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Pseudo-observables in Higgs decays

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We introduce a set of pseudo-observables (PO), defined from on-shell amplitudes, characterizing the properties of Higgs decays in generic extensions of the Standard Model with no new particles below the Higgs mass. These PO provide a generalization of the *kappa*-framework used by the LHC experiments and allow for the systematic inclusion of higher order QED corrections. Symmetries of the new-physics sector, such as CP invariance, lepton-universality, and custodial symmetry imply relations among the PO, that could be tested directly from Higgs data. They can be matched to any EFT approach to Higgs physics, providing predictions which can be tested experimentally.

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1. Introduction

After the discovery of the Higgs boson, $h(125)$, in July 2012 at the LHC and the measurement of its most important couplings to the Standard Model (SM) particles during the following three years, one of the main goals of future Higgs studies will be a more precise and complete characterization of all its properties. Given we presently do not know the specific theory lying beyond the SM, it is important to develop a framework capable of collecting all the experimental information which will be available on the Higgs with the least possible theoretical bias. At the same time a good framework should condensate the experimental information in a few well-defined quantities of easy theoretical interpretation.

Pseudo-observables (PO), defined directly from physical properties of on-shell amplitudes, are perfectly suited for this goal. Experimentally, PO correspond to some idealized observables, stripped of collider and soft radiation effects. Theoretically they are well defined objects in quantum field theory, related to physical properties of the process in question. In this context, we define a set of PO capable of describing in great generality all Higgs boson decays.

In this proceedings contribution we summarize the main points, referring to published works for the details [1, 2, 3]. In Sect. 2 we present the PO relevant to Higgs decays to two fermions while in Sect. 3 we describe the PO necessary to characterize the decays to vector currents, such as $h \to \gamma\gamma$ and $h \to 4f$, and how QED radiative corrections are a necessary – and sufficient – ingredient in order to reach the percent precision. In Sect. 4 and in Sect. 5 we study the predictions which follow from assuming specific symmetries of the new physics sector, or an underlying linear effective field theory.

2. Higgs decays to two fermions

The kinematics of two-body decays is fixed by momentum conservation. This implies that, if polarization of the final state is not observed, the only accessible observable is the decay rate. The Higgs PO relevant to Higgs decays to two fermions are [1, 4]

Process	$h \to bb$	$h \to \tau\tau$	$h \to cc$	$h \to \mu\mu$
PO	$\kappa_b,\ \lambda_b^{\rm CP}$	$\kappa_\tau,\ \lambda_\tau^{\rm CP}$	$\kappa_c,\ \lambda_c^{\rm CP}$	$\kappa_\mu,\ \lambda_\mu^{\rm CP}$

,

where, if h is a CP-even state, $\lambda_f^{\rm CP}$ are CP-violating PO. As in the widely used κ-formalism, the best SM prediction for the decay rate is recovered in the $\kappa_f \to 1$, $\lambda_f^{\rm CP} \to 0$ limit. With this notation, the inclusive decay rates are

$$\Gamma(h \to f\bar{f})_{\rm (incl)} = \left[\kappa_f^2 + (\lambda_f^{\rm CP})^2\right] \Gamma(h \to f\bar{f})^{\rm (SM)}_{\rm (incl)} \,, \tag{2.1}$$

where $\Gamma(h \to f\bar{f})^{\rm (SM)}_{\rm (incl)}$ is the best SM prediction for the decay rate, see e.g. Ref. [5]. The ratio $\lambda_f^{\rm CP}/\kappa_f$ can be probed only if the polarization of the final state fermions is accessible.

3. Higgs decays to spin-1 currents

Another important class of Higgs decays are those into two spin-1 currents. This class includes two-body on-shell decays into gauge bosons such as $h \to \gamma\gamma$ and $h \to Z\gamma$, as well as $h \to f\bar{f}\gamma$ and all $h \to 4f$ decays. The $h \to 4f$ amplitudes are particularly interesting since they allow us to probe the effective hW^+W^- and hZZ interaction terms, which cannot be probed on-shell.

