Experimental Probes of a Light CP-Odd Higgs Boson: Tevatron, LHC, Upsilon Decays, Muon g-2

Jack Gunion
U.C. Davis

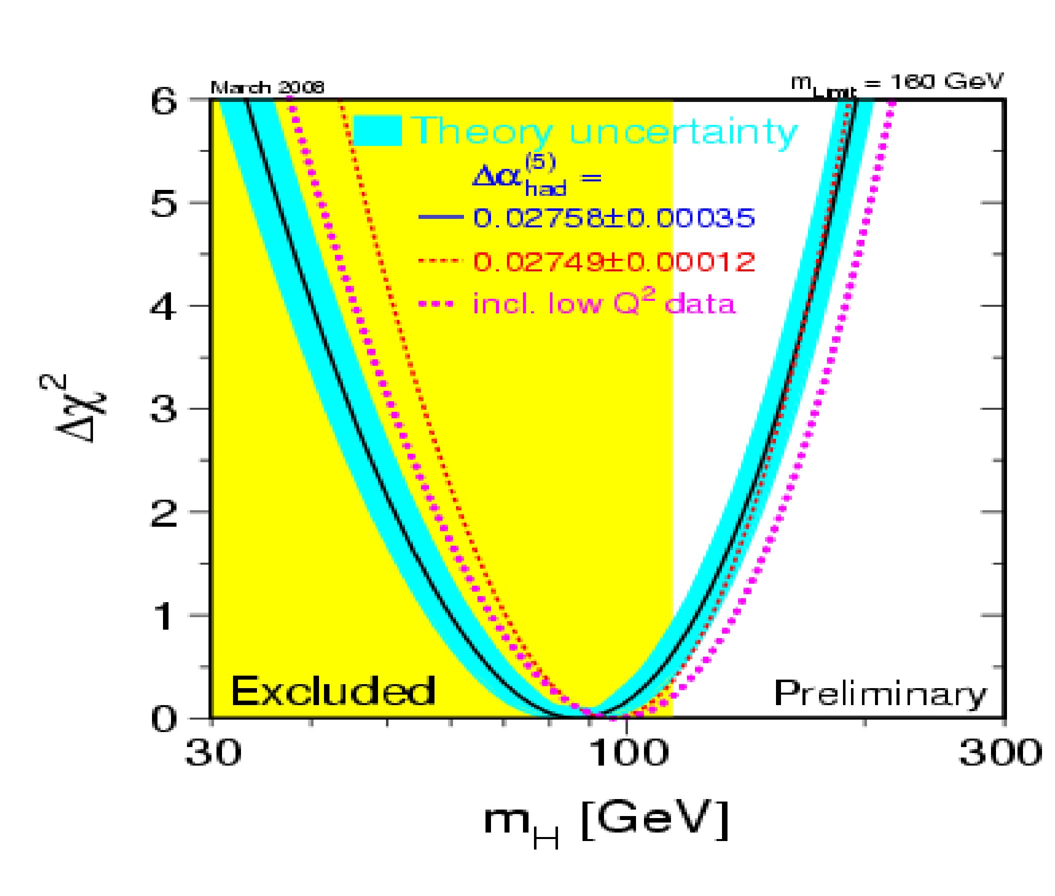
Fermilab BSM Tevatron/LHC Meeting, September 18, 2008

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.

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 Limit (GeV)	SM modes 114.4	2τ or $2b$ *only* 115	$2j$ 113	$WW^* + ZZ^*$ 100.7	$\gamma\gamma$ 117	$\not{E}$ 114	$4e, 4\mu, 4\gamma$ 114?
Mode Limit (GeV)	$4b$ 110	4τ 86	any (e.g. $4j$) 82	$2f + \not{E}$ 90?			

To have $m_H \leq 105~\mathrm{GeV}$ 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.

  The simplest possibility for explaining the excess is to have $B(H \to b\bar b) \sim 0.1 B(H \to b\bar b)_{SM}$ (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 $B(H \to aa) > 0.7$ (easy to achieve, e.g., in 2HDM-II models).

Constraints on a from LEP and Upsilon Decays

We will be especially interested in an a with $m_a < 2m_b$ and modest $ab\overline{b}$ coupling.

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

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

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.

