THE ELUSIVE HIGGS BOSON(S)

Jack Gunion
U.C. Davis

As you no doubt already know, we have an incredibly successful SM that explains everything we have observed in nature. The one uncertain ingredient is the mechanism by which elementary particles (quarks, leptons, W, Z) get mass.

The SM postulates the existence of a Higgs field and associated quantum degree of freedom called the Higgs boson. Masses of elementary particles arise from the non-zero value of the Higgs field throughout all of space.

WHAT IS THE HIGGS BOSON?

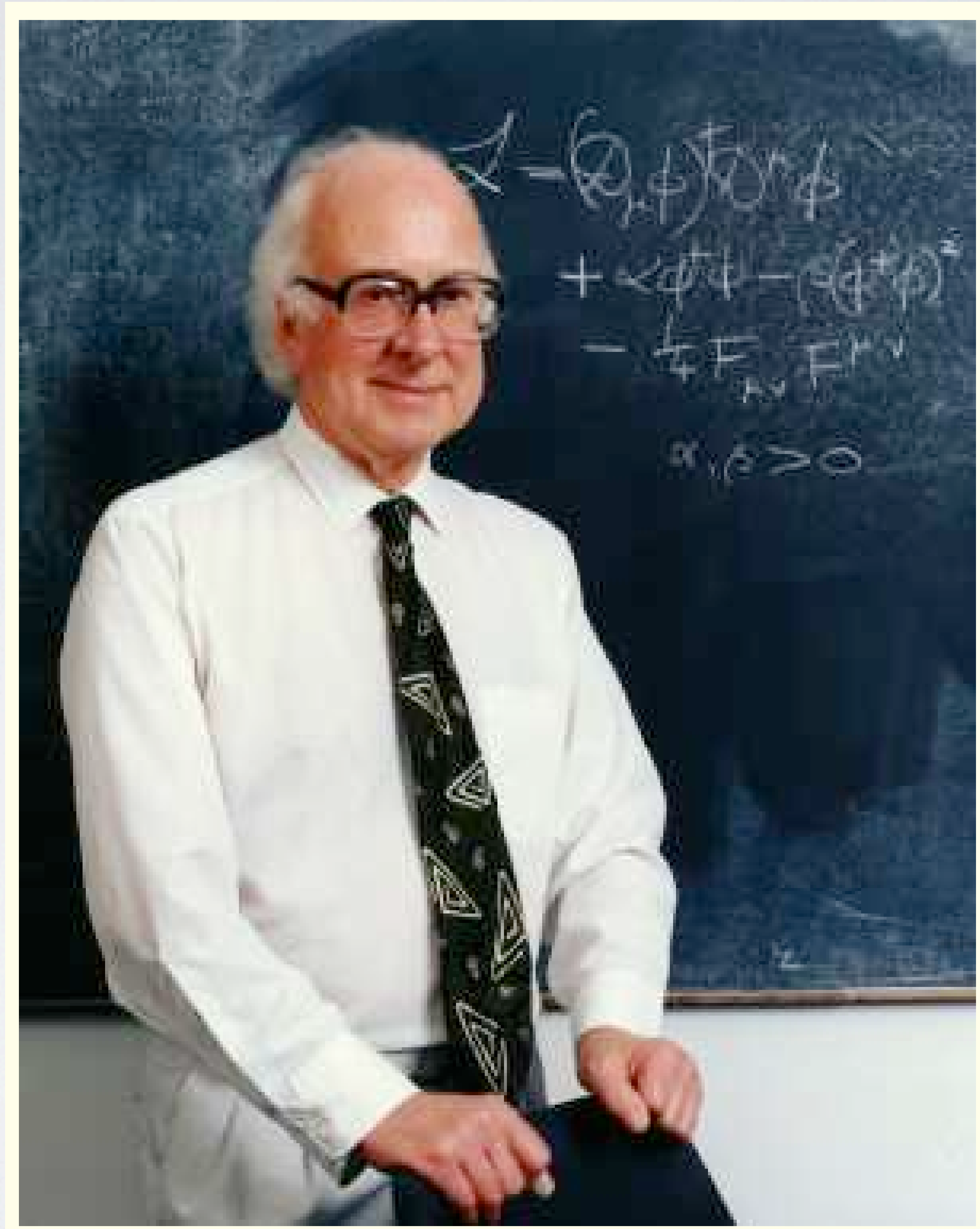
- The Higgs boson is the particle remnant (quantum degree of freedom) of the Higgs field whose vacuum expectation value is thought to give mass to every elementary particle.
- The Higgs particle is sometimes called the ``God" particle, a name originating from Leon Lederman's book.
Apparently, Lederman actually wanted to refer to the Higgs as that ``goddamn particle" but his editor wouldn't let him.
- Robert Brout and Francois Englert, in a co-authored paper, hit on the same idea at around the same.
- Guralnik, Hagen and Kibble also wrote a paper with similar ideas in the same time frame.

The idea behind the Higgs mechanism is sometimes depicted in cartoon fashion: a star enters a crowded room; people (the Higgs vacuum expectation value that fills the otherwise "empty" vacuum) gather around and slow down his/her movement . The more attractive the star, the greater the mass; $mass \propto \lambda_{star} \langle H \rangle$ **attractiveness is quantified by the star's coupling to the Higgs field.**

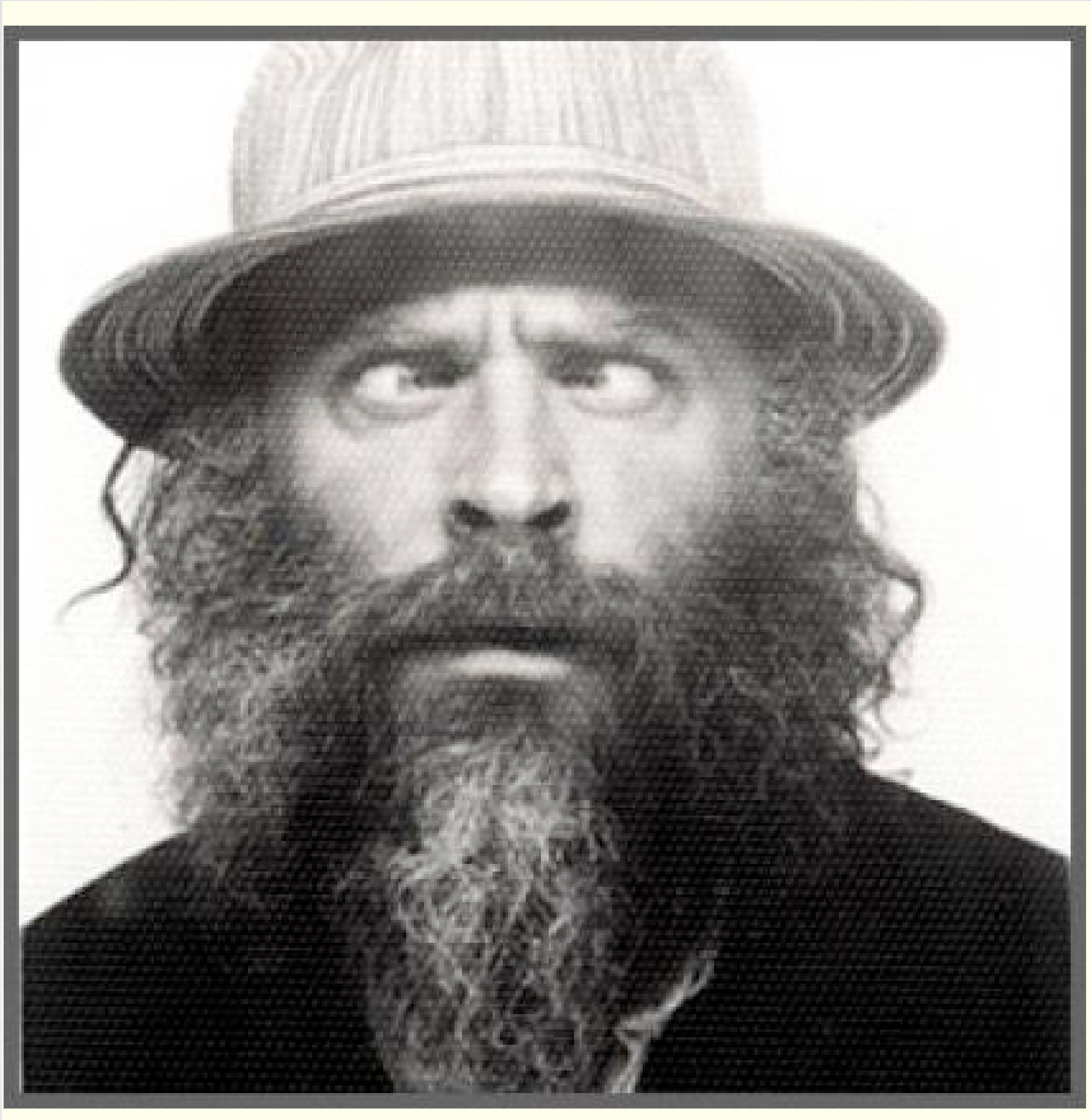
Symmetry Breaking: The room is filled with people vs. empty because pairs of people like to be together $(-\mu^2 H^2)$ **even if repelled by large numbers (** λH^4 **).**

As people enter and leave the circle of attraction, the fluctuations in the crowd would be the analogue of the Higgs boson quantum degree of freedom.

