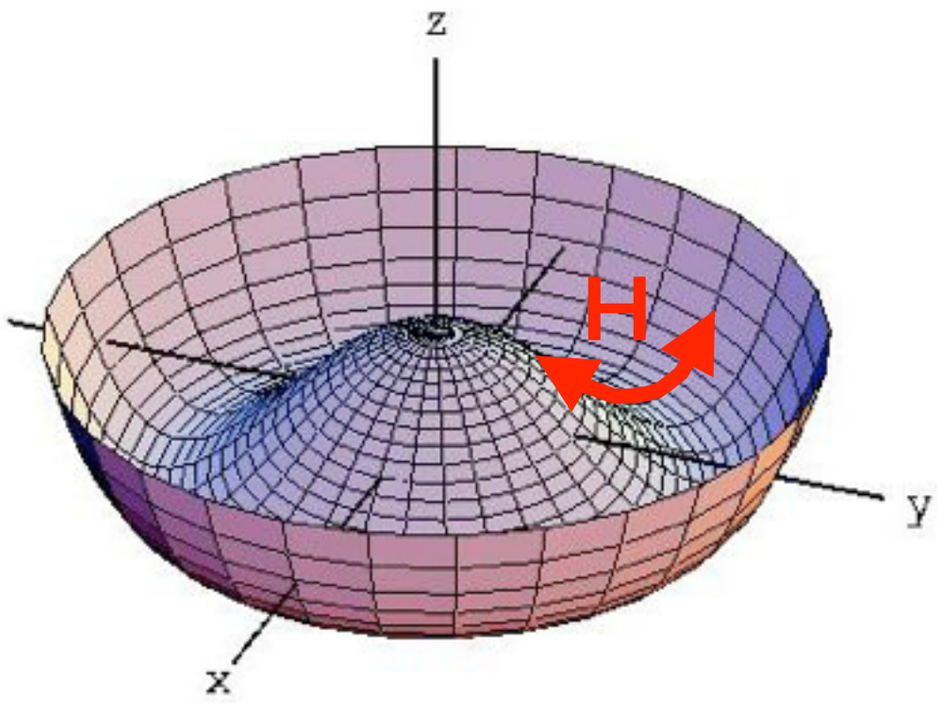
What have we learned after LHC first-run?

Implications of $m_H \approx 125$ GeV



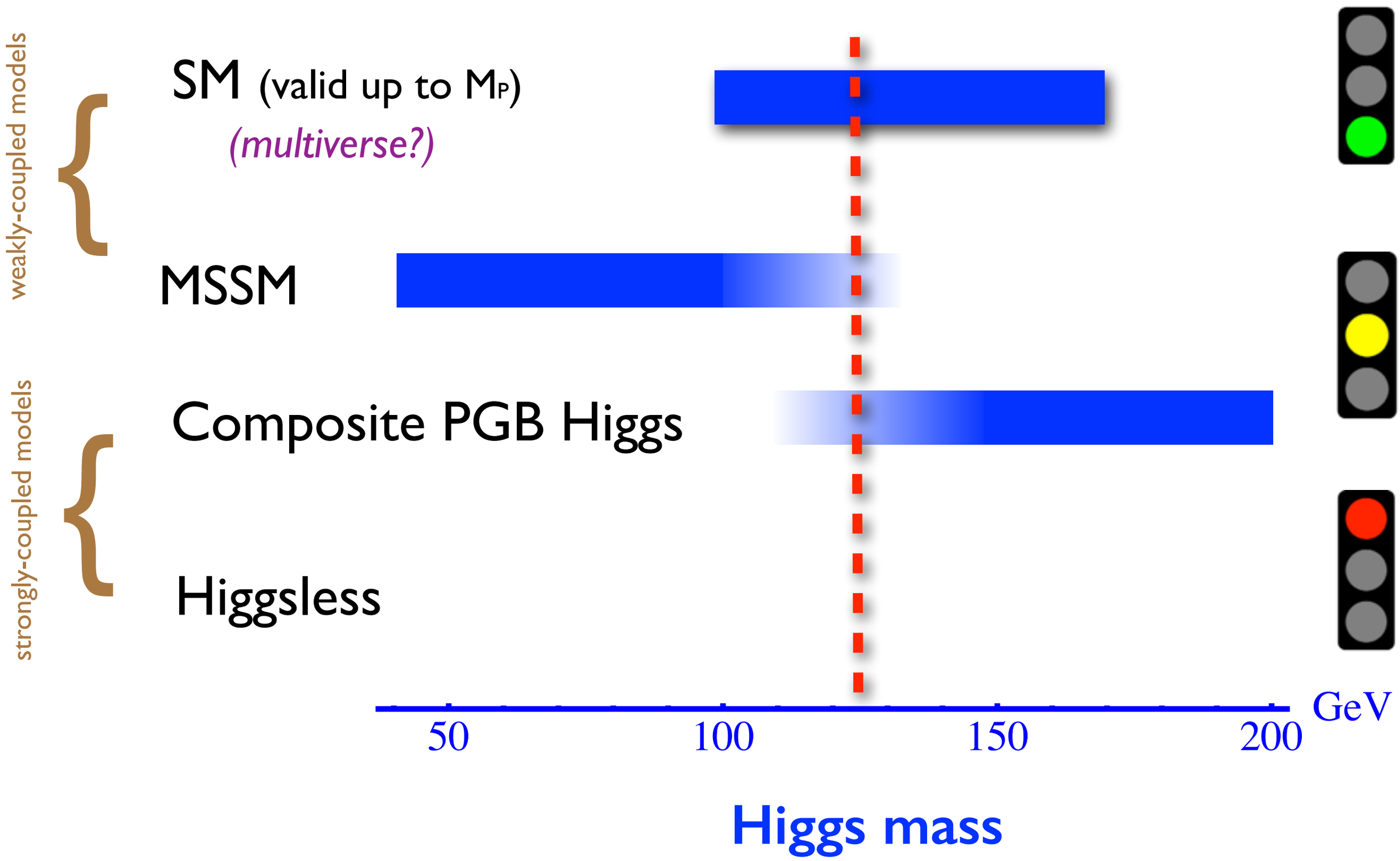
$$m_H \approx 125 \text{ GeV}$$

(the most relevant piece of LHC)

It has shaken the TH community:

No clear indication where this points to

Rough Higgs-mass range predictions

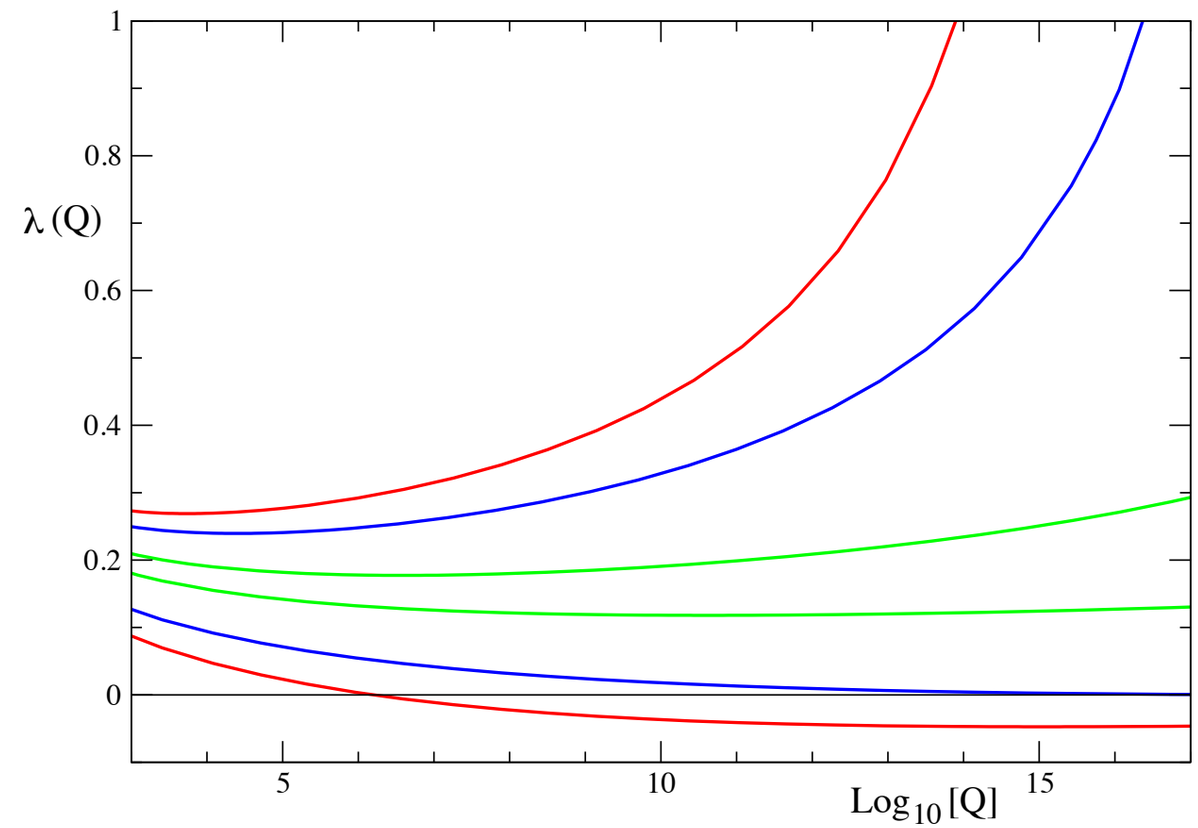


125 GeV SM Higgs

In the SM:

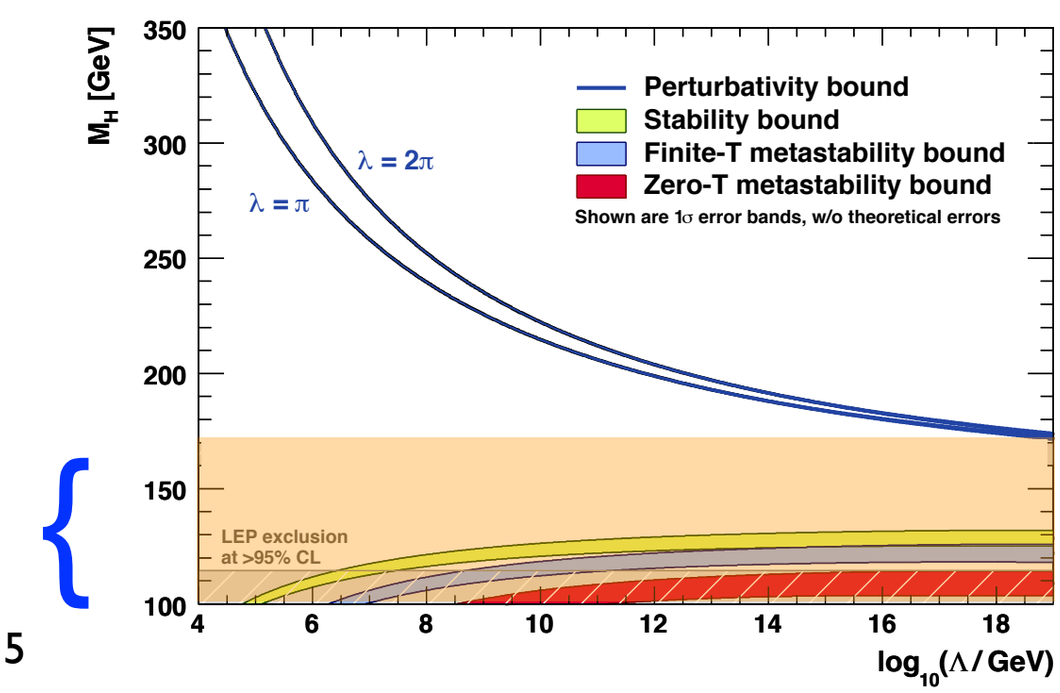
$$m_H^2 = \lambda v^2$$

Evolves with the energy



Demanding λ not too large (keep perturbativity),
not too negative that destabilizes the Higgs potential:

from Phys.Lett. B679 (2009) 369



Only a small window
in the Higgs mass
makes the SM consistent
all the way to the Planck scale

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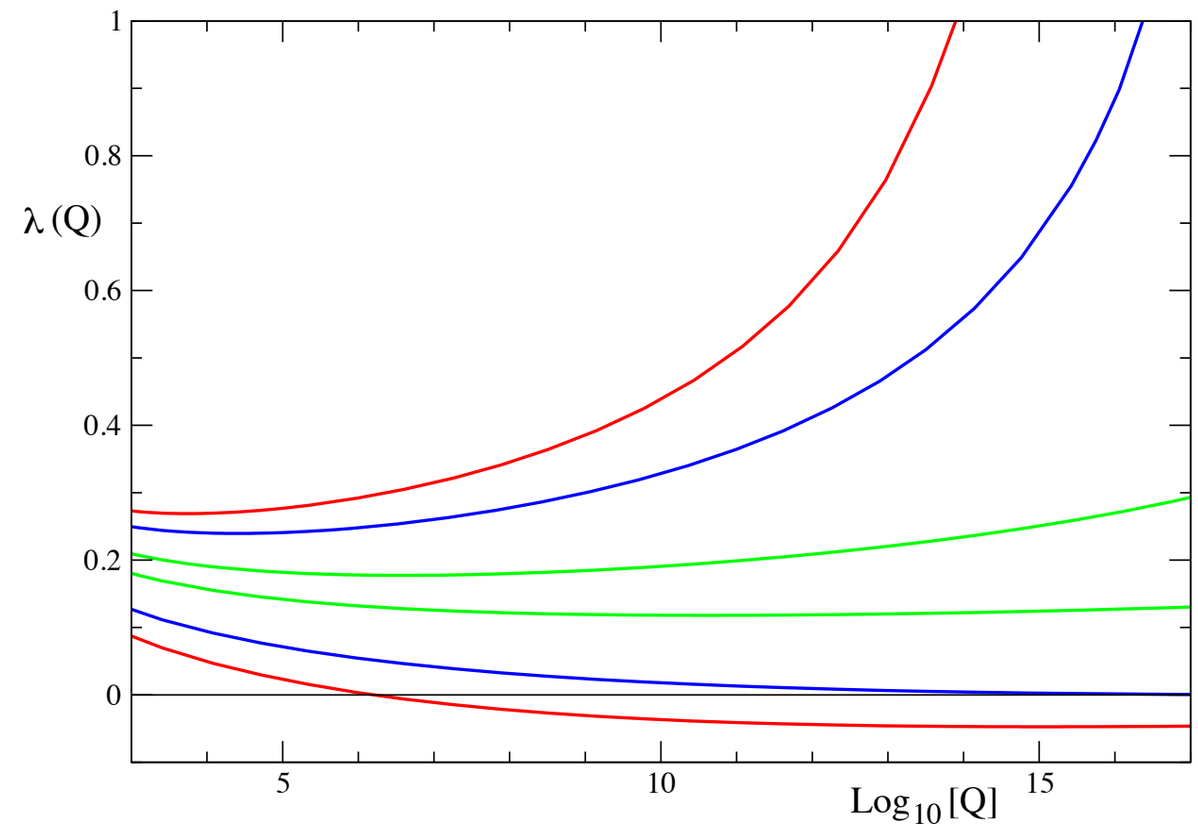
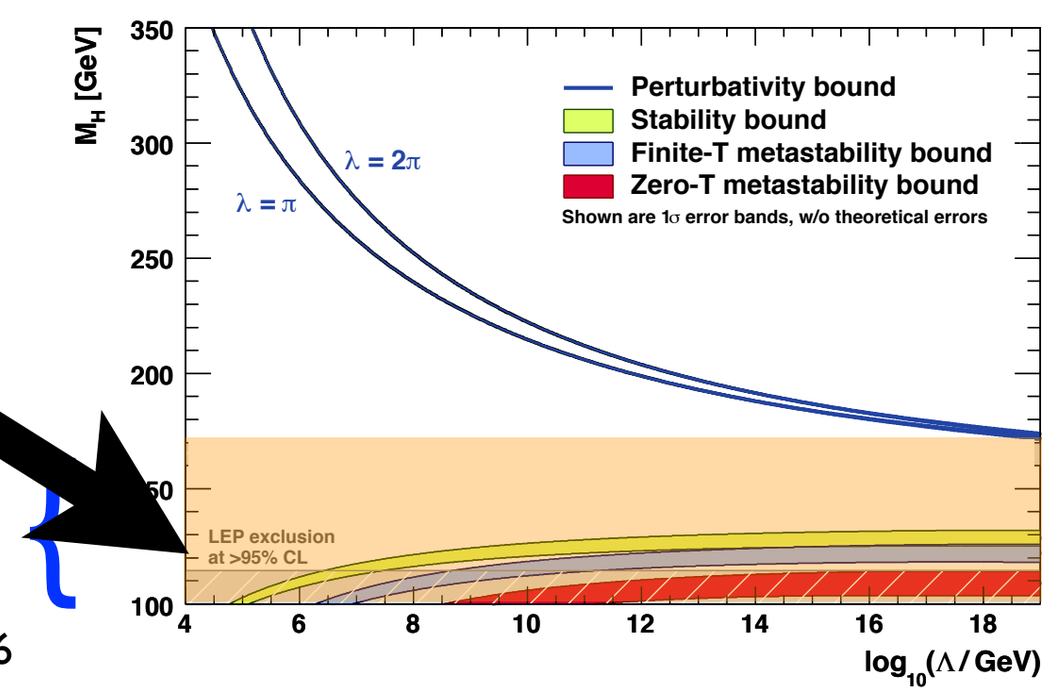


Demanding λ not too large (keep perturbativity),
not too negative that destabilizes the Higgs potential:

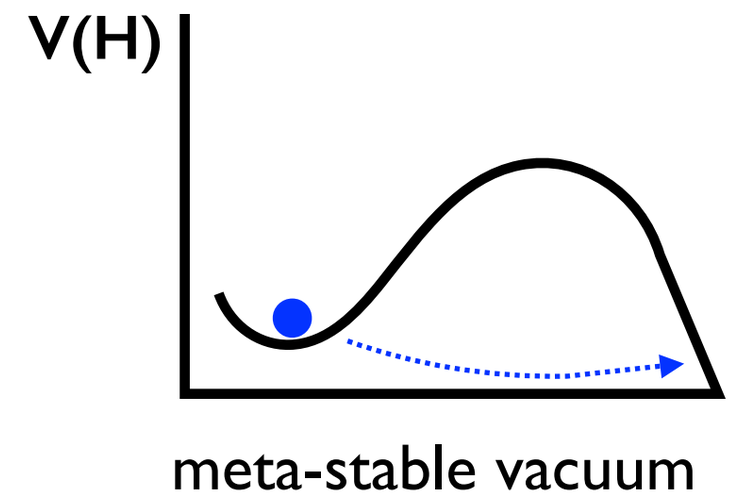
from Phys.Lett. B679 (2009) 369

A 125 GeV Higgs is in this window!

