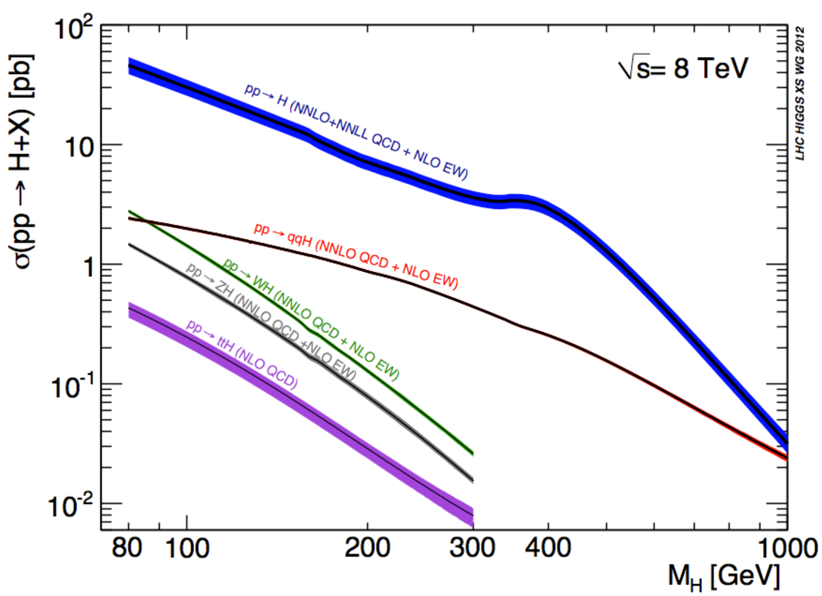
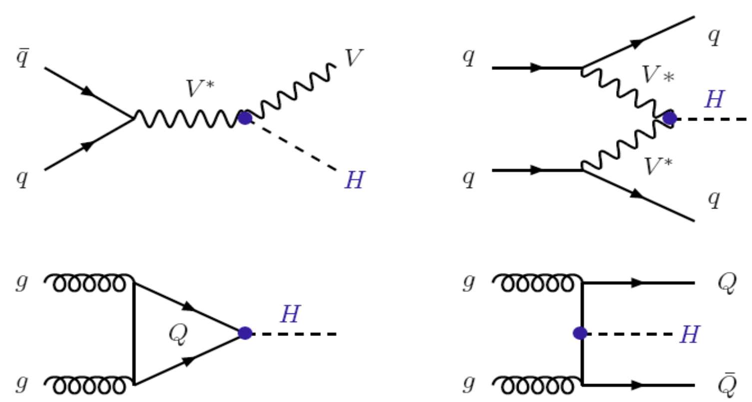
Higgs Physics (II): Mass and Couplings

Ian Low

Argonne/ Northwestern

August, 2013 @ SI 2013 Korea





Now we have established h(125) is not only a Higgs, but a Standard Model-like Higgs!

However, the answer to the 10-billion dollar question

Is it *the* Standard Model Higgs boson?

is much less clear....

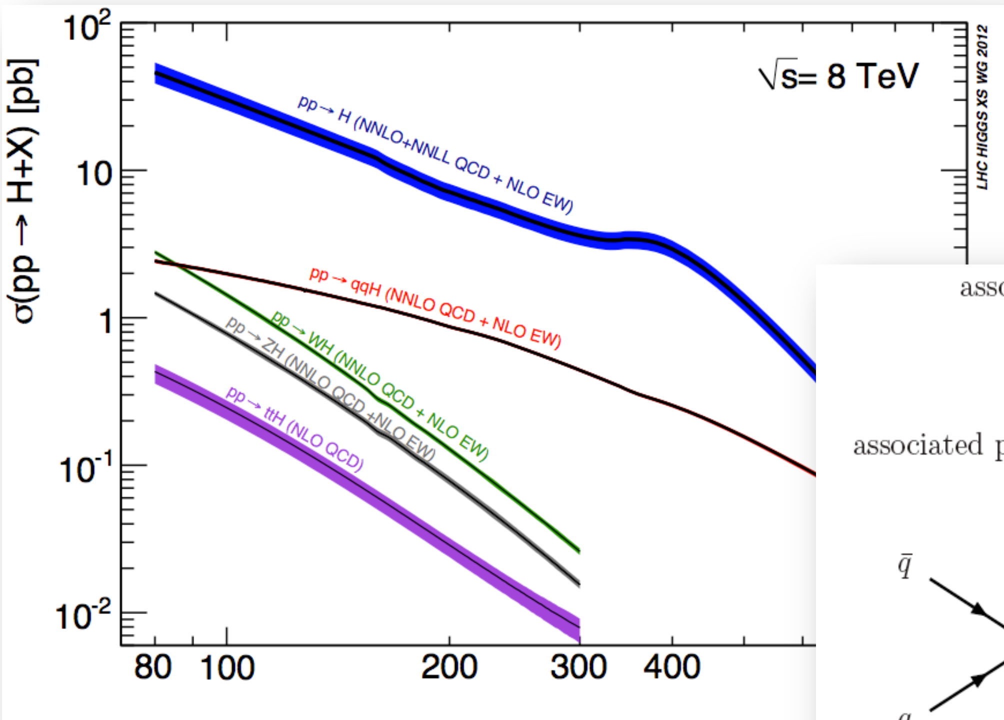
What is a Standard Model Higgs boson?

One peculiar feature of the SM Higgs is the only theoretically unknown parameter is its mass.

Once the mass is measured, all couplings are known and computed precisely in the SM!

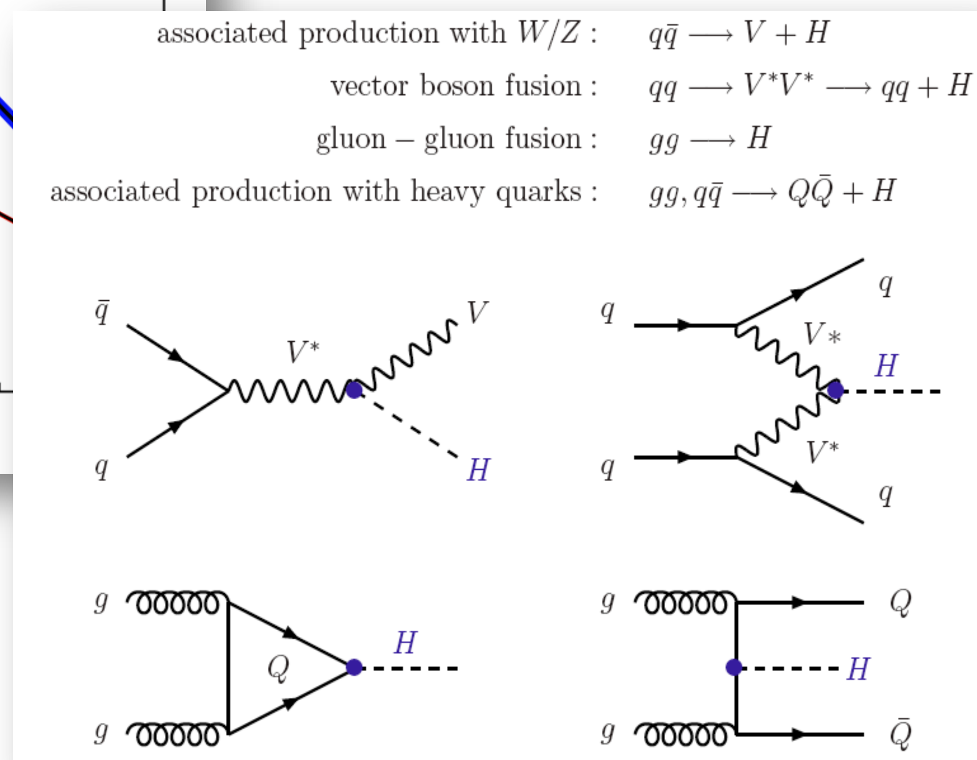
Since all the couplings are known, we can

- predict the production cross-section



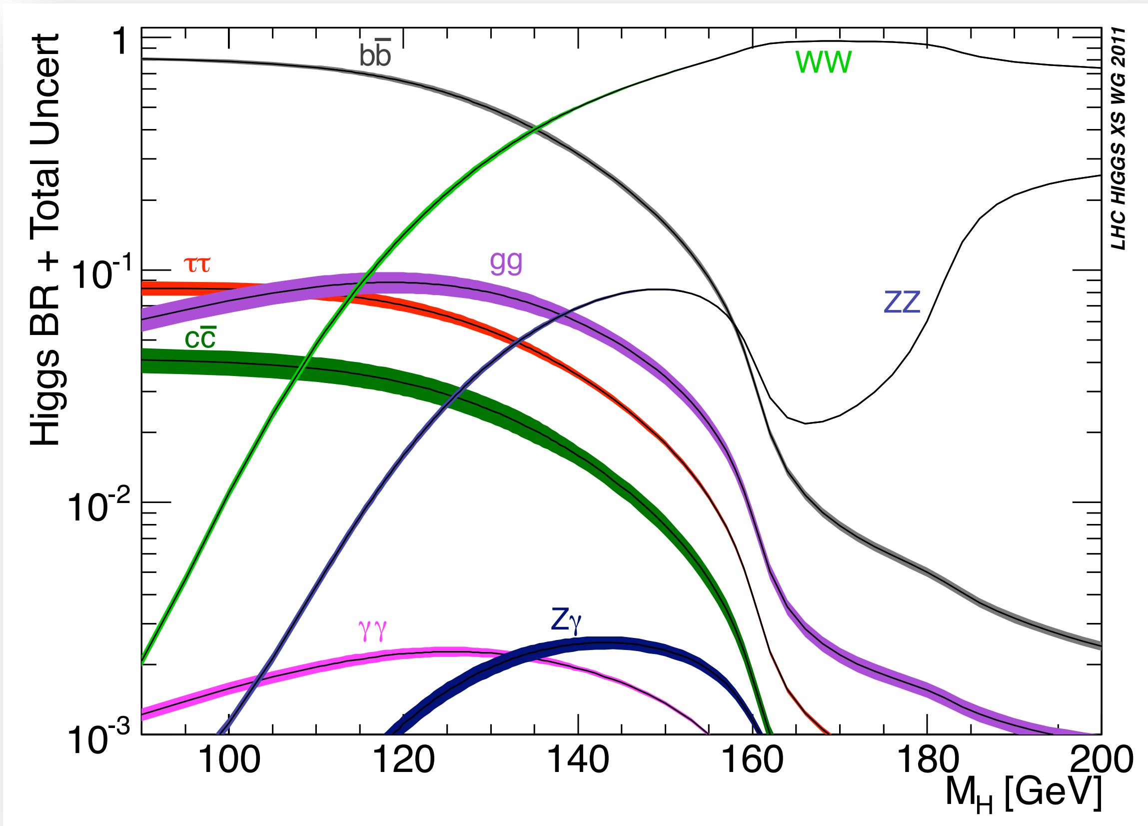
Higgs cross-section working group

A. Djouadi: hep-ph/0503172



Since all the couplings are known, we can

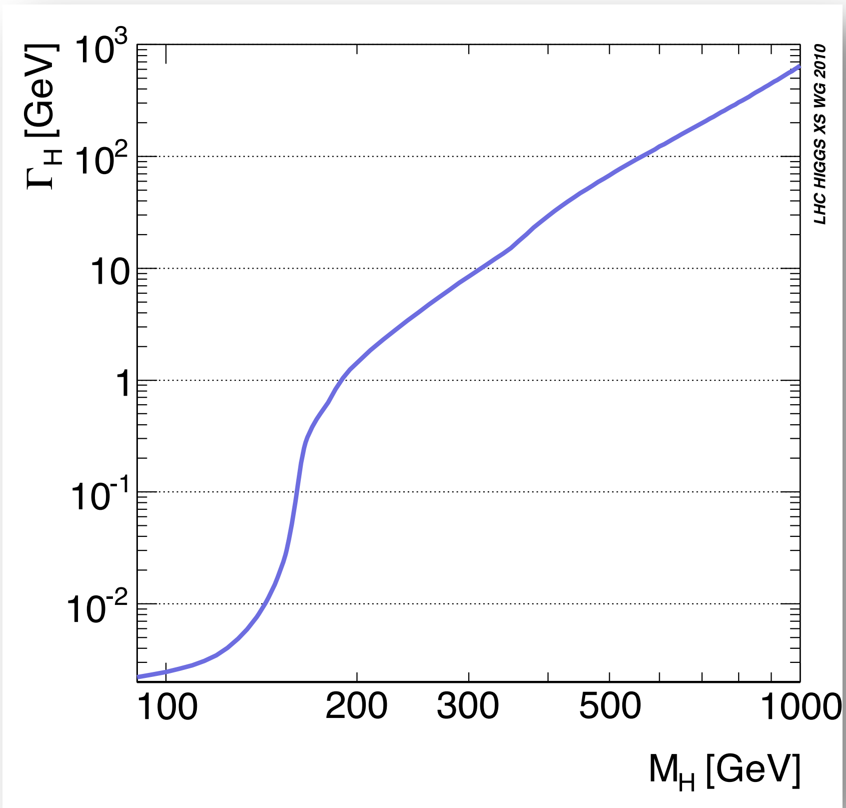
- predict the partial decay widths



Higgs cross-section working group

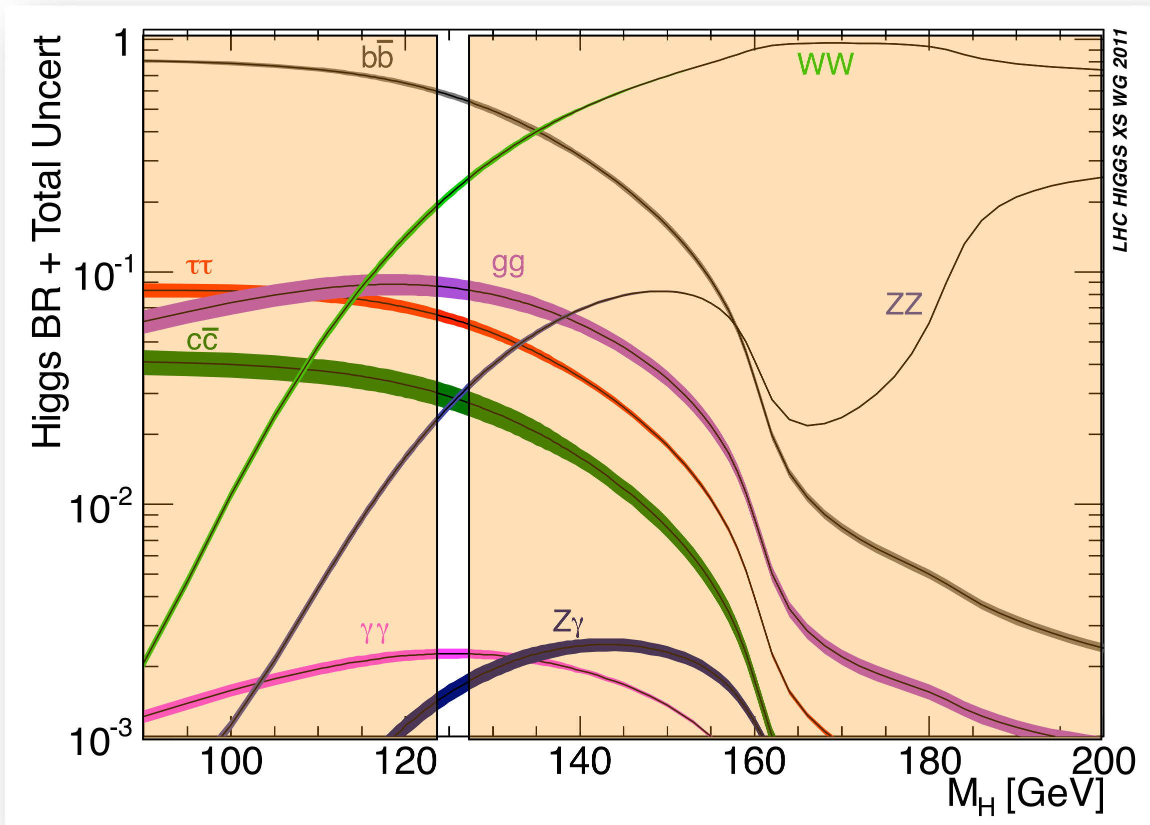
Since all the couplings are known, we can

