Quantum Numbers and Couplings of h(125)

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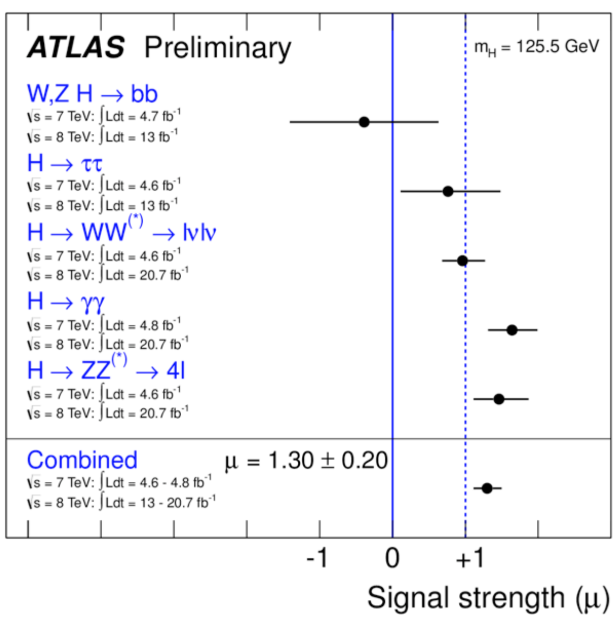
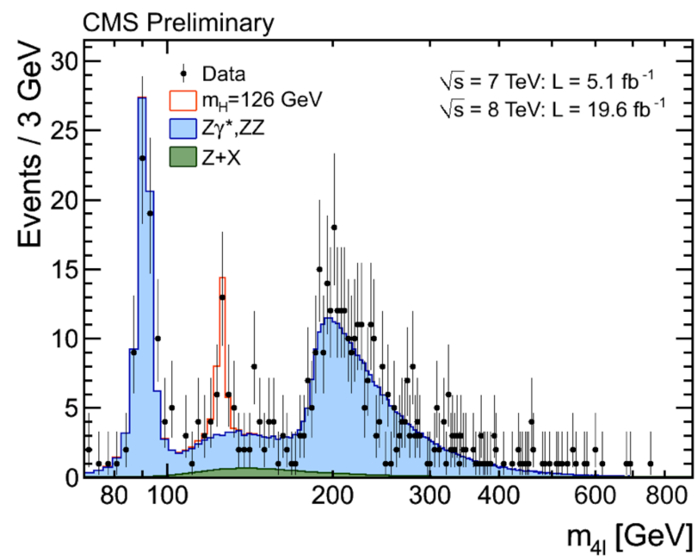
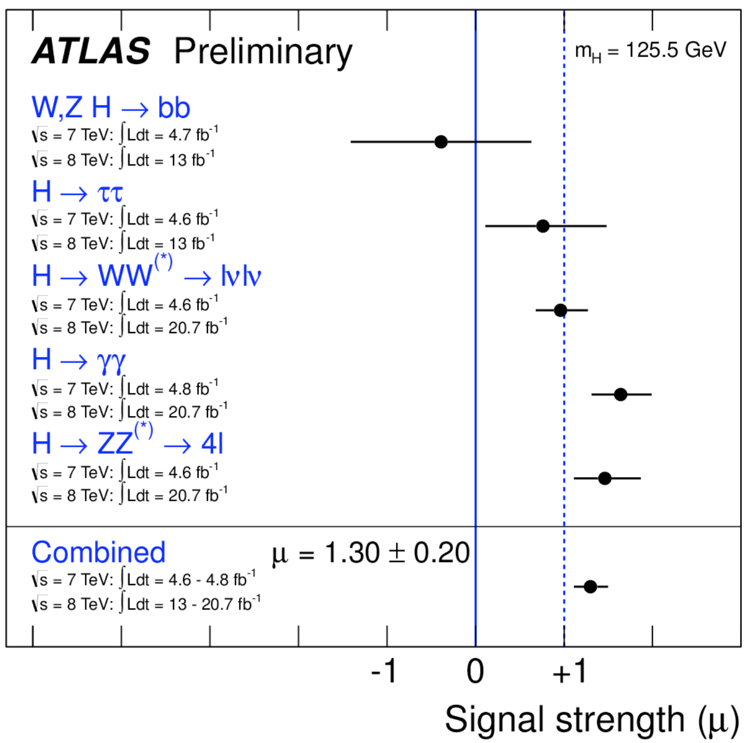
Argonne/ Northwestern

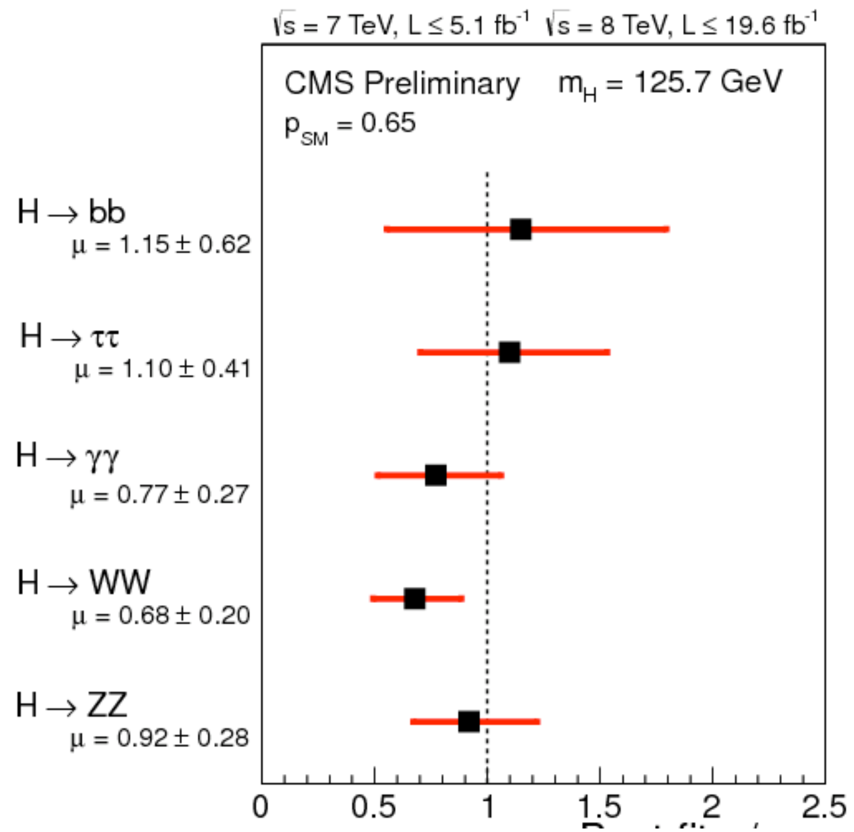
August 15, 2013 @ ISHEP 2013 in Beijing, China





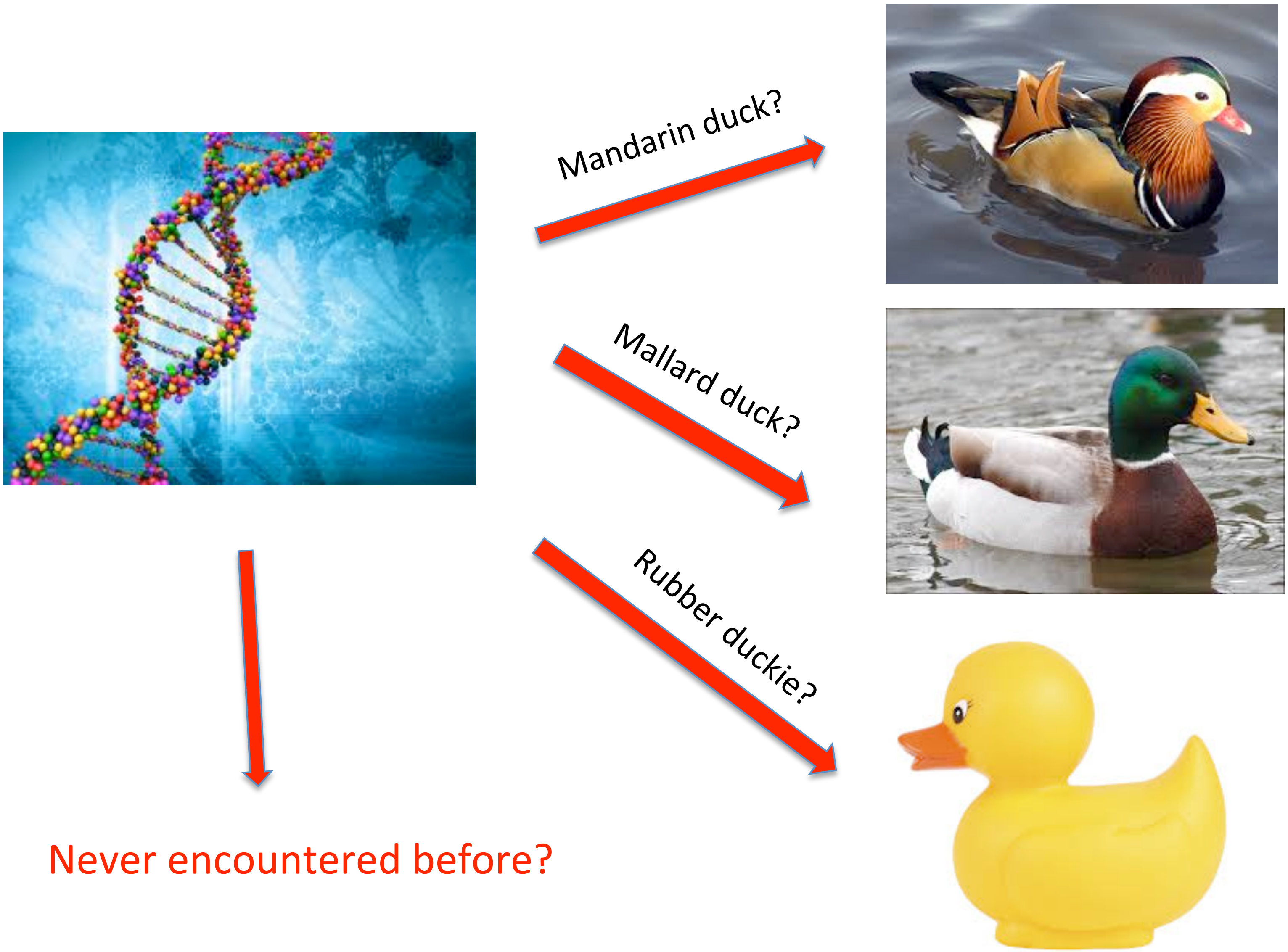
These two plots are worth a thousand words:





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

Our next job is to DNA-sequencing the Higgs to find out what kind of Higgs it is.



