HIGGS HUNTING UPDATE

Is it the "God" particle or the "goddamned"* particle?

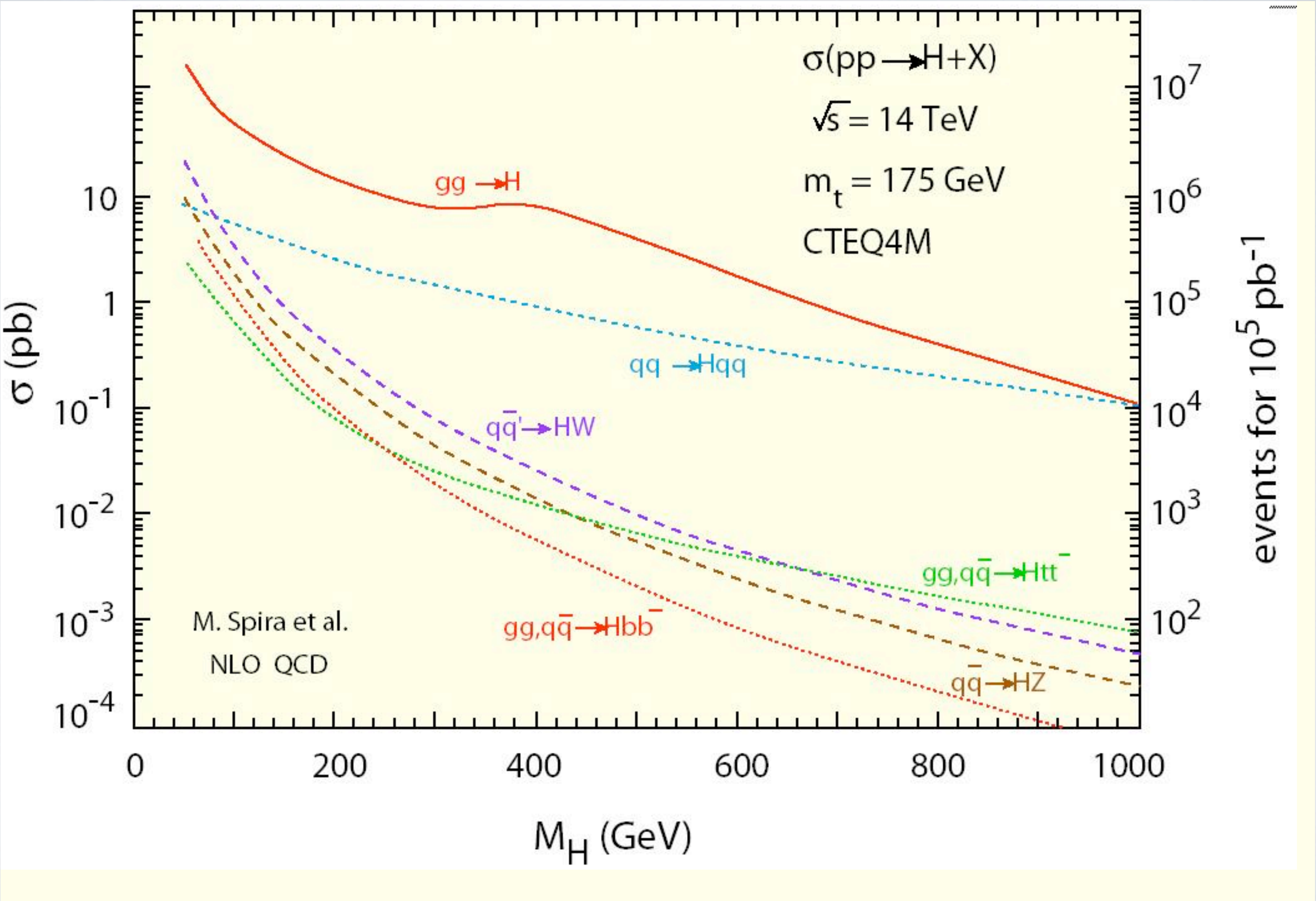
Jack Gunion
U.C. Davis

*Attributed to Leon Lederman.

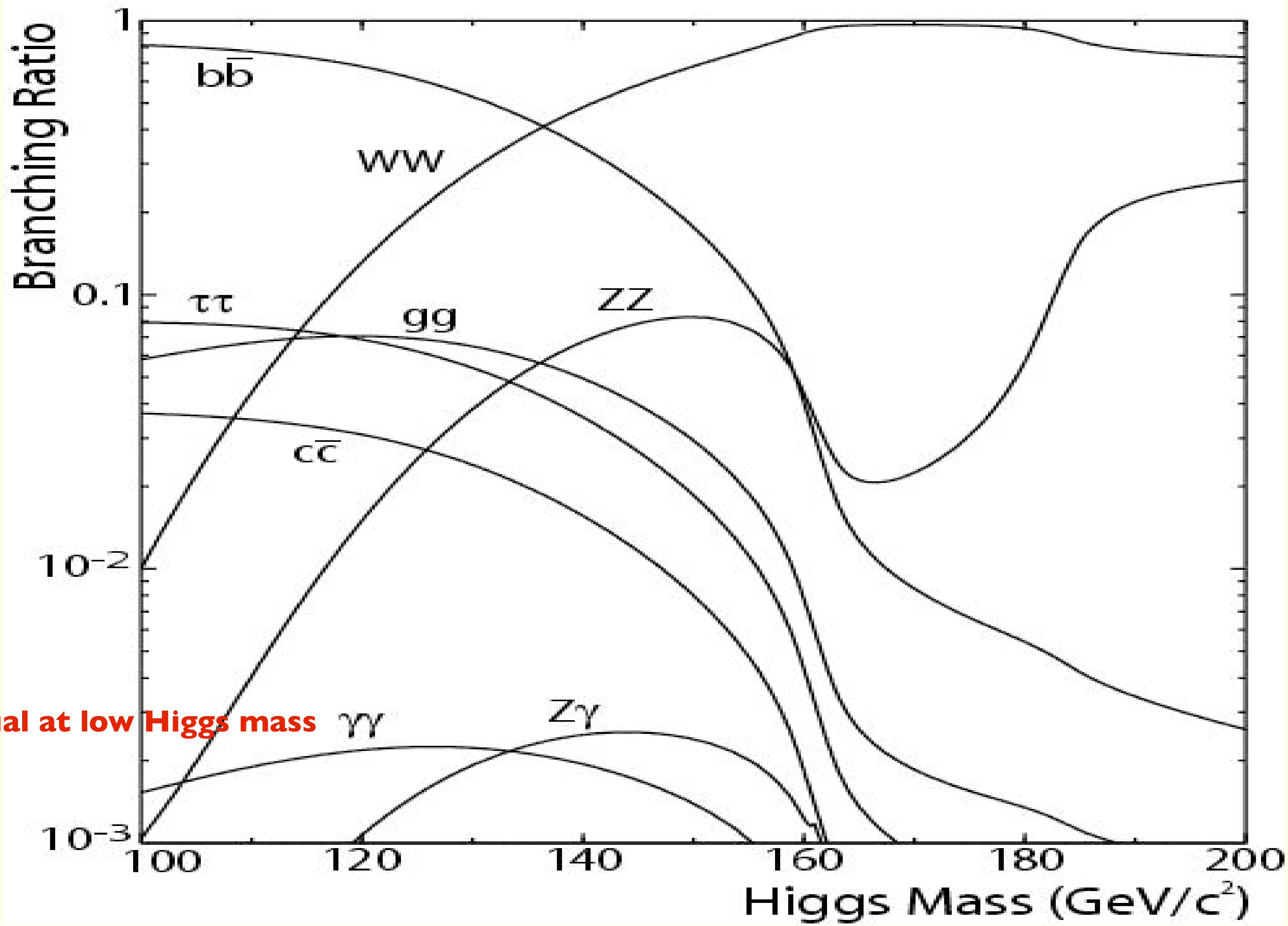
Synopsis/Outline

- Precision Electroweak (PEW) data prefer a light Higgs boson.
- Hierarchy prefers a SUSY solution.
- Gauge coupling unification prefers something close to the MSSM.
- Absence of EWSB fine-tuning requires a light SUSY spectrum (in particular, a light $\widetilde{t}$) and a light $\widetilde{t}$ implies that the SM-like Higgs of SUSY is light.
- Standard MSSM scenarios having a light Higgs with SM-like properties (for PEW perfection) are excluded by LEP.
- Some alternative SUSY models, including the NMSSM (which preserves all good MSSM features and solves the μ problem) give decay scenarios not ruled out by LEP for lighter Higgs mass.
- LHC strategies for finding the Higgs will need to change.

For a Higgs with SM couplings, cross sections are known.
For this talk, I assume only one Higgs carries all ZZ,WW coupling.



- **In the absence of new physics, Higgs decays are also determined by these same couplings.**



Crucial at low Higgs mass

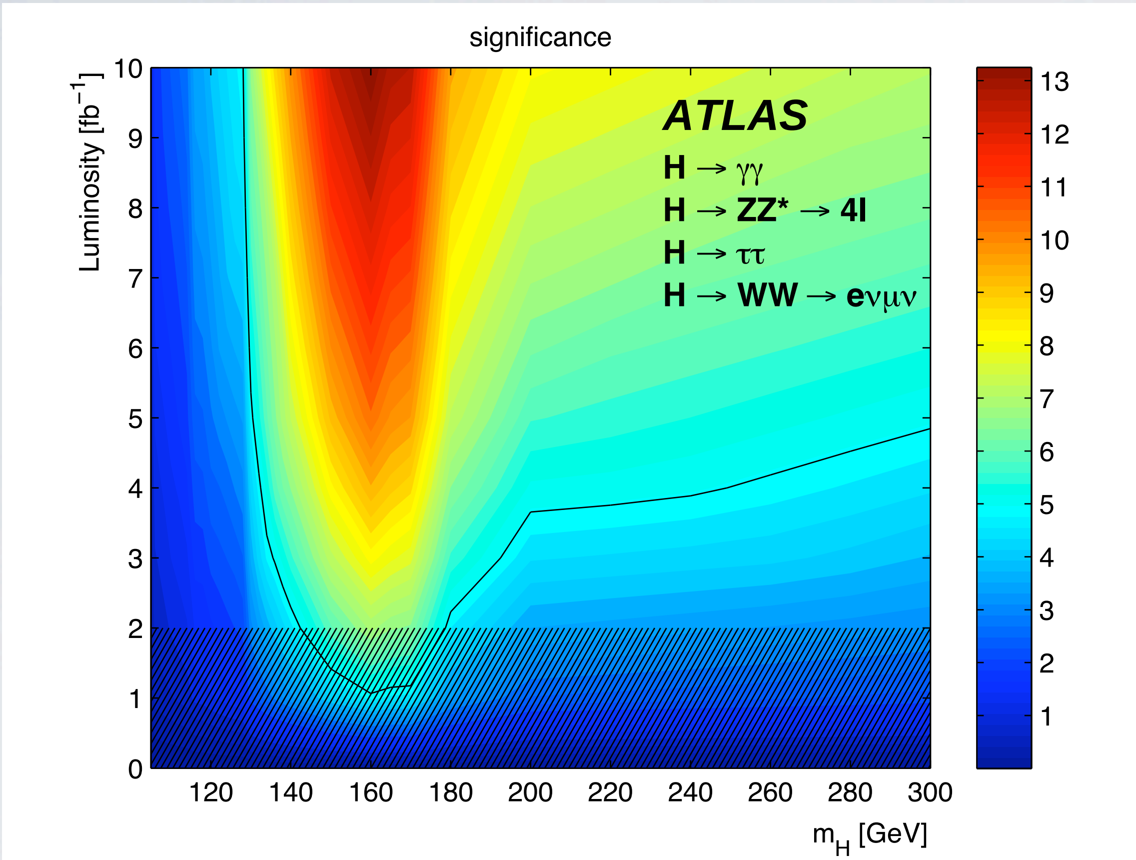


Figure 3: The discovery potential at ATLAS[6] for Standard Model Higgs boson searches.