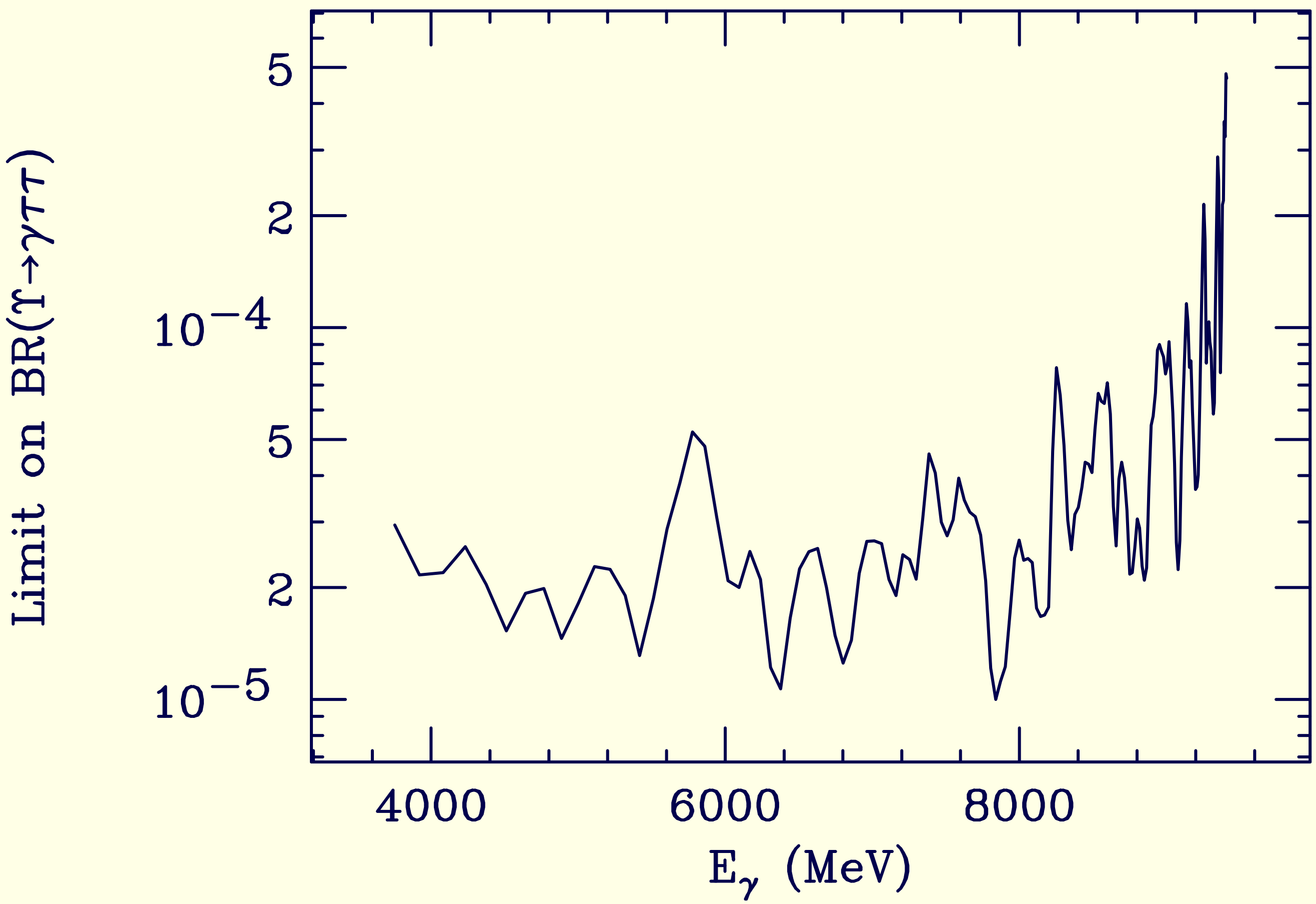


Figure 1: **Limits on $B(\Upsilon \to \gamma\tau^+\tau^-)$.**

- **For the most part the extracted $C_{ab\bar{b}}$ limits are quite model independent other than weak dependence on up-quark couplings (mostly top in gg coupling loop) through $B(a \to \tau\tau)$ and $B(a \to b\bar{b})$. The extracted limits appear in Fig. 2,**

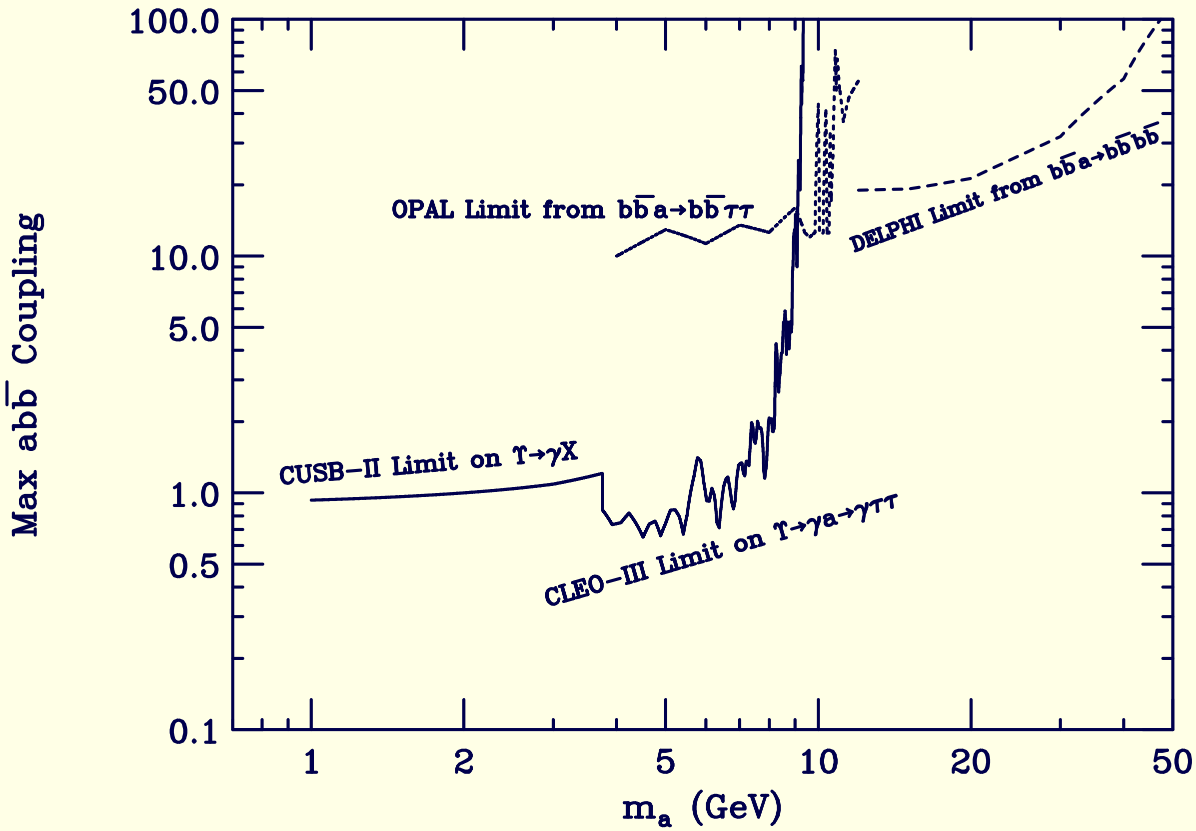


Figure 2: Limits on $C_{ab\bar{b}}$.

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

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

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 result.

  In the figure, the predictions for the cross section ratio for the a are: red crosses=$\tan\beta = 1$, blue diamonds=$\tan\beta = 2$, green crosses=$\tan\beta = 3$. Fortunately, the a and Υ cross sections are quite flat in y and only small $|y|$ production is kept in the experimental analysis.

  The a predictions employ the HIGLU program of Spira, Djouadi etal and agree with my own independent program.

