The Ideal Higgs Scenario and Its Ramifications

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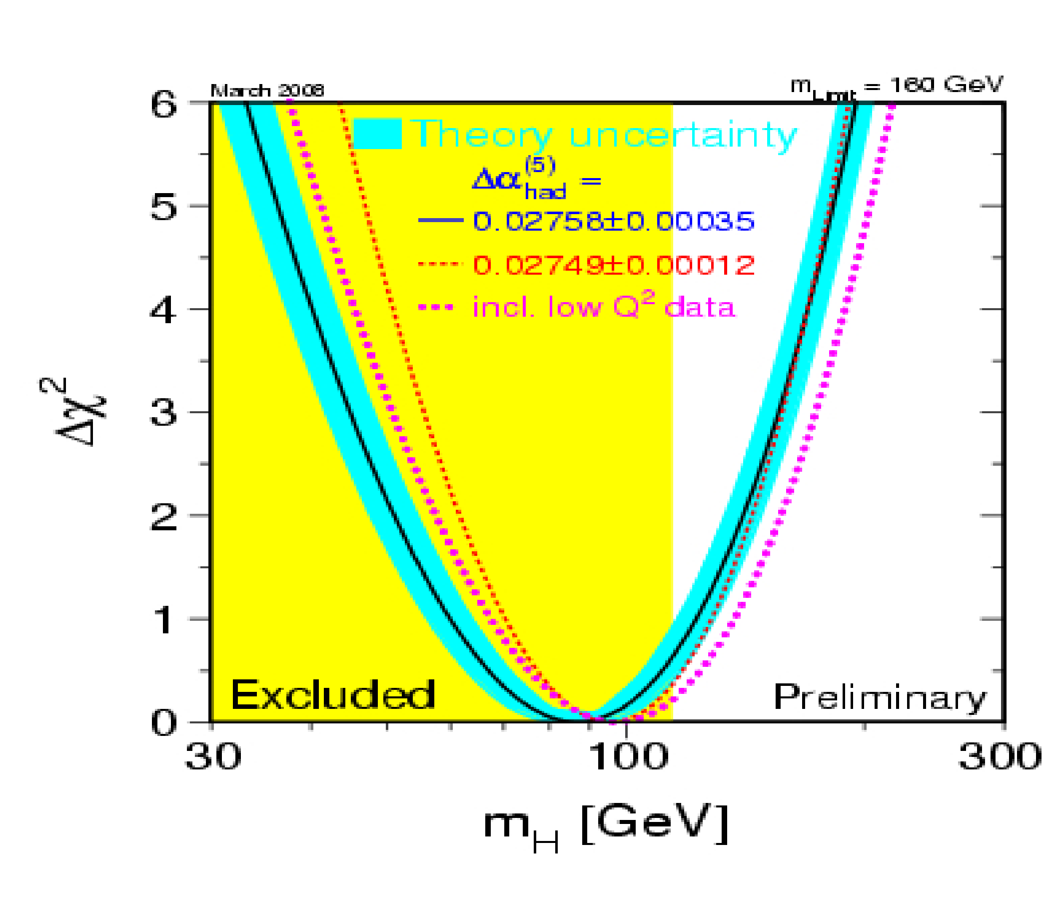
Outline

1. The "ideal" Higgs boson motivation for 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.
6. Anything to do with CDF Multi-muon events?

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).

- Thus, in an ideal model, a Higgs with SM-like ZZ coupling should have mass no larger than $105~{\rm GeV}$. Our generic notation will be H.

  But, at the same time, It should avoid the LEP limits on such a light Higgs. One generic possibility is for its decays to be non-SM-like.

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 $m_H \leq 105$ GeV requires one of the final three modes.

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

  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).

- **All of this can be accomplished in the NMSSM with no fine-tuning, ..., but for now I wish to be more general and only look at the generic possibility of suppressing the $H \to b\bar{b}$ branching ratio by having a light a ($m_a < 2m_b$ to avoid LEP $Z + b's$ limits) with $B(H \to aa) > 0.7$.**

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

The scenario (a) is easy to achieve in general 2HDM-II models, (b) is not possible in the MSSM, but (c) is 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 $h^\pm$.