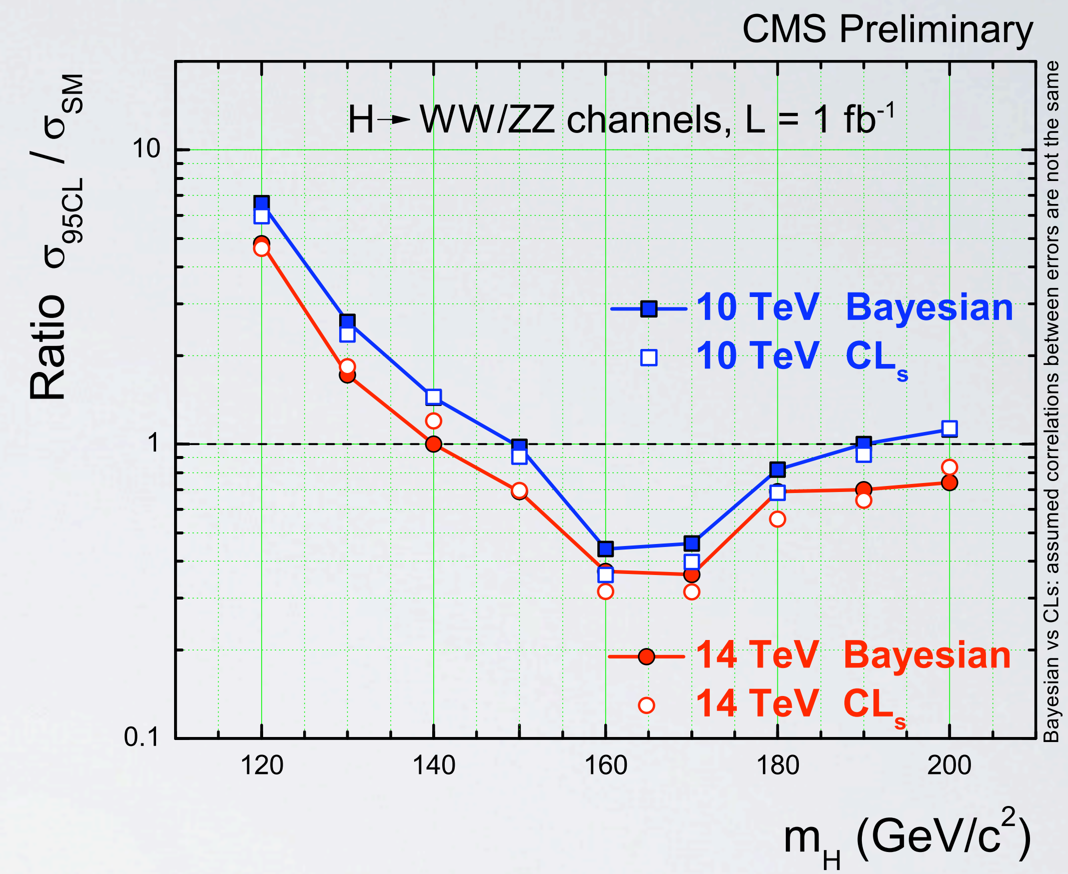
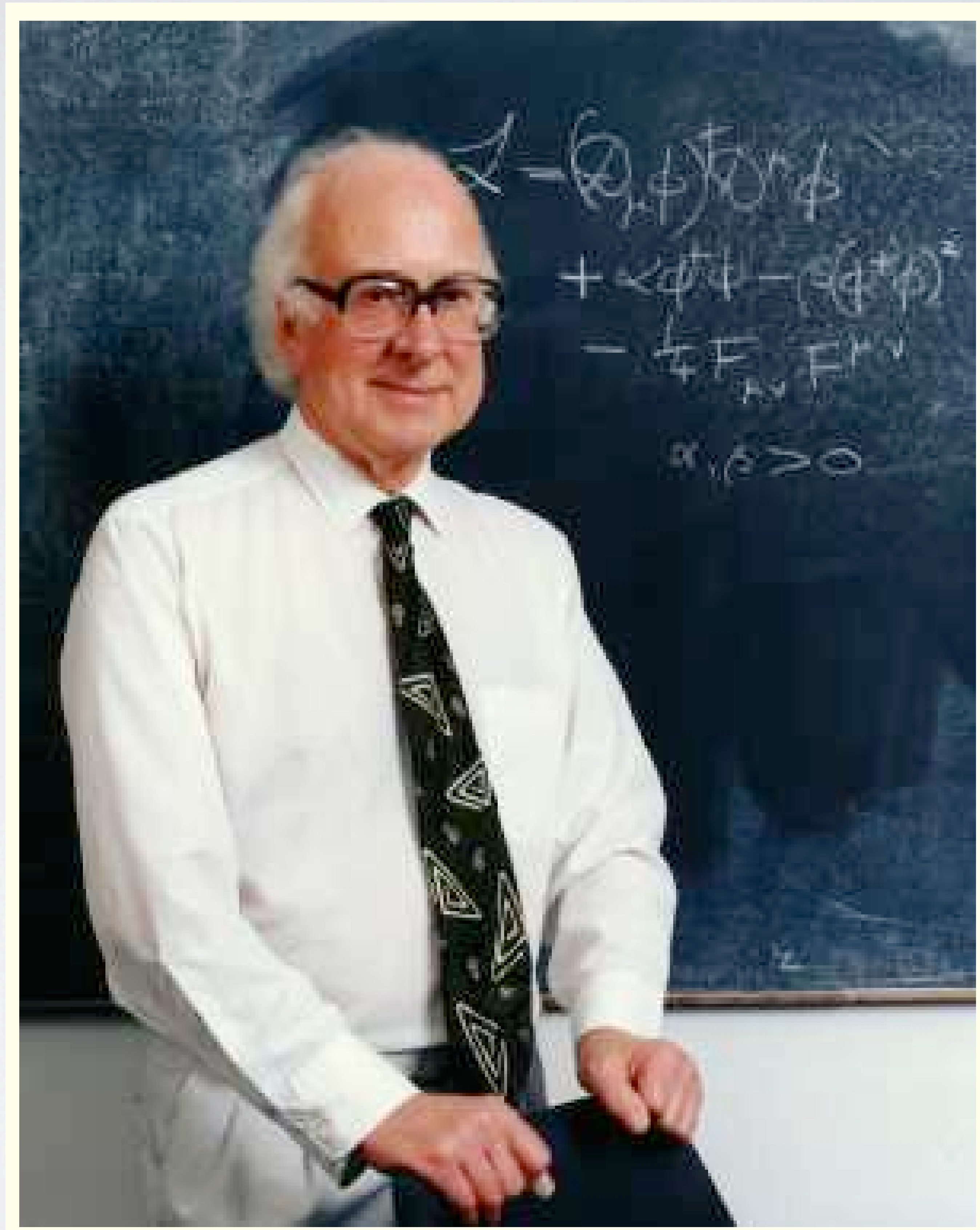


Figure 4: The updated[8] discovery potential at CMS for Standard Model Higgs boson searches.

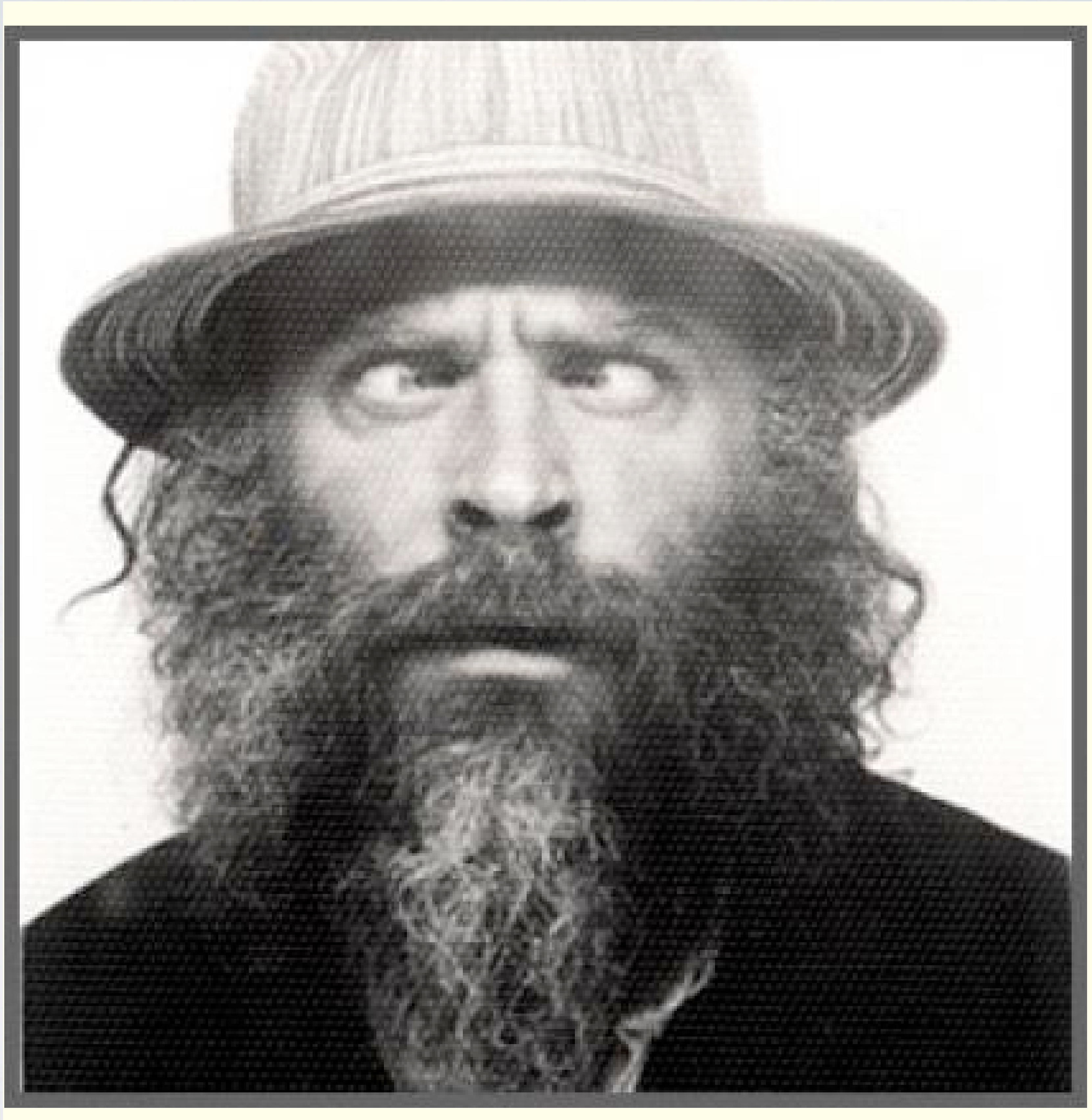
Detection of a light SM Higgs with mass just above 114 GeV is not easy!
Especially if the LHC has lower energy and low integrated L.
$H \to \gamma\gamma$ **is the primary detection mode.**

- **However, Beyond the SM physics could completely alter the Higgs decay patterns.**

So, what will the Higgs(es) look like?



So, what will the Higgs(es) look like?

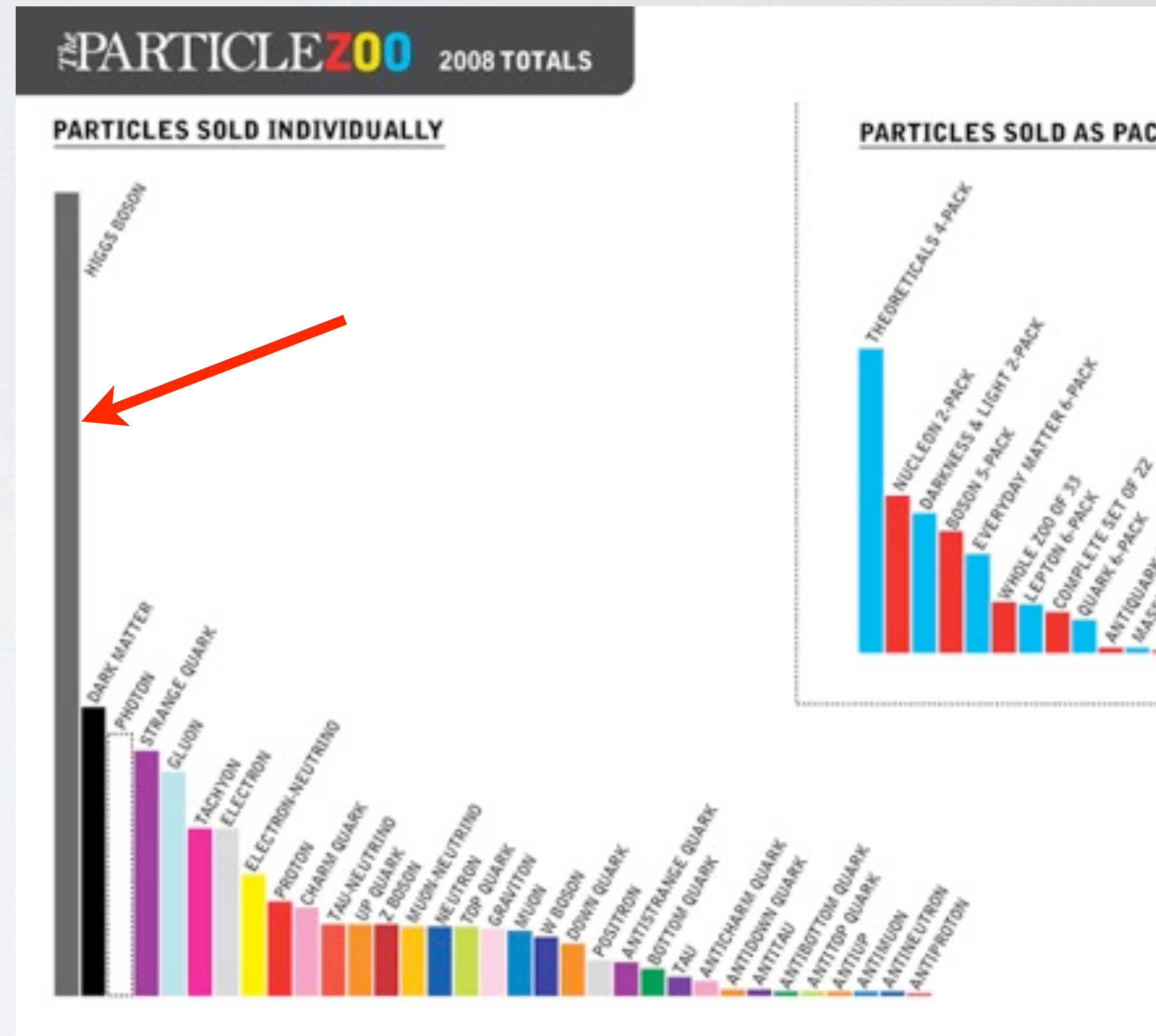


So, what will the Higgs(es) look like?

