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## Note on anomalous Higgs-boson couplings in effective field theory



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## ABSTRACT

We propose a parametrization of anomalous Higgs-boson couplings that is both systematic and practical. It is based on the electroweak chiral Lagrangian, including a light Higgs boson, as the effective field theory (EFT) at the electroweak scale  $v$ . This is the appropriate framework for the case of sizeable deviations in the Higgs couplings of order 10% from the Standard Model, considered to be parametrically larger than new-physics effects in the sector of electroweak gauge interactions. The role of power counting in identifying the relevant parameters is emphasized. The three relevant scales,  $v$ , the scale of new Higgs dynamics  $f$ , and the cut-off  $\Lambda = 4\pi f$ , admit expansions in  $\xi = v^2/f^2$  and  $f^2/\Lambda^2$ . The former corresponds to an organization of operators by their canonical dimension, the latter by their loop order or chiral dimension. In full generality the EFT is thus organized as a double expansion. However, as long as  $\xi \gg 1/16\pi^2$  the EFT systematics is closer to the chiral counting. The leading effects in the consistent approximation provided by the EFT, relevant for the presently most important processes of Higgs production and decay, are given by a few (typically six) couplings. These parameters allow us to describe the properties of the Higgs boson in a general and systematic way, and with a precision adequate for the measurements to be performed at the LHC. The framework can be systematically extended to include loop corrections and higher-order terms in the EFT.

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## 1. Introduction

The discovery of the Higgs boson at the Large Hadron Collider (LHC) [1] has focused current research in high-energy physics onto the detailed investigation of its properties. Observing deviations from the predictions of the Standard Model (SM) would give us important information on the dynamics of electroweak symmetry breaking. The question of how to obtain an efficient parametrization of Higgs couplings is under active discussion at present (see [2] and e.g. [3] for a specific proposal).

Assuming a mass gap, with new degrees of freedom not much below the TeV scale, a general and model-independent parametrization of new physics can be achieved within the framework of an effective field theory (EFT). The EFT as the low-energy approximation of new physics at high energies ('bottom-up' perspective) needs to be defined by its *particle content*, the relevant *symmetries*, and an appropriate *power counting*.

At present, data on Higgs-boson couplings [4] still allow deviations from the Standard Model of order 10%, much larger than in the sector of the usual electroweak precision tests with gauge bosons. This leads one to consider the interesting scenario, relevant

for Higgs studies at the LHC, in which non-standard contributions to Higgs couplings are indeed of this size. Such effects would point to a new-physics scale  $f$  of typically 500–1000 GeV, corresponding to deviations characterized by the parameter  $\xi \equiv v^2/f^2 = \mathcal{O}(10\%)$ , where  $v = 246$  GeV is the electroweak scale. Examples of such new dynamics in the Higgs sector at scale  $f$  are given, in particular, by models with a composite, pseudo-Goldstone Higgs particle [5–9], but also by other models with a modified Higgs sector at either weak or strong coupling.

Anomalous contributions, with respect to the Standard Model, of order  $\xi$  in the Higgs couplings will generically lead to a cut-off  $\Lambda = 4\pi f$  in the effective description of the new Higgs dynamics. This picture might be supplemented by TeV-scale (order  $f$ ) new degrees of freedom (non-standard fermions, extra pseudo-Goldstone bosons), understood to be integrated out in the EFT at the electroweak scale  $v$ .

As has been discussed in [10], the EFT can then be organized in full generality as a double expansion in  $\xi = v^2/f^2$  and  $f^2/\Lambda^2 = 1/16\pi^2$ , which are the two dimensionless parameters that can be formed out of the three relevant scales  $v$ ,  $f$  and  $\Lambda$ . They are both small under the condition  $v \ll f \ll \Lambda$ . The expansion in  $\xi$  amounts to an expansion of the Lagrangian in operators of increasing *canonical dimension* ( $d$ ). The expansion in  $f^2/\Lambda^2$  corresponds to a loop expansion or, equivalently, to an expansion

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in terms of increasing *chiral dimension* ( $\chi$ ). For the phenomenologically interesting case where  $\xi \gg f^2/\Lambda^2$ , the character of the expansion is dominated by chiral counting rather than by canonical dimensions. It is therefore convenient to phrase the effective theory from the outset in terms of the nonlinear electroweak chiral Lagrangian.<sup>1</sup> This automatically implies a resummation to all orders in  $\xi$ .