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 $C_{ab\overline{b}}$, where the generic $C_{af\overline{f}}$ is defined by

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

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

The most useful current limits on $C_{ab\overline{b}}$ 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 $e^+e^- \to b\overline{b}a \to b\overline{b}2\tau$ and DELPHI limits on $e^+e^- \to b\overline{b}a \to b\overline{b}b\overline{b}$.

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

The CLEO-III limits are now particularly strong.

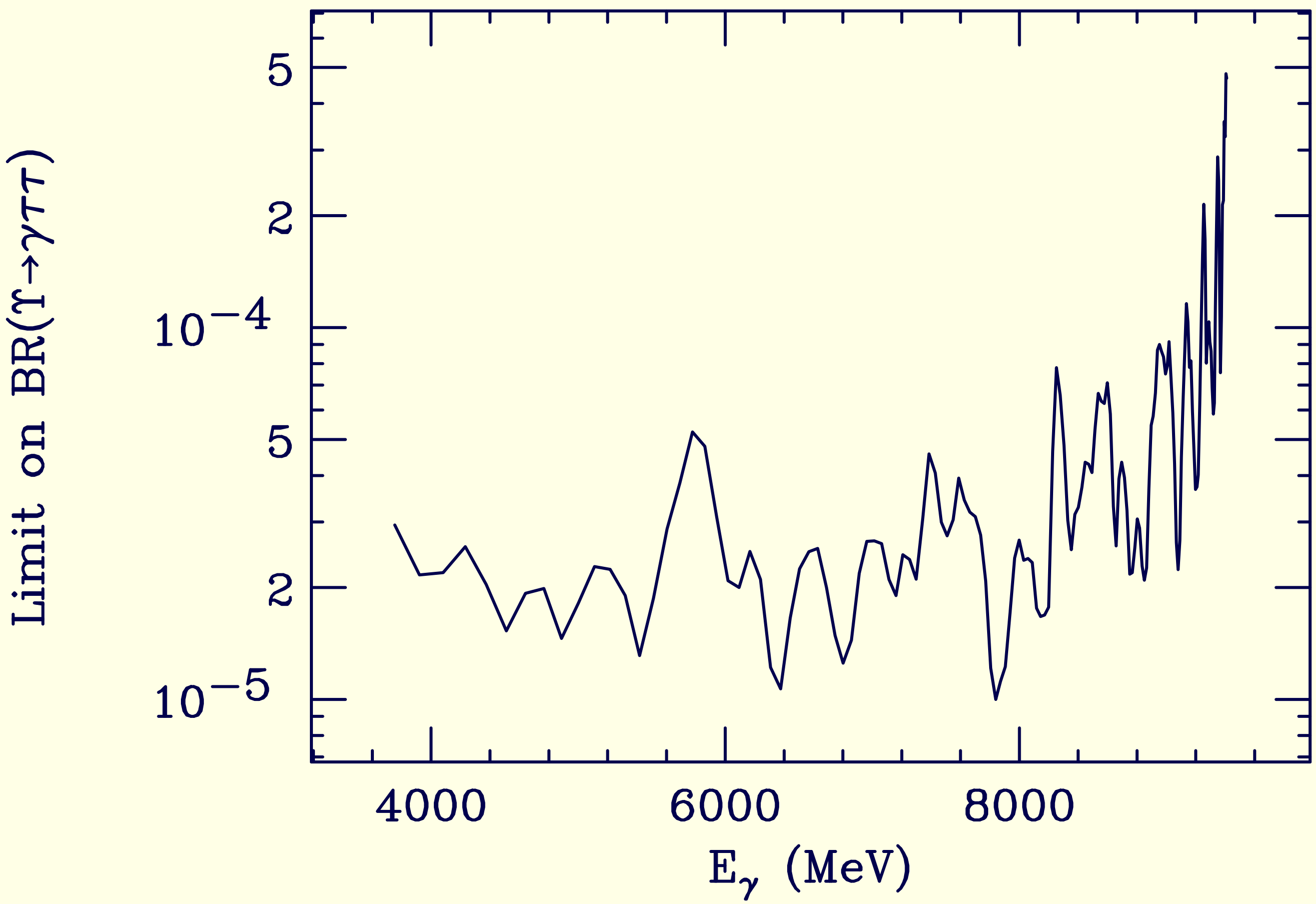


Figure 1: **Limits on $B(\Upsilon \to \gamma\tau^+\tau^-)$.**

