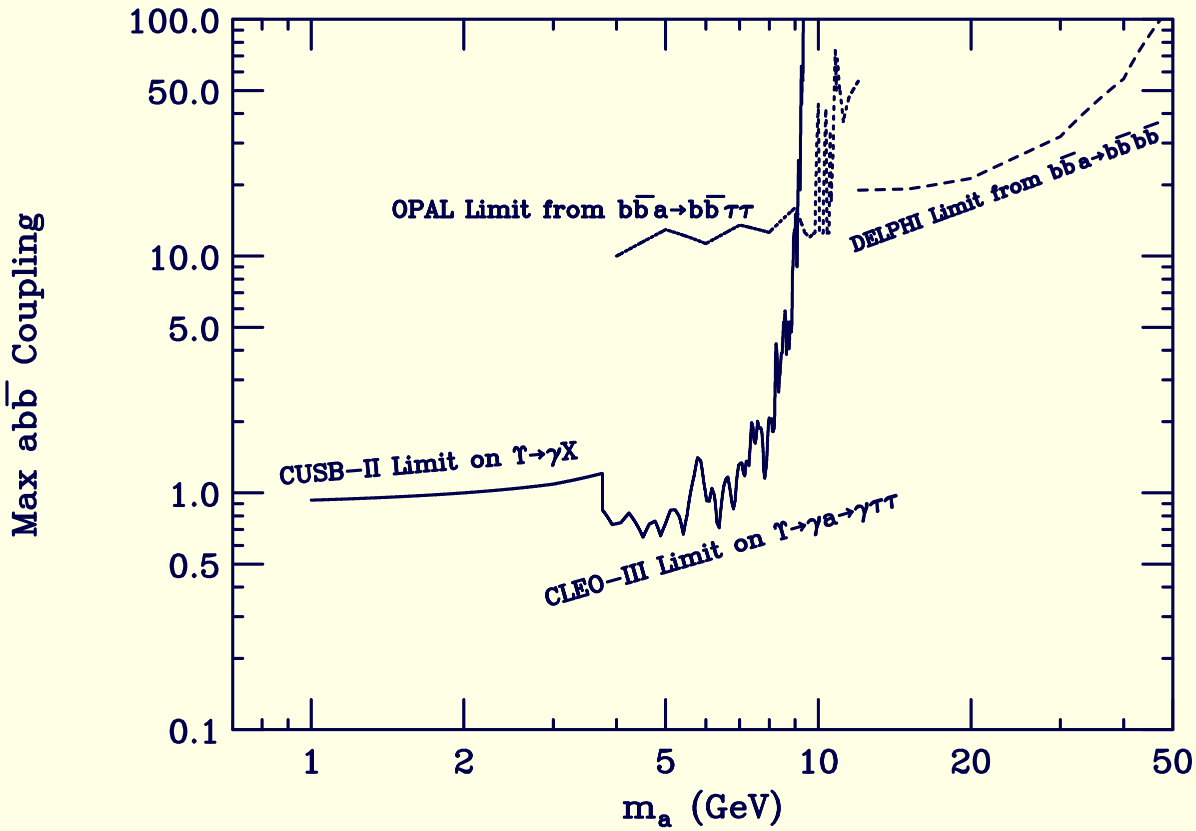


Figure 7: Limits on $C_{ab\bar b}$ from JFG, arXiv:0808.2509.

- **In the $\sim 9~\mathrm{GeV} \lesssim m_a \lesssim 12~\mathrm{GeV}$ 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.

  Perhaps now that the first η_b state has been observed, this region can be better pinned down. I have not incorporated recent work by Domingo *et al.* (arXiv:0810.4736) which models this mixing in a manner consistent with the available information. In any case, models predict many η-type states in this region, not just the one that has been observed.

- **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 $C_{ab\bar{b}}$ is needed.

  The plotted limits (mainly CLEO-III at high m_a) suggest that it is generically possible from $C_{ab\bar{b}}$ limits if $m_a > 9~\mathrm{GeV}$, but is not possible in the NMSSM scenarios with small light-a_1 fine-tuning since they do not have large $C_{ab\bar{b}}$.

- **We will see that $B(a_1 \to \mu^+\mu^-)$ 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.**