The interesting feature of parametrically larger new-physics effects in the Higgs sector ( $\sim 1/f^2$ ) than in the gauge sector ( $\sim 1/\Lambda^2$ ), in the context of composite-Higgs scenarios, has been pointed out in [16,17]. However, the EFT formulation discussed there (SILH Lagrangian) follows a dimensional counting to describe the leading effects, which is not fully adequate in this case [10].

Under the assumptions stated above, the leading new physics effects in the Higgs sector, of order  $\xi$ , will be essentially described by the leading-order chiral Lagrangian, with qualifications to be discussed below. As a consequence, most effects from the next-to-leading order chiral Lagrangian, of order  $\xi/16\pi^2 = v^2/\Lambda^2$  can be consistently neglected. This will result in a considerable reduction of the number of parameters, while still accounting for the dominant effects of new dynamics in the Higgs sector in a general and systematic way.

Similar parametrizations based on the leading-order chiral Lagrangian have been considered and employed before by many authors (see [18] and references therein). The essential new aspect of our discussion is that it is based on a general and consistent power counting and the consideration of the next-to-leading order chiral Lagrangian in assessing the size of subleading corrections.

The remainder of this note is organized as follows. Section 2 summarizes the effective Lagrangian and the underlying assumptions. Section 3 introduces our parametrization of anomalous Higgs couplings and outlines strategies for phenomenological applications. We conclude in Section 4.

## 2. Effective Lagrangian

The most important assumptions that define the EFT of new physics in the Higgs sector based on the electroweak chiral Lagrangian can be summarized as follows:

- (i) SM particle content.
- (ii) Symmetries:
  - SM gauge symmetries
  - conservation of lepton and baryon number
  - conservation at lowest order of custodial symmetry, CP invariance in the Higgs sector, lepton flavour.
 The symmetries under the third item may be violated at some level, but this would only affect terms at subleading order. We consider these assumptions as affecting the generality of the EFT only very mildly. Generalizations may in principle be introduced if necessary.
- (iii) Power counting by chiral dimensions (loop expansion):
 

The loop expansion is equivalent to the counting of chiral dimensions [13], with the simple assignment

  - 0 for bosons (gauge fields, Goldstones and Higgs)
  - 1 for each derivative, weak coupling (e.g. gauge or Yukawa), and fermion bilinear.

The loop order  $L$  of a term in the Lagrangian is equivalent to its chiral dimension (or chiral order)  $2L + 2$ . We note that the

loop expansion is not equivalent to a pure derivative counting in the presence of gauge interactions and fermions.

To leading order in chiral dimensions ( $\chi = 2$ ) the effective Lagrangian can then be written as [15]

$$\begin{aligned} \mathcal{L}_2 = & -\frac{1}{2}\langle G_{\mu\nu}G^{\mu\nu} \rangle - \frac{1}{2}\langle W_{\mu\nu}W^{\mu\nu} \rangle - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} \\ & + \bar{q}i\not{D}q + \bar{l}i\not{D}l + \bar{u}i\not{D}u + \bar{d}i\not{D}d + \bar{e}i\not{D}e \\ & + \frac{v^2}{4}\langle L_\mu L^\mu \rangle (1 + F_U(h)) + \frac{1}{2}\partial_\mu h \partial^\mu h - V(h) \\ & - v \left[ \bar{q} \left( Y_u + \sum_{n=1}^{\infty} Y_u^{(n)} \left( \frac{h}{v} \right)^n \right) U_{P+r} \right. \\ & + \bar{q} \left( Y_d + \sum_{n=1}^{\infty} Y_d^{(n)} \left( \frac{h}{v} \right)^n \right) U_{P-r} \\ & \left. + \bar{l} \left( Y_e + \sum_{n=1}^{\infty} Y_e^{(n)} \left( \frac{h}{v} \right)^n \right) U_{P-\eta} + \text{h.c.} \right] \end{aligned} \quad (1)$$

with  $L_\mu = iUD_\mu U^\dagger$ ,  $P_\pm = 1/2 \pm T_3$ . Here  $F_U = \sum_{n=1}^{\infty} f_{U,n}(h/v)^n$ ,  $V = v^4 \sum_{n=2}^{\infty} f_{V,n}(h/v)^n$ .

