

The Ideal Higgs Scenario and Its Ramifications

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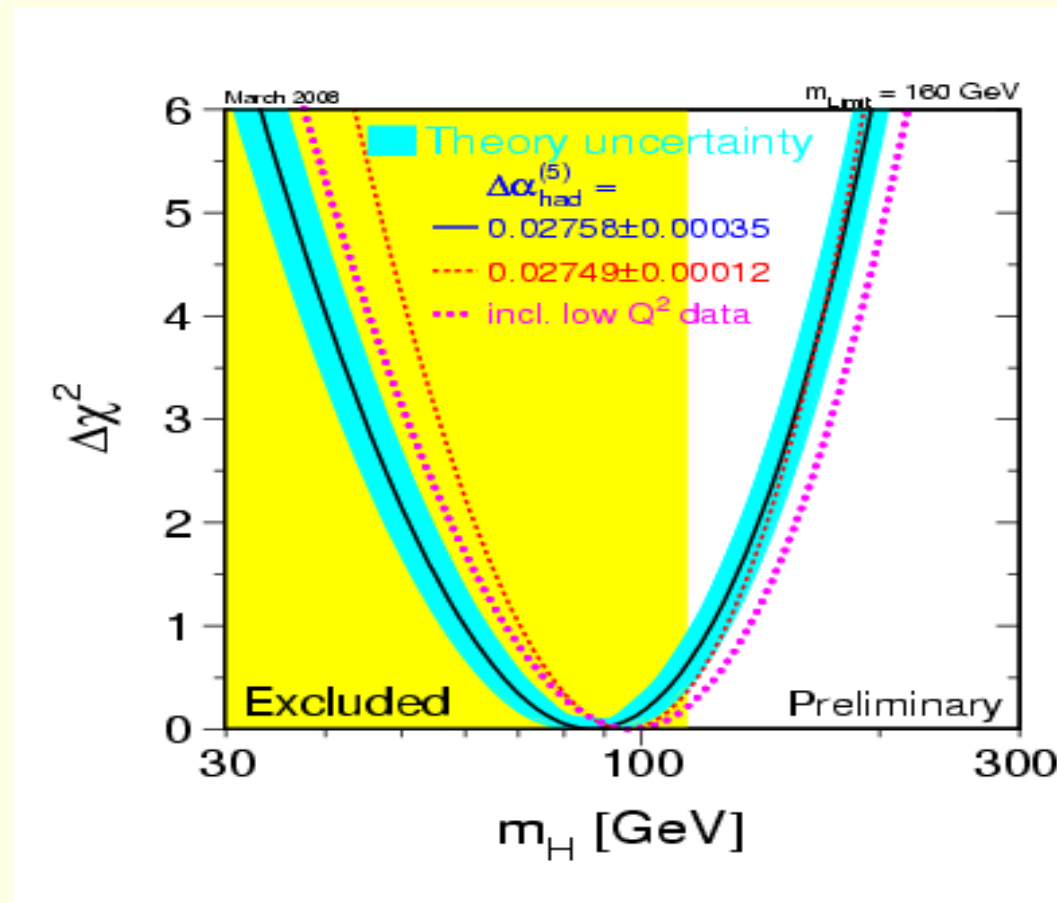
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Outline

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, $m_{h_{\text{SM}}} < 160$ GeV and the $\Delta\chi^2$ minimum is near 85 GeV when all data are included.

The latest m_W and m_t measurements also prefer $m_{h_{\text{SM}}} \sim 100$ GeV.

The blue-band plot may be misleading due to the discrepancy between the "leptonic" and "hadronic" measurements of $\sin^2 \theta_W^{\text{eff}}$, which yield $\sin^2 \theta_W^{\text{eff}} = 0.23113(21)$ and $\sin^2 \theta_W^{\text{eff}} = 0.23222(27)$, respectively. The SM has a CL of only 0.14 when all data are included.

If only the leptonic $\sin^2 \theta_W^{\text{eff}}$ measurements are included, the SM gives a fit with CL near 0.78. However, the central value of $m_{h_{\text{SM}}}$ is then near 50 GeV with a 95% CL upper limit of ~ 105 GeV (Chanowitz, [arXiv:0806.0890](https://arxiv.org/abs/0806.0890)).