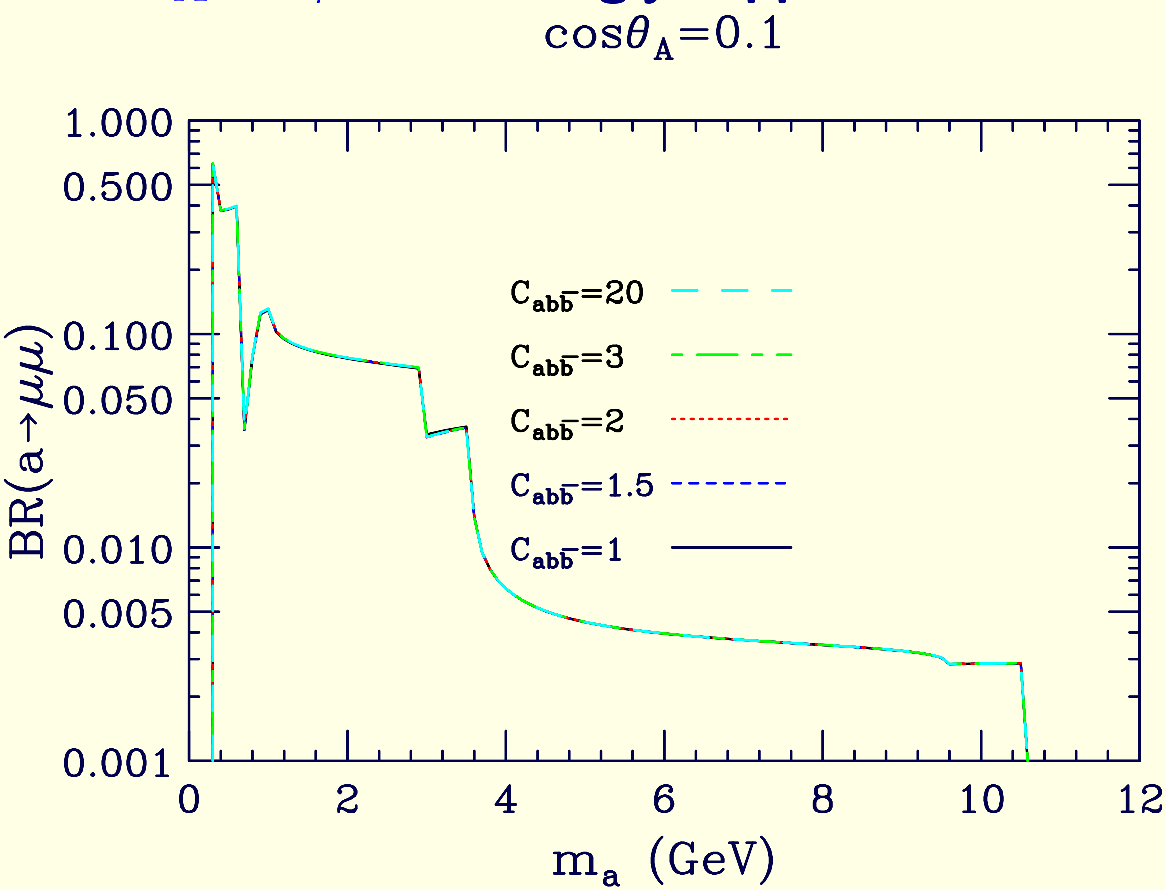


Figure 8: $B(a \to \mu^+\mu^-)$ **for preferred** $\cos\theta_A \lesssim 0.1$ **scenarios.**

- **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 $m_a < 2m_\tau$.

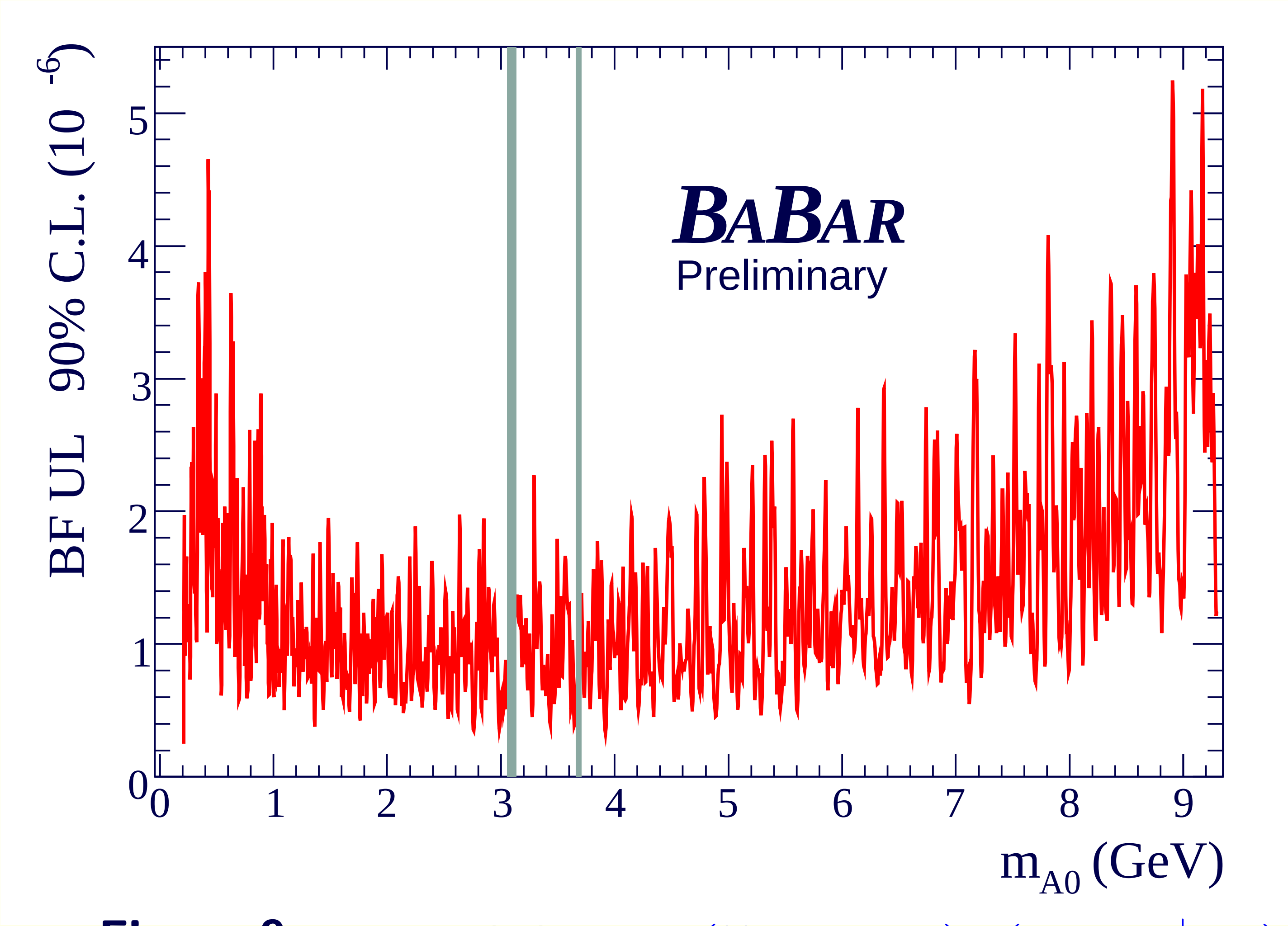


Figure 9: BaBar limits on $B(\Upsilon_{3S} \to \gamma a) B(a \to \mu^+\mu^-)$.

