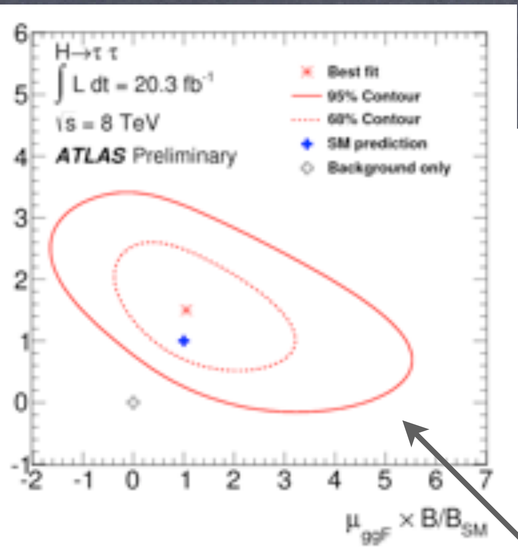
Adam Falkowski

Constraints on new physics from Higgs data

Puri, 13 December 2013

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

Higgs: the story so far



ATLAS			
Production	Decay	$\hat{\mu}$	Ref.
2D	$\gamma\gamma$	$1.55^{+0.33}_{-0.29}$	[5, 6]
	ZZ	$1.41^{+0.42}_{-0.33}$	[5, 7]
	WW	$0.98^{+0.33}_{-0.26}$	[5, 8]
	$\tau\tau$	$1.4^{+0.4}_{-0.5}$	[9]
VH	bb	$0.2^{+0.7}_{-0.6}$	[10]
ttH	bb	2.69 ± 5.53	[11]
	$\gamma\gamma$	-1.39 ± 3.18	[12]
inclusive	$Z\gamma$	2.96 ± 6.69	[13]
	$\mu\mu$	1.75 ± 4.26	[14]

CMS			
Production	Decay	$\hat{\mu}$	Ref.
2D	$\gamma\gamma$	$0.77^{+0.29}_{-0.26}$	[15]
	ZZ	$0.92^{+0.29}_{-0.24}$	[16]
	WW	$0.68^{+0.21}_{-0.19}$	[16]
	$\tau\tau$	0.87 ± 0.29	[17]
VH	bb	1.00 ± 0.49	[18]
VBF	bb	0.7 ± 1.4	[19]
ttH	bb	$1.0^{+1.9}_{-2.0}$	[20]
	$\gamma\gamma$	$-0.2^{+2.4}_{-1.9}$	[20]
	$\tau\tau$	$-1.4^{+6.3}_{-5.5}$	[20]
	multi-ℓ	$3.7^{+1.6}_{-1.4}$	[21]
inclusive	$Z\gamma$	-0.21 ± 4.86	[22]
	$\mu\mu$	$2.9^{+2.8}_{-2.7}$	[23]

How we interpret that

Effective Higgs Lagrangian

- Starting with SM + dimension 6 operators effective Lagrangian → For details see Eduard Masso's talk
- Ignoring 2-fermion vertex and dipole operators (most of them strongly constrained by precision measurements)
- Ignoring CP-violating operators (no interference in inclusive observables so effects expected smaller)
- Require no tree-level and no power divergent 1-loop corrections to electroweak precision observables

Simplified Effective Higgs Lagrangian

$$\mathcal{L}_{h,\text{sim}} = \frac{h}{v}\Big(\quad 2c_V m_W^2 W_\mu^+ W_\mu^- + c_V m_Z^2 Z_\mu Z_\mu$$

$$-c_u \sum_{q=u,c,t} m_q \bar{q} q - c_d \sum_{q=d,s,b} m_q \bar{q} q - c_l \sum_{l=e,\mu\tau} m_l \bar{l} l$$

$$+\frac{1}{4} c_{gg} G_{\mu\nu}^a G_{\mu\nu}^a - \frac{1}{4} c_{\gamma\gamma} \gamma_{\mu\nu} \gamma_{\mu\nu}$$

$$-\frac{1}{2} c_{WW} W_{\mu\nu}^+ W_{\mu\nu}^- - \frac{1}{4} c_{ZZ} Z_{\mu\nu} Z_{\mu\nu} - \frac{1}{2} c_{Z\gamma} \gamma_{\mu\nu} Z_{\mu\nu} \Big)$$

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

- Simpler effective theory with 7 free parameters
- Limit of SM+SILH with constraints $\bar{c}_T = \bar{c}_6 = 0 \quad \bar{c}_{HW} + \bar{c}_{HB} = 0 \quad \bar{c}_B + \bar{c}_{HB} = 0$
- Standard Model limit: $c_V = c_f = 1$, $c_{gg} = c_{\gamma\gamma} = c_{Z\gamma} = 0$

Global 7-parameter fit to Higgs couplings

Global fits

- I fit couplings of the effective theory to available ATLAS, CMS, and Tevatron data and EW precision tests from LEP, SLC, Tevatron
- For EW precision observables, I assume vanishing contributions to EW observables from higher dimensional operators at threshold Λ=3TeV (only running effect from threshold to EW scale included)
- Starting with unconstrained 7 parameter, below I give central value and 68%CL range. Then I'm moving to constrained 2 parameter fits motivated by new physics models
- Ignoring systematic and theory errors. Assuming errors in different channels are Gaussian and uncorrelated (except for in EW precision tests)
- But taking into account 2D likelihoods in the GGF-VBF plane, whenever available

Some related work

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[28] E. Masso and V. Sanz, "Limits on Anomalous Couplings of the Higgs to Electroweak Gauge Bosons from LEP and LHC," Phys. Rev. D **87** (2013) 033001 [arXiv:1211.1320 [hep-ph]].

[29] A. Azatov and J. Galloway, "Electroweak Symmetry Breaking and the Higgs Boson: Confronting Theories at Colliders," arXiv:1212.1380 [hep-ph].

[30] G. Belanger, B. Dumont, U. Ellwanger, J. F. Gunion and S. Kraml, "Higgs Couplings at the End of 2012," JHEP **1302** (2013) 053 [arXiv:1212.5244 [hep-ph]].

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[32] A. Celis, V. Ilisie and A. Pich, "LHC constraints on two-Higgs doublet models," arXiv:1302.4022 [hep-ph].

[33] G. Belanger, B. Dumont, U. Ellwanger, J. F. Gunion and S. Kraml, "Status of invisible Higgs decays," arXiv:1302.5694 [hep-ph].

[34] A. Falkowski, F. Riva and A. Urbano, "Higgs At Last," arXiv:1303.1812 [hep-ph].

[35] J. Cao, P. Wan, J. M. Yang and J. Zhu, "The SM extension with color-octet scalars: diphoton enhancement and global fit of LHC Higgs data," arXiv:1303.2426 [hep-ph].

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[40] B. Dumont, S. Fichet and G. von Gersdorff, "A Bayesian view of the Higgs sector with higher dimensional operators," arXiv:1304.3369 [hep-ph].

[41] P. Bechtle, S. Heinemeyer, O. Stl, T. Stefaniak and G. Weiglein, "HiggsSignals: Confronting arbitrary Higgs sectors with measurements at the Tevatron and the LHC," arXiv:1305.1933 [hep-ph].

[42] G. Belanger, B. Dumont, U. Ellwanger, J. F. Gunion and S. Kraml, "Global fit to Higgs signal strengths and couplings and implications for extended Higgs sectors," arXiv:1306.2941 [hep-ph].

[6] D. Carmi, A. Falkowski, E. Kuflik and T. Volansky, "Interpreting LHC Higgs Results from Natural New Physics Perspective," JHEP **1207** (2012) 136 [arXiv:1202.3144 [hep-ph]].

[7] A. Azatov, R. Contino and J. Galloway, "Model-Independent Bounds on a Light Higgs," JHEP **1204** (2012) 127 [arXiv:1202.3415 [hep-ph]].

[8] J. R. Espinosa, C. Grojean, M. Muhlleitner and M. Trott, "Fingerprinting Higgs Suspects at the LHC," JHEP **1205** (2012) 097 [arXiv:1202.3697 [hep-ph]].

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7 parameter fit

$$c_V = 1.04^{+0.03}_{-0.03}$$

$$c_u = 1.29^{+0.25}_{-0.35}$$

$$c_d = 1.03^{+0.27}_{-0.17}$$

$$c_l = 1.10^{+0.18}_{-0.15}$$

$$c_{gg} = -0.0044^{+0.0049}_{-0.0037}$$

$$c_{\gamma\gamma} = 0.0014^{+0.0011}_{-0.0010}$$

$$c_{Z\gamma} = 0.004^{+0.016}_{-0.030}$$

Belusca-Maito, AA
arXiv: 1311.1113

Best fit and 68% CL range for parameters (warning, some errors very non-Gaussian)

Islands of good fit with negative cu, cd, cl ignored here

$\Delta\chi^2 = \chi^2_{SM} - \chi^2_{min} \approx 5.3$, with 7 d.o.f.
the SM hypothesis is a too perfect fit :-(((

7 parameter fit

$$c_V = 1.04^{+0.03}_{-0.03}$$

It couples to W and Z mass!!!

using only Higgs data: $c_V = 1.03^{+0.08}_{-0.08}$

$$c_u = 1.29^{+0.25}_{-0.35}$$

2σ hint it couples to up quarks

$$c_d = 1.03^{+0.27}_{-0.17}$$

It couples to down quarks!

$$c_l = 1.10^{+0.18}_{-0.15}$$

It couples to leptons!

$$c_{gg} = -0.0044^{+0.0049}_{-0.0037}$$

No sign of direct coupling to gluons (c.f. effective c_{gg}=0.012 in SM)