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



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

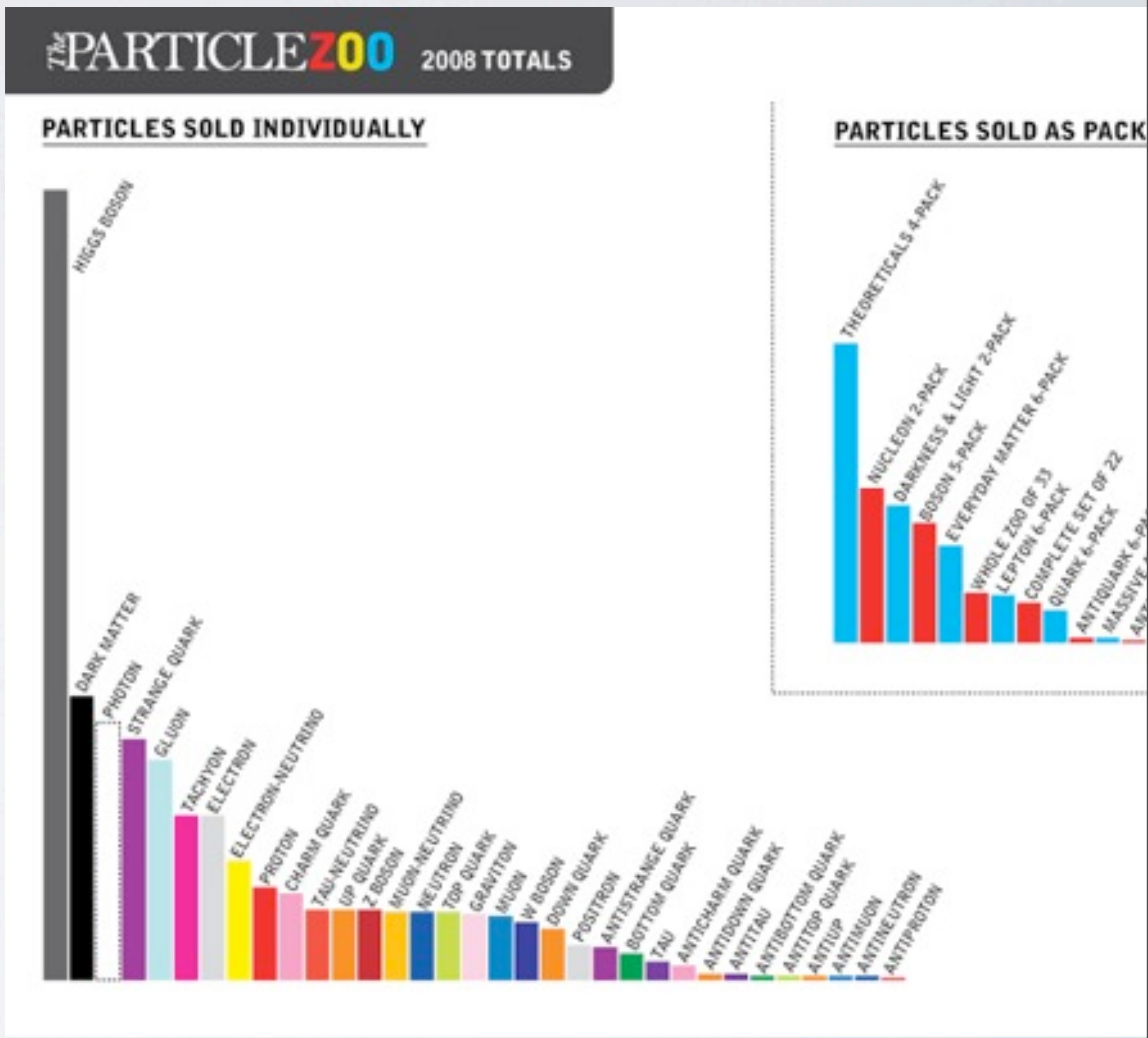


But, what will the Higgs(es) look like?

But, 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.

By far, the most popular particle.



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 disap-pointed; 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

Do we need a Higgs boson?

- $W_L W_L \to W_L W_L$, computed perturbatively, violates unitarity without including Higgs boson exchanges.

  In particular, $|\Re a_0| = \frac{s}{32\pi v^2} < \frac{1}{2}$ fails for $s \gtrsim 1~\mathrm{TeV}$.

- If the Higgs exchange diagrams of the SM are included, then $|\Re a_0| \overset{s\to\infty}{\longrightarrow} \frac{m_h^2}{8\pi v^2} < \frac{1}{2}$ for $m_h < 870~\mathrm{GeV}$.

What would happen in the former case? Clearly, $W_L W_L$ scattering becomes non-perturbative and the exact manner whereby unitarity is preserved would require some lattice implementation of the $\mathcal{A}(W_L W_L)$ calculation using the SM-Higgs Lagrangian.

We do not have the power to do such calculations at the moment. Would K-matrix unitarization, the BESS model, ... turn out to be the answer? We simply don't know.

And, how likely is it that the loop corrections to low-energy LEP, Tevatron, ... observables(which require knowledge of $\mathcal{A}(W_L W_L)$ and related) would be consistent with experimental constraints?

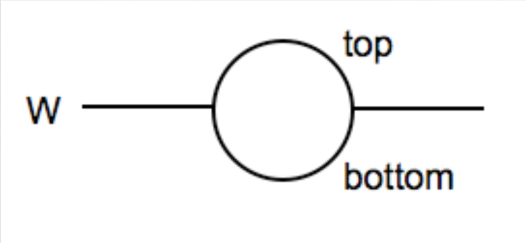
The BESS model inputs custodial SU(2) *and* an effective Higgs mass, Λ, *and* high mass resonances to fix things up.

My take: we really need a Higgs boson (or effective equivalent) to make sense of unitarity and precision data simultaneously.

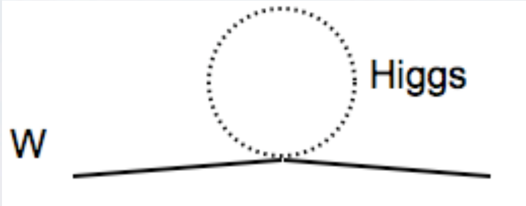
Extra dimensions can provide an alternative (e.g. excited W and Z states that fix up bad high energy behavior), but they have a considerable set of issues, in particular precision data. Although these can be overcome, I will not discuss extra dimension models here.

Quantum Loops: a big source of difficulty for the SM.

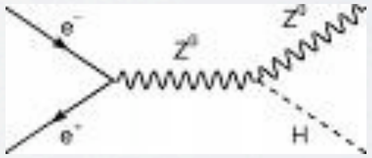
Precision Electroweak Data from LEP and Tevatron Creates large tension within the SM because of such loops!



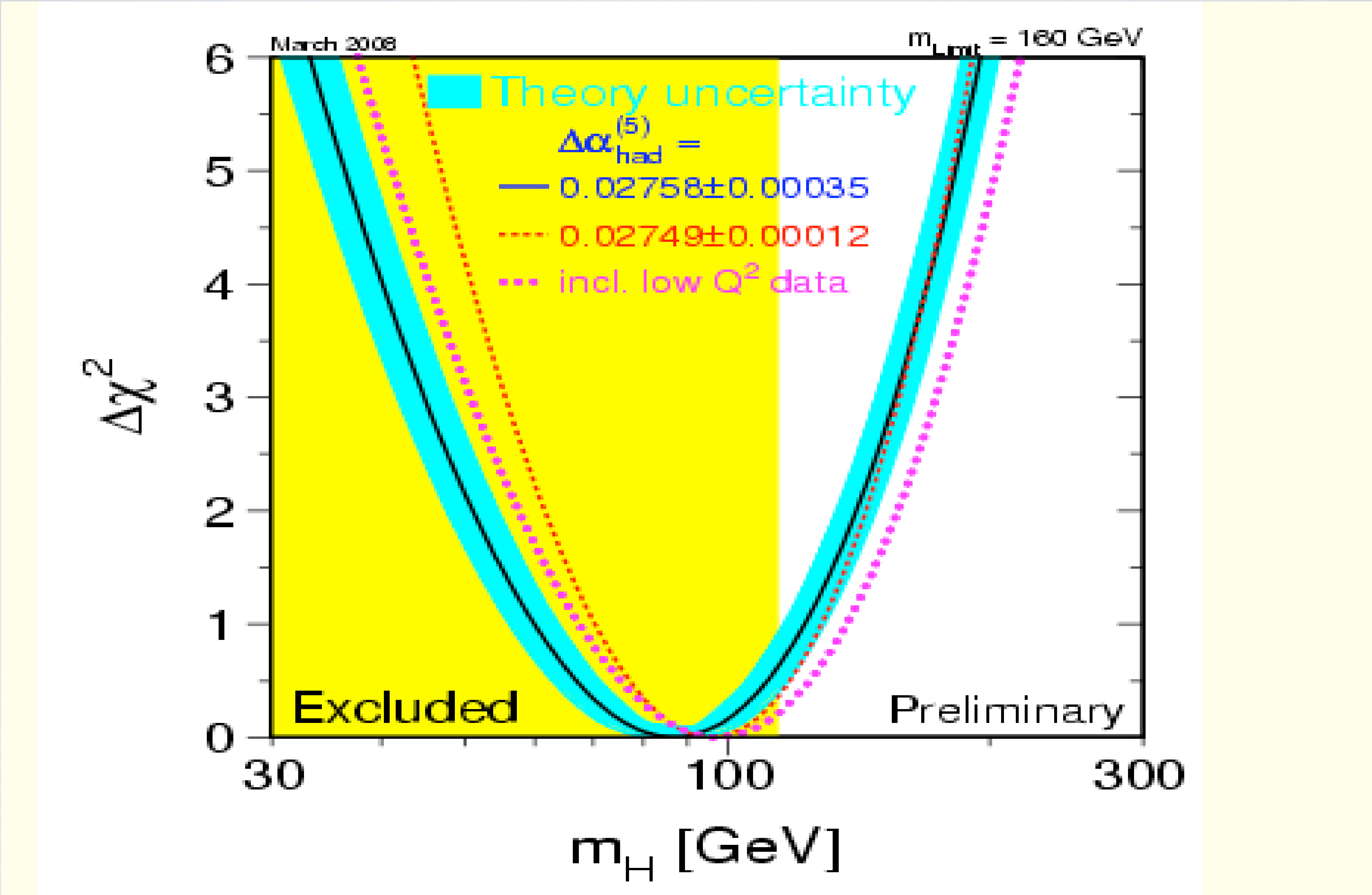
$$m_W = m_W^{tree} + c_1 m_{top}^2 + c_2 \log(m_H^2)$$



