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Higgs after Moriond

Genova, 18 April 2013

Based on work in collaboration with
Dean Carmi, Erik Kuflik, Francesco Riva, Alfredo Urbano, Tomer Volansky, Jure Zupan

Plan

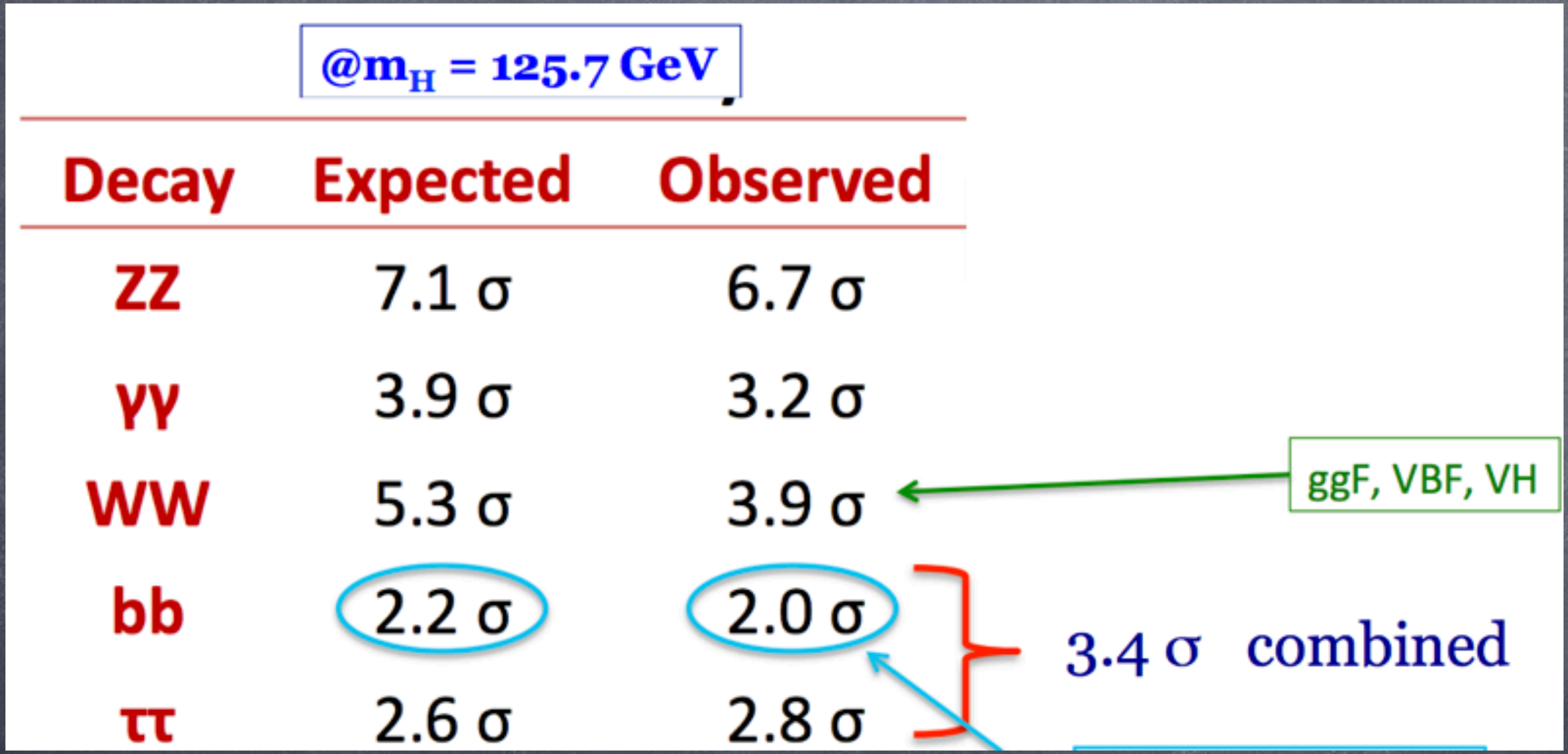
- What do we know from experiment?
- How to interpret that theoretically?
- State of art

What do we know from experiment

HIGGS: WHAT DO WE KNOW EXPERIMENTALLY

A Higgs particle has been discovered...

Significance in CMS, from C.Mariotti's talk April 15



@m_H = 125.7 GeV

Decay	Expected	Observed
ZZ	7.1 σ	6.7 σ
γγ	3.9 σ	3.2 σ
WW	5.3 σ	3.9 σ
bb	2.2 σ	2.0 σ
ττ	2.6 σ	2.8 σ

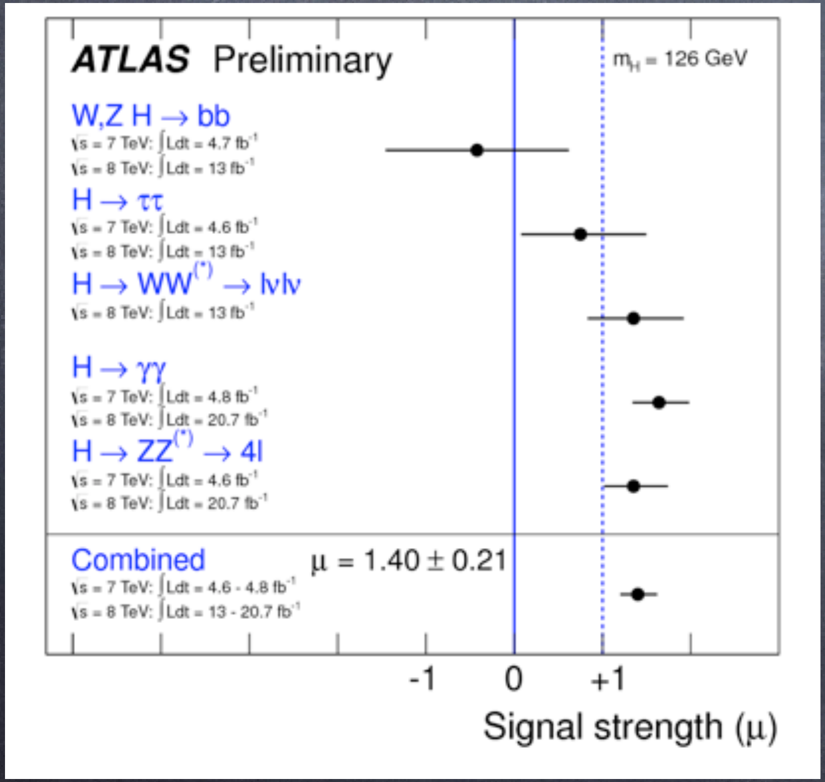
ggF, VBF, VH

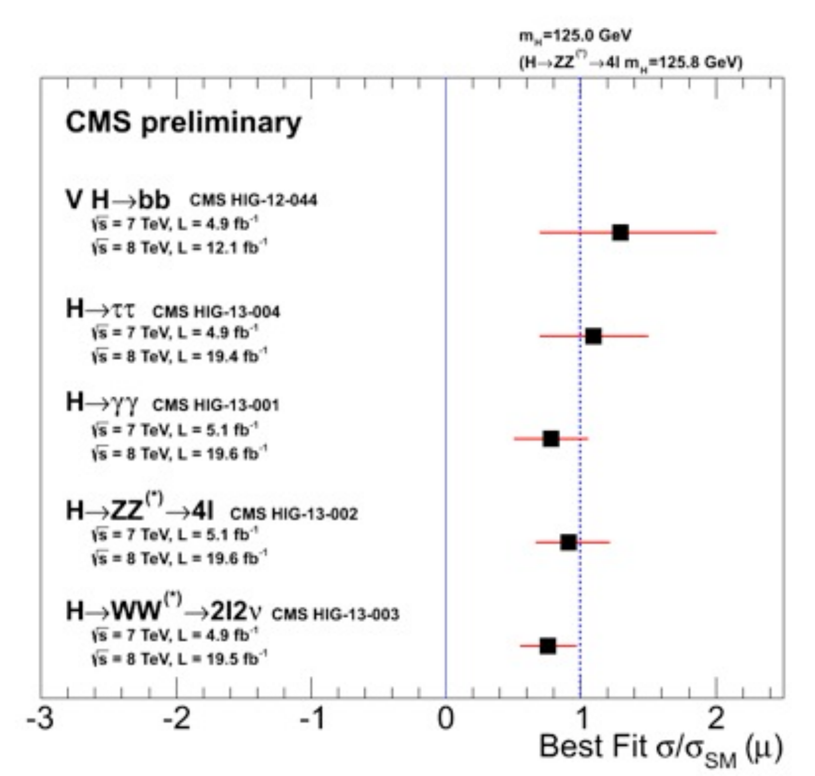
3.4 σ combined

The fact has been so firmly established that no one cares about the significance anymore ;-)

HIGGS: WHAT DO WE KNOW EXPERIMENTALLY

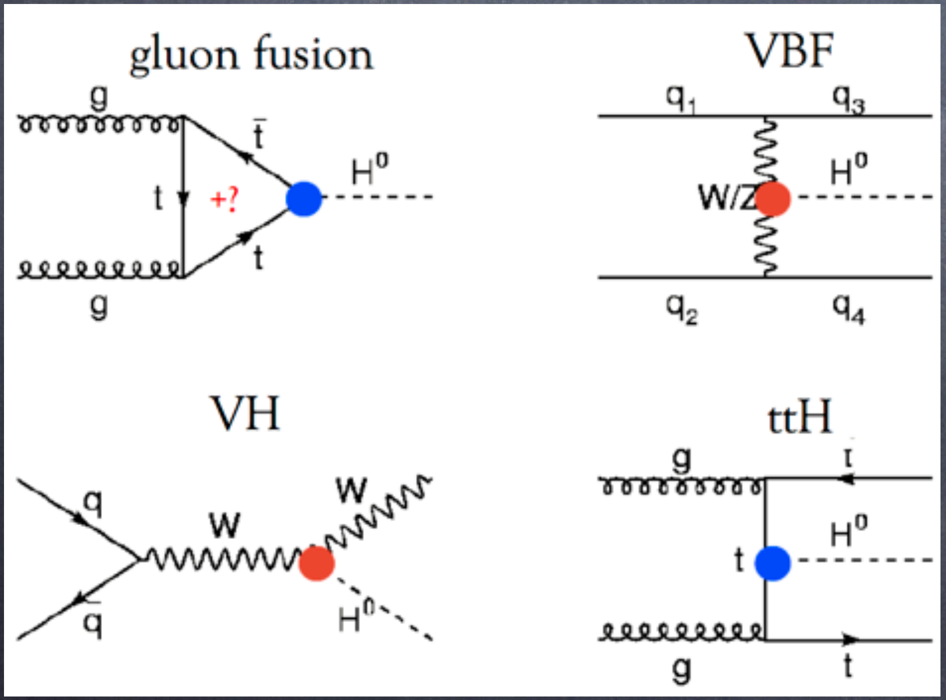
- Most transparent information about Higgs properties from measuring overall event rate in different decay channels...
- Presented as rate (μ or μ-hat) normalized to standard model prediction

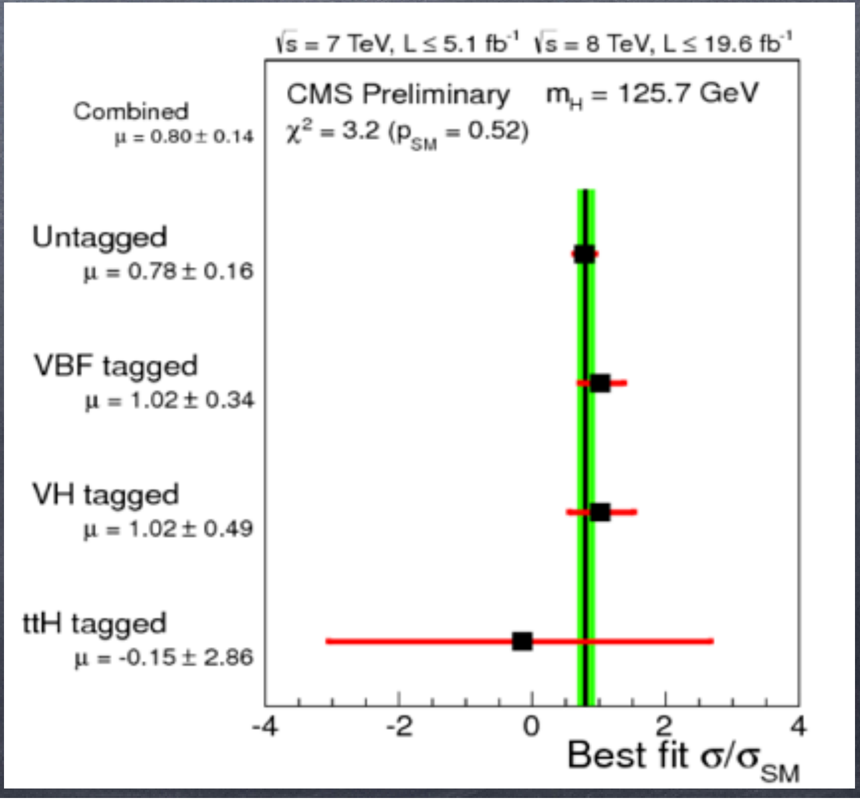




HIGGS: WHAT DO WE KNOW EXPERIMENTALLY

- Different Higgs production processes can be, to some extent, separated by experimental cuts
- Inclusive rates dominated by gluon fusion
- But one can choose cuts that greatly enhance VBF or W/Z +h contribution while keeping the signal at observable level
- Also, first reconnaissance attacks on tth



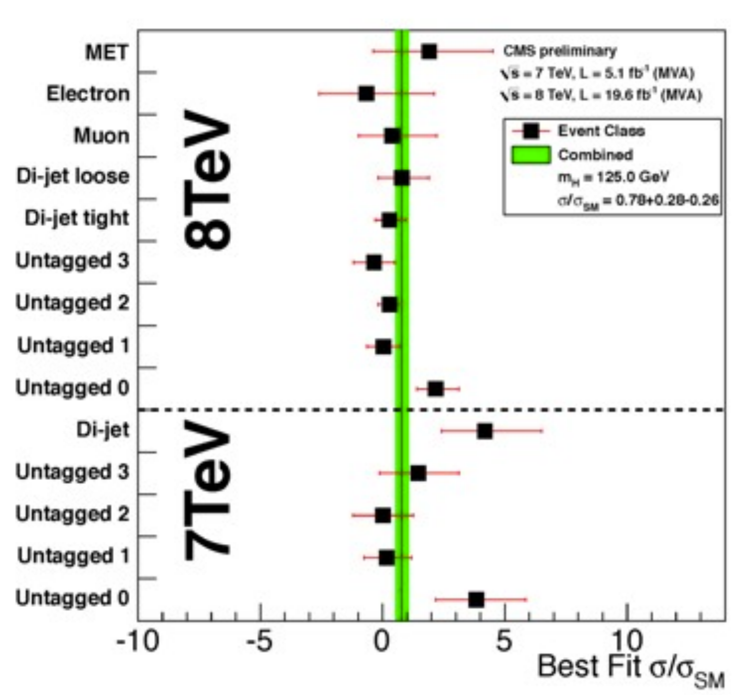


HIGGS: WHAT DO WE KNOW EXPERIMENTALLY

- Currently, 2 most sensitive Higgs channels are $h \to \gamma\gamma$ and $h \to ZZ^* \to 4l$
- Most favorable from the point of view of S/B (5σ discovery in $h \to \gamma\gamma$ alone in ATLAS and $h \to ZZ^* \to 4l$ alone in CMS)
- In both channels, kinematics can be fully reconstructed, and mass can be measured with ~1 GeV precision