- Thus, in an ideal model, a Higgs with SM-like ZZ coupling should have mass no larger than 105 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 Limit (GeV)	SM modes 114.4	2τ or $2b$ only 115	$2j$ 113	$WW^* + ZZ^*$ 100.7	$\gamma\gamma$ 117	\cancel{E} 114	$4e, 4\mu, 4\gamma$ 114?
Mode Limit (GeV)	$4b$ 110	4τ 86	any (e.g. $4j$) 82	$2f + \cancel{E}$ 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 $B(H \rightarrow b\bar{b}) \sim 0.1B(H \rightarrow b\bar{b})_{SM}$ (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 $H \rightarrow b\bar{b}$ branching ratio by having a light a ($m_a < 2m_b$ to avoid LEP $Z + b's$ limits) with $B(H \rightarrow aa) > 0.7$.

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

$$\tan \beta = \frac{h_u}{h_d}. \quad (1)$$

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 $C_{abb\bar{}}$, where the generic $C_{aff\bar{}}$ is defined by

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

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

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

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

The CLEO-III limits are now particularly strong.

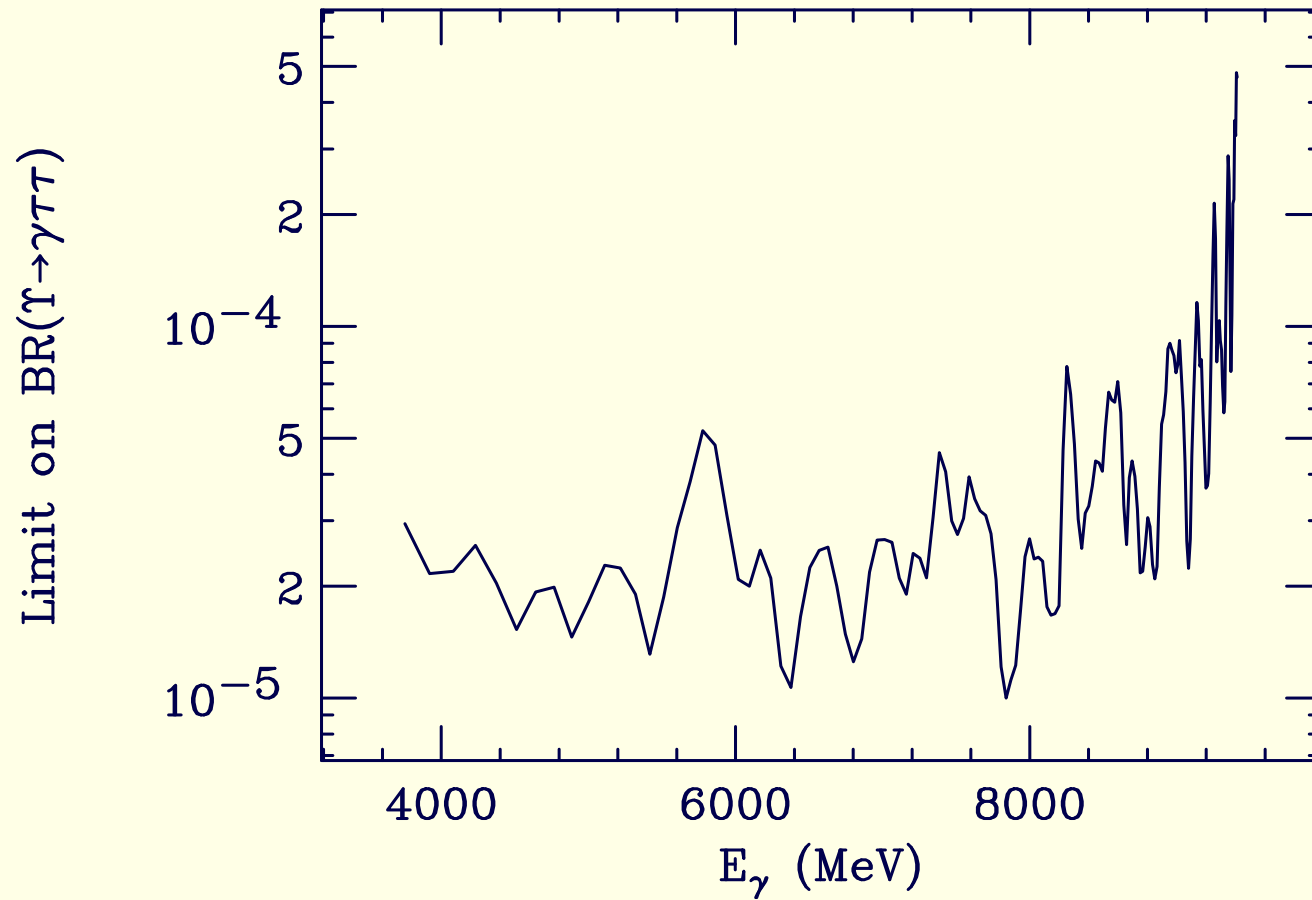


Figure 1: Limits on $B(\Upsilon \rightarrow \gamma\tau^+\tau^-)$.

- For the most part the extracted $C_{abb\bar{b}}$ 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 $B(a \rightarrow \tau\tau)$ and $B(a \rightarrow b\bar{b})$). The extracted limits on $C_{abb\bar{b}}$ appear in Fig. 2,

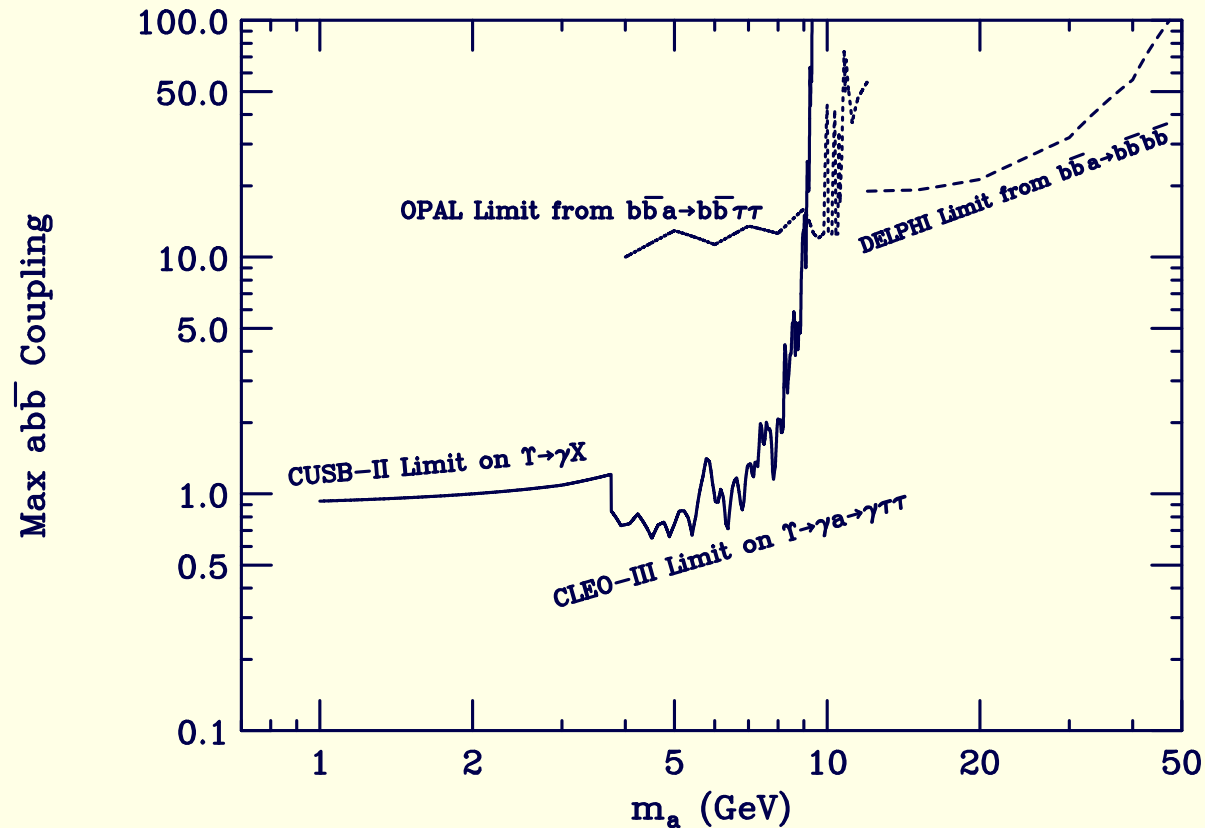


Figure 2: Limits on $C_{abb\bar{b}}$.

