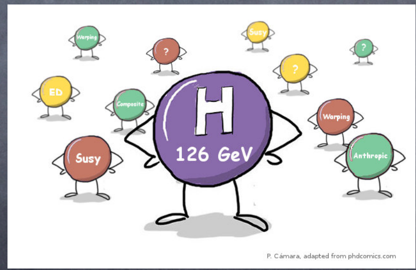
Adam Falkowski

Constraints on New Physics from Higgs Searches

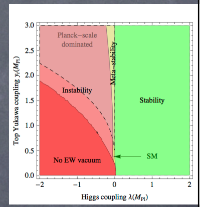
Why $m_H \approx 126$ GeV?, Madrid, 25 September 2013



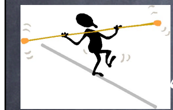
Based on work in collaboration with
Hermès Belusca, Dean Carmi, Erik Kuflik, Francesco Riva, Alfredo Urbano, Tomer Volansky, Jure Zupan

WHY MH≈126 GEV ?

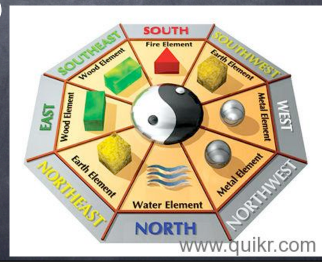
Answer #1: because Higgs mass "is maliciously designed to prolong the agony of Beyond Standard Model theorists" (NAH)



Answer #2a: Because it's the most dangerous place for Higgs mass to be (Buttazzo et al)



Answer #2b: "Multiple point criticality principle" (Frogatt,Nielsen)



Answer #3: Because the Higgs doublet mass parameter in the Lagrangian is mH^2 ≈ -mZ^2 (my fortune teller)

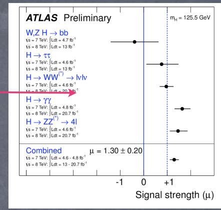
WHY MH≈126 GEV ?

My opinion: someone is pulling our leg

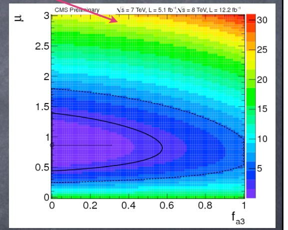
What have the Higgs hunters brought us

WHAT HAVE THE EXPERIMENTALISTS EVER DONE FOR US ?

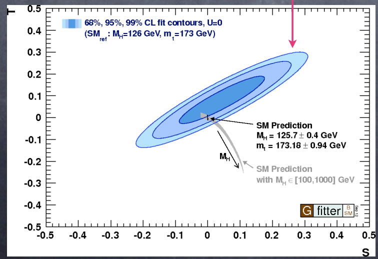
- Higgs production rates, split into separate production and decay channels



- Some information about tensor structure of the Higgs couplings

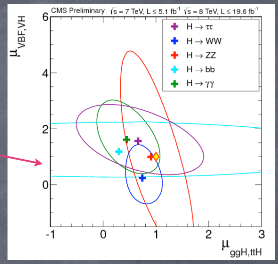


- Constraints on precision observables where Higgs enters indirectly

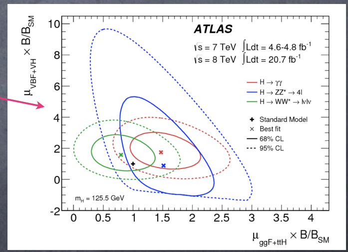


WHAT HAVE THE EXPERIMENTALISTS EVER DONE FOR US ?

- 2D likelihood contours for ggH and VBF/VH cross sections in the leading decay channels provided by experiment!



- Recently, 2D likelihood in the numerical form in the γγ, ZZ and WW channels from ATLAS! Going beyond Gaussian approximations now possible!!!



!We Want More!

- [6D likelihoods]: For each decay, provide likelihoods separated into all 5 production modes (ggF, VBF, WH, ZH, ttH).