DNA of the Higgs lies in the quantum numbers and, more generally, couplings.

I wish to distinguish two objects --

- Coupling structures: 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: magnitude of the coefficient multiplying the coupling structure in the lagrangian.

  Straightforward to measure if assuming only one structure.

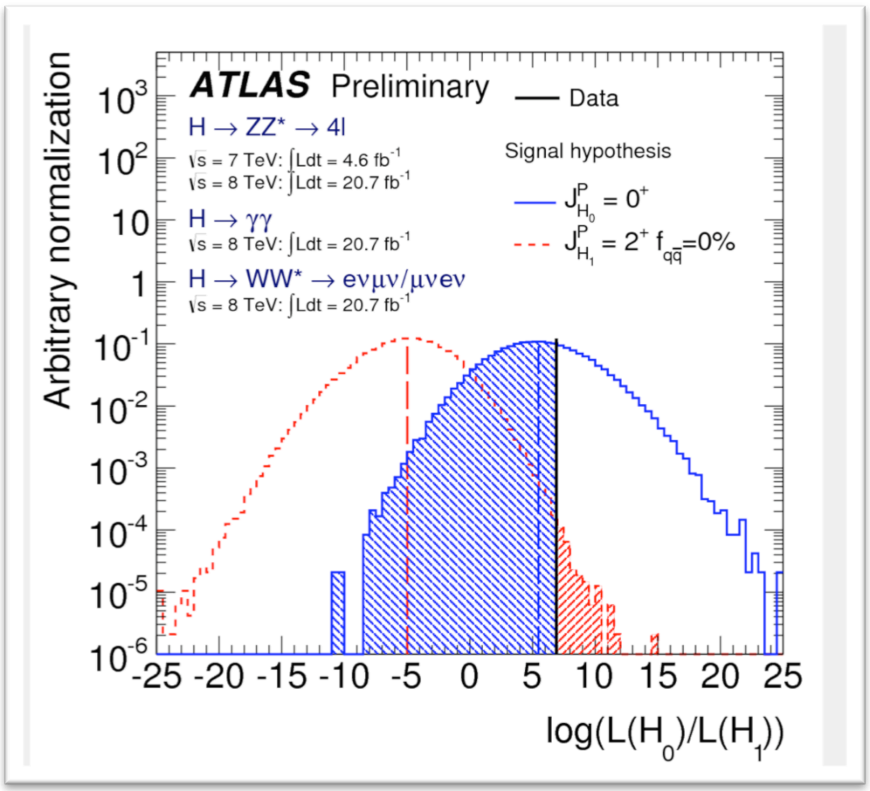
What is a Higgs boson anyway?

A Higgs boson is a particle that is

- Spin-0 (scalar)
- Charge and Parity (CP) even
- The neutral component of an electroweak doublet
- The origin of mass for W/Z bosons as well as the quarks and charged leptons

Spin measurement:
It relies on angular correlations in the decay products, most notably 4-lepton and diphoton final states.

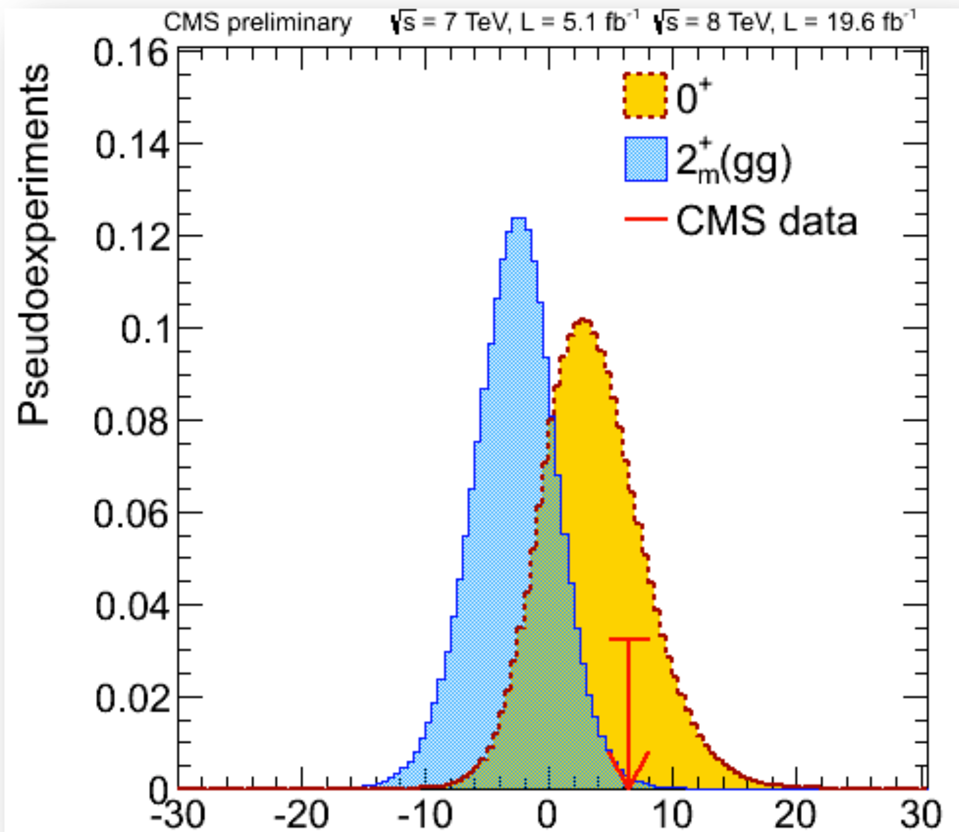
ATLAS angular analysis with spin-0 vs spin-2 (with minimal coupling)



Abvoe 99.9% C.L. exclusion!

Spin measurement:
It relies on angular correlations in the decay products, most notably 4-lepton and diphoton final states.

CMS 4-lepton analysis excluded spin-2 (with minimal coupling) at 98.5% C.L.



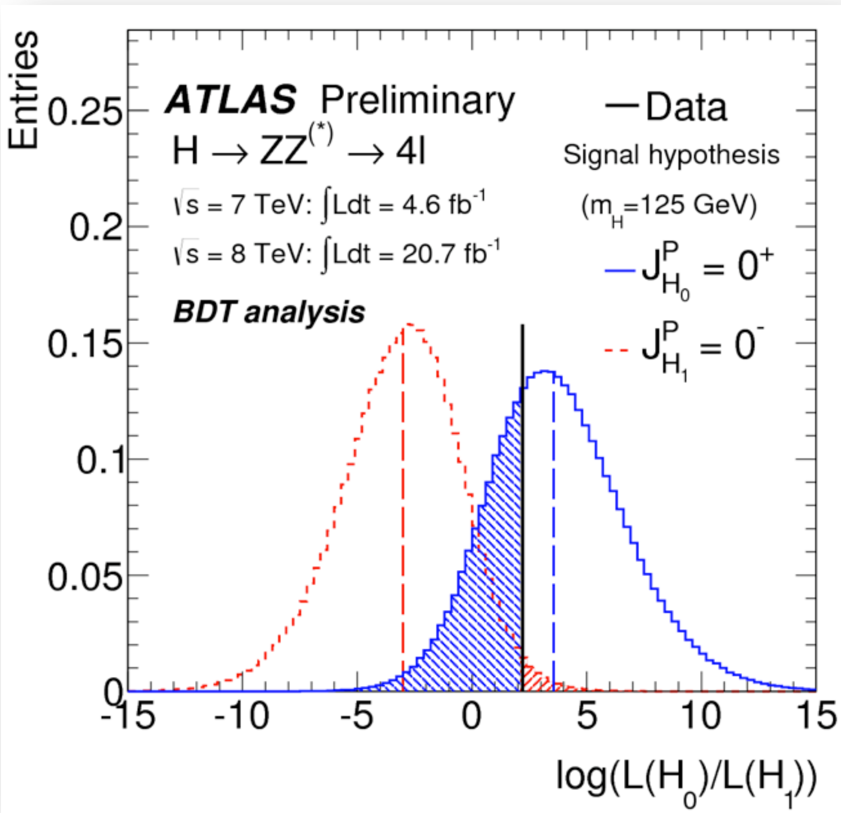
h(125) is

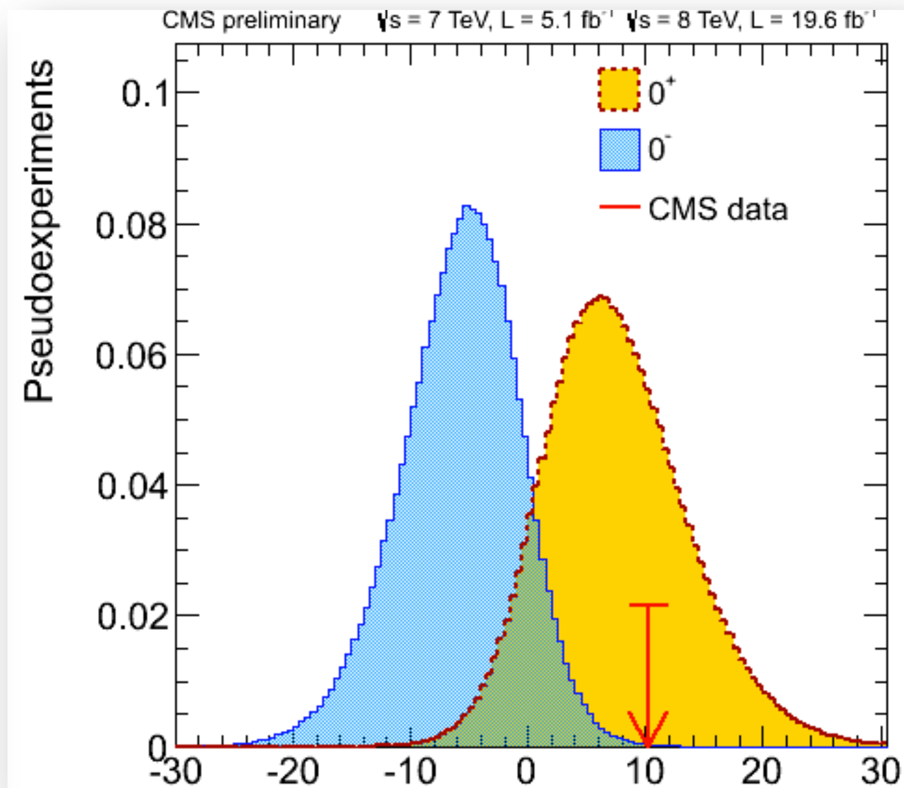
- most likely a spin-0 (scalar) particle. ✔

> "I would kill myself if it's spin-2." by a prominent theorist at KITP, Santa Barbara in December, 2012.

