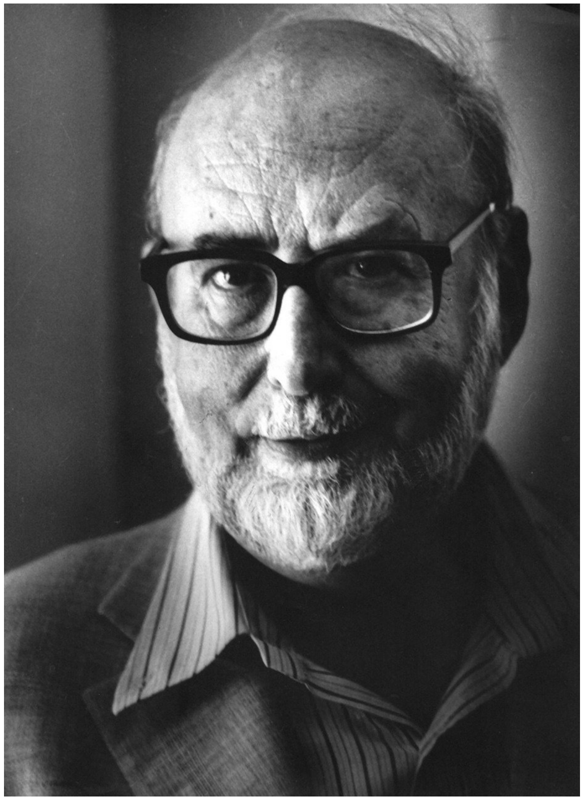
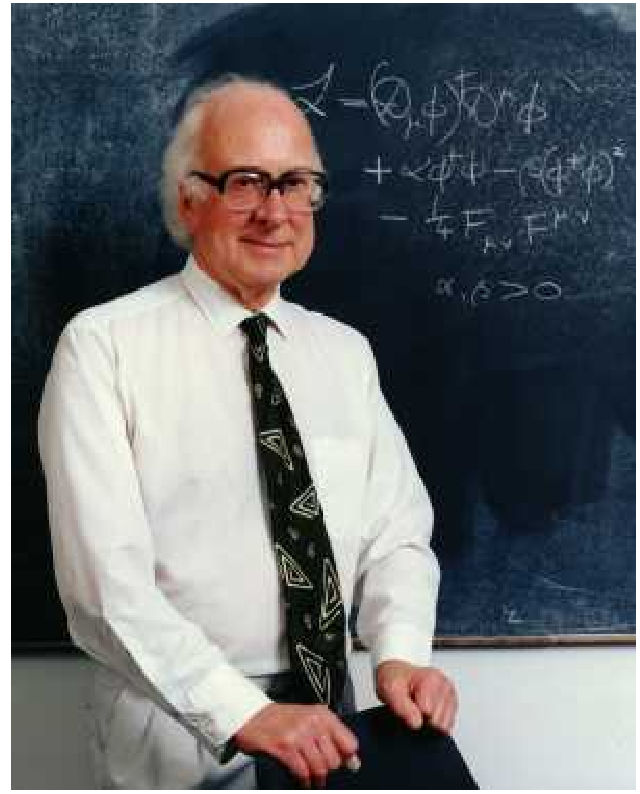
The Hunt for the





Boson

Jack Gunion
U.C. Davis

Scalars13, September 13, 2013

It's a great pleasure to see so many former/current collaborators and to return to

A brief history

The Higgs boson has been a primary focus, not to mention primary occupation, for many of us for many years.

The Higgs field and mechanism was originally postulated back in 1964 by BEH as well as Guralnik, Hagan and Kibble.

Important preceding work included that by Anderson who discussed spontaneous symmetry breaking in the context of solid state physics and showed how mass could arise in a theory with symmetries that appeared to forbid it. Nambu also had the basic idea in the particle physics context.

In 1967, Weinberg and Salam independently worked out the details in the context of the Standard Model.

In 1971-1972 'T Hooft and Veltman proved that renormalization of Yang-Mills was possible 1st for massless fields and in a 2nd paper for massive fields.

Around this same time, Ben Lee played a crucial role in "popularizing" the model and interest then exploded. It is a shame he is not around to see its fruition.

Still there was a lot of doubt. For example, in a 1974 RMP paper the comment was made that **"while no one doubted the mathematical correctness of these arguments, no one quite believed that nature was diabolically clever enough to take advantage of them."**

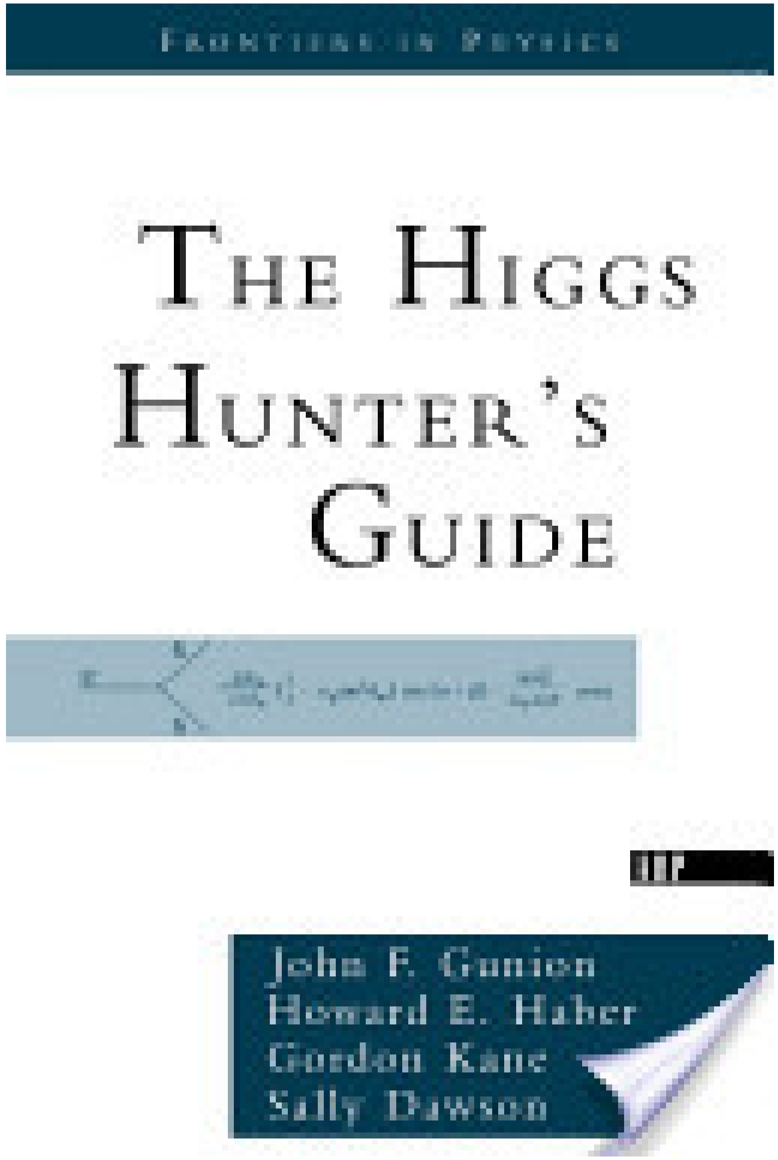
Of course, **Higgs field + QFT** $\Rightarrow$ **Higgs particle**.

The hunt for the Higgs was on!

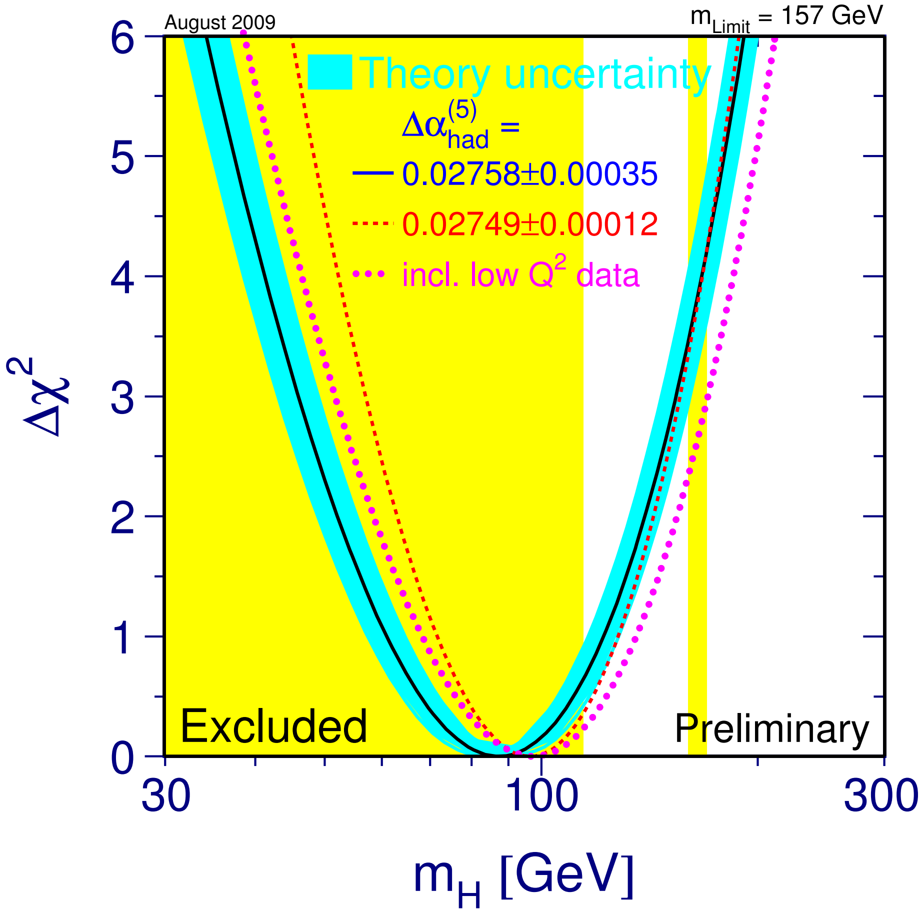
For me, the Higgs became a fascinating object and around 1984 I refocused my research in the direction of how to see it. I also immediately questioned whether the full story could really be as simple as envisioned in the SM.

In particular, the attractiveness of supersymmetry and especially of the MSSM seemed to make a multiple Higgs vision inevitable.