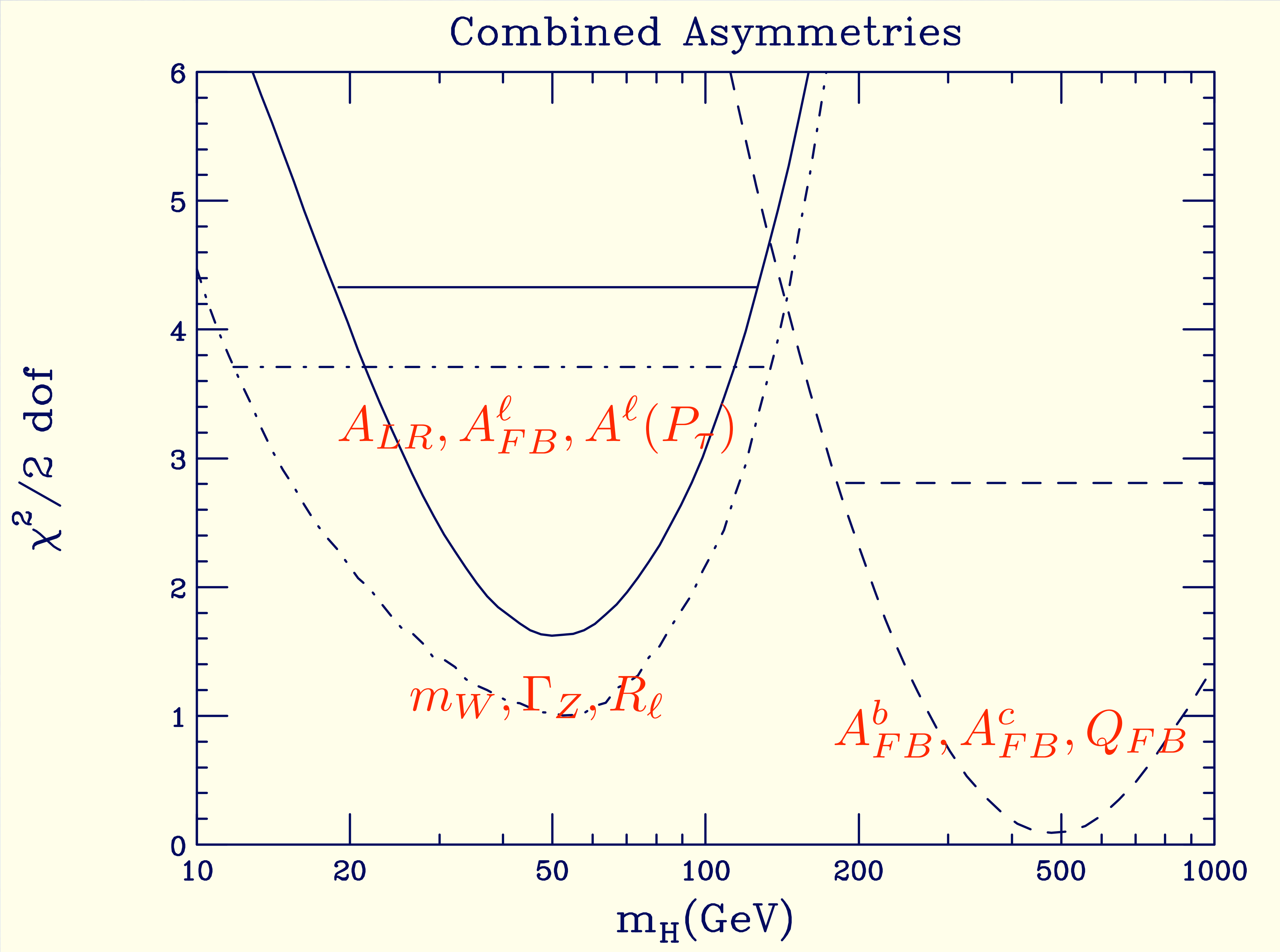
* LEP PEW overall fit prefers Higgs mass near 80 GeV w. 95% upper bound of about 160 GeV.
* LEP PEW data without hadronic asymmetries prefers Higgs mass of about 50 GeV and below 105 GeV at 95% CL.
* Tevatron W mass + top mass prefers quite light SM Higgs.
* **BUT!** LEP requires SM Higgs heavier than 114 GeV.



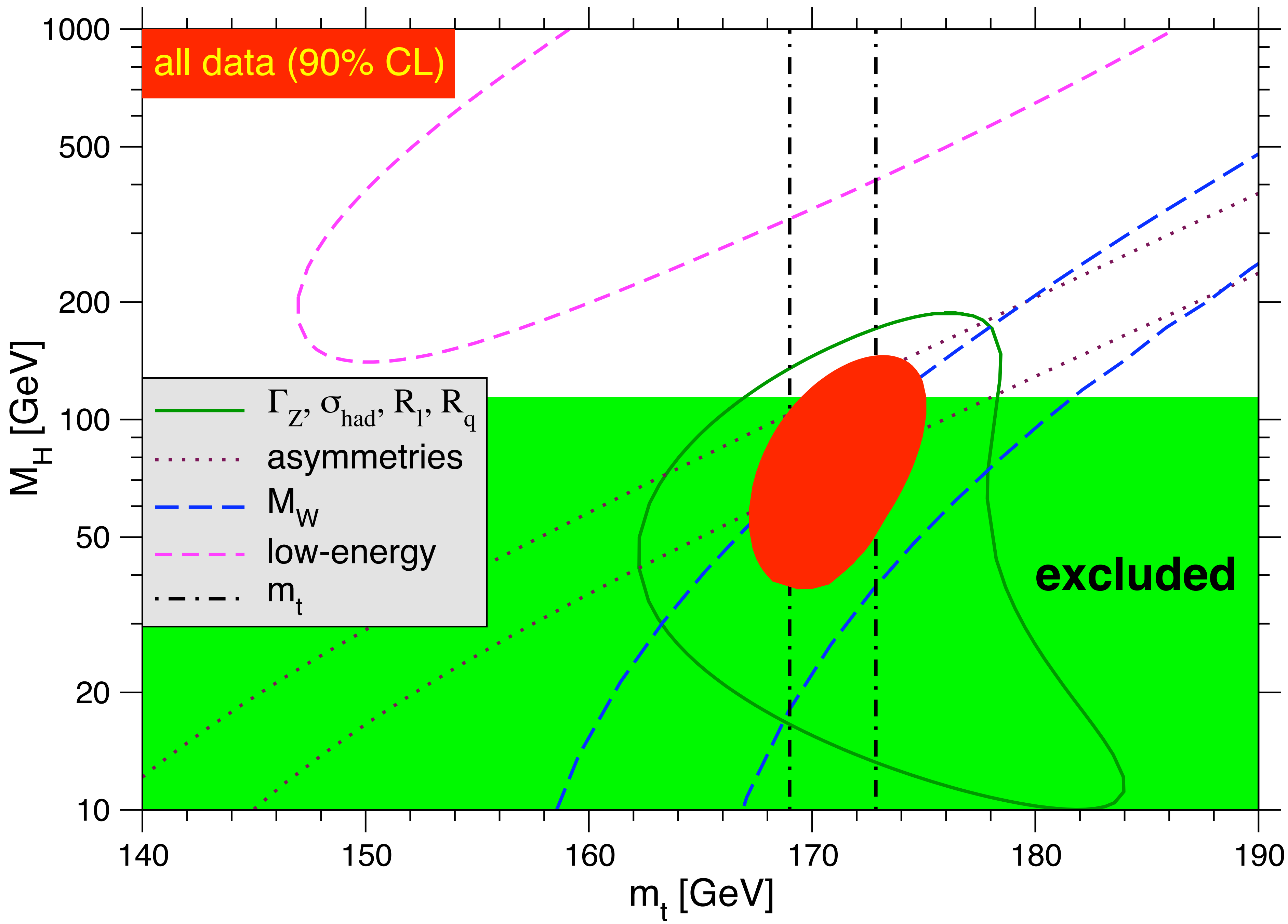
And, the Tevatron has excluded a range near $2m_W$