HIGGS: WHAT DO WE KNOW EXPERIMENTALLY

γγ



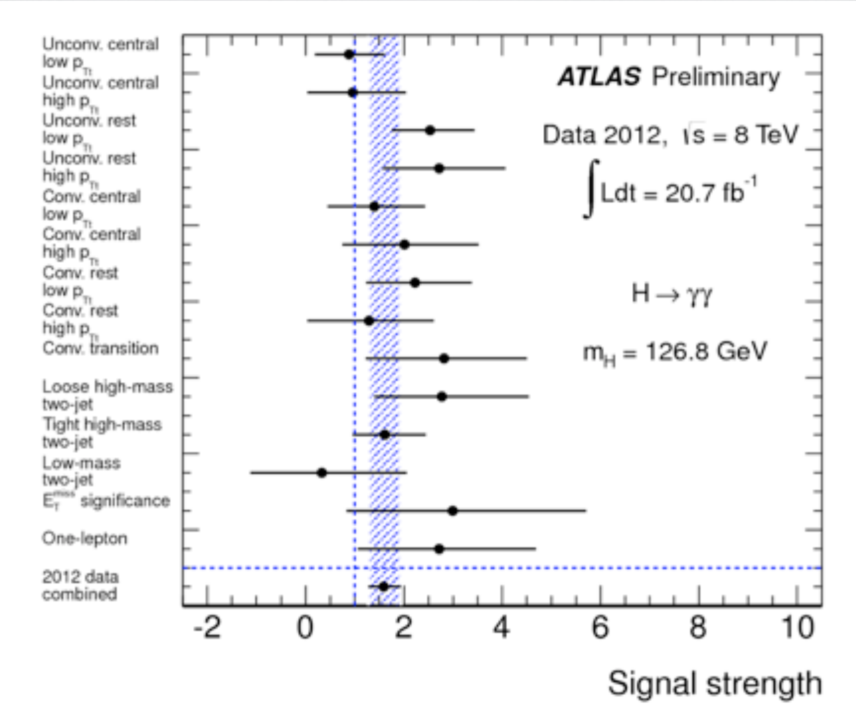
- Small deficit of inclusive rate:

$\mu = 0.78 \pm 0.28$

- Interesting excess in 7 TeV data in not borne out in 8 TeV
- Mass measured at:

$m_h = 125.0 \pm 0.7$ GeV

Larger rate and slightly smaller mass for cut based analysis



- $\sim 2\sigma$ excess of inclusive rate:

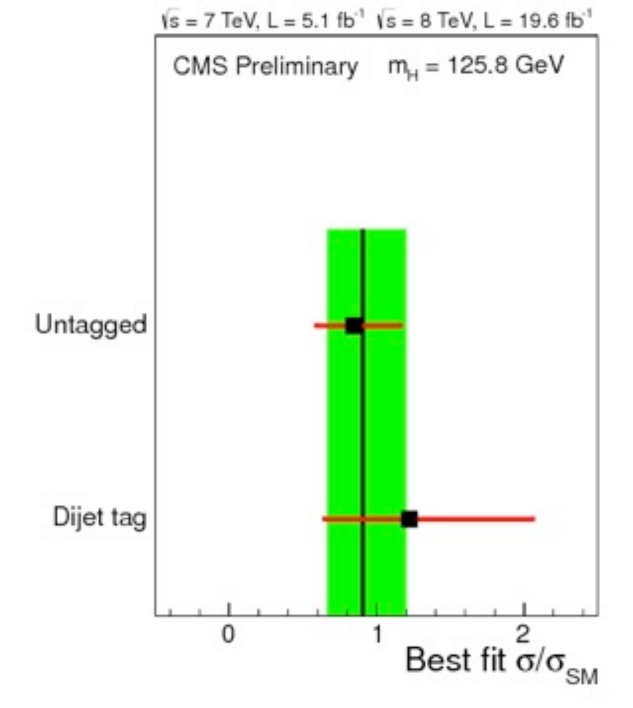
$\mu = 1.65 \pm 0.32$

- Excess quite stable from 7 to 8 TeV
- Mass measured at:

$m_h = 126.8 \pm 0.2 \pm 0.7$ GeV

HIGGS: WHAT DO WE KNOW EXPERIMENTALLY

ZZ

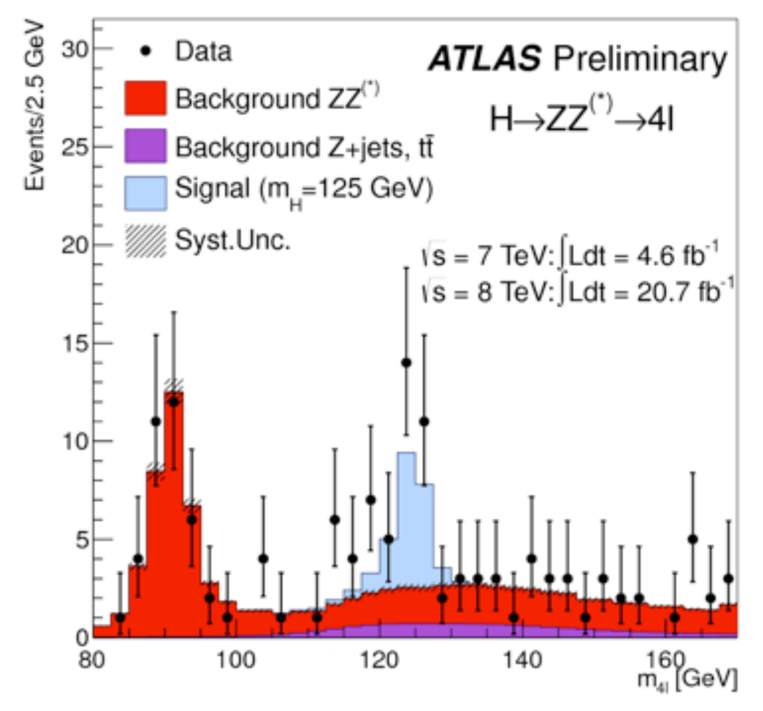


- Rate in good agreement with SM:

  $\mu = 0.92 \pm 0.28$

- Mass measured at:

  $m_h = 125.8 \pm 0.6$ GeV



- Rate in decent agreement with SM

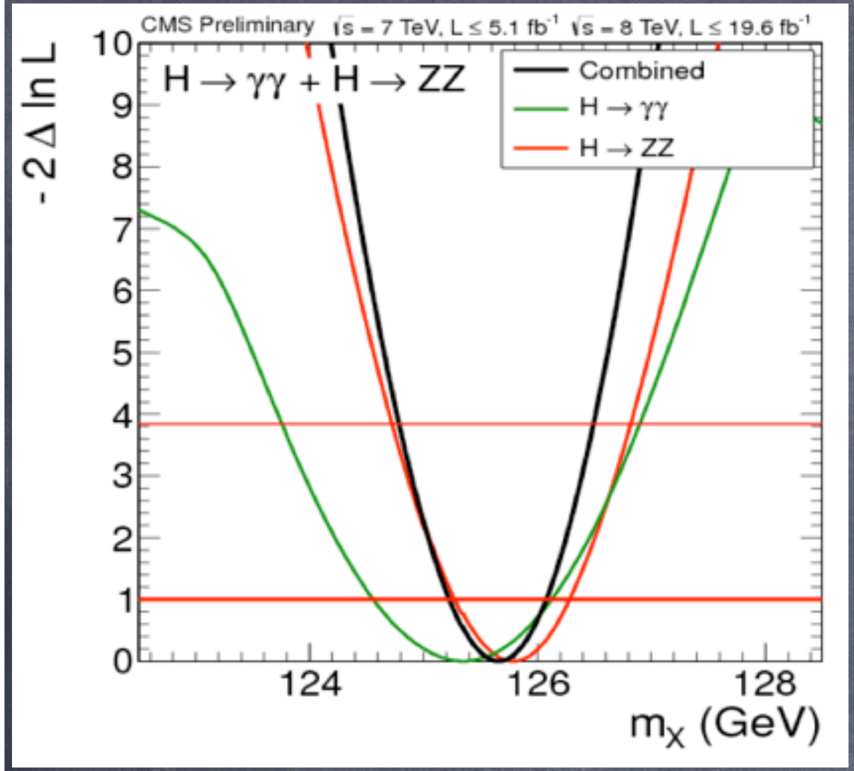
  $\mu = 1.7 \pm 0.4$

  (for mh=124.3 GeV, and 1.5 for mh = 125.5 GeV)

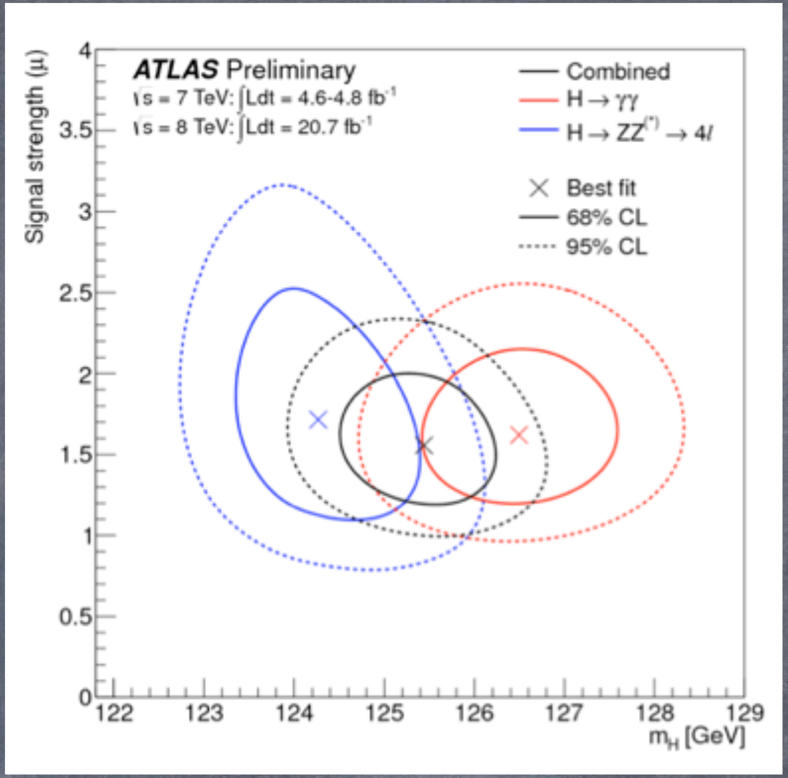
- Mass measured at:

  $m_h = 124.3 \pm 0.7$ GeV

HIGGS: WHAT DO WE KNOW EXPERIMENTALLY



m_h



Systematic error? Fluctuation? Anyway, less worrying than last year...

Mass combination:

m_h = 125.7 ± 0.4 GeV

Mass combination:

m_h = 125.5 ± 0.6 GeV

In spite of some jitters in ATLAS, experiments agree
that m_h is likely between 125 and 126 GeV
In this talk m_h = 126 GeV

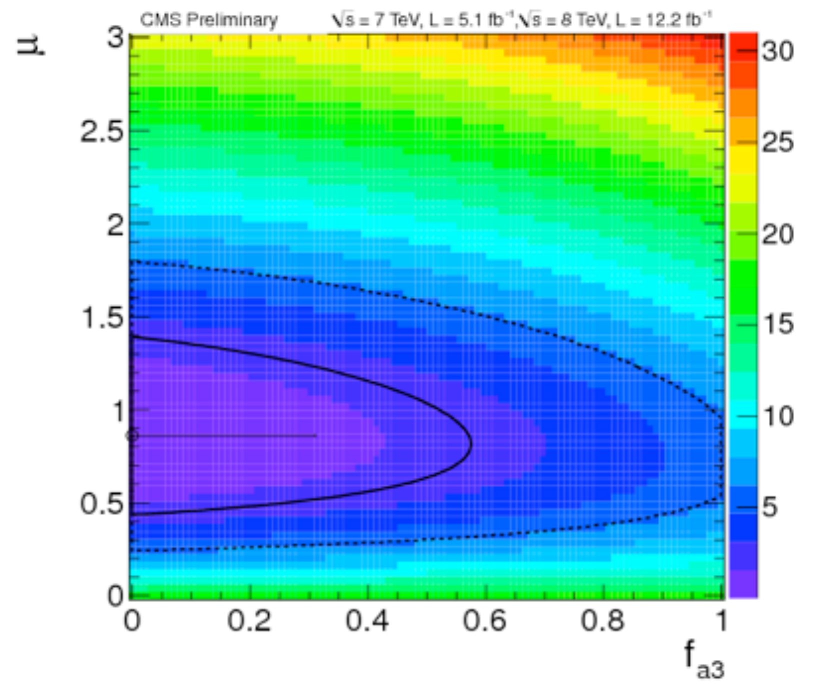
HIGGS: WHAT DO WE KNOW EXPERIMENTALLY

Besides,

- Evidence for Higgs in $WW^* \to 2l2\nu$ channel from both experiments, with rate in good agreement with SM
- Almost evidence in $h \to \tau\tau$ channel from CMS
- bb+W/Z channel not conclusive yet
- First limits on $Z\gamma$ rate, at the level of 15xSM for 125 GeV Higgs

HIGGS: WHAT DO WE KNOW EXPERIMENTALLY

- Besides, experiments start probing differential distributions of Higgs production direction and Higgs decay products
- Results presented in the context of "spin and parity measurements", but often relevant in a wider context



How to interpret that theoretically

Some different approaches

- Interpret the Higgs data in the context of an effective theory: systematic expansion of interactions of a Higgs-like scalar with the SM matter in powers of h/v and D^2/New physics scale^2

Default approach in this talk

- Interpret the Higgs data in the context of concrete model beyond the SM (MCHM5, MCHM14, LstH, MSSM, CMSSM,..., NMSSM,...)