This inspired "Higgs Bosons in Supersymmetric Models. 1." J.F. Gunion, Howard E. Haber, Aug 1984. Nucl.Phys. B272 (1986) 1, which in turn led to

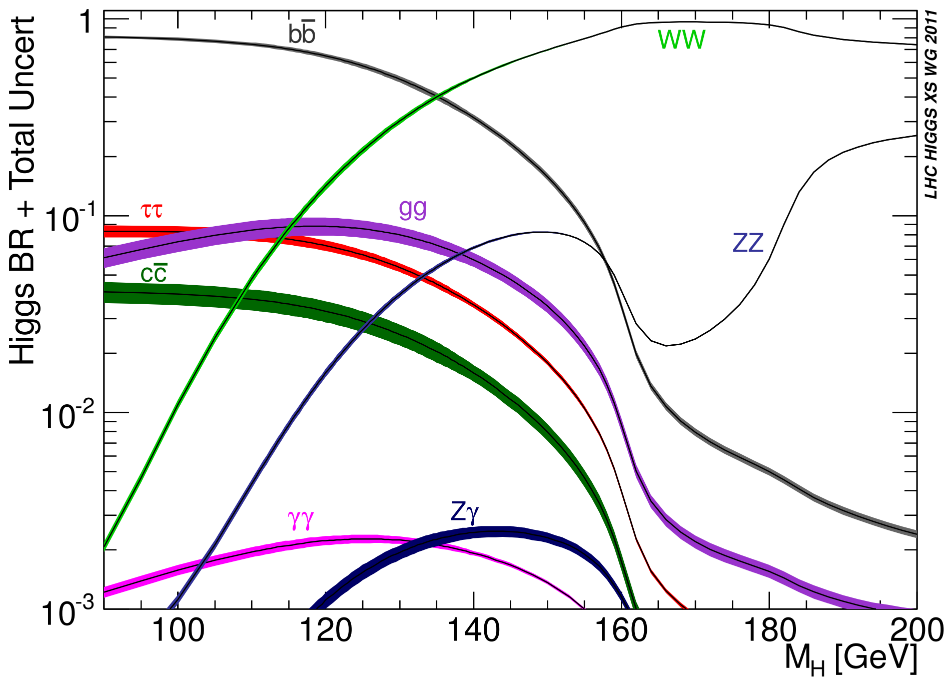

FRONTIERS IN PHYSICS
THE HIGGS HUNTER'S GUIDE
John F. Gunion
Howard E. Haber
Gordon Kane
Sally Dawson

Many accelerators came and went without discovering the Higgs boson, but LEP was particularly influential because of the precision electroweak measurements which can be summarized by the famous "blue band" plot.



Without other new physics, the Higgs prefers to be rather light and very possibly low enough in mass for LEP to discover it. But, LEP didn't find it.

The decay modes for a light SM Higgs were well known by this time $\Rightarrow$ main decay mode should be $b\bar{b}$, but many others also present. At LEP, the main production mode was $e^+e^- \to Z^* \to ZH$ and detection in the $Zb\bar{b}$ final state would have been easy.



Still, various new physics escapes were possible, in particular NP that gives a large ΔT can allow for a much heavier Higgs to be consistent with the 95% CL ellipse in the ΔS–ΔT plane. This could potentially have put the Higgs out of reach of a $500~\mathrm{GeV}$, or even $800~\mathrm{GeV}$ ILC. A plot in a 2HDM with small $m_{H^\pm} - m_H \sim few \quad \mathrm{GeV}$ is

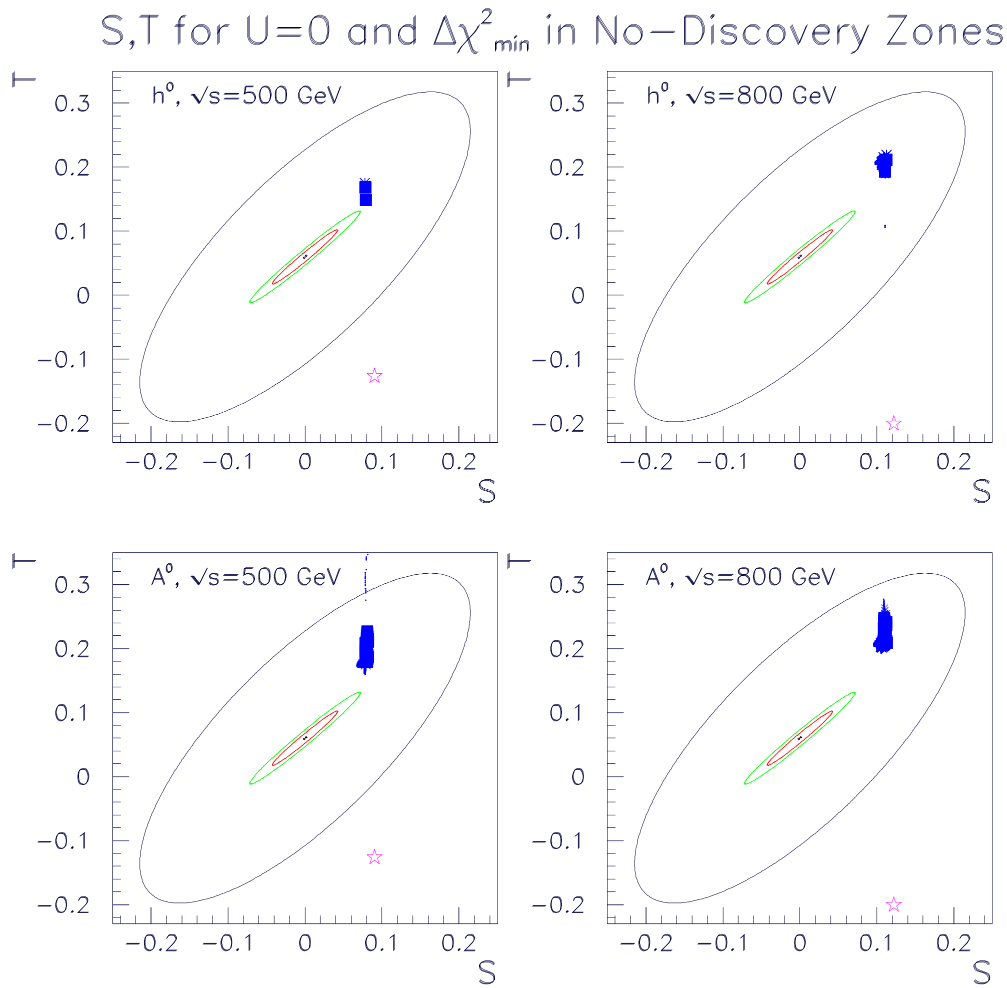
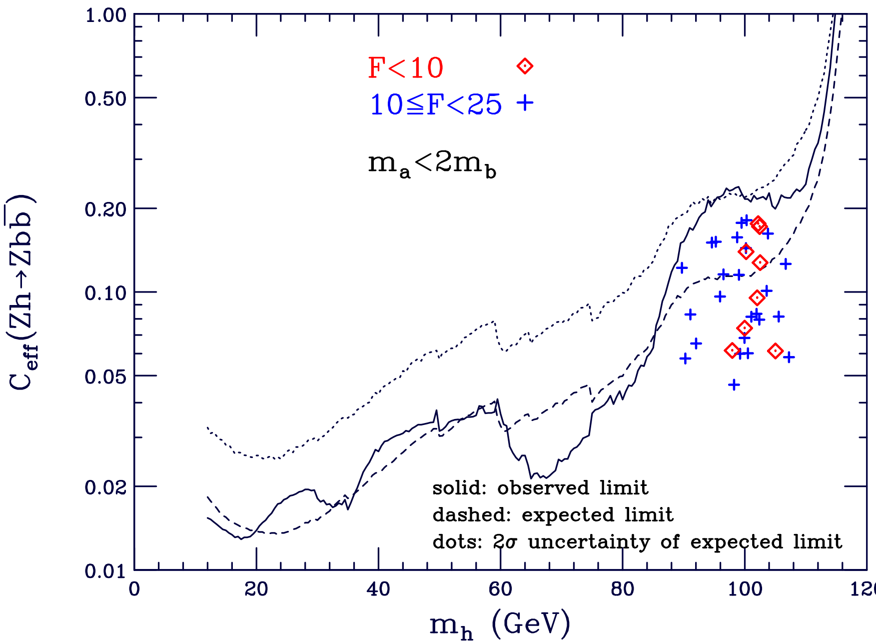


Figure 1: Chankowski, Farris, Grzadkowski, Gunion, Kalinowski Krawczyk, a special case of Peskin-Wells. Star shows result for $m_h = 500$ or $800~\mathrm{GeV}$ with $\Delta T_{NP} = 0$.

In fact, LEP found 20% of a Higgs boson at a mass of about $98\ \mathrm{GeV}$ (2σ).



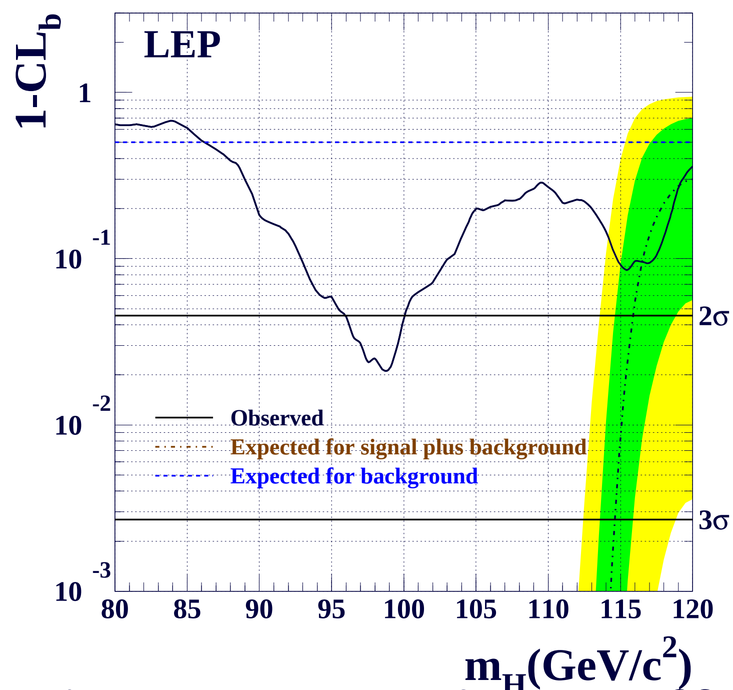


Figure 2: Plots for the $Zb\bar{b}$ final state. F is the m_Z-fine-tuning measure for the NMSSM.

At the time, it was fashionable to find excuses for not seeing the "main" Higgs boson (i.e. the one really responsible for the W and Z masses). One such excuse was dominance of the NMSSM decay mode $h_1 \to a_1 a_1$. Now we know that nature probably (more later) has not made use of this kind of decay.

Nonetheless, the NMSSM was and still is a very important model because of its ability to predict a Higgs mass as large as $125\ \mathrm{GeV}$ with much less fine-tuning as compared to the MSSM and as a prototype for the importance of singlet fields. This prompted my suggestion that we construct NMHDECAY (Ellwanger, Gunion, Hugonie) which has now morphed into NMSSMTools.

