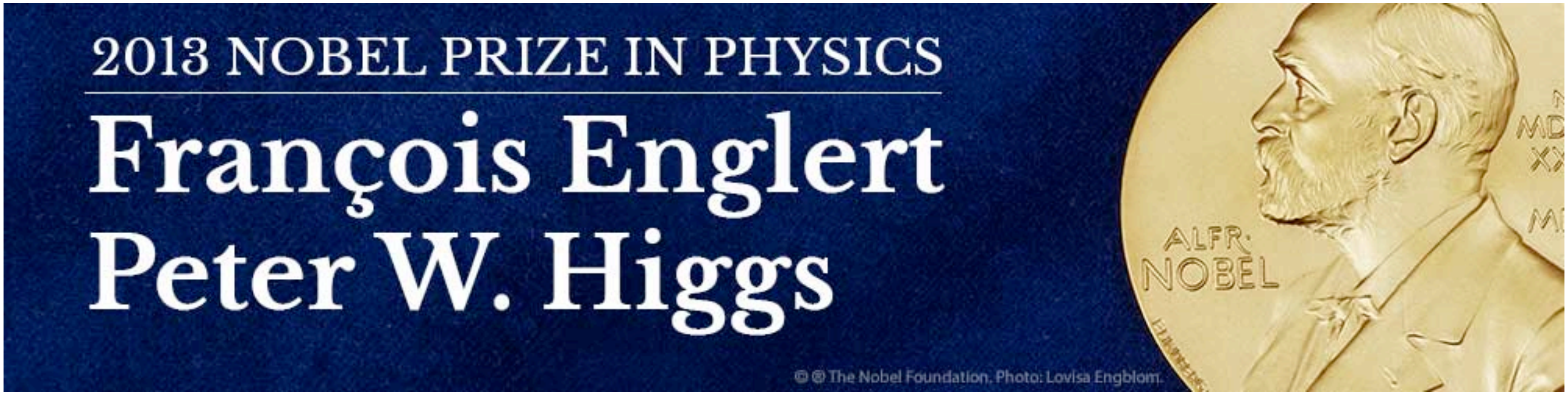
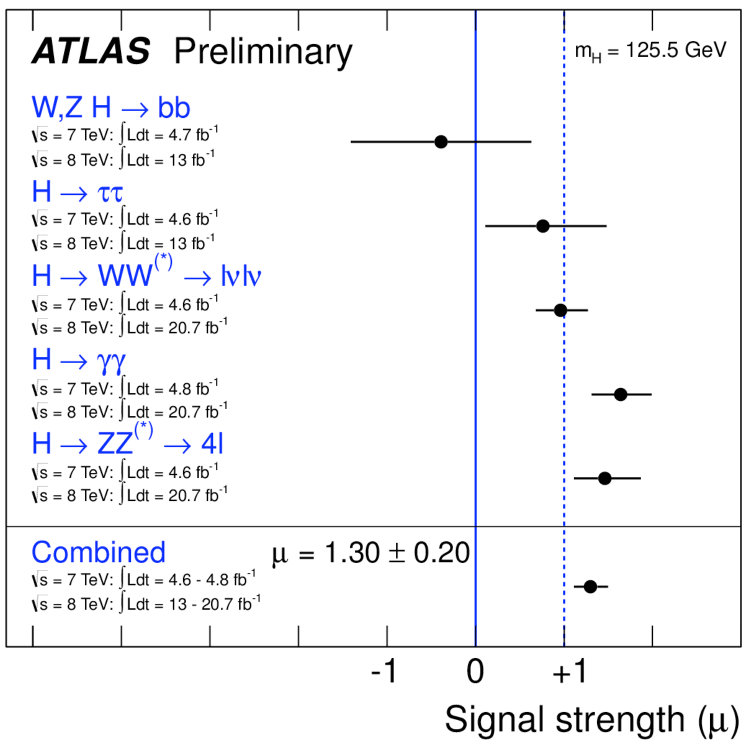
Now What? – My Own Prejudice

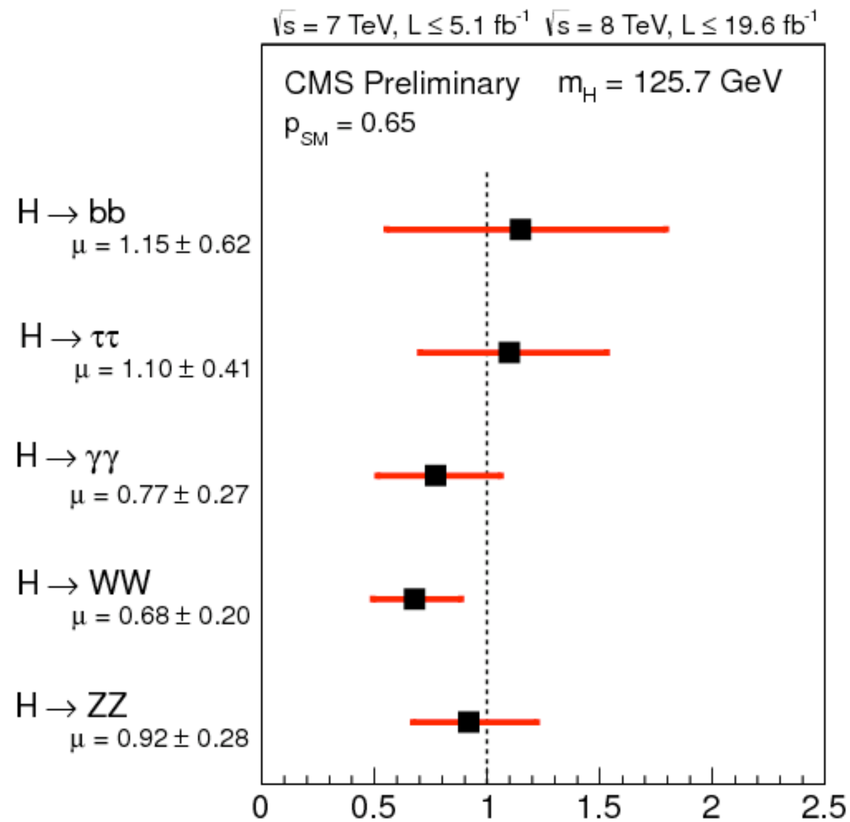
Ian Low
Argonne/ Northwestern
Oct 11, 2013 @ HEFT2013 in CERN



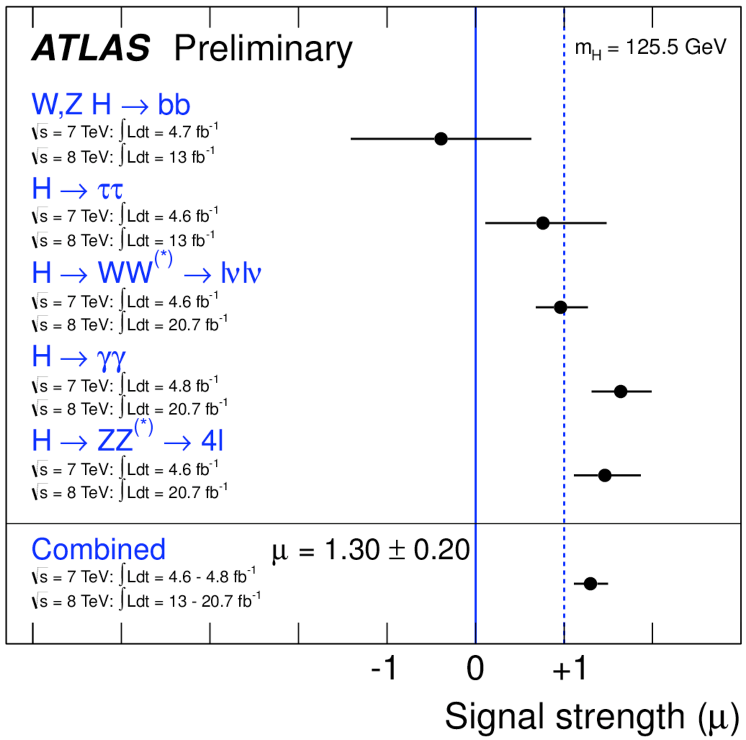
h(125) walks like a , quacks like a , so it is a …

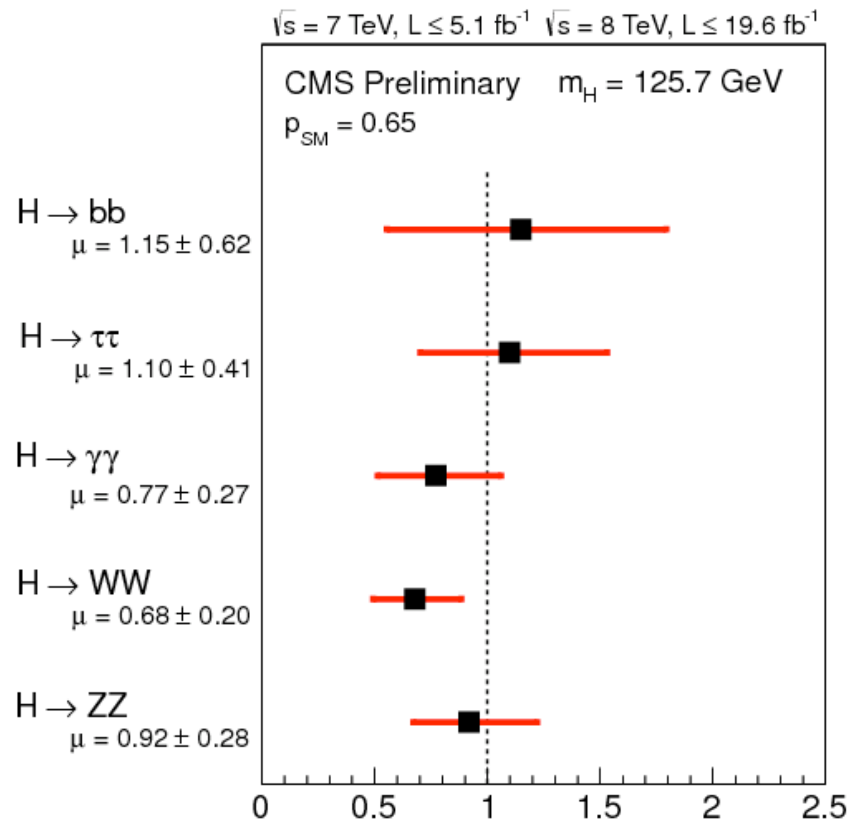
These two plots are worth a thousand words (and perhaps a Nobel Prize as well):





Not only is h(125) a Higgs boson, it is a “SM-like” Higgs boson:





The 10-billion dollar question:

Is it a Non-Standard Model Higgs boson?

A quote from Howie Haber:

> Such measurements can only be performed with limited precision at the LHC. Thus, the LHC can never claim a discovery of the SM Higgs boson; at best the LHC can claim the *discovery of a SM-like Higgs boson.*
>
> In contrast, if (some of) the measured values of the Higgs couplings differ significantly from the predicted SM values, then it is possible to *rule out the SM Higgs boson* at the LHC.

