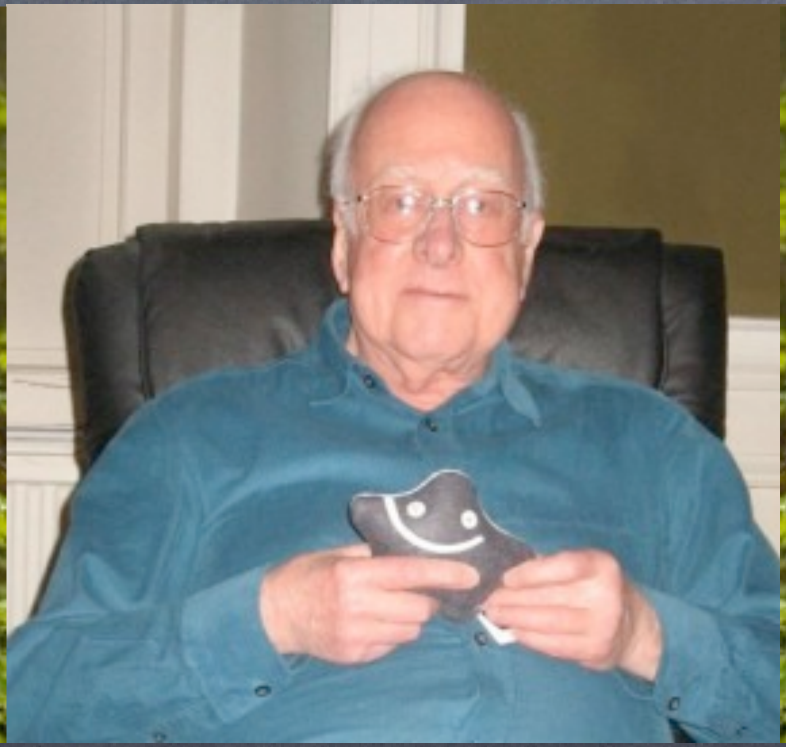
Adam Falkowski

Global Fits to Higgs Couplings

Higgs Hunting, Paris, 27 July 2013

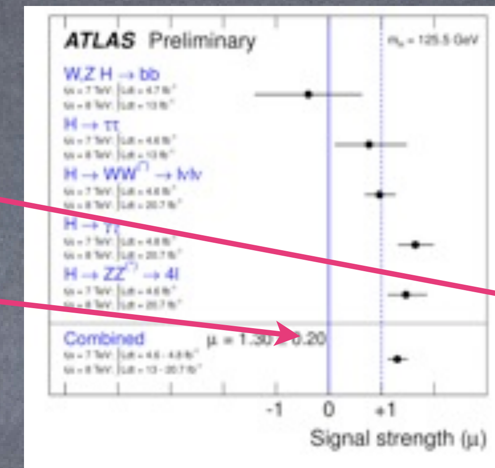



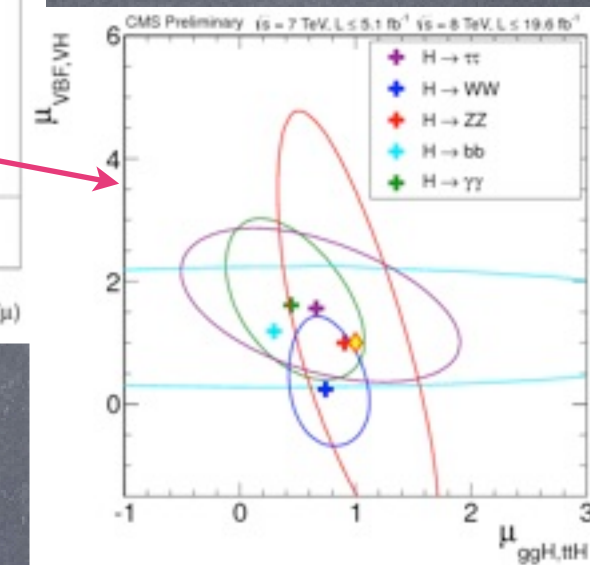

Based on work in collaboration with

Hermès Belusca, Dean Carmi, Erik Kuflik, Francesco Riva, Alfredo Urbano, Tomer Volansky, Jure Zupan

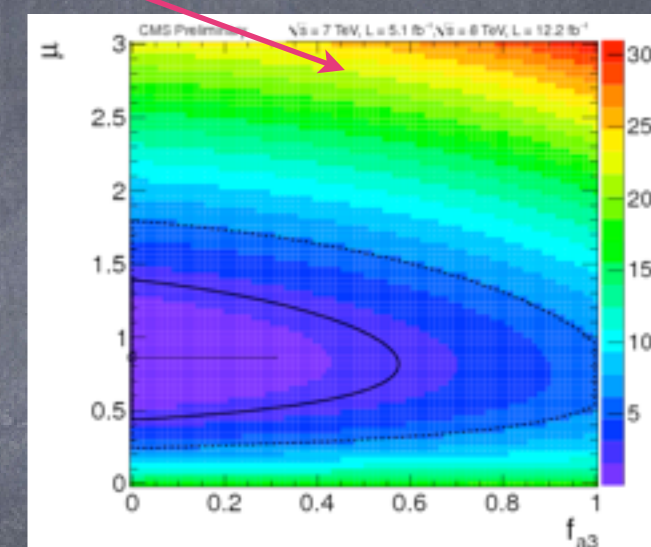
WHAT HAVE THE EXPERIMENTALISTS EVER DONE FOR US ?

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

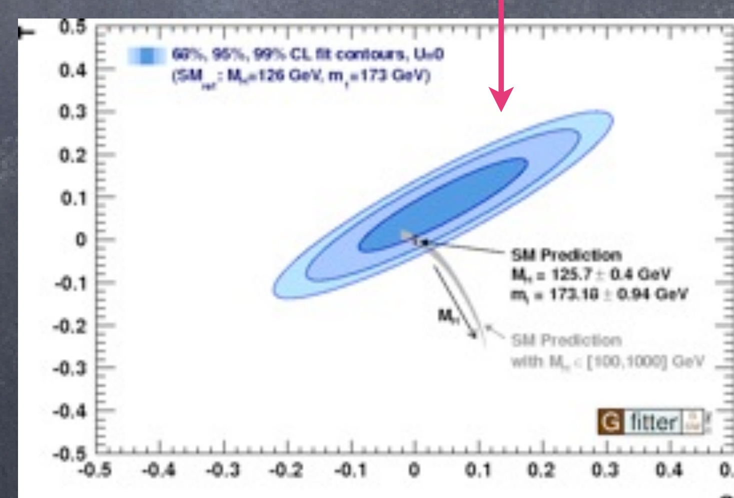




- Some information about tensor structure of the Higgs couplings



- Constraints on precision observables where Higgs enters indirectly



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

Higgs Effective Lagrangian

2 possible approaches

Default approach
in this talk

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

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

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

Effective Higgs Lagrangian

Critical Assumption (underlying effective theory approach)

There is no new particles with $m \lesssim m_h$ 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

d>6 dimensional operators; not important for Higgs studies, given current precision

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

Just neutrino masses, irrelevant for Higgs story

Includes operators modifying Higgs couplings!

- 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

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

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

No Higgs

Couplings to EW gauge bosons

Self-Couplings

Couplings to fermions

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

$$-\frac{h}{v} \sum_f m_f \bar{f} f$$

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

Effective Higgs Lagrangian

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

Higgs inside! Higgs inside! Higgs inside! Higgs inside!

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

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

2-fermion vertex corrections

2-fermion dipole operators

4-fermion operators

Gauge boson self-interactions

Violates CP

Warning: this splitting is to some extent basis dependent

Effective Higgs Lagrangian

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

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

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

Modify couplings of SM fermions to Z bosons, thus strongly constrained by EW measurements: quark operators at the level of 10^-2 (except top and bR), and lepton operators at the level of 10^-3

Not much room to affect LHC Higgs phenomenology

Effective Higgs Lagrangian

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

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

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

- Modify couplings of EDM and anomalous magnetic moments
- Extremely strong constraints on some operators, especially on imaginary parts
- Contribute to 3-body Higgs decay, so further suppression of effect on Higgs branching fractions

Effective Higgs Lagrangian

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

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

$$\begin{aligned}
&\frac{\bar c_H}{2v^2}\,\partial^\mu(H^\dagger H)\,\partial_\mu(H^\dagger H) + \frac{\bar c_T}{2v^2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar c_6\,\lambda}{v^2}\,(H^\dagger H)^3 \\
&+ \left(\left(\frac{\bar c_u}{v^2}\,y_u\,H^\dagger H\,\bar q_L H^c u_R + \frac{\bar c_d}{v^2}\,y_d\,H^\dagger H\,\bar q_L H d_R + \frac{\bar c_l}{v^2}\,y_l\,H^\dagger H\,\bar L_L H l_R\right) + h.c.\right) \\
&+ \frac{i\bar c_W\,g}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D}^\mu H\right)(D^\nu W_{\mu\nu})^i + \frac{i\bar c_B\,g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)(\partial^\nu B_{\mu\nu}) \\
&+ \frac{i\bar c_{HW}\,g}{m_W^2}\,(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{i\bar c_{HB}\,g'}{m_W^2}\,(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
&+ \frac{\bar c_\gamma\,g'^2}{m_W^2}\,H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{\bar c_g\,g_S^2}{m_W^2}\,H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}\,,
\end{aligned}$$

!CP and flavor assumed here!

