Extended electroweak precision fits and their implications

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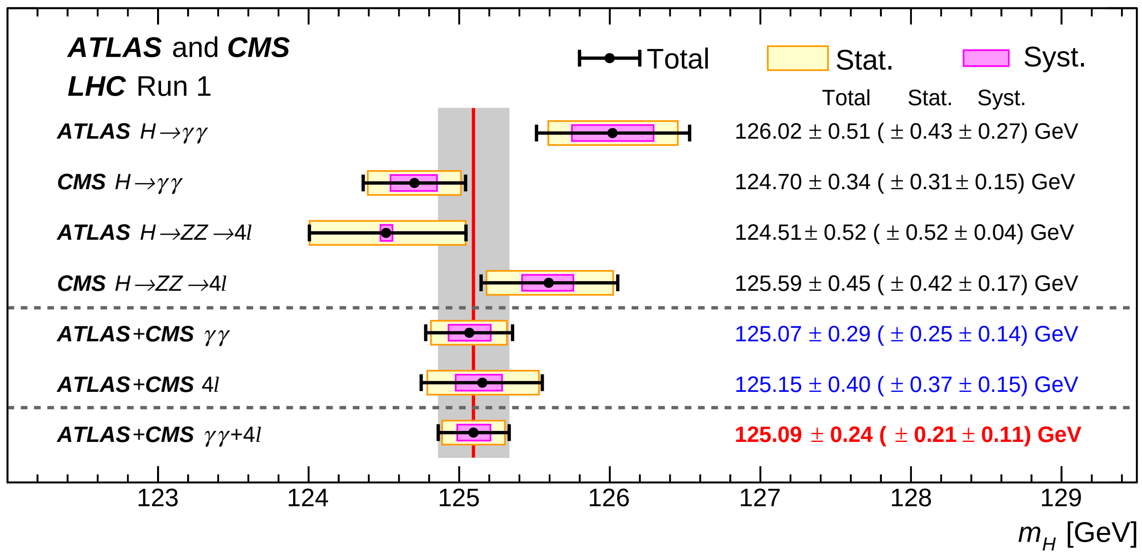
Stress-testing the Standard Model at the LHC

KITP, UC-Santa Barbara, May, 26^{th} 2016

Electroweak precision physics in the LHC era

- LHC, Run II: after the Higgs-boson discovery
  - ↪ M_H becomes a precision electroweak (EW) parameter;
  - ↪ precision fits now probe consistency of the Standard Model (SM) and can provide indirect evidence of new physics;
  - ↪ fits can be extended to include Higgs-boson results: rates and distributions;
  - ↪ actual sensitivity depends on experimental precision and theoretical accuracy.
- `HEPfit`: a global fit of existing electroweak precision data (EWPD) and Higgs-boson observables
  - → General framework, new features
  - → Results of EWPD fit, constraints on new physics
- Main results for Higgs-boson couplings and effective interactions
  - → In terms of κ_i rescaling factors.
  - → In terms of C_i coefficients of EFT operators.
- Outlook

LHC Run I has discovered the Higgs, measured its mass and spin . . .



ATLAS+CMS, Phys. Rev. Lett. 114, 191803

M_H is now among the EW precision observables!

Effects of New Physics can now be more clearly disentangled in both **EW observables** and **Higgs-boson couplings**

Moreover, from decays ($H \to VV$ and $H \to f\bar{f}$)

→ Spin: highly constrained to be $s = 0$

→ Parity: scalar vs pseudoscalar, exploring the tensor structure of decay amplitudes

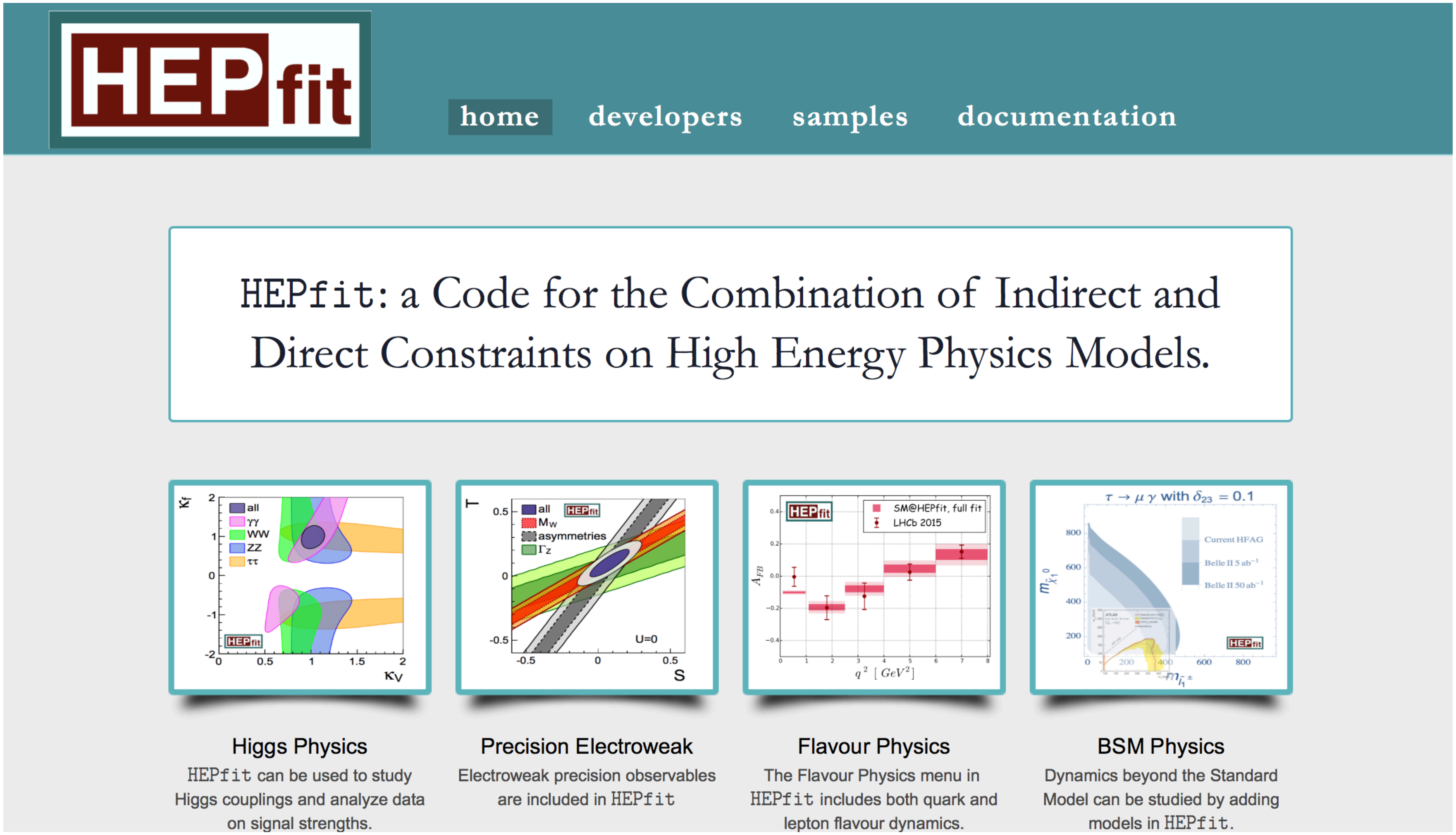
Fits of electroweak precision data

$\hookrightarrow$ see A. Freitas's talk

- Set of **input parameters**
  - $\rightarrow$ **fixed**: G_F, α (best measured)
  - $\rightarrow$ **floating**: M_Z, M_H, m_t, $\alpha_s(M_Z)$, $\Delta\alpha^{(5)}_{\rm had}$
- **Compute EW precision observables** (EWPO), including all known higher-order corrections (in a given renormalization scheme): M_W, Γ_W (LEP2/Tevatron), Z-pole observables: Γ_Z, A_f, ... (LEP/SLD)
- **Perform best fit** and compare with experimental measurement: tension might signal new physics.
- Parametrize new physics effects (ex: S, T, U parameters) and constrain deviations in terms of chosen parameters.
- Several groups:
  - $\rightarrow$ GAPP [Erler]
  - $\rightarrow$ ZFITTER: [Akhundov, Arbuzov, S.Riemann & T.Riemann]
  - $\rightarrow$ Gfitter: [Baak, Cúth, Haller, Hoecker, Kogler, Mönig, Schott, Stelzer]
  - $\rightarrow$ Now also part of $\boxed{\text{HEPfit}}$ $\longrightarrow$ HEPfit Collaboration.
    For this study: [de Blas, Ciuchini, Franco, Mishima, Pierini, L.R., Silvestrini]

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

HEPfit webpage: http://hepfit.roma1.infn.it



In this talk: EW precision physics and Higgs-boson physics

[de Blas, Ciuchini, Franco, Mishima, Pierini, L.R., Silvestrini]

arXiv:1410.4204, arXiv:1410.6940, update soon to appear ... arXiv:1606.xxxx

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 [→ see A. Freitas]
  - ↪ the NP corrections are at the lowest order in all SM couplings.
- Experimental results are taken from the most recent published analyses
- The fit procedure uses BAT (Bayesian Analysis Toolkit) with flat priors for all input parameters, and posteriors calculated using a Markov Chain Monte Carlo.

  (Caldwell, Kollar, Kröninger, arXiv:0808.2552+ Beaujean, Greenwald, Schulz)
- **Stand-alone** or **library mode** to **compute observables in a given model**:
  - ↪ **Implemented models**:
    - ↪ SM,
    - ↪ Oblique parameters (S,T,U), ε_i parameters, Modified $Zb\bar{b}$ couplings,
    - ↪ Modified Higgs couplings (κ_i), SMEFT (d=6),
    - ↪ 2HDM.
  - ↪ **Implemented observables**: EWPO, Flavor ($\Delta F = 2$, UT, B-decays).

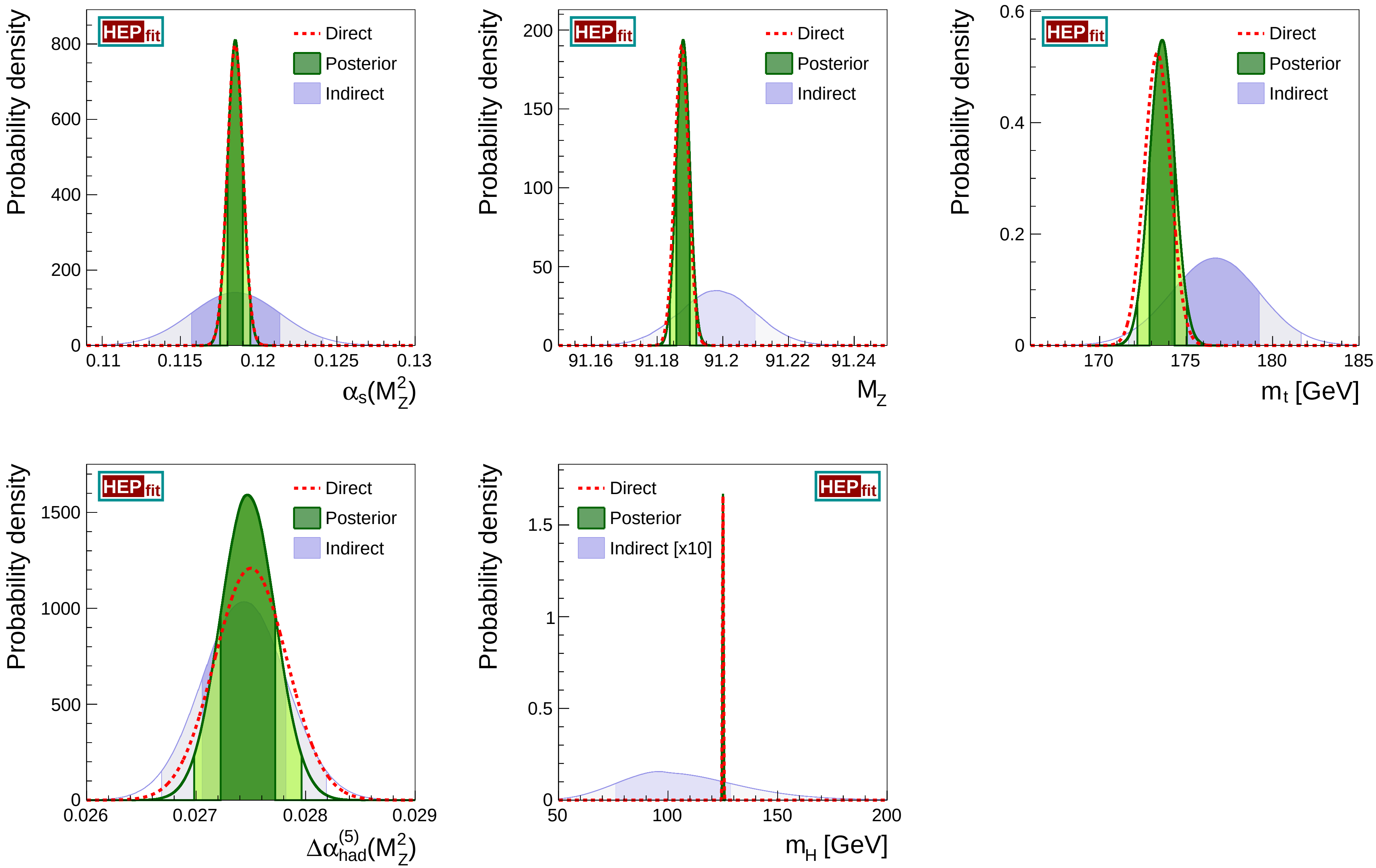
Results of SM fit to EW precision data

	Measurement	Result	Prediction	1D Pull	nD Pull
α_{M_Z}	0.11850 ± 0.00050	0.11850 ± 0.00049	0.1186 ± 0.0028	0.1	
$\delta\alpha_5^{\rm had}$	0.02750 ± 0.00033	0.02747 ± 0.00025	0.02743 ± 0.00038	-0.2	
M_Z [GeV]	91.1875 ± 0.0021	91.1879 ± 0.0021	91.198 ± 0.011	-0.9	
m_t [GeV]	173.34 ± 0.76	173.61 ± 0.73	176.7 ± 2.5	1.1	
m_H [GeV]	125.09 ± 0.24	125.09 ± 0.24	102.4 ± 26.4	-0.6	
M_W [GeV]	80.385 ± 0.015	80.3641 ± 0.0060	80.3601 ± 0.0066	-1.7	
Γ_W [GeV]	2.085 ± 0.042	2.08893 ± 0.00051	2.08893 ± 0.00051	0.0	
$\sin^2\theta_{\rm eff}^{\rm lept}$	0.2324 ± 0.0012	0.231466 ± 0.000086	0.231437 ± 0.000090	-0.8	
$P_\tau^{\rm pol} = \mathcal{A}_\ell$	0.1465 ± 0.0033	0.14746 ± 0.00068	0.14751 ± 0.00069	0.1	
Γ_Z [GeV]	2.4952 ± 0.0023	2.49445 ± 0.00040	2.49439 ± 0.00041	0.4	
σ_h^0 [nb]	41.540 ± 0.037	41.4878 ± 0.0031	41.4880 ± 0.0032	1.3	0.7
R_ℓ^0	20.767 ± 0.025	20.7516 ± 0.0034	20.7513 ± 0.0035	0.6	
$A_{\rm FB}^{0,\ell}$	0.0171 ± 0.0010	0.01631 ± 0.00015	0.01627 ± 0.00015	0.9	
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	0.14746 ± 0.00068	0.14762 ± 0.00076	1.7	
$\mathcal{A}_c$	0.670 ± 0.027	0.66809 ± 0.00030	0.66816 ± 0.00033	0.03	
$\mathcal{A}_b$	0.923 ± 0.020	0.934648 ± 0.000058	0.934661 ± 0.000064	-0.4	
$A_{\rm FB}^{0,c}$	0.0707 ± 0.0035	0.07389 ± 0.00037	0.07398 ± 0.00042	-0.9	1.5
$A_{\rm FB}^{0,b}$	0.0992 ± 0.0016	0.10337 ± 0.00048	0.10348 ± 0.00054	-2.5	
R_c^0	0.1721 ± 0.0030	0.172238 ± 0.000013	0.172239 ± 0.000013	-0.1	
R_b^0	0.21629 ± 0.00066	0.215784 ± 0.000025	0.215783 ± 0.000026	0.8	

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

$\rightarrow$ Very good agreement with both ZFITTER and Gfitter.

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



EW precision, example of future projections

Present

Observable	Exp. Error	Theor. Error
M_W [MeV]	15	4
$\sin^2\theta^l_{\rm eff}$ [10^{-5}]	16	4.5
Γ_Z[MeV]	2.3	0.5
R_b [10^{-5}]	66	15

Future

Observable	ILC	FCC-ee	CEPC	Theor. Error
M_W [MeV]	3-4	1	3	1
$\sin^2\theta^l_{\rm eff}$ [10^{-5}]	1	0.6	2.3	1.5
Γ_Z[MeV]	0.8	0.1	0.5	0.2
R_b [10^{-5}]	14	6	17	5-10

[A. Freitas, arXiv:1604.00406]

$\left(\delta m_t = 50 \text{ MeV},\ \delta\alpha_s = 0.001,\ \delta M_Z = 2.1 \text{ MeV},\ \delta(\Delta\alpha) \simeq 5\cdot 10^{-5}\right)$

ILC [e^+e^-, $\sqrt{s}$=90-500 GeV] $\rightarrow$ hep-ph/0106315, arXiv:1306.6352

FCC-ee [e^+e^-, $\sqrt{s}$=90-400 GeV] $\rightarrow$ arXiv:1308.6176

CEPC [e^-p, $\sqrt{s}$=90-250 GeV] $\rightarrow$ IHEP-CEPC-DR-2015-01

$\longrightarrow$ Theoretical errors may become leading source of error

Limits on beyond SM physics from EW precision data and Higgs-boson data

Parametrizing indirect evidence of new physics beyond the SM (BSM) in a **model-independent** way via

- Oblique corrections (ex.: S,T,U parameters)
- Non-standard $Zb\bar{b}$ couplings
- Non-standard Higgs couplings
- SM effective field theory (SMEFT)

Oblique parameters, S, T, U

[Peskin and Takeuchi, Phys. Rev. D46 (1992) 381]

Dominant effects of NP in gauge-boson vacuum polarization corrections,

$$\alpha S = 4e^2 \left[\Pi_{33}^{\mathrm{N}P\prime}(0) - \Pi_{3Q}^{\mathrm{N}P\prime}(0) \right]$$

$$\alpha T = \frac{e^2}{s_W^2 c_W^2 M_Z^2} \left[\Pi_{11}^{\mathrm{N}P}(0) - \Pi_{33}^{\mathrm{N}P}(0) \right]$$

$$\alpha U = 4e^2 \left[\Pi_{11}^{\mathrm{N}P\prime}(0) - \Pi_{33}^{\mathrm{N}P\prime}(0) \right]$$

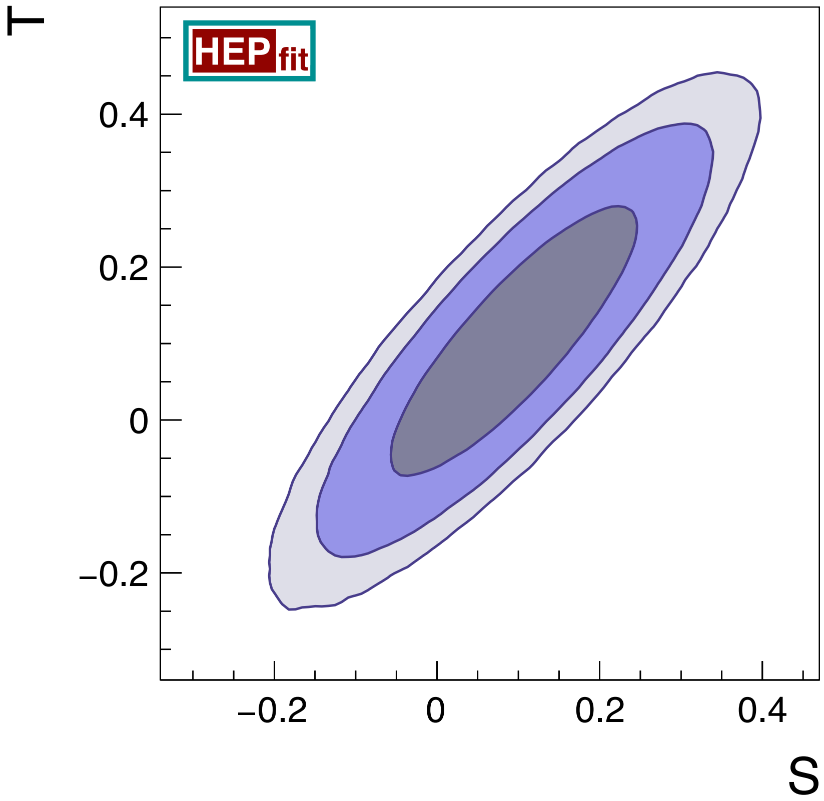
NP contributions to given EWPO (linearized in terms of S, T, U)

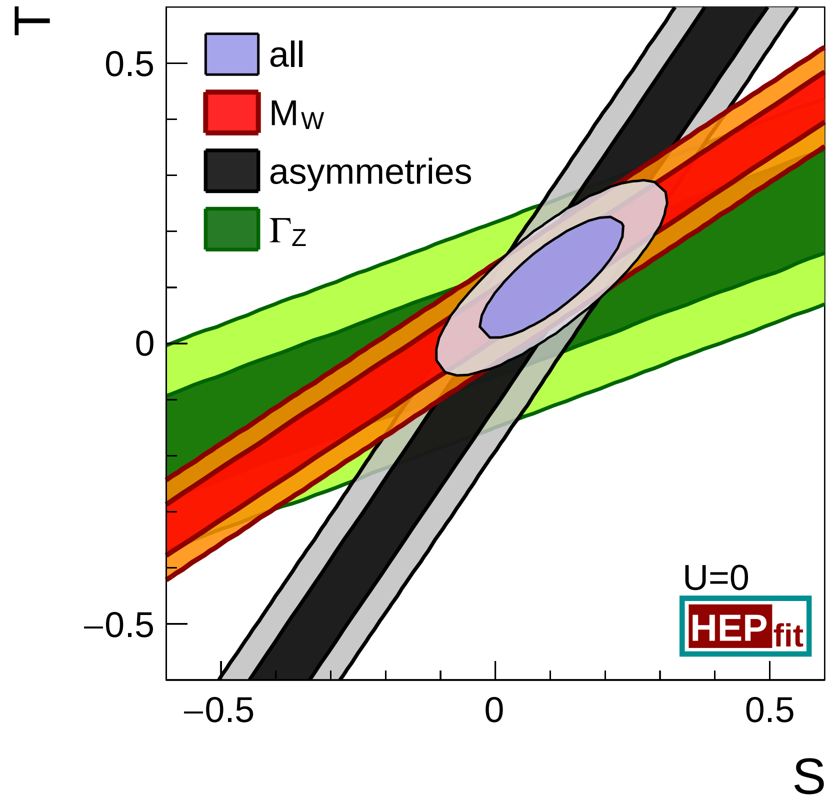
$$O = O_{\mathrm{SM}} + O_{\mathrm{NP}}(S, T, U)$$

$U \to$ NP contributions to M_W and Γ_W

$U \ll S, T$ in many NP models (linearly realized EWSB) $\to U = 0$

Equivalently: use $\varepsilon_{1,2,3,b}$ parameters [Altarelli, Barbieri, Phys. Lett. B253 (1991) 161]





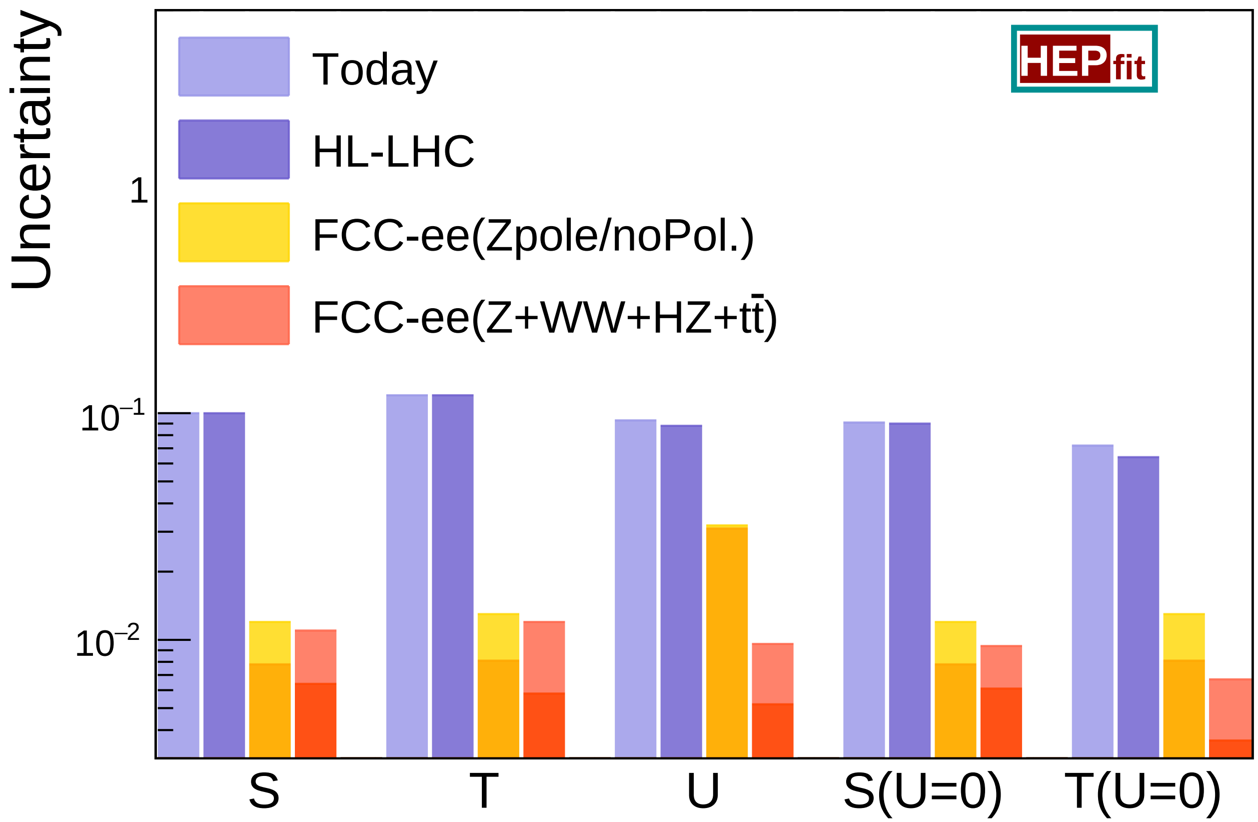
	Fit result	correlations		
S	0.09 ± 0.10	1.00		
T	0.10 ± 0.12	0.86	1.00	
U	0.01 ± 0.09	-054	-0.81	1.00

	Fit result	correlations	
S	0.10 ± 0.08	1.00	
T	0.12 ± 0.07	0.86	1.00

blue shaded areas $\rightarrow$ 68%, 95%, 99%

blue shaded areas $\rightarrow$ 68%, 95%

Preliminary:



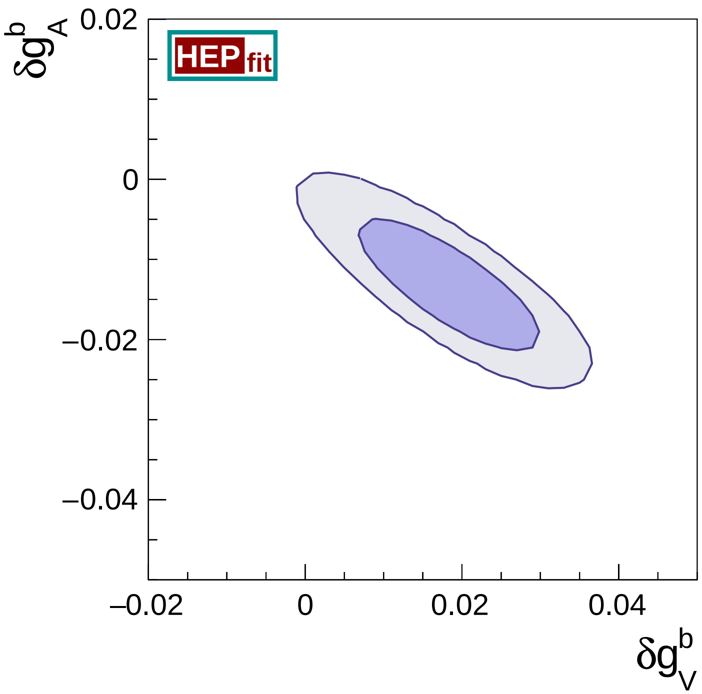
FCCee: several projected runs

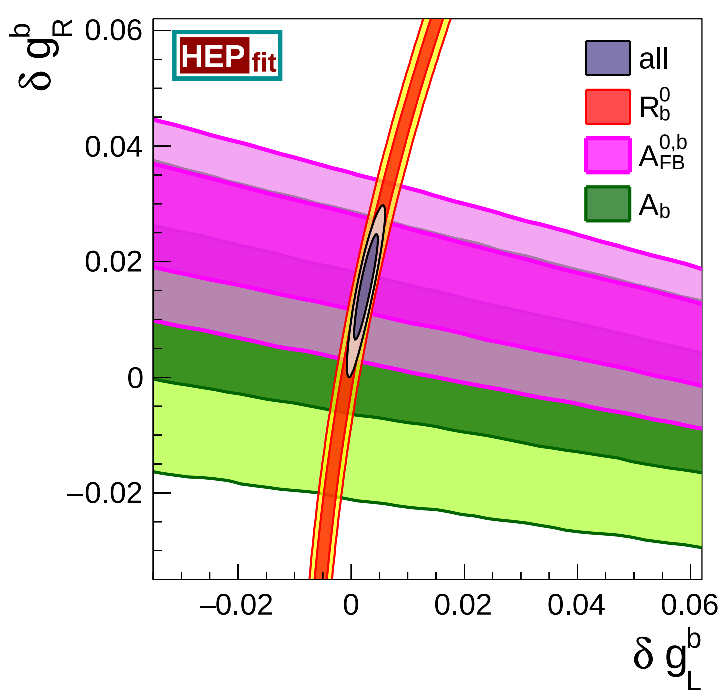
	Z pole	WW threshold	HZ threshold	$t\bar{t}$ threshold	above $t\bar{t}$ threshold
$\sqrt{s}$ [GeV]	90	160	240	350	> 350
$\mathcal{L}$ [ab^{-1}/yr]	86	15	3.5	1.0	1.0
Years of run	0.3/2.5	1	3	0.5	3
Events	$10^{12}/10^{13}$	6×10^{7}	2×10^{6}	2×10^{5}	7.5×10^{4}

Non-standard $Zb\bar{b}$ couplings

Tension in $A_{\rm FB}^{0,b}$ (pull of EWPO fit $\to 2.8\sigma$)

$$A_{\rm FB}^{0,b} = \frac{3}{4} A_e A_b \;,\;\; A_f = \frac{2\,{\rm Re}\frac{g_V^f}{g_A^f}}{1 + ({\rm Re}\frac{g_V^f}{g_A^f})^2} \;\longrightarrow\; g_i^b = g_{i,\rm SM}^b + \delta g_i^b \;\; {\scriptstyle (\rm i=V,A,L,R)}$$



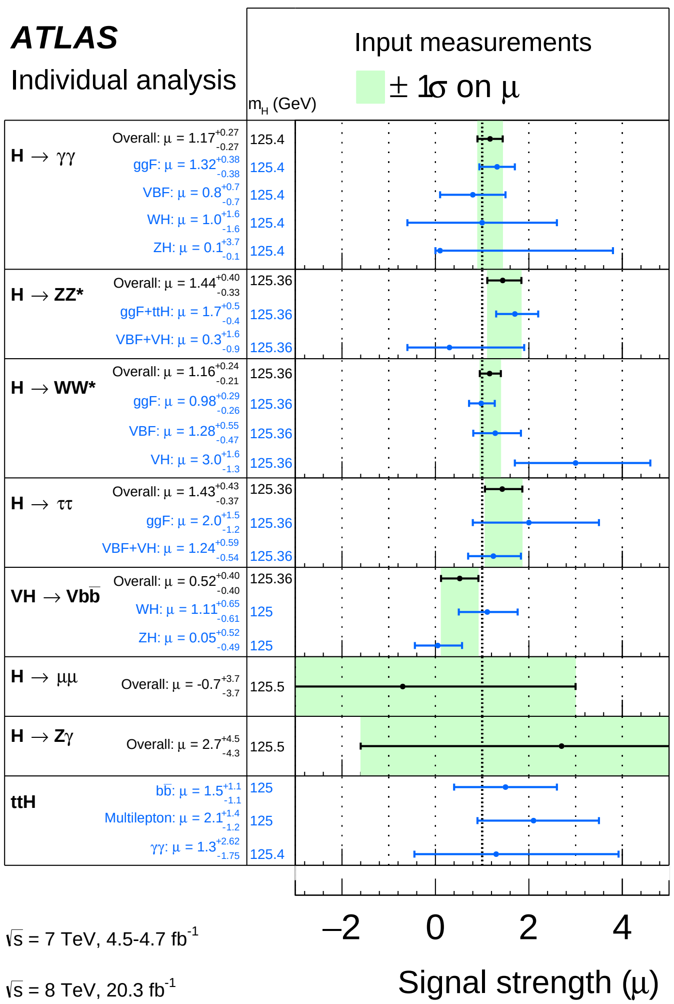


$$\delta A_{\rm FB}^{0,b}, \delta A_b \propto g_{L,\rm SM}^b \delta g_R^b - g_{R,\rm SM}^b \delta g_L^b$$

$$\delta R_b \propto g_{R,\rm SM}^b \delta g_R^b + g_{L,\rm SM}^b \delta g_L^b$$

	Fit result	correlations	
δg_R^b	0.016 ± 0.006	1.00	
δg_L^b	0.003 ± 0.001	0.90	1.00
δg_V^b	0.018 ± 0.007	1.00	
δg_A^b	-0.013 ± 0.005	-0.98	1.00

Higgs couplings analysis



ATLAS: arXiv:1507.04548

$\mu = \sum_i w_i r_i$ 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)

Non-standard Higgs-boson couplings

Minimal assumptions (inspired by strong-dynamics EWSB models):

- $\hookrightarrow$ only one Higgs boson below the cutoff Λ;
- $\hookrightarrow$ custodial symmetry approximately realized;
- $\hookrightarrow$ corrections from new physics flavor-diagonal and universal;
- $\hookrightarrow$ no NP corrections in Hgg, $H\gamma\gamma$, $HZ\gamma$ loop-induced couplings.

Ex.: Contino, Grojean, Moretti, Piccinini,Rattazzi, JHEP 1005 (2010) 089

$$\mathcal{L}_{\rm eff} = \frac{v^2}{4}\mathrm{tr}\left(D_\mu\Sigma^\dagger D^\mu\Sigma\right)\left(1+2\kappa_V\frac{h}{v}+\cdots\right) - m_i\bar{f}_L^i\left(1+2\kappa_f\frac{h}{v}+\cdots\right)f_R^i$$

where $\Sigma(x) = \exp i\sigma^a\chi^a(x)/v \rightarrow$ longitudinal W/Z polarizations.

Defining: $\kappa_X = g_X/g_X^{\rm SM}$ (SM $\rightarrow$ $\kappa_X = 1$),

$\kappa_V \rightarrow$ rescaling of all hVV couplings
$\kappa_f \rightarrow$ rescaling of all $hf\bar{f}$ couplings

Considering EWPO+κ_V only

κ_V also affect oblique corrections:

$$S = \frac{1}{12\pi}(1-\kappa_V^2)\log\frac{\Lambda^2}{M_h^2}$$

$$T = -\frac{3}{16\pi c_W^2}(1-\kappa_V^2)\log\frac{\Lambda^2}{M_h^2}$$

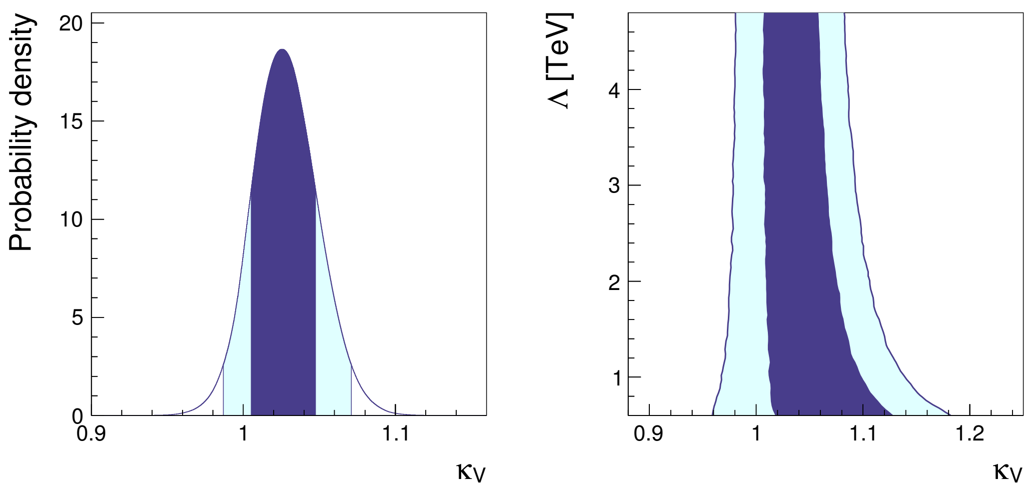
with $\Lambda = \frac{4\pi v}{\sqrt{|1-\kappa_V^2|}}$

	68%	95%
κ_V	1.026 ± 0.021	[0.987, 1.071]

at 95% c.l.:

$\kappa_V < 1 \rightarrow \Lambda > 19$ TeV

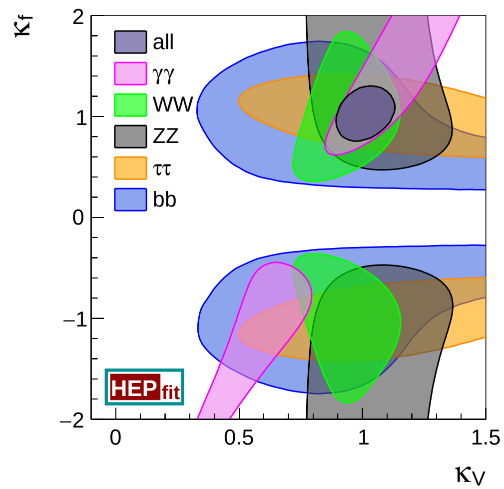
$\kappa_V > 1 \rightarrow \Lambda > 8.5$ TeV

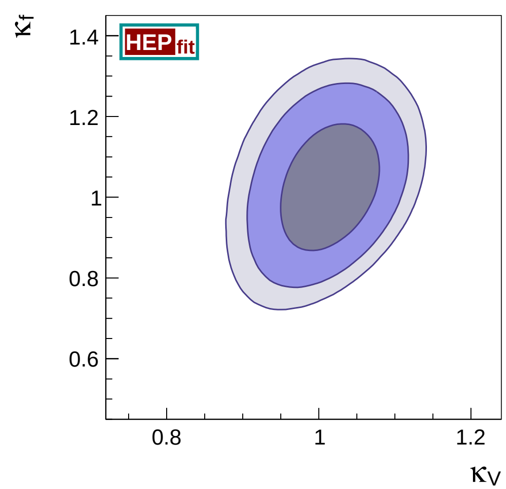


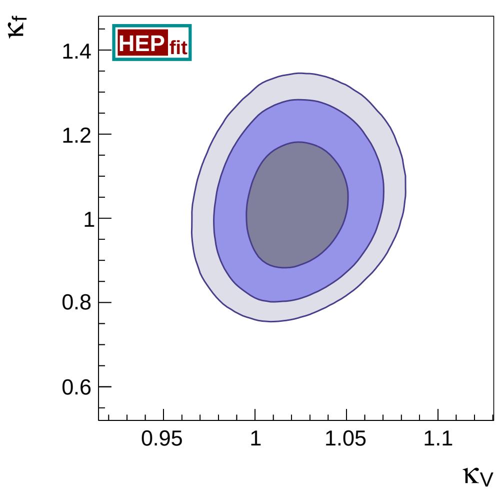
Considering both κ_V and κ_f

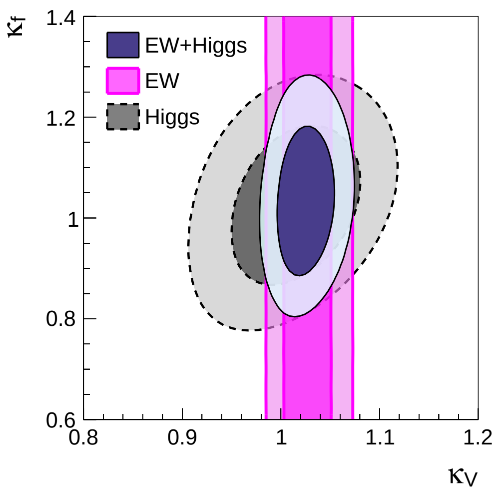
Higgs only

	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





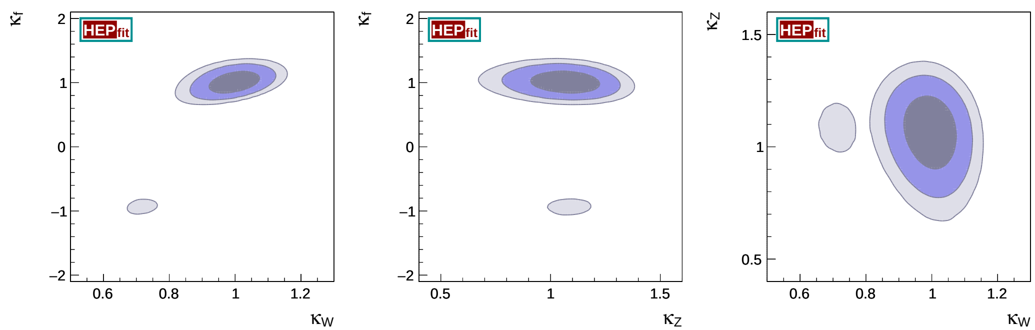




Higgs+EWPO

	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]	0.14	1.00

Zooming into κ_V and κ_f ...

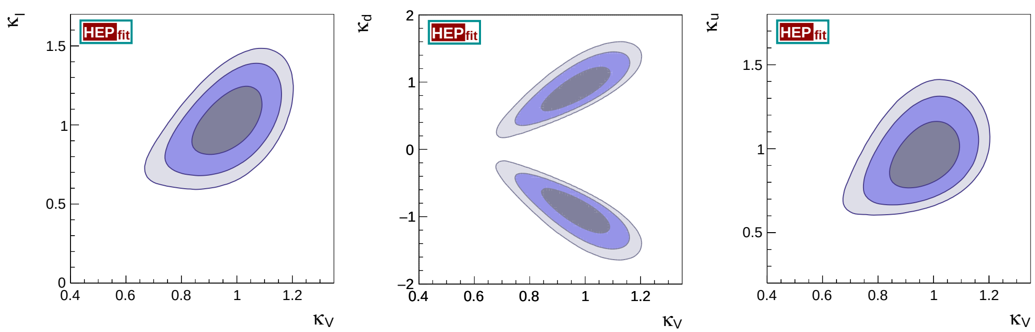


Custodial symmetry

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

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

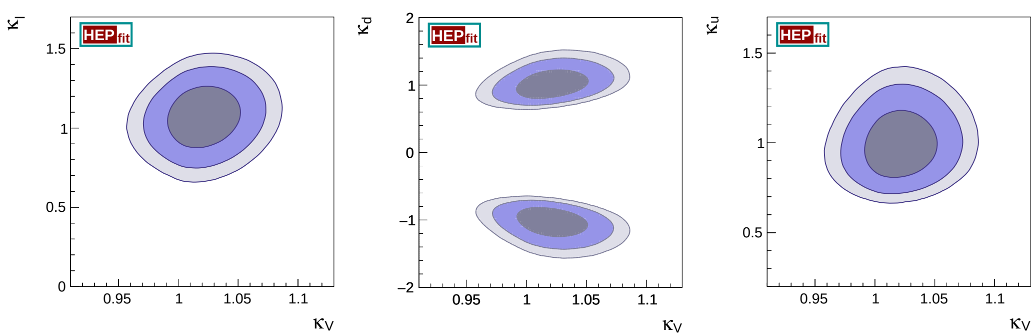


Flavor universality

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

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]	0.42	0.41	1.00	
κ_d	0.91 ± 0.21	[0.48, 1.35]	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	[0.79, 1.27]	0.10	0.24	1.00	
κ_d	1.01 ± 0.13	[0.76, 1.30]	0.31	0.38	0.78	1.00

SM Effective Field Theories

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

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

including **effects in NP on EWPO and SM Higgs-boson coupling**, but also **allowing for new structures**.

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 $C_i(\Lambda) \to C_i(\Lambda_{\text{EW}})$ more meaningful

→ otherwise take $C_i = C_i(\Lambda_{\text{EW}})$, no running included

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

bosonic operators

$\longrightarrow$ corrections to:

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

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

single-fermionic-vector-current operators

$\longrightarrow$ corrections to:

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

single-fermionic-scalar-current operators

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

$\longrightarrow$ corrections to:

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

four-fermion operator

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

$\longrightarrow$ corrections to:

- G_F extraction from μ decay

Notice: $V f \bar{f}$ 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 $\to G_F$, 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

$\delta_h \rightarrow$ NP corrections to h wave-function renormalization

$\delta_{G_F} \rightarrow$ NP corrections to G_F

95% bounds on coefficients of d=6 interactions

→ Switching on one operator at a time

Coefficient	**Only EW** C_i/Λ^2 [TeV^{-2}] at 95%	**Only Higgs** C_i/Λ^2 [TeV^{-2}] at 95%	**EW + Higgs** 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_{eH}	$--$	$[-0.027, 0.049]$	$[-0.027, 0.049]$
C_{uH}	$--$	$[-0.62, 0.33]$	$[-0.62, 0.33]$
C_{dH}	$--$	$[-0.062, 0.059]$	$[-0.062, 0.059]$
C_{LL}	$[-0.010, 0.022]$	$[-1.3, 0.9]]$	$[-0.010, 0.022]$

↪ see also Corbett, Eboli, Gonçalves, Gonzales-Fraile, Plehn, Rauch, arXiv:1505.0551

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_{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
C_{LL}	10.0	6.8	0.9	1.0	10.0	6.8

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

95% bounds on scale of new physics Λ - Present vs Future

	95% present bound on		95% future bound on	
Coefficient	$\frac{C_i}{\Lambda^2}$ [TeV^{-2}]	Λ [TeV] ($C_i = \pm 1$)	$\frac{C_i}{\Lambda^2}$ [TeV^{-2}]	Λ [TeV] ($C_i = \pm 1$)
C_{HWB}	[0.009, 0.003]	12	[0.0001, 0.0001]	93
C_{HD}	[0.027, 0.004]	6.6	[0.0005, 0.0005]	45
$C_{HL}^{(1)}$	[0.005, 0.012]	9.9	[0.0003, 0.0003]	56
$C_{HL}^{(3)}$	[0.011, 0.005]	10	[0.0002, 0.0002]	70
C_{He}	[0.015, 0.007]	8.6	[0.0003, 0.0003]	58
$C_{HQ}^{(1)}$	[0.027, 0.043]	5.3	[0.0018, 0.0018]	24
$C_{HQ}^{(3)}$	[0.011, 0.015]	9.1	[0.0005, 0.0005]	44
C_{Hu}	[0.071, 0.081]	3.7	[0.0035, 0.0035]	17
C_{Hd}	[0.14, 0.070]	2.9	[0.0046, 0.0046]	15
C_{LL}	[0.0096, 0.023]	7.3	[0.0003, 0.0003]	61

$\rightarrow$ Precision ($\times 10$) $\longrightarrow$ reach $\Lambda \simeq 100$ TeV

Outlook

- The SM offers a incredibly solid theoretical framework that we can use to extract indications of new physics.
- **Indirect evidence of new physics** from Higgs-boson and EW precision measurements can come **from the synergy between**
  - → accurate theoretical prediction,
  - → a systematic approach to the study of new effective interactions,
  - → the intuition and experience of many years of Beyond SM searches!
- **Increasing** the **precision** of input parameters could allow to **test higher scales of new physics**: a factor of 10 in precision could give access to scales as high as 100 TeV.
- **Direct evidence of new physics can boost this process**, as the discovery of a Higgs-boson has prompted and guided us in this new era of LHC physics.