In fact, the bar of being a SM Higgs is incredibly high because interactions of the SM Higgs with SM particles are completely determined by

1. Mass of the SM particle.
2. Higgs VEV ≈ 246 GeV.

(This includes the case of massless gauge bosons, *gg*, *γγ* and *Zγ*, which are set by Higgs interactions with other SM particles, in particular the W boson and the top quark masses.)

(Let's ignore neutrino for now.)

- First look at the interactions with massive gauge bosons:

$$\left(\frac{2m_W^2}{v}\,h\,W_\mu^+W^{-\mu} + \frac{m_Z^2}{v}\,h\,Z_\mu Z^\mu\right)$$

- Next are Higgs interactions with quarks and charged leptons:

$$\left(\frac{2m_W^2}{v}\,h\,W_\mu^+W^{-\,\mu}+\frac{m_Z^2}{v}\,h\,Z_\mu Z^\mu\right)$$

$$\sum_f \frac{m_f}{v} h\bar{f}f$$

- Then the self-interactions of the Higgs:

$$\left(\frac{2m_W^2}{v}\, h\, W_\mu^+ W^{-\,\mu} + \frac{m_Z^2}{v}\, h\, Z_\mu Z^\mu\right)$$

$$\sum_f \frac{m_f}{v} h \bar{f} f$$

$$\frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{v} h^3 + \frac{2m_h^2}{v^2} h^4$$

- Finally Higgs interactions with massless gauge bosons:

$$\left(\frac{2m_W^2}{v}\, h\, W_\mu^+ W^{-\,\mu} + \frac{m_Z^2}{v}\, h\, Z_\mu Z^\mu \right)$$

$$\sum_f \frac{m_f}{v} h \bar{f} f$$

$$\frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{v} h^3 + \frac{2m_h^2}{v^2} h^4$$

$$+ c_g \frac{\alpha_s}{12\pi v} h\, G^a_{\mu\nu} G^{a\,\mu\nu} + c_\gamma \frac{\alpha}{8\pi v} h\, F_{\mu\nu} F^{\mu\nu} + c_{Z\gamma} \frac{\alpha}{8\pi v s_w}\, h\, F_{\mu\nu} Z^{\mu\nu}$$

$$c_g^{(SM)}(125\ \text{GeV}) = 1\ , \qquad c_\gamma^{(SM)}(125\ \text{GeV}) = -6.48\ , \qquad c_{Z\gamma}^{(SM)}(125\ \text{GeV}) = 5.48\ .$$

To answer the 10-billion dollar question, we need to distinguish two objects --

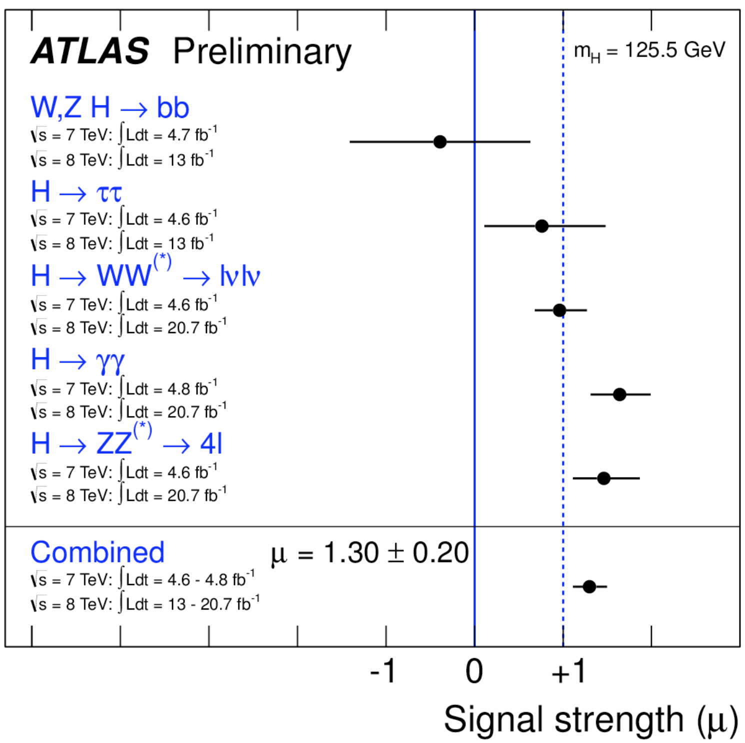
- Coupling structure: terms in the lagrangian that couple h(125) to matter fields, including self-couplings.

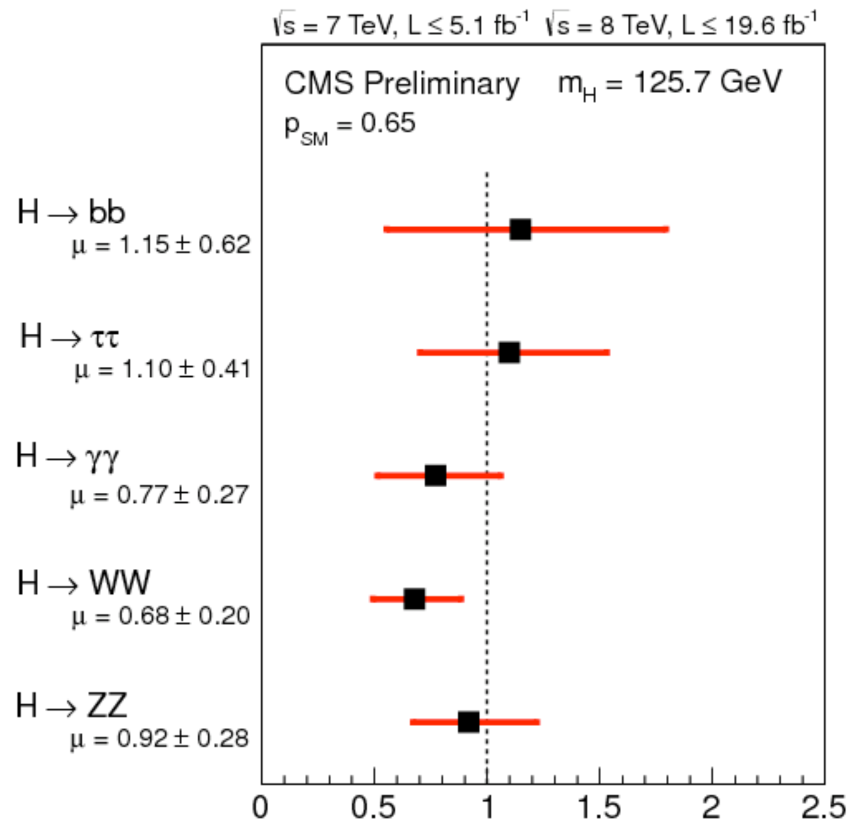
  Takes a lot of work to be sure; usually need angular correlations.

- Coupling strength: the coefficient multiplying the coupling structure in the lagrangian.

  Crucial to recognize that coupling strength fits depend on assuming particular coupling structures!

These are the fits for the "coupling strength" based on the SM Higgs coupling structure:





In the end, we need to measure

- all coupling strengths
- all coupling structures

and see if ***both*** agree with the SM expectations.

Signal strength is only part of the story, not the entirety!

There are many ways new physics could manifest itself even if the signal strengths seem to be consistent with the SM.

- h(125) could contain a small CP-odd mixture.

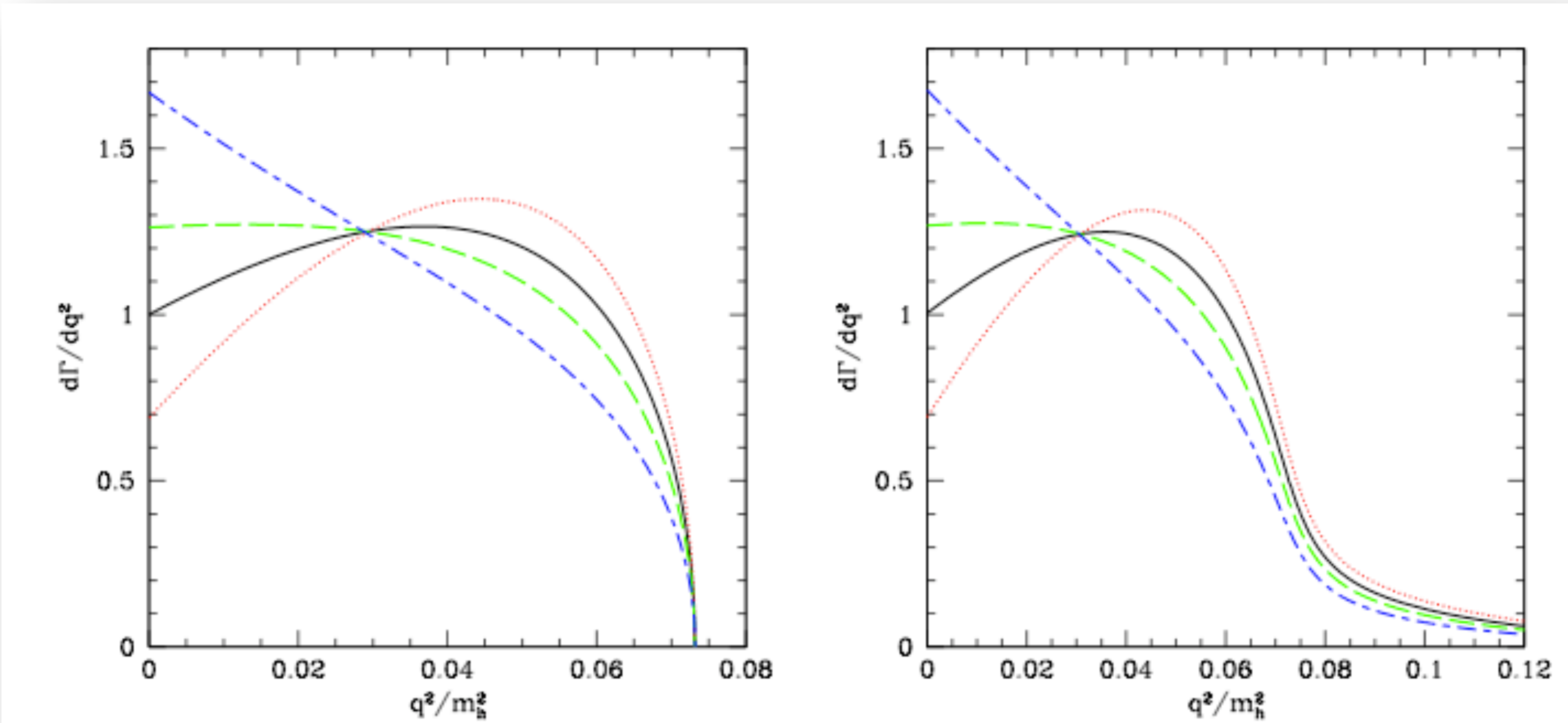
- h(125) could be a mixture from more than one electroweak doublets.

- h(125) could have couplings to exotic particles like the dark matter.

- h(125) may not fully unitarize WW scatterings.

In the past the emphasis has been on the coupling strength measurement, which could be misleading.

