CMS Prospects for Discovering a light CP-odd Higgs Boson and NMSSM Implications

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Who am I?

- Much of my work over the last 30 years can be characterized as being focused on going outside the conventional box.

  Some of the ideas for novel signatures that I initiated have now become conventional, often after being "rediscovered".

  Examples include:

  – I am to blame for your spending so many $'s on the EM calorimeter as a result of my proposal that a light Higgs could best be detected in the $h \to \gamma\gamma$ mode, provided the $M_{\gamma\gamma}$ resolution is excellent.

  – Proposed (with R. Barnett and H. Haber) the like-sign dilepton signal for SUSY.

  – At one of the Snowmass workshops a group of us developed the general idea of non-universal soft-masses and catalogued the representations

to which the F term responsible for SUSY breaking could belong and outlined the phenomenological implications (some cases having similar phenomenology to next two items).

– **First to propose (with H. Baer and Kingman Cheung) the idea of a light, perhaps LSP, gluino, and discuss how it would appear in a typical detector (charge exchange, intermittent heavily ionizing tracks, ...). Wrote related Monte Carlo for getting Tevatron limits.**

– **Developed (with C.H. Chen and M. Drees) the "O-II size-modulus dominated" SUSY breaking scenario, which is now known as AMSB. (In fact, Joe Lykken pointed out to me the equivalence of size-modulus dominance to loop-SUSY breaking, which is what AMSB is, but he did not write it up.)**
The AMSB scenario has many consequences such as the near degeneracy of the wino and LSP, with possible delayed decays and so forth.
Pursued lepton and hadron collider phenomenology with S. Mrenna (where we originated track/detector objects such as STUBs, KINKs and so forth that are being employed nowadays).

Signal	Definition
LHIT	Long, heavily–ionizing ($\geq$ 2MIP's as measured by SVX+CT+PS), large–p_T track that reaches the MC. The energy deposit in the HC in the track direction must be consistent with expected ionization energy deposit for the β measured (using TOF and/or SVX+CT+PS), i.e. no hadronic energy deposit.
TOF	A large–p_T track seen in the SVX and CT along with a signal in the TOF delayed by 500 ps or more (vs. a particle with $\beta = 1$). HC energy deposit (in the direction of the track) is required to be consistent with the ionization expected for the measured β (i.e. no hadronic deposit).
DIT	An isolated, large–p_T track in the SVX and CT that fails to reach the MC and deposits energy in the HC no larger than that consistent with ionization energy deposits for the measured (using SVX+CT+PS) β. Heavy ionization in the SVX+CT+PS, corresponding to $\beta < 0.8$ or $\beta < 0.6$ (DIT8 or DIT6), may be required.
KINK	A track that terminates in the CT, turning into a soft, but visible, charged–pion daughter–track at a substantial angle to parent.
STUB	An isolated, large–p_T (as measured using SVX) track that registers in all SVX layers, but does not pass all the way through the CT. Energy deposits in the EC and HC in the direction of the track should be minimal.
SNT	One or more STUB tracks with no additional trigger. Heavy ionization of the STUB in the SVX, corresponding to $\beta < 0.6$ (SNT6), may be required.
SMET	One or more STUB tracks with an $\not{E}_T > 35~\mathrm{GeV}$ trigger. Heavy ionization of the STUB in the SVX, corresponding to $\beta < 0.6$ (SMET6), may be required.
HIP	A high–impact–parameter ($b \geq 5\sigma_b$) track in the SVX, with large $\not{E}_T$ triggering, perhaps in association with a visible KINK in the SVX.
$\gamma + \not{E}_T$	Isolated, large–p_T photon and large $\not{E}_T$.
monojet+$\not{E}_T$	Large–p_T jet and large $\not{E}_T$.
mSUGRA–like	jet(s)+$\not{E}_T$, tri–leptons, like–sign di–leptons, *etc.*, except that the cross section for the $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$ tri–lepton signal can be suppressed.

Table 1: Summary of signals. MIP refers to a minimally–ionizing–particle such as a $\beta = 1$ muon.

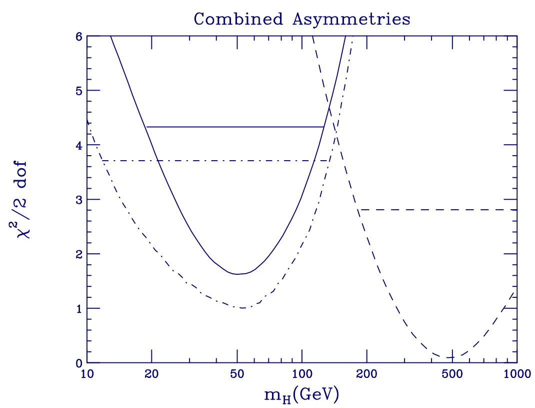
- **With H. Haber, developed the basics of SUSY Higgs theory and phenomenology.**
- **With Ellis, Haber, Zwirner, Roszkowski and others developed the basic Higgs phenomenology of the NMSSM.**
- **With Ellwanger and Hugonie developed the now widely used NMHDECAY program for NMSSM Higgs phenomenology with experimental constraints included.**
- **With Dermisek, developed the idea of solving the electroweak fine-tuning and precision electroweak problems by having a light Higgs (below LEP limits) that escapes LEP by virtue of $h \to aa$ decays with $m_a < 2m_B$.**
- **Currently working on techniques to observe such an NMSSM h and a, the latter being the subject of the talk to follow.**
- **Over the years, participated in many working groups thinking about trigger issues for Tevatron and LHC experiments.**

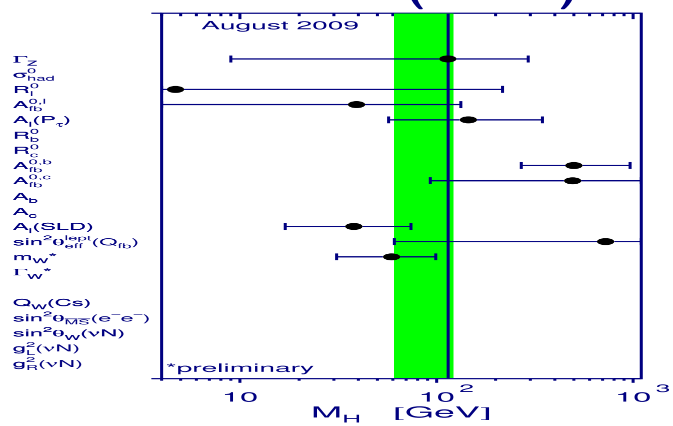
Motivations for light CP-odd Higgs search

1. **Lots of models, especially string models and extended SUSY models, have light CP-odd Higgs bosons.**

2. **There is particularly strong motivation in the context of Ideal NMSSM Higgs Scenarios defined as follows:**

   (a) Higgs should $\Rightarrow$ excellent precision electroweak (PEW) consistency.





Dropping hadronic asymmetries this $\Rightarrow$ $m_h < 105~\mathrm{GeV}$ if the h has SM-like WW, ZZ couplings, or more generally $m_{eff} < 105~\mathrm{GeV}$ where

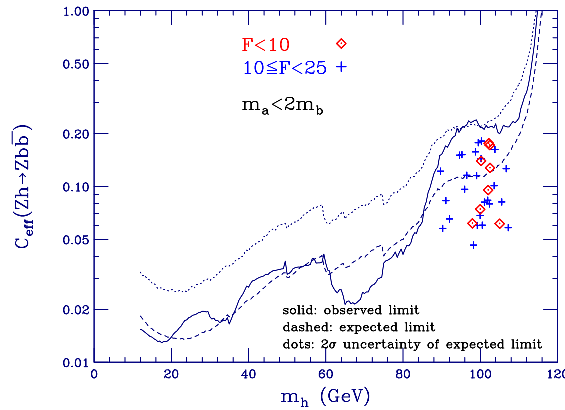
$$\ln m_{eff} \equiv [g_{ZZh_i}/g_{ZZh_{\rm SM}}]^2 \ln m_i \tag{1}$$

is the effective PEW mass for a collection of Higgs bosons with WW, ZZ couplings;

(b) **Consistency with LEP limits.**

$m_h > 114~\mathrm{GeV}$ is required without unusual decays $\Rightarrow$ unusual decays must dominate in the ideal case of $m_h < 105~\mathrm{GeV}$.

(c) **Consistency with $98~\mathrm{GeV}$ LEP excess?**



(d) **Low enough Higgs mass for electroweak baryogenesis independently $\Rightarrow$ $m_h, m_{eff} \lesssim 105~\mathrm{GeV}$ more or less.**

(e) **No hierarchy problem; *i.e.* the quadratically divergent loop contributions to the Higgs mass should be cut off by new physics at a scale of $\mathcal{O}(~\mathrm{TeV})$.**

(f) **Coupling constant unification without adhoc tuning of matter content and/or Lagrangian parameters.**

(g) **No electroweak finetuning;** *i.e.* **the value of** m_Z **is not simply input and/or is not strongly dependent on input global parameters at the GUT, or any other, scale.**

(h) **Consistency with triviality and vacuum stability constraints.**

All the above are possible in the Ideal NMSSM Higgs Scenarios.

Generic and NMSSM models that allow an Ideal Higgs

- **A particularly simple and generic way in which a light h can escape LEP limits is if $h \to aa$ (a is a light CP-odd Higgs) with large BR and $a \to \tau^+\tau^-$ or $a \to 2j$ ($a \to b\bar{b}$ does not allow $m_h < 105~\mathrm{GeV}$ to escape LEP limits).**

  Thus, one must have $m_a < 2m_B$.

  The very attractive NMSSM is perfect.

- **The NMSSM is obtained from the MSSM by adding a singlet chiral superfield $\widehat{S}$, yielding an extra CP-even Higgs $\Rightarrow h_{1,2,3}$, an extra CP-odd Higgs $\Rightarrow a_{1,2}$ and an extra neutralino.**

- **It provides an automatic solution to the μ problem, $\widehat{W} = \lambda \widehat{S}\widehat{H}_u\widehat{H}_d \to \mu_{\mathrm{eff}}\widehat{H}_u\widehat{H}_d$ with $\mu_{\mathrm{eff}} = \lambda\langle S\rangle$.**

- $h_1 \to a_1 a_1 \to 4\tau, 2\tau + 2j, 4j$ decays allow $m_{h_1} < 105~\mathrm{GeV}$, with $m_{h_1} \sim 100~\mathrm{GeV}$ certainly possible, while escaping LEP limits.

- Low electroweak finetuning (no worse than $5-10\%$, $F < 10-20$) is automatic if stop masses are low (and gluino mass is not large), in which case $m_{h_1} < 105~\mathrm{GeV}$ is **predicted** in the NMSSM context.

- A small value of $m_{a_1} < 2m_B$ does not require A_λ-A_κ ($V \ni A_\lambda S H_u H_d + \frac{1}{3} A_\kappa S^3$) finetuning (no worse than $5-10\%$ is very possible) and one finds $B(h_1 \to a_1 a_1) > 0.7$ so long as $\cos\theta_A$ does not fall below some minimum value — here, $\cos\theta_A$ is defined by

$$a_1 = \cos\theta_A a_{MSSM} + \sin\theta_A a_S\,. \tag{2}$$

  The tuning required to get $m_{a_1} < 2m_B$ and $B(h_1 \to a_1 a_1) > 0.7$ is called "light-a_1" finetuning — associated measure is G.

  Really small G typically yields a preference for rather well defined values of $\cos\theta_A$ when $\tan\beta$ is large.

- Of course, multi-singlet extensions of the NMSSM will expand the possibilities, and are typical of string models.

The problem is that Higgs detection in $h_1 \to a_1 a_1 \to 4\tau, 2\tau, 4j$ modes is quite difficult, especially at low $\tan\beta$ where $4j$ becomes dominant.

Thus, the Higgs could be "buried" under backgrounds at the LHC.

It then becomes particularly relevant to search directly for the light a_1.

Predictions regarding a light a and the NMSSM a_1

What limits on the a can be obtained from existing data?

- **Define a generic coupling to fermions by**

$$\mathcal{L}_{af\overline{f}} \equiv iC_{af\overline{f}} \frac{ig_2 m_f}{2m_W} \overline{f} \gamma_5 f a \,, \qquad (3)$$

At large $\tan\beta$, SUSY corrections $C_{ab\overline{b}} = C_{ab\overline{b}}^{tree}[1/(1+\Delta_b^{SUSY})]$ can be large and either suppress or enhance $C_{ab\overline{b}}$ relative to $C_{a\tau^-\tau^+}$. Will ignore.

- **To extract limits from the data on $C_{ab\overline{b}}$, we need to make some assumptions. Here, we presume a 2HDM(II) model as appropriate to the NMSSM and SUSY in general.**

Then, we can predict the branching ratios of the a. First $a \to \mu^+\mu^-$.