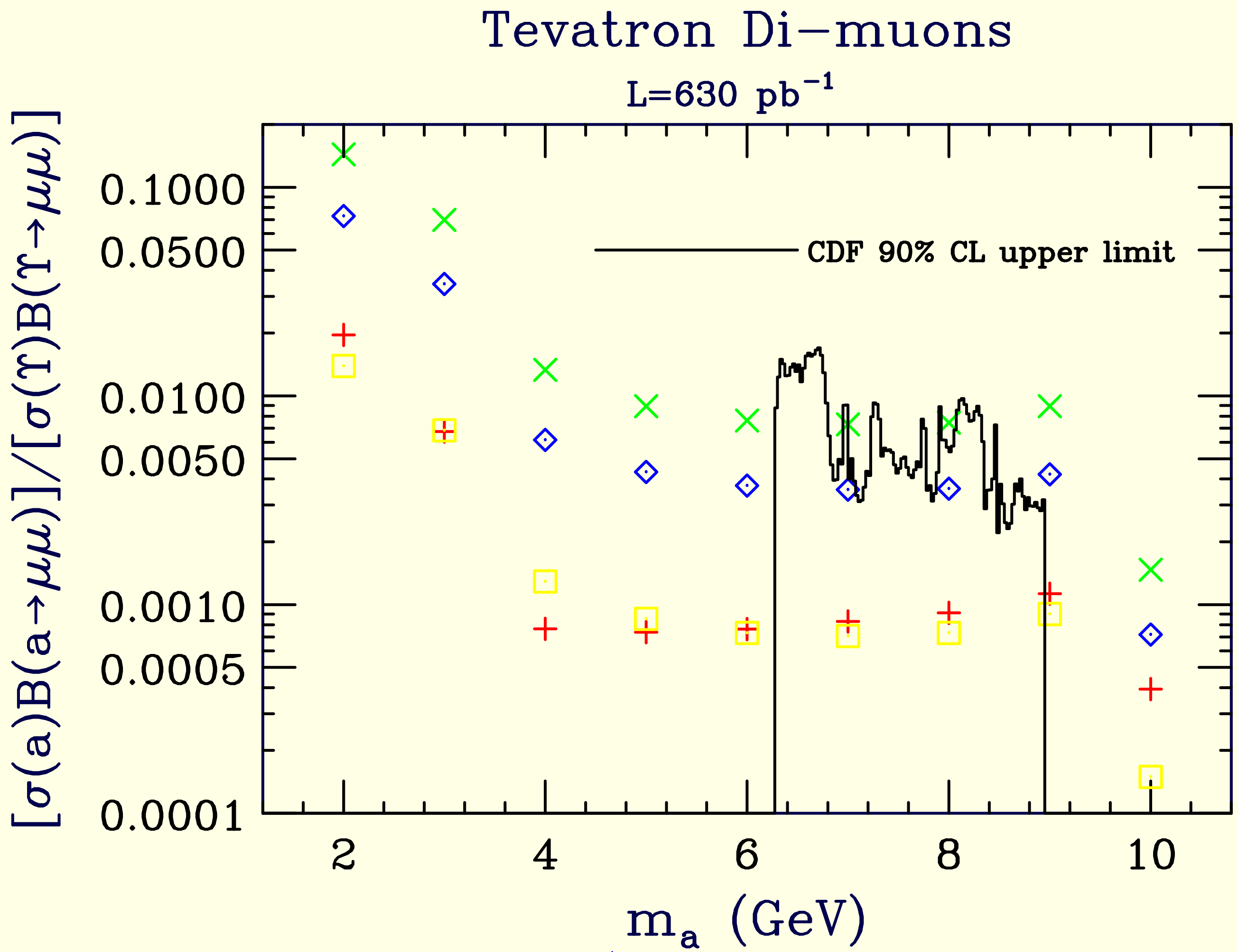


Figure 3: 90% CL limits on $\frac{\sigma(a)B(a\to\mu^+\mu^-)}{\sigma(\Upsilon)B(\Upsilon\to\mu^+\mu^-)}$ at small $|y|$ for $L = 630~\mathrm{pb}^{-1}$, compared to expectations for the a.

Why CDF stopped at $9~\mathrm{GeV}$ is not clear to me. It would certainly be very useful to at least go all the way to $B\overline{B}$ threshold (and perhaps a bit beyond since the complexity of the threshold region is such that the LEP limits on a light $h \to aa$ might still be obeyed for m_a somewhat above threshold).

Of course, as more integrated luminosity is accumulated, limits will improve.