- These operators affect the Higgs boson couplings directly measurable at the LHC!
- Some coefficients constrained by EWPT, but most could be order 1 without conflict with other experiments
- In fact, LHC Higgs data provide strongest constraint on most of these operators
- 11 parameters to determine from experiment

Effective Higgs Lagrangian

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

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

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

$$+\frac{H^\dagger H}{v^2}\left(i\tilde{c}_u \bar{q}_L H^c u_R + i\tilde{c}_d \bar{q}_L H d_R + i\tilde{c}_l \bar{L}_L H e_R + \text{h.c.}\right)$$

- No reason not to add CP violating interactions...
- ...but let's ignore those for a moment :-)

Effective Higgs Lagrangian

Summary of single Higgs couplings

$$\frac{\bar c_H}{2v^2}\,\partial^\mu(H^\dagger H)\,\partial_\mu(H^\dagger H) + \frac{\bar c_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \cancel{\frac{\bar c_6}{v^2}(H^\dagger H)^3}$$
$$+\left(\left(\frac{\bar c_u}{v^2}\,y_u\,H^\dagger H\,\bar q_L H^c u_R + \frac{\bar c_d}{v^2}\,y_d\,H^\dagger H\,\bar q_L H d_R + \frac{\bar c_l}{v^2}\,y_l\,H^\dagger H\,\bar L_L H l_R\right) + h.c.\right)$$
$$+\frac{i\bar c_W\,g}{2m_W^2}\left(H^\dagger\sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i + \frac{i\bar c_B\,g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu})$$
$$+\frac{i\bar c_{HW}\,g}{m_W^2}(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu} + \frac{i\bar c_{HB}\,g'}{m_W^2}(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$$
$$+\frac{\bar c_\gamma\,g'^2}{m_W^2}H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{\bar c_g\,g_S^2}{m_W^2}H^\dagger H G^a_{\mu\nu}G^{a\mu\nu},$$

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

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

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

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

Dictionary

$$\begin{aligned}
c_f &= 1 - \frac{\bar c_H}{2} - \bar c_f\\
c_V &= 1 - \frac{\bar c_H}{2}\\
c_{V,z} &= 1 - \frac{\bar c_H}{2} - 2\bar c_T\\
c_{gg} &= 16\frac{g_s^2}{g_L^2}\bar c_g\\
c_{\gamma\gamma} &= -16 s_w^2\bar c_\gamma\\
c_{Z\gamma} &= \frac{2s_w}{c_w}\left(\bar c_{HW} - \bar c_{HB} + 8s_w^2\bar c_\gamma\right)\\
c_{ZZ} &= 4\left(\bar c_{HW} + \bar c_{HB}\frac{s_w^2}{c_w^2} - 4\frac{s_w^4}{c_w^2}\bar c_\gamma\right)\\
c_{WW} &= 4\bar c_{HW}\\
\kappa_{Z\gamma} &= -\frac{2s_w}{c_w}\left(\bar c_{HW} - \bar c_{HB} + \bar c_W - \bar c_B\right)\\
\kappa_{ZZ} &= -2\left(\bar c_{HW} + \bar c_{HB}\frac{s_w^2}{c_w^2} + \bar c_W + \bar c_B\frac{s_w^2}{c_w^2}\right)\\
\kappa_{WW} &= -2\left(\bar c_{HW} + \bar c_W\right)
\end{aligned}$$

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

Effective Higgs Lagrangian

Summary of single Higgs couplings

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

- 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

$\Downarrow \qquad \Downarrow \qquad \Downarrow$

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

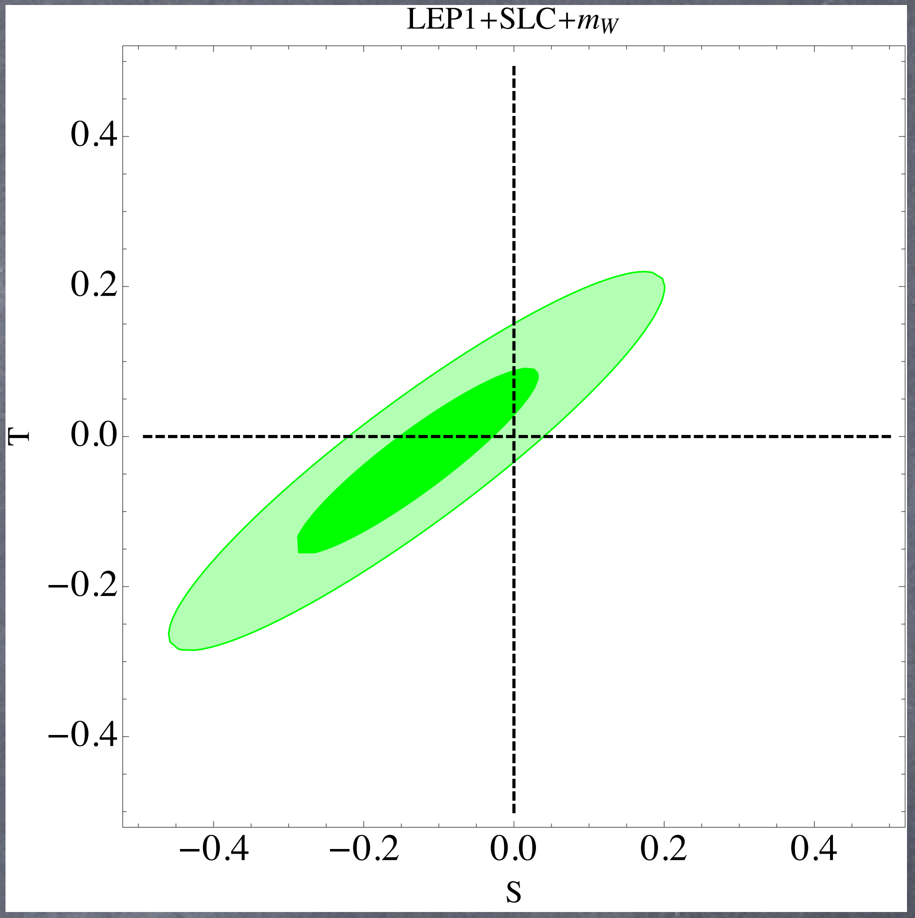
0-derivative couplings, present in SM

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

2-derivative, not present in SM

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



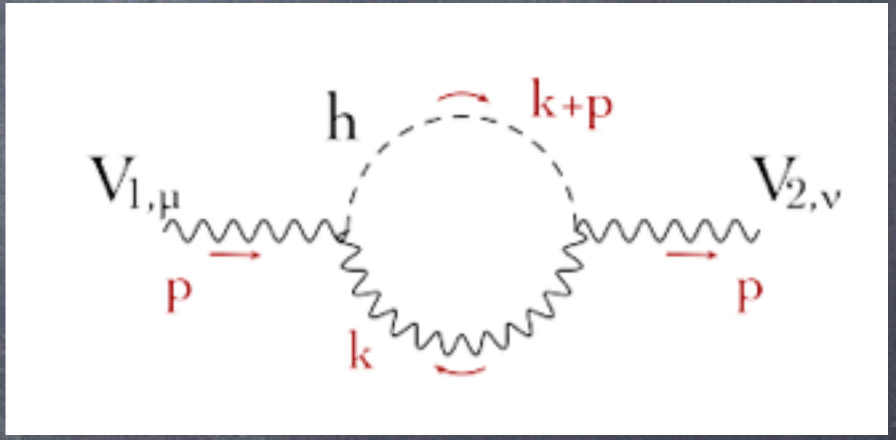
$$\Delta T = \alpha^{-1}\bar{c}_T \qquad \Rightarrow \qquad \bar{c}_T \lesssim 10^{-3}$$

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

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

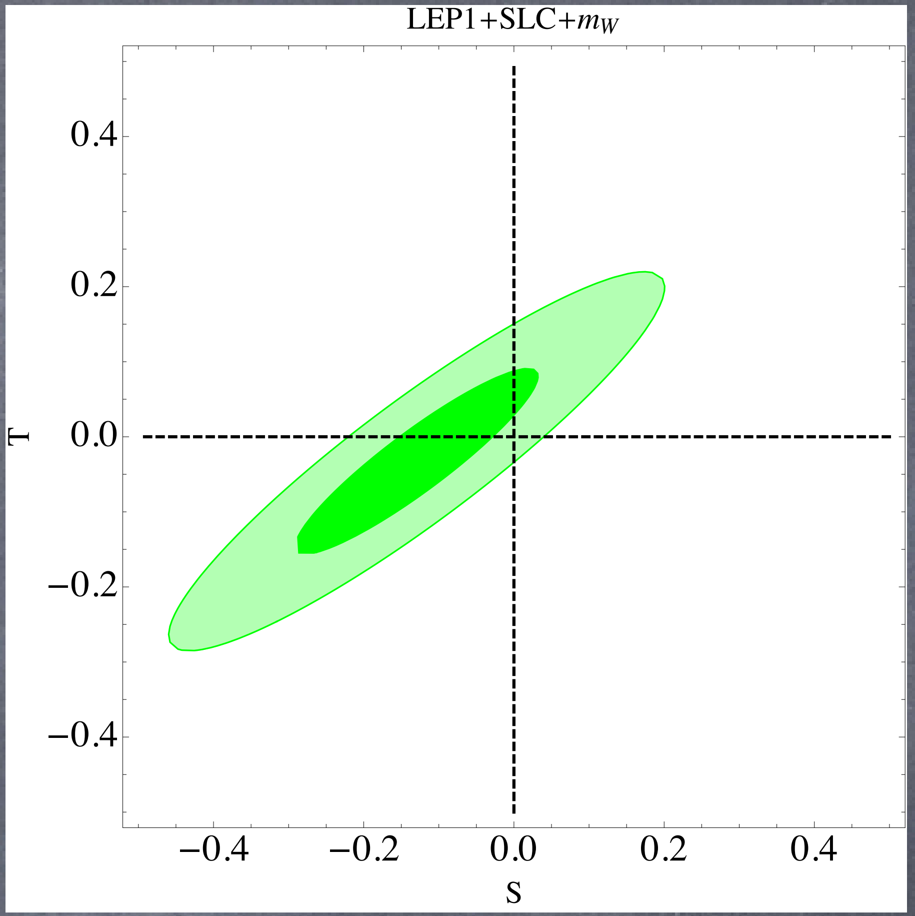
$$c_{V,z} = c_V$$

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

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

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

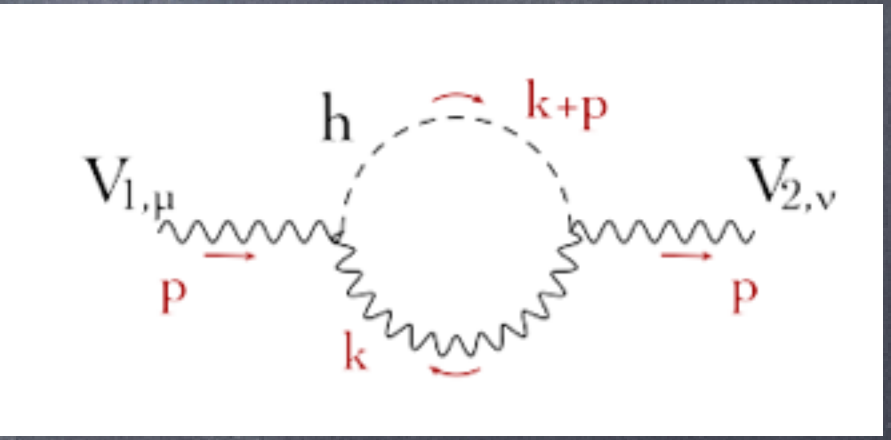


$$\Delta T = \alpha^{-1}\bar{c}_T \qquad \Rightarrow \qquad \bar{c}_T \lesssim 10^{-3}$$