Note than every particular BSM model is almost certainly wrong ;-)

Effective Higgs Lagrangian

[see also Contino et al., note for LHC HXSWG]

Double expansion:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\partial^0} + \mathcal{L}_{\partial^2} + \dots$$

Derivative expansion

$$\mathcal{L}_{\partial^n} = \mathcal{L}^{(0)}_{\partial^n} + \mathcal{L}^{(1)}_{\partial^n} + \dots$$

h/v expansion

Since currently (and for looong time) no experimental access to terms with 2 and more Higgs fields, only lowest non-trivial order (1) in h/v expansion considered here

ASSUMPTIONS

- There is no new particles with m≲mh and significant coupling to the Higgs

Crucial assumption for effective theory to be valid

Technicalities, that can be easily relaxed

- Higgs is a scalar particle (spin-0, positive parity)
- Higgs has no flavor-violating coupling (within generations of up quarks, down quarks, and leptons, couplings ratio scale with mass)
- Custodial symmetry (couplings to WW, ZZ, Zγ and γγ not independent)

Effective Higgs Lagrangian

$$\mathcal{L}^{(1)}_{\partial^0} = \frac{h}{v}\left\{ c_V\, 2m_W^2\, W^+_\mu W^-_\mu + c_V m_Z^2\, Z_\mu Z_\mu + \sum_{q=u,d,l}\sum_{i=1\ldots3} c_q m_{q_i} \bar{q}_i q_i \right\}$$

Custodial

Flavor

$$\cancel{\tilde{\mathcal{L}}^{(1)}_{\partial^0} = \frac{h}{v} i\bar{q}\gamma_5 q + \ldots}$$

parity

- Infinite number of parameters but for a given process at a given precision level only finite number of parameters enter

- Given QCD/PDF uncertainties, unlikely we'll ever need to go beyond 2-derivatives

- Unitary gauge (but trivial to integrate the Goldstone bosons back)

- SM limit:
  -all 0-derivative couplings equal 1,
  -all 2-derivative couplings equal 0

$$\begin{aligned}\mathcal{L}^{(1)}_{\partial^2} = -\frac{h}{4v}\{ & -c_{gg}\, G^a_{\mu\nu} G^a_{\mu\nu} + c_{\gamma\gamma}\, A_{\mu\nu} A_{\mu\nu} + 2c_{Z\gamma}\, Z_{\mu\nu} A_{\mu\nu} \\ & +2\left(c_{\gamma\gamma} + \frac{g_L}{g_Y} c_{Z\gamma}\right) W^+_{\mu\nu} W^-_{\mu\nu} + \left(c_{\gamma\gamma} + \frac{g_L^2 - g_Y^2}{g_L g_Y} c_{Z\gamma}\right) Z_{\mu\nu} Z_{\mu\nu} \\ & +\kappa_V (W^+_\mu \partial_\nu W^-_{\mu\nu} + \mathrm{h.c.}) + \kappa_V Z_\mu \partial_\nu Z_{\mu\nu} + \frac{g_L}{g_Y}\kappa_V Z_\mu \partial_\nu \gamma_{\mu\nu} \Big\} + \ldots\end{aligned}$$

(fermions)

Custodial

$$\cancel{\tilde{\mathcal{L}}^{(1)}_{\partial^2} = \frac{h}{v} Z_{\mu\nu} \tilde{Z}_{\mu\nu} + \ldots}$$

parity

Effective Higgs Lagrangian

EXTENSIONS

- Add parity-violating interactions

e.g. $\Delta\mathcal{L} = \sum_{\psi \in u,d,l} \tilde{c}_\psi \bar{\psi}\gamma_5\psi \frac{h}{v} + \frac{\alpha_{\rm em}}{8\pi}\tilde{c}_{\gamma\gamma}\frac{h}{v}\gamma_{\mu\nu}\tilde{\gamma}_{\mu\nu} + \ldots$

- Add invisible particle coupled to Higgs, so as to allow for invisible Higgs width

e.g. $\Delta\mathcal{L} = c_\chi \frac{h}{v}\bar{\chi}\chi$

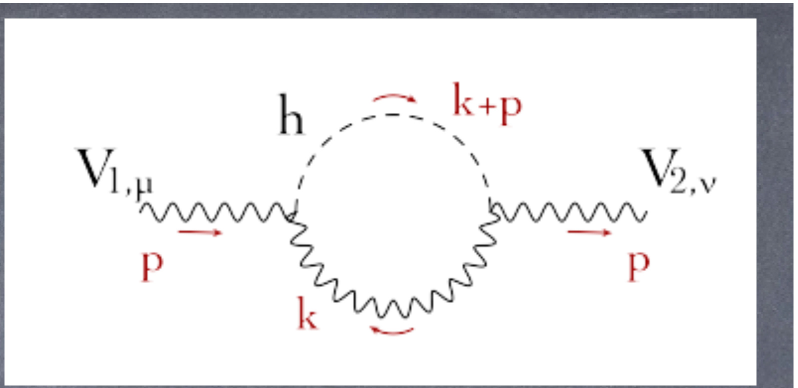
- Drop custodial symmetry assumptions

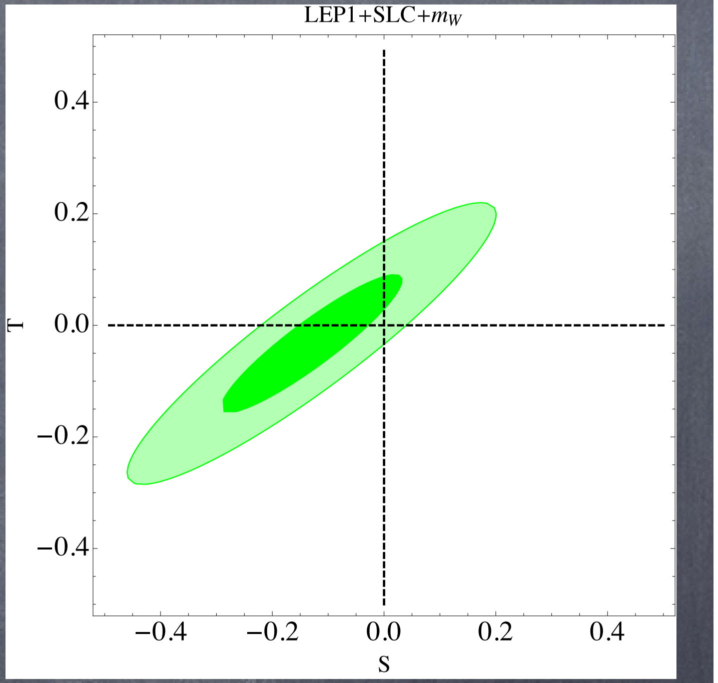
e.g. $\Delta\mathcal{L} = \Delta c_V \frac{h}{v} m_Z^2 Z_\mu Z_\mu + \ldots$

Quadratic divergences to T/U parameters - use with caution!

- If they discover a new particle at the LHC, I'll be delighted to add it to the effective lagrangian ;-)

Not anything goes





- Higgs contributes to 2-point functions of electroweak gauge bosons, whose physical combinations (summarized into oblique parameters S,T,....) are well measured at LEP
- In the SM, Higgs+SM loop contributions to oblique parameters are finite
- But when Higgs has non-standard couplings (or coupling values) corrections to oblique parameters become divergent
- If no custodial symmetry, quadratic or even quartic (when κ-couplings present) divergent corrections to T parameter
- But even with custodial symmetry quadratic divergences may arise if κV≠0
  Hence κV must be tiny and irrelevant for Higgs phenomenology unless we allow fine-tuning

$$\Delta S = \frac{g_Y^2}{g_L^2 + g_Y^2} \frac{\kappa_V (6 c_V + 9 c_{WW} + 17 \kappa_V)}{48 \pi^2 v^2} \Lambda^2 + \ldots$$

In the following we set κV=0

Simpler effective theory keeping the leading order parameters relevant for experimentally probed Higgs processes

$$\mathcal{L}_{eff} = c_V \frac{2m_W^2}{v} h\, W_\mu^+ W_\mu^- + c_V \frac{m_Z^2}{v} h\, Z_\mu Z_\mu$$

$$- c_t \sum_{u,c,t} \frac{m_q}{v} h\, \bar{u}_i u_i - c_b \sum_{d,s,b} \frac{m_q}{v} h\, \bar{d}_i d_i - c_\tau \sum_{e,\mu,\tau} \frac{m_q}{v} h\, \bar{l}_i l_i$$

$$- \frac{h}{4v} \left(c_{\gamma\gamma}\, A_{\mu\nu} A_{\mu\nu} + 2 c_{Z\gamma}\, Z_{\mu\nu} A_{\mu\nu} + c_{ZZ}\, Z_{\mu\nu} Z_{\mu\nu} + 2 c_{WW}\, W_{\mu\nu} W_{\mu\nu}^* - c_{gg}\, G_{\mu\nu}^a G_{\mu\nu}^a \right)$$

$$c_{ZZ} = c_{\gamma\gamma} + \frac{g_L^2 - g_Y^2}{g_L g_Y} c_{Z\gamma} \qquad c_{WW} = c_{\gamma\gamma} + \frac{g_L}{g_Y} c_{Z\gamma}$$

- Simpler effective theory with 7 free parameters
- Standard Model limit: $c_V=c_f=1$, $c_{gg}=c_{\gamma\gamma}=c_{Z\gamma}=0$

Effective theory and EWPT

Even with these restrictions divergent (but only log) corrections from Higgs to oblique parameters

$$\alpha T \approx \frac{3g_Y^2}{32\pi^2}\left(c_V^2-1\right)\log(\Lambda/m_Z)\,,$$

When coupling to mass deviates from SM

$$\alpha S \approx \frac{g_L g_Y}{48\pi^2(g_L^2+g_Y^2)}\left\{2g_L g_Y\left(1-c_V^2\right)+6c_V\left[2g_L g_Y c_{\gamma\gamma}+c_{Z\gamma}(g_L^2-g_Y^2)\right]\right.$$
$$\left.+3\left[g_L g_Y(c_{Z\gamma}^2-c_{\gamma\gamma}^2)-(g_L^2-g_Y^2)c_{\gamma\gamma}c_{Z\gamma}\right]\right\}\log(\Lambda/m_Z)\,,$$

$$\alpha W \approx \frac{g_L^2}{192\pi^2}\left(c_{\gamma\gamma}+\frac{g_L}{g_Y}c_{Z\gamma}\right)^2\log(\Lambda/m_Z)\,,$$

$$\alpha Y \approx \frac{g_L^2}{192\pi^2}\left(c_{\gamma\gamma}-\frac{g_Y}{g_L}c_{Z\gamma}\right)^2\log(\Lambda/m_Z)\,,$$

When 2-derivative couplings are present

Using STUVWXYZ parametrization of Barbieri et al from hep-ph/0405040:

$$\alpha S = -4\frac{g_L g_Y}{g_L^2+g_Y^2}\delta\Pi_{3B}^{(2)}, \quad \alpha T = \frac{\delta\Pi_{11}^{(0)}-\delta\Pi_{33}^{(0)}}{m_W^2}, \quad \alpha U = \frac{4g_Y^2}{g_L^2+g_Y^2}\left(\delta\Pi_{11}^{(2)}-\delta\Pi_{33}^{(2)}\right)$$

$$\alpha V = m_W^2\left(\delta\Pi_{11}^{(4)}-\delta\Pi_{33}^{(4)}\right), \quad \alpha W = -m_W^2\delta\Pi_{33}^{(4)}, \quad \alpha X = -m_W^2\delta\Pi_{3B}^{(4)}, \quad \alpha Y = -m_W^2\delta\Pi_{BB}^{(4)}. \quad \alpha Z = -m_W^2\Pi_{gg}^{(4}$$

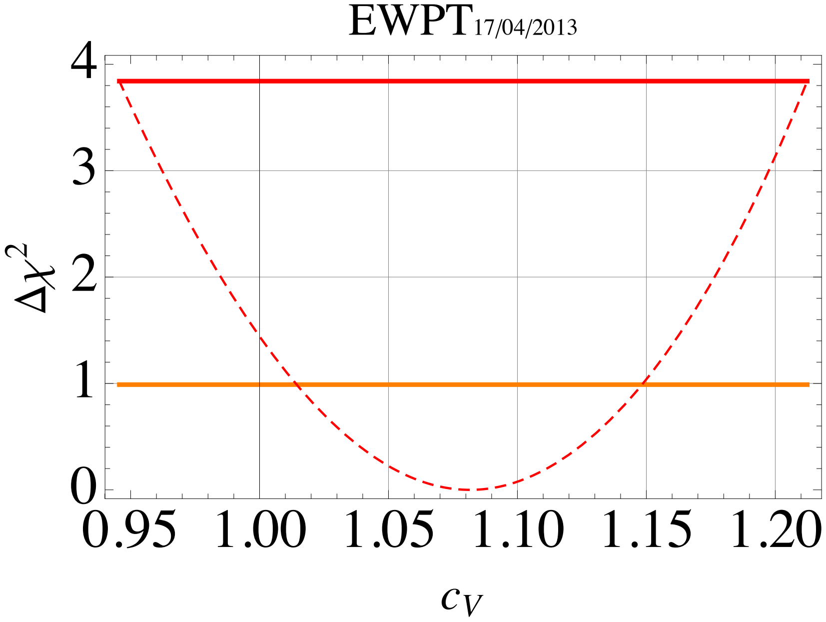
STWY are singled out because they correspond to dimension-6 BSM operators:

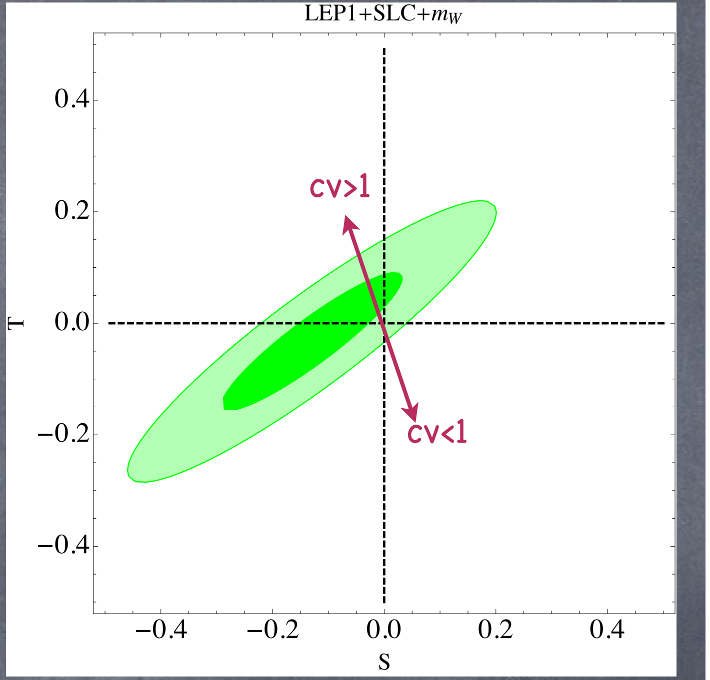
$$\frac{\alpha S(g_L^2+g_Y^2)}{4v^2 g_L g_Y}(H^\dagger\sigma^a H)W_{\mu\nu}^a B_{\mu\nu}-\frac{2\alpha T}{v^2}|H^\dagger D_\mu H|^2-\frac{\alpha W}{4m_W^2}(D_\rho W_{\mu\nu}^a)^2-\frac{\alpha Y}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$$

Effective theory and EWPT

cV<1 is like heavier Higgs
cV>1 is like lighter Higgs
Stringent limits on cV from EWPT alone:

Barbieri,Bellazzini,Rychkov,Varagnolo,
0706.0432

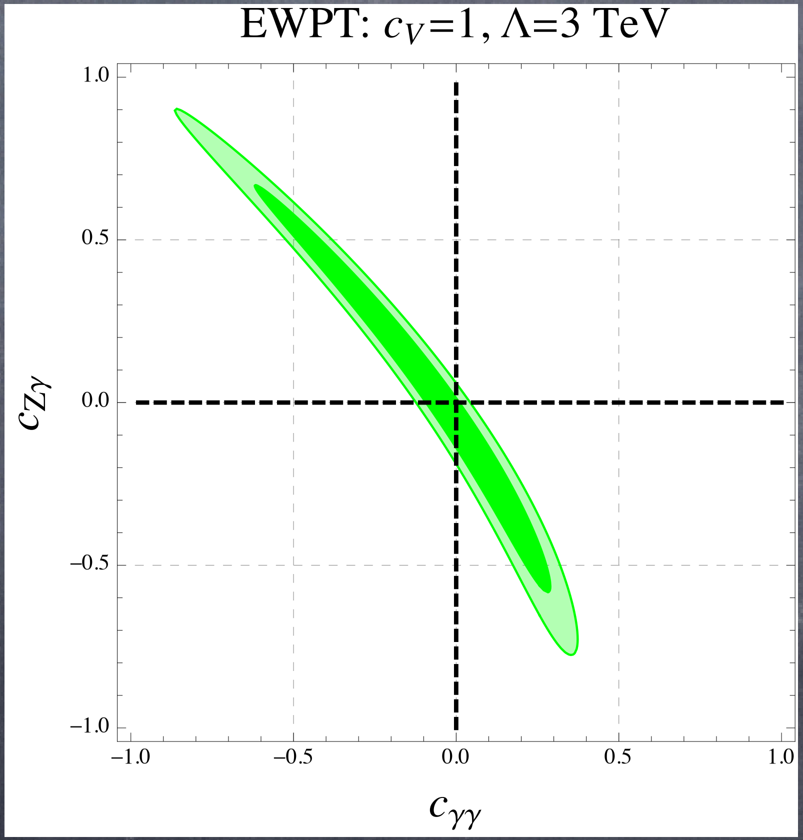




Unless tuned against other significant contributions to S and T

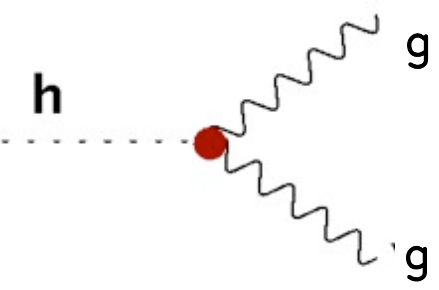
Effective theory and EWPT

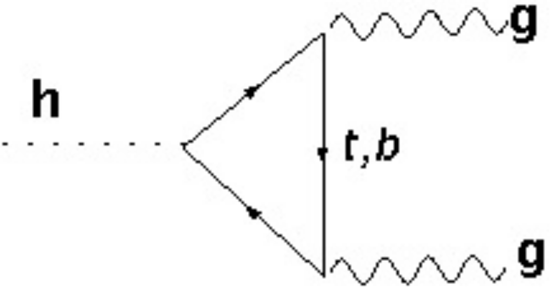
2-derivative couplings also constrained by EWPT, though less strongly