- 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. 2,

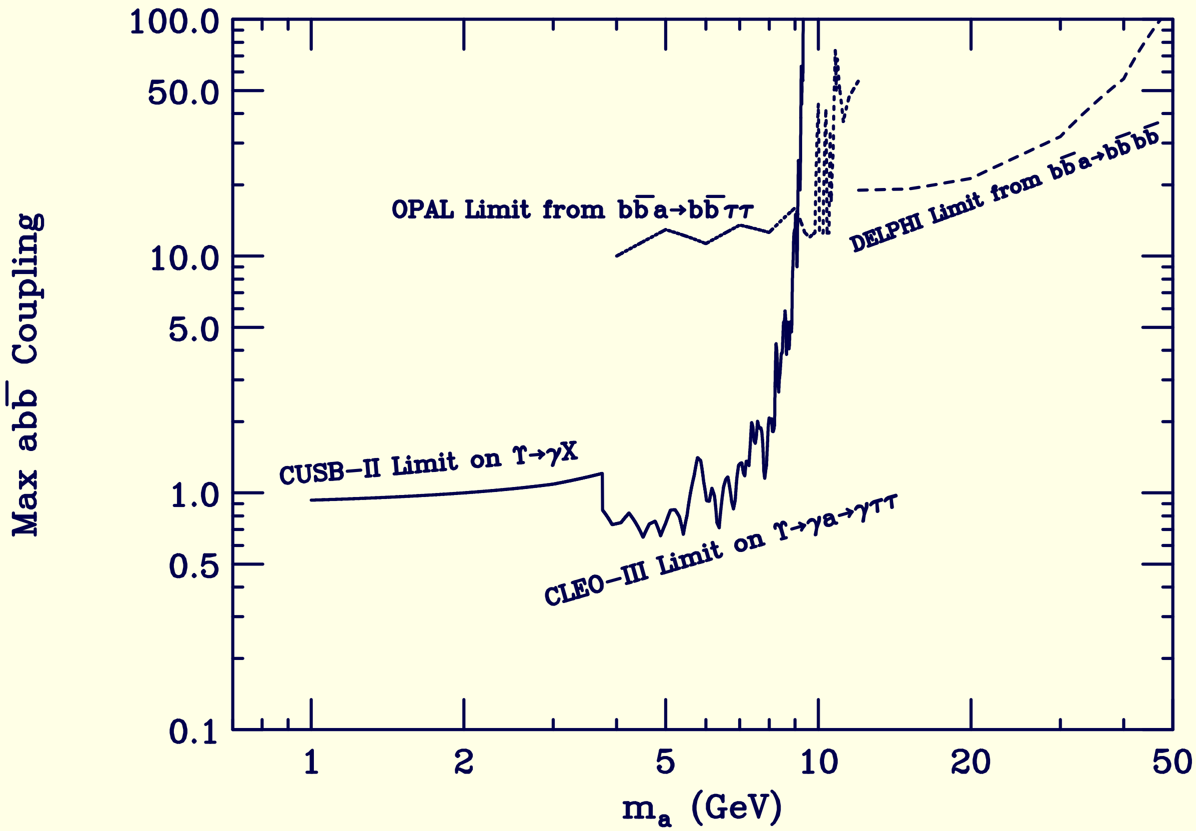


Figure 2: Limits on $C_{ab\bar{b}}$.

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

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 is employed, but there has been little recent work on this.

Perhaps now that the first η_b state has been observed, this region can be better pinned down.

Constraints from Tevatron and LHC

- However, 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 the a are (for $C_{ab\bar{b}} = \tan\beta$ and $C_{at\bar{t}} = \cot\beta$)): $+$'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.