Only a small window in the Higgs mass makes the SM consistent all the way to the Planck scale



For M_h~125 GeV, we are at the border of stability and meta-stability:



but do not worry, even in meta-stable,
lifetime of decay larger than the age of the universe!

125 GeV MSSM Higgs

In the MSSM:

$$\mathbf{M_h^2 \leq M_Z^2 + \Delta m^2}$$

➥ susy breaking term (at one-loop)

$$\mathbf{(125\ GeV)^2} \qquad \mathbf{(91\ GeV)^2} \qquad \mathbf{(86\ GeV)^2}$$

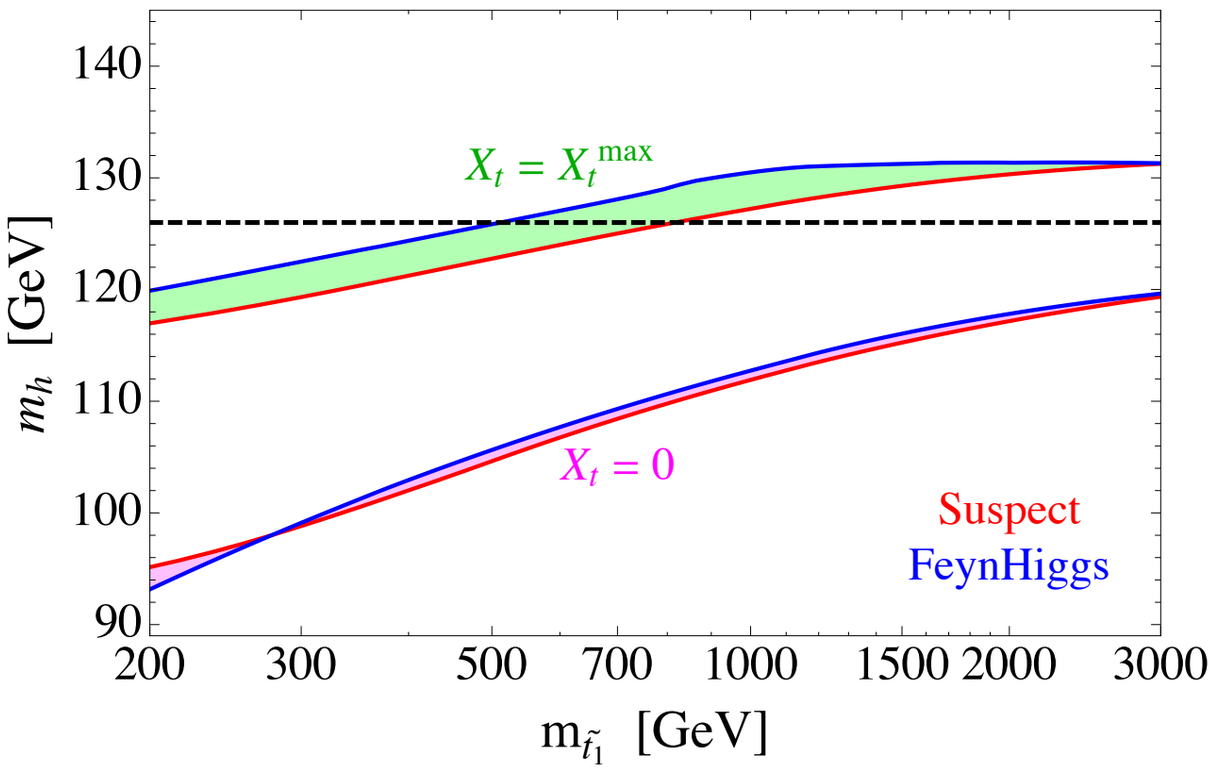
both have similar size:

Non-small Susy breaking terms

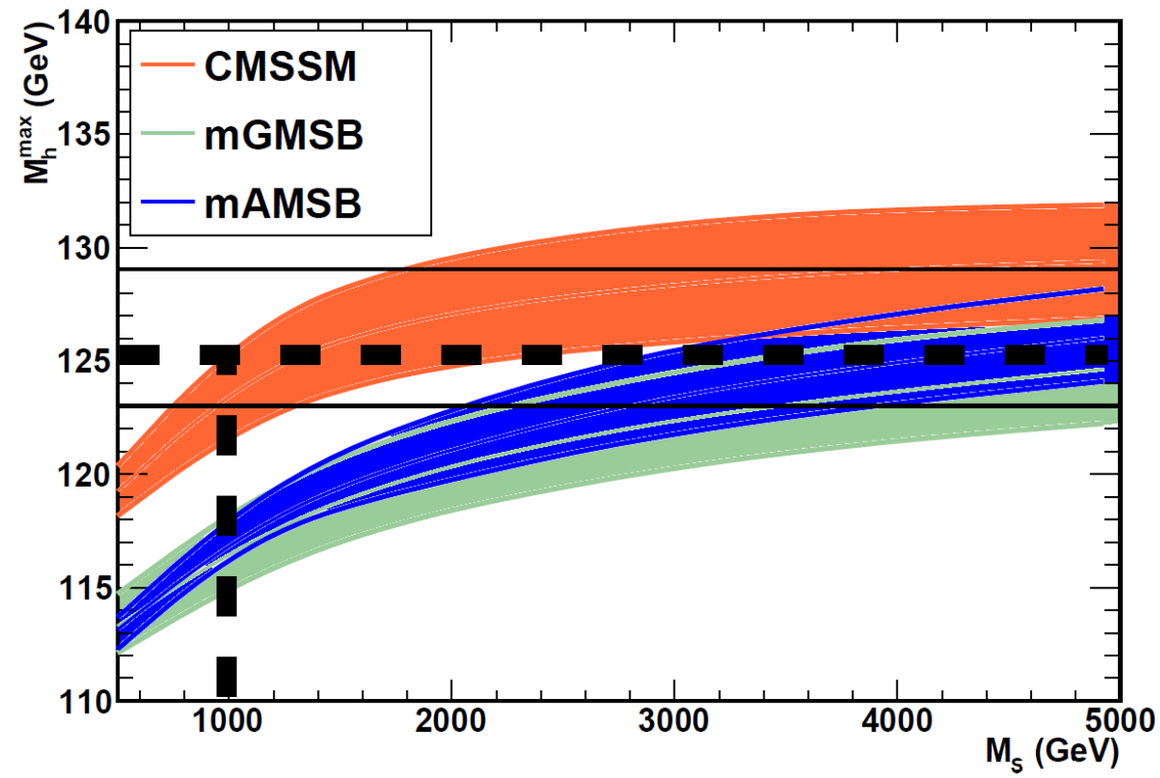
Bosons Fermions

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$

MSSM Higgs Mass



from JHEP 1204 (2012) 131



from arXiv:1207.1348

Very heavy stops (beyond LHC reach)
or large susy-breaking trilinear terms

➥**The MSSM is becoming unnatural**

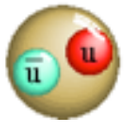
(>99% parameter space excluded)

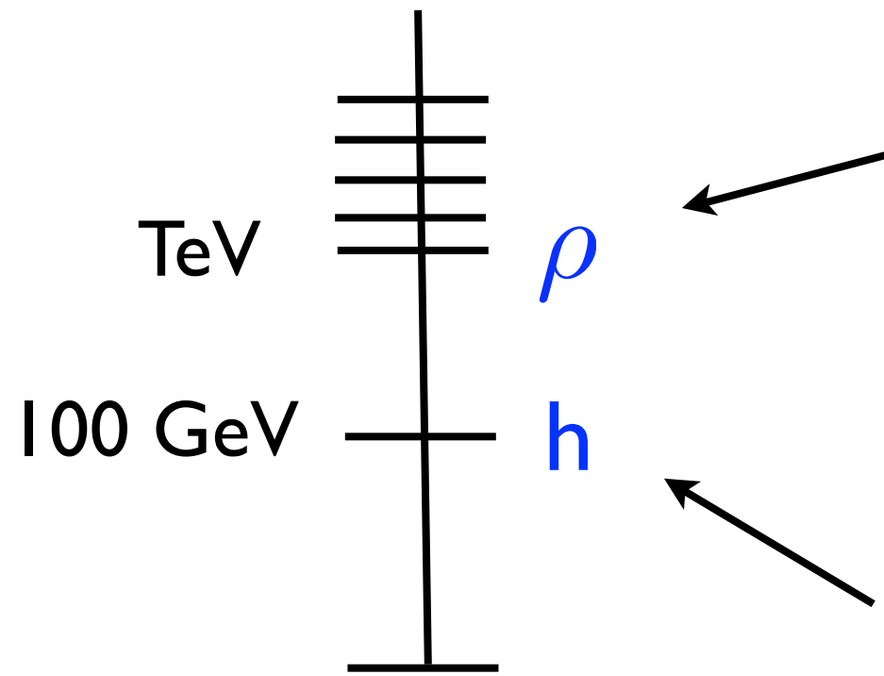
125 GeV Composite Pseudo-Goldstone Higgs

Higgs as a composite PGB:

Similarly as in QCD, we could have from a new TeV strong-sector:

Spectrum of
"mesons":





Other resonances
too heavy
to be seen at the LHC 8TeV

Pseudo-Goldstone
bosons (PGB)

(as pions in QCD)

Galloway, Evans, Luty, Tacchi 10

Example: Just take QCD (with two flavors)
replace **$SU(3)_c$** by **$SU(2)_c$**

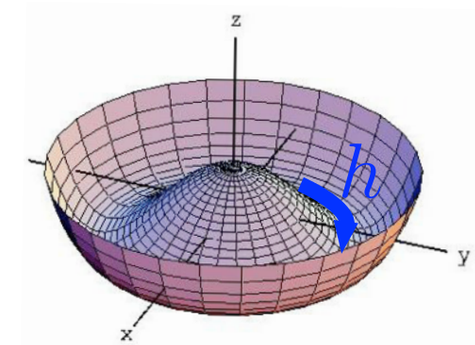
	$SU(3)_c$	**$SU(2)_c$**
Global symmetry:	**$SU(2)_L \otimes SU(2)_R$**	**$SU(4)$**
	$\langle\psi\psi\rangle \neq 0$ ↓	$\langle\psi\psi\rangle \neq 0$ ↓
	$SU(2)_V$	**$SO(5)$**
	3 Golstones = π^0, π^+, π^-	5 Goldstones = **Higgs doublet + singlet**

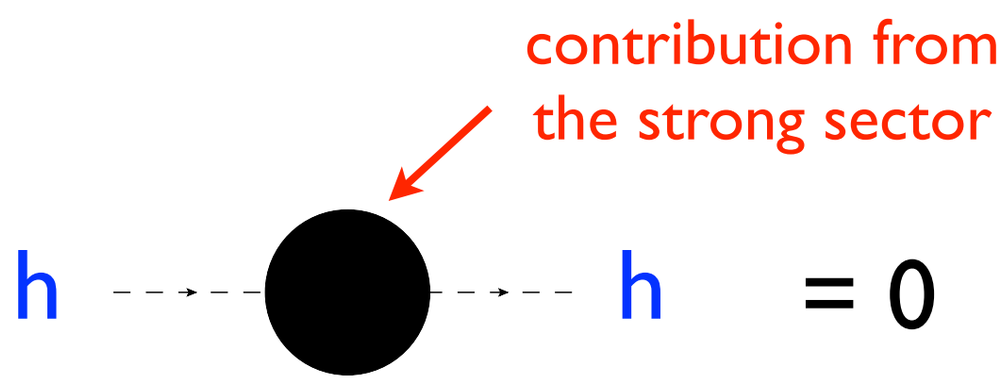
since $2 \sim \bar{2}$

$4 = 2_L + 2_R$

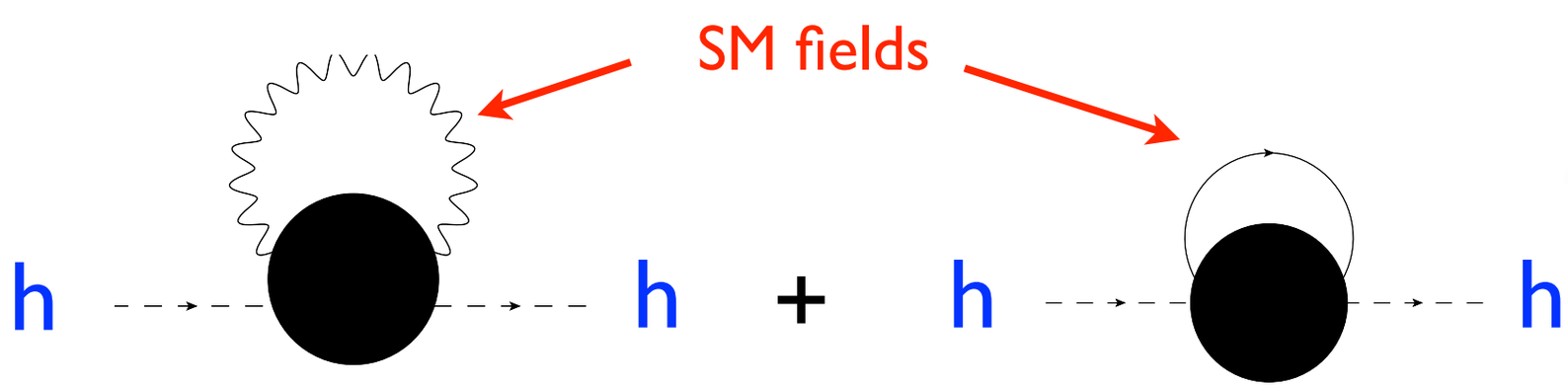
ψ_L, ψ_R^c

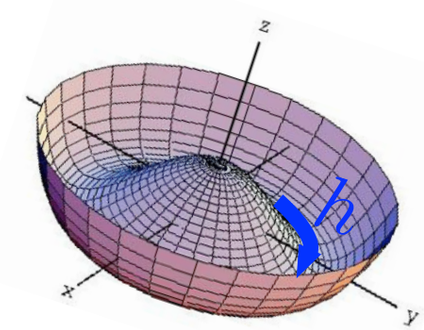
Light Higgs since its mass arises from one loop (explicit breaking of the global symmetry (h→h+c) due to the SM couplings):





= 0 it's a Goldstone





Tilt the potential

$$m_h^2 \sim \frac{(\mathrm{TeV})^2}{16\pi^2} \sim (100\ \mathrm{GeV})^2$$

Using techniques used in QCD, we can get for the minimal composite PGB Higgs :

Marzocca,Serone,Shu; AP, Riva 12

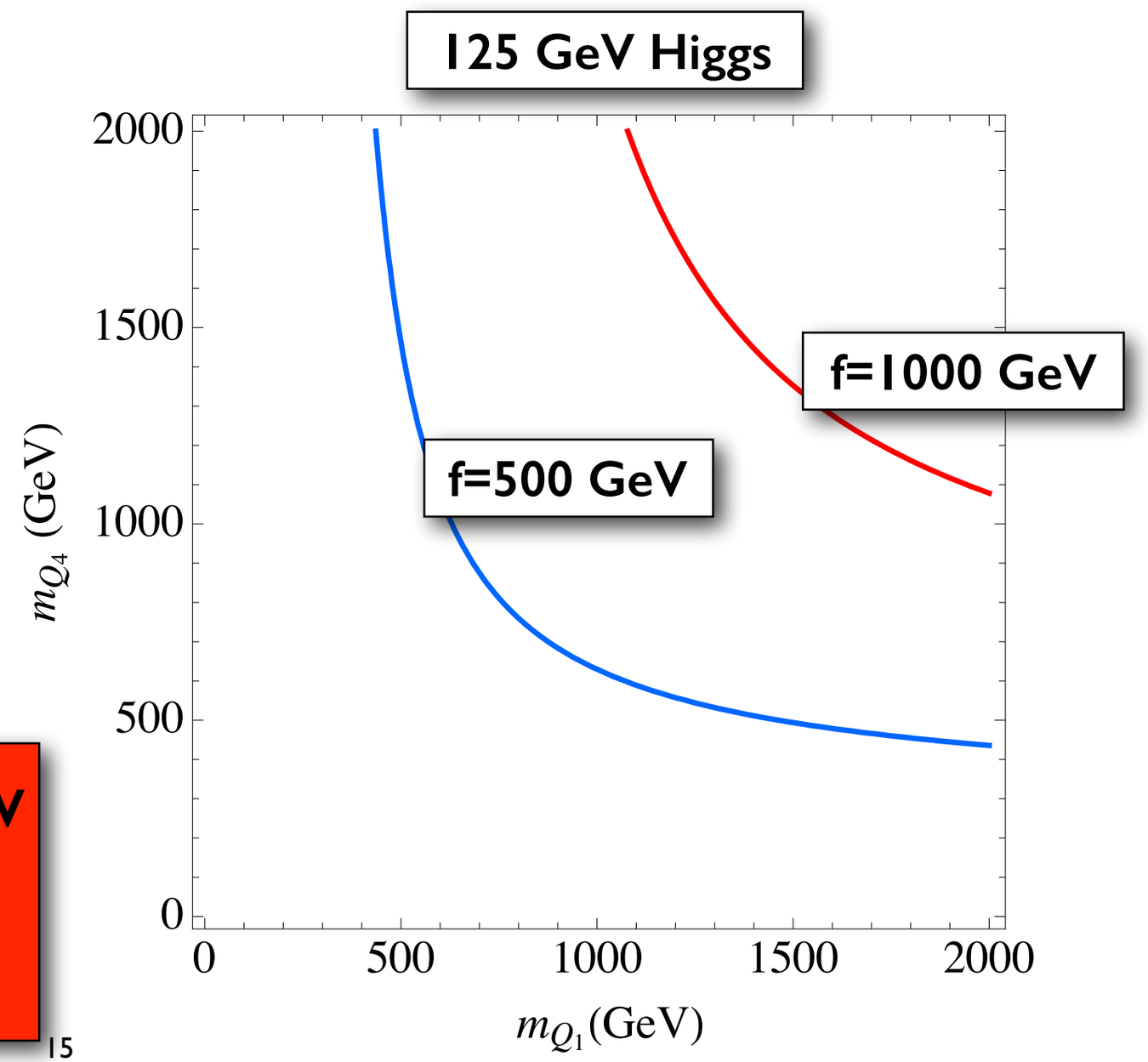
$$m_h^2 \simeq \frac{N_c}{\pi^2}\left[\frac{m_t^2}{f^2}\frac{m_{Q_4}^2 m_{Q_1}^2}{m_{Q_1}^2 - m_{Q_4}^2}\log\left(\frac{m_{Q_1}^2}{m_{Q_4}^2}\right)\right]$$