A recent study on h-> V + $l^+ l^-$:



$$\mathcal{A}_V^{\mathcal{F}} = C_V g_V^2 m_V \frac{\varepsilon_\mu J_\nu^{\mathcal{F}}}{(q^2 - m_V^2)} \left[f_1^V(q^2) g^{\mu\nu} + f_2^V(q^2) q^\mu q^\nu \right. \qquad (2)$$
$$\left. + f_3^V(q^2)(p \cdot q \; g^{\mu\nu} - q^\mu p^\nu) + f_4^V(q^2) \epsilon^{\mu\nu\rho\sigma} p_\rho q_\sigma \right].$$

Isidori et. al.: 1305.0663

See also Grinstein, et. al.: 1305.6938

Another example: CP-violation in Higgs to tau leptons.

$$-m_\tau \,\bar{\tau}\tau - \frac{y_\tau}{\sqrt{2}}\, h\bar{\tau}(\cos\Delta + \mathrm{i}\gamma_5 \sin\Delta)\tau$$

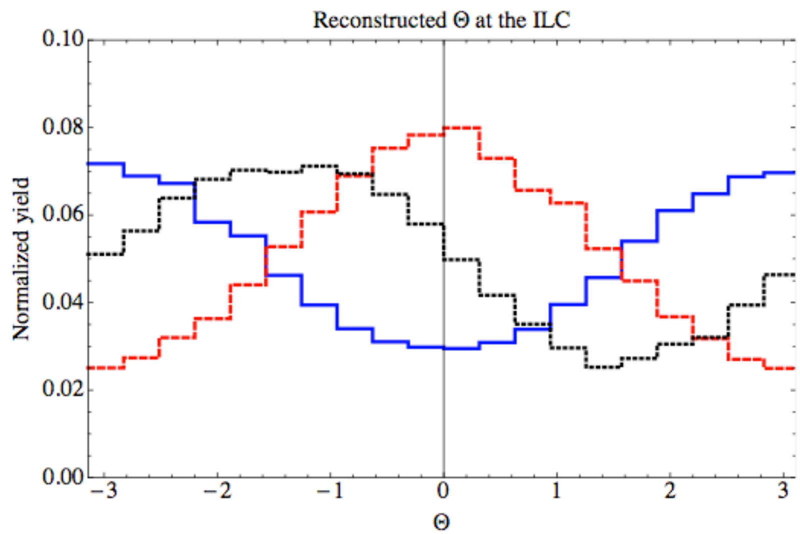
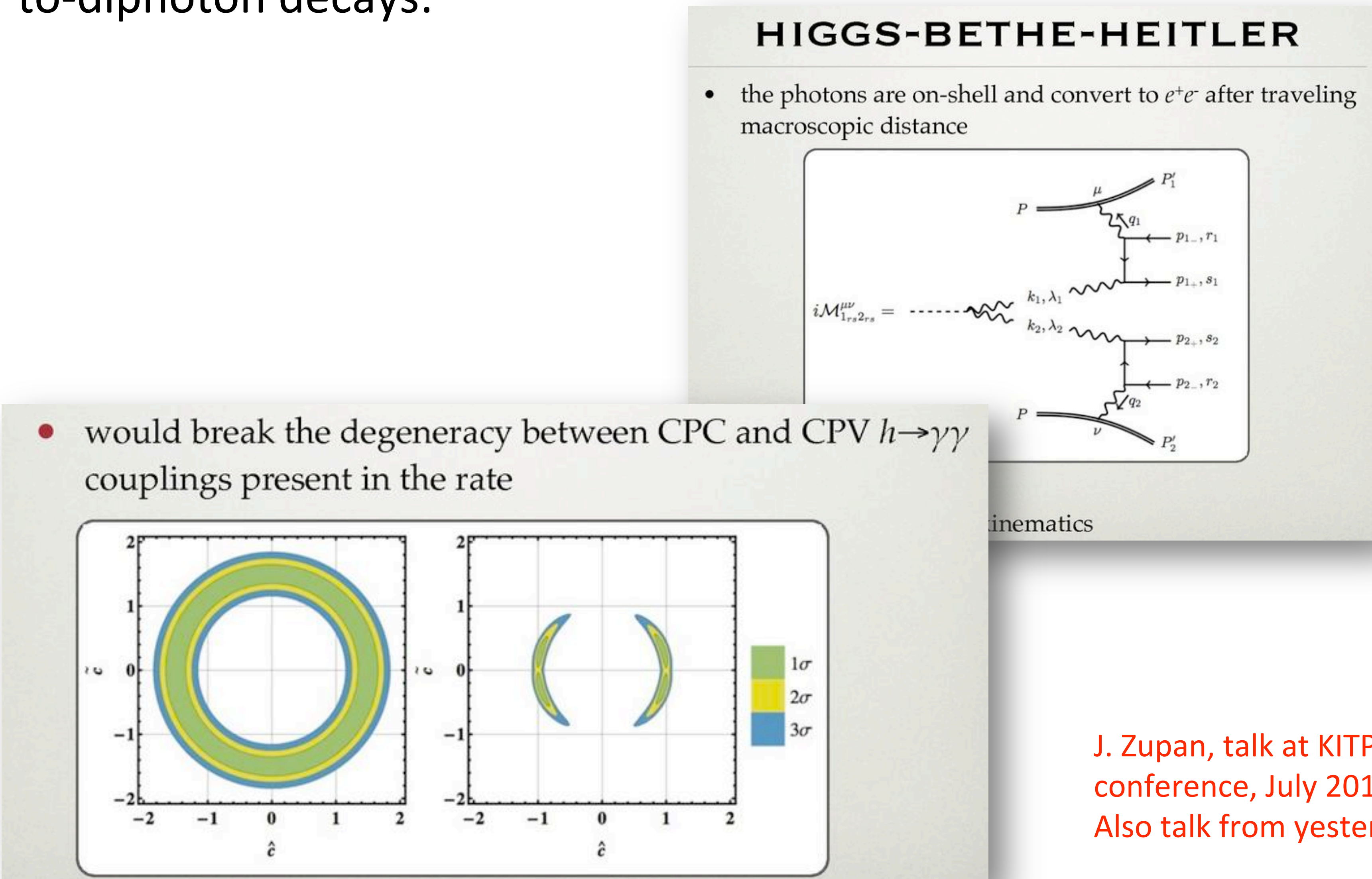


FIG. 5: The reconstructed Θ distribution at the ILC for $\Delta = 0$, $\Delta = \pi/4$, and $\Delta = \pi/2$.

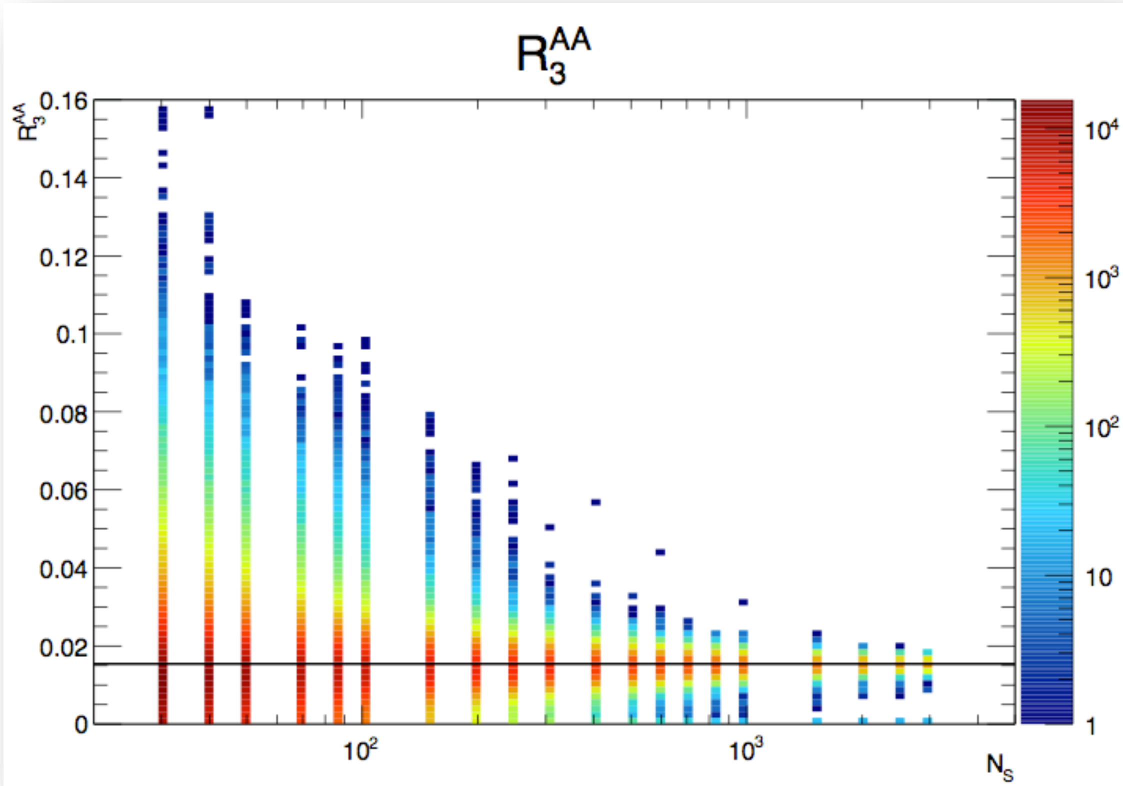
Harnik et. al.: 1308.1094

A third example, albeit very challenging, is CP violation in Higgs-to-diphoton decays:



J. Zupan, talk at KITP conference, July 2013.
Also talk from yesterday.

Alternatively, one could try to measure the CP-violation in Higgs-to-diphoton coupling in h->4 leptons events:



$$\Gamma_{ij}^{\mu\nu}(k,k') = \frac{1}{v}\Big(A_{1ij} m_Z^2 g^{\mu\nu} + A_{2ij}\left(k^\nu k'^\mu - k\cdot k' g^{\mu\nu}\right) + A_{3ij}\epsilon^{\mu\nu\alpha\beta} k_\alpha k'_{2\beta}\Big), \qquad (1)$$

where $ij = ZZ, Z\gamma$, or $\gamma\gamma$ and k and k' represent the

Chen and Vega-Morales: 1310.2893

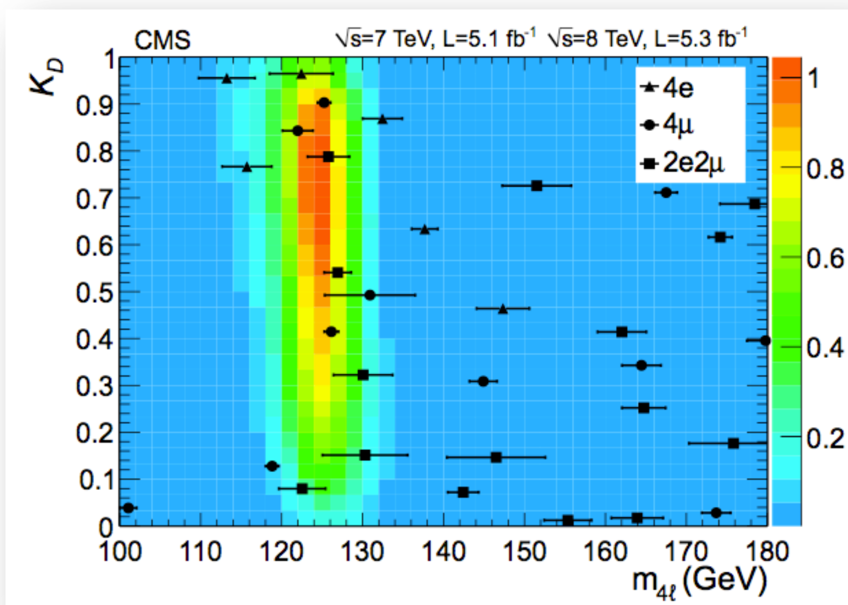
Main message:

Blindly fitting signal strength without properly considering coupling structures can be dangerous!!

