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Higgs Physics with Heavy New Physics

DAVID MARZOCCA

Physik-Institut, Universität Zürich, CH-8057 Zürich, Switzerland

marzocca@physik.uzh.ch

Abstract. 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. The same assumption of heavy new physics, augmented by assuming that the Higgs is part of an electroweak doublet, allows for the introduction of the linear effective field theory (SMEFT) for describing the effect of new physics at low energy. In this context, the PO can be matched to the Wilson coefficients of the SMEFT, providing a way to test experimentally the SMEFT predictions.

1 INTRODUCTION

One of the main goals of Higgs studies at the LHC Run-2 and at future colliders 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 results, referring to published works for the details [1, 2, 3, 4]. 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 the polarization of the final state is not observed, the only accessible observable is the decay rate. The Higgs PO relevant to decays into two fermions are defined by the amplitude [1, 5]

$$\mathcal{A}(h \to f\bar{f}) = -i\frac{y_{\text{eff}}^{f,\text{SM}}}{\sqrt{2}}\bar{f}\left(\kappa_f + i\lambda_f^{\text{CP}}\gamma_5\right)f\ . \tag{1}$$

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

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

where $\Gamma(h \to f\bar{f})^{\rm (SM)}_{\rm (incl)}$ is the best SM prediction for the decay rate, see e.g. Ref. [6], which fixes the parameter $y^{f,{\rm SM}}_{\rm eff}$. 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

A very important class of Higgs decays, thanks to the rich kinematics they offer, 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.

All the physical information on these processes is contained in the three-point correlation functions of the Higgs boson and two fermion currents (either both neutral or charged),

$$\langle 0 | \mathcal{T} \left\{ J^\mu_f(x), J^\nu_{f'}(y), h(0) \right\} | 0 \rangle \,, \tag{3}$$

where all the states are on-shell. These 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 implementation of PO in these Higgs production processes has been recently discussed in Ref. [7].

The correlation functions of Eq. (3) 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 $y = 0$. The Higgs PO are defined directly from the residues of these different poles. This implies they are gauge-invariant quantities defined at all orders in perturbation theory. Extracting this kinematical (pole) 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, 5].[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
$h \to \gamma\gamma$	$\kappa_{\gamma\gamma},\ \lambda^{\rm CP}_{\gamma\gamma}$
$h \to Z\gamma$	$\kappa_{Z\gamma},\ \lambda^{\rm CP}_{Z\gamma}$
$h \to \gamma 2\nu$	$\kappa_{Z\gamma},\ \lambda^{\rm CP}_{Z\gamma}$
$h \to \gamma 2\ell$	$\kappa_{\gamma\gamma},\ \lambda^{\rm CP}_{\gamma\gamma},\ \kappa_{Z\gamma},\ \lambda^{\rm CP}_{Z\gamma}$
$h \to Z 2\ell$	$\kappa_{ZZ},\ \epsilon_{ZZ},\ \epsilon^{\rm CP}_{ZZ},\ \kappa_{Z\gamma},\ \lambda^{\rm CP}_{Z\gamma},\ \epsilon_{Z\ell_L},\ \epsilon_{Z\ell_R}$
$h \to 2\ell 2\ell'$	$\kappa_{ZZ},\ \epsilon_{ZZ},\ \epsilon^{\rm CP}_{ZZ},\ \kappa_{Z\gamma},\ \lambda^{\rm CP}_{Z\gamma},\ \kappa_{\gamma\gamma},\ \lambda^{\rm CP}_{\gamma\gamma},\ \epsilon_{Z\ell_L},\ \epsilon_{Z\ell_R},\ \epsilon_{Z\ell'_L},\ \epsilon_{Z\ell'_R}$
$h \to 4\ell$	$\kappa_{ZZ},\ \epsilon_{ZZ},\ \epsilon^{\rm CP}_{ZZ},\ \kappa_{Z\gamma},\ \lambda^{\rm CP}_{Z\gamma},\ \kappa_{\gamma\gamma},\ \lambda^{\rm CP}_{\gamma\gamma},\ \epsilon_{Z\ell_L},\ \epsilon_{Z\ell_R}$
$h \to \bar{\ell}\ell 2\nu$	$\left\{ \begin{array}{l} \kappa_{ZZ},\ \epsilon_{ZZ},\ \epsilon^{\rm CP}_{ZZ},\ \kappa_{Z\gamma},\ \lambda^{\rm CP}_{Z\gamma},\ \epsilon_{Z\ell_L},\ \epsilon_{Z\ell_R},\ \epsilon_{Z\nu} \\ \kappa_{WW},\ \epsilon_{WW},\ \epsilon^{\rm CP}_{WW},\ \epsilon_{W\ell},\ \phi_{W\ell} \end{array} \right.$
$h \to \bar{\ell}\ell' 2\nu$	$\kappa_{WW},\ \epsilon_{WW},\ \epsilon^{\rm CP}_{WW},\ \epsilon_{W\ell},\ \phi_{W\ell},\ \epsilon_{W\ell'},\ \phi_{W\ell'}$