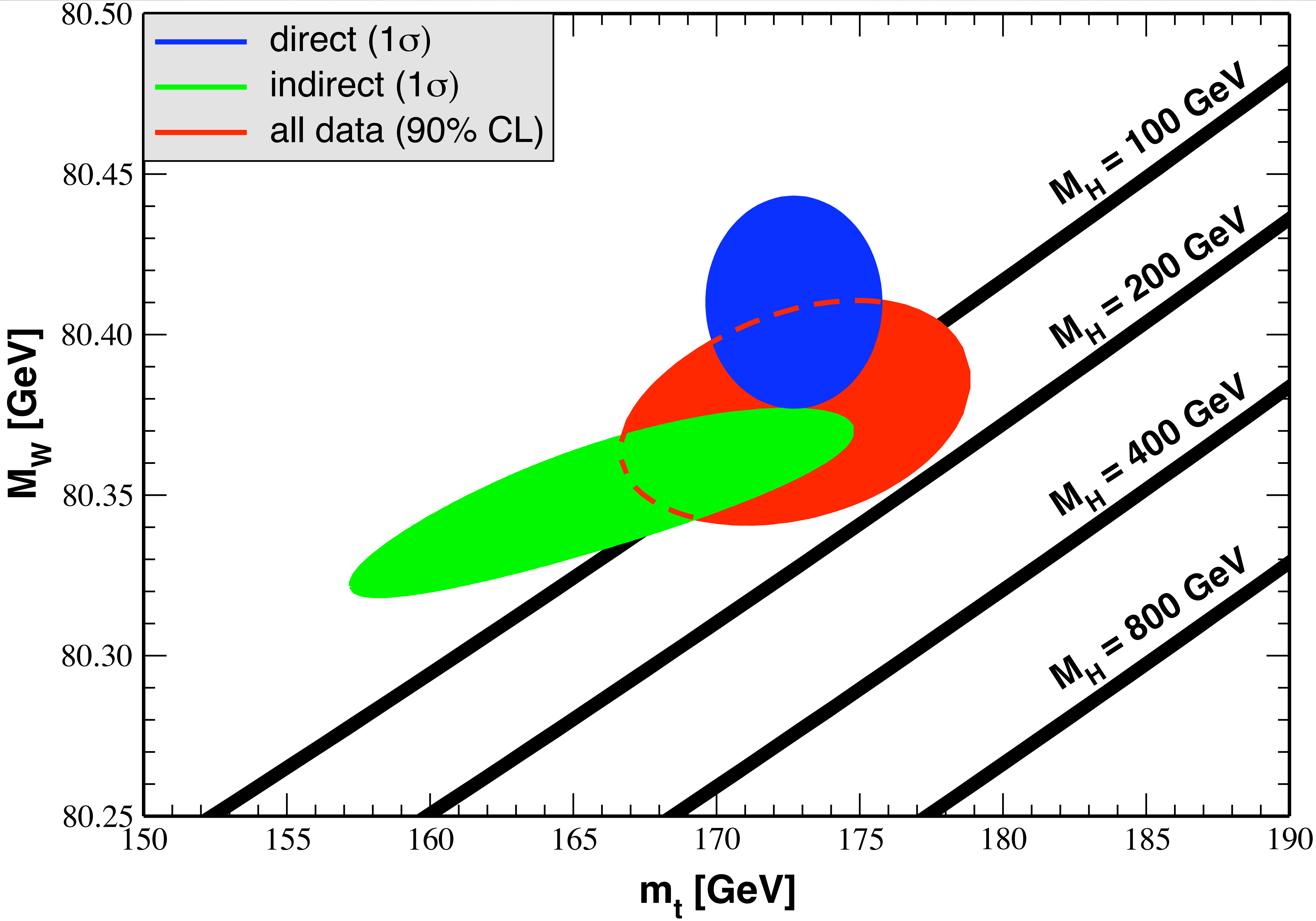
All LEP PEW data



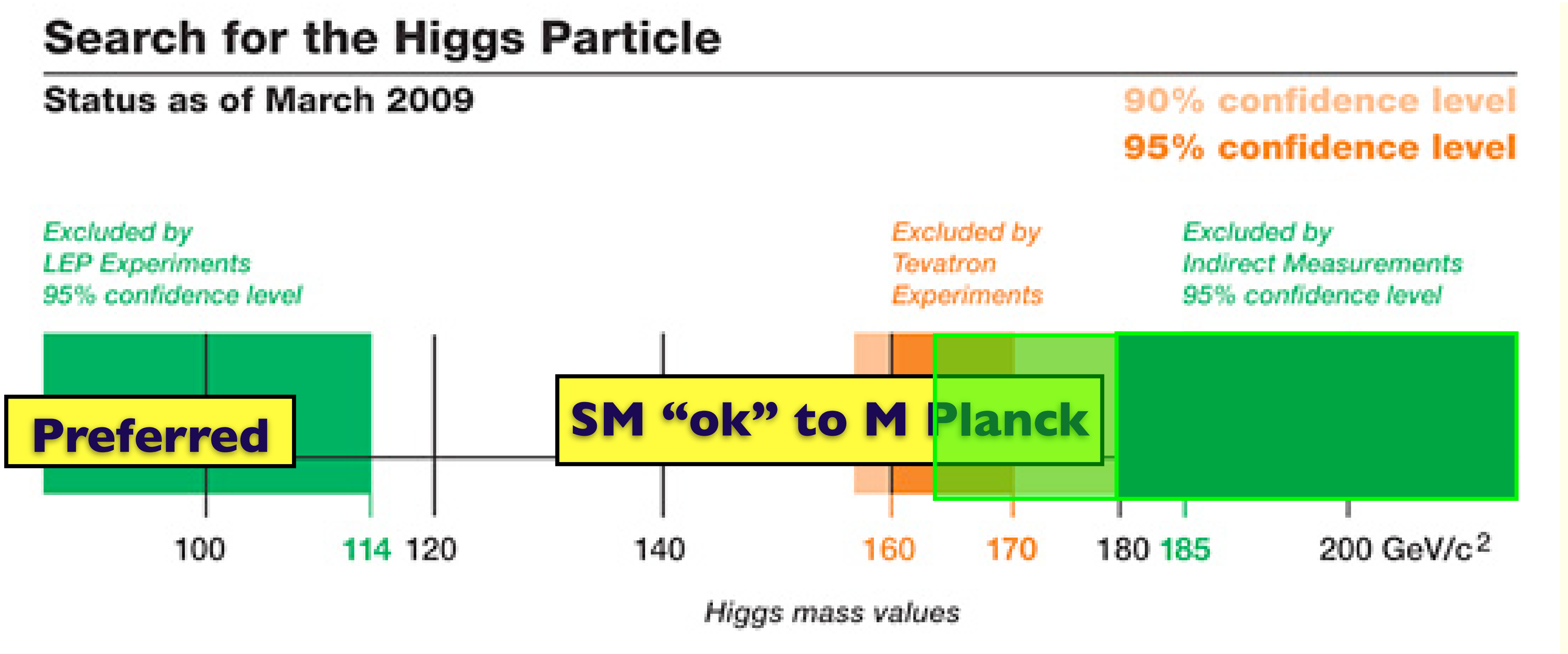
From Chanowitz.



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]



Λ^{SM}_{max}

✻ 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 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?			

The SM contains the seeds of its own “destruction”.

- 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 $130 \lesssim m_{h_{\rm SM}} \lesssim 180~{\rm GeV}$.

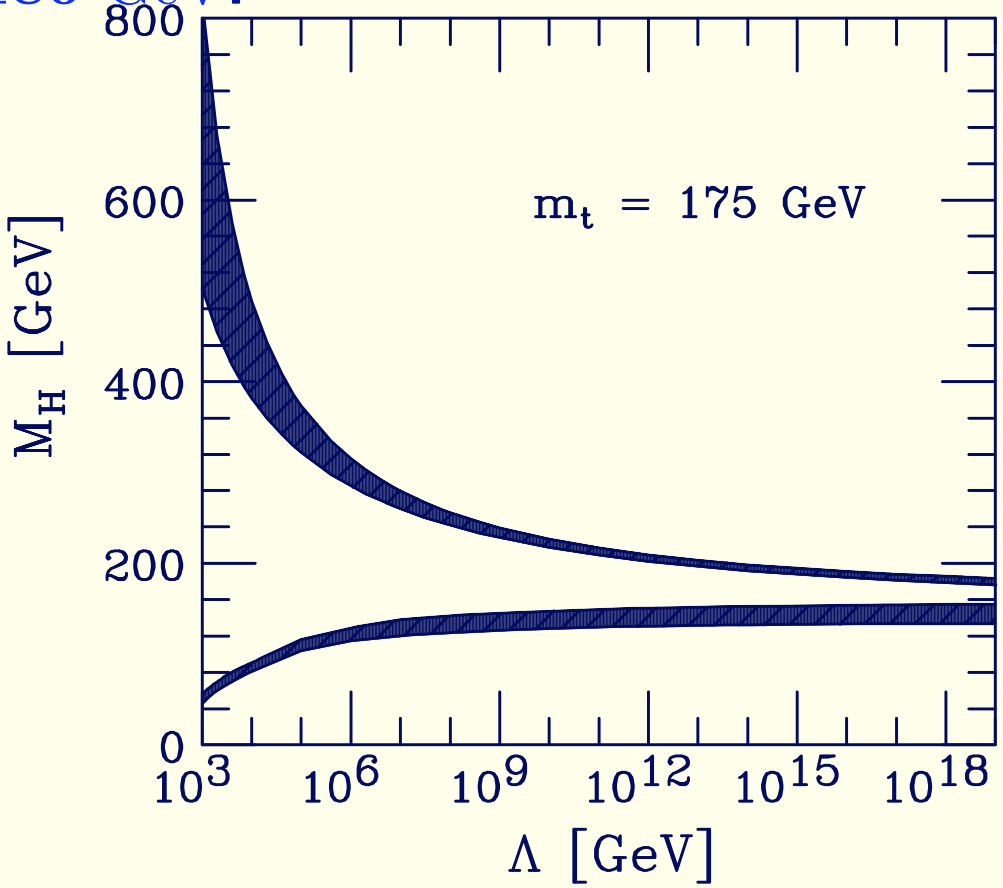


Figure 1: Triviality and global minimum constraints on $m_{h_{\rm SM}}$ vs. Λ.