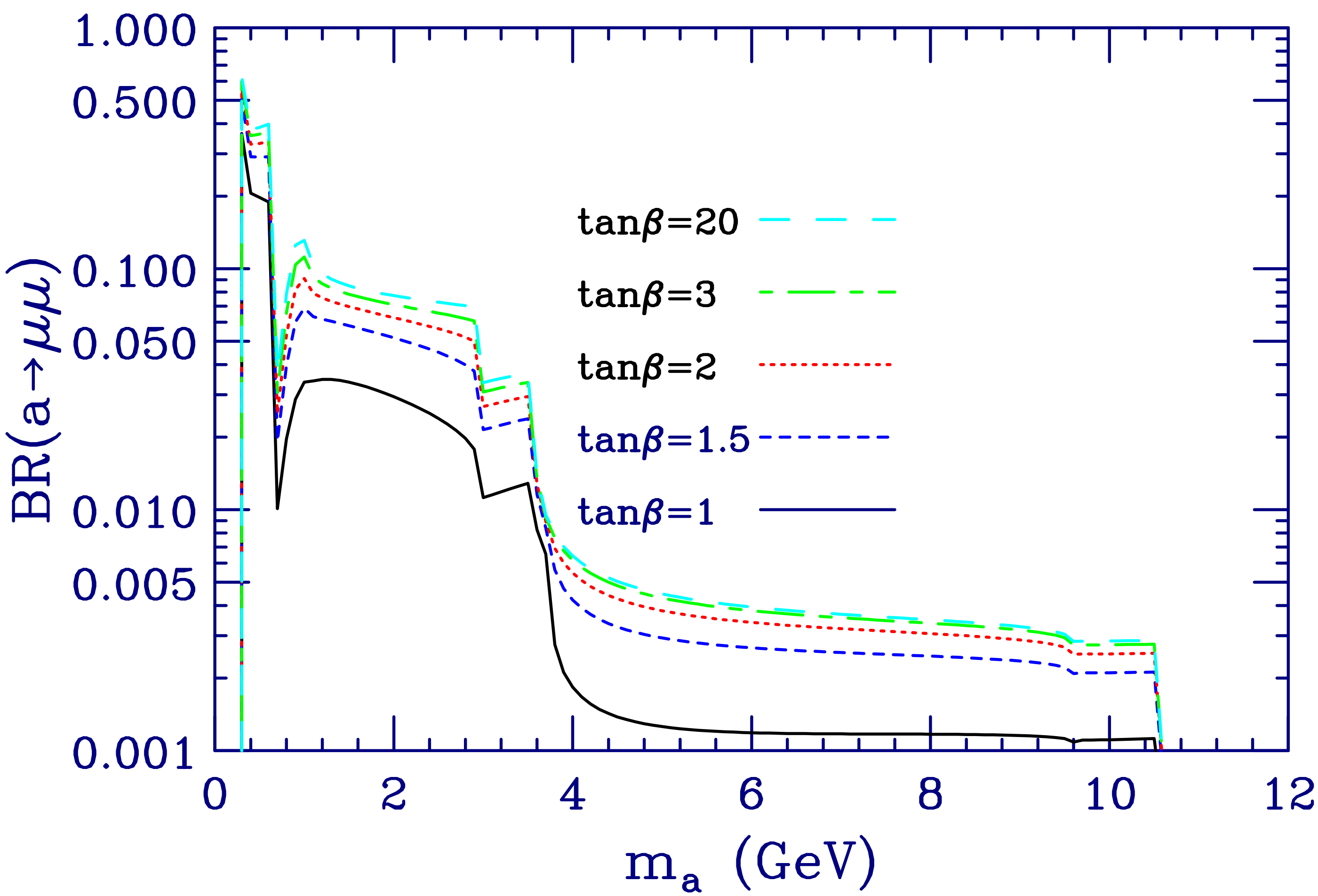


Figure 1: $B(a \to \mu^+\mu^-)$ **for various** $\tan\beta$ **values.**

- **It will also become important to know about** $B(a \to \tau^+\tau^-)$**. Note values**

at high $\tan\beta$ of $\sim \mathbf{0.75}$ ($i.e.$ below max of $\sim \mathbf{0.89}$) for $m_a \gtrsim \mathbf{10}$ GeV.

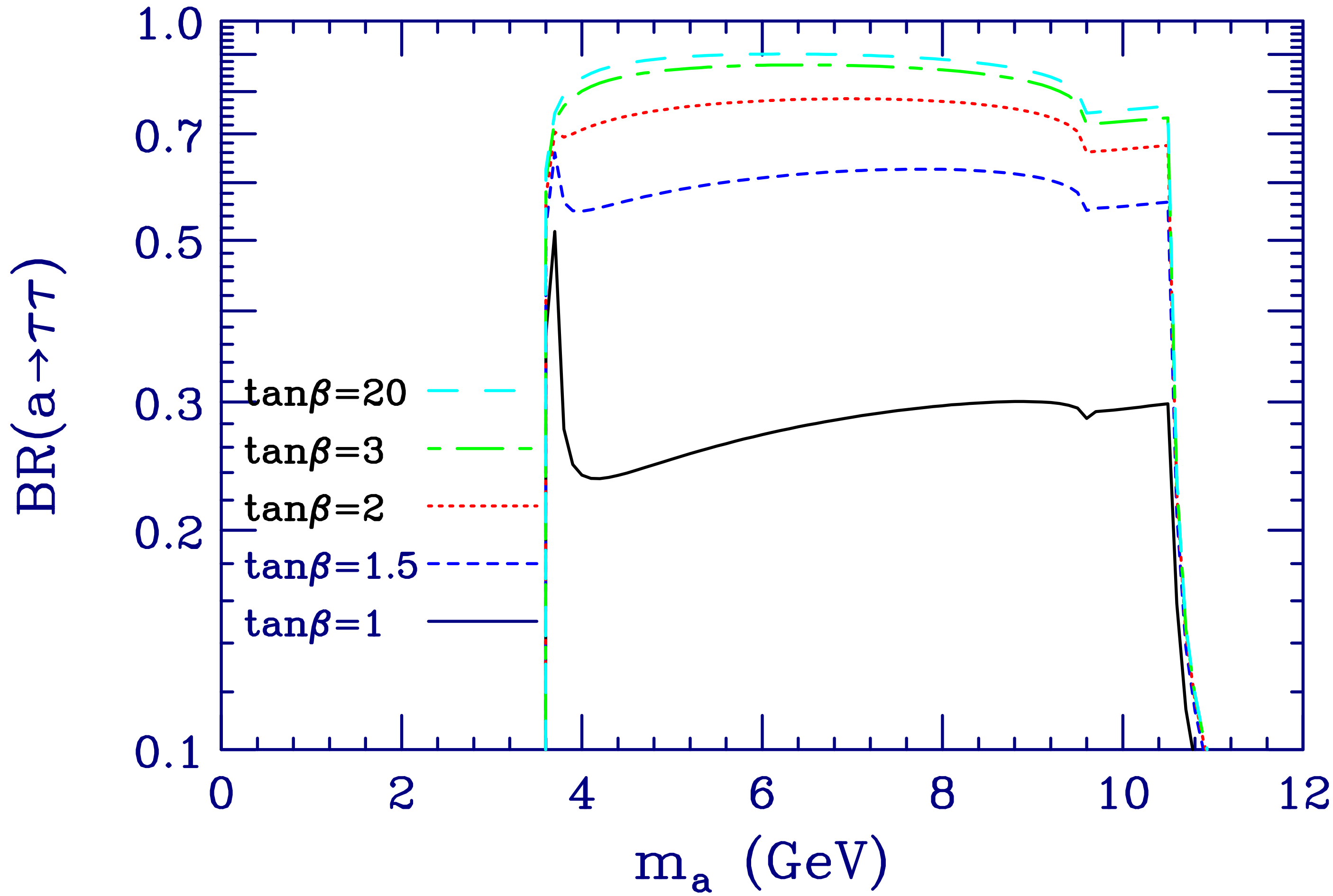


Figure 2: $B(a \to \tau^+\tau^-)$ **for various** $\tan\beta$ **values.**

- **Both are influenced by the structures in $B(a \to gg)$, which in particular gets substantial at high m_a where the b-quarks of the internal b-quark loop can be approximately on-shell.**

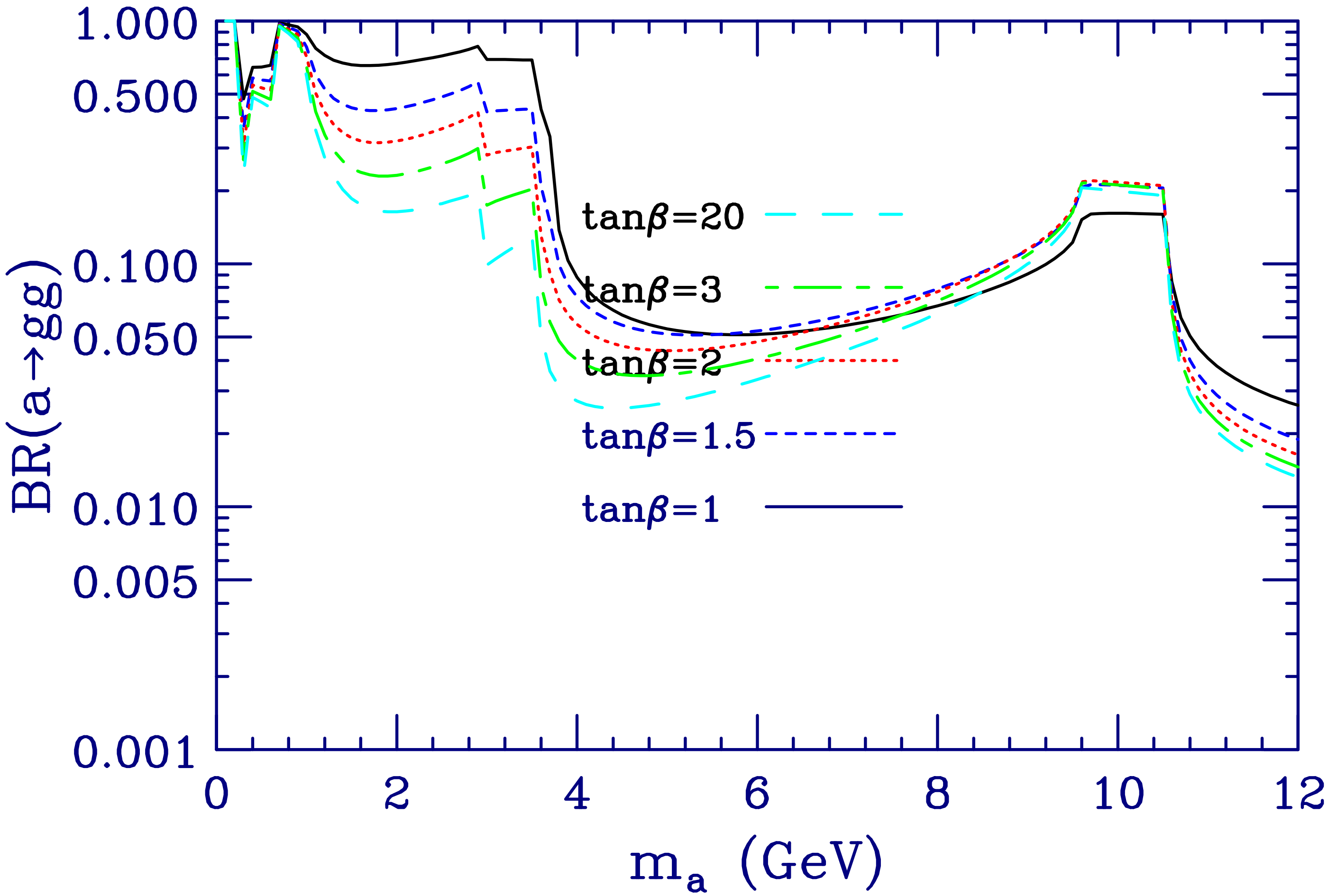


Figure 3: $B(a \to gg)$ **for various** $\tan\beta$ **values.**

- **The extracted $C_{ab\bar{b}}$ limits (JFG, arXiv:0808.2509 and JFG+Dermisek, arXiv:0911.2460; see also Ellwanger and Domingo, arXiv:0810.4736) appear in Fig. 4.**