NMSSMTools

TOOLS FOR THE CALCULATION OF THE

HIGGS AND SPARTICLE SPECTRUM IN THE NMSSM:

NMHDECAY, NMSPEC and NMGMSB

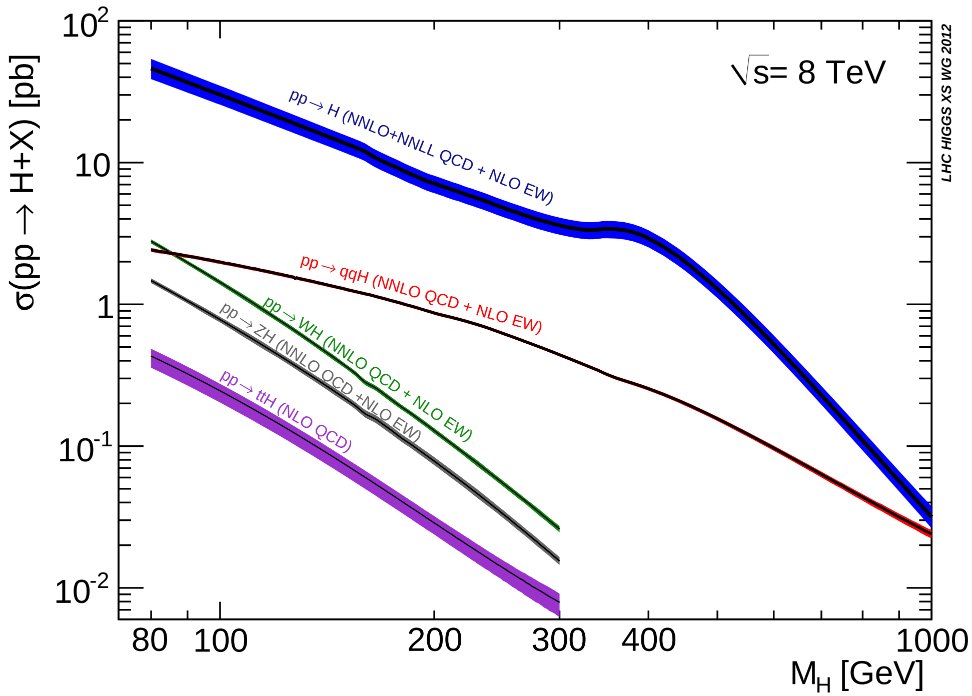
NMHDECAY

The Fortran code NMHDECAY computes the masses, couplings and decay widths of all Higgs bosons of the NMSSM, and the masses of all sparticles, in terms of its parameters at the electroweak (or susy breaking) scale: the Yukawa couplings lambda and kappa, the soft trilinear terms A_lambda and A_kappa, and tan(beta) and mu_eff = lambda*S. (Instead of A_lambda, the MSSM-like parameter M_A can also be used as input.) The computation of the Higgs spectrum includes leading electroweak corrections, two loop terms and propagator corrections. The computation of the decay widths is carried out as in HDECAY, but momentarily without three body decays. Each point in parameter space is checked against negative Higgs boson searches at LEP, and negative sparticle searches at LEP and the Tevatron, including unconventional channels relevant for the NMSSM. B physics constraints from b -> s gamma, Delta M_q, B -> mu+mu- and B+ -> tau+ nu_tau are included as in ref. [4] below. The dark matter relic density can be computed via a link to a NMSSM version of the MicrOMEGAs code [3]. SLHA conventions for input and output are used. NMHDECAY is part of the NMSSMTools package that can be downloaded below.

Authors: Ulrich Ellwanger*, John F. Gunion**, Cyril Hugonie*

Around the time of LEP the focus turned to hadron colliders.

The main production mechanisms were known.



Not long after LEP began operation (1989) the SSC was cancelled (1993) despite theoretical and simulation studies (initiated back in 1984 or so) showing that it could certainly discover the Higgs boson, whether heavy ($800~\mathrm{GeV}$) or as light as preferred by LEP. The latter was termed the "intermediate mass" region.

In the intermediate mass region, we realized that $H \to \gamma\gamma$ and $H \to ZZ \to 4\ell$ were going to critical — in these final states you can actually see the resonance peak.

The four key production and decay processes would then be:

$$\begin{array}{rl} gg \text{ fusion: ggF} & gg \to H \to \gamma\gamma; \quad gg \to H \to ZZ \to 4\ell \\ WW, ZZ \text{ fusion: VBF} & WW \to H \to \gamma\gamma; \quad WW \to H \to ZZ \to 4\ell\,, \end{array} \tag{1}$$

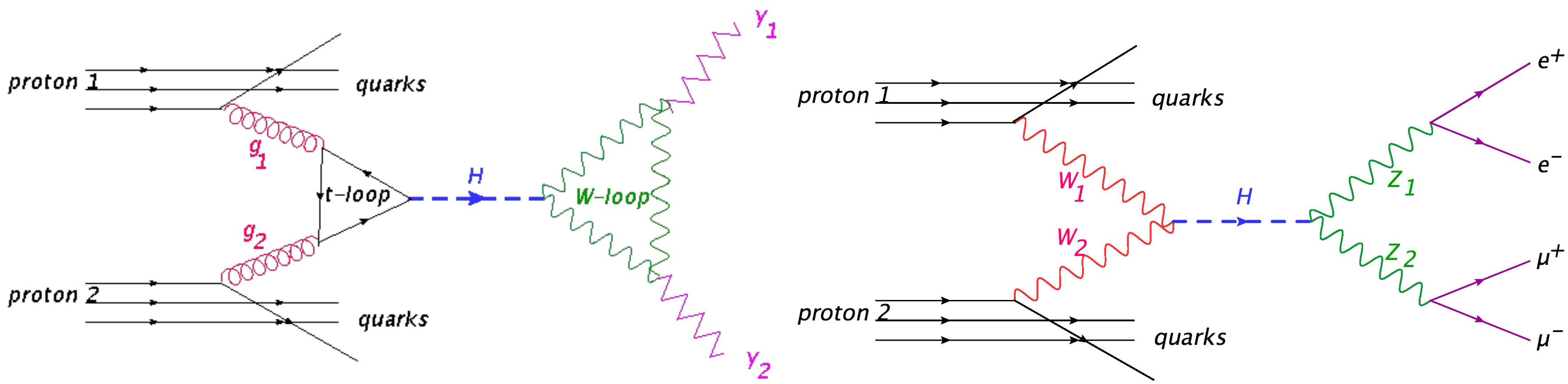


Figure 3: Sample diagrams. Note the loops for the gg and $\gamma\gamma$ couplings in the upper figure.

The latter, intermediate mass region fascinated many of us and I (with Soldate+Kalyniak and then Kane+Wudka) were the first (I think) to Monte Carlo signal and background in the $\gamma\gamma$ and 4ℓ final states and show that the SSC could indeed detect an intermediate mass Higgs boson. This was quickly confirmed by experimentalists (e.g. Albrow).

The 4ℓ mode was marginal much below $125~\mathrm{GeV}$, not because of background (which was very small) but because of low signal rate.

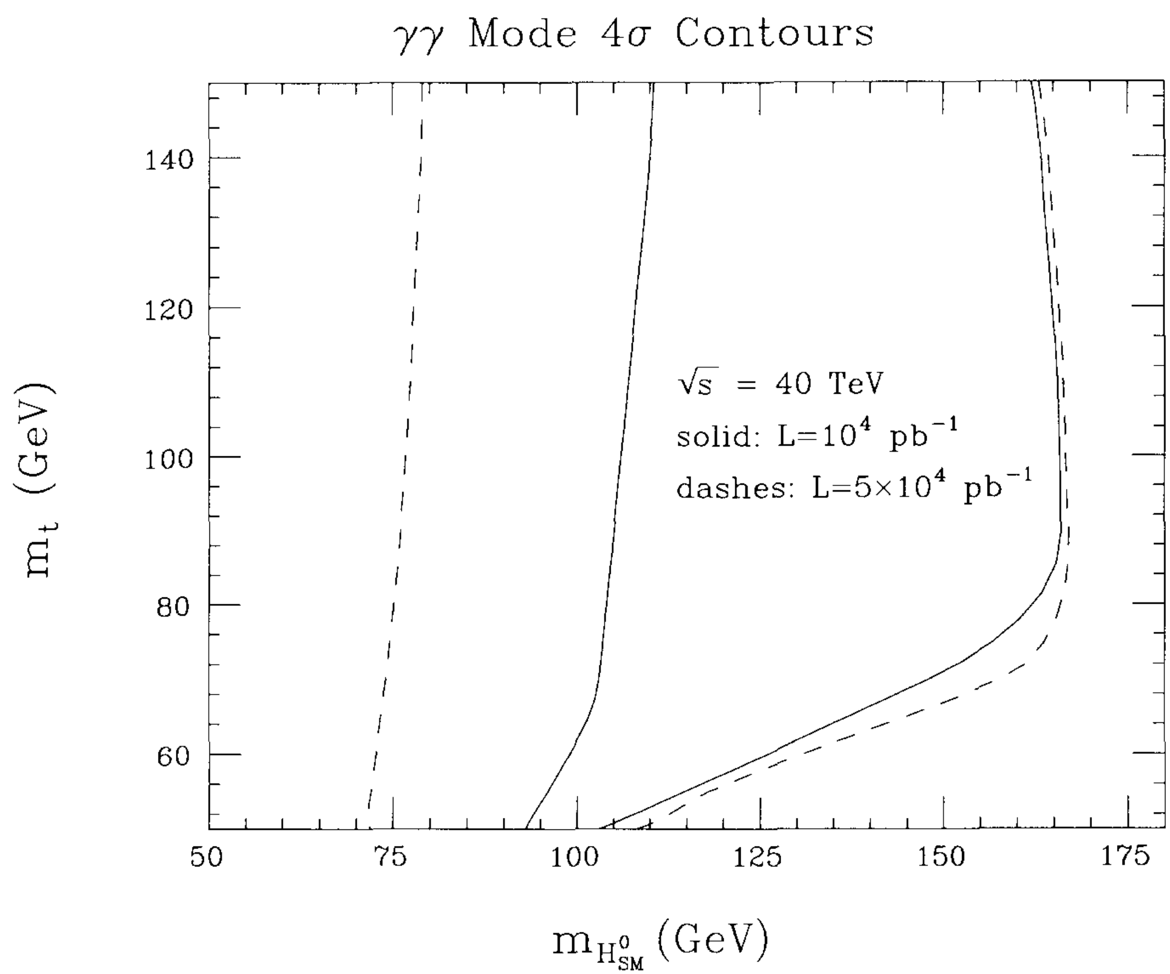
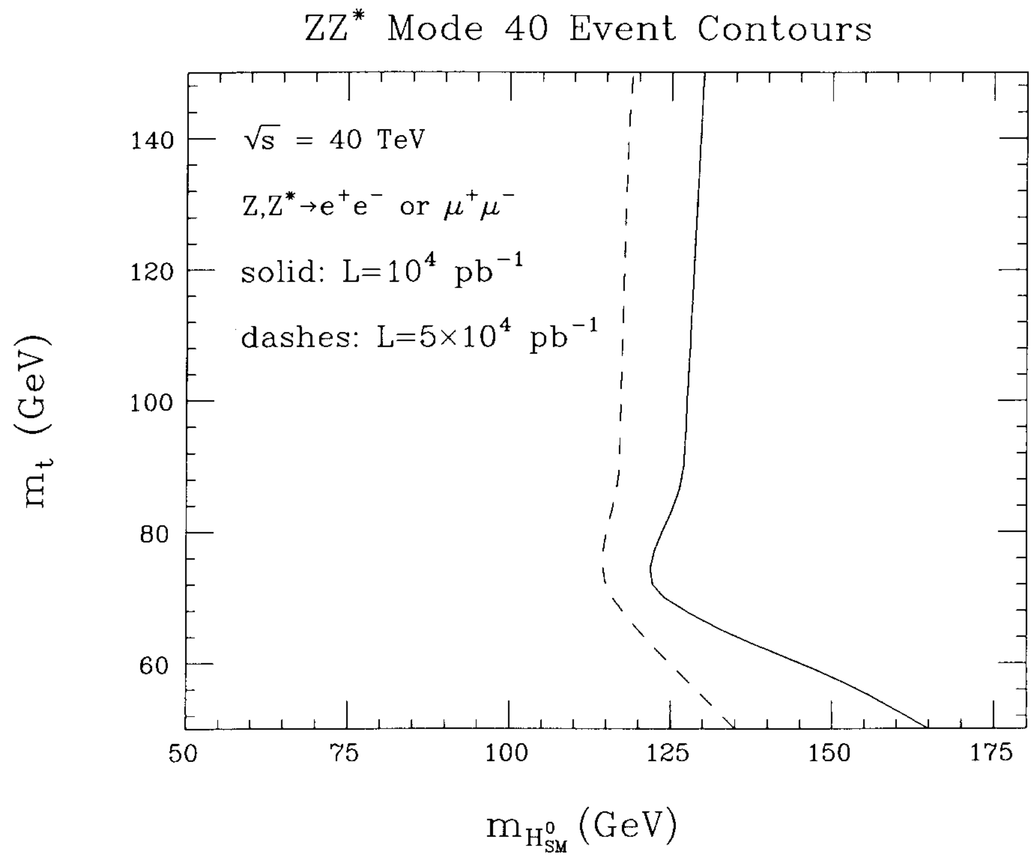