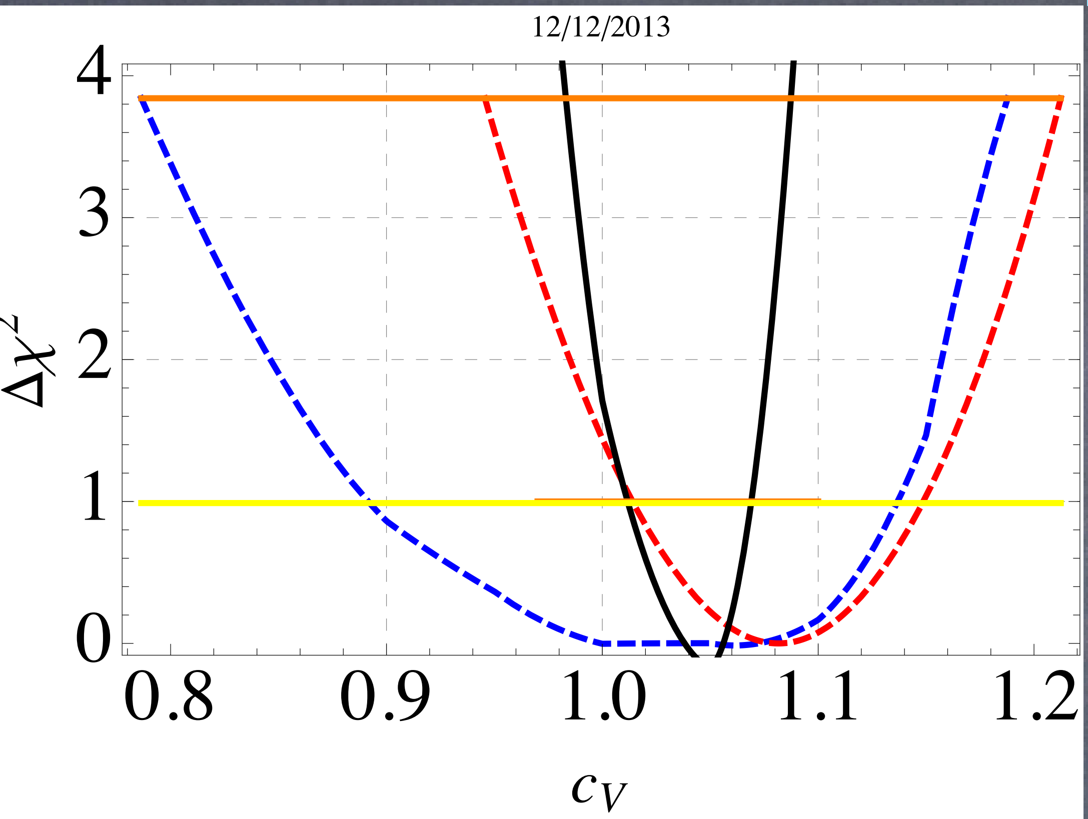
$$c_{\gamma\gamma} = 0.0014^{+0.0011}_{-0.0010}$$

Quite strong limit on coupling to photons (c.f. effective $c_{\gamma\gamma}$=0.0076 in SM)

$$c_{Z\gamma} = 0.004^{+0.016}_{-0.030}$$

Weak limit on coupling to Zγ due to weak experimental limits (c.f with effective $c_{Z\gamma}$=0.014 in SM)

7 parameter fit



Higgs data alone:

$c_V = 1.05^{+0.10}_{-0.15}$ $\quad 0.79 < c_V < 1.19 \quad$ @95% CL

EW data alone:

$c_V = 1.08^{+0.07}_{-0.07}$ $\quad 0.95 < c_V < 1.21 \quad$ @95% CL

Higgs+EW data:

$c_V = 1.04^{+0.03}_{-0.04}$ $\quad 0.98 < c_V < 1.09 \quad$ @95% CL

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

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7 parameter fit

Couplings to gluons and top probed by gluon fusion Higgs production mode

$$\frac{\sigma_{\rm ggF}}{\sigma_{\rm ggF}^{\rm SM}} = \frac{|\hat{c}_{gg}|^2}{|\hat{c}_{gg,\rm SM}|^2}$$

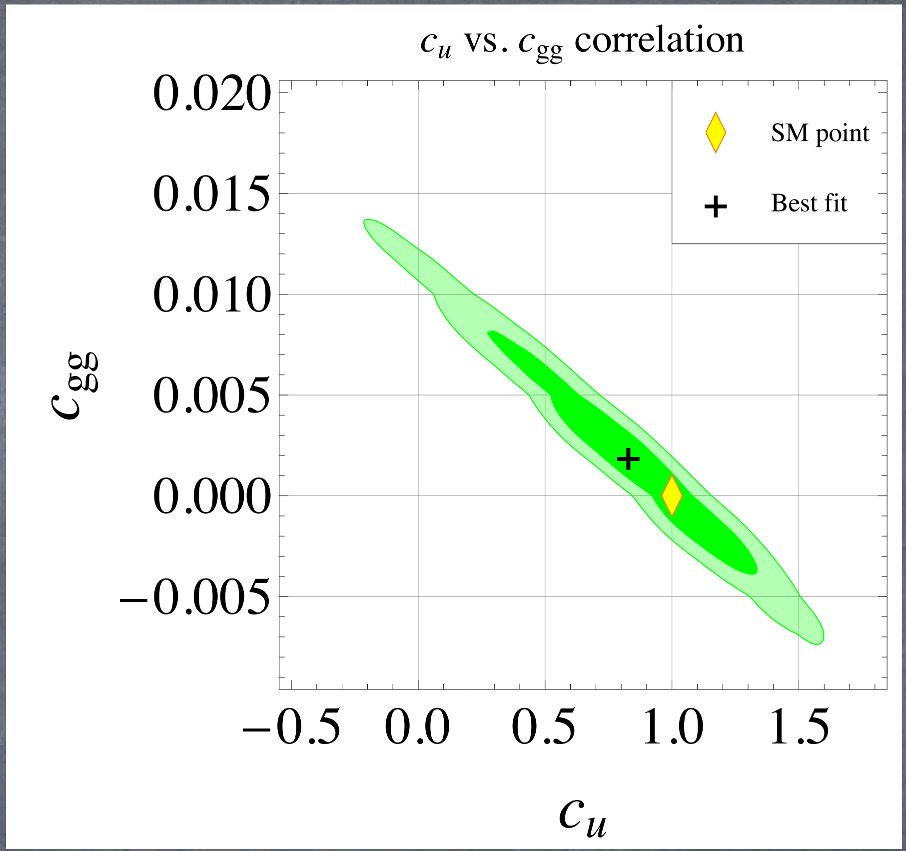
$$\hat{c}_{gg} \approx c_{gg} + 0.0128\, c_u$$

Constrained combination

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

Degeneracy between cgg and cu broken (slightly) by diphoton decays and by the tth production mode

$$\frac{\sigma_{\rm tth}}{\sigma_{\rm tth}^{\rm SM}} = |c_u|^2$$



ttH Channel	$\mu = \sigma/\sigma_{SM}$ ($m_H = 125.7$ GeV)
$\gamma\gamma$	$-0.2^{+2.4}_{-1.9}$
$b\bar{b}$	$+1.0^{+1.9}_{-2.0}$
$\tau\tau$	$-1.4^{+6.3}_{-5.5}$
4l	$-4.8^{+5.0}_{-1.2}$
3l	$+2.7^{+2.2}_{-1.8}$
Same-sign 2l	$+5.3^{+2.2}_{-1.8}$
Combined	$+2.5^{+1.0}_{-1.0}$

Current limits on tth production still weak

$$\frac{\sigma_{\rm tth}}{\sigma_{\rm tth}^{\rm SM}} = -0.4 \pm 2.7$$

ATLAS

Combined BB and γγ channels

$$\frac{\sigma_{\rm tth}}{\sigma_{\rm tth}^{\rm SM}} = 2.5 \pm 1.0$$

CMS

New CMS tth combo
HIG-12-035
HIG-13-015
HIG-13-019

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$$c_d = 1.03^{+0.27}_{-0.17}$$

It couples to down quarks! (actually, strongest constraints indirectly via total width)

$$c_l = 1.10^{+0.18}_{-0.15}$$

It couples to leptons!