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

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

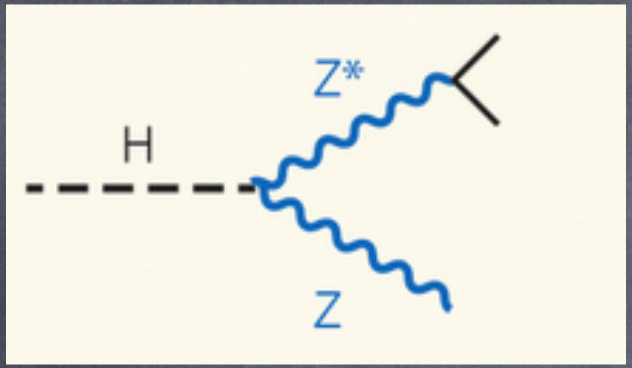
$$\mathcal{L}_{h,\text{sim}} = \frac{h}{v}\Big(\quad 2c_V m_W^2 W_\mu^+ W_\mu^- + c_V m_Z^2 Z_\mu Z_\mu$$
$$-c_u \sum_{q=u,c,t} m_q \bar{q} q - c_d \sum_{q=d,s,b} m_q \bar{q} q - c_l \sum_{l=e,\mu\tau} m_l \bar{l} l$$
$$+\frac{1}{4} c_{gg} G^a_{\mu\nu} G^a_{\mu\nu} - \frac{1}{4} c_{\gamma\gamma} \gamma_{\mu\nu}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

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

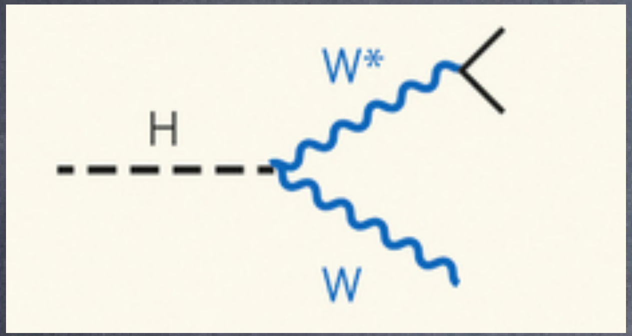
- Simpler effective theory with 7 free parameters
- <ALL> these parameters are meaningfully constrained by current Higgs data
- Limit of SM+SILH with constraints $\bar{c}_T = \bar{c}_6 = 0 \qquad \bar{c}_{HW} + \bar{c}_{HB} = 0 \qquad \bar{c}_B + \bar{c}_{HB} = 0$
- Standard Model limit: $c_V = c_f = 1$, $c_{gg} = c_{\gamma\gamma} = c_{Z\gamma} = 0$

Linking effective Lagrangian to observables

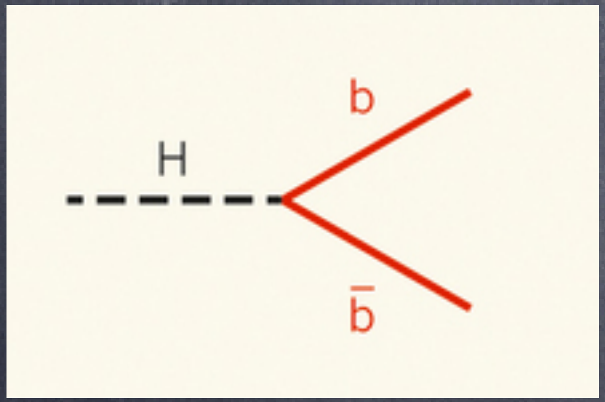
Tree-level Higgs decays



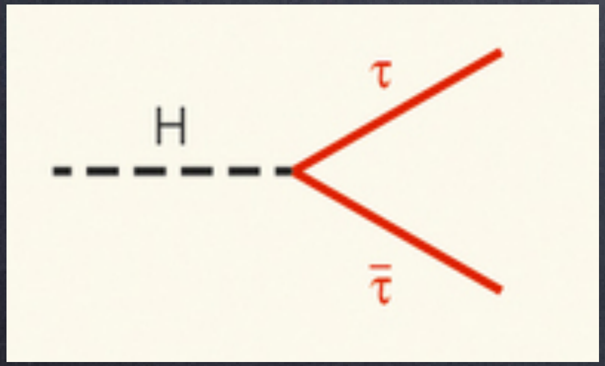
$$\frac{\Gamma_{ZZ^*}}{\Gamma^{\rm SM}_{ZZ^*}} \simeq c_V^2 + 0.26 c_V c_{ZZ} + 0.02 c_{ZZ}^2$$



$$\frac{\Gamma_{WW^*}}{\Gamma^{\rm SM}_{WW^*}} \simeq c_V^2 + 0.38 c_V c_{WW} + 0.05 c_{WW}^2$$



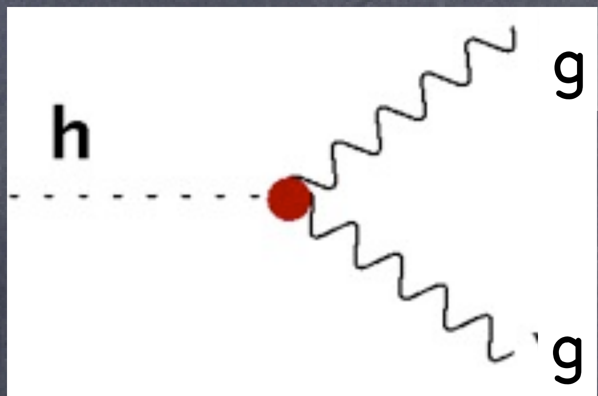
$$\frac{\Gamma_{bb}}{\Gamma^{\rm SM}_{bb}} \simeq c_d^2$$

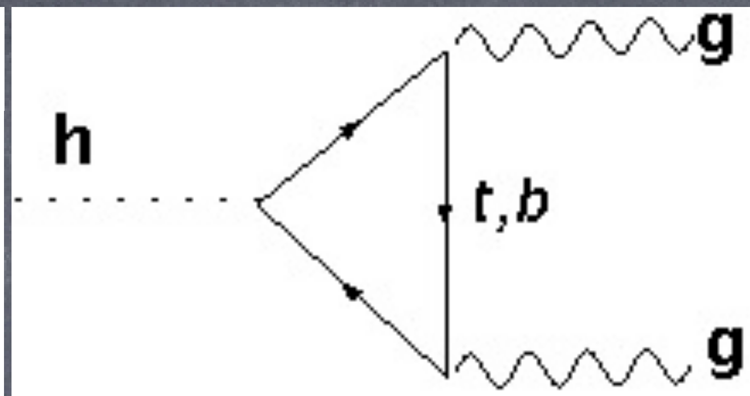


$$\frac{\Gamma_{\tau\tau}}{\Gamma^{\rm SM}_{\tau\tau}} \simeq c_l^2$$

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

1-Loop Higgs decays

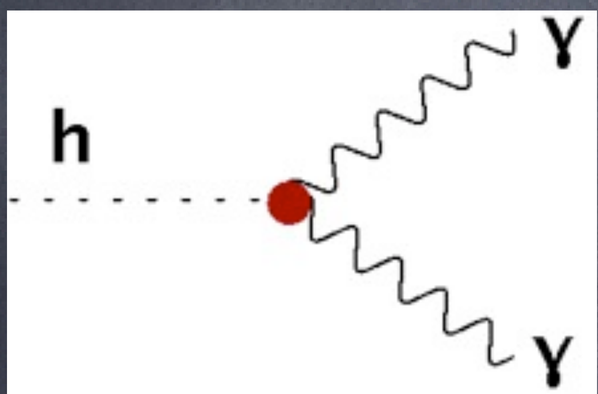


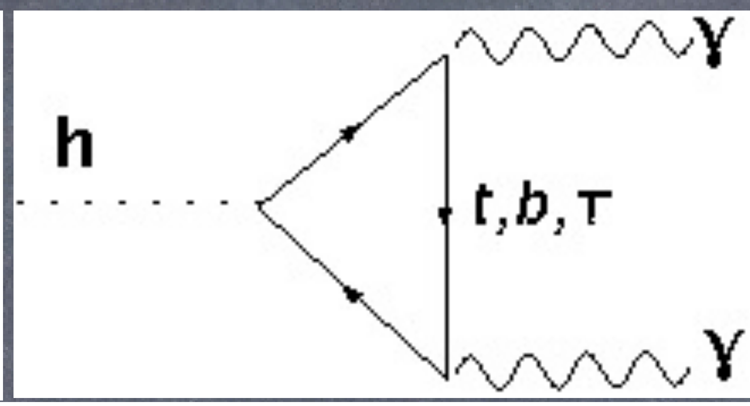


$$\frac{\Gamma_{gg}}{\Gamma_{gg}^{\rm SM}} \simeq \frac{|\hat{c}_{gg}|^2}{|\hat{c}_{gg,\rm SM}|^2}$$

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

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





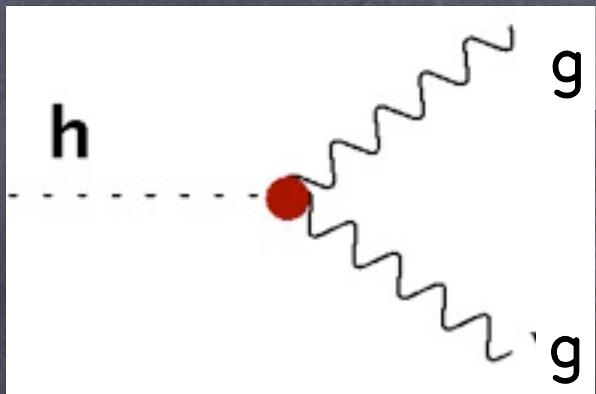
$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{\rm SM}} \simeq \frac{|\hat{c}_{\gamma\gamma}|^2}{|\hat{c}_{\gamma\gamma,\rm SM}|^2}$$