Effective theory: decay

$$\frac{\Gamma_{VV^*}}{\Gamma^{\rm SM}_{VV^*}} \approxeq |c_V|^2 \qquad \frac{\Gamma_{bb}}{\Gamma^{\rm SM}_{bb}} = |c_b|^2 \qquad \frac{\Gamma_{\tau\tau}}{\Gamma^{\rm SM}_{\tau\tau}} = |c_\tau|^2$$



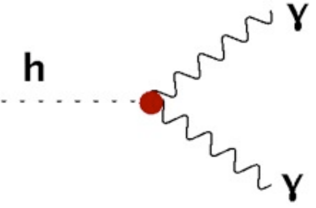


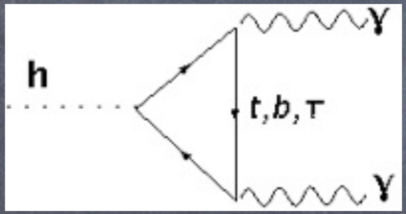
$$\frac{\Gamma_{gg}}{\Gamma^{\rm SM}_{gg}} \simeq \frac{|\hat{c}_{gg}|^2}{|\hat{c}_{gg,\rm SM}|^2}$$

$$\hat{c}_{gg} = c_{gg} + 10^{-2}\,[1.28\,c_t - (0.07 - 0.1\,i)\,c_b]$$

$$|\hat{c}_{gg,\rm SM}| \simeq 0.012$$

Naive one-loop results

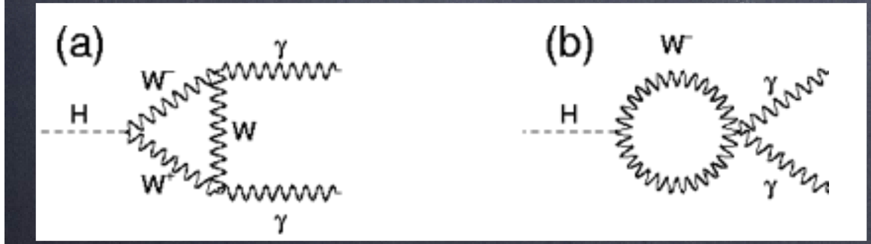




$$\frac{\Gamma_{\gamma\gamma}}{\Gamma^{\rm SM}_{\gamma\gamma}} \simeq \frac{|\hat{c}_{\gamma\gamma}|^2}{|\hat{c}_{\gamma\gamma,\rm SM}|^2}$$

$$\hat{c}_{\gamma\gamma} = c_{\gamma\gamma} + 10^{-2}\,(0.97\,c_V - 0.21\,c_t)\,,$$

$$|\hat{c}_{\gamma\gamma,\rm SM}| \simeq 0.0076,$$

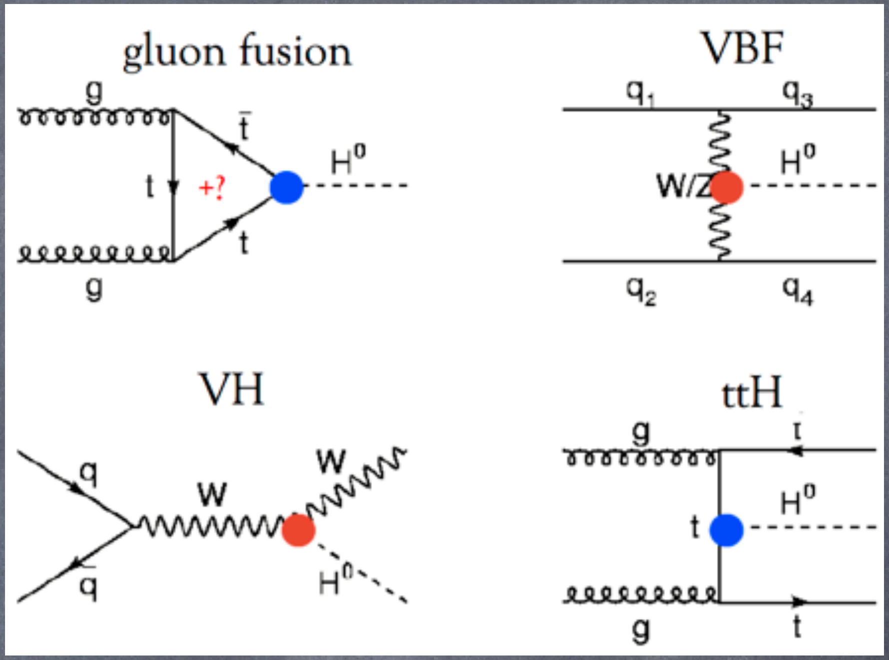


$$\frac{\Gamma_{Z\gamma}}{\Gamma^{\rm SM}_{Z\gamma}} \simeq \frac{|\hat{c}_{Z\gamma}|^2}{|\hat{c}_{Z\gamma,\rm SM}|^2}$$

$$\hat{c}_{Z\gamma} = c_{Z\gamma} + 10^{-2}\,(1.49\,c_V - 0.09\,c_t)\,,$$

$$|\hat{c}_{Z\gamma,\rm SM}| \simeq 0.014$$

Effective theory: production



- **Gluon fusion** (ggF), $gg \to h$+*jets*
- Vector boson fusion (VBF), $qq \to hqq$+*jets*
- Vector boson associated production (VH), $q\bar{q} \to hV$+*jets*
- Top quark associated production (tth), $gg \to tth$+*jets*

Production rates: $\frac{\sigma_{\rm ggF}}{\sigma^{\rm SM}_{\rm ggF}} = \frac{|\hat{c}_{gg}|^2}{|\hat{c}_{gg,\rm SM}|^2}$ $\frac{\sigma_{\rm VBF}}{\sigma^{\rm SM}_{\rm VBF}} \simeq |c_V|^2$ $\frac{\sigma_{\rm tth}}{\sigma^{\rm SM}_{\rm tth}} = |c_t|^2$

Significant effect of 2-derivative couplings on VH production modes:

$$\frac{\sigma_{WH}}{\sigma^{\rm SM}_{WH}} \simeq c_V^2 - 7.0\, c_V c_{Z\gamma} - 3.6\, c_V c_{\gamma\gamma} + 20.4\, c_{Z\gamma}^2 + 5.5\, c_{\gamma\gamma}^2 + 21.2\, c_{Z\gamma} c_{\gamma\gamma},$$

$$\frac{\sigma_{ZH}}{\sigma^{\rm SM}_{ZH}} \simeq c_V^2 - 5.7\, c_V c_{Z\gamma} - 3.4\, c_V c_{\gamma\gamma} + 14.9\, c_{Z\gamma}^2 + 4.3\, c_{\gamma\gamma}^2 + 15.0\, c_{Z\gamma} c_{\gamma\gamma}$$

Effective theory: rates

Observables are rates in various Higgs channels, which are convolution of production, partial decay and total decay width
e.g.

$$\hat{\mu}_{\gamma\gamma}^{ggF} \simeq \frac{|\hat{c}_{gg}|^2}{|\hat{c}_{gg,\mathrm{SM}}|^2} \frac{|\hat{c}_{\gamma\gamma}|^2}{|\hat{c}_{\gamma\gamma,\mathrm{SM}}|^2} \frac{1}{C_{\mathrm{tot}}^2}$$

$$|C_{\mathrm{tot}}|^2 = \frac{\Gamma_{\mathrm{tot}}}{\Gamma_{\mathrm{tot,SM}}} \approx 0.56 c_b^2 + 0.03 c_t^2 + 0.06 c_\tau^2 + 0.26 c_V^2 + 0.09 \frac{|\hat{c}_{gg}|^2}{|\hat{c}_{gg,\mathrm{SM}}|^2}$$

Furthermore, rates measured by experiment typically depend on different production modes (sometimes event different decay channels)
e.g.

$$\hat{\mu}_{\gamma\gamma}^{THM2J} = \epsilon_{\mathrm{ggF}}^{THM2J} \hat{\mu}_{\gamma\gamma}^{ggF} + \epsilon_{\mathrm{VBF}}^{THM2J} \hat{\mu}_{\gamma\gamma}^{VBF} + \epsilon_{\mathrm{VH}}^{THM2J} \hat{\mu}_{\gamma\gamma}^{VH} + \epsilon_{\mathrm{ttH}}^{THM2J} \hat{\mu}_{\gamma\gamma}^{ttH}$$

24% 76% 0.1% 0.1%

Thus, effectively, each observable depends on all parameters of effective theory

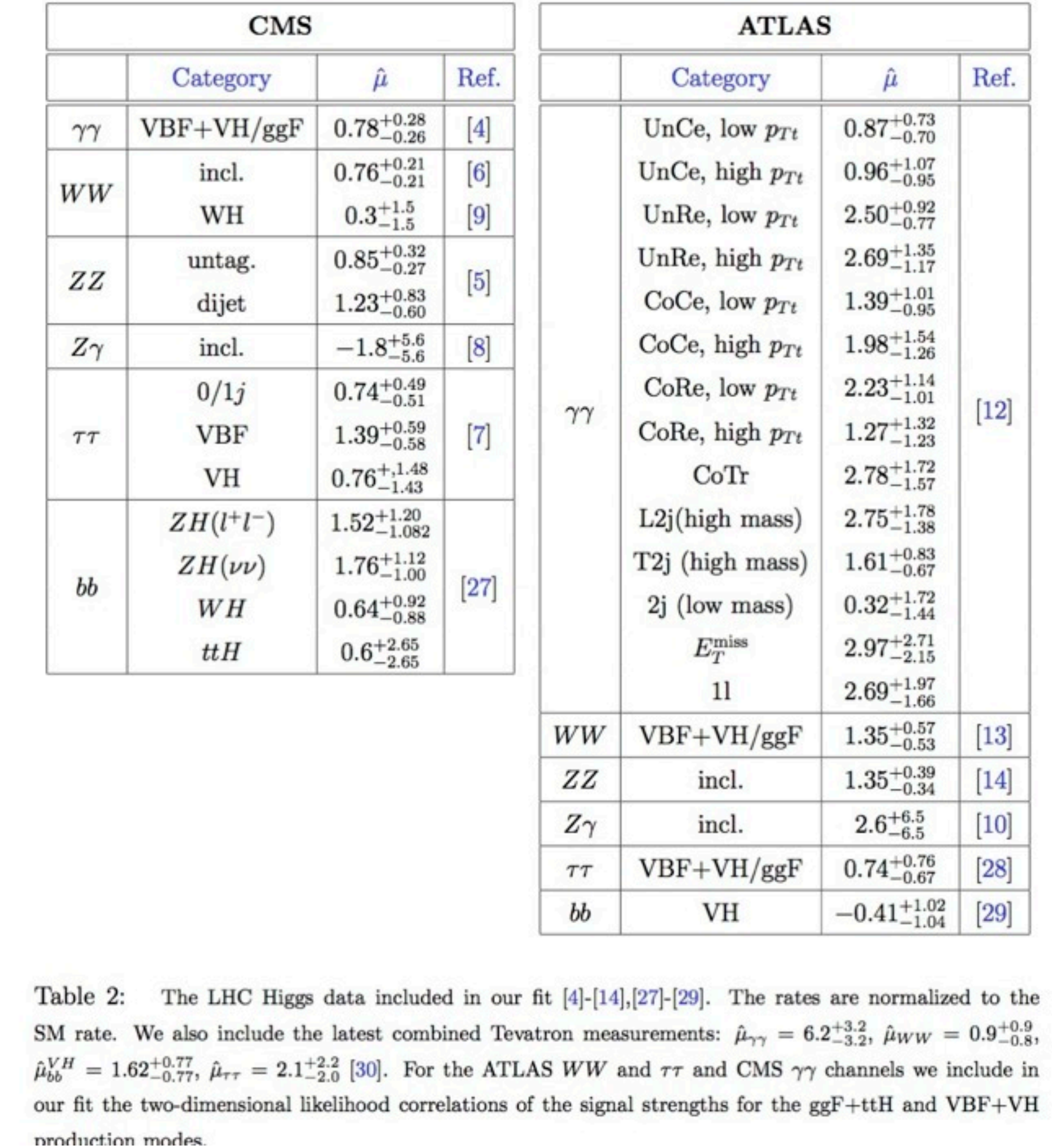
State of Art

Disclaimer: similar or exactly the same fits done independently by numerous theorist groups;
too many to cite them all, so in this talk no references at all, so as not to miss someone ;-)

Global fits

- We fit couplings of the effective theory to available ATLAS, CMS, and Tevatron data and EW precision tests from LEP, SLC, Tevatron
- Starting with unconstrained 7 parameter, than moving to constrained 2 parameter fits motivated by new physics models
- Assuming errors in different channels are Gaussian and uncorrelated (except in EW precision tests)
- But taking into account the efficiencies of various subchannels to different Higgs production processes, whenever available

Global fits



CMS			
	Category	$\hat{\mu}$	Ref.
$\gamma\gamma$	VBF+VH/ggF	$0.78^{+0.28}_{-0.26}$	[4]
WW	incl.	$0.76^{+0.21}_{-0.21}$	[6]
	WH	$0.3^{+1.5}_{-1.5}$	[9]
ZZ	untag.	$0.85^{+0.32}_{-0.27}$	[5]
	dijet	$1.23^{+0.83}_{-0.60}$	
$Z\gamma$	incl.	$-1.8^{+5.6}_{-5.6}$	[8]
$\tau\tau$	$0/1j$	$0.74^{+0.49}_{-0.51}$	[7]
	VBF	$1.39^{+0.59}_{-0.58}$	
	VH	$0.76^{+1.48}_{-1.43}$	
bb	$ZH(l^+l^-)$	$1.52^{+1.20}_{-1.082}$	[27]
	$ZH(\nu\nu)$	$1.76^{+1.12}_{-1.00}$	
	WH	$0.64^{+0.92}_{-0.88}$	
	ttH	$0.6^{+2.65}_{-2.65}$	

ATLAS			
	Category	$\hat{\mu}$	Ref.
$\gamma\gamma$	UnCe, low p_{Tt}	$0.87^{+0.73}_{-0.70}$	[12]
	UnCe, high p_{Tt}	$0.96^{+1.07}_{-0.95}$	
	UnRe, low p_{Tt}	$2.50^{+0.92}_{-0.77}$	
	UnRe, high p_{Tt}	$2.69^{+1.35}_{-1.17}$	
	CoCe, low p_{Tt}	$1.39^{+1.01}_{-0.95}$	
	CoCe, high p_{Tt}	$1.98^{+1.54}_{-1.26}$	
	CoRe, low p_{Tt}	$2.23^{+1.14}_{-1.01}$	
	CoRe, high p_{Tt}	$1.27^{+1.32}_{-1.23}$	
	CoTr	$2.78^{+1.72}_{-1.57}$	
	L2j(high mass)	$2.75^{+1.78}_{-1.38}$	
	T2j (high mass)	$1.61^{+0.83}_{-0.67}$	
	2j (low mass)	$0.32^{+1.72}_{-1.44}$	
	E_T^{miss}	$2.97^{+2.71}_{-2.15}$	
	1l	$2.69^{+1.97}_{-1.66}$	
WW	VBF+VH/ggF	$1.35^{+0.57}_{-0.53}$	[13]
ZZ	incl.	$1.35^{+0.39}_{-0.34}$	[14]
$Z\gamma$	incl.	$2.6^{+6.5}_{-6.5}$	[10]
$\tau\tau$	VBF+VH/ggF	$0.74^{+0.76}_{-0.67}$	[28]
bb	VH	$-0.41^{+1.02}_{-1.04}$	[29]

Table 2: The LHC Higgs data included in our fit [4]-[14],[27]-[29]. The rates are normalized to the SM rate. We also include the latest combined Tevatron measurements: $\hat{\mu}_{\gamma\gamma} = 6.2^{+3.2}_{-3.2}$, $\hat{\mu}_{WW} = 0.9^{+0.9}_{-0.8}$, $\hat{\mu}_{bb}^{VH} = 1.62^{+0.77}_{-0.77}$, $\hat{\mu}_{\tau\tau} = 2.1^{+2.2}_{-2.0}$ [30]. For the ATLAS WW and $\tau\tau$ and CMS $\gamma\gamma$ channels we include in our fit the two-dimensional likelihood correlations of the signal strengths for the ggF+ttH and VBF+VH production modes.