$N_c=3$

f = Decay-constant of the PGB Higgs

(model dependent but expected f ~ v)

mass of color vector-like fermions with EM charges 5/3,2/3,-1/3



Fermion resonances below the TeV that should be seen at the LHC

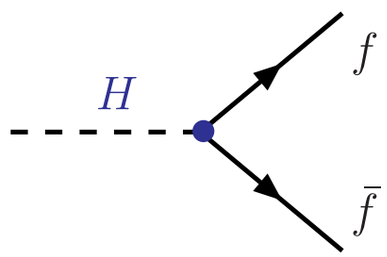
Implications from Higgs-coupling measurements

Main pieces of information to be extracted from data:

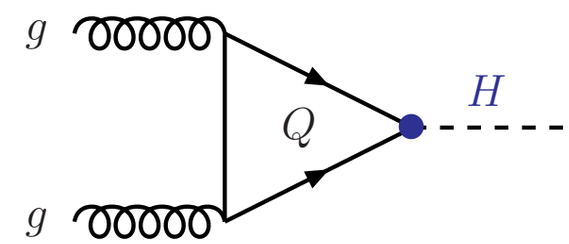
$$\mathcal{L} = g_{hff} h \bar{f}_L f_R + h.c. + g_{hVV} h V^\mu V_\mu + g_{hGG} h G^{\mu\nu} G_{\mu\nu} + g_{h\gamma\gamma} h F^{\mu\nu} F_{\mu\nu}$$

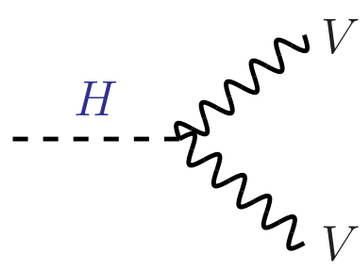
$V = W, Z$

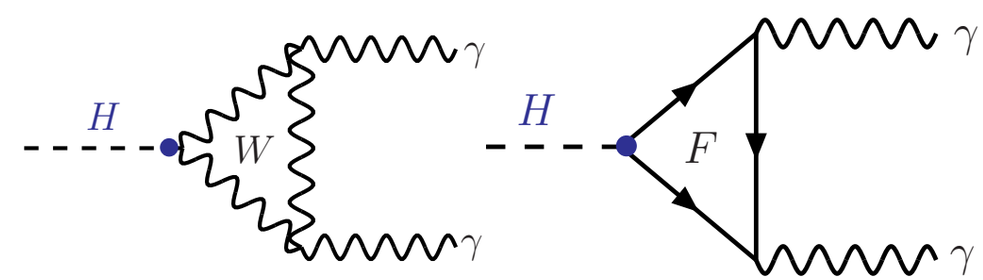
(other Lorentz structures are possible, but we neglect them for the moment)

1) 

f=fermions

3) 

2) 

4) 

☛ **they determine the nature of the Higgs**

Main pieces of information to be extracted from data:

$$\mathcal{L} = g_{hff} h \bar{f}_L f_R + h.c. + g_{hVV} h V^\mu V_\mu + g_{hGG} h G^{\mu\nu} G_{\mu\nu} + g_{h\gamma\gamma} h F^{\mu\nu} F_{\mu\nu}$$

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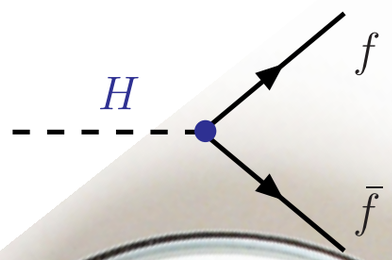
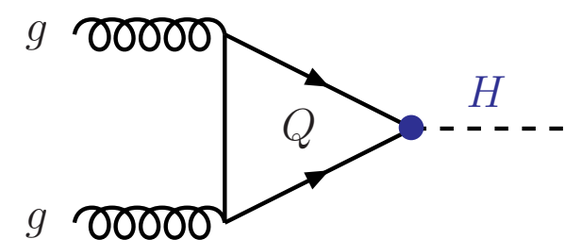
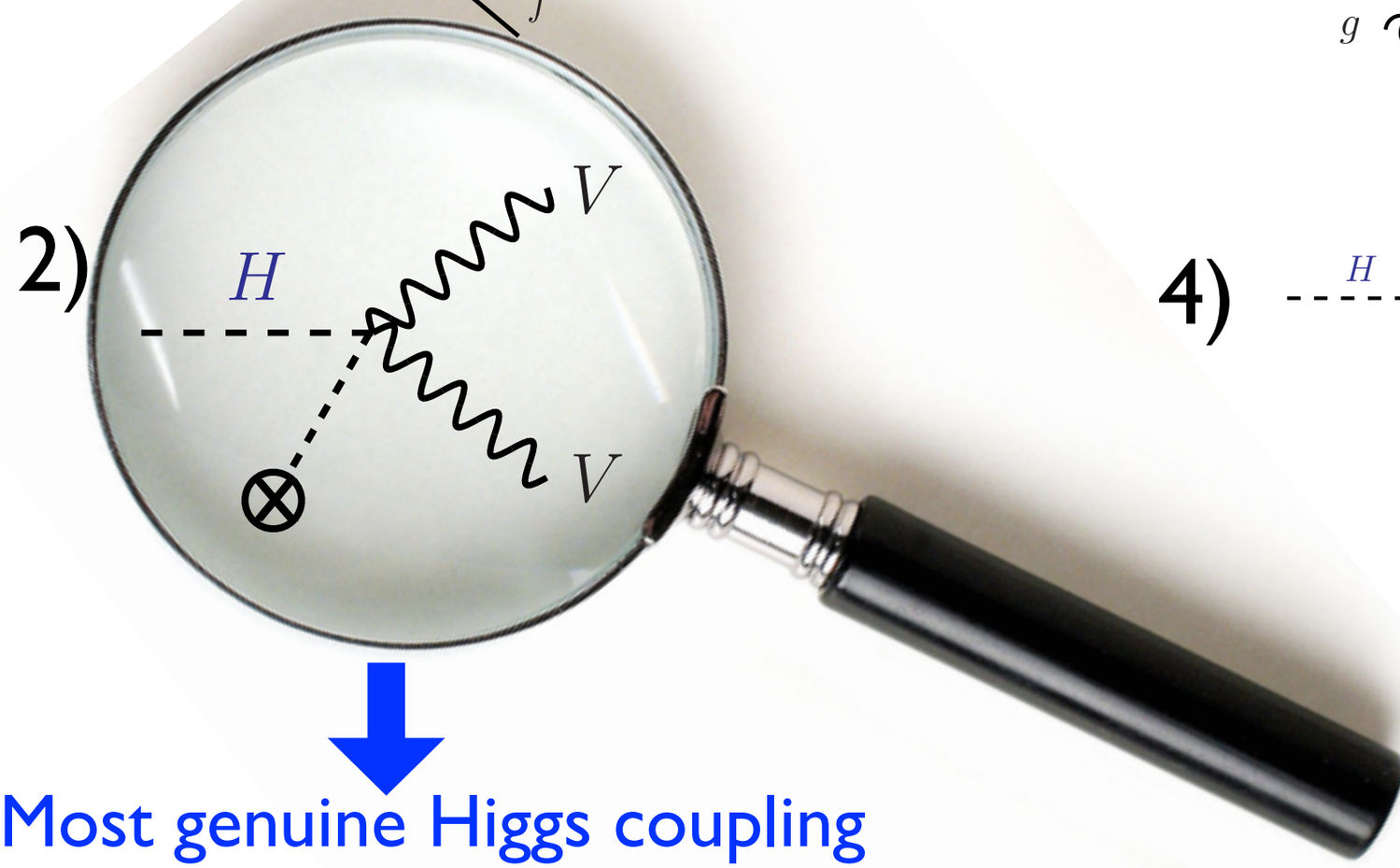
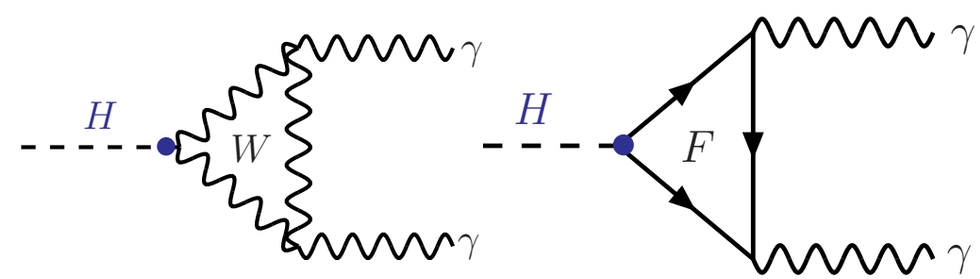
1) 

f=fermions

3) 

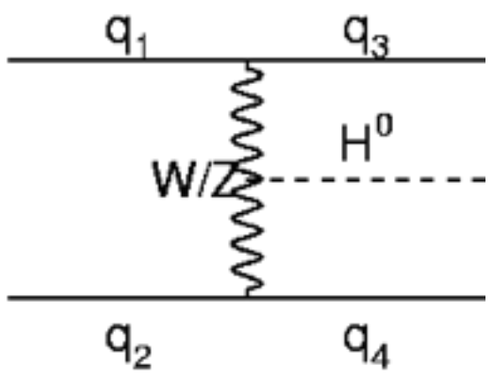
2) 

4) 

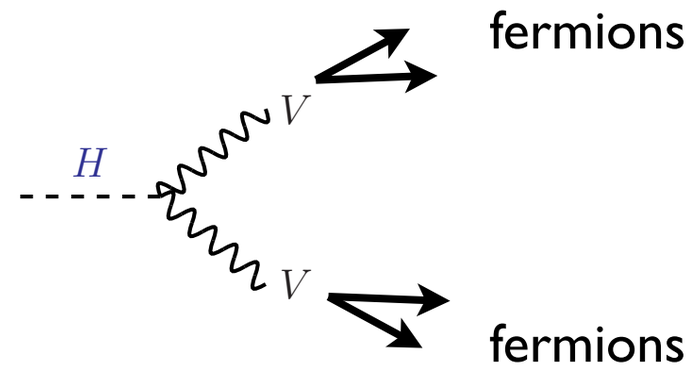
Most genuine Higgs coupling
(discloses its role in EWSB)

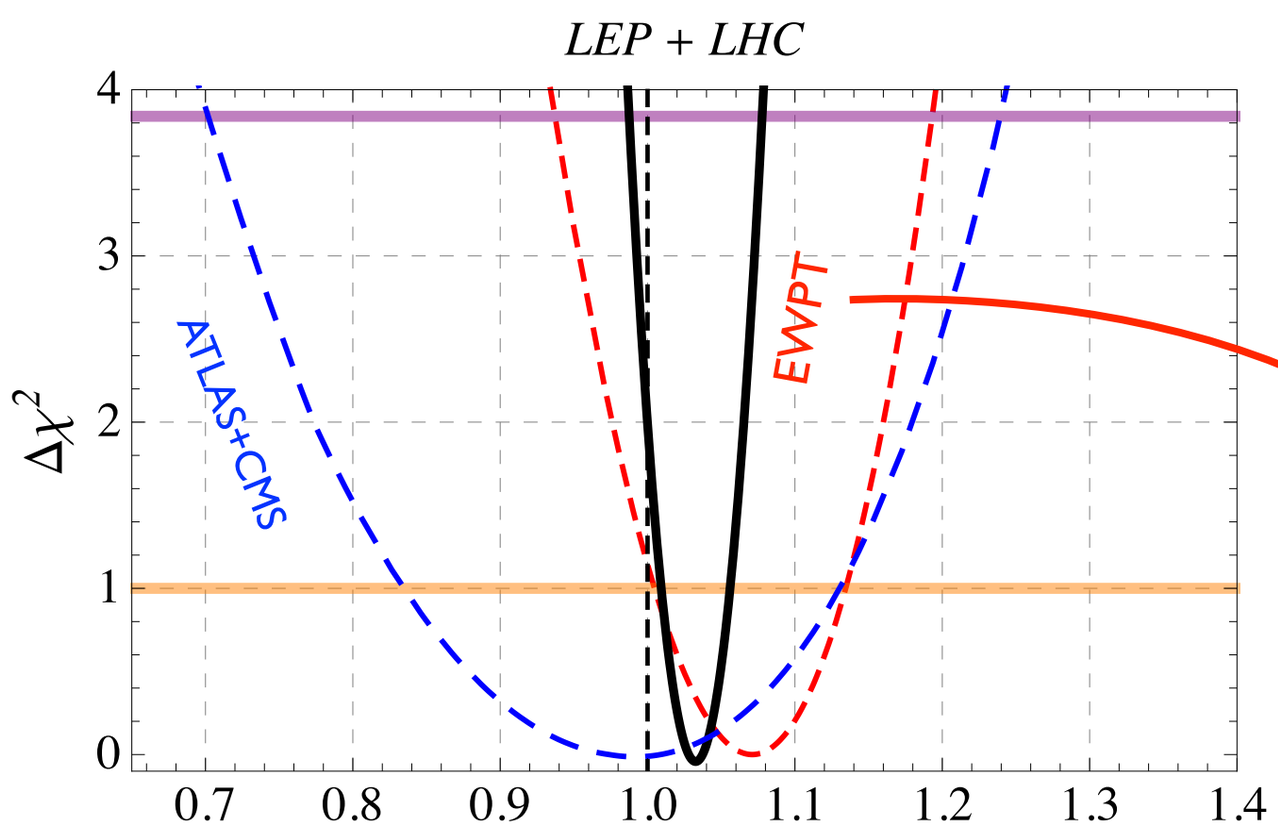
But present data is telling us that the 125 GeV state has to do with EWSB

at the LHC:



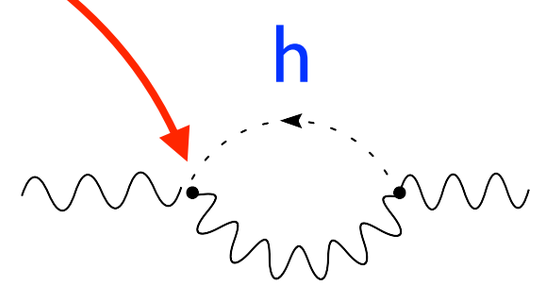
x





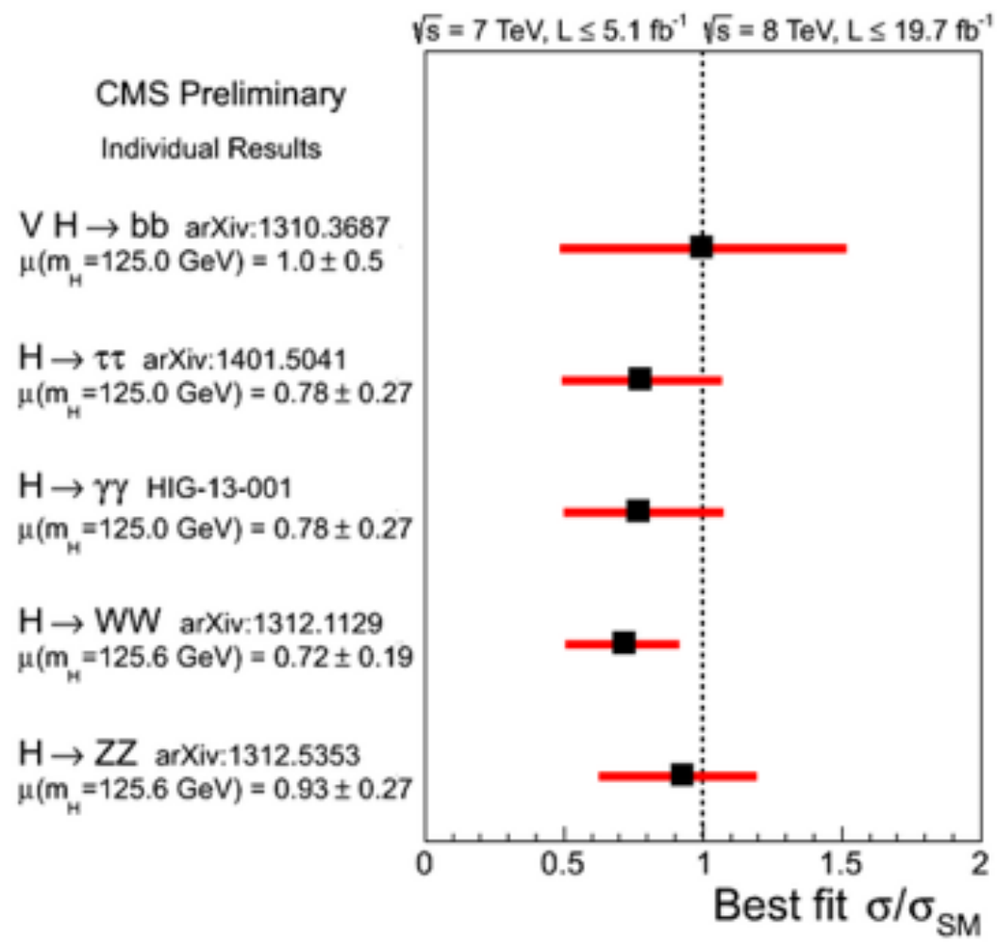
$$\frac{g_{hVV}}{g_{hVV}^{\rm SM}}$$

Falkowski,Riva,Urbano
arXiv:1303.1812

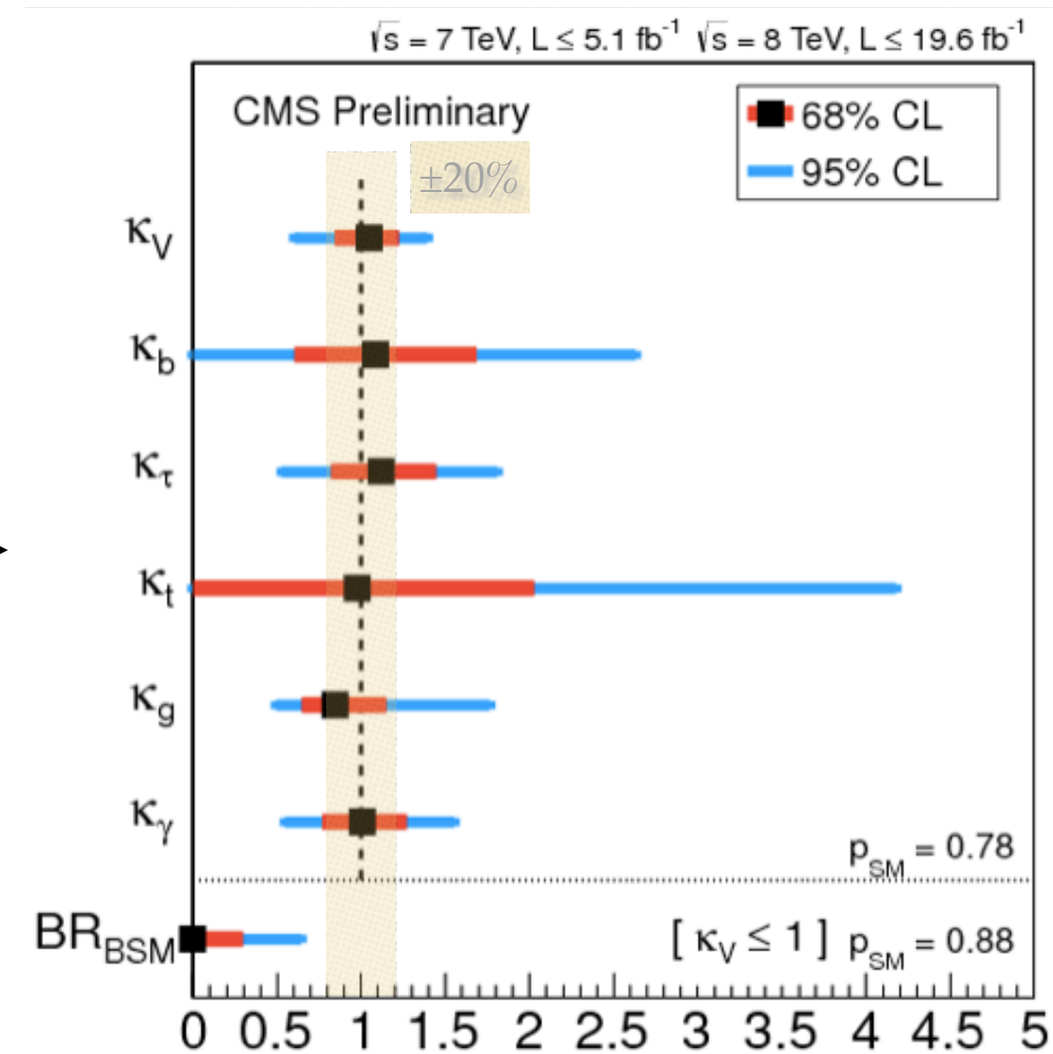


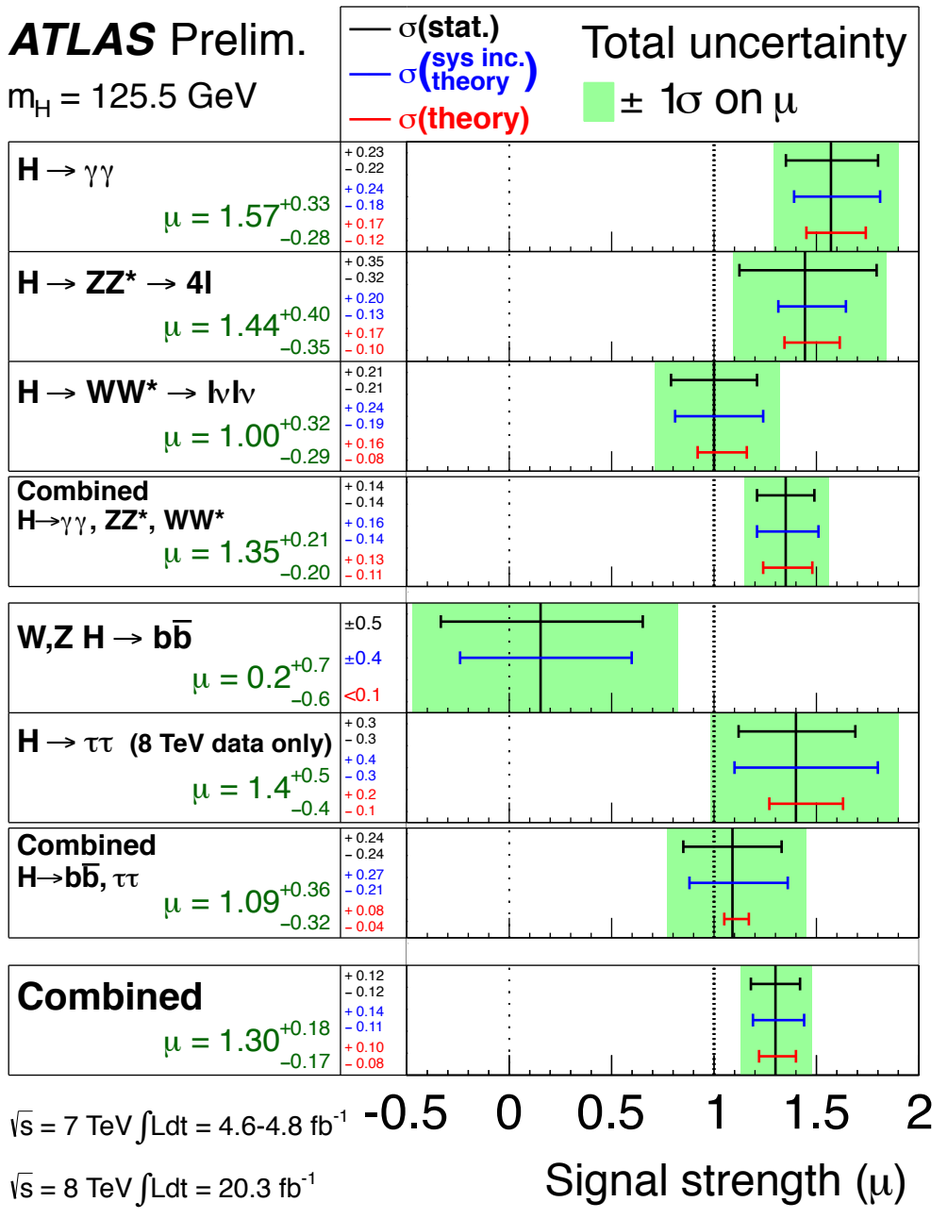
Affects the Z propagator, whose properties were well-measured at LEP

Higgs coupling determination



$$\kappa_i = \frac{g_{hii}}{g_{hii}^{\mathrm{SM}}}$$





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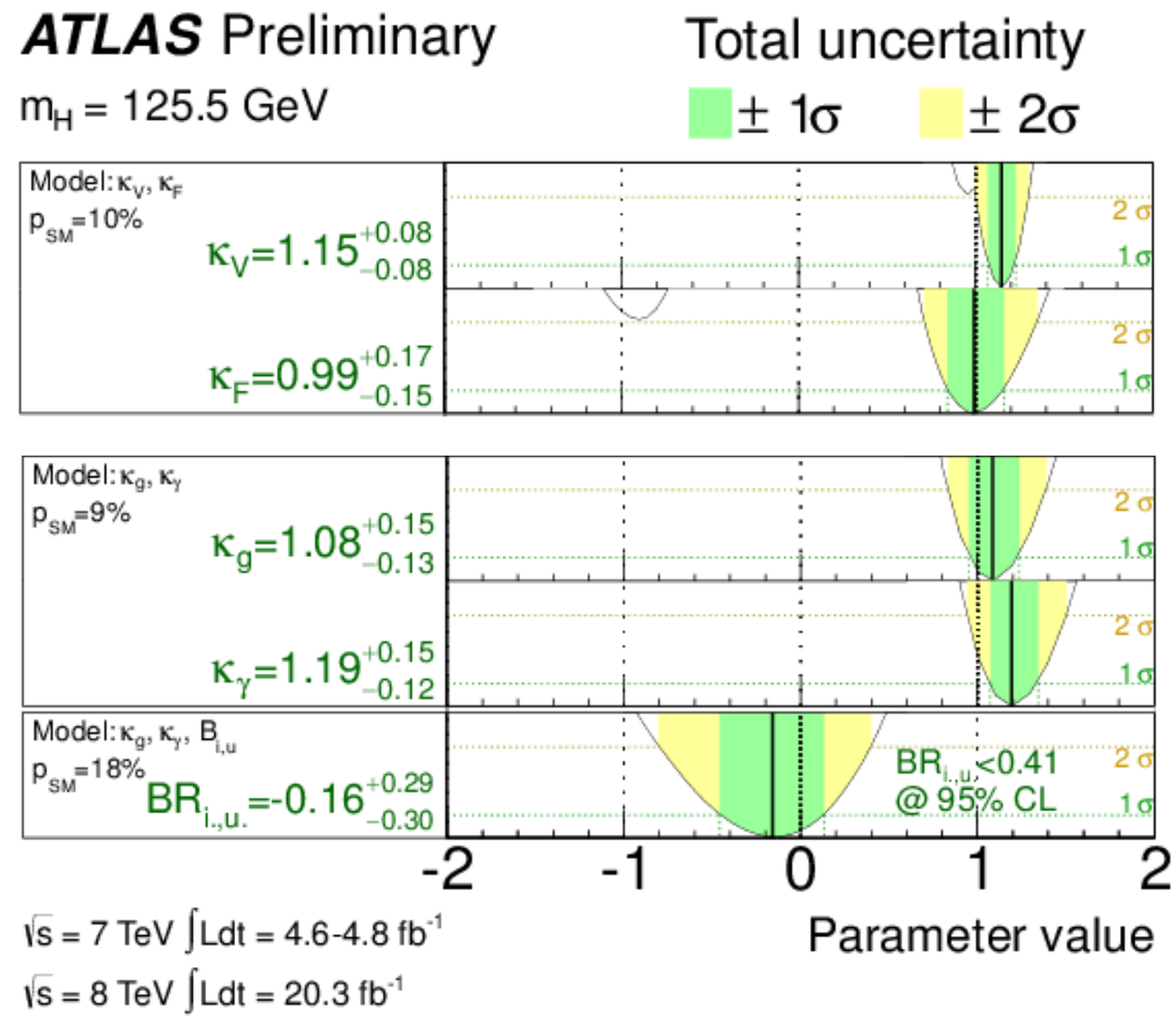


The **different origins** of the Higgs
give **different predictions** for the Higgs couplings

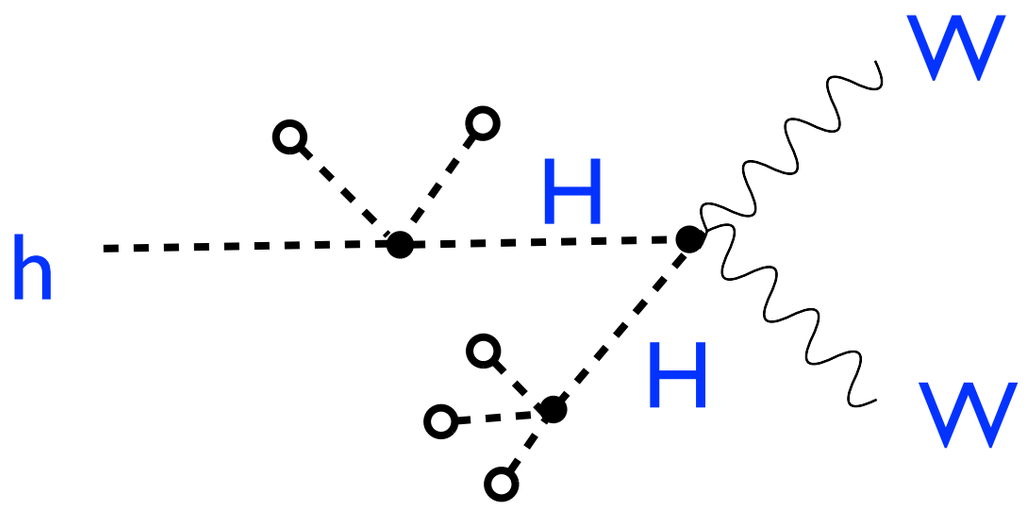
Two examples:

a) **Supersymmetry (MSSM)**
with a Heavy spectrum $M_{susy} \gg m_W$

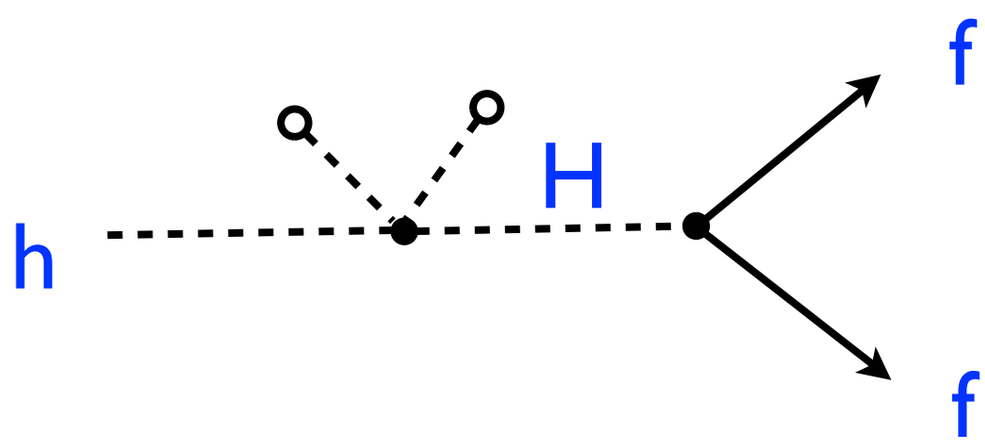
b) **Composite PGB Higgs**

MSSM with heavy spectrum (≫100 GeV)

Main effects from the **2nd Higgs doublet:**



$$\sim \frac{v^4}{M_H^4} \; v^2$$



$$\sim \frac{v^2}{M_H^2}$$

Dominant effect!

Superpartners can only modify Higgs couplings at the loop-level:
Only stops/sbottoms give some contribution to hgg/hγγ (not very large)

Corrections to h coupling to fermions:

$$c_i = \frac{g_{hii}}{g_{hii}^{\rm SM}}$$

1) MSSM (no mixing):

$$c_b \approx 1 + \frac{m_h^2 - m_Z^2 \cos 2\beta}{m_H^2},$$

$$c_t \approx 1 - (\cot\beta)^2 \frac{m_h^2 - m_Z^2 \cos 2\beta}{m_H^2}$$

2) MSSM (with extra D-terms):

$$c_b \approx 1 + 2\frac{m_h^2}{m_H^2}\frac{t_\beta^2}{t_\beta^2 - 1}$$

$$c_t \approx 1 - 2\frac{m_h^2}{m_H^2}\frac{1}{t_\beta^2 - 1}.$$

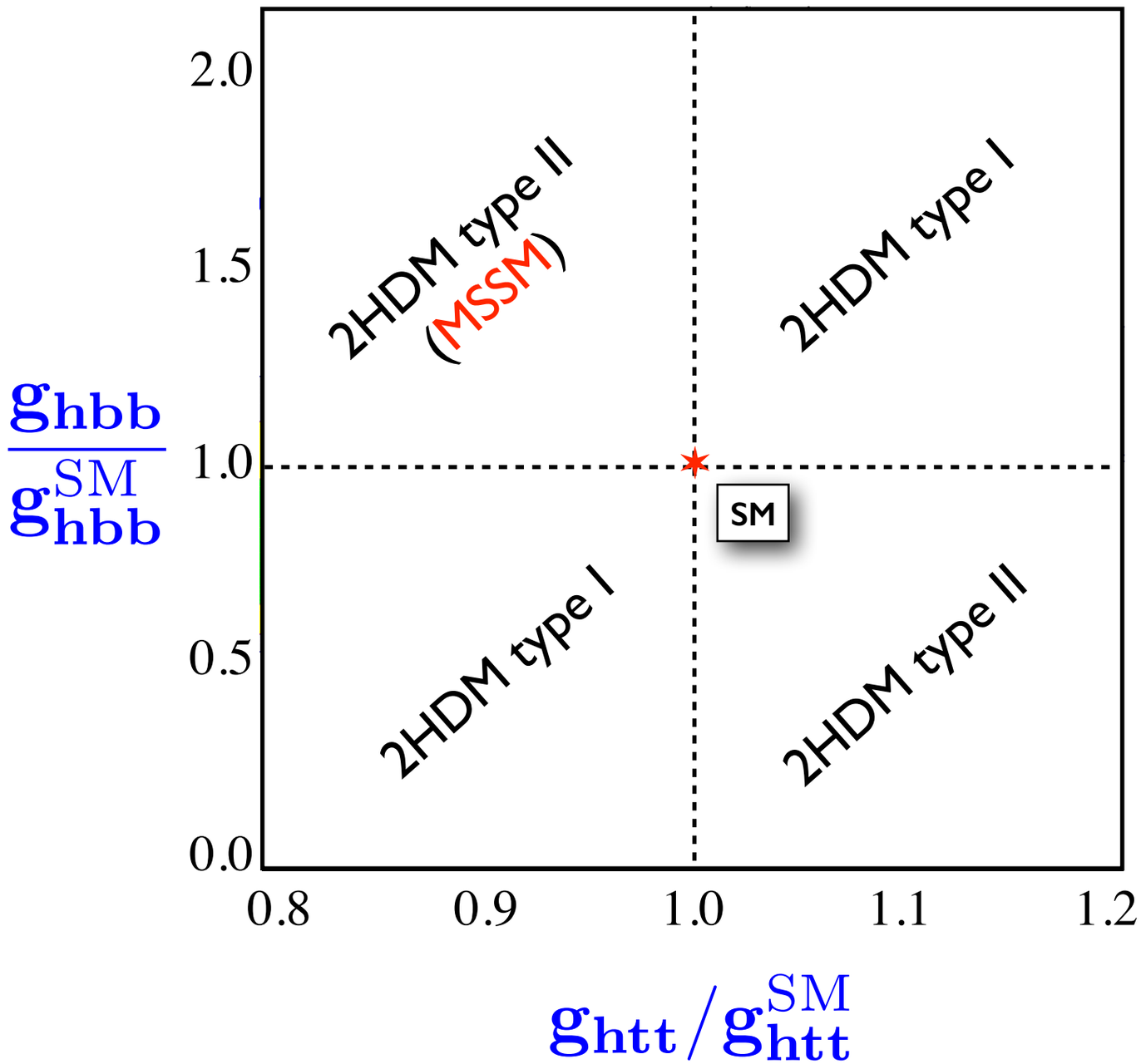
3) NMSSM (with heavy singlet and light stops):