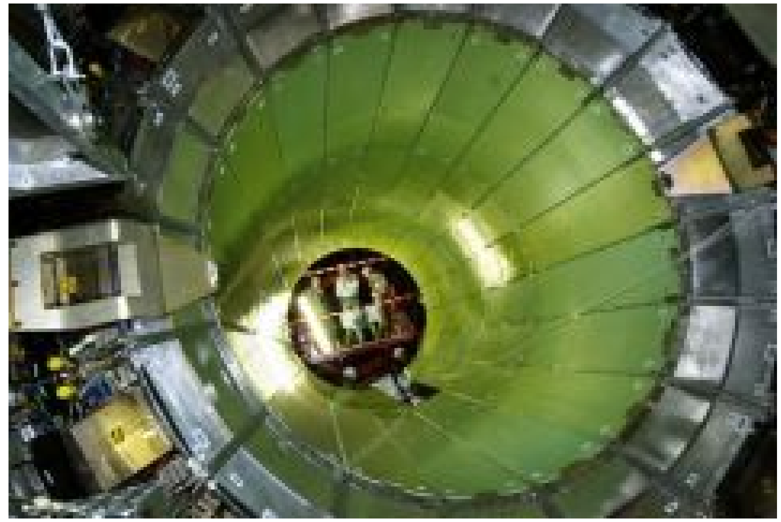
TABLE 1

$M_{\ell^+\ell^-}$ cuts: Associated signal and background event rates

$m_{H^0_{SM}}$ (GeV)	$M_{\ell^+\ell^-}$ cut	$m_t = 55$ GeV	$m_t = 90$ GeV	Background
120	10 GeV	3	13	2
140	20 GeV	16	110	3
160	25 GeV	44	248	2
170	30 GeV	54	87	2
180	40 GeV	84	143	8



Following the SSC cancellation, these studies were redone and improved for the LHC. They led directly to the proposals for and construction of very precise electromagnetic calorimeters for the ATLAS and CMS collaborations. They cost a lot but proved worth the cost and effort when it came to the actual Higgs discovery.



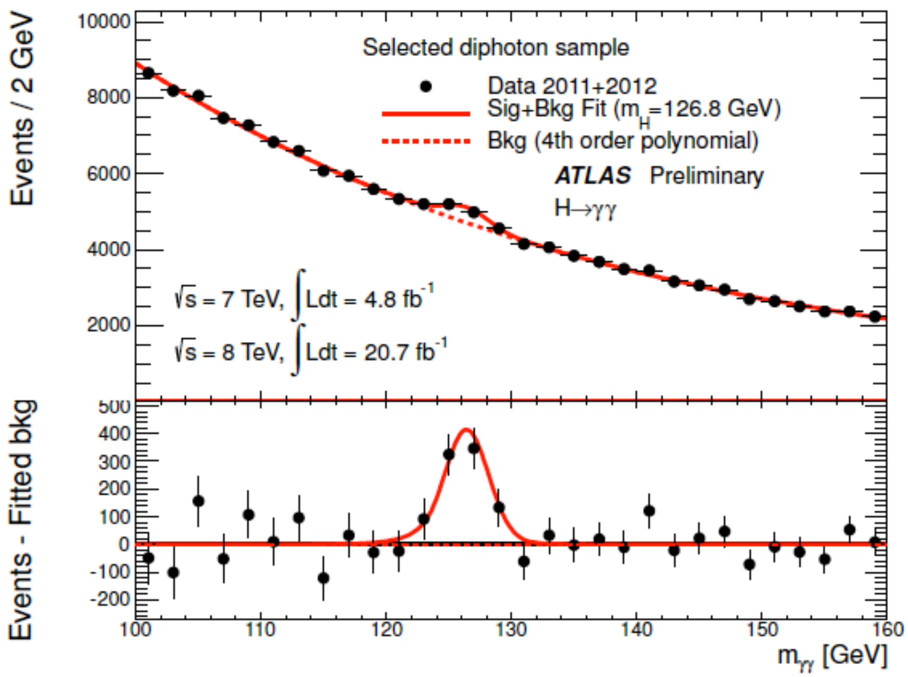
Also critical were the muon chambers — muons were clearly going to provide a very clean signal if the Higgs mass was large enough. Dick Lander at UCD proposed a small compact muon detector for the SSC that eventually morphed into CMS when taken over to the LHC.

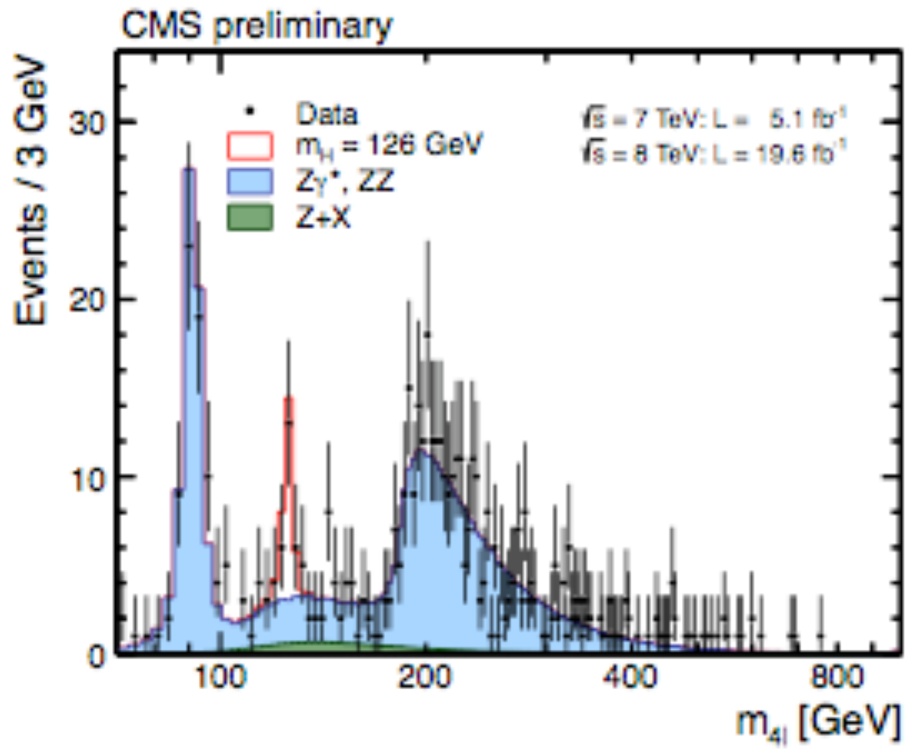
Finally, in 2012 after the LHC accident and repair, the Higgs particle or something a lot like it (we think) was found (July 4 being the official date) !

And the primary discovery modes were precisely the $H \to ZZ \to 4\ell$ and $H \to \gamma\gamma$

modes that were clearly going to be crucial if the LEP blue-band curve was taken as a guide.

The current status of the signal is unassailable. And, it looks very SM-like (more later — see also talk by Kraml).





The observed $m_H \sim 125\ \mathrm{GeV}$ is very exciting, both experimentally and theoretically, given the large number of production/decay modes in which a signal can be seen and given the fact that $125\ \mathrm{GeV}$ is close to being too large for SUSY to "naturally" predict and too small for the SM to be valid all the way to the Planck scale.

Quantifying the observed signal

- Production modes: **ggF, ttH, VBF, VH**

- Decay modes: $\gamma\gamma$, $ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$ and $\tau\tau$

- Deviations from custodial symmetry are now strongly constrained

  Hence, one can assume that the VBF and VH production modes both depend on a single generalized coupling of the Higgs boson to $V = W, Z$.

- It is also convenient to combine ggF and ttH.

Eventually, one will want to separate all initial and final state μ's.

- If we have custodial symmetry and if $b\bar{b}$ and $\tau\tau$ rescale by a common factor as in many models, then we are left with two independent production modes (VBF+VH) and (ggF+ttH), and three independent final states $\gamma\gamma$, $VV^{(*)}$ and $b\bar{b} = \tau\tau$.

- In recent publications by the ATLAS and CMS collaborations, likelihoods are given in the (VBF+VH) and (ggF+ttH) plane for relative signal strengths μ_i in the specific final states $\gamma\gamma$, $ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$, $\tau\tau$.

  Using the the ellipses provided, we (Belanger, Dumont, Ellwanger, Gunion, Kraml) are able to include the rather important correlations due to mutually common errors of the (VBF+VH) and (ggF+ttH) production processes.

- We combine the information provided by ATLAS, CMS and the Tevatron on the likelihoods as function of the six independent signal strengths μ_i defined above.

  An illustration of the kind of plots we combine are those for ATLAS as given below —though not perfect ellipses, we fit them as ellipses and then combine with other experiments.