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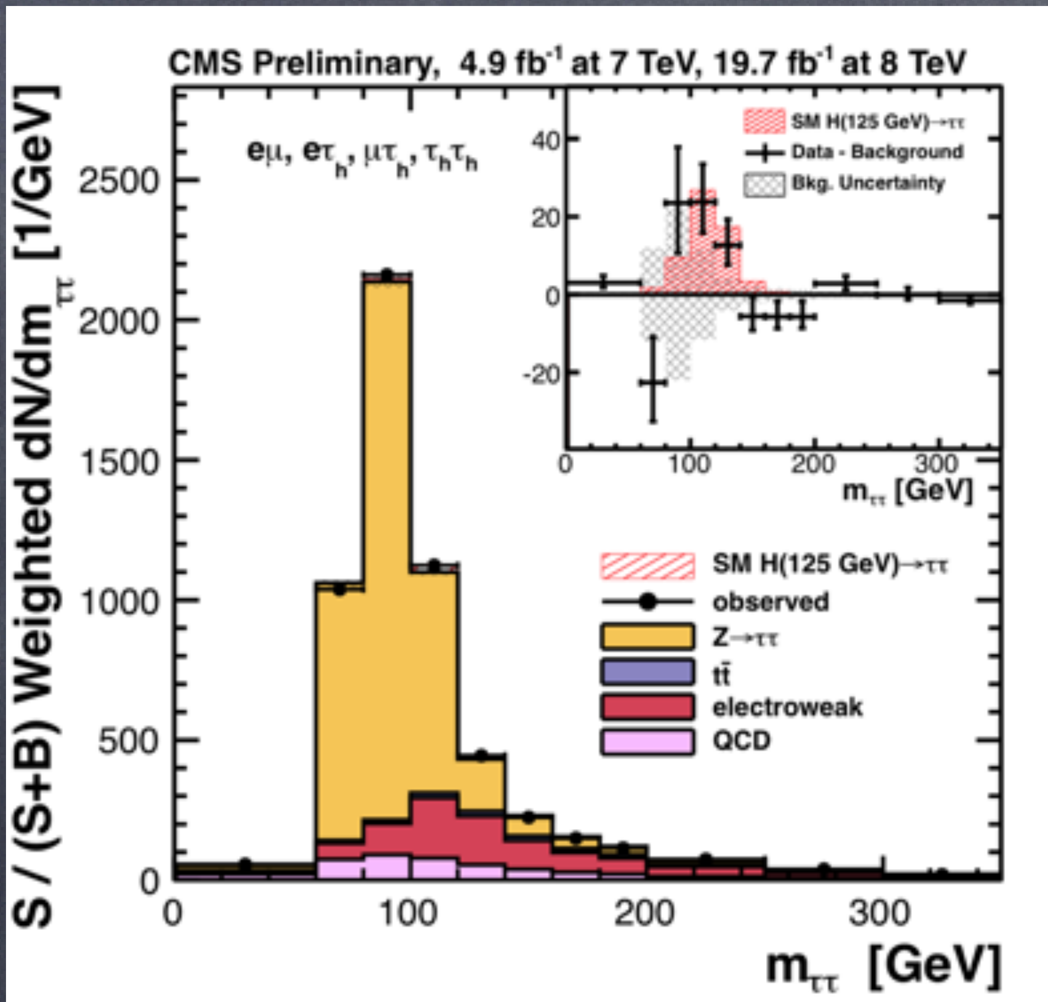
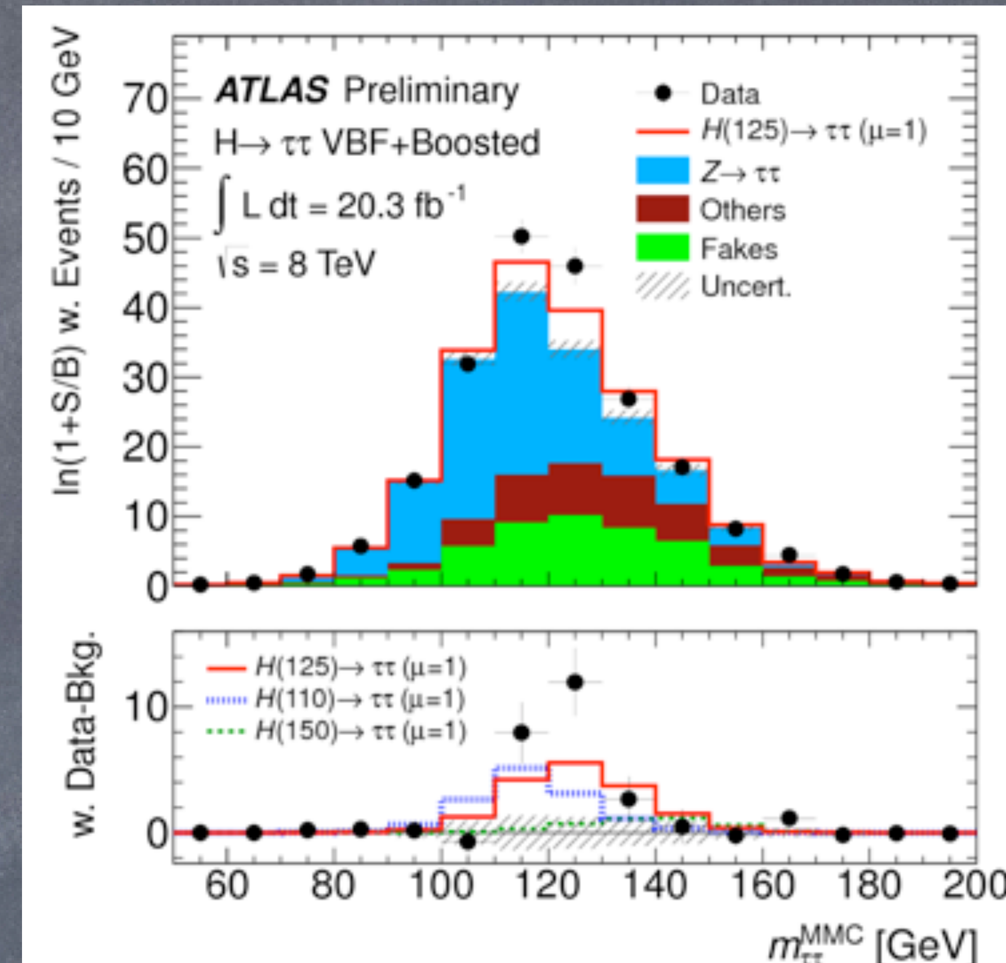
NEW! PROGRESS IN ττ CHANNEL



ττ

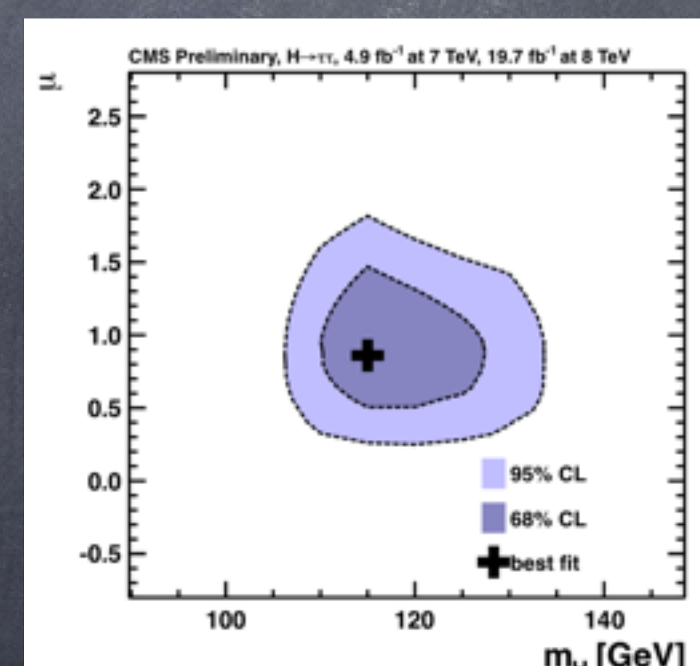


- Rate in good agreement with SM

$\mu = 0.87 \pm 0.29$

- Rate slightly larger than in SM

$\mu = 1.4{-}0.4{+}0.5$



Mass resolution much worse in this channel

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$$c_{\gamma\gamma} = 0.0014^{+0.0011}_{-0.0010}$$ Quite strong limit on coupling to photons (c.f. effective $c_{\gamma\gamma}$=0.0076 in SM)

$$c_{Z\gamma} = 0.004^{+0.016}_{-0.030}$$ Weak limit on coupling to Zγ due to weak experimental limits (c.f with effective $c_{Z\gamma}$=0.014 in SM)

What does it mean for generic new physics

Operator $$\frac{c}{\Lambda^2}\partial^\mu(H^\dagger H)\partial_\mu(H^\dagger H) \quad \Rightarrow \quad \delta c_V = -\frac{cv^2}{\Lambda^2}$$

95%CL Limit $$|\delta c_V| \lesssim 0.1 \quad \Rightarrow \quad \Lambda \gtrsim 800\text{GeV}\, c^{1/2}$$

Operator $$\frac{c\alpha_s}{16\pi\Lambda^2}H^\dagger H G^a_{\mu\nu}G^a_{\mu\nu} \quad \Rightarrow \quad \delta c_{gg} = -\frac{c\alpha_s v^2}{4\pi\Lambda^2}$$