Effective Theory Parameter Fits

$$\mathcal{L}_{eff} = c_V \frac{2m_W^2}{v} h\, W_\mu^+ W_\mu^- + c_V \frac{m_Z^2}{v} h\, Z_\mu Z_\mu$$
$$- c_t \sum_{u,c,t} \frac{m_q}{v} h\, \bar{u}_i u_i - c_b \sum_{d,s,b} \frac{m_q}{v} h\, \bar{d}_i d_i - c_\tau \sum_{e,\mu,\tau} \frac{m_q}{v} h\, \bar{l}_i l_i$$
$$- \frac{h}{4v} \left(c_{\gamma\gamma}\, A_{\mu\nu} A_{\mu\nu} + 2 c_{Z\gamma}\, Z_{\mu\nu} A_{\mu\nu} + c_{ZZ}\, Z_{\mu\nu} Z_{\mu\nu} + 2 c_{WW}\, W_{\mu\nu} W^*_{\mu\nu} - c_{gg}\, G^a_{\mu\nu} G^a_{\mu\nu} \right)$$

Why fit?

- Because it’s fun
- Because it may gives hints what kind of new physics could be realized in nature and prompt new theoretical directions
- For example: fits to early Higgs data were suggesting cV > 1, and prompted studies of Higgs sectors with triplets where it’s possible
- For example: fits to early Higgs data suggesting large new contributions to cγγ prompted more in-depth studies (collider pheno, stability, etc.) of theories with light charged particles strongly coupled to the Higgs
- Ultimately, to prove it’s just the SM in a model independent and prejudice free fashion :-(((

Effective Theory Parameter Fits

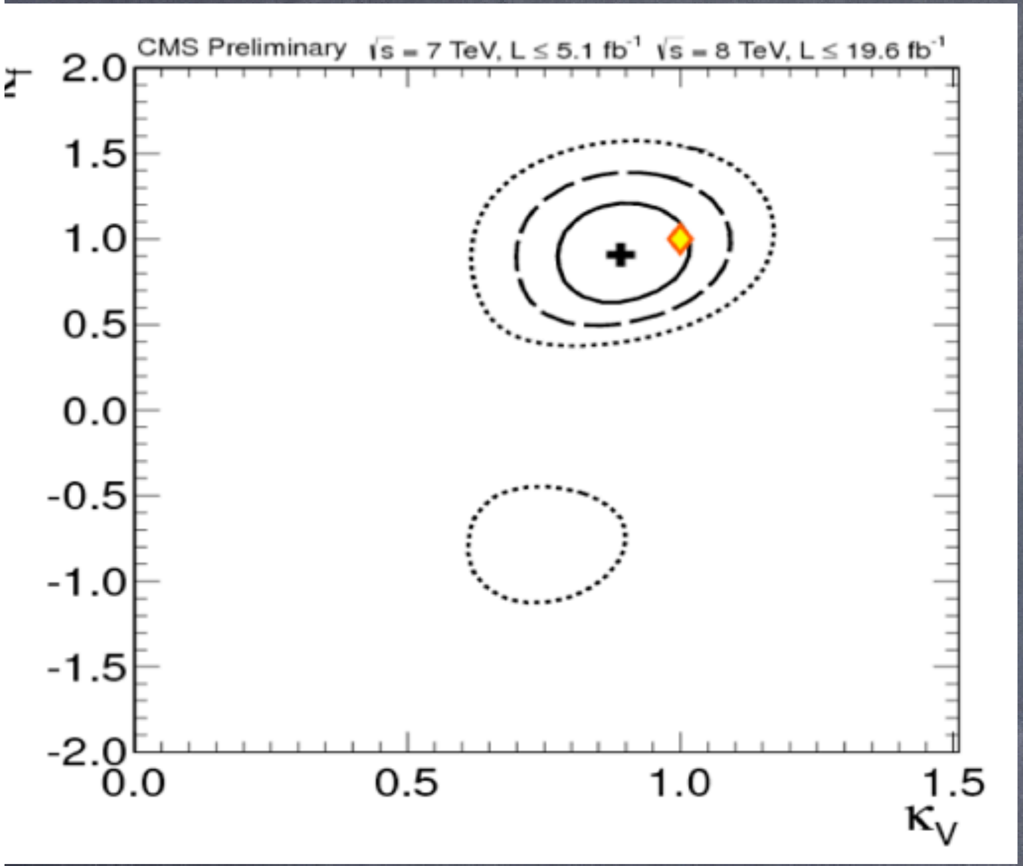
$$\mathcal{L}_{eff} = c_V \frac{2m_W^2}{v} h\, W_\mu^+ W_\mu^- + c_V \frac{m_Z^2}{v} h\, Z_\mu Z_\mu$$
$$- c_t \sum_{u,c,t} \frac{m_q}{v} h\, \bar{u}_i u_i - c_b \sum_{d,s,b} \frac{m_q}{v} h\, \bar{d}_i d_i - c_\tau \sum_{e,\mu,\tau} \frac{m_q}{v} h\, \bar{l}_i l_i$$
$$- \frac{h}{4v} \left(c_{\gamma\gamma}\, A_{\mu\nu} A_{\mu\nu} + 2c_{Z\gamma}\, Z_{\mu\nu} A_{\mu\nu} + c_{ZZ}\, Z_{\mu\nu} Z_{\mu\nu} + 2c_{WW}\, W_{\mu\nu} W^*_{\mu\nu} - c_{gg}\, G^a_{\mu\nu} G^a_{\mu\nu} \right)$$

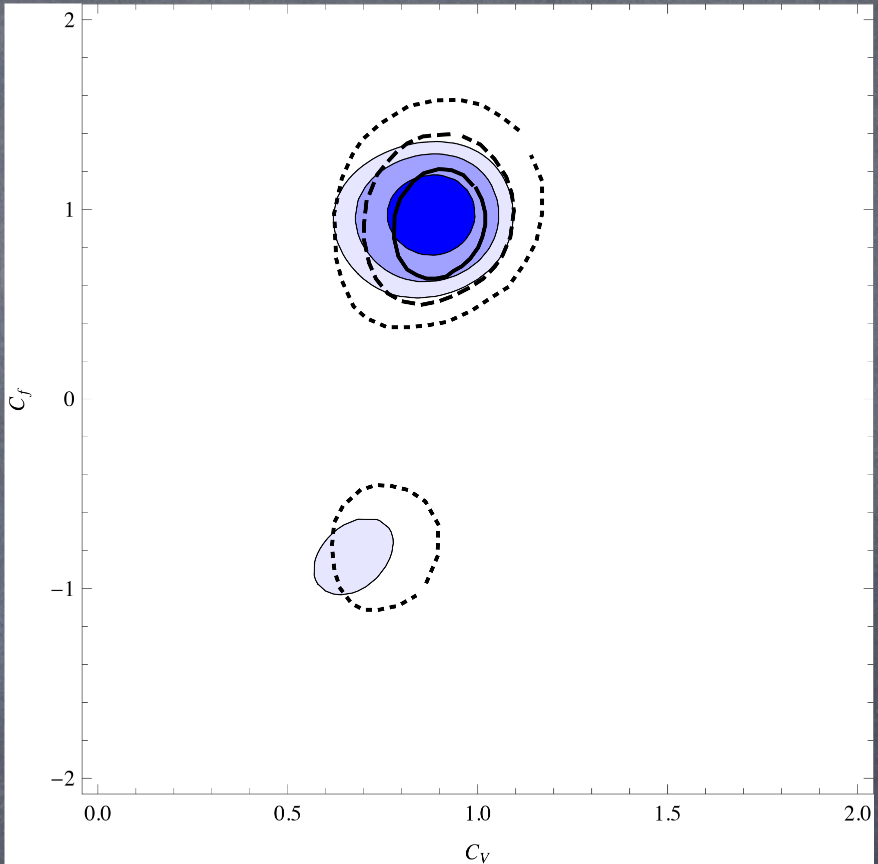
Should theorists fit?

- Asymptotically, no...
- Theorists cannot properly take into account all systematics and correlations
- OK as long as the errors are dominated by statistics, but we're close to the point where they are not

Comparison of naive and professional fits

Fit to vector and fermion couplings, CMS data only





Our fits somewhat underestimate errors

But crudely they select the same regions of the parameter space

For the moment, naive fits have advantage of combining ATLAS+CMS+Tevatron, which probably smoothes out the edges...

7 parameter fit

Not displayed other islands with negative cV, cb, cτ

Best fit and 1σ range for parameters:

$c_V = 1.04 \pm 0.03$

It couples to W and Z mass!!!

$c_t = 1.3 \pm 0.7$

Too early to say whether it couples to top due to weak limits on tth production

$c_b = 1.00 \pm 0.22$

It couples to fermions!

$c_\tau = 1.00 \pm 0.20$

$c_{gg} = -0.005 \pm 0.011$

Weak limit on coupling to gluons due to degeneracy with ct (c.f. effective cgg=0.012 in SM)

$c_{\gamma\gamma} = 0.0015 \pm 0.002$

Quite strong limit on coupling to photons c.f effective cγγ=0.0076 in SM)

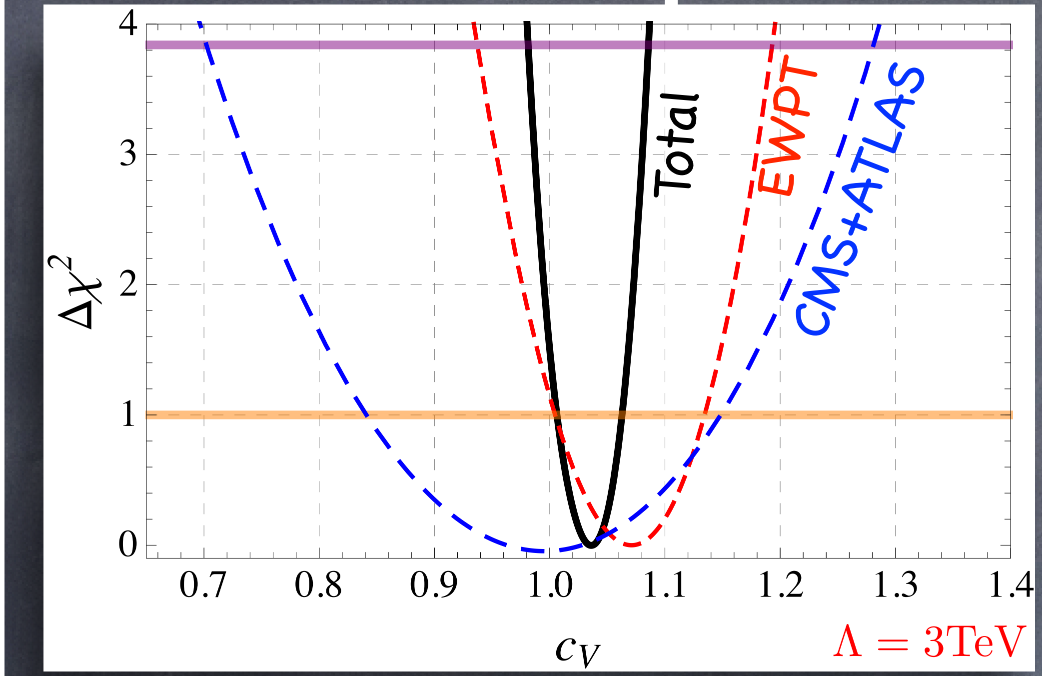
$c_{Z\gamma} = -0.003 \pm 0.022$

Weak limit on coupling to Zγ due to weak experimental limits (c.f with effective cZγ=0.014 in SM)

$\Delta\chi^2 = \chi^2_{SM} - \chi^2_{min} = 5.1$, with 7 d.o.f.

the SM hypothesis is a perfect fit :-(((

7 parameter fit



- Overwhelming evidence it is a Higgs boson
- Statement independent of possible higher order couplings to W and Z
- Smells like the Higgs boson

Higgs at Last !!!!!

- A Higgs is a scalar particle that takes part in electroweak breaking, that is to say, it couples to W and Z mass so as to unitarize their scattering amplitudes
- For a unique Higgs with $c_V=1$ it gets promoted to the SM Higgs

Still some chance it's not the SM Higgs boson...