- [Tensor structure]: For decay channels sensitive to tensor structure for Higgs couplings provide likelihood separated into each allowed form factor (expanded in momentum).

$$\mathcal{A}(H \to V^1_\mu V^2_\nu) = \frac{1}{v}\left(F_1(p_1^2, p_2^2) 2 m_V^2 \eta_{\mu\nu} + F_2(p_1^2, p_2^2) p_{1\nu} p_{2\mu} + F_3(p_1^2, p_2^2) \epsilon_{\mu\nu\rho\sigma} p_1^\rho p_2^\sigma\right) ,$$

Boudjema et al. 1307.5865

- [Fiducial cross sections]: Asymptotically, publish a set of cross sections and acceptances.

$$\sigma_i^{\rm fid} = \sum_j A_{ij}^{\rm th} \times \sigma_j^{\rm tot},$$

What to do with it

Now we need a framework to interpret all this in the context of physics beyond the Standard Model

- Interpret the Higgs data in the context of an effective theory: systematic expansion of all possible interactions between Higgs and other SM fields

Default approach in this talk

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

Also a valid approach, but mind that any particular BSM model is almost certainly wrong ;-)

Effective Lagrangian for Higgs interactions

Effective Higgs Lagrangian

Critical Assumption (underlying effective theory approach)

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

Technical Assumption (to organize expansion of eff. theory interactions)

Higgs is scalar particle embedded in field H that transforms as $2_{1/2}$ representation under $SU(2)_W \times U(1)_Y$.
Expansion in operator dimension

Alternative option: derivative expansion as in ChPT for QCD

Typically, Further "Backdoor" Assumptions (to reduce # of parameters, may and should be relaxed when more data available)

- No flavor-violating Higgs couplings
- No CP violating Higgs couplings
- Custodial symmetry
- No large cancellations in electroweak precision observables
- etc

Effective Higgs Lagrangian

Expansion in operator dimensions

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \mathcal{L}_{d=5} + \mathcal{L}_{d=6} + \ldots$$

- $\mathcal{L}_{d=5}$: Just neutrino masses, irrelevant for Higgs story
- $\mathcal{L}_{d=6}$: Includes operators modifying Higgs couplings!
- $\ldots$: d>6 dimensional operators; not important for Higgs studies, given current precision

- Dimension-6 operators enumerated long ago by Buchmuller and Wyler (‘86). Minimal complete set of operators written down in Grzadkowski,Iskrzynski,Misiak,Rosiek, 1008.4884
- After removing redundant operators one ends up with 59 dimension-6 operators (for 1 generation), including 28 operators that involve the Higgs field
- One convenient basis to write down these operators is the so-called SILH basis, Giudice,Grojean,Pomarol,Rattazzi, hep-ph/0703164; see Contino et al. 1303.3876 for a recent reappraisal

Effective Higgs Lagrangian

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \mathcal{L}_{d=5} + \mathcal{L}_{d=6} + \ldots$$

$$\mathcal{L}_{\rm SM} = D_\mu H^\dagger D_\mu H + m_H^2 H^\dagger H - \lambda (H^\dagger H)^2 - \left(\frac{y_{ij}}{\sqrt{2}} H \bar{\psi}_i \psi_j + \text{h.c.} \right) + \ldots$$

No Higgs

Couplings to EW gauge bosons

Self-Couplings

Couplings to fermions

$$\mathcal{L}_{\rm Higgs} = \frac{h}{v} \left(2 m_W^2 \, W_\mu^+ W_\mu^- + m_Z^2 \, Z_\mu Z_\mu - \sum_f m_f \bar{f} f \right) + \mathcal{O}(h^2)$$

In the SM Lagrangian, Higgs couples to mass of EW bosons and fermions

Effective Higgs Lagrangian

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \mathcal{L}_{d=5} + \mathcal{L}_{d=6} + \dots$$

$$\mathcal{L}_{d=6} = \mathcal{L}_{\rm SILH} + \mathcal{L}_{\rm 2FV} + \mathcal{L}_{\rm 2FD} + \mathcal{L}_{\rm 4F} + \mathcal{L}_{\rm Gauge} + \mathcal{L}_{\rm CPB}$$