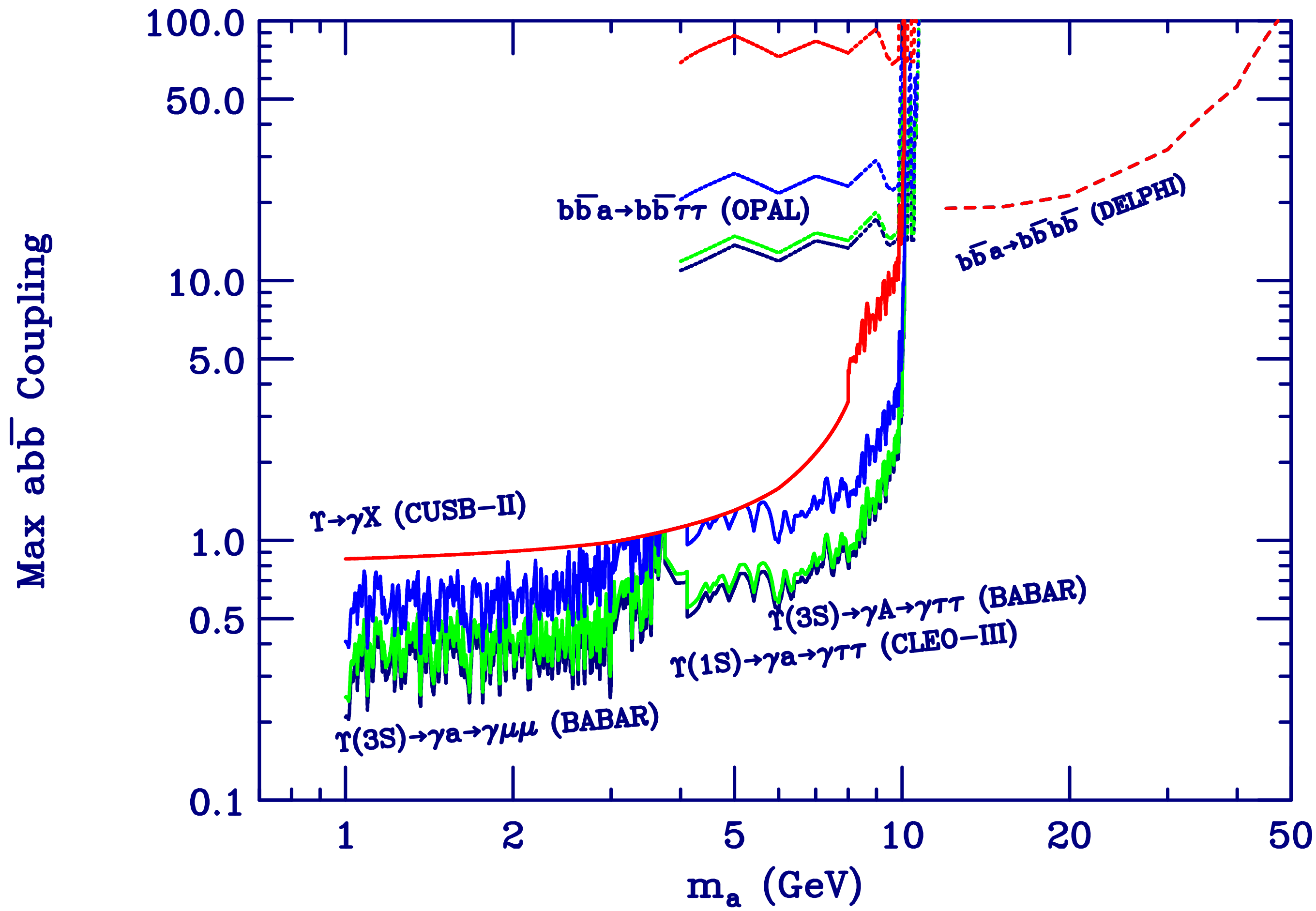


Figure 4: Limits on $C_{ab\bar{b}}$ from JFG, arXiv:0808.2509 and JFG+Dermisek, arXiv:0911.2460. These limits include recent BaBar $\Upsilon_{3S} \to \gamma\mu^+\mu^-$ and $\gamma\tau^+\tau^-$ limits. Color code: $\tan\beta = 0.5$; $\tan\beta = 1$; $\tan\beta = 2$; $\tan\beta \geq 3$.

- **What are the implications in the NMSSM context?**

$$C_{ab\bar{b}} = \cos\theta_A \tan\beta \quad (4)$$

In the NMSSM, the limits on $C_{ab\bar{b}}$ imply limits on $\cos\theta_A$ for any given choice of $\tan\beta$.

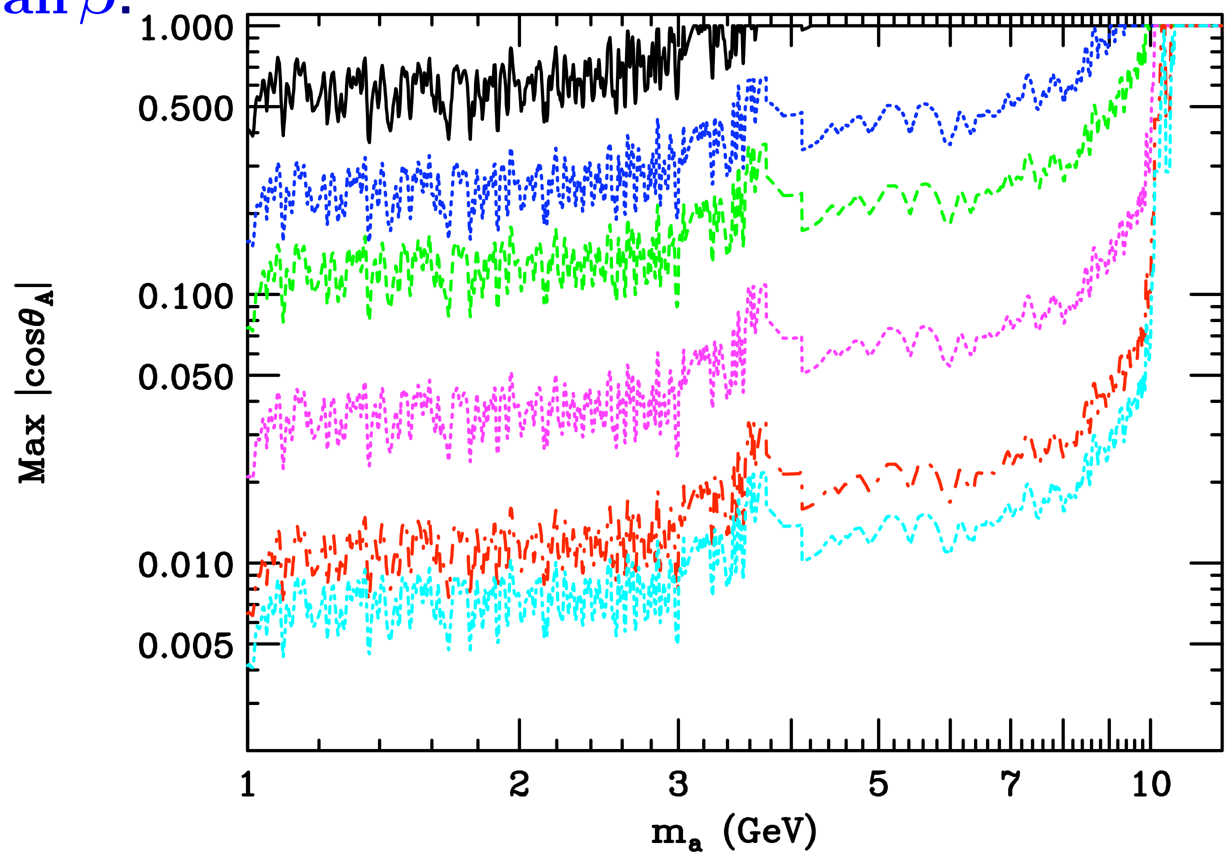


Figure 5: **Curves are for $\tan\beta = 1$ (upper curve), 1.7, 3, 10, 32 and 50 (lowest curve).**

What is the impact on "ideal" scenarios with low F. Examine the light-a finetuning measure G as a function of $\cos\theta_A$.

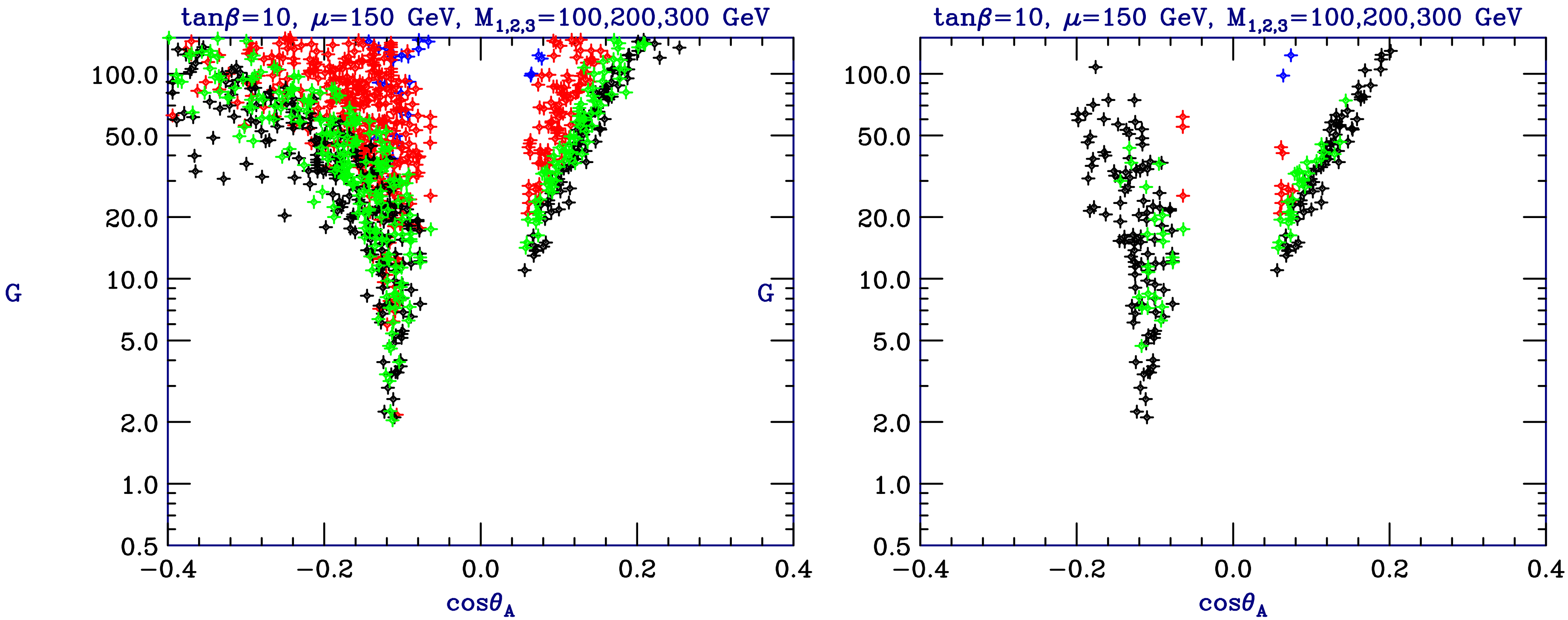


Figure 6: Results of $\mu = 150$ GeV and $\tan\beta = 10$ scan. Note that many points with low m_{a_1} and large $|\cos\theta_A|$ are eliminated, including almost all the $m_{a_1} < 2m_\tau$ points and most of the $2m_\tau < m_{a_1} < 7.5$ GeV points, leaving mainly 7.5 GeV $< m_{a_1} < 8.8$ GeV and 8.8 GeV $< m_{a_1} < 10$ GeV points.

Note the lower limit on $|\cos\theta_A|$ which results from the requirement $B(h_1 \to a_1 a_1) > 0.7$ for evading $e^+e^- \to Zh_1 \to Z + b's$ LEP limits.

- Thus, we have a convergence whereby low "light-a" fine tuning in the NMSSM and direct $\Upsilon_{3S} \to \gamma\mu^+\mu^-$ limits single out the $m_a > 7.5~\mathrm{GeV}$ part of parameter space.

  LHC studies of light h NMSSM scenarios should (and have) focused on this case.

  With regard to the a itself, we should focus on Tevatron and LHC probes of a light a with $2m_\tau < m_a < 2m_B$.

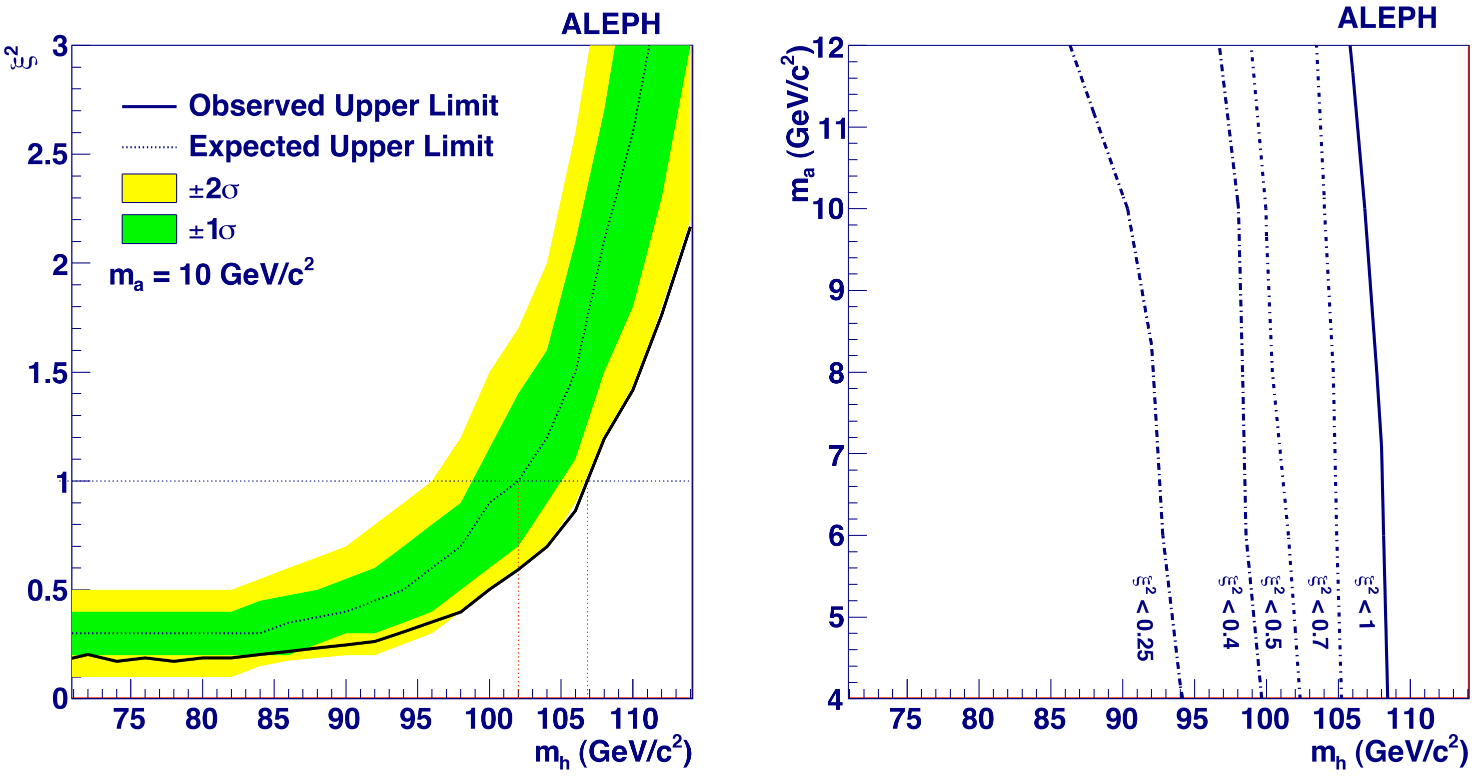
  Of course, the Tevatron and LHC *can* probe $m_a < 2m_\tau$:

  1. $B(a \to \mu^+\mu^-)$ is much larger. BUT
  2. Acceptance is presumably smaller because of p_T distributions for the μ's shifting down.
  3. Backgrounds are presumably larger.