CP measurement:
It relies on angular correlations in 4-lepton final states, since diphoton channel doesn't have enough discriminating power.

Both ATLAS and CMS 4-lepton analyses excluded CP-odd scalar :





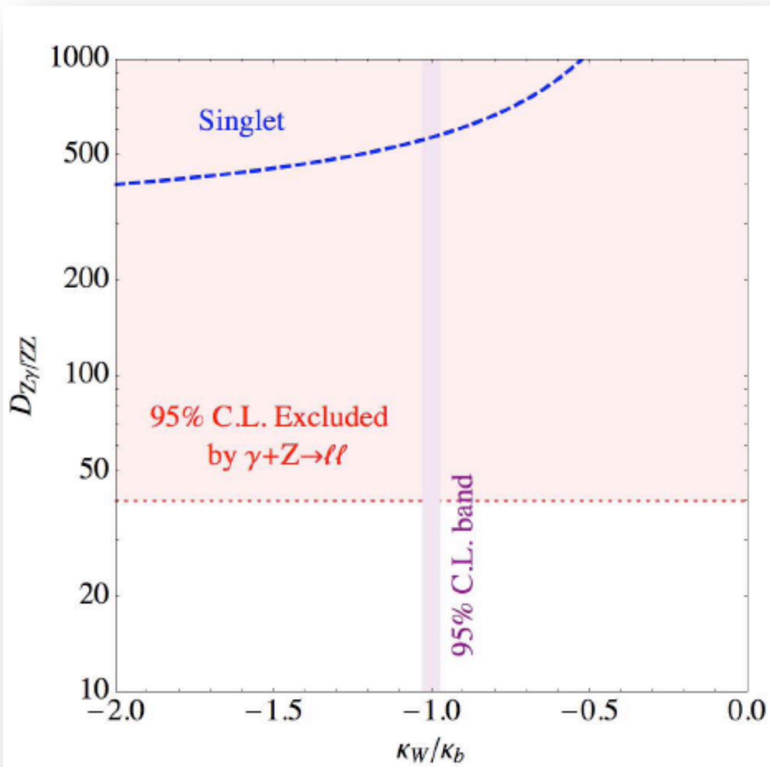
h(125) is

- most likely a spin-0 (scalar) particle. ✔
- most likely Charge and Parity (CP) even. ✔

Electroweak quantum number relies on two measurements:

- Higgs decays to Z + photon can be used to exclude an electroweak singlet scalar with dim-5 coupling to gauge bosons (ie non-dilatonic singlet)

$$\kappa_W \frac{\alpha_{em}}{4\pi s_w^2} \frac{S}{4m_S} W^a_{\mu\nu} W^{a\,\mu\nu} + \kappa_B \frac{\alpha_{em}}{4\pi c_w^2} \frac{S}{4m_S} B_{\mu\nu} B^{\mu\nu}$$



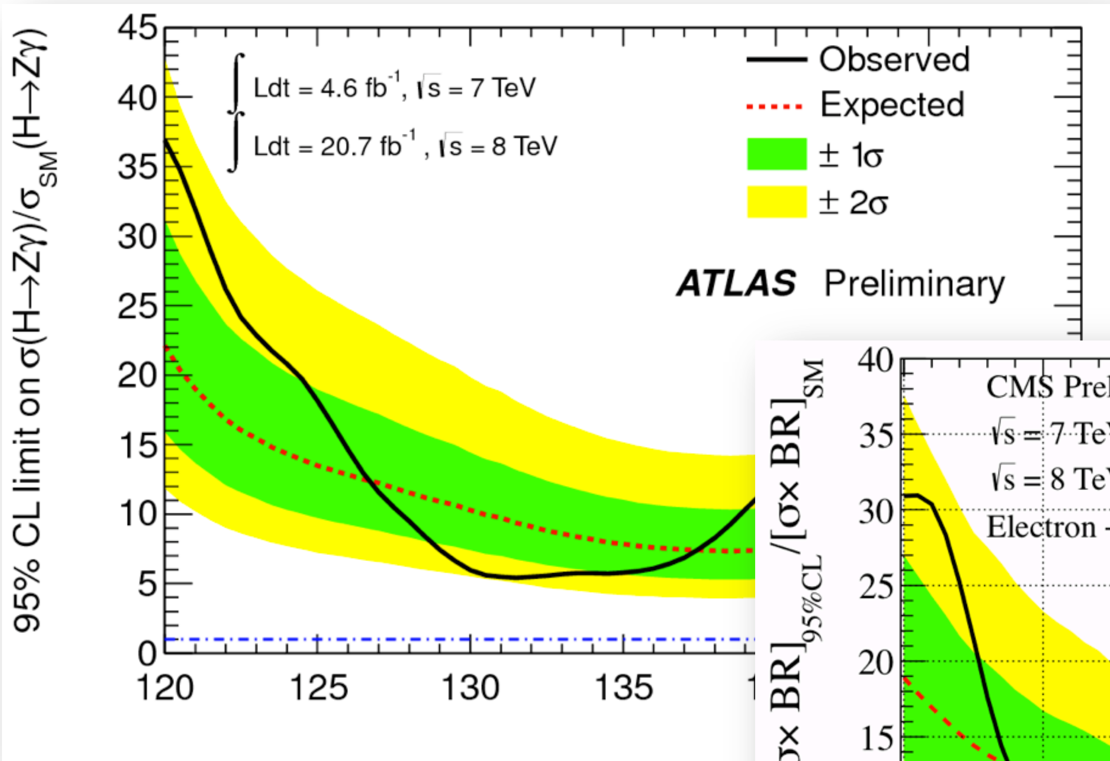
Using two parameters to fit WW, ZZ, and diphoton channel, the resulting Z+ photon rate turns out to be 500 times larger than SM expectation.

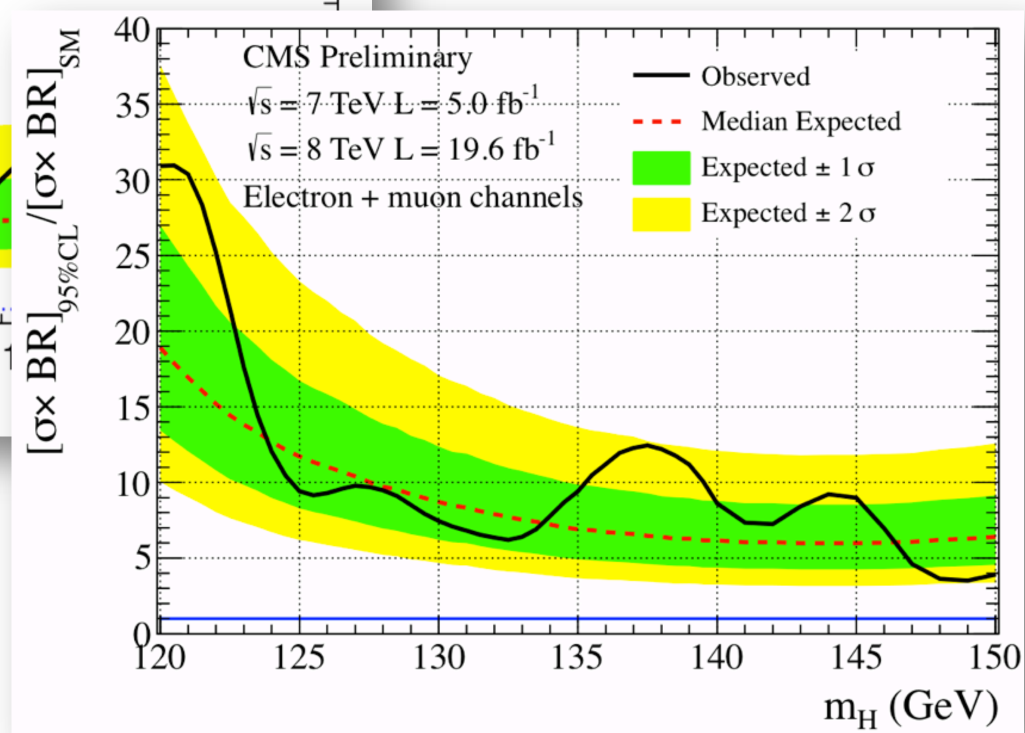
IL and Lykken, 1005.0872

IL, Lykken, and Shaughnessy,1105.4587

IL, Lykken, and Shaughnessy, 1207.1093

ATLAS and CMS finally gave due attention to Z+photon channel:





It is possible to use larger representations of $SU(2)_L$ while satisfying the electroweak constraint of $\Delta\rho \approx 1$.