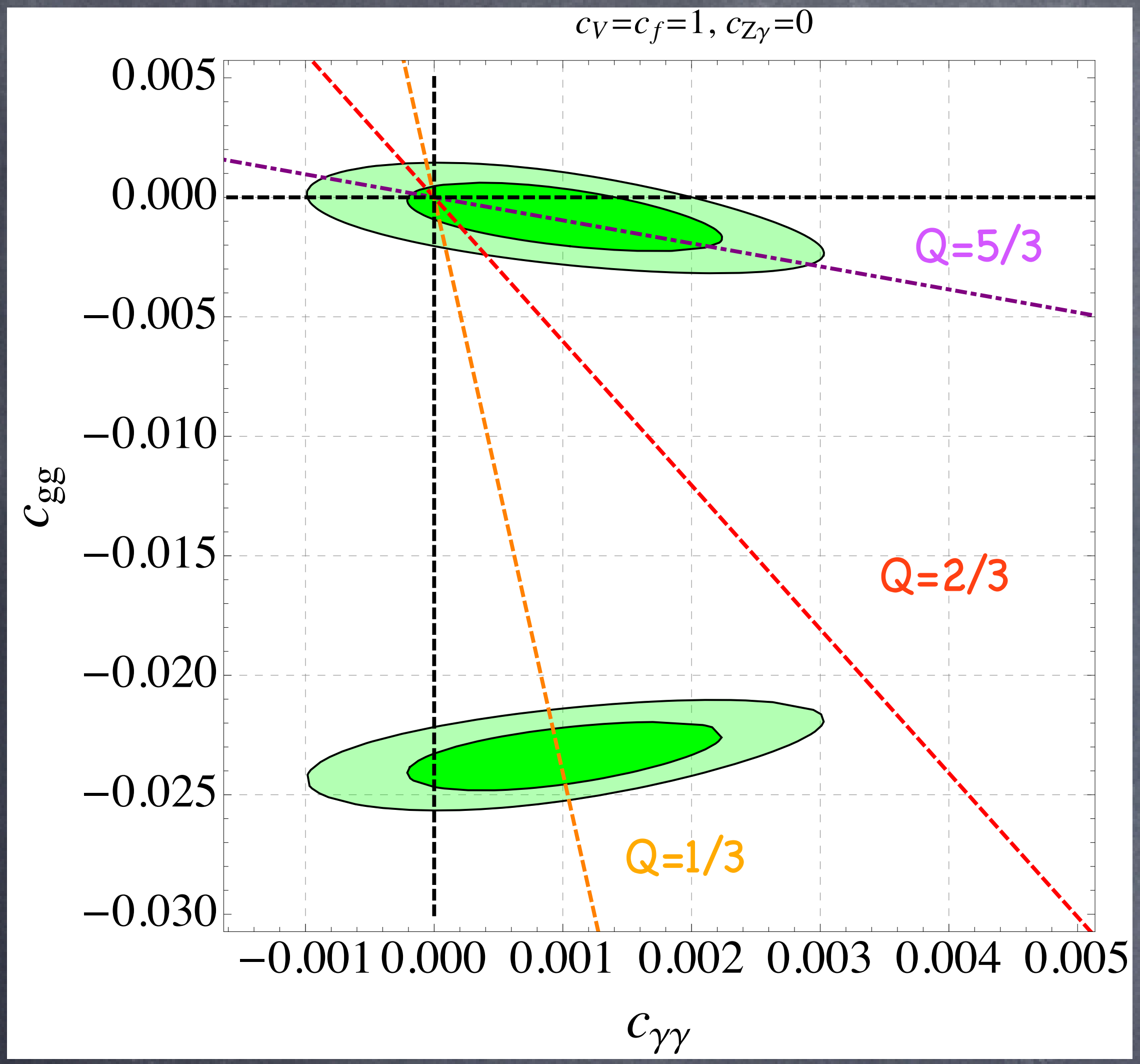
95%CL Limit $$|\delta c_{gg}| \lesssim 0.01 \quad \Rightarrow \quad \Lambda \gtrsim 250\text{GeV}\, c^{1/2}$$

and so on...

Model Dependent Limits

New physics in loops

2-parameter fits: loop inspired



Assume Higgs couples to new scalars or fermions

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

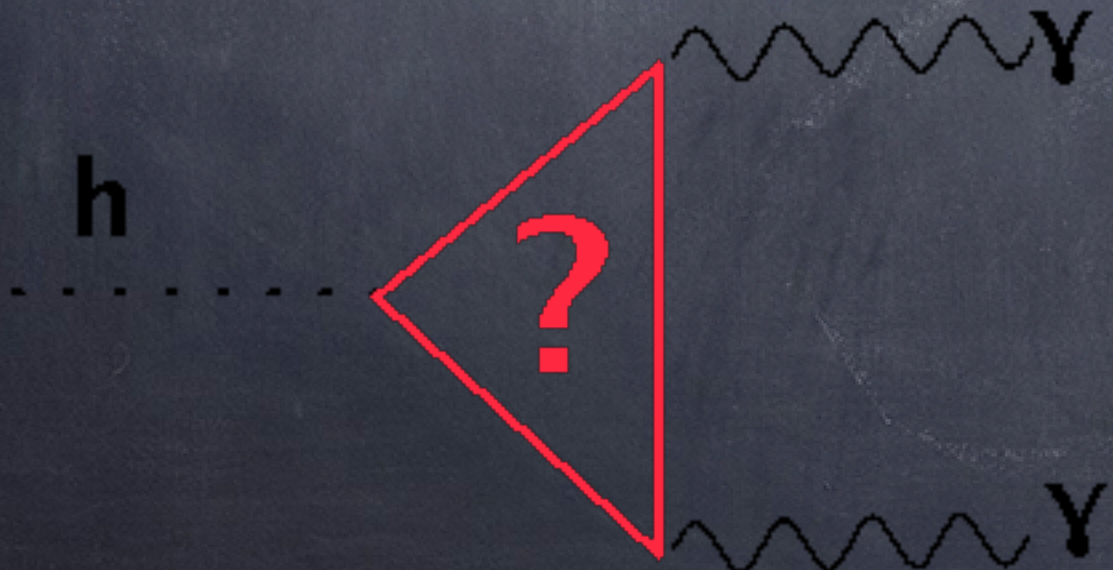
Heavy scalar or fermion in color representation r and charge Q contributes to eff. Lagrangian as

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

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

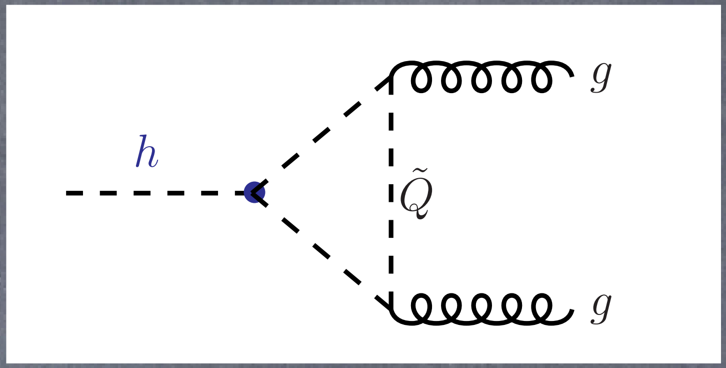
For fundamental color representation (quark)

C_2=1/2 and d=3



Supersymmetric top partners (stops)

- If 2 stops are light and there's no mixing between left and right-handed stops, lower limit on the mass from Higgs searches around 380 GeV

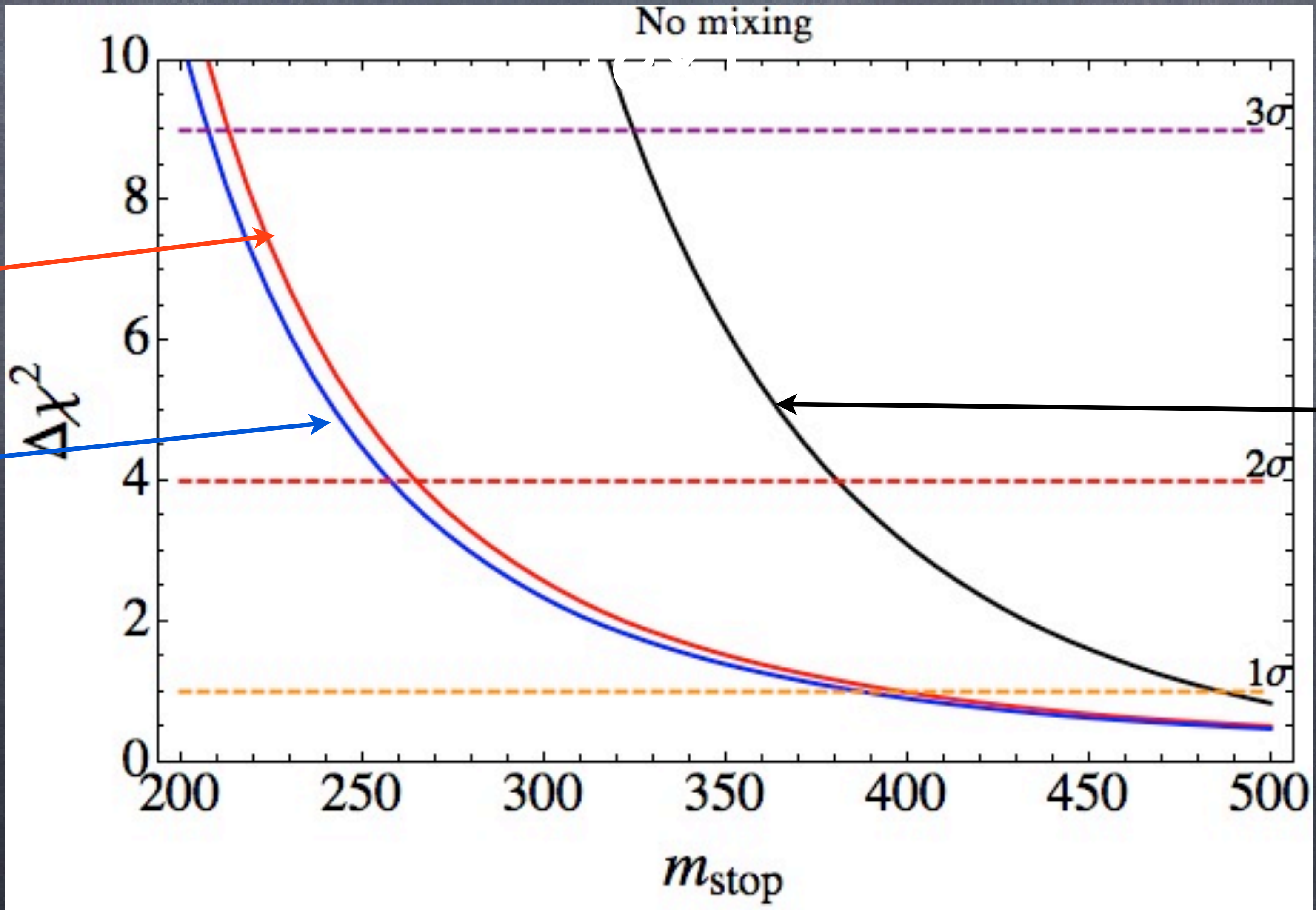


- If only 1 stop is light and mixing is small, then limit around 260 GeV

- But for large mixing the coupling the Higgs may be reduced, in which case the limit goes away