$$c_b \approx 1 - \frac{t_\beta^2 - 1}{2}\frac{m_h^2 - m_Z^2}{m_H^2}$$

$$c_t \approx 1 + \frac{t_\beta^2 - 1}{2t_\beta^2}\frac{m_h^2 - m_Z^2}{m_H^2}$$

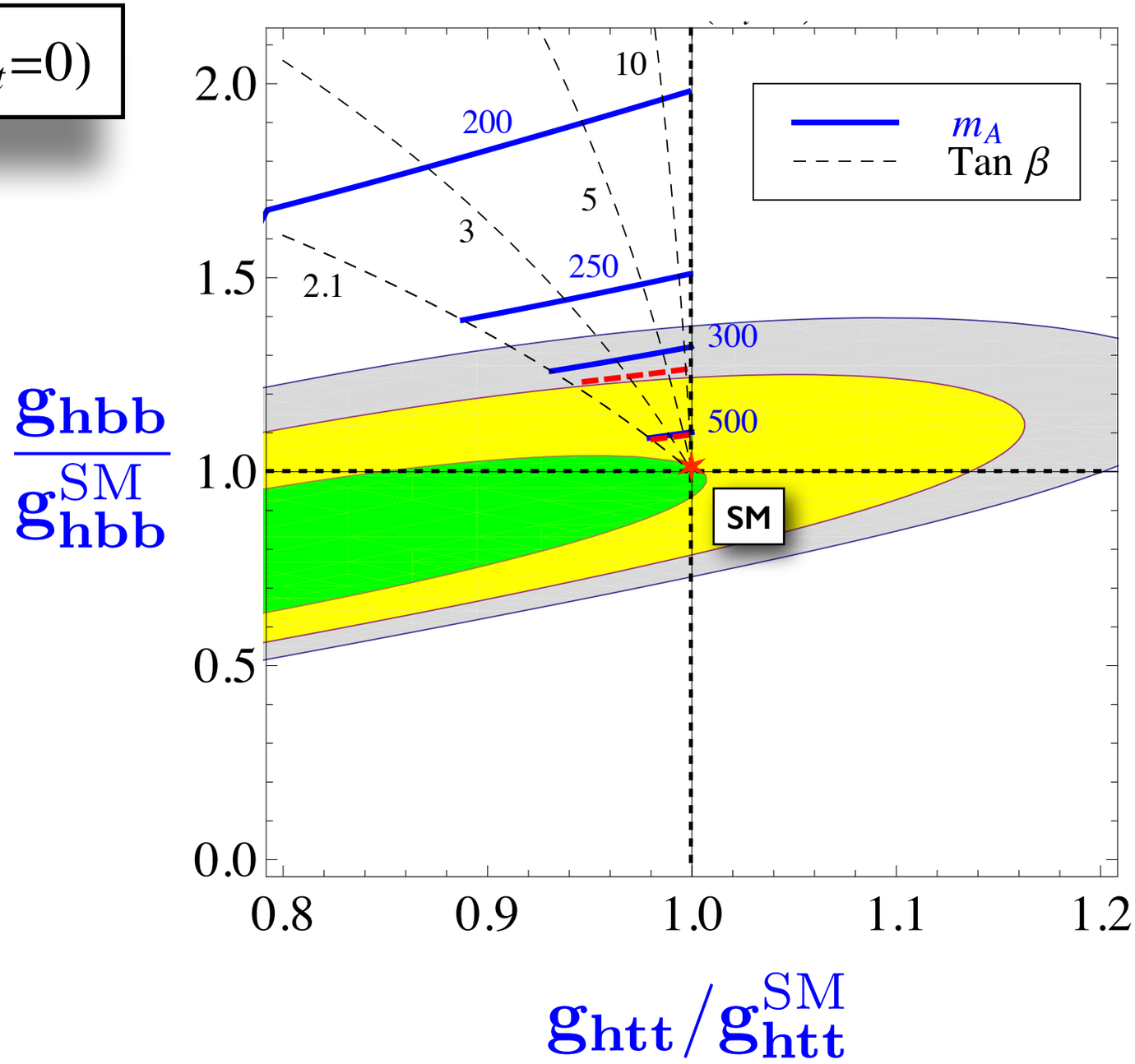
from arXiv:1212.524

Relevant plane for susy Higgs couplings:



Relevant plane for susy Higgs couplings:

MSSM (X_t=0)

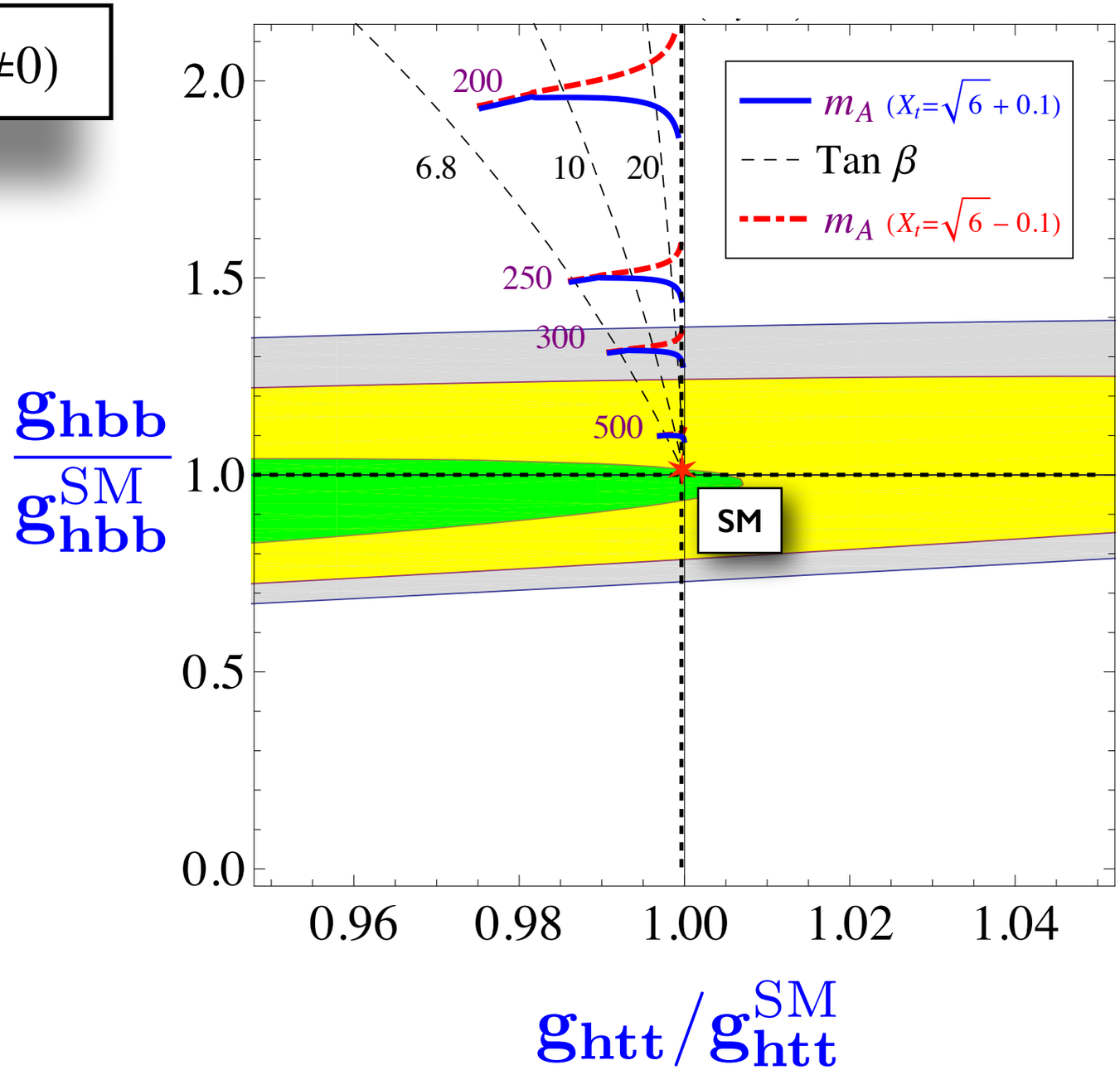


from arXiv:1212.524

(data before Moriond 13)

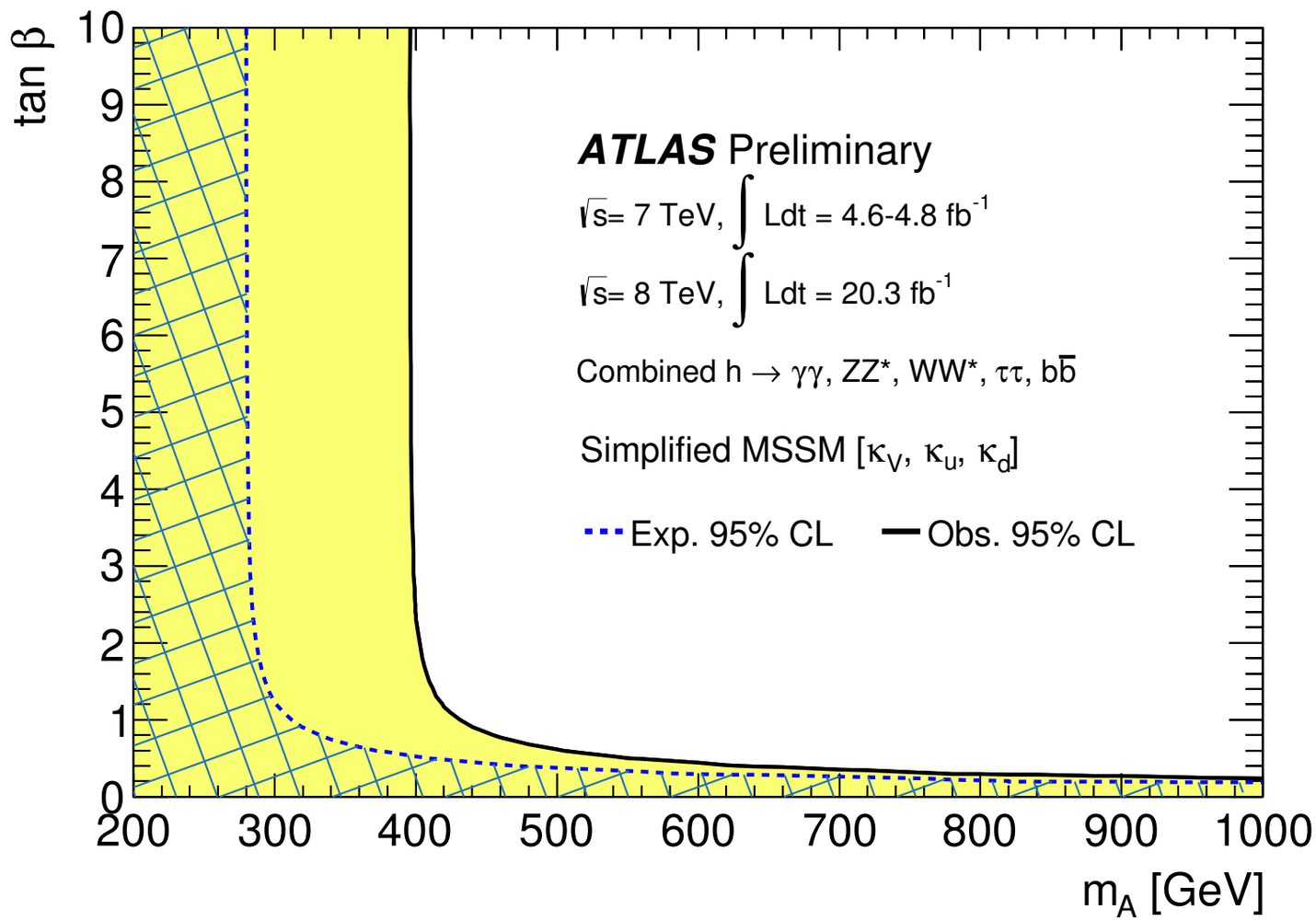
Relevant plane for susy Higgs couplings:

MSSM ($X_t \neq 0$)



from arXiv:1212.524

Higgs coupling measurements are already **ruling out** susy-parameter space



Composite Higgs scenarios

Composite PGB Higgs couplings

Couplings dictated by symmetries (as in the QCD chiral Lagrangian)

Giudice,Grojean,AP,Rattazzi 07
AP,Riva 12

$$\frac{g_{hWW}}{g_{hWW}^{\rm SM}} = \sqrt{1 - \frac{v^2}{f^2}}$$

f = Decay-constant of the PGB Higgs

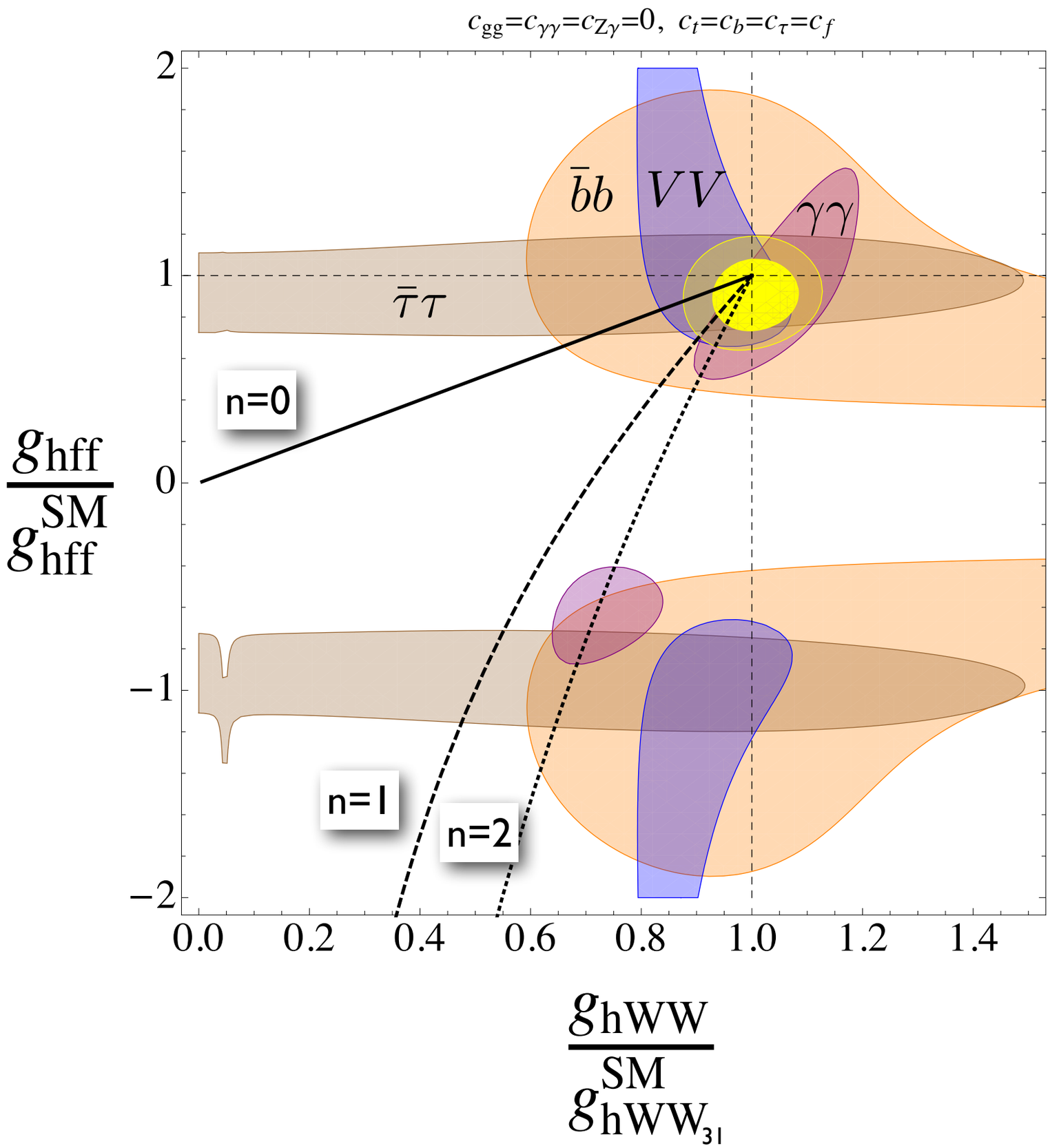
(model dependent but expected f ~ v)

$$\frac{g_{hff}}{g_{hff}^{\rm SM}} = \frac{1 - (1+n)\frac{v^2}{f^2}}{\sqrt{1 - \frac{v^2}{f^2}}} \qquad n = 0, 1, 2, ...$$

$\mathrm{MCHM}_{5,10}$

small deviations on the h$\gamma\gamma$(gg)-coupling due to the Goldstone nature of the Higgs

ATLAS+CMS:

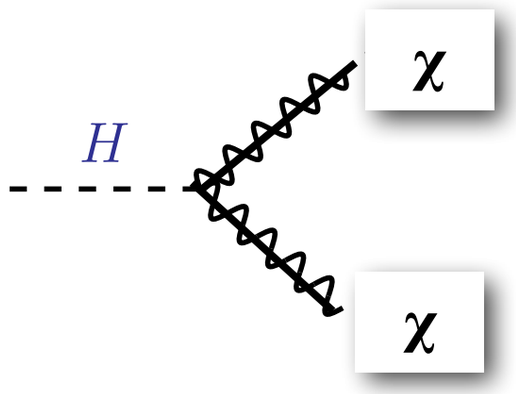


arXiv:1303.1812

↳ Too premature to see deviations for v/f ~ 0.5!