There's only one other possibility in terms of the coupling to WW and ZZ,

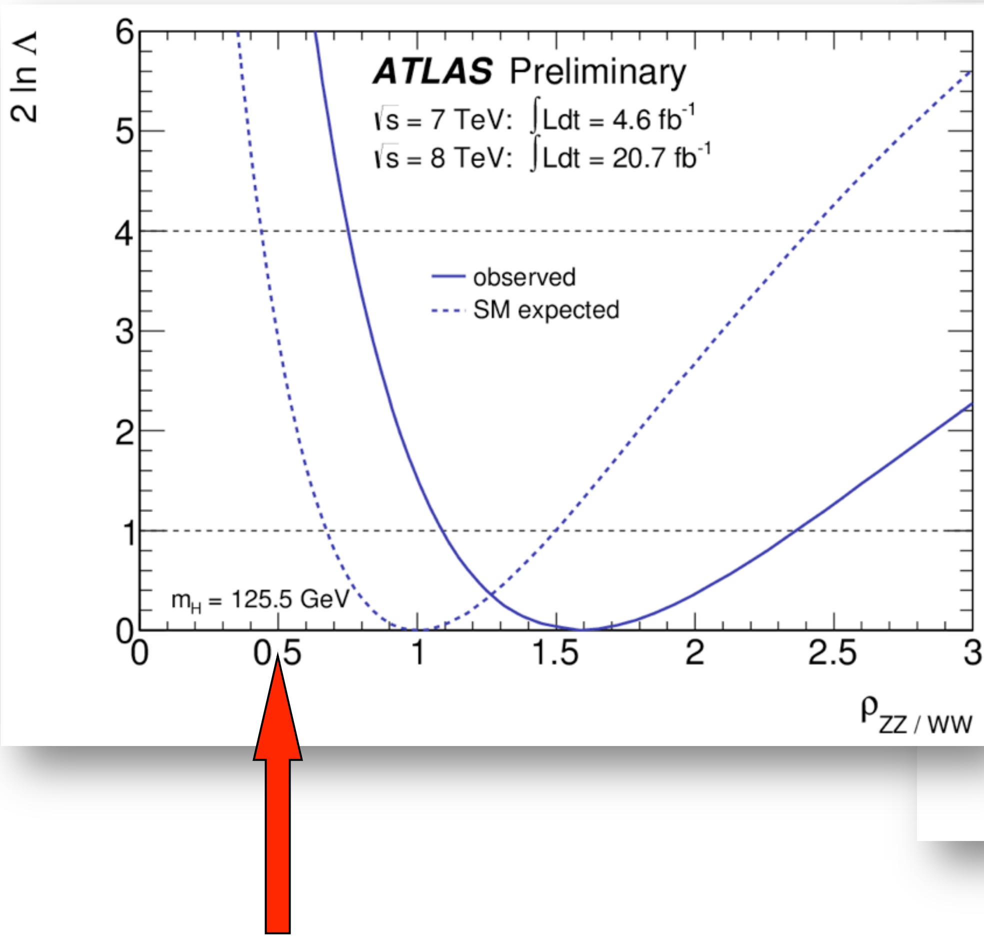
$$\frac{g_{h_5^0 WW}}{g_{h_5^0 ZZ}} = -\frac{c_w^2}{2}$$

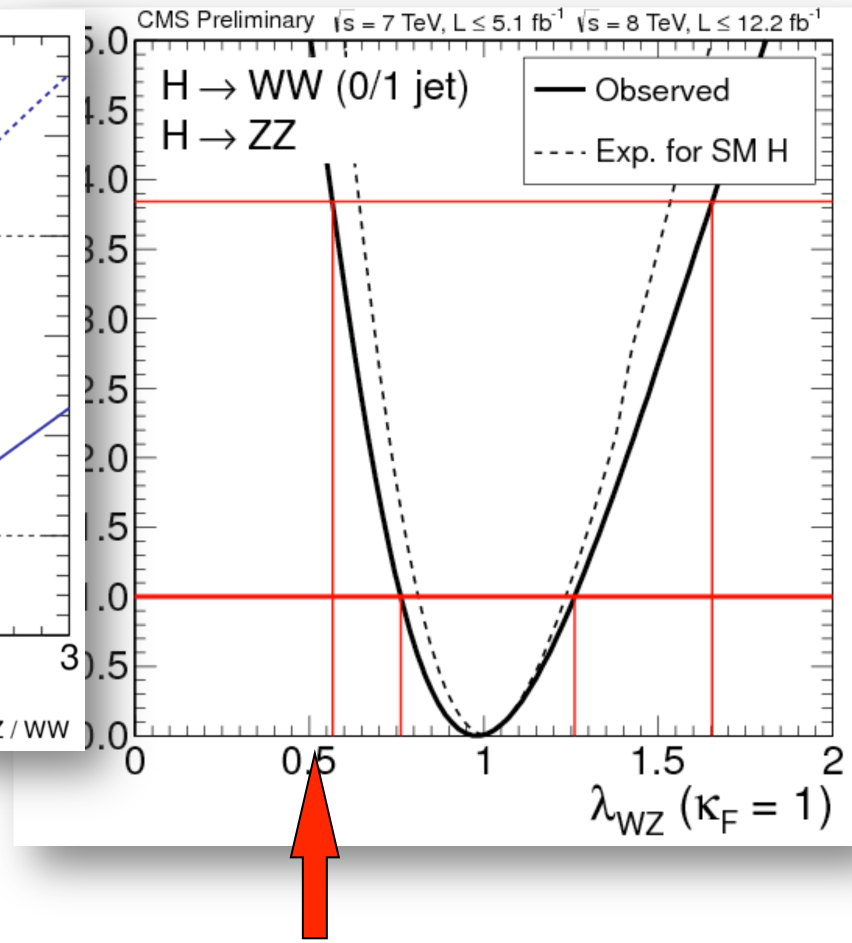
IL and Lykken:1005.0872

which includes the case of a custodially invariant triplet scalar!

See also Georgi and Machacek, NPB (1985)
Gunion, Vega, and Wudka, PRD (1990)

- The second measurement on the electroweak quantum number is WW/ZZ ratio:





A triplet scalar is excluded beyond 95% C.L.!

h(125) is

- most likely a spin-0 (scalar) particle. ✔
- most likely Charge and Parity (CP) even. ✔
- most likely the neutral component of an electroweak doublet. ✔

Source of mass for W and Z bosons:

- This is a corollary of the fact that it is an CP-even scalar and an electroweak doublet scalar.

Consider the general couplings of a scalar with two Z bosons:

the other two terms are from electroweak singlet scalars!!

$$\mathcal{L}_{eff} = \frac{1}{2} m_S\, S \left(c_1 Z^{\nu} Z_{\nu} + \frac{1}{2}\frac{c_2}{m_S^2} Z^{\mu\nu} Z_{\mu\nu} + \frac{1}{4}\frac{c_3}{m_S^2} \epsilon_{\mu\nu\rho\sigma} Z^{\mu\nu} Z^{\rho\sigma} \right)$$

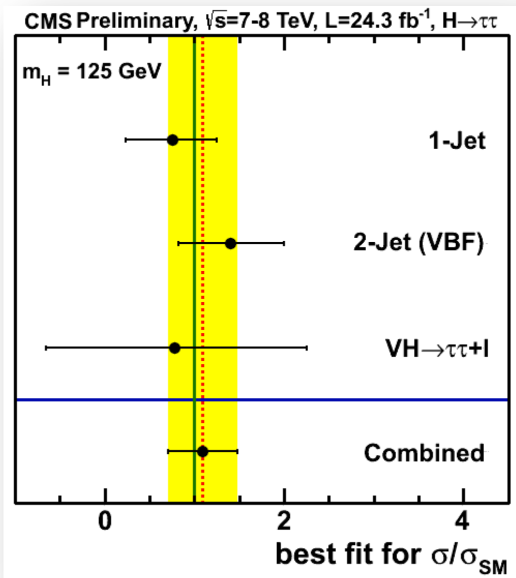
higgs mechanism predicts only this term!

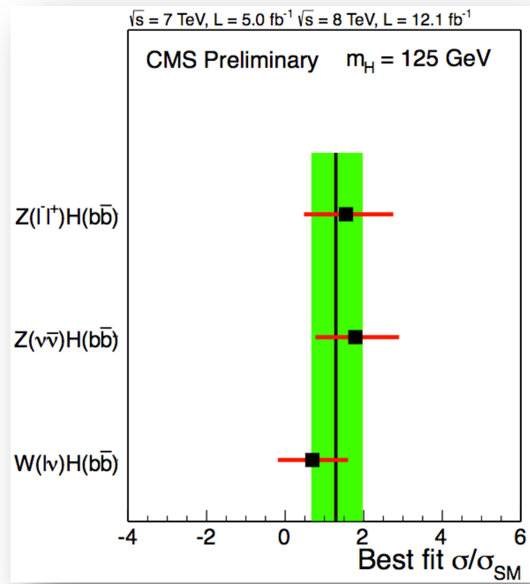
h(125) is

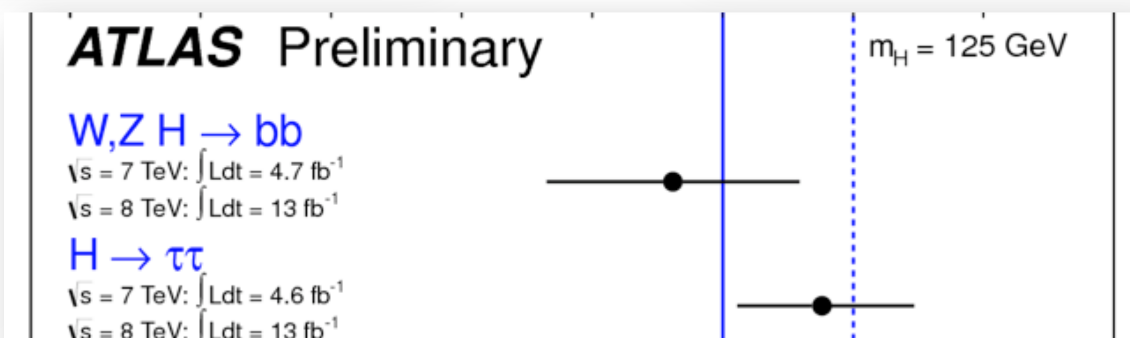
- most likely a spin-0 (scalar) particle. ✔
- most likely Charge and Parity (CP) even. ✔
- most likely the neutral component of an electroweak doublet. ✔
- most likely the origin of mass for W/Z bosons and ✔