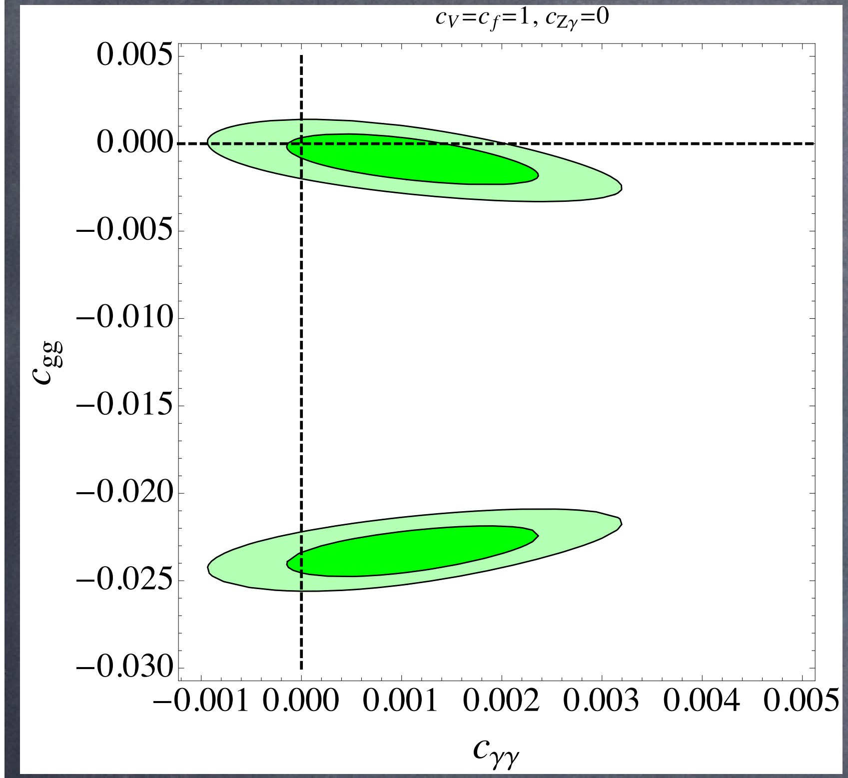
2 parameter fits

- We also consider 2D planes in the parameter space of our simpler effective theory
- Fit 2 parameters, while fixing (not marginalizing over) the remaining ones
- The choice of free and fixed parameters motivated by popular models of new physics
- Showing 1 sigma bands for the combined results in the most important Higgs decay channels
- Combined 68%/95% CL regions corresponding to $\Delta\chi^2 \lesssim 2.3/6.0$, respectively

New physics in loops

2-parameter fits: loop inspired

Loop-induced new physics



- Only 2-derivative Higgs couplings to gluons and photons vary; other couplings kept at SM values

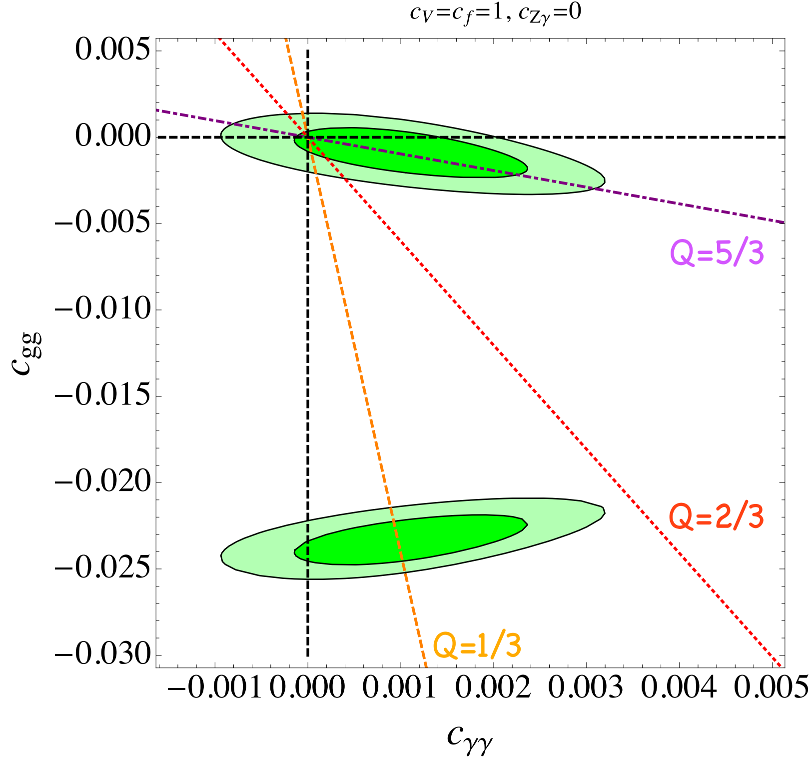
- On this plane, no significant variation of χ2 in Vh→bb and h→ττ channel, only h→γγ and h→VV* channels relevant

- Good fit when cgg and cγγ very small, or when significant but fine-tuned against SM contributions

- 2 islands have exactly the same χ2. The lower corresponds to cgg contributing to gg→h amplitude approximately twice as much as SM top loop but with opposite sign

- There are also 2 other mirror islands at cγγ≈-0.016

2-parameter fits: loop inspired



Assume Higgs couples to new scalars or fermions

$$\mathcal{L} = -c_s \frac{2m_s^2}{v} h S^\dagger S - c_f \frac{m_f}{v} h \bar{f} f$$

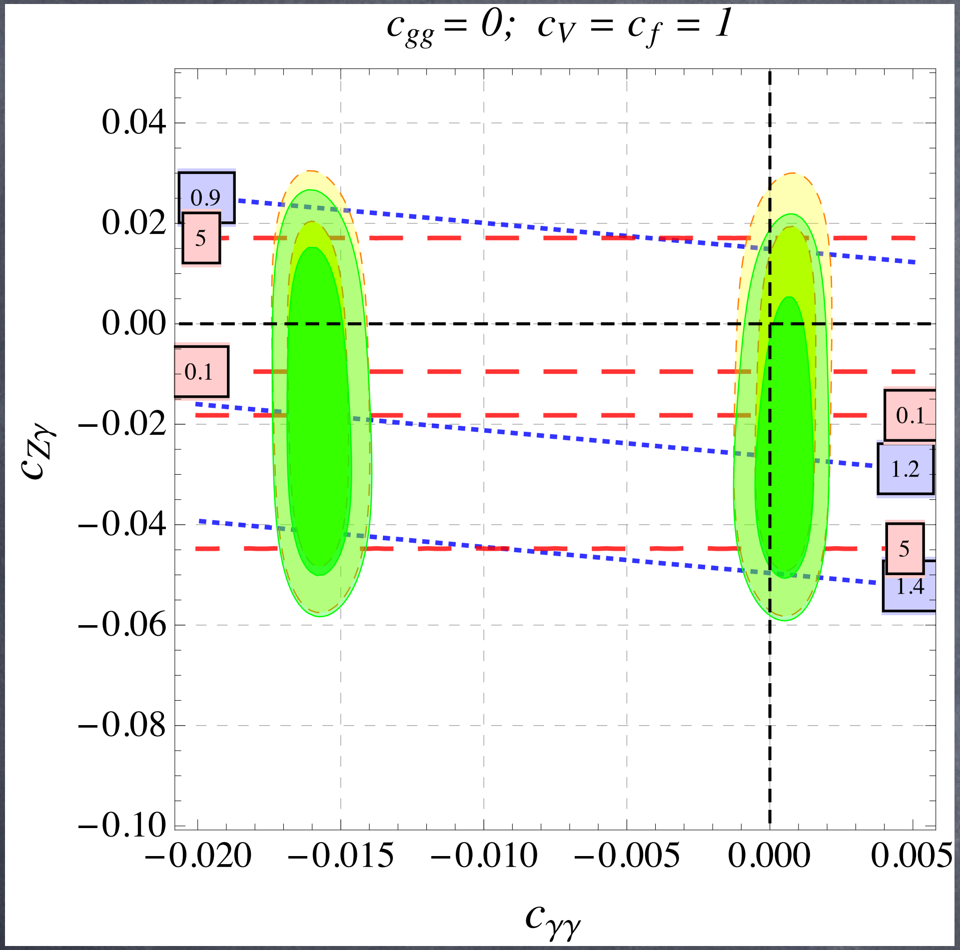
Heavy scalar or fermion in color representation r and charge Q contributes to eff. Lagrangian as

$$\delta c_{gg} = \frac{\alpha_s}{\pi}\left(\frac{2}{3} c_f C_2(r_f) + \frac{1}{6} c_s C_2(r_s)\right)$$

$$\delta c_{\gamma\gamma} = -\frac{\alpha_s}{\pi}\left(\frac{2}{3} c_f Q_f^2 d(r_f) + \frac{1}{6} c_s Q_s^2 d(r_s)\right)$$

For fundamental color representation (quark)
$C_2=1/2$ and d=3

2-parameter fits: loop inspired



- For colorless new physics, parametrization in the cγγ-cZγ plane relevant

- Currently, constraints on cZγ from Higgs and EWPT competitive

- Zγ rate can be enhance by factor of ~5 without conflict with EWPT

- Large cZγ means large cWW and cZZ ⇒ enhancement of VH production by 50% possible

Composite Higgs

Slides in this subsection stolen from Francesco Riva

Minimal Composite Higgs Model

Like QCD: (techni)quarks, strong dynamics, global symmetry

New "quarks"

M_{PL}

Hierarchy

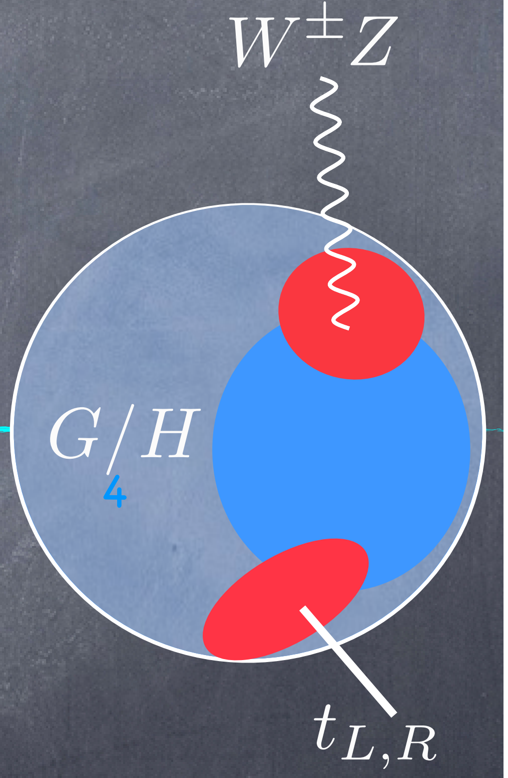
Global symmetry
$G = SO(5)$ 10

dynamically generated

f=TeV

Composite states
(incl. scalars)

$H = SO(4)$ 6

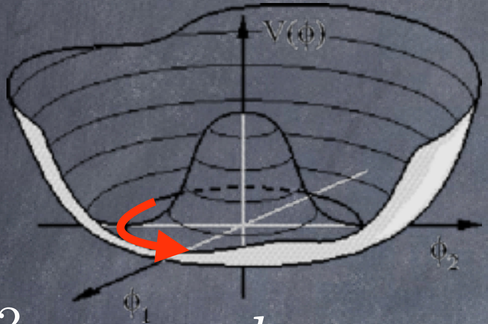


4 naturally light
composite PseudoGoldstone bosons = Higgs doublet

Kaplan,Georgi,Dimopoulos,Dugan,Galison '84; Agashe,Contino,DaRold,Pomarol '05 -'07

NGBHiggs couplings to SM fields

Higgs = Goldstone Boson of SO(5)/SO(4)



described by angular variable $\sin\frac{h}{f}$

$$\frac{g^2}{4}f^2\sin^2\frac{h}{f}W_\mu W^\mu \overset{h\to\langle h\rangle+h}{=} \frac{g^2}{4}\overbrace{f^2\sin^2\frac{\langle h\rangle}{f}}^{v^2}W_\mu W^\mu + \frac{g^2}{2}f\sin\frac{\langle h\rangle}{f}\sqrt{1-\sin^2\frac{\langle h\rangle}{f}}\,hW_\mu W^\mu+..$$

$$c_V=\sqrt{1-\frac{v^2}{f^2}}$$

Coupling to W and
model independent

$$c_f=\frac{1+2m-(1+2m+n)v^2/f^2}{\sqrt{1-v^2/f^2}}$$

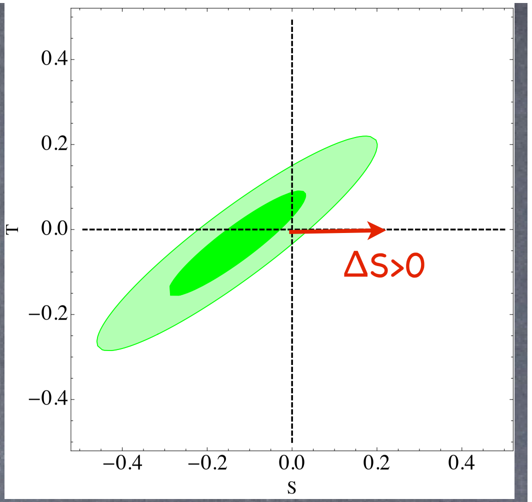
Coupling to fermions
model dependent $m_t\sim\sin^{2m+1}\left(\frac{h}{f}\right)\cos^n\left(\frac{h}{f}\right)$

Pomarol,Riva,'12

Composite Higgs and EWPT

Integrating out composite resonances produces a shift of S

$$\Delta S = 8\pi v^2/m_\rho^2 \qquad m_\rho \approx 0.8\tilde{g}f$$

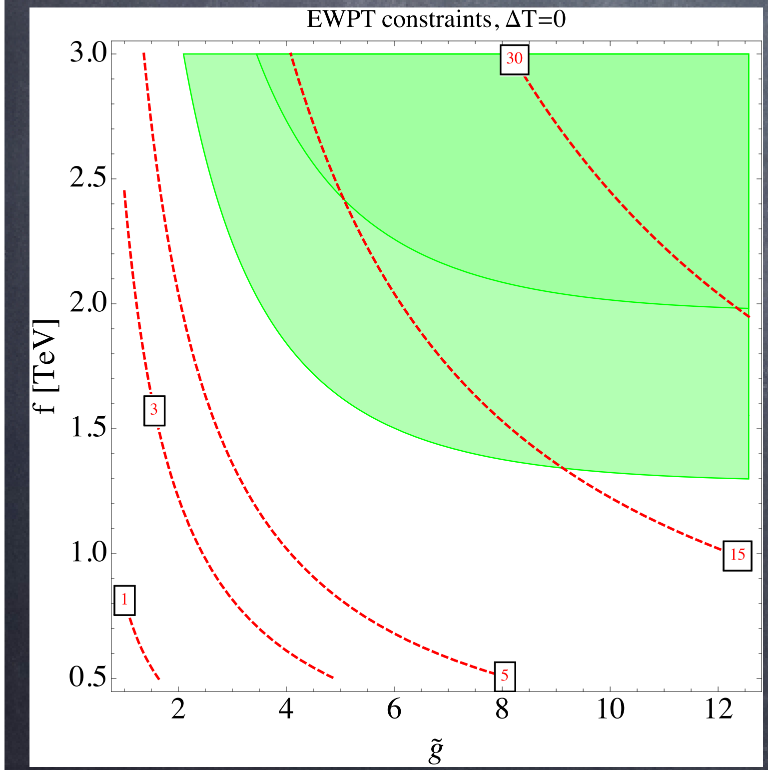


Also, a shift of S and T due to cV<1

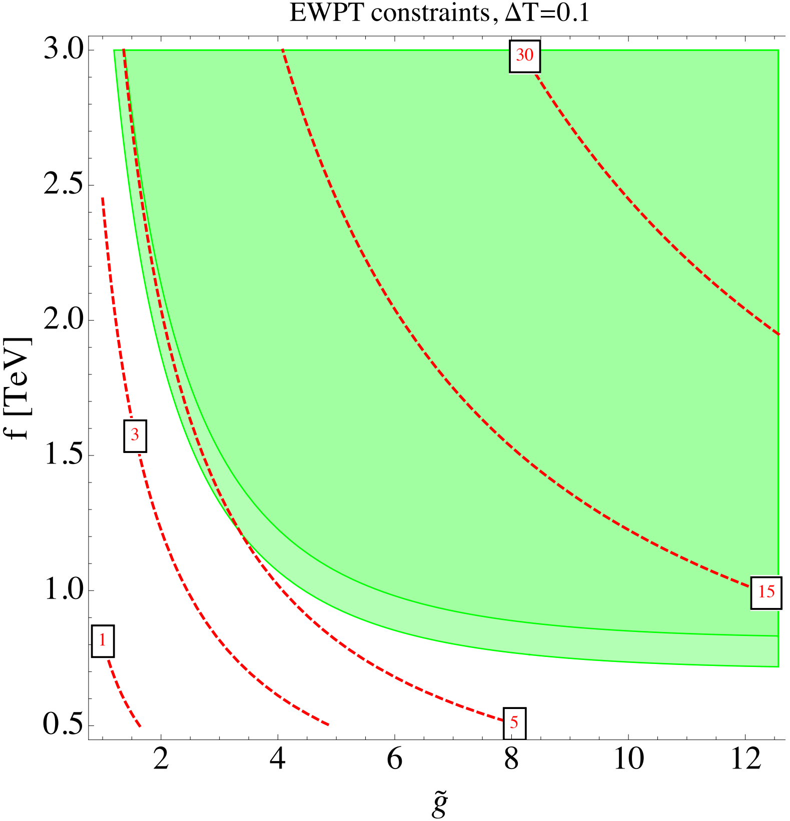
$$\Delta T \approx -\frac{3(g_L^2+g_Y^2)}{8\pi g_L^2}\frac{v^2}{f^2}\log(m_\rho/m_Z)\,,$$

$$\Delta S \approx \frac{1}{6\pi}\frac{v^2}{f^2}\log(m_\rho/m_Z)$$

But there can be other corrections to S and T, e.g. from heavy fermions...