In addition to the leading-order terms, the Higgs-photon-photon and Higgs-gluon-gluon couplings, of the form

$$hF^{\mu\nu}F_{\mu\nu}, \quad hG^{\mu\nu}G_{\mu\nu} \quad (2)$$

from the Lagrangian of chiral dimension 4 have to be included to account for all the leading effects. This is because these couplings are loop-induced in the Standard Model and the relative corrections at chiral dimension 4 are also of order  $\xi$ . In contrast, the corresponding terms

$$hW^{+\mu\nu}W_{\mu\nu}^-, \quad hZ^{\mu\nu}Z_{\mu\nu} \quad (3)$$

are subleading compared to the dominant  $hWW$  and  $hZZ$  couplings from (1) and can be neglected. The same is true, in particular, for modifications of the gauge-fermion couplings, which also arise at chiral dimension 4. Focusing on the modified Higgs coupling in  $h \rightarrow ZZ^* \rightarrow 4l$ , for instance, and assuming Standard-Model couplings for  $Z \rightarrow ll$ , is therefore a consistent approximation.

If custodial symmetry is only broken by weak perturbations every spurion that breaks this symmetry will come with a chiral dimension and operators breaking custodial symmetry will be further suppressed.

## 3. Parametrization of Higgs couplings

Based on the discussion of power counting in the previous section we can now define the parametrization of the Higgs couplings in a systematic way. With the foreseeable precision of the data at the LHC, we are predominantly sensitive to leading deviations from the SM. The main input given by the experiments are the signal strengths  $\mu$ . We will therefore start from  $\mu$  and consider the leading deviations given by the power counting of the EFT. The signal strength is defined as

$$\mu = \frac{\sigma(X) \cdot BR(h \rightarrow Y)}{\sigma(X)_{\text{SM}} \cdot BR(h \rightarrow Y)_{\text{SM}}}, \quad (4)$$

where  $\sigma(X)$  denotes the production cross section of the Higgs in the process  $X$  and  $BR(h \rightarrow Y)$  is the branching ratio of Higgs decaying to the final state  $Y$ . Possible processes in the production are gluon fusion, Higgs-strahlung from vector bosons, vector boson fusion and  $t\bar{t}$  fusion:  $X \in \{ggH, WH/ZH, VBF, ttH\}$ . The relevant

<sup>1</sup> The chiral Lagrangian for the (Higgs-less) electroweak Standard Model has first been developed in [11]. The extension with a light Higgs boson has been treated in [12–15]. A complete presentation of power counting and next-to-leading order terms has been given in [13–15].

decay channels are Higgs to bottom quark pairs, tau leptons, as well as  $W$ ,  $Z$  and photon pairs:  $Y \in \{bb, \tau\tau, WW, ZZ, \gamma\gamma\}$ .

These Standard Model processes already fall in two categories: tree and loop-level induced processes. The tree-level processes can be affected by the leading order Lagrangian and power counting tells us that deviations of order  $\mathcal{O}(\xi)$  might be expected. The loop-induced processes ( $ggH$ ,  $\gamma\gamma H$ ) are suppressed by a factor of  $1/16\pi^2$  with respect to the tree level ones. However, there are local terms at next-to-leading order (chiral order 4) in the Lagrangian with size of order  $\mathcal{O}(\xi/16\pi^2)$ . This means that such corrections are of  $\mathcal{O}(\xi)$  relative to the SM and have to be kept as well. The Lagrangian that results from these considerations is given by

$$\begin{aligned} \mathcal{L} = & 2c_V \left( m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu \right) \frac{h}{v} \\ & - c_t y_t \bar{t} t h - c_b y_b \bar{b} b h - c_\tau y_\tau \bar{\tau} \tau h \\ & + \frac{e^2}{16\pi^2} c_{\gamma\gamma} F_{\mu\nu} F^{\mu\nu} \frac{h}{v} + \frac{g_s^2}{16\pi^2} c_{gg} \langle G_{\mu\nu} G^{\mu\nu} \rangle \frac{h}{v} \end{aligned} \quad (5)$$