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 NMSSM scenarios with $B(h_1 \to a_1 a_1) > 0.7$ are eliminated; only a few at $\tan\beta \lesssim 3$ survive.

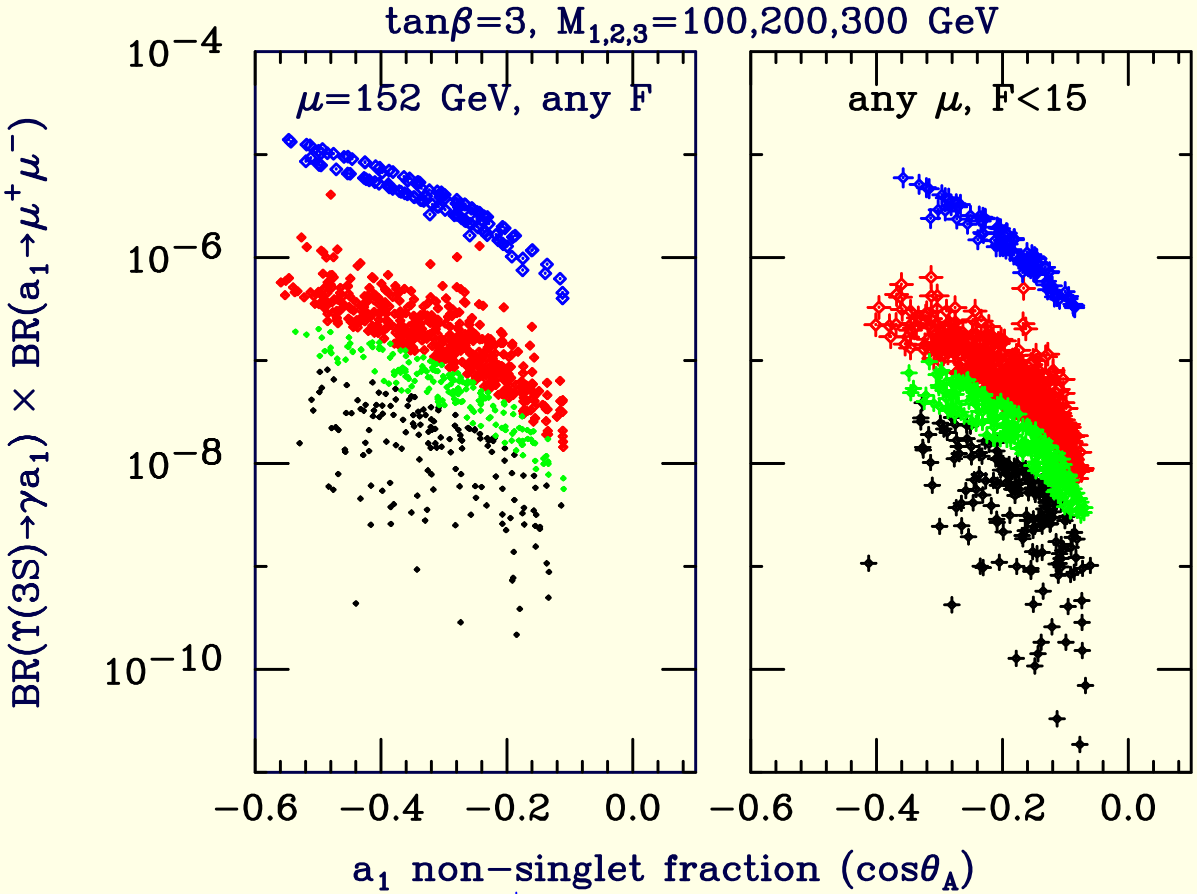


Figure 10: $B(\Upsilon_{3S} \to \gamma a_1) \times B(a_1 \to \mu^+\mu^-)$ for NMSSM scenarios with various ranges for m_{a_1}: blue = $m_{a_1} < 2m_\tau$; red = $2m_\tau < m_{a_1} < 7.5~\mathrm{GeV}$; light grey (green) = $7.5~\mathrm{GeV} < m_{a_1} < 8.8~\mathrm{GeV}$; and black = $8.8~\mathrm{GeV} < m_{a_1} < 2m_B~\mathrm{GeV}$. 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 $m_{a_1} < 2m_B$.

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 rules out this possibility (JFG+Dermisek, in preparation). And LHC constraints on the a or a_1 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 $L = 630~\mathrm{pb}^{-1}$ 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 $m_\epsilon = 7.2$ GeV and can be adopted to limit this same ratio for a general a or the NMSSM a_1.

One must compute the a cross section as a function of $\cos\theta_A$ and $\tan\beta$

coming from $gg \to a$ and higher order diagrams. The resulting Tevatron limits, formulated in terms of $\cos\theta_A$, are shown below in comparison to CLEO-III limits (from the $a \to \tau^+\tau^-$ channel).