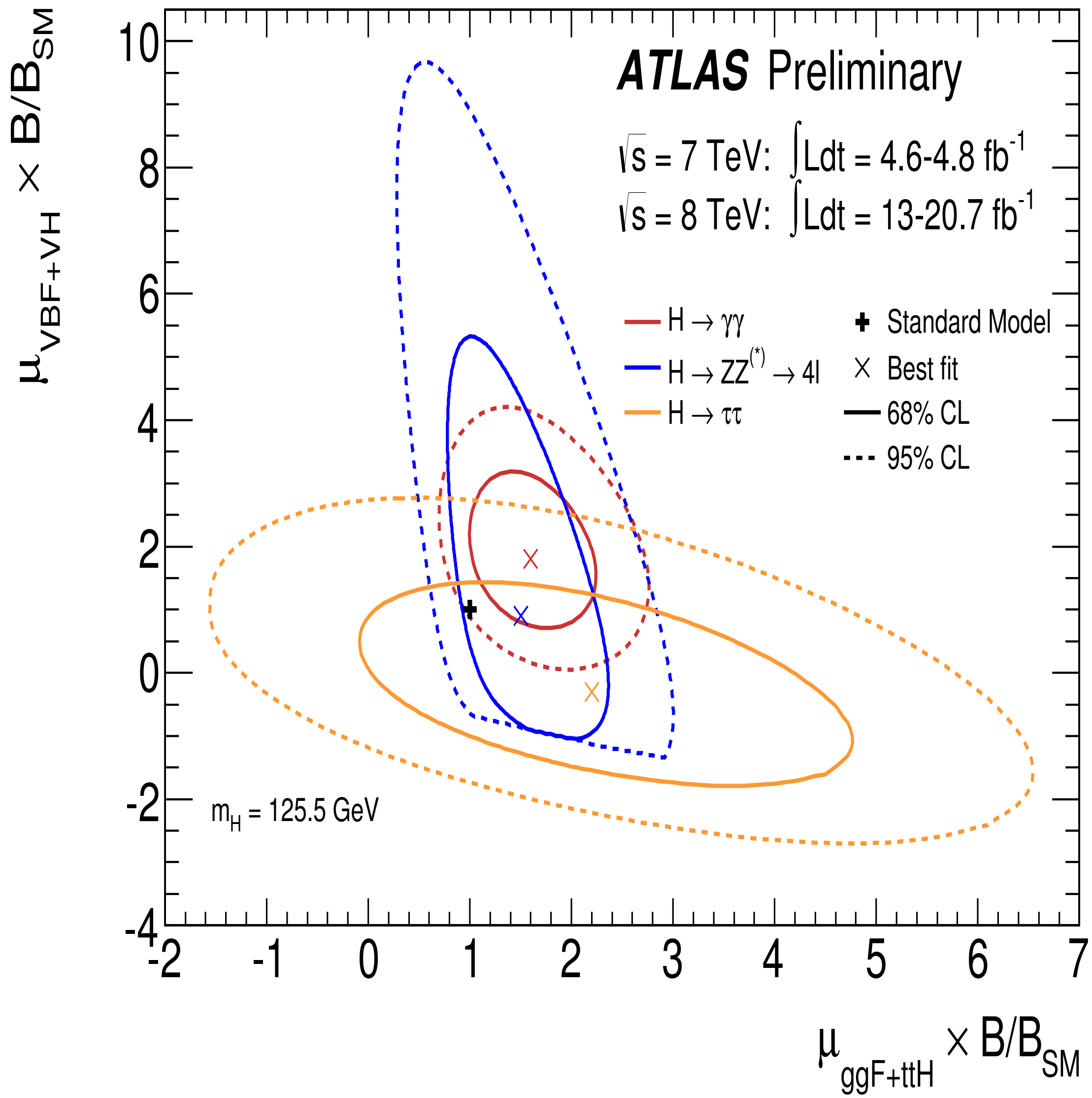


Figure 4: ATLAS results, including 4ℓ, $\gamma\gamma$ and $\tau\tau$.

- The results appear in the following figure.

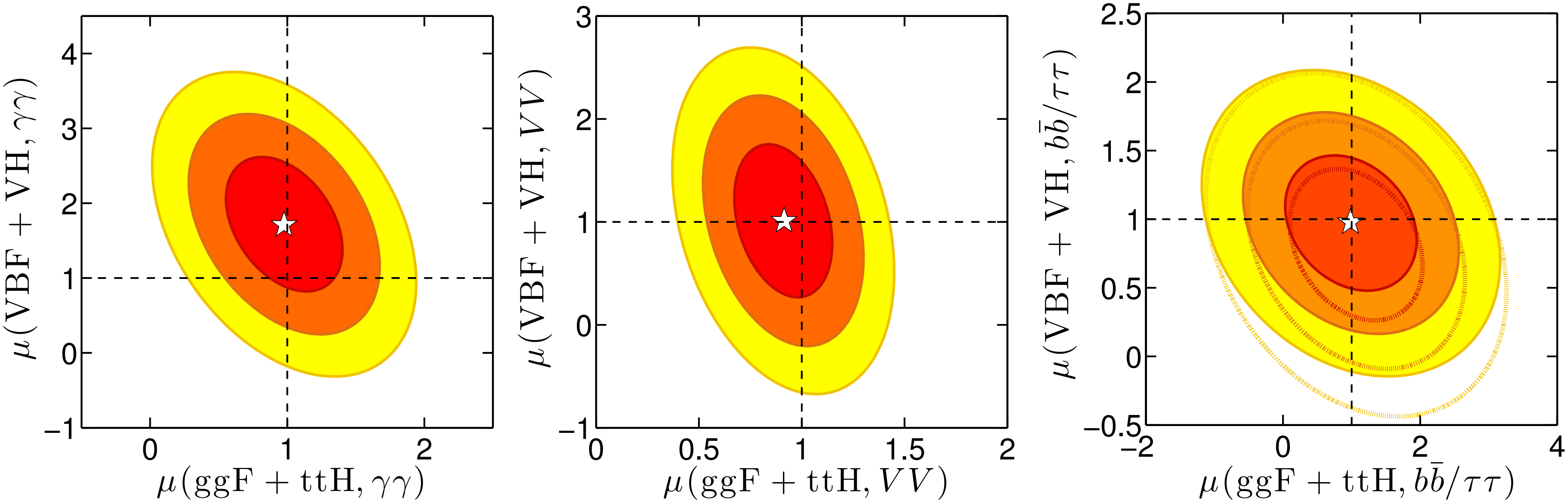


Figure 5: Combined signal strength ellipses for the $\gamma\gamma$, $VV = ZZ, WW$ and $DD = b\bar{b}, \tau\tau$ channels. The filled red, orange and yellow ellipses show the 68%, 95% and 99.7% CL regions, respectively, derived by combining the ATLAS, CMS and Tevatron results. The line contours in the right-most plot show how these ellipses change when neglecting the Tevatron results. The white stars mark the best-fit points.

Certainly, the SM is doing quite well. More details will be given by Kraml. Fitting to relative couplings constants for the SM-like Lagrangian, one finds that C_U, C_D, C_V are fully consistent with SM-like values of unity, while extra contributions to the $\gamma\gamma$ and gg loop diagrams are consistent with being absent.

But, *is it* the SM Higgs?

- For example, there are lots of NMSSM scenarios for which it need not be. Possibilities include:
  - A $98\ \mathrm{GeV}$ Higgs, the h_1, consistent with the 20%$\times$SM LEP excess, plus a $125\ \mathrm{GeV}\ h_2$, consistent with LHC results. (Belanger, Ellwanger, Jiang, Gunion, Kraml, Schwarz, JHEP 1301 (2013) 069)
  - A $125\ \mathrm{GeV}\ h_1$ and a $\sim 135\ \mathrm{GeV}\ h_2$ that could describe excesses in the later region in the CMS $\gamma\gamma$ mode and the Tevatron WH with $H \to b\bar{b}$ excess. (Belanger, Ellwanger, Gunion, Jiang, Kraml, arXiv:1208.4952)
  - Degenerate Higgs bosons, $m_{h_1} \sim m_{h_2} \sim 125\ \mathrm{GeV}$ with signals in the various final states being shared by the two Higgs bosons. (Gunion, Jiang, Kraml, Phys.Rev. D86 (2012) 071702)

    While this latter case was of particular interest when deviations from the SM results for $\gamma\gamma$ (especially) were present, it is also possible to have degenerate signals that combine to give a very SM-like result.