where  $y_f = m_f/v$ . The SM at tree level is given by  $c_V = c_t = c_b = c_\tau = 1$  and  $c_{gg} = c_{\gamma\gamma} = 0$ . Deviations due to new physics are expected to start at  $\mathcal{O}(\xi)$ . The couplings written in (5) are obtained from the effective Lagrangian in (1) by extracting the terms with a single field  $h$ , in unitary gauge for the  $W$  and  $Z$ , and neglecting (small) flavour violation and light fermions. According to the assumptions stated in Section 2 custodial symmetry holds at leading order, implying  $c_W \equiv c_Z \equiv c_V$ . In addition, the local terms with  $c_{\gamma\gamma}$  and  $c_{gg}$  have to be added.

The terms that we may neglect in our analysis fall into two groups: i) Terms at the same (chiral) order of the EFT but with a numerically very small impact on current observables. Examples for this group are the  $hZ\gamma$  local operator and the coupling to light fermions. ii) Terms of higher order in the chiral expansion, which can be neglected based on the EFT power counting. Operators of this type are for example the NLO contributions to  $hW^+W^-$  and  $hZZ$  in (3).

The fact that operators of group ii) can be neglected is illustrated e.g. by the analysis of the contributions of NLO operators to  $h \rightarrow Z\ell^+\ell^-$  [19]. In processes with off-shell Higgs production, the energy relevant for the higher-derivative Higgs couplings can become numerically larger than the scale  $v$  and lead to some enhancement of these corrections. However, as for any EFT, the size of higher-order corrections is required to be sufficiently small in order to ensure the validity of the EFT expansion.

The discussion above shows that the  $\kappa$ -formalism [20] that is widely used as a simple approximation is indeed not only motivated phenomenologically but can be justified from an effective field theory. The first deviations from the SM are expected to be in the event rates. Deviations in the shapes are subleading compared to them. However, there is one main difference between the approach presented here and the  $\kappa$ -formalism described in [20]. The  $\kappa_i$ 's for the one-loop processes of Higgs coupling to a pair of photons/gluons are either given as a function of the modified couplings of Higgs to vectors/fermions or as a free parameter describing in addition possible new particles in the loop as a point interaction. Our approach takes both of these possibilities separately into account. Even though the number of free parameters is not changed, this makes the interpretation of the results more transparent.

A numerical analysis of the currently accessible Higgs channels within the framework described above will be presented elsewhere [21]. Such an analysis could further be extended to additional processes, for instance  $h \rightarrow Z\gamma$  decay or double-Higgs production.

Once the experimental precision improves to the (sub)percent level in the Higgs couplings, the analysis outlined above has to be generalized beyond the lowest order. This can be done in a systematic way by considering the two groups of operators that have been neglected in a first approximation.

#### 4. Conclusions

The upcoming run of the LHC has the potential to detect anomalous Higgs-boson couplings, where new-physics effects may still be of order 10%, considerably larger than in the well-tested electroweak gauge sector. In this note we have put forward a formalism able to describe these potential new-physics effects in a model-independent way.

- We have argued that the electroweak chiral Lagrangian, including a light Higgs boson, is a suitable framework to test such a scenario, which is particularly relevant phenomenologically during the coming years.
- The chiral Lagrangian, being an effective field theory, comes naturally with a power counting that allows for well-defined approximations and for systematic improvements including higher-order corrections.
- The leading-order chiral Lagrangian, which precisely captures the potentially sizable new-physics effects in the Higgs sector, can be used as a first, well-defined approximation. It has the practical benefit of reducing the number of relevant parameters to a manageable set. With slight modifications, it actually amounts to an effective-field theory justification of the usual  $\kappa$ -formalism.
- The chiral Lagrangian is based on a loop expansion or, equivalently, a power counting in terms of chiral dimensions (0 for bosons, 1 for derivatives, weak couplings and fermion bilinears). This is in contrast to the more common counting in terms of canonical dimension, which implies a different ordering of operators in the effective theory that does not naturally single out the new-physics effects in the Higgs sector as the dominant ones.

While the chiral Lagrangian description has been used before in phenomenological applications, we have emphasized here the role of chiral counting in establishing a parametrization of anomalous Higgs couplings.

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