The Ideal Higgs Scenario and Its Implications

Jack Gunion
U.C. Davis

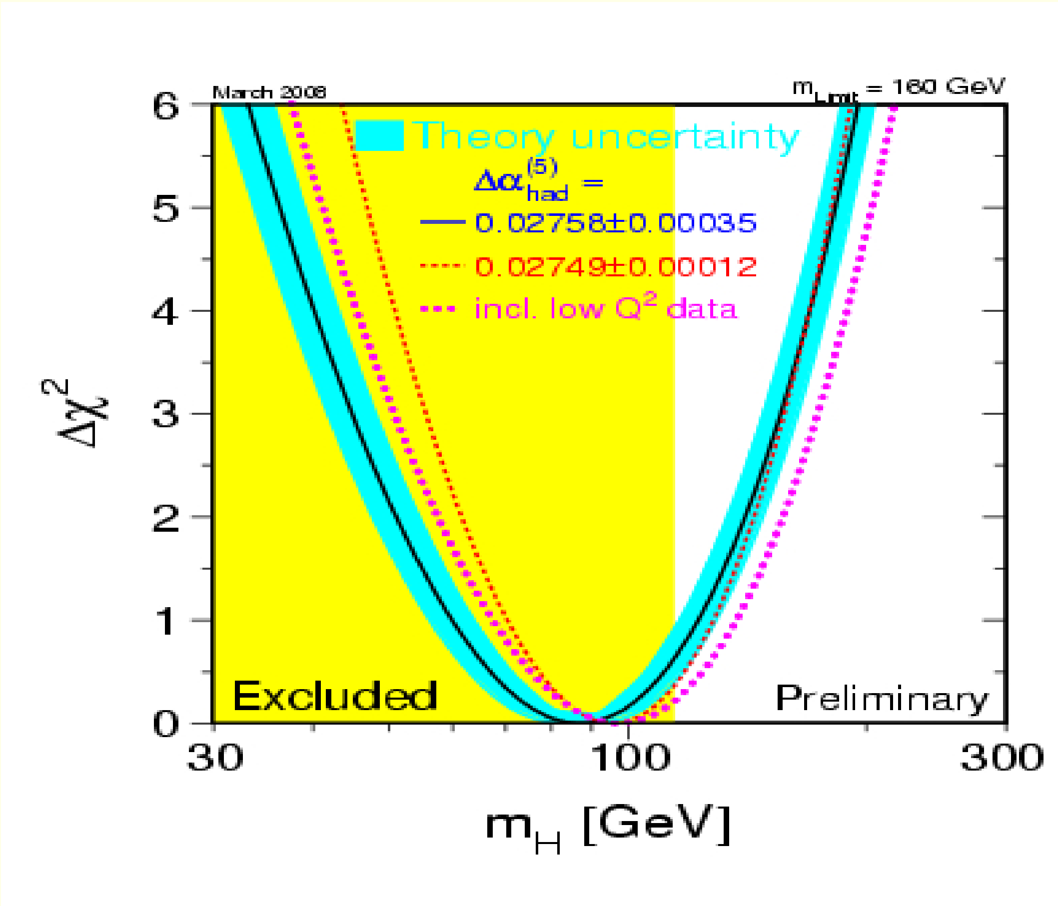
Workshop on Higgs Boson Phenomenology, Zurich, January 9, 2009

Outline

1. The "ideal" Higgs scenario and a light a with $m_a < 2m_b$.
2. Constraints from LEP and Upsilon Decays.
3. Constraints from Tevatron and LHC.
4. Relation to a_μ.
5. The NMSSM context and scenarios with $\tan\beta \geq 3$.
6. Detecting the h_1 of the NMSSM when $h_1 \to a_1 a_1 \to 4\tau$ is dominant.
7. The NMSSM scenarios with $\tan\beta < 3$.

Criteria for an ideal Higgs theory

- **The theory should predict a Higgs with SM coupling-squared to WW, ZZ and with mass in the range preferred by precision electroweak data. The latest plot is:**



At 95% CL, $m_{h_{\rm SM}} < 160\ {\rm GeV}$ 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 $m_{h_{\rm SM}} \sim 100\ {\rm GeV}$.

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).

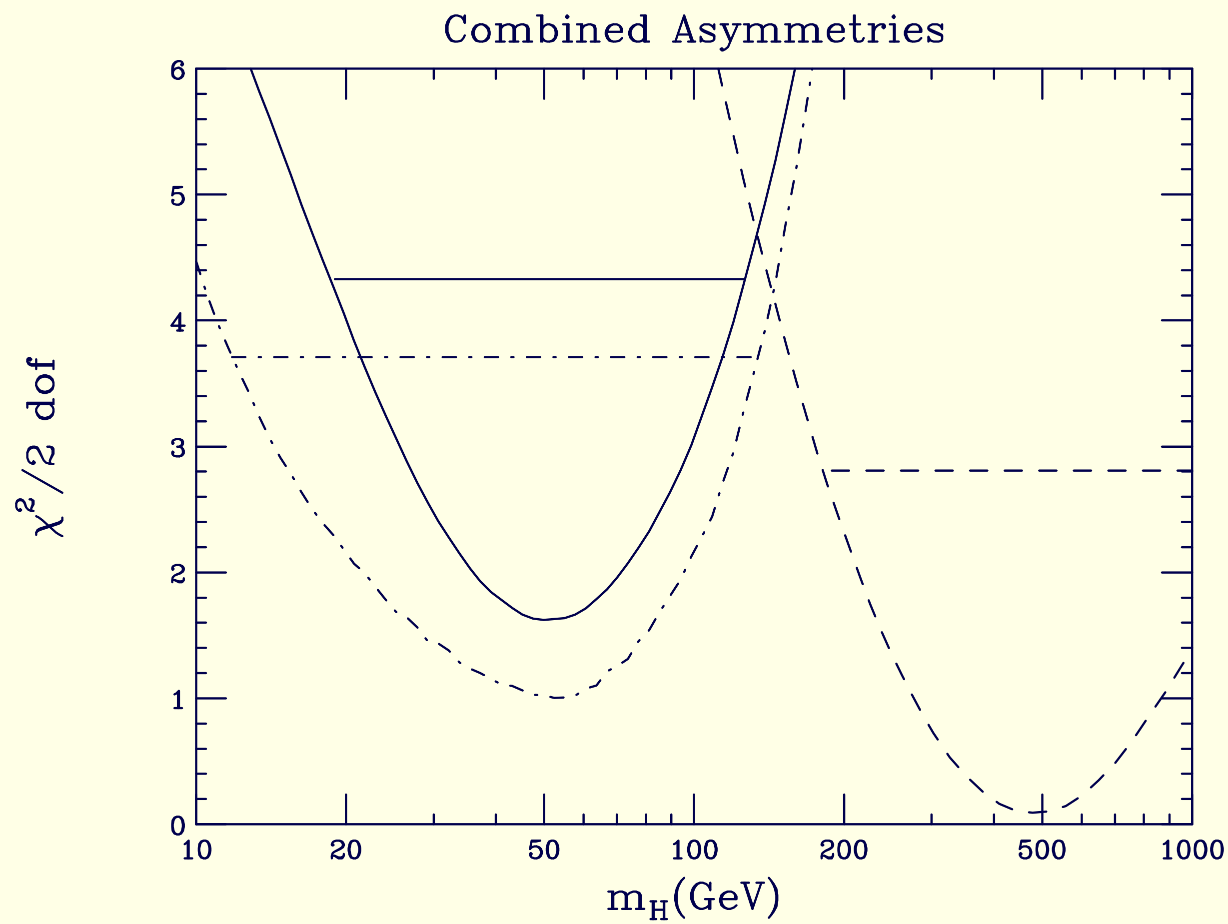


Figure 1: χ^2 distributions as a function of m_H from the combination of the three leptonic asymmetries A_{LR}, A^{ℓ}_{FB}, $A_{\ell}(P_{\tau})$ (solid line); the three hadronic asymmetries A^b_{FB}, A^c_{FB}, and Q_{FB} (dashed line); and the three m_H-sensitive, nonasymmetry measurements, m_W, Γ_Z,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

  But, at the same time, the H must escape the LEP limits on m_H.