  Studies of $m_a < 2m_\tau$ cases at hadron colliders are worth pursuing since they might completely eliminate all such NMSSM ideal Higgs scenarios, irrespective of G.

  Here we will focus on $m_a > 2m_\tau$.

- **In fact, results from ALEPH further shift the focus to high m_a in the NMSSM context.**



(a) (b)

But, notice the huge difference between expected and observed limits.

- **Comparison to NMSSM ideal scenarios:**

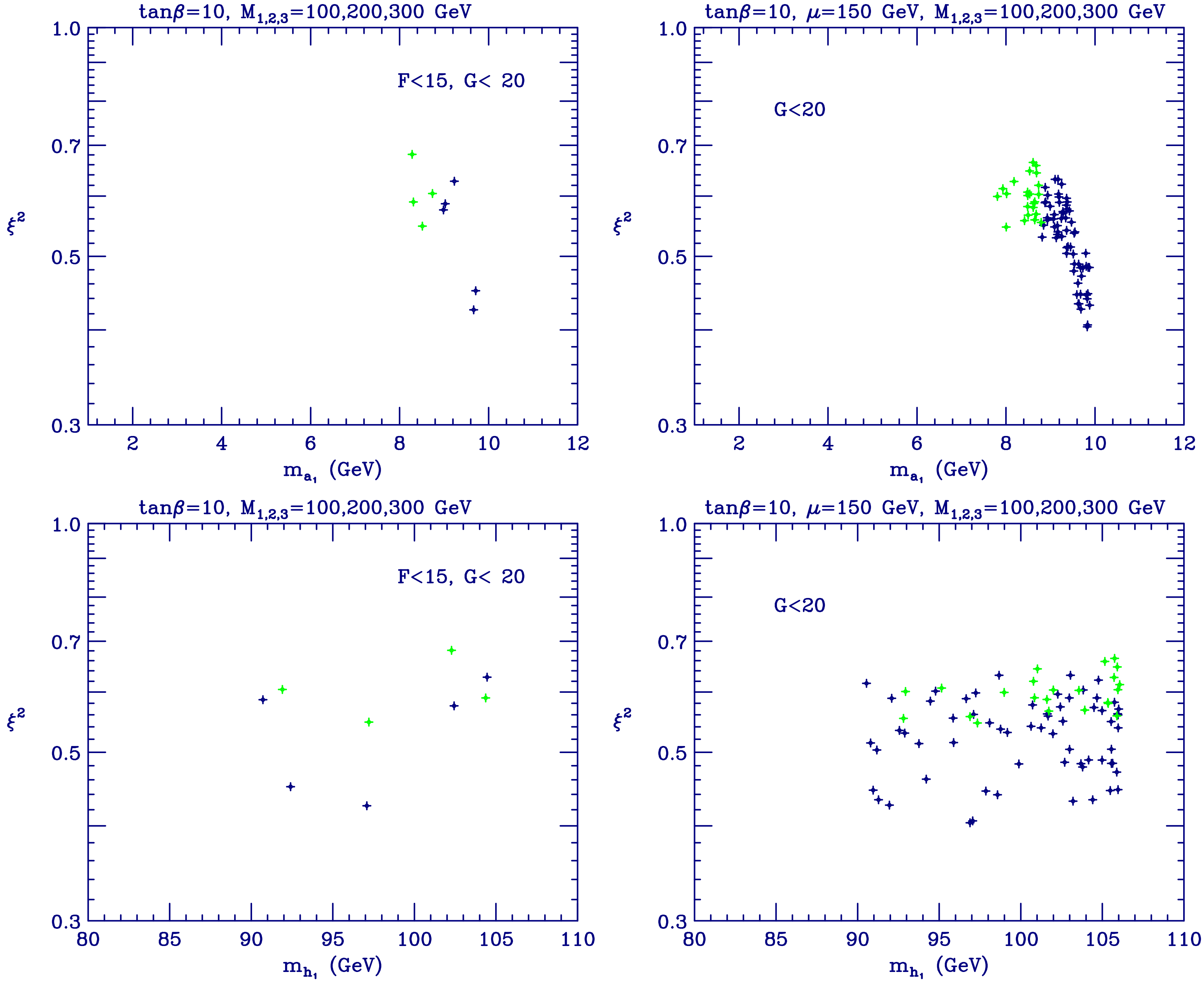


Figure 7: ξ^2 vs. m_{a_1} and m_{h_1} for $\tan\beta = 10$; $|\cos\theta_A| < \cos\theta_A^{\max}$; general scan and fixed μ scan.

What actually survives ALEPH limits?

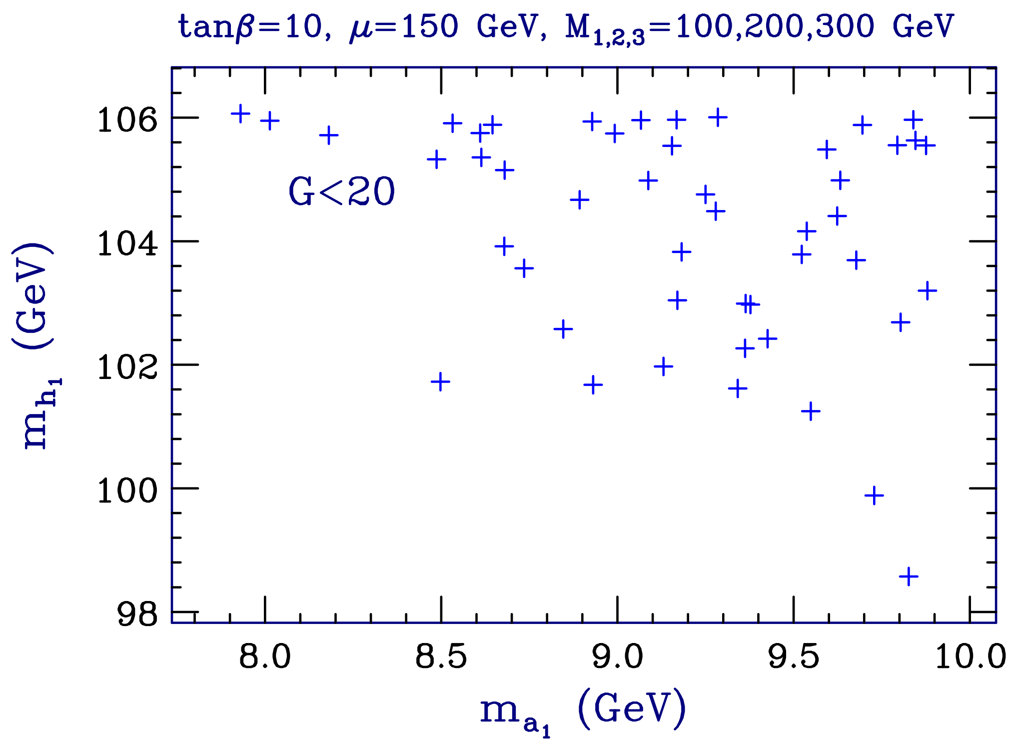


Figure 8: **Points with $G < 20$ at $\tan\beta = 10$ that survive $|\cos\theta_A|$ and ALEPH limits.**

- **For $\tan\beta = 3$, no scan points survive the ALEPH limits. m_{h_1} is typically $\lesssim 95~\mathrm{GeV}$, for which ALEPH limits are strong.**

- **For $\tan\beta \leq 2$ one finds that ξ^2 declines significantly, and will escape ALEPH limits more easily.**

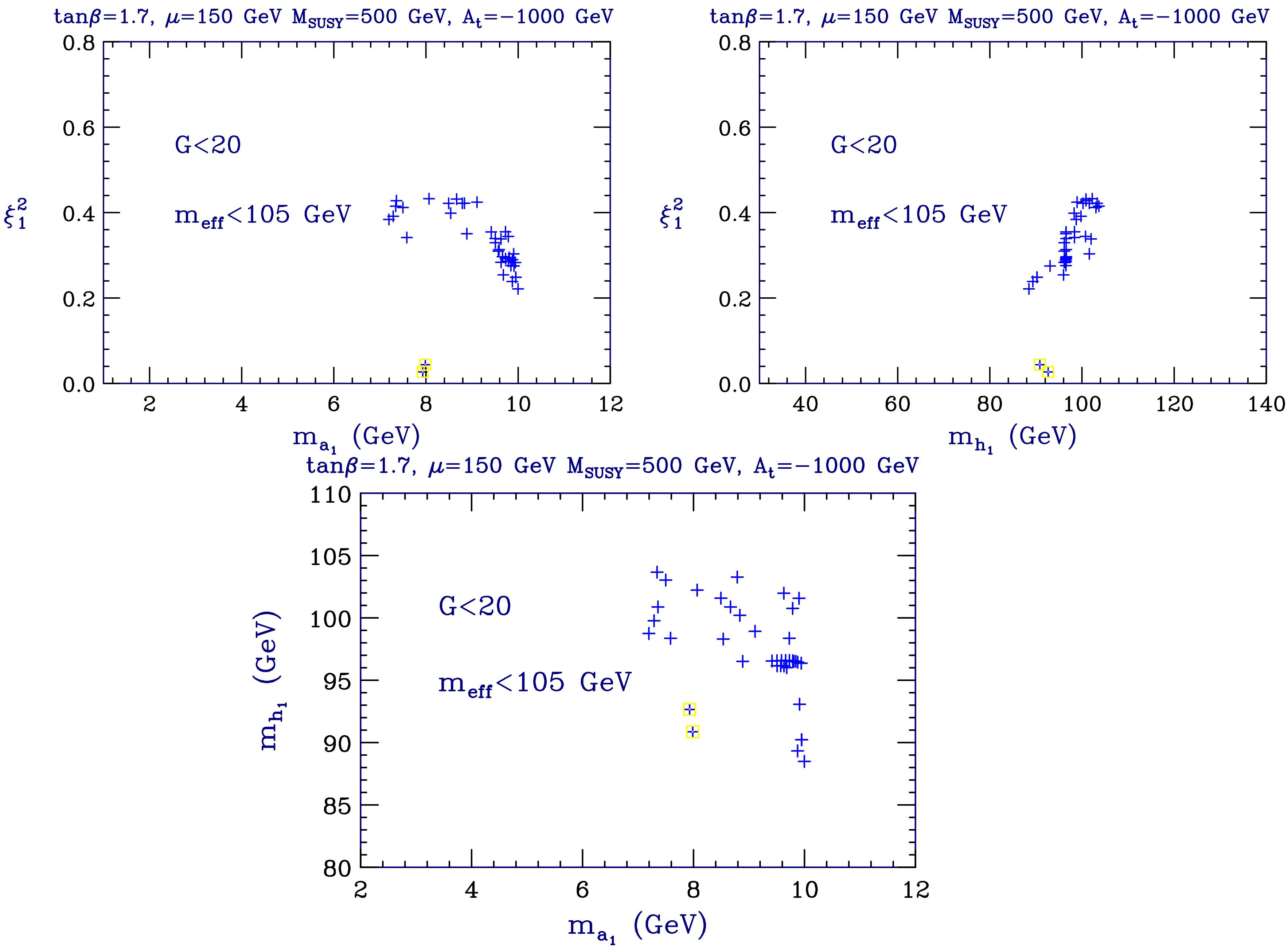


Figure 9: **Upper plots show ξ_1^2 vs. m_{a_1} and m_{h_1} for $\tan\beta = 1.7$; $|\cos\theta_A| < \cos\theta_A^{\max}$, $m_{eff} < 105$ GeV. Yellow squares have $B(h_1 \to a_1 a_1) < 0.7$ but still escape usual LEP limits. Bottom plot shows the points that survive the ALEPH limits.**

Probing the a at the Tevatron and LHC

- As we have seen, the Upsilon constraints on a light a run out for $m_a > M_{\Upsilon_{3S}}$. Tevatron data provides some constraints in this region.