So, what will the Higgs(es) look like?

If you are too impatient to wait to find a Higgs at the LHC, then you can buy one online.

Attraction of the unknown + familiarity breeds contempt = Higgs by far, the most popular particle.



J. Gunion, PPC09, May 18, 2009

Or, perhaps you should write a letter to the Higgs.

Dear Higgs Boson,

We know you're out there. We can feel you now. We know that you're afraid. You're afraid of us; you're afraid of change. We don't know the future. We didn't write this to tell you how this is going to end. We wrote this to tell you how it's going to begin.

As you know, our Large Hadron Collider has had some setbacks due to a.... uh... "transformer malfunction" but we know it was you. You sabotaged our machine. We hope you've been enjoying your vacation because we're scheduled to restart in September 2009 and we're pissed.

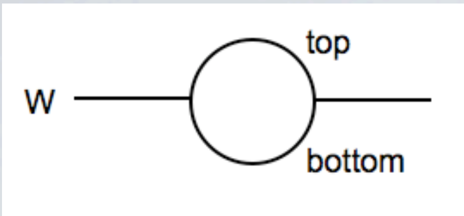
....so run and hide, asshole. Run and hide. If you should get careless and allow yourself to get detected by the Tevatron, we are going to be supremely disappointed; because we want to find you first, and when we do, rest assured we are not going to publish right away. We're going to teach you some manners first.

Love,

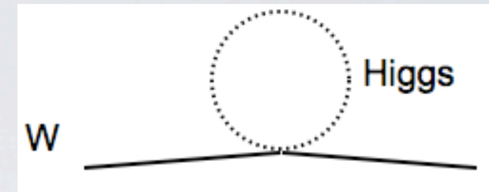
CERN

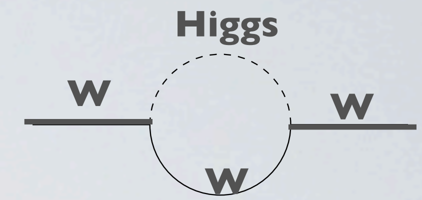
CERN may come to regret this hope.

Precision Electroweak data from LEP and the Tevatron creates large tension within the SM.



$$m_W = m_W^0 + c_1 m_t^2 + c_2 \log m_H^2$$



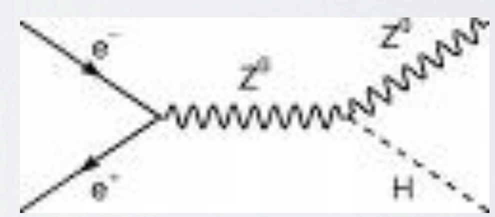


- **LEP PEW overall fit prefers Higgs mass near 80 GeV w. 95% upper bound of about 160 GeV.**

- **LEP PEW data without hadronic asymmetries prefers Higgs mass of about 50 GeV and below 105 GeV at 95% CL.**

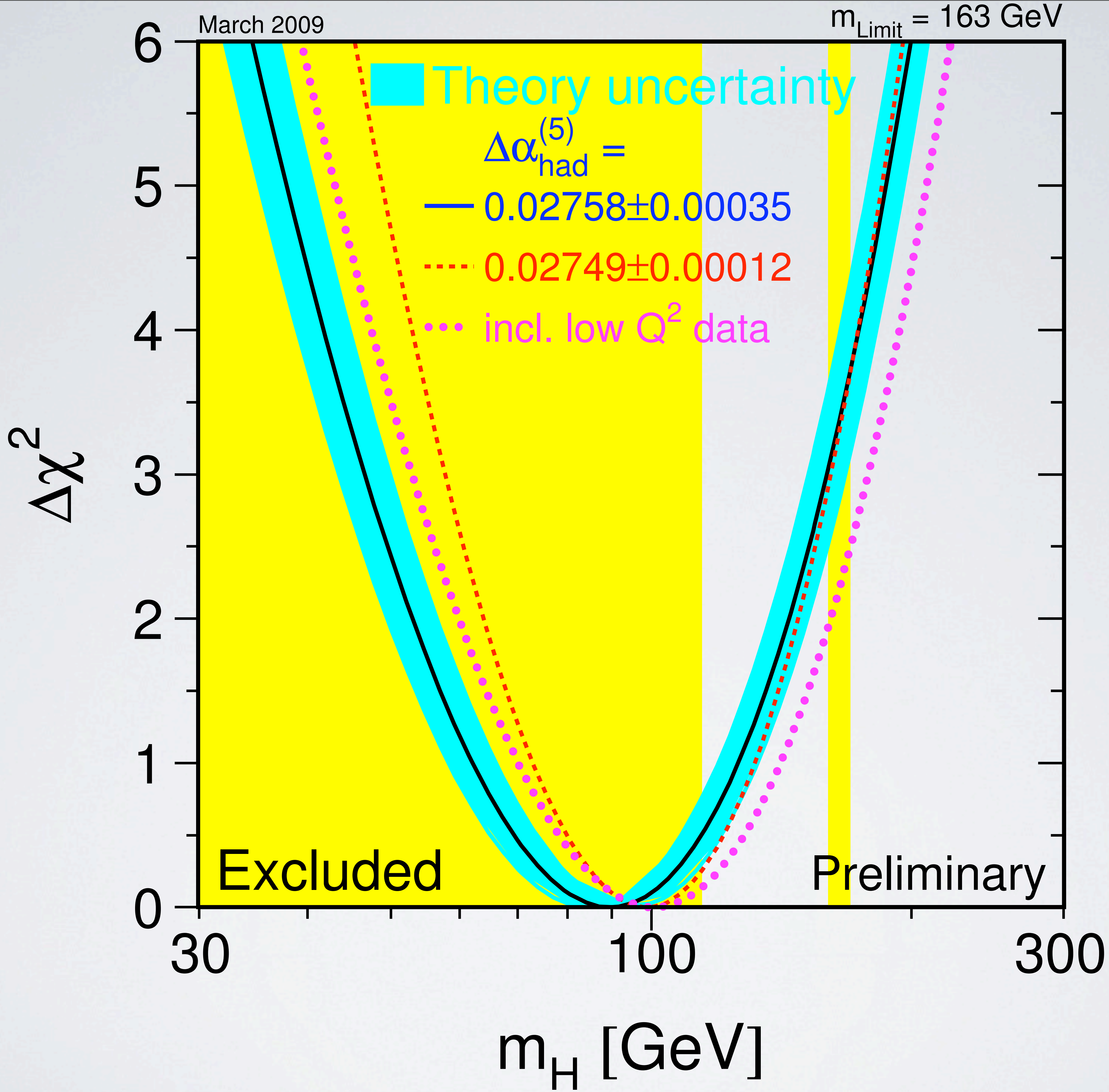
- **Tevatron W mass + top mass prefers quite light SM Higgs.**

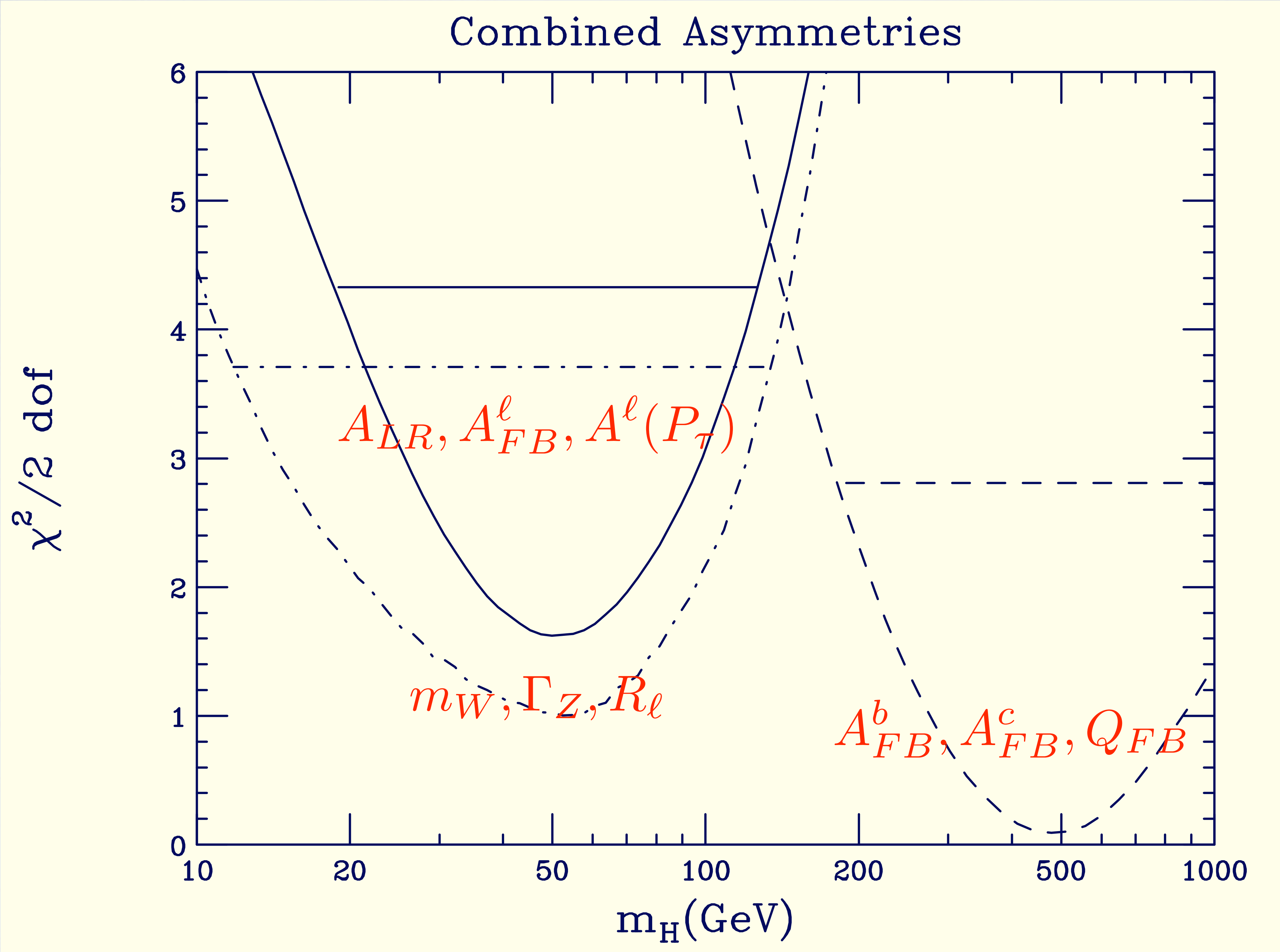
- **BUT! LEP requires SM Higgs heavier than 114 GeV.**