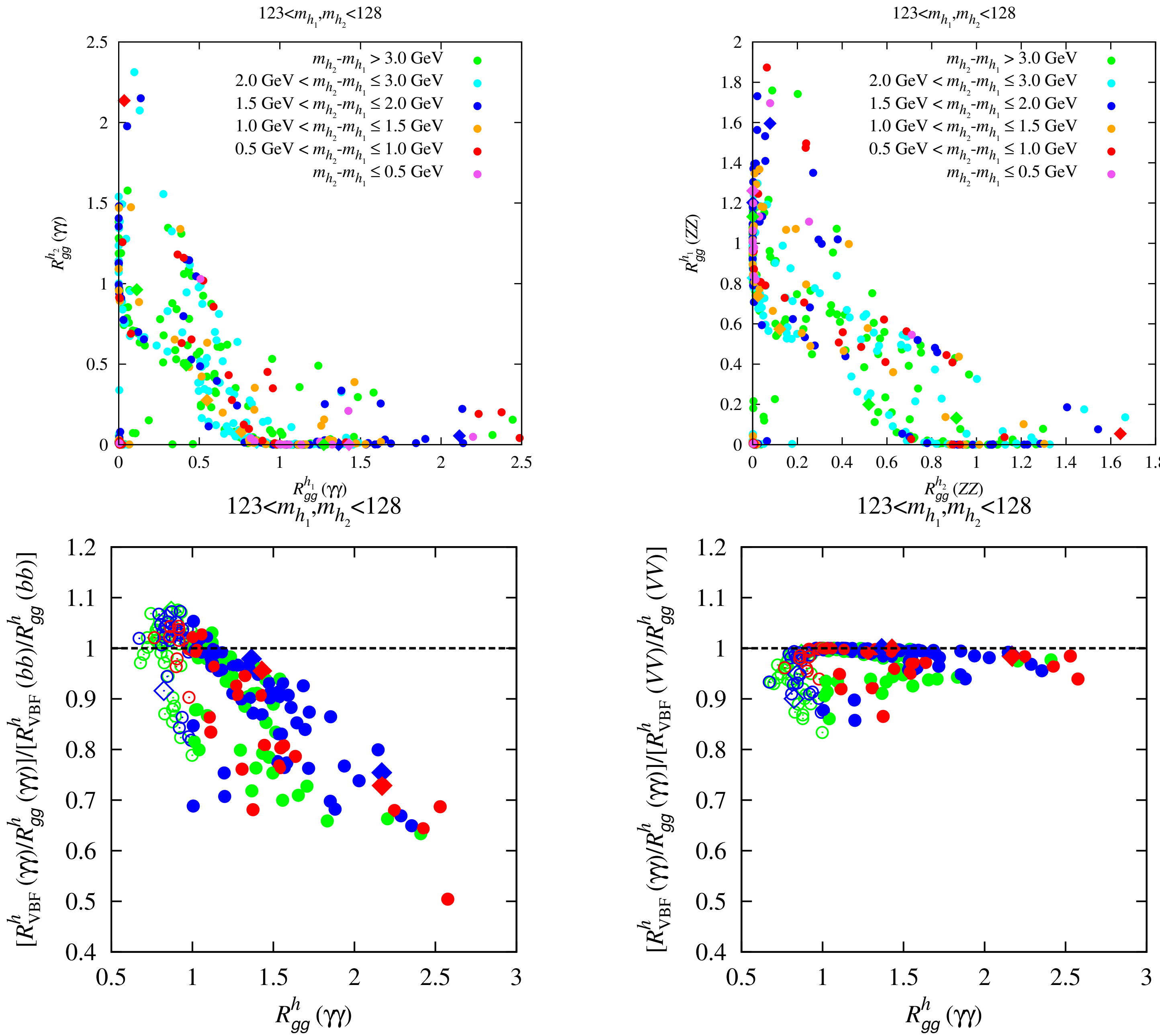


Figure 6: Top: Individual h_1 and h_2 contributions for $m_{h_1} \sim m_{h_2}$. Bottom: Ratios of double ratios, which must $= 1$ for a single Higgs, but generally $\neq 1$ for 2 or more degenerate Higgs, as functions of $R^h_{gg}(\gamma\gamma)$ (from Gunion, Jiang, Kraml, Phys.Rev.Lett. 110 (2013) 051801).

- Higgs-radion mixing model (Dominici, Gunion, Toharia, Phys.Lett. B712 (2012) 70-80)

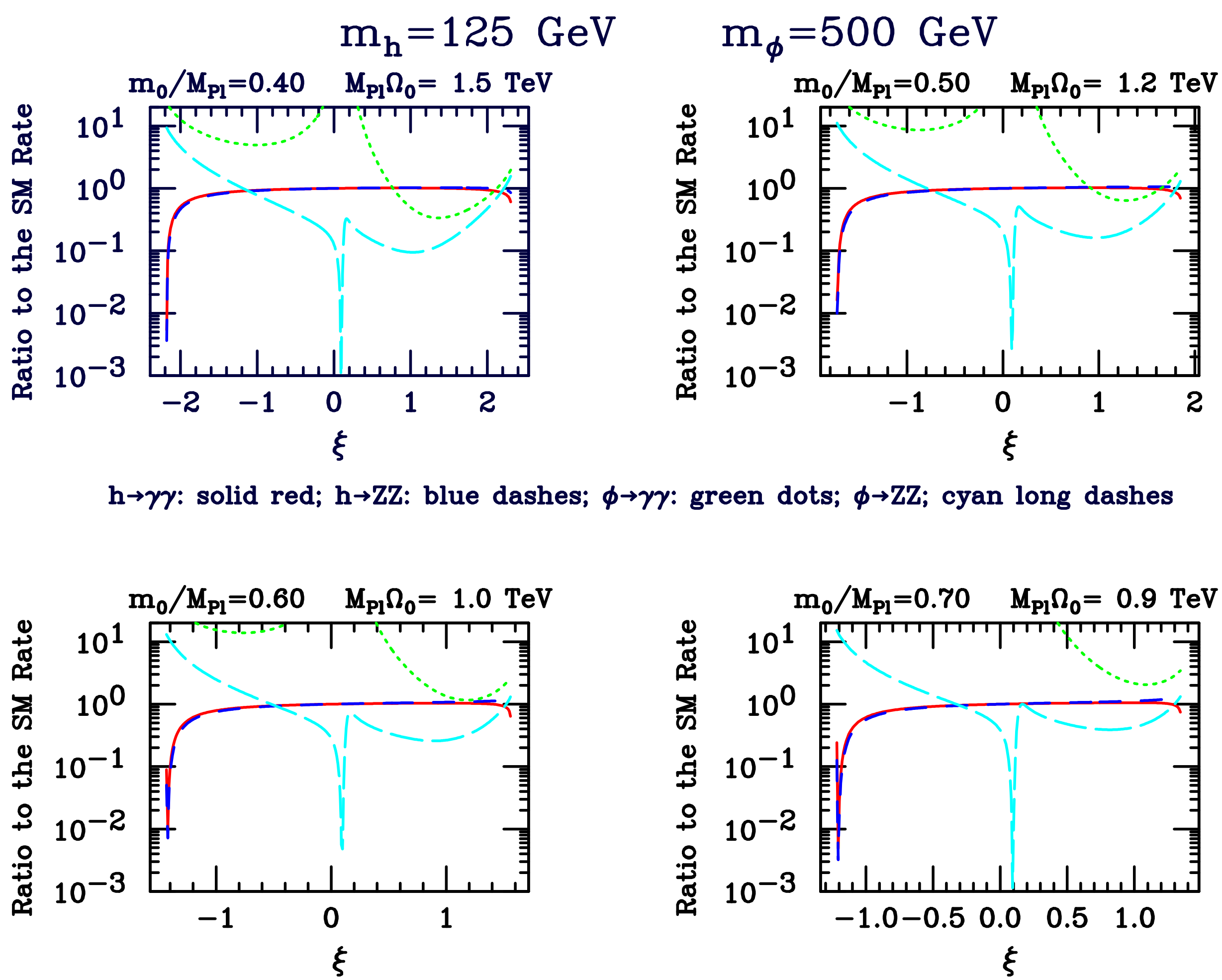


Figure 7: Higgs-radion mixing: Consistency for h with SM like results in $\gamma\gamma$ and ZZ is possible. Heavy ϕ varies greatly.

Degeneracy of the h and ϕ is also possible. One typically finds much bigger deviations of double ratios from being equal, related to anomalous gg and $\gamma\gamma$ couplings of the radion.

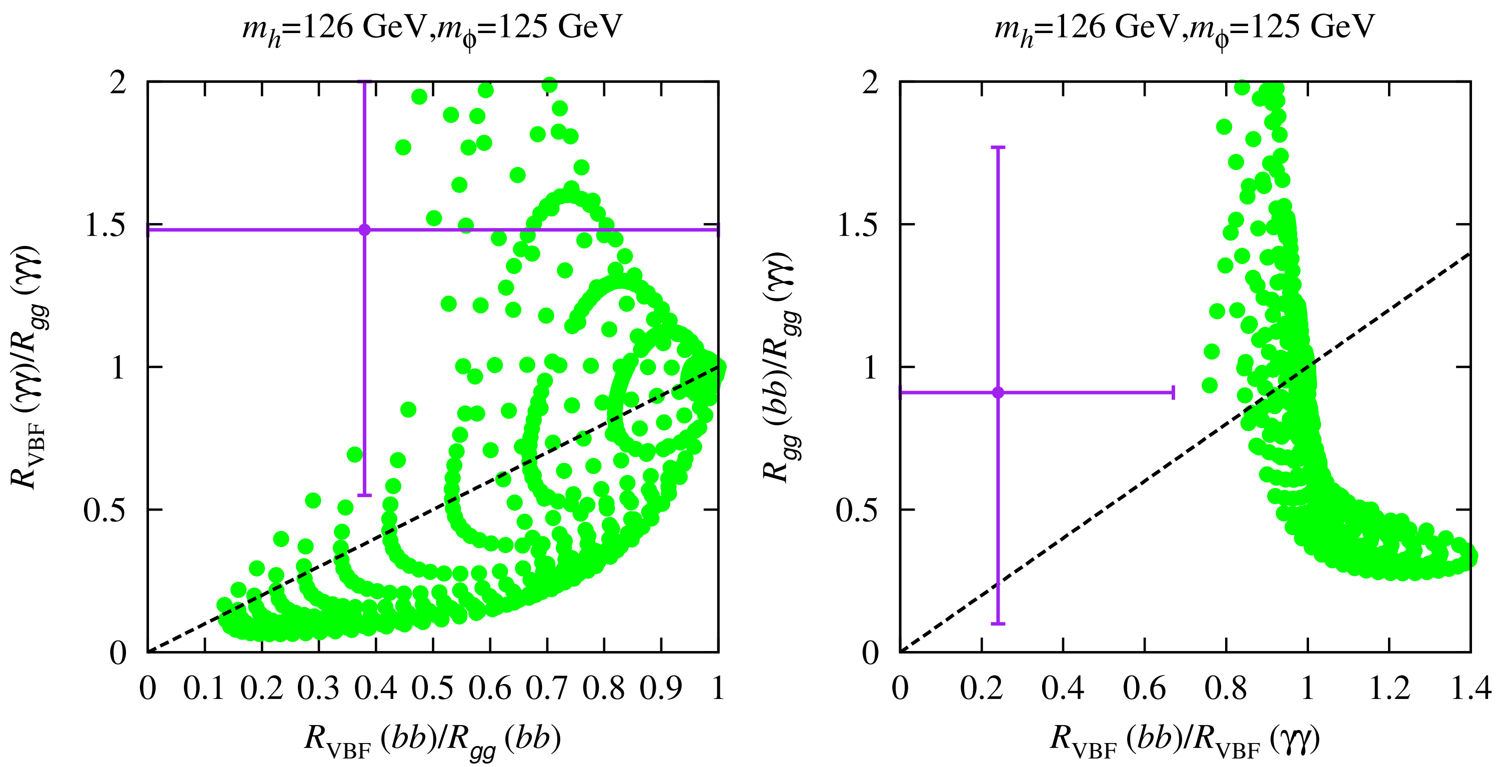
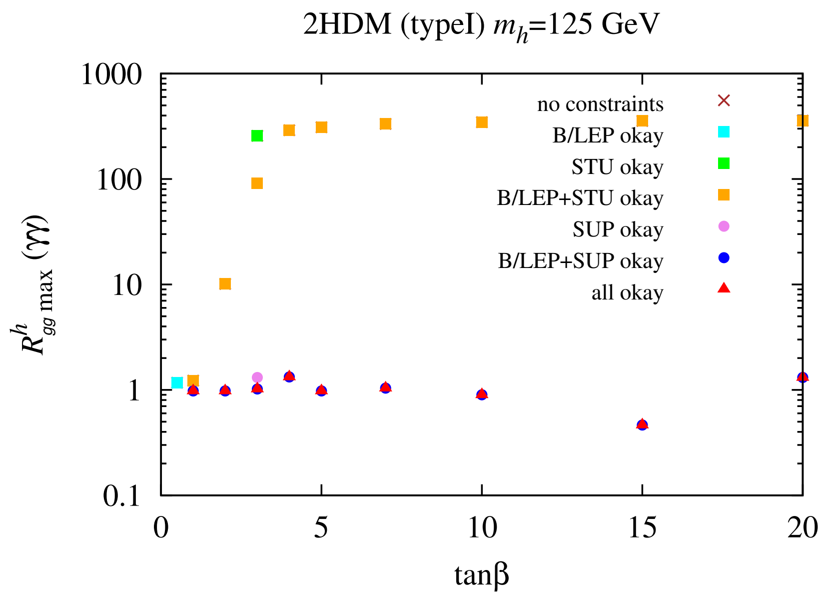
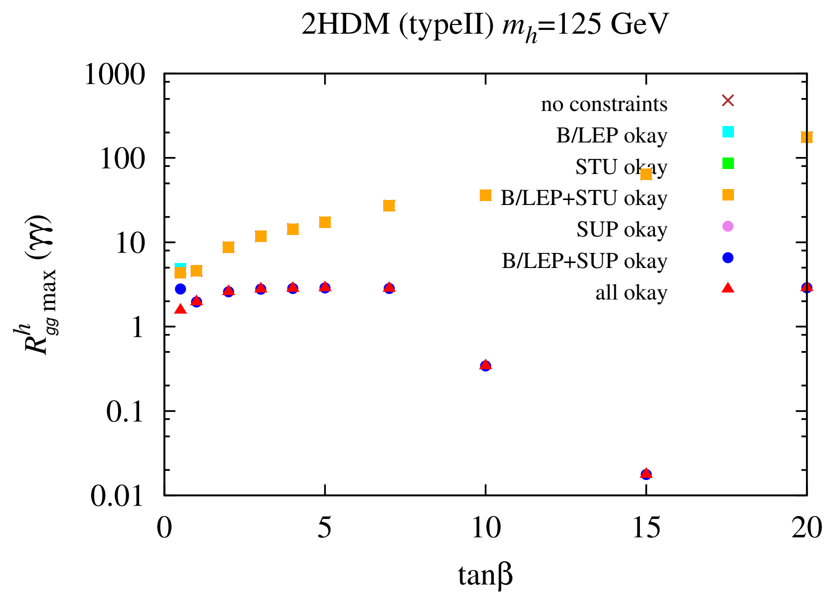