  There are only two generic possibilities:

  1. **Spread the Higgs out (JFG+Espinosa, see also van der Bij) to such an extent that LEP sensitivity (always based on examining a given bin) no longer applies. (Not easy if $\sum_i g^2_{WWi} m_i^2 \lesssim (105~\mathrm{GeV})^2$ is imposed.)**
  2. **Allow the Higgs decays to be non-SM-like in such a way as to avoid strongest LEP limits.**

Table 1: LEP m_H Limits for a H with SM-like ZZ coupling, but varying decays.

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.

N.B. The 4τ mode LEP limit can be raised to higher mass. Chris Tully and postdoc are working on the 4τ final state in L3 context with $Z \to \nu\overline{\nu}$. Perhaps in 6 months or so will know something.

- Perhaps the ideal Higgs should be such as to predict the 2.3σ excess at $M_{b\overline{b}} \sim 98~\mathrm{GeV}$ seen in the $Z + b\overline{b}$ final state.

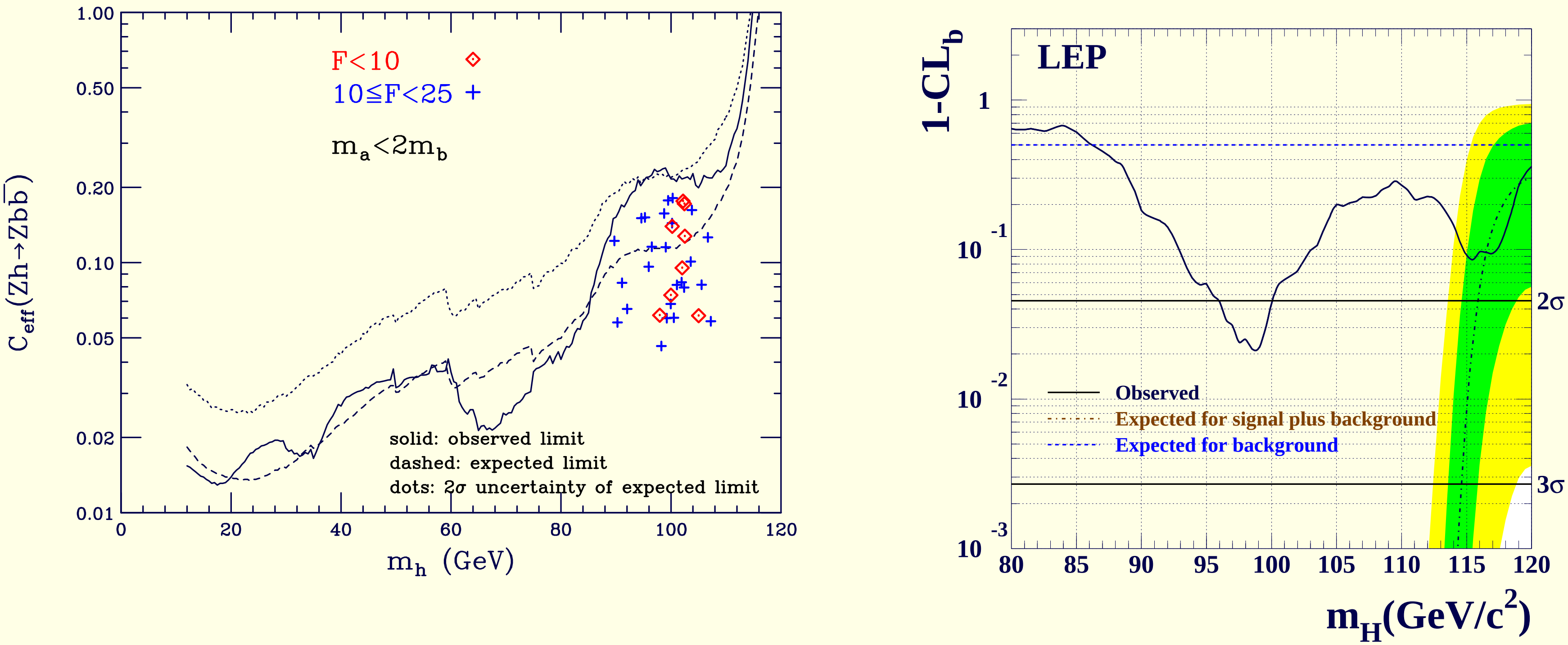


Figure 2: Plots for the $Zb\overline{b}$ final state. F is the m_Z-fine-tuning measure for the NMSSM.

The simplest possibility for explaining the excess is to have $m_H \sim 100$ 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 possibility is to suppress the $H \to b\bar{b}$ branching ratio by having a light a with $B(H \to aa) > 0.7$ and $m_a < 2m_b$ (in order to avoid LEP $Z + 4b$ limit).

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

  This scenario is: (a) easy to achieve in general 2HDM-II models, (b) not possible in the MSSM, (c) a very natural possibility in the NMSSM where a light a corresponds to a $U(1)_R$ symmetry limit.

- **Two-Higgs Doublet (2HDM) type-II and related reminders:**

  $\langle H_u \rangle = h_u$ gives mass to up-type quarks and $\langle H_d \rangle = h_d$ gives mass to down-type quarks and leptons. $v^2 = h_u^2 + h_d^2$ is fixed by the value of m_Z^2. Given this, it is useful to define the remaining free parameter of the Higgs sector as

$$\tan\beta = \frac{h_u}{h_d}\,. \tag{1}$$

In the 2HDM, the physical Higgs particles are the CP-even h, H, the CP-odd A, and the charged Higgs pair $H^\pm$.

The MSSM Higgs sector is a constrained 2HDM-II model.

The NMSSM Higgs sector has an additional (complex) singlet Higgs field and Higgs particles h_1, h_2, h_3, a_1, a_2 and $h^\pm$ (CP conserving case).

- Typical string models predict a plethora of light a's and light h's that have fermionic couplings, even if not WW couplings. $\Rightarrow$ very important to pursue strongest possible limits on light spin-0 states.

Constraints on a from LEP and Upsilon Decays

To fit with the Ideal Higgs scenario, we are especially interested in an a with $m_a < 2m_b$.

- Of particular importance are the constraints on $C_{ab\bar{b}}$, where the generic $C_{af\bar{f}}$ is defined by

$$\mathcal{L}_{af\bar{f}} \equiv iC_{af\bar{f}} \frac{ig_2 m_f}{2m_W} \overline{f} \gamma_5 f a \,. \quad (2)$$

We will only discuss models in which $C_{ab\bar{b}} = C_{a\mu^-\mu^+}$. (To escape, requires 3 or more doublets.)

The most useful current limits on $C_{ab\bar{b}}$ for a light a come from CUSB-II (old 90% CL) limits on $B(\Upsilon \to \gamma X)$ (where X is assumed to be visible), recent CLEO-III limits on $B(\Upsilon \to \gamma a)$ assuming $a \to 2\tau$, OPAL limits on $e^+e^- \to b\bar{b}a \to b\bar{b}2\tau$ and DELPHI limits on $e^+e^- \to b\bar{b}a \to b\bar{b}b\bar{b}$.

(The Tevatron limits on $b\bar{b}a \to b\bar{b}2\tau$ apply for quite high m_a, beyond the region we wish to focus on.)

The CLEO-III limits are now particularly strong.