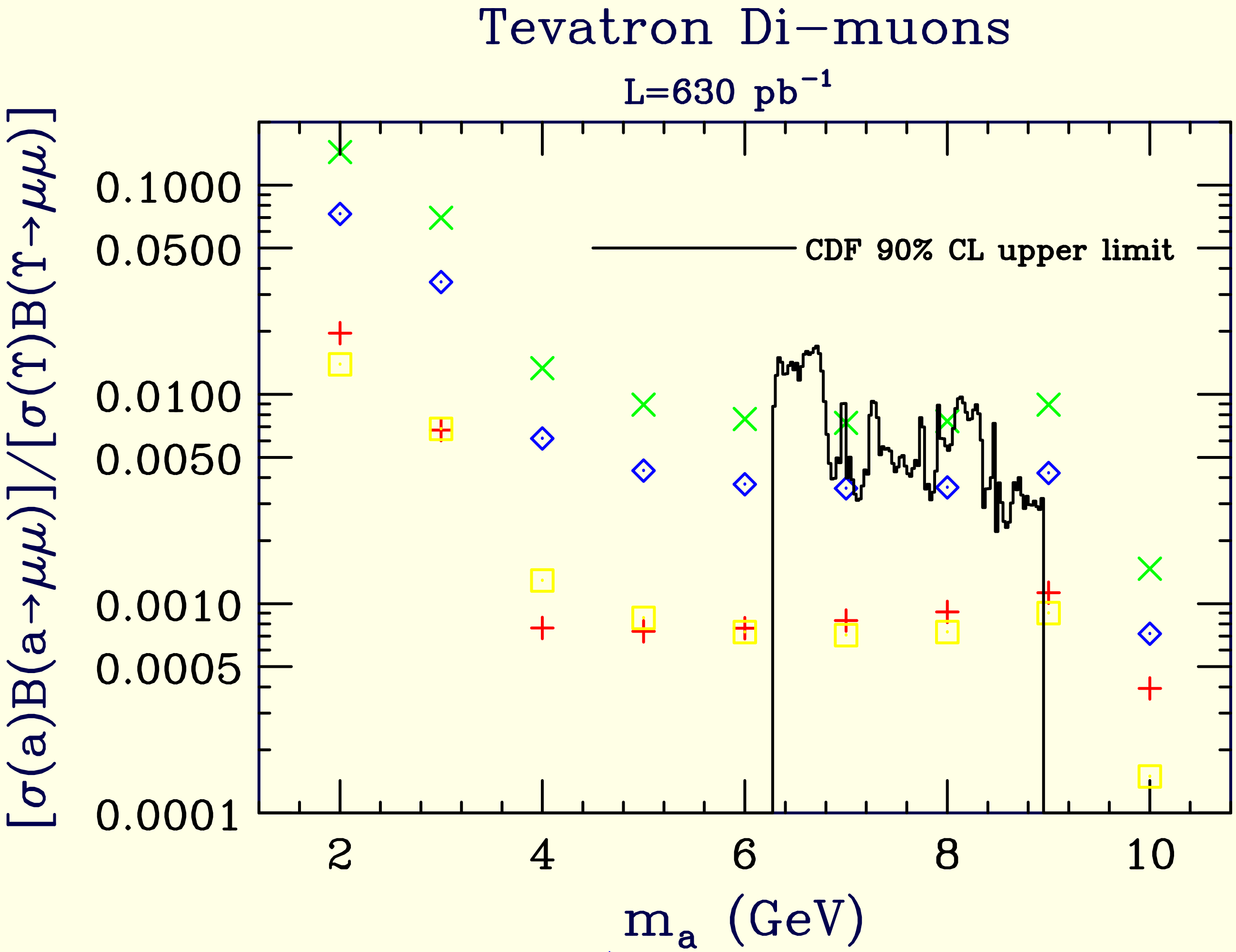


Figure 3: 90% CL limits on $\frac{\sigma(a)B(a\to\mu^+\mu^-)}{\sigma(\Upsilon)B(\Upsilon\to\mu^+\mu^-)}$ at small $|y|$ for $L = 630~\mathrm{pb}^{-1}$, compared to expectations for the a for $C_{ab\bar b} = \tan\beta = 1/C_{at\bar t} =1$, 2, 3 in the 2HDM-II. Also shown (□'s) are the predictions for 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 $6-9$ GeV region in Fig. 4 (below):**