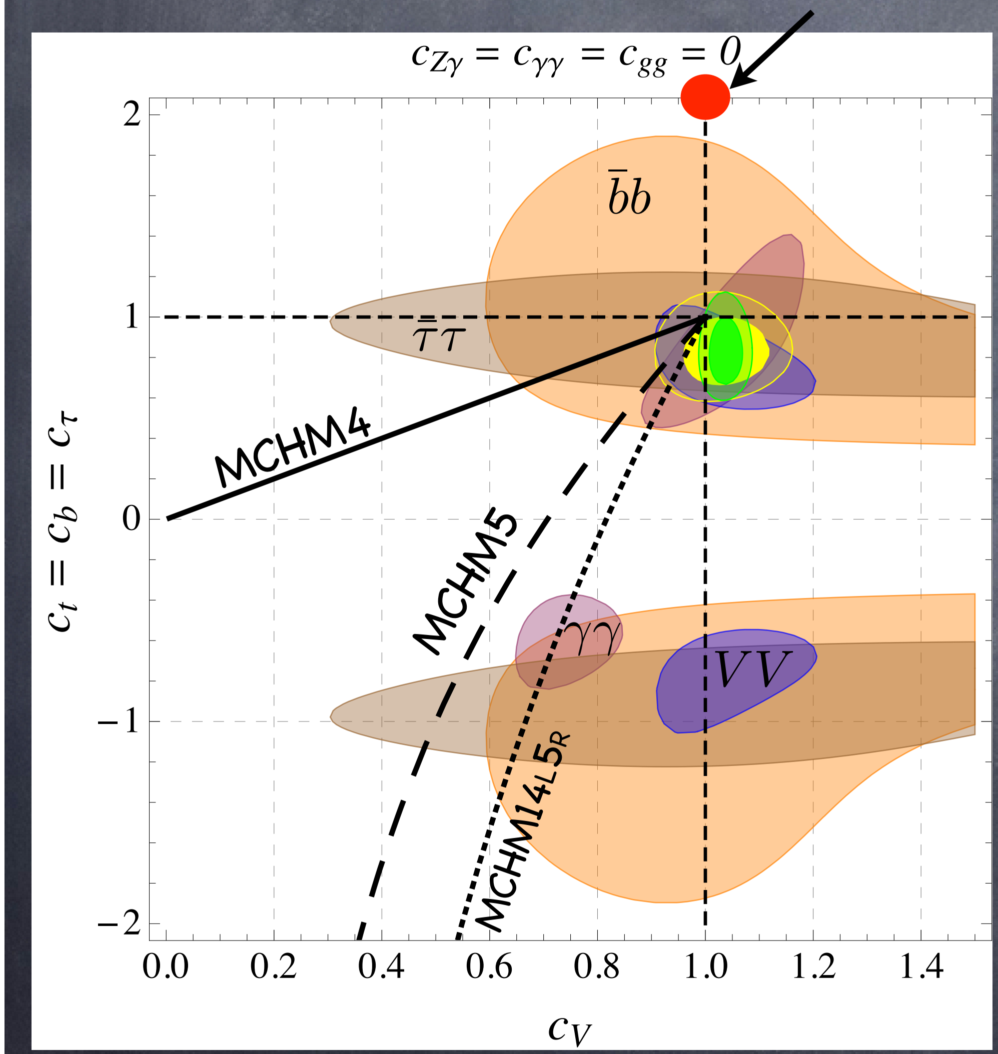
f>1.3 TeV (less than 5% corrections to Higgs rates)

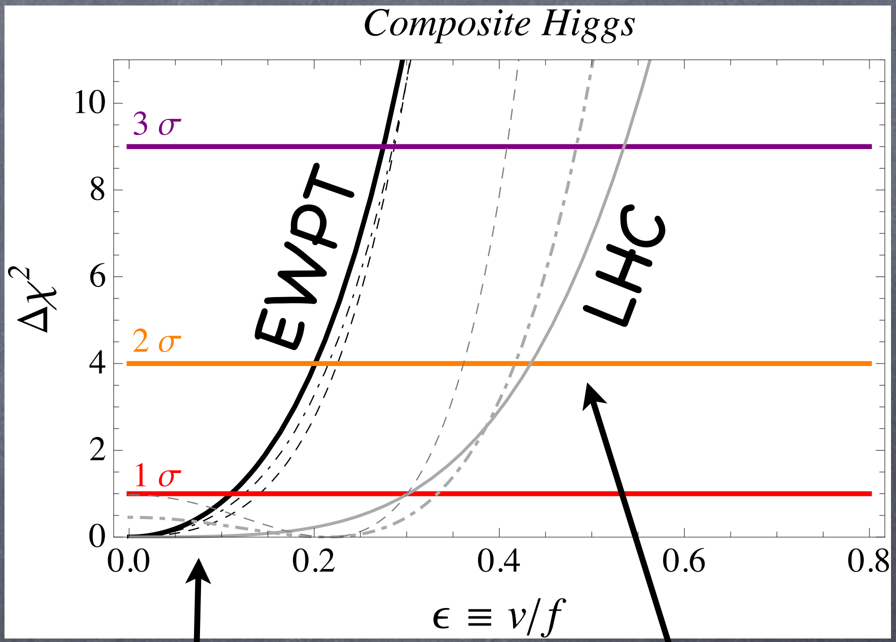


with ΔT~0.1, f below TeV allowed (>10% corrections)

NGBHiggs couplings to SM fields

$m \neq 0$ excluded





Strong sector contributions can weaken this bound

(not this)

2HDM

Slides in this subsection stolen from Francesco Riva

Two Higgs Doublets Models

heavy Higgs ⟷ modified Higgs couplings

$$m_h^2 \approx m_Z^2 + 16\delta_\lambda v^2$$

$$125^2\mathrm{GeV}^2 = 91^2\mathrm{GeV}^2 + 86^2\mathrm{GeV}^2$$

Need ~~SUSY~~ contributions to V(h,H

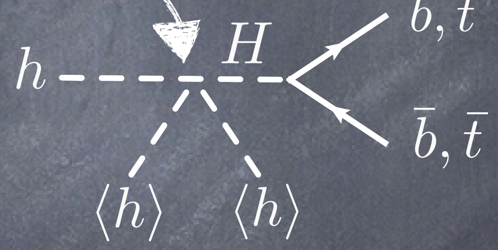
(Heavy stops,D-terms,F-terms,...)

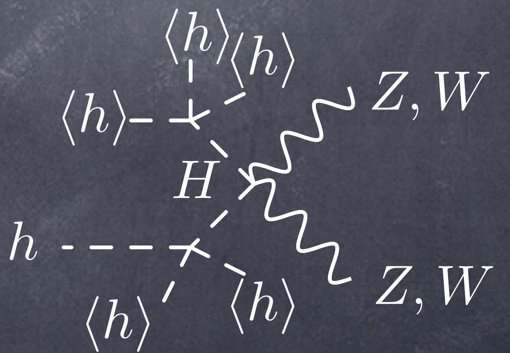
$$\Delta V = \delta_\lambda h^4 + \delta h^3 H + \ldots$$

$$\frac{y_b}{y_b^{SM}} = 1 - 4\delta \tan\tilde{\beta}\,\frac{v^2}{m_H^2}$$

$$\frac{y_t}{y_t^{SM}} = 1 + 4\delta \cot\tilde{\beta}\,\frac{v^2}{m_H^2}$$

$$\Delta c_V \sim \frac{v^4}{m_H^4} \sim 0$$





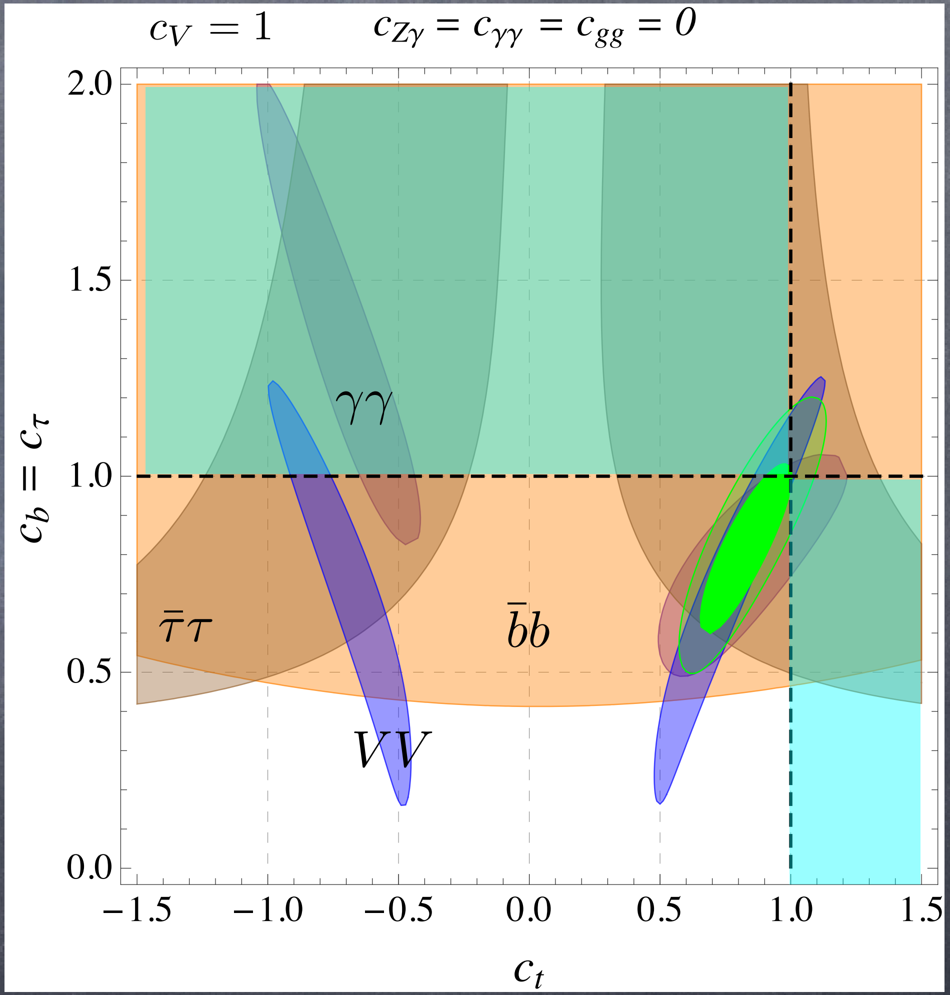
Blum,D'Agnolo,Fan'12; Azatov,Chang,Craig,Galloway'12
Montull,Gupta, Riva, '12

*Ignoring loop effects that couple b and Hu (Gupta,Rzehak,Wells'12)

Two Higgs Doublets Models

$$m_h^2 \approx m_Z^2 + 16\delta_\lambda v^2$$

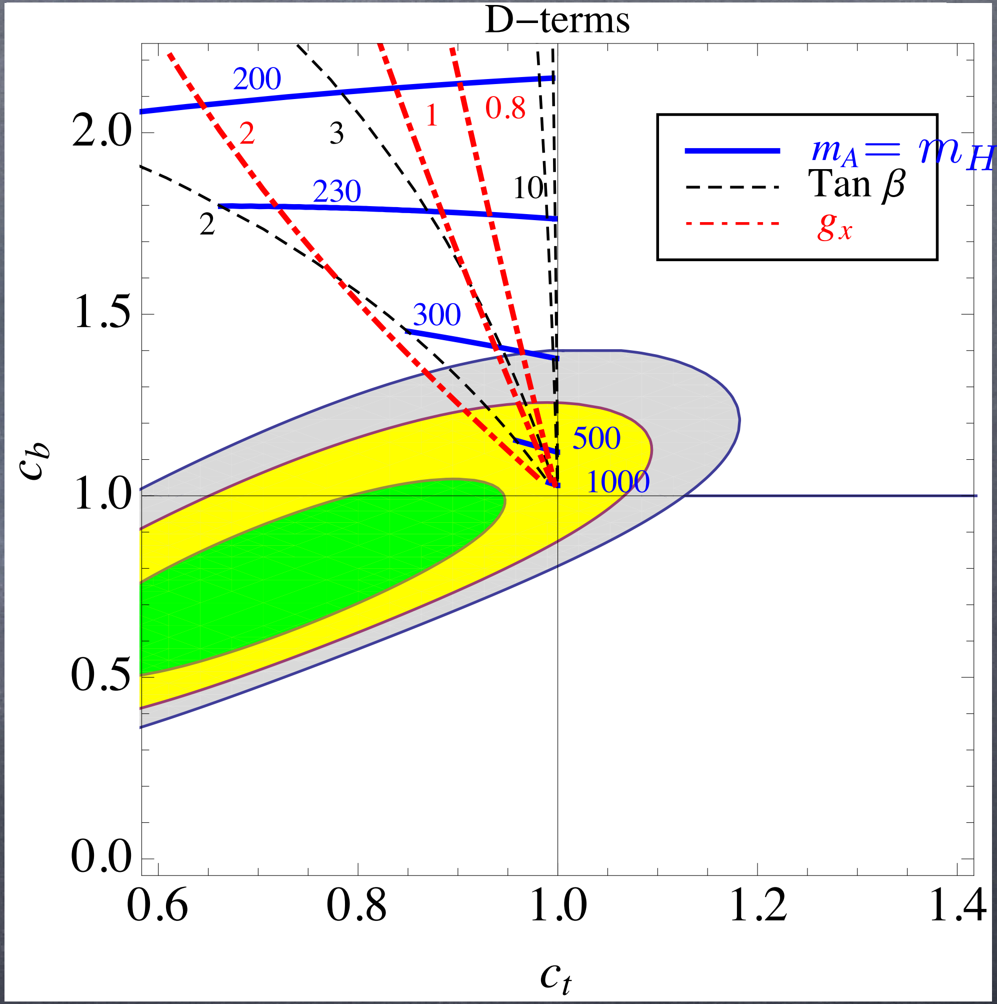
$$\boxed{\begin{aligned} \frac{y_b}{y_b^{SM}} &= 1 - 4\delta \tan\tilde{\beta}\,\frac{v^2}{m_H^2} \\ \frac{y_t}{y_t^{SM}} &= 1 + 4\delta \cot\tilde{\beta}\,\frac{v^2}{m_H^2} \end{aligned}}$$



Two Higgs Doublets Models, SUSY

$$m_h^2 \approx m_Z^2 + 16\delta_\lambda v^2$$

$$\boxed{\begin{aligned} \frac{y_b}{y_b^{SM}} &= 1 - 4\delta \tan\tilde{\beta}\,\frac{v^2}{m_H^2} \\ \frac{y_t}{y_t^{SM}} &= 1 + 4\delta \cot\tilde{\beta}\,\frac{v^2}{m_H^2} \end{aligned}}$$