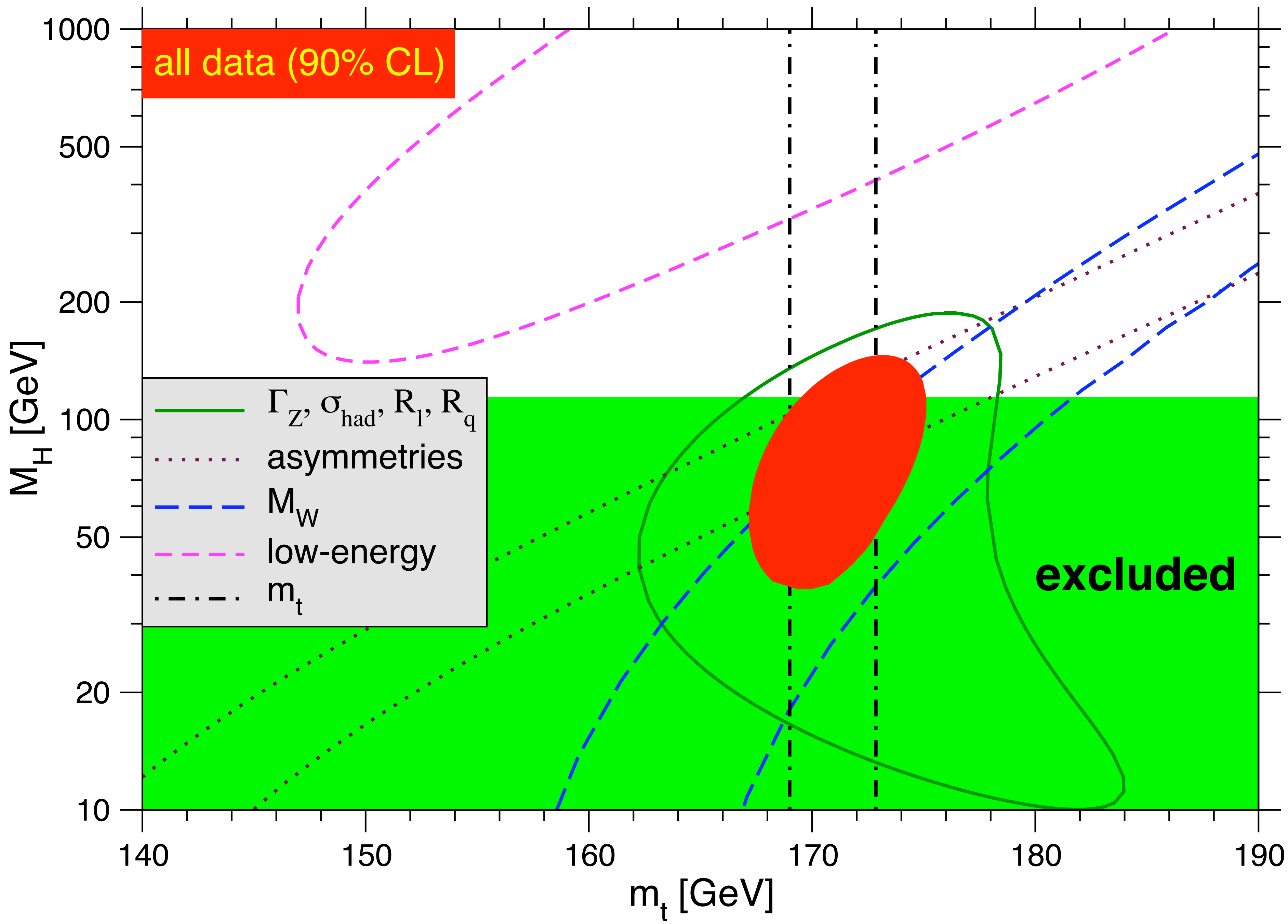
And, the Tevatron has excluded a range near $2m_W$.

Don't forget: low Higgs mass is also good for electroweak baryogenesis.

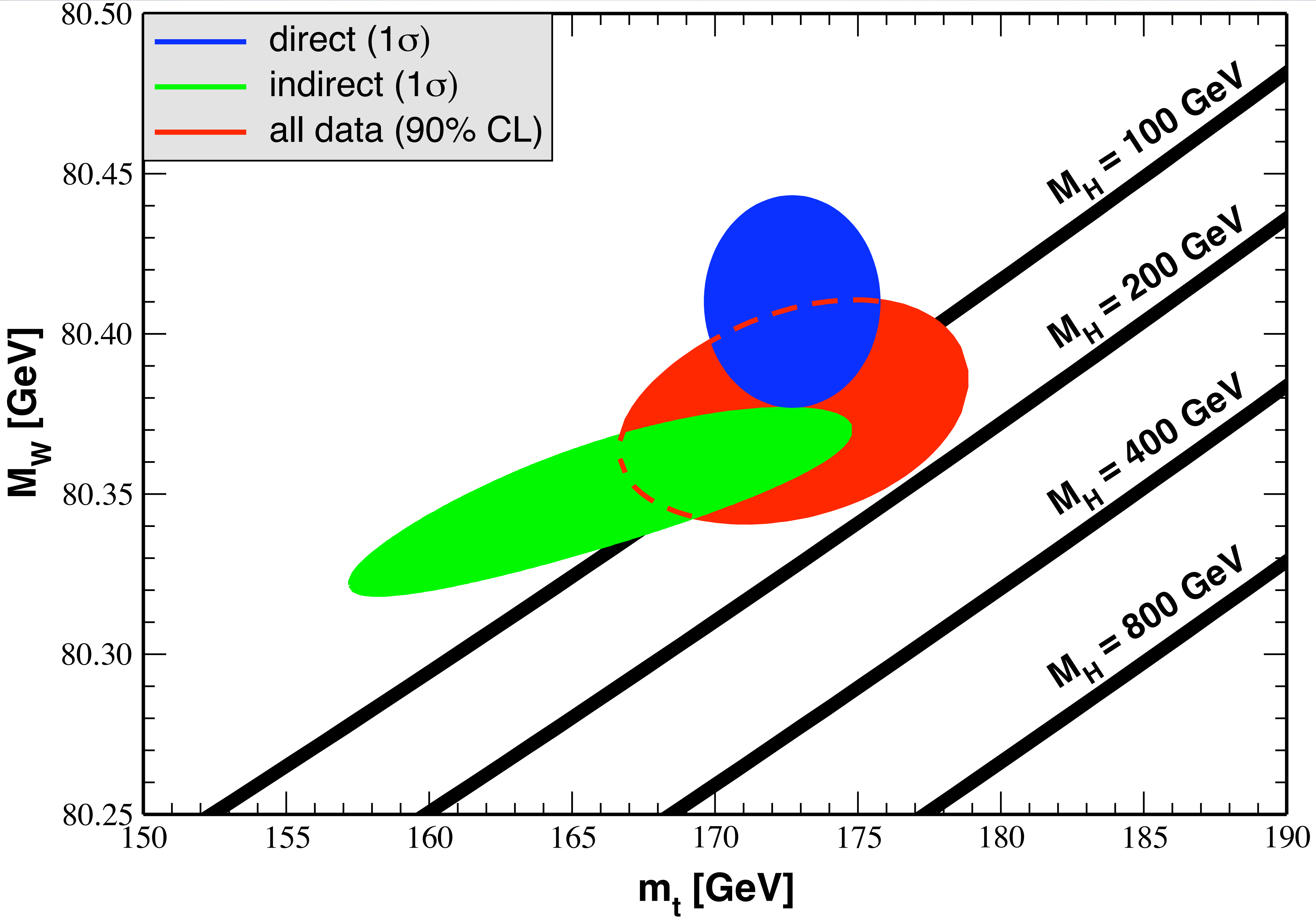

March 2009
m_{Limit} = 163 GeV
Theory uncertainty
$\Delta\alpha^{(5)}_{had}$ =
0.02758±0.00035
0.02749±0.00012
incl. low Q^2 data
Excluded
Preliminary
$\Delta\chi^2$
m_H [GeV]
0
1
2
3
4
5
6
30
100
300



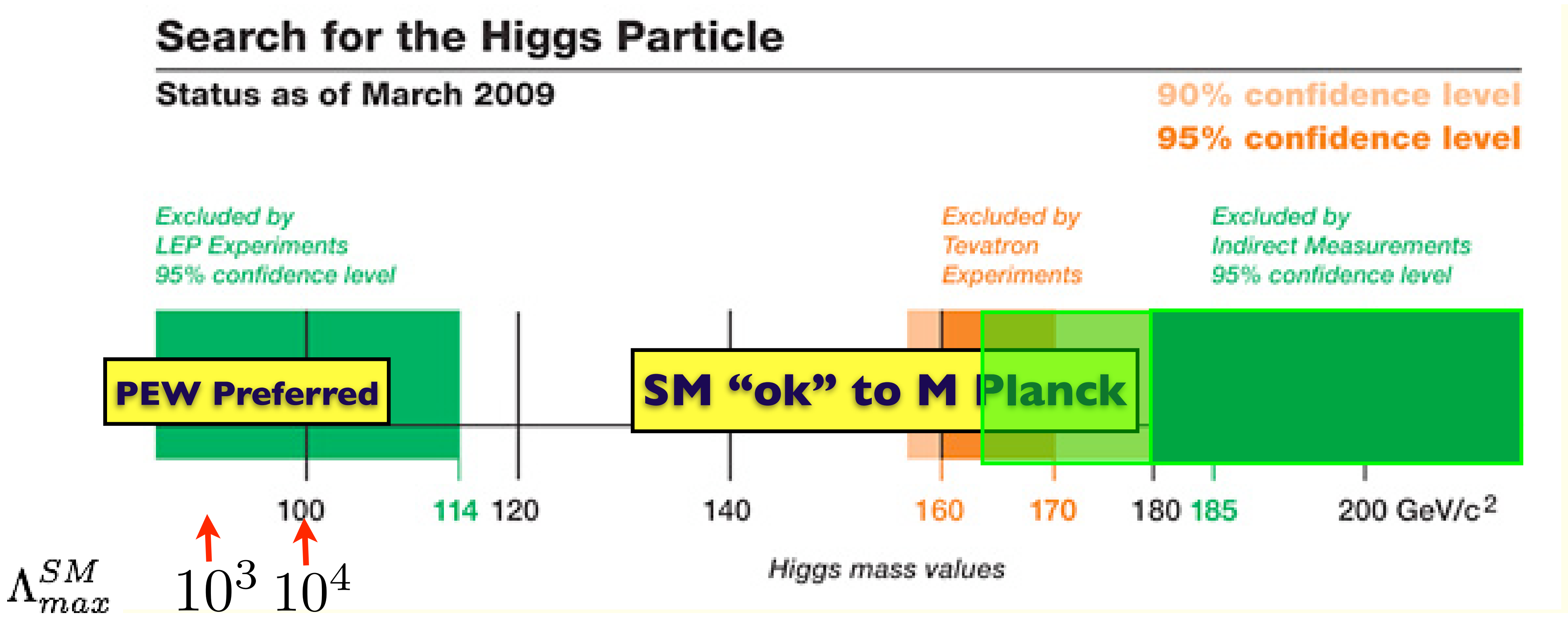
From Chanowitz.



Contours are at one sigma. Red blob =90% CL all data



direct (1σ)
indirect (1σ)
all data (90% CL)
M_H = 100 GeV
M_H = 200 GeV
M_H = 400 GeV
M_H = 800 GeV
80.50
80.45
80.40
80.35
80.30
80.25
150
155
160
165
170
175
180
185
190
M_W [GeV]
m_t [GeV]



✱ ESCAPE = BSM decays

Table 1: LEP m_H Limits for a H with SM-like ZZ coupling, but varying decays. See (S. Chang, R. Dermisek, J. F. Gunion and N. Weiner, Ann. Rev. Nucl. Part. Sci. 58, 75 (2008) [arXiv:0801.4554 [hep-ph]]).

Invisible decays don't "help"

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?			

When must new physics appear if the SM is treated as an effective theory?

- the Higgs self coupling should not blow up below scale Λ; $\Rightarrow$ upper bound on $m_{h_{\rm SM}}$ as function of Λ.

- the Higgs potential should not develop a new minimum at large values of the scalar field of order Λ; $\Rightarrow$ lower bound on $m_{h_{\rm SM}}$ as function of Λ.

These two constraints imply that the SM can be valid all the way up to $M_{\rm P}$ if $130 \lesssim m_{h_{\rm SM}} \lesssim 180$ GeV.