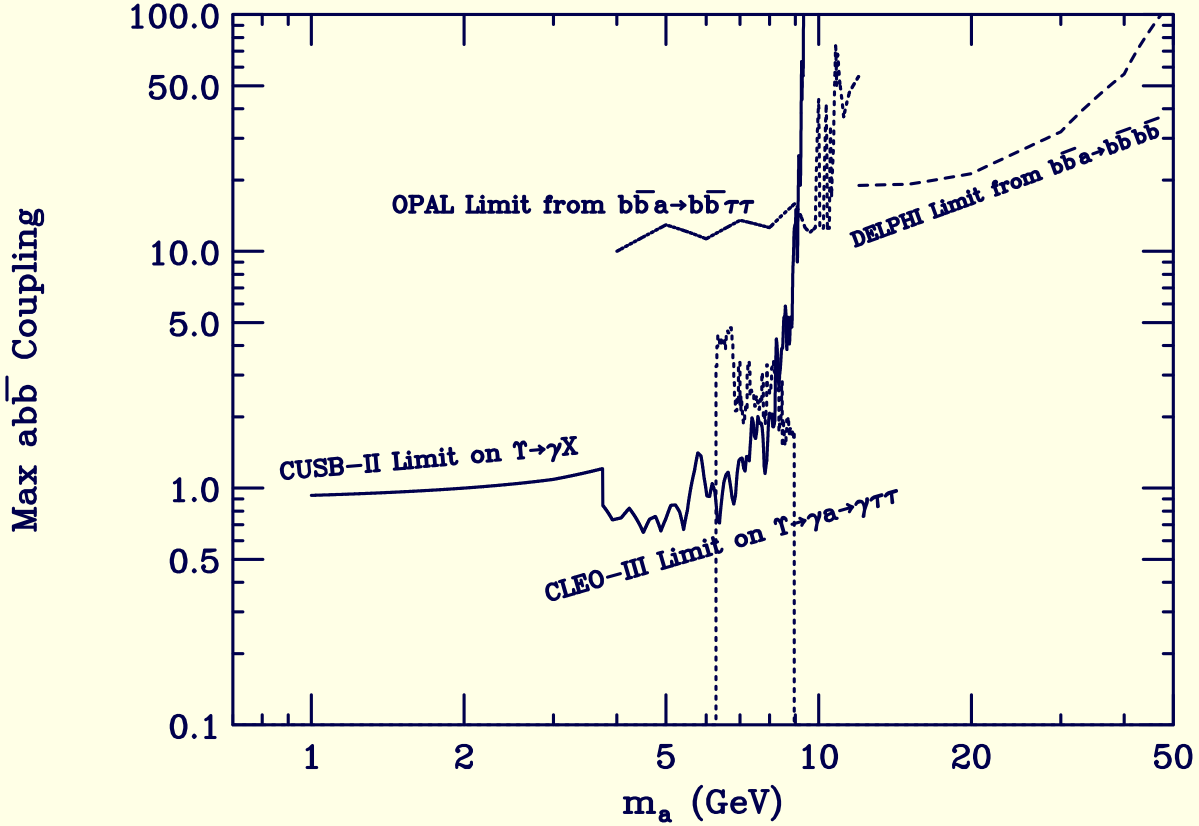


Figure 4: Limits on $C_{ab\bar{b}}$ including those from the Tevatron analysis.

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

CDF should push analysis above $9~\mathrm{GeV}$ to at least the $B\overline{B}$ threshold (and perhaps a bit beyond since the threshold region is complex and LEP limits on a light $h \to aa$ might still be obeyed for m_a somewhat above threshold). Did multi-μ events prevent this? (more later)

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?

- 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 $\Upsilon \to \gamma a$ and $gg \to a \to \mu^+\mu^-$ limits.

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 5 (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.