- predict the total decay width

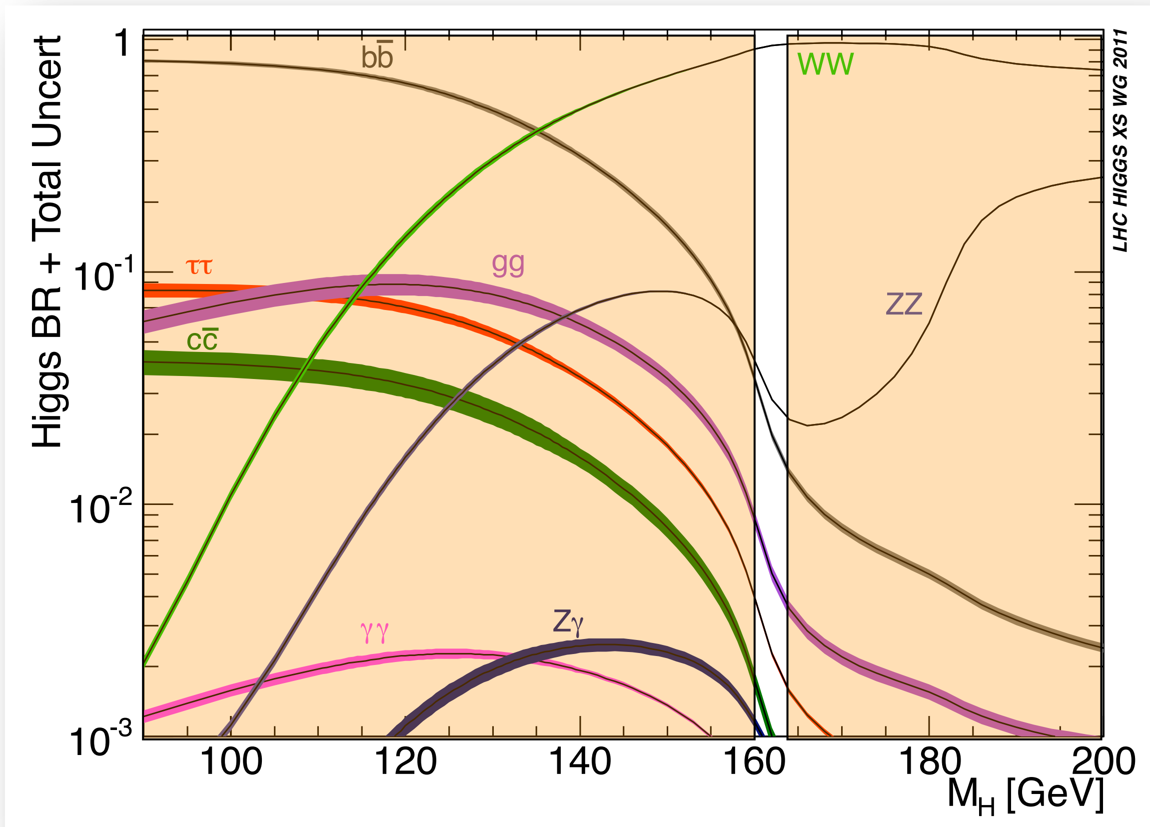


Higgs cross-section working group

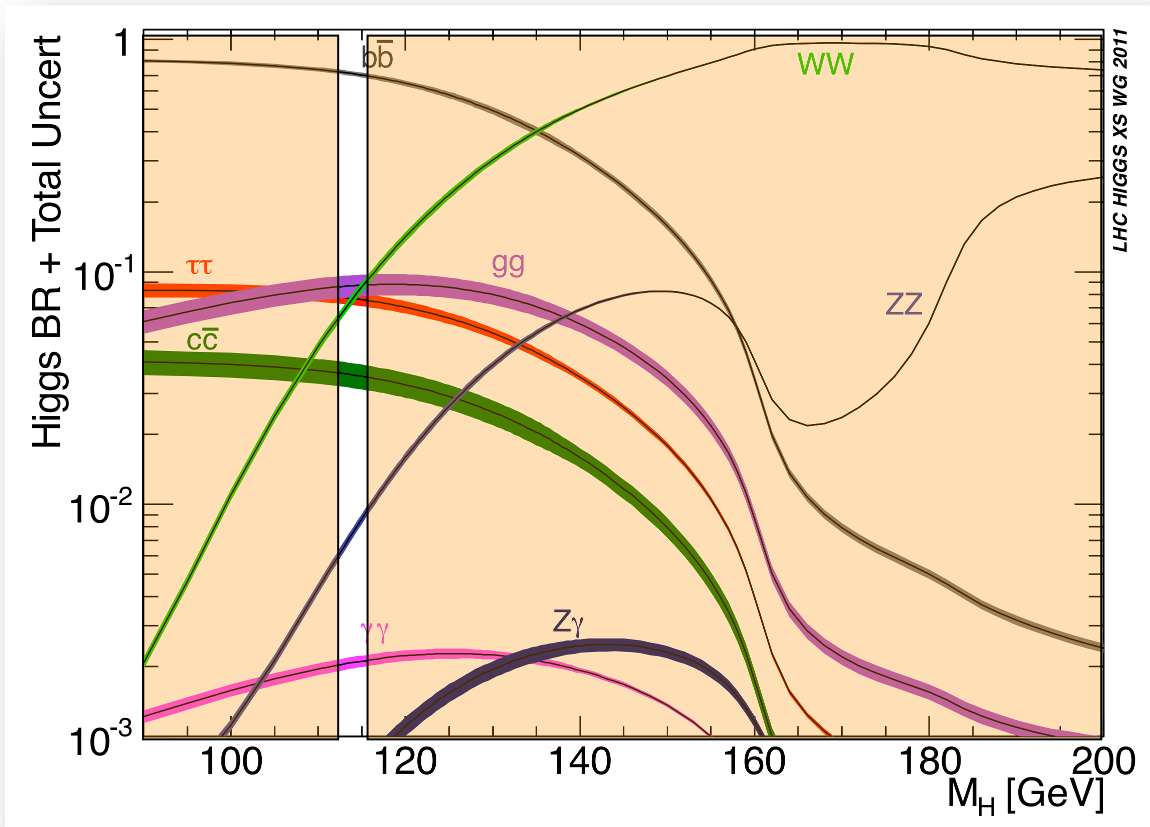
A 125 GeV Higgs lives in a very interesting mass range. We can probe a variety of its couplings!



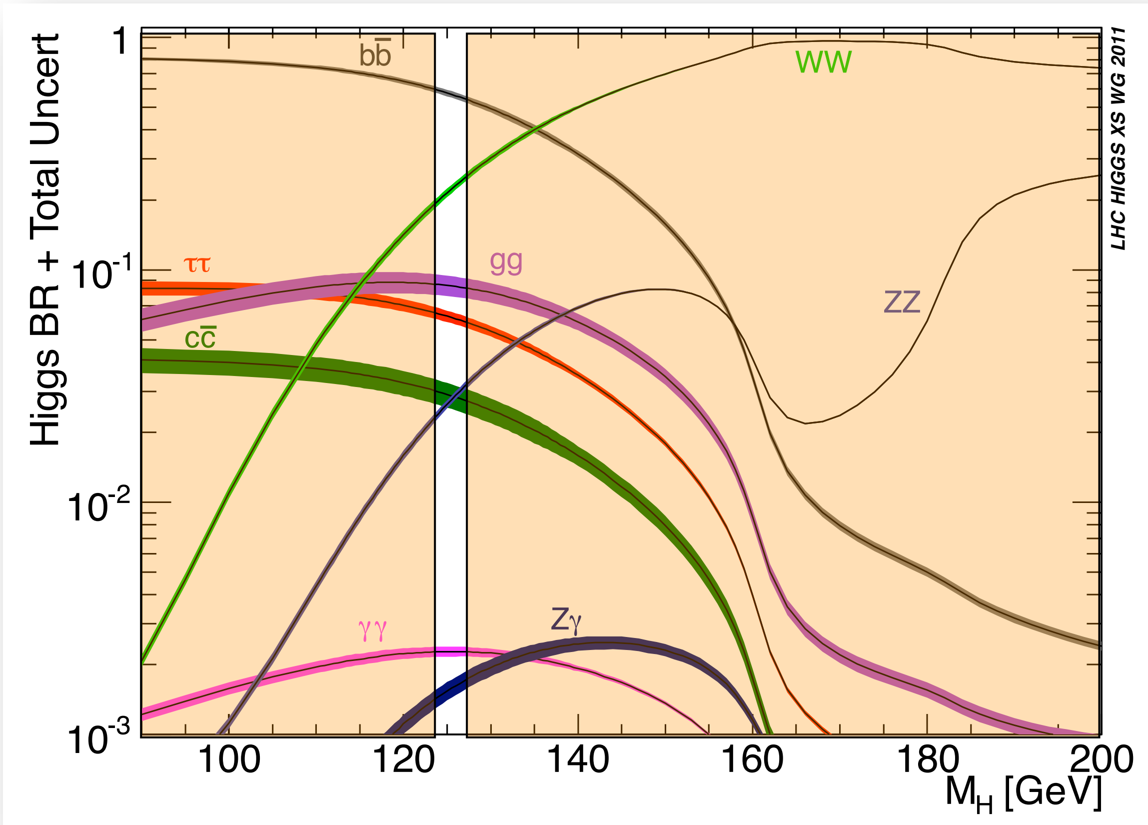
This is not the case if it were a bit heavier. Then we can only measure its couplings to gauge bosons:



Or if it were a bit lighter, we can only measure its couplings to fermions:



Nature has been kind to us!



What are being measured?

- Mass of the Higgs

  (relatively) easy to measure with precision.

- Event rates in bbar, gg, WW, ZZ, and diphoton channels.

  (much) harder to measure with precision.

$$B\sigma(p\bar{p} \to h \to X_{\rm SM}) \equiv \sigma(p\bar{p} \to h) \times br(h \to X_{\rm SM})$$

$$br(h \to X_{\rm SM}) = \frac{\Gamma(h \to X_{\rm SM})}{\Gamma_{\rm total}}$$

The annoying thing about the mass:

We can't predict it!

There are two free parameters in the Higgs potential:

$$V(H) = \frac{\lambda}{2}\left(H^\dagger H - \frac{v^2}{2}\right)^2 \qquad \langle H \rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

The Higgs mass is controlled by the quartic coupling:

$$m_h^2 = \lambda v^2 \ , \qquad v \approx 246 \quad \mathrm{GeV}$$

So knowing the mass gives an estimate on the quartic coupling:

$$m_h \approx 125 \quad \mathrm{GeV} \quad \Rightarrow \quad \lambda \approx 0.26$$

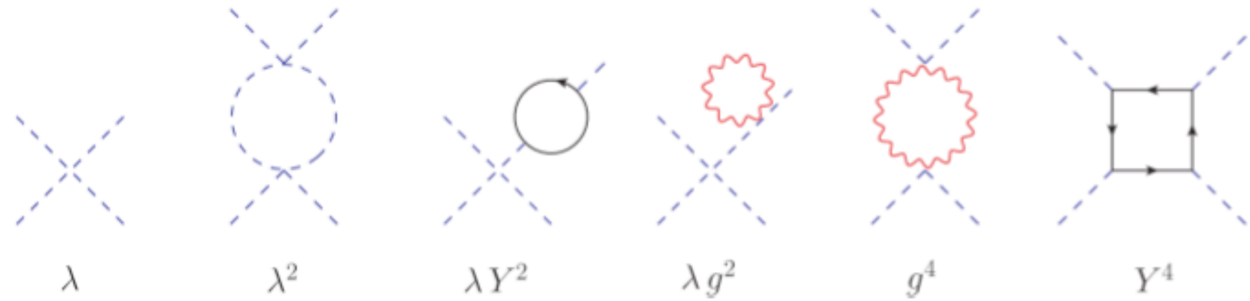
This number should be thought of as the input value of running quartic coupling at the weak scale:

$$\lambda(m_h) \approx 0.26$$

Let's first consider the implication of such a quartic coupling in the SM, and discuss theories beyond SM later.

The renormalization group evolution of the quartic coupling can be studied in the SM and is known to two-loop.

λ runs



$$\frac{d\lambda}{d\ln\mu} = \frac{1}{16\pi^2}\left[+24\lambda^2 + \lambda\left(4N_c Y_t - 9g^2 - 3g'^2\right) - 2N_c Y_t^4 + \frac{9}{8}g^4 + \frac{3}{8}g'^4 + \frac{3}{4}g^2 g'^2 + \ldots\right]$$

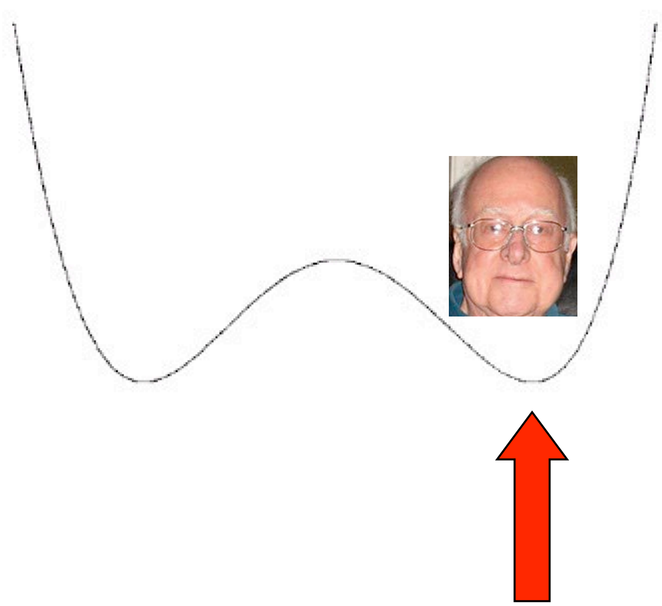
M_H large: λ^2 wins $\quad \lambda(M_t) \to \lambda(\mu) \gg 1 \quad$ non-perturbative regime, Landau pole

M_H small: $-Y_t^4$ wins $\quad \lambda(M_t) \to \lambda(\mu) \ll 1$

Slides from Degrassi, talk at KITP, July 2013

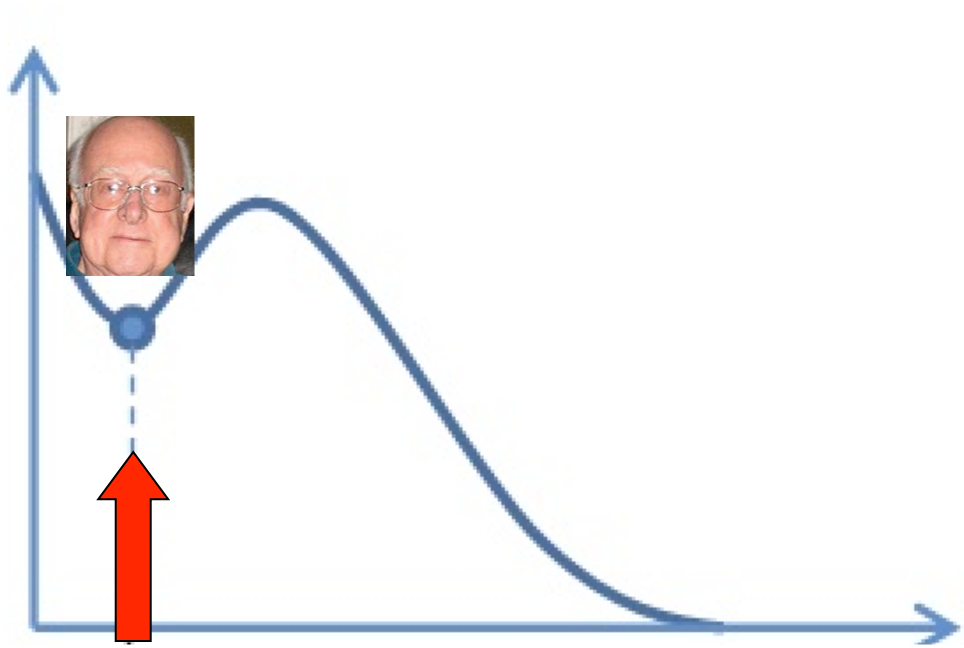
- If the quartic grows as it runs to higher energy, it would eventually becomes strongly coupled.
- But if the quartic decreases and becomes negative toward higher energy, we would have a problem:

Recall the potential energy of the Higgs looks like:



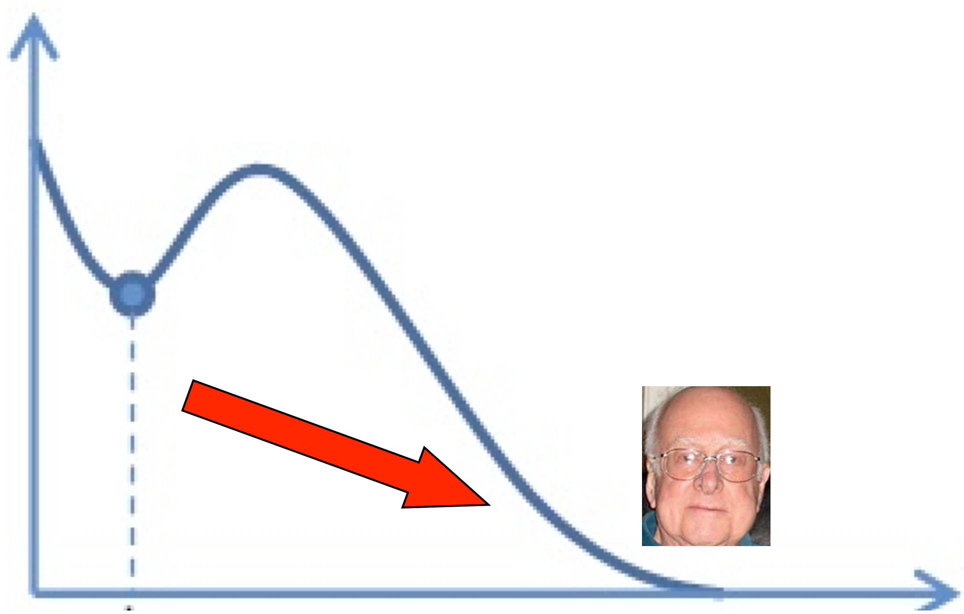
True vacuum, where our Universe sits

When the quartic turns negative, the original “electroweak-breaking” vacuum could be just a false vacuum!