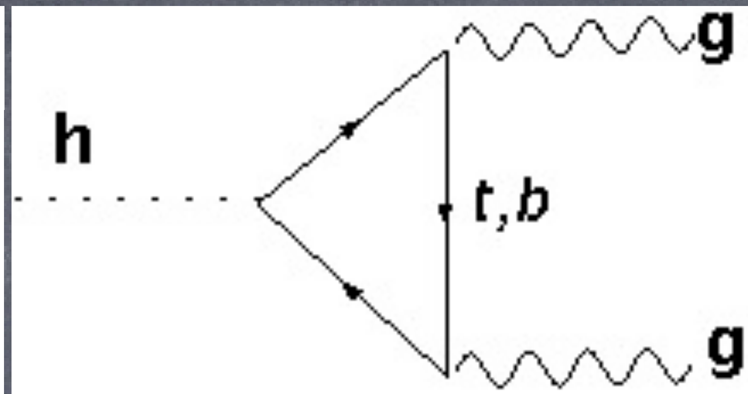
$$\hat{c}_{\gamma\gamma} = c_{\gamma\gamma} + 10^{-2}\,[0.97\, c_V - 0.21\, c_u + \dots]$$

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

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

1-Loop Higgs decays

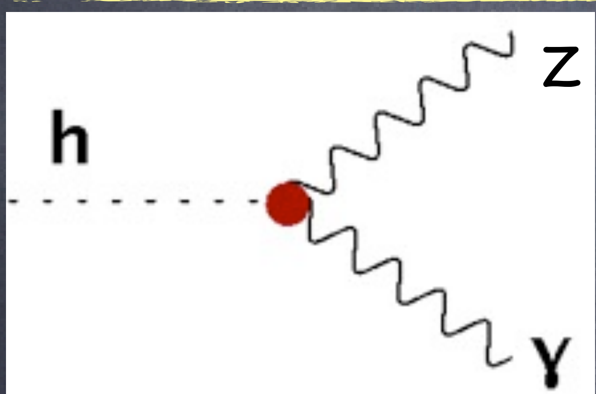


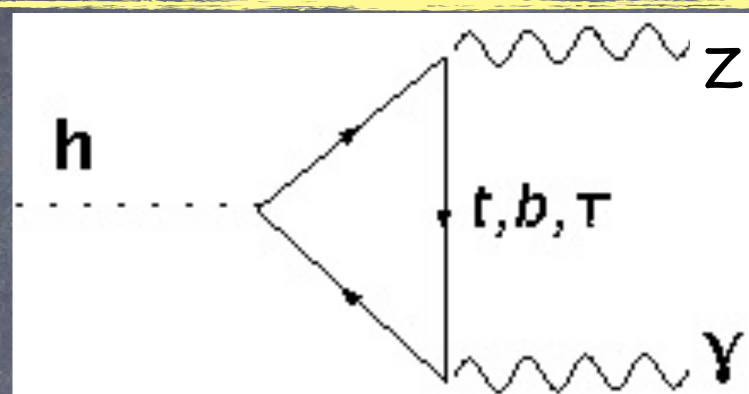


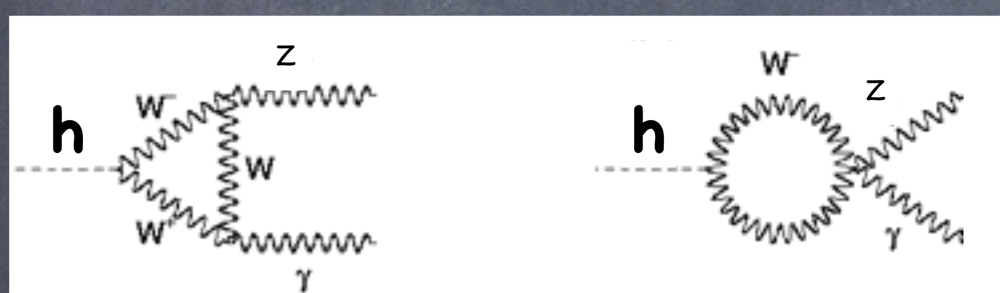
$$\frac{\Gamma_{gg}}{\Gamma_{gg}^{\mathrm{SM}}} \simeq \frac{|\hat{c}_{gg}|^2}{|\hat{c}_{gg,\mathrm{SM}}|^2}$$

$$\hat{c}_{gg} = c_{gg} + 10^{-2}\left[1.28\, c_u - (0.07 - 0.1\, i)\, c_d + \ldots\right]$$

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







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

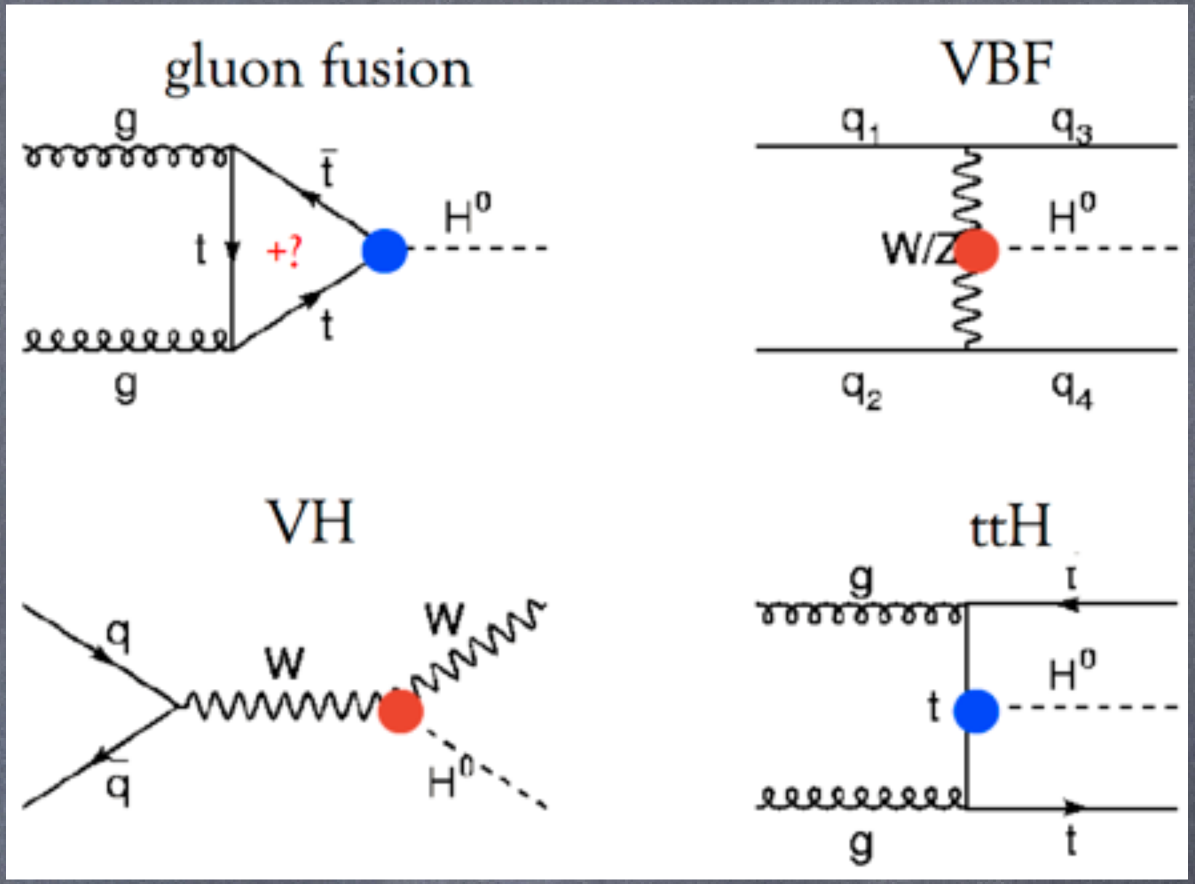
$$\hat{c}_{Z\gamma} = c_{Z\gamma} + 10^{-2}\left[1.49\, c_V - 0.09\, c_u + \ldots\right]$$

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

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

Higgs production

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



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

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

$$\frac{\sigma_{WH}}{\sigma_{WH}^{\rm SM}} \simeq c_V^2 - 3.6 c_V c_{WW} + 5.5 c_{WW}^2$$

$$\frac{\sigma_{ZH}}{\sigma_{ZH}^{\rm SM}} \simeq c_V^2 - 1.0 c_V c_{Z\gamma} - 3.4 c_V c_{ZZ} + 2.4 c_{Z\gamma}^2 + 2.7 c_{Z\gamma} c_{ZZ} + 4.3 c_{ZZ}^2$$

Higgs rates

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

$$\hat{\mu}_{\gamma\gamma}^{ggF} = \frac{\sigma_{\rm ggF}}{\sigma_{\rm ggF}^{\rm SM}} \frac{\Gamma_{\gamma\gamma}}{\Gamma_{\rm tot}} \frac{\Gamma_{\rm tot,SM}}{\Gamma_{\gamma\gamma}^{\rm SM}} \simeq \frac{|\hat{c}_{gg}|^2}{|\hat{c}_{gg,\rm SM}|^2} \frac{|\hat{c}_{\gamma\gamma}|^2}{|\hat{c}_{\gamma\gamma,\rm SM}|^2} \frac{\Gamma_{\rm tot,SM}}{\Gamma_{\rm tot}}$$

$$\frac{\Gamma_{\rm tot}}{\Gamma_{\rm tot,SM}} \approx 0.56 c_d^2 + 0.03 c_u^2 + 0.06 c_l^2 + 0.26 c_V^2 + 0.09 \frac{|\hat{c}_{gg}|^2}{|\hat{c}_{gg,\rm SM}|^2}$$