Invisible Higgs decay

Possible in certain models:



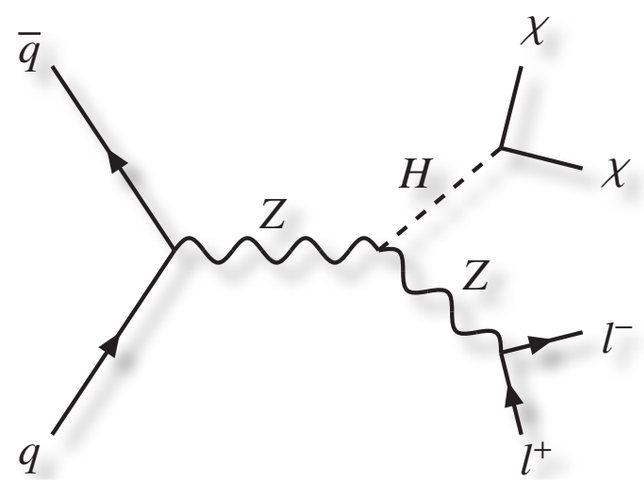
for example:

χ = Dark Matter = extra scalar, neutralinos, …

(or χ χ = gravitino + neutrino, as in models in which the Higgs is the susypartner of the neutrino)

arXiv:1211.4526

Bounds on invisible Higgs decay



stable particle

missing E_T + l^+l^-

ATLAS (4.7+13.0 fb^{-1}):

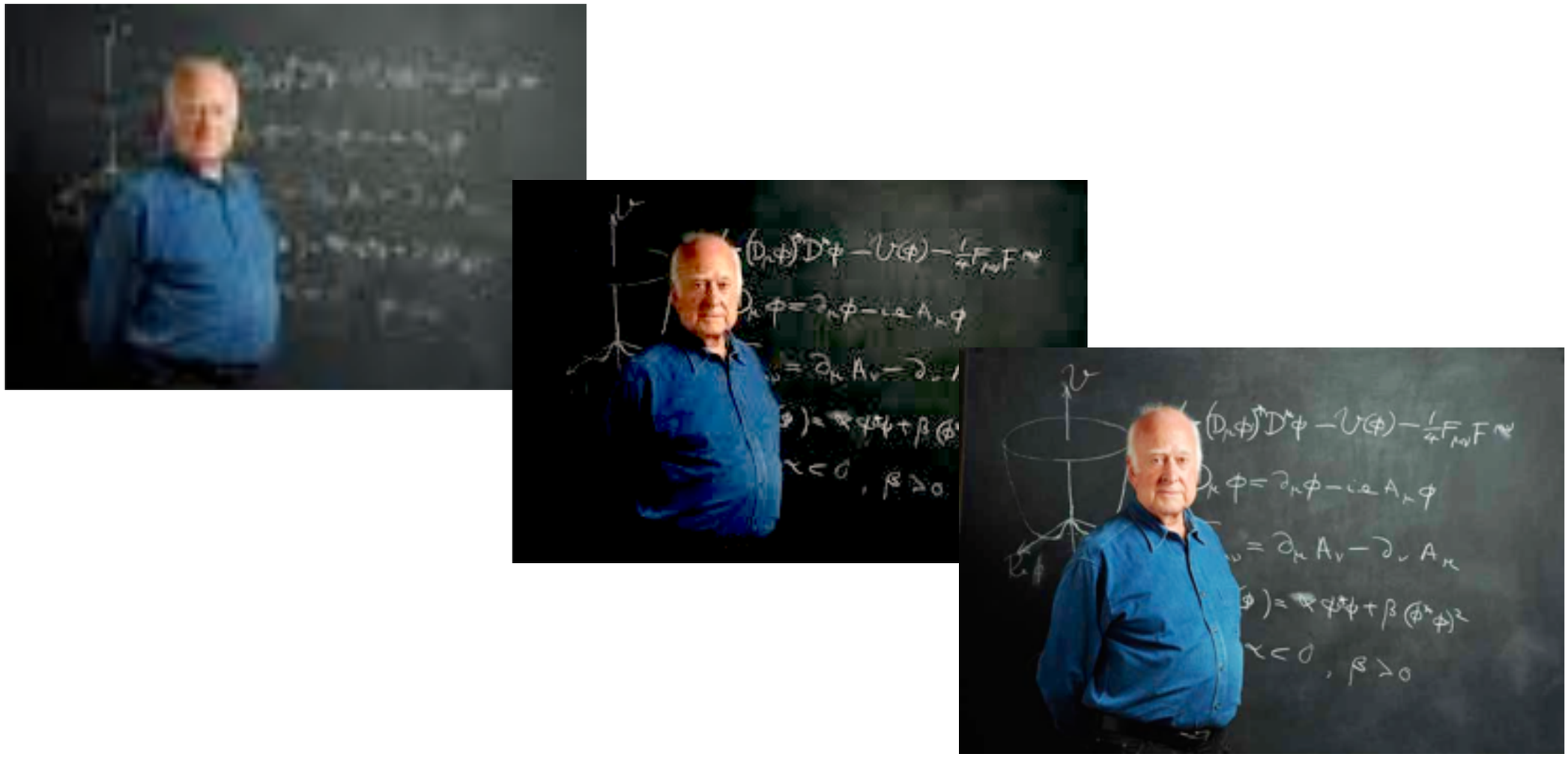
- **Br(H→χχ) < 65%** (84% exp.) @ 95% CL, m_H = 125 GeV

CMS (5+20 fb^{-1}):

- **Br(H→χχ) < 75%** (91% exp.) @ 95% CL, m_H = 125 GeV

Future...

towards a better image of the Higgs



- **A better Higgs-mass measurement?**

Finding $m_H \approx 125$ GeV shook us,
but knowing $m_H = 125.457...$ GeV will leave us indifferent

Probably only "true-believers" of the SM up to the Planck scale would like to know m_H in order to learn about the stability of the Higgs potential

But also strong dependence on top-mass and α_s !

- **A better Higgs-mass measurement?**

Finding $m_H \approx 125$ GeV shook us,
but knowing $m_H = 125.457...$ GeV will leave us indifferent

- **Spin, CP determination of H?**

↪ If one trusted theorist in the search for the Higgs,
trust them now!! **It is s=0 and CP-even**

Of course, it is good to check, but the outcome
as interesting as knowing who will win today's game ***Brazil-Cameroon***

- **Better determination of couplings?** Absolutely ✓

Parametrization of BSM effects in Higgs physics

Assuming a large new-physics scale, $\Lambda >> m_W$:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

NP scale

dim=6

"Non-renormalizable theories are as renormalizable as renormalizable theories"
S. Weinberg
(means: take $E<\Lambda$ and no problems)

➡ e.g. $|H|^2 G^A_{\mu\nu} G^{A\mu\nu}$

give the deviations
to SM Higgs physics from BSM

➡ effective theory for Higgs physics
➡ approach valid for all BSM with heavy particles !

How many Higgs coupling can deviate from SM ?
(not effecting other experiments)

Eight! *(assuming CP-conservation)*

arXiv: 1308.1879;1308.2803

$|H|^2 G^A_{\mu\nu} G^{A\mu\nu}$ → **GG→h**

$|H|^2 B_{\mu\nu} B^{\mu\nu}$ → **h→γγ**

$|H|^2 W^a_{\mu\nu} W^{\mu\nu\, a}$ → **h→Zγ**

$|H|^2 |D_\mu H|^2$ → **h→VV*** (custodial invariant)

$|H|^6$ → **Affects h³: It can be measured in the far future by GG→hh**

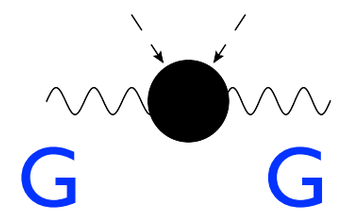
$|H|^2 \bar{f}_L H f_R + h.c.$ → **h→bb,ττ**

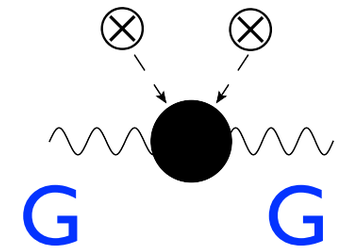
(f=t,b,τ) htt deviation → **GG→tth**

How many Higgs coupling can deviate from SM ?
(not effecting other experiments)

Effects that on the vacuum, $\phi = v$, give only a redefinition of the SM couplings:

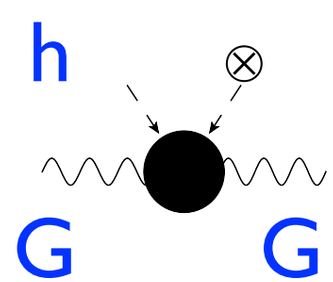
e.g. $$\frac{1}{g_s^2} G_{\mu\nu}^2 + \frac{|H|^2}{\Lambda^2} G_{\mu\nu}^2 \to \left(\frac{1}{g_s^2} + \frac{v^2}{\Lambda^2} \right) G_{\mu\nu}^2$$





Not physical!

But can affect h physics:



affects GG →h!

How many Higgs coupling can deviate from SM ?
(not effecting other experiments)

Effects that on the vacuum, $\phi = v$, give only a redefinition of the SM couplings:

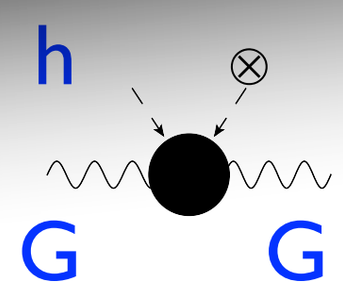
e.g. $\frac{1}{\ldots}G^2_{\mu\nu} + \frac{|H|^2}{\ldots}G^2 \ldots \left(1 \ldots \right)$

$V = W, Z$

$$\mathcal{L} = g_{hff}\, h \bar{f}_L f_R + h.c. + g_{hVV}\, h V^\mu V_\mu$$
$$+ g_{hGG}\, h G^{\mu\nu} G_{\mu\nu} + g_{h\gamma\gamma}\, h F^{\mu\nu} F_{\mu\nu}$$

$$+ g_{hZ\gamma}\, F_Z^{\mu\nu} F_{\mu\nu} + g_{3h}\, h^3$$

But can affect h physics:



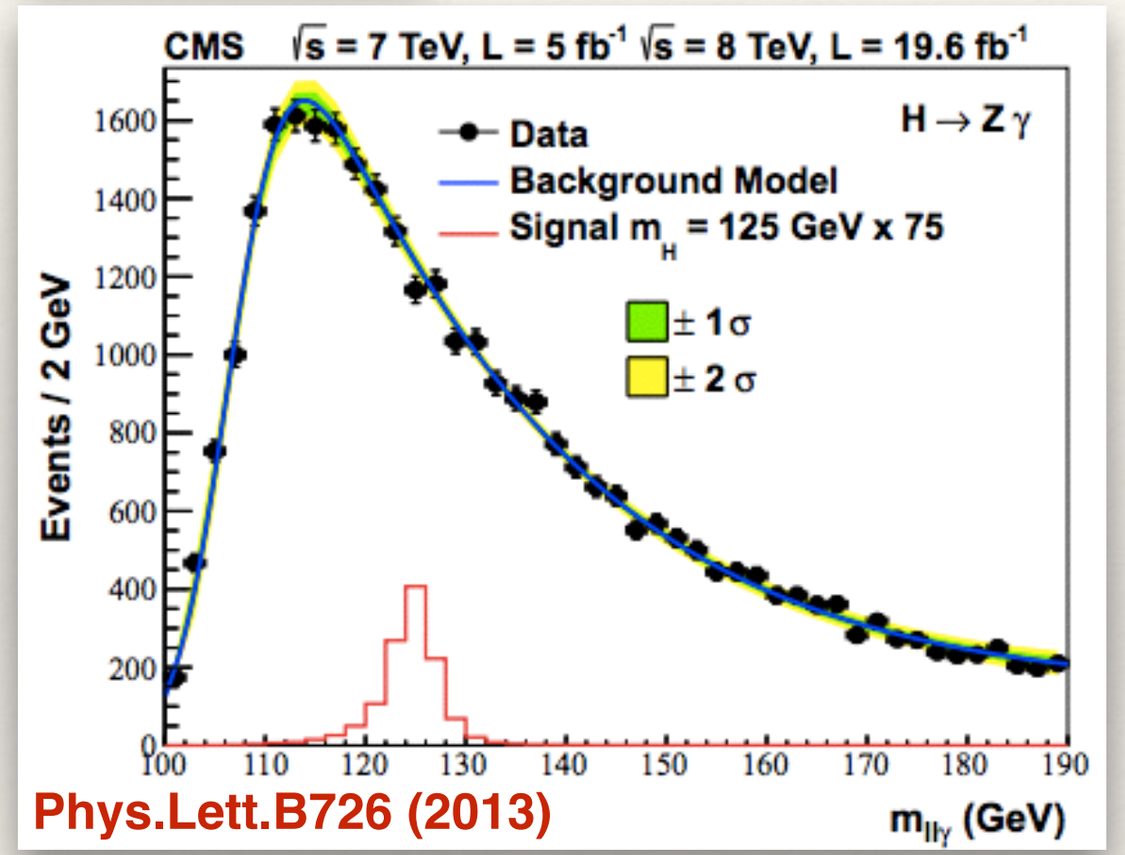
affects GG →h!

$|H|^2$

(f=t,b,τ)

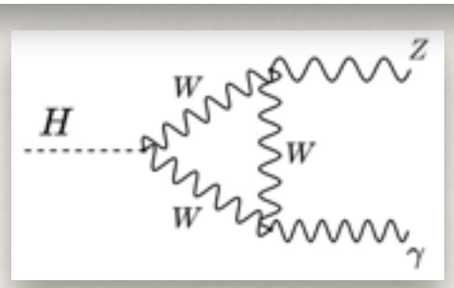
htt deviation

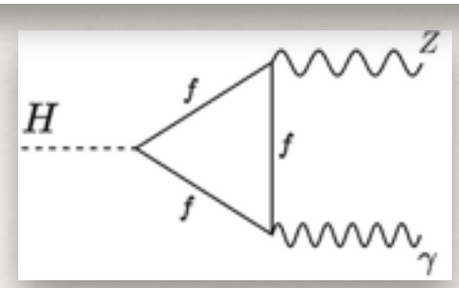
Experimental bound on h→Zγ



Phys.Lett.B726 (2013)

CMS ($H \to Z\gamma$): $\mu < 9$ (9 expected) at 95% CL





BR~0.001
small in the SM
since it comes
at one-loop:

still allow to be
9 x BR_{SM}

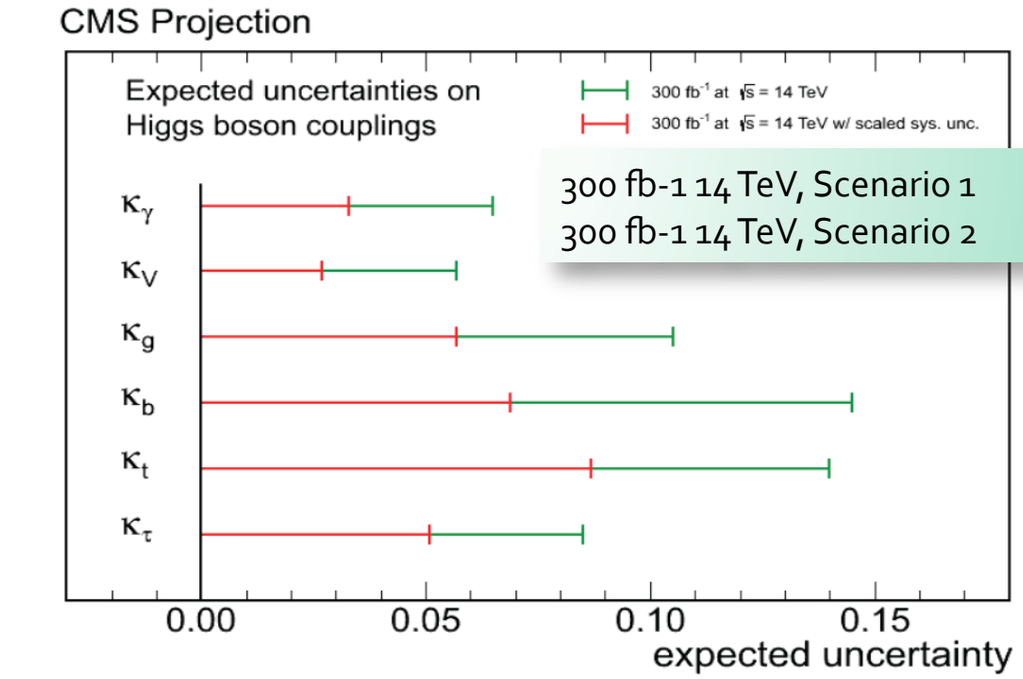
... last hope for finding O(1) deviations?