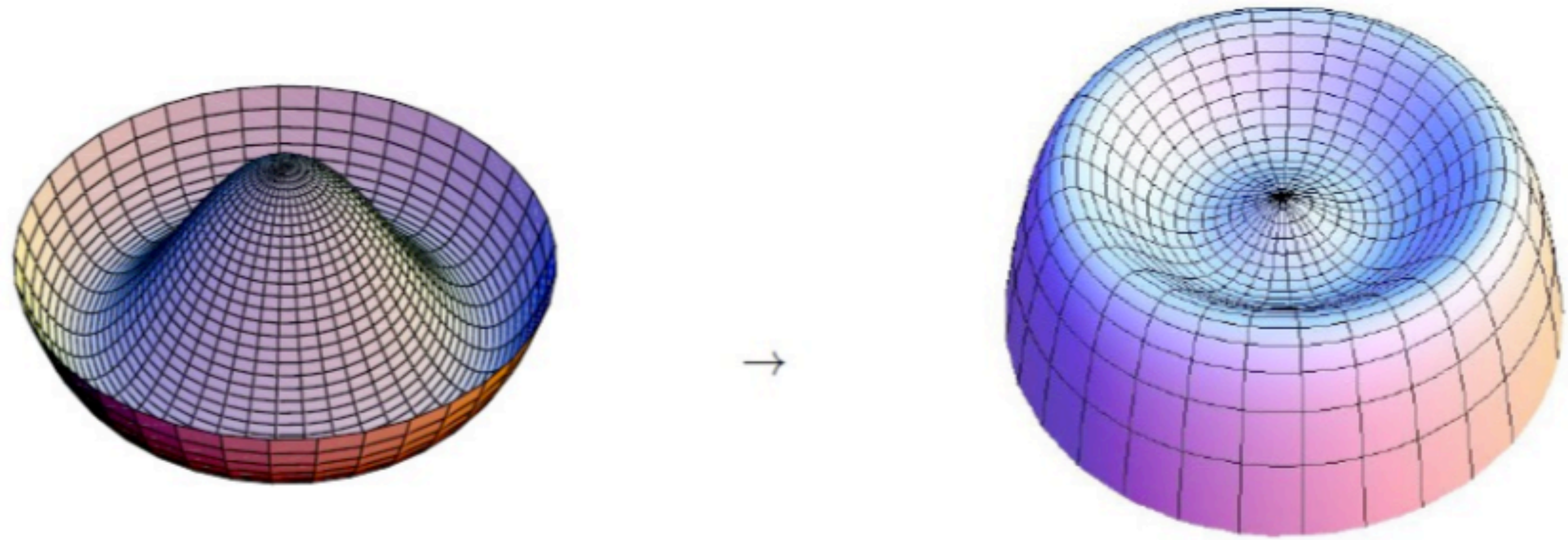


False vacuum, where we are sitting today

Quantum mechanics dictates that eventually our Universe will tunnel into the true vacuum, and the world we know it today may end…



Quantum mechanical tunneling always exists!



If your mexican hat turns out to be a dog bowl you have a problem...

from A. Strumia

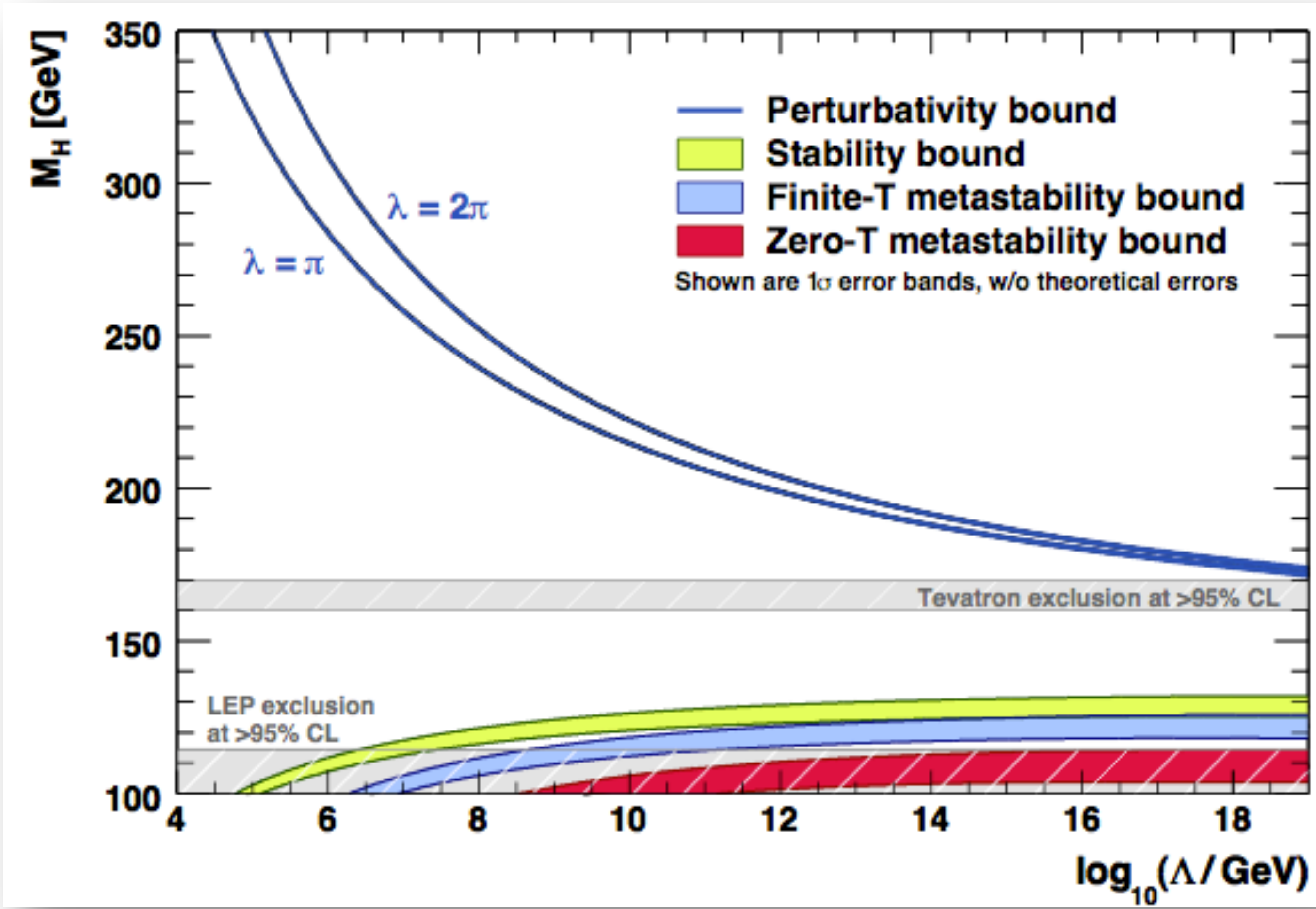
Slide from Degrass, talk at KITP, July 2013

The only way out is if the tunneling lifetime is larger than the age of the Universe:

$$\tau \geq 13.75 \text{ billion years}$$

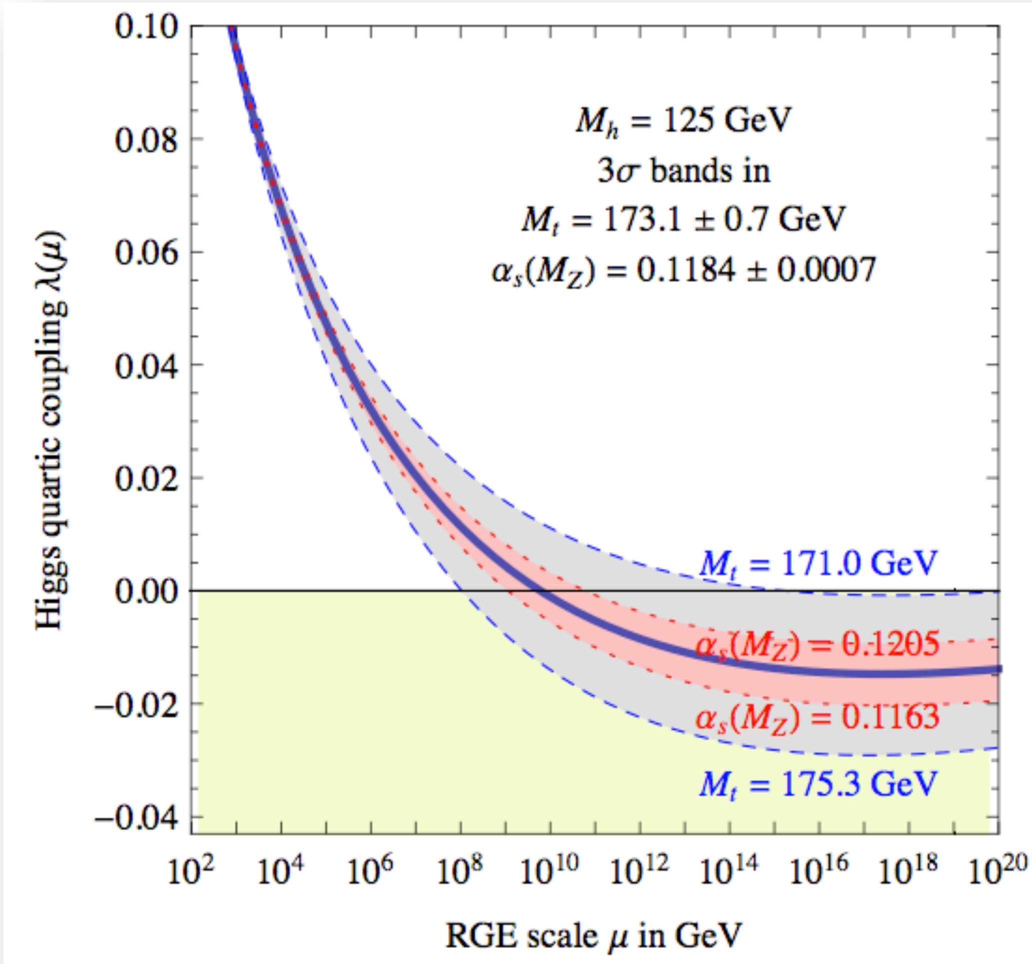
This is called metastability.

Whether we have a mexican hat or a dog bowl depends on the Higgs mass and other SM input parameters:



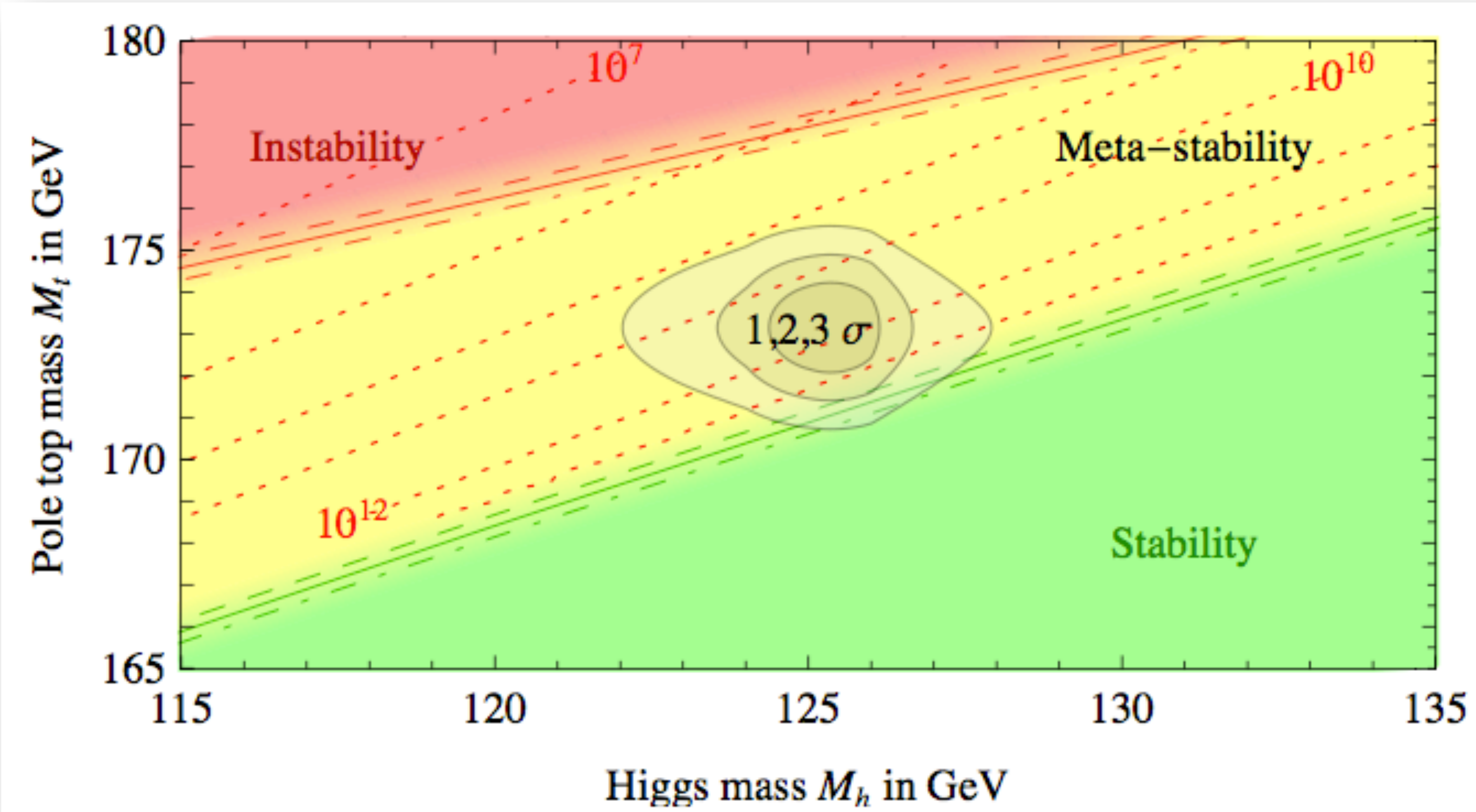
Ellis et. al.: 0906.0954

- For a 125 GeV Higgs, it turns out the SM quartic coupling *almost* vanishes at the Planck scale:



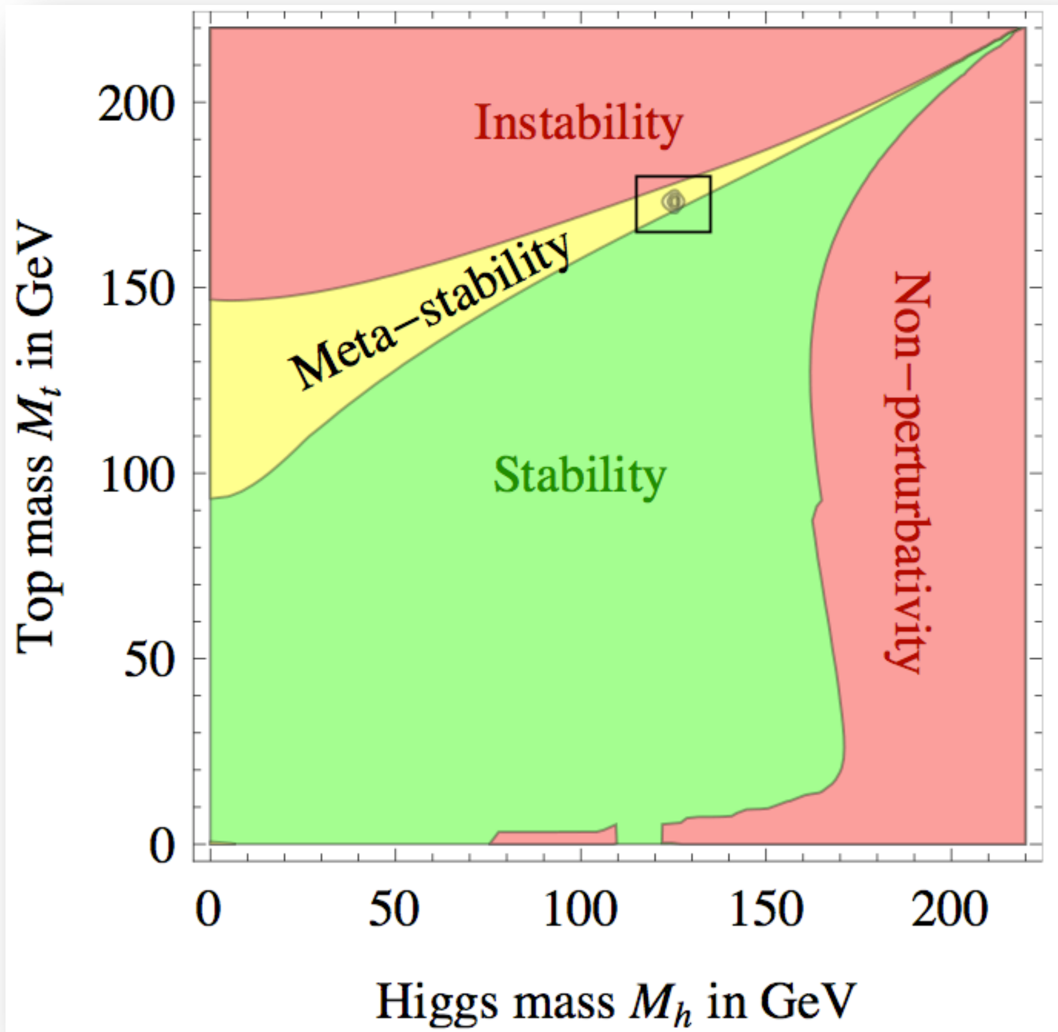
Degrassi et. al.: 1205.6497.

And our Universe is only metastable:



Degrassi et. al.: 1205.6497.

Moreover, we are a very special bunch:



Degrassi et. al.: 1205.6497.

So it seems, like it or not, we are all living on the edge. Very much so!!

Beyond the SM, in any given theory, the quartic coupling has two generic sources:

$$\lambda = \lambda^{(\mathrm{tree})} + \lambda^{(1-\mathrm{loop})}$$

- If the tree-level quartic is already O(1), then we don't learn much about the theory. (It's just a free parameter!)

- But if the tree-level quartic is small, a large one-loop correction is needed to get to 125 GeV !

A new particle with a significant coupling to the Higgs should exist in order to give a large one-loop contribution,

$$M_{\mathrm{new}} \geq \mathcal{O}(\mathrm{TeV})$$

At the same this new particle would introduce fine-tuning in the Higgs mass, typically at O(%) or worse!

Not many theories have a small tree-level quartic. The most (in)famous example is

The MSSM: $\lambda_{\rm mssm}^{\rm (tree)} \leq 0.14$

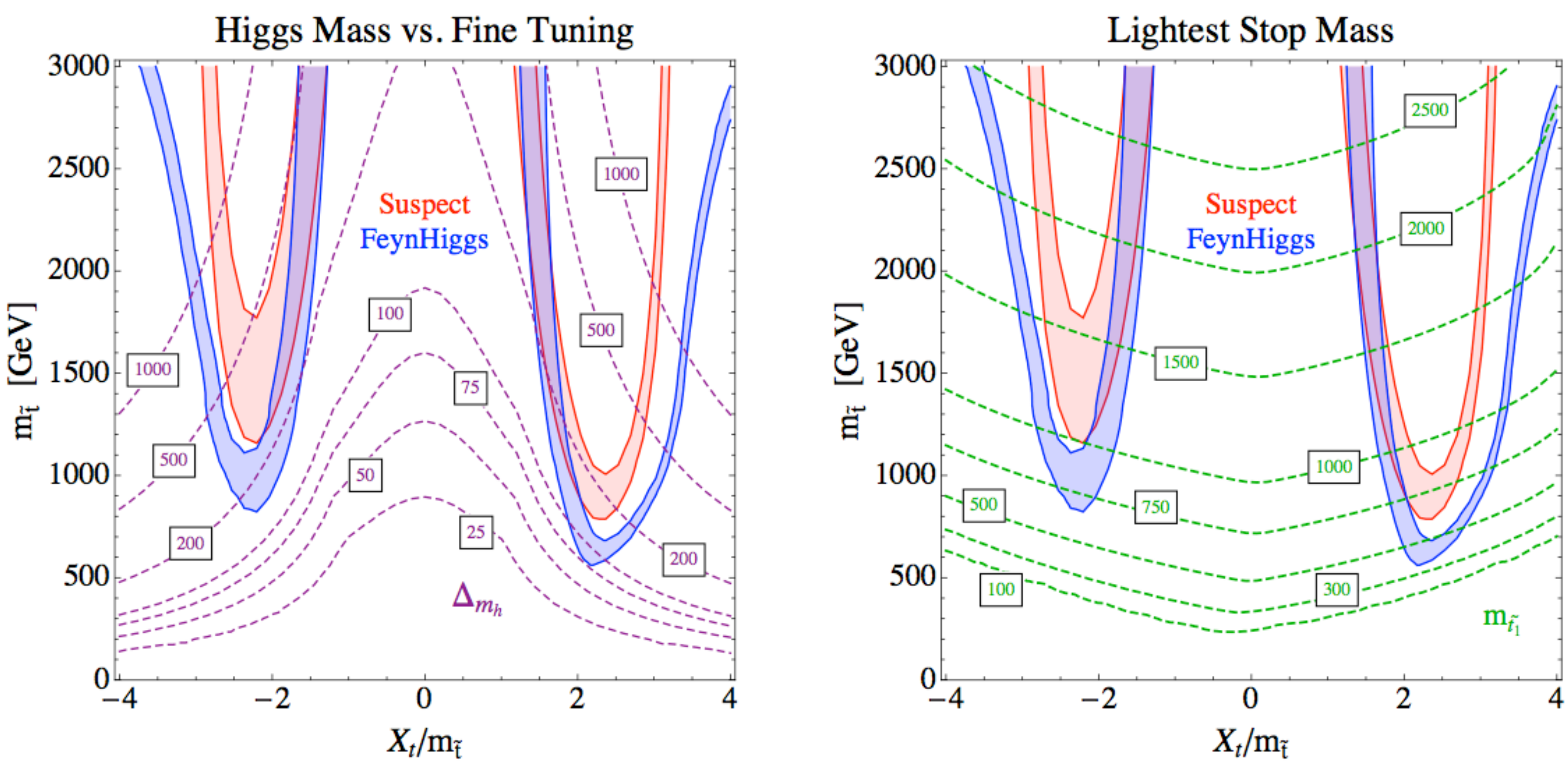
(The less famous example is the Georgi-Kaplan composite Higgs.)

- A 125 GeV Higgs is bad news for the naturalness of this class of theories.
- A 125 GeV Higgs also points to a very specific region of parameter space.

In MSSM if we consider a Higgs mass around 125 GeV,

- Top squarks are heavier than O(1 TeV), unless large mixing is turned on.
- MSSM fine-tuned at less than one percent level.

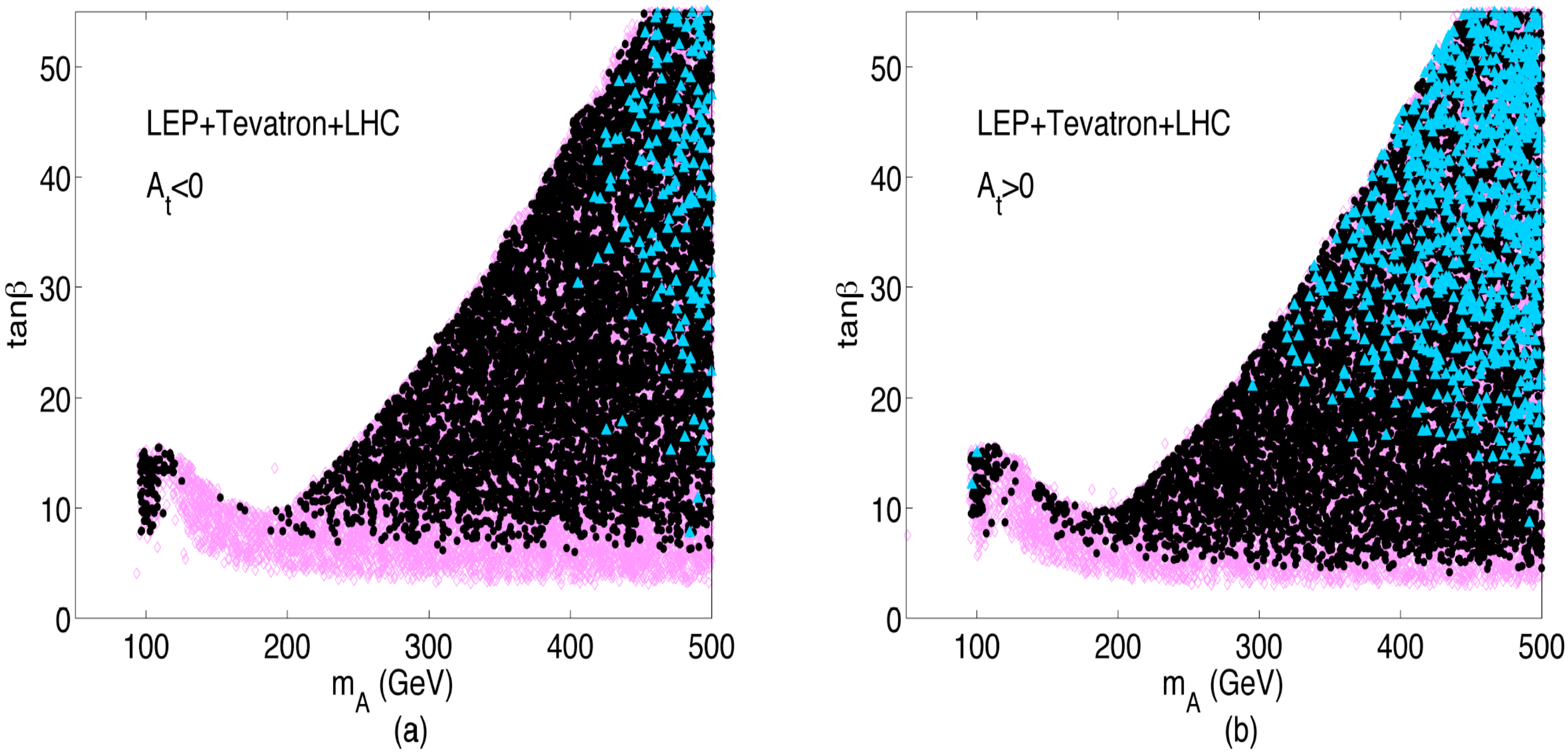
Color bands are for 124-126 GeV mass:



Hall, Spinner, Ruderman: 1112.2703

- Special corners in m_A - $\tan\beta$ plane:

Black dots are for 123-127 GeV mass:



Christensen, Han, Su: 1203.3207

However, once we go outside of MSSM, for example by adding an extra singlet to MSSM, little information is carried by the Higgs mass measurements.

Most theories do have a sizeable tree-level quartic coupling.

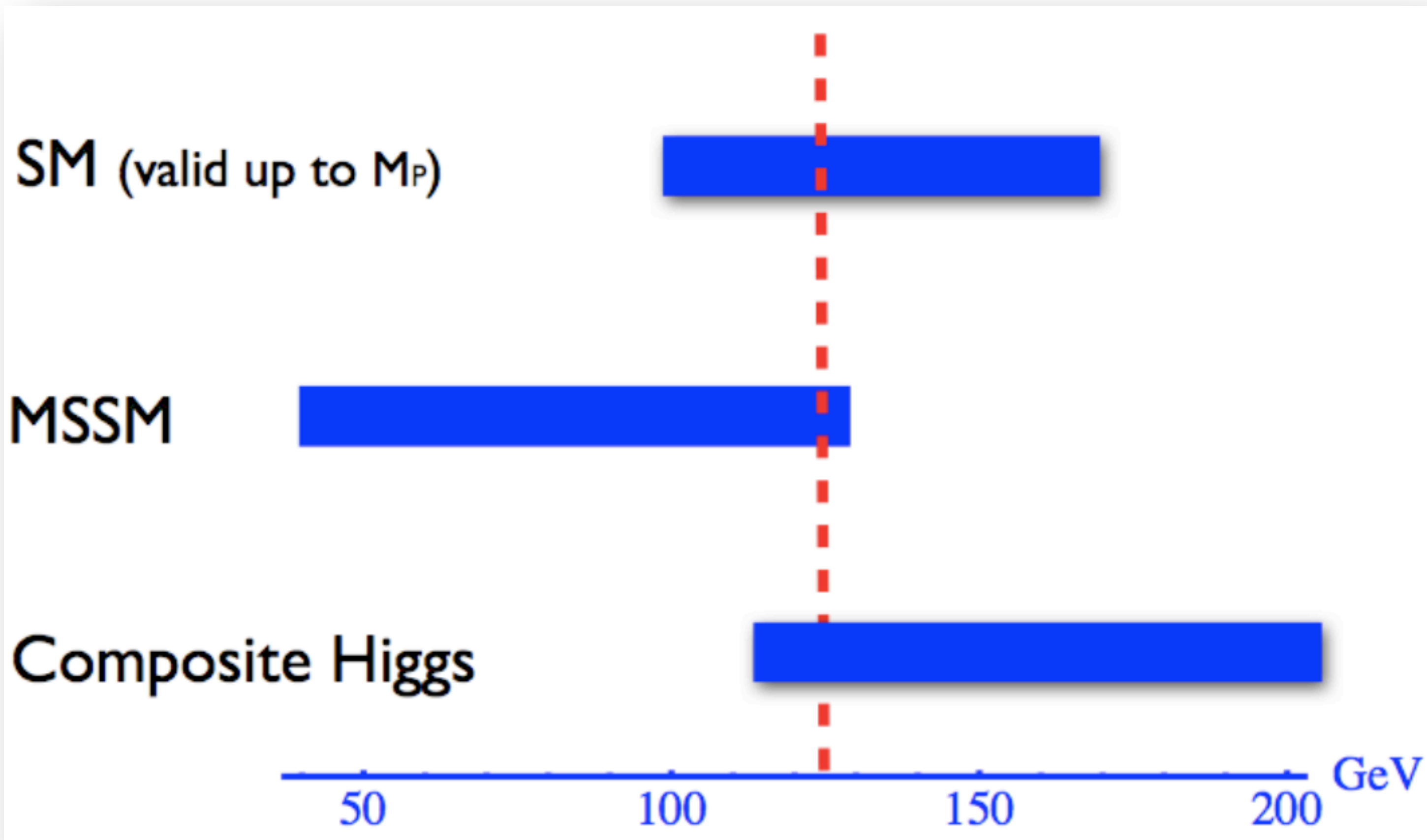
(Again, Higgs mass is a free parameter and cannot be predicted!)

Sometimes, the problem is the tree-level quartic is generically O(1), then the Higgs mass would come out to be a little too heavy for 125 GeV.