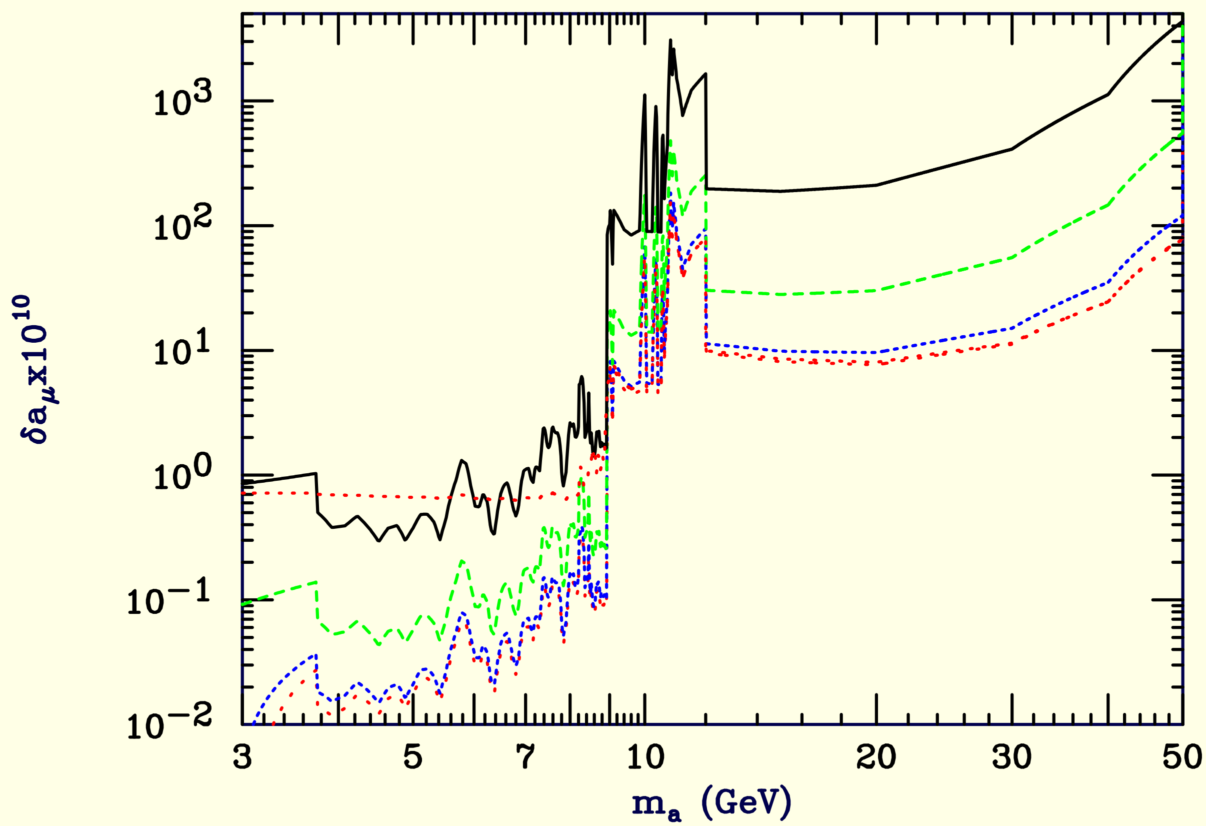


Figure 5: Results for $\delta a_\mu^{\max}$ from a CP-odd a for various $R_{b/t}^2 = C_{ab\bar b}/C_{at\bar t}$ models are plotted after incorporating the $C_{ab\bar b}$ experimental limits. Curves are for $R_{b/t} = 1, 3, 10, 50$ and for the 2HDM-II prediction of $R_{b/t} = \tan\beta = C_{ab\bar b}$ (which looks like $R_{b/t} = 50$ for $m_a \gtrsim 9~\mathrm{GeV}$ 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 ~ 700 GeV (required for $W_L W_L \to W_L W_L$ unitarity) is avoided if $m_{\widetilde{t}} \lesssim 1$ 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, $\mu \sim few \times 100~\mathrm{GeV}$ is needed to avoid various experimental limits and yet have a SM-like Higgs that is good for precision electroweak data.

However, theoretically, $\mu \sim M_{\mathrm{P}}$ 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

$$W \ni \lambda \widehat{S} \widehat{H}_u \widehat{H}_d + \frac{\kappa}{3} \widehat{S}^3 \,. \tag{4}$$

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

  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 $\lesssim 1~\mathrm{TeV}$ in order to avoid fine-tuning in getting a Higgs mass-squared that is in the right balk park).

- **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.

- 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 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:

$$a_1 = \cos\theta_A A_{MSSM} + \sin\theta_A A_S \,. \tag{5}$$

- 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 $m_{a_1} > 7.5~\mathrm{GeV}$ (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 $7.5~\mathrm{GeV} \lesssim m_{a_1} \lesssim 10 - 11~\mathrm{GeV}$ region.

  Typically one must gain a factor of 2 to 3 improvement in $|C_{ab\bar{b}}|$ limits relative to current limits, which statistically means a factor of about 10 in luminosity.