D-Terms: $\Delta V = \kappa\left(|H_1^0|^2 - |H_2^0|^2\right)^2$

$$\delta = -\frac{m_h^2}{2v^2}\frac{t_\beta}{t_\beta^2 - 1}$$

Two Higgs Doublets Models, SUSY

$$m_h^2 \approx m_Z^2 + 16\delta_\lambda v^2$$

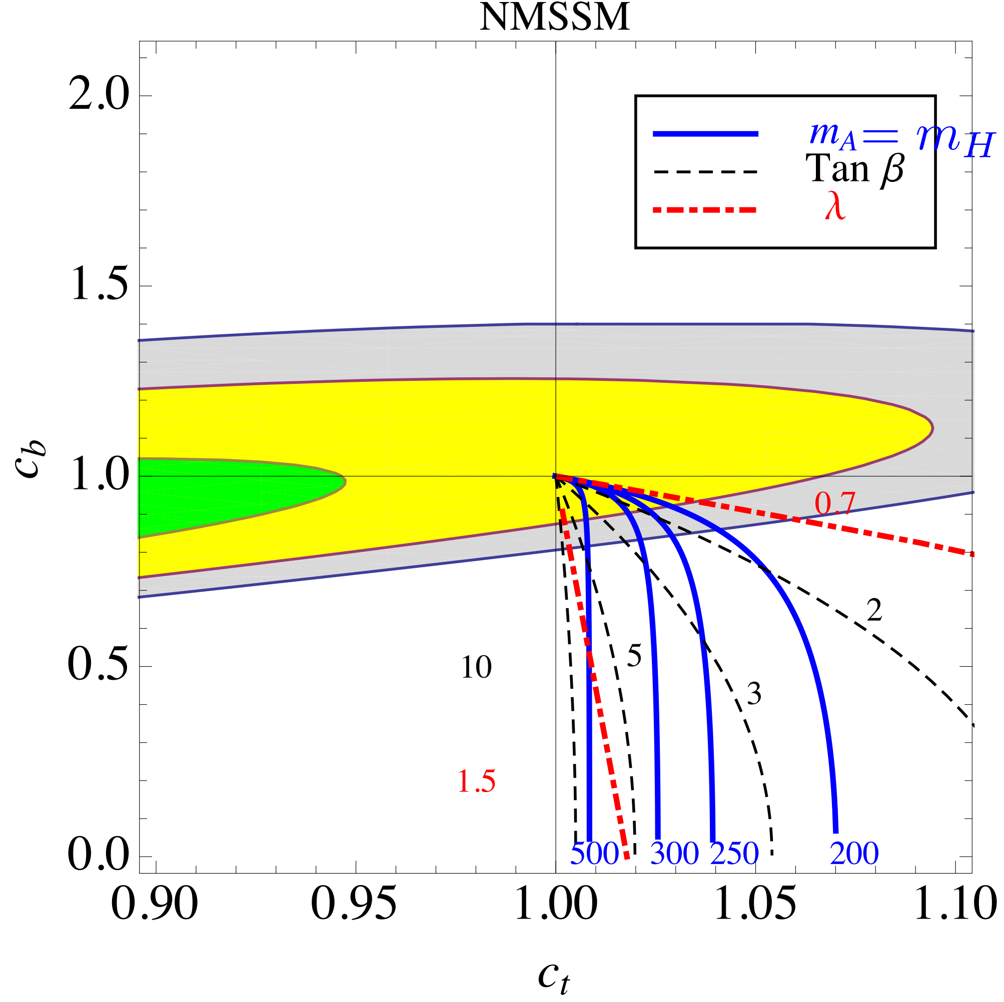
$$\boxed{\begin{aligned}\frac{y_b}{y_b^{SM}} &= 1 - 4\delta \tan\tilde{\beta}\,\frac{v^2}{m_H^2}\\ \frac{y_t}{y_t^{SM}} &= 1 + 4\delta \cot\tilde{\beta}\,\frac{v^2}{m_H^2}\end{aligned}}$$

F-Terms (no mixing):

$$\Delta V = -\lambda_S^2 (H_1 H_2)^2 \frac{m_S}{M_S}$$

$$\Delta c_b \approx -t_\beta^2 (60\text{GeV}/m_H)^2$$

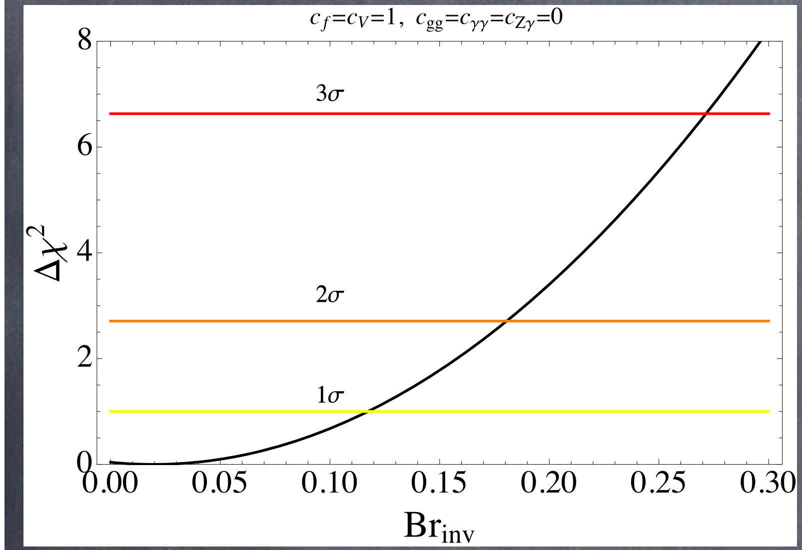
$$\Delta c_t \approx (60\text{GeV}/m_H)^2$$

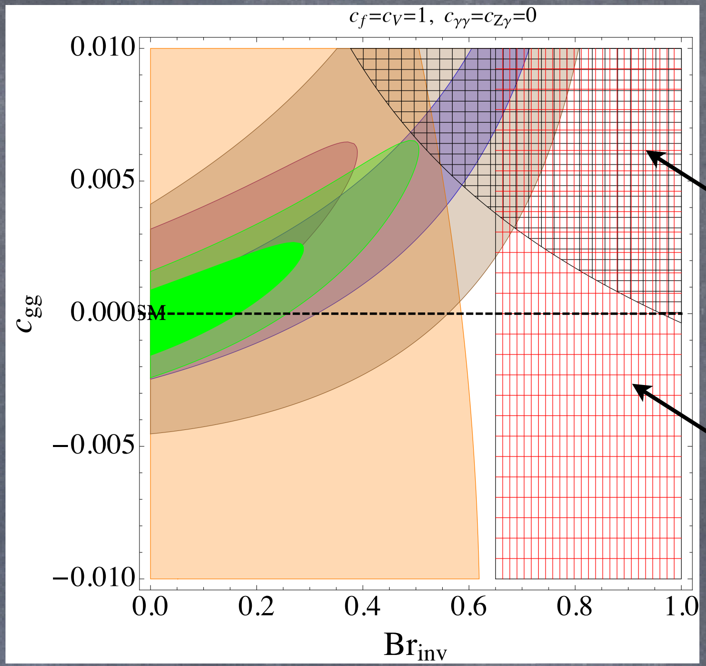


Higgs Portal

2 parameter fits: invisible width allowed

Higgs-portal inspired new physics





Excluded by monojet searches in CMS and ATLAS Djouadi et al. 1205.3169

Excluded by ATLAS ZH→invisible search

- If all couplings at SM value, invisible branching fraction larger than 18% disfavored at 95% CL
- Allowing invisible width and simultaneously new contributions to Higgs couplings to gluons gives more wiggle room
- For the sake of the fit, “invisible branching fraction” could be “branching fraction into anything that LHC is currently insensitive to”, for example h->4j
- But for truly invisible width, monojet searches and ATLAS LEP-like search place non-trivial bounds on this parameter space!

To Take Away

- Higgs!!!
- Effective Theory!!!
- Measuring inclusive and exclusive Higgs rates in many channels allowed us to constrain some leading order coefficients of the effective theory operators
- Thanks to EW precision observables subleading operators also constrained
- Awfully good agreement with the SM so far
- Robust constraints on some Higgs couplings, especially the couplings to the W and Z bosons
- More updates coming ($h \to bb$, tth, exotic channels) but the basic picture unlikely to change during before 2015
- Looking at differential distributions of Higgs decay products one can probe 2-derivative operators in the effective theory

Backup

If there's time, but there never is

Effective Higgs Lagrangian

GOING FURTHER

- Higgs rates are degenerate between p^2 and p^4 coefficients. For example, increased H→ZZ rate can be obtained by increasing cV or cZZ or κZ

- But differential distributions of Higgs decay products in ZZ, WW and Zγ channels will be different

$$\mathcal{L}_{p^2}^{(1)} = \frac{h}{v}\left\{ c_V 2m_W^2\, W_\mu^+ W_\mu^- + c_V m_Z^2\, Z_\mu Z_\mu + \sum_{q=u,d,l}\sum_{i=1\ldots3} c_q m_{q_i} \bar{q}_i q_i \right\}$$

$$\begin{aligned}\mathcal{L}_{p^4}^{(1)} = \frac{h}{v}\frac{\alpha}{\pi}\Big\{ & \frac{c_{gg}}{12} G_{\mu\nu}^a G_{\mu\nu}^a + c_{\gamma\gamma}\, A_{\mu\nu}A_{\mu\nu} + 2c_{Z\gamma}\, Z_{\mu\nu}A_{\mu\nu} \\ & +2\left(c_{\gamma\gamma} + \frac{g_L}{g_Y} c_{Z\gamma}\right) W_{\mu\nu}^+ W_{\mu\nu}^- + \left(c_{\gamma\gamma} + \frac{g_L^2 - g_Y^2}{g_L g_Y} c_{Z\gamma}\right) Z_{\mu\nu} Z_{\mu\nu} \\ & +\kappa_V (W_\mu^+ \partial_\nu W_{\mu\nu}^- + \text{h.c.}) + \kappa_V Z_\mu \partial_\nu Z_{\mu\nu} + \frac{g_L}{g_Y}\kappa_V Z_\mu \partial_\nu \gamma_{\mu\nu} \Big\} + \ldots\end{aligned}$$

Higher order operators in h→ZZ→4l

In progress with A.Azatov,C.Grojean,E. Kuflik, T.Volansky; see also Chen et al 1211.1959

General amplitude:

Cao et al. 1001.3396

$$\mathcal{M}[h \to Z_\mu(k_1)Z_\nu(k_2)] = \frac{1}{v}\left(2m_{V_1}^2 F_0^{ZZ}\eta_{\mu\nu} + F^{ZZ}\left(k_\nu^1 k_\mu^2 - \eta_{\mu\nu}k_1\cdot k_2\right) + \tilde{F}^{ZZ}\epsilon_{\mu\nu\alpha\beta}k_1^\alpha k_2^\beta\right)$$

SM: $F_0^{ZZ} \approx 1$ $F^{ZZ} = \mathcal{O}(\alpha_2/4\pi)$ $\tilde{F}^{ZZ} \approx 0$

Not considered in any analysis so far

Effective BSM operators: $\mathcal{L}_{\mathrm{BSM,eff}} = \frac{h}{v}\left(\delta c_V m_Z^2 Z_\mu^2 + \frac{c_{ZZ}}{4}Z_{\mu\nu}^2 + \frac{\tilde{c}_{ZZ}}{4}Z_{\mu\nu}\tilde{Z}_{\mu\nu} - \kappa_{ZZ}Z_\mu\partial_\nu Z_{\mu\nu}\right)$

One might also include effective Zγ operators but here assuming they'll be constrained by Zγ rate anytime soon

Contribution to form factors:

$$F_0^{ZZ} = c_V - \kappa_{ZZ}\frac{k_1^2+k_2^2}{2m_Z^2}$$

$$F^{ZZ} = c_{ZZ}$$

$$\tilde{F}^{ZZ} = \tilde{c}_{ZZ}$$

CMS analysis discriminates between: $\kappa_{ZZ} = c_{ZZ} = \tilde{c}_{ZZ} = 0$ and $c_V = \kappa_{ZZ} = c_{ZZ} = 0$

"scalar" "pseudoscalar"

Higher order operators in h→ZZ→4l

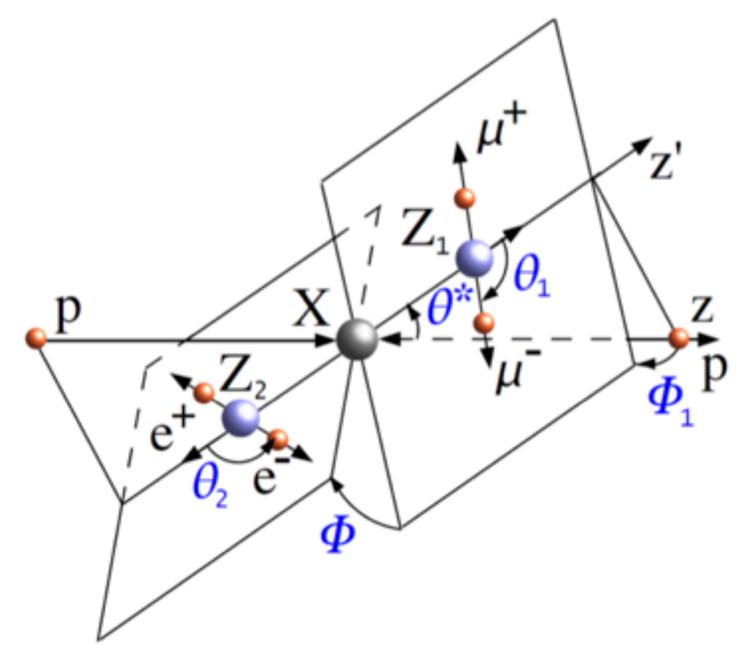
Total width in this channel:

$$\Gamma_{h\to ZZ^*} \approx \left(3.1(F_0^{ZZ})^2 - 0.77 F_0^{ZZ} F^{ZZ} + 0.065(F^{ZZ})^2 + 0.026(\tilde{F}^{ZZ})^2\right) \mathrm{keV}$$

But, weak dependence on higher dim operators, and degeneracy with cg...

A better approach to constraining the 2-derivative couplings:

- Lowest order 0-derivative operator leads to larger coupling of Higgs to longitudinal polarizations
- Higher order 2-derivative operators lead to larger coupling of Higgs to transverse polarizations
- By looking at the angular distributions of the leptons from Z decay one can measure the relative fraction of transverse and longitudinal polarizations in Z decay, and thus constrain higher-dimensional operators



Higher order operators in h→ZZ→4l

Complicated functions of m*

$$\frac{d\Gamma}{dm_*\, d\cos\theta_1\, d\cos\theta_2} \sim f_T(m_*)\left[\left(4m_Z^2F_0^{ZZ}-(m_h^2-m_Z^2-m_*^2)F^{ZZ}\right)^2+\left((m_h^2-m_Z^2+m_*^2)^2-4m_Z^2m_*^2\right)\left(\tilde{F}^{ZZ}\right)^2\right] * \left[\left(1+\cos\theta_1^2\right)\left(1+\cos\theta_2^2\right)\right]$$
$$+f_L(m_*)\left[(m_h^2-m_Z^2-m_*^2)F_0^{ZZ}-m_*^2F^{ZZ}\right]^2\left[\sin^2\theta_1\sin^2\theta_2\right]$$

Differential distributions (in approximation of one on-shell Z):

m* - invariant mass of off-shell Z
θ1,2 - polar angle between other Z direction and l- in the rest frame of Z

other angles φ, φ*, θ* irrelevant