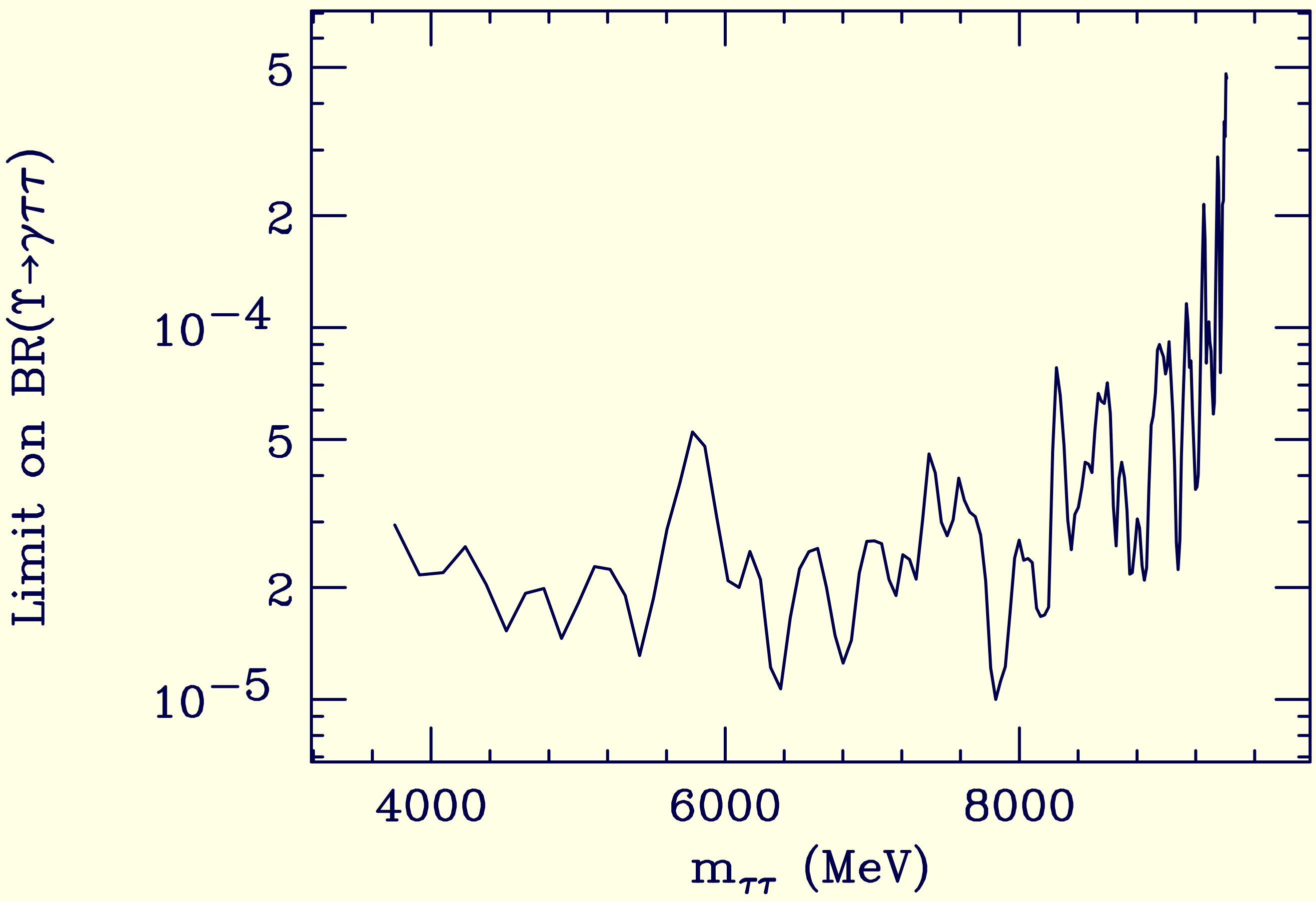


Figure 3: CLEO-III limits on $B(\Upsilon \to \gamma\tau^+\tau^-)$.

- For the most part the extracted $C_{ab\bar{b}}$ limits (JFG, arXiv:0808.2509) are quite model-independent other than weak dependence on up-quark couplings (mostly via the top gg coupling loop, but also through $B(a \to \tau\tau)$ and $B(a \to b\bar{b})$). The extracted limits on $C_{ab\bar{b}}$ appear in Fig. 4,

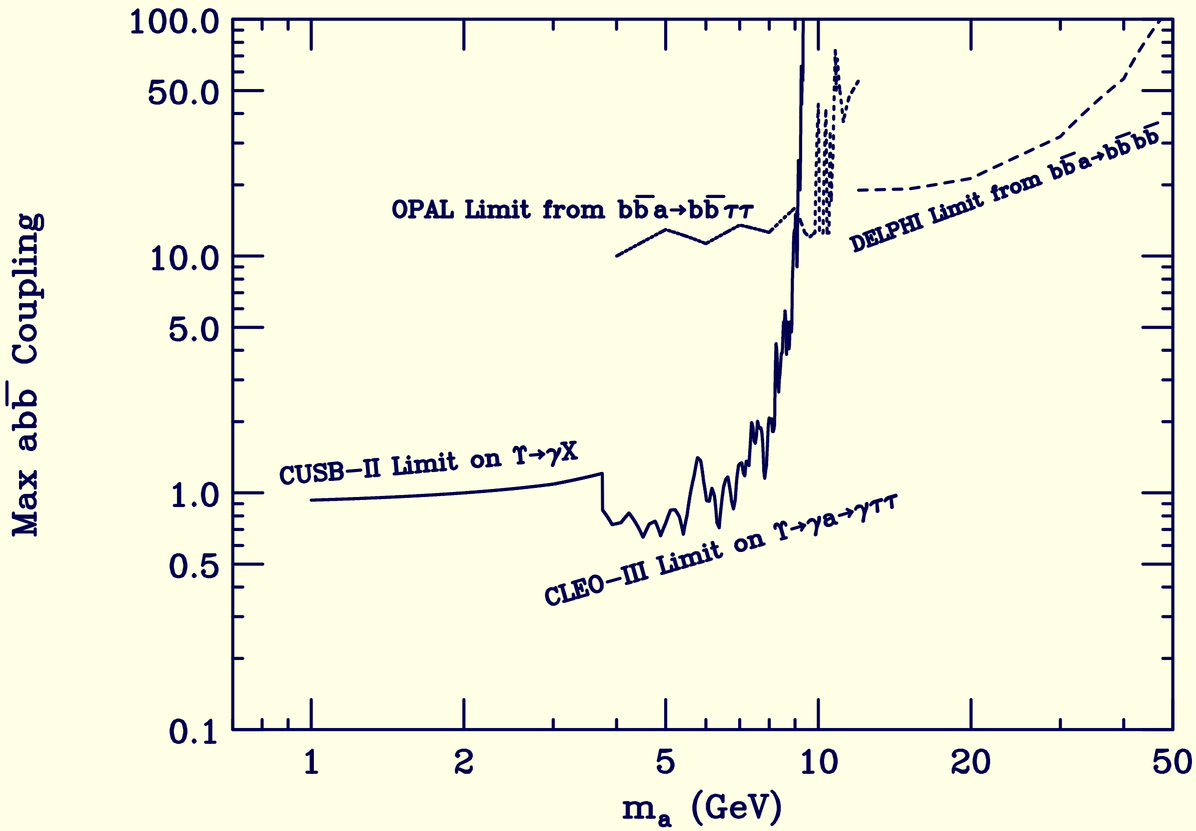


Figure 4: Limits on $C_{ab\bar{b}}$.

Notes:

1. The most unconstrained region is that with $m_a > 8$ GeV, especially $9 \text{ GeV} < m_a < 12 \text{ GeV}$.
2. In the $\sim 9 \text{ GeV} \lesssim m_a \lesssim 12 \text{ GeV}$ 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 states in this region, not just the one that has been observed.

Constraints from Tevatron and LHC

- We (JFG+Dermisek) have recently discovered that Tevatron data on the di-muon spectrum also has an impact.

  In particular, a recent CDF analysis has been directly employed to place a 90% CL upper limit on $\sigma(\epsilon) \times B(\epsilon \to \mu^+\mu^-)$, where the ϵ is some narrow resonance, relative to the measured $\sigma(\Upsilon) \times B(\Upsilon \to \mu^+\mu^-)$.

  The histogram shown in the following figure is the CDF $630~\mathrm{pb}^{-1}$ result.