To measure <u>both</u> coupling structures and coupling strengths, we need to extract maximal information out of experimental data.

Theoretically, the maximal amount of information is given by the matrix element of a given process.

The procedure to implement the above idea is called "Matrix Element Method," which was applied in the discovery of h(125) in the 4-lepton channel by CMS and the subsequent study on spin/CP of h(125).



Fortunately, there's now serious effort undertaken jointly by both theorists and experimentalists (mostly CMS?) to implement the Matrix Element Method.

They include

- JHU/Fermilab: mixed numerical/analytical approach.

- Caltech/Fermilab/Orsay: analytical approach in the 4-lepton channels.

- Florida: numerical approach in the 4-lepton channels.

- Non-American (Europe/India): incorporates NLO effects numerically.

(Numerical approach allows for hypothesis testing, while analytical approach allows for parameter extractions.)

It is a worthy effort that requires a tremendous amount of dedication and work!

But we need an all-out effort before to being able to answer the 10-billion dollar question!

On the other hand, in the signal strengths deviations are not expected to be large, since "decoupling" dictates the size of deviations to be

$$\mathcal{O}\left(\frac{v^2}{m_{\rm new}^2}\right) \approx 5\,\% \times \left(\frac{1\ {\rm TeV}}{m_{\rm new}}\right)^2$$

Some people are declaring "disappointments" that we have not seen deviations in Higgs measurements.

I believe the disappointers are misinformed, because the current 20-30% uncertainty is nowhere close to being able to establish a credible deviation!

So,

The era of precision Higgs measurements has just begun!

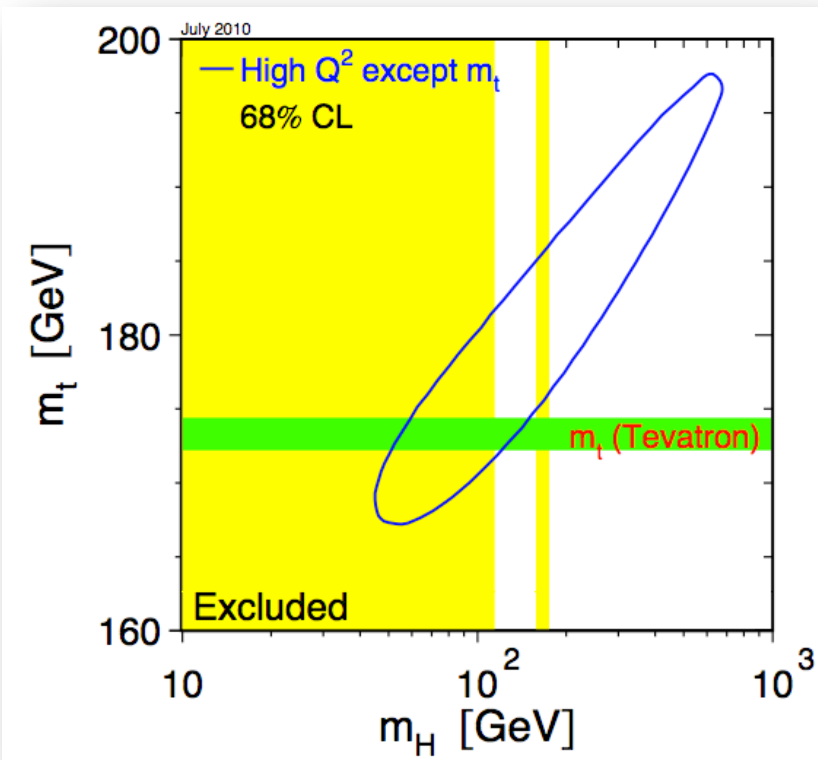
This is part of a two-pronged approach to discovering new physics beyond the Standard Model:

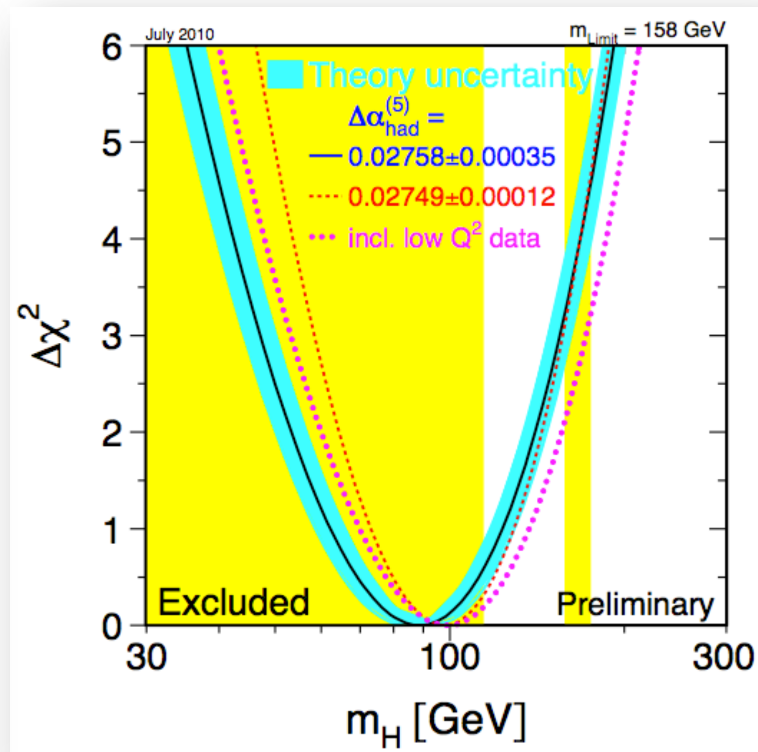
- Searching for phenomena unexpected from the SM
- Precise measurements of SM predictions

We will see that it is important to consider both aspects!

Historically, the two-pronged approach has worked very well, especially for the last two particles we discovered:

	all Z-pole data	all Z-pole data plus m_t	all Z-pole data plus m_W, Γ_W	all Z-pole data plus m_t, m_W, Γ_W
m_t [GeV]	173^{+13}_{-10}	$173.3^{+1.1}_{-1.1}$	179^{+12}_{-9}	$173.4^{+1.1}_{-1.1}$
m_H [GeV]	111^{+190}_{-60}	117^{+58}_{-40}	146^{+241}_{-81}	89^{+35}_{-26}





Continuing the analogy, one can even consider two classes of observables in precision Higgs measurements:

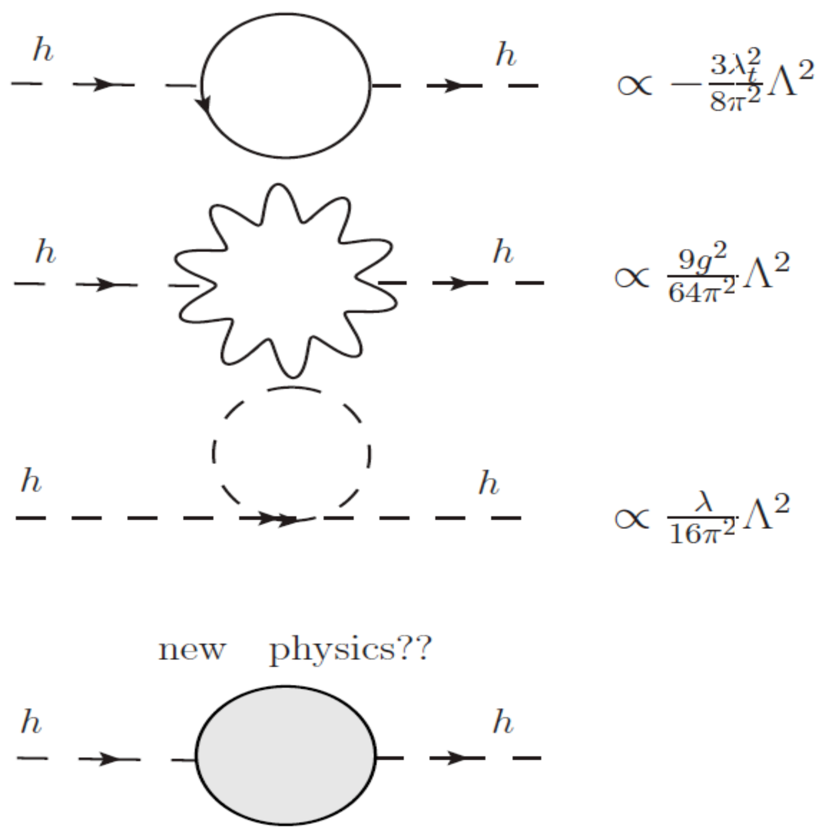
- Oblique observables: corrections entering self-energies of the Higgs boson

- Non-oblique observables: vertex corrections of Higgs couplings to fermions.

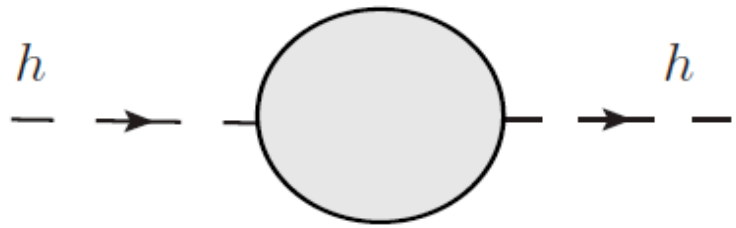
Let's consider them in turn.