Figure 8: Figure shows only a small part of the full range of vertical axis.

- The pure 2HDM (Drozd, Grzadkowski, Gunion, Jiang — see also Ferreira, Haber, Santos and Silva): before imposing Higgs fit.





The top two plots show the maximum $R^h_{gg}(\gamma\gamma)$ values in the Type I (left) and Type II (right) models for $m_h = 125~\mathrm{GeV}$ as a function of $\tan\beta$ after imposing various constraints — the red squares survive all. Scenarios with $m_H = 125~\mathrm{GeV}$ rather similar.

Degenerate h-H, h-A, H-A scenarios are also interesting and can give enhanced rates or SM-like rates.

- The 2HDM Again — all constraints, including Higgs fits, imposed at 95% CL (Dumont, Gunion, Jiang, Kraml

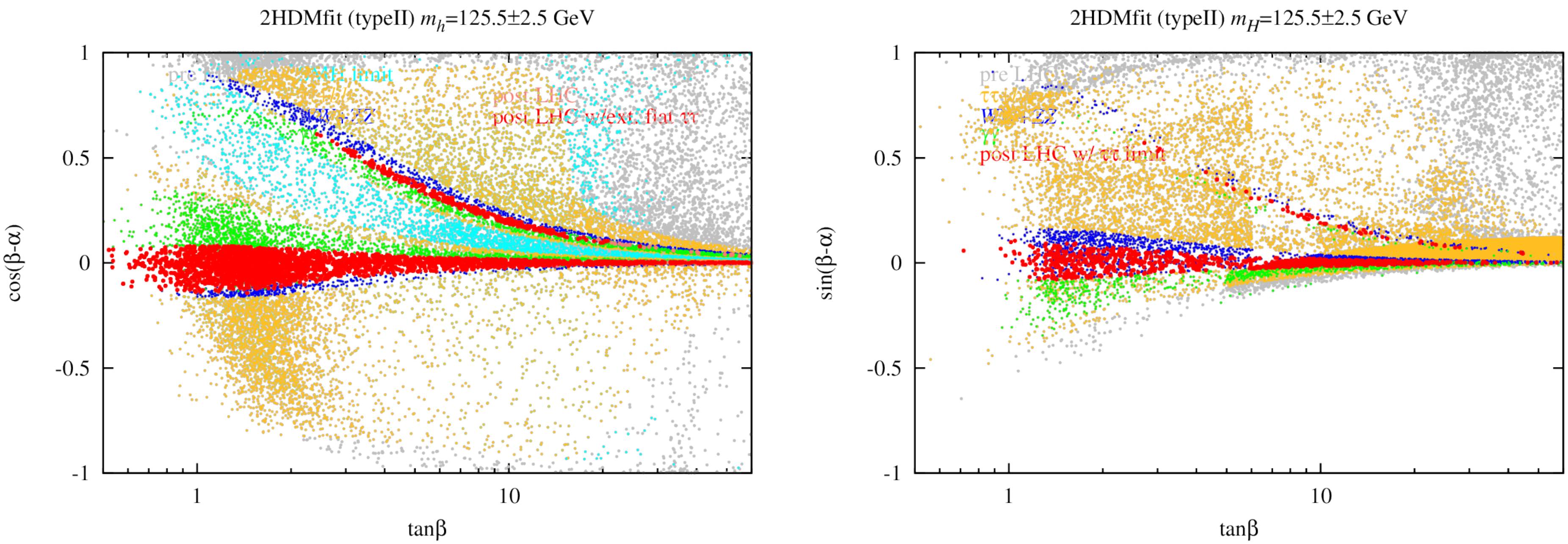


Figure 9: Constraints on the 2HDM models of Type II in the $\cos(\beta-\alpha)$ versus $\tan\beta$ plane for $m_h \sim 125.5$ GeV and in the $\sin(\beta-\alpha)$ versus $\tan\beta$ plane for $m_H \sim 125.5$ GeV. Red points obey all LHC Higgs measurements at 95% CL.

The SM limit is $\cos(\beta-\alpha) \to 0$ for $m_h \sim 125$ GeV and $\sin(\beta-\alpha) \to 0$ for $m_H \sim 125$ GeV. For Type II there is a main branch that is very SM-like, but also an alternative branch that is quite different. What will the future LHC run say?

Of course, an important question is whether the Higgs bosons other than the one with mass of order 125 GeV will be observable or not.

This can be revealed by using the well known μ (or R) ratios discussed earlier, but now for the heavier Higgs, for a given rate relative to the corresponding rate for the SM Higgs boson.

The ZZ ratios for the case of $m_h \sim 125.5~\mathrm{GeV}$ and Type II appear in Fig. 10.

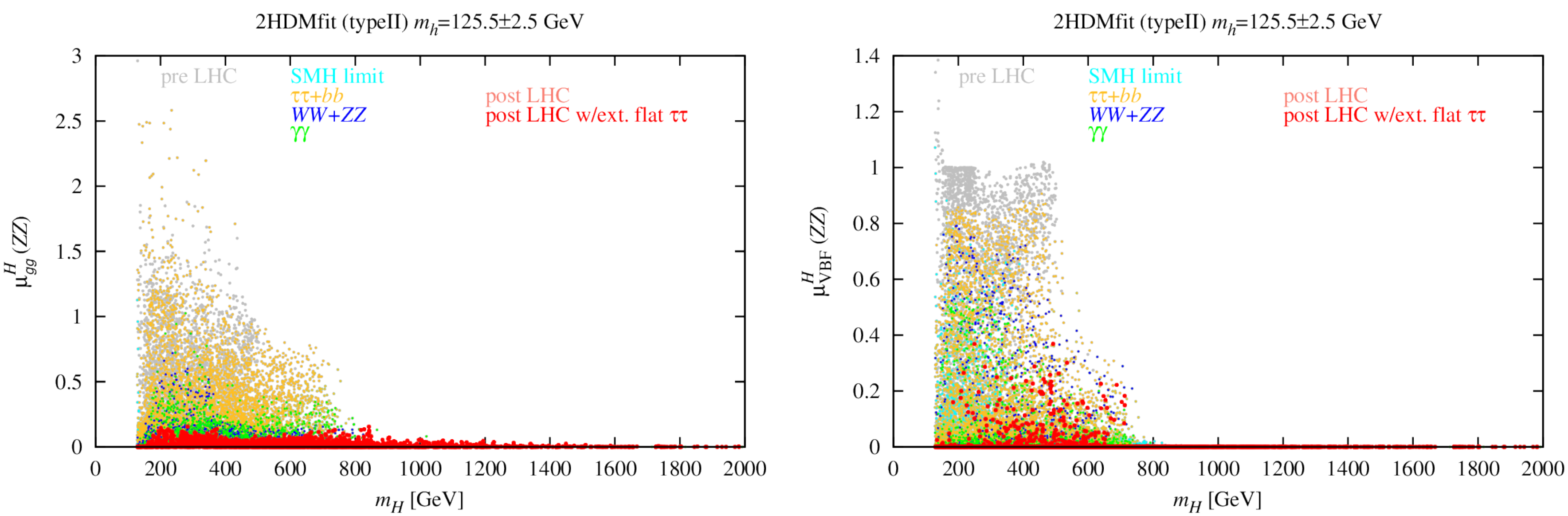


Figure 10: μ_{ggF} and μ_{VBF} ratios for $H \to ZZ$ as a function of m_H.

There we see that the $gg \to H \to ZZ$ rate is generally small relative to the SM, but nonetheless can be large enough to be observable at the next LHC run.

Also of potential interest are the rates for $gg \to H, A \to \tau\tau$ and for $gg \to H \to hh$. Results appear in Fig. 11. Cross sections are potentially observable for some parameter choices.