Higgs interactions with itself, SM gauge bosons and Yukawa interactions with fermions

$$\frac{\bar{c}_H}{2v^2}\partial^\mu(H^\dagger H)\,\partial_\mu(H^\dagger H) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\,\lambda}{v^2}\left(H^\dagger H\right)^3$$
$$+ \left(\left(\frac{\bar{c}_u}{v^2}\,y_u\,H^\dagger H\,\bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2}\,y_d\,H^\dagger H\,\bar{q}_L H d_R + \frac{\bar{c}_l}{v^2}\,y_l\,H^\dagger H\,\bar{L}_L H l_R\right) + h.c.\right)$$
$$+ \frac{i\bar{c}_W\,g}{2m_W^2}\left(H^\dagger\sigma^i\overleftrightarrow{D}^\mu H\right)(D^\nu W_{\mu\nu})^i + \frac{i\bar{c}_B\,g'}{2m_W^2}\left(H^\dagger\overleftrightarrow{D}^\mu H\right)(\partial^\nu B_{\mu\nu})$$
$$+ \frac{i\bar{c}_{HW}\,g}{m_W^2}(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu} + \frac{i\bar{c}_{HB}\,g'}{m_W^2}(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$$
$$+ \frac{\bar{c}_\gamma\,g'^2}{m_W^2}H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{\bar{c}_g\,g_S^2}{m_W^2}H^\dagger H G^a_{\mu\nu}G^{a\mu\nu}\,,$$

2-fermion vertex corrections

$$\frac{i\bar{c}_{Hq}}{v^2}(\bar{q}_L\gamma^\mu q_L)\left(H^\dagger\overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}'_{Hq}}{v^2}(\bar{q}_L\gamma^\mu\sigma^i q_L)\left(H^\dagger\sigma^i\overleftrightarrow{D}_\mu H\right)$$
$$+ \frac{i\bar{c}_{Hu}}{v^2}(\bar{u}_R\gamma^\mu u_R)\left(H^\dagger\overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}_{Hd}}{v^2}(\bar{d}_R\gamma^\mu d_R)\left(H^\dagger\overleftrightarrow{D}_\mu H\right)$$
$$+ \left(\frac{i\bar{c}_{Hud}}{v^2}(\bar{u}_R\gamma^\mu d_R)\left(H^{c\dagger}\overleftrightarrow{D}_\mu H\right) + h.c.\right)$$
$$+ \frac{i\bar{c}_{HL}}{v^2}(\bar{L}_L\gamma^\mu L_L)\left(H^\dagger\overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}'_{HL}}{v^2}(\bar{L}_L\gamma^\mu\sigma^i L_L)\left(H^\dagger\sigma^i\overleftrightarrow{D}_\mu H\right)$$
$$+ \frac{i\bar{c}_{Hl}}{v^2}(\bar{l}_R\gamma^\mu l_R)\left(H^\dagger\overleftrightarrow{D}_\mu H\right),$$

2-fermion dipole operators

$$\frac{\bar{c}_{uB}\,g'}{m_W^2}\,y_u\,\bar{q}_L H^c\sigma^{\mu\nu}u_R\,B_{\mu\nu} + \frac{\bar{c}_{uW}\,g}{m_W^2}\,y_u\,\bar{q}_L\sigma^i H^c\sigma^{\mu\nu}u_R\,W^i_{\mu\nu} + \frac{\bar{c}_{uG}\,g_S}{m_W^2}\,y_u\,\bar{q}_L H^c\sigma^{\mu\nu}\lambda^a u_R\,G^a_{\mu\nu}$$
$$+ \frac{\bar{c}_{dB}\,g'}{m_W^2}\,y_d\,\bar{q}_L H\sigma^{\mu\nu}d_R\,B_{\mu\nu} + \frac{\bar{c}_{dW}\,g}{m_W^2}\,y_d\,\bar{q}_L\sigma^i H\sigma^{\mu\nu}d_R\,W^i_{\mu\nu} + \frac{\bar{c}_{dG}\,g_S}{m_W^2}\,y_d\,\bar{q}_L H\sigma^{\mu\nu}\lambda^a d_R\,G^a_{\mu\nu}$$
$$+ \frac{\bar{c}_{lB}\,g'}{m_W^2}\,y_l\,\bar{L}_L H\sigma^{\mu\nu}l_R\,B_{\mu\nu} + \frac{\bar{c}_{lW}\,g}{m_W^2}\,y_l\,\bar{L}_L\sigma^i H\sigma^{\mu\nu}l_R\,W^i_{\mu\nu} + h.c.$$