In Higgs oblique observables, Naturalness plays an important role:

one-loop quadratic divergences in the Higgs self-energy is cut off by some "blob" at the TeV scale:



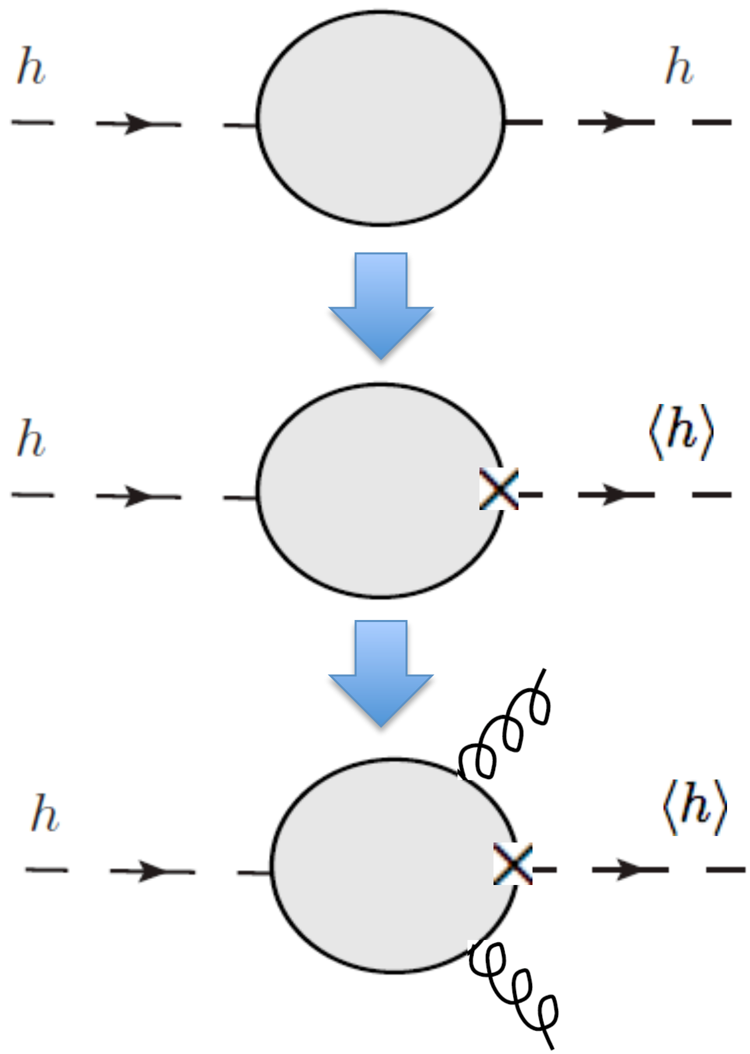
Lock up 10 model-builders in one room and they'll come up with 10^N (N>1) models for the "blob" in no time:



However, no matter what the blob is,

- if it carries QCD color, Higgs-glue-glue coupling will be modified.
- if it carries weak isopsin or hypercharge, Higgs-photon-photon and Higgs-Z-photon couplings will be modified.

It is simple to see how these statements come about:

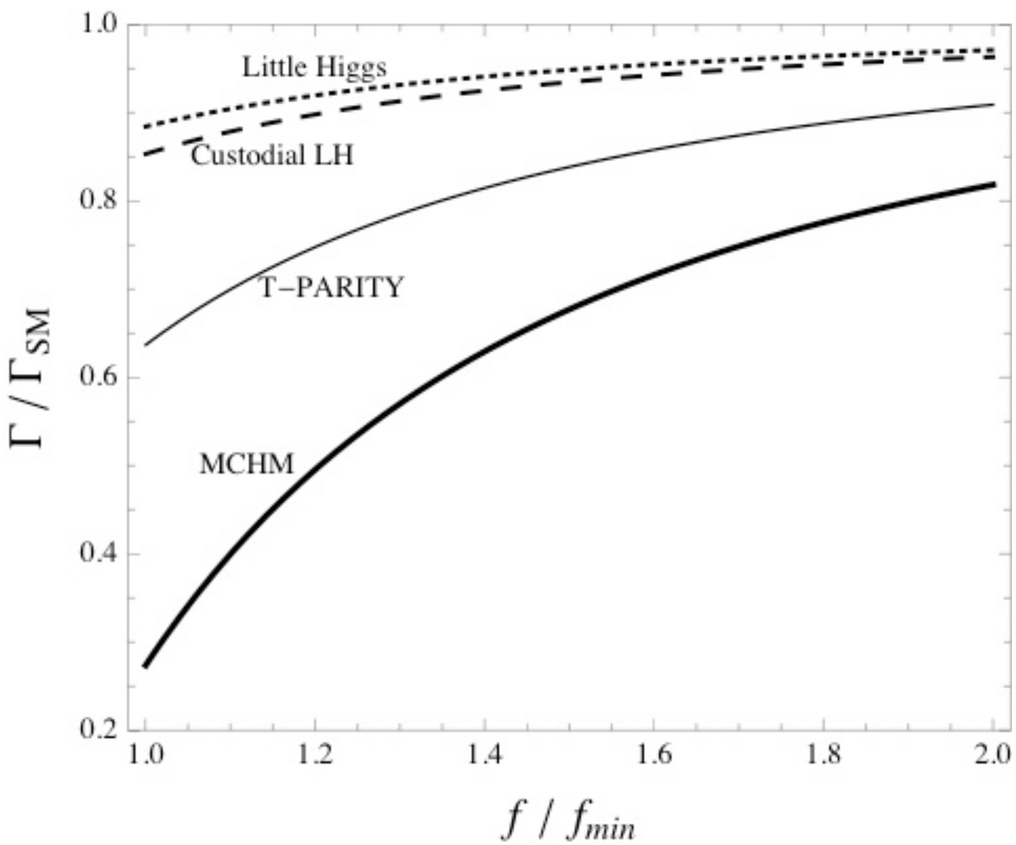


- Loop-induced couplings are the new oblique observables.

- In "natural" EWSB these couplings are modified naturally.

- Any observed modification in loop-induced couplings is a smoking-gun signal for (un)naturalness.

A “reduced” gluon coupling is a smoking-gun signal for “Naturalness,”



In composite Higgs models
this coupling is always suppressed!

IL, Rattazzi, Vichi:0907.5413
IL and Vichi:1010.2753

A “reduced” gluon coupling is a smoking-gun signal for “Naturalness,” while an “enhanced” gluon coupling may suggest fine-tuned Higgs mass.

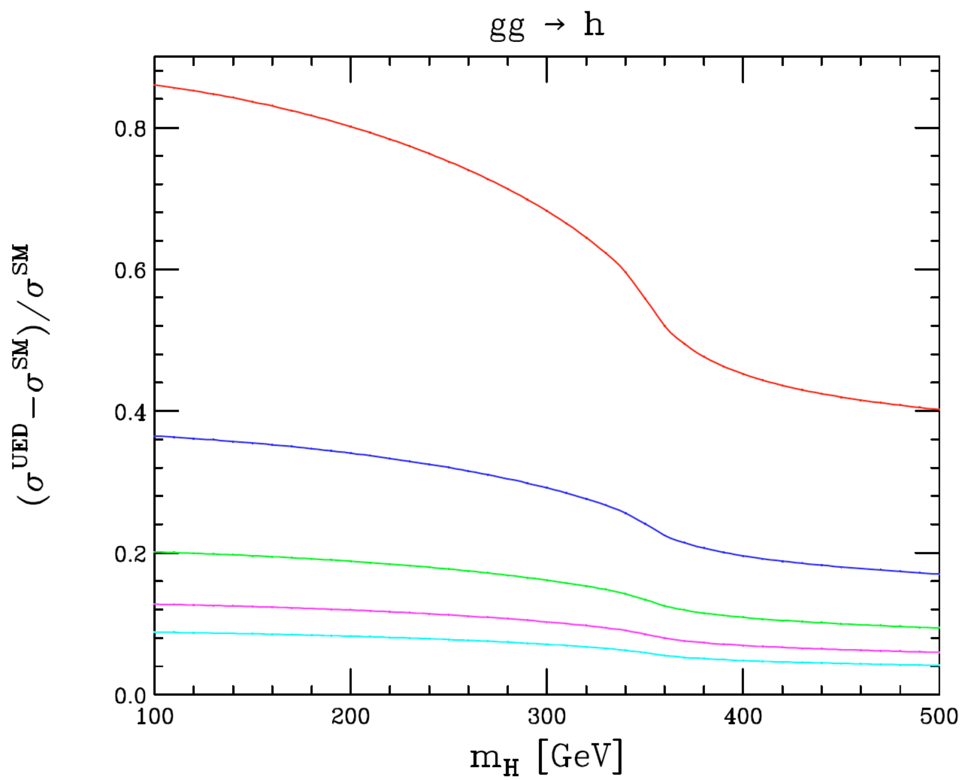
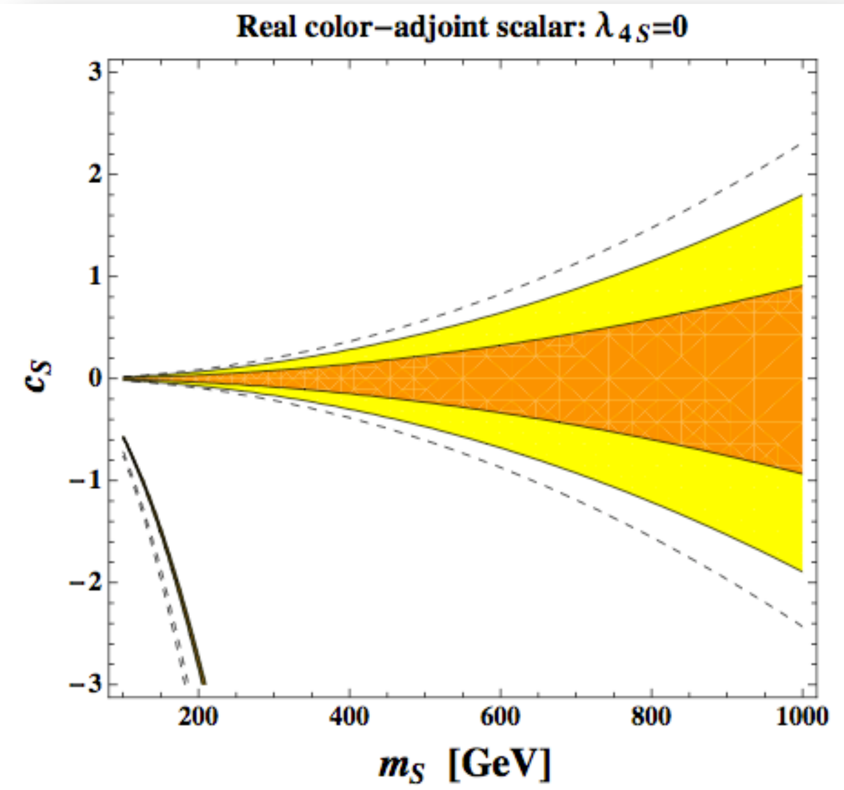


Figure 1: The fractional deviation of the $gg \to h$ production rate in the UED model as a function of m_H; from top to bottom, the results are for $m_1 = 500, 750, 1000, 1250, 1500$ GeV.

F. Petriello, hep-ph/0204067

However, at the level of O(5%) accuracy, higher-order corrections may become important especially for loop-induced couplings.

as a function of the new particle mass and its coupling to the Higgs. The orange and yellow region are for deviations within 5% and 10%, respectively. For comparison, we also show in dashed lines the contour of 10% deviation from only retaining the LO effect in new particles.

