Extraction of Yukawa couplings from Higgs decay

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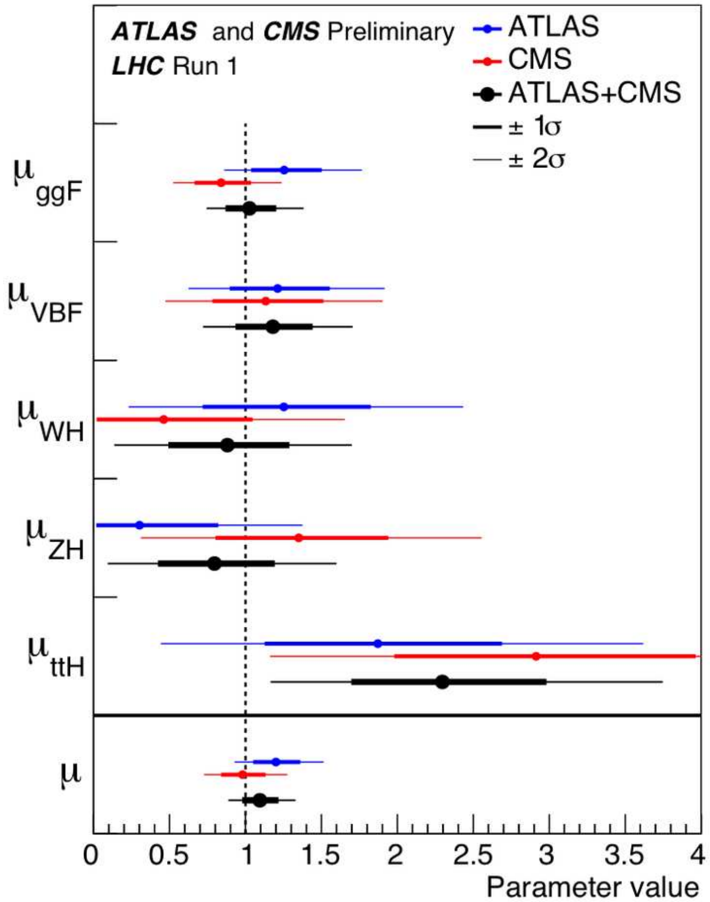
Outline

- How much do we know about the Higgs?
- Higgs Yukawas, from top to up
- Generalized Yukawas
- Fitting with EFTs
- Summary and outlook

A Higgs, but the Higgs?

- Higgs discovery at the LHC confirms the Standard Model as an excellent low-energy approximation to the electroweak interactions. However, extremely hard to get to LEP precision in the Higgs sector. Higgs couplings currently SM-like to $\mathcal{O}(10\%)$.



A Higgs, but the Higgs?

- The Higgs mechanism was already established long before the Higgs discovery (Goldstones giving mass to the W and Z gauge bosons). What we now know is that $v = 246$ GeV is really a scalar vev (and not a condensate).

- Even a slight deviation from the SM Higgs makes the theory nonrenormalizable and the presence of new physics a necessity.

- In the SM, Higgs is proportional to the mass: experimental challenge, especially for light fermions... At the same time, opportunity for BSM detection.

- The flavor hierarchy problem is still with us.

Higgs anomalous couplings at the LHC

Run-2 prospects:

[Numbers borrowed from H. Kroha at Aspen 2014]

$\Delta\mu/\mu[\%](300\ \text{fb}^{-1})$	$\gamma\gamma$	WW	ZZ	$\tau\tau$	bb	$\mu\mu$	$Z\gamma$
ATLAS	14 (9)	13 (8)	12 (6)	22 (16)	—	39 (38)	147 (145)
CMS	12 (6)	11 (6)	11 (7)	14 (8)	14 (11)	42 (40)	62 (62)

$\Delta\kappa/\kappa[\%](300\ \text{fb}^{-1})$	$\gamma\gamma$	WW	ZZ	gg	$\tau\tau$	bb	tt	$\mu\mu$	$Z\gamma$
ATLAS	13 (8)	8 (7)	8 (7)	11 (9)	18 (13)	κ_τ	22 (20)	23 (21)	79 (78)
CMS	7 (5)	6 (4)	6 (4)	8 (6)	8 (6)	13 (10)	15 (14)	23 (23)	41 (41)

Precision goal between $5-10\%$. With $3000\ \text{fb}^{-1}$, not below few $\%$.