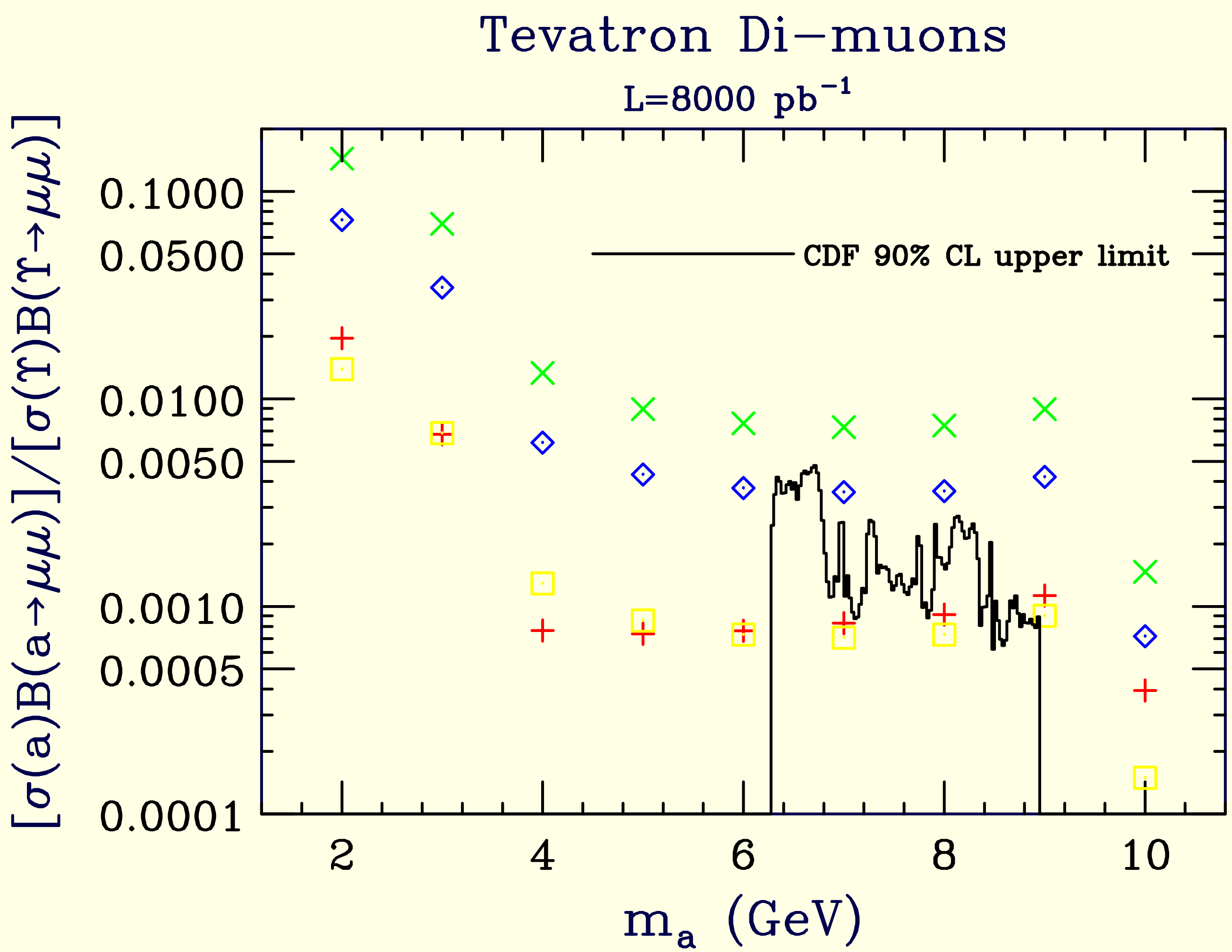


Figure 4: **90% CL limits on** $\frac{\sigma(a)B(a\to\mu^+\mu^-)}{\sigma(\Upsilon)B(\Upsilon\to\mu^+\mu^-)}$ **at small** $|y|$ **for** $L = 8~\mathrm{fb}^{-1}$.

- **Now use interpolation to turn the $630\ \mathrm{pb}^{-1}$ limits into limits on $C_{ab\bar{b}}$.**

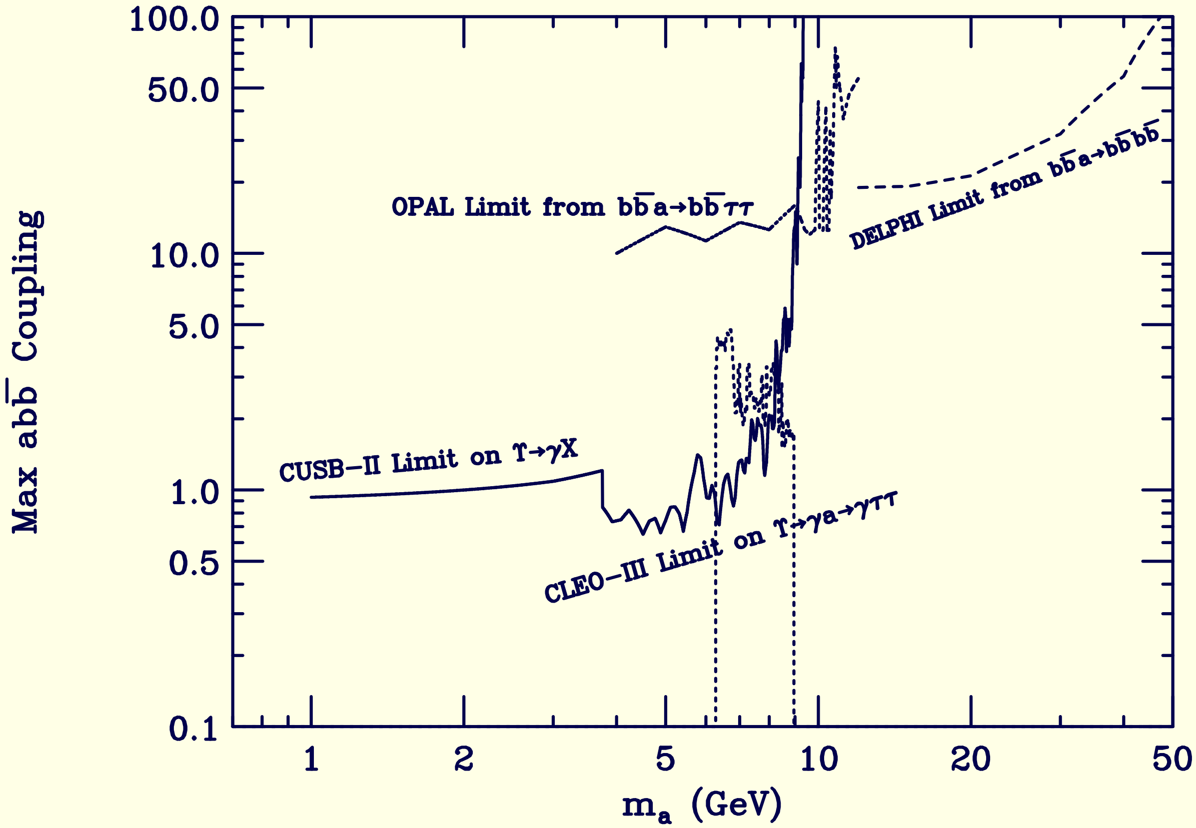


Figure 5: **Limits on $C_{ab\bar{b}}$ including those from the Tevatron analysis.**

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

There is one caveat. In the CDF analysis, the μ's are required to be

isolated. Radiative corrections include some g radiation diagrams. The extent to which this would cause the μ's to not be isolated would require a detailed MC. If you keep only virtual NLO diagrams, then the $K \sim 2.5$ factor for full NLO declines to about $K \sim 2$ and limits are a bit weaker.