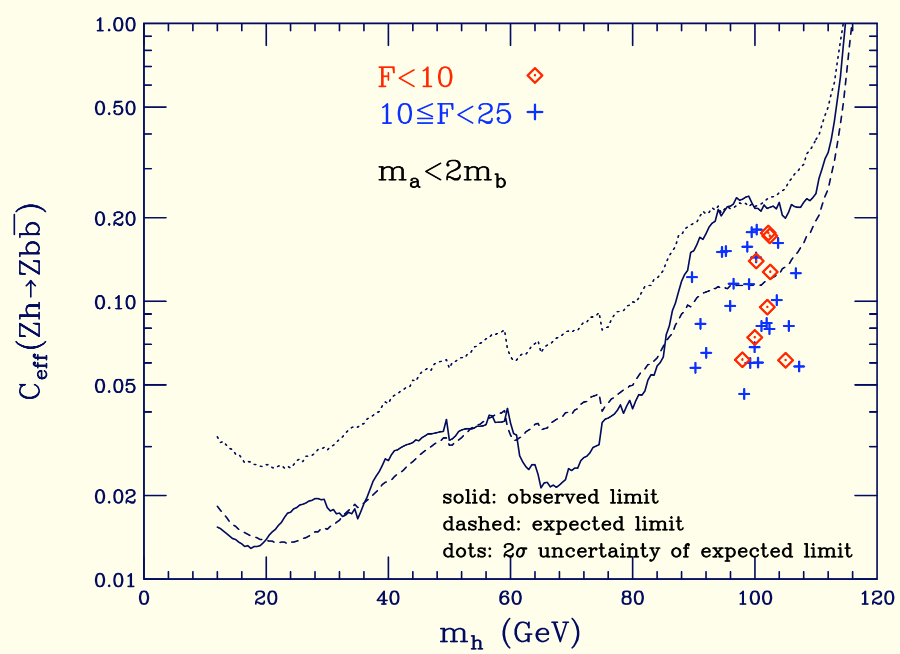
One generic way of having a low LEP limit on m_H is to suppress the $H \to b\bar{b}$ branching ratio by having a light a (or h)with $B(H \to aa) > 0.7$ and $m_a < 2m_b$ (in order to avoid LEP $Z + 4b$ limit at $110~\mathrm{GeV}$, i.e. above ideal). $a \to \tau^+\tau^-$ for $m_a > 2m_\tau$ or jj for $m_a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

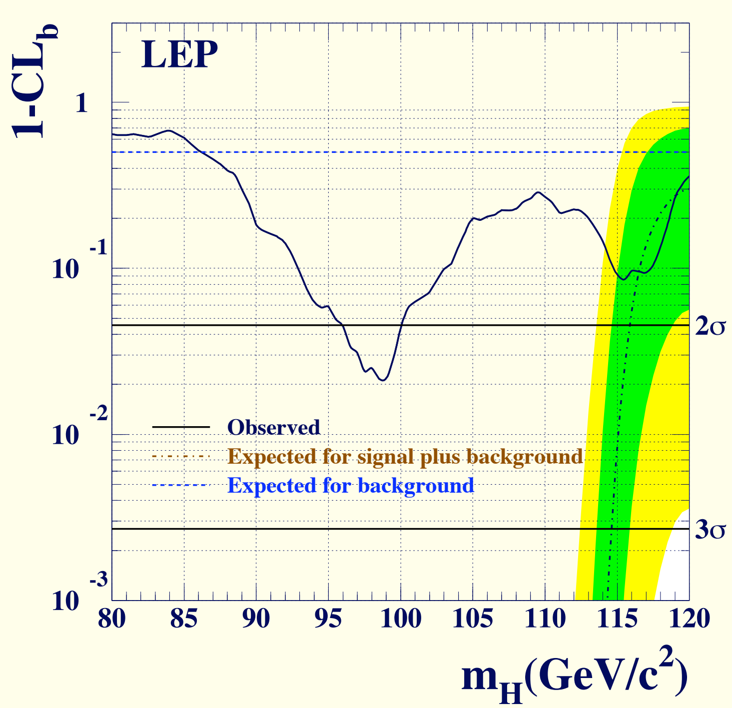
See: (R. Dermisek and J. F. Gunion, Phys. Rev. Lett. 95, 041801 (2005) [arXiv:hep-ph/0502105]; R. Dermisek and J. F. Gunion, Phys. Rev. D 73, 111701 (2006) [arXiv:hep-ph/0510322])

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

An attractive possibility is that $m_H \sim 100$ GeV and $BR(H \to b\bar{b}) \sim 0.1$.

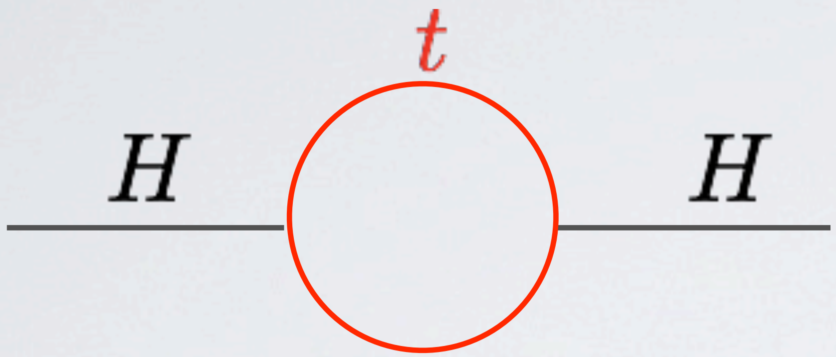
This would explain the most significant LEP excess (2.3σ).





The 2nd major implication of Quantum Loops: the Hierarchy Problem

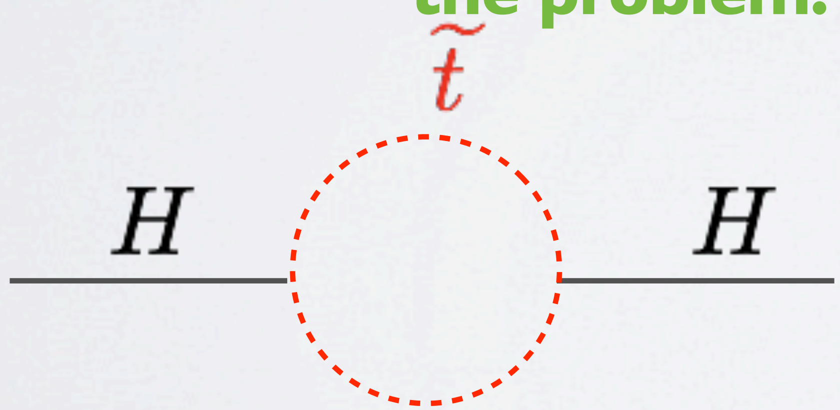
The Higgs mass itself acquires a large loop correction from the top quark loop.



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

We need a light Higgs for unitarity and for PEW, but if the cutoff is large this requires extreme cancellation between the loop and tree-level terms.

Supersymmetry is the only theory that provides a solution *and* that could potentially be consistent (no high-scale completion required) all the way to the GUT scale. It provides a spin-0 stop whose loop cancels the problem. (fermi-statistics)



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

So long as $m_{\tilde{t}}$ is not above 1 TeV, cancellation of the quadratics is not too highly tuned.

In the minimal supersymmetric model (MSSM) there is a partner for every SM particle (1/2 unit of spin different) and two Higgs fields.

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

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

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

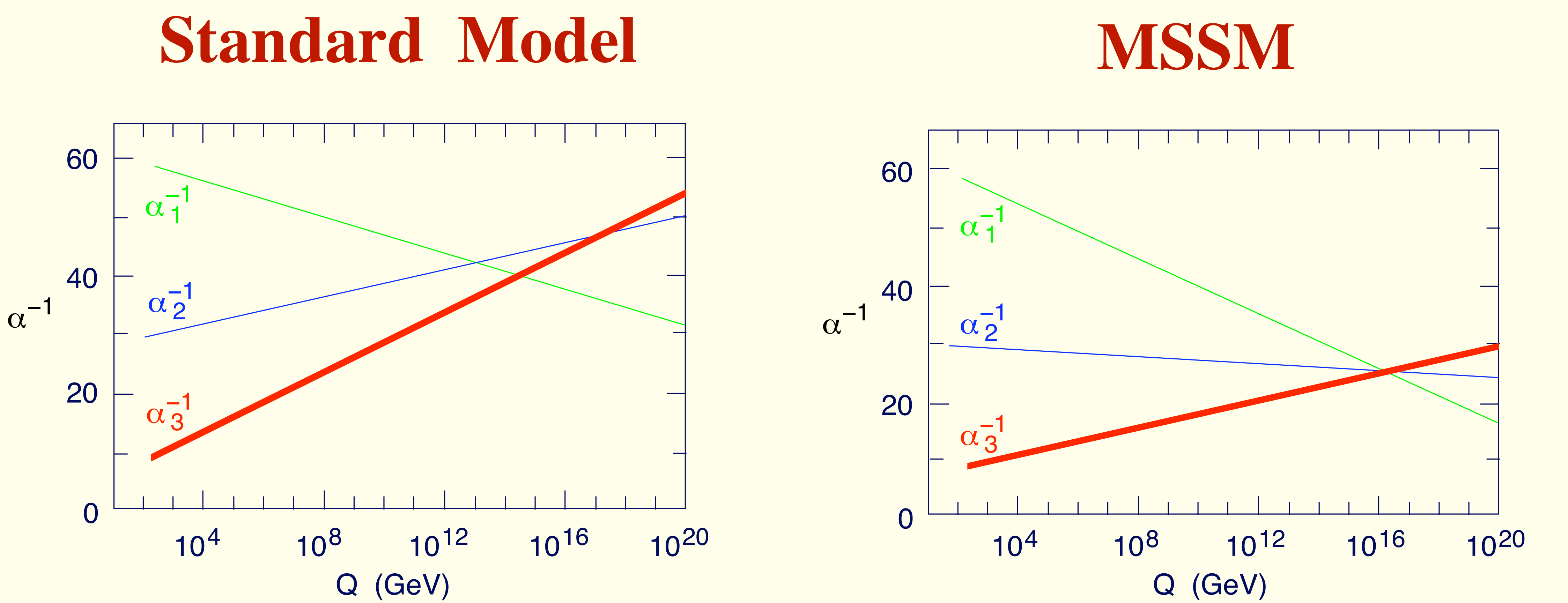


Figure 4: Unification of couplings constants ($\alpha_i = g_i^2/(4\pi)$) in the minimal supersymmetric model (MSSM) as compared to failure without supersymmetry.