Source of mass for quarks and charged leptons:

- It does seem to decay to fermions with SM strength:





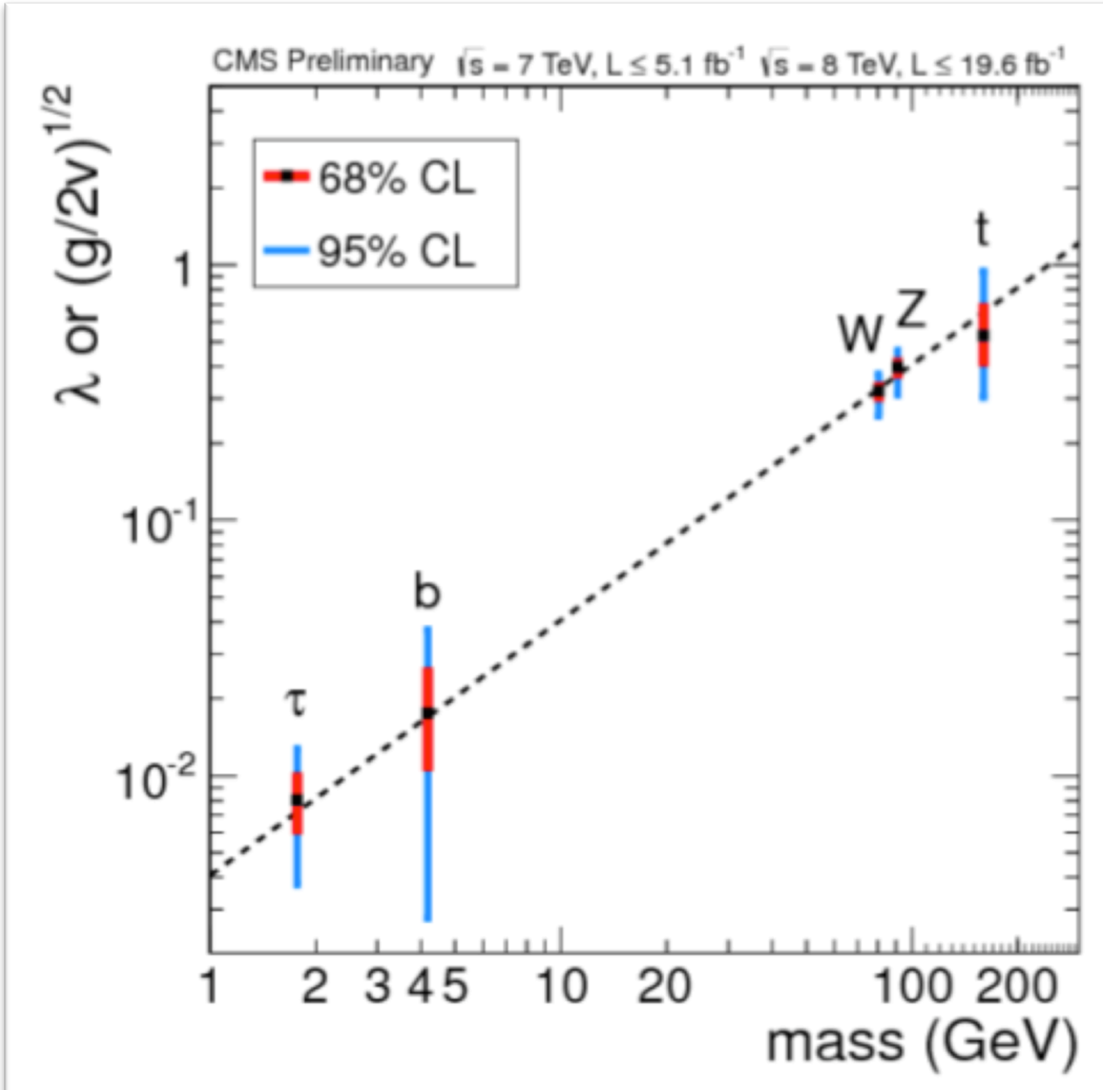


h(125) is

- most likely a spin-0 (scalar) particle. ✔
- most likely Charge and Parity (CP) even. ✔
- most likely the neutral component of an electroweak doublet. ✔
- most likely the origin of mass for W/Z bosons and ✔
- probably the origin of mass for the quarks and charged leptons. ✔

It is a Higgs boson!

A very nice figure showing h(125) as the origin of mass:



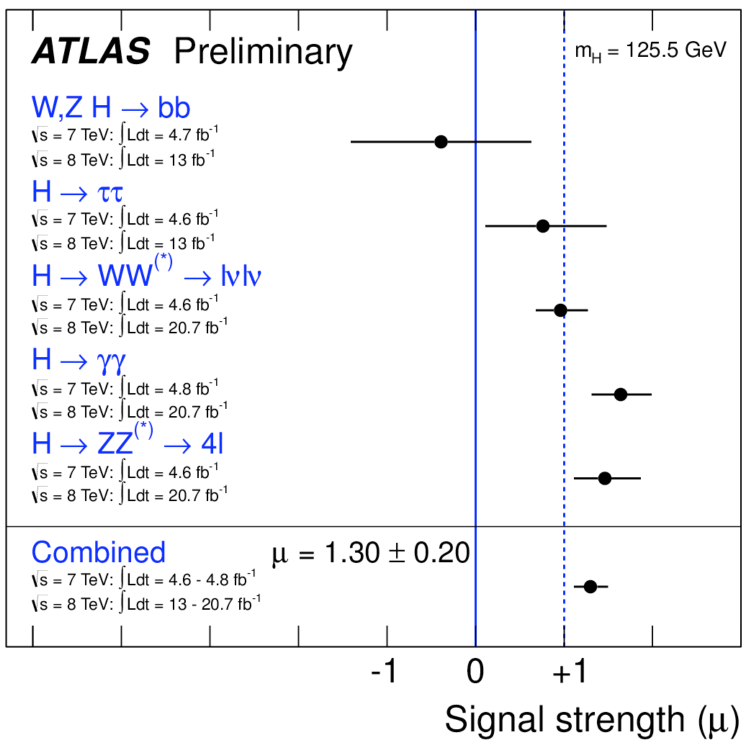
Now we know, by and large, the h(125) “coupling structure” to matter:

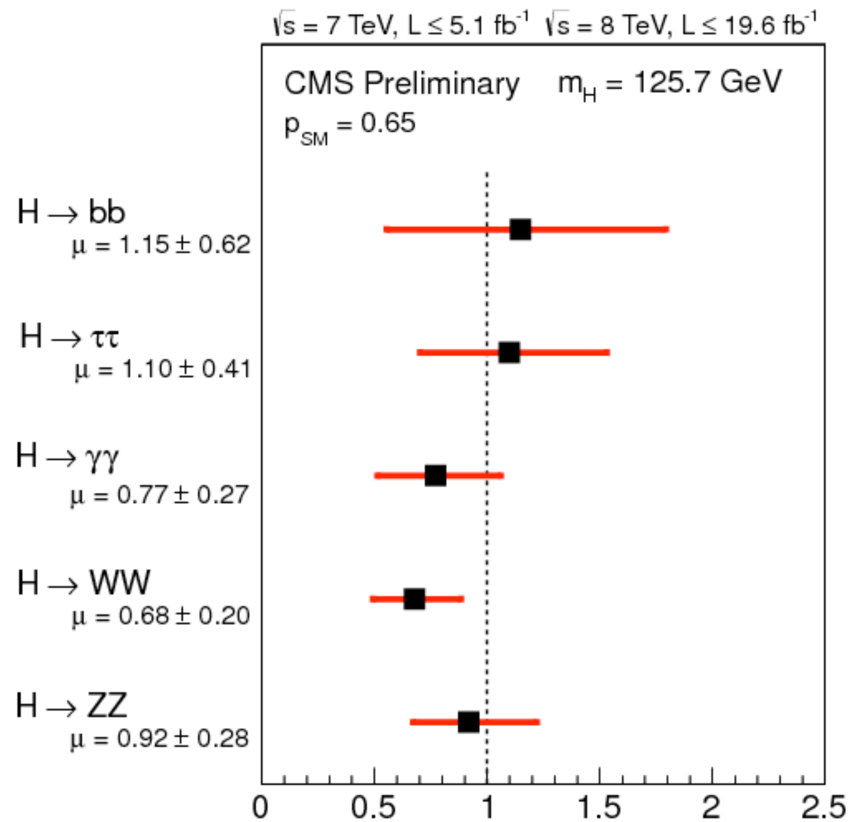
$$c_V\left(\frac{2m_W^2}{v}\,h\,W_\mu^+W^{-\,\mu}+\frac{m_Z^2}{v}\,h\,Z_\mu Z^\mu\right)$$

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

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

These are the fits for the "coupling strength" based on certain assumptions on the coupling structure:





It is clear that h(125) is Standard Model-like.

The billion-dollar question is whether it is *the* Standard Model Higgs?

- Are the coupling strengths modified from SM expectations?

- Are there additional coupling structures not detected so far (even if all signal strengths conform to SM expectation)??

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

h(125) could be a mixture from more than one electroweak doublets, singlets, or triplets.

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

h(125) itself may not fully unitarize VV scatterings.

More importantly, the natural size of deviations from SM is

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

Some people are declaring "disappointments" that we have found a SM Higgs boson and no sign of new physics.

I believe the disappointers are misinformed, because the current 20-30% uncertainty is not close to being able to establish a credible deviation!