The CDF multi-muon events and NMSSM extensions.

- **There is nothing sacred about having just one additional singlet superfield. A large fraction of string models have multiple singlets.**

- **Suppose we have S, S_1 and S_2.**

  We then have 5 CP-even states and 4 CP-odd states.

- **$\langle S \rangle$ provides μ as before.**

- **One scenario (a variant of Ellwanger et. al.): I try to preserve the ideal scenario, but also get multi-muon events.**

  1. **Pull an A, h, H mainly from the $H_u - H_d$ sector.**
     Pull a_1 mainly out of S — i.e. mainly S-singlet.
     We assume $m_{a_1} \gtrsim 2m_\tau$ is needed to avoid light-a_1-fine-tuning.

As in the ideal Higgs scenario, $m_h \lesssim 100~\mathrm{GeV}$ is wanted for precision electroweak and a_1 must have some minimal amount of doublet in order for $B(h \to a_1 a_1)$ to be large enough for h to evade LEP limits.

Ignore the CP-even partner of a_1, which we assume is heavy (and is mainly S-singlet).

2. Pull $h_1$and h_2 out of the S_1 and S_2 singlets. These are quite light states with masses in the $10~\mathrm{GeV}$ to $20~\mathrm{GeV}$ range and they have very small Yukawa couplings (implying that higgs to higgs pair chain decays are probable).
3. The envisioned decay sequence for the multi-muon events is $H \to h_1 h_1$ with $h_1 \to 2h_2 \to 4a_1 \to 8\tau$.

   Each τ then decays to μ and so each side of the event has 8μ.
4. To describe the observed events, $m_H \sim 100~\mathrm{GeV}$ is needed and $\sigma(gg \to H) \gtrsim 100~\mathrm{pb}$ is required.

   Since H is largely doublet, $\sigma(gg \to H)$ can be enhanced to needed $\gtrsim 100~\mathrm{pb}$ level for $\tan\beta > 30$.
5. Finally, one of the Higgs in the chain must be long-lived. This cannot be a_1 since $B(h \to a_1 a_1)$ would then, as described earlier, not be large

enough for h to escape the LEP limit.

Probably can make h_1 or h_2 long lived by making one of them nearly entirely singlet. However, this is uncertain without a real calculation since, say, $h_1 \to \gamma\gamma$ is mediated by chargino/higgsino loops and this decay might take over, as it does in the case of a pure singlet a_1 in the simple NMSSM (K. Cheung et al).

(Might also be a problem for the Ellwanger et. al. model where a_1 is supposed to have a long lifetime. Did they look at the one-loop induced $a_1 \to \gamma\gamma$ decay?)

6. Of course, simultaneously one could have the Ellwanger et. al. process $gg \to A$ production with $A \to h_1 a_2$ and $a_2 \to h_1 a_1$ (my labeling switches a_1 and a_2 of Ellwanger et. al.), with subsequent decays of h_1 as before.

   One side of the event has 8μ and the other side then has 10μ.

7. Where are the pure e and mixed e, μ events?

   Are electron efficiencies so much worse?

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 small-$\cos\theta_A$, $m_a \lesssim 2m_b$ 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 $m_a \lesssim 2m_B$ 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.

- **In the NMSSM:**

  The preferred NMSSM models do not have large $C_{ab\bar{b}} = \cos\theta_A \tan\beta$ coupling.

  Instead, small light-a_1-fine-tuning models with high $\tan\beta$ have small $\cos\theta_A$ for which $C_{ab\bar{b}} = \cos\theta_A \tan\beta \lesssim 1$.

  At low $\tan\beta$, $\cos\theta_A$ is larger than 1 for an attractive class of models and Tevatron data might be able to rule out such scenarios for somewhat lower L.

  The multi-muon CDF events might have an extended NMSSM explanation.

  But, one must explain absence of similar multi-e events.

  And, it is likely that the narrow $a_1 \to \mu^+\mu^-$ peak would be observable since $B(a_1 \to \mu^+\mu^-)/B(a_1 \to \tau^+\tau^-) \gtrsim 0.0035$ is not that small, especially if m_{a_1} is so close to $2m_\tau$ as to make the a_1 long-lived (mostly singlet also required of course).

  Why didn't they do a narrow peak analysis along the lines of what I discussed earlier? (Strassler)