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 $\sigma(\epsilon) \times B(\epsilon \rightarrow \mu^+ \mu^-)$, where the ϵ is some narrow resonance, relative to the measured $\sigma(\Upsilon) \times B(\Upsilon \rightarrow \mu^+ \mu^-)$.

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

In the figure, the predictions for the cross section ratio for the a are (for $C_{abb} = \tan \beta$ and $C_{att} = \cot \beta$): $+$'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.

Tevatron Di-muons

$L=630 \text{ pb}^{-1}$

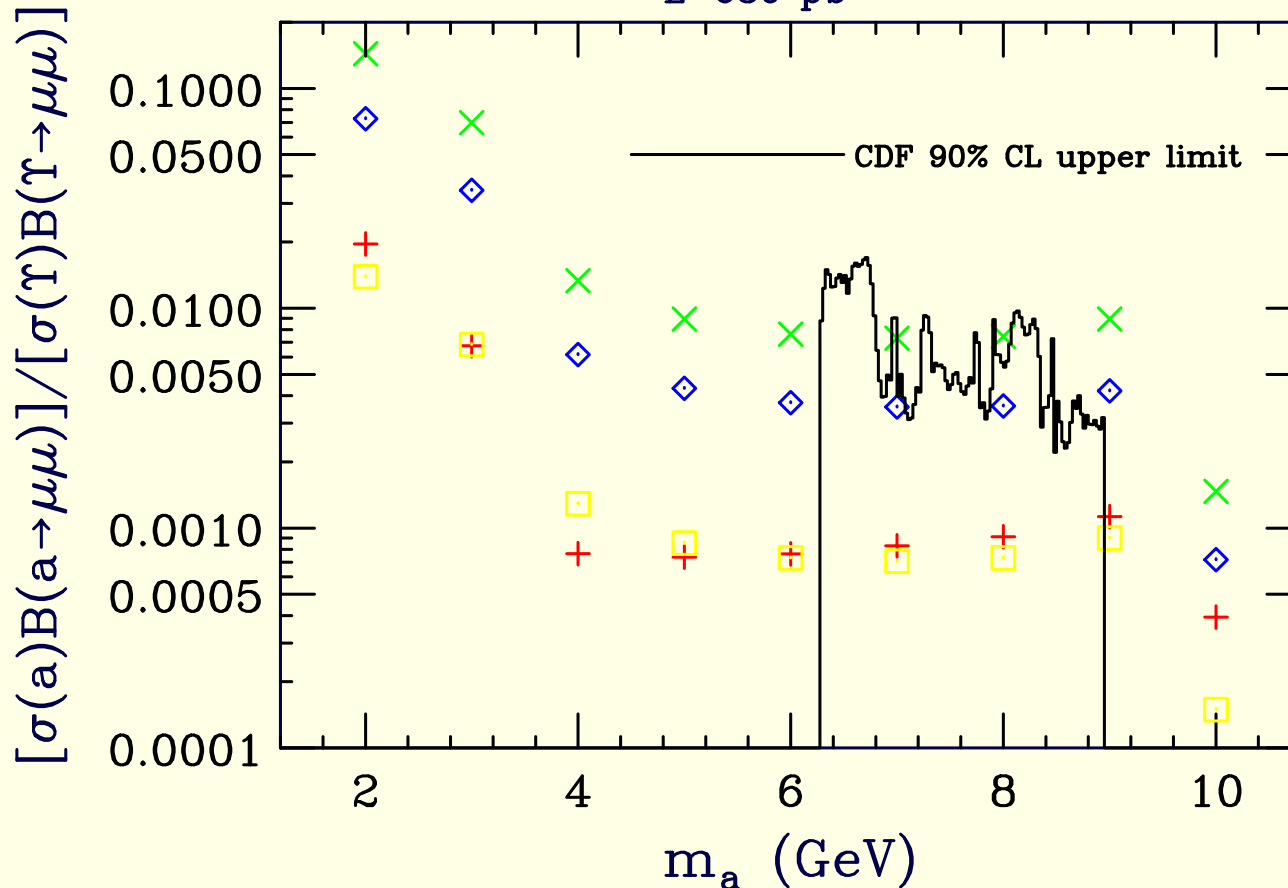


Figure 3: 90% CL limits on $\frac{\sigma(a)B(a \rightarrow \mu^+ \mu^-)}{\sigma(\Upsilon)B(\Upsilon \rightarrow \mu^+ \mu^-)}$ at small $|y|$ for $L = 630 \text{ pb}^{-1}$, compared to expectations for the a for $C_{abb} = \tan \beta = 1/C_{att} = 1, 2, 3$ in the 2HDM-II. Also shown (\square 's) are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