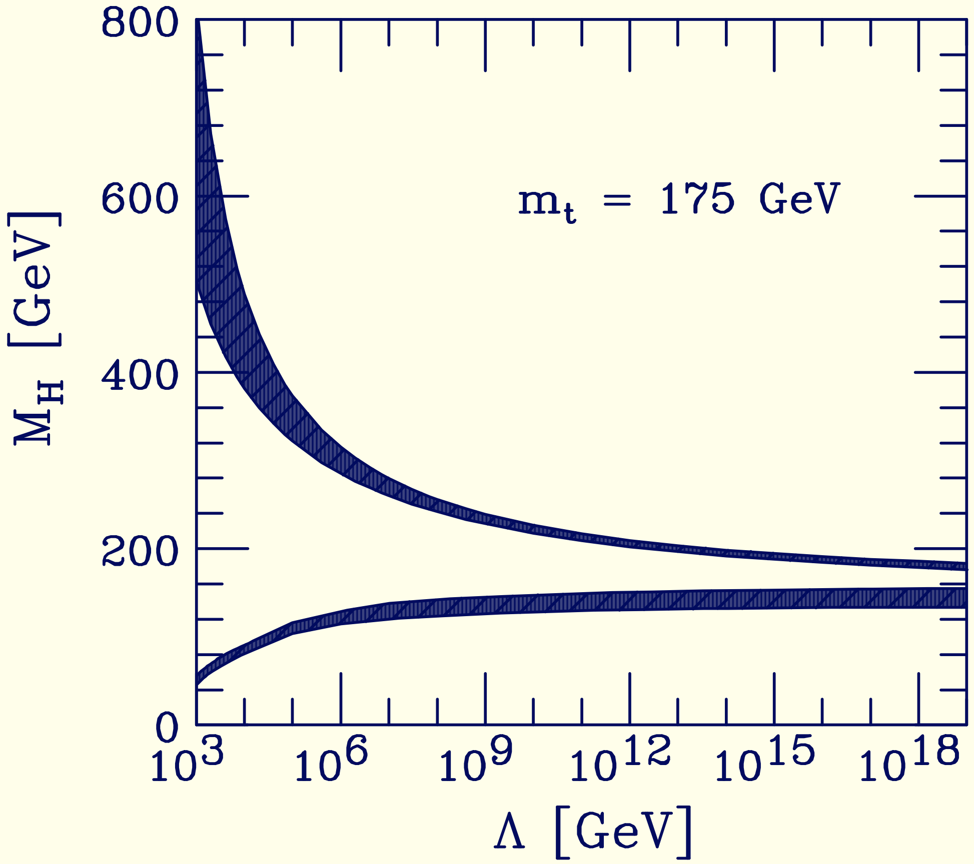


Figure 1: Triviality and global minimum constraints on $m_{h_{\rm SM}}$ vs. Λ.

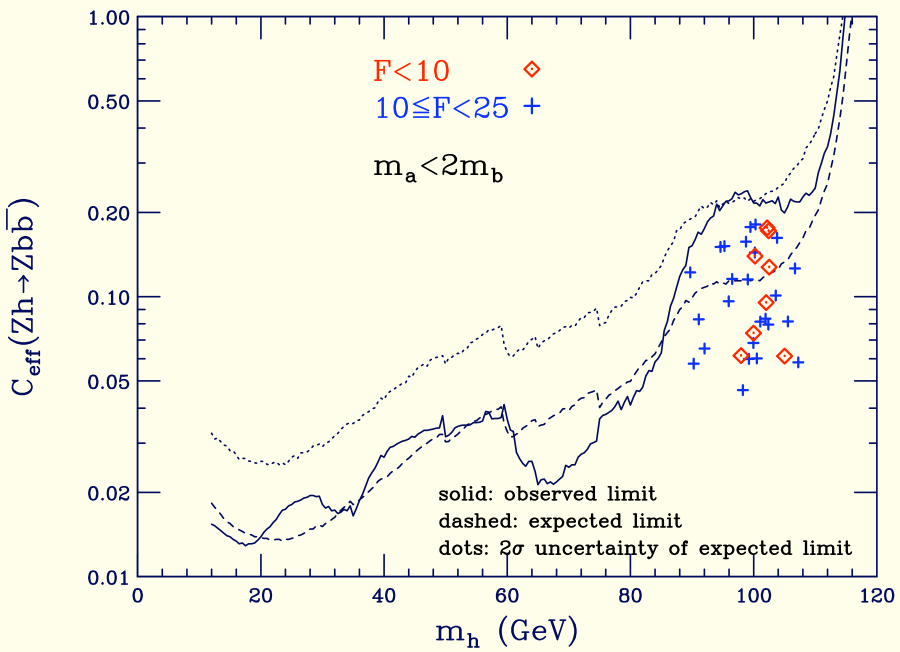
One generic way of having a low LEP limit on m_H is to suppress the $H \to b\bar{b}$ branching ratio by having a light a (or h)with $B(H \to aa) > 0.7$ and $m_a < 2m_b$ (to avoid LEP $Z + 4b$ limit at $110~\mathrm{GeV}$, i.e. above ideal). For $2m_\tau < m_a < 2m_b$, $a \to \tau^+\tau^-$. For $m_a < 2m_\tau$, $a \to jj$.

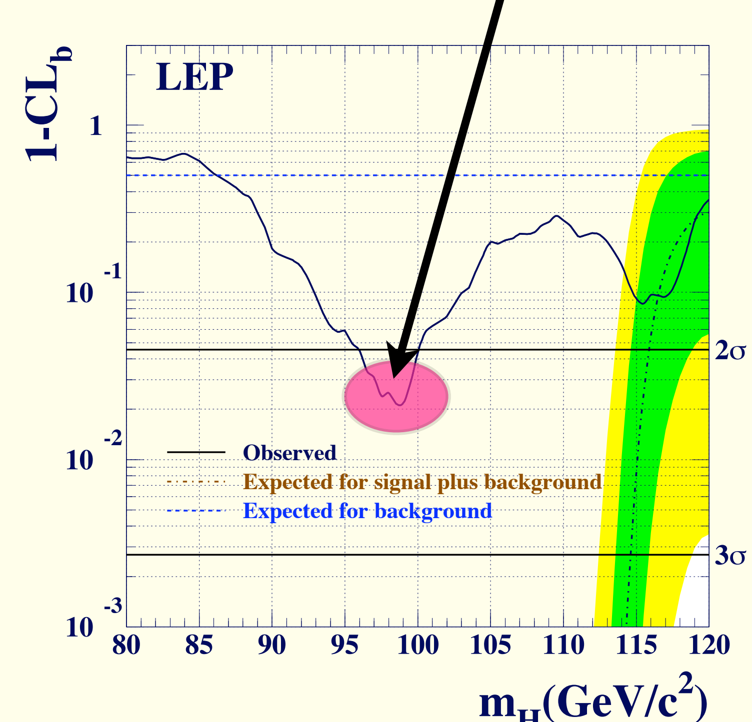
See: (R. Dermisek and J. F. Gunion, Phys. Rev. Lett. 95, 041801 (2005) [arXiv:hep-ph/0502105]; R. Dermisek and J. F. Gunion, Phys. Rev. D 73, 111701 (2006) [arXiv:hep-ph/0510322])

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

An attractive possibility: $m_H \sim 100~\mathrm{GeV}$ and $BR(H \to b\bar{b}) \sim 0.$

Explains largest LEP excess (2.3 sigma).

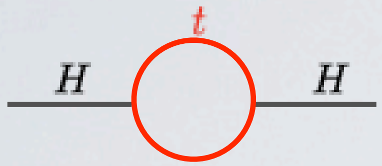




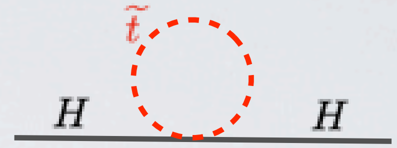
Extra Higgs (complex) singlets are abundant in most string vacua, but especially well-motivated in SUSY.

Why SUSY?

Solves hierarchy problem if at a TeV and PEW needs new physics there anyway.



$m_H^2 = (m_H^0)^2 - c\Lambda^2$



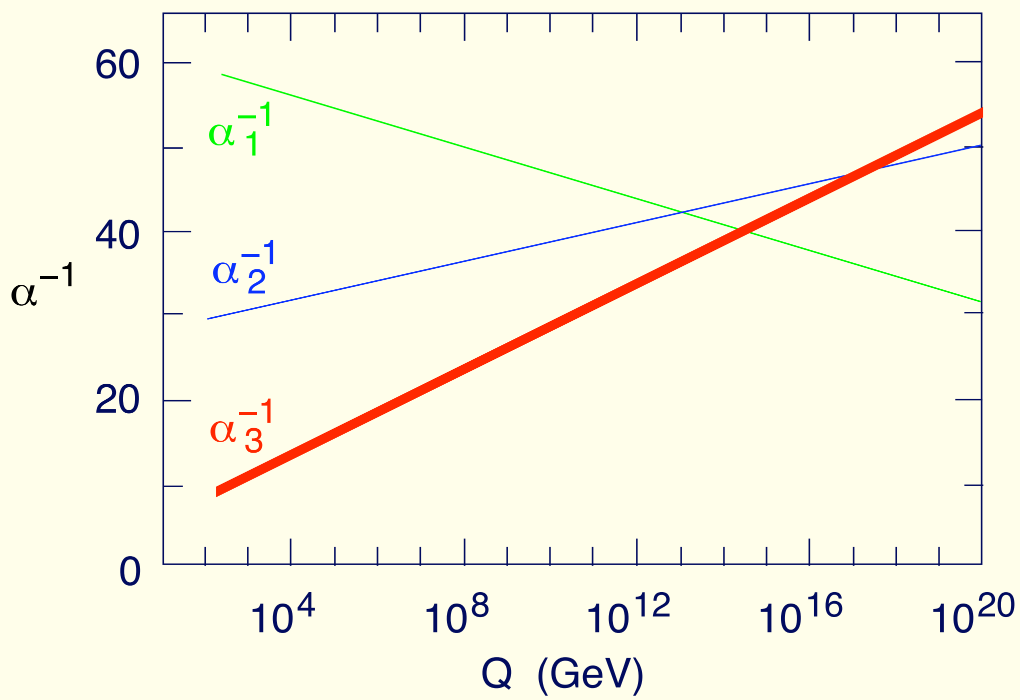
$\delta m_H^2 \sim c(\Lambda^2 + m_{\tilde{t}}^2)$

- **The MSSM comes close to being very nice.**

If we assume that all sparticles reside at the $\mathcal{O}(1\ \mathrm{TeV})$ scale and that μ is also $\mathcal{O}(1\ \mathrm{TeV})$, then, the MSSM has two particularly wonderful properties.

1. $\boxed{\textbf{Gauge Coupling Unification}}$

Standard Model



MSSM

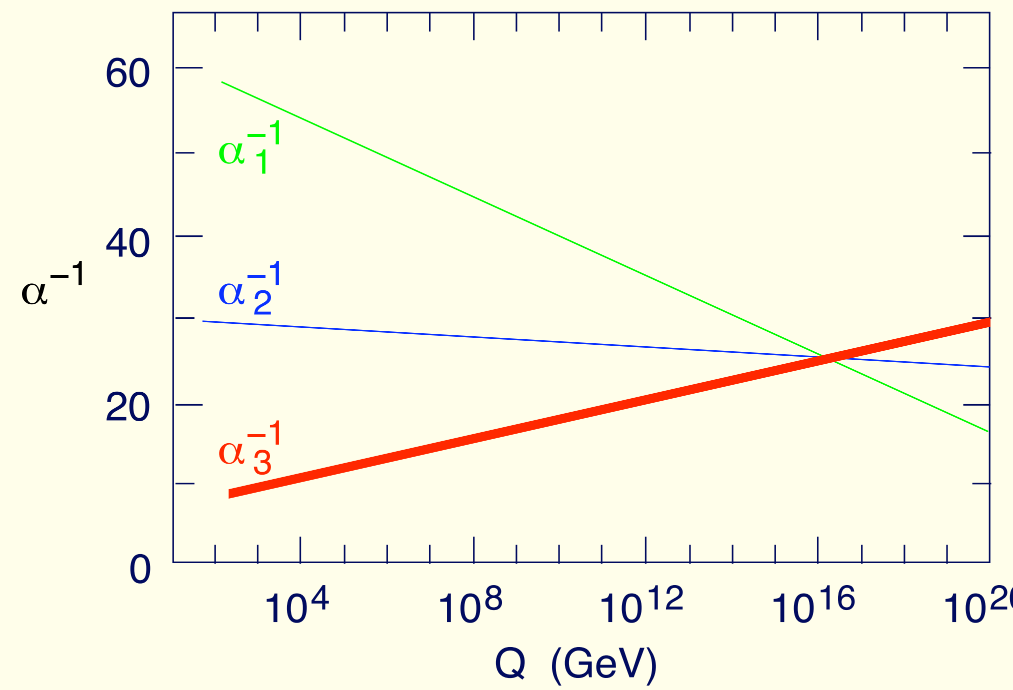


Figure 4: Unification of couplings constants ($\alpha_i = g_i^2/(4\pi)$) in the minimal supersymmetric model (MSSM) as compared to failure without supersymmetry.