  In the figure, the predictions for the cross section ratio for a 2HDM-II a ($C_{ab\bar b} = \tan\beta$ and $C_{at\bar t} = \cot\beta$)) are: $+$'s=$\tan\beta = 1$, $\diamond$'s=$\tan\beta = 2$, $\times$'s=$\tan\beta = 3$. Fortunately, the a and Υ cross sections are quite flat in y and only small $|y|$ production is kept in the experimental analysis.

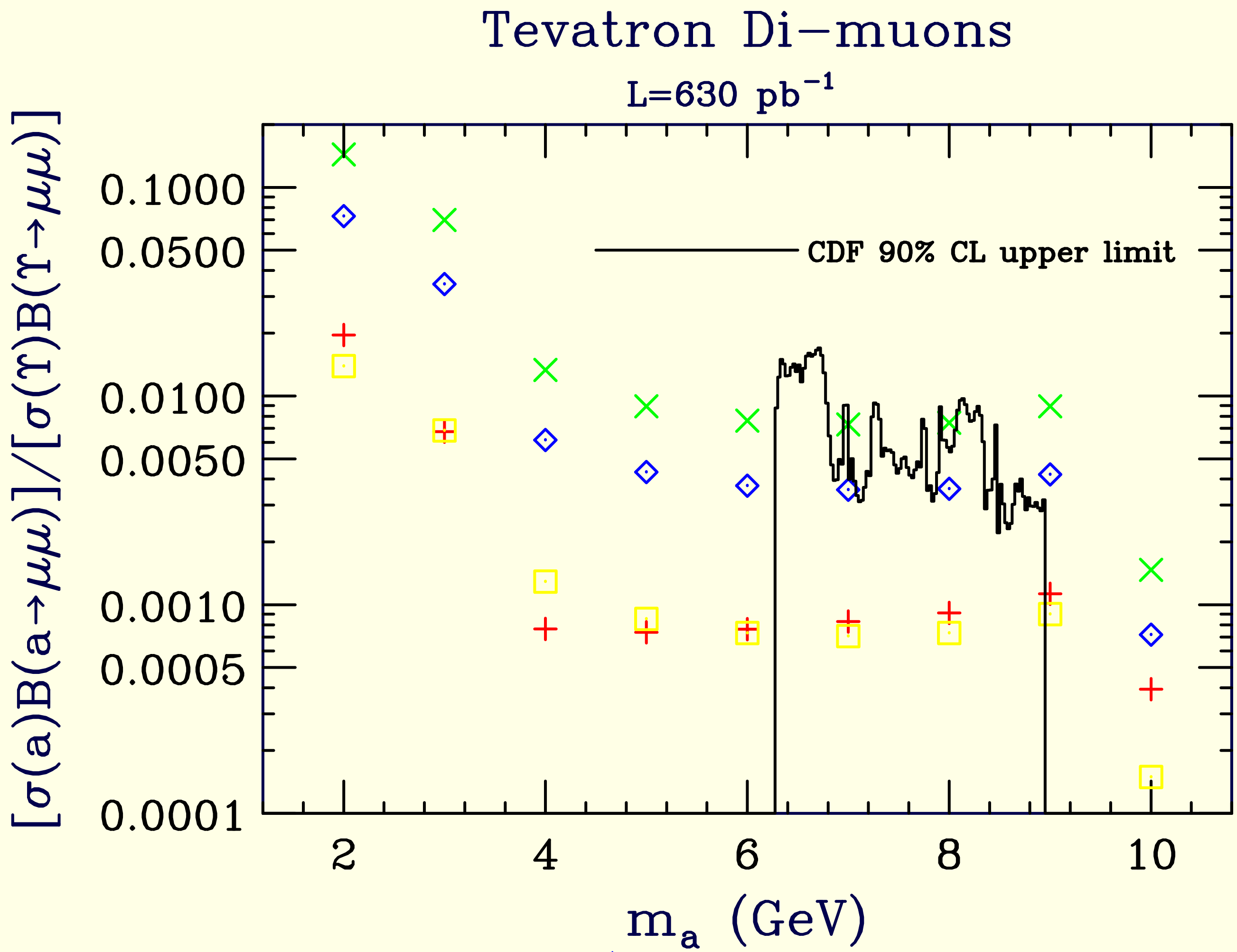


Figure 5: **90% CL limits on $\frac{\sigma(a)B(a\to\mu^+\mu^-)}{\sigma(\Upsilon)B(\Upsilon\to\mu^+\mu^-)}$ at small $|y|$ for $L = 630~\mathrm{pb}^{-1}$, compared to expectations for the a for $C_{ab\bar b} = \tan\beta = 1/C_{at\bar t} =1$, 2, 3 in the 2HDM-II. Also shown (□'s) are the predictions for the NMSSM with $\tan\beta = 10$ and $\cos\theta_A = 0.1$ for which $C_{ab\bar b} = \tan\beta\cos\theta_A = 1$ and $C_{at\bar t} = \cot\beta\cos\theta_A = 1/100$ — not much different from the $C_{ab\bar b} = \tan\beta = 1/C_{at\bar t} = 1$ case.**

- **Translating the $630\ \mathrm{pb}^{-1}$ results into limits on $C_{ab\bar b}$ gives the dotted histogram in the $6-9\ \mathrm{GeV}$ region in Fig. 6 (below):**

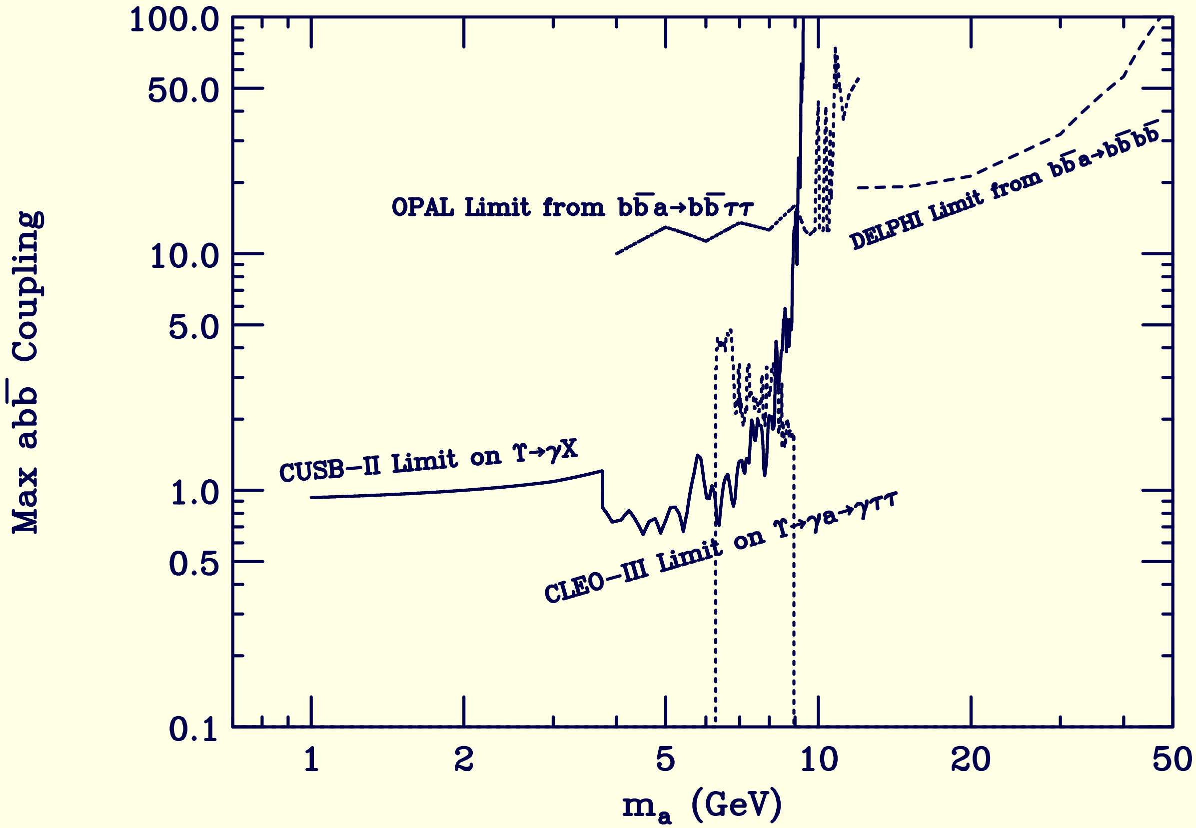


Figure 6: Limits on $C_{ab\bar b}$ including those from the Tevatron analysis.