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

Higgs couplings vs 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

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

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

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

When 2-derivative couplings are present

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

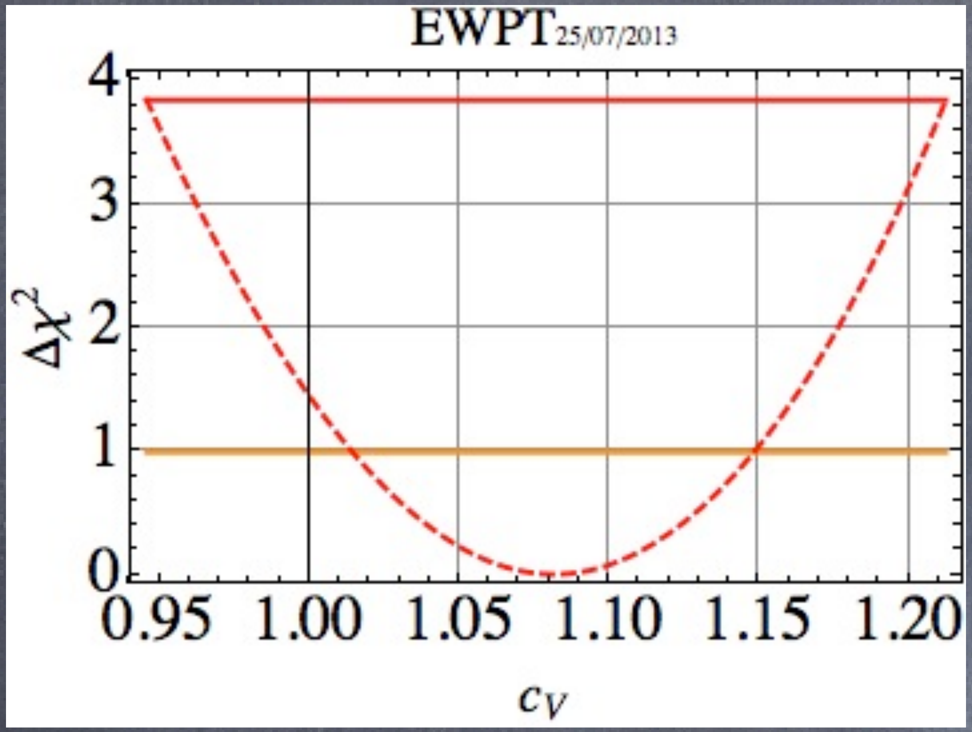
$$\alpha S = -4\frac{g_Lg_Y}{g_L^2+g_Y^2}\delta\Pi_{3B}^{(2)},\quad \alpha T = \frac{\delta\Pi_{11}^{(0)}-\delta\Pi_{33}^{(0)}}{m_W^2},\quad \alpha U = \frac{4g_Y^2}{g_L^2+g_Y^2}\left(\delta\Pi_{11}^{(2)}-\delta\Pi_{33}^{(2)}\right)$$

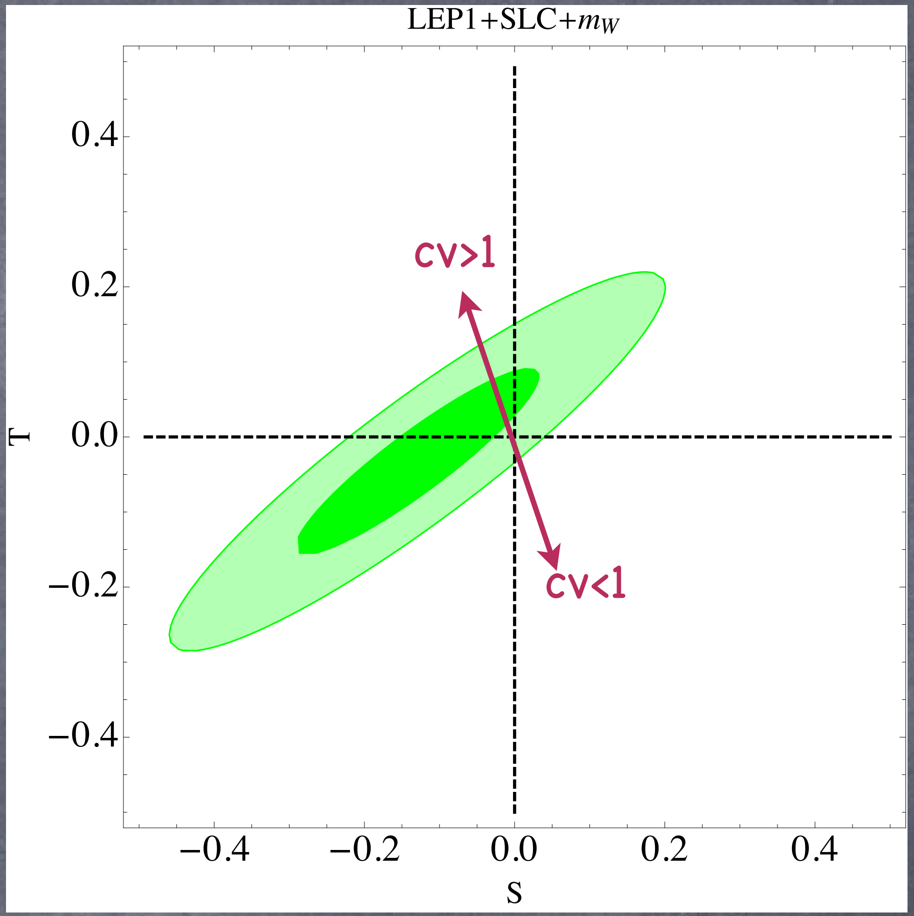
$$\alpha V = m_W^2\left(\delta\Pi_{11}^{(4)}-\delta\Pi_{33}^{(4)}\right),\quad \alpha W = -m_W^2\delta\Pi_{33}^{(4)},\quad \alpha X = -m_W^2\delta\Pi_{3B}^{(4)},\quad \alpha Y = -m_W^2\delta\Pi_{BB}^{(4)}.\quad \alpha Z = -m_W^2\Pi_{g}$$

Higgs couplings vs 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





Caveats:

- Constraints depend (logarithmically) on cut-off scale of effective theory, here chosen at 3 TeV
- Constraints can go away at the price of tuning Higgs contributions to S and T against other significant contributions from BSM

Higgs couplings vs EWPT

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

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

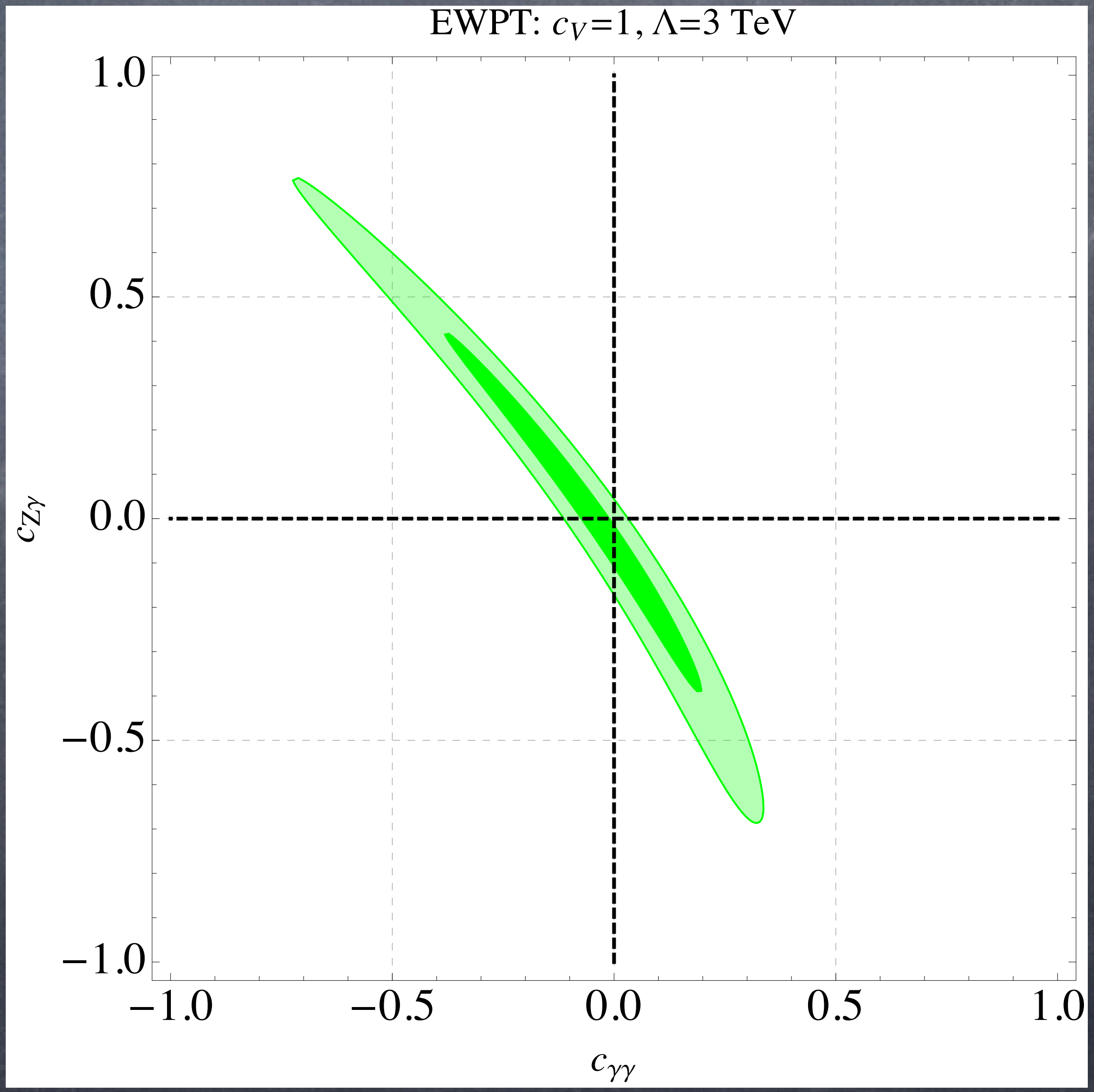
$$\alpha S \approx \frac{g_L g_Y}{48\pi^2(g_L^2+g_Y^2)}\Big\{2g_Lg_Y\left(1-c_V^2\right)+6c_V\left[2g_Lg_Yc_{\gamma\gamma}+c_{Z\gamma}(g_L^2-g_Y^2)\right]$$
$$+3\left[g_Lg_Y(c_{Z\gamma}^2-c_{\gamma\gamma}^2)-(g_L^2-g_Y^2)c_{\gamma\gamma}c_{Z\gamma}\right]\Big\}\log(\Lambda/m_Z)\,,$$

This combination enters linearly (when cV=1) and therefore is strongly constrained

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

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

Orthogonal combination of cγγ and cZγ enters quadratically, and therefore is less constrained



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

- Starting with unconstrained 7 parameter, than 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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[29] A. Azatov and J. Galloway, "Electroweak Symmetry Breaking and the Higgs Boson: Confronting Theories at Colliders," arXiv:1212.1380 [hep-ph].

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

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[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]].

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[9] M. Klute, R. Lafaye, T. Plehn, M. Rauch and D. Zerwas, "Measuring Higgs Couplings from LHC Data," Phys. Rev. Lett. **109** (2012) 101801 [arXiv:1205.2699 [hep-ph]].