Higgs Yukawa couplings

Current precision/bounds on Yukawas:

κ_t (global fit)	1.34 ± 0.19
κ_b $(H \to b\bar{b})$	0.71 ± 0.31
κ_τ $(H \to \tau\bar{\tau})$	0.97 ± 0.23
κ_c $(H \to c\bar{c})$	$< 230(6.2)$
κ_s $(H \to \phi\gamma)$	—
κ_μ $(H \to \mu\bar{\mu})$	≤ 7.0
κ_e $(H \to e\bar{e})$	$< 611(150)$
κ_d $(H \to \rho\gamma)$	—
κ_u $(H \to \rho\gamma)$	—

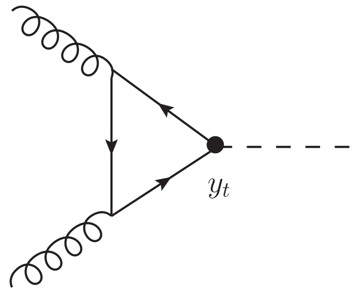
where

$$\kappa_f = \frac{y_f}{y_f^{SM}}$$

- For off-shell Higgs one has to fight against (dominant) backgrounds with gluon, Z and photon exchange. Efficient flavor tagging is also a challenge.
- Alternative: on-shell Higgs with hadronic states, but extremely suppressed.

Third generation: y_t

- Cannot be extracted from Higgs decay but fundamental for Higgs production through gluon fusion.



- Global fits give

$$\kappa_t \sim 1.4(0.3)$$

- At a linear collider one could reach the few percent precision. At a VLHC, similar precision in associated $t\bar{t}h$ production [Belyaev et al, hep-ph/0110274]

- Its value is also important for Higgs inflation.

$H \to b\bar{b}, \tau\bar{\tau}$

Best overall channels: substantial decay rates and good flavor tagging.

- b quark: Large coupling, large decay rate (57%), good bottom tagging.
- Experimentally one determines the $m_{\bar{b}b}$ invariant mass, unfortunately with a large uncertainty (irreducible backgrounds).
- A naive average from CMS and ATLAS gives

$$\kappa_\tau = 0.71 \pm 0.31$$

- An alternative to fight the backgrounds is to consider $H \to \Upsilon\gamma$, but extremely suppressed, Br$[H \to \Upsilon\gamma] \sim 10^{-9}$.
- τ lepton: Competitive with $H \to b\bar{b}$, though with smaller decay rate (6%).
- A naive average gives

$$\kappa_\tau = 0.97 \pm 0.23$$

Muons and electrons

- Small branching ratio, Br$\sim 2.2 \cdot 10^{-4}$, big backgrounds, but very good tagging ($\delta m_{\mu\mu} \sim 2 - 3\%$). The current bounds are (ATLAS and CMS)

$$\kappa_\mu \leq 7.0(7.2), \qquad \kappa_\mu \leq 7.4(6.5)$$

- Electrons limit at

$$\kappa_e \leq 611$$

from direct search could go down to 150 at the end of Run-2.

Second generation quarks

s quark: best candidate decay mode, $Br[h \to \phi\gamma] \sim 10^{-6}$. Still small.

c quark: different strategies.

- Exclusive hadronic decay $h \to J/\psi\gamma$. However, $Br[h \to J/\psi\gamma \to \mu^+\mu^-\gamma] = 1.8 \cdot 10^{-7}$. [Bodwin et al'13; Kagan et al'15; König et al'15].

- $pp \to W/Zh(h \to c\bar{c})$. Relies on c-tagging. [Perez et al'14-16]

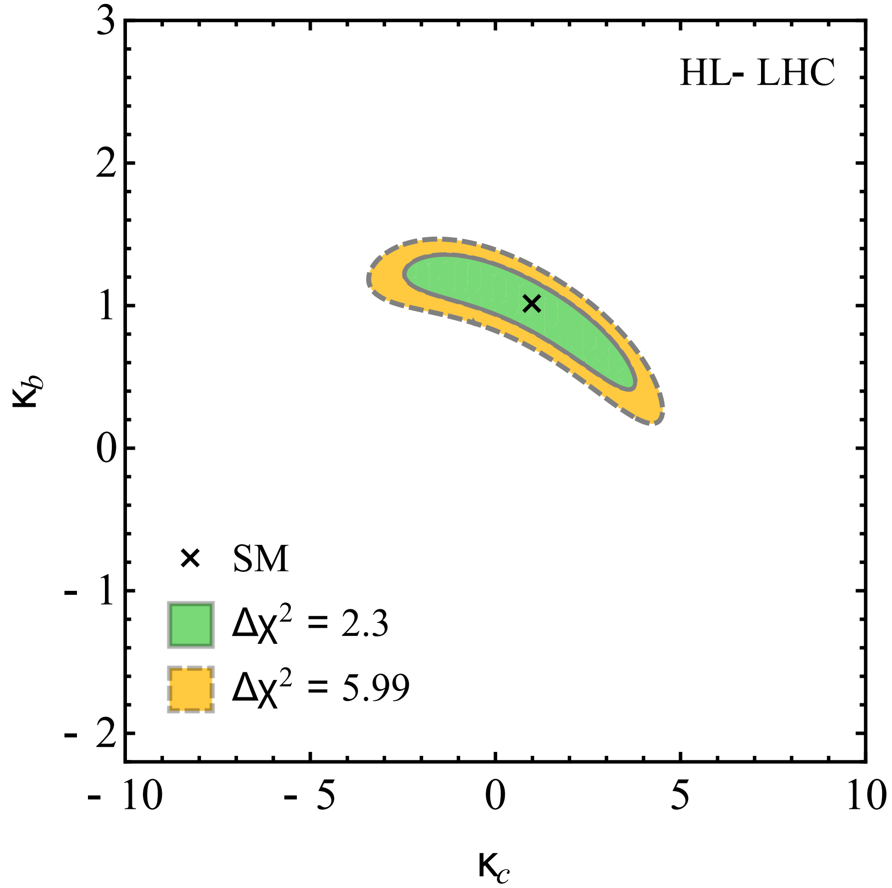
- $pp \to hc$. Relies on c-tagging. [Brivio et al'15]

- Transverse momentum distribution of Higgs plus jets $gg \to hj$ [Bishara et al'17]
  Enhancement of the form

$$\kappa_Q \frac{m_Q^2}{m_h^2} \log^2\left(\frac{p_\perp^2}{m_Q^2}\right)$$

  due to interference with the top. With quark initiated production ($gQ \to hQ, Q\bar{Q} \to hg$), scaling goes like κ_Q^2.

Second generation quarks



- Current constraint on $\kappa_c \in [-16, 18]$ (run I), projected $\kappa_c \in [-0.6, 3.0]$ (HL-LHC).
- Current best constraint from global fit, $\kappa_c \sim 6.2$.

Light quark Yukawas

- The previous problems get even more acute for light quarks. $h \to \rho\gamma$ small but best chance through Higgs decays.
- Alternative mechanisms really needed.
- Atomic clock transitions [Delaunay et al, 1601.05087]
- Charge asymmetry in $hW^{\pm} \to \ell^{\pm}(\ell^{\pm}\nu jj)$ [Yu, 1609.06592]
- Both of them face other challenges...

Generalized Yukawas

- So far, only the SM (Yukawa) couplings considered.
- If BSM physics is present, one expects generalized Yukawa interactions (e.g. $hh\bar{t}t$). Different approaches in the literature.
- Higgs-dependent Yukawa couplings: [Giudice et al, 0804.1753]

$$Y_{ij}(H) = \sum_{n=0}^{\infty} c_{ij}^{(n)} \left(\frac{H^\dagger H}{M^2} \right)^n$$

- Linear EFT:

$$\frac{H^\dagger H}{\Lambda^2} (\bar{Q}_L \tilde{H} t_R)$$

  dimension-6 operator extending the SM (subleading contribution)
- Nonlinear EFT:

$$Y_{ij}(h) = Y_{ij} + \sum_{n=1}^{\infty} Y_{ij}^{(n)} \left(\frac{h}{v} \right)^n$$

  No dimensional penalty, $Y_{ij}(h)$ is a leading order function.
- Interesting to probe this different pictures in, e.g., double Higgs production.

EFTs for Higgs Yukawa interactions

- Linear and nonlinear EFTs are the most general ways to fit Higgs data consistently.

- Both EFT generate the same vertex corrections, but at different orders in the expansion.

- Linear EFT is a theory with a SM Higgs plus new physics. Renormalizable but not a framework to test the Higgs hypothesis. Corrections typically of $\mathcal{O}(v^2/\Lambda^2 \sim \%)$ in both Higgs and gauge-fermion sectors.

- Nonlinear EFT: nonstandard Higgs plus new physics. Renormalizable order by order. Corrections in the Higgs sector are leading, $\mathcal{O}(10\%)$ or less, corrections to gauge-fermion sector loop-suppressed (permil or less).

- Bottomline: Any set of operators used to fit have some underlying theoretical (dynamical) assumptions. One needs to be consistent with the choice.

$$\mathcal{L}_Y = -\frac{y_f}{\sqrt{2}} \left(\kappa_f \bar{f} f + i \tilde{\kappa}_f \bar{f} \gamma_5 f \right) h$$

  If embedded in a nonlinear framework, κ_f could be sizeable. In the linear framework it should be a $\mathcal{O}(\%)$ deviation from the SM.

What experimentalists measure: the κ formalism

- Signal-strength based parametrization of Higgs decay channels:

$$\mu_j = \frac{\Gamma_j^{\exp}}{\Gamma_j^{SM}}$$

- Limited scope: conceived for potential deviations in rates (scope of Run I).

- Upgrading needed to go beyond, e.g., study kinematical distributions (scope of Run $\geq$ II).

- QFT interpretation: modification of SM vertices. Typically parametrized as

$$\mathcal{L}_\kappa = 2\kappa_V\left(m_W^2 W_\mu W^\mu + \frac{m_Z^2}{2} Z_\mu Z^\mu\right)\frac{h}{v} - \sum_{f=t,b,\tau}\kappa_f\, y_f \bar{f} f h + \kappa_{gg}\frac{g_s^2}{16\pi^2} G_{\mu\nu}G^{\mu\nu}\frac{h}{v} + \kappa_{\gamma\gamma}\frac{e^2}{16\pi^2} F_{\mu\nu}F^{\mu\nu}\frac{h}{v}$$

- A priori not clear how to upgrade it (renormalizability and unitarity are lost...). It has even been claimed it is inconsistent...

- SM is UV-complete, $\mathcal{L}_\kappa$ can only be an EFT.

Fitting with EFTs

- EFTs are more than effective operators, they are an expansion in some small parameter(s). When fitting one should implement also the hierarchy that results.

- Bayesian statistics right tool (priors) [Phillips et al, arXiv:0808.3643]

- Consider again

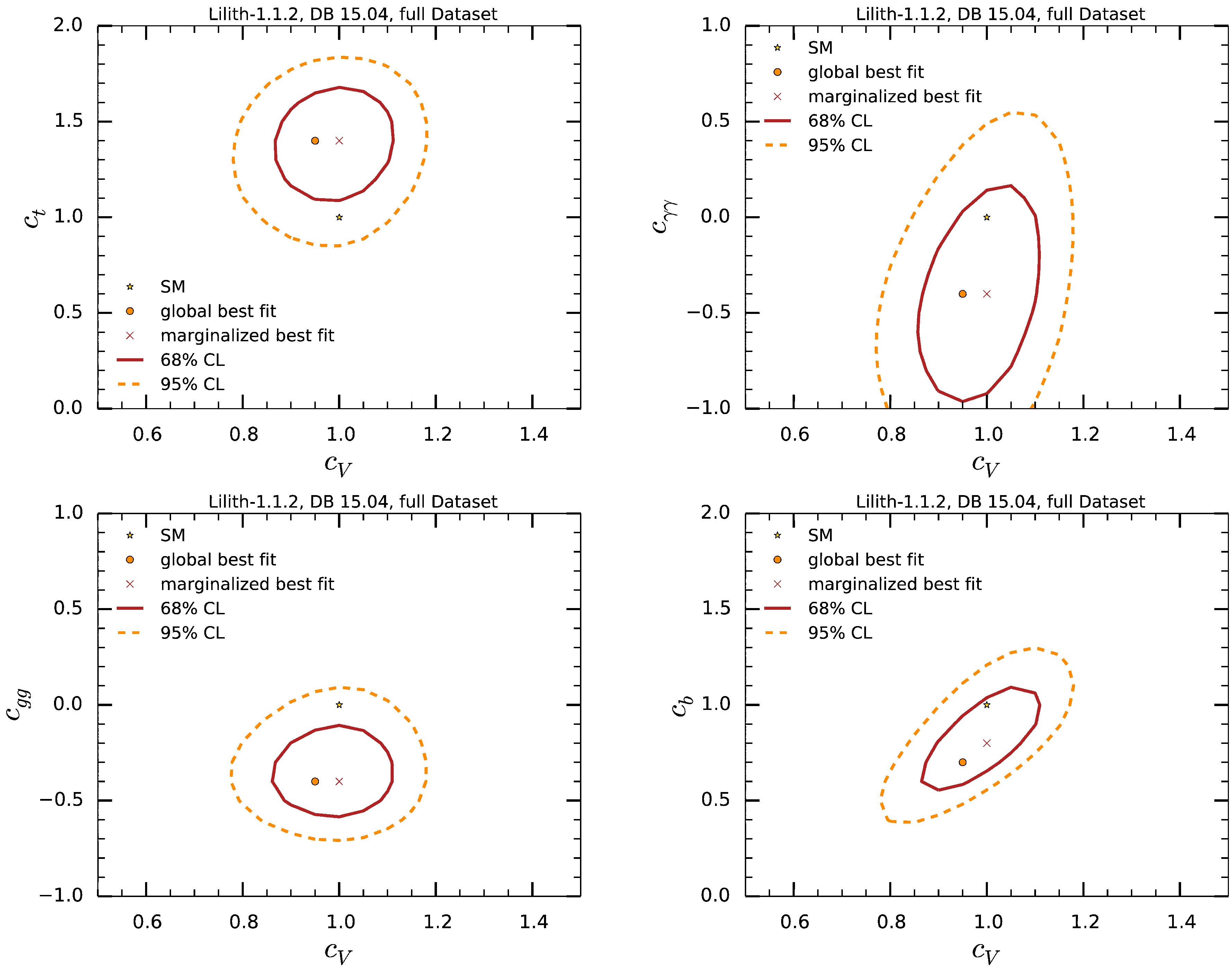
$$\mathcal{L}_Y = -\frac{y_f}{\sqrt{2}} \left(\kappa_f \bar{f} f + i \tilde{\kappa}_f \bar{f} \gamma_5 f \right) h$$

If one does not constrain (with priors) κ_f to deviate at the most $\mathcal{O}(\%)$, one is implicitly employing a nonlinear EFT.

Application: Experiment is allowing right now deviations in the SM couplings around $10 - 20\%$. The biggest effects are still described by a nonlinear EFT at LO. Fit to experimental data with only 6 parameters [Buchalla,O.C.,Celis,Krause'15]

$$\mathcal{L}_0 = 2 c_V \left(m_W^2 W_\mu W^\mu + \frac{m_Z^2}{2} Z_\mu Z^\mu \right) \frac{h}{v} - \sum_{f=t,b,\tau} c_f \, y_f \bar{f} f h + c_{gg} \frac{g_s^2}{16\pi^2} G_{\mu\nu} G^{\mu\nu} \frac{h}{v} + c_{\gamma\gamma} \frac{e^2}{16\pi^2} F_{\mu\nu} F^{\mu\nu} \frac{h}{v}$$

- Looks very similar to the κ formalism. Actually the nonlinear EFT is its natural theoretical embedding...


Lilith-1.1.2, DB 15.04, full Dataset
SM
global best fit
marginalized best fit
68% CL
95% CL
c_t
c_V
$c_{\gamma\gamma}$
c_{gg}
c_b

Summary and outlook

- A Higgs has been discovered but it will take a long time to test the SM scalar sector below the percent level.

- Yukawa couplings: flavor tagging is hard. Especially for first and second generations going beyond Higgs decay is mandatory. Lots of new ideas on how to increase sensitivity.

- Important to have a well-defined theoretical framework (EFT) and implement its power counting (with Bayesian priors) when fitting the data.

- κ formalism can be embedded in a nonlinear EFT.