The Tevatron limits are the best for $\sim 8\ \mathrm{GeV} < m_a < \sim 9\ \mathrm{GeV}$.

CDF should push analysis above $9\ \mathrm{GeV}$ to at least the $B\overline{B}$ threshold (and perhaps a bit beyond since LEP limits on a light $h \to aa$ might still be obeyed for m_a somewhat above threshold). Did multi-μ events prevent this? No: since μ isolation required for this analysis.

Limits will improve as more integrated luminosity is accumulated/analyzed.

- What about the LHC? A careful analysis is required. New issues include:

  1. Triggering on soft muons.
     Probably a recoiling jet is required to boost the μ momenta.
  2. $b\overline{b}$ backgrounds will be bigger than at the Tevatron.
  3. Muon isolation is clearly trickier, especially at higher luminosity.
  4. Low $\mathcal{L}$ running might provide the optimal situation since you can simply take all data and then work on it.
  5. Is LHCb better than CMS/ATLAS?

- Overall, crucial to pursue both Υ decays and hadron Drell-Yan spectrum limits to maximize constraints.

Implications for a_μ

- 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 $\Delta a_\mu \sim 30 \times 10^{-10}$.

- The maximum possible value of δa_μ from the a occurs for the maximum allowed $C_{ab\bar{b}}$ regardless of the value $R^2_{b/t} = C_{ab\bar{b}}/C_{at\bar{t}}$ (for the 2HDM-II, $R^2_{b/t} = \tan^2\beta = C^2_{ab\bar{b}}$, but for more complicated Higgs sectors, very different values for this ratio are possible). Note: $C_{at\bar{t}}$ enters at the two loop-level.

  Figure 7 (next page) shows that it is quite improbable that a light a could explain Δa_μ, regardless of the $R_{b/t}$ choice.

  Only in the small window in m_a from about $8~\mathrm{GeV}$ ($9.5~\mathrm{GeV}$ for 2HDM-II) up to $\sim 12~\mathrm{GeV}$, where $C_{ab\bar{b}}$ limits are the weakest ($C_{ab\bar{b}} \lesssim 15 - 60$), might it be possible.

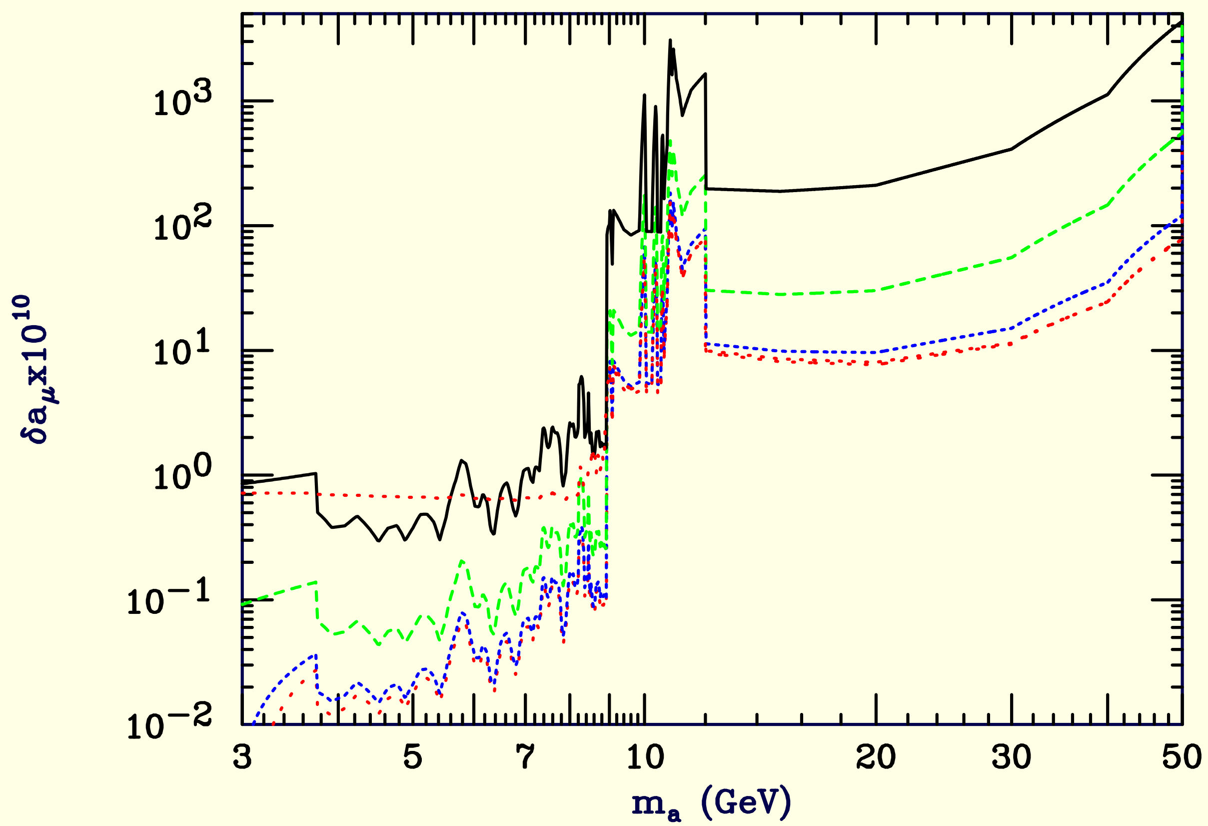


Figure 7: Results for $\delta a_\mu^{\rm max}$ from a CP-odd a for various $R_{b/t}^2 = C_{ab\bar b}/C_{at\bar t}$ models are plotted after incorporating the $C_{ab\bar b}$ experimental limits. Curves are for $R_{b/t} = 1, 3, 10, 50$. The 2HDM-II prediction corresponds to $R_{b/t} = \tan\beta = C_{ab\bar b}$ and is the same as the $R_{b/t} = 50$ curve for $m_a \gtrsim 9~{\rm GeV}$ and is the isolated red curve at lower m_a.)

The NMSSM Context

The ideal Higgs scenario is naturally realized in the very attractive Next-to-Minimal Supersymmetric Model (JFG+Dermisek):

Motivations for SUSY and for the NMSSM version thereof

- **SUSY cures the hierarchy problem coming from the top-quark loop correction to the Higgs mass-squared by introducing a canceling stop-squark loop. Fine-tuning of the Higgs mass to be below $\sim \mathbf{700}\ \mathrm{GeV}$ (required for $W_L W_L \to W_L W_L$ unitarity) is avoided if $m_{\widetilde{t}} \lesssim \mathbf{1}\ \mathrm{TeV}$.**

- **But, the Minimal Supersymmetric Model requires a term in the superpotential of form**

$$W \ni \mu \widehat{H}_u \widehat{H}_d \,, \tag{3}$$

where $\widehat{H}_u$ and $\widehat{H}_d$ are the Higgs superfields whose scalar components acquire vevs that gives rise to the up-type and down-type quark masses, respectively.

Phenomenologically, $\mu \sim few \times 100$ GeV is needed to avoid various experimental limits and yet have a SM-like Higgs that is good for precision electroweak data.

However, theoretically, $\mu \sim M_{\rm Pl}$ is expected (or $\mu = 0$ because of a discrete symmetry). This is called the μ problem.

- The NMSSM is obtained from the MSSM by adding a superfield $\widehat{S}$ that is a SM singlet which provides a beautiful solution to the μ problem.

  Starting from the superpotential

$$W \ni \lambda \widehat{S} \widehat{H}_u \widehat{H}_d + \frac{\kappa}{3} \widehat{S}^3 . \quad (4)$$

  one gets $\mu \sim \lambda \langle S \rangle$ and $\langle S \rangle$ will be of order 1 TeV.

