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Higgs as a BSM probe

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Summary. — One of the most important ways to explore BSM at the LCH Run-2 is to study the properties of the Higgs boson. In order to do so in a consistent and model-independent framework, we introduce a set of pseudo-observables (PO), defined from on-shell amplitudes, characterising the properties of Higgs production and decay processes in generic extensions of the Standard Model with no new particles below the Higgs mass. These PO provide a generalisation of the κ-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 and fermion universality imply relations among the PO, that could be tested directly from Higgs data. The further assumption that the Higgs is part of an electroweak doublet allows for the introduction of the linear effective field theory (SMEFT) to describe the effect of new physics at low energy. In this context, PO can be matched to the Wilson coefficients of the SMEFT, providing a way to test experimentally the SMEFT predictions by combining Higgs data with other electroweak processes.

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 characterisation of all its properties. Given that we presently do not know the specific theory lying beyond the Standard Model (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 (such as Lorentz structures and residues of one-particle poles), are perfectly suited for this goal. Experimentally, PO correspond to some idealised 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 and electroweak (EW) production processes.

In this proceedings contribution we summarise the main results, referring to published works for the details [1-5]. In sect. **2** we present the PO relevant to Higgs decays to two fermions while in sect. **3** we describe the PO necessary to characterise the decays to vector currents, such as $h \to \gamma\gamma$ and $h \to 4f$, as well as EW Higgs production processes. 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 of scalar particles is fixed by momentum conservation. This implies that, if the polarization of the final state is not observed, the only physical observable experimentally accessible is the decay rate. In full generality, the Higgs PO relevant to two-fermion decays are defined by the amplitude [1,6]

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

where $f = b, \tau, c, \mu, \ldots$ and, if h is a CP-even state, $\delta_f^{\rm CP}$ are CP-violating PO. With this definition, the inclusive decay rates are

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

where $\Gamma(h \to f\bar{f})^{\rm (SM)}_{\rm (incl)}$ is the best SM prediction for the decay rate, see *e.g.* ref. [7], which fixes the parameter $y_{\rm eff}^{f,{\rm SM}}$. This means that, as in the widely used κ-formalism, the best SM prediction for the decay rate is recovered in the $\kappa_f \to 1$, $\delta_f^{\rm CP} \to 0$ limit. The ratio $\delta_f^{\rm CP}/\kappa_f$ can be probed only if the polarisation of the final state fermions is accessible [6].

3. – Four-fermion Higgs decays and EW Higgs production

A very 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, as well as because they offer a very rich kinematics.

To the same category belong also the EW Higgs production processes, such as vector-boson-fusion (VBF) and associated Vh production ($pp \to h + W/Z$). The reason for such a connection is due to the crossing symmetry of the relevant scattering amplitudes: they all are described by the three-point correlation function of the on-shell Higgs and two on-shell electroweak currents

$$\langle 0|\mathcal{T}\left\{J_f^\mu(x), J_{f'}^\nu(y), h(0)\right\}|0\rangle, \tag{3}$$

All the physical information on these processes is contained in this object. The difference among them lies in the kinematical region probed and in the specific fermion current considered.

Lorentz symmetry reduces the number of possible tensor structure in eq. (3) to only three. Moreover, these correlation functions contain physical poles corresponding to the propagation of intermediate EW gauge bosons (γ, Z, $W^\pm$), *i.e.* non-local terms in which

TABLE I. – *Summary of the PO appearing in EW Higgs decays and in the VBF and Vh production processes specified in the first column (see main text). The PO appearing in the second column are the independent ones under the assumption of flavour universality and CP invariance. By relaxing flavour universality (CP-invariance) one should also add the PO in the third (fourth) column. The terms between square brakes in the lower table are the PO present both in production and decays.*