The purpose of our approach is to characterize, as precisely as possible, the three point function of the Higgs boson and two fermion currents (either both neutral or charged),

$$\langle 0 | \mathscr{T} \left\{ J_f^\mu(x), J_{f'}^\nu(y), h(0) \right\} |0\rangle \ , \tag{3.1}$$

where all the states are on-shell. These correlation functions are probed by the experiments in $h \to 4f$ decays, as well as in Higgs associated production ($pp \to h + W, Z$) and in Higgs production via vector-boson fusion. In the following we focus on the decays.

The correlation functions of Eq. (3.1) contain physical poles corresponding to the propagation of intermediate electroweak (EW) gauge bosons, i.e. non-local terms in which $x, y \neq 0$. Generic heavy new physics also generates local terms in which x and/or $y = 0$. A great simplification is obtained by recognizing that completely local terms, i.e. contributions in which both $x = y = 0$, are necessarily generated by local operators of scaling dimension bigger than 6, thus strongly suppressed if the scale of new physics is above the EW scale. This classification of the different structures in the amplitude in terms of their physical pole structure (double, single or no-poles) allows us to define the PO from the residues of these poles. Such a definition is gauge-invariant and well-defined from the QFT point of view. It also provides a direct link between the PO and specific kinematical properties of the events. Extracting this kinematical structure from data would allow us both to determine the effective coupling of h to all the SM gauge bosons, as well as to investigate possible couplings of h to new massive states.

The explicit expansion of the amplitude and the definition of the PO can be found in Refs. [1, 4].[1] We present here a summary of all the Higgs decay processes (into on-shell particles) contained in this class and the PO necessary to describe each of them:

Process	PO
$h \to \gamma\gamma$	$\kappa_{\gamma\gamma},\ \lambda^{\rm CP}_{\gamma\gamma}$
$h \to Z\gamma$	$\kappa_{Z\gamma},\ \lambda^{\rm CP}_{Z\gamma}$
$h \to \gamma 2\nu$	$\kappa_{Z\gamma},\ \lambda^{\rm CP}_{Z\gamma}$
$h \to \gamma 2\ell$	$\kappa_{\gamma\gamma},\ \lambda^{\rm CP}_{\gamma\gamma},\ \kappa_{Z\gamma},\ \lambda^{\rm CP}_{Z\gamma}$
$h \to Z 2\ell$	$\kappa_{ZZ},\ \epsilon_{ZZ},\ \epsilon^{\rm CP}_{ZZ},\ \kappa_{Z\gamma},\ \lambda^{\rm CP}_{Z\gamma},\ \epsilon_{Z\ell_L},\ \epsilon_{Z\ell_R}$
$h \to 2\ell 2\ell'$	$\kappa_{ZZ},\ \epsilon_{ZZ},\ \epsilon^{\rm CP}_{ZZ},\ \kappa_{Z\gamma},\ \lambda^{\rm CP}_{Z\gamma},\ \kappa_{\gamma\gamma},\ \lambda^{\rm CP}_{\gamma\gamma},\ \epsilon_{Z\ell_L},\ \epsilon_{Z\ell_R},\ \epsilon_{Z\ell'_L},\ \epsilon_{Z\ell'_R}$
$h \to 4\ell$	$\kappa_{ZZ},\ \epsilon_{ZZ},\ \epsilon^{\rm CP}_{ZZ},\ \kappa_{Z\gamma},\ \lambda^{\rm CP}_{Z\gamma},\ \kappa_{\gamma\gamma},\ \lambda^{\rm CP}_{\gamma\gamma},\ \epsilon_{Z\ell_L},\ \epsilon_{Z\ell_R}$
$h \to \bar\ell\ell 2\nu$	$\begin{cases} \kappa_{ZZ},\ \epsilon_{ZZ},\ \epsilon^{\rm CP}_{ZZ},\ \kappa_{Z\gamma},\ \lambda^{\rm CP}_{Z\gamma},\ \epsilon_{Z\ell_L},\ \epsilon_{Z\ell_R},\ \epsilon_{Z\nu} \\ \kappa_{WW},\ \epsilon_{WW},\ \epsilon^{\rm CP}_{WW},\ \epsilon_{W\ell},\ \phi_{W\ell} \end{cases}$
$h \to \bar\ell\ell' 2\nu$	$\kappa_{WW},\ \epsilon_{WW},\ \epsilon^{\rm CP}_{WW},\ \epsilon_{W\ell},\ \phi_{W\ell},\ \epsilon_{W\ell'},\ \phi_{W\ell'}$