  Indeed, since λ and κ are dimensionless, all dimensionful quantities, including $\langle S \rangle$ are set by the scale of supersymmetry breaking (and above we noted that the scale of supersymmetry breaking as represented by $m_{\widetilde{t}}$ must be $\lesssim 1$ TeV in order to avoid fine-tuning in getting a Higgs mass-squared that cures the quadratic divergence hierarchy problem).

- Meanwhile, the NMSSM preserves the "good" MSSM features: coupling constant unification and RGE generation of EWSB.

- The NMSSM also allows a solution to the "other" fine-tuning problem of the MSSM, namely, how precisely must the GUT-scale parameters of the model (e.g. soft-SUSY-breaking masses) be tuned to obtain the observed value of m_Z^2 after RGE evolution to low-energies.

- In any supersymmetric model, the value of m_Z^2 is least sensitive to the GUT-scale parameters if the stops have $m_{\widetilde t} \lesssim 350~\mathrm{GeV}$.

  For such stop masses, the lightest CP-even Higgs (whether h in the MSSM or h_1 in the NMSSM) will have mass $\lesssim 100~\mathrm{GeV}$.

  In the MSSM, this is a problem since the h has SM-like couplings and decays so that LEP requires $m_h > 114~\mathrm{GeV}$. A high level of GUT-scale parameter fine-tuning is required to get m_Z^2 correct if $m_h > 114~\mathrm{GeV}$.

  In the NMSSM, an h_1 with $m_{h_1} \lesssim 100~\mathrm{GeV}$ escapes LEP limits if

$h_1 \to a_1 a_1$ is large and $m_{a_1} < 2m_b$. Fine-tuning of GUT-scale parameters to get the observed m_Z^2 is not required.

Indeed, the absolute minimum of the m_Z^2 fine-tuning measure

$$F = \mathrm{Max}_p \left| \frac{p}{m_Z} \frac{\partial m_Z}{\partial p} \right| , \tag{5}$$

where $p \in \left\{ M_{1,2,3}, m_Q^2, m_U^2, m_D^2, m_{H_u}^2, m_{H_d}^2, m_S^2, A_t, \lambda, \kappa, \ldots \right\}$ (all at M_U), occurs precisely when h_1 has SM-like coupings to $WW, ZZ, f\overline{f}$ and has $m_{h_1} \sim 100~\mathrm{GeV}$ (for $\tan\beta \geq 5$), and escapes LEP limits via large $B(h_1 \to a_1 a_1)$ with $m_{a_1} < 2m_b$. (JFG+Dermisek)

- Previously, the NMSSM and similar MSSM extensions were used to raise the Higgs mass above $114~\mathrm{GeV}$ for lower $\overline{m_{\widetilde{t}}}$ (thereby reducing EWSB fine-tuning).

  The precision electroweak data now imply that this is not the most motivated route. It is best to use the NMSSM to allow a light Higgs with very SM-like ZZ, WW coupling to evade LEP limits via extra decays.

- **An important question:** Is fine-tuning of GUT-scale parameters (namely the A_λ and A_κ soft-SUSY-breaking parameters associated with the λ and κ superpotential terms) required to achieve the above a_1 properties.

  The answer is not necessarily. To understand this statement, what is needed to avoid "light-a_1 fine-tuning" and implications of the preferred scenarios, we need to learn a bit more about the NMSSM.

- First, starting from GUT-scale parameters A_λ and A_κ close to zero (the $U(1)_R$ symmetry limit) and evolving gives low-scale A_λ and A_κ values that will typically yield a light a_1.

  The real question is will $B(h_1 \to a_1 a_1)$ be large enough ($\gtrsim 0.7$).

- In the NMSSM context, a crucial quantity for the latter is $\cos\theta_A$, the coefficient of the MSSM-like doublet Higgs component of the a_1:

$$a_1 = \cos\theta_A A_{MSSM} + \sin\theta_A A_S \,. \quad (6)$$

- One finds that to achieve $B(h_1 \to a_1 a_1) > 0.7$ for $m_{a_1} < 2m_b$ will not require fine-tuning, provided $m_{a_1} > 7.5$ GeV (implying $a_1 \to \tau^+\tau^-$) and $C_{ab\bar{b}} = \cos\theta_A \tan\beta$ has absolute value $\lesssim 1$! (This is relaxed in certain scenarios with $\tan\beta \leq 3$.)

- Further, for any $\tan\beta$ value there is a lower bound on $|\cos\theta_A|$ required to get $B(h_1 \to a_1 a_1) > 0.7$. In the end, $|C_{ab\bar{b}}| \gtrsim 0.35$ is required.

- As a result, The a_1 of the NMSSM Ideal Higgs scenario might in fact be observed if Υ decays and the Tevatron di-muon spectrum can both be pushed to the $|C_{ab\bar{b}}| < 1$ level in the 7.5 GeV $\lesssim m_{a_1} \lesssim 10 - 11$ GeV region.

  Typically one must gain a factor of 2 to 3 improvement in $|C_{ab\bar{b}}|$ limits relative to current limits, statistically $\Rightarrow \sim \times 10$ for L.

- **Final note** GUT scale parameters that yield these NMSSM scenarios are very attractive in that they are "no-scale"-like — most dimensionful parameters *e.g.* $m_{H_u}^2, m_{H_d}^2, m_S^2, A_t, A_\lambda, A_\kappa, \ldots$ are small at M_U.

Detecting the h_1.

LHC

All standard LHC channels fail: *e.g.* $B(h_1 \to \gamma\gamma)$ **is much too small because of large** $B(h_1 \to a_1 a_1)$**.**

The possible new LHC channels include:

1. $WW \to h_1 \to a_1 a_1 \to 4\tau$.

   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).**

2. $t\bar{t}h_1 \to t\bar{t}a_1 a_1 \to t\bar{t}\tau^+\tau^-\tau^+\tau^-$.

   Study begun.

3. $\widetilde{\chi}_2^0 \to h_1 \widetilde{\chi}_1^0$ **with** $h_1 \to a_1 a_1 \to 4\tau$.

(Recall that the $\widetilde{\chi}_2^0 \to h_1 \widetilde{\chi}_1^0$ channel provides a signal in the MSSM when $h_1 \to b\bar{b}$ decays are dominant.)

4. Last, but definitely not least: diffractive production $pp \to pph_1 \to ppX$.

   The mass M_X can be reconstructed with roughly a $1-2$ 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.

   Our (JFG, Forshaw, Pilkington, Hodgkinson, Papaefstathiou: arXiv:0712.3510) results are that one expects about 3 clean, *i.e.* reconstructed and tagged, events with very small background (~ 0.1 event) per $90~\mathrm{fb}^{-1}$ of luminosity.

   $\Rightarrow$ clearly a high luminosity game.

   We estimate the significance, S, of the observation by equating the probability of $s+b$ events given a Poisson distribution with mean b to the probability of S standard deviations in a Gaussian distribution.

Signal significances are plotted in Fig. 8 for a variety of luminosity and triggering assumptions.