2. RGE EWSB

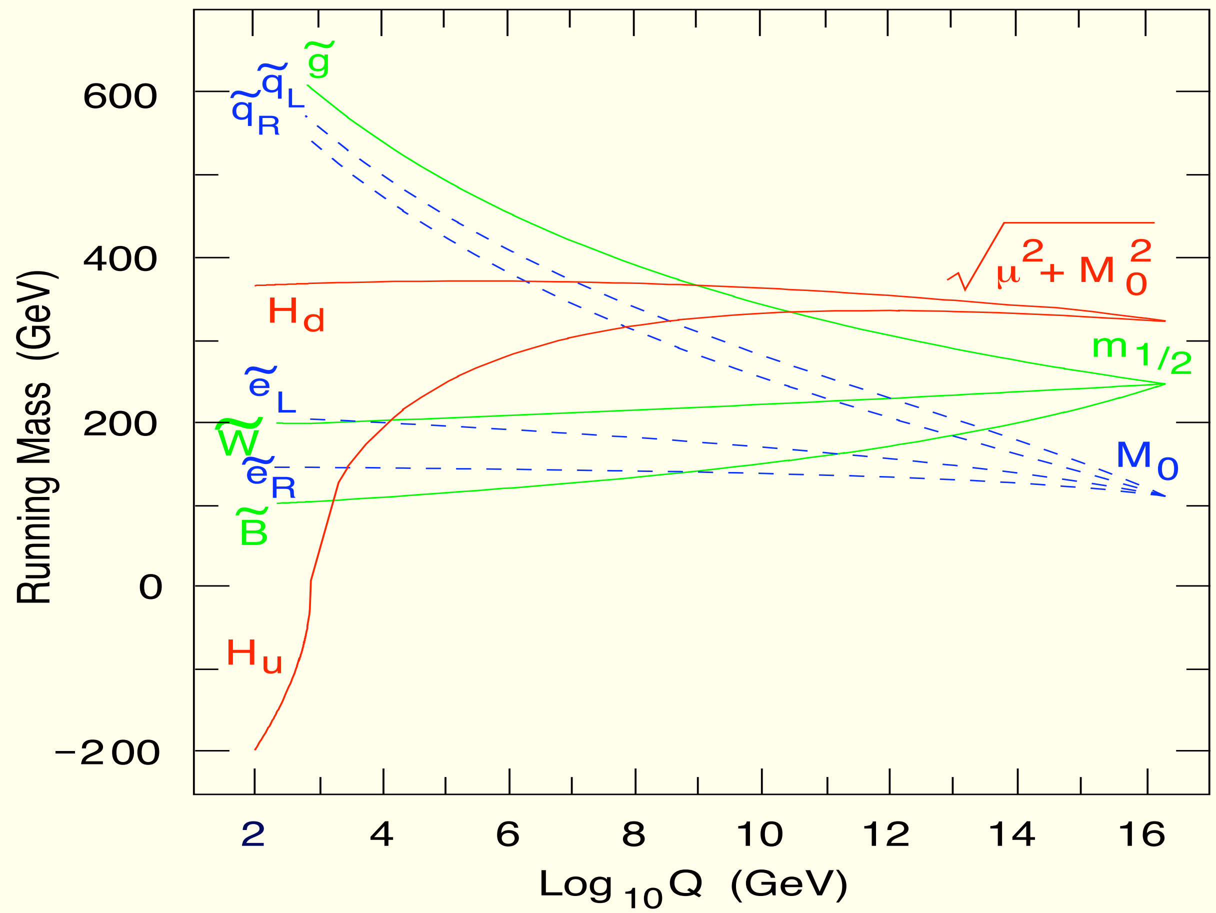


Figure 5: Evolution of the (soft) SUSY-breaking masses or masses-squared, showing how $m^2_{H_u}$ is driven < 0 at low $Q \sim \mathcal{O}(m_Z)$.

But, must one fine-tune the GUT scale parameters to get correct Z mass?

F **measures the degree to which GUT parameters must be tuned.**

Want $F < 10$ **. This requires** $m_{\tilde{t}} < 400$ GeV **and a light gluino.**

For such a stop mass the MSSM and other SUSY models <u>*predict*</u> that $m_h < 110$ GeV **.**

MSSM Higgs sector: h, H, A **with** h **typically SM-like unless it is very light and** H **is SM-like.**

The problem: the light Higgs of the MSSM decays like the SM Higgs and is basically excluded for $m_h < 114 \text{ GeV}$. This implies that $m_{\tilde{t}} > 800 \text{ GeV}$ which in turn implies $F > 50$ = very bad!

What is needed is a SUSY model for which the stop mass can be low but for which the resulting light <100 GeV Higgs is not excluded by LEP.

LEP exclusion can be avoided by having unusual decays as seen earlier.

My favorite SUSY model is the Next to Minimal Supersymmetric Model (NMSSM). It has an a *of the type needed* and retains the supersymmetric solution to the hierarchy problem.

The a comes mainly from the singlet, S , field that solves the famous mu-problem of the MSSM and was the initial motivation for the NMSSM.

$$W \ni \mu \widehat{H}_u \widehat{H}_d \quad \text{MSSM} \quad vs. \quad W \ni \lambda \widehat{S} \widehat{H}_u \widehat{H}_d \to \lambda \langle S \rangle \widehat{H}_u \widehat{H}_d \quad \text{NMSSM}$$

A_λ, A_κ are the new soft-SUSY-breaking parameters.

The required properties of the a are natural in the NMSSM. In particular, there is a $U(1)_R$ symmetry in the limit of $A_\lambda, A_\kappa \to 0$ that, if exact, predicts that the a would be massless. This symmetry, if exact at the GUT scale, is weakly broken in evolving down from the GUT scale.

And, very importantly, the NMSSM yields (like the MSSM) gauge coupling unification and "radiative" electroweak symmetry breaking.

Other SUSY decays that would escape strongest LEP limits:

$$h \to \widetilde{\chi}_1^0 + \widetilde{\chi}_2^0 \to \widetilde{\chi}_1^0 + \widetilde{\chi}_1^0 + f\overline{f} \to E_{miss} + f\overline{f}$$

$$h \to \widetilde{\chi}_1^0 + \widetilde{\chi}_1^0 \to \widetilde{G} + \widetilde{G} + \gamma + \gamma \to E_{miss} + \gamma + \gamma$$

LEP limits for the latter are not known, but maybe they would have noticed this decay if the Higgs were below 114 GeV?

Note: the above are some natural cases assuming R-parity conserving SUSY so that there will be a dark matter candidate. There are many more SUSY models with unusual Higgs decays related to R-parity violation and similar that would, however, not allow for a dark matter particle.

There are also many BSM approaches in which the electroweak Higgs (i.e. the one with ZZ coupling) decays invisibly.

As noted earlier, LEP constrains an invisibly decaying Higgs as strongly as if it decayed a la SM. From the PEW perspective this is not desirable.

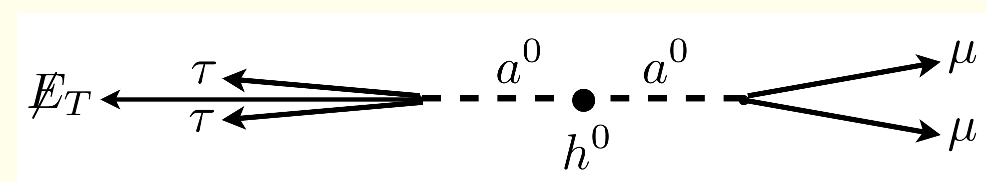
Detecting the light h of the NMSSM

LHC

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

The possible new LHC channels include:

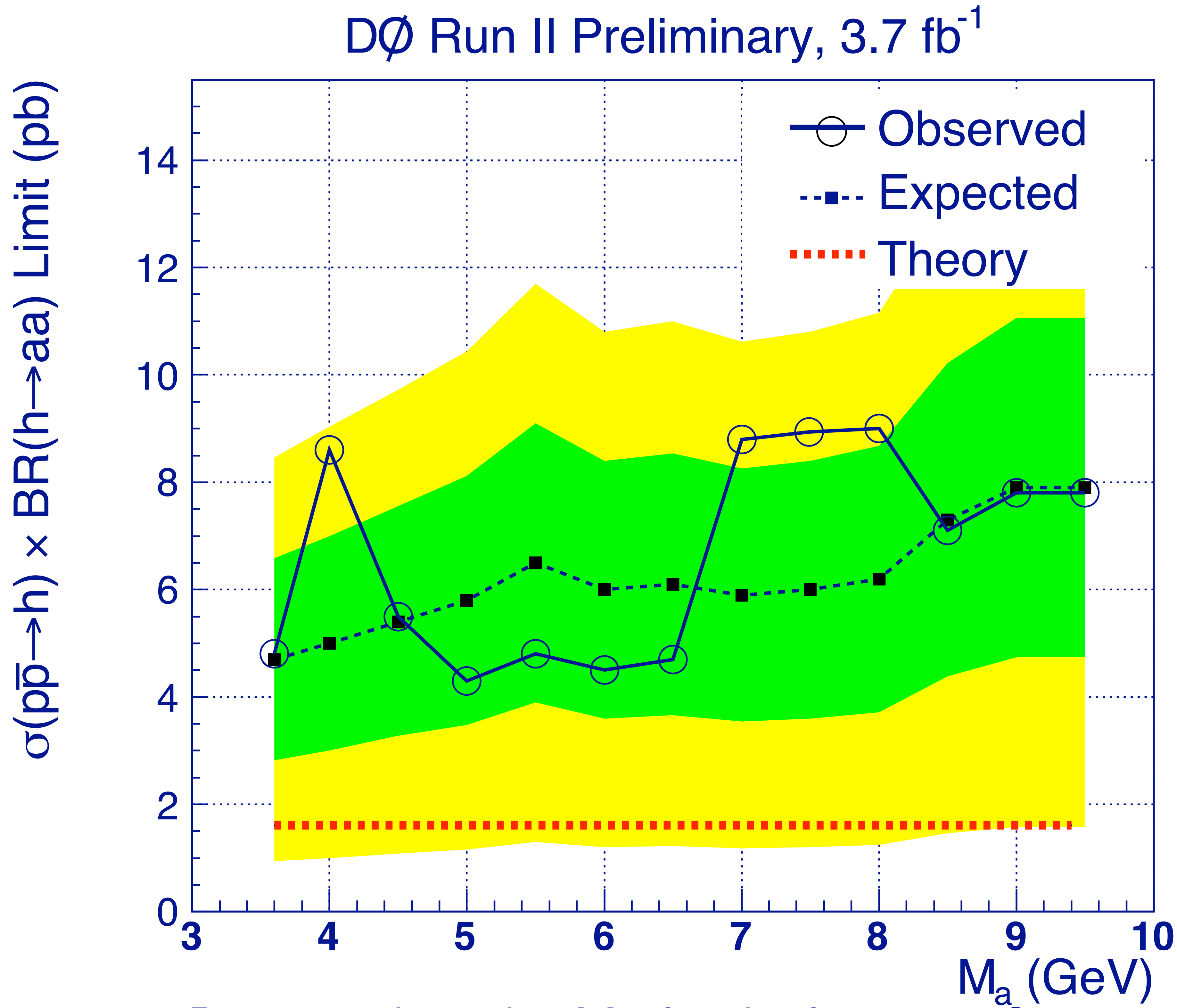
1. $gg \to h \to aa \to 4\tau$ and $2\tau + \mu^+\mu^-$



Always use μ tag for accepted events. $2\tau + 2\mu$ is main signal source after cuts.

There is an actual D0 analysis (A. Haas et. al.) of this mode using about $L \sim 4~\mathrm{fb}^{-1}$ of data. There is even a small $\sim 1\sigma$ excess. They estimate about $L \sim 40~\mathrm{fb}^{-1}$ would be needed for a 5σ signal but even a $\sim 3\sigma$ signal

as possible for $L \sim 20\ \mathrm{fb}^{-1}$ would be exciting.



Presented at the Moriond winter conference.

A theoretical study (Wacker et.al.) suggests that a $> 3\sigma$ signal would be possible at the LHC after the first 3 years or so of running.

2. $WW \to h \to aa \to \tau^+\tau^- + \tau^+\tau^-$.

   Key will be to tag relevant events using spectator quarks and require very little activity in the central region by keeping only events with 4 or 6 tracks.

   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). More shortly.

3. $t\bar{t}h \to t\bar{t}aa \to t\bar{t} + \tau^+\tau^- + \tau^+\tau^-$.

   No study yet. Would isolated tracks/leptons from τ's make this easier than $t\bar{t}h \to t\bar{t}b\bar{b}$?

4. $W, Z + h \to W, Z + aa \to W, Z + \tau^+\tau^- + \tau^+\tau^-$.

   Leptons from W, Z and isolated tracks/leptons from τ's would provide a clean signal. No study yet.