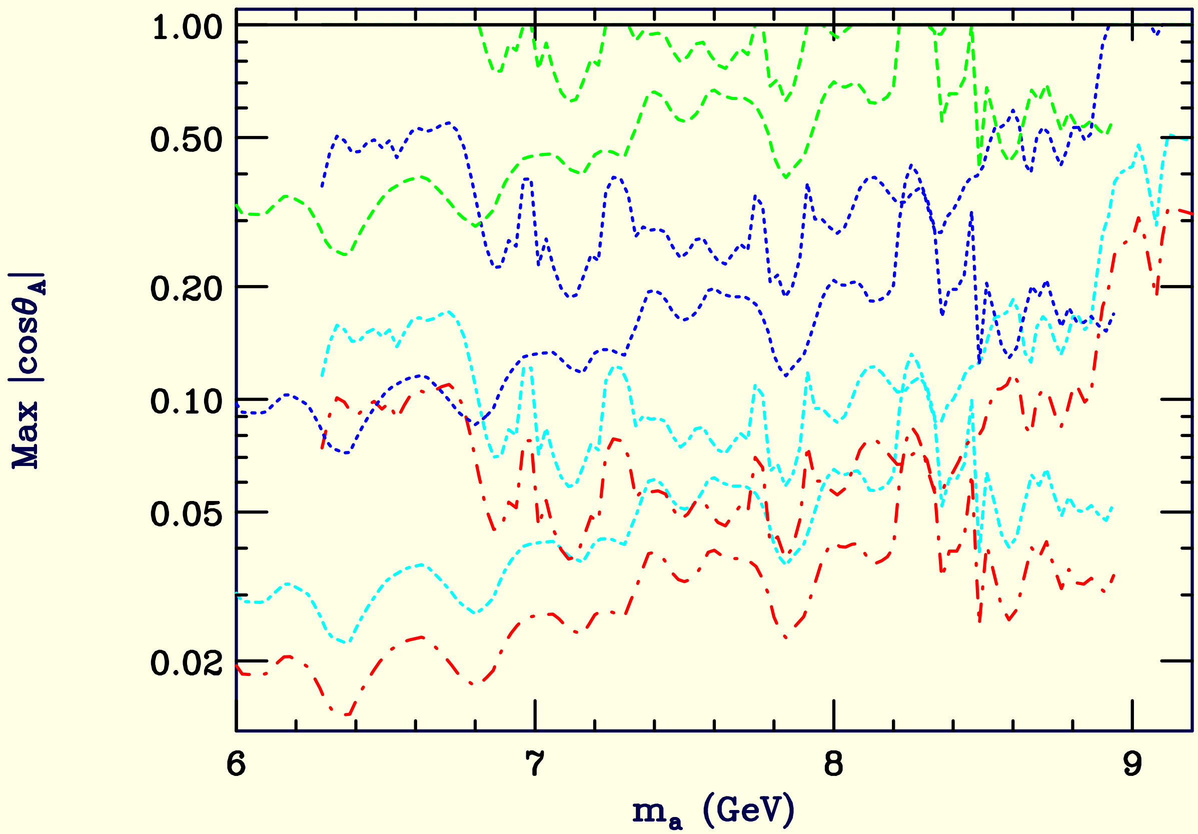


Figure 11: CLEO-III limits compared to $L = 630~\mathrm{pb}^{-1}$ CDF limits. Curves are for $\tan\beta = 1$ (highest), 3, 10, 32 and 50 (lowest). The CDF limits cross below the CLEO-III limits for $m_{a_1} \gtrsim 8.3~\mathrm{GeV}$.

BaBar Υ_{3S} limits appear to be very close to the Tevatron limits in the plotted mass range.

We can also extrapolate to $L = 10~\mathrm{fb}^{-1}$. The comparison of $C_{ab\bar{b}}$ limits is below.