This turns out to be the case in the PNGB Higgs (composite Higgs) models, where the quartic size is set by the top Yukawa:

$$\lambda \sim y_t \qquad\qquad m_h \geq m_t = 172 \quad \text{GeV}$$

In the end, 125 GeV is in a sort of “no man’s land” for BSM theories:



Pomarol, ICHEP ‘12

Next let's turn to the other quantity that we measure: the event rate.

the event rate for a particular production mechanism X of the new boson S, which subsequently decays into Y final states:

$$B\sigma_X(Y) \equiv \sigma(X \to S)\frac{\Gamma(S \to Y)}{\Gamma_{\rm tot}}$$

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The good thing about the event rate: We can predict it precisely!

The not-so-good thing about the event rate: We can't interpret it simply!

Any deviation in a given channel could be due to

1. Increased production cross section
2. Reduced total width
3. Increased partial decay width

To answer the question of whether it's the SM Higgs, we need to measure

- all production cross sections
- all partial decay widths
- the total decay width

and see if ***all*** of the above agree with the SM expectations.

We are not quite close to answering this question!

(It's not easy being a SM Higgs; the bar is extremely high…)

Since it is clear that h(125) is at least Standard Model-like, let's assume its couplings are also SM-like, with arbitrary strength for now:

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

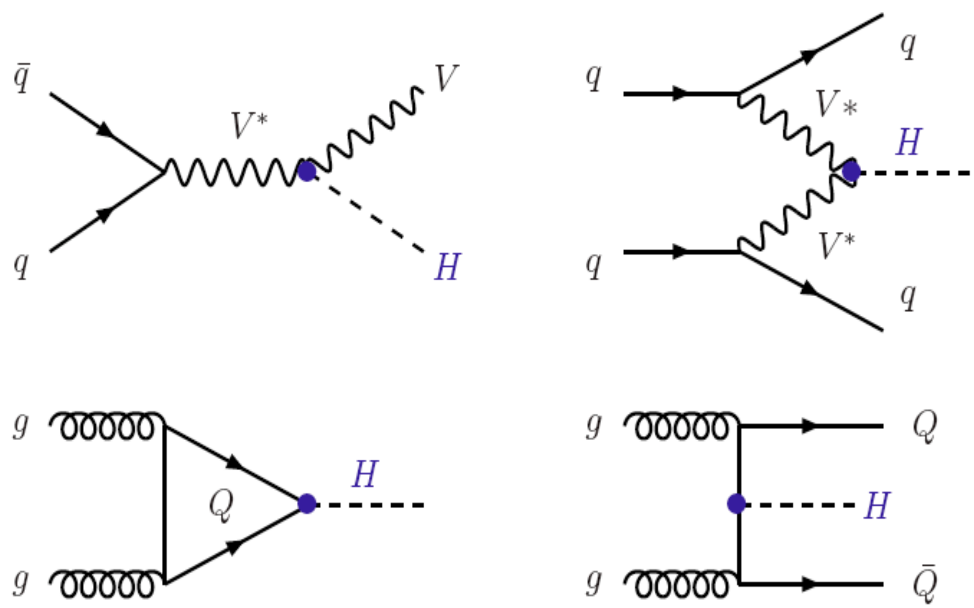
$$+ \sum_f c_f \frac{m_f}{v} h \bar{f} f$$

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

Red boxes are tree-level couplings, while blue box contains loop-induced couplings.

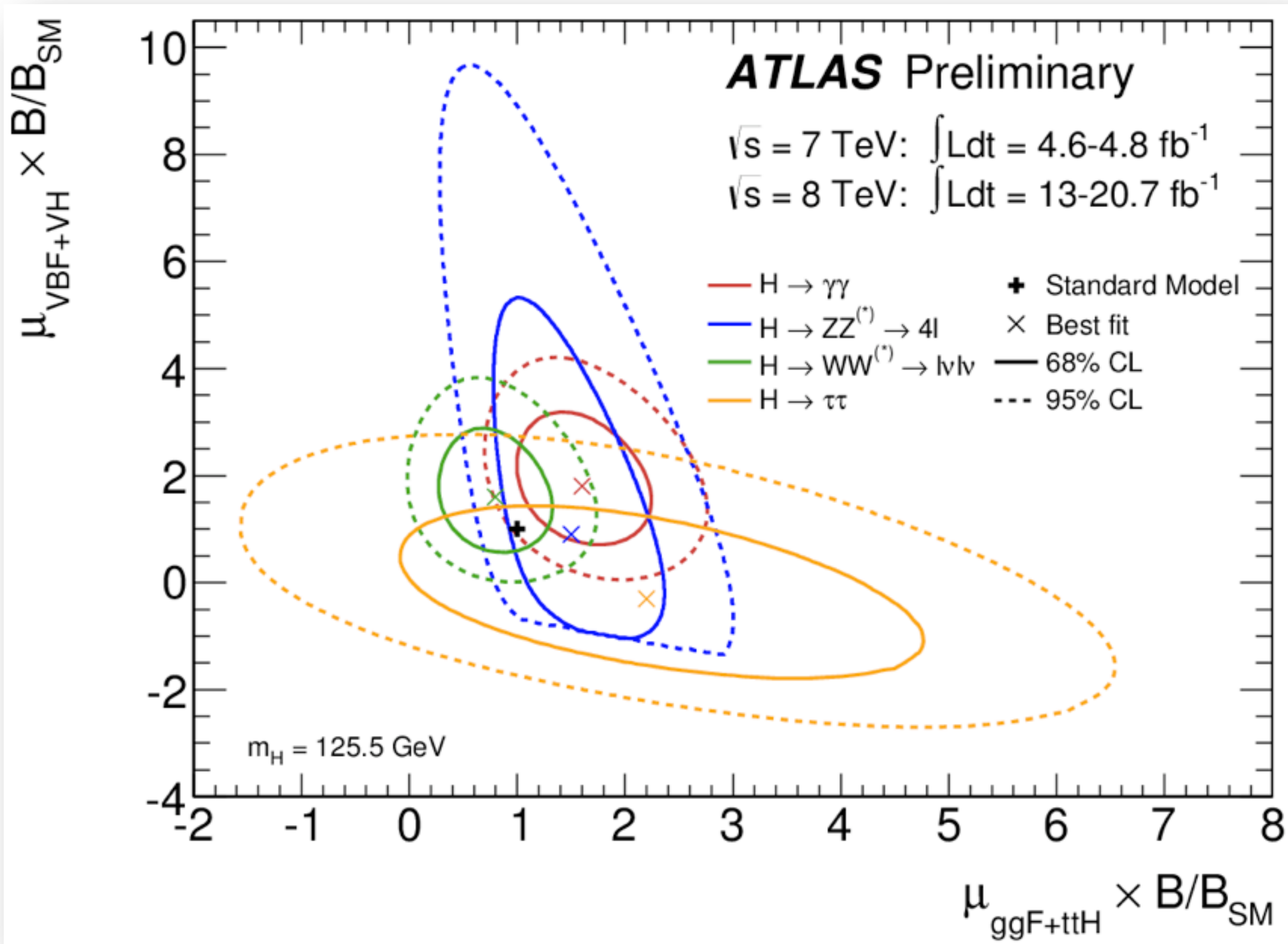
Recall the four different Higgs production channels at the LHC:

$$\begin{aligned}
\text{associated production with } W/Z: &\quad q\bar{q} \longrightarrow V + H \\
\text{vector boson fusion}: &\quad qq \longrightarrow V^*V^* \longrightarrow qq + H \\
\text{gluon} - \text{gluon fusion}: &\quad gg \longrightarrow H \\
\text{associated production with heavy quarks}: &\quad gg, q\bar{q} \longrightarrow Q\bar{Q} + H
\end{aligned}$$



A. Djouadi: hep-ph/0503172

- ATLAS/CMS results on production strengths:



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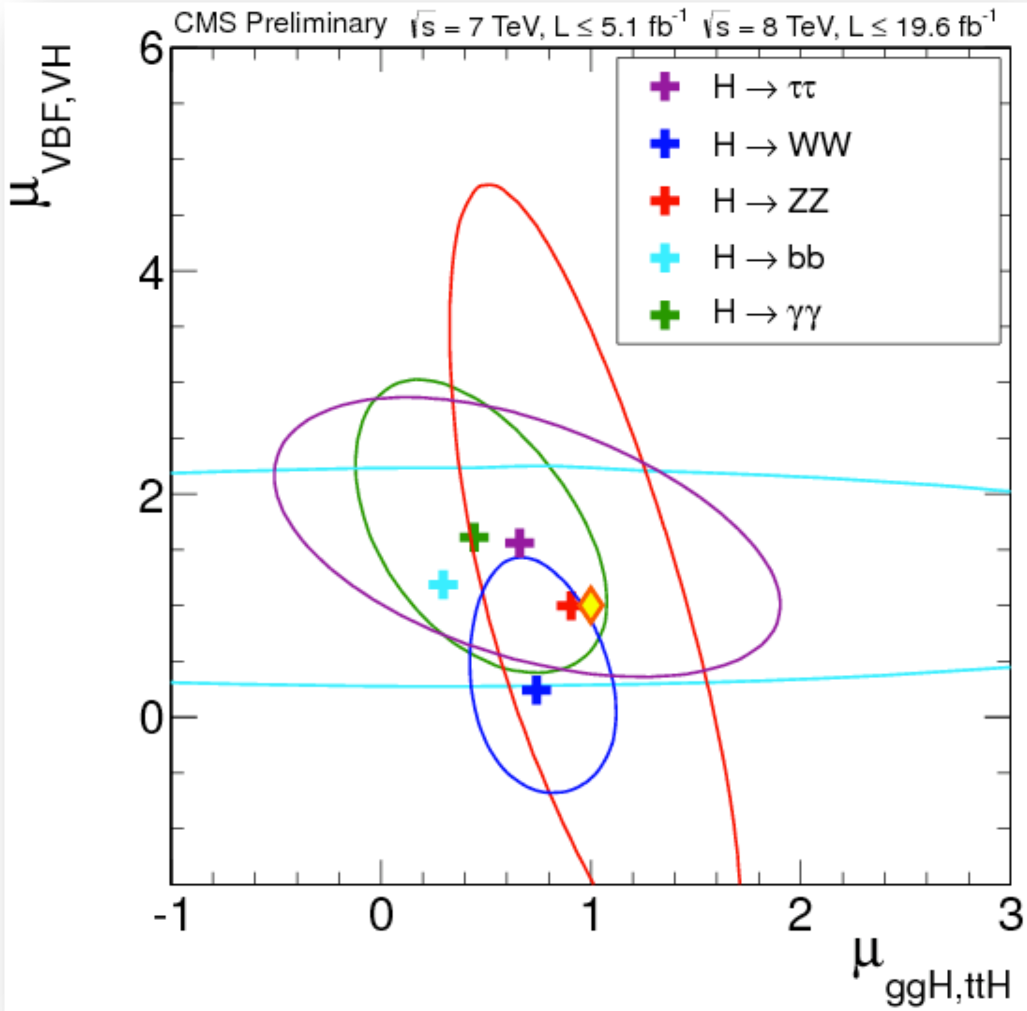
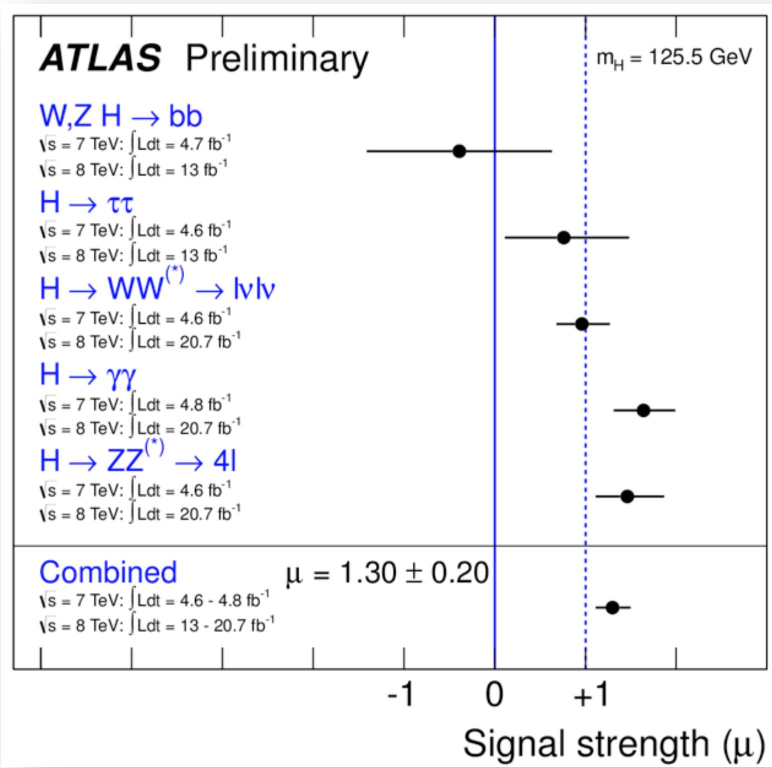
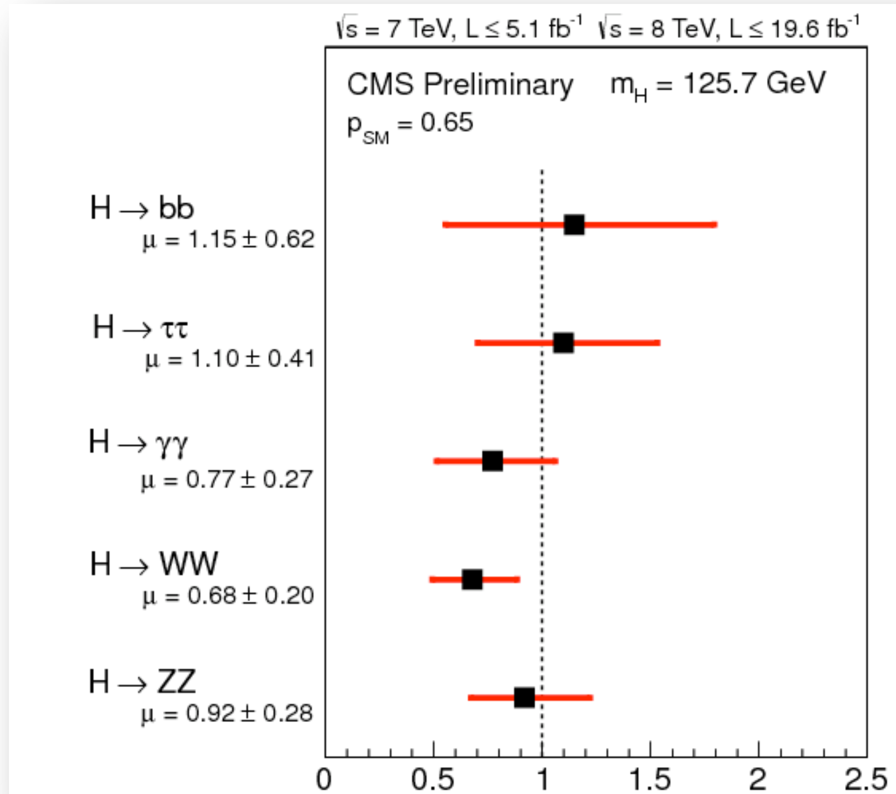


SM is consistent within 2sigma contour.
But since when is 2sigma consistency good enough?