LH stop

RH stop

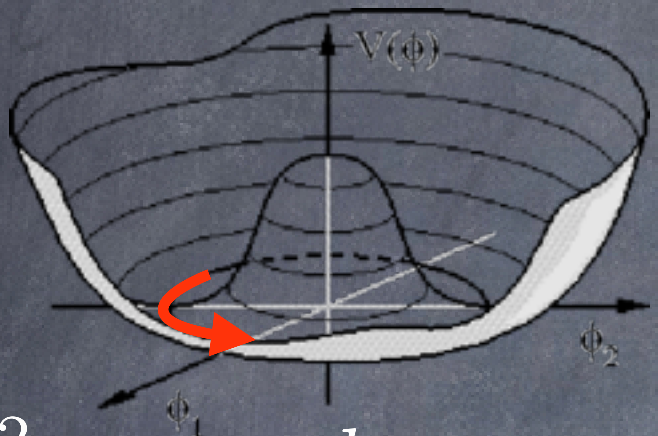


LH+RH stop

Composite Higgs

GBHiggs couplings to SM fields

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



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

$h \to \langle h\rangle + h$

$$\frac{g^2}{4} f^2 \sin^2\frac{h}{f} W_\mu W^\mu = \frac{g^2}{4} f^2 \sin^2\frac{\langle h\rangle}{f} W_\mu W^\mu$$

v^2

$$+ \frac{g^2}{2} f \sin\frac{\langle h\rangle}{f}\sqrt{1-\sin^2\frac{\langle h\rangle}{f}}\, hW_\mu W^\mu + ..$$

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

Coupling to W and model independent

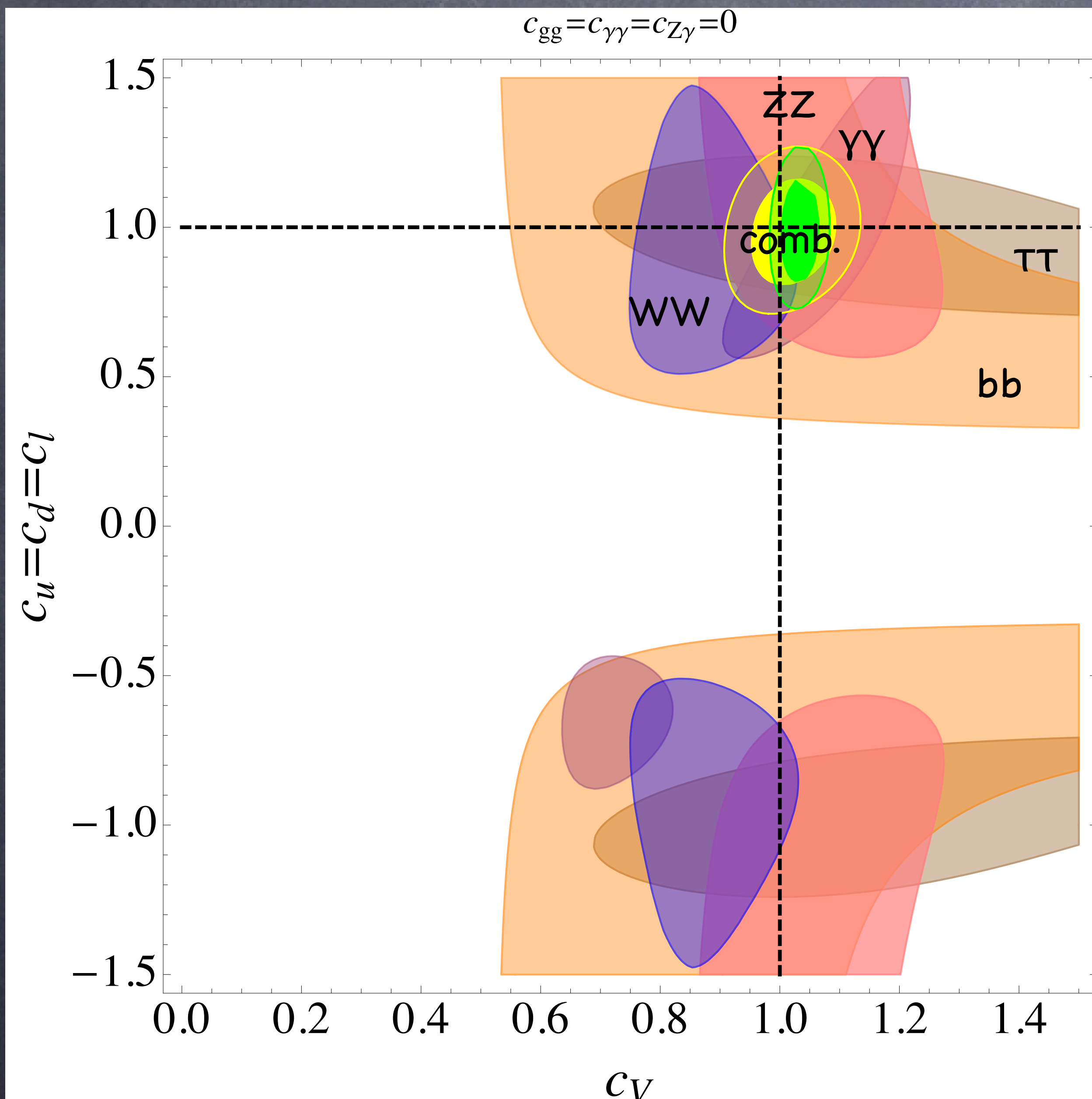
$$c_f = \frac{1+2m-(1+2m+n)v^2/f^2}{\sqrt{1-v^2/f^2}}$$

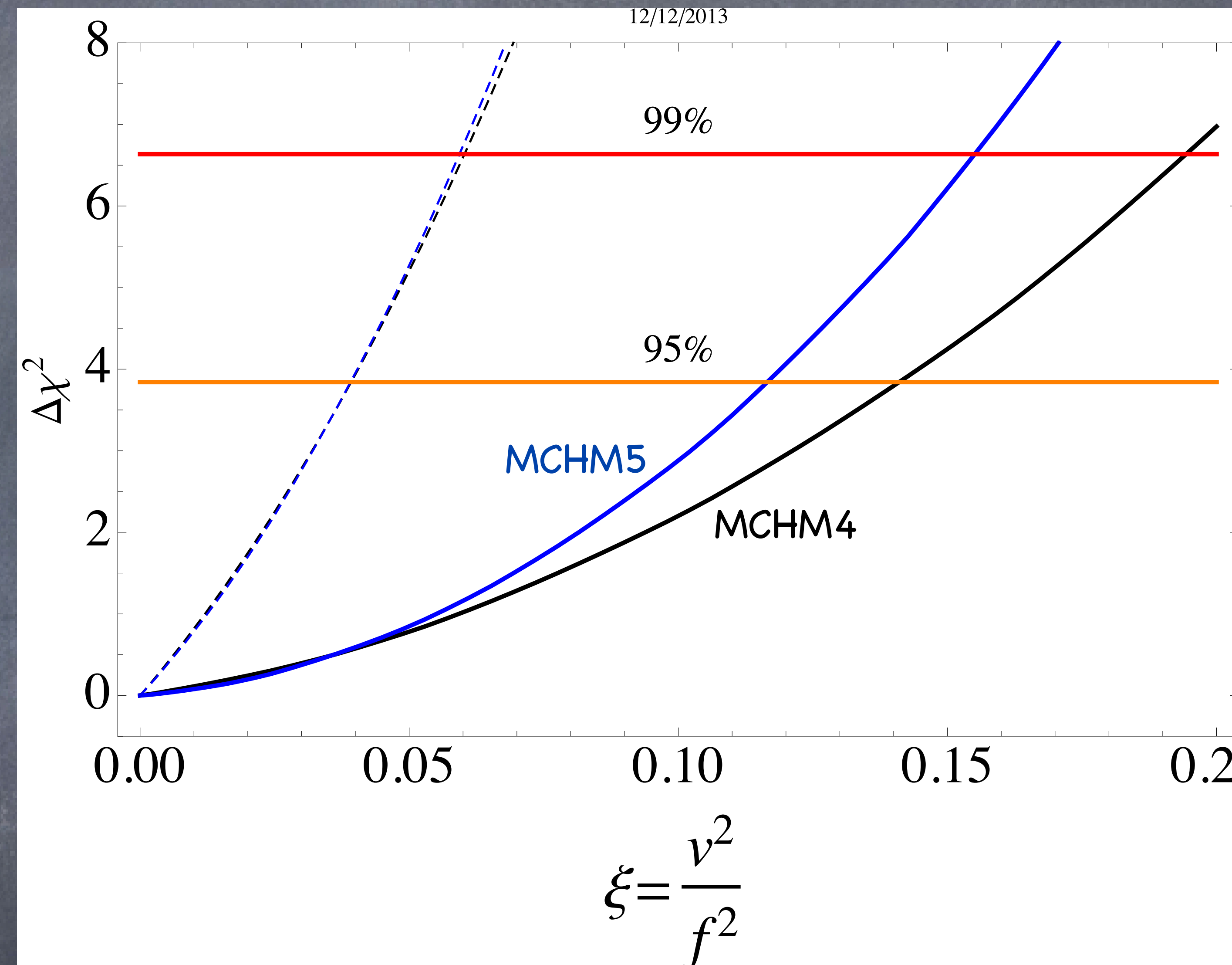
Coupling to fermions model dependent $m_t \sim \sin^{2m+1}\left(\frac{h}{f}\right)\cos^n\left(\frac{h}{f}\right)$