7 Parameter Fit

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7 parameter fit

$$c_V = 1.04^{+0.03}_{-0.03}$$
$$c_u = 0.55^{+0.66}_{-1.72}$$
$$c_d = 1.03^{+0.26}_{-0.20}$$
$$c_l = 1.04^{+0.21}_{-0.21}$$
$$c_{gg} = 0.005^{+0.022}_{-0.031}$$
$$c_{\gamma\gamma} = 0.0001^{+0.0018}_{-0.0021}$$
$$c_{Z\gamma} = 0.006^{+0.015}_{-0.028}$$

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

$\Delta\chi^2 = \chi^2_{SM} - \chi^2_{min} = 4.9$, with 7 d.o.f.
the SM hypothesis is a perfect fit :-(((

7 parameter fit

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

It couples to W and Z mass!!!

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

$$c_u = 0.55^{+0.66}_{-1.72}$$

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

$$c_d = 1.03^{+0.26}_{-0.20}$$

$$c_l = 1.04^{+0.21}_{-0.21}$$

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

$$c_{gg} = 0.005^{+0.022}_{-0.031}$$

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

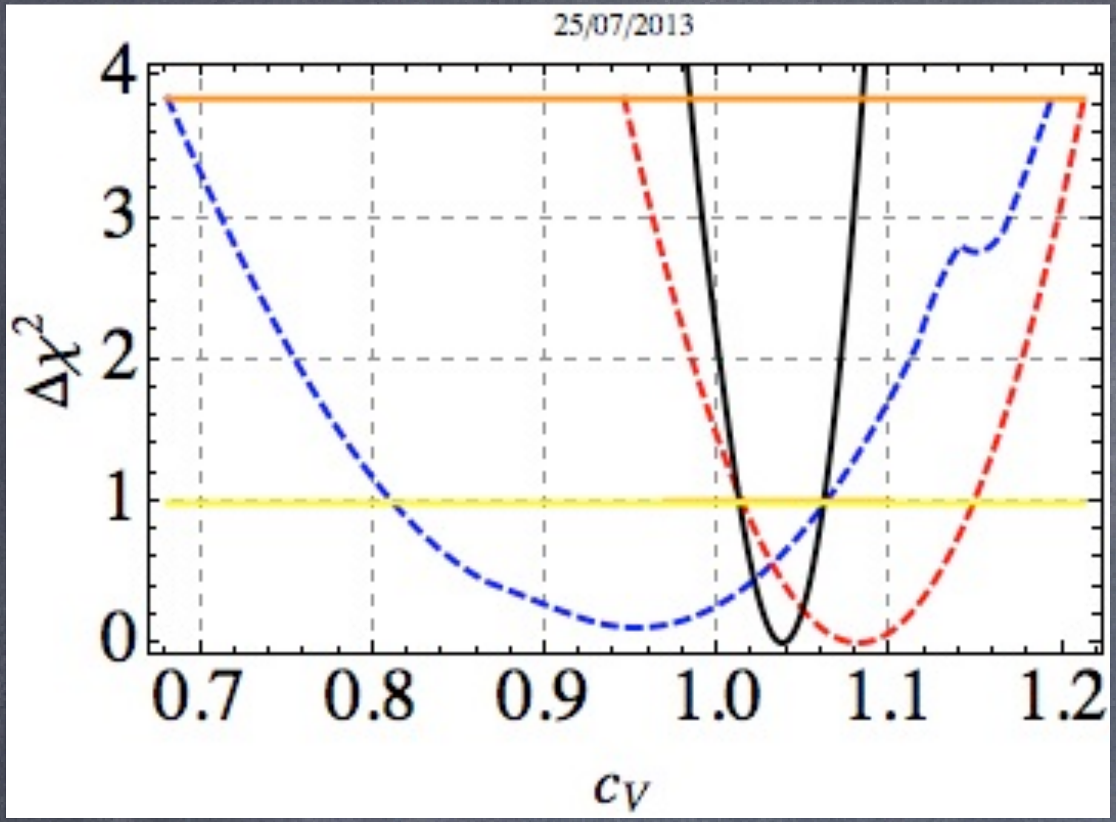
$$c_{\gamma\gamma} = 0.0001^{+0.0018}_{-0.0021}$$

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



- 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

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

7 parameter fit

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

It couples to W and Z mass!!!

$$c_u = 0.55^{+0.66}_{-1.72}$$

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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

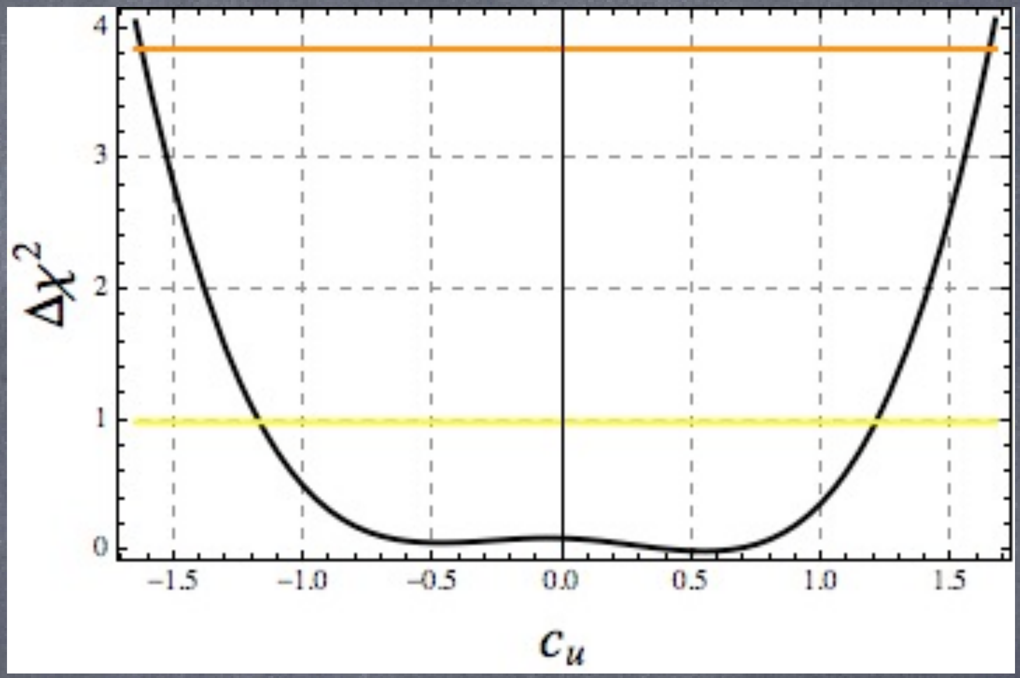
Couplings to gluons and top probed mostly by gluon fusion Higgs production mode

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

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

Constrained combination

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



In a general situation, 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

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

It couples to W and Z mass!!!

$$c_u = 0.55^{+0.66}_{-1.72}$$

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

$$c_d = 1.03^{+0.26}_{-0.20}$$

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$$c_{gg} = 0.005^{+0.022}_{-0.031}$$

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

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

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

It couples to W and Z mass!!!

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$$c_{gg} = 0.005^{+0.022}_{-0.031}$$

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)

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

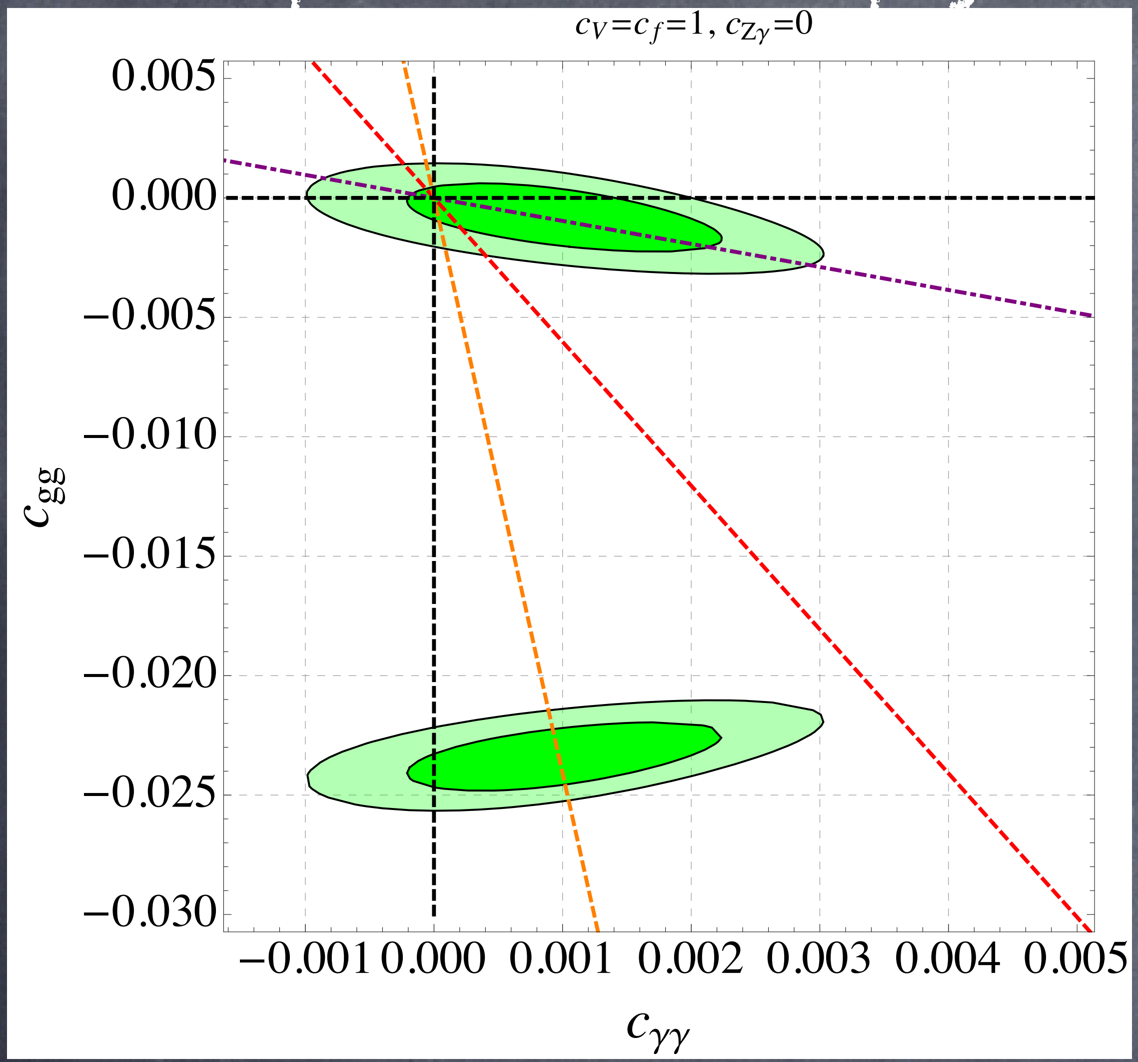
Weak limit on coupling to Zγ due to weak experimental limits (c.f with effective $c_{Z\gamma}$=0.014 in SM)