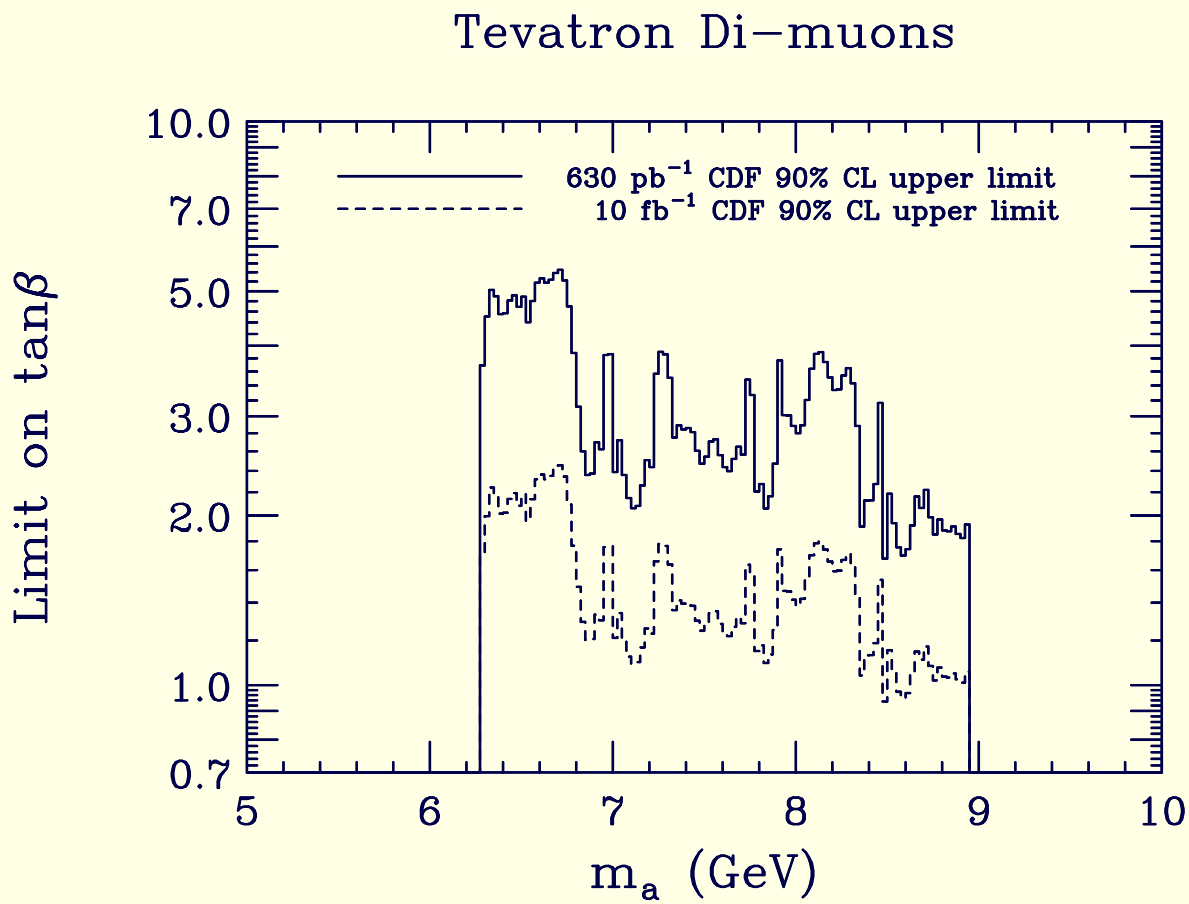


Figure 12: $L = 630~\mathrm{pb}^{-1}$ vs. $L = 10~\mathrm{fb}^{-1}$ CDF limits on $C_{ab\bar{b}}$ using $\tan\beta = C_{ab\bar{b}}$ notation..

Note that the $L = 10~\mathrm{fb}^{-1}$ statistically extrapolated limits are approaching the $\tan\beta = C_{ab\bar{b}} \sim 1$ level that begins to impact the most preferred

NMSSM scenarios.

For $M_{\mu^+\mu^-} > 9\ \mathrm{GeV}$, CDF has not presented results obtained using the ratio R. Instead, we use the event number plots that extend to larger $M_{\mu^+\mu^-}$. We adopt the conservative approach of assuming that a 5σ excess in any given bin would have been seen.

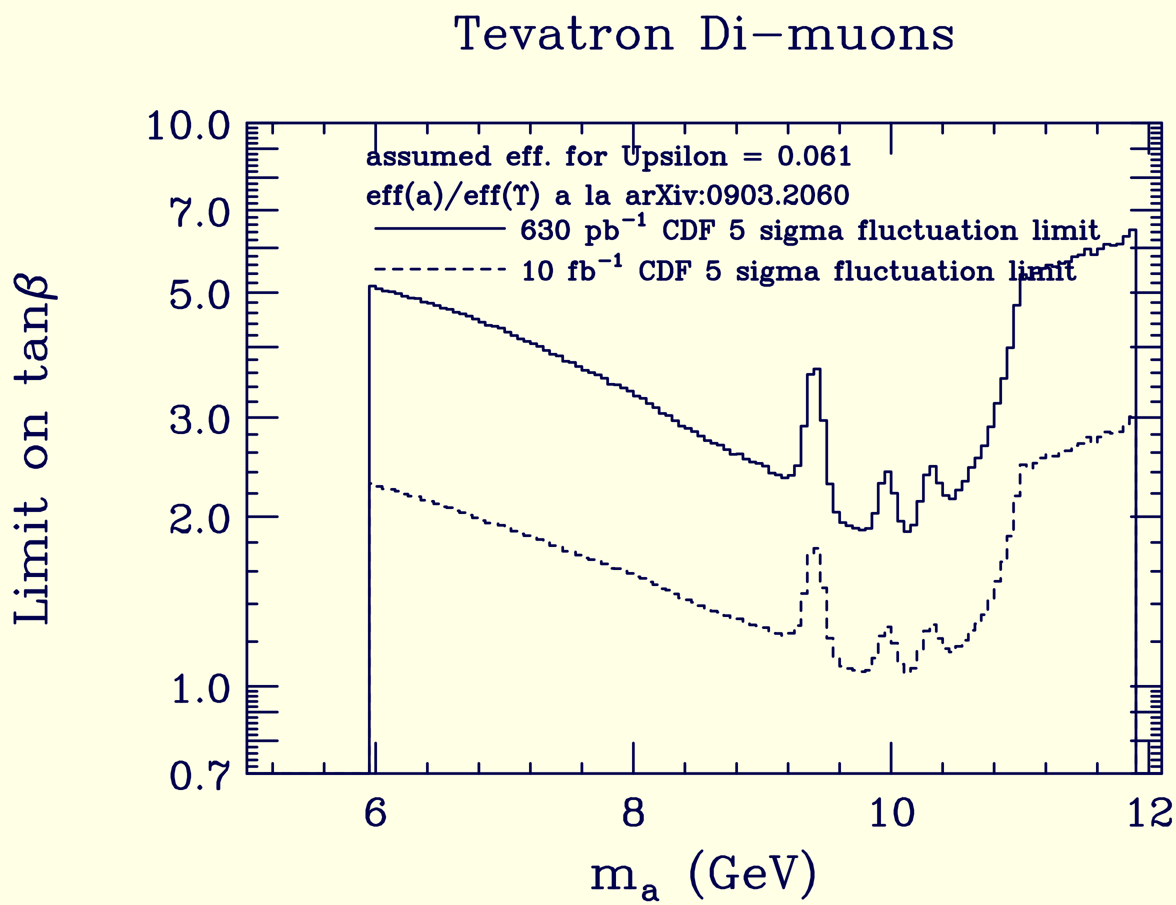


Figure 13: $L = 630\ \mathrm{pb}^{-1}$ and $10\ \mathrm{fb}^{-1}$ limits based on no 5σ excess in any bin.

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 by CMS and ATLAS, and for reasons that I am still trying to explore with the experimentalists the di-muon background in the CMS studies is larger than that in the ATLAS studies. Also, only ATLAS has presented public results — see Fig. 14.