4-fermion operators

Gauge boson self-interactions

CP Violating interactions

$$\frac{i\tilde{c}_{HW}\,g}{m_W^2}(D^\mu H)^\dagger\sigma^i(D^\nu H)\tilde{W}^i_{\mu\nu} + \frac{i\tilde{c}_{HB}\,g'}{m_W^2}(D^\mu H)^\dagger(D^\nu H)\tilde{B}_{\mu\nu}$$
$$+ \frac{\tilde{c}_\gamma\,g'^2}{m_W^2}H^\dagger H B_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{\tilde{c}_g\,g_S^2}{m_W^2}H^\dagger H G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$
$$+ \frac{\tilde{c}_{3W}\,g^3}{m_W^2}\epsilon^{ijk}W^{i\,\nu}_{\mu}W^{j\,\rho}_{\nu}\tilde{W}^{k\,\mu}_{\rho} + \frac{\tilde{c}_{3G}\,g_S^3}{m_W^2}f^{abc}G^{a\,\nu}_{\mu}G^{b\,\rho}_{\nu}\tilde{G}^{c\,\mu}_{\rho}\,,$$

After including dimension-6 operators:

- Higgs couplings to matter no longer fixed by mass
- New tensors structures appear in vertices

Effective Higgs Lagrangian

SILH Lagrangian

$$\frac{\bar{c}_H}{2v^2}\partial^\mu(H^\dagger H)\,\partial_\mu(H^\dagger H) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\lambda}{v^2}(H^\dagger H)^3$$
$$+\left(\left(\frac{\bar{c}_u}{v^2}y_u\,H^\dagger H\,\bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2}y_d\,H^\dagger H\,\bar{q}_L H d_R + \frac{\bar{c}_l}{v^2}y_l\,H^\dagger H\,\bar{L}_L H l_R\right) + h.c.\right)$$
$$+\frac{i\bar{c}_W\,g}{2m_W^2}\left(H^\dagger\sigma^i \overleftrightarrow{D}^\mu H\right)(D^\nu W_{\mu\nu})^i + \frac{i\bar{c}_B\,g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)(\partial^\nu B_{\mu\nu})$$
$$+\frac{i\bar{c}_{HW}\,g}{m_W^2}(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu} + \frac{i\bar{c}_{HB}\,g'}{m_W^2}(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$$
$$+\frac{\bar{c}_\gamma\,g'^2}{m_W^2}H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{\bar{c}_g\,g_S^2}{m_W^2}H^\dagger H G^a_{\mu\nu}G^{a\mu\nu},$$

$\Downarrow$ $\Downarrow$ $\Downarrow$

- 11 parameters of SILH Lagrangian translates to modifications of 5 SM 0-derivative Higgs boson couplings and 8 new 2-derivate couplings

0-derivative couplings, present in SM

$$\frac{h}{v}\Big(\quad 2c_V m_W^2 W^+_\mu W^-_\mu + c_{V,z} m_Z^2 Z_\mu Z_\mu$$
$$-c_u\sum_{q=u,c,t} m_q\bar{q}q - c_d\sum_{q=d,s,b} m_q\bar{q}q - c_l\sum_{l=e,\mu\tau} m_l\bar{l}l$$

2-derivative, not present in SM

$$+\frac{1}{4}c_{gg}G^a_{\mu\nu}G^a_{\mu\nu} - \frac{1}{4}c_{\gamma\gamma}\gamma_{\mu\nu}\gamma_{\mu\nu}$$
$$-\frac{1}{2}c_{WW}W^+_{\mu\nu}W^-_{\mu\nu} - \frac{1}{4}c_{ZZ}Z_{\mu\nu}Z_{\mu\nu} - \frac{1}{2}c_{Z\gamma}\gamma_{\mu\nu}Z_{\mu\nu}$$
$$+\kappa_{Z\gamma}\partial_\nu\gamma_{\mu\nu}Z_\mu + \kappa_{ZZ}\partial_\nu Z_{\mu\nu}Z_\mu + (\kappa_{WW}\partial_\nu W^+_{\mu\nu}W^-_\mu + \text{hc})\Big)$$