(possibility in composite Higgs models)

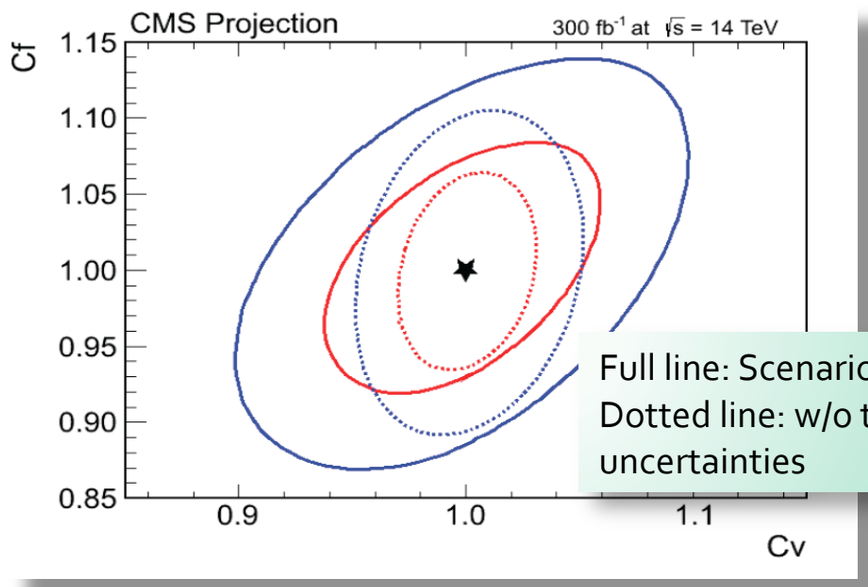
Don't expect high-precision measurements of Higgs couplings:

Projected Higgs couplings with 300 fb^{-1}

- Two scenarios:
  - Scenario 1: same systematics as in 2012
  - Scenario 2: theory systematics scaled by a factor ½, other systematics scaled by $1/\sqrt{(\int L dt)}$



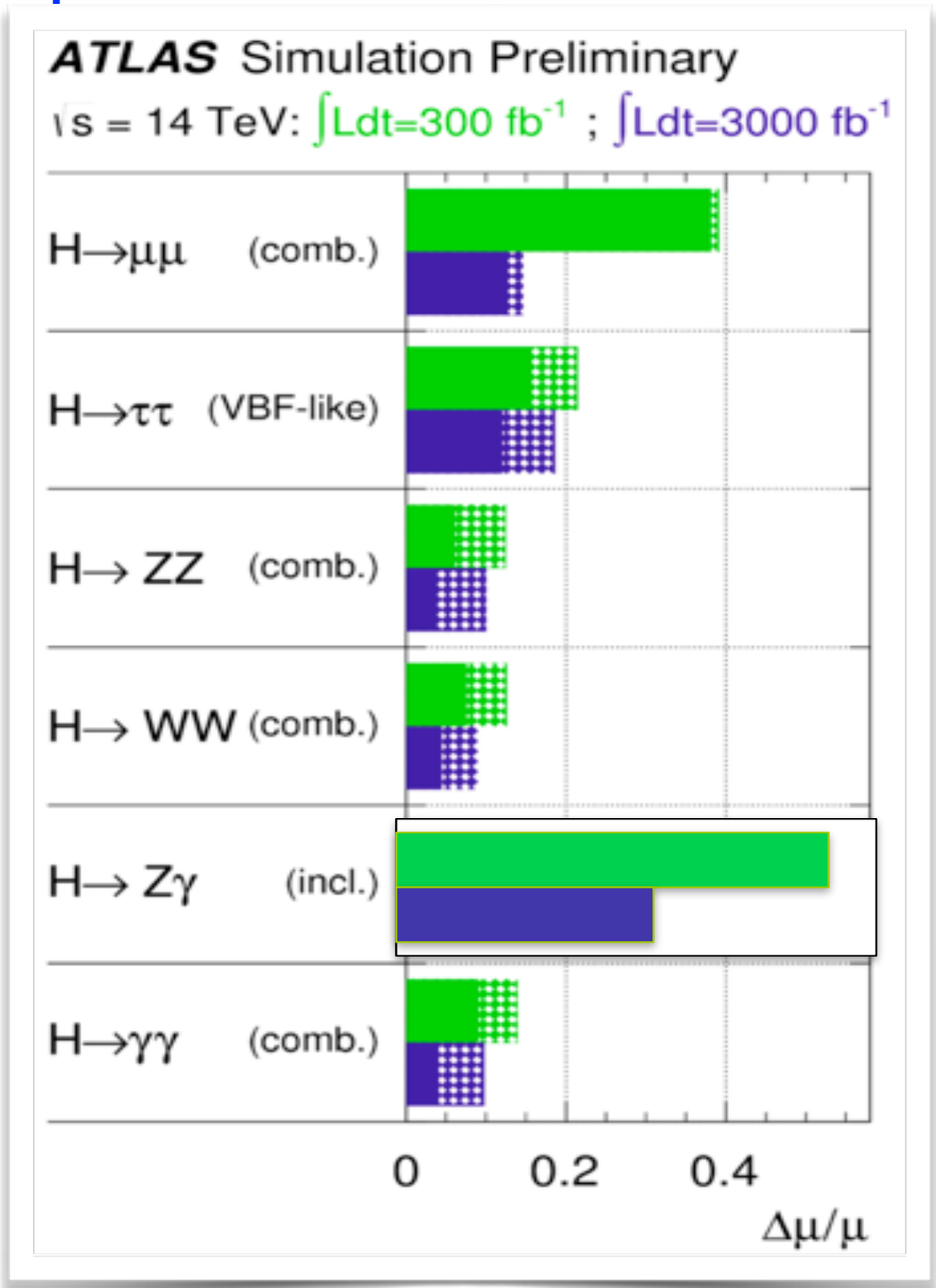
300 fb-1 14 TeV, Scenario 1
300 fb-1 14 TeV, Scenario 2



Full line: Scenario 1
Dotted line: w/o theory uncertainties

☛ **Linear colliders have a point here!**

Don't expect high-precision measurements of Higgs couplings:



☛ **Linear colliders have a point here!**

Higgs coupling accuracy in different colliders

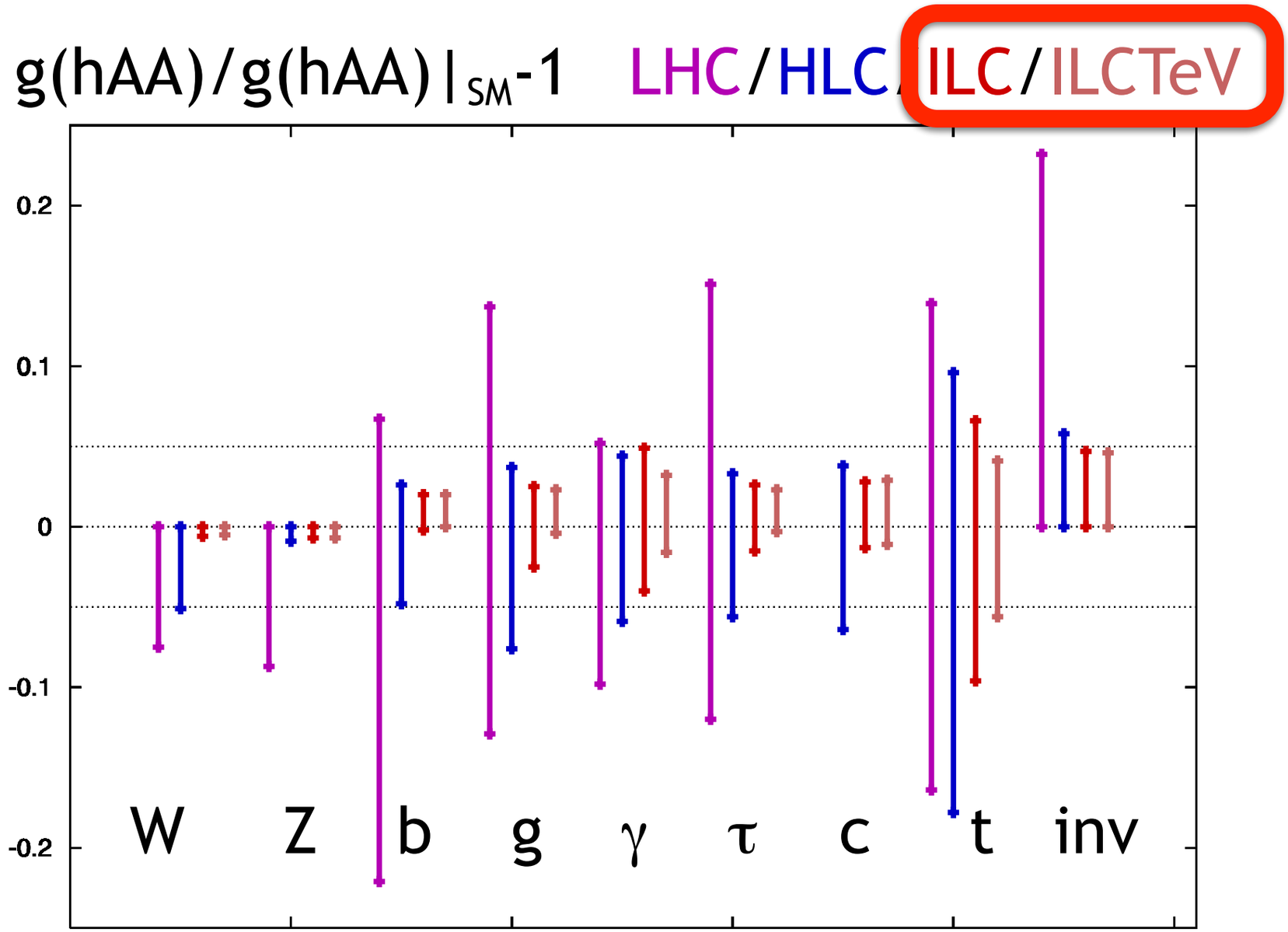
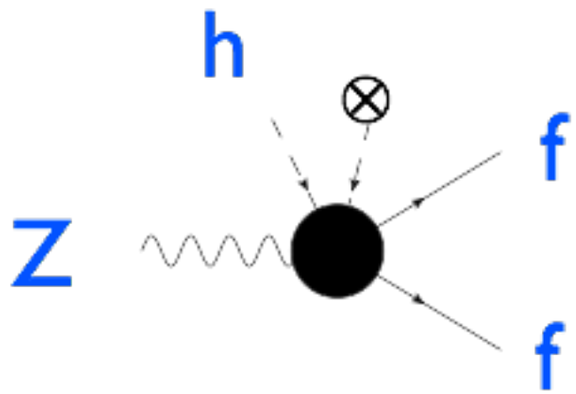


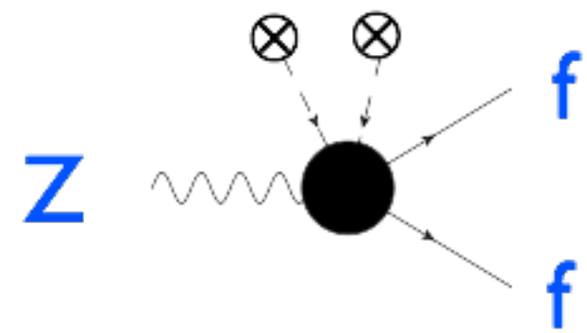
Figure 2: Comparison of the capabilities of LHC and ILC for model-independent measurements of Higgs boson couplings. The plot shows (from left to right in each set of error bars) 1 σ confidence intervals for LHC at 14 TeV with 300 fb^{-1}, for ILC at 250 GeV and 250 fb^{-1} ('HLC'), for the full ILC program up to 500 GeV with 500 fb^{-1} ('ILC'), and for a program with 1000 fb^{-1} for an upgraded ILC at 1 TeV ('ILCTeV'). The marked horizontal band represents a 5% deviation from the Standard Model prediction for the coupling.

Other Higgs couplings
e.g., form-factors (momentum-dependence)

Already tested in other experiments:

e.g. 

$$= \frac{1}{2v} \times$$

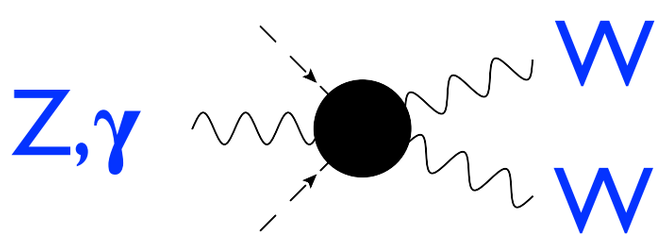


$$H^\dagger D_\mu H \bar{f} \gamma^\mu f$$

Modifications in h→Zff related to Z→ff

Constrained by LEP1 at the per-mille level!

& also constraints from triple gauge-boson couplings:

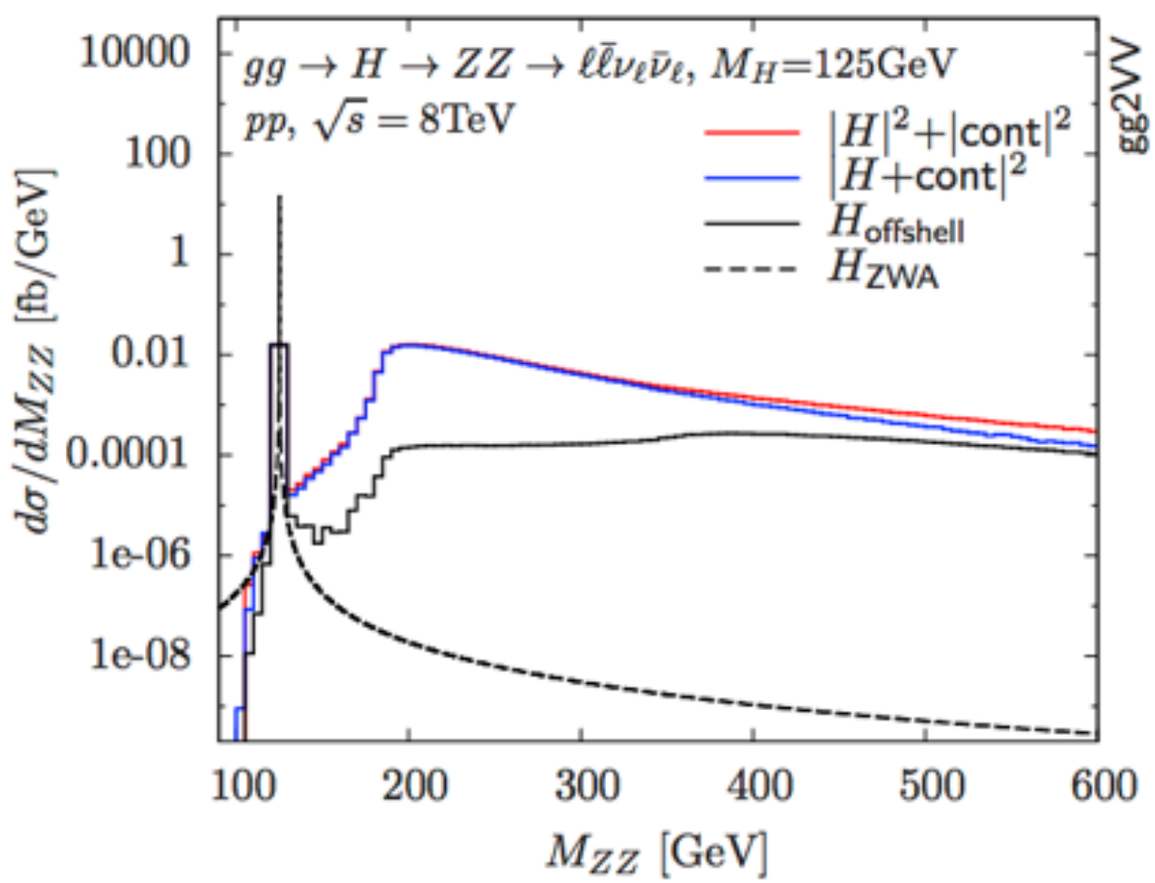


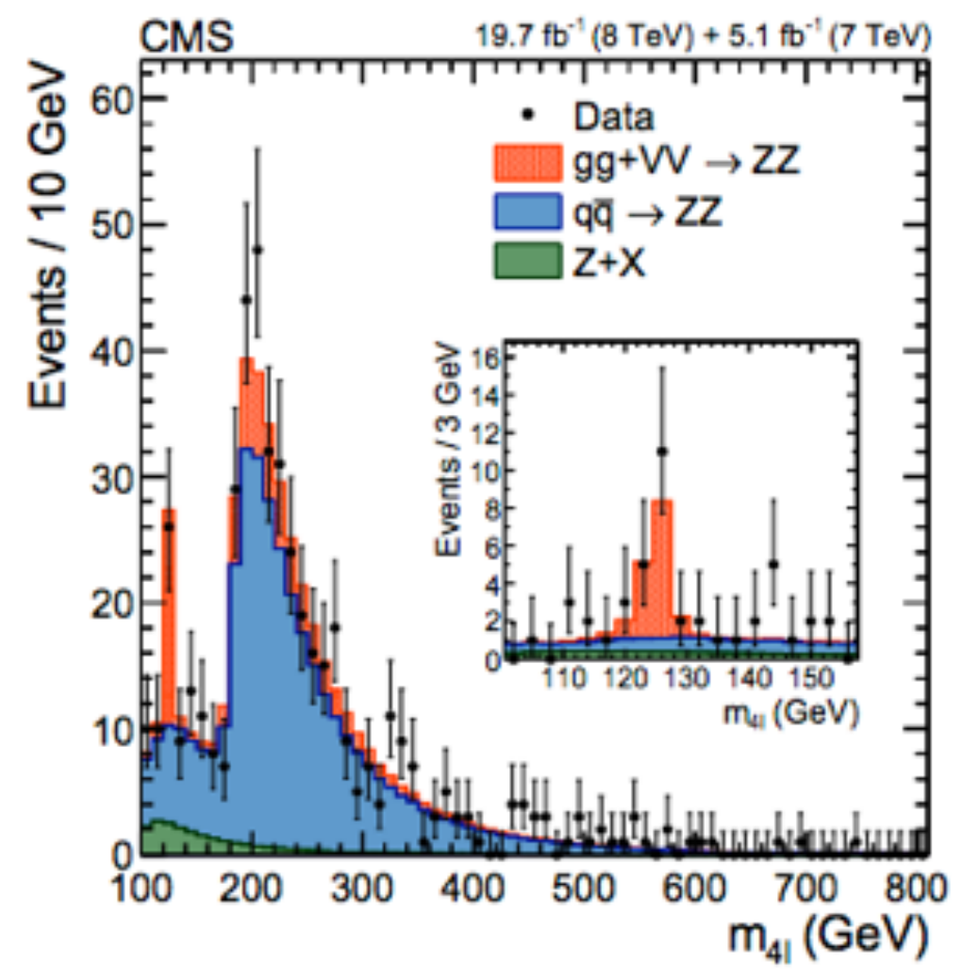
from e.g. $(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$