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 $\lambda^{\rm CP}_x$, $\epsilon^{\rm CP}_x$ 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.

Radiative corrections

While the PO, defined from the correlation function in Eq. (3), 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.

[1] Here we use the same notation for the PO as in [5].

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 peak in the spectrum. Including such effects is thus necessary in order to reach $\sim$ 10 % precision 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 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.

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* [5]. 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 $U(3)^5$ group. In terms of Higgs PO it implies that the contact terms are independent on the generation.

$$\epsilon_{Z\ell_L} = \epsilon_{Z\ell'_L} , \qquad \epsilon_{Z\ell_R} = \epsilon_{Z\ell'_R} , \qquad \epsilon_{Z\nu_\ell} = \epsilon_{Z\nu_{\ell'}} , \qquad \epsilon_{W\ell_L} = \epsilon_{W\ell'_L} , \qquad \phi_{W\ell_L} = \phi_{W\ell'_L} . \tag{4}$$

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

$$\lambda_{\gamma\gamma}^{\rm CP} = \lambda_{Z\gamma}^{\rm CP} = \epsilon_{ZZ}^{CP} = \epsilon_{WW}^{CP} = \phi_{We_L} = \phi_{W\mu_L} = 0 . \tag{5}$$

Custodial symmetry. This is an accidental approximate symmetry of the SM, explicitly broken only by the hypercharge and by the small Yukawa couplings. It protects the electroweak ρ parameter from receiving sizable corrections. If the new physics sector also respects this symmetry then some relations among the PO can be obtained, see Refs. [1, 8]:

$$\epsilon_{WW} = c_w^2 \epsilon_{ZZ} + 2 c_w s_w \epsilon_{Z\gamma} + s_w^2 \epsilon_{\gamma\gamma} , \tag{6}$$

$$\epsilon_{WW}^{CP} = c_w^2 \epsilon_{ZZ}^{CP} + 2 c_w s_w \epsilon_{Z\gamma}^{CP} + s_w^2 \epsilon_{\gamma\gamma}^{CP} , \tag{7}$$

$$\kappa_{WW} - \kappa_{ZZ} = -\frac{2}{g}\left(\sqrt{2}\epsilon_{W\ell_L^i} + 2 c_w \epsilon_{Z\ell_L^i}\right) , \tag{8}$$

$$\epsilon_{W\ell_L^i} = \frac{c_w}{\sqrt{2}}(\epsilon_{Z\nu_L^i} - \epsilon_{Z\ell_L^i}) . \tag{9}$$

5 HIGGS PO IN THE LINEAR EFT

If the Higgs boson, h, is part of a $SU(2)_L$ 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 Standard Model linear effective field theory (SMEFT). Under these assumptions, many processes involving the Higgs can be related to EW precision observables, well measured at LEP, which do not involve the physical Higgs particle. Testing if such relations are satisfied represents a very powerful tool to test the SMEFT assumption. Working at the leading order in the effective theory, the Higgs PO