2 Parameter Fit

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

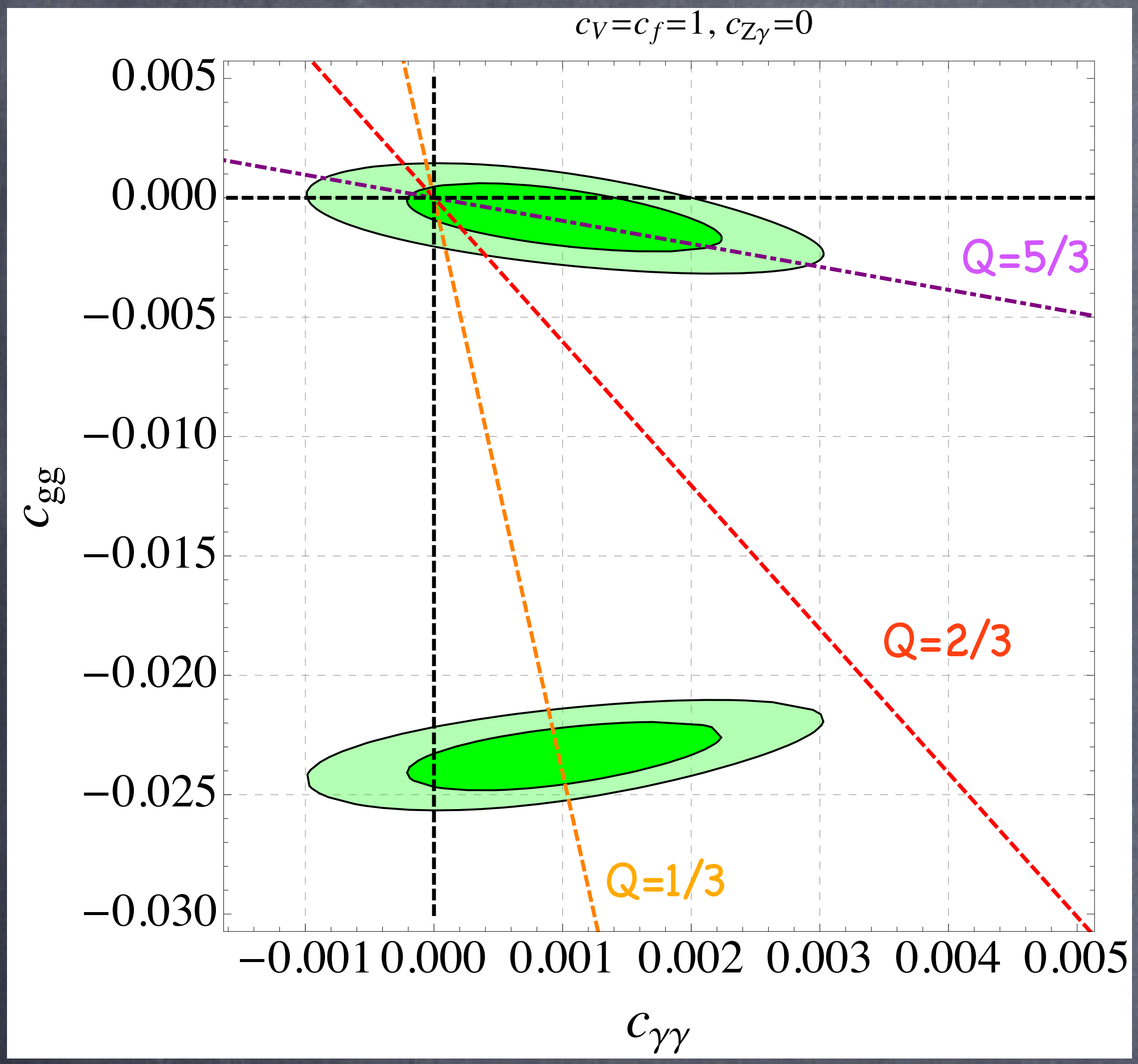
- On this plane, no significant variation of χ2 in Vh→bb and h→ττ channel, only h→γγ and h→VV* channels relevant

- 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

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

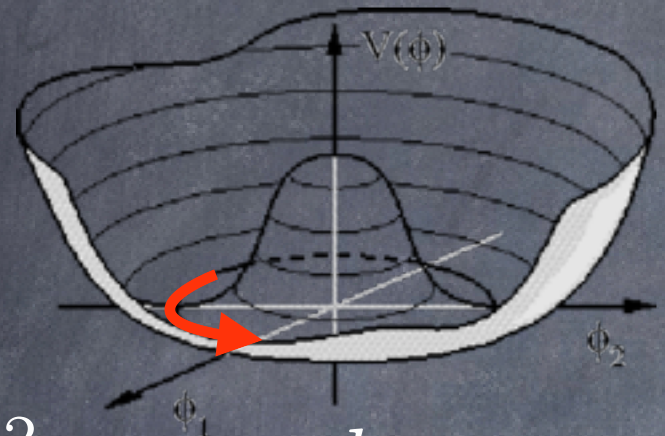
$$\delta c_{\gamma\gamma} = -\frac{\alpha_s}{\pi}\left(\frac{2}{3} c_f Q_f^2 d(r_f) + \frac{1}{6} c_s Q_s^2 d(r_s)\right)$$

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

Composite Higgs

NGBHiggs couplings to SM fields

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



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

$$\frac{g^2}{4} f^2 \sin^2\frac{h}{f} W_\mu W^\mu \overset{h \to \langle h\rangle + h}{=} \frac{g^2}{4} \overbrace{f^2 \sin\frac{\langle h\rangle}{f}^2}^{v^2} W_\mu W^\mu$$

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

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

Coupling to W and
model independent

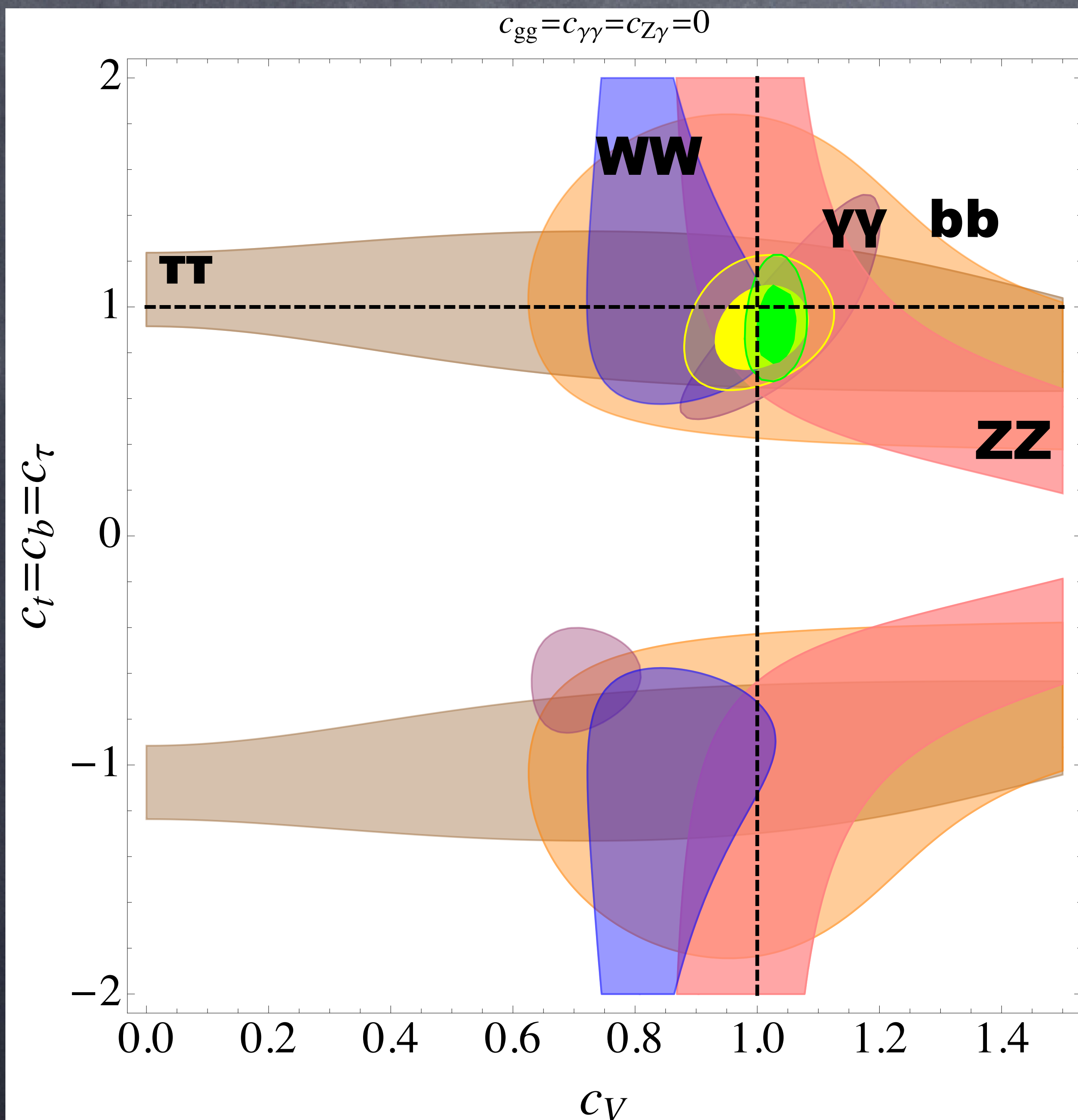
$$c_f = \frac{1+2m-(1+2m+n)v^2/f^2}{\sqrt{1-v^2/f^2}}$$