- Translating the 630 pb^{-1} results into limits on $C_{abb\bar{b}}$ gives the dotted histogram in the $6 - 9 \text{ GeV}$ region in Fig. 4 (below):

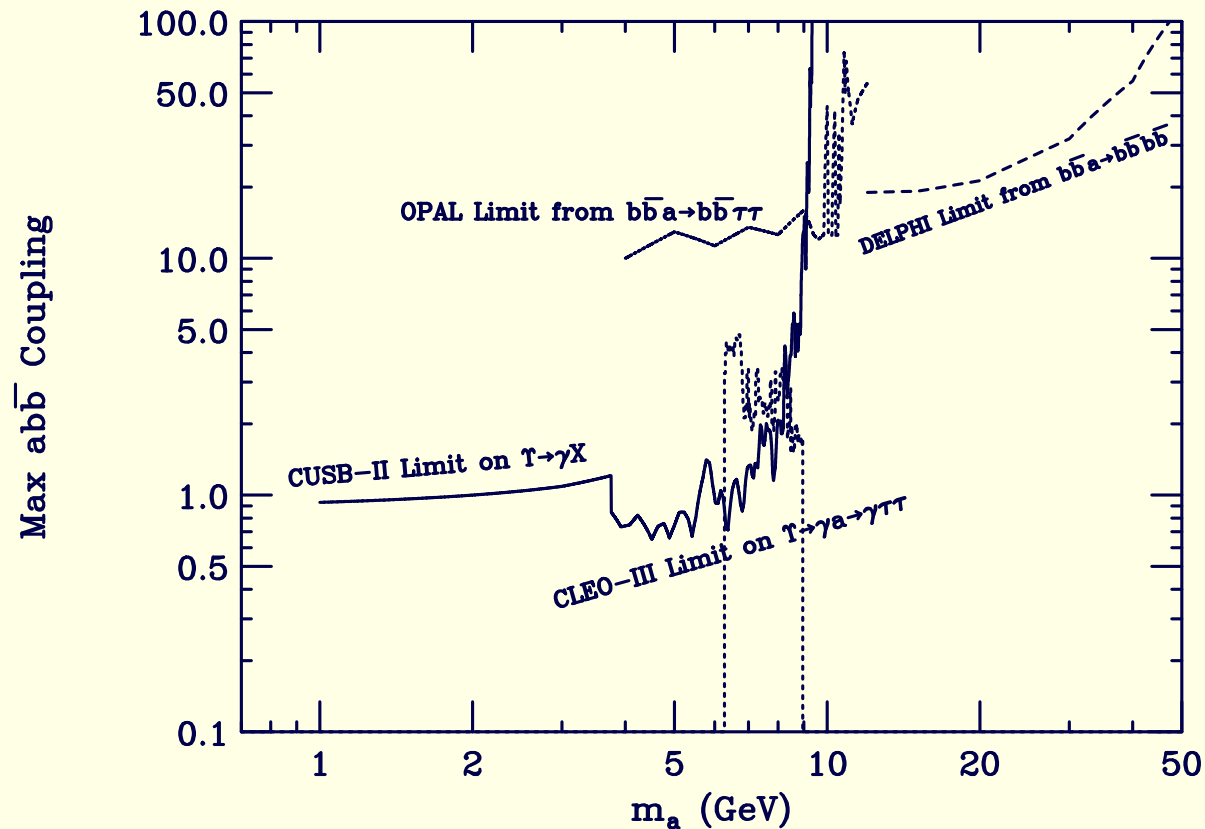


Figure 4: Limits on $C_{abb\bar{b}}$ including those from the Tevatron analysis.