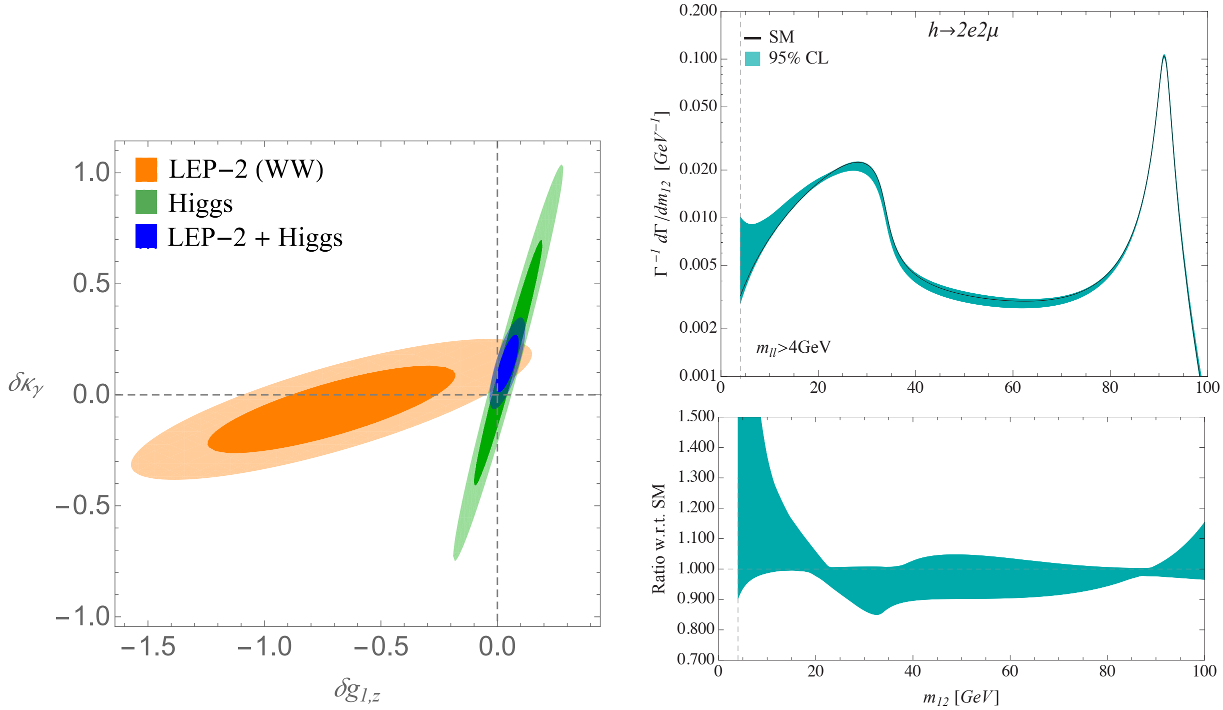

FIGURE 1. Left: Allowed 68% and 95% CL region in the $\delta g_{1,z}$-$\delta\kappa_\gamma$ plane after considering LEP-2 WW production data (TGC), Higgs data, and the combination of both datasets. **Right:** Allowed variation of the normalized differential decay rate $h \to 2e2\mu$ in m_{ee} (or, equivalently, $m_{\mu\mu}$) when varying all the PO withing the 95% CL bounds from our combined LEP-2 plus Higgs fit.

can be expressed as linear combinations of the Wilson coefficients of the dimension-6 operators [1, 2]. Analogously, the EW pseudo-observables, in particular 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 [9, 1, 2].

One the one hand, this allows to combine Higgs data with LEP-I and LEP-II data (mainly WW production) in order to derive strong and robust bounds on the EFT coefficients, in particular the TGC. In Ref. [4] we performed a combined fit of LEP-II WW production data [10] and Higgs data from the LHC Run-I in the context of the SMEFT, assuming minimal flavor violation. In Fig. 1 (left) we show the bounds we obtain in two TGC parameters, when all other coefficients entering the fit are profiled. While both LEP-II and Higgs data present a flat directions in this plane when taken separately, the combination of the two datasets allows to cast strong bounds on all TGC. On the other hand, via this global analysis it is possible to derive strong bounds on the Higgs PO [2, 4] 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 shows that flavor non-universal effects are strongly suppressed due to the LEP-I bounds and that the deviations in the di-lepton invariant mass spectrum are constrained to be smaller than ~ 10 %, as shown in Fig. 1 (right). Such bounds can be interpreted as predictions of the linear EFT approach, which can be tested by Higgs data. Any 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 $SU(2)_L$ doublet (at least in part), or could also signal deviations from flavour universality in the lepton sector.

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