- What about the LHC?

This requires work. 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. Interestingly, early low $\mathcal{L}$ running might provide the optimal situation since you can simply take all data and then work on it.
   An interesting plot from ICHEP is shown below.

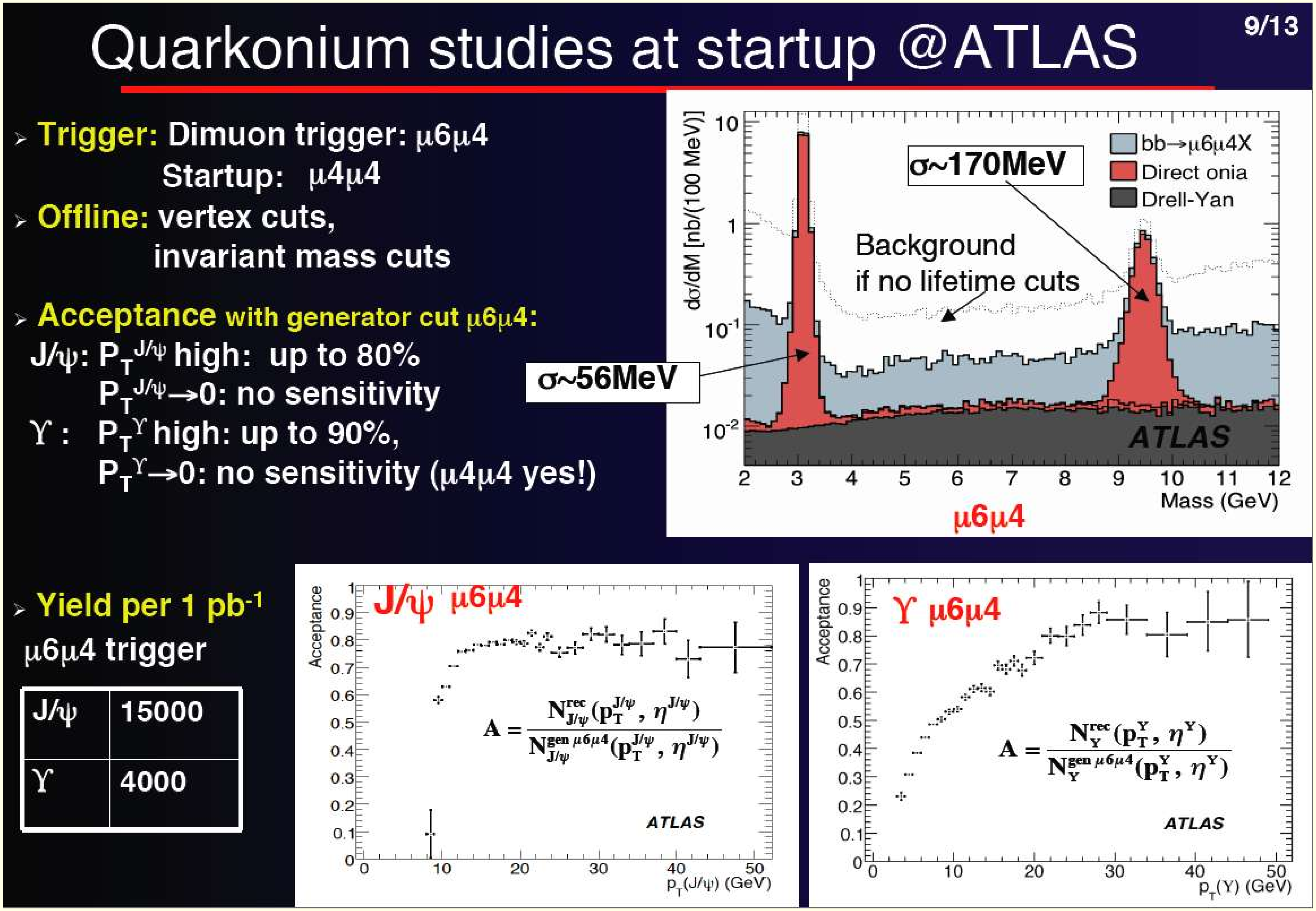


Figure 6: LHC di-muon slide from ICHEP.

After cuts (including requiring high p_T for the di-muon pair) the study finds about 4000 events for each $L = 1\ \mathrm{pb}^{-1}$. Early running at low L will probably give about $100\ \mathrm{pb}^{-1}$ (Jeffrey Berryhill's talk), implying about $400,000$ LHC events.

For $630\ \mathrm{pb}^{-1}$, the CDF analysis retained $52,700$ events. For $8\ \mathrm{fb}^{-1}$ one gets $669,206$ events (assuming simple L scaling), and so it is not clear if LHC will do better given that their criteria retain some $b\overline{b}$ background in addition to the Drell-Yan events that are the only Tevatron background.

5. Can CMS find a way to do low mass di-muons when running at high $\mathcal{L}$? Well, of course you can reduce your trigger rate by requiring large p_T, but backgrounds might become more insidious.
6. Could LHCb do better?

Implications for a_μ

- Let us accept the current limits on $C_{ab\bar{b}}$.

- 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, corresponding to the maximum allowed $C_{ab\bar{b}}$, as a function of m_a for fixed values of $R^2_{b/t} = C_{ab\bar{b}}/C_{at\bar{t}}$ and for the 2HDM-II $R^2_{b/t} = \tan^2\beta$ case are shown in Fig. 7.

  One sees that it is quite improbable that a light a could explain Δa_μ.

  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.