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

CDF should push analysis above 9 GeV to at least the $B\bar{B}$ threshold (and perhaps a bit beyond since the threshold region is complex and LEP limits on a light $h \rightarrow aa$ 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. $b\bar{b}$ 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 $\Upsilon \rightarrow \gamma a$ and $gg \rightarrow a \rightarrow \mu^+ \mu^-$ limits.

Implications for a_μ

- Given $C_{abb\bar{}}$ 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 $C_{abb\bar{}}$ regardless of the value $R_{b/t}^2 = C_{abb\bar{}}/C_{att\bar{}}$ (for the 2HDM-II, $R_{b/t}^2 = \tan^2 \beta = C_{abb\bar{}}^2$, but for more complicated Higgs sectors, very different values for this ratio are possible). Note: $C_{att\bar{}}$ 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 GeV (9.5 GeV for 2HDM-II) up to ~ 12 GeV, where $C_{abb\bar{}}$ limits are the weakest ($C_{abb\bar{}} \lesssim 15 - 60$), might it be possible.

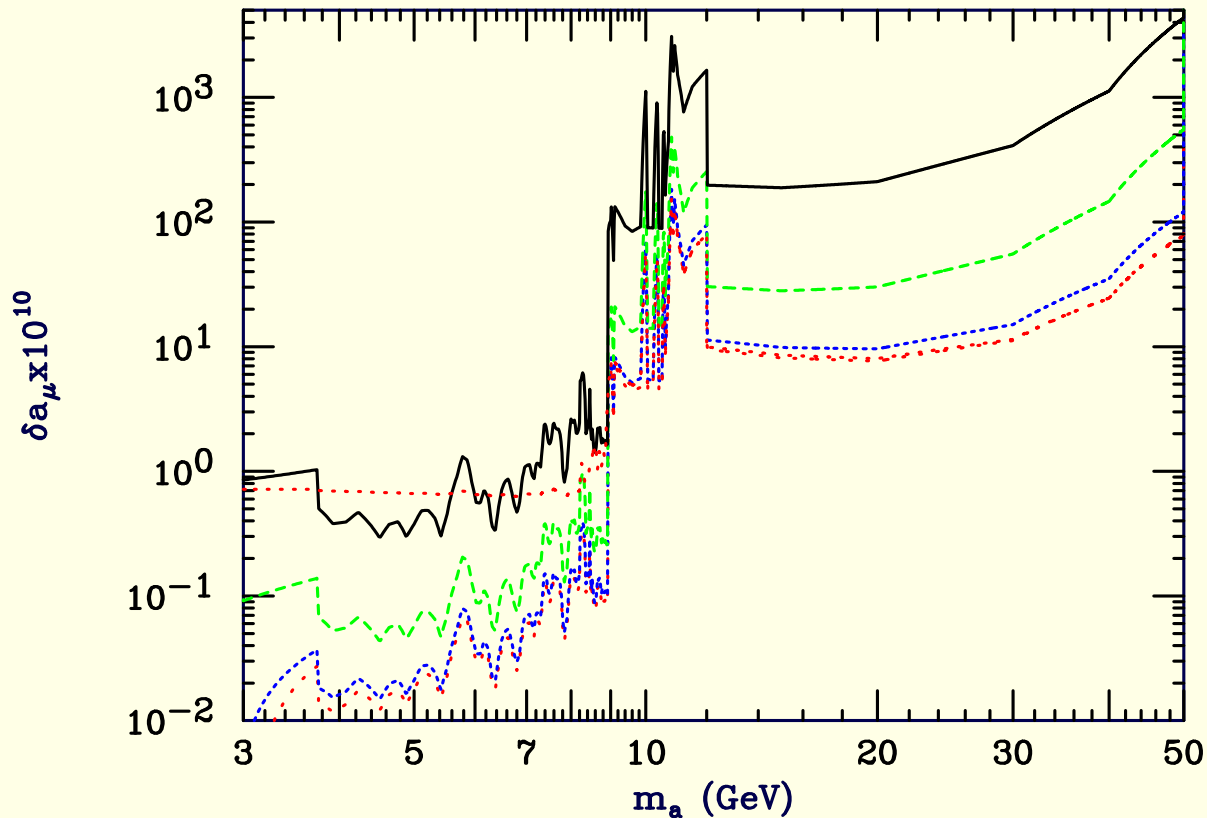


Figure 5: Results for δa_μ^{\max} from a CP-odd a for various $R_{b/t}^2 = C_{abb}/C_{att}$ models are plotted after incorporating the C_{abb} experimental limits. Curves are for $R_{b/t} = 1, 3, 10, 50$ and for the 2HDM-II prediction of $R_{b/t} = \tan \beta = C_{abb}$ (which looks like $R_{b/t} = 50$ for $m_a \gtrsim 9$ 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 $W_L W_L \rightarrow W_L W_L$ unitarity) is avoided if $m_{\tilde{t}} \lesssim 1$ TeV.
- But, the Minimal Supersymmetric Model requires a term in the superpotential of form