5. $\widetilde{\chi}_2^0 \to h\widetilde{\chi}_1^0$ with $h \to aa \to 4\tau$.

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

6. Last, but definitely not least: diffractive production $pp \to pph \to ppX$.

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. 6 for a variety of luminosity and triggering assumptions.

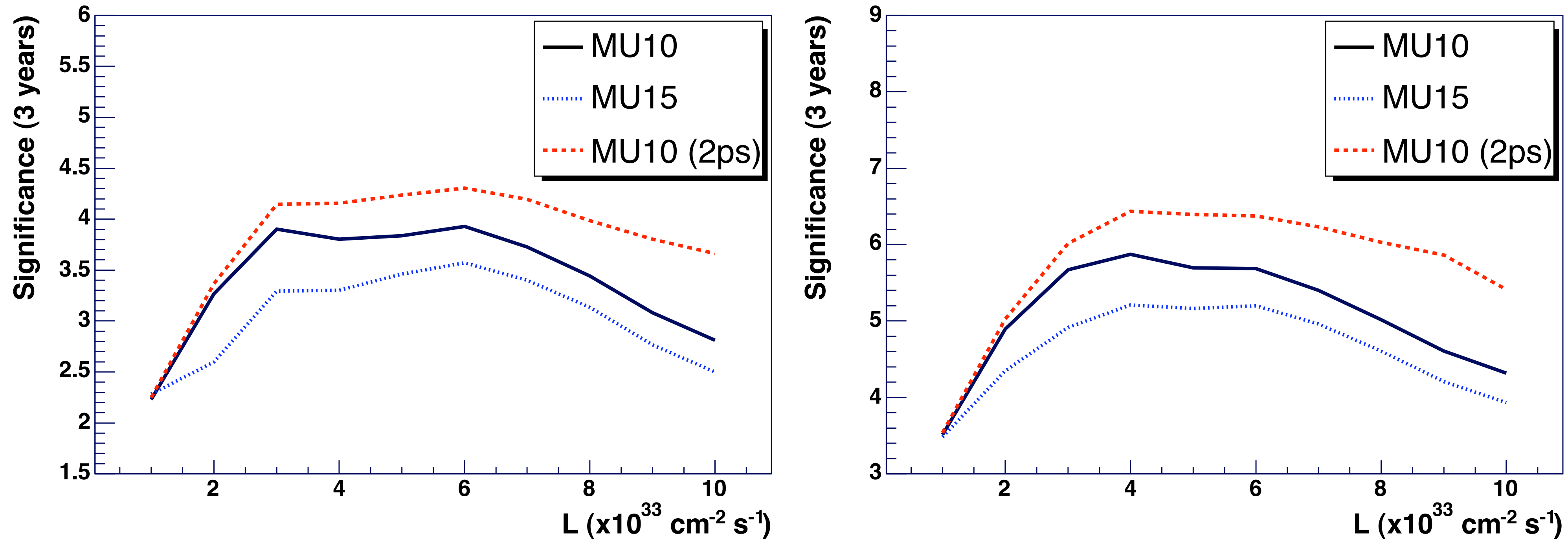


Figure 6: (a) The significance for three years of data acquisition at each luminosity. (b) Same as (a) but with twice the data. Different lines represent different μ trigger thresholds and different forward detector timing. Some experimentalists say more efficient triggering is possible, doubling the 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 source 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

$$p_i^{vis} = f_i \, p_{a,i} \tag{25}$$

  where $1 - f_i$ is the fraction of the a momentum carried away by neutrals.

- $\boxed{pp \to pph \text{ case}}$

  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.

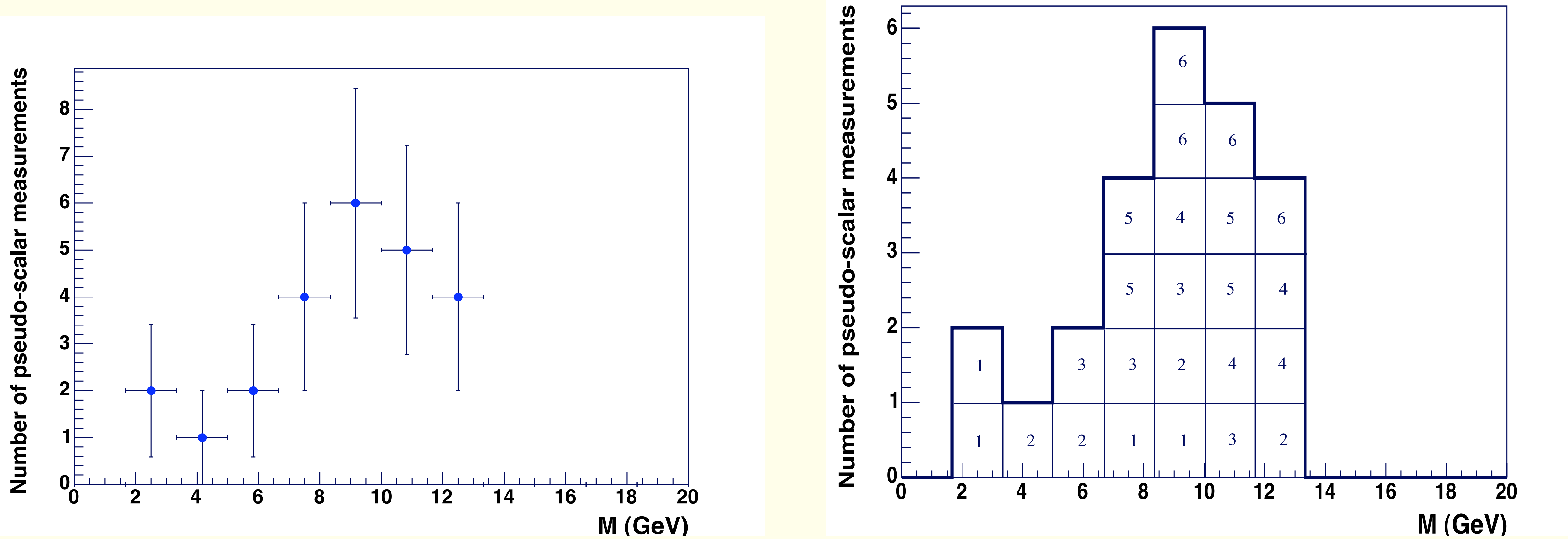


Figure 7: (a) A typical a mass measurement. (b) The same content as (a) but with the breakdown showing the 4 Higgs mass measurements for each of the 6 events, labeled $1-6$ in the histogram.

Figure 7 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.

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 $m_h = 100$ GeV and SM-like WWh coupling, $\sigma(WW \to h) \sim 7$ pb, implying 7×10^5 events before cuts for $L = 100$ 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.
This gives two equations in the two unknown $f_{1,2}$ and allows us to solve and construct mass peaks.

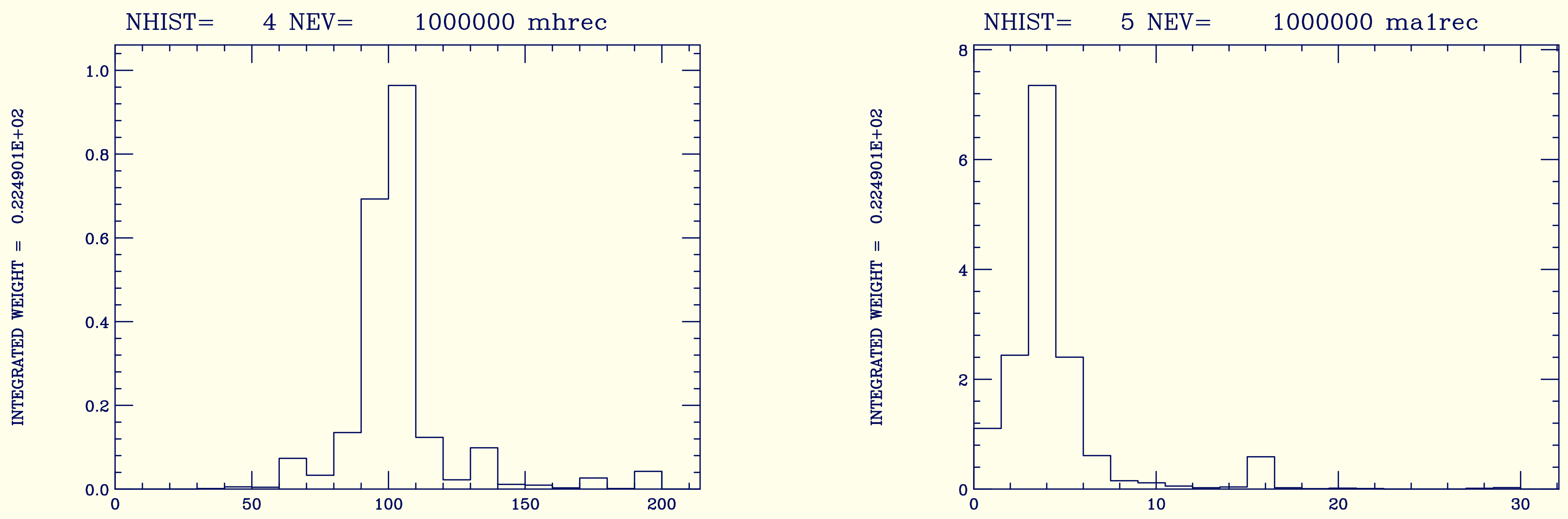


Figure 8: (a) A typical h mass distribution. (b) A typical a mass distribution. No cuts imposed; signal only

A few further points regarding a light a

- The a is largely singlet: $a = \cos\theta_A a_{MSSM} + \sin\theta_A a_S$ with $\cos\theta_A$ small.

- Define a generic coupling to fermions by

$$\mathcal{L}_{af\bar{f}} \equiv iC_{af\bar{f}} \frac{ig_2 m_f}{2m_W} \bar{f}\gamma_5 f a\,, \quad \text{then} \quad C_{ab\bar{b}} = \cos\theta_A \tan\beta \qquad (13)$$

- The extracted $C_{ab\bar{b}}$ limits (JFG, arXiv:0808.2509; see also Ellwanger and Domingo) are quite model-independent. The extracted limits on $C_{ab\bar{b}}$ appear in Fig. 5,

- The most unconstrained region is that with $m_a > 8$ GeV, especially $9\ \text{GeV} < m_a < 12\ \text{GeV}$. = region with least "light-a_1" tuning in NMSSM.

- Except for this region, a further factor of 3 improvement to $C_{ab\bar{b}} < 0.3$ would start to rule out or observe the $a = a_1$ of the most favored NMSSM scenarios.

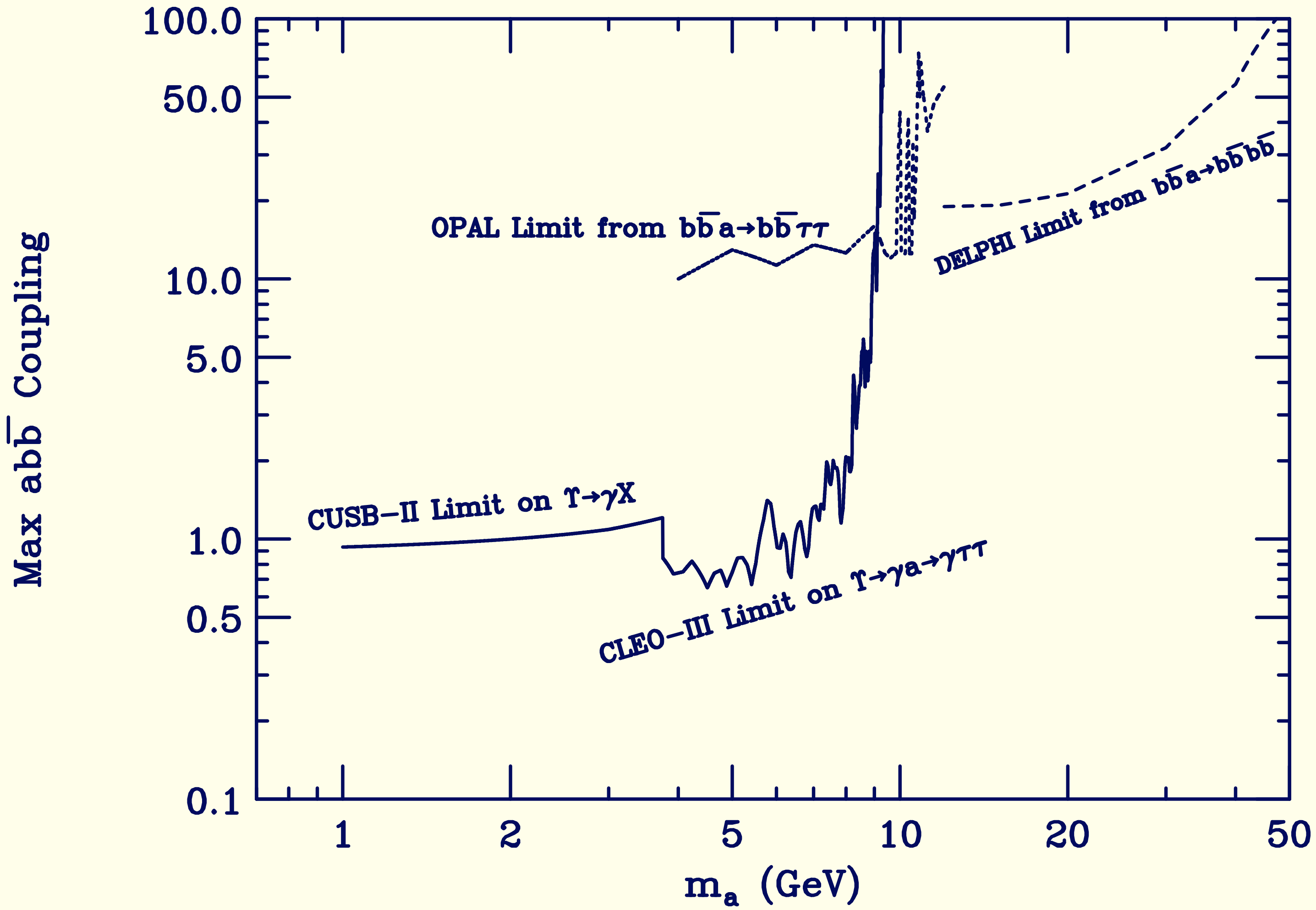


Figure 5: Limits on $C_{ab\bar{b}}$.