  The LHC will do much better.

  (JFG+Dermisek, arXiv:0911.2460)

- At a hadron collider, one studies $gg \to a \to \mu^+\mu^-$ and reduces the heavy flavor background by isolation cuts on the muons.

  At lowest order, the gga coupling is induced by quark loops.

  Higher order corrections, both virtual and real ($e.g.$ for the latter $gg \to ag$) are, however, very significant.

- **The Tevatron**

  From a CDF analysis in the $6.3\ \mathrm{GeV} - 9\ \mathrm{GeV}$ mass window, one finds that the Tevatron will provide interesting constraints for $L = 10~\mathrm{fb}^{-1}$.

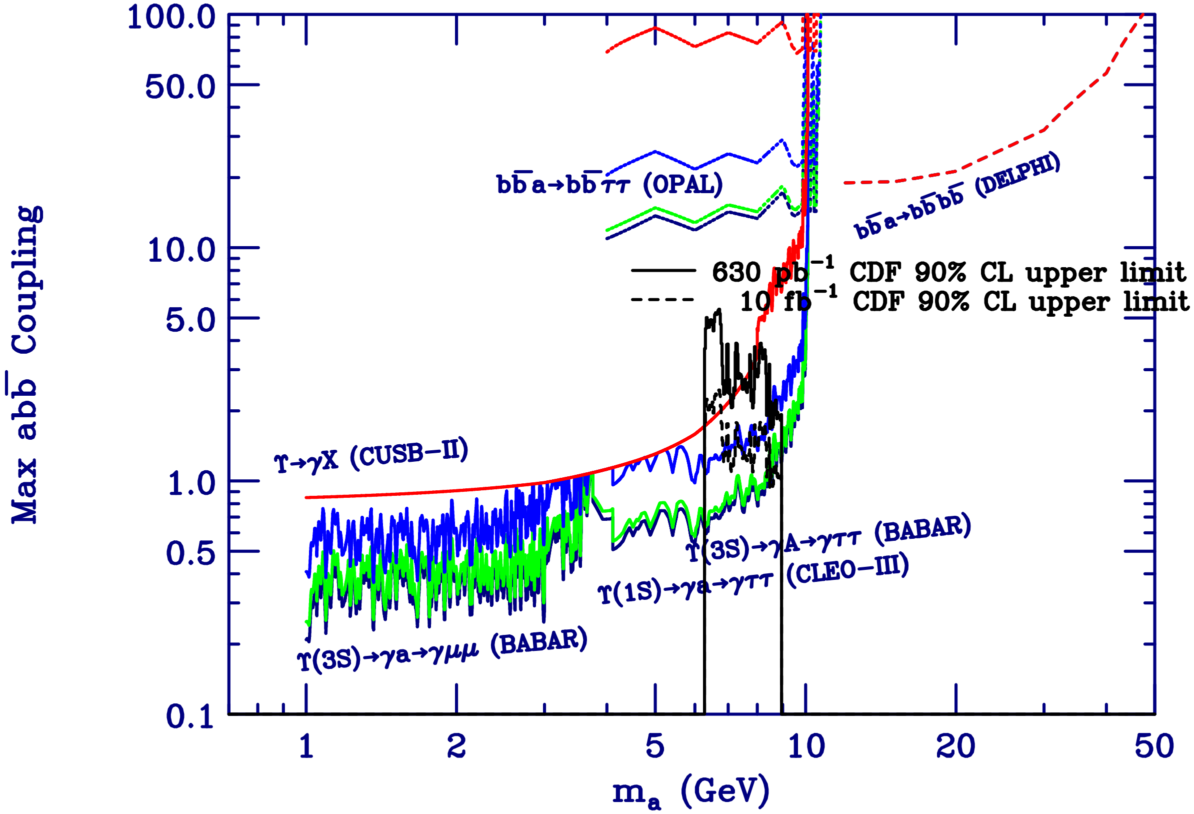


Figure 10: Tevatron limits (roughly $\tan\beta$-independent for $\tan\beta > 2$) compared to previous plot limits for $\tan\beta =$0.5, 1, 2, ≥ 3.

For $M_{\mu^+\mu^-} > 9~\mathrm{GeV}$, CDF did not perform a detailed analysis.

Instead, we used the event number plots that extend to larger $M_{\mu^+\mu^-}$. We ask for the $|C_{ab\bar{b}}|$ limits assuming no 90% CL (1.686σ) fluctuation in $S/\sqrt{B}$-optimized m_a interval of $2\sqrt{2}\sigma_r$, where σ_r is the $M_{\mu^+\mu^-}$ resolution.

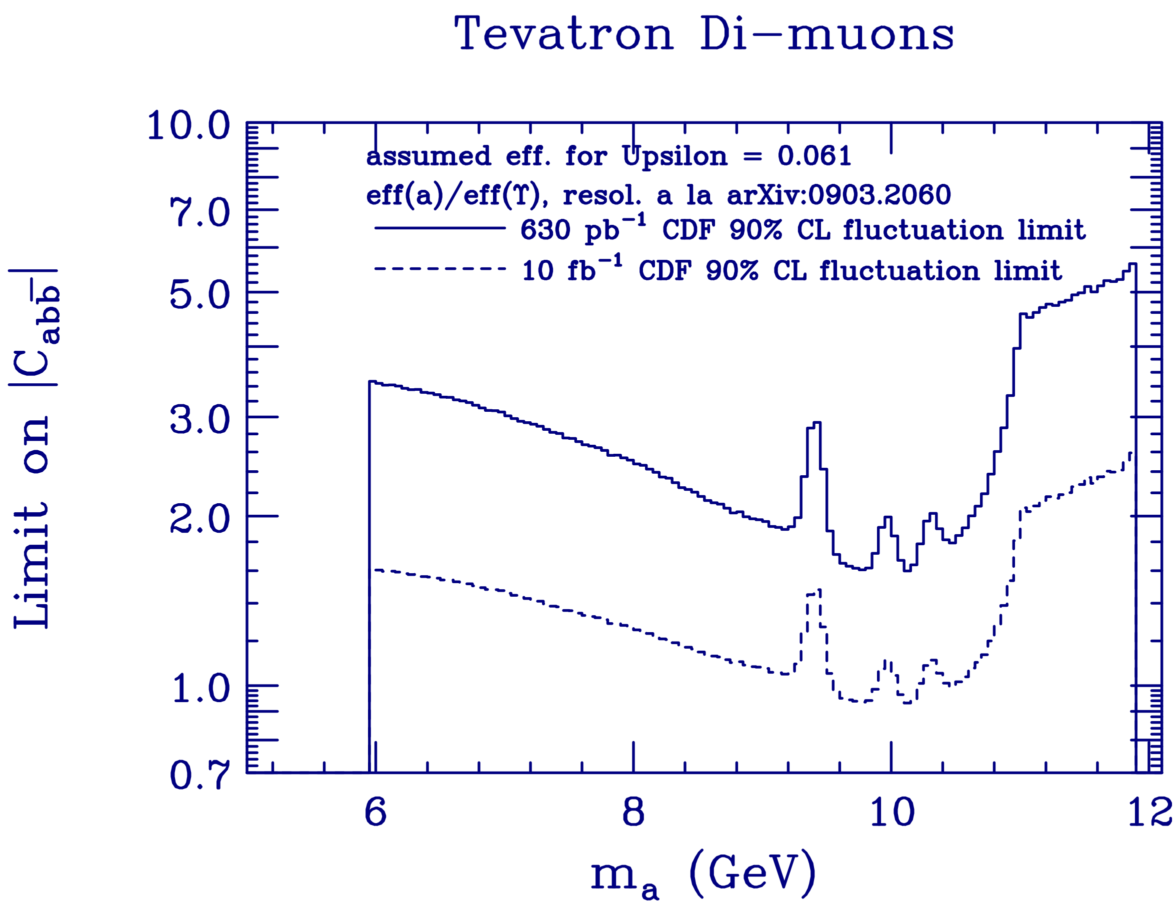


Figure 11: $L = 630~\mathrm{pb}^{-1}$ and $10~\mathrm{fb}^{-1}$ limits based on no 1.686σ excess in optimal interval. They are $\tan\beta$-independent for $\tan\beta > 2$.

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?**

The cross sections vary slowly with $\sqrt{s}$. At $m_a = 10$ GeV and $\tan\beta = 10$, one finds (for $\cos\theta_A = 1$) $\sigma_{NLO}(1.96, 7, 10, 14 \text{ TeV}) \sim 1.5 \times 10^5, 5 \times 10^5, 7 \times 10^5, 9 \times 10^5$ pb.

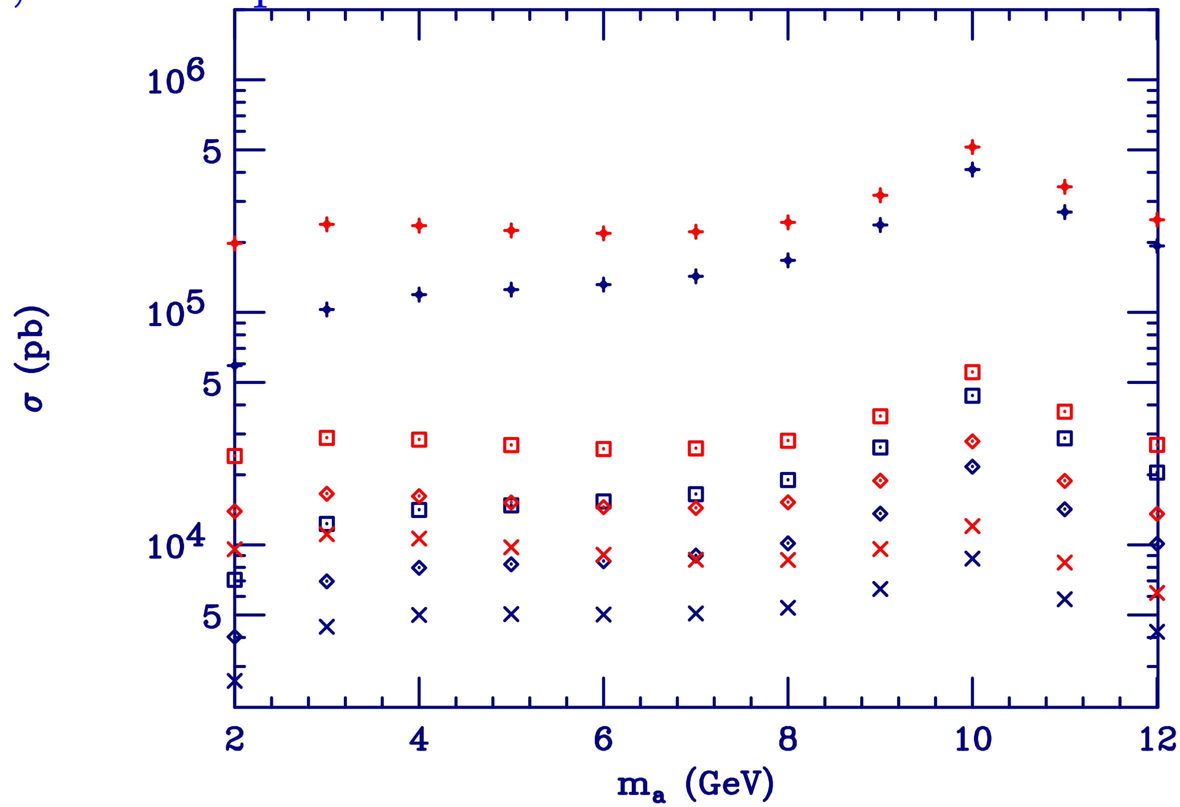


Figure 12: LHC, $\sqrt{s} = 7$ TeV cross sections for $\tan\beta = 1, 2, 3, 10$ (lowest to highest point sets). Factor of about $3\times$Tevatron at higher m_a.

ATLAS

ATLAS has presented public, but incomplete results — see Fig. 13.