$$W \ni \mu \widehat{H}_u \widehat{H}_d, \quad (3)$$

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

However, theoretically, $\mu \sim M_{\text{P}}$ 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 \hat{S} that is a SM singlet which provides a beautiful solution to the μ problem.

Starting from the superpotential

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

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 $m_{\tilde{t}}$ must be $\lesssim 1 \text{ TeV}$ in order to avoid fine-tuning in getting a Higgs mass-squared that is in the right ballpark).

- 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 $m_{\tilde{t}} \lesssim 350$ GeV.

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

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

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

$h_1 \rightarrow a_1 a_1$ 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 $B(h_1 \rightarrow a_1 a_1)$ 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 :

$$a_1 = \cos \theta_A A_{MSSM} + \sin \theta_A A_S. \quad (5)$$

- One finds that to achieve $B(h_1 \rightarrow a_1 a_1) > 0.7$ for $m_{a_1} < 2m_b$ will not require fine-tuning, provided $m_{a_1} > 7.5$ GeV (implying $a_1 \rightarrow \tau^+ \tau^-$) and $C_{abb} = \cos \theta_A \tan \beta$ 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 $B(h_1 \rightarrow a_1 a_1) > 0.7$. In the end, $|C_{abb}| \gtrsim 0.35$ 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 $|C_{abb}| < 1$ 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 $|C_{abb}|$ 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, $m_h \lesssim 100 \text{ GeV}$ is wanted for precision electroweak and a_1 must have some minimal amount of doublet in order for $B(h \rightarrow a_1 a_1)$ 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 GeV to 20 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 $H \rightarrow h_1 h_1$ with $h_1 \rightarrow 2h_2 \rightarrow 4a_1 \rightarrow 8\tau$.

Each τ then decays to μ and so each side of the event has 8μ .

4. To describe the observed events, $m_H \sim 100 \text{ GeV}$ is needed and $\sigma(gg \rightarrow H) \gtrsim 100 \text{ pb}$ is required.

Since H is largely doublet, $\sigma(gg \rightarrow H)$ can be enhanced to needed $\gtrsim 100 \text{ pb}$ level for $\tan\beta > 30$.

5. Finally, one of the Higgs in the chain must be long-lived. This cannot be a_1 since $B(h \rightarrow a_1 a_1)$ 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, $h_1 \rightarrow \gamma\gamma$ 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 $a_1 \rightarrow \gamma\gamma$ decay?)

6. Of course, simultaneously one could have the Ellwanger et. al. process $gg \rightarrow A$ production with $A \rightarrow h_1 a_2$ and $a_2 \rightarrow h_1 a_1$ (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 $m_h < 105$ GeV (escaping LEP limits because $B(h \rightarrow aa \rightarrow 4\tau)$ 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 $C_{abb\bar{b}}$ 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 $a \rightarrow \mu^+\mu^-$ 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 $pp \rightarrow pph$ and $WW \rightarrow h$ with $h \rightarrow aa \rightarrow 4\tau$ search modes.

- For a generic 2HDM-II model, there is only a small $10 \text{ GeV} < m_a < 12 \text{ GeV}$ window left for which the a might explain Δa_μ and this is possible only if $C_{abb} = \tan \beta$ 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 $C_{abb} = \cos \theta_A \tan \beta$ coupling.

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

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 $a_1 \rightarrow \mu^+ \mu^-$ peak would be observable since $B(a_1 \rightarrow \mu^+ \mu^-) / B(a_1 \rightarrow \tau^+ \tau^-) \gtrsim 0.0035$ is not that small.

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

(Note: in the analysis discussed earlier, the muons were required to be isolated. This means that the multi-muon events would have been discarded.)