In this table $\ell = e, \mu, \tau$ while ν indicates any of the three neutrino species. The W boson contact terms are in general complex numbers: $\epsilon_{W\ell} e^{i\phi_{W\ell}}$. The $\lambda_x^{\rm CP}$, $\epsilon_x^{\rm CP}$ and $\phi_{W\ell}$ terms describe CP-violating interactions if the Higgs is a CP-even state. Since many PO enter in more than one process, the best constraints will be obtained by combining different Higgs decay channels.

[1] Here we use the same notation for the PO as in [4].

3.1 Radiative corrections

While the PO, defined from the correlation function in Eq. (3.1), describe in full generality the *short-distance* physics of $h \to 4\ell$ decays, in order to compare this amplitude decomposition with data also the *long-distance* contribution due to soft and collinear photon emission (i.e. the leading QED radiative corrections) must be taken into account. By assuming that these long-distance effects are free from new physics contribution, they can be implemented via universal convolution functions (or, equivalently, QED showering algorithms), independently on the short-distance contributions to the amplitude.

In Ref. [3] we showed that soft and collinear QED radiation induces a $\sim 15\%$ effect on the di-lepton invariant mass spectrum. This enhancement is due both to the $\sim \log(m_h^2/m_*^2)$ factor, where m_* is the infrared cutoff, and to the presence of the Z boson mass peak in the spectrum. Including such effects is thus necessary in order to derive precise bounds on the PO. Moreover, by comparing our results to the full next-to-leading-order (NLO) computation of the amplitude in the SM, we showed that the inclusion of QED effects is sufficient to within an accuracy of $\sim 1\%$. The inclusion of soft and collinear QED corrections allows then to match the PO to some specific theory at NLO accuracy. The same QED radiation effects can be obtained, on an event-by-event basis, also by showering algorithms such as PHOTOS or PYTHIA and thus can be easily implemented in phenomenological analysis.

3.2 Tools

In order to facilitate the experimental analysis of Higgs decays in this framework, we implemented the Higgs PO presented here in a FeynRules model, *HiggsPO* [4]. This package can be used to generate Higgs decay events within MadGraph5_aMC@NLO. The Higgs production part, as well as final state showering effects, can be simulated by other dedicated codes.

4. Symmetry limits

Symmetries of the new physics sector predict relations among the PO. On the one hand, these relations can be used, by assuming some symmetry, to reduce the number of independent PO to be studied. On the other hand, and more importantly, testing directly these relations from Higgs data would provide a precious insight into the symmetries of the new physics sector [1].

Flavor universality. This corresponds to enlarging the flavor symmetry to the $\mathrm{U}(3)^5$ group. In terms of Higgs PO it implies that the contact terms are independent on the generations:

$$\varepsilon_{Z\ell_L} = \varepsilon_{Z\ell'_L}\,, \qquad \varepsilon_{Z\ell_R} = \varepsilon_{Z\ell'_R}\,, \qquad \varepsilon_{Z\nu_\ell} = \varepsilon_{Z\nu_{\ell'}}\,, \qquad \varepsilon_{W\ell_L} = \varepsilon_{W\ell'_L}\,, \qquad \phi_{W\ell_L} = \phi_{W\ell'_L}\,. \tag{4.1}$$