In other words,

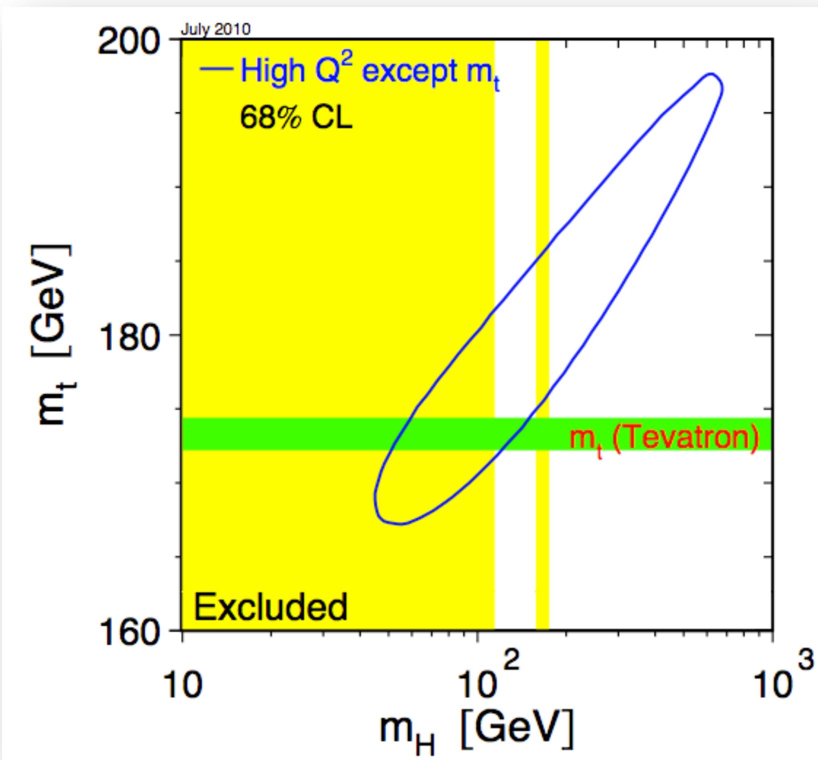
The era of precision Higgs measurements has just begun!

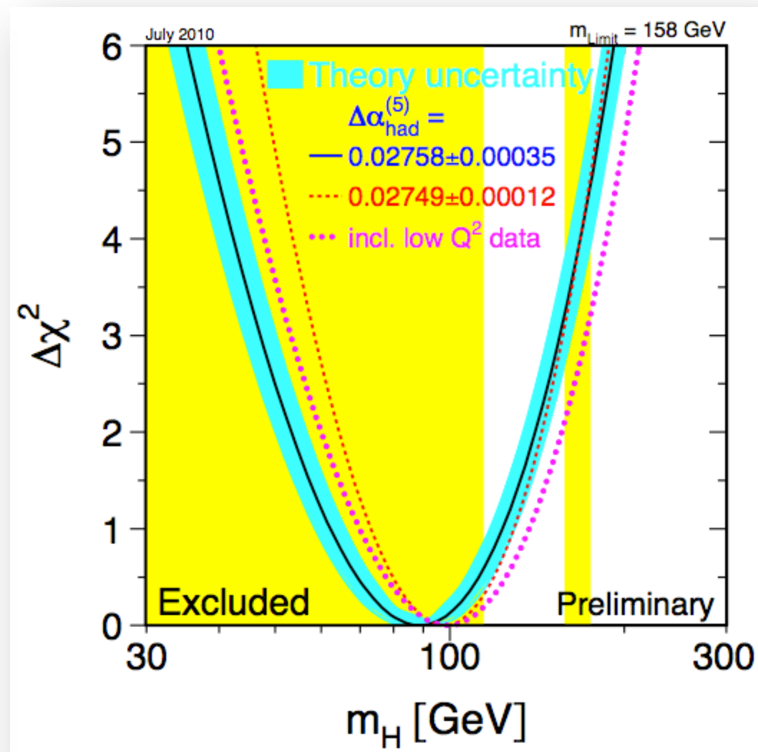
This is part of a two-pronged approach to discovering new physics beyond the Standard Model:

- Searching for phenomenon unexpected from the SM
- Precise measurements of SM expectations

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}

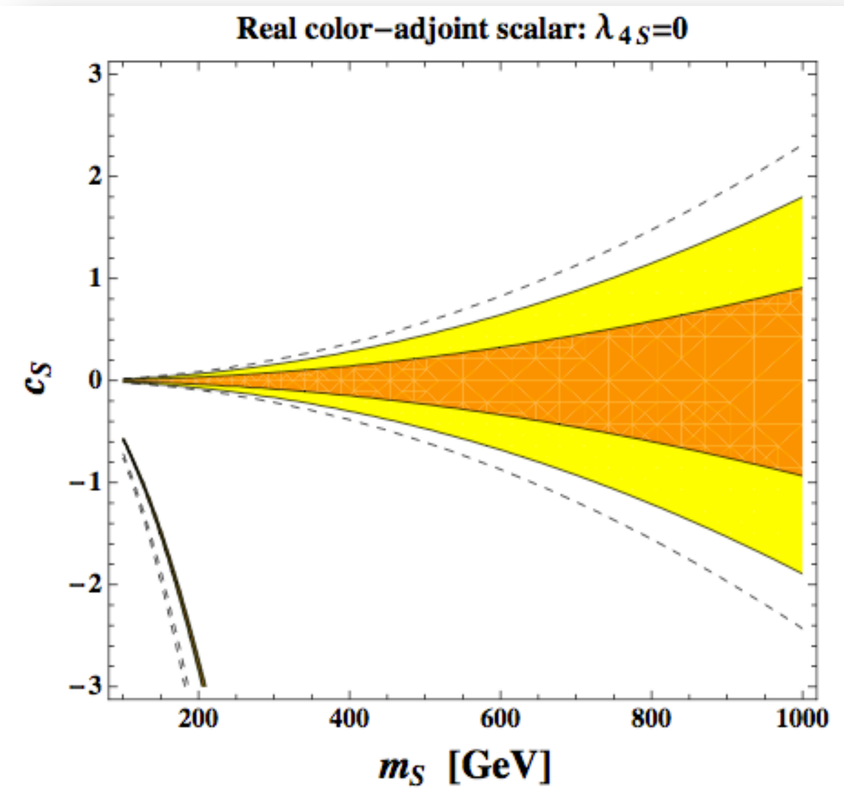




There have been many studies on how new physics could modify the signal strength of h(125).

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

I would like to emphasize the importance of searching for both new coupling structures and deviations in coupling strengths.

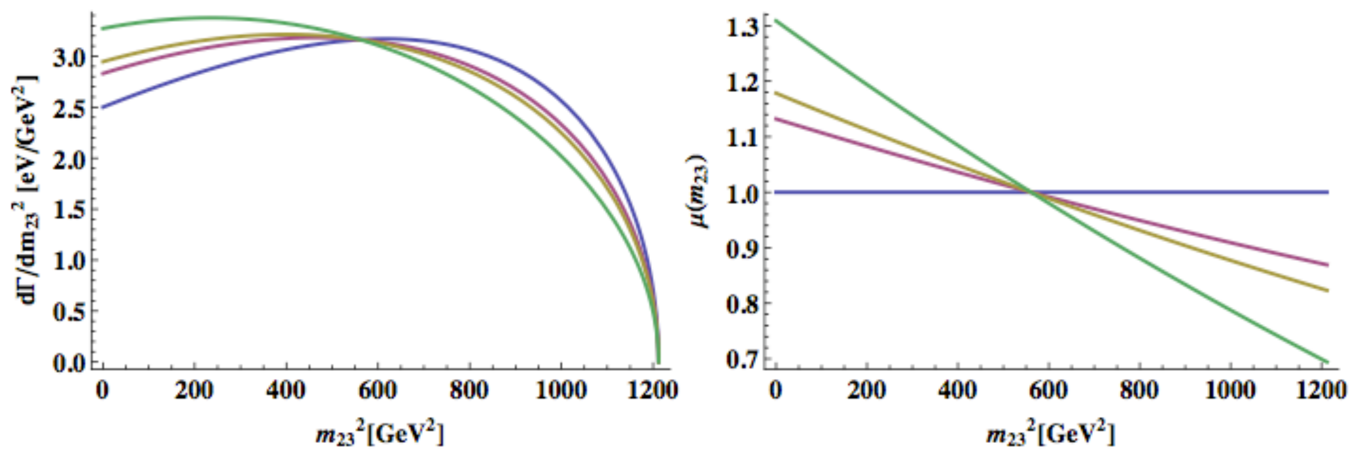


FIG. 3: Contributions to $h \to Z\ell\bar{\ell}$ from $\mathcal{O}_{ZJ}$. The differential decay rate and differential signal strength as a function of m_{23}^2 are shown on the left and right respectively. The curves correspond to the SM (blue); $c_R = 0.99$, $c_L = 0$ (red); $c_L = -1.15$, $c_R = 0$ (yellow); and $c_R = -c_L = 1.07$ (green). $\mu = 1$ in each of these cases.

$$\frac{e}{s_W c_W}\left(\frac{c_{\ell Z}}{v}\bar{\ell}\sigma^{\mu\nu}\ell Z_{\mu\nu} + \bar{\ell}\gamma^{\mu}(c_L P_L + c_R P_R)\ell Z_{\mu}\right)\frac{h}{v}$$