2. RGE EWSB

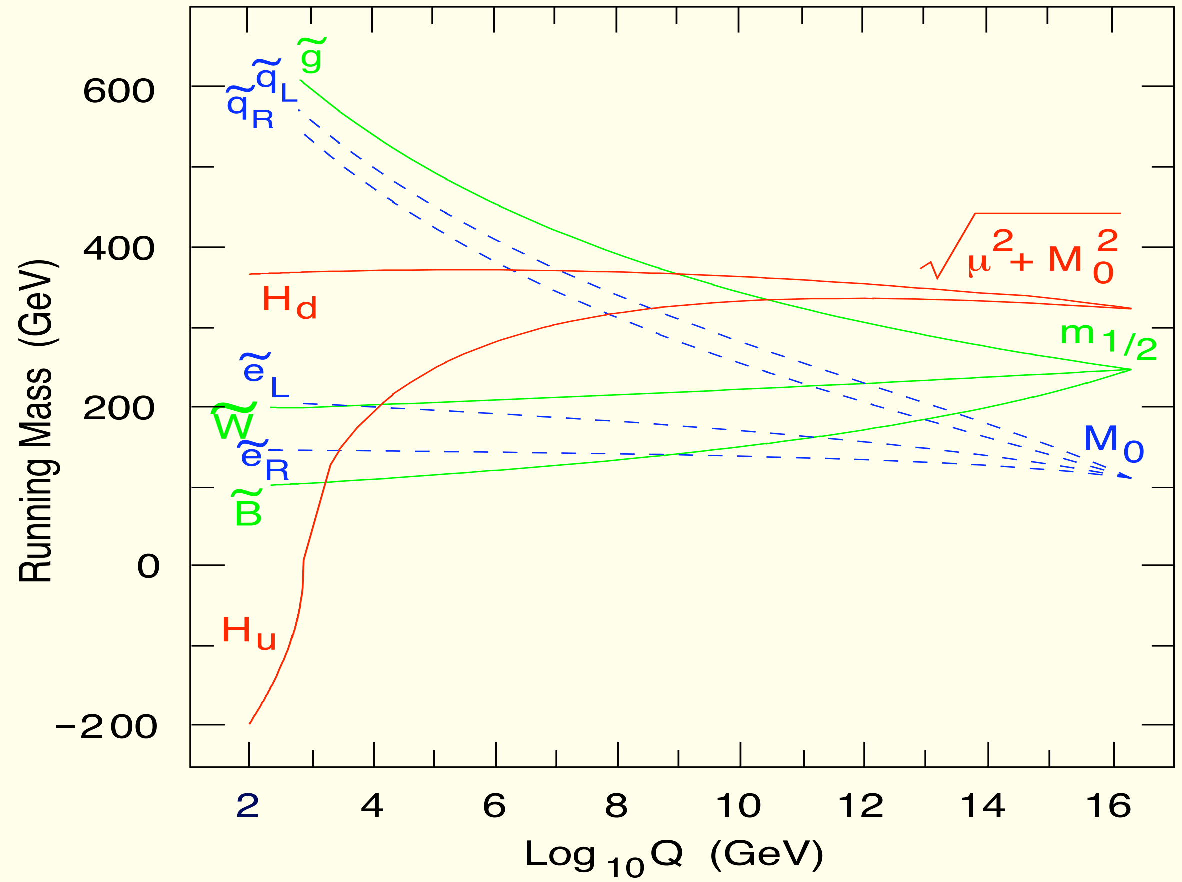


Figure 5: Evolution of the (soft) SUSY-breaking masses or masses-squared, showing how $m^2_{H_u}$ is driven < 0 at low $Q \sim \mathcal{O}(m_Z)$.

Recall that a negative tree-level mass is needed to have symmetry breaking in the vacuum leading to <H> = non-zero. In SUSY, this is almost automatic.

NB: the scale evolution depicted in the above plots is also due to the fact that constants are not constants in QFT --- they depend on the scale of measurement due to loop corrections.

In fact, the MSSM not only solves the hierarchy problem, but also *predicts* that the H is below 110 GeV when the stop is below about 400 GeV.

Not only does this work perfectly for PEW constraints, but also such a light stop solves the "electroweak" fine-tuning problem.

The degree of electroweak fine-tuning, F, specifies how precisely the GUT scale parameters must be tuned in order to get the observed value of the Z mass.

F<10 (no worse than10% tuning) is desirable, and is obtained provided the stop has mass < 400 GeV.

The problem: the light Higgs of the MSSM decays like the SM Higgs and is basically excluded for $m_h < 114$ GeV. This $\Rightarrow$ that $m_{\widetilde{t}} > 800$ GeV, which in turn $\Rightarrow F > 50$ or so = 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.

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

The required properties of the *a* are natural in the NMSSM. In particular, there is a symmetry 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.

The NMSSM yields (like the MSSM) gauge coupling unification and "radiative" electroweak symmetry breaking.

Other unusual decays that would have escaped LEP limits are also possible in SUSY, including the MSSM. Interesting possibilities are:

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

and

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

(Maybe LEP limits for the latter could be obtained that would be near 114 GeV, but there is no explicit limit at the moment.)

Note: we stick to R-parity conserving SUSY so that there will be a dark matter candidate. There are many SUSY models with unusual higgs decays related to R-parity violation and similar.

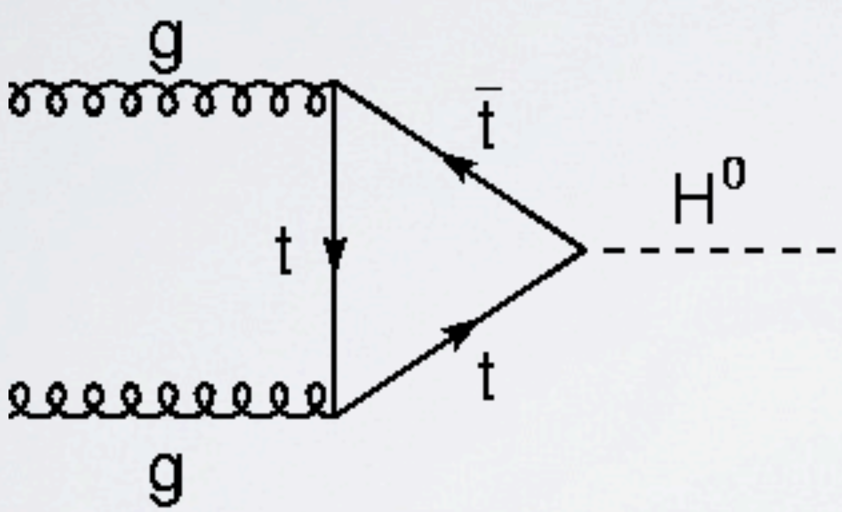
There are also many BSM approaches in which the electroweak Higgs decays invisibly.

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.

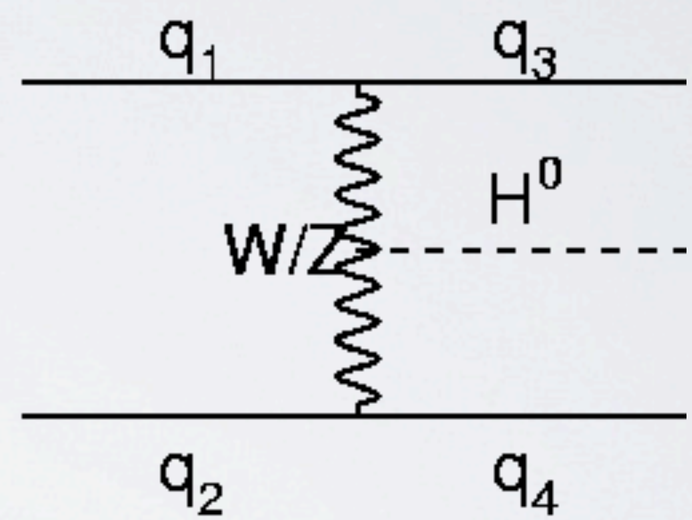
A problem is that a Higgs boson with unusual decays is probably even harder to detect than the SM H in pp collisions at the LHC.