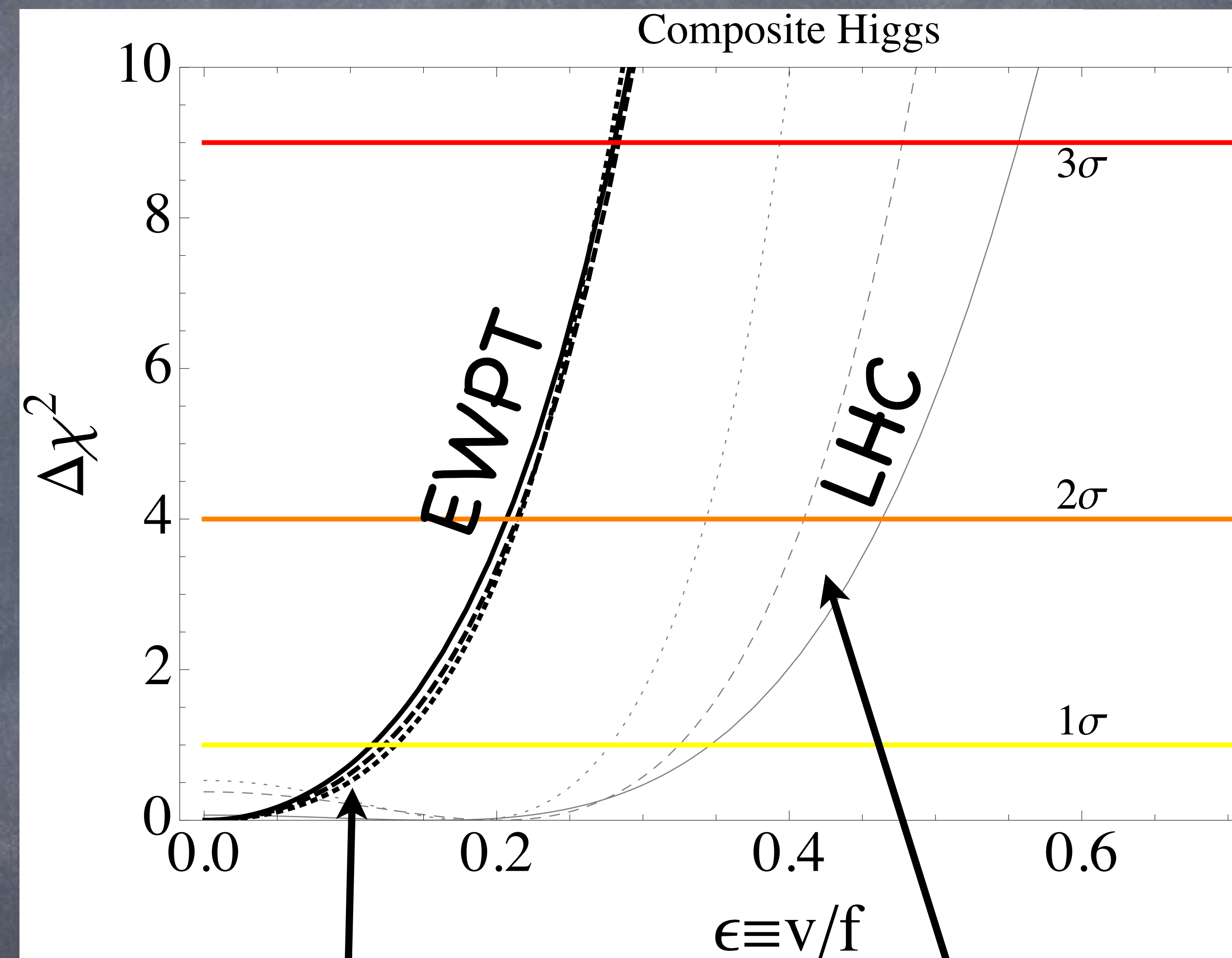
Coupling to fermions
model dependent $\quad m_t \sim \sin^{2m+1}\left(\frac{h}{f}\right)\cos^n\left(\frac{h}{f}\right)$

Pomarol,Riva,'12

Slide stolen from Francesco Riva

NGBHiggs couplings to SM fields





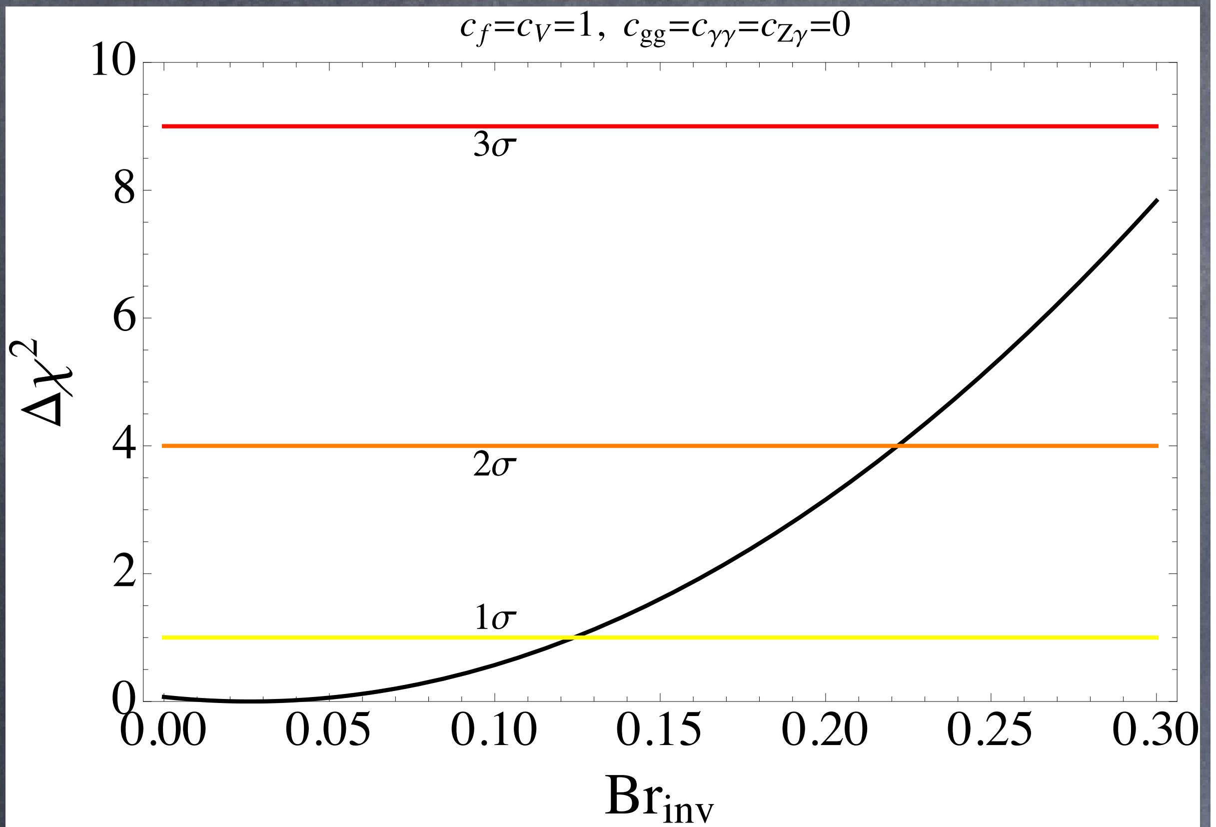
Strong sector contributions can weaken this bound

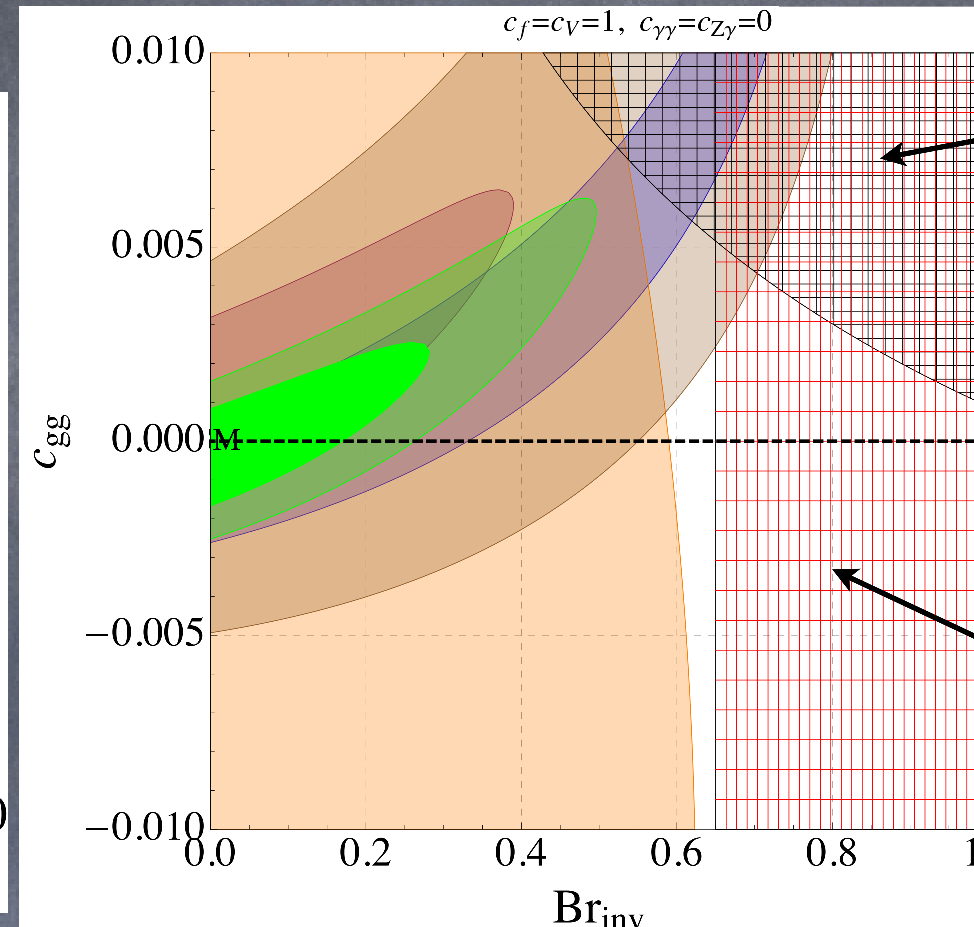
(not this)

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 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!

How can we do better?

Boudjema et al.
1307.5865

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

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

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

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

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

Conclusions

- Higgs !!!
- Effective Theory !!!