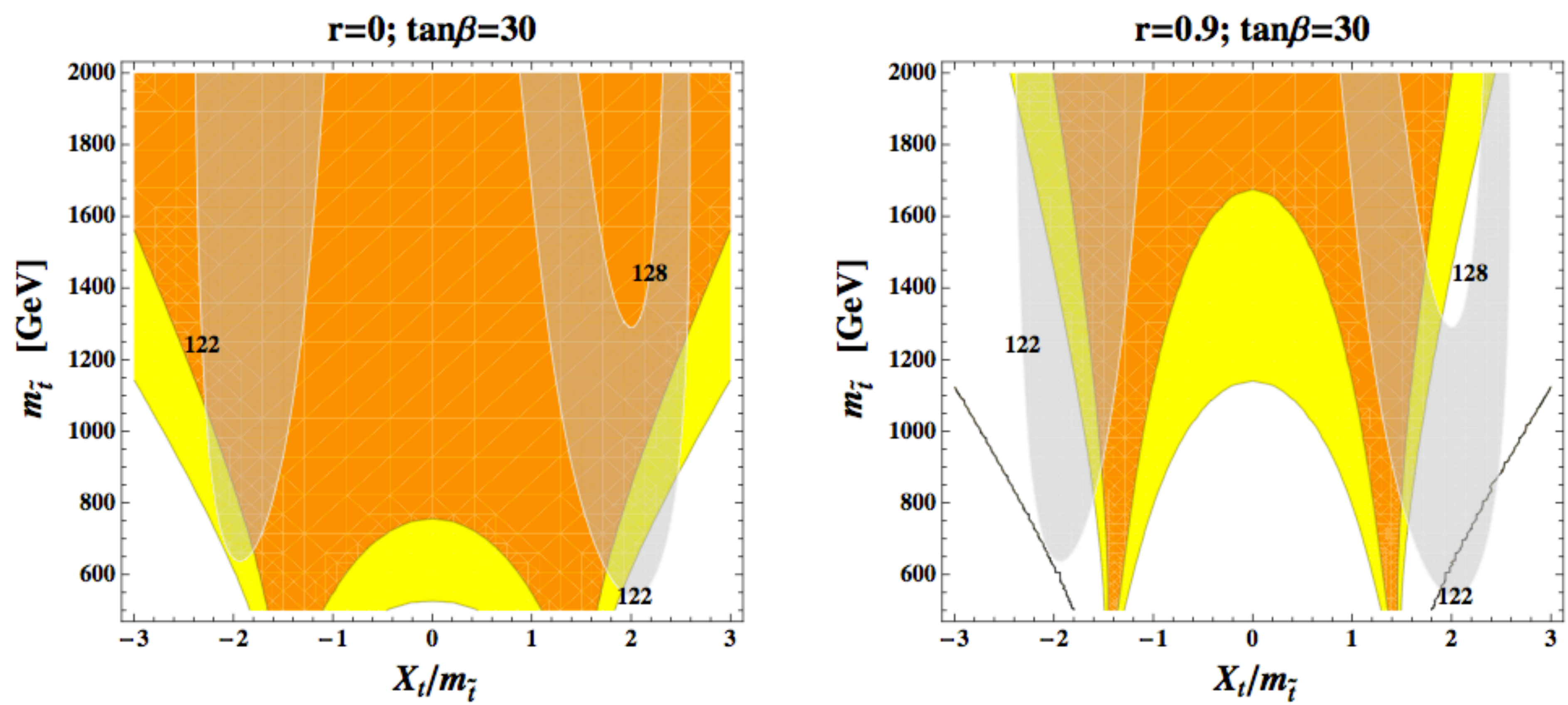


$$\mathcal{O}_S = c_S H^\dagger H S^\dagger S$$

The limit on the mass change by O(100 GeV) without NLO effects.

Gori and IL: 1307.0496

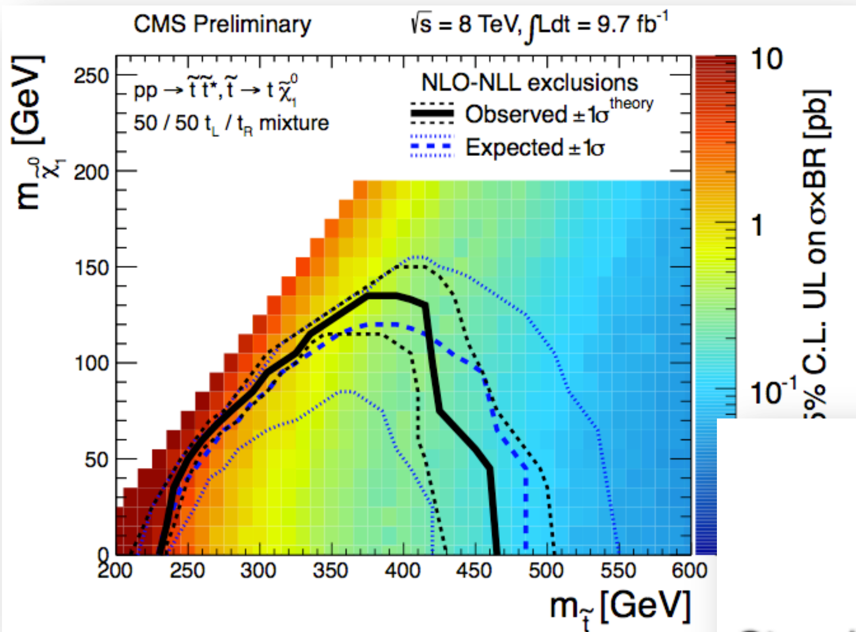
When there's more than one particle in the loop, things change drastically.
E.g., SUSY has two stops:



This is independent of MSSM and applies to SUSY in general!

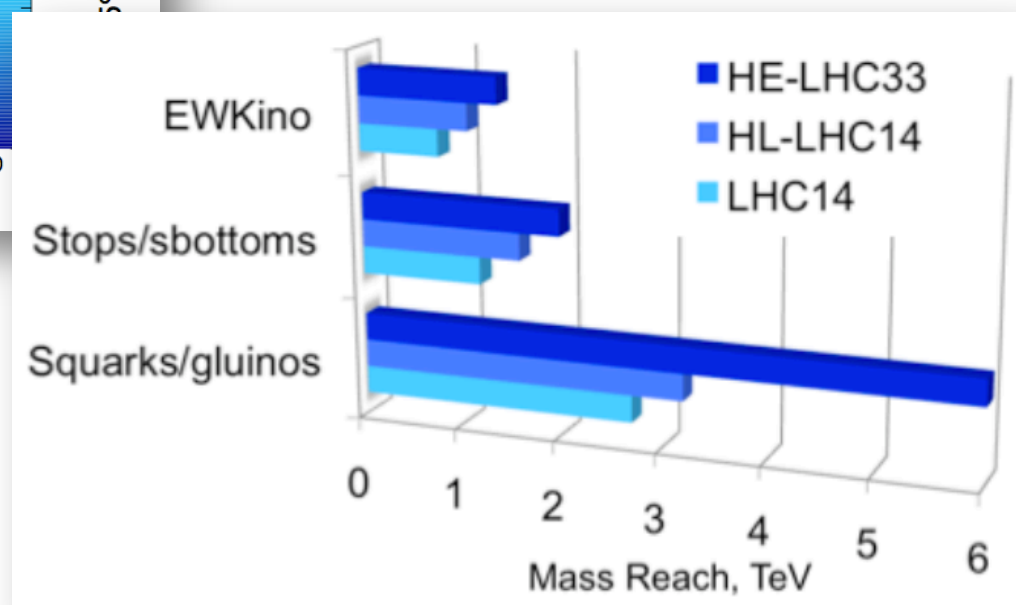
Gori and IL: 1307.0496

One is tempted to compare the bound from precision Higgs measurements with those from direct searches at the LHC:



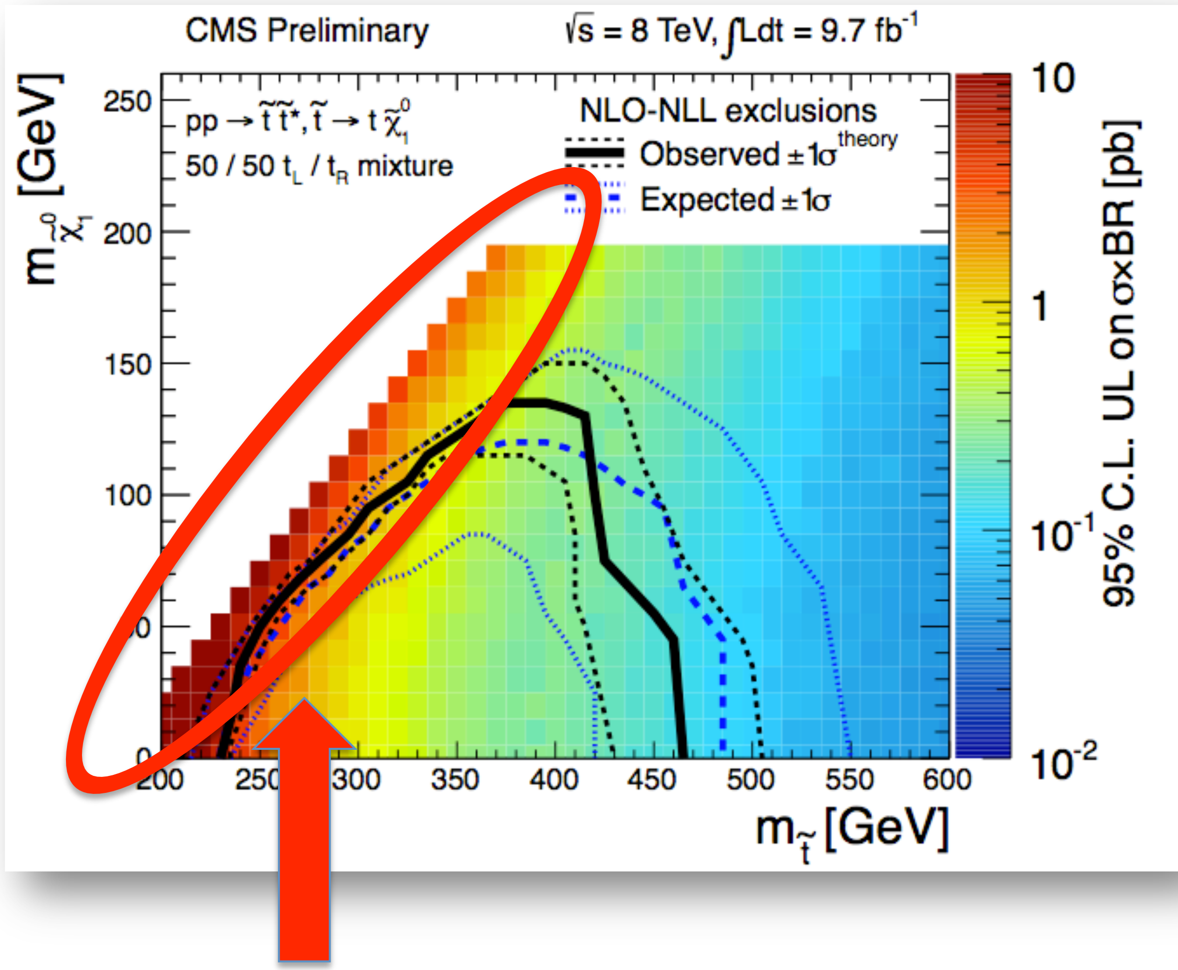
Current bound < 600-700 GeV

Projection for 14 TeV LHC is about 1.2 TeV!



Physics Briefing Book for “European Strategy for Particle Physics”

It is important to recall that direct searches always depend on the decay final states and the rest of the spectrum:



Direct searches have less/no acceptances in this region due to kinematics, hence the degraded limits.

Constraints from precision Higgs measurements, on the other hand, involve a different set of assumptions from the direct searches.

So precision measurements and direct searches are very much complementary to each other!