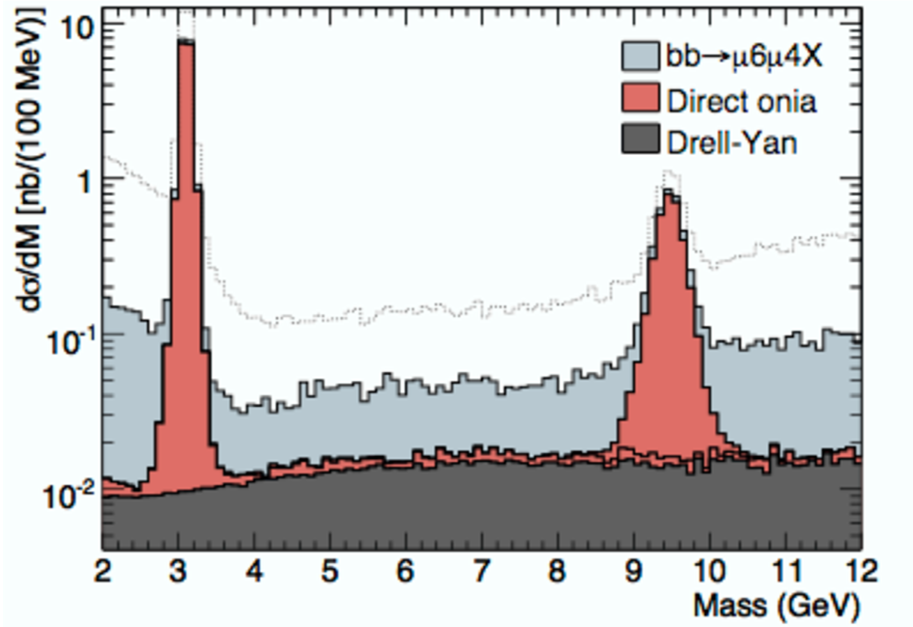


Figure 13: ATLAS dimuon spectrum prediction after corrections for acceptance and efficiencies (D. D. Price, arXiv:0808.3367 [hep-ex].).

In the above figure, the Drell-Yan background is much smaller than the heavy flavor background, even after muon isolation cuts.

The efficiencies for acceptance, reconstruction and isolation are already built into the $b\bar{b}$ and Υ_{1S} contributions of Fig. 13.

- After accounting for the need to double the plotted continuum background and the resolutions $\sigma_r(M_{\mu^+\mu^-})$ ($54~\mathrm{MeV}$ at J/ψ and $170~\mathrm{MeV}$ at Υ_{1S}), we compute the number, $N_{\Delta M_{\mu^+\mu^-}}$, of background events in an interval of total width $\Delta M_{\mu^+\mu^-} = 2\sqrt{2}\sigma_r$ (the interval that maximizes $S/\sqrt{B}$).

- We then consider the $a \to \mu^+\mu^-$ signal rates.

  An ATLAS Monte Carlo gives a net efficiency for the a of $\epsilon_{ATLAS} = 0.1$. In the hope that this can eventually be improved, we write

$$\epsilon_{ATLAS} = 0.1r\,. \tag{5}$$

  Consider $\tan\beta = 10$ and $\cos\theta_A = 0.1$ (middle range of most preferred NMSSM models).

  Including $B(a \to \mu^+\mu^-)$, ϵ_{ATLAS}, the bin acceptance factor of $Erf(1) =$

0.8427 for the ideal interval being employed, and multiplying by $(\cos\theta_A)^2$ we obtain the following results.

Table 2: Luminosities (fb^{-1}) needed for 5σ if $\tan\beta = 10$ and $\cos\theta_A = 0.1$.

Case	$m_a = 8\ \mathrm{GeV}$	$m_a = M_{\Upsilon_{1S}}$	$m_a \lesssim 2m_B$
ATLAS LHC7	$17/r^2$	$63/r^2$	$9/r^2$
ATLAS LHC10	$13/r^2$	$48/r^2$	$7/r^2$
ATLAS LHC14	$10/r^2$	$37/r^2$	$5.4/r^2$

The required L's away from the Upsilon resonance may be achieved after a year or two of LHC operation. Can r be improved?

CMS?

- Working subgroup: Chiara Mariotti, Max Chertok, Maria Assunta Borgia, Pietro Govoni, Leonardo di Matteo, Mario Pelliccioni and me.

  Monte Carlos were run, acceptances and efficiencies for backgrounds and signal were evaluated and signal significances computed.

  For the signal, PYTHIA was employed for light A and then cross section was normalized to HIGLU predictions for integrated cross section. Gluon radiation in PYTHIA mimics that present in $gg \to a + NLO$. Signal width = resolution dominated.

  For background, used ppMuX sample and $\Upsilon(nS)$ production ala PYTHIA.

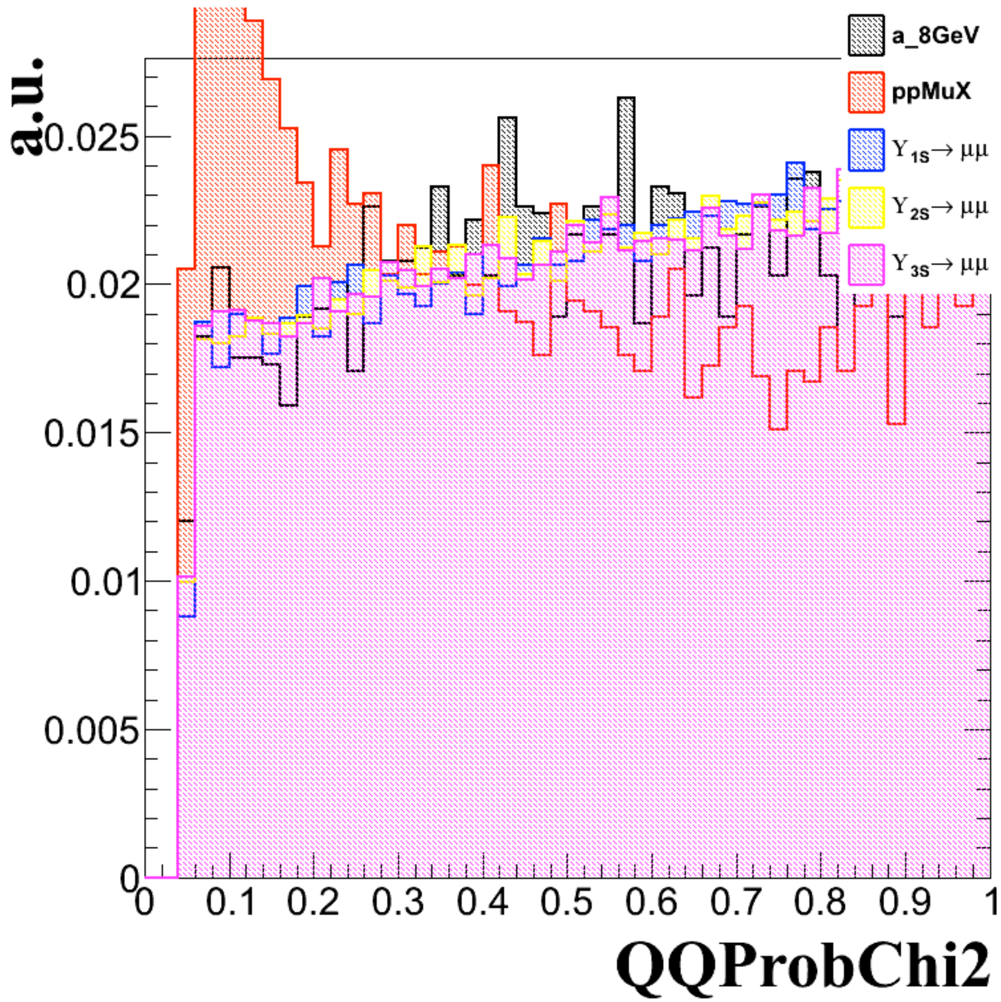
Muon Requirements: same as for Quarkonia studies

- Muon Trigger: SingleMu3
- TK muon selectors: TM2DCompatibilityTight, TMLastStationOptimizedLowP
- pseudorapidity range $\eta \in [-2.4, 2.4]$
- $p_T > 3$ GeV
- p of the tracker muon in the forward region > 4.5 GeV.
- number of hits per track > 12
- number of hits in the pixels > 2
- χ^2/dof of the global muons < 20
- χ^2/dof of the tracker muons < 5
- $|d0| < 2$
- $|dz| < 25$

$\mu^+\mu^-$ candidates

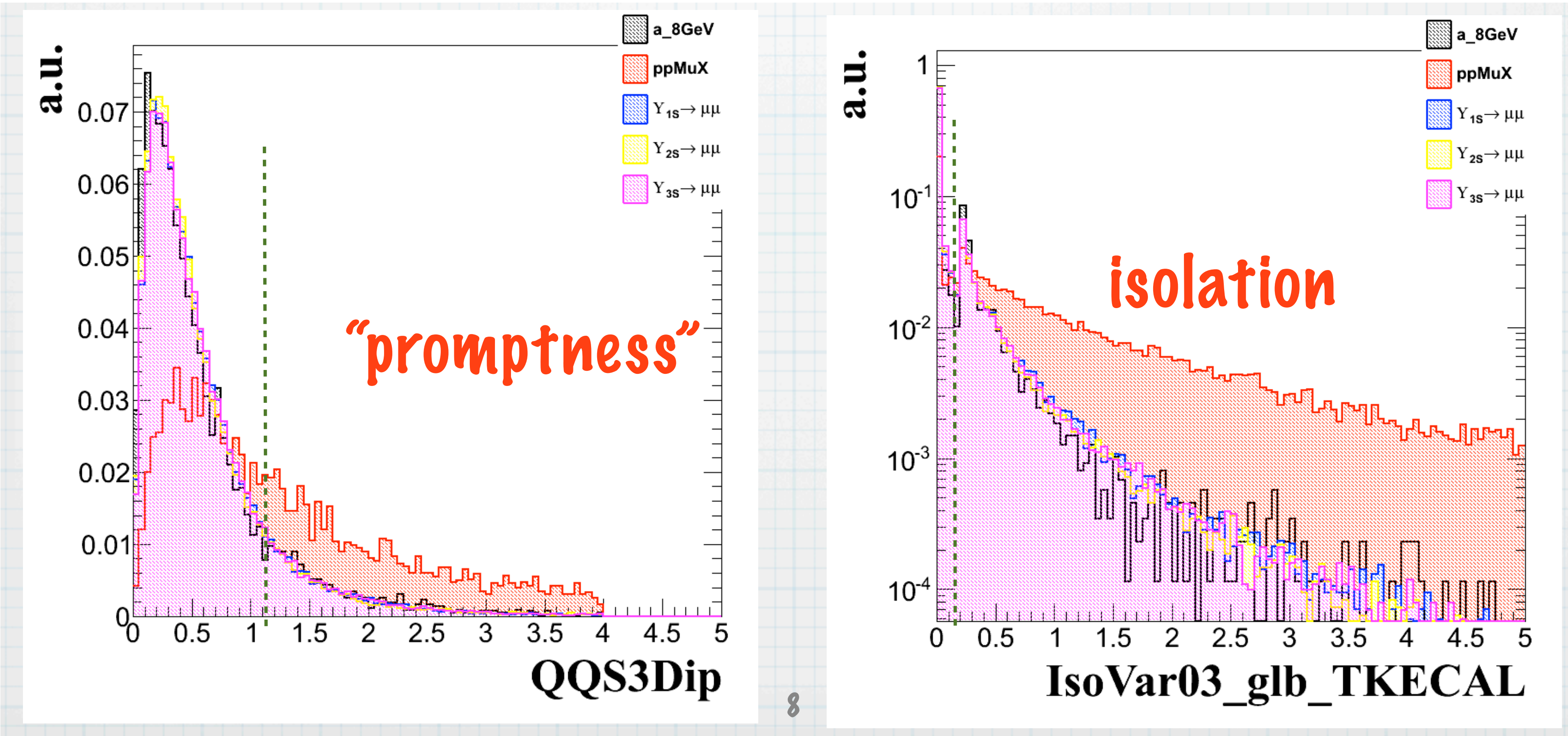
- 2 GLB muons if present, GLB+TRK otherwise.
- $p > 6$ GeV in the fwd region ($|\eta| > 1.1$) for TRK muons