Pomarol,Riva,'12

Slide stolen from Francesco Riva

Composite Higgs Fits





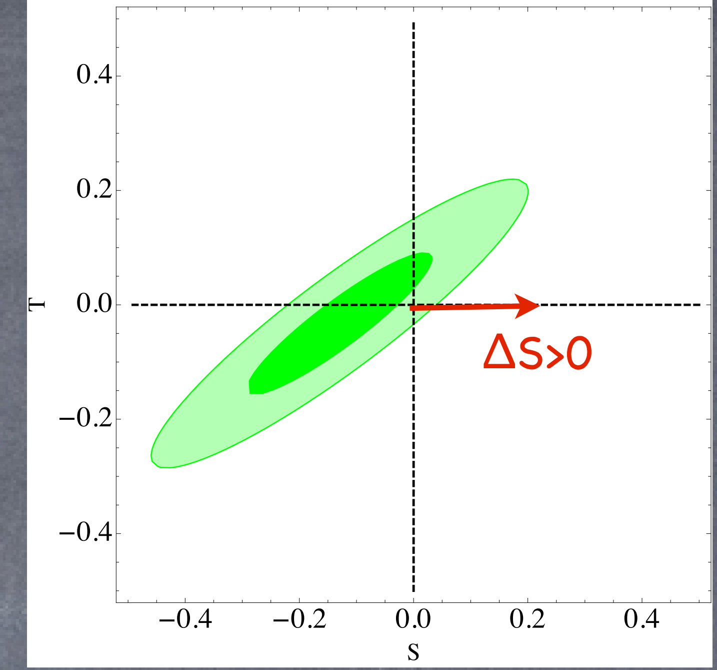
Higgs data: f≳700 GeV

Higgs+EW data: f≳1.2 TeV

Composite Higgs and EWPT

Integrating out composite resonances produces a shift of S

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

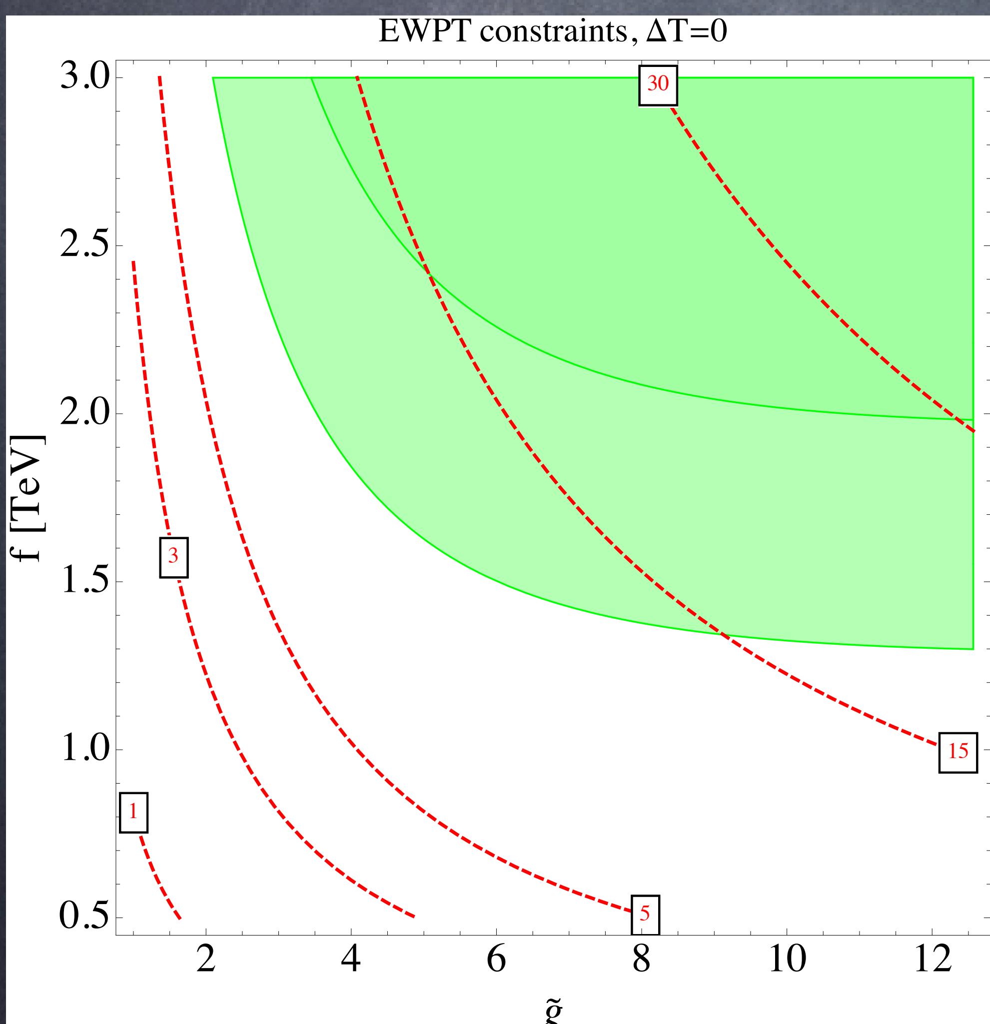


Also, a shift of S and T due to cV<1

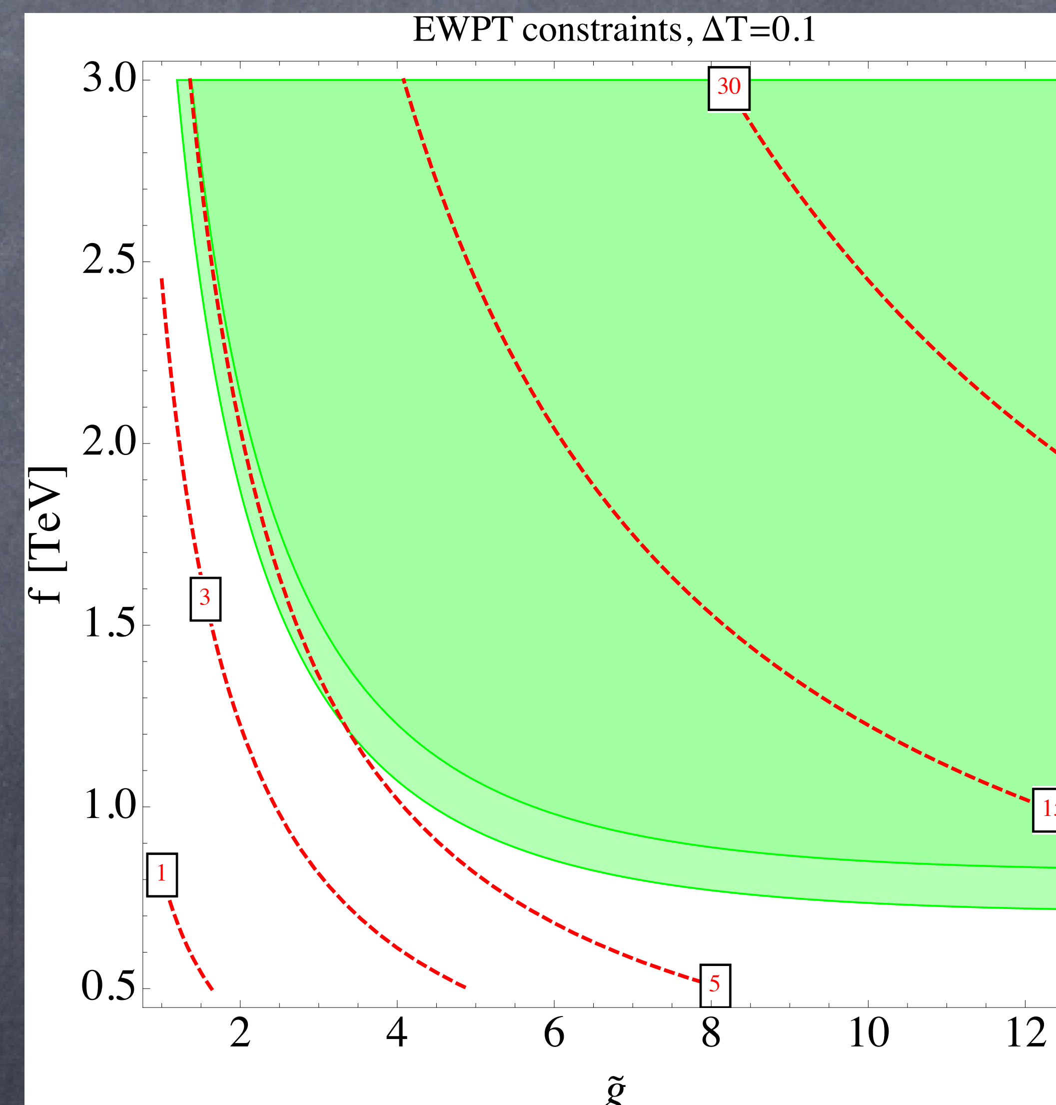
$$\Delta T \approx -\frac{3(g_L^2+g_Y^2)}{8\pi g_L^2}\frac{v^2}{f^2}\log(m_\rho/m_Z),$$