Higgs (EW) decay amplitudes

<table>
<tr><th>Amplitudes</th><th>Flavour + CP</th><th>Flavour Non Univ.</th><th>CPV</th></tr>
<tr><td>$h \to \gamma\gamma, 2e\gamma, 2\mu\gamma$
$4e, 4\mu, 2e2\mu$</td><td>$\kappa_{ZZ}, \kappa_{Z\gamma}, \kappa_{\gamma\gamma}, \epsilon_{ZZ}$
$\epsilon_{Ze_L}, \epsilon_{Ze_R}$</td><td>$\epsilon_{Z\mu_L}, \epsilon_{Z\mu_R}$</td><td>$\epsilon^{CP}_{ZZ}, \delta^{CP}_{Z\gamma}, \delta^{CP}_{\gamma\gamma}$</td></tr>
<tr><td rowspan="2">$h \to 2e2\nu, 2\mu2\nu, e\nu\mu\nu$</td><td rowspan="2">$\kappa_{WW}, \epsilon_{WW}$
$\epsilon_{Z\nu_e}$, $\mathrm{Re}(\epsilon_{We_L})$</td><td>$\epsilon_{Z\nu_\mu}$, $\mathrm{Re}(\epsilon_{W\mu_L})$</td><td>$\epsilon^{CP}_{WW}$, $\mathrm{Im}(\epsilon_{We_L})$</td></tr>
<tr><td colspan="2">$\mathrm{Im}(\epsilon_{W\mu_L})$</td></tr>
</table>

Higgs (EW) production amplitudes

<table>
<tr><th>Amplitudes</th><th>Flavour + CP</th><th>Flavour Non Univ.</th><th>CPV</th></tr>
<tr><td>VBF neutral curr.
and Zh</td><td>$[\kappa_{ZZ}, \kappa_{Z\gamma}, \kappa_{\gamma\gamma}, \epsilon_{ZZ}]$
$\epsilon_{Zu_L}, \epsilon_{Zu_R}, \epsilon_{Zd_L}, \epsilon_{Zd_R}$</td><td>$\epsilon_{Zc_L}, \epsilon_{Zc_R}$
$\epsilon_{Zs_L}, \epsilon_{Zs_R}$</td><td>$[\epsilon^{CP}_{ZZ}, \delta^{CP}_{Z\gamma}, \delta^{CP}_{\gamma\gamma}]$</td></tr>
<tr><td rowspan="2">VBF charged curr.
and Wh</td><td rowspan="2">$[\kappa_{WW}, \epsilon_{WW}]$
$\mathrm{Re}(\epsilon_{Wu_L})$</td><td>$\mathrm{Re}(\epsilon_{Wc_L})$</td><td>$[\epsilon^{CP}_{WW}]$, $\mathrm{Im}(\epsilon_{Wu_L})$</td></tr>
<tr><td colspan="2">$\mathrm{Im}(\epsilon_{Wc_L})$</td></tr>
</table>

$x, y \neq 0$. Generic heavy new physics, when integrated out, also generates local terms in which x and/or $y = 0$. The Higgs PO are defined directly from the residues of these different poles in each Lorentz structure, after a momentum expansion for $E^2 \ll m^2_{NP}$, where E is the relevant energy of the process and m_{NP} is the new physics scale. This is equivalent to assuming that further poles due to new physics are beyond the kinematical region probed by the process in question. The definition of PO from residues of poles in on-shell amplitudes guarantees their gauge invariance. Extracting this kinematical structure from data would allow us both to determine the effective coupling of h to all the SM gauge bosons and 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. [1,5,6]([1]). We present in table I a summary of all the Higgs PO relevant for this class of Higgs decays and EW production processes, classified for each process and for given assumptions on the symmetry of the new physics sector (such as flavour universality and/or CP-invariance).

VBF and Vh production. – All the flavour-universal PO entering in EW Higgs production also contribute to $h \to 4f$ decays, where they are expected to be measured with higher accuracy. On the other hand, the only PO which depend on the specific fermion current relevant to each process are the contact terms ϵ_{Zf} and ϵ_{Wf}. For this reason, these PO are the most interesting to study when considering EW Higgs production. Since they belong to the same Lorentz structure as the SM terms proportional to κ_{ZZ}, κ_{WW}, the most important observable sensitive to their presence is the differential cross section in the invariant mass of the respective fermion current [5].

([1]) Here we use the same notation for the PO as in [6].