– **dimuon vertex probability > 0.05.**

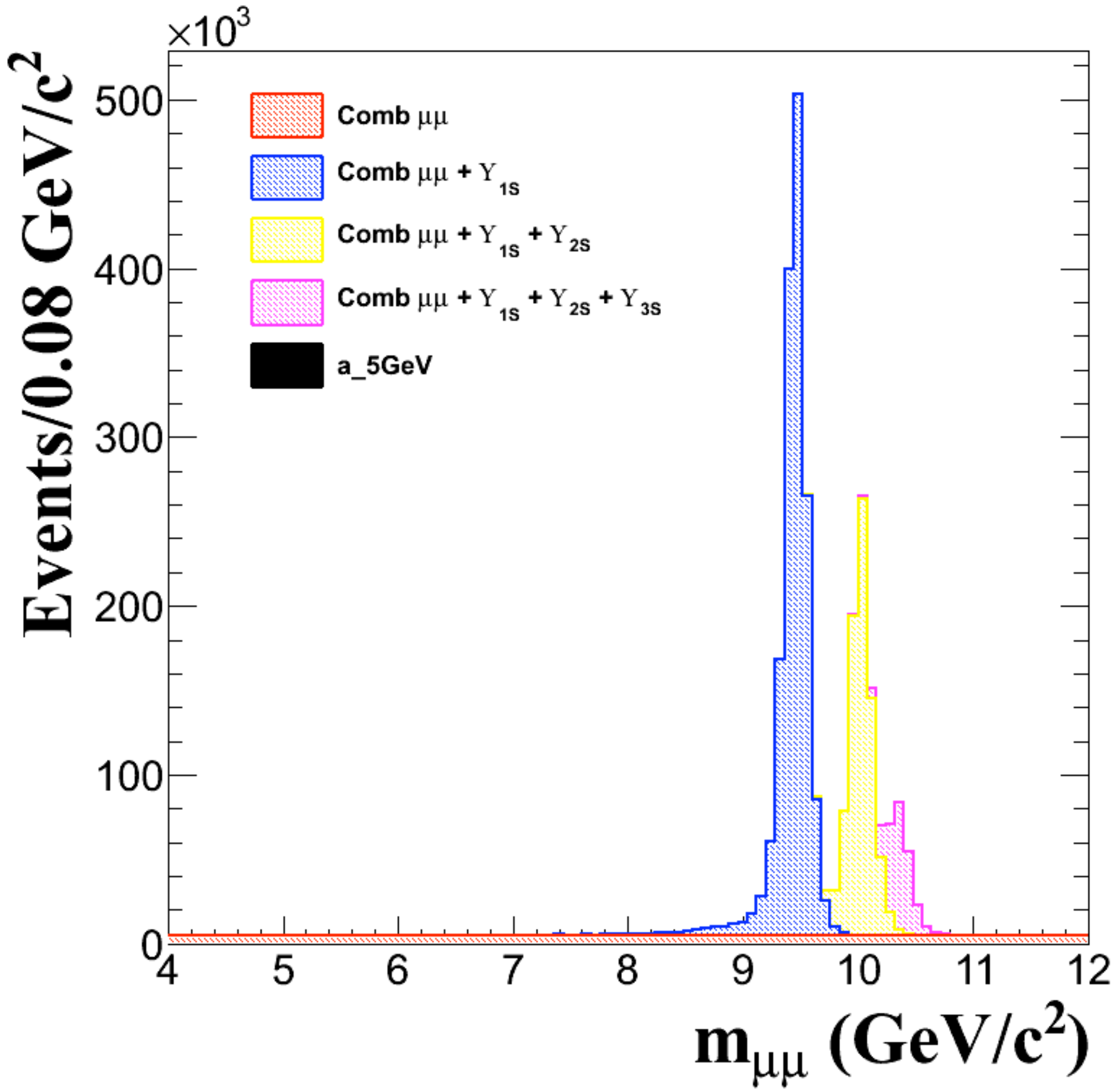


Vertex probability plot. Cut was to require > 0.05. Clearly very efficient for a events.

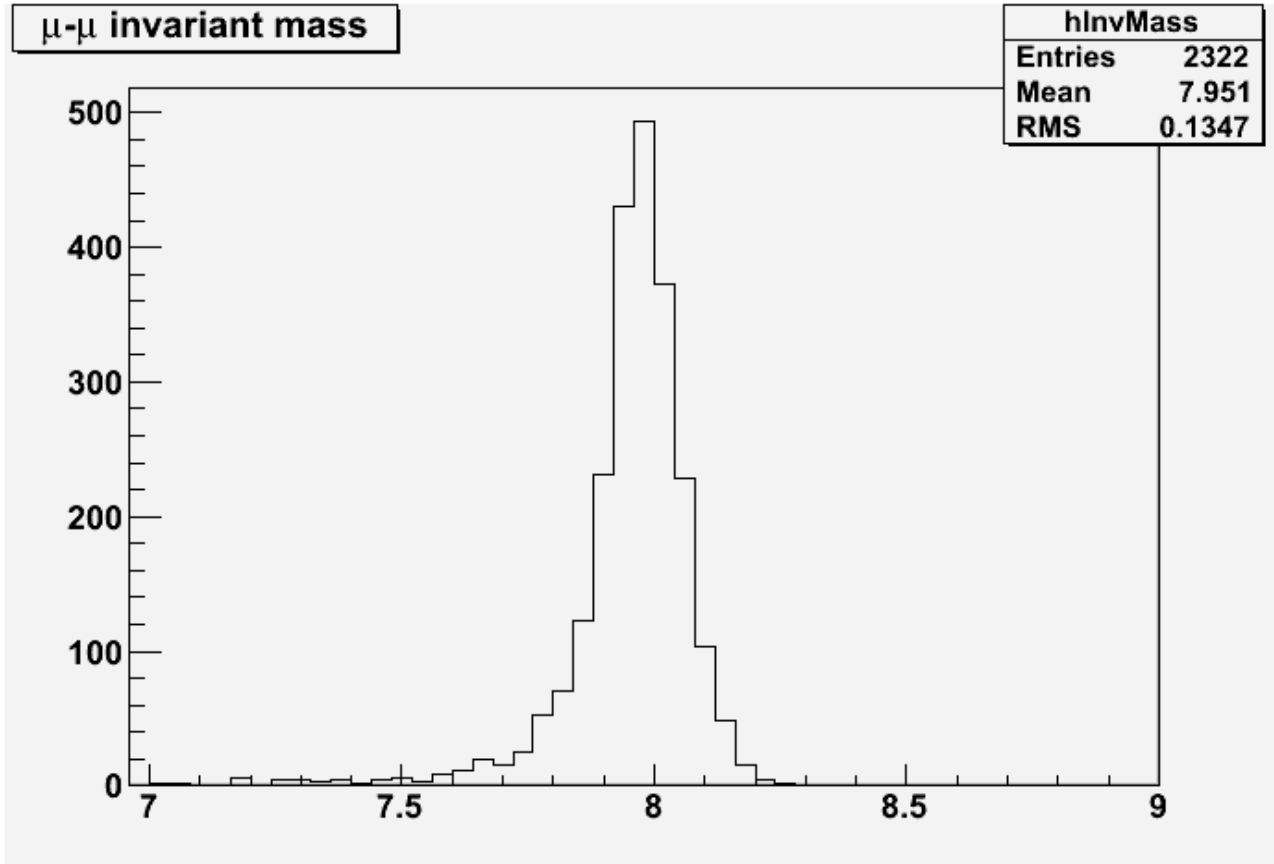
- promptness > 1.05
  "promptness" = compatibility with the primary vertex. basically the 3D vertex divided by the error on it.
- keep events with isolation var < 0.14
  isolation variable $= (ecalIso + tkIso)/p_T$.
  $tkIso = \sum p_T$ and $ecalIso = \sum E_T$ for tracks within $\Delta R = \sqrt{\Delta_\eta^2 + \Delta_\phi^2} = 0.3$ of muon.



The background for $L = 500\ \mathrm{pb}^{-1}$ (but with incorrect errors since too few MC events).



A typical signal shape.



Bin size $= 40$ MeV. **For estimates of** $S/\sqrt{B}$ **will use** $\sigma_r = 85$ MeV **for Gaussian width (obtained from Gaussian fit to central component of distribution) and "optimal" bin width for** $S/\sqrt{B}$ **maximum of** $2\sqrt{2}\sigma_r \sim 240$ MeV.

Backgrounds and a few representative signal cross sections ($\times B(a \to \mu^+\mu^-)$) and net efficiencies are tabulated below. There $\epsilon = \epsilon_{accept} \times \epsilon_{reco} \times \epsilon_{HLT}$. For example, at $m_a = 8~\mathrm{GeV}$ we find $\epsilon_{reco}^{CMS} = 29\%$, $\epsilon_{HLT}^{CMS} = 92\%$ and $\epsilon_{accept} = 48\% \Rightarrow \epsilon^{CMS} = 12.96\%$.

Sample	Gen ev.	Reco ev.	σ(pb)	ε	Reco ev. (500pb^{-1})
ppMuX	10414205	212	85000000	2.04E-05	865164
Y(1S)	100K	24780	14000	24,8%	1734600
Y(2S)	100K	29744	5600	29,7%	832832
Y(3S)	100K	30434	1600	30,4%	243472
a^0 (5GeV)	19800	1073	3,61	5,4%	98
a^0 (6GeV)	19600	1351	2,03	6,9%	70
a^0 (7GeV)	18600	1630	4,95	8,8%	217
a^0 (8GeV)	18600	2395	5,14	12,9%	331
a^0 (9GeV)	18800	2728	10,8	14,6%	786
a^0 (10GeV)	17800	3419	29,92	19,2%	2873
a^0 (10.5GeV)	19800	4233	29,92	21,4%	3198

- A sample plot showing the above tabulated $m_a = 8~\mathrm{GeV}$ and $m_a = 10~\mathrm{GeV}$ signals for $L = 500~\mathrm{pb}^{-1}$ is given below.

  The background was first fit with smooth curves and then random $\sqrt{N}$ fluctuations were applied to each bin. The original smooth curve was then subtracted.

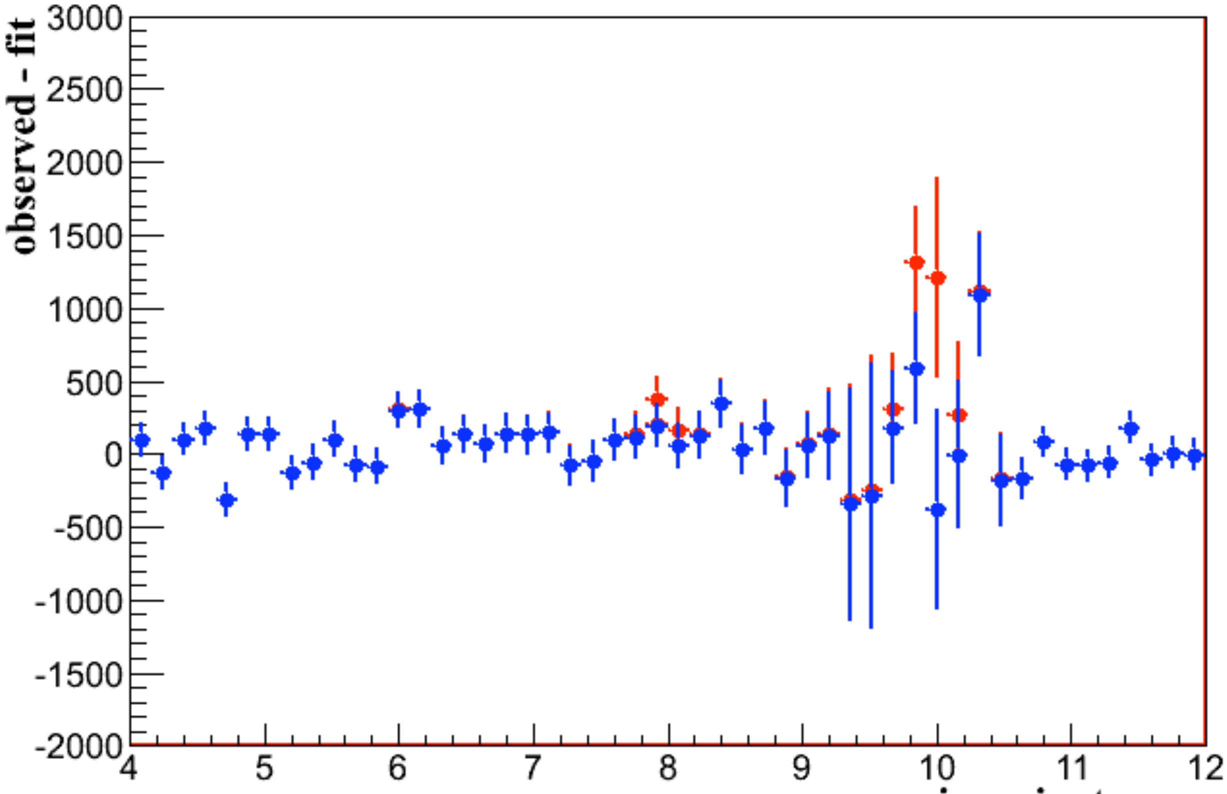


Figure 14: blue points=background only; red points have signals at $m_a = 8$ GeV ($S/\sqrt{S+B} = 1.81$) and $m_a = 10$ GeV ($S/\sqrt{S+B} = 2.8$ if you know upsilon peak normalization exactly) added with $\sigma(a)B(a \to \mu^+\mu^-)$ as given in the previous table.

A Survey of all NMSSM Ideal Higgs Models

- We employ the same $\epsilon(m_a)$ as given earlier, and use $\sigma(a)B(a \to \mu^+\mu^-)$ as predicted within the NMSSM model.

  Background is the same as already plotted. The mass window employed is

$2\sqrt{2}\sigma_r$, which optimizes $S/\sqrt{B}$.

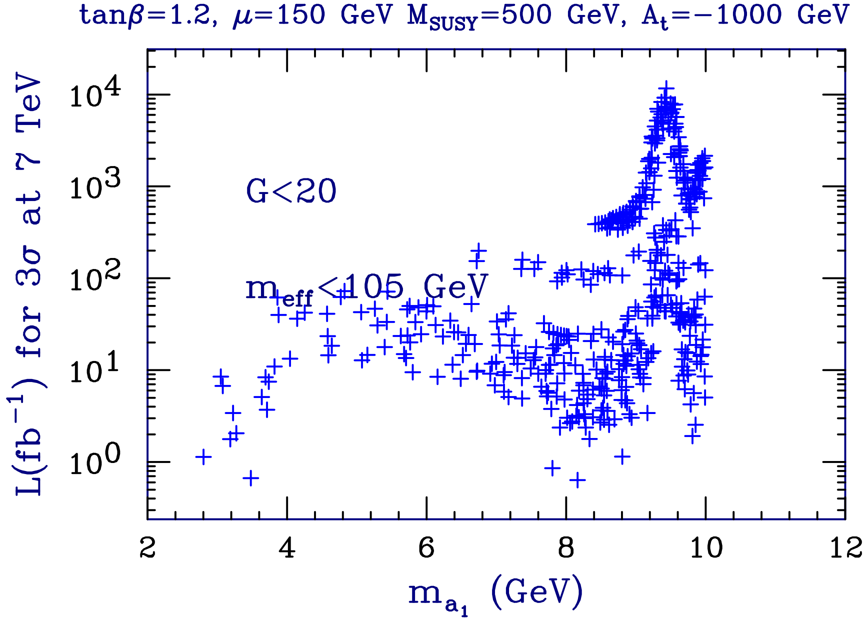
In the Upsilon peak regions the results are too naive since one must use some technique to normalize the Upsilon peaks themselves.