Dictionary

$$c_f = 1 - \frac{\bar{c}_H}{2} - \bar{c}_f$$
$$c_V = 1 - \frac{\bar{c}_H}{2}$$
$$c_{V,z} = 1 - \frac{\bar{c}_H}{2} - 2\bar{c}_T$$
$$c_{gg} = 16\frac{g_s^2}{g_L^2}\bar{c}_g$$
$$c_{\gamma\gamma} = -16 s_w^2\bar{c}_\gamma$$
$$c_{Z\gamma} = \frac{2s_w}{c_w}\left(\bar{c}_{HW} - \bar{c}_{HB} + 8s_w^2\bar{c}_\gamma\right)$$
$$c_{ZZ} = 4\left(\bar{c}_{HW} + \bar{c}_{HB}\frac{s_w^2}{c_w^2} - 4\frac{s_w^4}{c_w^2}\bar{c}_\gamma\right)$$
$$c_{WW} = 4\bar{c}_{HW}$$
$$\kappa_{Z\gamma} = -\frac{2s_w}{c_w}\left(\bar{c}_{HW} - \bar{c}_{HB} + \bar{c}_W - \bar{c}_B\right)$$
$$\kappa_{ZZ} = -2\left(\bar{c}_{HW} + \bar{c}_{HB}\frac{s_w^2}{c_w^2} + \bar{c}_W + \bar{c}_B\frac{s_w^2}{c_w^2}\right)$$
$$\kappa_{WW} = -2\left(\bar{c}_{HW} + \bar{c}_W\right)$$

$s_W = \sin(\theta_W)$
$c_W = \cos(\theta_W)$

Effective Higgs Lagrangian

SILH Lagrangian

$$\frac{\bar{c}_H}{2v^2}\partial^\mu(H^\dagger H)\,\partial_\mu(H^\dagger H) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\lambda}{v^2}(H^\dagger H)^3$$
$$+ \left(\left(\frac{\bar{c}_u}{v^2}\, y_u\, H^\dagger H\, \bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2}\, y_d\, H^\dagger H\, \bar{q}_L H d_R + \frac{\bar{c}_l}{v^2}\, y_l\, H^\dagger H\, \bar{L}_L H l_R\right) + h.c.\right)$$
$$+ \frac{i\bar{c}_W\, g}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i + \frac{i\bar{c}_B\, g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu})$$
$$+ \frac{i\bar{c}_{HW}\, g}{m_W^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{i\bar{c}_{HB}\, g'}{m_W^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$
$$+ \frac{\bar{c}_\gamma\, g'^2}{m_W^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{\bar{c}_g\, g_S^2}{m_W^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}\,,$$

- 11 parameters of SILH Lagrangian translate to modifications of 5 SM 0-derivative Higgs boson couplings and 8 new 2-derivate couplings
- one relation among cVV and one among κVV

$$c_{WW} = c_w^2 c_{ZZ} + 2 s_w c_w c_{Z\gamma} + s_w^2 c_{\gamma\gamma}$$
$$\kappa_{WW} = c_w^2 \kappa_{ZZ} + c_w s_w \kappa_{Z\gamma}$$

⇓ ⇓ ⇓

0-derivative couplings, present in SM

$$\frac{h}{v}\Big(\quad 2c_V m_W^2 W^+_\mu W^-_\mu + c_{V,z} m_Z^2 Z_\mu Z_\mu$$
$$- c_u \sum_{q=u,c,t} m_q \bar{q}q - c_d \sum_{q=d,s,b} m_q \bar{q}q - c_l \sum_{l=e,\mu\tau} m_l \bar{l}l$$
$$+ \frac{1}{4} c_{gg} G^a_{\mu\nu} G^a_{\mu\nu} - \frac{1}{4} c_{\gamma\gamma}\gamma_{\mu\nu}\gamma_{\mu\nu}$$
$$- \frac{1}{2} c_{WW} W^+_{\mu\nu} W^-_{\mu\nu} - \frac{1}{4} c_{ZZ} Z_{\mu\nu} Z_{\mu\nu} - \frac{1}{2} c_{Z\gamma}\gamma_{\mu\nu} Z_{\mu\nu}$$
$$+ \kappa_{Z\gamma}\partial_\nu \gamma_{\mu\nu} Z_\mu + \kappa_{ZZ}\partial_\nu Z_{\mu\nu} Z_\mu + (\kappa_{WW}\partial_\nu W^+_{\mu\nu} W^-_\mu + \mathrm{hc})\Big)$$

2-derivative, not present in SM

Simplified Effective Higgs Lagrangian

- Including the full set of dimension-6 operators is the only correct approach in the long run, but not practical at this point of history