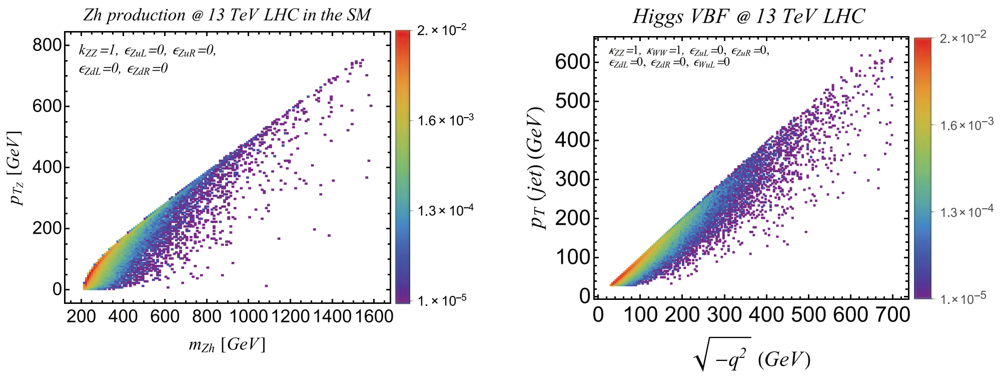

Fig. 1. – Left: correlation between the p_T^Z and the invariant mass m_{Zh} in Zh production. Right: correlation between the invariant mass of the VBF t-channel current, $\sqrt{-q^2}$, and the p_T of the corresponding VBF-jet. Both plots have been obtained in the SM for the LHC at 13 TeV.

In associated Vh production this corresponds to the invariant mass of the Vh system, m_{Vh}, while in VBF this is given by the two momentum transfers in the t-channel between the initial partons and the final VBF-jets. It is clear that this quantity is not easily accessible at a hadron collider. Similarly, also m_{Vh} could be inaccessible, or not clean, in some Higgs decay channels. It is then important to find experimentally accessible observables which are highly correlated with these invariant masses. As we show in fig. 1, these are the p_T^V of the gauge boson in the case of Vh production, and the two $p_T^{j_{1,2}}$ of the two VBF-jets in VBF production. Experimentally, it is crucial to extract as precisely as possible the differential cross sections in these quantities, from which the PO can be fitted. Note that this can be done in conjunction with a suitable binning in the simplified template cross section framework.

These kinematical variables are also the ones which control the momentum expansion which is at the basis of the PO decomposition. To address this issue, and allow for an interpretation of the results in a large class of models, it is important to report the results of various PO fits with different experimental upper cuts on these variables [5, 8].

Radiative corrections. – While the PO, defined from the correlation function in eq. (3), describe in great generality the *short-distance* physics of these Higgs processes, in order to compare this amplitude decomposition with data also the *long-distance* contribution due to soft and collinear photon and/or gluon emission (*i.e.* the leading QED/QCD 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, showering algorithms), independently of the short-distance contributions to the amplitude.

As is well-known, for example in the context of Z decays, and as was shown explicitly in ref. [3], soft and collinear QED radiation induces a $\sim$15% effect on the di-lepton invariant mass spectrum in $h \to 4\ell$ decays. The large size of the effect 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. 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 impact of QCD corrections to EW Higgs production processes was studied in refs. [9, 5], where it was shown that their impact on differential distributions can be as large as $\sim 20\%$. However, by a suitable choice of factorisation and renormalisation scales, the NLO QCD corrections have been shown to be sufficiently flat for a large kinematical region of interest [5], and the residual theoretical error due to higher-order QCD corrections can be estimated to be at the percent level.

The inclusion of soft and collinear QED and QCD corrections thus allows to match the PO to specific theories at NLO accuracy.

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, as shown in table I. 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].

Flavour universality. – This corresponds to assuming a $U(3)^5$ flavour symmetry. In terms of Higgs PO it implies that the contact terms are independent on the generation,

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

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

$$\delta^{\mathrm{CP}}_{\gamma\gamma} = \delta^{\mathrm{CP}}_{Z\gamma} = \epsilon^{CP}_{ZZ} = \epsilon^{CP}_{WW} = \phi_{We_L} = \phi_{W\mu_L} = 0. \tag{5}$$

Stages. – By assuming both flavour universality and CP-invariance, the number of independent PO entering each process can be greatly reduced, see table I. This fact can be useful to simplify the fit in an early stage, where the number of events for the relevant process is not enough to allow for a large number of free parameters.