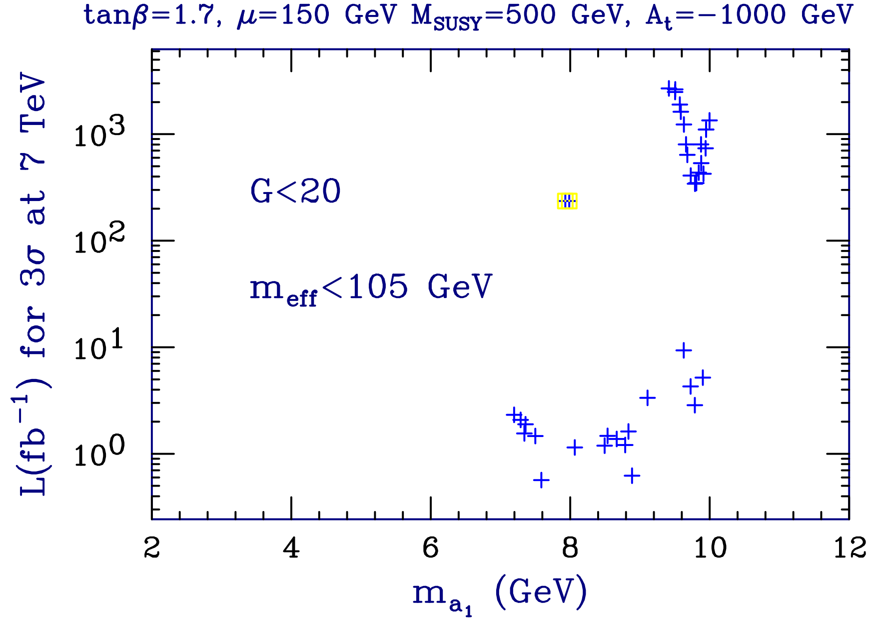
- What is plotted is the $\sqrt{s} = 7~\mathrm{TeV}$ integrated L required to obtain a 3σ signal level above background.

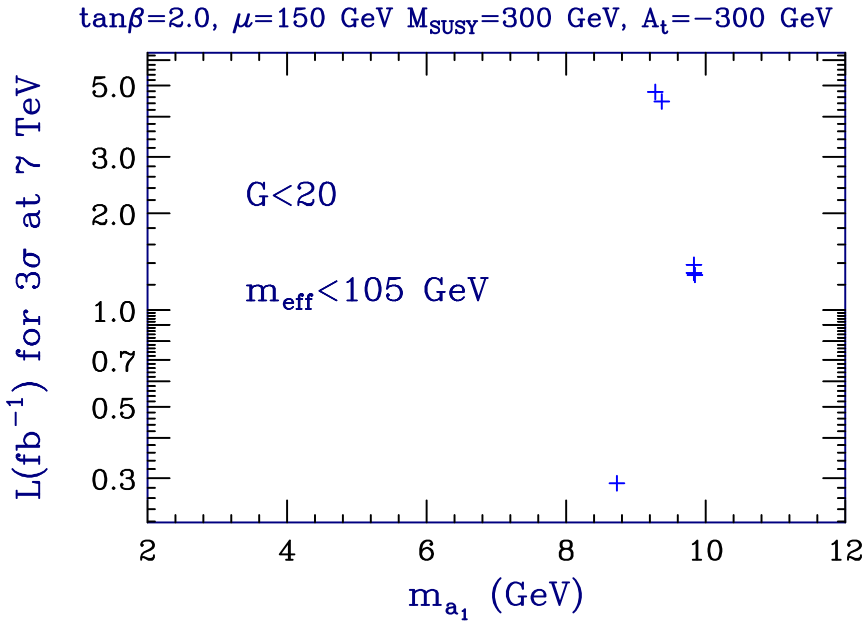
- You will see an obvious increase in the required L in the vicinity of the Υ resonances, especially the Υ_{1S}.

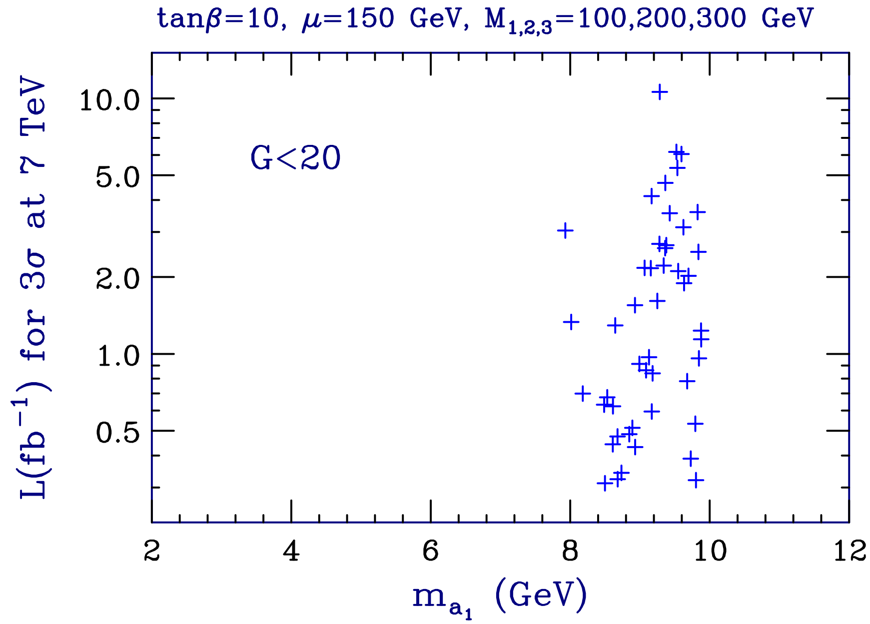
- At higher $\tan\beta \geq 2$, $L = 10~\mathrm{fb}^{-1}$ will cover all the NMSSM points.

- But, for $\tan\beta \leq 1.7$, there is a large range of acceptable $\cos\theta_A$ values some of which have small magnitude and therefore small LHC cross section. In addition, $B(a \to \mu^+\mu^-)$ declines at small $\tan\beta$. Lots of points will need to await higher energy and large L.


tanβ=1.2, μ=150 GeV M_SUSY=500 GeV, A_t=−1000 GeV
G<20
m_eff<105 GeV
L(fb⁻¹) for 3σ at 7 TeV
m_a1 (GeV)


tanβ=1.7, μ=150 GeV M_SUSY=500 GeV, A_t=−1000 GeV
G<20
m_eff<105 GeV
L(fb⁻¹) for 3σ at 7 TeV
m_a1 (GeV)


tanβ=2.0, μ=150 GeV M_SUSY=300 GeV, A_t=−300 GeV
G<20
m_eff<105 GeV
L(fb⁻¹) for 3σ at 7 TeV
m_a1 (GeV)


tanβ=10, μ=150 GeV, M_1,2,3=100,200,300 GeV
G<20
L(fb⁻¹) for 3σ at 7 TeV
m_a1 (GeV)

Another way of viewing these constraints is in terms of the $|\cos\theta_A|$ limits as discussed earlier. The relevant plot for $1~\mathrm{fb}^{-1}$ of data at $7~\mathrm{TeV}$ is below, again ignoring the issue of exactly how to normalize the $\Upsilon(nS)$ backgrounds.

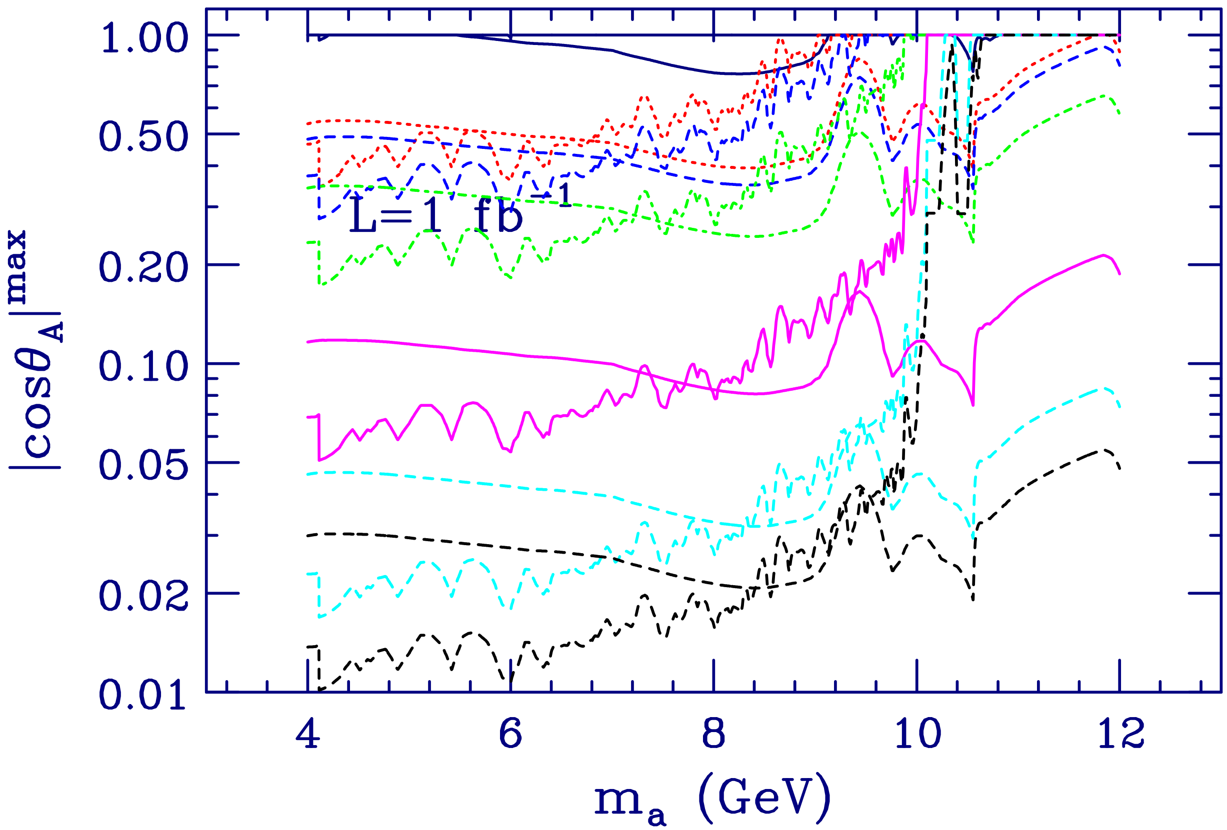


Figure 15: Jiggly curves that run out above Υ are those from BaBar $\Upsilon(nS) \to \gamma\mu^+\mu^-$ and $\gamma\tau^+\tau^-$. Smooth curves with "Upsilon peak" are LHC expectations for $L = 1~\mathrm{fb}^{-1}$ at $\sqrt{s} = 7~\mathrm{TeV}$. Observe that the LHC wins for $m_a \gtrsim 8~\mathrm{GeV}$.

Main ideas for getting control in the $\Upsilon(nS)$ peak regions are based on assuming signal is present only in one peak region.

1. **Use theory to compute expected ratios for $1S : 2S : 3S$ and look for agreement in one ratio and disagreement in other ratios.**

   Proper understanding of $\Upsilon(nS)$ production, including p_T and η distributions at NLO, is needed to avoid too large systematic error.

2. **Use $\Upsilon(nS) \to e^+e^-$ observations to normalize the peaks, assuming (as observed) lepton universality for the $\Upsilon(nS)$ decays.**

   Of course electron efficiencies will be more poorly known than muon efficiencies and so we plan to explore using double ratios:

$$\frac{\left[\frac{\sigma(\Upsilon_{1S}\to\mu^+\mu^-)}{\sigma(\Upsilon_{2S}\to\mu^+\mu^-)}\right]}{\left[\frac{\sigma(\Upsilon_{1S}\to e^+e^-)}{\sigma(\Upsilon_{2S}\to e^+e^-)}\right]} \qquad \frac{\left[\frac{\sigma(\Upsilon_{2S}\to\mu^+\mu^-)}{\sigma(\Upsilon_{3S}\to\mu^+\mu^-)}\right]}{\left[\frac{\sigma(\Upsilon_{2S}\to e^+e^-)}{\sigma(\Upsilon_{3S}\to e^+e^-)}\right]} \tag{6}$$

   for which some of the efficiency uncertainties should cancel.

Conclusions

In case you hadn't noticed, we 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".

The first sign of the Higgs sector could be detection of a light a.

Meanwhile, all I can do is watch and wait (but perhaps not from quite so close a viewpoint).