Nevertheless, worthy to explore as already started at the LHC

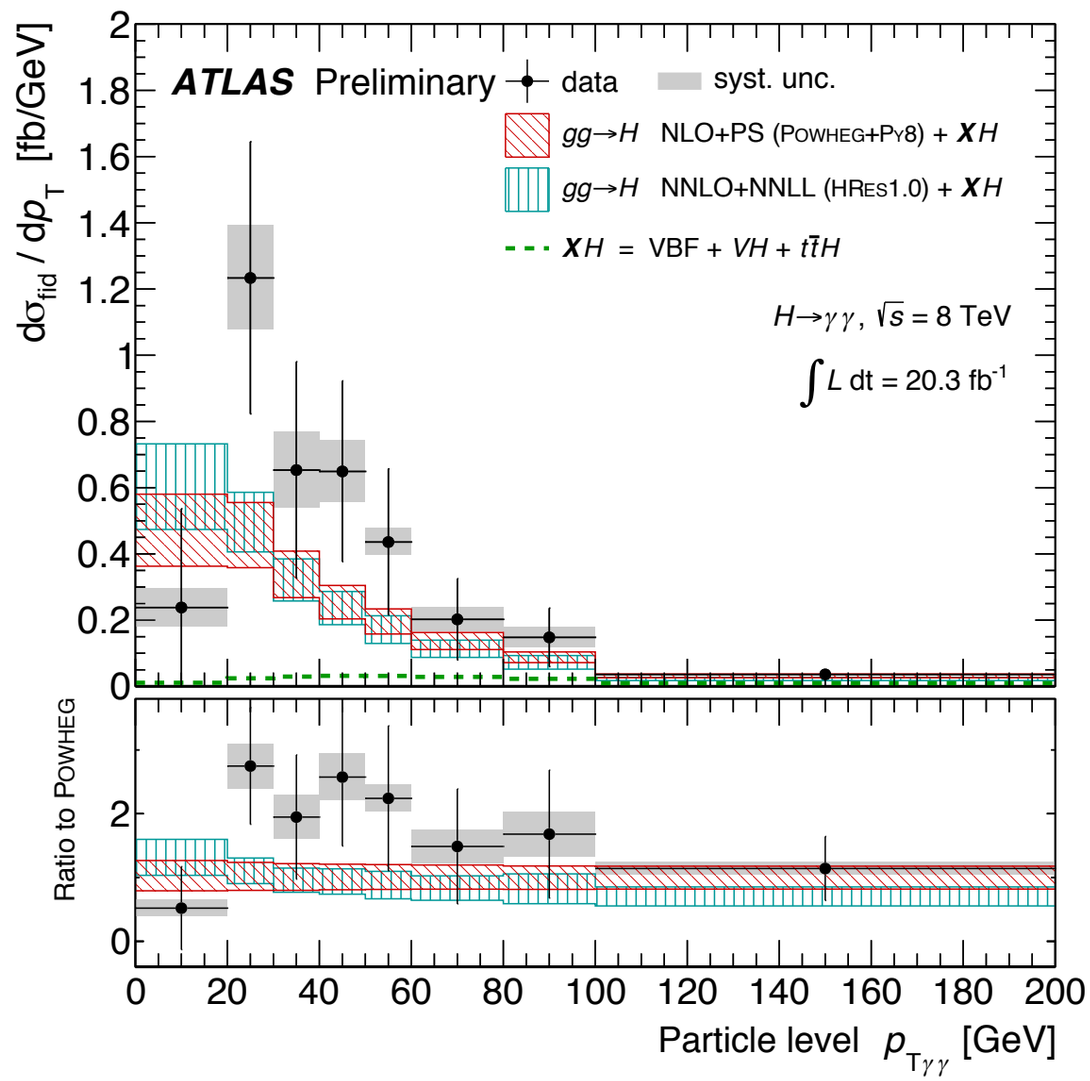
Off-shell Higgs couplings:

$pp \to H^* \to ZZ^* \to 4l$

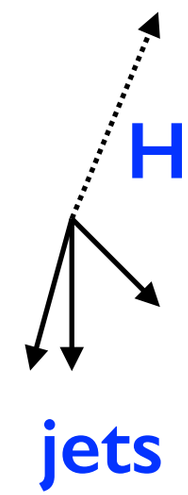




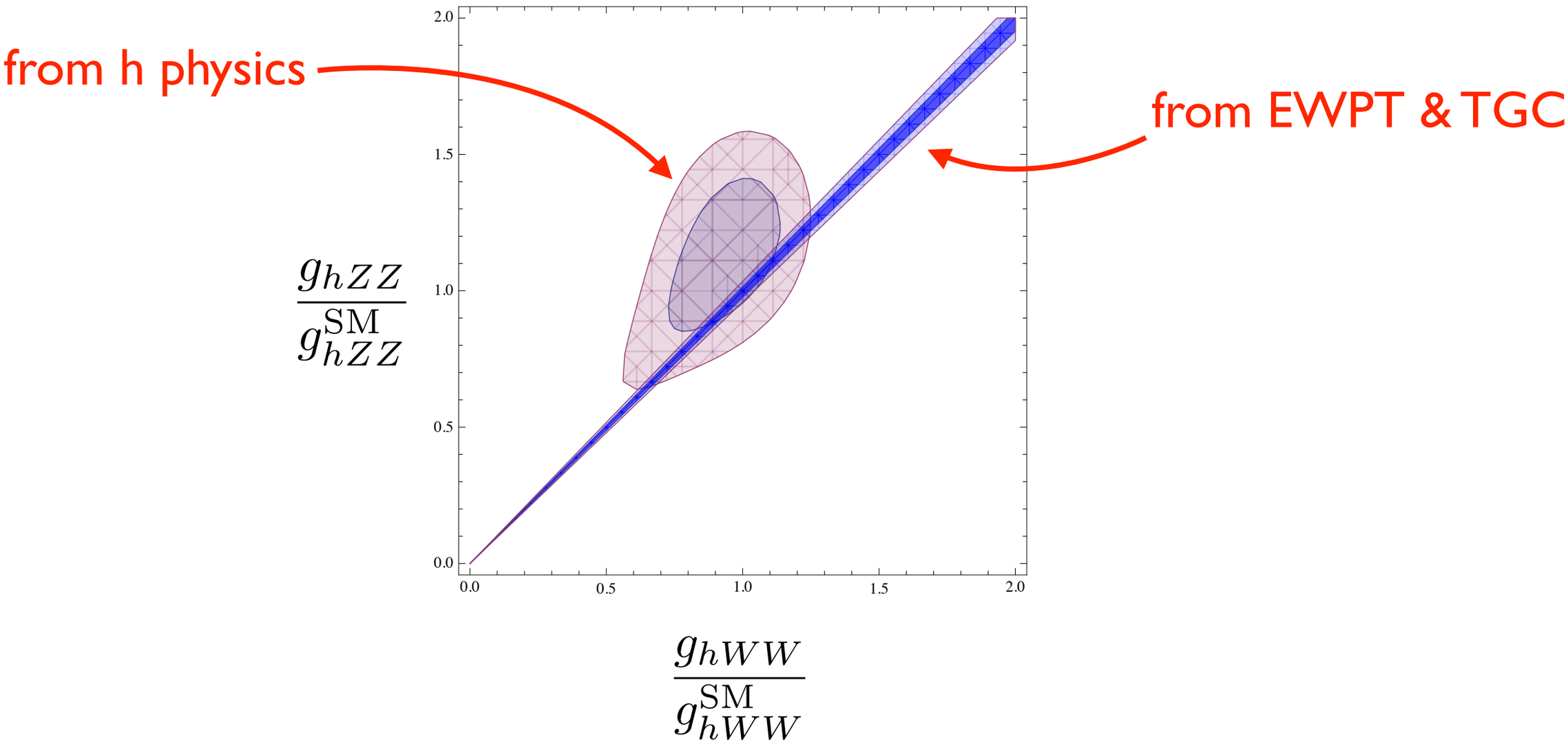
Momentum distribution in H→γγ



(a) $p_{\mathrm{T}}^{\gamma\gamma}$



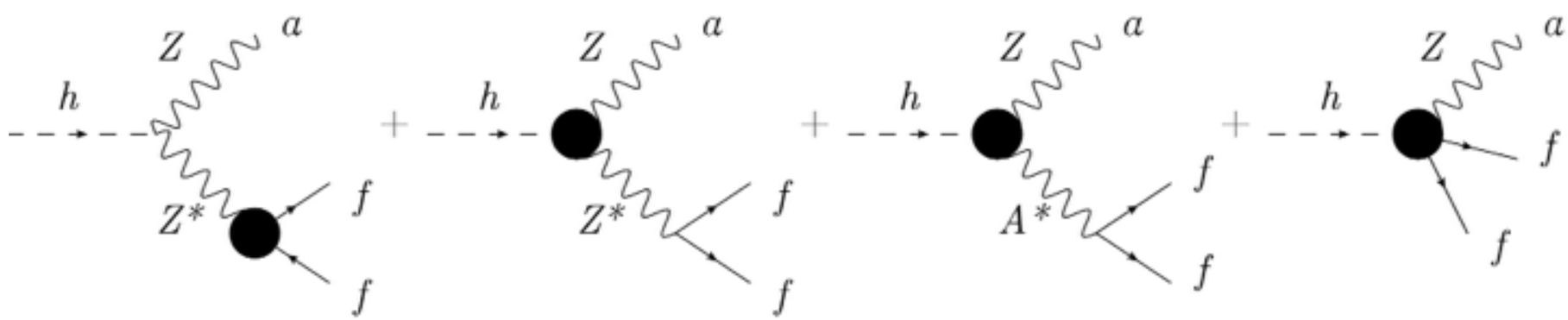
Deviations in hWW vs hZZ



➥ **No large custodial-breaking effects allowed**

In the future:

h→Wff, Zff form-factors:

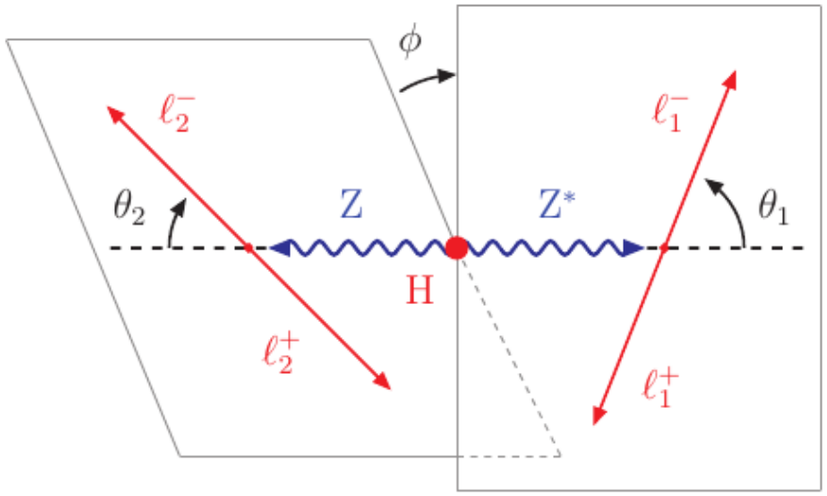


(assuming m_f=0 and CP-conservation)

$$\mathcal{M}(h \to V J_f) = (\sqrt{2} G_F)^{1/2} \epsilon^{*\mu}(q)\, J_f^{V\,\nu}(p) \left[A_f^V \eta_{\mu\nu} + B_f^V \left(p \cdot q\, \eta_{\mu\nu} - p_\mu q_\nu \right) \right]$$

$$A_f^V = a_f^V + \widehat{a}_f^V \frac{p^2 + M_V^2}{p^2 - M_V^2} \qquad B_f^V = b_f^V \frac{1}{p^2 - M_V^2} + \widehat{b}_f^V \frac{1}{p^2}$$

➥ to be measured in momentum/angle distributions

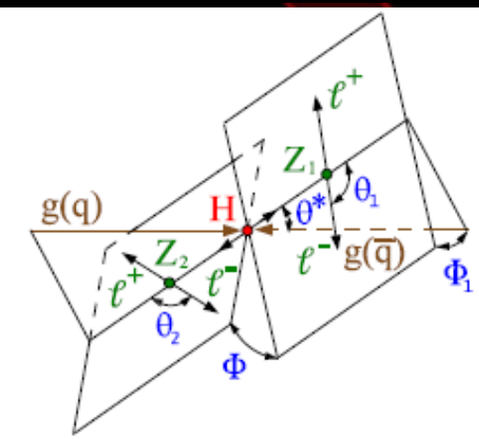


~ order one bounds from SM values expected after the end of run2

Higgs Boson Properties: Field Strength Tensor Structure via H→ZZ*→4ℓ

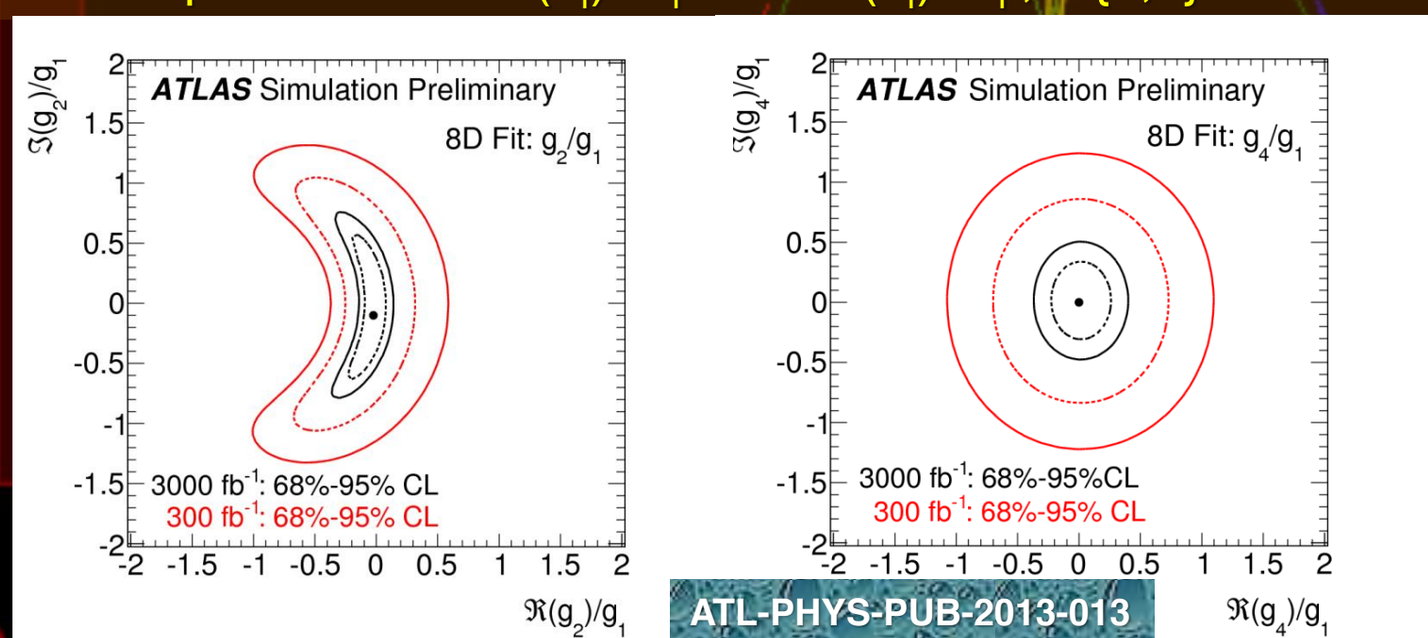
$$A(H \to ZZ) = v^{-1}\left(a_1 m_Z^2 \epsilon_1^* \epsilon_2^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

SM tree process | loop CP-even contributions | CP-odd contributions (BSM)



$(m_{4l}, m_{Z_{1,2}}, \theta_{1,2}, \varphi, \varphi_1, \theta^*)$

- Test for presence of extra anomalous CP-even (coupling $a_2 \leftrightarrow g_2$) and CP-odd (coupling $a_3 \leftrightarrow g_4$) components
- 8D fit involving kinematical variables sensitive to a_2 and a_3 with free parameters $Re(a_i)/a_1$ and $Im(a_i)/a_1$, i={2,3}



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- 95% CL limits: (0,0) corresponds to pure CP-even '0+' SM state
- Factor ~2-3 improvement in precision between 300 and 3000fb-1

Luminosity	$\lvert g_4\rvert/g_1$	$\Re(g_4)/g_1$	$\Im(g_4)/g_1$	$\lvert g_2\rvert/g_1$	$\Re(g_2)/g_1$	$\Im(g_2)/g_1$
300 fb-1	1.20	(-0.88, 0.91)	(-1.02, 1.05)	1.02	(-0.84,0.44)	(-1.19, 1.18)
3000 fb-1	0.60	(-0.30, 0.33)	(-0.39, 0.42)	0.60	(-0.30,0.11)	(-0.71, 0.68)

Conclusions

With the Higgs ➠ the SM is completed

➥ No need for anything else
to (at least) around the Planck scale

… but very unnatural theory !

Expected "deformations" from SM properties

To see them, we must test the Higgs very well

If not found… ☛ Multiverse?

If we find them in $h \to ff$ only ☛ probably MSSM

In a reduction of couplings ☛ probably Composite Higgs