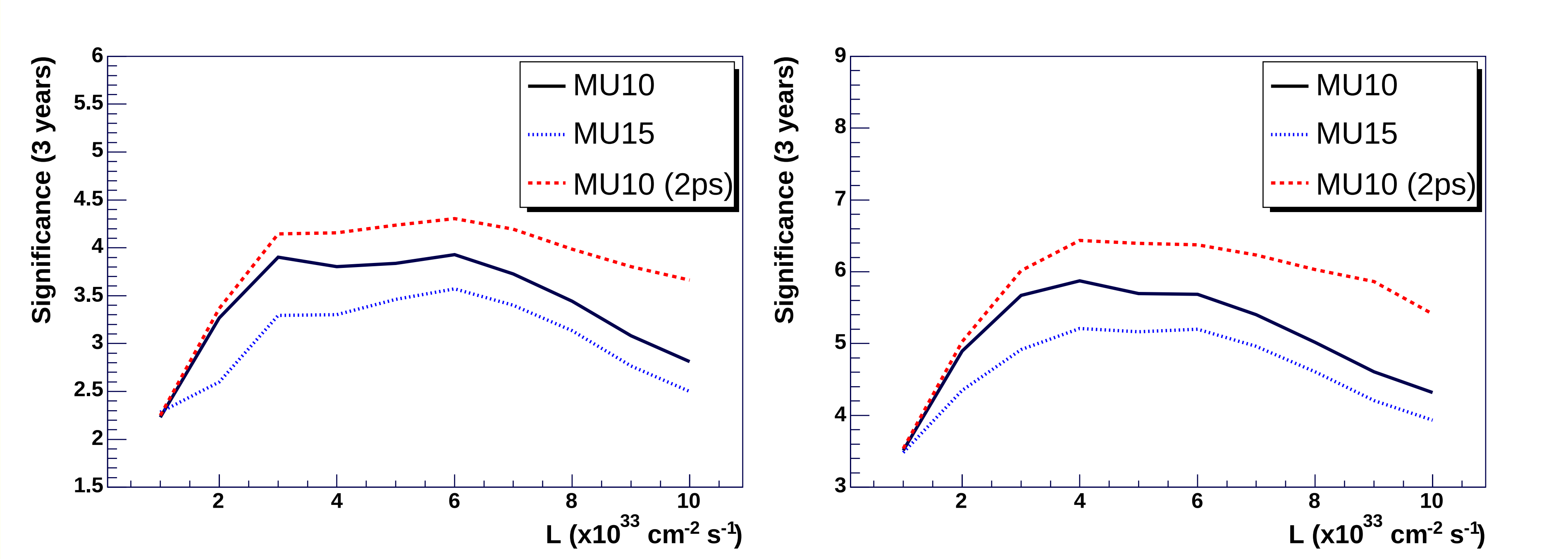


Figure 8: (a) The significance for three years of data acquisition at each luminosity. (b) Same as (a) but with twice the data. Different lines represent different μ trigger thresholds and different forward detector timing. Some experimentalists say more efficient triggering is possible, doubling the 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 originating 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

$$p_i^{vis} = f_i \, p_{a,i} \tag{7}$$

  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.

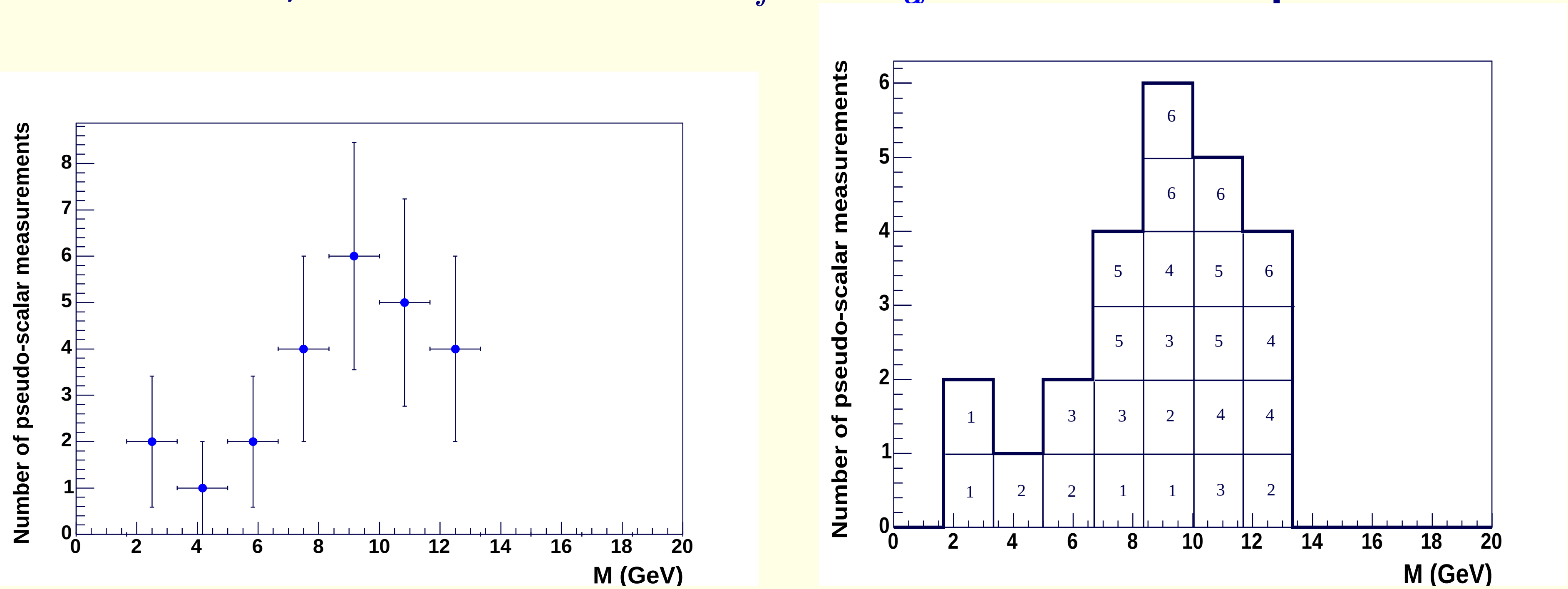


Figure 9: (a) A typical a mass measurement. (b) The same content as (a) but with the breakdown showing the 4 Higgs mass measurements for each of the 6 events, labeled $1 - 6$ in the histogram.

Figure 9 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.

In the right-hand figure the integer in each box labels one of the 6 signal events.

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.

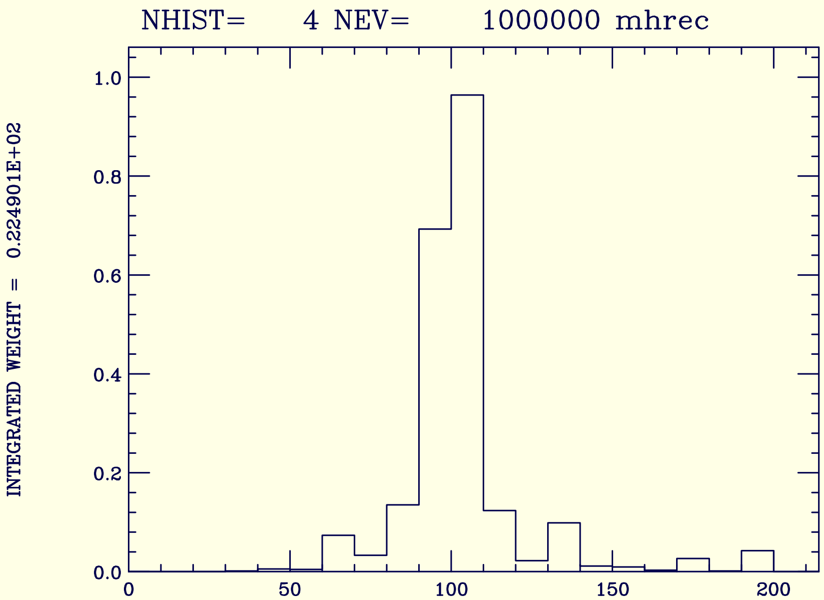
  In fact, in this case, p_T^h must be large enough that the a's are not back to back; this is the case for almost all events even before cuts.

  We then have the two equations that can be solved for f_1 and f_2:

$$p_h^x = \frac{(p_1^{vis})_x}{f_1} + \frac{(p_2^{vis})_x}{f_2} \quad p_h^y = \frac{(p_1^{vis})_y}{f_1} + \frac{(p_2^{vis})_y}{f_2}\,. \tag{8}$$

  Of course, this follows very much the same pattern as in $WW \to h_{\mathrm{SM}}$ with $h_{\mathrm{SM}} \to \tau^+\tau^-$ decays. Use of the collinear τ decay approximation and using the same equations for the visible τ decay products yields a pretty good $h_{\rm SM}$ mass peak in the LHC studies done of this mode.

