Global analysis of non-standard Higgs-boson couplings with HEPfit

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Thanks to the extended `HEPfit` collaboration.

Outline

- Motivations and general framework
  - → LHC-Run I: found $M_H \simeq 125$ GeV, new physics → TeV range.
  - → LHC-Run II: higher statistics, higher precision, new mass thresholds.
  - → Explore indirect evidence of new physics from electroweak+Higgs fits while searching for direct evidence.
  - → Model-independent Higgs-boson studies: EFT approach.
- The `HEPfit` package: a global fit of existing electroweak precision data and Higgs-boson observables
  - → General structure of the package, main ingredients.
  - → Statistical analysis handled using a Bayesan approach (BAT).
  - → Structured to allow both a model-independent and a model-specific fit.
- Main results for Higgs-boson couplings and effective interactions
  - → In terms κ_i rescaling factors.
  - → In terms of C_i coefficients of EFT operators.
- Outlook and conclusions

References

Results have been presented at several meetings, in particular:

- → Lepton-Photon 2015: see plenary talk by M. Ciuchini
- → SUSY 2015: see parallel talks by J. de Blas and P. Ayan (on `HEPfit`)

and will soon appear in a paper together with the official release of `HEPfit`.

A first round of results were published in last year ICHEP 2014 proceedings:
→ arXiv:1410.4204 and arXiv:1410.6940

Previous paper on EW fit based on `SUSYfit`:
→ Ciuchini, Franco, Mishima, Silvestrini, arXiv:1306.4644

The `HEPfit` developer repository: `https://github.com/silvest/HEPfit`

General Framework

EFT extension of the SM Lagrangian by $d > 4$ operators,

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d, \quad \text{with} \quad \mathcal{L}_d = \sum_i C_i \mathcal{O}_i, \quad [\mathcal{O}_i] = d\,,$$

We consider:

- → $d = 6$ operators only, obeying SM gauge symmetry, L and B conservation
- → one Higgs doublet of $SU(2)_L$, linearly realized SSB
- → assuming flavor universality: 59 operators

  [basis by Grzadkowski et al., JHEP 1010 (2010) 085]
- → CP even and with at least one Higgs: 27 operators
- → contributing to the observables considered: 17 operators
- → with a specific model in mind: running $C_i(\Lambda) \to C_i(M_{EW})$ more meaningful
- → otherwise take $C_i = C_i(M_{EW})$, no running included

$$
\begin{aligned}
\mathcal{O}_{HG} &= (H^\dagger H)\, G^A_{\mu\nu} G^{A\mu\nu} \\
\mathcal{O}_{HW} &= (H^\dagger H)\, W^I_{\mu\nu} W^{I\mu\nu} \\
\mathcal{O}_{HB} &= (H^\dagger H)\, B_{\mu\nu} B^{\mu\nu} \\
\mathcal{O}_{HWB} &= (H^\dagger \tau^I H)\, W^I_{\mu\nu} B^{\mu\nu} \\
\mathcal{O}_{HD} &= (H^\dagger D^\mu H)^* \,(H^\dagger D_\mu H) \\
\mathcal{O}_{H\Box} &= (H^\dagger H)^* \Box (H^\dagger H)
\end{aligned}
$$

bosonic operators

$\longrightarrow$ corrections to:

- oblique parameters
- hVV
- WWZ and $WW\gamma$

$$
\begin{aligned}
\mathcal{O}^{(1)}_{HL} &= (H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{L}\gamma^\mu L) \\
\mathcal{O}^{(3)}_{HL} &= (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\overline{L}\,\tau^I \gamma^\mu L) \\
\mathcal{O}_{He} &= (H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{e}_R \gamma^\mu e_R) \\
\mathcal{O}^{(1)}_{HQ} &= (H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{Q}\gamma^\mu Q) \\
\mathcal{O}^{(3)}_{HQ} &= (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\overline{Q}\,\tau^I \gamma^\mu Q) \\
\mathcal{O}_{Hu} &= (H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{u}_R \gamma^\mu u_R) \\
\mathcal{O}_{Hd} &= (H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{d}_R \gamma^\mu d_R) \\
\mathcal{O}_{Hud} &= i(\widetilde{H}^\dagger D_\mu H)(\overline{u}_R \gamma^\mu d_R)
\end{aligned}
$$

single-fermionic-vector-current operators

$\longrightarrow$ corrections to:

- $hf\bar{f}$
- $Vf\bar{f}$

single-fermionic-scalar-current operators

$$\boxed{\begin{aligned} \mathcal{O}_{eH} &= (H^\dagger H)(\bar{L}\, e_R H) \\ \mathcal{O}_{uH} &= (H^\dagger H)(\bar{Q}\, u_R \widetilde{H}) \\ \mathcal{O}_{dH} &= (H^\dagger H)(\bar{Q}\, d_R H) \end{aligned}}$$

⟶ corrections to:

- oblique parameters
- Yukawa couplings
- $h f \bar{f}$

four-fermion operator

$$\boxed{\mathcal{O}_{LL} = (\bar{L}\gamma^\mu L)(\bar{L}\gamma^\mu L)}$$

⟶ corrections to:

- G_F extraction from μ decay

<u>Notice</u>: $V f \bar{f}$ and indirect effects (e.g. G_F) strongly constrained by EW precision observables.

Upon SSB, direct effect on Higgs-boson couplings

$$\mathcal{L}_{\text{Higgs}} = \mathcal{L}_{hVV} + \mathcal{L}_{hff} + \mathcal{L}_{hVff} + \mathcal{L}_{hTff}$$

each term contains the interactions to either vector bosons or fermions.

Ex.1: $\mathcal{L}_{hVV}$ contains all the non-fermionic interactions with the SM vector bosons,

$$\begin{aligned}\mathcal{L}_{hVV} = h\Big(& g^{(1)}_{hZZ} Z_{\mu\nu} Z^{\mu\nu} + g^{(2)}_{hZZ} Z_\nu \partial_\mu Z^{\mu\nu} + g^{(3)}_{hZZ} Z_\mu Z^\mu - \\ & + g_{hAA} A_{\mu\nu} A^{\mu\nu} + g^{(1)}_{hZA} Z_{\mu\nu} A^{\mu\nu} + g^{(2)}_{hZA} Z_\nu \partial_\mu A^{\mu\nu} - \\ & + g^{(1)}_{hWW} W^+_{\mu\nu} W^{-\,\mu\nu} + \Big(g^{(2)}_{hWW} W^+_\nu D_\mu W^{-\,\mu\nu} + (g^{(2)}_{hWW})^* W^-_\nu D_\mu W^{+\,\mu\nu} \Big) \\ & + g^{(3)}_{hWW} W^+_\mu W^{-\,\mu} + g_{hGG} \mathrm{Tr}\left[G_{\mu\nu} G^{\mu\nu} \right] \Big)\end{aligned}$$

where (both directly and indirectly → G_F, field renormalization, ...),

$C_{HG} \longrightarrow g_{hGG}$

$C_{HW} \longrightarrow g^{(1)}_{hWW}$

$C_{HW},\ C_{HB},\ C_{HWB} \longrightarrow g^{(1)}_{hZZ},\ g^{(1)}_{hZA},\ g^{(1)}_{hAA}$

$C_{HD} \longrightarrow g^{(3)}_{hZZ}$

while Ex. 2: $\mathcal{L}_{hff}$ contains the interactions with the fermions only:

$$\mathcal{L}_{hff} = h \sum_f g_{hff} \overline{f_L} f_R + \text{h.c.}$$

where,

$C_{eH} \longrightarrow g_{h\tau\tau}$

$C_{uH} \longrightarrow g_{hcc}, g_{htt}$

$C_{dH} \longrightarrow g_{hbb}$

The corresponding rescaling factors $\kappa_V = \frac{g_{hVV}}{g^{SM}_{hVV}}$ and $\kappa_f = \frac{g_{hff}}{g^{SM}_{hff}}$, are

$\kappa_Z = 1 + \delta_h + \frac{1}{2}\frac{v^2}{\Lambda^2} C_{HD} - \frac{1}{2}\delta_{G_F}$

$\kappa_W = 1 + \delta_h - \frac{1}{2}(c_W^2 - s_W^2)(4 s_W c_W \frac{v^2}{\Lambda^2} C_{HWB} + c_W^2 \frac{v^2}{\Lambda^2} C_{HD} + \delta_{G_F})$

$\kappa_f = 1 + \delta_h - \frac{1}{2}\delta_{G_F} - \frac{v}{m_f}\frac{v^2}{\Lambda^2}\frac{C_{fH}}{\sqrt{2}}$

where

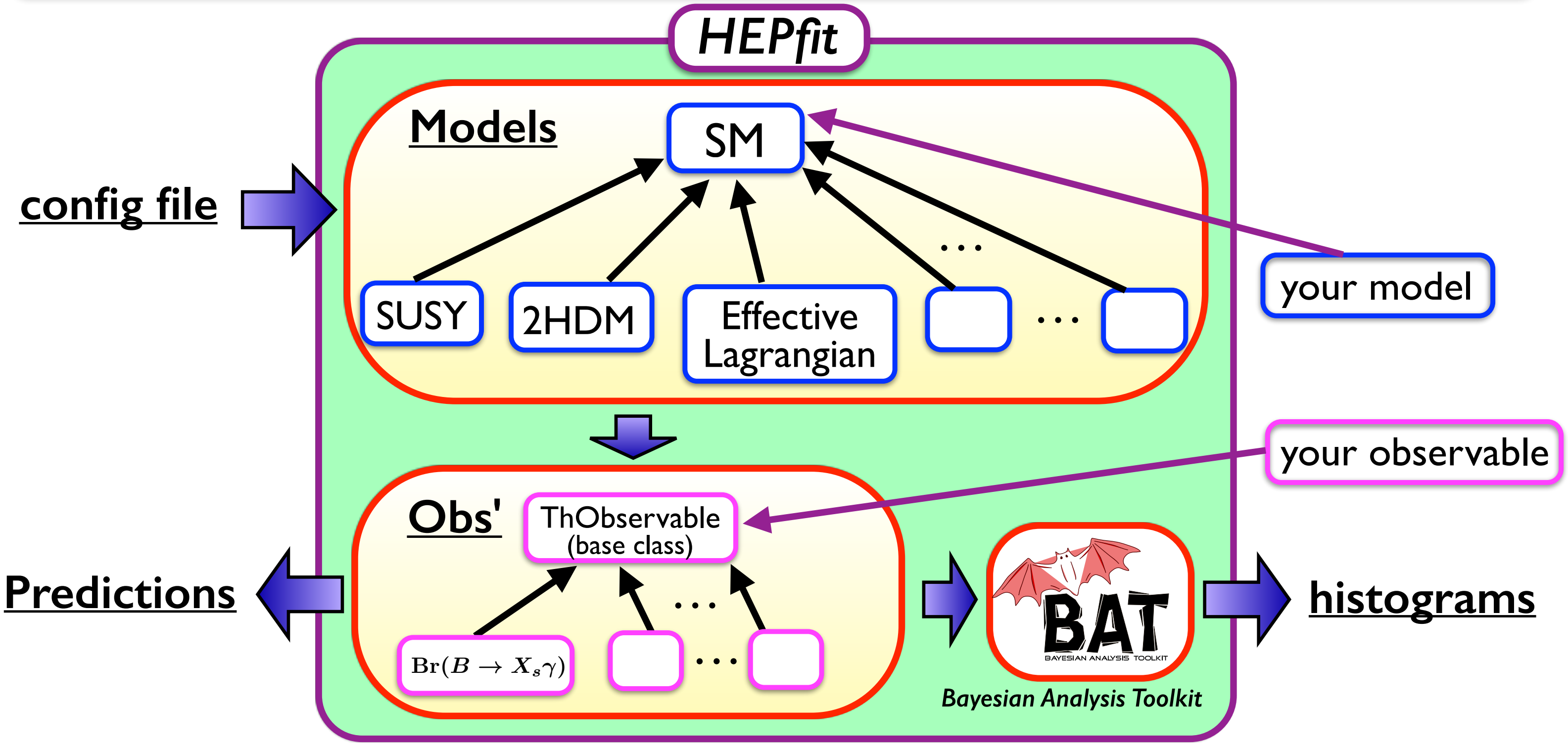
δ_h → NP corrections to h wave-function renormalization

δ_G → NP corrections to G_F

The fitting procedure → `HEPfit`

- Both electroweak and Higgs observables are calculated as a SM core plus corrections:
  - ↪ the SM cores include all existing higher order corrections
  - ↪ the NP corrections are at the lowest order in all SM couplings.
- Experimental results are taken from the most recent published analyses
  - ↪ see Higgs analyses example on next slide
- The fit procedure uses BAT (Bayesan Analysis Toolkit) where experimental likelihoods are taken as priors, and posteriors are calculated using a Markov Chain Monte Carlo.

  (Caldwell et al., arXiv:0808.2552)
- Original code `SUSYfit` morphed into a completely new object: `HEPfit`



HEPfit

config file

Models

SM

SUSY

2HDM

Effective Lagrangian

. . .

your model

Obs'

ThObservable (base class)

$\mathrm{Br}(B \to X_s \gamma)$

. . .

your observable

Predictions

BAT

Bayesian Analysis Toolkit

histograms

Courtesy of S. Mishima

→ stand-alone mode: to compute a Bayesan statistical analysis. or

→ library mode: to compute observables in a given model (`libHEPfit.a` and `HEPfit.h`)

→ add external modules for your favorite model

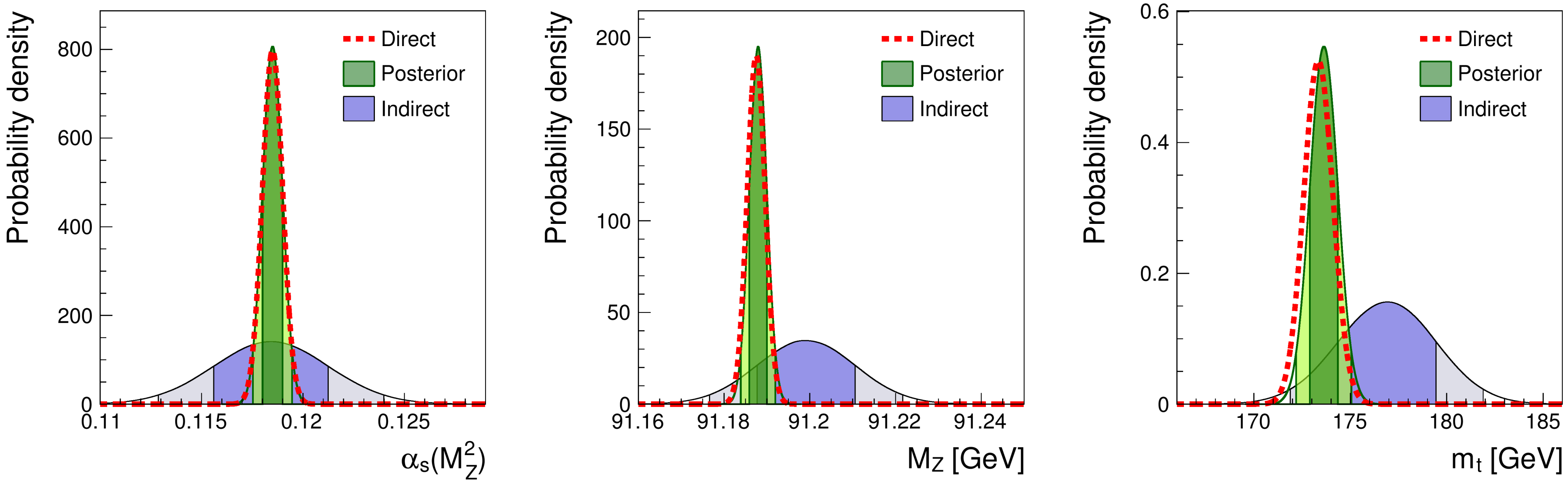
The SM fit to ElectroWeak Precision Observables

	Data	Fit	Indirect	Pull
$\alpha_s(M_Z^2)$	0.1185 ± 0.0005	0.1185 ± 0.0005	0.1184 ± 0.0028	-0.0
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$	0.02750 ± 0.00033	0.02741 ± 0.00026	0.02725 ± 0.00042	-0.5
M_Z [GeV]	91.1875 ± 0.0021	91.1879 ± 0.0020	91.199 ± 0.011	$+1.0$
m_t [GeV]	173.34 ± 0.76	173.6 ± 0.7	176.9 ± 2.5	$+1.3$
m_H [GeV]	125.09 ± 0.24	125.09 ± 0.24	97.40 ± 25.59	-0.9
M_W [GeV]	80.385 ± 0.015	$80.365 \pm 0.006xs$	80.361 ± 0.007	-1.4
Γ_W [GeV]	2.085 ± 0.042	2.0890 ± 0.0005	2.0890 ± 0.0005	$+0.1$
Γ_Z [GeV]	2.4952 ± 0.0023	2.4945 ± 0.0004	2.4945 ± 0.0004	-0.3
σ_h^0 [nb]	41.540 ± 0.037	41.488 ± 0.003	41.488 ± 0.003	-1.4
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	0.2324 ± 0.0012	0.23144 ± 0.00009	0.23144 ± 0.00009	-0.8
$P_\tau^{\rm pol}$	0.1465 ± 0.0033	0.1477 ± 0.0007	0.1477 ± 0.0007	$+0.4$
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	0.1477 ± 0.0007	0.1472 ± 0.0008	-1.9
$\mathcal{A}_c$	0.670 ± 0.027	0.6682 ± 0.0003	0.6682 ± 0.0003	-0.1
$\mathcal{A}_b$	0.923 ± 0.020	0.93466 ± 0.00006	0.93466 ± 0.00006	$+0.6$
$A_{\rm FB}^{0,\ell}$	0.0171 ± 0.0010	0.0164 ± 0.0002	0.0163 ± 0.0002	-0.8
$A_{\rm FB}^{0,c}$	0.0707 ± 0.0035	0.0740 ± 0.0004	0.0740 ± 0.0004	$+0.9$
$A_{\rm FB}^{0,b}$	0.0992 ± 0.0016	0.1035 ± 0.0005	0.1039 ± 0.0005	$+2.8$
R_ℓ^0	20.767 ± 0.025	20.752 ± 0.003	20.752 ± 0.003	-0.6
R_c^0	0.1721 ± 0.0030	0.17224 ± 0.00001	0.17224 ± 0.00001	$+0.0$
R_b^0	0.21629 ± 0.00066	0.21578 ± 0.00003	0.21578 ± 0.00003	-0.8

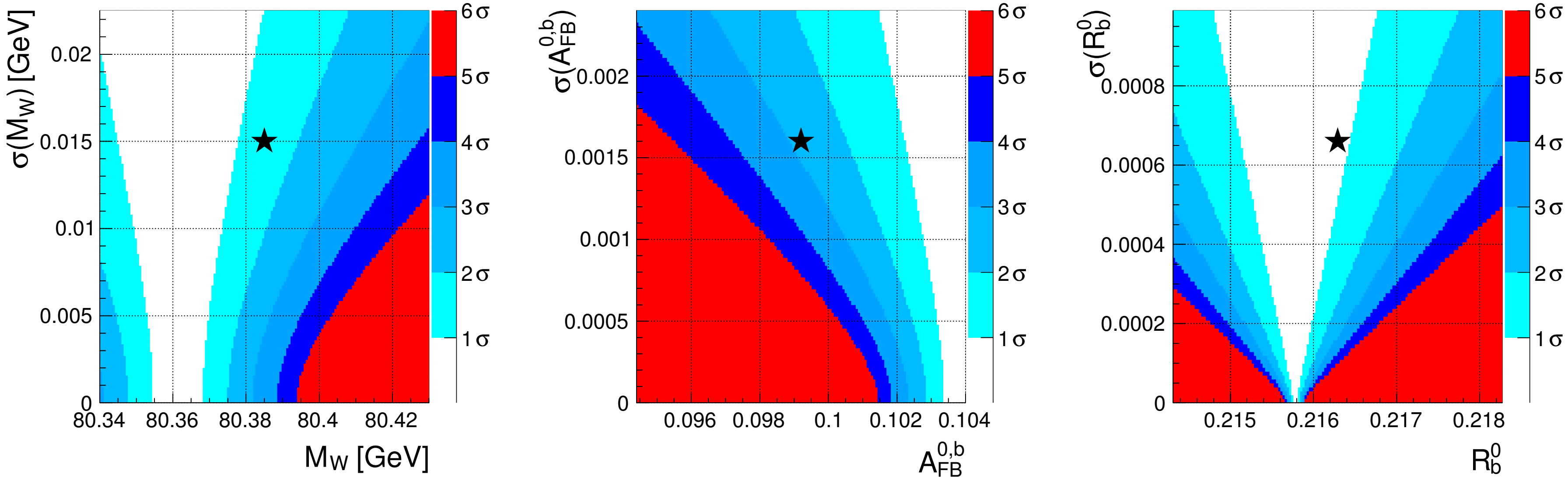
(indirect: determined without using the corresponding exp. information)

Validated agains ZFITTER: thanks to the Authors.

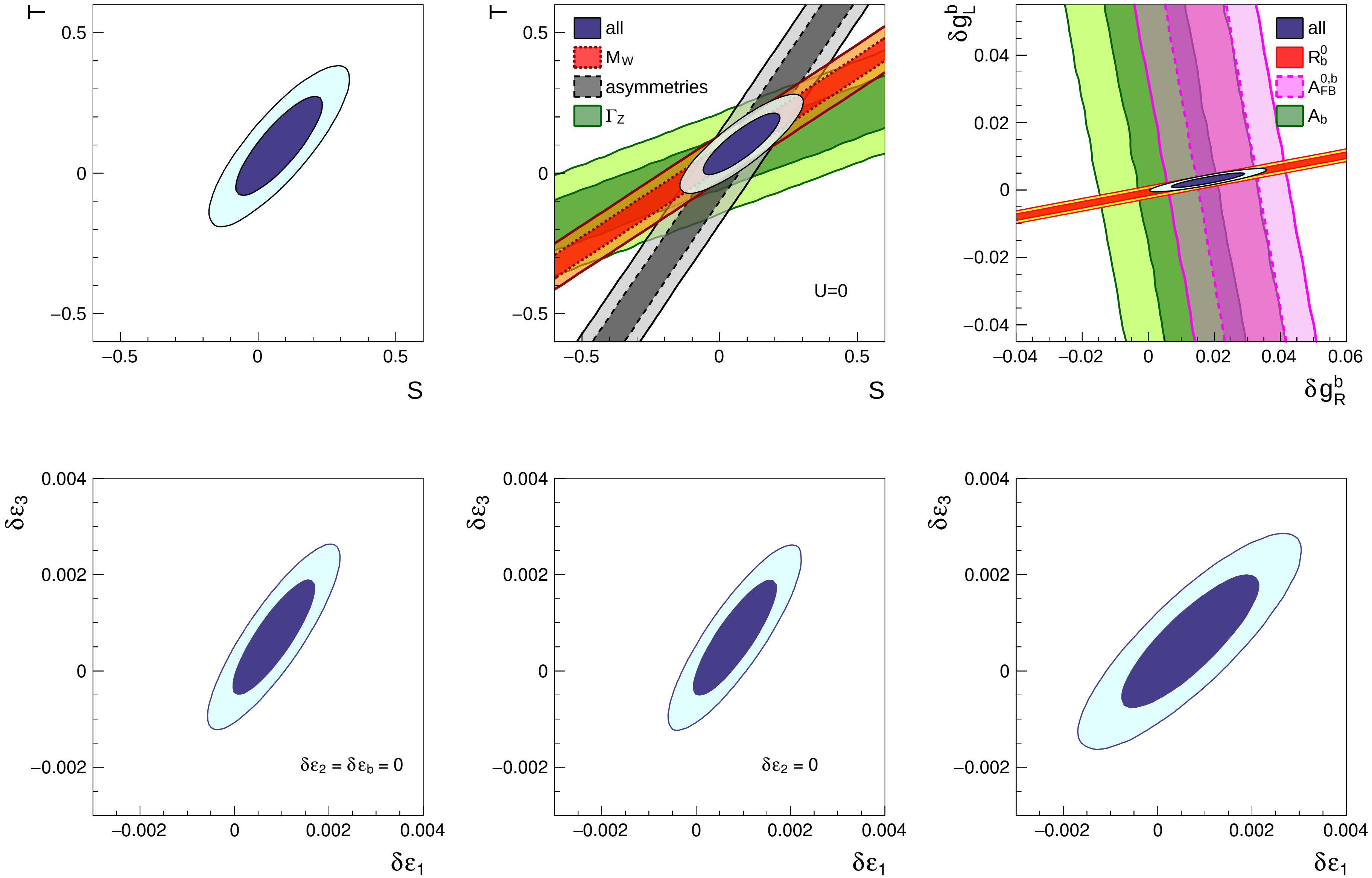
Good agreement between direct and indirect determination of the values of the input parameters



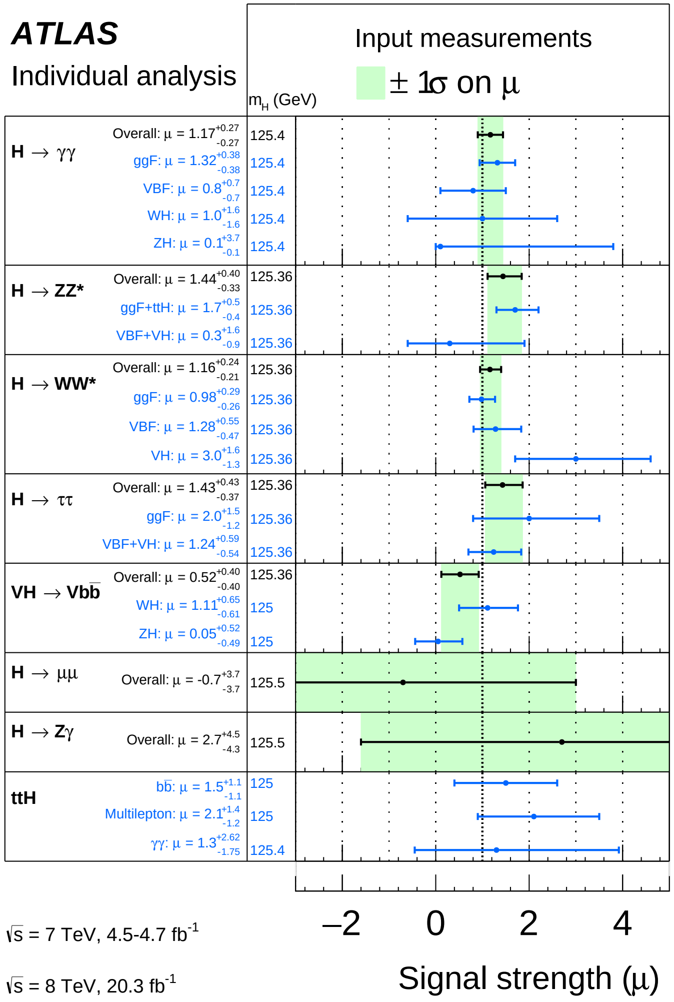
fit of EWPO



Limits on BSM physics from EWPO



Higgs couplings analysis



ATLAS: arXiv:1507.04548

$$\mu = \sum_i w_i r_i \quad \text{where}$$

$$w_i = \frac{[\sigma \times \mathrm{Br}]_i}{[\sigma_{\mathrm{SM}} \times \mathrm{Br}_{\mathrm{SM}}]_i}$$

$$r_i = \frac{\epsilon_i [\sigma_{\mathrm{SM}} \times \mathrm{Br}_{\mathrm{SM}}]_i}{\sum_j \epsilon_j^{\mathrm{SM}} [\sigma_{\mathrm{SM}} \times \mathrm{Br}_{\mathrm{SM}}]_j}$$

$$\sigma_i = \sigma_i^{\mathrm{SM}} + \delta\sigma_i$$

$$\Gamma_j = \Gamma_j^{\mathrm{SM}} + \delta\Gamma_j$$

$\sigma_i^{\mathrm{SM}}, \Gamma_j^{\mathrm{SM}} \rightarrow$ YR of HXSWG

$\delta\sigma_i \rightarrow$ FR+Madgraph+Kfactors

$\delta\Gamma_j \rightarrow$ eHdecay

$h\gamma\gamma$: ATLAS(1408.7084), CMS(1407.0558)

$h\tau\tau$: ATLAS(1501.04943), CMS(1401.5041)

hZZ: ATLAS(1408.5191), CMS(1412.8662)

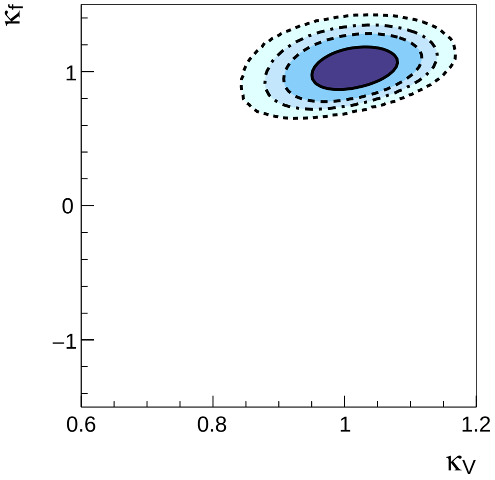
hWW: ATLAS(1412.2641,1506.06641),
CMS(1312.1129)

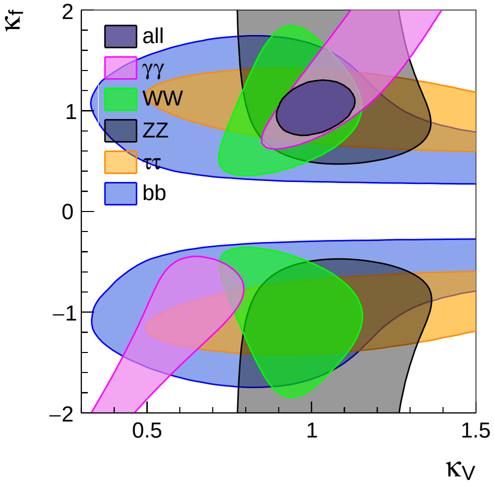
hbb: ATLAS(1409.6212, 1503.05066),
CMS(1310.3687, 1408.1682),
CDF (1301.6668), D0 (1303.0823)

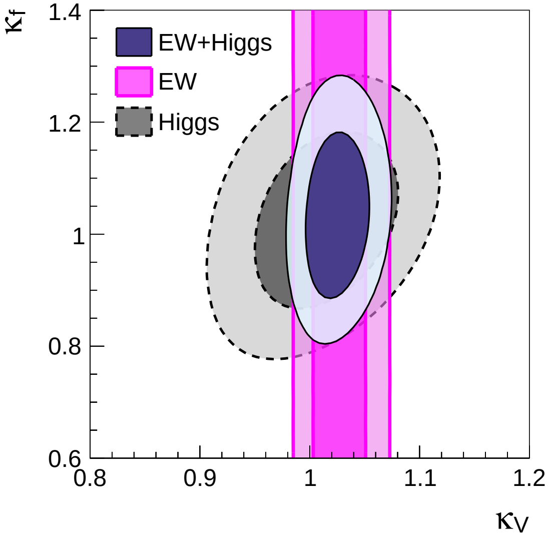
Bounds on EFT in terms of κ_V and κ_f

Higgs only

	68%	95%	correlation	
κ_V	1.01 ± 0.04	[0.93, 1.10]	1.00	
κ_f	1.03 ± 0.10	[0.83, 1.23]	0.31	1.00



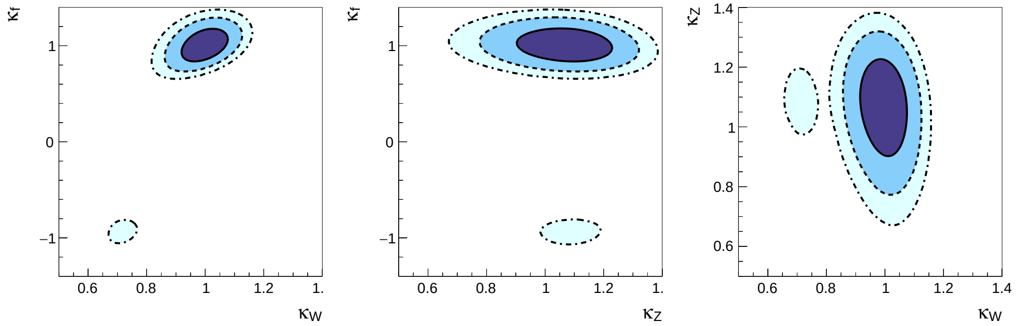




Higgs+EWPO

	68%	95%	correlation	
κ_V	1.02 ± 0.02	[0.99, 1.06]	1.00	
κ_f	1.03 ± 0.10	[0.85, 1.23]	0.15	1.00

Zooming into κ_V and κ_f . . .

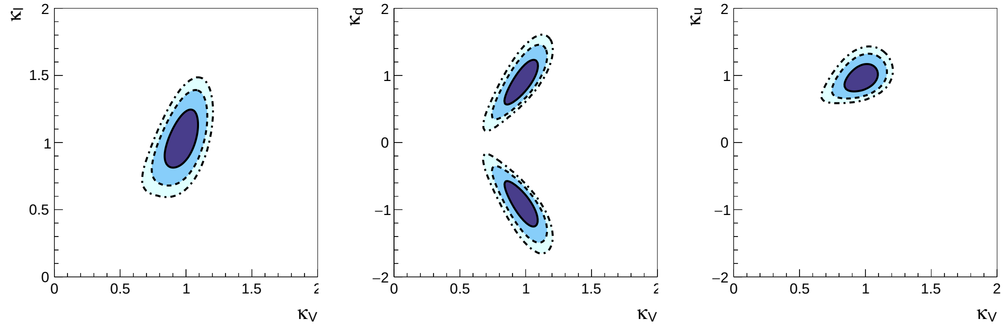


Custodial symmetry

$(\kappa_V \to \kappa_W, \kappa_Z)$

Higgs only

	68%	95%	correlation		
κ_W	1.00 ± 0.05	[0.89, 1.10]	1.00		
κ_Z	1.07 ± 0.11	[0.85, 1.27]	−0.17	1.00	
κ_f	1.01 ± 0.11	[0.80, 1.22]	0.41	−0.14	1.00

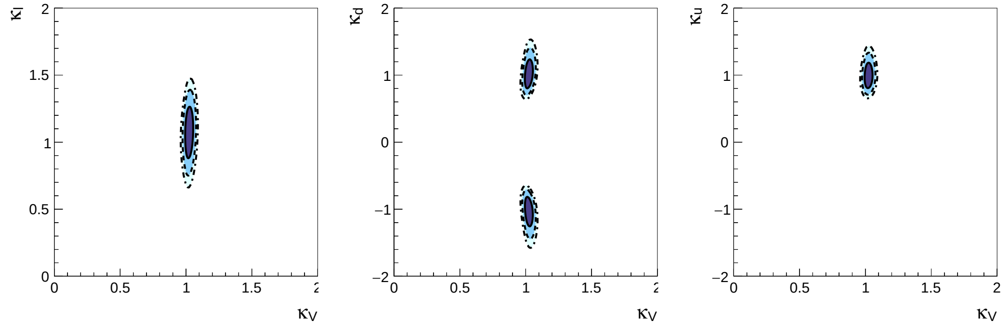


Flavor universality

$(\kappa_f \to \kappa_u, \kappa_d, \kappa_l)$

Higgs only

	68%	95%	correlation			
κ_V	0.97 ± 0.08	[0.80, 1.13]	1.00			
κ_l	1.01 ± 0.14	[0.73, 1.30]	0.54	1.00		
κ_u	0.97 ± 0.13	[0.73, 1.25]	0.43	0.41	1.00	
κ_d	0.91 ± 0.21	[0.48, 1.34]	0.81	0.61	0.77	1.00



Higgs+EWPO

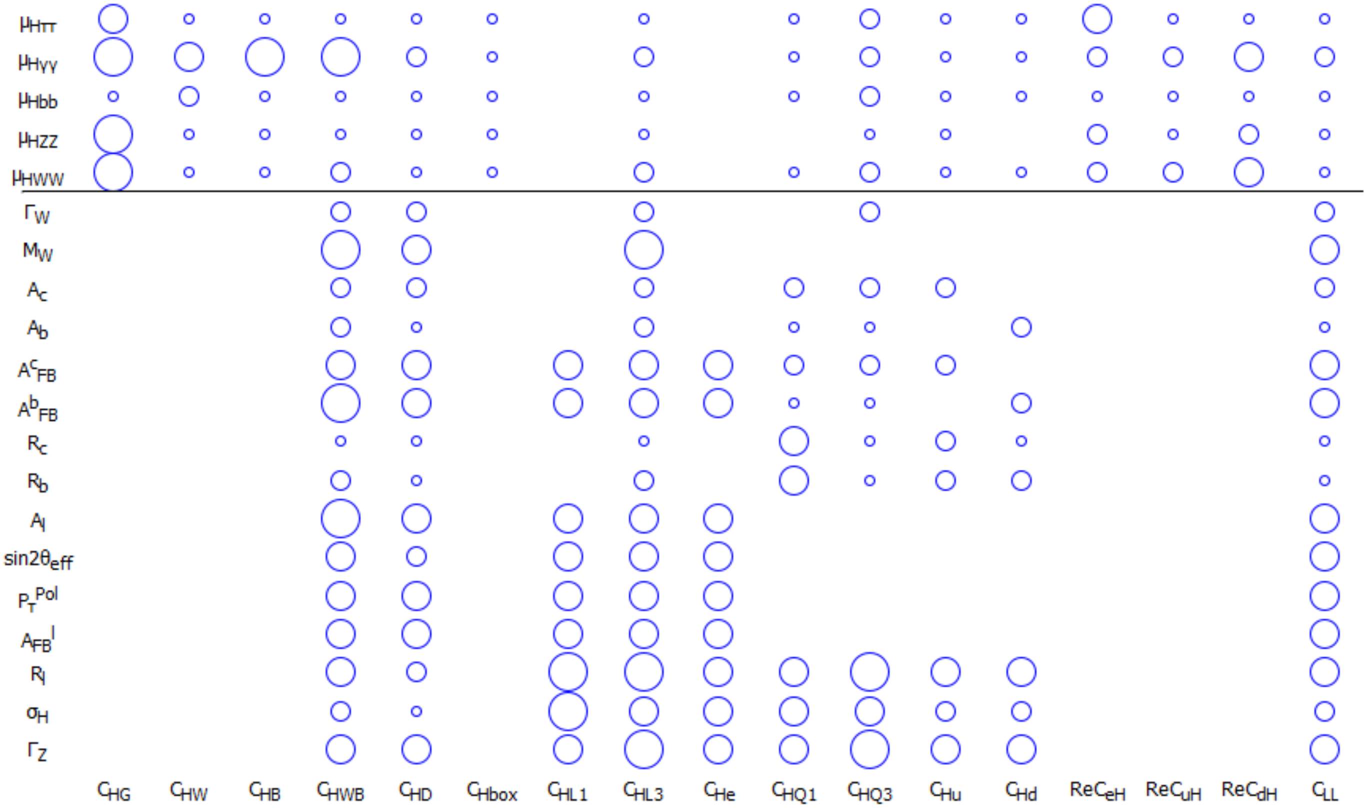
	68%	95%	correlation			
κ_V	1.02 ± 0.02	[0.99, 1.06]	1.00			
κ_l	1.07 ± 0.12	[0.82, 1.32]	0.15	1.00		
κ_u	1.01 ± 0.12	[0.80, 1.27]	0.10	0.24	1.00	
κ_d	1.01 ± 0.13	[0.77, 1.31]	0.31	0.38	0.78	1.00

95% bounds on coefficients of d=6 interactions

→ Switching on one operator at a time

	Only EW	**Only Higgs**	**EW + Higgs**
Coefficient	C_i/Λ^2 [TeV^{-2}] at 95%	C_i/Λ^2 [TeV^{-2}] at 95%	C_i/Λ^2 [TeV^{-2}] at 95%
C_{HG}	$--$	$[-0.0051, 0.0092]$	$[-0.0051, 0.0092]$
C_{HW}	$--$	$[-0.034, 0.014]$	$[-0.034, 0.014]$
C_{HB}	$--$	$[-0.0087, 0.0040]$	$[-0.0087, 0.0040]$
C_{HWB}	$[-0.010, 0.004]$	$[-0.008, 0.017]$	$[-0.0073, 0.0053]$
C_{HD}	$[-0.032, 0.005]$	$[-1.1, 1.6]$	$[-0.032, 0.005]$
$C_{H\Box}$	$--$	$[-1.4, 1.3]$	$[-1.4, 1.3]$
$C_{HL}^{(1)}$	$[-0.005, 0.012]$	$--$	$[-0.005, 0.012]$
$C_{HL}^{(3)}$	$[-0.012, 0.006]$	$[-0.47, 0.66]$	$[-0.012, 0.006]$
C_{He}	$[-0.017, 0.005]$	$--$	$[-0.017, 0.005]$
$C_{HQ}^{(1)}$	$[-0.027, 0.041]$	$[-2, 11]$	$[-0.027, 0.041]$
$C_{HQ}^{(3)}$	$[-0.011, 0.013]$	$[-0.42, 0.05]$	$[-0.012, 0.013]$
C_{Hu}	$[-0.071, 0.077]$	$[-4.6, 0.8]$	$[-0.072, 0.076]$
C_{Hd}	$[-0.14, 0.06]$	$[-2, 14]$	$[-0.14, 0.06]$
C_{Hud}	$--$	$--$	$--$
C_{eH}	$--$	$[-0.027, 0.049]$	$[-0.027, 0.049]$
C_{uH}	$--$	$[-0.62, 0.33]$	$[-0.62, 0.33]$
C_{dH}	$--$	$[-0.062, 0.059]$	$[-0.062, 0.059]$

Correlations among coefficients? Interesting to study patterns



bigger dots → better constrained ($\Lambda = 1$ TeV)

95% bounds on scale of new physics Λ

	Only EW		**Only Higgs**		**EW + Higgs**	
	Λ [TeV]		Λ [TeV]		Λ [TeV]	
Coefficient	$C_i = -1$	$C_i = 1$	$C_i = -1$	$C_i = 1$	$C_i = -1$	$C_i = 1$
C_{HG}	−−	−−	14.1	10.4	14.1	10.4
C_{HW}	−−	−−	5.5	8.4	5.5	8.4
C_{HB}	−−	−−	10.7	15.7	10.7	15.7
C_{HWB}	9.8	15.1	11.3	7.7	11.7	13.7
C_{HD}	5.6	14.1	0.9	0.8	5.6	14.0
$C_{H\Box}$	−−	−−	0.8	0.9	0.8	0.9
$C_{HL}^{(1)}$	14.1	9.3	−−	−−	14.1	9.3
$C_{HL}^{(3)}$	9.3	12.8	1.5	1.2	9.3	12.7
C_{He}	7.7	13.6	−−	−−	7.7	13.6
$C_{HQ}^{(1)}$	6.0	5.0	0.7	0.3	6.0	5.0
$C_{HQ}^{(3)}$	9.4	8.7	1.5	4.4	9.2	8.9
C_{Hu}	3.8	3.6	0.5	1.1	3.7	3.6
C_{Hd}	2.7	4.0	0.6	0.3	2.7	4.0
C_{Hud}	−−	−−	−−	−−	−−	−−
C_{eH}	−−	−−	6.0	4.5	6.0	4.5
C_{uH}	−−	−−	1.3	1.7	1.3	1.7
C_{dH}	−−	−−	4.0	4.1	4.0	4.1

$\rightarrow$ For $|C_i| \simeq 1$ NP is beyond LHC reach, need perturbative C_i.

Outlook and Conclusions

- Indirect evidence for new physics might play a crucial role in Run II of the LHC, although we hope it won't be everything we'll have.
- The EFT formalism offers the possibility of a general and systematic approach to study indirect effects of new physics living at higher energy scales.
- We have presented a new global model-independent analysis of EWPO and Higgs observables (signal strengths) based on the EFT extension of SM up to $d = 6$ operators.
- Fit performed through **`HEPfit`** using the Bayesan Analysis Toolkit (BAT). Bounds derived for Higgs-boson anomalous couplings
  - → in terms κ_i rescaling factors.
  - → in terms of C_i coefficients of EFT operators ($\leftrightarrow \Lambda$).

  Nice interplay of EWPO+Higgs observables in constraining NP.
- $C_i \simeq 1$ seems to push Λ beyond LHC reach, perturbative coefficients still allow for not too large Λ.
- One important ingredient that is usually very powerful in discriminating against new physics is flavor: we will include it gradually.

- Assuming/not assuming a model is a double-edged sword: `HEPfit` allows you to do both. It will be interesting to study model-independent patterns that could push us beyond the investigation of individual coefficients.
- The formalism of EFT is very powerful: still we need to understand its applicability to the case at hand before we can really profit from the full RGE machinery that comes with it.