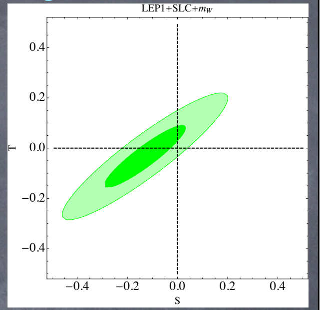
- In the following, simplified effective Higgs Lagrangian, after imposing some reasonable and motived assumptions:
  - Ignoring 2-fermion vertex and dipole operators (most of them strongly constrained by precision measurements)
  - Ignoring CP-violating operators (no interference in observables so effects expected smaller)
  - Require no power divergent 1-loop corrections to oblique parameters S T W Y (custodial symmetry + 1 more condition)

Simplified Effective Higgs Lagrangian

Some parameters of SILH Lagrangian are strongly constrained by electroweak precision tests. In particular, tree level contributions to S and T

$$\Delta T = \alpha^{-1}\bar{c}_T \qquad \Rightarrow \qquad \bar{c}_T \lesssim 10^{-3}$$

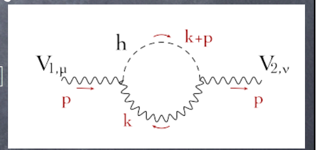
$$\Delta S = \frac{16\pi}{g_L^2}\left(\bar{c}_B + \bar{c}_W\right) \qquad \Rightarrow \qquad \bar{c}_B + \bar{c}_W \lesssim 10^{-3}$$



At 1 loop, power divergent contributions to oblique parameters

$$\alpha T \sim \frac{\Lambda^4}{16\pi^2 v^2 m_W^2}\left[\kappa_{WW}^2 - c_w^2(\kappa_{ZZ}^2 + \kappa_{Z\gamma}^2)\right] + \frac{\Lambda^2}{16\pi^2 v^2}\left[c_{V,z}^2 - c_V^2 + \ldots\right]$$

$$\alpha U \sim \frac{\Lambda^2}{16\pi^2 v^2}\left[c_{WW}^2 - c_w^2(c_{ZZ}^2 + c_{Z\gamma}^2) - c_w s_w(c_{ZZ}c_{Z\gamma} + c_{Z\gamma}c_{\gamma\gamma}) - s_w^2(c_{\gamma\gamma}^2 + c_{Z\gamma}^2)\right]$$



To avoid it, impose custodial symmetry relations

$$c_{V,z} = c_V$$

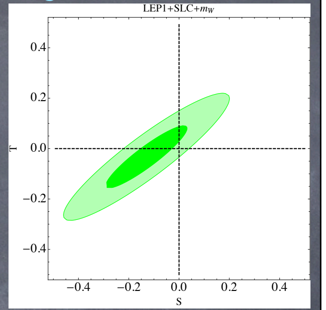
$$\kappa_{WW} = \kappa_{ZZ} \qquad \kappa_{WW} = c_w^2\kappa_{ZZ} + c_w s_w \kappa_{Z\gamma}$$

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

Simplified Effective Higgs Lagrangian

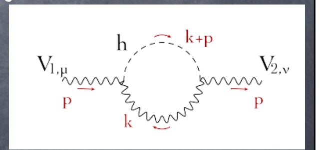
Some parameters of SILH Lagrangian are strongly constrained by electroweak precision tests. In particular, tree level contributions to S and T

$$\Delta T = \alpha^{-1}\bar{c}_T \qquad \Rightarrow \qquad \bar{c}_T \lesssim 10^{-3}$$



$$\Delta S = \frac{16\pi}{g_L^2}\left(\bar{c}_B + \bar{c}_W\right) \qquad \Rightarrow \qquad \bar{c}_B + \bar{c}_W \lesssim 10^{-3}$$

At 1 loop, power divergent contributions to oblique parameters



$$S \sim \frac{s_w^2 \kappa_{WW}(6c_V + 9c_{WW} + 17\kappa_{WW})}{48\pi^2 v^2}\Lambda^2$$