- Signal strengths in various decay channels:

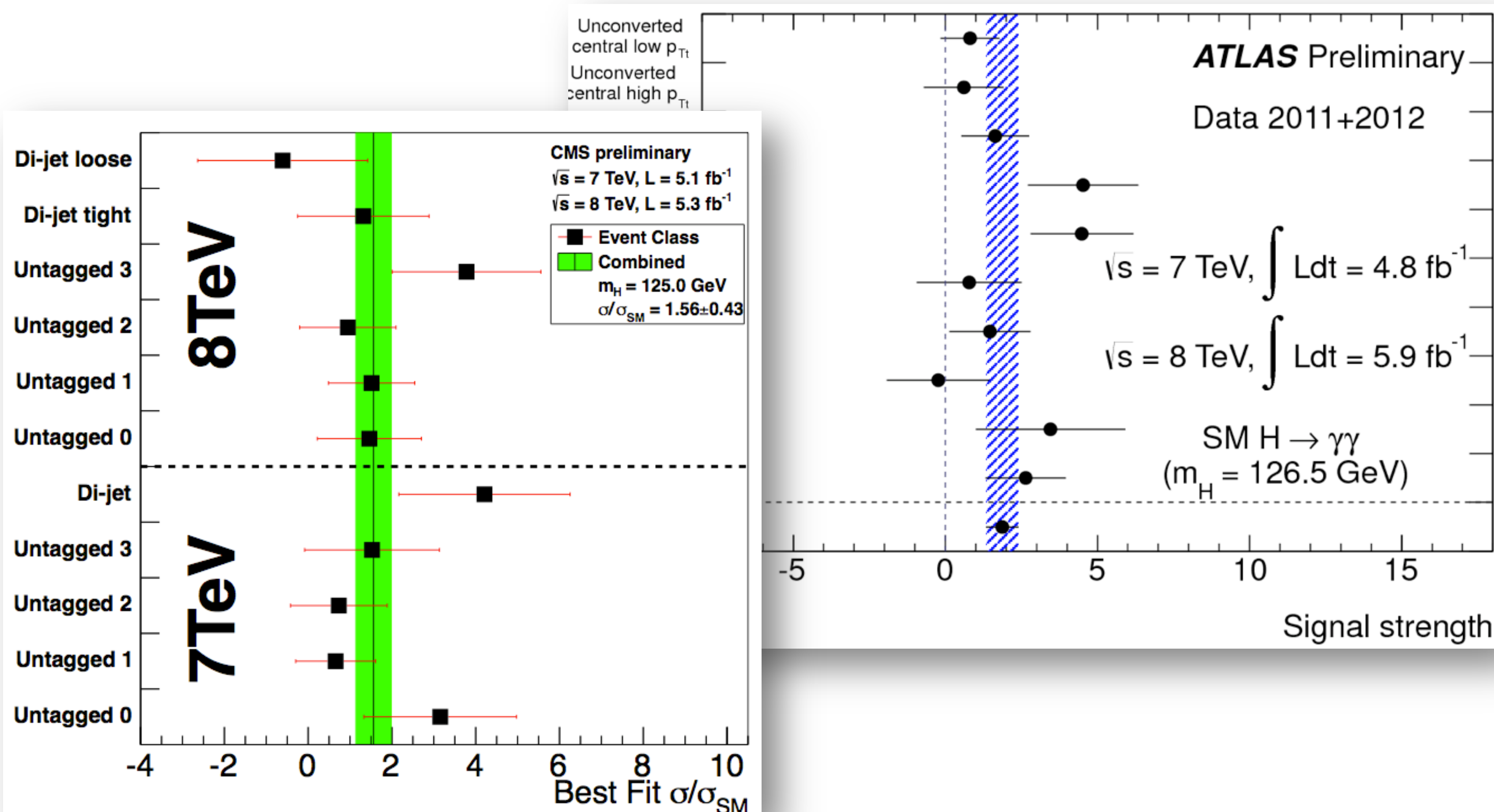




Again SM is by and large consistent within 2sigma level.

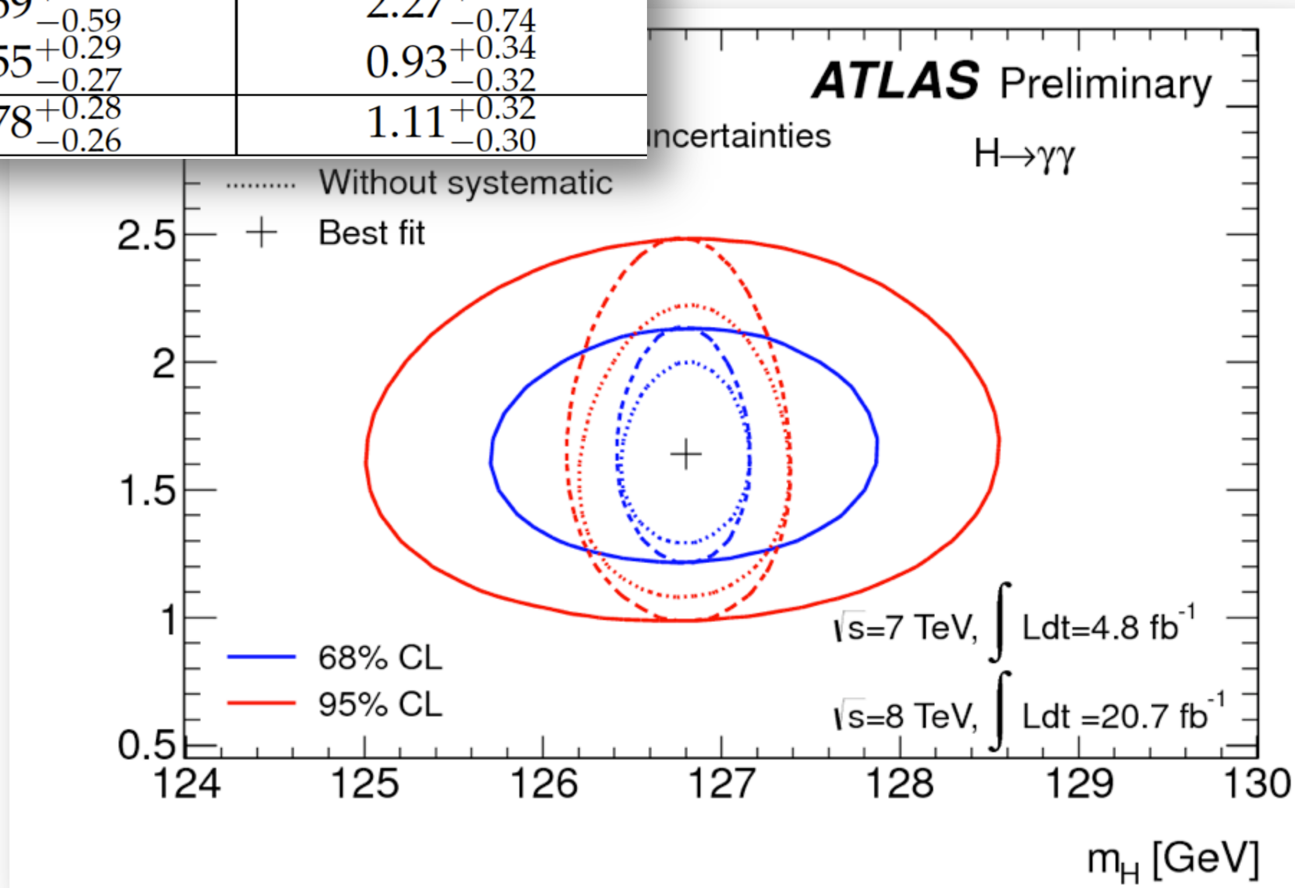
Parameter fitting is a complicated business, and it crucially depends on the assumptions. A case in point is the Higgs-to-diphoton signal strength.

On July 4^{th} 2012 both ATLAS and CMS reported significantly enhanced signal strength in the diphoton channel:

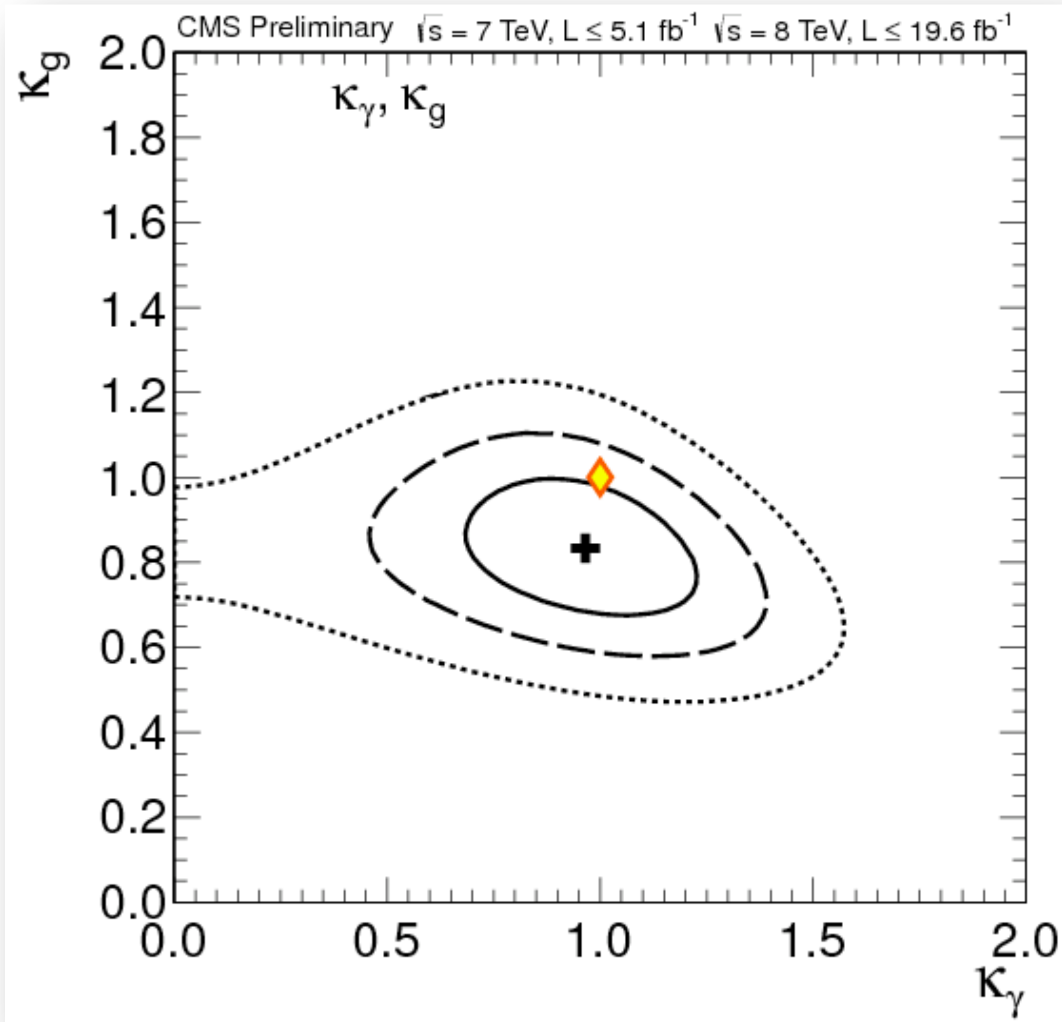


The excess subsequently went away for CMS using the full dataset, but is still there in ATLAS data:

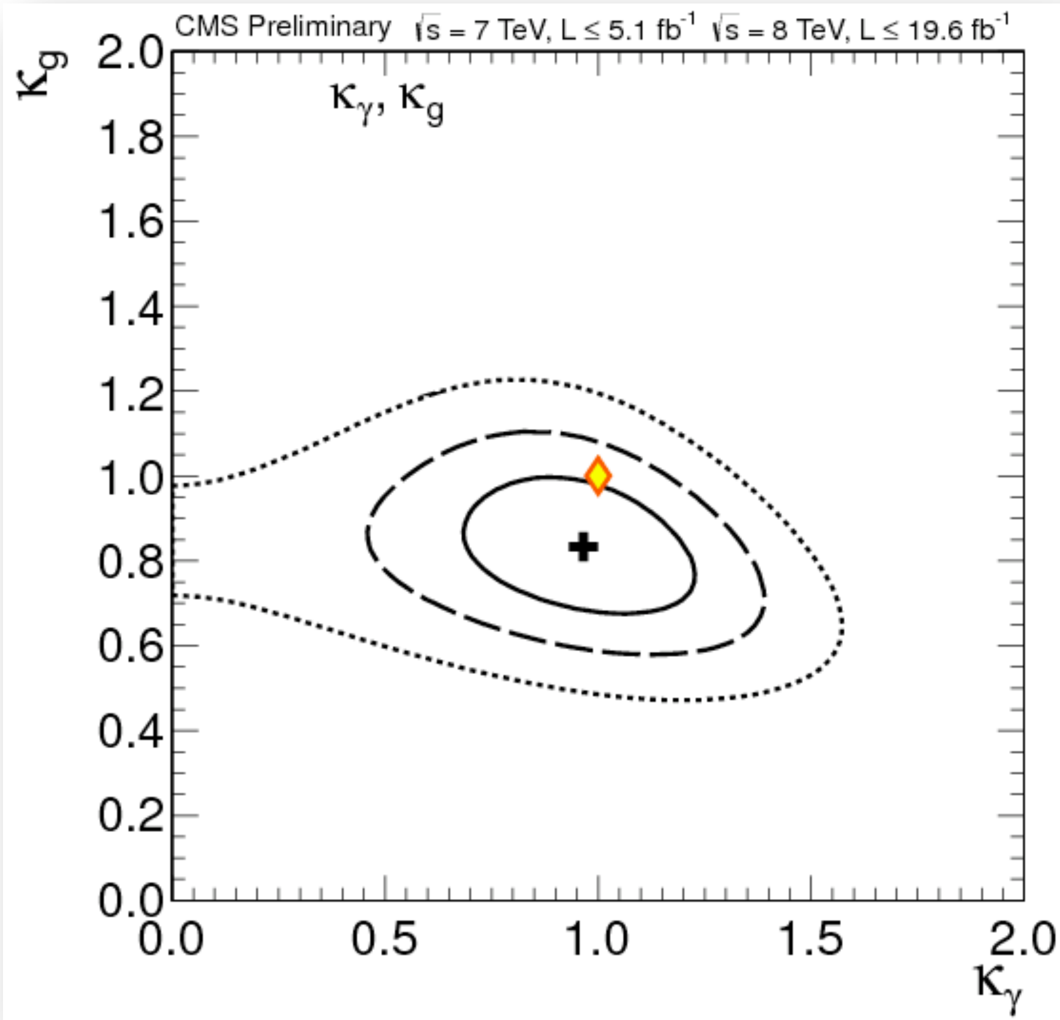
	MVA analysis (at m_{H}=125 GeV)	cut-based analysis (at m_{H}=124.5 GeV)
7 TeV	$1.69^{+0.65}_{-0.59}$	$2.27^{+0.80}_{-0.74}$
8 TeV	$0.55^{+0.29}_{-0.27}$	$0.93^{+0.34}_{-0.32}$
7 + 8 TeV	$0.78^{+0.28}_{-0.26}$	$1.11^{+0.32}_{-0.30}$



However, if we now fit the gluon coupling and photon coupling simultaneously, while fixing everything else to SM values:



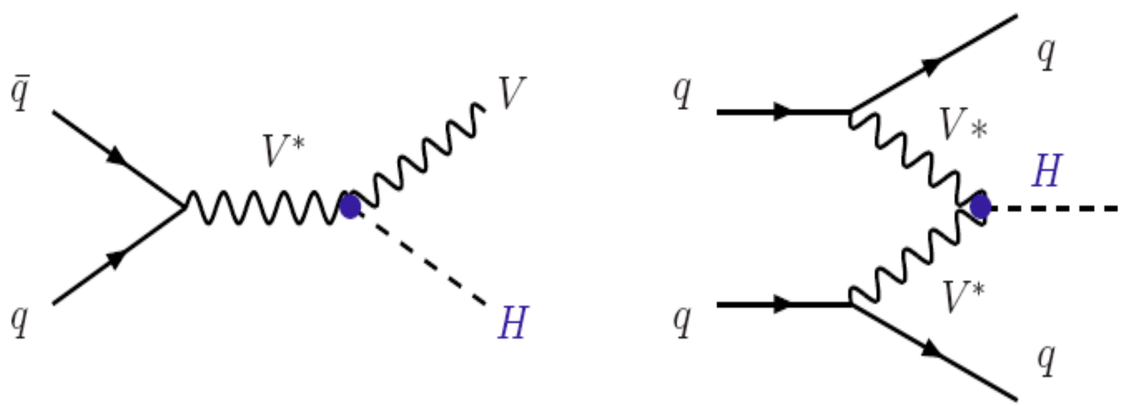
You see the best fit is a SM coupling to photons and a reduced coupling to gluons, with plenty of room for an enhanced diphoton coupling!