Here we provide an example of how, by combining different channels, an early analysis of Higgs data can be performed with a limited number of PO. The $\kappa_{\gamma\gamma}$ and $\kappa_{Z\gamma}$ PO can be constrained by the $h \to \gamma\gamma$ and $h \to Z\gamma$ processes, respectively. Even the present bounds on these PO already imply that their contribution to $h \to 4f$ decays or EW Higgs production is negligible in an early stage of sensitivity. The remaining PO in $h \to 4e$, 4μ, $2e2\mu$ are then only κ_{ZZ}, $\epsilon_{Z\ell_L}$, $\epsilon_{Z\ell_R}$, and ϵ_{ZZ}. In particular, the latter can be extracted looking at angular distribution in the four leptons. Similarly, the PO entering in $h \to e\mu 2\nu, 2e2\nu, 2\mu 2\nu$ processes are only κ_{WW}, $\epsilon_{W\ell_L}$, $\epsilon_{Z\nu}$, and ϵ_{WW}.

Regarding EW Higgs production, the remaining PO which do not enter already in Higgs decays are only the contact terms. Under the symmetry assumptions above, these are only ϵ_{Wu_L} in Wh, $\epsilon_{Zu_L}, \epsilon_{Zu_R}, \epsilon_{Zd_L}, \epsilon_{Zd_R}$ in Zh, and all of them in VBF.

5. – Higgs PO and the SMEFT

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,

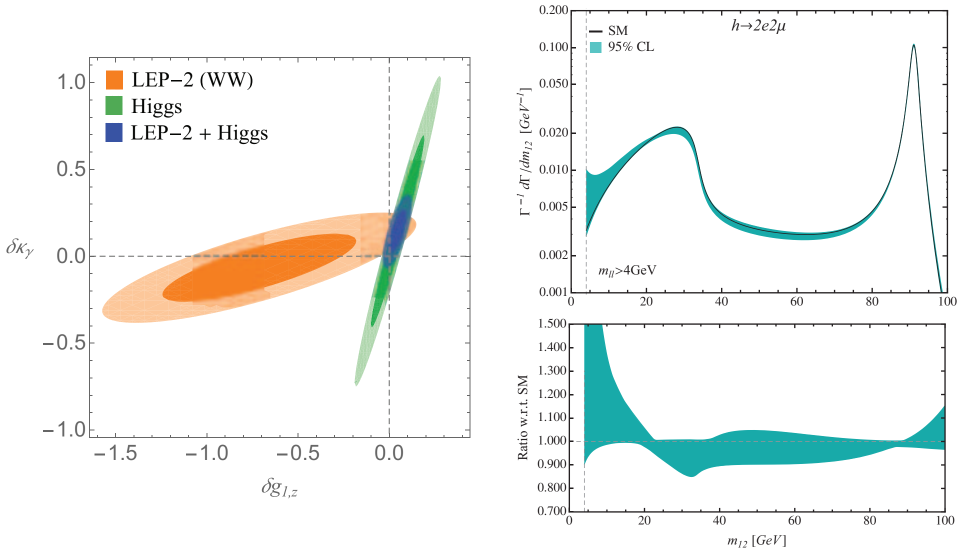

Fig. 2. – Left: allowed 68% and 95% CL region in the $\delta g_{1,z}$-$\delta\kappa_\gamma$ plane after considering LEP-2 WW production data (TGC), Higgs data, and the combination of both datasets. Right: allowed variation of the normalized differential decay rate $h \to 2e2\mu$ in m_{ee} (or, equivalently,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

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 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 [1, 2, 10].

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 [11] and Higgs data from the LHC Run-I in the context of the SMEFT, assuming flavour universality. In fig. 2 (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 direction 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 flavour 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 $\sim 10\%$, as shown in fig. 2 (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 new physics sector.

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