First, since H couples proportional to mass and the colliding quarks inside the protons have very small masses, one must employ "higher order" production mechanisms such as

$qq \to q'q'W^+W^- \to q'q'H$

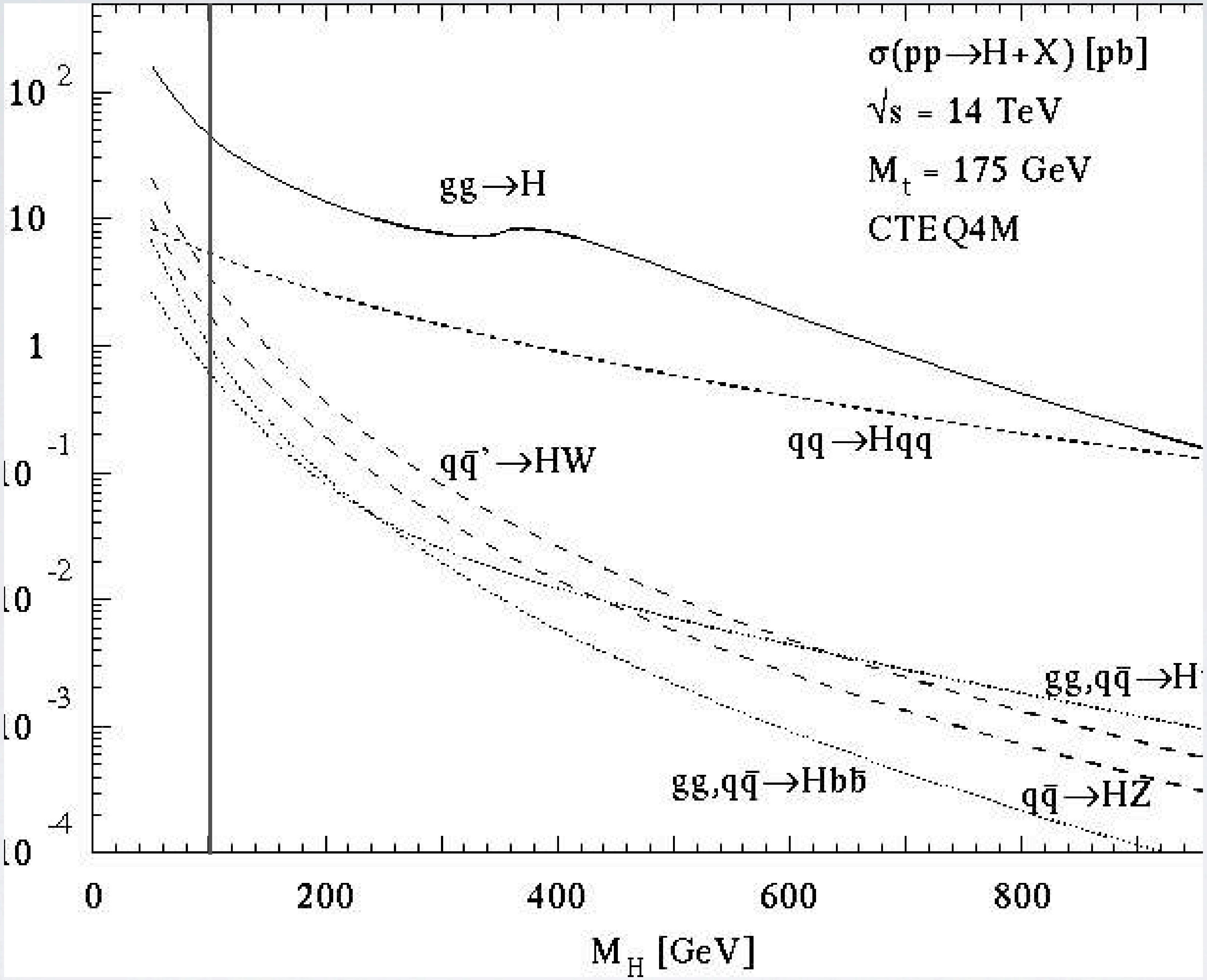


$qq \to q'q'W^+W^- \to q'q'H$



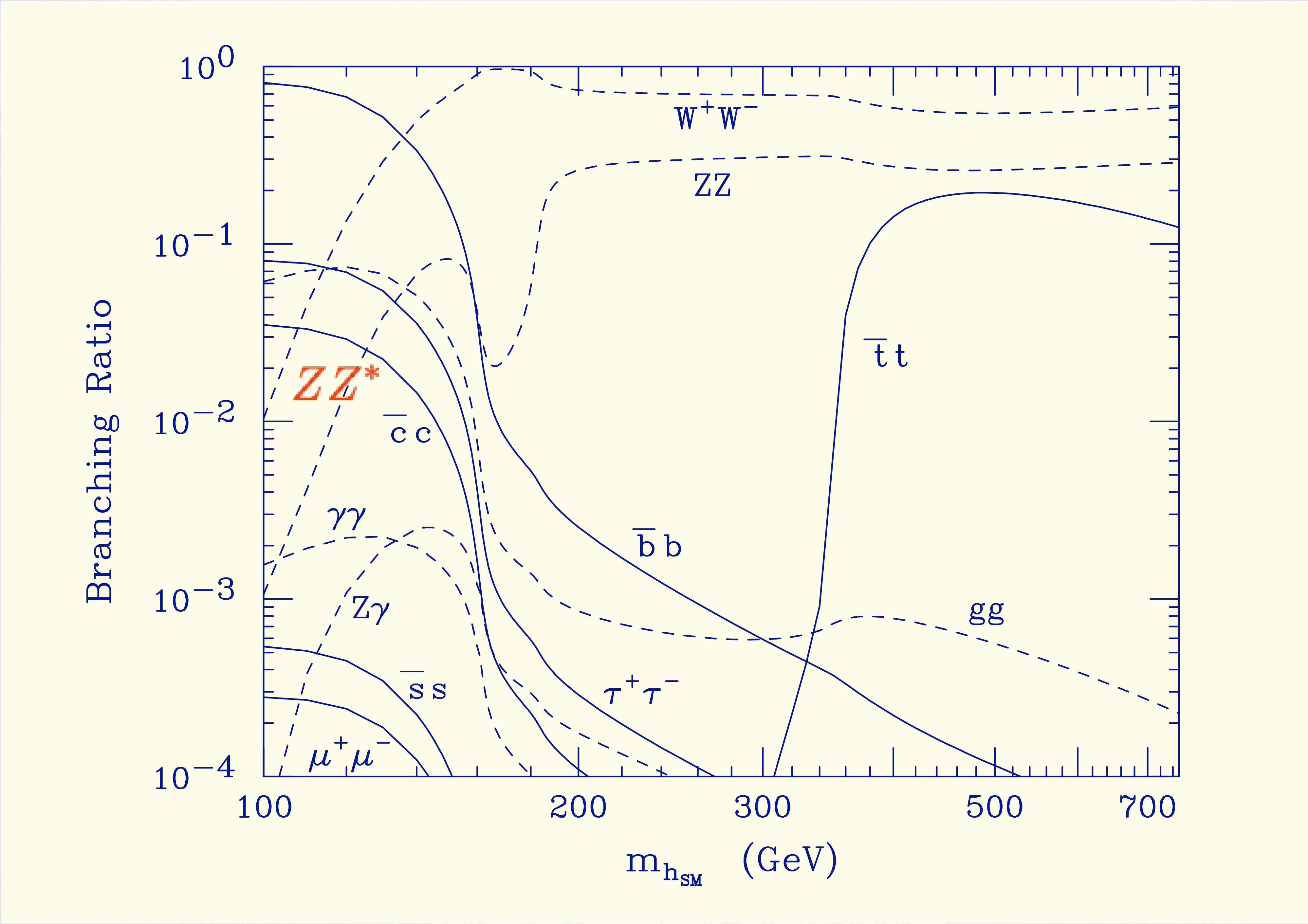
The resulting cross sections are ok given L=30 fb-1, but the H events are still relatively rare and must be extracted from the much higher frequency events related to the strong interactions.

For $m_H = 100$ GeV, we expect ~ 40000 $gg \to H$ events and ~ 6000 $qq \to q'q'WW \to q'q'H$ events per $L = fb^{-1}$.



However, what will the Higgs "look like"?

In the Standard Model, since the Higgs couples according to mass its decay widths will be proportional to mass-squared, *assuming decay not forbidden or suppressed by kinematics. A light Higgs is particularly tricky; basically the two-photon channel is the only possibly detectable final state for a SM Higgs below 100 GeV.*