- 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 (Drees+Hikasa: Phys.Rev.D41:1547,1990) is employed.

Actually, the Tevatron has a chance to make a valuable contribution with large integrated L.

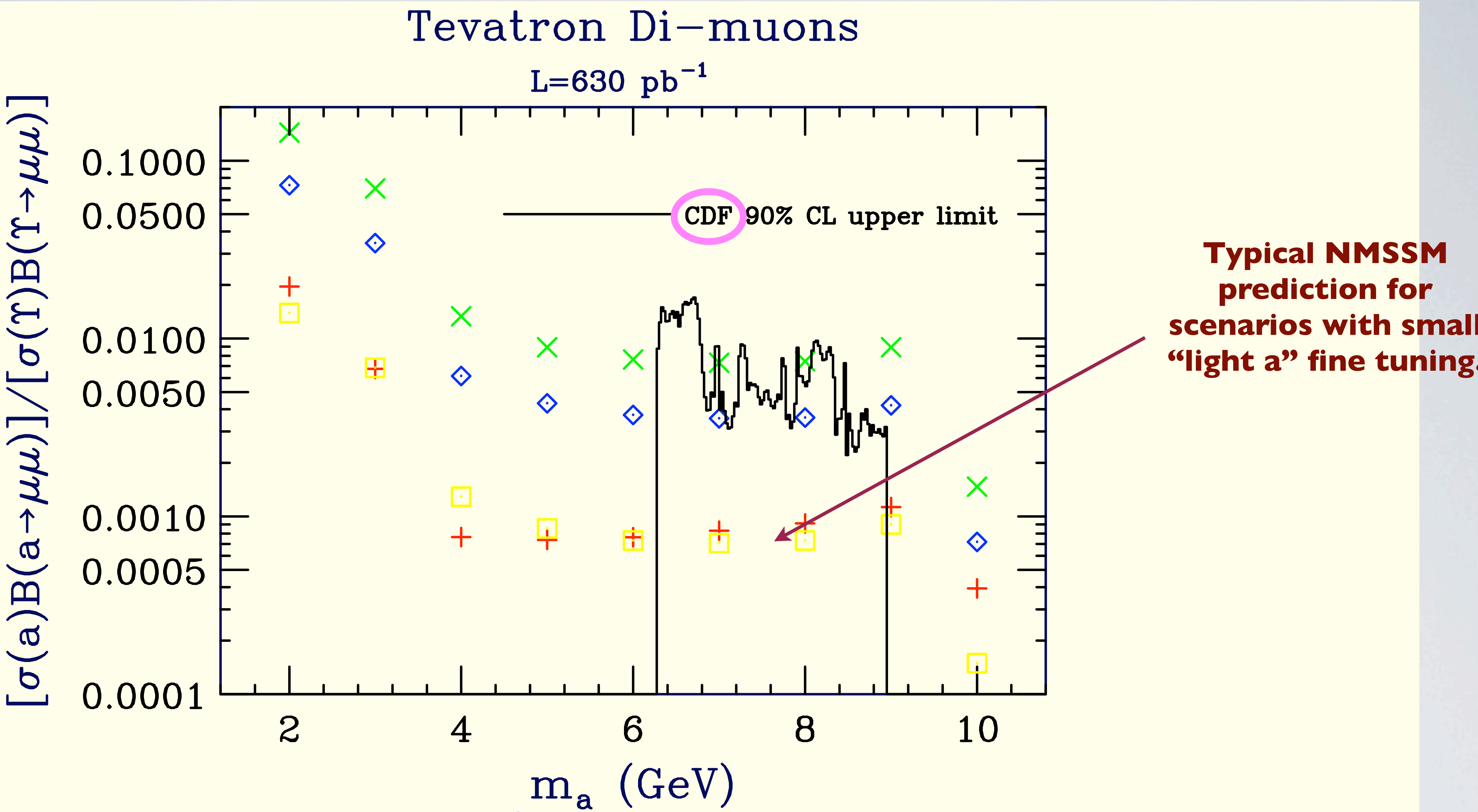


Figure 5: 90% CL limits on $\frac{\sigma(a)B(a\to\mu^+\mu^-)}{\sigma(\Upsilon)B(\Upsilon\to\mu^+\mu^-)}$ at small $|y|$ for $L = 630\ \mathrm{pb}^{-1}$, compared to expectations for the a for $C_{ab\bar{b}} = \tan\beta = 1/C_{at\bar{t}} = 1$, 2, 3 in the 2HDM-II. Also shown (□'s) are the predictions 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):**

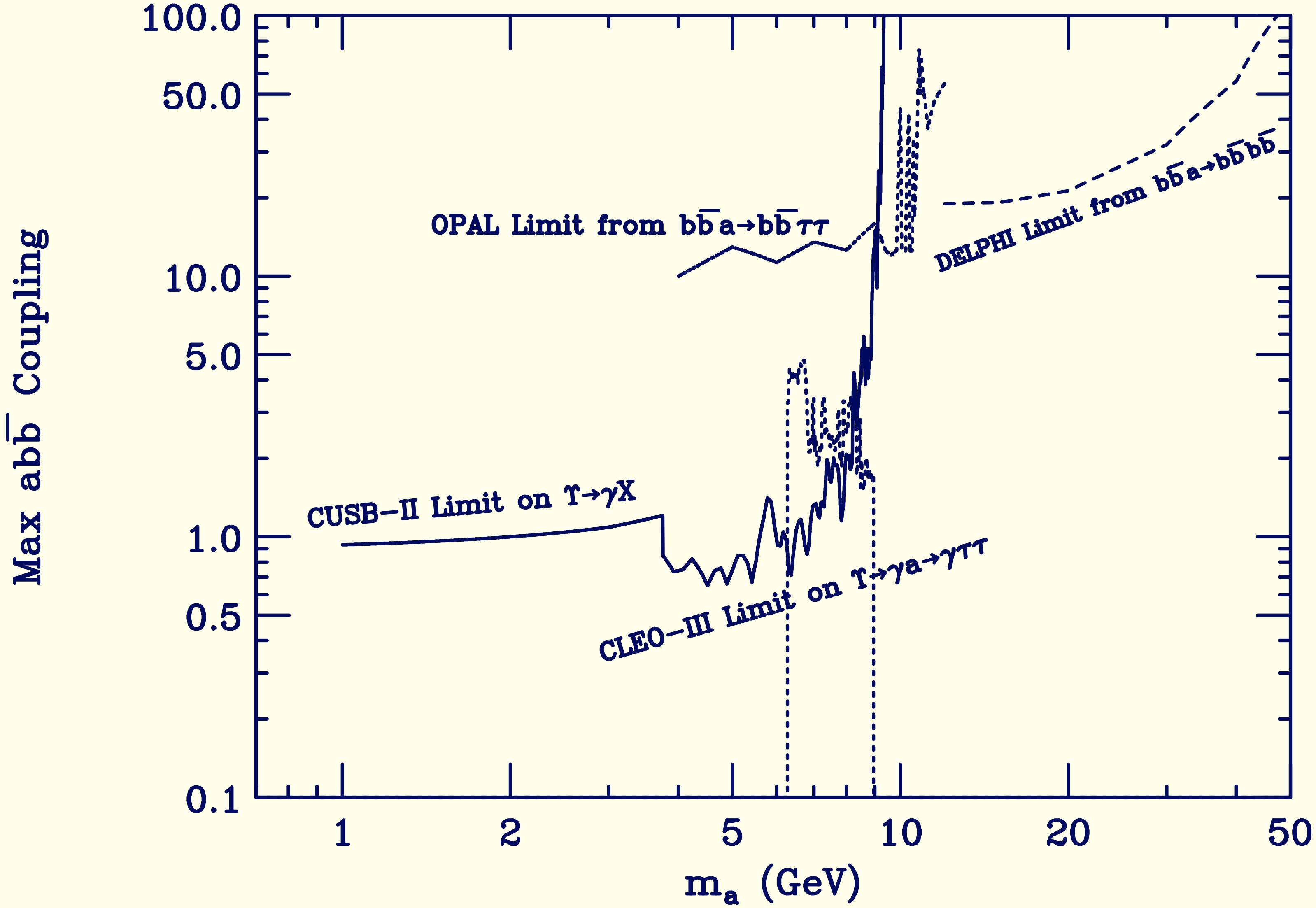


Figure 6: **Limits on $C_{ab\bar{b}}$ including those from the Tevatron analysis.**

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

Other related scenarios

- $m_a < 2m_\tau$ (in NMSSM has large "light-a" fine tuning, but ....)

  Can no longer use special τ characteristics; $a \to gg, c\bar{c}, \ldots$ dominant.

  Larger $B(a \to \mu^+\mu^-)$, but larger DY related backgrounds; could D0 analysis be made to work in $gg \to h \to aa \to jj\mu^+\mu^-$ channel?

- A string of Higgs, as possibly hinted at by the CDF multi-muon events.

  The SM-like Higgs could then decay into a string of Higgs bosons.

- Drop dark matter requirement: $\Rightarrow$ huge plethora of possibilities in SUSY.

  Includes "hidden valley" decays, R-parity violating decays, ...

ILC

At the ILC, there is no problem since $e^+e^- \to ZX$ will reveal a $M_X \sim m_h \sim 90-100~\mathrm{GeV}$ peak no matter how the h decays.

Going Crazy waiting for the Higgs?

• If you really want to go to extremes, imagine many Higgs bosons in the mass region below 100 GeV. If in SUSY context, use multiple singlets mixing with the two doublets to avoid losing gauge coupling unification.

• Each would decay in some exotic, LEP-escaping manner and each would have weaker coupling to ZZ than the SM Higgs and thus lower rate anyway.

• Such scenarios arise in deconstructed unHiggs theories.

• It is easy to get an effectively very low average Higgs mass in the precision electroweak sense.

• Sharing of the top loop among many doublet Higgs bosons delays the quadratic hierarchy problem to higher scales. But, not good for coupling unification --- in SUSY context, keep SUSY scale near 1 TeV.

• Detection of such a continuum of Higgs at the LHC would be really hard!
The ILC would manage ok, but needs full L (300 fb-1) for guarantee.

Meanwhile, all I can do is watch and wait (but maybe not from such a close distance).

Conclusions: where is  ?

- I am going crazy waiting for the Higgs and it is premature to claim we know where or how to find it.
- We could have simply missed it at LEP.
- There is a strong preference for a rather light Higgs boson --- PEW, SUSY+EWSB fine-tuning, ...
- It must decay in non-SM ways to avoid LEP limits.
- Many very attractive models based on SUSY allow for the needed kinds of decays.
- Searches for a Higgs decaying in exotic ways are quite challenging at hadron colliders.
- If no Higgs is seen after a number of LHC years, is it safe to conclude that there is no Higgs?
- Check WW scattering (hard!).
- Build ILC/CLIC (2020, but Higgs detection easy once built).
- If the light Higgs/SUSY scenario is correct, SUSY particles should be light (as preferred by no EWSB fine tuning) and easily seen at the LHC!