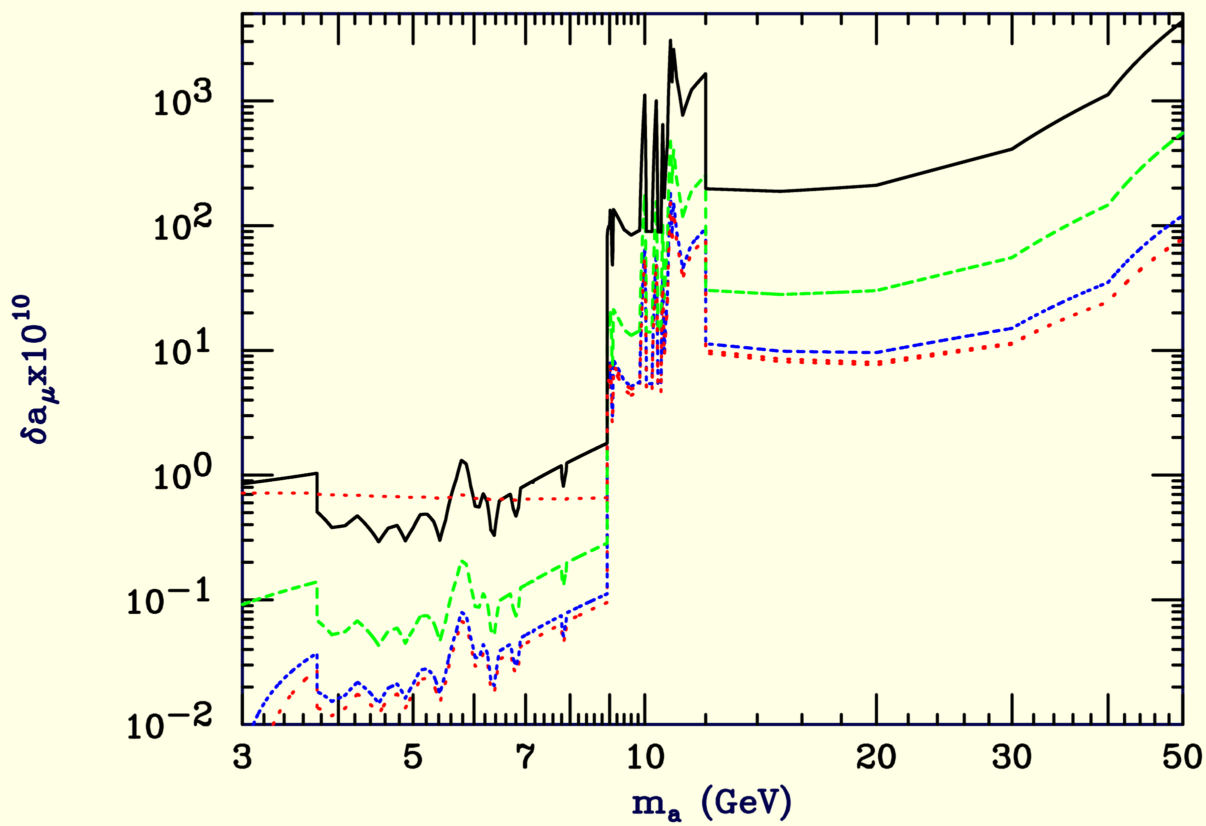


Figure 7: Results for $\delta a_\mu^{\max}$ from a CP-odd a for various $R_{b/t}^2 = C_{ab\bar{b}}/C_{at\bar{t}}$ models are plotted after incorporating the $C_{ab\bar{b}}$ experimental limits. Curves are for $R_{b/t} = 1, 3, 10, 50$ and for the 2HDM-II prediction of $R_{b/t} = \tan\beta$ (which looks like $R_{b/t} = 50$ at large m_a and is the isolated red curve at low m_a.)

The NMSSM Context

Recall:

- The NMSSM is the simplest theory for which a light ($m_{h_1} < 105~\mathrm{GeV}$) Higgs boson with SM-like ZZ coupling (perfect for electroweak precision data) is possible and that for such m_{h_1} one does not have to fine-tune the high scale (e.g. GUT-scale) parameters of the theory.

- Such an h_1 escapes LEP limits if $h_1 \to a_1 a_1$ is large and $m_{a_1} < 2m_b$.

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

$$a_1 = \cos\theta_A A_{MSSM} + \sin\theta_A A_S \,. \quad (2)$$

- To achieve the desired a_1 properties can require some fine-tuning. A measure is G.