Grinstein, et. al.: 1305.6938

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

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

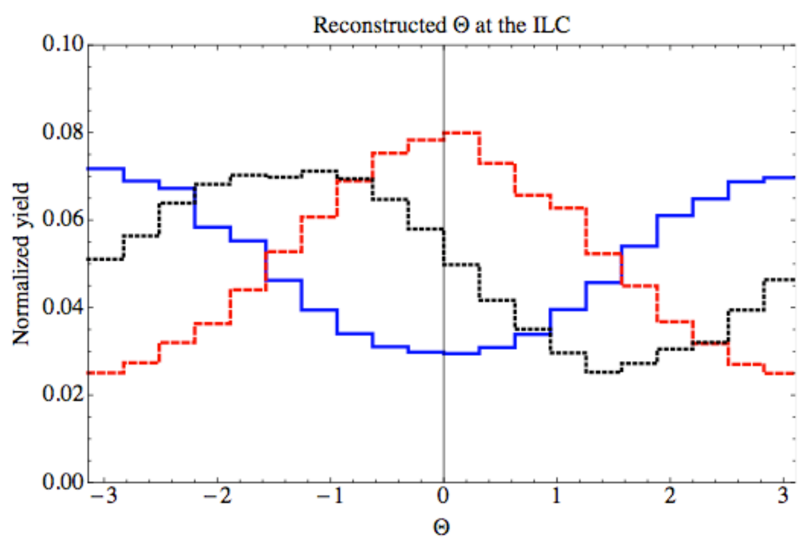
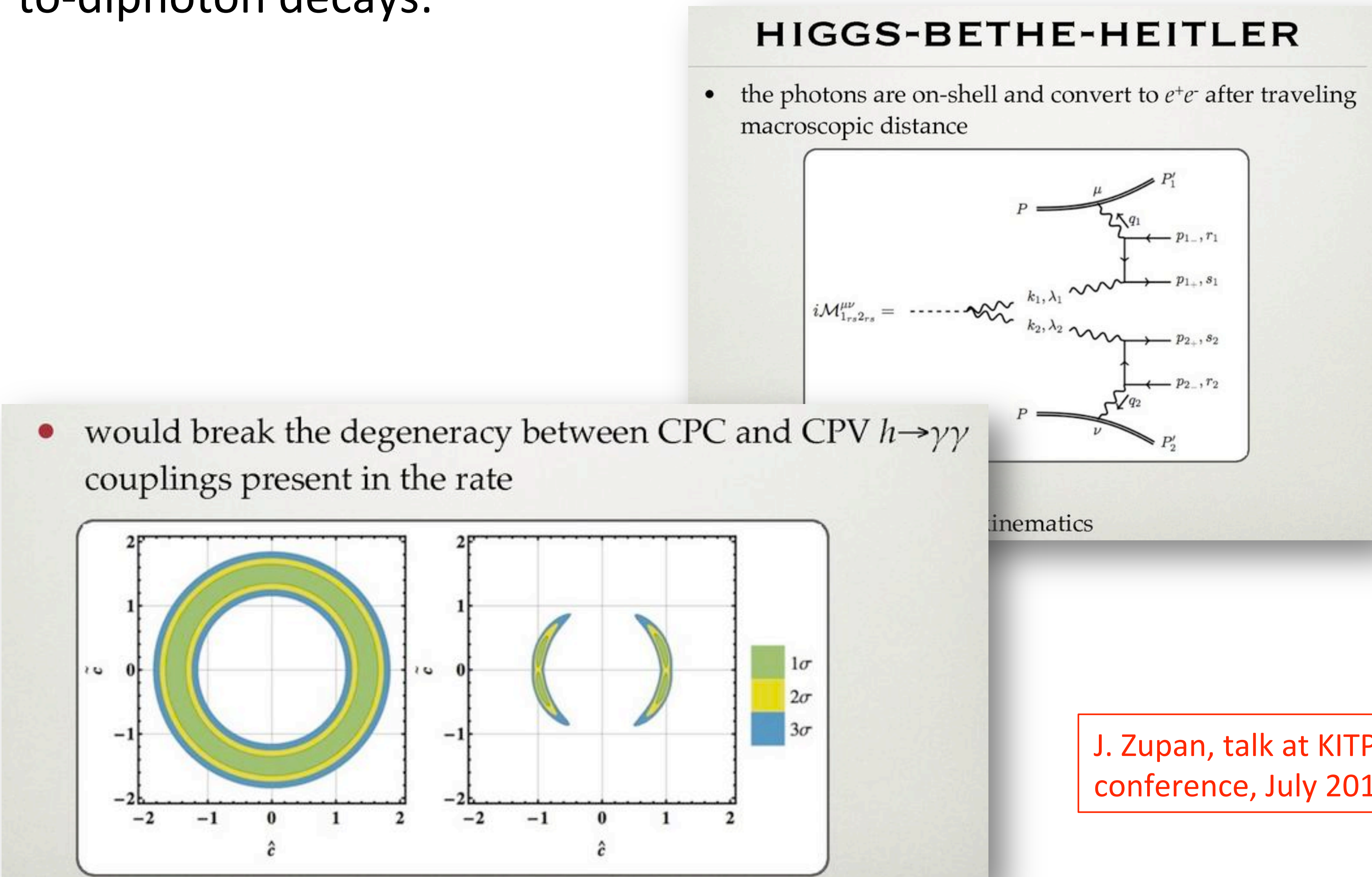


FIG. 5: The reconstructed Θ distribution at the ILC for $\Delta = 0$, $\Delta = \pi/4$, and $\Delta = \pi/2$.

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.

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.

A common folklore:

In models with an extended Higgs sector, the existence of a SM-like Higgs boson means all non-SM-like scalars are heavy and the Higgs sector at low energies is also Standard Model-like.

This turns out to be completely false!

It was pointed out more than 10 years ago that, even in two-Higgs-doublet-Models (THDM), there are regions of parameter space where a SM-like Higgs exists while the heavy CP-even and pseudo-scalar Higgs bosons are not heavy.

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= existence of a SM-like Higgs.

MSSM augmented by a triplet scalar:

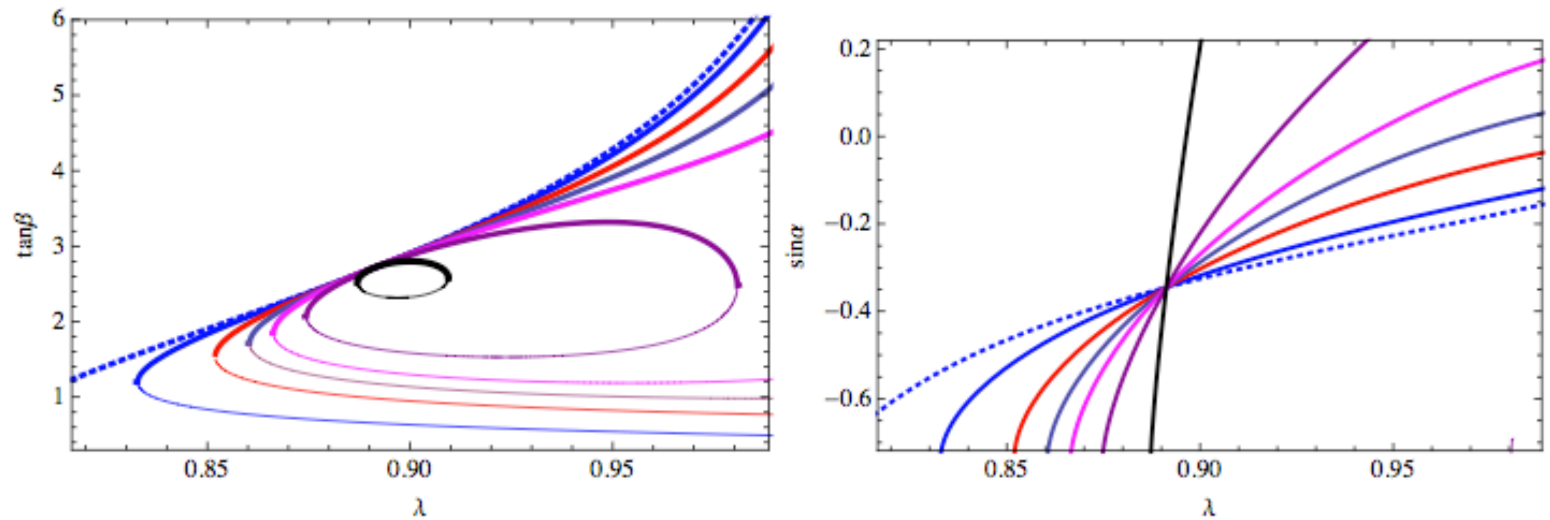


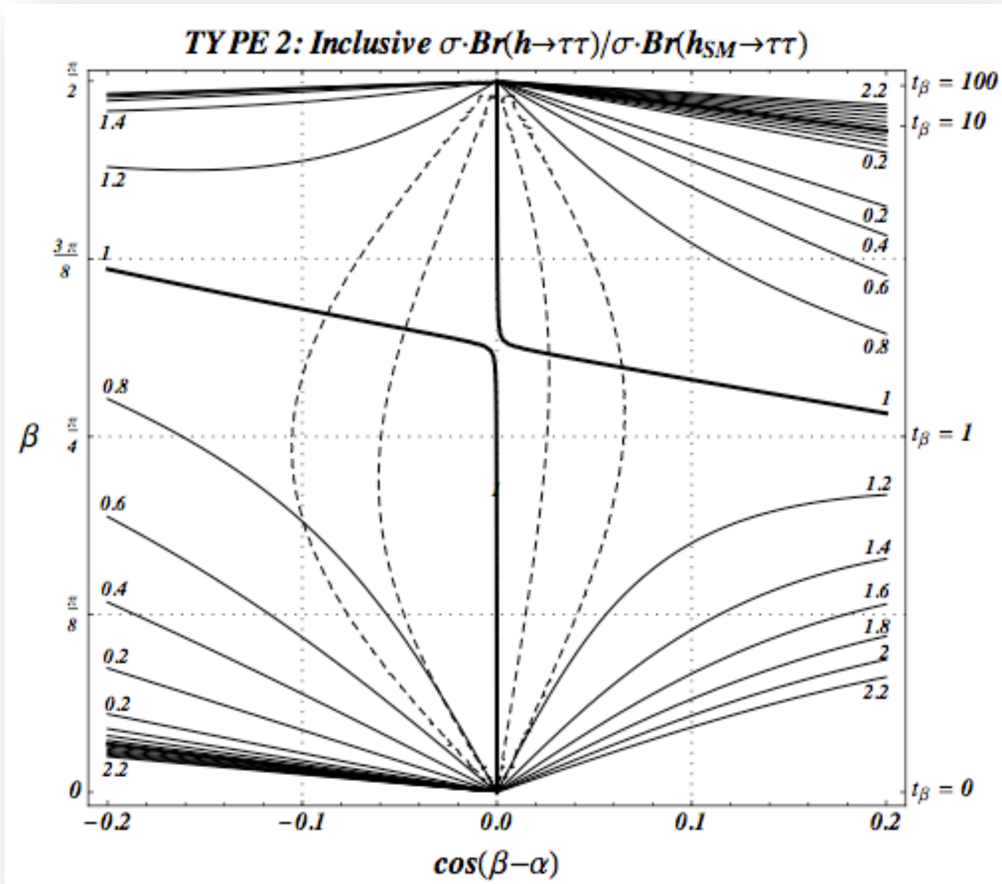
Figure 1: *Left panel:* $\tan\beta$ *as a function of* λ *providing* $m_h = 126\,GeV$ *in the decoupling limit or large* m_A *(blue dotted) and for* m_A = *200 GeV (blue solid), 155 GeV (red solid), 145 GeV (grey solid), 140 GeV (magenta solid), 135 GeV (purple solid) and 130 GeV (black solid). The other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

Delgado et. al.: 1303.0800

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

Alignment= existence of a SM-like Higgs.