- A signal only Monte-Carlo run without lepton or tag jet momentum smearing yields encouraging results



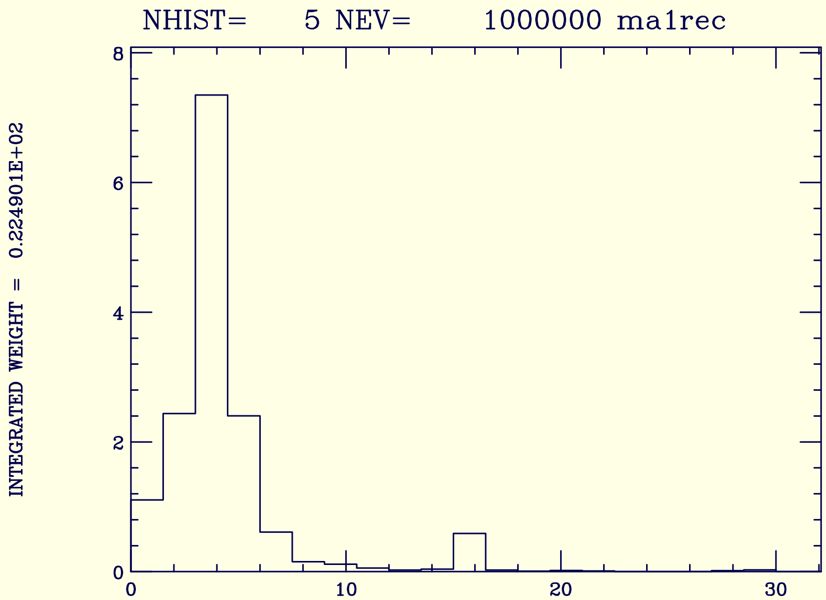


Figure 10: (a) A typical h mass distribution. (b) A typical a mass distribution. No cuts imposed; signal only

- We have now developed cuts that we are relatively certain will control backgrounds nicely. These cuts do not change the mass reconstruction above significantly, even after including PGS (CMS) smearing.

ILC

At the ILC, there is no problem since $e^+e^- \to ZX$ will reveal the $M_X \sim m_{h_1} \sim 100~\mathrm{GeV}$ peak no matter how the h_1 decays.

But the ILC is decades away.

NMSSM Scenarios with $\tan\beta \lesssim 2$

- 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 $m_{a_1} < 2m_b$. (JFG+Dermisek)

- h_1 need not be exactly SM-like — h_2 can be light enough ($\sim 100~\mathrm{GeV}$) for precision electroweak when it participates in WW coupling squared.

- Relevant scenarios arise most often if $\cos^2\theta_A > 0.5$, especially if $\tan\beta = 2$. Current limits on $\cos^2\theta_A$ imply that $m_{a_1} > 7.5~\mathrm{GeV}$ is needed to have this large a value of $\cos^2\theta_A$.

- 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 $m_{4\tau} < 89~\mathrm{GeV}$ (at best — lower if ZZh_1 coupling is somewhat suppressed).

2. $B(h^+ \to W^+ a_1)$ is often large, and $e^+e^- \to h^+h^- \to W^+W^-a_1a_1$ with $a_1 \to 2\tau$ was not directly searched for.
3. $B(h^+ \to \tau^+\nu)$ is frequently 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. $B(h_2 \to a_1a_1)$ and/or $B(h_2 \to Za_1)$ are large.
   Thus, even if $e^+e^- \to Zh_2$ has large σ (which is often the case since m_{h_2} is not large), would not have seen it since the $h_2 \to Za_1$ decay was never looked for and an incomplete job was done on $h_2 \to a_1a_1 \to 4\tau$.
5. For $\tan\beta = 1.7$ it is easy to find cases where $e^+e^- \to Zh_1 \to Zb\bar{b}$ and/or $e^+e^- \to Zh_2 \to Zb\bar{b}$ would yield a substantial contribution to the LEP $0.1 \times SM$ excess near $m_{b\bar{b}} \sim 98~\mathrm{GeV}$.

Table 2: Selected $\tan\beta = 1.7$ points for which m_{h_1} and corresponding m_{h_2} lie within the LEP excess region and the corresponding $C_V^2(h_1)B(h_1 \to b\bar{b})$ and $C_V^2(h_2)B(h_2 \to b\bar{b})$ values. All have $\cos^2\theta_A \gtrsim 0.5$ and $m_{a_1} > 7.5~\mathrm{GeV}$.

m_{h_1}	$C_V^2(h_1)B(h_1 \to b\bar{b})$	m_{h_2}	$C_V^2(h_2)B(h_2 \to b\bar{b})$
93.1	0.0684	96.2	0.1590
90.7	0.0560	96.6	0.1726
90.2	0.1171	97.2	0.1468
88.3	0.0557	97.0	0.1803
87.8	0.0974	97.5	0.1609
90.7	0.0560	96.6	0.1727
92.7	0.1748	97.2	0.1037
90.9	0.0599	97.1	0.1416

- To observe or constrain the a_1 in these $\cos^2\theta_A > 0.5$ scenarios will most likely require both B-factory Υ results and Tevatron high luminosity data.

- High Tevatron L would also better limit $B(t \to h^+ b)$ which at the moment is allowed up to the 40% level since these decays are included in the way CDF and D0 determine the $t\bar{t}$ cross section for the $h^+ \to W^+ a_1$ decays.

Conclusions

- A light a with $m_a < 2m_b$ of the "ideal" Higgs scenario with $m_h < 105\ \mathrm{GeV}$ (escaping LEP limits because $B(h \to aa \to 4\tau)$ is large) might be discoverable in the di-muon spectrum at the Tevatron or LHC.

- Alternatively, the Tevatron and LHC might be able to place limits on the $C_{ab\bar{b}}$ of a light a that would be difficult to reconcile with a specific model.

  This appears to be within reach even for the most preferred $\cos\theta_A \tan\beta \lesssim 1$, $m_a \lesssim 2m_b$ high-$\tan\beta$ NMSSM models.

  Already, the less preferred, larger $|\cos\theta_A|$ models in the high-$\tan\beta$ NMSSM scenarios are being ruled out over part of the relevant mass region beyond that accessible in Υ decays.

  Potentially, the hadron colliders could go to higher di-muon masses and they definitely should.

- **Having both Υ decay and hadron collider data appears to be crucial.**

  The former covers the low m_a region (where the di-muon Drell-Yan background overwhelms the hadron collider $a \to \mu^+\mu^-$ signal and muon triggering becomes hard).

  The latter is the only way (and apparently a viable way) to access the higher $M_\Upsilon - 1~\mathrm{GeV} \lesssim m_a \lesssim 2m_B$ and above threshold regions.

- **If we were to see an a with the right properties, this would give enormous impetus to focusing on the $pp \to pph$ and $WW \to h$ with $h \to aa \to 4\tau$ search modes.**

- **For a generic 2HDM-II model, there is only a small $10~\mathrm{GeV} < m_a < 12~\mathrm{GeV}$ window left for which the a might explain Δa_μ and this is possible only if $C_{ab\bar{b}} = \tan\beta$ is large.**

  It would appear that extending the hadron colliders to high enough m_a to rule this out is possible.

- **Other models we had no time to discuss.**
  - **The $U(1)MSSM$ is an alternative to the NMSSM solution to avoiding the PQ symmetry (that would lead to a massless pseudoscalar).**
    There are many attractive scenarios with a light SM-like h_1 that decays to light singlet-like Higgs bosons and/or light neutralinos.
    The mixture of possible final states presents even more challenges for h_1 discovery at the LHC than do the light-a_1 NMSSM scenarios.
  - **Models that link multiple singlet theories to the CDF multi-muon events excess can be constructed.**
    There are lots of multiple singlet scenarios that both give excellent precision electroweak because a SM-like h_1 has $m_{h_1} < 100~\mathrm{GeV}$, escaping LEP limits because of large $B(h_1 \to a_1 a_1)$, and for which the rest of the Higgs sector provides the CDF multi-muon excesses through decays of another light Higgs to $\tau^+\tau^-$.
    Of course, the big question is where are the corresponding multi-electron event excesses.