To avoid it, impose custodial symmetry + 1 more relation

$$c_{V,z} = c_V$$

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

$$\kappa_{WW} = 0 \quad \kappa_{ZZ} = 0 \quad \kappa_{Z\gamma} = 0$$

Simplified Effective Higgs Lagrangian

$$\mathcal{L}_{h,\rm sim} = \frac{h}{v}\Big(2c_V m_W^2 W_\mu^+ W_\mu^- + c_V m_Z^2 Z_\mu Z_\mu - c_u \sum_{q=u,c,t} m_q \bar{q}q - c_d \sum_{q=d,s,b} m_q \bar{q}q - c_l \sum_{l=e,\mu\tau} m_l \bar{l}l + \frac{1}{4}c_{gg}G^a_{\mu\nu}G^a_{\mu\nu} - \frac{1}{4}c_{\gamma\gamma}\gamma_{\mu\nu}\gamma_{\mu\nu} - \frac{1}{2}c_{WW}W^+_{\mu\nu}W^-_{\mu\nu} - \frac{1}{4}c_{ZZ}Z_{\mu\nu}Z_{\mu\nu} - \frac{1}{2}c_{Z\gamma}\gamma_{\mu\nu}Z_{\mu\nu}\Big)$$

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

- Simpler effective theory with 7 free parameters
- <ALL> these parameters are meaningfully constrained by current Higgs data
- 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 Fit

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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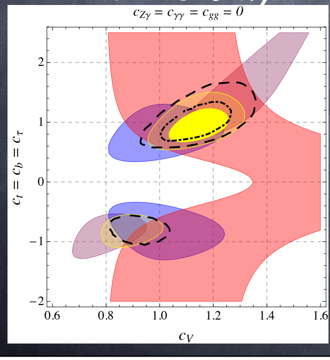
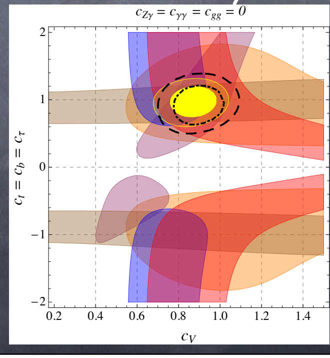
Does it make any sense?

- Naive theorist level combinations ignore important issues about systematics and correlations
- However, comparing directly with analogous fits performed by experiments so far one always finds a decent agreement (errors slightly underestimated, but the favored region of parameter space always similar)

ATLAS only



CMS only



7 Parameter Fit

7 parameter fit

$$c_V = 1.04^{+0.03}_{-0.04}$$

$$c_u \in (-1.3, 1.3)$$

$$c_d = 1.02^{+0.12}_{-0.17}$$

$$c_l = 0.98^{+0.21}_{-0.21}$$

$$c_{gg} \in (-0.026, 0.026)$$

$$c_{\gamma\gamma} = 0.0001^{+0.0018}_{-0.0021}$$

$$c_{Z\gamma} = 0.006^{+0.015}_{-0.028}$$

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

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

Fit as of 23/09/2013

(thanks to Hermès Belusca)

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

7 parameter fit

$c_V = 1.04^{+0.03}_{-0.04}$ → It couples to W and Z mass!!!

using only Higgs data: $c_V = 0.97^{+0.10}_{-0.16}$

$c_u \in (-1.3, 1.3)$ → Too early to say whether it couples to top due to weak limits on $t\bar{t}h$ production

$c_d = 1.02^{+0.12}_{-0.17}$

$c_l = 0.98^{+0.21}_{-0.21}$

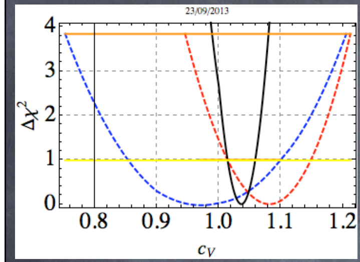
→ It couples to fermions! (actually constraints on cd indirectly via constraints on total width)

$c_{gg} \in (-0.026, 0.026)$ → Weak limit on coupling to gluons due to degeneracy with c_u (c.f. effective cgg=0.012 in SM)

$c_{\gamma\gamma} = 0.0001^{+0.0018}_{-0.0021}$ → Quite strong limit on coupling to photons (c.f. effective $c_{\gamma\gamma}$=0.0076 in SM)

$c_{Z\gamma} = 0.006^{+0.015}_{-0.028}$ → 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:

$c_V = 0.98^{+0.12}_{-0.13}$ $\quad 0.75 < c_V < 1.21$ @95% CL

EW data alone:

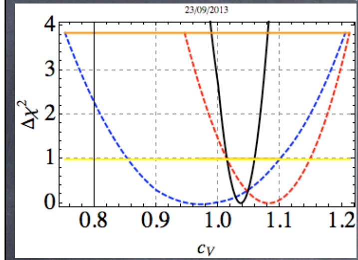
$c_V = 1.08^{+0.07}_{-0.07}$ $\quad 0.95 < c_V < 1.21$ @95% CL

Higgs+EW data:

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

7 parameter fit



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

One can still hope it's not the SM Higgs boson... but no experimental hints in that direction

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

7 parameter fit

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7 parameter fit

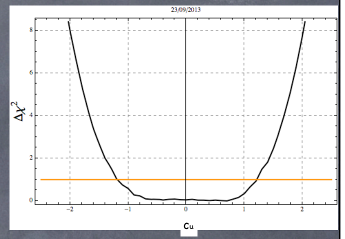
Couplings to gluons and top probed mostly by gluon fusion Higgs production mode

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

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

Constrained combination

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



For most Higgs observables, degeneracy between cgg and cu
Only broken by the tth production mode

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

Current limits on tth production still weak

$$\frac{\sigma_{\rm tth}}{\sigma_{\rm tth}^{\rm SM}} \frac{{\rm Br}(h \to bb)}{{\rm Br}(h \to bb)_{\rm SM}} = 2.6 \pm 5.4$$

ATLAS

$$\frac{\sigma_{\rm tth}}{\sigma_{\rm tth}^{\rm SM}} = 0.74^{+1.34}_{-1.30}$$

CMS combined
HIG-13-019-pas

7 parameter fit

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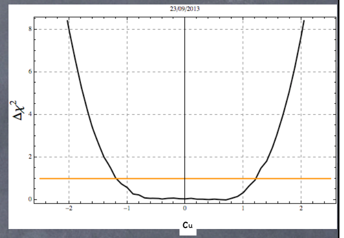
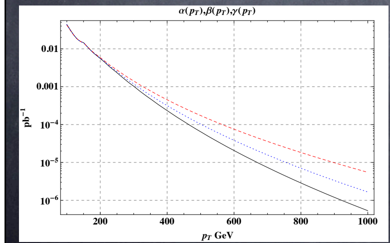
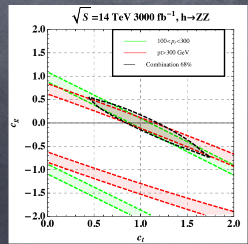


For most Higgs observables, degeneracy between cgg and cu
In the future, broken also by Higgs production at high pT

Azatov, Paul, 1309.5273





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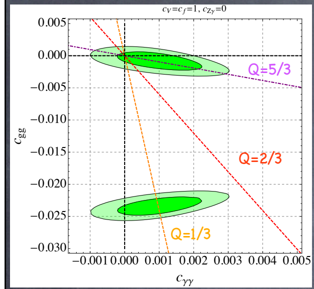
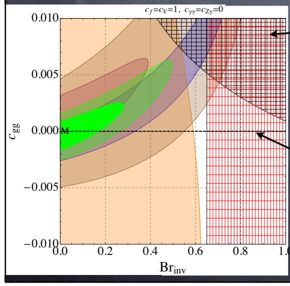
2 Parameter Fits

2-parameter fits

New-Physics-in-Loops-inspired

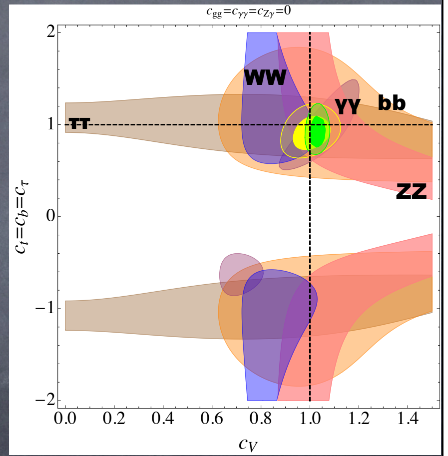




Excluded by monojet searches in CMS and ATLAS Djouadi et al. 1205.3169

Excluded by ATLAS and CMS ZH→invisible search

Composite-Higgs-inspired



Conclusions

- Combination of Higgs and electroweak data puts strong constraint on dimension-6 operators containing Higgs
- Constraints on 7 leading parameters governing Higgs interactions with matter at the level between 10% and 100%
- No slightest hint of new physics yet