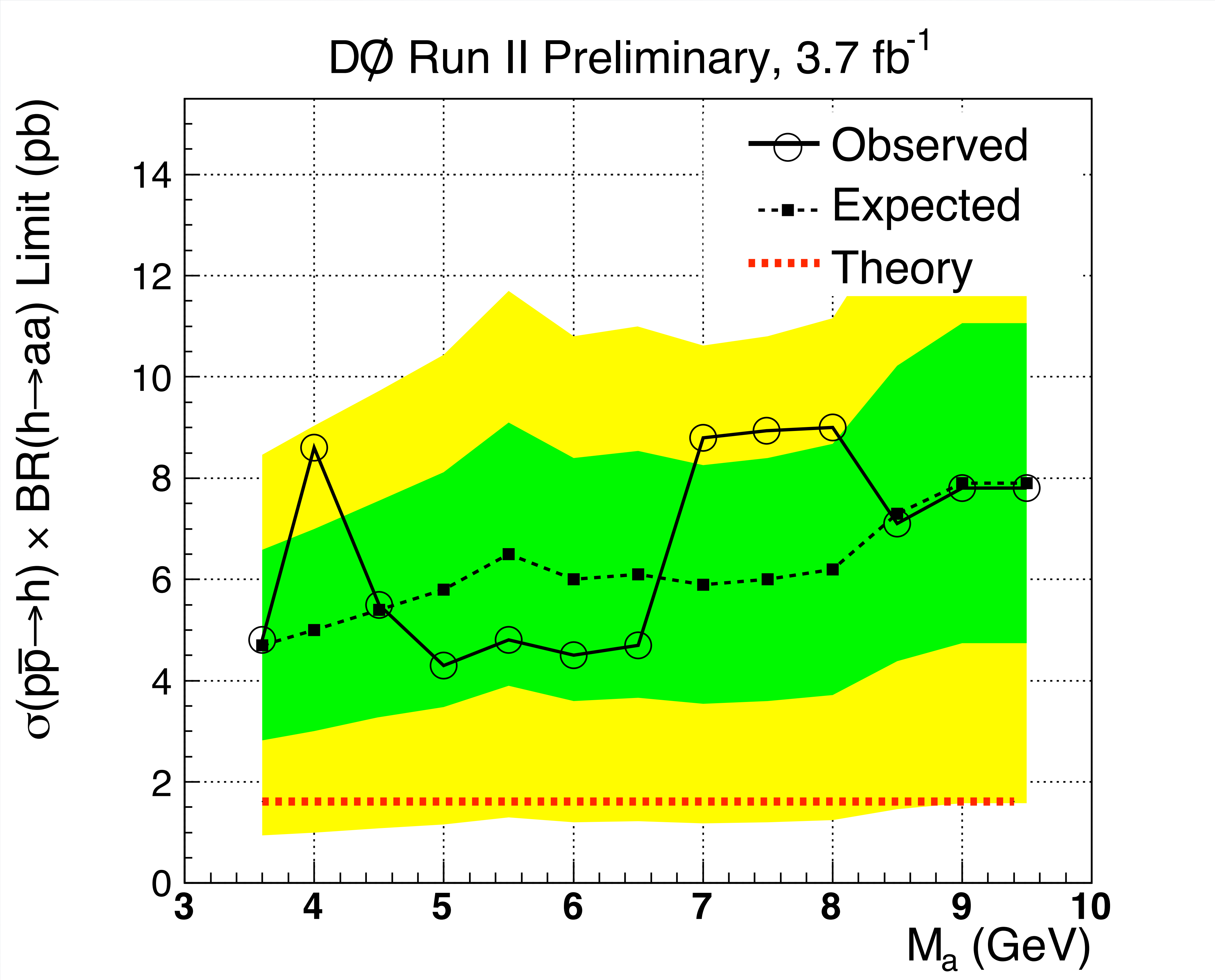


And, we have strong motivation for the possibility that the Higgs that couples to mass (there are typically others that don't in SUSY, ...) will not "look like" (i.e. decay like) it would in the simple SM.

If the NMSSM scenario is correct, the best approaches appear to be:
$$gg \to h \to aa \to \mu^+\mu^- + \tau^+\tau^-,$$
taking advantage of the small but non-negligible $BR(a \to \mu^+\mu^-) \sim 3 \times 10^{-3}$, and possibly
$$WW \to h \to \tau^+\tau^- + \tau^+\tau^-$$
taking advantage of the facts that you can tag the event using the spectator q's and that aside from this the event should be "quiet" aside from very low multiplicity τ decays — collinearity for decay products from each a also helps.

A Tevatron analysis of the former (Haas et.al.) indicates sensitivity to the former for 40 fb-1. Currently (L=4 fb-1) D0 observes a tiny excess (1 sigma) over expected background. The LHC (theorist-level) estimates of Wacker et.al. suggest good sensitivity after a few years of running.

WW fusion to an *h* decaying to *aa* becomes interesting at the LHC. Sensitivity analyzes are ongoing.


DØ Run II Preliminary, 3.7 fb^{-1}
Observed
Expected
Theory
σ(pp̄→h) × BR(h→aa) Limit (pb)
0
2
4
6
8
10
12
14
3
4
5
6
7
8
9
10
M_a (GeV)

A final possibility is diffractive Higgs production $pp \to pph$ with $h \to aa \to \tau^+\tau^- + \tau^+\tau^-$ for which m_h can be reconstructed using the final tagged (FP420) protons — resolution for m_h of order 2 GeV is predicted. The problem is that the rate is quite low and at least $L = 100\ fb^{-1}$ will be needed (JFG, Forshaw, Pilkington et.al.). Events are isolated by requiring a small number of central tracks.

The diffractive technique is the proton collider equivalent of the linear collider process $e^+e^- \to Z^* \to Zh$ with $Z \to e^+e^-$ or $\mu^+\mu^-$. There, one uses the measured Z momentum in conjunction with the known initial energy to determine the missing mass of X in the $Z + X$ final state and looks for a peak in m_X. Such a peak will be very prominent regardless of how the h decays.

A relatively low energy (300 GeV e.g.) linear collider would be the ultimate tool for exploring in detail the properties of a light Higgs boson of the mass preferred by PEW, fine-tuning .....

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

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

- The extracted $C_{ab\overline{b}}$ limits (JFG, arXiv:0808.2509; see also Ellwanger and Domingo) are quite model-independent. The extracted limits on $C_{ab\overline{b}}$ appear in Fig. 5,
- The most unconstrained region is that with $m_a > 8~\mathrm{GeV}$, especially $9~\mathrm{GeV} < m_a < 12~\mathrm{GeV}$. = region with least "light-a_1" tuning in NMSSM.
- Except for this region, a further factor of 3 improvement to $C_{ab\overline{b}} < 0.3$ would start to rule out or observe the $a = a_1$ of the most favored NMSSM scenarios.

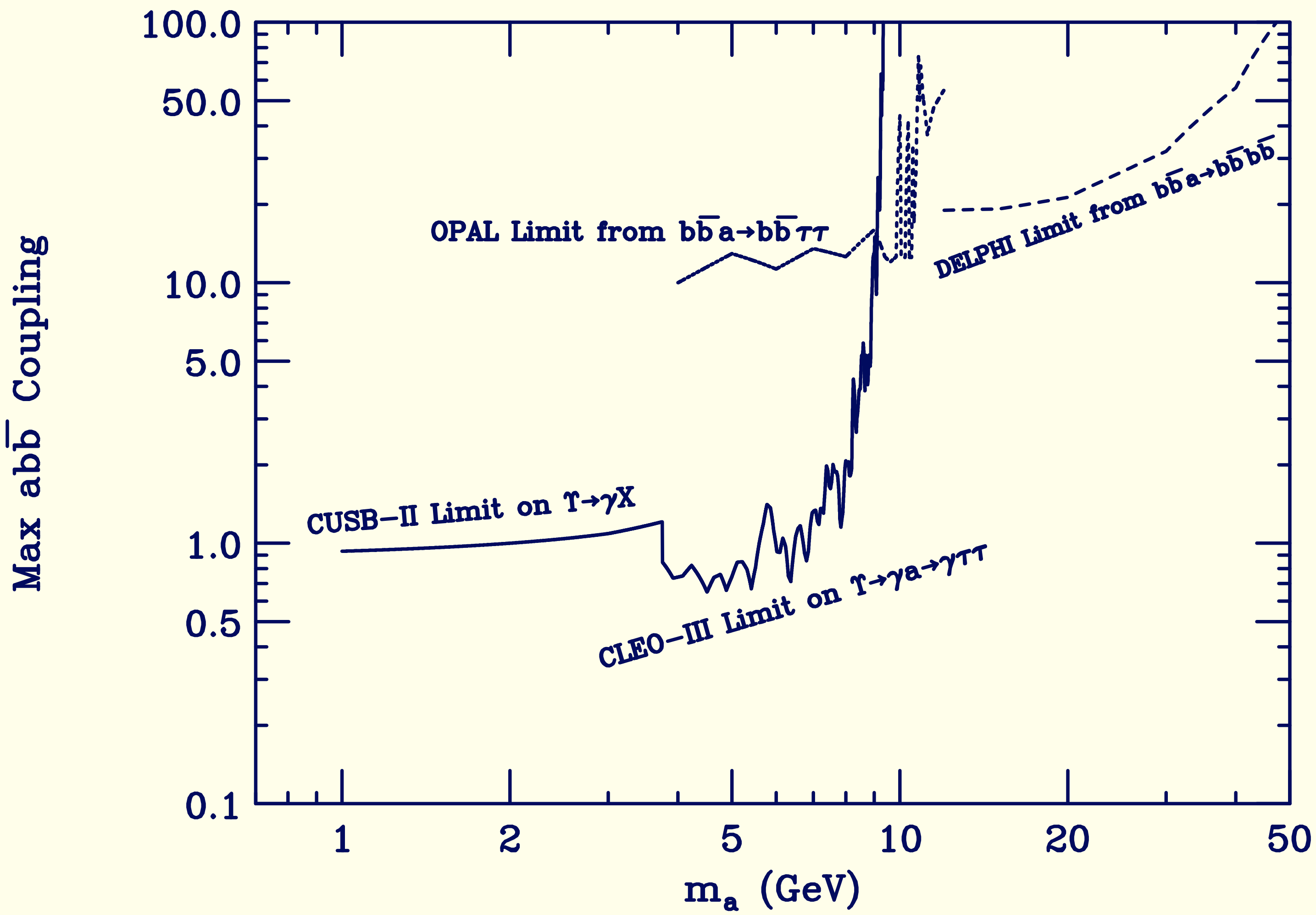


Figure 5: Limits on $C_{ab\bar{b}}$.

- **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.

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.
- 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 Higgs bosons delays the quadratic hierarchy problem to higher scales.
- Detection of such a continuum of Higgs at the LHC would be really hard!

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).