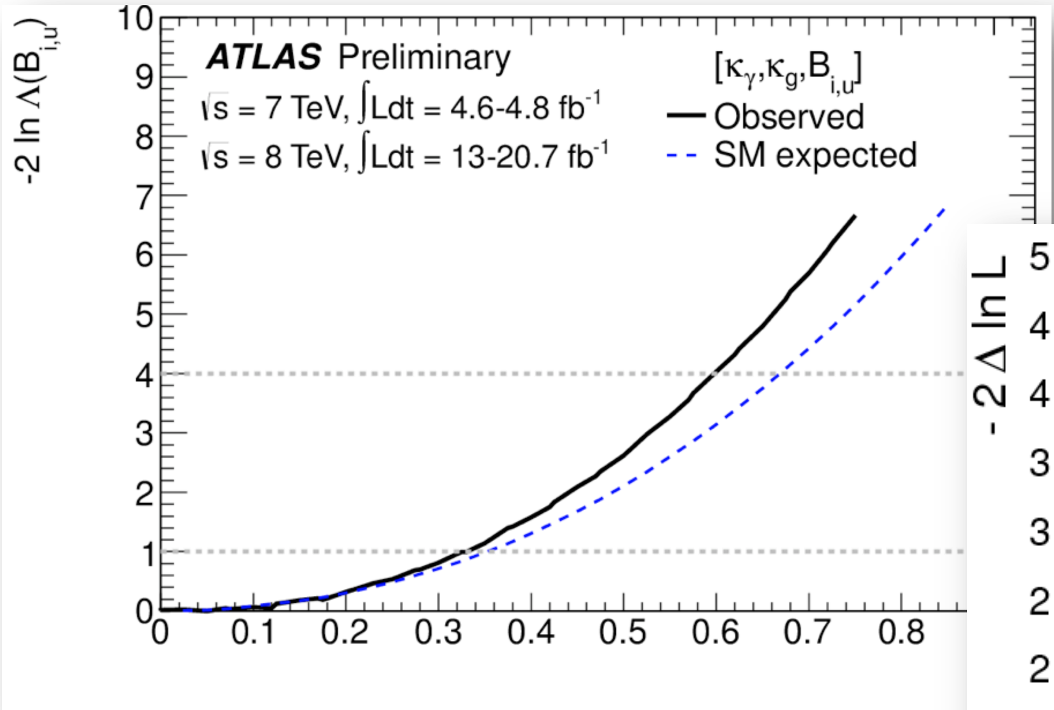
- As for total width, we know next to nothing due to lack of direct measurements.

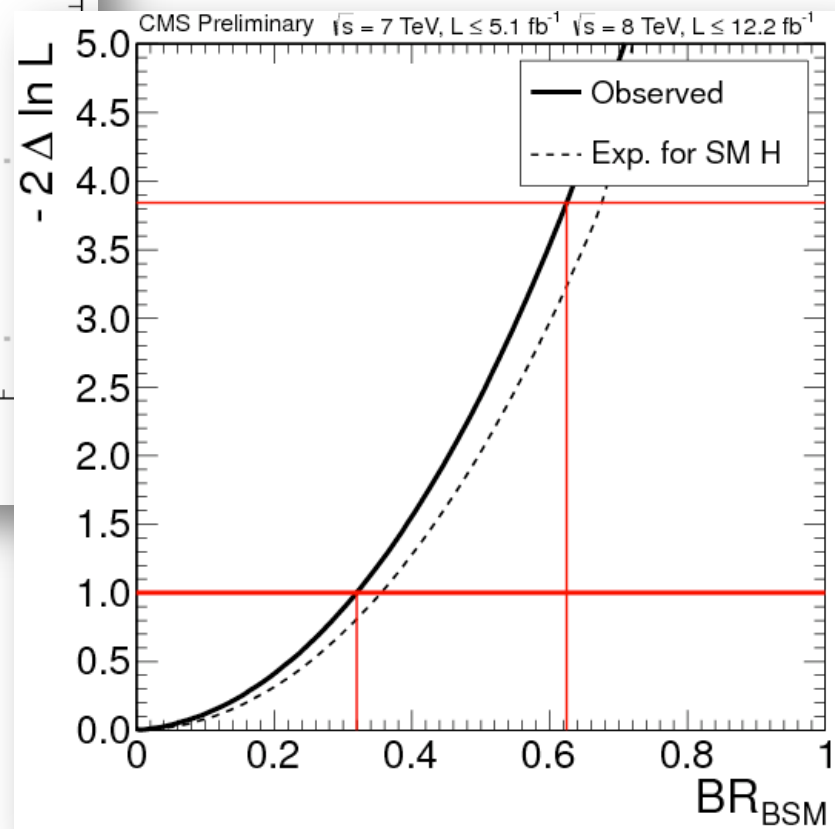
- Same goes for invisible decay width.

  In principle one can measure the invisible width directly in VBF+MET or VH+MET, but they are hard.



But since total width enters into the branching fraction, there are indirect measurements, if certain assumptions are made:





Branching fraction of invisible decays < 60% at 95 % C.L.

Bottom line:

Buyers be aware! Assume your own risk!!

Given all these subtleties and complications, the question of ”Is it *the* Standard Model Higgs?” is far from being settled.

- 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.
- New particles could couple to SM only through the Higgs, thereby altering the loop-induced couplings.
- h(125) itself may not fully unitarize VV scatterings.

More importantly, the natural size of deviations from SM in the Higgs sector is

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

One could ask why the deviation is not linear in v/M, which is what happens usually when there is a small interference effect:

$$|1+\epsilon|^2 \approx 1 + 2\epsilon$$

This parametric dependence is due to Weinberg:

- No deviations at LEP implies a (perhaps) small separation between the weak scale and the next energy scale:

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{c_i}{\Lambda^p}\mathcal{O}_i^{(4+p)} + \cdots$$

- Ignoring neutrino mass for now, $p \geq 2$! (Weinberg, '79)

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \cdots$$

- So in the previous slide,

$$\epsilon \sim \frac{v^2}{m_{\rm new}^2}\ , \qquad |1+\epsilon|^2 \approx 1 + \mathcal{O}\left(\frac{v^2}{m_{\rm new}^2}\right)$$

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

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

In other words,

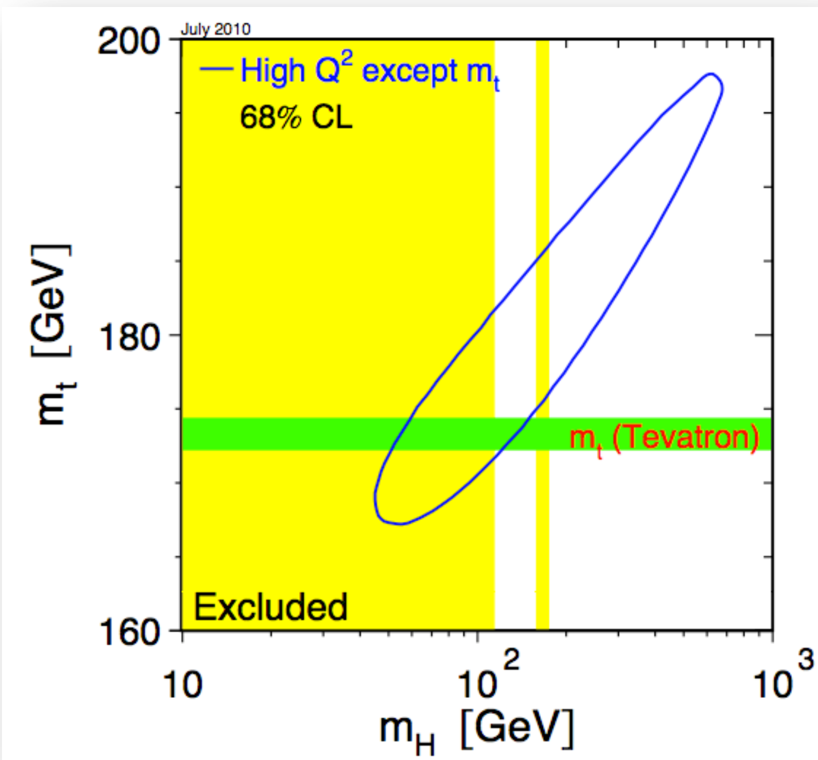
We are entering the era of precision Higgs measurements!

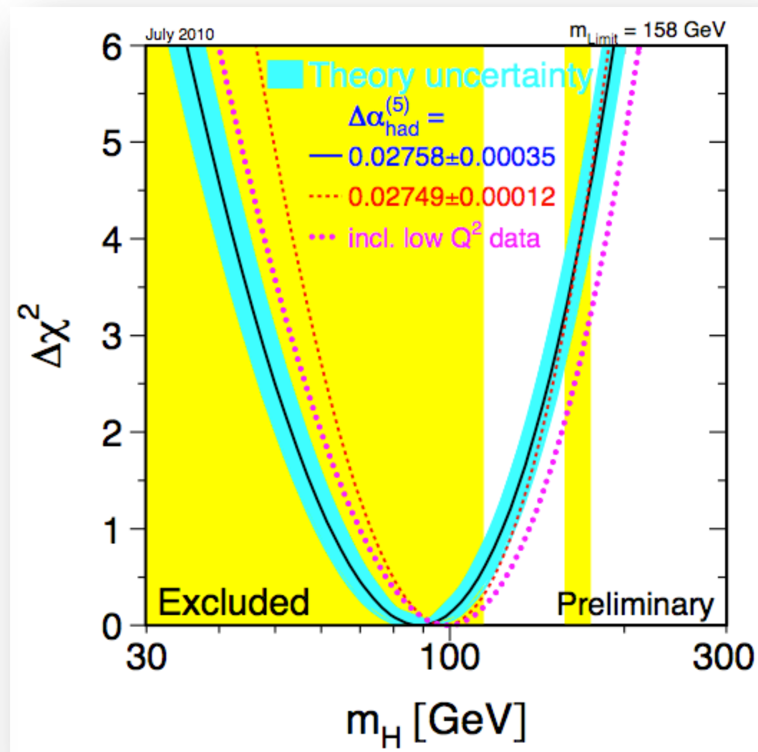
This is part of a two-pronged approach to discovering new physics beyond the Standard Model:

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

Historically, the two-pronged approach has worked very well in the context of precision electroweak measurements, 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}





Precision Higgs measurements should try to determine the following two components:

- 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.

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

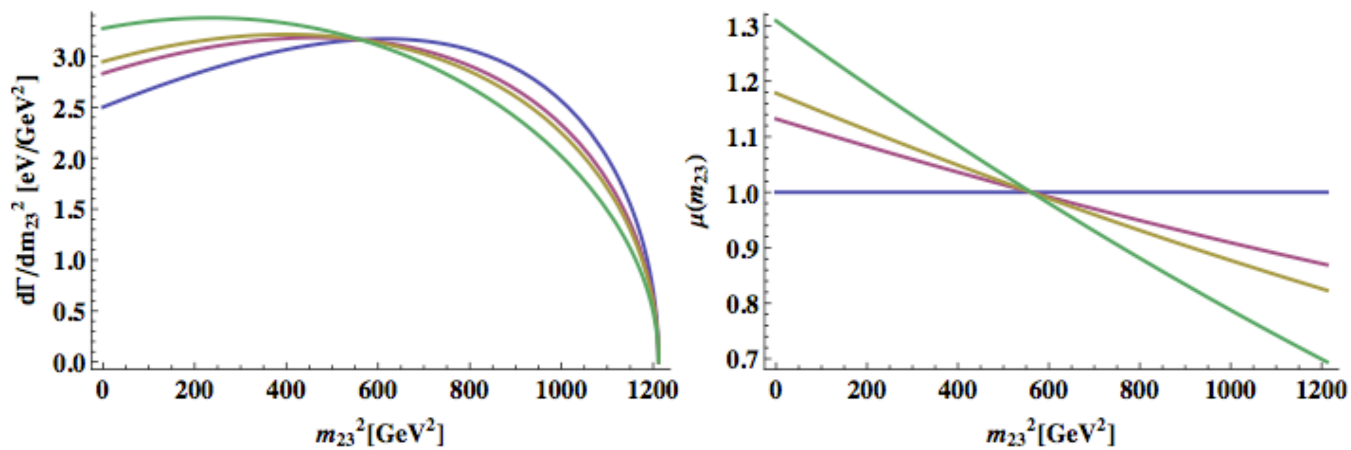


FIG. 3: Contributions to $h \to Z\ell\bar{\ell}$ from $\mathcal{O}_{ZJ}$. The differential decay rate and differential signal strength as a function of m_{23}^2 are shown on the left and right respectively. The curves correspond to the SM (blue); $c_R = 0.99$, $c_L = 0$ (red); $c_L = -1.15$, $c_R = 0$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

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

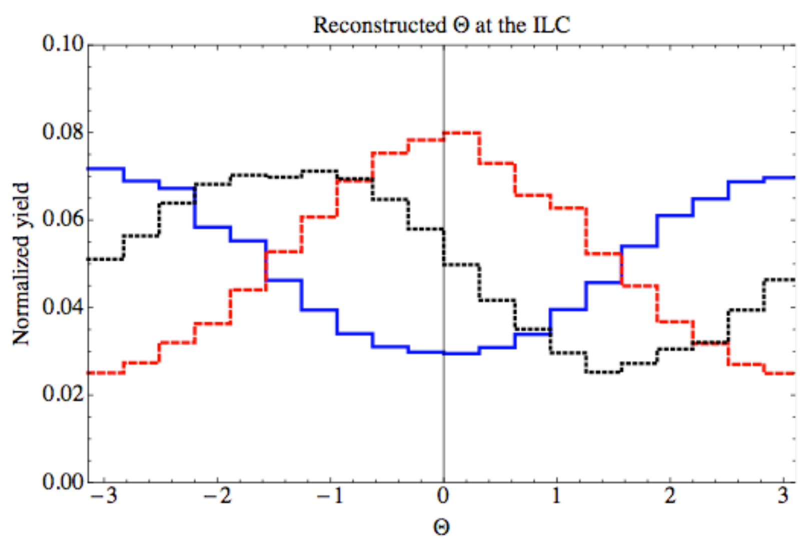
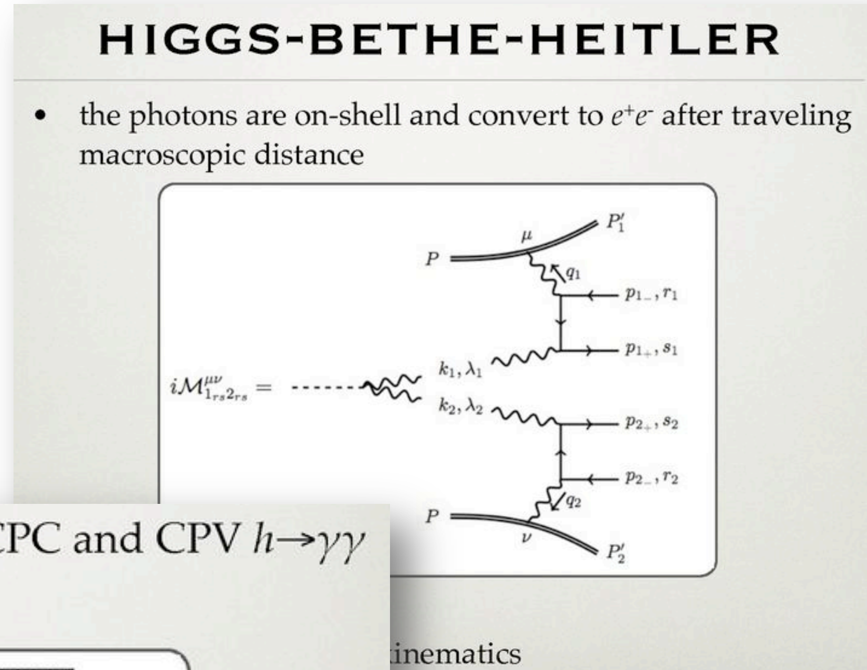
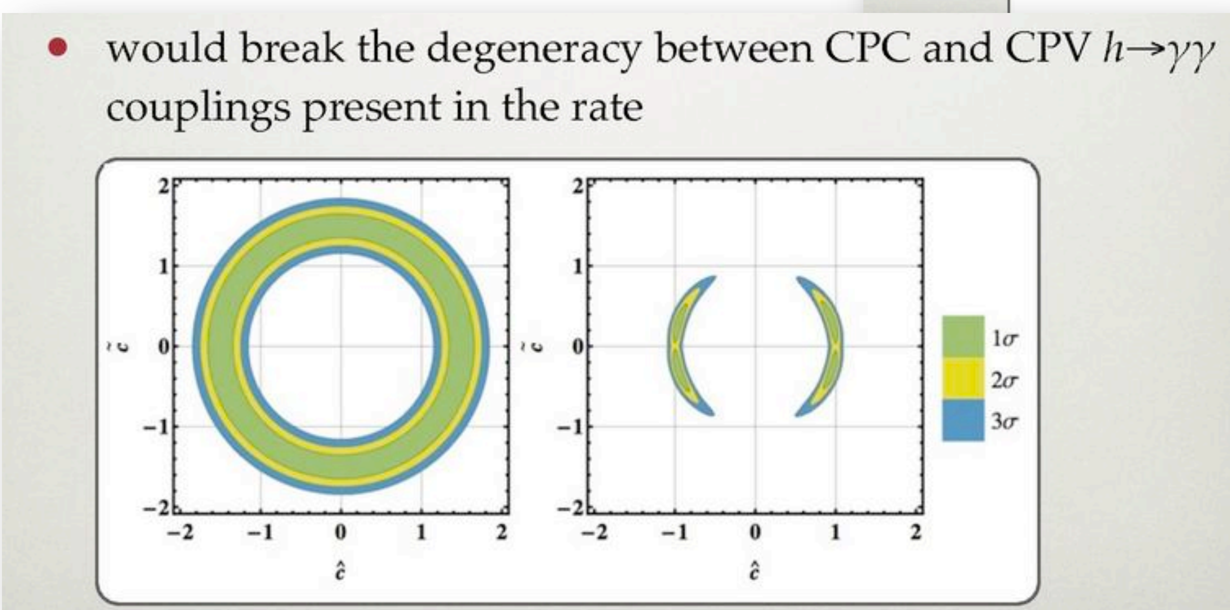


FIG. 5: The reconstructed Θ distribution at the ILC for $\Delta = 0$, $\Delta = \pi/4$, and $\Delta = \pi/2$.