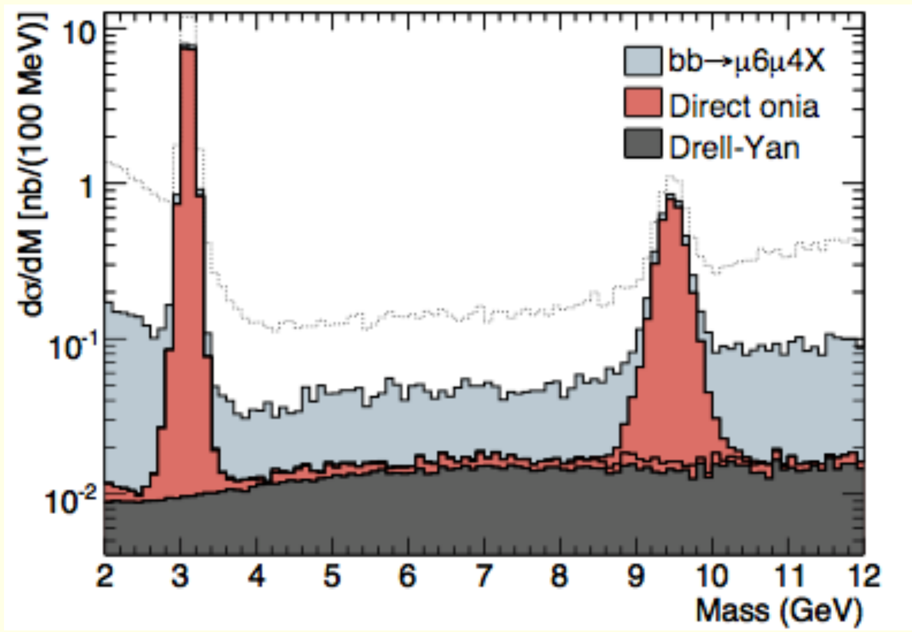


Figure 14: ATLAS dimuon spectrum prediction after corrections for acceptance and efficiencies.

My analysis follows:

1. Fig. 14 (which assumed $\sqrt{s} = 14~\mathrm{TeV}$) shows a background level of order $d\sigma/dM_{\mu^+\mu^-} \sim 50 - 90~\mathrm{pb}/0.1~~\mathrm{GeV}$ (where the mass resolution is comparable to the $0.1~~\mathrm{GeV}$ bin size) in the part of the $M_{\mu^+\mu^-} \in [8~\mathrm{GeV}, 10~\mathrm{GeV}]$ region outside the Υ peak region.
2. For $L = 10~\mathrm{pb}^{-1}$, the statistical errors for the event number per bin estimated from the above plot are of order 0.03 to 0.05 in this same mass range.
3. The σ for $a_1 \to \mu^+\mu^-$ (all events will fall into one bin) assuming $\tan\beta = 10$ and $\cos\theta_A = 0.1$ will range from $4000 - 9000~\mathrm{pb} \times [B(a_1 \to \mu^+\mu^-) \sim 0.003] \sim 12 - 27~\mathrm{pb}$ to be compared to the 1σ errors of ~ 1.5 to ~ 4.5 per bin over this same mass interval (outside the Upsilon resonance region).
4. The resulting statistical significance of the a_1 one-bin peak then varies from $\sim 8\sigma$ at $m_{a_1} = 8~\mathrm{GeV}$ to $\sim 6\sigma$ at $m_{a_1} = 10~\mathrm{GeV}$.

This looks quite promising and such a study should not suffer that much from running at $\sqrt{s} = 10~\mathrm{TeV}$.

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.

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

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_1 with $m_{a_1} < 2m_b$.
- h_1 need not be exactly SM-like — h_2 can be light enough (~ 100 GeV) for precision electroweak when $g^2_{h_2WW}$ is substantial.
- Relevant scenarios arise most often for $C_{ab\bar{b}} \gtrsim 1$ especially if $\tan\beta = 2$. Current limits imply that $m_{a_1} > 7.5$ GeV is needed for $C_{ab\bar{b}} > 1$.
- The multiple LEP (and Tevatron) escapes:

  1. $B(h_1 \to a_1 a_1)$ is large, and $e^+e^- \to Zh_1 \to Za_1a_1 \to Z4\tau$ is only constrained for $m_{4\tau} < 86$ GeV (at best — lower if ZZh_1 coupling is somewhat suppressed).

2. $B(h^+ \to W^+ a_1)$ is often large, and $e^+e^- \to h^+h^- \to W^+W^- a_1 a_1$ with $a_1 \to 2\tau$ 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. $B(h_2 \to a_1 a_1)$ and/or $B(h_2 \to Z a_1)$ are large.
   Thus, even if $e^+e^- \to Z h_2$ has large σ (which is often the case since m_{h_2} is not large), would not have seen it since the $h_2 \to Z a_1$ decay was never looked for and an incomplete job was done on $h_2 \to a_1 a_1 \to 4\tau$.
5. For $\tan\beta = 1.7$ it is easy to find cases where $e^+e^- \to Z h_1 \to Z b\bar{b}$ *and* $e^+e^- \to Z h_2 \to Z b\bar{b}$ would yield a substantial contribution to the LEP $0.1 \times SM$ excess near $m_{b\bar{b}} \sim 98~\mathrm{GeV}$.
6. To observe or constrain the a_1 for these $m_{a_1} > 7.5~\mathrm{GeV}$, large $C_{ab\bar{b}}$ scenarios will most likely require both B-factory Υ results and Tevatron high luminosity data.
7. High Tevatron L would also better limit $B(t \to h^+ b)$ which at the moment is allowed up to the 40% level as these decays are included in the way CDF and D0 determine the $t\bar{t}$ cross section for the $h^+ \to W^+ a_1$.

