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Precision constraints on non-standard Higgs-boson couplings with HEPfit

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We present results from a model-independent analysis of the current constraints on new physics corrections to the Standard Model Higgs interactions based on the HEPfit package. We combine Higgs-physics results obtained by the Large Hadron Collider (LHC) at 7 and 8 TeV with bounds from electroweak precision observables, and translate our limits on the Standard Model Higgs couplings into bounds on the Wilson coefficients of the Standard Model gauge invariant dimension-six effective Lagrangian used to parametrize the effets of new physics.

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1. Introduction

Looking for Indirect evidence of new physics (NP) beyond the Standard Model (SM) has become a strong component of the Large Hadron Collider (LHC) physics program. Run I of the LHC has discovered a Higgs boson with very similar characteristic to the Higgs boson of the Standard Model (H). The study of the properties of the Higgs boson discovered at the LHC, in conjunction with improved fits to electroweak precision observables (EWPO) that take into account recent progress in theoretical calculations and experimental measurements, offers a very constrained framework to explore new physics effects and will be an essential component of Run II of the LHC.

Since the Higgs-boson mass (m_H) has now been measured, the Higgs-boson couplings to SM particles are completely predicted except for the residual arbitrariness introduced by the Yukawa couplings to fermions, which are nevertheless very constrained by the precise measurement of fermion masses. This means that any deviation from the SM predictions will provide unambiguous evidence for new physics (NP). Unfortunately, large deviations from the SM expectations are already ruled out (except possibly in the couplings to light fermions and/or $H \to Z\gamma$). This, in conjunction with the absence of any other direct NP signal so far, leads us to expect a deviation at the level of no more than a few percents. Hence, a rigorous study of the Higgs-boson couplings in the Run-II of the LHC and also in the high luminosity phase is mandatory.

Although new particles at the TeV scale or below are perfectly allowed by the LHC data, it is interesting to study the sensitivity of the current Higgs-boson related measurements to short-distance physics assuming an effective field theory framework. Indeed, The effects of NP on EWPO and on Higgs-boson couplings can be systematically studied in the context of an effective field theory that adds to the Lagrangian of the SM new effective interactions of the SM fields in the form of higher-dimension ($d > 4$) local operators that preserve the SM gauge symmetry, namely

$$\mathscr{L}_{\text{Eff}} = \mathscr{L}_{\text{SM}} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} \mathscr{L}_d, \quad \text{with} \quad \mathscr{L}_d = \sum_i C_i \mathscr{O}_i, \quad [\mathscr{O}_i] = d\,, \tag{1.1}$$

where the dependence on Λ, the scale at which direct evidence of new-physics degrees of freedom is expected, has been made explicit. Given the precision of current observables, and assuming the new physics is around or above the TeV scale, it suffices for our purposes to truncate the previous effective Lagrangian at the dimension-six order. More details of the dimension-six effective Lagrangian and of the basis of effective operators used in our study will be given in Section 4. The effective Lagrangian approach to the study of NP effects in Higgs-boson couplings has been the object of a vibrant theoretical activity in the recent past and several contributions have set the way for and developed in parallel to our study [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44]. In Sec. 4 we will briefly comment on the use we have done of existing developments, and on comparisons we have performed with existing results. More details will be given in a forthcoming publication [45].

In this work we focus on the effects induced by these new interactions in Higgs observables as well as in electroweak precision data. The effects of new physics, i.e. of the heavier degrees of freedom that are part of the ultraviolet completion of the SM, are then encoded in the Wilson coefficients C_i associated with each operator O_i. By including the dependence of EWPO and

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Higgs-boson couplings on the C_i coefficients in a global fit of existing experimental measurements, a first conservative determination of the allowed range of each coefficient can be derived under very general assumptions, and a lower bound can be placed on the expected scale of new physics (Λ). This is what is achieved with the `HEPfit` package[1] (formerly `SUSYfit`), a stand-alone program to perform Bayesan statistical analyses of electroweak precision data (including Higgs-boson observables) in the SM and beyond using the Bayesan Analysis Toolkit (BAT). Results from the initial stages of this project were presented in [46, 47] and have by now been updated by using all most recent experimental and theoretical results. This exercise prepares the field for a time when more informations about new physics will come during Run II, hopefully including direct evidence, and set the stage for more constraining fits that at the moment would only be possible by renouncing model independence.

In the following we review the main results of the `HEPfit` project. In particular, we start by summarizing in Sections 2 results for the EW precision fits of the Standard Model, while we illustrate in Sections 3 and 4 the constraints we obtain for non-standard Higgs couplings, as well as the model-independent constraints imposed on generic new-physics contributions to EWPO and Higgs couplings from dimension-six effective interactions. In Section 5 we present some final remarks.

2. Electroweak precision fit in the Standard Model

The first application of the new `HEPfit` code has been to reproduce and update the EW precision fit previously obtained with `SUSYfit` [47], a detailed explanation of which can be found in Ref [23] and references therein. The `HEPfit` code is a completely newly structured version of the original `SUSYfit` code that allows to work in any given extension of the SM (SUSY, 2HDM, the generic $L_{\rm Eff}$ of Eq. (1.1), ...) when this is added to the main SM core as an external module. Based on a Markov Chain Monte Carlo, `HEPfit` performs Bayesan statistical analyses of electroweak precision data (including Higgs-boson observables) using the Bayesan Analysis Toolkit (BAT). Experimental likelihoods have been used as priors for all input parameters. Parameters and results for various EWPO are summarized in Table 1 together with their experimental measurements (data) . With respect to Ref. [47], we have updated m_H[2]. In the fourth column, we also present the indirect determinations of the input parameters and the EWPO obtained without using the corresponding experimental information but assuming a flat prior for the parameter or the observable under consideration. The values in the last column show the compatibility between the data and the indirect determination (pull, in units of standard deviations) [48]. All results have been validated against `ZFITTER` [49].

Corrections to EWPO in a given NP scenario can then be constrained in terms of the oblique parameters S, T, and U introduced in Ref. [50, 51] if NP mainly affects the vacuum-polarization amplitudes of gauge bosons, or in terms of the ε_i parameters introduced in Ref. [52, 53, 54] in models where sizable effects appear also in top-quark and Higgs-boson observables. Both parametriza-

[1] The `HEPfit` is available under the GNU General Public License (GPL) from `https://github.com/silvest/HEPfit`.

[2] The results presented here do not include yet the new results on m_t from ATLAS ($m_t = 172.99 \pm 0.91$ GeV), CMS ($m_t = 172.38 \pm 0.66$ GeV), and the Tevatron ($m_t = 174.34 \pm 0.63$ GeV).

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	Data	Fit	Indirect	Pull
$\alpha_s(M_Z^2)$	0.1185 ± 0.0005	0.1185 ± 0.0005	0.1184 ± 0.0028	-0.0
$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$	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	$+0.4$
$\mathscr{A}_\ell$ (SLD)	0.1513 ± 0.0021	0.1477 ± 0.0007	0.1472 ± 0.0008	-1.9
$\mathscr{A}_c$	0.670 ± 0.027	0.6682 ± 0.0003	0.6682 ± 0.0003	-0.1
$\mathscr{A}_b$	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

Table 1: Experimental data and SM fit results for the five input parameters and fifteen EWPO considered in this study. The values in the column "Indirect" are determined without using the corresponding experimental information, while those in the column "Pull" represent the pulls in units of standard deviations [48].

tion are implemented in `HEPfit` following the detailed treatment of Ref. [23]. Given the only minor change in the input value of m_H with respect to Ref. [47], the results for both the oblique parameters and the ε_i parameters are basically unchanged with respect to Ref. [47] and we do not further discuss them here.

3. Constraints on Higgs couplings

On top of fitting to the standard set of EWPO, we have considered all most recent measurements of Higgs-boson signal strengths ($\mu = \sigma/\sigma_{\rm SM}$) taken from Refs. [55, 56] for $H \to \gamma\gamma$, Refs. [57, 58] for $H \to \tau^+\tau^-$, Refs. [59, 60] for $H \to ZZ$, Refs. [61, 62, 63] for $H \to W^+W^-$, and Refs. [64, 65, 66, 67] as well as the Tevatron papers [68, 69] for $H \to b\bar{b}$. The Higgs-boson signal strength μ of a a specific analysis can be calculated as

$$\mu = \sum_i w_i r_i \quad \text{where} \quad r_i = \frac{(\sigma \times Br)_i}{(\sigma_{\rm SM} \times Br_{\rm SM})_i} \quad \text{and} \quad w_i = \frac{\varepsilon_i(\sigma_{\rm SM} \times Br_{\rm SM})_i}{\sum_j \varepsilon_j(\sigma_{\rm SM} \times Br_{\rm SM})_j} \,, \tag{3.1}$$

where the sum runs over all channels which can contribute the the final state of the analysis. The SM Higgs-boson production cross section (including QCD and, when available, EW corrections)

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	68%	95%	Correlations	
κ_V	0.98 ± 0.05	[0.88, 1.07]	1.00	
κ_f	0.92 ± 0.10	[0.75, 1.12]	0.47	1.00

Table 2: SM-like solution in the fit of κ_V and κ_f to the Higgs-boson signal strengths.

	68%	95%	Correlations	
κ_V	1.02 ± 0.02	[0.98, 1.06]	1.00	
κ_f	0.96 ± 0.08	[0.81, 1.14]	0.21	1.00

Table 3: Same as Table 2 but considering both the Higgs-boson signal strengths and the EWPO.

are taken from Ref. [70] and the SM Higgs boson decay rates are taken from [20]. In the presence of NP the relative experimental efficiencies, ε_i, will in general be different from their values in the SM. In particular, the appearance of new tensor structures in the vertices can modify the kinematic distribution of the final-state particles, thereby changing the efficiencies. In this work, we assume that this effect is negligible and use the SM weight factors throughout. This assumption is valid for small deviations from the SM couplings so that kinematic distributions are not changed significantly.

Considering the very minimal scenario in which there is only one Higgs-boson below the cutoff Λ, custodial symmetry is approximately realized, and corrections from NP are flavour diagonal and universal, it is first of all important to check existing constraints on generic anomalous Higgs couplings to vector bosons (HVV) and fermions ($Hf\bar{f}$). It is customary to describe anomalous couplings in terms of scaling factors κ_V and κ_f defined as the ratio between the Higgs couplings including new physics effects and the corresponding coupling in the pure SM. We do not introduce new couplings that are not already in the SM and, for loop-induced couplings (Hgg, $H\gamma\gamma$, and $HZ\gamma$), we do not assume NP contributions in the loop. For a detailed description of the relations between scale factors and the Higgs-boson signal strengths we refer to Ref. [70].

The two-dimensional probability distributions for κ_V and κ_f obtained from the ft to Higgs-boson signal strengths are summarized in Table 2 and shown in Fig. 1 at 68%, 95%, 99%, and 99.9%, where only the parameter space with positive κ_V is presented. The region with negative κ_f is disfavored in the fit. The left-hand-side plot shows the fit obtained from the individual decay channels, while the right-hand-side plot gives the result obtained from combination of all decay channels. Note that theoretical predictions are symmetric under the exchange $\{\kappa_V,\ \kappa_f\} \leftrightarrow \{-\kappa_V,\ -\kappa_f\}$. The effect of performing a combined fit of both Higgs-signal strengths and EWPO is summarized in Table 3 and illustrated in Fig. 2. It is interesting to notice how the constraint on κ_V from EWPO is stronger than from the Higgs-boson strengths alone.

If we rescale the HZZ and HW^+W^- couplings independently introducing both κ_Z and κ_W (keeping a unique κ_f) we obtain the fit results summarized in Table 4 and the corresponding probability distributions shown in Fig. 3, which are consistent with custodial symmetry. We notice that theoretical predictions are symmetric under the exchanges $\{\kappa_W,\ \kappa_f\} \leftrightarrow \{-\kappa_W,\ -\kappa_f\}$ and/or $\kappa_Z \leftrightarrow -\kappa_Z$, where κ_Z can flip the sign independent of κ_W, since the interference between the W and Z contributions to the vector-boson fusion cross section is negligible. Hence we have considered only the parameter space where both κ_W and κ_Z are positive. Moreover, we do not fit to the EWPO,

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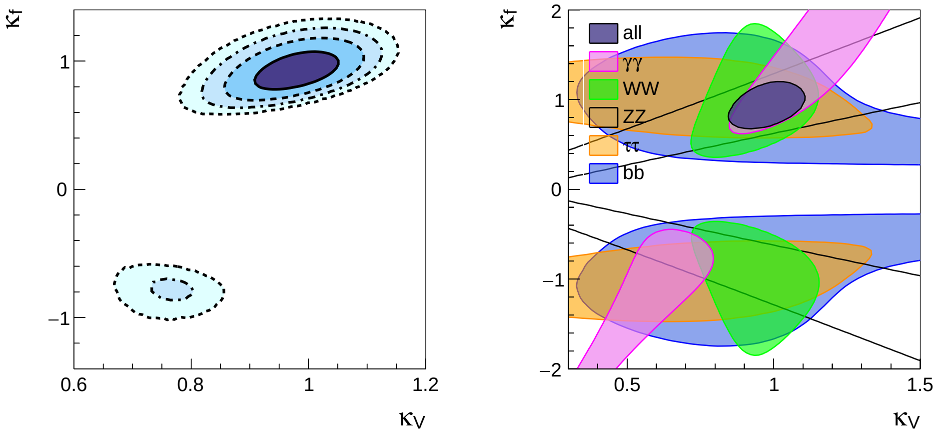

Figure 1: Left: Two-dimensional probability distributions for κ_V and κ_f at 68%, 95%, 99%, and 99.9% (darker to lighter), obtained from the fit to the Higgs-boson signal strengths. Right: Constraints from individual channels at 95%.

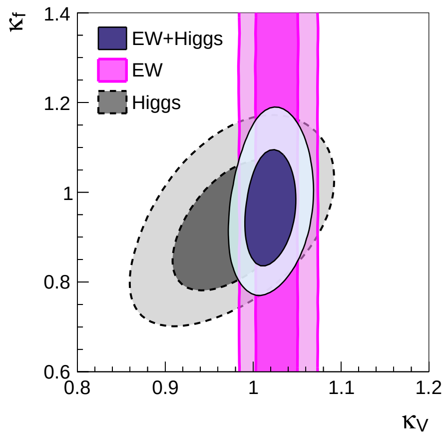

Figure 2: Two-dimensional probability distributions for κ_V and κ_f at 68% (the dark region) and 95% (the light region), obtained from the fit to the Higgs-boson signal strengths and the EWPO.

since setting $\kappa_W \neq \kappa_Z$ generates power divergences in the oblique corrections, indicating that the detailed information on the UV theory is necessary for calculating the oblique corrections.

Finally, if we lift flavour universality and introduce different rescaling factors for charged leptons (κ_l), up-type quarks (κ_u), and down-type quarks (κ_d), while keeping a unique rescaling factor κ_V for both HVV couplings, we obtain the constraints on the scale factors from the Higgs-boson signal strengths presented in Table 5 and in the top plots of Fig. 4. By adding the EWPO to the fit, the constraints become stronger as shown in Table 6 and in the bottom plots of Fig. 4. In this case, the Higgs-boson signal strengths are symmetric under the exchanges $\kappa_\ell \leftrightarrow -\kappa_\ell$ and/or $\{\kappa_V,\ \kappa_u,\ \kappa_d\} \leftrightarrow \{-\kappa_V,\ -\kappa_u,\ -\kappa_d\}$. Therefore, we consider only the parameter space where both κ_V and κ_ℓ are positive.

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	68%	95%	Correlations		
κ_W	0.98 ± 0.05	[0.88, 1.07]	1.00		
κ_Z	0.98 ± 0.12	[0.74, 1.22]	0.08	1.00	
κ_f	0.94 ± 0.10	[0.74, 1.14]	0.31	0.48	1.00

Table 4: SM-like solution in the fit of κ_W, κ_Z, and κ_f to the Higgs-boson signal strengths.

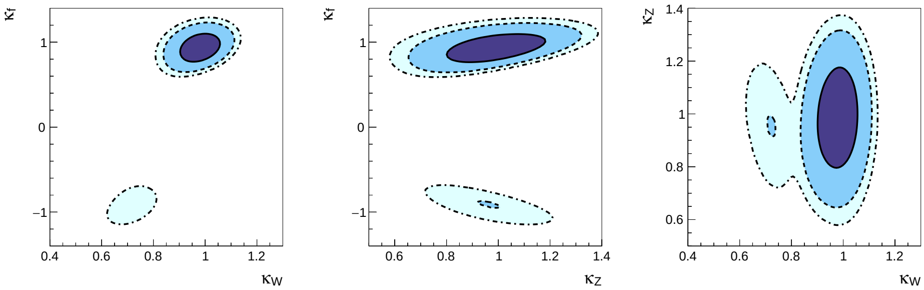

Figure 3: Two-dimensional probability distributions for κ_W and κ_f (left), for κ_Z and κ_f (center), and for κ_W and κ_Z (right) at 68%, 95%, and 99% (darker to lighter), obtained from the fit to the Higgs-boson signal strengths.

	68%	95%	Correlations			
κ_V	0.94 ± 0.08	[0.78, 1.09]	1.00			
κ_ℓ	0.86 ± 0.14	[0.58, 1.14]	0.33	1.00		
κ_u	0.95 ± 0.11	[0.75, 1.19]	0.26	0.27	1.00	
κ_d	0.86 ± 0.17	[0.55, 1.21]	0.81	0.41	0.58	1.00

Table 5: SM-like solution in the fit of κ_V, κ_ℓ, κ_u, and κ_d to the Higgs-boson signal strengths.

	68%	95%	Correlations			
κ_V	1.02 ± 0.02	[0.98, 1.06]	1.00			
κ_ℓ	0.92 ± 0.13	[0.63, 1.18]	0.09	1.00		
κ_u	0.98 ± 0.11	[0.78, 1.22]	0.07	0.23	1.00	
κ_d	1.00 ± 0.11	[0.80, 1.24]	0.33	0.30	0.66	1.00

Table 6: Same as Table 5, but considering both the Higgs-boson signal strengths and the EWPO.

4. Constraints on effective interactions from new physics

As discussed in Section 1, we choose to describe new physics effects in a model-independent way by using an effective Lagrangian approach that complements the SM Lagrangian by a complete set of gauge-invariant dimension-six operators (see Eq. (1.1). Several operator bases have been proposed in the literature [71, 11, 72, 73]. Despite physical results must be independent of the basis we use in our computations, for specific purposes the choice of one particular basis may be more convenient than others. Also, although all bases are physically equivalent, one must be careful when comparing the physical interpretations of particular operators. In particular, the same operators can have a different physical meaning in different bases since the dependence of physical observable on the corresponding Wilson coefficients might involve similar yet slightly different

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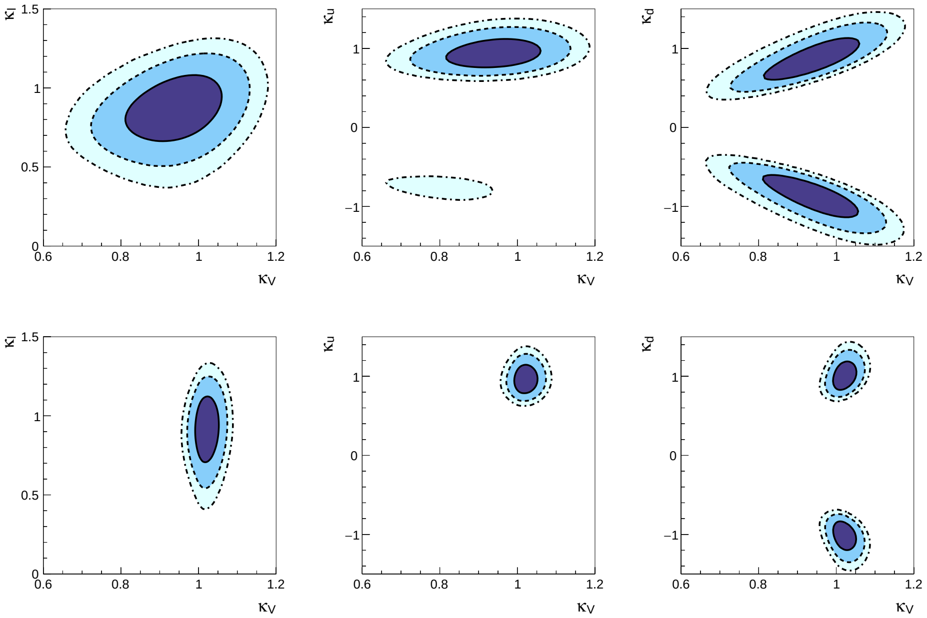

Figure 4: Two-dimensional probability distributions for κ_V and κ_ℓ, for κ_V and κ_u, and for κ_V and κ_d , at 68%, 95%, and 99% (darker to lighter), obtained from the fit to the Higgs-boson signal strengths only (top plots) orthe combination of Higgs-boson signal strengths and EWPO (bottom plots).

linear combinations of coefficients and can therefore provide very different constraints on the coefficients themselves. In particular, the basis presented by the authors of [73], which we will refer to as the GIMR basis, is quite easy to relate to electroweak precision data and Higgs observables by means of shifts of the couplings to the SM bosons.

Indeed, in our study we adopt the GIMR basis which consists of a total of 59 independent effective operators, barring the flavour structure of the operators themselves. Among the 59 operators of Ref. [73] we can distinguish 15 bosonic operators, 19 single-fermionic-current operators and 25 four-fermion operators for each fermion generation. Since in this study we limit ourselves to electroweak and Higgs-boson signal strength observables (extending the previous work by some of us [2, 23, 27]), we consider only a subset of operators. In particular, we only consider operators involving one or more Higgs fields. Operators which involve fermionic fields are assumed to be flavour diagonal and family universal. Moreover, we restrict this study to Charge-Parity (*CP*) even operators only. As the Wilson coefficients are generated at the scale Λ, ideally, one should also use the Renormalization Group Equations (RGE) to evolve them from the scale Λ to the energy scale relevant for the process of interest[3]. In this work we neglect the effect of RGE. This also means that we do not account for possible effects of mixing among different operators as induced by the RGE scale evolution. These effects can be very important, but they can be included only if the complete structure of the RGE scale evolution is considered, in order to avoid inconsistencies. Also, it brings to the analysis a level of sophistication that it is probably worth including when more is known of the nature of NP causing the non-standard interactions described by the $d = 6$ operators. We will

[3]The anomalous dimension matrix for all the 2499 operators of which the basis consists when the operator flavour structure is included has been computed in [14, 15, 16].

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explore this aspect of the problem in future studies. In the following, we introduce our notations and list all the operators relevant for our study.

- Bosonic operators:

$$\mathscr{O}_{HG} = (H^\dagger H)\, G^A_{\mu\nu} G^{A\mu\nu}\ , \tag{4.1}$$
$$\mathscr{O}_{HW} = (H^\dagger H)\, W^I_{\mu\nu} W^{I\mu\nu}\ , \tag{4.2}$$
$$\mathscr{O}_{HB} = (H^\dagger H)\, B_{\mu\nu} B^{\mu\nu}\ , \tag{4.3}$$
$$\mathscr{O}_{HWB} = (H^\dagger \tau^I H)\, W^I_{\mu\nu} B^{\mu\nu}\ , \tag{4.4}$$
$$\mathscr{O}_{HD} = (H^\dagger D^\mu H)^* \,(H^\dagger D_\mu H)\ , \tag{4.5}$$

where τ^I are the three Pauli matrices.

The Wilson coefficients for the operators $\mathscr{O}_{HWB}$ and $\mathscr{O}_{HD}$ (we denote them by C_{HWB} and C_{HD} respectively) are related to the well known Peskin and Takeuchi parameters S and T [50] by,

$$S = \frac{4 s_W c_W}{\alpha_{\rm em}(M_Z)} \frac{\mathrm{v}^2}{\Lambda^2} C_{HWB}\ , \tag{4.6}$$
$$T = -\frac{1}{2\alpha_{\rm em}(M_Z)} \frac{\mathrm{v}^2}{\Lambda^2} C_{HD}\ , \tag{4.7}$$

where c_W and s_W are the cosine and sine of the weak mixing angle θ_W respectively, v is the Vacuum Expectation Value (VEV) of the Higgs field, and $\alpha_{\rm em}$ is the electromagnetic fine-structure constant.

In addition to the above operators, there are two more purely bosonic operators involving only the Higgs-boson field, namely,

$$\mathscr{O}_{H\Box} = (H^\dagger H)\Box(H^\dagger H) \quad \text{and} \tag{4.8}$$
$$\mathscr{O}_{H} = (H^\dagger H)^3\ . \tag{4.9}$$

The operator $\mathscr{O}_{H\Box}$ contributes to the wave-function renormalization of the Higgs field and $\mathscr{O}_H$ contributes to the Higgs potential, i.e., the VEV v and the SM Higgs-boson self coupling λ. We will see later that this makes $\mathscr{O}_{H\Box}$ poorly constrained and $\mathscr{O}_H$, which does not affect our observables at all, remains unconstrained by our analysis. A joint measurement of the Higgs mass m_H and the self-coupling λ is required to constrain this operator. There are 8 more bosonic operators (6 *CP* odd + 2 *CP* even) in the total 15 bosonic operators listed in [73], but they either do not involve any Higgs field or are CP-odd. Thus, we do not consider them in our analysis.

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- Single-fermionic-current operators:

$$\mathcal{O}_{HL}^{(1)} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{L}\gamma^\mu L) \,, \tag{4.10}$$

$$\mathcal{O}_{HL}^{(3)} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{L}\tau^I\gamma^\mu L) \,, \tag{4.11}$$

$$\mathcal{O}_{He} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R) \,, \tag{4.12}$$

$$\mathcal{O}_{HQ}^{(1)} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{Q}\gamma^\mu Q) \,, \tag{4.13}$$

$$\mathcal{O}_{HQ}^{(3)} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\overline{Q}\tau^I\gamma^\mu Q) \,, \tag{4.14}$$

$$\mathcal{O}_{Hu} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R) \,, \tag{4.15}$$

$$\mathcal{O}_{Hd} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R) \,, \tag{4.16}$$

$$\mathcal{O}_{Hud} = i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_R\gamma^\mu d_R) \,. \tag{4.17}$$

As we consider flavour-diagonal couplings only, all the above operators except $\mathcal{O}_{Hud}$ are hermitian. Here, $\widetilde{H} = i\tau^2 H^*$ and the hermitian derivatives have been defined as,

$$H^\dagger \overleftrightarrow{D}_\mu H = H^\dagger(D_\mu H) - (D_\mu H)^\dagger H \text{ and} \tag{4.18}$$

$$H^\dagger \overleftrightarrow{D}^I_\mu H = H^\dagger\tau^I(D_\mu H) - (D_\mu H)^\dagger\tau^I H \,. \tag{4.19}$$

There are also (non-hermitian) operators involving scalar fermionic currents,

$$\mathcal{O}_{eH} = (H^\dagger H)(\bar{L}e_R H) \,, \tag{4.20}$$

$$\mathcal{O}_{uH} = (H^\dagger H)(\bar{Q}u_R\widetilde{H}) \,, \tag{4.21}$$

$$\mathcal{O}_{dH} = (H^\dagger H)(\bar{Q}d_R H) \,. \tag{4.22}$$

Once the Higgs field gets a VEV, these operators modify the SM Yukawa couplings. There are 8 more operator structures which involve tensor fermionic currents. We do not consider them in the analysis presented here.

Using `HEPfit`, we consider only one Wilson coefficient at a time and fit it first to the EWPO and Higgs-boson observables separately, and then to the combination of both. Our results are summarized in Table 7 where we show the 95% probability regions for the Wilson coefficients assuming the NP scale to be 1 TeV. It can be observed that except for $\mathcal{O}_{HWB}$ the Electroweak precision constraints are much stronger than the Higgs signal strength data for all the operators which contribute to the EWPO. The strong constraint on C_{HWB} from the Higgs data is due to its contribution to the Higgs decay to two photons which is loop suppressed in the SM. More precisely, the direct NP contribution to the $H\gamma\gamma$ vertex can be written as,

$$\mathcal{L}_{NP} \subset \frac{\mathrm{v}}{\Lambda^2}(-c_W s_W C_{HWB} + s_W^2 C_{HW} + c_W^2 C_{HB})F_{\mu\nu}F^{\mu\nu}H \,, \tag{4.23}$$

which has to be compared with the SM vertex $c_\gamma \frac{\alpha_{\rm em}}{8\pi\mathrm{v}} F_{\mu\nu}F^{\mu\nu}H$ with $c_\gamma \approx -6.48$. Eq. (4.23) also explains why the bounds on C_{HW} and C_{HB} are rather strong from the Higgs signal strength data.

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	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}	$--$	$[-0.062, 0.059]$	$[-0.062, 0.059]$

Table 7: Fit results for the coefficients of the dimension six operators at 95% probability. The fit is performed switching on one operator at a time. Bounds from only EWPO, only Higgs signal strengths and the combined ones are shown separately.

The tight constraint on the operator $\mathscr{O}_{HG}$ can also be understood in a similar way. It contributes to the Higgs-boson production through gluon fusion,

$$\mathscr{L}_{NP} \subset \frac{\mathrm{v}}{\Lambda^2} C_{HG}\, G^A_{\mu\nu} G^{\mu\nu A} H\,, \tag{4.24}$$

which should be compared to the SM contribution $\frac{\alpha_s}{12\pi \mathrm{v}} G^A_{\mu\nu} G^{\mu\nu A} H$, where α_s is the chromomagnetic fine-structure constant.

The bounds on the dimension-6 operator coefficients in Table 7 can also be translated into bounds on the NP scale for fixed values of the coefficients. We show them in Table 8 for two values, $C_i = 1$ and $C_i = -1$. Clearly, for $|C_i| = 1$, and without further knowledge of possible correlations among subsets of operators, our fit seems to indicate that the scale of new physics Λ is beyond LHC reach. However, for perturbative C_i new physics at scales Λ of $O(\mathrm{TeV})$ cannot be excluded. Moreover, correlations among coefficients may indicate the possibility of cancellations that can weaken the constraints on Λ. Assuming correlations is in conflict with the model-independent approach to the study of NP effects in Higgs coupling that we have emphasized in our study. However, indications of correlations among coefficients that influence the same physical observables can be suggestive, and we have explored it. The pictorial representation of our results is given in Fig. 5 where the circles indicate the fact that a given Wilson coefficient directly contributes to a spe-

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	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

Table 8: Lower bounds on the NP scale in TeV obtained by setting $C_i = \pm 1$.

cific physical observable and the size of the circles represents their statistical significance: smaller circles correspond to very poorly bounded operators, bigger circles to very constrained ones.

5. Conclusions

After the discovery of a SM-like Higgs boson during Run I of the LHC the possibility of using SM and Higgs-boson precision measurements as a portal to new physics has become a reality. Through the steady improvement of both theoretical and experimental accuracies, electroweak and Higgs-boson precision physics could lead us a long way towards determining the ultraviolet completion of the SM and the more fundamental origin of the spontaneously broken realization of the electroweak symmetry.

Indirect searches for new physics are indeed as important as ever in the physics program of Run II of the LHC: they will probe physics at inaccessible high scales and provide clues on the nature of new particles. In this context, it is very valuable, if not essential, to provide a complete and consistent framework in which all available experimental data, from precision measurements of electroweak observables and Higgs-boson couplings to flavour-physics results, can be analyzed to constrain the theory in a statistically significant way. This is the aim of the new `HEPfit` project that we have reviewed in this proceedings, and of which we have presented preliminary results from the analysis of the 7 and 8 TeV Run I LHC data.

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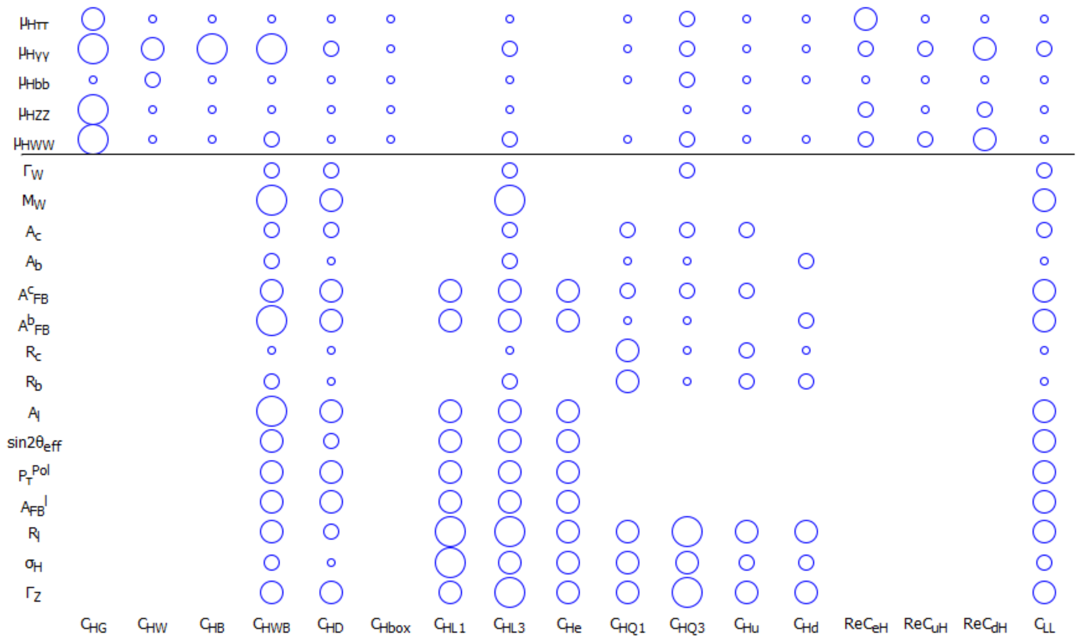

Figure 5: Correlation among Wilson coefficients of the the $d = 6$ basis of operators and physical observables entering the precision fit.

On the theoretical side, the effective field theory approach emerges as the most systematic among many attempts to parametrize the indirect effects of new physics on different electroweak and Higgs-physics observables, and understand their patterns. In general, in an ultraviolet (UV) complete model several operators are generated with specific relations among their coefficients. However, given the state of our knowledge about UV physics, any theoretical bias is premature and considering definite combinations of the operators in a fit is not strongly motivated. Here we have studied only one NP operator at a time. Barring accidental cancellations, our results should provide a conservative estimate of the bounds even in relatively general scenarios.

The summary of our results is presented in Tables 1-6 and in Figs. 1-5. It is interesting that there is a strong hierarchy among the lower bounds on NP scales of different operators. It ranges from ~ 1 TeV (bound from $C_{H\Box}$) to $\sim$ 10-15 TeV (bound from, e.g., C_{HB}). We also observe that in general, when both EWPO and Higgs-boson data are at play, the strongest bounds are placed by the EWPO data, with the only exception of the operator $\mathscr{O}_{HWB}$, where the bound from Higgs strength data is comparable to that obtained from EWPO. On the other hand, there are operators (e.g., $\mathscr{O}_{HG,HW,HB}$) which are only constrained by the Higgs data. The operator with rather strong bounds are the ones that contribute to loop-suppressed processes in the SM.

Moreover, when we switch on one operator at a time and assume $C_i = \pm 1$, preliminary results

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presented here indicate that the NP scale is beyond the reach of LHC energy for most of the operators. However, these bounds can be weaker, and scales $\Lambda \sim$ TeV still allowed, if the coefficients are smaller or specific correlations among the NP operators are present. A visualization of the possible existing correlations among different new-physics contributions is presented in Fig. 5. The case is clear to push for precision physics on both the theoretical and experimental side: a factor of ten improvement in the inputs of the study presented in these proceedings would allow to probe scales up to 100 TeV and/or to constrain the interactions of lighter new particles, and would therefore have a strong impact on direct searches.

Finally, we emphasize that projects like `HEPfit` are modular and can be improved by including more accurate theoretical calculations and experimental measurements as well as by adding new constraints (e.g. flavour-physics observables). Improved results will be essential to shed light on the nature of new physics beyond the Standard Model, therefore allowing more focused searches and more effective choices for the development of future colliders.

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