Next let's consider non-oblique observables, more specifically the *hbb* and *hττ* couplings, which are expected to be measured most precisely.

- Corrections to these observables are more somewhat more complicated, and we chose to analyze them in models with an extended Higgs sector, 2HDMs in particular.

- For many years, getting a SM-like Higgs out of the lightest CP-even Higgs in 2HDMs relies on "decoupling limit," where all non-standard scalars are much heavier than the *Z* boson mass.

“Decoupling limit” has dominated so much of people’s thinking that it has become a folklore!

In fact, it was already pointed out more than 10 years ago that, there could be a SM-like Higgs without decoupling non-SM scalars:

V. A SM-LIKE HIGGS BOSON WITHOUT DECOUPLING

We have demonstrated above that the decoupling limit (where $m_A^2 \gg |\lambda_i| v^2$) implies that $|c_{\beta-\alpha}| \ll 1$. However, the $|c_{\beta-\alpha}| \ll 1$ limit is more general than the decoupling limit. From eq. (36), one learns that $|c_{\beta-\alpha}| \ll 1$ implies that either (i) $m_A^2 \gg \lambda_A v^2$, and/or (ii) $|\widehat{\lambda}| \ll 1$ subject to the condition specified by eq. (33). Case (i) is the decoupling limit described in Section 3. Although case (ii) is compatible with $m_A^2 \gg \lambda_i v^2$, which is the true decoupling limit, there is no requirement *a priori* that m_A be particularly large [as long as eq. (33) is satisfied]. It is even possible to have $m_A < m_h$, implying that all Higgs boson masses are $\lesssim \mathcal{O}(v)$, in contrast to the true decoupling limit. In this latter case, there does not exist an effective low-energy scalar theory consisting of a single Higgs boson.

Gunion and Haber, hep-ph/0207010

The phenomenon of “alignment without decoupling” was (re)discovered very recently by two groups.

Alignment= lightest CP-even Higgs being SM-like.

MSSM augmented by a triplet scalar:

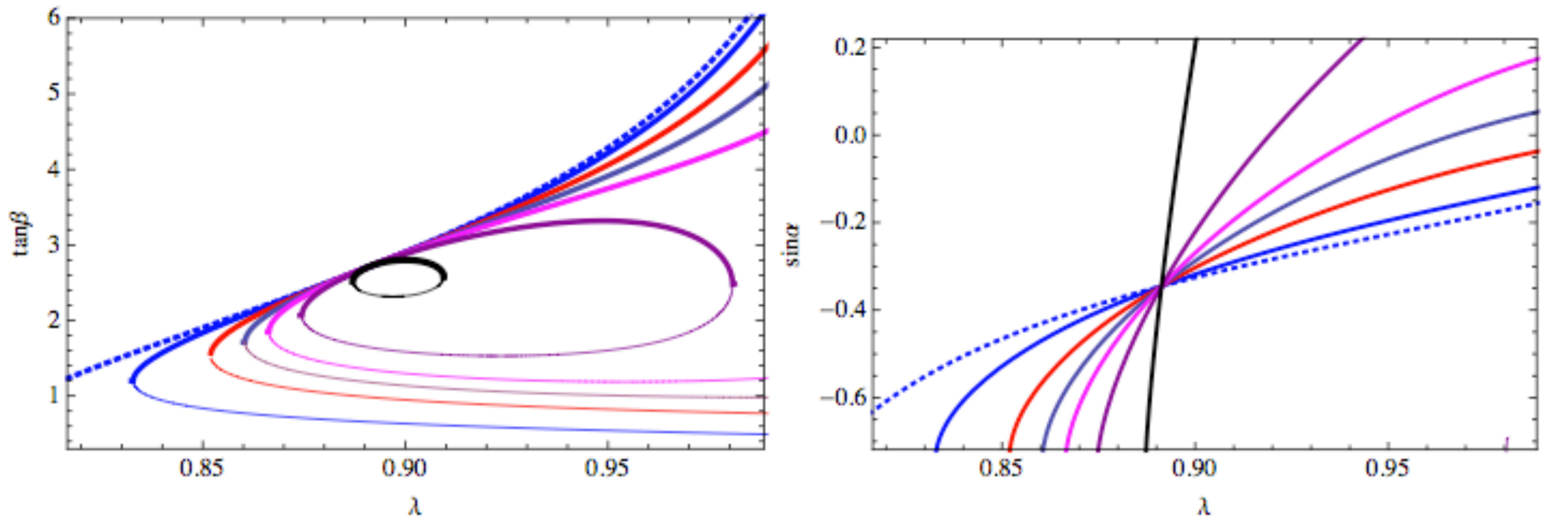


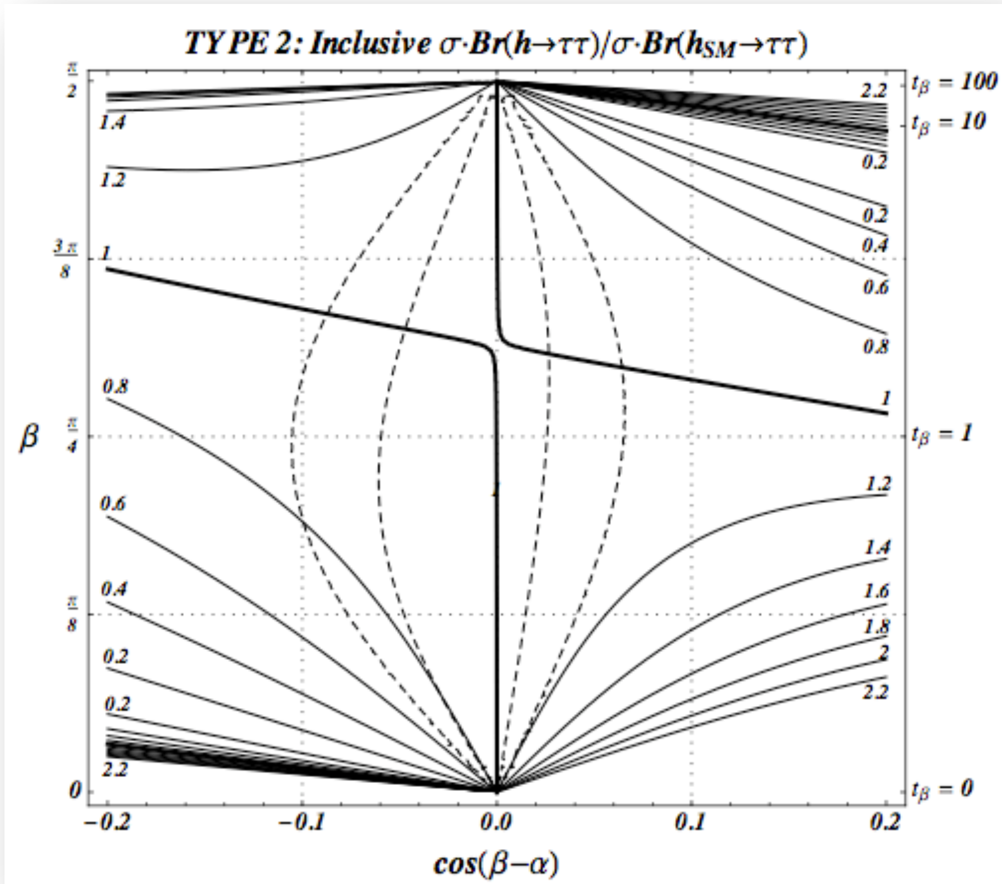
Figure 1: *Left panel:* $\tan\beta$ *as a function of* λ *providing* $m_h = 126\,GeV$ *in the decoupling limit or large* m_A *(blue dotted) and for* $m_A = 200$ *GeV (blue solid), 155 GeV (red solid), 145 GeV (grey solid), 140 GeV (magenta solid), 135 GeV (purple solid) and 130 GeV (black solid). The other parameter inputs are those of eq.* (2.16). *Right panel: The same but for* $\sin\alpha$ *as a function of* λ.

Delgado, Nardini and Quiros.: 1303.0800

The phenomenon of “alignment without decoupling” was (re)discovered very recently by two groups.

Alignment= lightest CP-even Higgs being SM-like.

Scanning over general THDMs:



Craig, Galloway and Thomas: 1305.2424

At first sight, the “alignment without decoupling” seems quite mysterious.

Until one realizes that the alignment occurs whenever the CP-even mass eigenbasis coincides with the “Higgs basis,” where all the VEV is rotated into one of the Higgs doublet.

Then at second sight it seems the other Higgs does not couple to W/Z (at the tree-level) and become an inert Higgs.

It turns out the heavy CP-even Higgs still have couplings to SM fermions that are enhanced by tanbeta. So it is not inert!

Decoupling is one way to turn off the big H coupling to W/Z bosons, but it is NOT the only way!

This is the scalar potential for a general CP-conserving THDM:

$$
\begin{aligned}
V \;=\;& m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + \text{h.c.}) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 \\
&+\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\
&+\left\{\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + [\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)]\Phi_1^\dagger\Phi_2 + \text{h.c.}\right\} \;,
\end{aligned}
$$

Absence of tree-level FCNC requires $\lambda_6 = \lambda_7 = 0$. (Glashow-Weinberg condition.)

In this case, one can only find "alignment without decoupling" can low tanbeta.

Moreover these solutions are fine-tuned, because they require choosing specific value of λ_2 .

Carena, IL, Shah, Wagner: 1310.2248

More explicitly, this is the alignment conditions:

$$m_h^2 = v^2 \left(\lambda_1 c_\beta^2 + 3\lambda_6 s_\beta c_\beta + \tilde{\lambda}_3 s_\beta^2 + \lambda_7 t_\beta s_\beta^2\right)$$

$$m_h^2 = v^2 \left(\lambda_2 s_\beta^2 + 3\lambda_7 s_\beta c_\beta + \tilde{\lambda}_3 c_\beta^2 + \lambda_6 t_\beta^{-1} c_\beta^2\right)$$

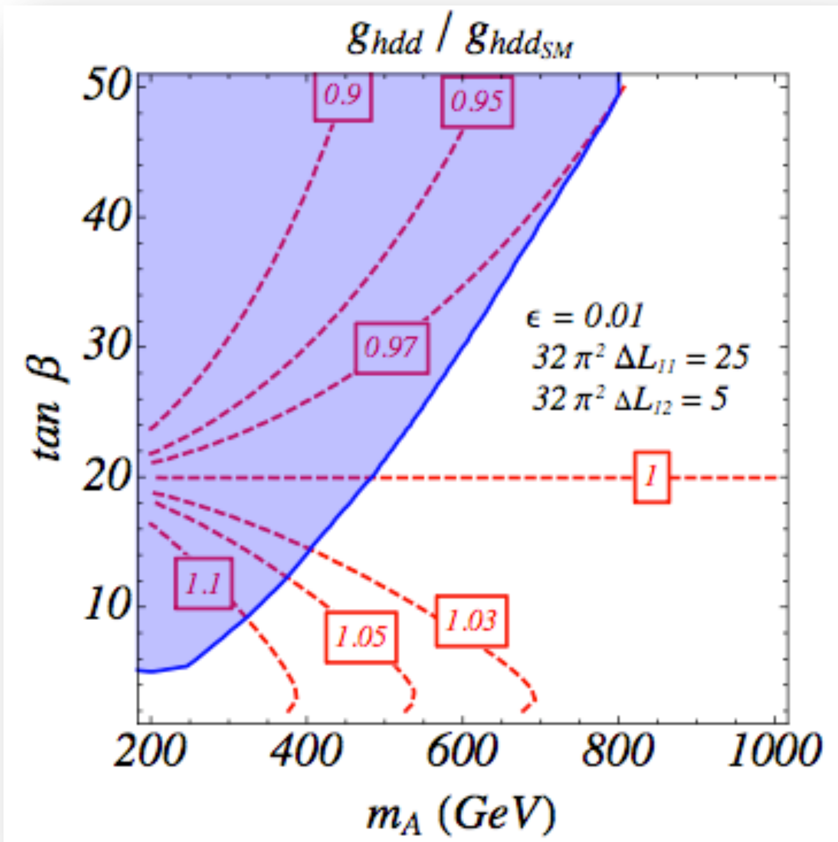
In the large tanbeta limit, the second condition only depends on λ_2 :

$$m_h^2 - \lambda_2 v^2 = \mathcal{O}\left(\frac{1}{t_\beta^2}, \frac{\lambda_7}{t_\beta}, \frac{\lambda_6}{t_\beta^3}\right)$$

So the two conditions decouple, thereby reducing the amount of "tuning" required.