Detecting the light h of the NMSSM

LHC

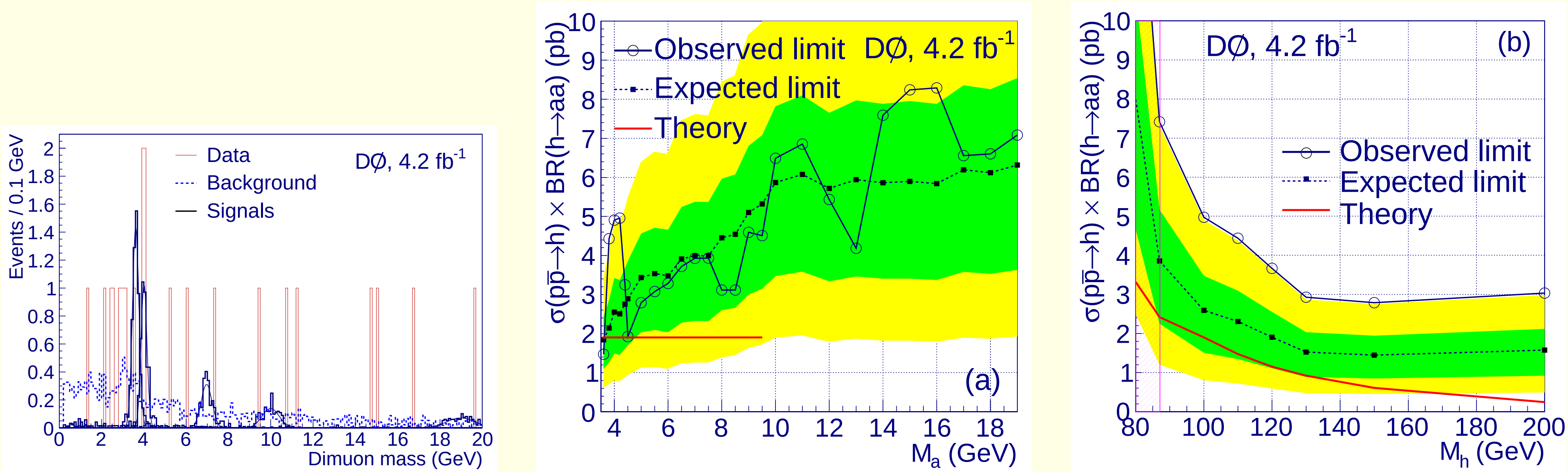
All standard LHC channels fail: *e.g.* $B(h \to \gamma\gamma)$ is much too small because of large $B(h \to aa)$.

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. 15 for a variety of luminosity and triggering assumptions.**

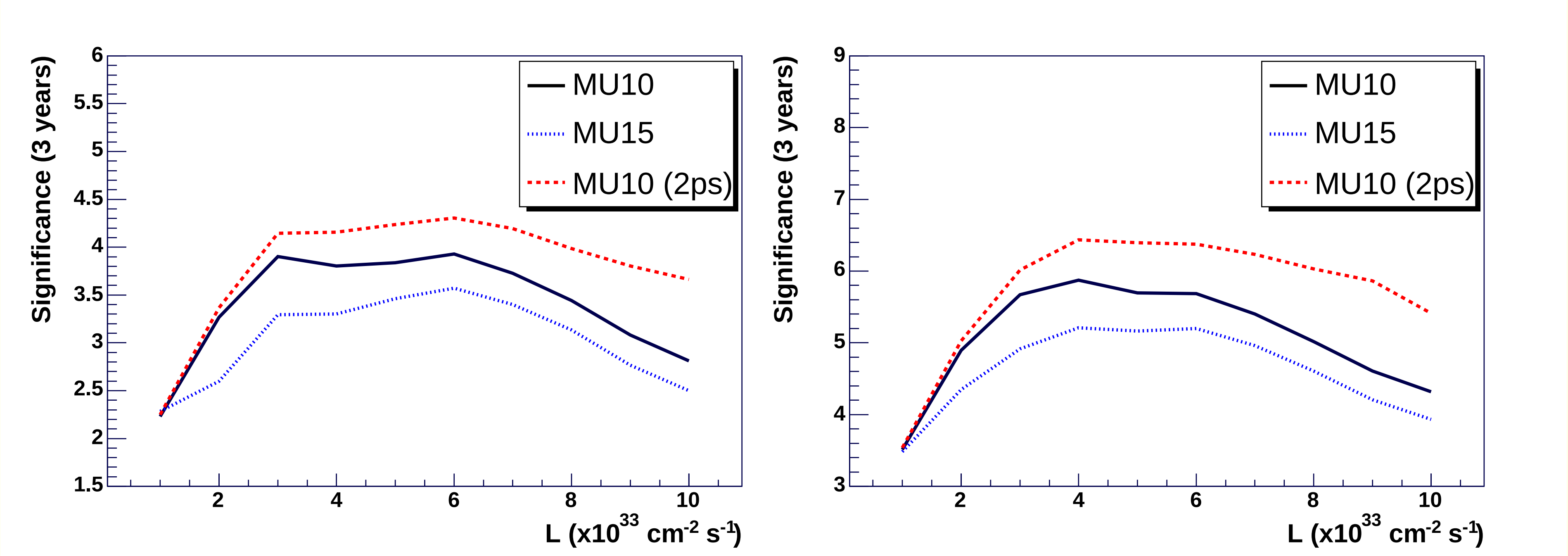


Figure 15: (a) The significance for three years of data acquisition at each luminosity. (b) Same as (a) but with twice the data. Different lines represent different μ trigger thresholds and different forward detector timing. Some experimentalists say more efficient triggering is possible, doubling the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

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

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

- $\boxed{pp \to pph \text{ case}}$

  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.