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

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)

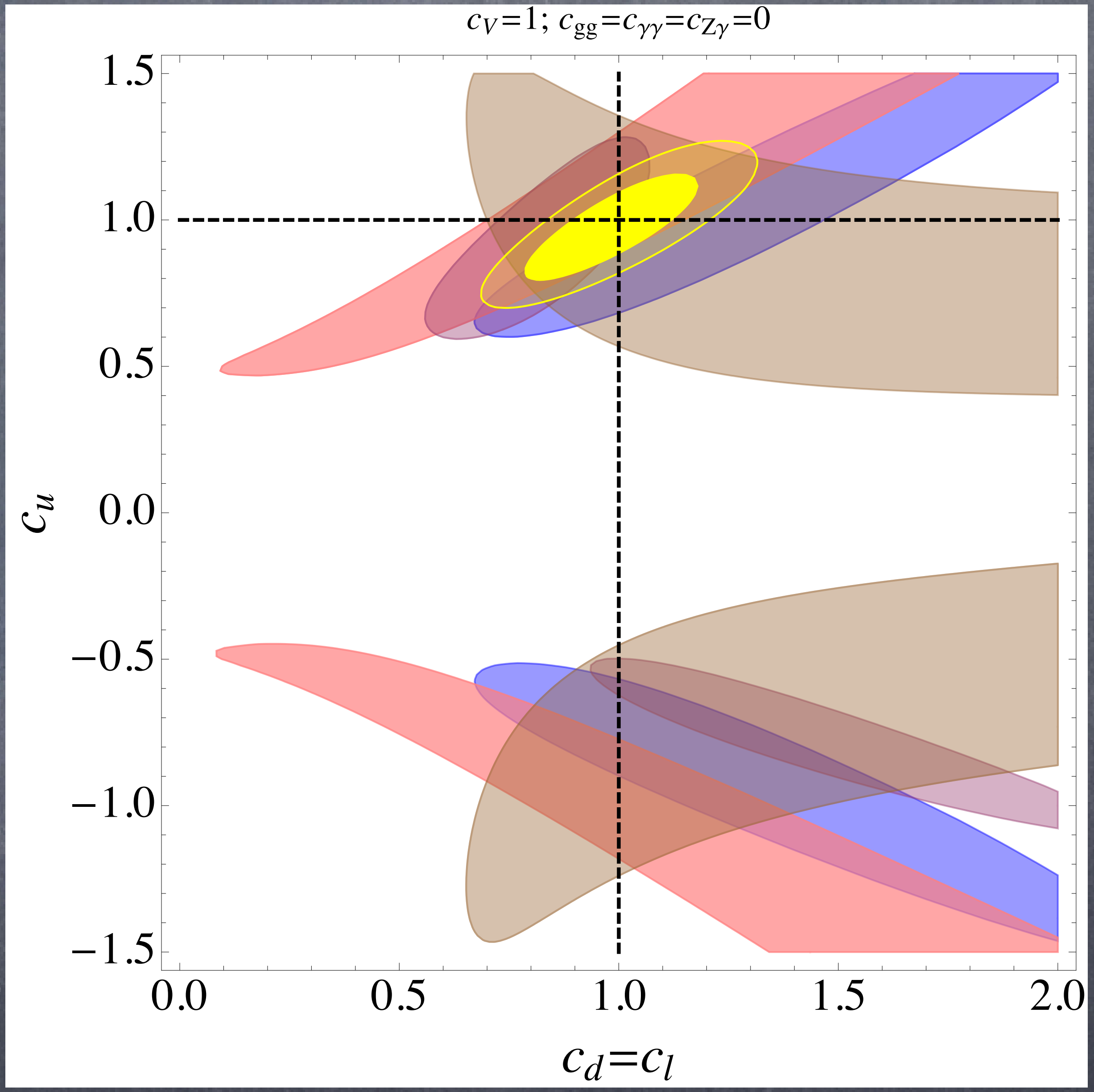
2HDM

Type II 2 Higgs Doublet Models

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

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

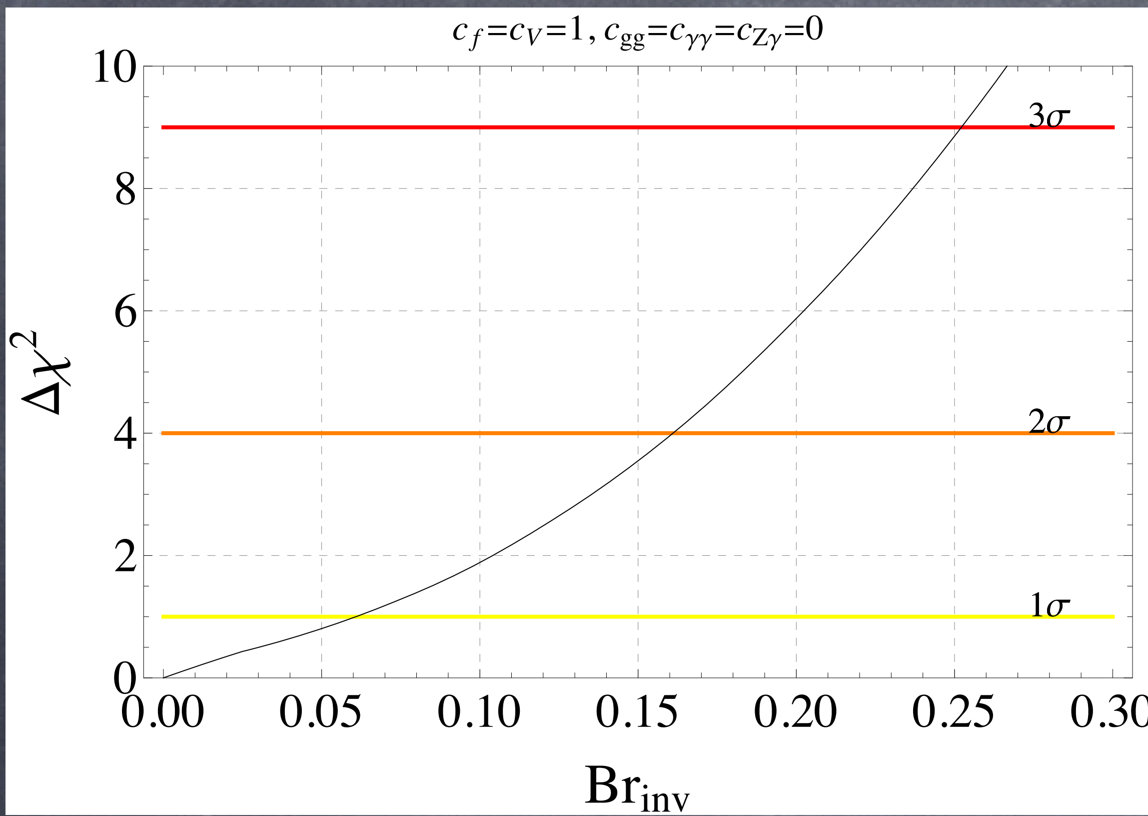
$$\Delta c_V \sim \frac{v^4}{m_H^4} \sim 0$$

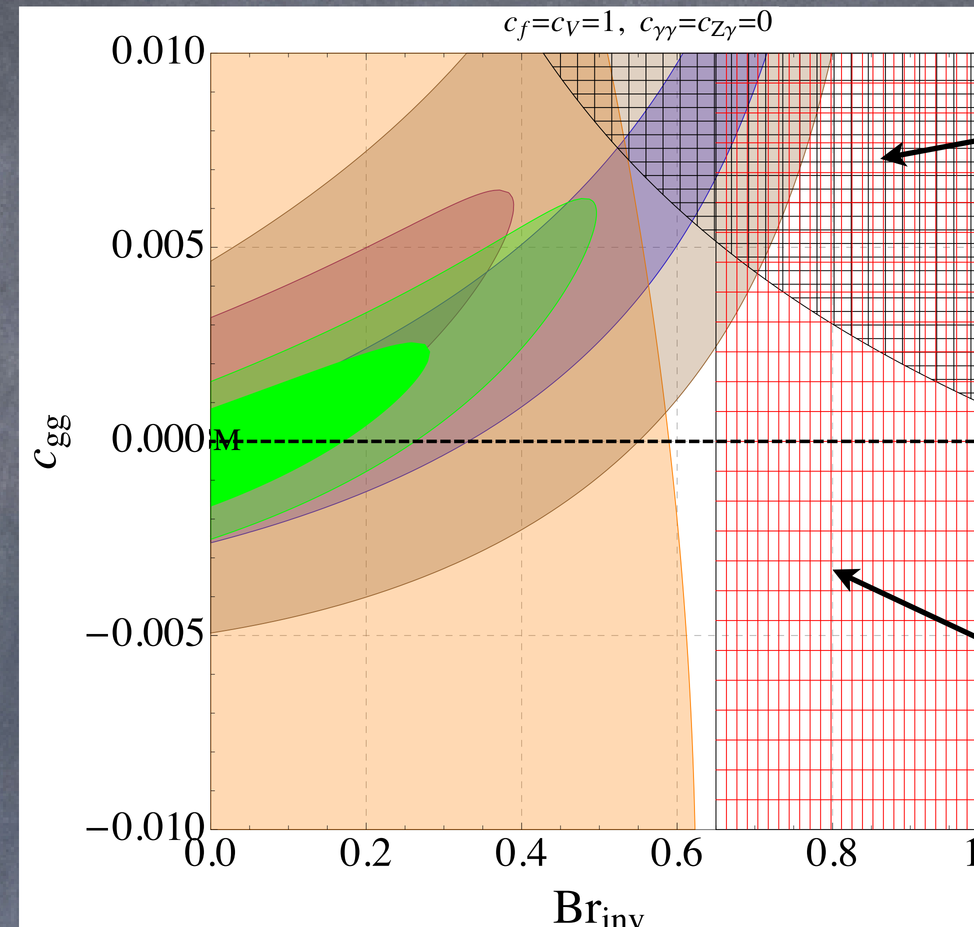


Higgs Portal

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 and CMS H→invisible searches

- If all couplings at SM value, invisible branching fraction larger than 22% 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!