CP conservation. If the Higgs is a CP-even state and CP is conserved, then various PO vanish:

$$\lambda_{\gamma\gamma}^{\mathrm{CP}} = \lambda_{Z\gamma}^{\mathrm{CP}} = \varepsilon_{ZZ}^{CP} = \varepsilon_{WW}^{CP} = \phi_{We_L} = \phi_{W\mu_L} = 0\,. \tag{4.2}$$

Custodial symmetry. This symmetry means that the new physics sector is invariant under the custodial symmetry group $\mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(2)_\mathrm{R}$, spontaneously broken to the diagonal $\mathrm{SU}(2)_{\mathrm{L+R}}$ by the Higgs vacuum expectation value. This global symmetry is explicitly broken in the SM by the

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hypercharge and by the Yukawa couplings; we assume these are the only two sources of breaking of custodial symmetry. The relations among the PO following from this symmetry are [1, 6]:

$$\varepsilon_{WW} = c_w^2 \varepsilon_{ZZ} + 2 c_w s_w \varepsilon_{Z\gamma} + s_w^2 \varepsilon_{\gamma\gamma} \,, \tag{4.3}$$

$$\varepsilon_{WW}^{CP} = c_w^2 \varepsilon_{ZZ}^{CP} + 2 c_w s_w \varepsilon_{Z\gamma}^{CP} + s_w^2 \varepsilon_{\gamma\gamma}^{CP} \,, \tag{4.4}$$

$$\kappa_{WW} - \kappa_{ZZ} = -\frac{2}{g}\left(\sqrt{2}\varepsilon_{We_L^i} + 2 c_w \varepsilon_{Ze_L^i}\right) \,, \tag{4.5}$$

where $\varepsilon_{\gamma\gamma,Z\gamma} \equiv \kappa_{\gamma\gamma,Z\gamma}\varepsilon^{\rm SM}_{\gamma\gamma,Z\gamma}$, $\varepsilon^{\rm CP}_{\gamma\gamma,Z\gamma} \equiv \lambda^{\rm CP}_{\gamma\gamma,Z\gamma}\varepsilon^{\rm SM}_{\gamma\gamma,Z\gamma}$ and $\varepsilon^{\rm SM}_{\gamma\gamma} \approx 3.81 \times 10^{-3}$, $\varepsilon^{\rm SM}_{Z\gamma} \approx 6.91 \times 10^{-3}$ are the (loop level) SM contributions to the PO [1, 4].

5. Higgs PO in the linear EFT

If the Higgs boson, h, is part of a doublet and the new physics is above the EW scale, a good description of deformations from the SM at the EW scale is provided by the linear effective field theory (EFT), where one adds dimension-6 gauge-invariant operators to the SM Lagrangian. Under this assumption, the h field appears in the effective SM+NP Lagrangian through the combination $(v+h)^n$, where v is the $\mathrm{SU}(2)_{\mathrm{L}}$-breaking vacuum expectation value. This implies that processes involving the Higgs particle can be related to EW precision observables, well measured at LEP, which do not involve the physical Higgs boson. Testing if such relations are satisfied represents a very powerful tool to discriminate linear and non-linear EFT approaches to Higgs physics.

Working at leading-order in the EFT, the Higgs PO can be expressed as linear combinations of the Wilson coefficients of the dim-6 operators. Analogously, the EW PO, such as the Z- and W-pole effective couplings, the W mass, and the anomalous triple gauge boson couplings (TGC), can be expressed as linear combinations of the same Wilson coefficients. By inverting these linear combinations it is possible to derive basis-independent relations between Higgs and EW PO [7, 1, 2]:

$$\begin{aligned}
\varepsilon_{Zf} &= \frac{2 m_Z}{v}\left(\delta g^{Zf} - (c_\theta^2 T_f^3 + s_\theta^2 Y_f)\mathbf{1}_3 \delta g_{1,z} + t_\theta^2 Y_f \mathbf{1}_3 \delta\kappa_\gamma\right) \,, \\
\varepsilon_{Wf} &= \frac{\sqrt{2} m_W}{v}\left(\delta g^{Wf} - c_\theta^2 \mathbf{1}_3 \delta g_{1,z}\right) \,, \\
\kappa_{WW} - \kappa_{ZZ} &= -2 s_\theta^2 \delta g_{1,z} + 2 t_\theta^2 \delta\kappa_\gamma + 4\delta m \,,
\end{aligned} \tag{5.1}$$

where $\{c_\theta, s_\theta, t_\theta\}$ denote respectively the cosine, sine and tangent of the Weinberg angle. Here $\delta m \equiv \delta m_W / m_W$, δg^{Zf} and δg^{Wf} are the anomalous effective on-shell Z and W couplings to the fermion f, $\delta g_{1,z}$ and $\delta\kappa_\gamma$ are the effective anomalous TGC (see Ref. [8] for the definition of the various terms). The remaining nine Higgs PO, $\varepsilon^{(CP)}_{ZZ,WW,Z\gamma,\gamma\gamma}$ and κ_{ZZ}, are not constrained by EW data alone. However, only five of them are independent in the linear EFT due to the following relations:

$$\delta\varepsilon_{ZZ} = \delta\varepsilon_{\gamma\gamma} + \frac{2}{t_{2\theta}}\delta\varepsilon_{Z\gamma} - \frac{1}{c_\theta^2}\delta\kappa_\gamma \,, \tag{5.2}$$

$$\delta\varepsilon_{WW} = c_\theta^2 \delta\varepsilon_{ZZ} + s_{2\theta}\delta\varepsilon_{Z\gamma} + s_\theta^2 \delta\varepsilon_{\gamma\gamma} \,, \tag{5.3}$$

and likewise for their CP counterparts (see also Refs. [6, 7, 8]).

All W- and Z-pole observables relevant to Higgs decays have been constrained by LEP with (sub)percent precision [9]. This implies that the linear EFT predicts, from LEP data, flavor universality in the contact terms. It also means that all the above Higgs PO, except κ_{ZZ}, depend approximately only on the two TGC, $\delta g_{1,z}$ and $\delta \kappa_\gamma$ (constrained at the $\mathscr{O}(10\%)$ level [10]), and on $\delta\varepsilon_{\gamma\gamma}$ and $\delta\varepsilon_{Z\gamma}$ (constrained by LHC at the permil and percent level respectively, see Ref. [2] for details).

Combining all these data it is possible to derive bounds on the Higgs PO [2] and study the size of the allowed effects in the $h \to 4\ell$ phenomenology, in particular in the decay rate and in the 4ℓ spectrum distributions. Our study [2] shows that, while the rate can vary by $\mathscr{O}(1)$ effects, the constraints on flavour non-universal effects imply $\frac{\Gamma(h\to 2e2\mu)}{\Gamma_{\rm SM}(h\to 2e2\mu)} \approx \frac{\Gamma(h\to 4e,4\mu)}{\Gamma_{\rm SM}(h\to 4e,4\mu)}$. Moreover, deviations in the di-lepton invariant mass spectrum are constrained to be smaller than $\mathscr{O}(10\%)$. Any eventual observation of deviations from these predictions would have deep consequences for our understanding of the NP sector: it would imply that the Higgs is not part of an $SU(2)_{\rm L}$ doublet (at least in part), or could also signal deviations from flavour universality in the lepton sector.

6. Conclusion

We presented a general framework to parametrize Higgs decays in terms of a set of pseudo-observables, defined from physical properties of the decay amplitudes. These PO can be dressed with QED soft and collinear radiation in order to achieve percent precision and have been implemented in montecarlo tools for events generation. They can be used to test specific symmetries of the new physics sector using Higgs data only and can be easily matched to the SM linear effective field theory, or other new physics models. This provides predictions for the PO that can be tested by data, providing an important insight into the physics beyond the SM.

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