Scanning over general THDMs:



Craig et. al.: 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 “physical 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.

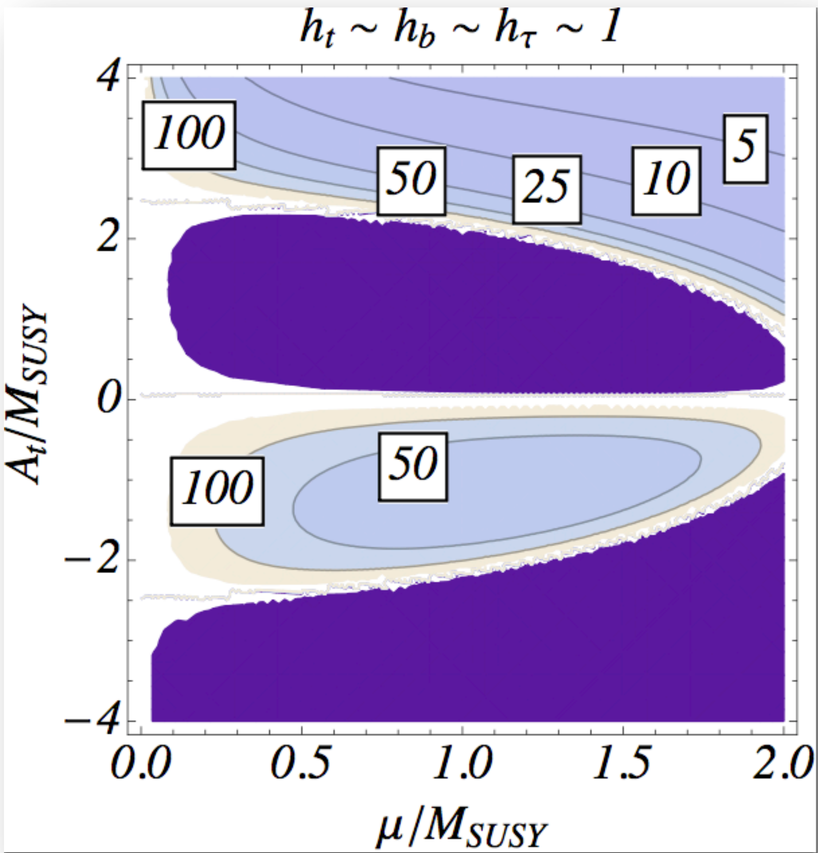
Moreover these solutions are fine-tuned, because they require choosing specific value of λ_2 .

Carena, IL, Shah, Wagner: 1308.nnnn

However, 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 that does not require fine-tuning.

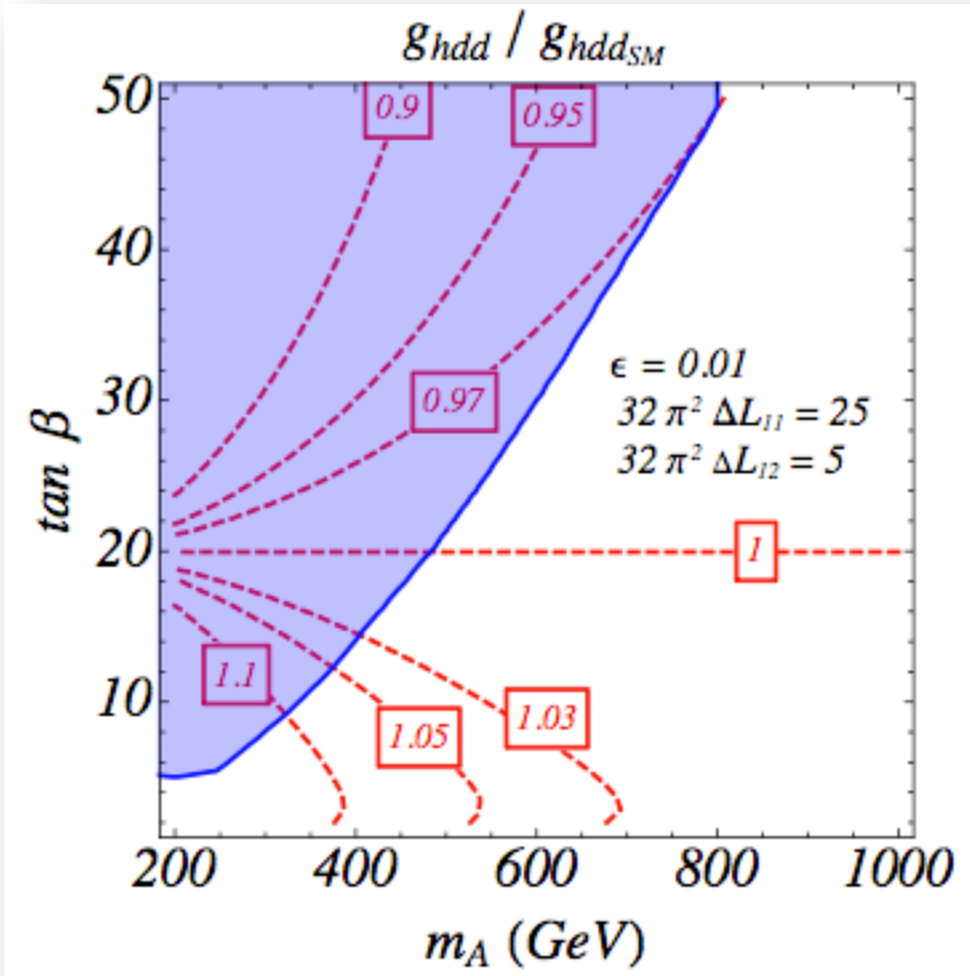
Then “alignment without decoupling” occur generically in general THDM and the MSSM.



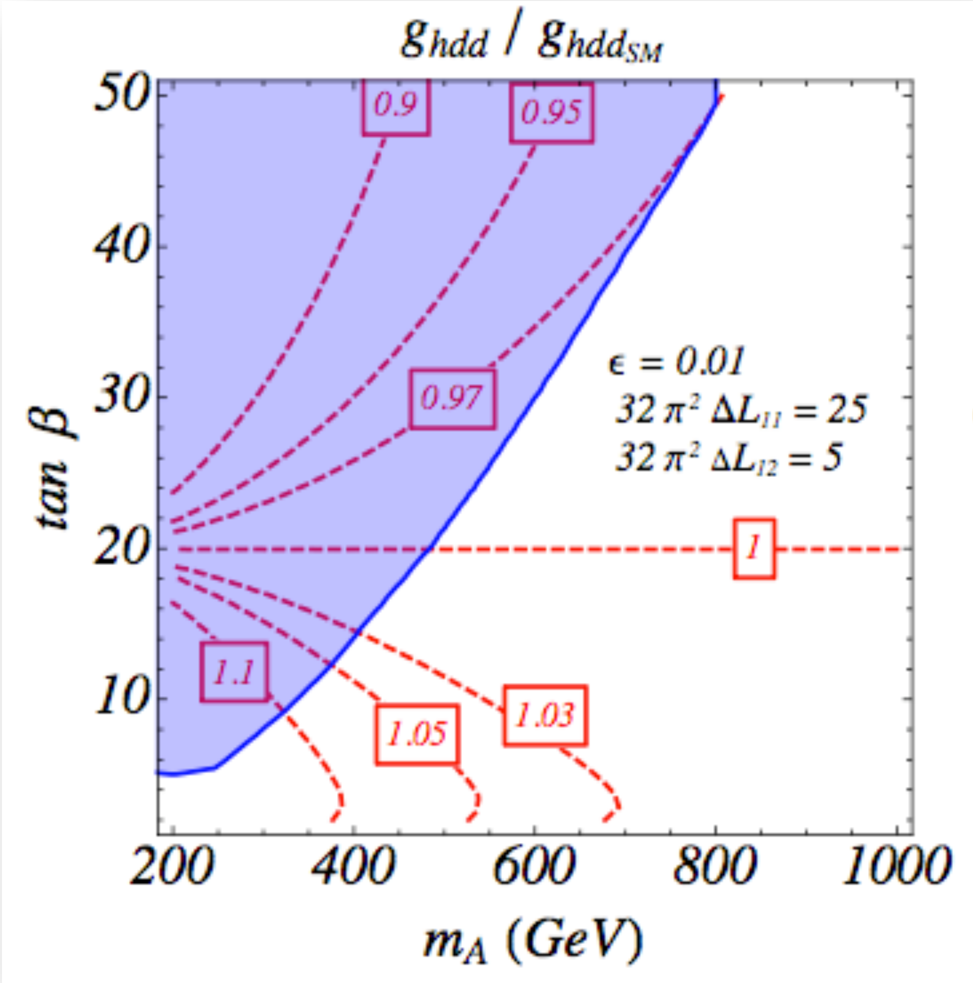
Contours represent values of tanbeta at the alignment limit.

Carena, IL, Shah, Wagner: 1308.nnnn

The lightest CP-Higgs in MSSM could be SM-like even for m_A that are of the order of a few hundreds GeV!



At the same time, this plot shows precision measurements on Higgs couplings to fermions are effective in constraining the infamous Wedge Region, which is otherwise difficult to probe in direct searches.



This scenario exemplifies the complementarity of precision Higgs measurements and direct searches and the importance of taking 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!

- Precision Higgs measurements can probe regions of parameter space that are difficult to access in direct searches.

Summary:

- h(125) indeed is a Higgs boson, a SM-like Higgs boson.
- Both coupling structures and coupling strengths need to be explored.
- Precision Higgs measurements and direct searches go hand-in-hand and should be pursued together.

An exciting era and still lots to be done!!