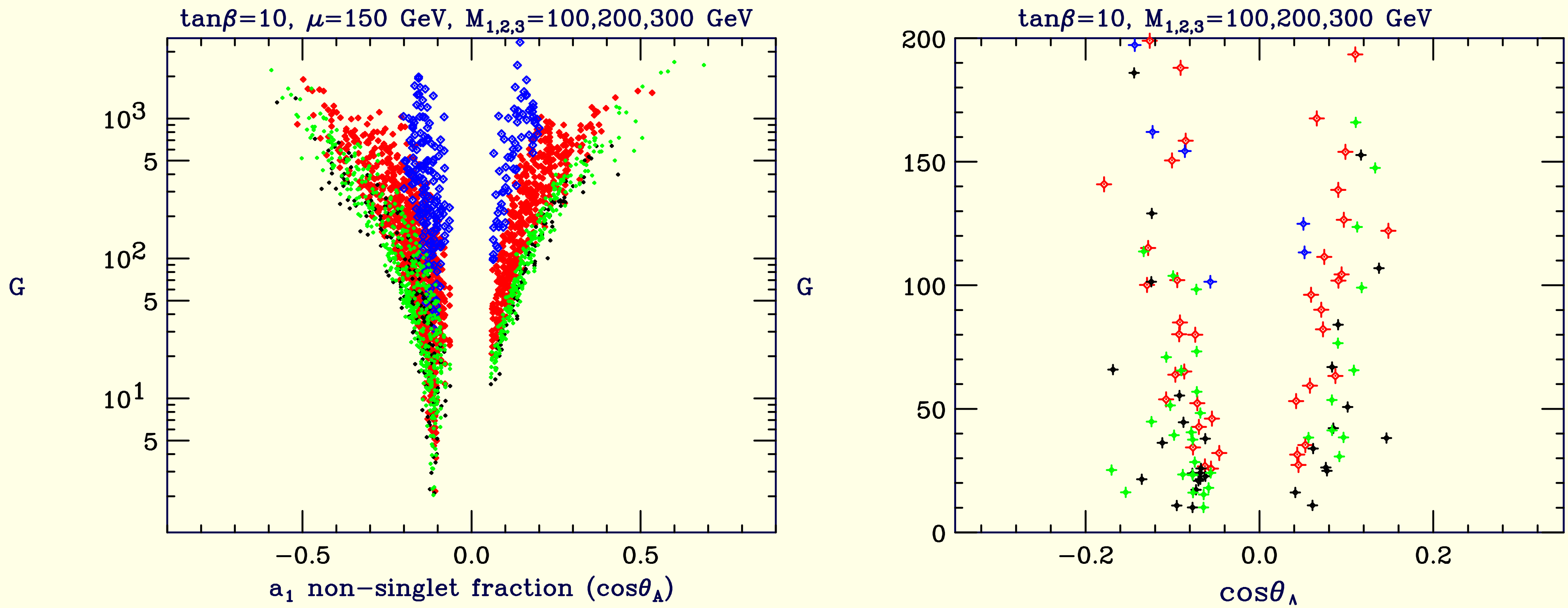


Figure 8: G vs. $\cos\theta_A$ for $M_{1,2,3} = 100, 200, 300$ GeV and $\tan\beta = 10$ from $\mu_{\rm eff} = 150$ GeV scan (left) and for points with $F < 15$ (right) having $m_{a_1} < 2m_b$ and large enough $B(h_1 \to a_1 a_1)$ to escape LEP limits. The color coding is: blue $= m_{a_1} < 2m_\tau$; 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.

Note:

1. The blue $+$'s, which are the points with $m_{a_1} < 2m_\tau$, have rather large G and tend to require precise tuning of A_λ and A_κ (the relevant soft parameters) at scale M_U.
2. Really small G occurs for $m_{a_1} > 7.5~\mathrm{GeV}$ and $\cos\theta_A \sim -0.1$.
   As we have seen, $9~\mathrm{TeV} < m_{a_1} < 2m_b$ is poorly constrained by Υ decays, but the Tevatron provides some constraints.
   For instance, the small G scenarios with m_{a_1} in this region have

$$C_{ab\bar{b}} \sim \cos\theta_A \tan\beta \sim -1. \tag{3}$$

3. Fortunately, there is a lower bound on $|\cos\theta_A|$, see Fig. 8. It arises because $B(h_1 \to a_1 a_1)$ falls below 0.75 for too small $|\cos\theta_A|$.
   As a result, $C_{ab\bar{b}}$ can never be too far below 1.

- A convenient way to visualize the impact of experimental constraints in the NMSSM case is to plot the maximum value of $\cos\theta_A$ that is allowed as a function of m_{a_1} for various fixed $\tan\beta$ values.

  The result is Fig. 9.

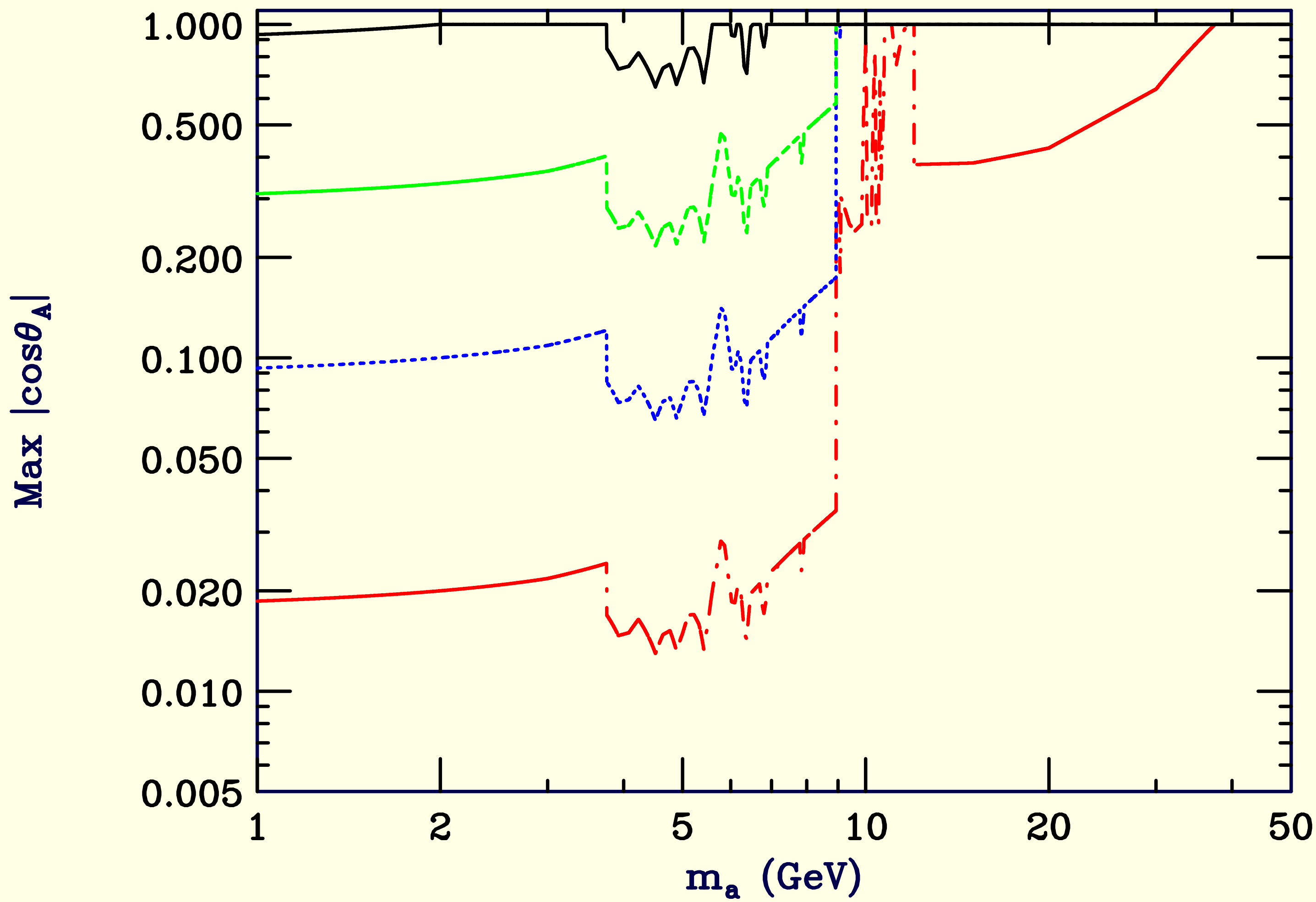


Figure 9: The maximum value of $|\cos\theta_A|$ as a function of m_{a_1} for $\tan\beta = 1, 3, 10, 50$.