Exotic Higgs Decays

Exotic Higgs Decays - Why?

- Indirect constraints (via visible decays) allow for up to ~25% branching fraction into exotic states (if the Higgs production rate is as in the SM), or even up to ~50% with some conspiracy (if the Higgs production rate is enhanced). That means the LHC cross section for exotic Higgs decays could easily be order picobarn

- The SM Higgs width is just 4 MeV, so even weakly coupled new physics can lead to a significant branching fraction for exotic decays. E.g., a new scalar X coupled as $c|H|^2 |X|^2$ corresponds to $BR(h \to X^*X)=10\%$ BR for $c \sim 0.01$.

- Thanks to the large Higgs cross section even tiny exotic branching fractions may possibly be probed. For spectacular enough signatures we can probe $BR \sim O(10^{-5})$ now and $BR \sim O(10^{-8})$ in the asymptotic future. [Note that the Higgs was first <u>discovered</u> in the diphoton ($BR \sim 10^{-3}$) and 4-lepton ($BR \sim 10^{-4}$) channels]

Exotic Higgs Decays - How?

New light degrees of freedom affecting Higgs decays

No new light degrees of freedom beyond those of the SM

SM+X

Multiple possibilities, large model dependence

HEFT

Leading effects expected from dimension 6 operators beyond the SM

Exotic Higgs Decays: SM+X

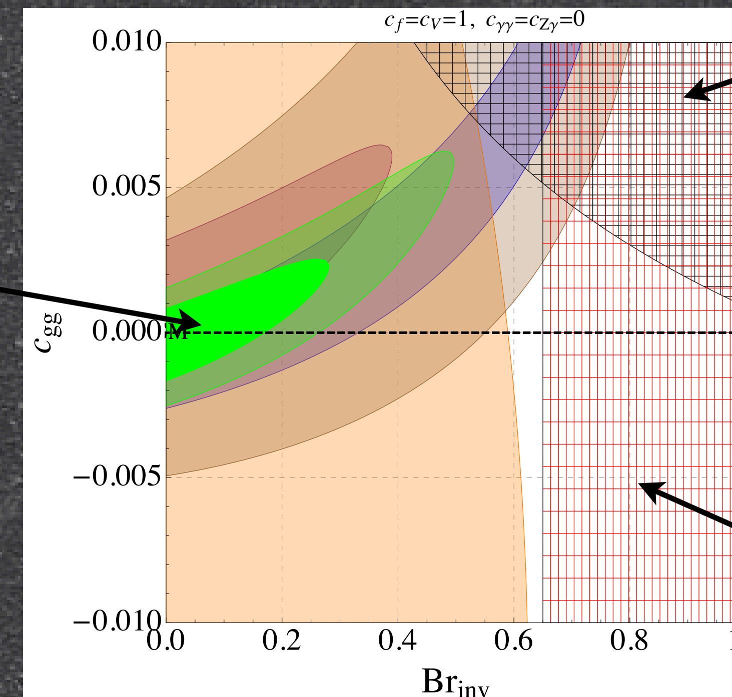
Examples:

h → invisible

h → XX, possible e.g. Higgs portal DM models

$$X^2|H|^2$$

Searches ongoing, interesting experimental limits, but somewhat stronger indirect limits



Favored

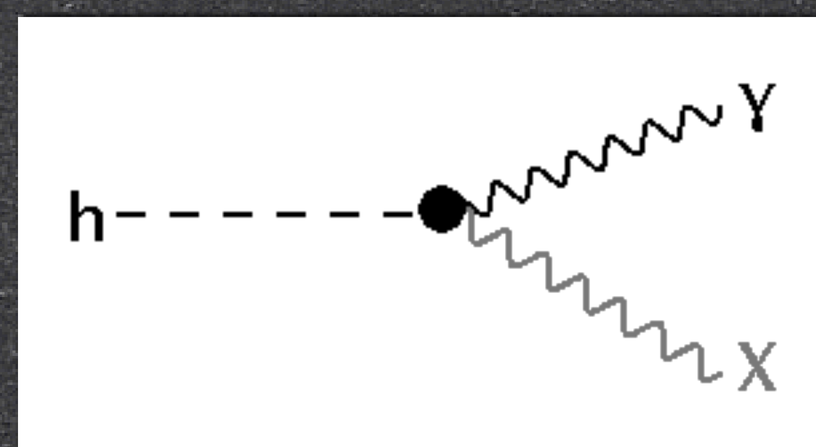
Excluded by monojets

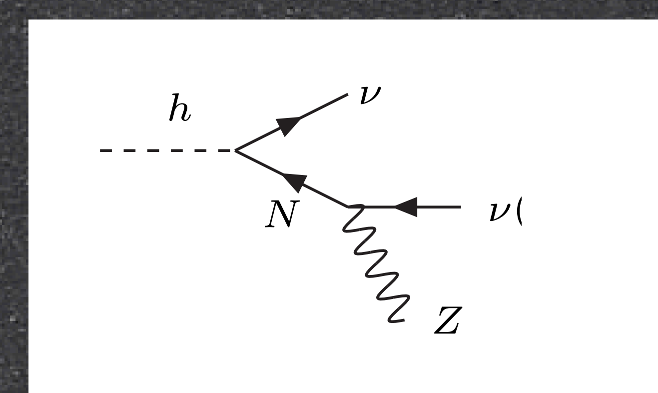
Excluded by ZH→invisible

h → monophoton/monoZ

h → XV, possible e.g. in hypercharge portal models or in inverse see-saw

$$|H|^2 X_{\mu\nu} B_{\mu\nu}$$





No experimental limits whatsoever, and I'm not aware of ongoing experimental searches....

Exotic Higgs Decays: SM+X

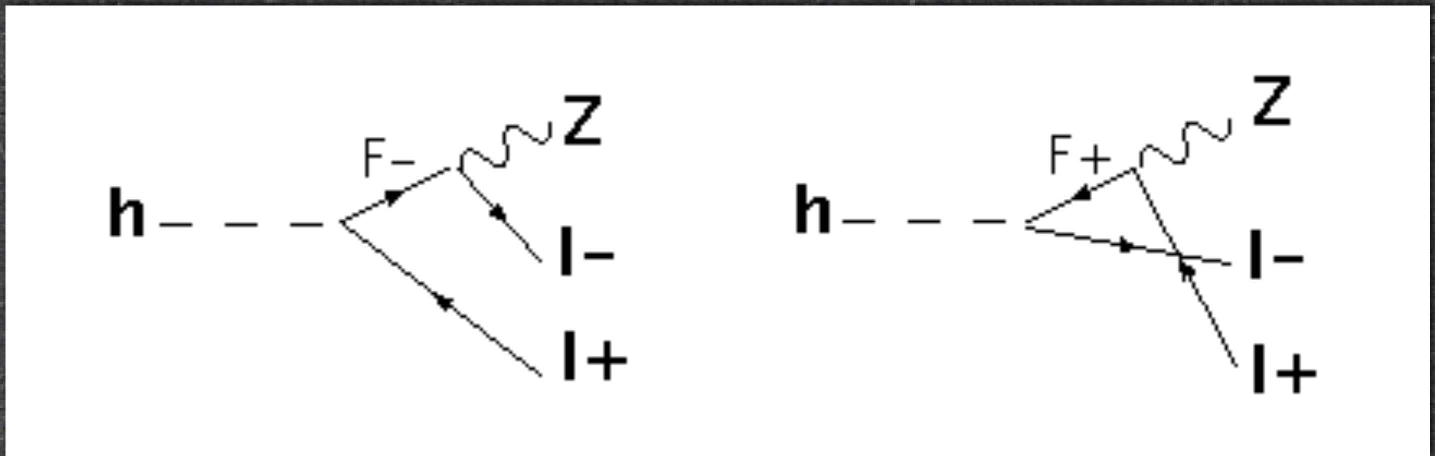
Examples:

h → Four Fermions

e.g. h → lX → Zll → 4l

$$y h \bar{X} l + \mathrm{h.c.}$$

$$g Z_\mu \bar{X} \gamma_\mu l + \mathrm{h.c.}$$



Not so fast: recent trilepton bounds exclude $X \to Ze$ or $X \to Z\mu$ with <125 GeV, but $X \to Z\tau$ is OK

AA, Straub, Vicente, in progress

- can arise e.g. in models of composite leptons

- F can be lighter than 125 GeV for all we know, so Higgs can decay to on-shell F

- Yukawa coupling as small as 0.01 leads to BR(h→lX)~0.01

- Distinct kinematics from the golden channel (Z-l resonance,)

- If F couples to 2 different fermions then Z l l‘ signatures with no SM background

work in progress with R.Vega-Morales

Conclusions

- Higgs is here to stay.
- In first approximation looks very much like the SM Higgs
- Combination of Higgs and electroweak data puts strong constraint on certain dimension-6 operators containing Higgs field
- 68% CL constraints on 7 leading parameters governing Higgs interactions with matter at the level between 5-30%
- No slightest hint of new physics at this point