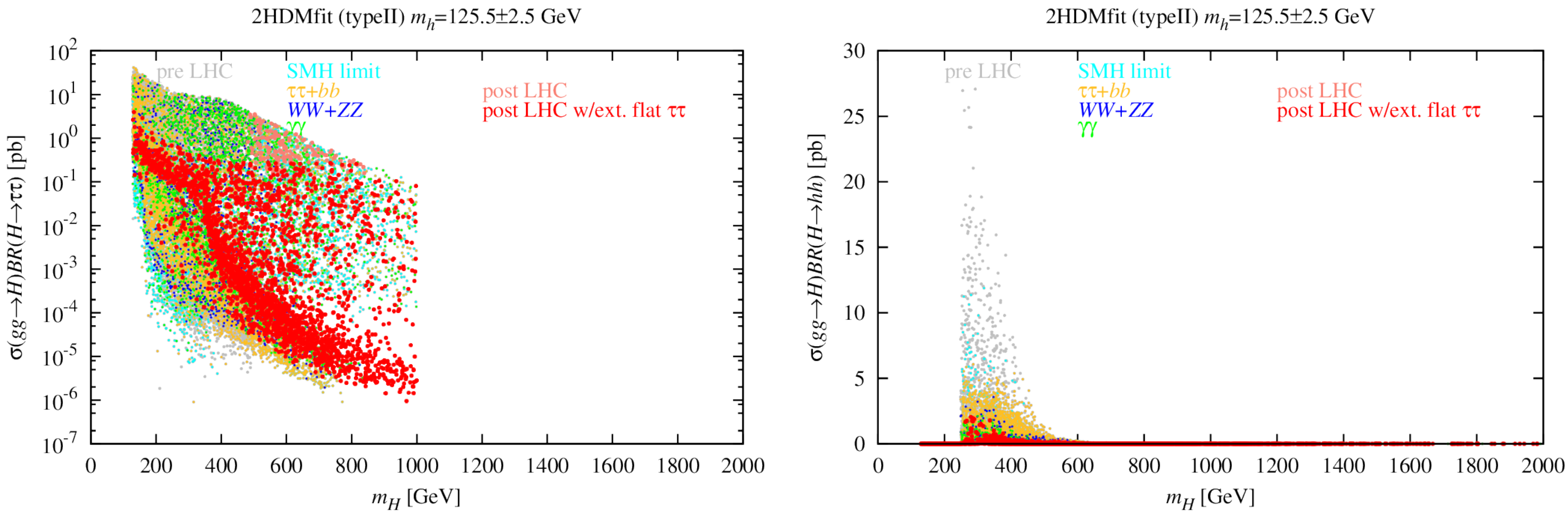
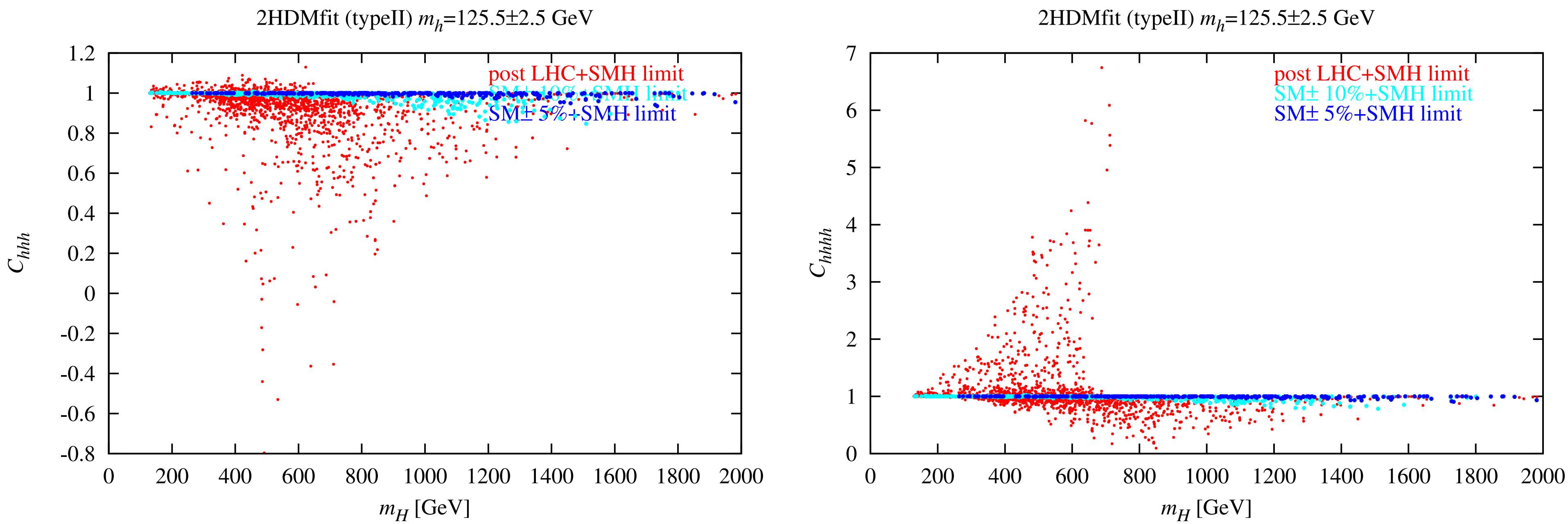


Figure 11: For $m_h \sim 125.5~\mathrm{GeV}$, we plot $\sigma_{gg}^H \times \mathcal{B}(H \to \tau\tau)$ and $\sigma_{gg}^H \times \mathcal{B}(H \to hh)$ as a function of m_H.

We can also imagine a time when all rates are confirmed to be SM-like to within

$\pm 10\%$ or $\pm 5\%$ and ask what the ILC could do if it measures self-couplings.



It would appear that the precision needed to see even the largest predicted deviations is very much at the edge of what the ILC might achieve.

- The pMSSM (Dumont, Gunion, Kraml, Sekmen)

The phenomenological MSSM (pMSSM) makes no assumptions about GUT scale unification — all parameters (16) are set at the electroweak scale. One can ask if the current precision of Higgs measurements has any impact on the SUSY particles (once all other constraints from B physics and so forth are applied). A sample result after a huge scan is shown below.

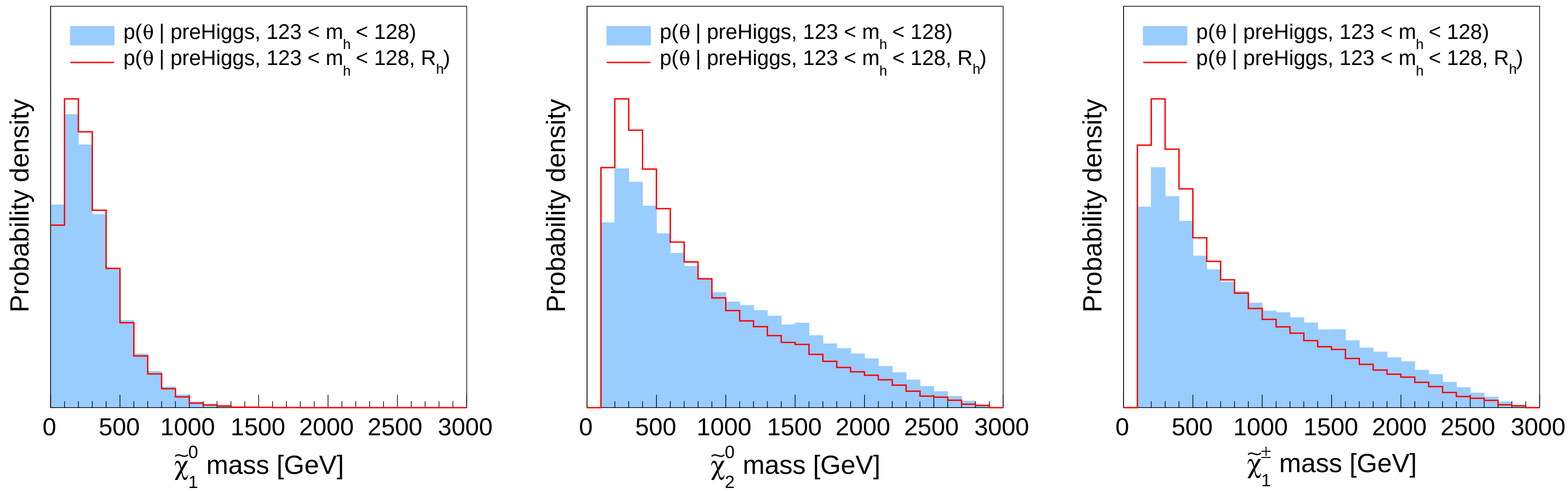


Figure 12: Marginalized 1D posterior densities for various pMSSM model parameters. The light blue histograms show the distributions based on the "preHiggs" measurements of Table **??** plus requiring in addition $m_h \in [123, 128]$ GeV. The red lines are the distributions when taking into account the measured Higgs signal strengths in the various channels.

Effects of the Higgs observations on the sparticle masses are shown in Fig. 12. A summary is the following:

- there is substantially increased probability for smaller $m_{\widetilde{\chi}_2^0}$ and $m_{\widetilde{\chi}_1^\pm}$;
- there is a small shift towards smaller $m_{\widetilde{g}}$;
- $m_{\tilde{t}_1}, m_{\tilde{t}_2}, m_{\tilde{b}_1}$ are all shifted to higher values, as needed to get the predicted mass of the h into the $[123, 130]~\mathrm{GeV}$ range.

- Finally, there is the very crucial issue of unseen (but not truly invisible) Higgs decays, a primary example being the NMSSM $h_1 \to a_1 a_1$ channel —- it is not dead! How can that be?

  There is a well-known flat direction in the Higgs fitting game. Let us postulate an unseen (U) mode (such as aa) with branching ratio $\mathcal{B}_U$. Then, if the LHC signal rates are well fit by certain choices of C_U, C_D, C_V (say with $\Delta C_\gamma = \Delta C_g = 0$) for $\mathcal{B}_U = 0$ then an equally good fit for any value of $\mathcal{B}_U$ is obtained by the rescaling

$$C_i^2 \to \frac{C_i^2}{1 - \mathcal{B}_U} \qquad (2)$$

  Notes:

1. If U is an invisible final state, $\mathcal{B}_U$ is already significantly constrained by ZH with $H \to$ invisible limits so that there are limits to this game in that case. But, if $U = aa$ or $6g$ or .... then reliable constraints are not yet available.
2. Precision electroweak constraints depend on $C_V^2 \ln(m_H)$ and $C_U^2 m_t^2$ and so will limit this game as well.

Still, first estimates suggest that $\mathcal{B}_U$ as large as 50%, corresponding to a rescaling of C^2 upwards by as much as a factor of 2 will survive as a possibility.

This gives a greatly increased rate for actually observing a difficult channel such as $H \to aa$ given that $\mathcal{B}_U \sim \frac{1}{2}$ and production rates are increased by a factor of 2.

Conclusions

- It seems likely that the Higgs responsible for EWSB has emerged.
- At the moment, there is no sign of other Higgs-like signals except $\sim 1\sigma$ hints at $\sim 135~\mathrm{GeV}$ and the old LEP excess at $98~\mathrm{GeV}$.
- Survival of enhanced signals for the $125~\mathrm{GeV}$ state (as still seen by ATLAS) would be one of the most exciting outcomes of the current LHC run and would guarantee years of theoretical and experimental exploration of BSM models with elementary scalars.
- Close to SM signals at the LHC would imply that a linear collider or LEP3 or muon collider is needed to look for BSM physics indirectly via deviations of Higgs properties from the SM.
- Although current data is converging to a SM-like Higgs, there is still room for additional Higgs bosons in important model classes.

Thus, we must push hard to improve errors on the nature of the 125 GeV state since even small deviations could be a first sign of such additional states.

Following G. Ross's question of **Whither SUSY?** (he insists we should not consider the Wither SUSY option) we can ask **Whither Higgs?** — fortunately, **we need not worry about Wither Higgs**.

While the waiting for a 1st Higgs signal is over, watching for more Higgs or some sign of BSM is not: