LHC HXSWG interim recommendations to explore the coupling structure of a Higgs-like particle

LHC Higgs Cross Section Working Group, Light Mass Higgs Subgroup
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Abstract

This document presents an interim framework in which the coupling structure of a Higgs-like particle can be studied. After discussing different options and approximations, recommendations on specific benchmark parametrizations to be used to fit the data are given.

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1 Introduction

The recent observation of a new massive neutral boson by ATLAS and CMS [1, 2], as well as evidence from the Tevatron experiments [3], opens a new era where characterization of this new object is of central importance.

The Standard Model (SM), as any renormalizable theory, makes very accurate predictions for the coupling of the Higgs boson to all other known particles. These couplings directly influence the rates of production and decay of the Higgs boson. Therefore, measurement of the production and decay rates of the observed state yields information that can be used to probe whether data are compatible with the SM predictions for the Higgs boson.

While coarse features of the observed state can be inferred from the information that the experiments have made public, only a consistent and combined treatment of the data can yield the most accurate picture of the coupling structure. Such a treatment must take into account all the systematic and statistical uncertainties considered in the analyses, as well as the correlations among them.

This document outlines an interim framework to explore the coupling structure of the recently observed state. The framework proposed in this recommendation should be seen as a continuation of the model-independent analysis of the Higgs couplings initiated in Refs. [4–11]. It bears many resemblances to the original studies on the LHC sensitivity of the Higgs couplings [12–15] and follows closely the methodology proposed in the recent phenomenological works [16–18] which has been further extended in several directions [19–56] along the lines that are formalized in the present recommendation. While the interim framework is not final, it has an accuracy that matches the statistical power of the datasets that the LHC experiments can hope to collect until the end of the 2012 LHC run and is an explicit attempt to provide a common ground for the dialogue in the, and between the, experimental and theoretical communities.

Based on that framework, a series of benchmark parametrizations are presented. Each benchmark parametrization allows to explore specific aspects of the coupling structure of the new state. The parametrizations have varying degrees of complexity, in a bid to cover the most interesting possibilities that can be realistically tested with the LHC 7 and 8 TeV datasets. On the one hand, the framework and benchmarks were designed to provide a recommendation to experiments on how to perform coupling fits that are useful for the theory community. On the other hand the theory community can prepare for results based on the framework discussed in this document.

Finally, avenues that can be pursued to improve upon this interim framework and recommendations on how to probe the tensor structure will be discussed in a future document.

2 Panorama of experimental measurements at the LHC

In 2011, the LHC delivered an integrated luminosity of slightly less than 6 fb^{-1} of proton–proton (pp) collisions at a center-of-mass energy of 7 TeV to the ATLAS and CMS experiments. By July 2012, the LHC delivered more than 6 fb^{-1} of pp collisions at a center-of-mass energy of 8 TeV to both experiments. For this dataset, the instantaneous luminosity reached record levels of approximately $7 \cdot 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, almost double the peak luminosity of 2011 with the same 50 ns bunch spacing. The 2012 pp run will continue until the end of the year, hopefully delivering about 30 fb^{-1} per experiment.

At the LHC a SM-like Higgs boson is searched for mainly in four exclusive production processes: the predominant gluon fusion $\mathrm{gg} \to \mathrm{H}$, the vector boson fusion $\mathrm{qq}' \to \mathrm{qq}'\mathrm{H}$, the associated production with a vector boson $\mathrm{q\overline{q}} \to W\mathrm{H}/Z\mathrm{H}$ and the associated production with a top-quark pair $\mathrm{q\overline{q}}/\mathrm{gg} \to \mathrm{t\overline{t}H}$. The main search channels are determined by five decay modes of the Higgs boson, the $\gamma\gamma$, $\mathrm{ZZ}^{(*)}$, $\mathrm{WW}^{(*)}$, $\mathrm{b\overline{b}}$ and $\tau^+\tau^-$ channels. The mass range within which each channel is effective and the production processes for which exclusive searches have been developed and made public are indicated in Table 1. A detailed description of the Higgs search analyses can be found in Refs. [1, 2].

Table 1: Summary of the Higgs boson search channels for $m_{\mathrm{H}} < 130$ GeV in the ATLAS and CMS experiments by July 2012. The √ symbol indicates exclusive searches targetting the inclusive $\mathrm{gg} \to \mathrm{H}$ production, the associated production processes (with a vector boson or a top quark pair) or the vector boson fusion (VBF) production process.

Channel	m_{H}(GeV)	ggH		VBF		VH		$\mathrm{t\overline{t}H}$	
		ATLAS	CMS	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
$\mathrm{H} \to \gamma\gamma$	110–150	√	√	√	√	-	-	-	-
$\mathrm{H} \to \tau^+\tau^-$	110–145	√	√	√	√	√	√	-	-
$\mathrm{H} \to \mathrm{b\overline{b}}$	110–130	-	-	-	-	√	√	-	√
$\mathrm{H} \to \mathrm{ZZ}^{(*)} \to \ell^+\ell^-\ell^+\ell^-$	110–600	√	√	-	-	-	-	-	-
$\mathrm{H} \to \mathrm{WW}^{(*)} \to \ell^+\nu\ell^-\overline{\nu}$	110–600	√	√	√	√	√	√	-	-

Both the ATLAS and CMS experiments observe an excess of events for Higgs boson mass hypotheses near $\sim$ 125 GeV. The observed combined significances are 5.9σ for ATLAS [1] and 5.0σ for CMS [2], compatible with their respective sensitivities. Both observations are primarily in the $\mathrm{H} \to \gamma\gamma$, $\mathrm{H} \to \mathrm{ZZ}^{(*)} \to \ell^+\ell^-\ell^+\ell^-$ and $\mathrm{H} \to \mathrm{WW}^{(*)} \to \ell^+\nu\ell^-\overline{\nu}$ channels. For the $\mathrm{H} \to \gamma\gamma$ channel, excesses of 4.5σ and 4.1σ are observed at Higgs boson mass hypotheses of 126.5 GeV and 125 GeV, in agreement with the expected sensitivities of around 2.5σ and 2.8σ, in the ATLAS and CMS experiments respectively. For the $\mathrm{H} \to \mathrm{ZZ}^{(*)} \to \ell^+\ell^-\ell^+\ell^-$ channel, the significances of the excesses are 3.6σ and 3.2σ at Higgs boson mass hypotheses of 125 GeV and 125.6 GeV, in the ATLAS and CMS experiments respectively. The expected sensitivities at those masses are 2.7σ in ATLAS and 3.8σ in CMS respectively. For the low mass resolution $\mathrm{H} \to \mathrm{WW}^{(*)} \to \ell^+\nu\ell^-\overline{\nu}$ channel ATLAS observes an excess of 2.8σ (2.3σ expected) and CMS observes 1.6σ (2.4σ expected) for a Higgs boson mass hypotheses of $\sim$ 125 GeV. The other channels do not contribute significantly to the excess, but are nevertheless individually compatible with the presence of a signal.

The ATLAS and CMS experiments have also reported compatible measurements of the mass of the observed narrow resonance yielding:

$$126.0 \pm 0.4(\text{stat.}) \pm 0.4(\text{syst.})\ \text{GeV(ATLAS)},$$
$$125.3 \pm 0.4(\text{stat.}) \pm 0.5(\text{syst.})\ \text{GeV(CMS)}.$$

3 Interim framework for the search of deviations

The idea behind this framework is that all deviations from the SM are computed assuming that there is only one underlying state at ~ 125 GeV. It is assumed that this state is a Higgs boson, i.e. the excitation of a field whose vacuum expectation value (VEV) breaks electroweak symmetry, and that it is SM-like, in the sense that the experimental results so far are compatible with the interpretation of the state in terms of the SM Higgs boson. No specific assumptions are made on any additional states of new physics that could influence the phenomenology of the 125 GeV state, such as additional Higgs bosons (which could be heavier but also lighter than 125 GeV), additional scalars that do not develop a VEV, and new fermions and/or gauge bosons that could interact with the state at 125 GeV, giving rise, for instance, to an invisible decay mode.

The purpose of this framework is to either confirm that the light, narrow, resonance indeed matches the properties of the SM Higgs, or to establish a deviation from the SM behaviour, which would rule out the SM if sufficiently significant. In the latter case the next goal in the quest to identify the nature of electroweak symmetry breaking (EWSB) would obviously be to test the compatibility of the observed patterns with alternative frameworks of EWSB.

In investigating the experimental information that can be obtained on the coupling properties of the new state near 125 GeV from the LHC data to be collected in 2012 the following assumptions are made[1]:

- The signals observed in the different search channels originate from a single narrow resonance with a mass near 125 GeV. The case of several, possibly overlapping, resonances in this mass region is not considered.
- The width of the assumed Higgs boson near 125 GeV is neglected, i.e. the zero-width approximation for this state is used. Hence the product $\sigma \times BR(ii \to \mathrm{H} \to ff)$ can be decomposed in the following way for all channels:

  $$\sigma \times BR(ii \to \mathrm{H} \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}} \tag{1}$$

  where σ_{ii} is the production cross section through the initial state ii, Γ_{ff} the partial decay width into the final state ff and Γ_{H} the total width of the Higgs boson.

Within the context of these assumptions, in the following a simplified framework for investigating the experimental information that can be obtained on the coupling properties of the new state is outlined. In general, the couplings of the assumed Higgs state near 125 GeV are “pseudo-observables”, i.e. they cannot be directly measured. This means that a certain “unfolding procedure” is necessary to extract information on the couplings from the measured quantities like cross sections times branching ratios (for specific experimental cuts and acceptances). This gives rise to a certain model dependence of the extracted information. Different options can be pursued in this context. One possibility is to confront a specific model with the experimental data. This has the advantage that all available higher-order corrections within this model can consistently be taken into account and also other experimental constraints (for instance from direct searches or from electroweak precision data) can be taken into account. However, the results obtained in this case are restricted to the interpretation within that particular model. Another possibility is to use a general parametrization of the couplings of the new state without referring to any particular model. While this approach is clearly less model-dependent, the relation between the extracted coupling parameters and the couplings of actual models, for instance the SM or its minimal supersymmetric extension (MSSM), is in general non-trivial, so that the theoretical interpretation of the extracted information can be difficult. It should be mentioned that the results for the signal strengths of individual search channels that have been made public by ATLAS and CMS, while referring just to a particular

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[1] The experiments are encouraged to test the assumptions of the framework, but that lies outside the scope of this document.

search channel rather than to the full information available from the Higgs searches, are nevertheless very valuable for testing the predictions of possible models of physics beyond the SM.

In the SM, once the numerical value of the Higgs mass is specified, all the couplings of the Higgs boson to fermions, bosons and to itself are specified within the model. It is therefore in general not possible to perform a fit to experimental data within the context of the SM where Higgs couplings are treated as free parameters. While it is possible to test the overall compatibility of the SM with the data, it is not possible to extract information about deviations of the measured couplings with respect to their SM values.

A theoretically well-defined framework for probing small deviations from the SM predictions — or the predictions of another reference model — is to use the state-of-the-art predictions in this model (including all available higher-order corrections) and to supplement them with the contributions of additional terms in the Lagrangian. In such an approach and in general, not only the coupling strength, i.e. the absolute value of a given coupling, will be modified, but also the tensor structure of the coupling. For instance, the $\mathrm{HW^+W^-}$ LO coupling in the SM is proportional to the metric tensor $g^{\mu\nu}$, while anomalous couplings will generally also give rise to other tensor structures, however compatible with the SU(2)×U(1) symmetry and the corresponding Ward-Slavnov-Taylor identities. As a consequence, kinematic distributions will in general be modified when compared to the SM case.

Since the reinterpretation of searches that have been performed within the context of the SM is difficult if effects that change kinematic distributions are taken into account and since not all the necessary tools to perform this kind of analysis are available yet, the following additional assumption is made in this simplified framework:

- Only modifications of couplings strengths, i.e. of absolute values of couplings, are taken into account, while the tensor structure of the couplings is assumed to be the same as in the SM prediction. This means in particular that the observed state is assumed to be a CP-even scalar.

3.1 Definition of coupling scale factors

In order to take into account the currently best available SM predictions for Higgs cross sections, which include higher-order QCD and EW corrections [57–59], while at the same time introducing possible deviations from the SM values of the couplings, the predicted SM Higgs cross sections and partial decay widths are dressed with scale factors κ_i. The scale factors κ_i are defined in such a way that the cross sections σ_{ii} or the partial decay widths Γ_{ii} associated with the SM particle i scale with the factor κ_i^2 when compared to the corresponding SM prediction. Table 2 lists all relevant cases. Taking the process $\mathrm{gg} \to \mathrm{H} \to \gamma\gamma$ as an example, one would use as cross section:

$$(\sigma \cdot \mathrm{BR})\,(\mathrm{gg} \to \mathrm{H} \to \gamma\gamma) \quad = \quad \sigma_{\mathrm{SM}}(\mathrm{gg} \to \mathrm{H}) \cdot \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to \gamma\gamma) \cdot \frac{\kappa_{\mathrm{g}}^2 \cdot \kappa_{\gamma}^2}{\kappa_{\mathrm{H}}^2} \qquad (2)$$

where the values and uncertainties for both $\sigma_{\mathrm{SM}}(\mathrm{gg} \to \mathrm{H})$ and $\mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to \gamma\gamma)$ are taken from Ref. [59] for a given Higgs mass hypothesis.

By definition, the currently best available SM predictions for all $\sigma \times \mathrm{BR}$ are recovered when all $\kappa_i = 1$. In general, this means that for $\kappa_i \neq 1$ higher-order accuracy is lost. Nonetheless, NLO QCD corrections essentially factorize with respect to coupling rescaling, and are accounted for wherever possible. This approach ensures that for a true SM Higgs boson no artifical deviations (caused by ignored NLO correactions) are found from what is considered the SM Higgs boson hypothesis. The functions $\kappa_{\mathrm{VBF}}^2(\kappa_{\mathrm{W}}, \kappa_{\mathrm{Z}}, m_{\mathrm{H}})$, $\kappa_{\mathrm{g}}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, m_{\mathrm{H}})$, $\kappa_{\gamma}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_{\tau}, \kappa_{\mathrm{W}}, m_{\mathrm{H}})$ and $\kappa_{\mathrm{H}}^2(\kappa_i, m_{\mathrm{H}})$ are used for cases where there is a non-trivial relationship between scale factors κ_i and cross sections or (partial) decay widths, and are calculated to NLO QCD accuracy. The functions are defined in the following sections and all required input parameters as well as example code can be found in Refs. [59, 60].

Production modes

$$\frac{\sigma_{\mathrm{ggH}}}{\sigma_{\mathrm{ggH}}^{\mathrm{SM}}} = \begin{cases} \kappa_{\mathrm{g}}^{2}(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, m_{\mathrm{H}}) \\ \kappa_{\mathrm{g}}^{2} \end{cases} \tag{3}$$

$$\frac{\sigma_{\mathrm{VBF}}}{\sigma_{\mathrm{VBF}}^{\mathrm{SM}}} = \kappa_{\mathrm{VBF}}^{2}(\kappa_{\mathrm{W}}, \kappa_{\mathrm{Z}}, m_{\mathrm{H}}) \tag{4}$$

$$\frac{\sigma_{\mathrm{WH}}}{\sigma_{\mathrm{WH}}^{\mathrm{SM}}} = \kappa_{\mathrm{W}}^{2} \tag{5}$$

$$\frac{\sigma_{\mathrm{ZH}}}{\sigma_{\mathrm{ZH}}^{\mathrm{SM}}} = \kappa_{\mathrm{Z}}^{2} \tag{6}$$

$$\frac{\sigma_{\mathrm{t\bar{t}H}}}{\sigma_{\mathrm{t\bar{t}H}}^{\mathrm{SM}}} = \kappa_{\mathrm{t}}^{2} \tag{7}$$

Detectable decay modes

$$\frac{\Gamma_{\mathrm{WW}^{(*)}}}{\Gamma_{\mathrm{WW}^{(*)}}^{\mathrm{SM}}} = \kappa_{\mathrm{W}}^{2} \tag{8}$$

$$\frac{\Gamma_{\mathrm{ZZ}^{(*)}}}{\Gamma_{\mathrm{ZZ}^{(*)}}^{\mathrm{SM}}} = \kappa_{\mathrm{Z}}^{2} \tag{9}$$

$$\frac{\Gamma_{\mathrm{b\bar{b}}}}{\Gamma_{\mathrm{b\bar{b}}}^{\mathrm{SM}}} = \kappa_{\mathrm{b}}^{2} \tag{10}$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{\mathrm{SM}}} = \kappa_{\tau}^{2} \tag{11}$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{\mathrm{SM}}} = \begin{cases} \kappa_{\gamma}^{2}(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_{\tau}, \kappa_{\mathrm{W}}, m_{\mathrm{H}}) \\ \kappa_{\gamma}^{2} \end{cases} \tag{12}$$

$$\frac{\Gamma_{\mathrm{Z}\gamma}}{\Gamma_{\mathrm{Z}\gamma}^{\mathrm{SM}}} = \begin{cases} \kappa_{(\mathrm{Z}\gamma)}^{2}(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_{\tau}, \kappa_{\mathrm{W}}, m_{\mathrm{H}}) \\ \kappa_{(\mathrm{Z}\gamma)}^{2} \end{cases} \tag{13}$$

Currently undetectable decay modes

$$\frac{\Gamma_{\mathrm{t\bar{t}}}}{\Gamma_{\mathrm{t\bar{t}}}^{\mathrm{SM}}} = \kappa_{\mathrm{t}}^{2} \tag{14}$$

$$\frac{\Gamma_{\mathrm{gg}}}{\Gamma_{\mathrm{gg}}^{\mathrm{SM}}} \quad : \quad \text{see Section 3.1.2}$$

$$\frac{\Gamma_{\mathrm{c\bar{c}}}}{\Gamma_{\mathrm{c\bar{c}}}^{\mathrm{SM}}} = \kappa_{\mathrm{t}}^{2} \tag{15}$$

$$\frac{\Gamma_{\mathrm{s\bar{s}}}}{\Gamma_{\mathrm{s\bar{s}}}^{\mathrm{SM}}} = \kappa_{\mathrm{b}}^{2} \tag{16}$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma_{\mu^-\mu^+}^{\mathrm{SM}}} = \kappa_{\tau}^{2} \tag{17}$$

Total width

$$\frac{\Gamma_{\mathrm{H}}}{\Gamma_{\mathrm{H}}^{\mathrm{SM}}} = \begin{cases} \kappa_{\mathrm{H}}^{2}(\kappa_i, m_{\mathrm{H}}) \\ \kappa_{\mathrm{H}}^{2} \end{cases} \tag{18}$$

Table 2: LO coupling scale factor relations for Higgs boson cross sections and partial decay widths relative to the SM. For a given m_{H} hypothesis, the smallest set of degrees of freedom in this framework comprises κ_{W}, κ_{Z}, κ_{b}, κ_{t}, and κ_{τ}. For partial widths that are not detectable at the LHC, scaling is performed via proxies chosen among the detectable ones. Additionally, the loop-induced vertices can be treated as a function of other κ_i or effectively, through the κ_{g} and κ_{γ} degrees of freedom which allow probing for BSM contributions in the loops. Finally, to explore invisible or undetectable decays, the scaling of the total width can also be taken as a separate degree of freedom, κ_{H}, instead of being rescaled as a function, $\kappa_{\mathrm{H}}^{2}(\kappa_i)$, of the other scale factors.

3.1.1 Scaling of the VBF cross section

κ^2_{VBF} refers to the functional dependence of the VBF[2] cross section on the scale factors κ^2_{W} and κ^2_{Z}:

$$\kappa^2_{\mathrm{VBF}}(\kappa_{\mathrm{W}}, \kappa_{\mathrm{Z}}, m_{\mathrm{H}}) = \frac{\kappa^2_{\mathrm{W}} \cdot \sigma_{\mathrm{W}F}(m_{\mathrm{H}}) + \kappa^2_{\mathrm{Z}} \cdot \sigma_{\mathrm{Z}F}(m_{\mathrm{H}})}{\sigma_{\mathrm{W}F}(m_{\mathrm{H}}) + \sigma_{\mathrm{Z}F}(m_{\mathrm{H}})} \tag{19}$$

The W- and Z-fusion cross sections, $\sigma_{\mathrm{W}F}$ and $\sigma_{\mathrm{Z}F}$, are taken from Refs. [61,62]. The interference term is $< 0.1\%$ in the SM and hence ignored [63].

3.1.2 Scaling of the gluon fusion cross section and of the $\mathrm{H} \to \mathrm{gg}$ decay vertex

κ^2_{g} refers to the scale factor for the loop-induced production cross section σ_{ggH}. Since the decay width Γ_{gg} is not observable at the LHC, its constribution to the total width is also considered.

Gluon fusion cross-section scaling

As NLO QCD corrections factorize with the scaling of the electroweak couplings with κ_{t} and κ_{b}, the function $\kappa^2_{\mathrm{g}}(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, m_{\mathrm{H}})$ can be calculated in NLO QCD:

$$\kappa^2_{\mathrm{g}}(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, m_{\mathrm{H}}) = \frac{\kappa^2_{\mathrm{t}} \cdot \sigma^{\mathrm{tt}}_{\mathrm{ggH}}(m_{\mathrm{H}}) + \kappa^2_{\mathrm{b}} \cdot \sigma^{\mathrm{bb}}_{\mathrm{ggH}}(m_{\mathrm{H}}) + \kappa_{\mathrm{t}}\kappa_{\mathrm{b}} \cdot \sigma^{\mathrm{tb}}_{\mathrm{ggH}}(m_{\mathrm{H}})}{\sigma^{\mathrm{tt}}_{\mathrm{ggH}}(m_{\mathrm{H}}) + \sigma^{\mathrm{bb}}_{\mathrm{ggH}}(m_{\mathrm{H}}) + \sigma^{\mathrm{tb}}_{\mathrm{ggH}}(m_{\mathrm{H}})} \tag{20}$$

Here, $\sigma^{\mathrm{tt}}_{\mathrm{ggH}}$, $\sigma^{\mathrm{bb}}_{\mathrm{ggH}}$ and $\sigma^{\mathrm{tb}}_{\mathrm{ggH}}$ denote the square of the top-quark contribution, the square of the bottom-quark contribution and the top-bottom interference, respectively. The interference term ($\sigma^{\mathrm{tb}}_{\mathrm{ggH}}$) is negative for a light mass Higgs, $m_{\mathrm{H}} < 200$ GeV. Within the LHC Higgs Cross Section Working Group (for the evaluation of the MSSM cross section) these contributions were evaluated, where for $\sigma^{\mathrm{bb}}_{\mathrm{ggH}}$ and $\sigma^{tb}_{\mathrm{ggH}}$ the full NLO QCD calculation included in *HIGLU* [64] was used. For $\sigma^{\mathrm{tt}}_{\mathrm{ggH}}$ the NLO QCD result of *HIGLU*was supplemented with the NNLO corrections in the heavy-top-quark limit as implemented in *GGH@NNLO* [65], see Ref. [57, Sec. 6.3] for details.

Partial width scaling

In a similar way, NLO QCD corrections for the $\mathrm{H} \to \mathrm{gg}$ partial width are implemented in *HDECAY* [66–68]. This allows to treat the scale factor for Γ_{gg} as a second order polynomial in κ_{b} and κ_{t}:

$$\frac{\Gamma_{\mathrm{gg}}}{\Gamma^{\mathrm{SM}}_{\mathrm{gg}}(m_{\mathrm{H}})} = \frac{\kappa^2_{\mathrm{t}} \cdot \Gamma^{\mathrm{tt}}_{\mathrm{gg}}(m_{\mathrm{H}}) + \kappa^2_{\mathrm{b}} \cdot \Gamma^{\mathrm{bb}}_{\mathrm{gg}}(m_{\mathrm{H}}) + \kappa_{\mathrm{t}}\kappa_{\mathrm{b}} \cdot \Gamma^{\mathrm{tb}}_{\mathrm{gg}}(m_{\mathrm{H}})}{\Gamma^{\mathrm{tt}}_{\mathrm{gg}}(m_{\mathrm{H}}) + \Gamma^{\mathrm{bb}}_{\mathrm{gg}}(m_{\mathrm{H}}) + \Gamma^{\mathrm{tb}}_{\mathrm{gg}}(m_{\mathrm{H}})} \tag{21}$$

The terms $\Gamma^{\mathrm{tt}}_{\mathrm{gg}}$, $\Gamma^{\mathrm{bb}}_{\mathrm{gg}}$ and $\Gamma^{\mathrm{tb}}_{\mathrm{gg}}$ are defined like the σ_{ggH} terms in Eq. (20). The $\Gamma^{ii}_{\mathrm{gg}}$ correspond to the partial widths that are obtained for $\kappa_i = 1$ and all other $\kappa_j = 0, j \neq i$. The cross-term $\Gamma^{\mathrm{tb}}_{\mathrm{gg}}$ can then be derived by calculating the SM partial width by setting $\kappa_{\mathrm{b}} = \kappa_{\mathrm{t}} = 1$ and subtracting $\Gamma^{\mathrm{tt}}_{\mathrm{gg}}$ and $\Gamma^{\mathrm{bb}}_{\mathrm{gg}}$ from it.

Effective treatment

In the general case, without the assumptions above, possible non-zero contributions from additional particles in the loop have to be taken into account and κ^2_{g} is then treated as an effective coupling scale factor parameter in the fit: $\sigma_{\mathrm{ggH}}/\sigma^{\mathrm{SM}}_{\mathrm{ggH}} = \kappa^2_{\mathrm{g}}$. The effective scale factor for the partial gluon width Γ_{gg} should behave in a very similar way, so in this case the same effective scale factor κ_{g} is used: $\Gamma_{\mathrm{gg}}/\Gamma^{\mathrm{SM}}_{\mathrm{gg}} = \kappa^2_{\mathrm{g}}$. As the contribution of Γ_{gg} to the total width is <10% in the SM, this assumption is believed to have no measurable impact.

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[2] Vector Boson Fusion is also called Weak Boson Fusion, as only the weak bosons W and Z contribute to the production.

3.1.3 Scaling of the $\mathrm{H} \to \gamma\gamma$ *partial decay width*

Like in the previous section, κ_γ^2 refers to the scale factor for the loop-induced $\mathrm{H} \to \gamma\gamma$ decay. Also for the $\mathrm{H} \to \gamma\gamma$ decay NLO QCD corrections exist and are implemented in *HDECAY*. This allows to treat the scale factor for the $\gamma\gamma$ partial width as a second order polynomial in κ_b, κ_t, κ_τ, and κ_W:

$$\kappa_\gamma^2(\kappa_\mathrm{b}, \kappa_\mathrm{t}, \kappa_\tau, \kappa_\mathrm{W}, m_\mathrm{H}) \;=\; \frac{\sum_{i,j} \kappa_i \kappa_j \cdot \Gamma_{\gamma\gamma}^{ij}(m_\mathrm{H})}{\sum_{i,j} \Gamma_{\gamma\gamma}^{ij}(m_\mathrm{H})} \tag{22}$$

where the pairs (i, j) are $\mathrm{bb}, \mathrm{tt}, \tau\tau, \mathrm{WW}, \mathrm{bt}, \mathrm{b}\tau, \mathrm{bW}, \mathrm{t}\tau, \mathrm{tW}, \tau\mathrm{W}$. The $\Gamma_{\gamma\gamma}^{ii}$ correspond to the partial widths that are obtained for $\kappa_i = 1$ and all other $\kappa_j = 0, (j \neq i)$. The cross-terms $\Gamma_{\gamma\gamma}^{ij}, (i \neq j)$ can then be derived by calculating the partial width by setting $\kappa_i = \kappa_j = 1$ and all other $\kappa_l = 0, (l \neq i, j)$, and subtracting $\Gamma_{\gamma\gamma}^{ii}$ and $\Gamma_{\gamma\gamma}^{jj}$ from them.

Effective treatment

In the general case, without the assumption above, possible non-zero contributions from additional particles in the loop have to be taken into account and κ_γ^2 is then treated as an effective coupling parameter in the fit.

3.1.4 Scaling of the $\mathrm{H} \to \mathrm{Z}\gamma$ *decay vertex*

Like in the previous sections, $\kappa_{(\mathrm{Z}\gamma)}^2$ refers to the scale factor for the loop-induced $\mathrm{H} \to \mathrm{Z}\gamma$ decay for which NLO QCD corrections exist and are implemented in *HDECAY*. This allows to treat the scale factor for the $\mathrm{Z}\gamma$ partial width as a second order polynomial in κ_b, κ_t, κ_τ, and κ_W:

$$\kappa_{(\mathrm{Z}\gamma)}^2(\kappa_\mathrm{b}, \kappa_\mathrm{t}, \kappa_\tau, \kappa_\mathrm{W}, m_\mathrm{H}) \;=\; \frac{\sum_{i,j} \kappa_i \kappa_j \cdot \Gamma_{\mathrm{Z}\gamma}^{ij}(m_\mathrm{H})}{\sum_{i,j} \Gamma_{\mathrm{Z}\gamma}^{ij}(m_\mathrm{H})} \tag{23}$$

where the pairs (i, j) are $\mathrm{bb}, \mathrm{tt}, \tau\tau, \mathrm{WW}, \mathrm{bt}, \mathrm{b}\tau, \mathrm{bW}, \mathrm{t}\tau, \mathrm{tW}, \tau\mathrm{W}$. The $\Gamma_{\mathrm{Z}\gamma}^{ij}$ are calculated in the same way as for Eq. (22).

Effective treatment

In the general case, without the assumption above, possible non-zero contributions from additional particles in the loop have to be taken into account and $\kappa_{(\mathrm{Z}\gamma)}^2$ is then treated as an effective coupling parameter in the fit.

3.1.5 Scaling of the total width

The total width Γ_H is the sum of all Higgs partial decay widths. Under the assumption that no additional BSM Higgs decay modes (into either invisible or undetectable final states) contribute to the total width, Γ_H is expressed as the sum of the scaled partial Higgs decay widths to SM particles, which combine to a total scale factor κ_H^2 compared to the SM total width $\Gamma_\mathrm{H}^\mathrm{SM}$:

$$\kappa_\mathrm{H}^2(\kappa_i, m_\mathrm{H}) \;=\; \sum_{\substack{j = \mathrm{WW}^{(*)}, \mathrm{ZZ}^{(*)}, \mathrm{b\bar{b}}, \tau^-\tau^+, \\ \gamma\gamma, \mathrm{Z}\gamma, \mathrm{gg}, \mathrm{t\bar{t}}, \mathrm{c\bar{c}}, \mathrm{s\bar{s}}, \mu^-\mu^+}} \frac{\Gamma_j(\kappa_i, m_\mathrm{H})}{\Gamma_\mathrm{H}^\mathrm{SM}(m_\mathrm{H})} \tag{24}$$

Effective treatment

In the general case, additional Higgs decay modes to BSM particles cannot be excluded and the total width scale factor κ_{H}^2 is treated as free parameter.

The total width Γ_{H} for a light Higgs with $m_{\mathrm{H}} \sim 125$ GeV is not expected to be directly observable at the LHC, as the SM expectation is $\Gamma_{\mathrm{H}} \sim 4$ MeV, several orders of magnitude smaller than the experimental mass resolution. There is no indication from the results observed so far that the natural width is broadened by new physics effects to such an extent that it could be directly observable. Furthermore, as all LHC Higgs channels rely on the identification of Higgs decay products, there is no way of measuring the total Higgs width indirectly within a coupling fit without using assumptions. This can be illustrated by assuming that all cross sections and partial width are increased by a common factor $\kappa_i^2 = r > 1$. If simultaneously the Higgs total width is increased by the square of the same factor $\kappa_{\mathrm{H}}^2 = r^2$ (for example by postulating some BSM decay mode) the experimental visible signatures in all Higgs channels would be indistinguishable from the SM.

Hence without further assumptions only ratios of scale factors κ_i can be measured at the LHC, where at least one of the ratios needs to include the total width scale factor κ_{H}^2. Such a definition of ratios absorbs two degrees of freedom (e.g. a common scale factor to all couplings and a scale factor to the total width) into one ratio that can be measured at the LHC. In order to go beyond the measurement of ratios of coupling scale factors to the determination of absolute coupling scale factors κ_i additional assumptions are necessary to remove one degree of freedom. Possible assumptions are:

- No new physics in Higgs decay modes (Eq. 24).
- $\kappa_{\mathrm{W}} \leq 1, \kappa_{\mathrm{Z}} \leq 1$. If one combines this assumption with the fact that all Higgs partial decay widths are positive definite and the total width is bigger than the sum of all (known) partial decay width, this is sufficient to give a lower and upper bound on all κ_i and also determine a possible branching ratio $\mathrm{BR}_{\mathrm{inv.,undet.}}$ into final states invisible or undetectable at the LHC. This is best illustrated with the $\mathrm{VH}(\mathrm{H} \to \mathrm{VV})$ process:

$$\begin{array}{rrcl}
 & \sigma_{\mathrm{VH}} \cdot \mathrm{BR}(\mathrm{H} \to \mathrm{VV}) & = & \dfrac{\kappa_{\mathrm{V}}^2 \cdot \sigma_{\mathrm{VH}}^{\mathrm{SM}} \cdot \kappa_{\mathrm{V}}^2 \cdot \Gamma_{\mathrm{V}}^{\mathrm{SM}}}{\Gamma_{\mathrm{H}}} \\
\text{and} & \Gamma_{\mathrm{H}} & > & \kappa_{\mathrm{V}}^2 \cdot \Gamma_{\mathrm{V}}^{\mathrm{SM}} \qquad (25) \\
\text{give combined:} & \sigma_{\mathrm{VH}} \cdot \mathrm{BR}(\mathrm{H} \to VV) & < & \dfrac{\kappa_{\mathrm{V}}^2 \cdot \sigma_{\mathrm{VH}}^{\mathrm{SM}} \cdot \kappa_{\mathrm{V}}^2 \cdot \Gamma_{\mathrm{V}}^{\mathrm{SM}}}{\kappa_{\mathrm{V}}^2 \cdot \Gamma_{\mathrm{V}}^{\mathrm{SM}}} \\
\Longrightarrow & \kappa_{\mathrm{V}}^2 & > & \dfrac{\sigma_{\mathrm{VH}} \cdot \mathrm{BR}(\mathrm{H} \to \mathrm{VV})}{\sigma_{\mathrm{VH}}^{\mathrm{SM}}} \qquad (26)
\end{array}$$

If more final states are included in Eq. (25), the lower bounds become tighter and together with the upper limit assumptions on κ_{W} and κ_{Z}, absolute measurements are possible. However, uncertainties on all κ_i can be very large depending on the accuracy of the $\mathrm{b\overline{b}}$ decay channels that dominate the uncertainty of the total width sum.

In the following benchmark parametrizations always two versions are given: one without assumptions on the total width and one assuming no beyond SM Higgs decay modes.

3.2 Further assumptions

3.2.1 Theoretical uncertainties

The quantitative impact of theory uncertainties in the Higgs production cross sections and decay rates is discussed in detail in Ref. [57].

Such uncertainties will directly affect the determination of the scale factors. In particular, the uncertainty from missing higher-order contributions can be larger than what was estimated in Ref. [57].

In practice, the cross section predictions with their uncertainties as tabulated in Ref. [57] are used as such so that for $\kappa_i = 1$ the recommended SM treatment is recovered. Without a consistent electroweak NLO calculation for deviations from the SM, electroweak corrections and their uncertainties for the SM prediction ($\sim 5\%$ in gluon fusion production and $\sim 2\%$ in the di-photon decay) are naively scaled together. In the absence of explicit calculations this is the currently best available approach in a search for deviations from the SM Higgs prediction.

3.2.2 *Limit of the zero-width approximation*

Concerning the zero-width approximation (ZWA), it should be noted that in the mass range of the narrow resonance the width of the Higgs boson of the Standard Model (SM) is more than four orders of magnitude smaller than its mass. Thus, the zero-width approximation is in principle expected to be an excellent approximation not only for a SM-like Higgs boson below ~ 150 GeV but also for a wide range of BSM scenarios which are compatible with the present data. However, it has been shown in Ref. [69] that this is not always the case even in the SM. The inclusion of off-shell contributions is essential to obtain an accurate Higgs signal normalization at the 1% precision level. For $\mathrm{gg}\ (\to \mathrm{H}) \to \mathrm{VV}$, $\mathrm{V} = \mathrm{W}, \mathrm{Z}$, $\mathcal{O}(10\%)$ corrections occur due to an enhanced Higgs signal in the region $M_{\mathrm{VV}} > 2\,M_{\mathrm{V}}$, where also sizeable Higgs-continuum interference occurs. However, with the accuracy anticipated to be reached in the 2012 data these effects play a minor role.

3.2.3 *Signal interference effects*

A possible source of uncertainty is related to interference effects in $\mathrm{H} \to 4\,$fermion decay. For a light Higgs boson the decay width into 4 fermions should always be calculated from the complete matrix elements and not from the approximation

$$\mathrm{BR}(\mathrm{H} \to \mathrm{VV}) \times \mathrm{BR}^2(\mathrm{V} \to \mathrm{f\bar{f}}) \tag{27}$$

This approximation, based on the ZWA, neglects both off-shell effects and interference between diagrams where the intermediate gauge bosons couple to different pairs of final-state fermions. As shown in Chapter 2 of Ref. [58], the interference effects not included in Eq. (27) amount to 10% for the decay $\mathrm{H} \to \mathrm{e^+e^-e^+e^-}$ for a 125 GeV Higgs. Similar interference effects of the order of 5% are found for the $\mathrm{e^+\nu_e e^-\bar{\nu}_e}$ and $\mathrm{q\bar{q}q\bar{q}}$ final states.

The experimental analyses take into account the full NLO 4-fermion partial decay width [70–72]. The partial width of the 4-lepton final state (usually described as $\mathrm{H} \to \mathrm{ZZ^{(*)}} \to 4\mathrm{l}$) is scaled with κ_{Z}^2. Similary, the partial width of the 2-lepton, 2-jet final state (usually described as $\mathrm{H} \to \mathrm{ZZ^{(*)}} \to 2\mathrm{l}2\mathrm{q}$) is scaled with κ_{Z}^2. The partial width of the low mass 2-lepton, 2-neutrino final state (usually described as $\mathrm{H} \to \mathrm{WW^{(*)}} \to \mathrm{l\nu\, l\nu}$, although a contribution of $\mathrm{H} \to \mathrm{Z^{(*)}Z} \to \mathrm{ll\,\nu\nu}$ exists and is taken into account) is scaled with κ_{W}^2.

3.2.4 *Treatment of* $\Gamma_{\mathrm{c\bar{c}}}$, $\Gamma_{\mathrm{s\bar{s}}}$, $\Gamma_{\mu^-\mu^+}$ *and light fermion contributions to loop-induced processes*

When calculating $\kappa_{\mathrm{H}}^2(\kappa_i, m_{\mathrm{H}})$ in a benchmark parametrization, the final states $\mathrm{c\bar{c}}$, $\mathrm{s\bar{s}}$ and $\mu^-\mu^+$ (currently unobservable at the LHC) are tied to κ_i scale factors which can be determined from the data. Based on weak isospin symmetry considerations, the following choices are made:

$$\frac{\Gamma_{\mathrm{c\bar{c}}}}{\Gamma_{\mathrm{c\bar{c}}}^{\mathrm{SM}}(m_{\mathrm{H}})} = \kappa_{\mathrm{c}}^2 = \kappa_{\mathrm{t}}^2 \tag{28}$$

$$\frac{\Gamma_{\mathrm{s\bar{s}}}}{\Gamma^{\mathrm{SM}}_{\mathrm{s\bar{s}}}(m_{\mathrm{H}})} = \kappa_{\mathrm{s}}^2 = \kappa_{\mathrm{b}}^2 \tag{29}$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma^{\mathrm{SM}}_{\mu^-\mu^+}(m_{\mathrm{H}})} = \kappa_{\mu}^2 = \kappa_{\tau}^2 \tag{30}$$

Following the rationale of Ref. [57, Sec. 9], the widths of $\mathrm{e^-e^+}$, $\mathrm{u\bar{u}}$, $\mathrm{d\bar{d}}$ and neutrino final states are neglected.

Through interference terms, these light fermions also contirbute to the loop-induced $\mathrm{gg} \to \mathrm{H}$ and $\mathrm{H} \to \mathrm{gg}, \gamma\gamma, \mathrm{Z}\gamma$ vertices. In these cases, the assumptions $\kappa_{\mathrm{c}} = \kappa_{\mathrm{t}}$, $\kappa_{\mathrm{s}} = \kappa_{\mathrm{b}}$ and $\kappa_{\mu} = \kappa_{\tau}$ are made.

3.2.5 Approximation in associated ZH *production*

When scaling the associated ZH production mode, the contribution from $\mathrm{gg} \to \mathrm{ZH}$ through a top-quark loop is neglected. This is estimated to be around 5% of the total associated ZH production cross section [57, Sec. 4.3].

4 Benchmark parametrizations

In putting forward a set of benchmark parametrizations based on the framework described in the previous section several considerations were taken into account. One concern is the stability of the fits which typically involve several hundreds of nuisance parameters. With that in mind, the benchmark parametrizations avoid quotients of parameters of interest. Another constraint that heavily shapes the exact choice of parametrization is consistency among the uncertainties that can be extracted in different parametrizations. Some coupling scale factors enter linearly in loop-induced photon and gluon vertices. For that reason, all scale factors are defined at the same power, leading to what could be misconstrued as an abundance of squared expressions. Finally, the benchmark parametrizations are chosen such that some potential physics cases can be probed and the parameters of interest are chosen so that at least some are expected to be determined.

For every benchmark parametrization, two variations are provided:

1. The total width is scaled assuming that there are no invisible or undetected widths. In this case $\kappa_{\mathrm{H}}^2(\kappa_i)$ is a function of the free parameters.
2. The total width scale factor is absorbed into the parametrization. In this case no assumption is done and there will be a parameter of the form $\kappa_{ij} = \kappa_i \cdot \kappa_j / \kappa_{\mathrm{H}}$.

The benchmark parametrizations are given in tabular form where each cell corresponds to the scale factor to be applied to a given combination of production and decay mode.

For every benchmark parametrization, a list of the free parameters and their relation to the framework parameters is provided. To reduce the amount of symbols in the tables, m_{H} is omitted throughout. In practice, m_{H} can either be fixed to a given value or profiled together with other nuisance parameters.

4.1 One common scale factor

The simplest way to look for a deviation from the predicted SM Higgs coupling structure is to leave the overall signal strength as a free parameter. This is presently done by the experiments, with ATLAS finding $\mu = 1.4 \pm 0.3$ at 126.0 GeV [1] and CMS finding $\mu = 0.87 \pm 0.23$ at 125.5 GeV [2].

In order to perform the same fit in the context of the coupling scale factor framework, the only difference is that $\mu = \kappa^2 \cdot \kappa^2 / \kappa^2 = \kappa^2$, where the three terms κ^2 in the intermediate expression account for production, decay and total width scaling, respectively (Table 3).

Common scale factor

Free parameter: $\kappa (= \kappa_{\rm t} = \kappa_{\rm b} = \kappa_{\tau} = \kappa_{\rm W} = \kappa_{\rm Z})$.

	$\rm H \to \gamma\gamma$	$\rm H \to ZZ^{(*)}$	$\rm H \to WW^{(*)}$	$\rm H \to b\bar{b}$	$\rm H \to \tau^-\tau^+$
ggH $\rm t\bar{t}H$ VBF WH ZH	κ^2				

Table 3: The simplest possible benchmark parametrization where a single scale factor applies to all production and decay modes.

This parametrization, despite providing the highest experimental precision, has several clear shortcomings, such as ignoring that the role of the Higgs boson in providing the masses of the vector bosons is very different from the role it has in providing the masses of fermions.

4.2 Scaling of vector boson and fermion couplings

In checking whether an observed state is compatible with the SM Higgs boson, one obvious question is whether it fulfills its expected role in EWSB which is intimately related to the coupling to the vector bosons $\rm (W, Z)$.

Therefore, assuming that the SU(2) custodial symmetry holds, in the simplest case two parameters can be defined, one scaling the coupling to the vector bosons, $\kappa_{\rm V} (= \kappa_{\rm W} = \kappa_{\rm Z})$, and one scaling the coupling common to all fermions, $\kappa_{\rm f} (= \kappa_{\rm t} = \kappa_{\rm b} = \kappa_{\tau})$. Loop-induced processes are assumed to scale as expected from the SM structure.

In this parametrization, presented in Table 4, the gluon vertex loop is effectively a fermion loop and only the photon vertex loop requires a non-trivial scaling, given the contributions of the top-quark, bottom-quark, and W-boson, as well as their (destructive) interference.

Boson and fermion scaling without invisible or undetectable widths

Free parameters: $\kappa_{\rm V} (= \kappa_{\rm W} = \kappa_{\rm Z})$, $\kappa_{\rm f} (= \kappa_{\rm t} = \kappa_{\rm b} = \kappa_{\tau})$.

	$\rm H \to \gamma\gamma$	$\rm H \to ZZ^{(*)}$	$\rm H \to WW^{(*)}$	$\rm H \to b\bar{b}$	$\rm H \to \tau^-\tau^+$
ggH $\rm t\bar{t}H$	$\frac{\kappa_{\rm f}^2 \cdot \kappa_{\gamma}^2(\kappa_{\rm f}, \kappa_{\rm f}, \kappa_{\rm f}, \kappa_{\rm V})}{\kappa_{\rm H}^2(\kappa_i)}$	$\frac{\kappa_{\rm f}^2 \cdot \kappa_{\rm V}^2}{\kappa_{\rm H}^2(\kappa_i)}$		$\frac{\kappa_{\rm f}^2 \cdot \kappa_{\rm f}^2}{\kappa_{\rm H}^2(\kappa_i)}$	
VBF WH ZH	$\frac{\kappa_{\rm V}^2 \cdot \kappa_{\gamma}^2(\kappa_{\rm f}, \kappa_{\rm f}, \kappa_{\rm f}, \kappa_{\rm V})}{\kappa_{\rm H}^2(\kappa_i)}$	$\frac{\kappa_{\rm V}^2 \cdot \kappa_{\rm V}^2}{\kappa_{\rm H}^2(\kappa_i)}$		$\frac{\kappa_{\rm V}^2 \cdot \kappa_{\rm f}^2}{\kappa_{\rm H}^2(\kappa_i)}$	

Boson and fermion scaling without assumptions on the total width

Free parameters: $\kappa_{\rm VV} (= \kappa_{\rm V} \cdot \kappa_{\rm V} / \kappa_{\rm H})$, $\lambda_{\rm fV} (= \kappa_{\rm f} / \kappa_{\rm V})$.

	$\rm H \to \gamma\gamma$	$\rm H \to ZZ^{(*)}$	$\rm H \to WW^{(*)}$	$\rm H \to b\bar{b}$	$\rm H \to \tau^-\tau^+$
ggH $\rm t\bar{t}H$	$\kappa_{\rm VV}^2 \cdot \lambda_{\rm fV}^2 \cdot \kappa_{\gamma}^2(\lambda_{\rm fV}, \lambda_{\rm fV}, \lambda_{\rm fV}, 1)$	$\kappa_{\rm VV}^2 \cdot \lambda_{\rm fV}^2$		$\kappa_{\rm VV}^2 \cdot \lambda_{\rm fV}^2 \cdot \lambda_{\rm fV}^2$	
VBF WH ZH	$\kappa_{\rm VV}^2 \cdot \kappa_{\gamma}^2(\lambda_{\rm fV}, \lambda_{\rm fV}, \lambda_{\rm fV}, 1)$	$\kappa_{\rm VV}^2$		$\kappa_{\rm VV}^2 \cdot \lambda_{\rm fV}^2$	

$\kappa_i^2 = \Gamma_{ii} / \Gamma_{ii}^{\rm SM}$

Table 4: A benchmark parametrization where custodial symmetry is assumed and vector boson couplings are scaled together ($\kappa_{\rm V}$) and fermions are assumed to scale with a single parameter ($\kappa_{\rm f}$).

This parametrization, though exceptionally succinct, makes a number of assumptions, which are expected to be object of further scrutiny with the accumulation of data at the LHC. The assumptions naturally relate to the grouping of different individual couplings or to assuming that the loop amplitudes are those predicted by the SM.

4.3 Probing custodial symmetry

One of the best motivated symmetries in case the new state is responsible for electroweak symmetry breaking is that which links its coupling to the W and Z bosons. Since $\mathrm{SU}(2)_\mathrm{V}$ or custodial symmetry is an approximate symmetry of the SM (e.g. $\Delta\rho \neq 0$), it is important to test whether data are compatible with the amount of violation allowed by the SM at NLO.

In this parametrization, presented in Table 5, $\lambda_{\mathrm{WZ}}(=\kappa_\mathrm{W}/\kappa_\mathrm{Z})$ is the main parameter of interest. Though providing interesting information, both κ_Z and κ_f can be thought of as nuisance parameters when performing this fit. In addition to the photon vertex loop not having a trivial scaling, in this parametrization also the individual W and Z boson fusion contributions to the vector boson fusion production process need to be resolved.

4.4 Probing the fermion sector

There are extensions of the SM where different Higgs bosons couple differently to different types of fermions.

Given how the gluon-gluon fusion production process is dominated by the top-quark coupling, and how there are two decay modes involving fermions, one way of splitting fermions that is within experimental reach is to consider up-type fermions (top quark) and down-type fermions (bottom quark and tau lepton) separately. In this parametrization, presented in Table 6, the relevant parameter of interest is $\lambda_{\mathrm{du}}(=\kappa_\mathrm{d}/\kappa_\mathrm{u})$, the ratio of the scale factors of the couplings to down-type fermions, $\kappa_\mathrm{d}=\kappa_\tau(=\kappa_\mu)=\kappa_\mathrm{b}(=\kappa_\mathrm{s})$, and up-type fermions, $\kappa_\mathrm{u}=\kappa_\mathrm{t}(=\kappa_\mathrm{c})$.

Alternatively one can consider quarks and leptons separately. In this parametrization, presented in Table 7, the relevant parameter of interest is $\lambda_{\mathrm{lq}}(=\kappa_\mathrm{l}/\kappa_\mathrm{q})$, the ratio of the coupling scale factors to leptons, $\kappa_\mathrm{l}=\kappa_\tau(=\kappa_\mu)$, and quarks, $\kappa_\mathrm{q}=\kappa_\mathrm{t}(=\kappa_\mathrm{c})=\kappa_\mathrm{b}(=\kappa_\mathrm{s})$.

One further combination of top-quark, bottom-quark and tau-lepton, namely scaling the top-quark and tau-lepton with a common parameter and the bottom-quark with another parameter, can be envisaged and readily parametrized based on the interim framework but is not put forward as a benchmark.

4.5 Probing the loop structure and invisible or undetectable decay of new particles

It is possible that in nature there are particles not predicted by the SM. Depending on their properties, new particles may influence the partial width of the gluon and/or photon vertices.

In this parametrization, presented in Table 8, each of the loop-induced vertices is represented by an effective scale factor, κ_g and κ_γ.

Particles not predicted by the SM may also give rise to invisible or undetectable decays. Invisible decays might show up as a MET signature and could potentially be measured at the LHC with dedicated analyses. An example of an undetectable final state would be a multi-jet signature that cannot be separated from QCD backgrounds at the LHC and hence not detected. With sufficient data it can be envisaged to disentangle the invisible and undetectable components.

In order to probe this possibility, instead of absorbing the total width into another parameter or leaving it free, a different parameter is introduced, $\mathrm{BR}_{\mathrm{inv.,undet.}}$. The definition of $\mathrm{BR}_{\mathrm{inv.,undet.}}$ is relative to the rescaled total width, $\kappa_\mathrm{H}^2(\kappa_i)$, and can thus be interpreted as the invisible or undetectable fraction of the total width.

Probing custodial symmetry without invisible or undetectable widths

Free parameters: κ_{Z}, $\lambda_{\mathrm{WZ}}(=\kappa_{\mathrm{W}}/\kappa_{\mathrm{Z}})$, $\kappa_{\mathrm{f}}(=\kappa_{\mathrm{t}}=\kappa_{\mathrm{b}}=\kappa_{\tau})$.

	$\mathrm{H}\to\gamma\gamma$	$\mathrm{H}\to\mathrm{ZZ}^{(*)}$	$\mathrm{H}\to\mathrm{WW}^{(*)}$	$\mathrm{H}\to\mathrm{b}\overline{\mathrm{b}}$	$\mathrm{H}\to\tau^-\tau^+$
ggH $\mathrm{t\bar{t}H}$	$\frac{\kappa_{\mathrm{f}}^2\cdot\kappa_\gamma^2(\kappa_{\mathrm{f}},\kappa_{\mathrm{f}},\kappa_{\mathrm{f}},\kappa_{\mathrm{Z}}\lambda_{\mathrm{WZ}})}{\kappa_{\mathrm{H}}^2(\kappa_i)}$	$\frac{\kappa_{\mathrm{f}}^2\cdot\kappa_{\mathrm{Z}}^2}{\kappa_{\mathrm{H}}^2(\kappa_i)}$	$\frac{\kappa_{\mathrm{f}}^2\cdot(\kappa_{\mathrm{Z}}\lambda_{\mathrm{WZ}})^2}{\kappa_{\mathrm{H}}^2(\kappa_i)}$	$\frac{\kappa_{\mathrm{f}}^2\cdot\kappa_{\mathrm{f}}^2}{\kappa_{\mathrm{H}}^2(\kappa_i)}$	
VBF	$\frac{\kappa_{\mathrm{VBF}}^2(\kappa_{\mathrm{Z}},\kappa_{\mathrm{Z}}\lambda_{\mathrm{WZ}})\cdot\kappa_\gamma^2(\kappa_{\mathrm{f}},\kappa_{\mathrm{f}},\kappa_{\mathrm{f}},\kappa_{\mathrm{Z}}\lambda_{\mathrm{WZ}})}{\kappa_{\mathrm{H}}^2(\kappa_i)}$	$\frac{\kappa_{\mathrm{VBF}}^2(\kappa_{\mathrm{Z}},\kappa_{\mathrm{Z}}\lambda_{\mathrm{WZ}})\cdot\kappa_{\mathrm{Z}}^2}{\kappa_{\mathrm{H}}^2(\kappa_i)}$	$\frac{\kappa_{\mathrm{VBF}}^2(\kappa_{\mathrm{Z}},\kappa_{\mathrm{Z}}\lambda_{\mathrm{WZ}})\cdot(\kappa_{\mathrm{Z}}\lambda_{\mathrm{WZ}})^2}{\kappa_{\mathrm{H}}^2(\kappa_i)}$	$\frac{\kappa_{\mathrm{VBF}}^2(\kappa_{\mathrm{Z}},\kappa_{\mathrm{Z}}\lambda_{\mathrm{WZ}})\cdot\kappa_{\mathrm{f}}^2}{\kappa_{\mathrm{H}}^2(\kappa_i)}$	
WH	$\frac{(\kappa_{\mathrm{Z}}\lambda_{\mathrm{WZ}})^2\cdot\kappa_\gamma^2(\kappa_{\mathrm{f}},\kappa_{\mathrm{f}},\kappa_{\mathrm{f}},\kappa_{\mathrm{Z}}\lambda_{\mathrm{WZ}})}{\kappa_{\mathrm{H}}^2(\kappa_i)}$	$\frac{(\kappa_{\mathrm{Z}}\lambda_{\mathrm{WZ}})^2\cdot\kappa_{\mathrm{Z}}^2}{\kappa_{\mathrm{H}}^2(\kappa_i)}$	$\frac{(\kappa_{\mathrm{Z}}\lambda_{\mathrm{WZ}})^2\cdot(\kappa_{\mathrm{Z}}\lambda_{\mathrm{WZ}})^2}{\kappa_{\mathrm{H}}^2(\kappa_i)}$	$\frac{(\kappa_{\mathrm{Z}}\lambda_{\mathrm{WZ}})^2\cdot\kappa_{\mathrm{f}}^2}{\kappa_{\mathrm{H}}^2(\kappa_i)}$	
ZH	$\frac{\kappa_{\mathrm{Z}}^2\cdot\kappa_\gamma^2(\kappa_{\mathrm{f}},\kappa_{\mathrm{f}},\kappa_{\mathrm{f}},\kappa_{\mathrm{Z}}\lambda_{\mathrm{WZ}})}{\kappa_{\mathrm{H}}^2(\kappa_i)}$	$\frac{\kappa_{\mathrm{Z}}^2\cdot\kappa_{\mathrm{Z}}^2}{\kappa_{\mathrm{H}}^2(\kappa_i)}$	$\frac{\kappa_{\mathrm{Z}}^2\cdot(\kappa_{\mathrm{Z}}\lambda_{\mathrm{WZ}})^2}{\kappa_{\mathrm{H}}^2(\kappa_i)}$	$\frac{\kappa_{\mathrm{Z}}^2\cdot\kappa_{\mathrm{f}}^2}{\kappa_{\mathrm{H}}^2(\kappa_i)}$	

Probing custodial symmetry without assumptions on the total width

Free parameters: $\kappa_{\mathrm{ZZ}}(=\kappa_{\mathrm{Z}}\cdot\kappa_{\mathrm{Z}}/\kappa_{\mathrm{H}})$, $\lambda_{\mathrm{WZ}}(=\kappa_{\mathrm{W}}/\kappa_{\mathrm{Z}})$, $\lambda_{FZ}(=\kappa_{\mathrm{f}}/\kappa_{\mathrm{Z}})$.

	$\mathrm{H}\to\gamma\gamma$	$\mathrm{H}\to\mathrm{ZZ}^{(*)}$	$\mathrm{H}\to\mathrm{WW}^{(*)}$	$\mathrm{H}\to\mathrm{b}\overline{\mathrm{b}}$	$\mathrm{H}\to\tau^-\tau^+$
ggH $\mathrm{t\bar{t}H}$	$\kappa_{\mathrm{ZZ}}^2\lambda_{FZ}^2\cdot\kappa_\gamma^2(\lambda_{FZ},\lambda_{FZ},\lambda_{FZ},\lambda_{\mathrm{WZ}})$	$\kappa_{\mathrm{ZZ}}^2\lambda_{FZ}^2$	$\kappa_{\mathrm{ZZ}}^2\lambda_{FZ}^2\cdot\lambda_{\mathrm{WZ}}^2$	$\kappa_{\mathrm{ZZ}}^2\lambda_{FZ}^2\cdot\lambda_{FZ}^2$	
VBF	$\kappa_{\mathrm{ZZ}}^2\kappa_{\mathrm{VBF}}^2(1,\lambda_{\mathrm{WZ}}^2)\cdot\kappa_\gamma^2(\lambda_{FZ},\lambda_{FZ},\lambda_{FZ},\lambda_{\mathrm{WZ}})$	$\kappa_{\mathrm{ZZ}}^2\kappa_{\mathrm{VBF}}^2(1,\lambda_{\mathrm{WZ}}^2)$	$\kappa_{\mathrm{ZZ}}^2\kappa_{\mathrm{VBF}}^2(1,\lambda_{\mathrm{WZ}}^2)\cdot\lambda_{\mathrm{WZ}}^2$	$\kappa_{\mathrm{ZZ}}^2\kappa_{\mathrm{VBF}}^2(1,\lambda_{\mathrm{WZ}}^2)\cdot\lambda_{FZ}^2$	
WH	$\kappa_{\mathrm{ZZ}}^2\lambda_{\mathrm{WZ}}^2\cdot\kappa_\gamma^2(\lambda_{FZ},\lambda_{FZ},\lambda_{FZ},\lambda_{\mathrm{WZ}})$	$\kappa_{\mathrm{ZZ}}^2\cdot\lambda_{\mathrm{WZ}}^2$	$\kappa_{\mathrm{ZZ}}^2\lambda_{\mathrm{WZ}}^2\cdot\lambda_{\mathrm{WZ}}^2$	$\kappa_{\mathrm{ZZ}}^2\lambda_{\mathrm{WZ}}^2\cdot\lambda_{FZ}^2$	
ZH	$\kappa_{\mathrm{ZZ}}^2\cdot\kappa_\gamma^2(\lambda_{FZ},\lambda_{FZ},\lambda_{FZ},\lambda_{\mathrm{WZ}})$	κ_{ZZ}^2	$\kappa_{\mathrm{ZZ}}^2\cdot\lambda_{\mathrm{WZ}}^2$	$\kappa_{\mathrm{ZZ}}^2\cdot\lambda_{FZ}^2$	

$\kappa_i^2=\Gamma_{ii}/\Gamma_{ii}^{\mathrm{SM}}$

Table 5: A benchmark parametrization where custodial symmetry is probed through the λ_{WZ} parameter.

Probing up-type and down-type fermion symmetry without invisible or undetectable widths

Free parameters: $\kappa_V (= \kappa_Z = \kappa_W)$, $\lambda_{du} (= \kappa_d/\kappa_u)$, $\kappa_u (= \kappa_t)$.

	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH	$\frac{\kappa_g^2(\kappa_u\lambda_{du},\kappa_u)\cdot\kappa_\gamma^2(\kappa_u\lambda_{du},\kappa_u,\kappa_u\lambda_{du},\kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_g^2(\kappa_u\lambda_{du},\kappa_u)\cdot\kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_g^2(\kappa_u\lambda_{du},\kappa_u)\cdot(\kappa_u\lambda_{du})^2}{\kappa_H^2(\kappa_i)}$	
$t\bar{t}H$	$\frac{\kappa_u^2\cdot\kappa_\gamma^2(\kappa_u\lambda_{du},\kappa_u,\kappa_u\lambda_{du},\kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_u^2\cdot\kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_u^2\cdot(\kappa_u\lambda_{du})^2}{\kappa_H^2(\kappa_i)}$	
VBF WH ZH	$\frac{\kappa_V^2\cdot\kappa_\gamma^2(\kappa_u\lambda_{du},\kappa_u,\kappa_u\lambda_{du},\kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_V^2\cdot\kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_V^2\cdot(\kappa_u\lambda_{du})^2}{\kappa_H^2(\kappa_i)}$	

Probing up-type and down-type fermion symmetry without assumptions on the total width

Free parameters: $\kappa_{uu} (= \kappa_u \cdot \kappa_u/\kappa_H)$, $\lambda_{du} (= \kappa_d/\kappa_u)$, $\lambda_{Vu} (= \kappa_V/\kappa_u)$.

	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH	$\kappa_{uu}^2\kappa_g^2(\lambda_{du},1)\cdot\kappa_\gamma^2(\lambda_{du},1,\lambda_{du},\lambda_{Vu})$	$\kappa_{uu}^2\kappa_g^2(\lambda_{du},1)\cdot\lambda_{Vu}^2$		$\kappa_{uu}^2\kappa_g^2(\lambda_{du},1)\cdot\lambda_{du}^2$	
$t\bar{t}H$	$\kappa_{uu}^2\cdot\kappa_\gamma^2(\lambda_{du},1,\lambda_{du},\lambda_{Vu})$	$\kappa_{uu}^2\cdot\lambda_{Vu}^2$		$\kappa_{uu}^2\cdot\lambda_{du}^2$	
VBF WH ZH	$\kappa_{uu}^2\lambda_{Vu}^2\cdot\kappa_\gamma^2(\lambda_{du},1,\lambda_{du},\lambda_{Vu})$	$\kappa_{uu}^2\lambda_{Vu}^2\cdot\lambda_{Vu}^2$		$\kappa_{uu}^2\lambda_{Vu}^2\cdot\lambda_{du}^2$	

$\kappa_i^2 = \Gamma_{ii}/\Gamma_{ii}^{SM}$, $\kappa_d = \kappa_b = \kappa_\tau$

Table 6: A benchmark parametrization where the up-type and down-type symmetry of fermions is probed through the λ_{du} parameter.

Probing quark and lepton fermion symmetry without invisible or undetectable widths

Free parameters: $\kappa_V (= \kappa_Z = \kappa_W)$, $\lambda_{lq} (= \kappa_l/\kappa_q)$, $\kappa_q (= \kappa_t = \kappa_b)$.

	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH $t\bar{t}H$	$\frac{\kappa_q^2\cdot\kappa_\gamma^2(\kappa_q,\kappa_q,\kappa_q\lambda_{lq},\kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_q^2\cdot\kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_q^2\cdot\kappa_q^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_q^2\cdot(\kappa_q\lambda_{lq})^2}{\kappa_H^2(\kappa_i)}$
VBF WH ZH	$\frac{\kappa_V^2\cdot\kappa_\gamma^2(\kappa_q,\kappa_q,\kappa_q\lambda_{lq},\kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_V^2\cdot\kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_V^2\cdot\kappa_q^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_V^2\cdot(\kappa_q\lambda_{lq})^2}{\kappa_H^2(\kappa_i)}$

Probing quark and lepton fermion symmetry without assumptions on the total width

Free parameters: $\kappa_{qq} (= \kappa_q \cdot \kappa_q/\kappa_H)$, $\lambda_{lq} (= \kappa_l/\kappa_q)$, $\lambda_{Vq} (= \kappa_V/\kappa_q)$.

	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH $t\bar{t}H$	$\kappa_{qq}^2\cdot\kappa_\gamma^2(1,1,\lambda_{lq},\lambda_{Vq})$	$\kappa_{qq}^2\cdot\lambda_{Vq}^2$		κ_{qq}^2	$\kappa_{qq}^2\cdot\lambda_{lq}^2$
VBF WH ZH	$\kappa_{qq}^2\lambda_{Vq}^2\cdot\kappa_\gamma^2(1,1,\lambda_{lq},\lambda_{Vq})$	$\kappa_{qq}^2\lambda_{Vq}^2\cdot\lambda_{Vq}^2$		$\kappa_{qq}^2\cdot\lambda_{Vq}^2$	$\kappa_{qq}^2\lambda_{Vq}^2\cdot\lambda_{lq}^2$

$\kappa_i^2 = \Gamma_{ii}/\Gamma_{ii}^{SM}$, $\kappa_l = \kappa_\tau$

Table 7: A benchmark parametrization where the quark and lepton symmetry of fermions is probed through the λ_{lq} parameter.

One particularity of this benchmark parametrization is that it should allow any theoretical prediction involving new particles to be projected into the $(\kappa_{\rm g}, \kappa_\gamma)$ or $(\kappa_{\rm g}, \kappa_\gamma, \mathrm{BR}_{\rm inv.,undet.})$ spaces.

It can be noted that the benchmark parametrization including $\mathrm{BR}_{\rm inv.,undet.}$ can be recast in a form that allows for an interpretation in terms of a tree-level scale factor and the loop-induced scale factors with the following substitutions: $\kappa_j \to \kappa'_j/\kappa_{\rm tree}$ (with $j = \mathrm{g}, \gamma$) and $(1 - \mathrm{BR}_{\rm inv.,undet.}) \to \kappa^2_{\rm tree}$.

4.6 A minimal parametrization without assumptions on new physics contributions

Finally, the following parametrization gathers the most important degrees of freedom considered before, namely $\kappa_{\rm g}$, κ_γ, $\kappa_{\rm V}$, $\kappa_{\rm f}$. The parametrization, presented in Table 9, is chosen such that some parameters are expected to be reasonably constrained by the LHC data in the near term, while other parameters are not expected to be as well constrained in the same time frame.

It should be noted that this is a parametrization which only includes trivial scale factors.

With the presently available analyses and data, $\kappa^2_{\rm gV} = \kappa^2_{\rm g} \cdot \kappa^2_{\rm V}/\kappa^2_{\rm H}$ seems to be a good choice for the common κ_{ij} parameter.

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Probing loop structure without invisible or undetectable widths

Free parameters: κ_{g}, κ_{γ}.

	$\mathrm{H}\to\gamma\gamma$	$\mathrm{H}\to\mathrm{ZZ}^{(*)}$	$\mathrm{H}\to\mathrm{WW}^{(*)}$	$\mathrm{H}\to\mathrm{b\bar{b}}$	$\mathrm{H}\to\tau^-\tau^+$
ggH	$\frac{\kappa_{\mathrm{g}}^2\cdot\kappa_{\gamma}^2}{\kappa_{\mathrm{H}}^2(\kappa_i)}$	$\frac{\kappa_{\mathrm{g}}^2}{\kappa_{\mathrm{H}}^2(\kappa_i)}$			
$\mathrm{t\bar{t}H}$ VBF WH ZH	$\frac{\kappa_{\gamma}^2}{\kappa_{\mathrm{H}}^2(\kappa_i)}$	$\frac{1}{\kappa_{\mathrm{H}}^2(\kappa_i)}$			

Probing loop structure allowing for invisible or undetectable widths

Free parameters: κ_{g}, κ_{γ}, $\mathrm{BR}_{\mathrm{inv.,undet.}}$.

	$\mathrm{H}\to\gamma\gamma$	$\mathrm{H}\to\mathrm{ZZ}^{(*)}$	$\mathrm{H}\to\mathrm{WW}^{(*)}$	$\mathrm{H}\to\mathrm{b\bar{b}}$	$\mathrm{H}\to\tau^-\tau^+$
ggH	$\frac{\kappa_{\mathrm{g}}^2\cdot\kappa_{\gamma}^2}{\kappa_{\mathrm{H}}^2(\kappa_i)/(1-\mathrm{BR}_{\mathrm{inv.,undet.}})}$	$\frac{\kappa_{\mathrm{g}}^2}{\kappa_{\mathrm{H}}^2(\kappa_i)/(1-\mathrm{BR}_{\mathrm{inv.,undet.}})}$			
$\mathrm{t\bar{t}H}$ VBF WH ZH	$\frac{\kappa_{\gamma}^2}{\kappa_{\mathrm{H}}^2(\kappa_i)/(1-\mathrm{BR}_{\mathrm{inv.,undet.}})}$	$\frac{1}{\kappa_{\mathrm{H}}^2(\kappa_i)/(1-\mathrm{BR}_{\mathrm{inv.,undet.}})}$			

$\kappa_i^2 = \Gamma_{ii}/\Gamma_{ii}^{\mathrm{SM}}$

Table 8: A benchmark parametrization where effective vertex couplings are allowed to float through the κ_{g} and κ_{γ} parameters. Instead of absorbing κ_{H}, explicit allowance is made for a contribution from invisible or undetectable widths via the $\mathrm{BR}_{\mathrm{inv.,undet.}}$ parameter.

Probing loops while allowing other couplings to float without invisible or undetectable widths

Free parameters: κ_{g}, κ_{γ}, $\kappa_{\mathrm{V}}(=\kappa_{\mathrm{W}}=\kappa_{\mathrm{Z}})$, $\kappa_{\mathrm{f}}(=\kappa_{\mathrm{t}}=\kappa_{\mathrm{b}}=\kappa_{\tau})$.

	$\mathrm{H}\to\gamma\gamma$	$\mathrm{H}\to\mathrm{ZZ}^{(*)}$	$\mathrm{H}\to\mathrm{WW}^{(*)}$	$\mathrm{H}\to\mathrm{b\bar{b}}$	$\mathrm{H}\to\tau^-\tau^+$
ggH	$\frac{\kappa_{\mathrm{g}}^2\cdot\kappa_{\gamma}^2}{\kappa_{\mathrm{H}}^2(\kappa_i)}$	$\frac{\kappa_{\mathrm{g}}^2\cdot\kappa_{\mathrm{V}}^2}{\kappa_{\mathrm{H}}^2(\kappa_i)}$		$\frac{\kappa_{\mathrm{g}}^2\cdot\kappa_{\mathrm{f}}^2}{\kappa_{\mathrm{H}}^2(\kappa_i)}$	
$\mathrm{t\bar{t}H}$	$\frac{\kappa_{\mathrm{f}}^2\cdot\kappa_{\gamma}^2}{\kappa_{\mathrm{H}}^2(\kappa_i)}$	$\frac{\kappa_{\mathrm{f}}^2\cdot\kappa_{\mathrm{V}}^2}{\kappa_{\mathrm{H}}^2(\kappa_i)}$		$\frac{\kappa_{\mathrm{f}}^2\cdot\kappa_{\mathrm{f}}^2}{\kappa_{\mathrm{H}}^2(\kappa_i)}$	
VBF WH ZH	$\frac{\kappa_{\mathrm{V}}^2\cdot\kappa_{\gamma}^2}{\kappa_{\mathrm{H}}^2(\kappa_i)}$	$\frac{\kappa_{\mathrm{V}}^2\cdot\kappa_{\mathrm{V}}^2}{\kappa_{\mathrm{H}}^2(\kappa_i)}$		$\frac{\kappa_{\mathrm{V}}^2\cdot\kappa_{\mathrm{f}}^2}{\kappa_{\mathrm{H}}^2(\kappa_i)}$	

Probing loops while allowing other couplings to float allowing for invisible or undetectable widths

Free parameters: $\kappa_{\mathrm{gV}}(=\kappa_{\mathrm{g}}\cdot\kappa_{\mathrm{V}}/\kappa_{\mathrm{H}})$, $\lambda_{\mathrm{Vg}}(=\kappa_{\mathrm{V}}/\kappa_{\mathrm{g}})$, $\lambda_{\gamma\mathrm{V}}(=\kappa_{\gamma}/\kappa_{\mathrm{V}})$, $\lambda_{\mathrm{fV}}(=\kappa_{\mathrm{f}}/\kappa_{\mathrm{V}})$.

	$\mathrm{H}\to\gamma\gamma$	$\mathrm{H}\to\mathrm{ZZ}^{(*)}$	$\mathrm{H}\to\mathrm{WW}^{(*)}$	$\mathrm{H}\to\mathrm{b\bar{b}}$	$\mathrm{H}\to\tau^-\tau^+$
ggH	$\kappa_{\mathrm{gV}}^2\cdot\lambda_{\gamma\mathrm{V}}^2$	κ_{gV}^2		$\kappa_{\mathrm{gV}}^2\cdot\lambda_{\mathrm{fV}}^2$	
$\mathrm{t\bar{t}H}$	$\kappa_{\mathrm{gV}}^2\lambda_{\mathrm{Vg}}^2\lambda_{\mathrm{fV}}^2\cdot\lambda_{\gamma\mathrm{V}}^2$	$\kappa_{\mathrm{gV}}^2\lambda_{\mathrm{Vg}}^2\lambda_{\mathrm{fV}}^2$		$\kappa_{\mathrm{gV}}^2\lambda_{\mathrm{Vg}}^2\lambda_{\mathrm{fV}}^2\cdot\lambda_{\mathrm{fV}}^2$	
VBF WH ZH	$\kappa_{\mathrm{gV}}^2\lambda_{\mathrm{Vg}}^2\cdot\lambda_{\gamma\mathrm{V}}^2$	$\kappa_{\mathrm{gV}}^2\lambda_{\mathrm{Vg}}^2$		$\kappa_{\mathrm{gV}}^2\lambda_{\mathrm{Vg}}^2\cdot\lambda_{\mathrm{fV}}^2$	

$\kappa_i^2 = \Gamma_{ii}/\Gamma_{ii}^{\mathrm{SM}}$, $\kappa_{\mathrm{V}}=\kappa_{\mathrm{W}}=\kappa_{\mathrm{Z}}$, $\kappa_{\mathrm{f}}=\kappa_{\mathrm{t}}=\kappa_{\mathrm{b}}=\kappa_{\tau}$

Table 9: A benchmark parametrization where effective vertex couplings are allowed to float through the κ_{g} and κ_{γ} parameters and the gauge and fermion couplings through the unified parameters κ_{V} and κ_{f}.

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Appendices

A Maximal parametrization

Table A.1 presents the relations in a fit only with simple scale factors. It should be noted that the number of degrees of freedom is too large to make such a fit feasible in the near future.

Several choices are possible for κ_{ij}. With the currently available channels, $\kappa_{\mathrm{gZ}} = \kappa_{\mathrm{g}} \cdot \kappa_{\mathrm{Z}} / \kappa_{\mathrm{H}}$ seems most appropriate, as shown in table A.1. The more appealing choices using vector boson scattering $\kappa_{\mathrm{WW}} = \kappa_{\mathrm{W}} \cdot \kappa_{\mathrm{W}} / \kappa_{\mathrm{H}}$ or $\kappa_{\mathrm{ZZ}} = \kappa_{\mathrm{Z}} \cdot \kappa_{\mathrm{Z}} / \kappa_{\mathrm{H}}$ will not be as good until more data is accumulated.

B LO SM-inspired loop parametrizations

This appendix collects LO SM-inspired relations that can be used as scale factors of couplings involving loops.

These are not recommended and are considered obsolete.

Gluon vertex loop

Under the assumption that the only relevant contributions to σ_{ggH} and Γ_{gg} are from top-quark and bottom-quark loops, $\kappa_{\mathrm{g}}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, m_{\mathrm{H}})$ is a scaling function depending on the scale factors κ_{b} and κ_{t}:

$$\kappa_{\mathrm{g}}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, m_{\mathrm{H}}) \quad = \quad \frac{|\kappa_{\mathrm{b}} A_{\mathrm{b}}(m_{\mathrm{H}}) + \kappa_{\mathrm{t}} A_{\mathrm{t}}(m_{\mathrm{H}})|^2}{|A_{\mathrm{b}}(m_{\mathrm{H}}) + A_{\mathrm{t}}(m_{\mathrm{H}})|^2} \tag{B.1}$$

where $A_{\mathrm{b,t}}$ denotes the bottom-quark and top-quark amplitudes in the SM [73, Eq. (21)].

Photon vertex loop

Under the assumption that the only relevant contributions to $\Gamma_{\gamma\gamma}$ are from W-boson, top-quark, and bottom-quark loops, $\kappa_{\gamma}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_{\mathrm{W}}, m_{\mathrm{H}})$ is a scaling function depending on the scale factors κ_{b}, κ_{t} and κ_{W}:

$$\kappa_{\gamma}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_{\mathrm{W}}, m_{\mathrm{H}}) \quad = \quad \frac{|\kappa_{\mathrm{b}} A'_{\mathrm{b}}(m_{\mathrm{H}}) + \kappa_{\mathrm{t}} A'_{\mathrm{t}}(m_{\mathrm{H}}) + \kappa_{\mathrm{W}} A'_{\mathrm{W}}(m_{\mathrm{H}})|^2}{|A'_{\mathrm{b}}(m_{\mathrm{H}}) + A'_{\mathrm{t}}(m_{\mathrm{H}}) + A'_{\mathrm{W}}(m_{\mathrm{H}})|^2} \tag{B.2}$$

where $A'_{\mathrm{b,t,W}}$ denotes the bottom-quark, top-quark, and W-boson amplitudes in the SM, including color and charge factors [73, Eq. (1)].

Zγ vertex loop

Under the assumption that the only relevant contributions to $\Gamma_{\mathrm{Z}\gamma}$ are from W-boson, top-quark, and bottom-quark loops, $\kappa_{(\mathrm{Z}\gamma)}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_{\mathrm{W}}, m_{\mathrm{H}})$ is a scaling function depending on the scale factors κ_{b}, κ_{t} and κ_{W}:

$$\kappa_{(\mathrm{Z}\gamma)}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_{\mathrm{W}}, m_{\mathrm{H}}) \quad = \quad \frac{|\kappa_{\mathrm{b}} B_{\mathrm{b}}(m_{\mathrm{H}}) + \kappa_{\mathrm{t}} B_{\mathrm{t}}(m_{\mathrm{H}}) + \kappa_{\mathrm{W}} B_{\mathrm{W}}(m_{\mathrm{H}})|^2}{|B_{\mathrm{b}}(m_{\mathrm{H}}) + B_{\mathrm{t}}(m_{\mathrm{H}}) + B_{\mathrm{W}}(m_{\mathrm{H}})|^2} \tag{B.3}$$

where $B_{\mathrm{b,t,W}}$ denotes the bottom-quark, top-quark, and W-boson amplitudes in the SM [74, Eq. (7)]. In the SM, $\kappa_{(\mathrm{Z}\gamma)}^2 \sim \kappa_{\mathrm{W}}^2$ to within 10%.

Treatment of m_{b}

Wherever the b-quark mass, m_{b}, appears in the κ_{g}^2 and $\kappa_{(Z\gamma)}^2$ above (Eqs. (B.1) and (B.3), respectively), the pole mass $M_{\mathrm{b}} = 4.49$ GeV is used.

Based on the results of Ref. [73], for κ_{γ}^2, Eq. (B.2), the running mass $m_{\mathrm{b}}(\mu), \mu = m_{\mathrm{H}}/2$ is used.

Maximal parametrization allowing other couplings to float

Free parameters: $\kappa_{gZ}(=\kappa_g \cdot \kappa_Z/\kappa_H)$, $\lambda_{\gamma Z}(=\kappa_\gamma/\kappa_Z)$, $\lambda_{WZ}(=\kappa_W/\kappa_Z)$, $\lambda_{bZ}(=\kappa_b/\kappa_Z)$, $\lambda_{\tau Z}(=\kappa_\tau/\kappa_Z)$, $\lambda_{Zg}(=\kappa_Z/\kappa_g)$, $\lambda_{tg}(=\kappa_t/\kappa_g)$.

	$H \rightarrow \gamma\gamma$			$H \rightarrow ZZ^{(*)}$			$H \rightarrow WW^{(*)}$			$H \rightarrow b\bar{b}$			$H \rightarrow \tau^-\tau^+$		
ggH	κ^2_{gZ}	1	$\lambda^2_{\gamma Z}$	κ^2_{gZ}	1	1	κ^2_{gZ}	1	λ^2_{WZ}	κ^2_{gZ}	1	λ^2_{bZ}	κ^2_{gZ}	1	$\lambda^2_{\tau Z}$
$t\bar{t}H$	κ^2_{gZ}	λ^2_{tg}	$\lambda^2_{\gamma Z}$	κ^2_{gZ}	λ^2_{tg}	1	κ^2_{gZ}	λ^2_{tg}	λ^2_{WZ}	κ^2_{gZ}	λ^2_{tg}	λ^2_{bZ}	κ^2_{gZ}	λ^2_{tg}	$\lambda^2_{\tau Z}$
VBF	κ^2_{gZ}	$\lambda^2_{Zg}\kappa^2_{VBF}(1,\lambda_{WZ})$	$\lambda^2_{\gamma Z}$	κ^2_{gZ}	$\lambda^2_{Zg}\kappa^2_{VBF}(1,\lambda_{WZ})$	1	κ^2_{gZ}	$\lambda^2_{Zg}\kappa^2_{VBF}(1,\lambda_{WZ})$	λ^2_{WZ}	κ^2_{gZ}	$\lambda^2_{Zg}\kappa^2_{VBF}(1,\lambda_{WZ})$	λ^2_{bZ}	κ^2_{gZ}	$\lambda^2_{Zg}\kappa^2_{VBF}(1,\lambda_{WZ})$	$\lambda^2_{\tau Z}$
WH	κ^2_{gZ}	$\lambda^2_{Zg}\lambda^2_{WZ}$	$\lambda^2_{\gamma Z}$	κ^2_{gZ}	$\lambda^2_{Zg}\lambda^2_{WZ}$	1	κ^2_{gZ}	$\lambda^2_{Zg}\lambda^2_{WZ}$	λ^2_{WZ}	κ^2_{gZ}	$\lambda^2_{Zg}\lambda^2_{WZ}$	λ^2_{bZ}	κ^2_{gZ}	$\lambda^2_{Zg}\lambda^2_{WZ}$	$\lambda^2_{\tau Z}$
ZH	κ^2_{gZ}	λ^2_{Zg}	$\lambda^2_{\gamma Z}$	κ^2_{gZ}	λ^2_{Zg}	1	κ^2_{gZ}	λ^2_{Zg}	λ^2_{WZ}	κ^2_{gZ}	λ^2_{Zg}	λ^2_{bZ}	κ^2_{gZ}	λ^2_{Zg}	$\lambda^2_{\tau Z}$

$\kappa_i^2 = \Gamma_{ii}/\Gamma_{ii}^{SM}$

Table A.1: A benchmark parametrization without assumptions and maximum degrees of freedom. The colors denote the common factor (black) and the factors related to the production (blue) and decay modes (red). Ones are used to denote the trivial factor.