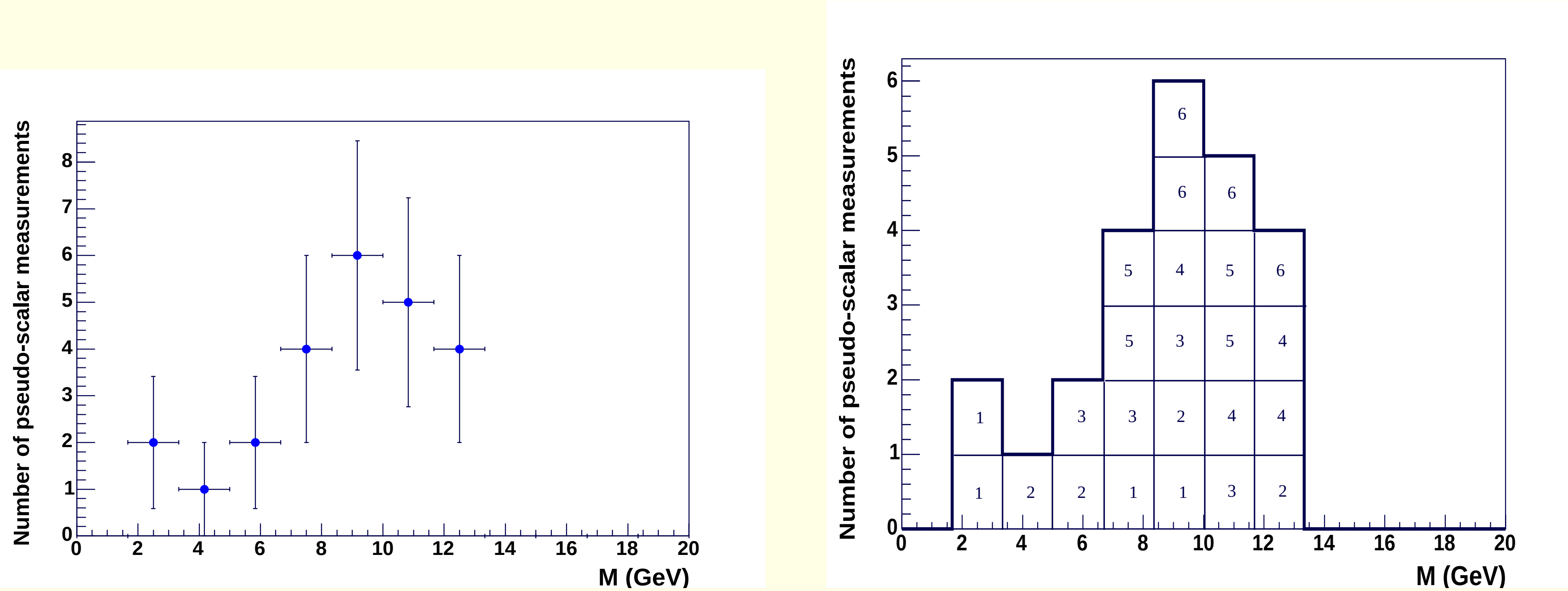


Figure 16: (a) A typical a mass measurement. (b) The same content as (a) but with the breakdown showing the 4 Higgs mass measurements for each of the 6 events, labeled $1-6$ in the histogram.

Figure 16 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.

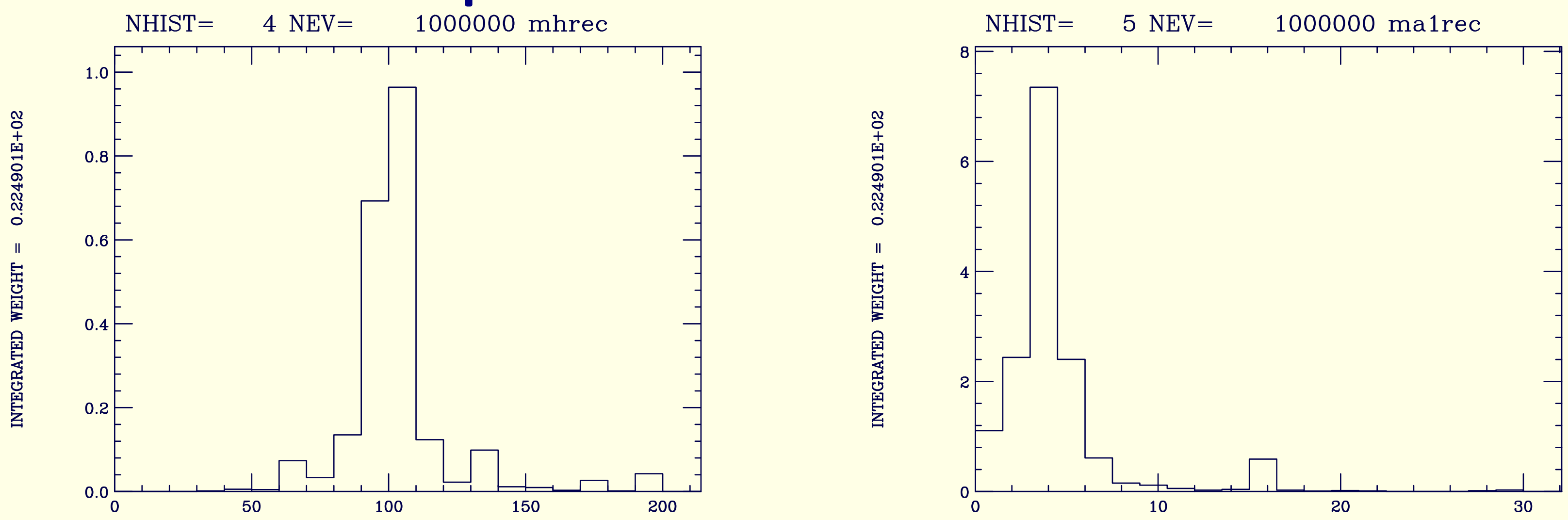


Figure 17: (a) A typical h mass distribution. (b) A typical a mass distribution. No cuts imposed; signal only.

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.

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

- **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.**

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

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

  ILC

  At the ILC, there is no problem since $e^+e^- \to ZX$ will reveal a $M_X \sim m_h \sim 90 - 100~\mathrm{GeV}$ peak no matter how the h decays.

  If there are many 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.

  But the ILC is decades away.

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).