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.

As for the coupling strength measurement, even if we can measure the event rates very precisely, two related major issues in the Higgs coupling fit are

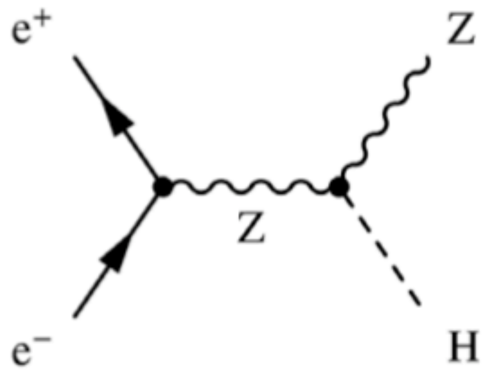
- Always measure σ x BR and not possible to separate the two at the LHC.

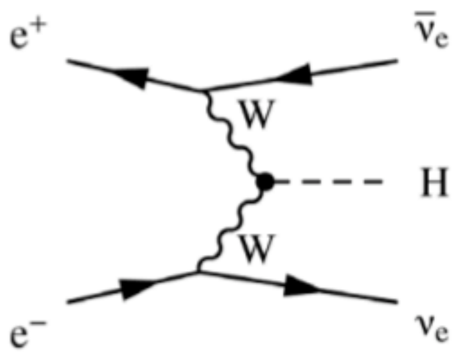
- A related issue is direct measurements of the total width and the invisible width very challenging, if not impossible altogether.

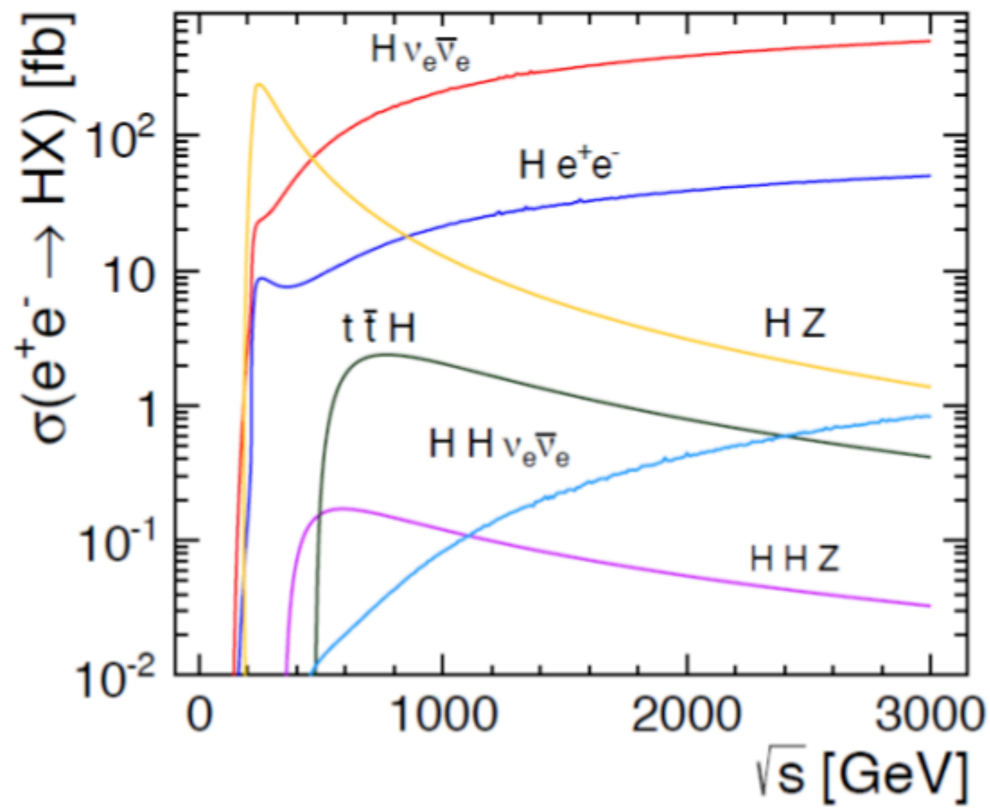
Are there ways to avoid these two issues?

YES, but we need a lepton collider!

Higgs production at a lepton collider:







Slides from Jianming Qian:

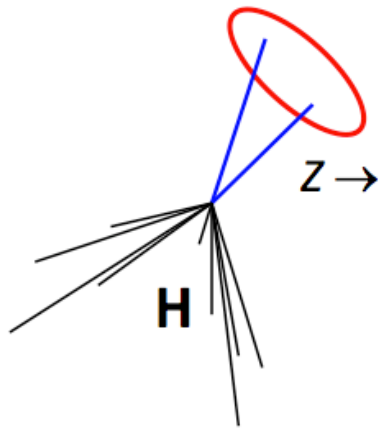
e^+e^- collisions:

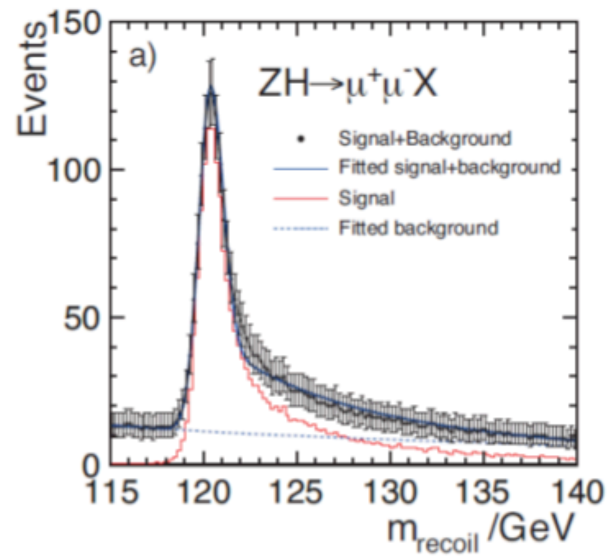
ZH production provides a way to tag the Higgs without looking at it's decay $\Rightarrow$ allow to measure σ and BR separately

$e^+e^- \to ZH$ with

$Z \to \ell^+\ell^-$

$H \to X$





$$m^2_{\text{recoil}} = \left(\sqrt{s} - E_{\ell\ell}\right)^2 - |\vec{p}_{\ell\ell}|^2$$

Jianming Qian (University of Michigan) 9

The beauty of knowing the CM energy!
The same trick allow for direct measurements of total width and invisible width!

What are the options for lepton (as well as hadron) colliders?

pp colliders

	Years	E_{cm} TeV	Luminosity $10^{34}cm^{-2}s^{-1}$	Int. Luminosity fb^{-1}
Design LHC	2014-21	14	1-2	300
HL-LHC	2024-30	14	5	3000
HE-LHC	>2035	26-33*	2	100-300/y
V-LHC**	>2035	42-100		

* 16-20 T dipole field
** 80 km Tunnel

e+e- colliders

	Years	E_{cm} GeV	Luminosity $10^{34}cm^{-2}s^{-1}$	Tunnel length km
ILC 250	<2030	250	0.75	
ILC 500		500	1.8	~30
ILC 1000		1000		~50
CLIC 500	>2030	500	2.3(1.3)	~13
CLIC 1400		1400(1500)	3.2(3.7)	~27
CLIC 3000		3000	5.9	~48
LEP3	>2024	240	1	LEP/LHC ring
TLEP	>2030	240	5	80 (ring)
TLEP		350	0.65	80 (ring)

Other options:

$\mu^+\mu^-$ and $\gamma\gamma$ colliders with similar physics as e^+e^- colliders

LHeC for ep collisions

See ES Briefing Book for references

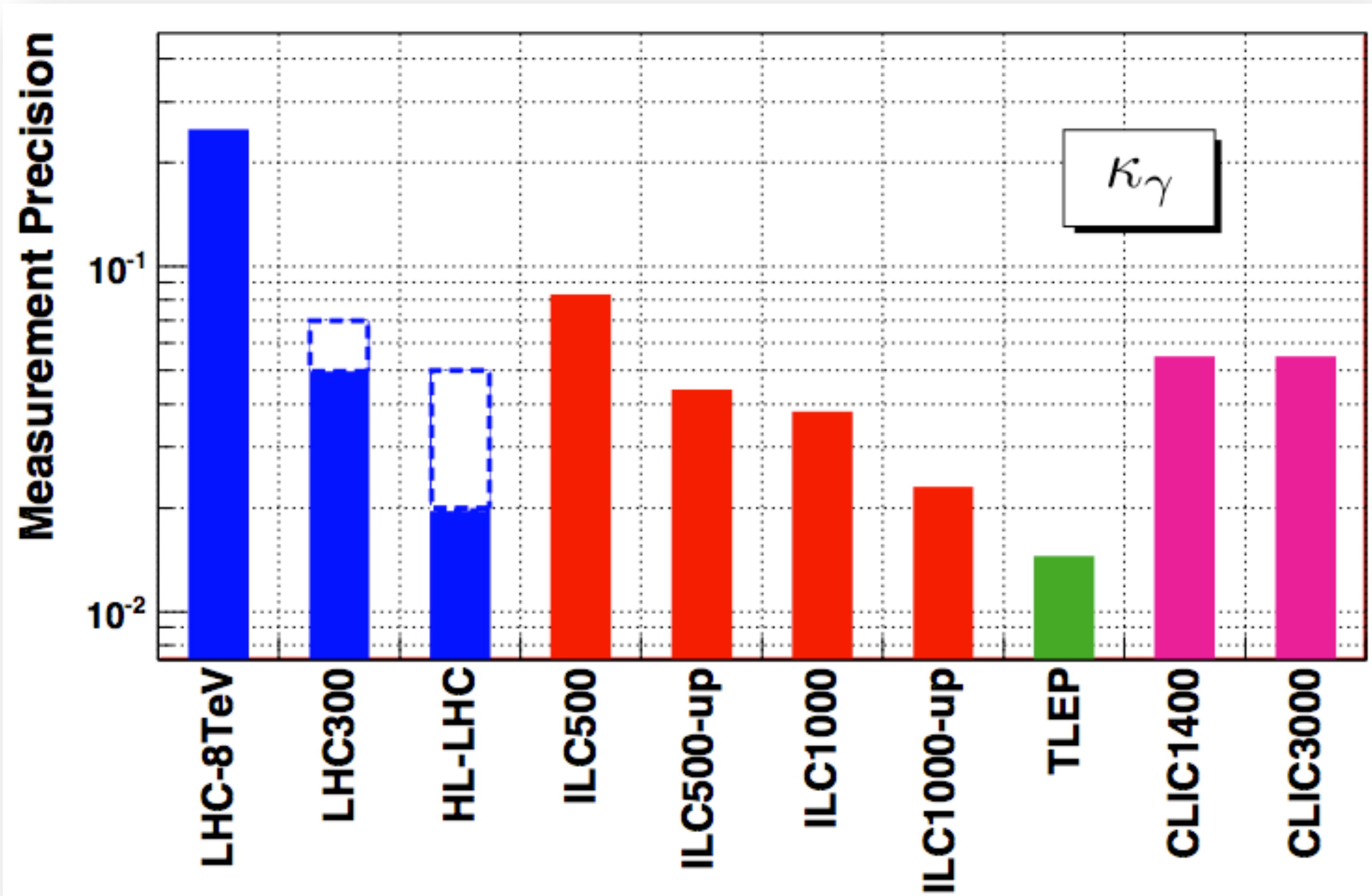
ISHP2013, Beijing, 16-8-2013
~~P Jenni, Freiburg and CERN~~

HE Frontier, European Strategy

29

Slide from Peter Jenni in Beijing

Comparison of how well the Higgs-to-diphoton coupling can be measured:



US Snowmass Higgs group report

Comparison of precision among Lepton colliders:

Facility		ILC		ILC(LumiUp)	TLEP (4 IP)			CLIC	
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350	350	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	$1150+1600+2500^{\ddagger}$	10000	+2600	500	+1500	+2000
$P(e^-, e^+)$	$(-0.8, +0.3)$	$(-0.8, +0.3)$	$(-0.8, +0.2)$	(same)	$(0, 0)$	$(0, 0)$	$(-0.8, 0)$	$(-0.8, 0)$	$(-0.8, 0)$
Γ_H	11%	5.9%	5.6%	2.7%	1.9%	1.0%	9.2%	8.5%	8.4%
BR_{inv}	< 0.69%	< 0.69%	< 0.69%	< 0.32%	0.19%	< 0.19%	tbd	tbd	tbd
κ_γ	18%	8.4%	4.1%	2.4%	1.7%	1.5%	–	5.9%	<5.9%
κ_g	6.4%	2.4%	1.8%	0.93%	1.1%	0.8%	4.1%	2.3%	2.2%
κ_W	4.8%	1.4%	1.4%	0.65%	0.85%	0.19%	2.6%	2.1%	2.1%
κ_Z	1.3%	1.3%	1.3%	0.61%	0.16%	0.15%	2.1%	2.1%	2.1%
κ_μ	–	–	16%	10%	6.4%	6.2%	–	11%	5.6%
κ_τ	5.7%	2.4%	1.9%	0.99%	0.94%	0.54%	4.0%	2.5%	<2.5%
κ_c	6.8%	2.9%	2.0%	1.1%	1.0%	0.71%	3.8%	2.4%	2.2%
κ_b	5.3%	1.8%	1.5%	0.74%	0.88%	0.42%	2.8%	2.2%	2.1%
κ_t	–	14%	3.2%	2.0%	–	13%	–	4.5%	<4.5%

US Snowmass Higgs group report

Comparison of precision among hadron colliders:

Facility			CLIC	
$\sqrt{s}$ (GeV)	250		1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	250		+1500	+2000
$P(e^-, e^+)$	$(-0.8, +0.3)$	(−	$(-0.8, 0)$	$(-0.8, 0)$
Γ_H	11%		8.5%	8.4%
BR_{inv}	$< 0.69\%$		tbd	tbd
κ_γ	18%		5.9%	<5.9%
κ_g	6.4%		2.3%	2.2%
κ_W	4.8%		2.1%	2.1%
κ_Z	1.3%		2.1%	2.1%
κ_μ	–		11%	5.6%
κ_τ	5.7%		2.5%	<2.5%
κ_c	6.8%		2.4%	2.2%
κ_b	5.3%		2.2%	2.1%
κ_t	–		4.5%	<4.5%

Coupling parameter	300 fb^{-1}	3000 fb^{-1}
7-parameter fit		
κ_γ	$5 - 7\%$	$2 - 5\%$
κ_g	$6 - 8\%$	$3 - 5\%$
κ_W	$4 - 6\%$	$2 - 5\%$
κ_Z	$4 - 6\%$	$2 - 4\%$
κ_u	$14 - 15\%$	$7 - 10\%$
κ_d	$10 - 13\%$	$4 - 7\%$
κ_ℓ	$6 - 8\%$	$2 - 5\%$
Γ_H	$12 - 15\%$	$5 - 8\%$
additional measurements		
$\kappa_{Z\gamma}$	$41 - 41\%$	$10 - 12\%$
κ_μ	$34 - 35\%$	$9 - 11\%$
BR_{BSM}	$< 14 - 18\%$	$< 7 - 11\%$

US Snowmass Higgs group report

Thus with a new lepton collider or a high luminosity LHC upgrade, we may have a chance of probing TeV scale physics with precision Higgs measurements.