Taking the blue $\tan\beta = 10$ curve as an example, you will see that $\cos\theta_A^{\max} \sim 0.16$ at $m_{a_1} \lesssim 9~\mathrm{GeV}$. With $8~\mathrm{fb}^{-1}$ of Tevatron data, the projected limits are just on the verge of constraining our most ideal small-G

scenario for $\tan\beta = 10$ which has $\tan\beta\cos\theta_A = -1$ and is represented by the yellow squares of Fig. 10 (a repeat of Fig. 4).

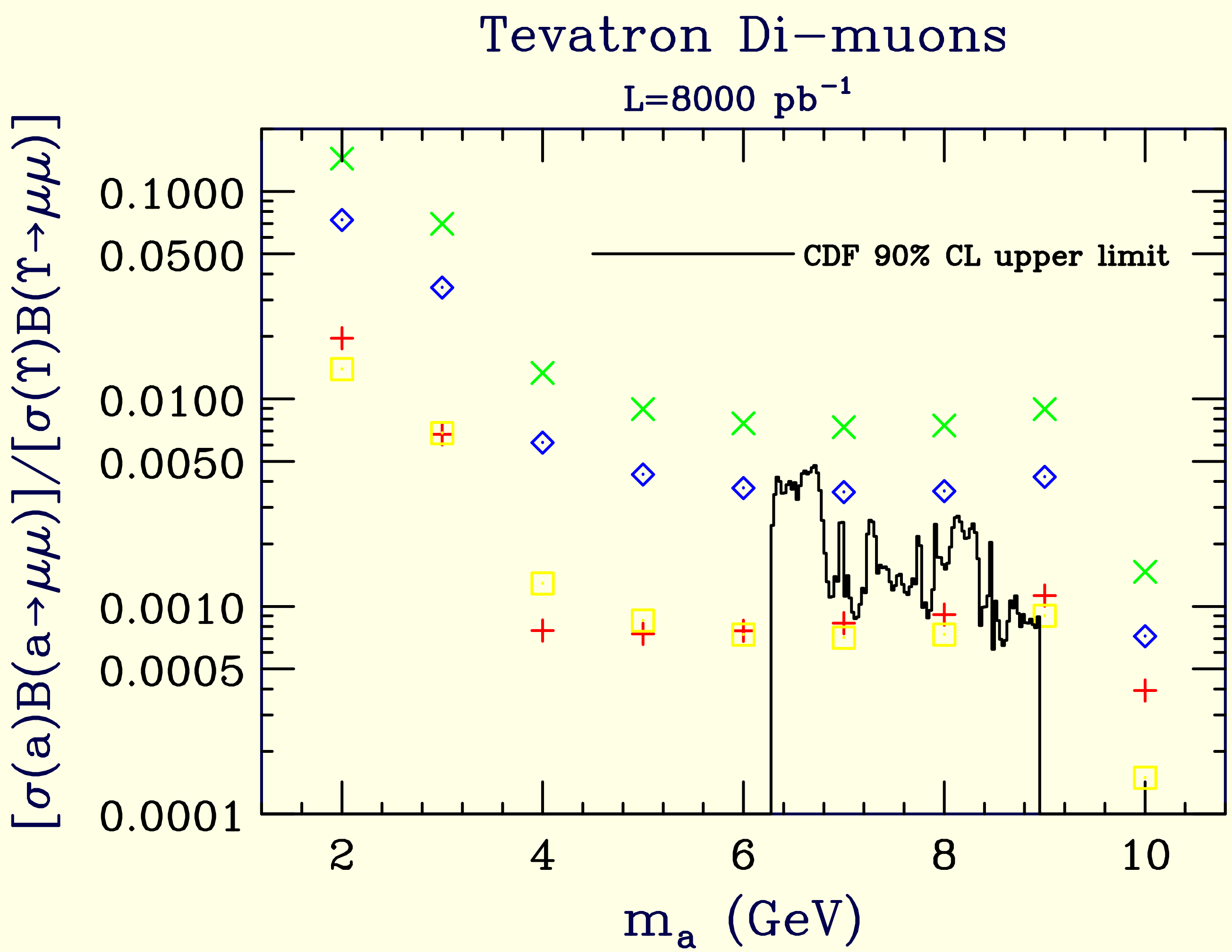


Figure 10: 90% CL limits on $\frac{\sigma(a)B(a\to\mu^+\mu^-)}{\sigma(\Upsilon)B(\Upsilon\to\mu^+\mu^-)}$ at small $|y|$ for $L = 8~\text{fb}^{-1}$.

(Small changes relative to the red pluses of $\tan\beta = 1$ occur because of re-weighting of the top loop in $gg \to a$ fusion.)

Of course, if $K \sim 2$ vs. the $K \sim 2.5$ used in the plot applies then the constraint is more marginal.

Hopefully, D0 will weigh in with a result that can be combined with CDF.

And, hopefully, both will extend their results above $9~\mathrm{GeV}$ to cover all the way up to $m_{a_1} = 2m_B$ and somewhat above, thereby completely covering the region for which an ideal Higgs scenario is possible and Υ decays can never access.

- **NOTE:** Dermisek will talk about low $\tan\beta < 2$ NMSSM scenarios.

  One finds that G is quite small if $\cos\theta_A \sim -0.5$, which would imply that the corresponding yellow squares would be lower by a significant factor (of $2-3$ — rates scale roughly as $(\cos\theta_A \tan\beta)^2$ since for low m_{a_1} the bottom loop dominates the gga_1 coupling for $\tan\beta > 1$).

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 ($i.e.$ largish G) 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-G 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 large ($|\cos\theta_A| \sim 0.5$) for the small-G preferred models, but $C_{ab\bar{b}} \sim \cos\theta_A \tan\beta$ has magnitude $\lesssim 1$.