In general, λ_7 and λ_6 will be induced at the loop-level generically and acquire small values.

In this case there exist large tanbeta solutions for which "alignment without decoupling" occur.



Alignment could occur in the MSSM for $\mu \approx M_{SUSY}$

At the alignment limit, m_A can be arbitrary!

In MSSM "alignment without decoupling" usually happens at tanbeta > 10.

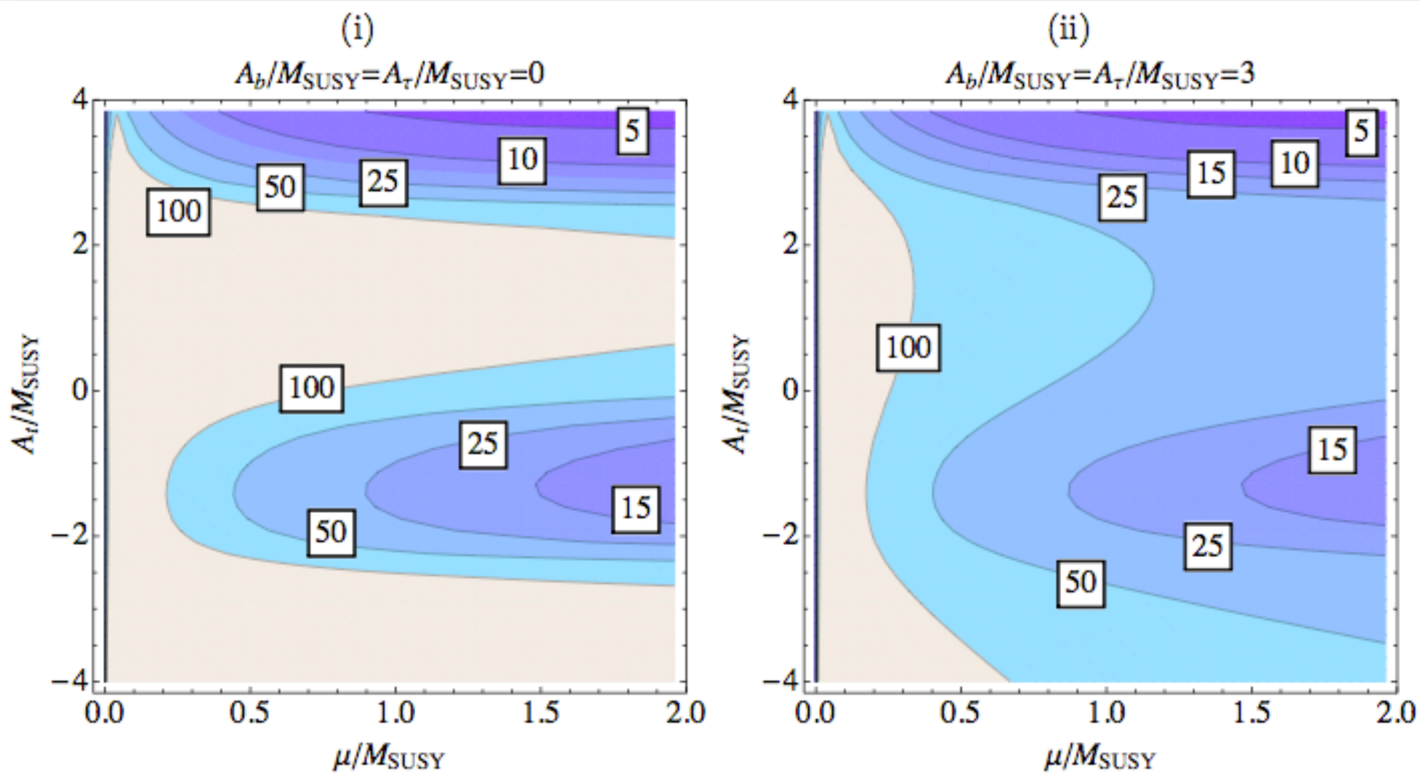
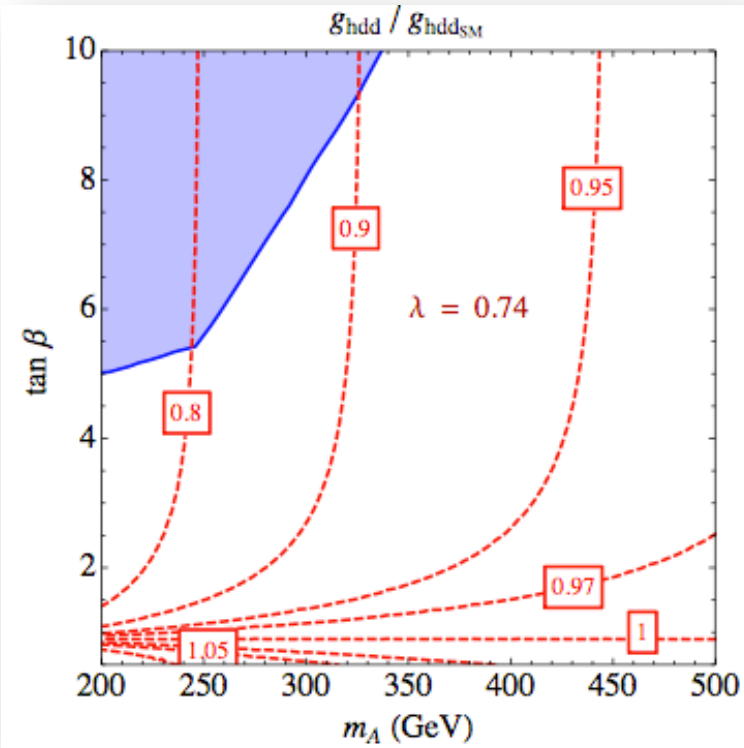
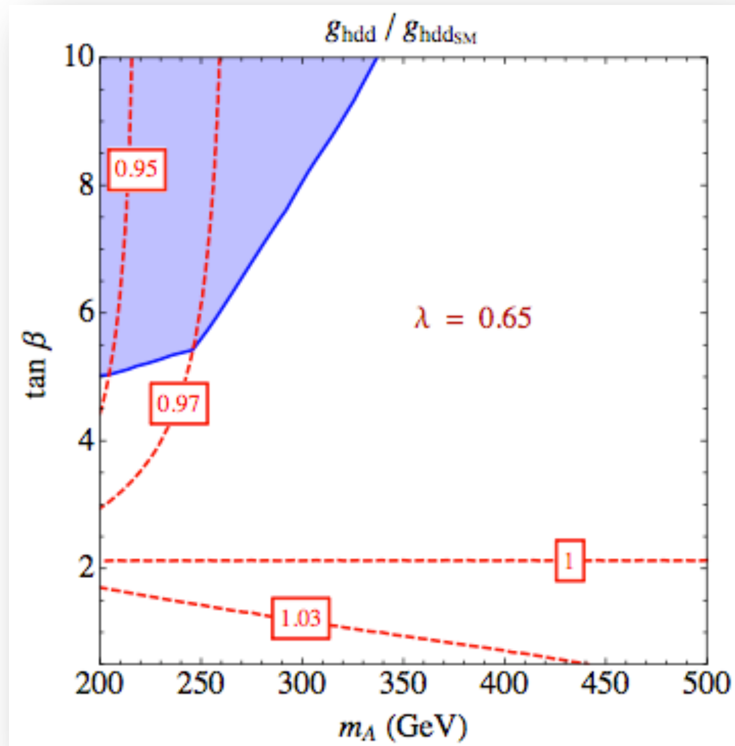


FIG. 5: Same as Fig. 3 but now showing alignment values of t_β under the assumptions: (i) $A_b = A_\tau = 0$ and (ii) $A_b/M_{SUSY} = A_\tau/M_{SUSY} = 3$. Only one set of solutions appear in these cases.

In NMSSM there's an interesting coincidence that alignment without decoupling occurs at $\lambda \approx 0.7$, where the Higgs mass is least fine-tuned, and at low tanbeta.

$$\Delta_S \mathcal{W} = \lambda S H_u H_d$$





This scenario again exemplifies the importance of using a two-pronged approach:

Even if h(125) couplings are very SM-like, new physics does not need to be heavy and a light extended Higgs sector could still be waiting to be discovered!

Last but not least, there are two important questions one would like to know about h(125):

- Does it have the self-coupling predicted by the SM?
- Does it unitarize WW scatterings?

However, these questions are notoriously difficult to study at the LHC, because we are limited by the small rates for these two processes.

Moreover, precise determination of coupling structures of h(125) is also limited by the statistics.

If you are frustrated, what I will show next should liberate your mind…

Comparison of Higgs cross-section at 14 and 100 TeV:

Process	$\sqrt{s}$ = 14 TeV	$\sqrt{s}$ = 100 TeV	
ggF[a]	50.35 pb	740.3 pb (14.7)	15-fold increase
VBF[b]	4.40 pb	82.0 pb (18.6)	20-fold increase
WH[c]	1.63 pb	15.90 pb (9.7)	10-fold increase
ZH[c]	0.904 pb	11.26 pb (12.5)	12-fold increase
ttH[d]	0.623 pb	37.9 pb (61)	60-fold increase
$gg \rightarrow HH^{e}(\lambda=1)$	33.8 fb	1.42 pb (42)	50-fold increase

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HiggsEuropeanStrategy2012

There's been recent discussion on the possibility of a 100 TeV pp collider from the perspective of direct searches.

However, 100 TeV collider should also be every Higgs worker's dream come true!

It is not just about discovering new particles. It is about whether the new particles, if any, have anything to do with EWSB!

Simple homework assignment:

Go home and come up with one Higgs measurement you most desperately want to know.

Then make the comparison between 14 and 100 TeV using the cross-section I showed you.

Homer Simpson has a famous quote:

If something's hard to do, then it's not worth doing.

My version:

If something's hard to measure, then it's worth measuring at a 100 TeV collider!