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Higgs couplings parameterisations

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Summary. — The discovery of a Higgs boson at the Large Hadron Collider (LHC) has provided a proof of the structure for the spontaneous breaking of the electroweak interactions, described as a gauge theory, in its simplest and most concise form. However this simple description in terms of a single complex scalar doublet giving rise to the masses of the weak gauge bosons and to a physical scalar Brout-Englert-Higgs boson demands closer scrutiny, both for the detailed properties of the boson couplings with respect to the values expected from the Standard Model (SM) and with respect to the existence of other scalar states. Indeed extensions of the SM built to answer more detailed questions about the weak interactions and beyond, typically require either an extended scalar sector or a composite nature for the Higgs boson, or both. These detailed analyses can be performed at different levels, going from simple coupling-based descriptions inspired from the experimental measurements of the Higgs boson properties, to effective Lagrangian descriptions, to studies performed in specific models. In any case no description is completely general as a set of assumptions are required as starting points for its validity. Instead of selecting specific models I will mainly discuss in the following a coupling-based description, both for a single physical neutral scalar field and for two neutral scalar fields, as this is relevant in various extensions of the SM.

PACS 12.15.-y – Electroweak interactions.
PACS 14.80.Bn – Standard-model Higgs bosons.
PACS 14.80.Da – Supersymmetric Higgs bosons.
PACS 14.80.Ec – Other neutral Higgs bosons.

1. – Introduction

The discovery of a Brout-Englert-Higgs boson [1,2] by the ATLAS [3] and the CMS [4] Collaborations at the LHC has successfully confirmed the particle content of the SM, however the detailed analysis of the precise properties of the Higgs boson just started and will be an intense field of study for many years, at the experimental level and on the theory side, both for the need of precise calculations in the SM and its extensions and for model building in the quest of a more fundamental theory. The fact that searches for extra particles have so far only provided bounds but no discovery allows to parameterise at least in a first approximation the physics of the Higgs sector in terms of effective couplings assuming that the possible extra particles coming from extensions of the SM do not bring explicit kinematical effects and can be therefore included in modifications of the couplings. The only exception I shall consider in the following is the possibility of a second neutral scalar in the physical spectrum and in particular the possibility that this second Higgs boson is lighter than the already discovered one at 126 GeV. This possibility is interesting as bounds on this case are relevant in different extensions of the SM and the simple formalism used for describing one Higgs boson can be easily extended.

Finally the choice of a particular parameterisation depends on a balance of the quantity and quality of the available experimental data, purpose for the parameterisation and degree of model independence. At present only simple parameterisations with a limited number of fit parameters can be performed, but this situation will improve with the forthcoming years with new data runs at the LHC. I shall discuss few of these possibilities without aiming at a complete description. The choice I will make for this parameterisation is particularly well motivated for testing models Beyond the Standard Model (BSM).

From the experimental point of view one can just parameterise Higgs physics in terms of observed quantities such as branching ratios and cross sections as for example proposed in ref. [5], where cross sections and partial decay widths are multiplied by a pre-factor. The advantage of such an approach is its simple link to the experimentally observed quantities. However with such a choice the correlations among the different parameters are not explicit, in particular between tree level and loop induced observables (remember that one of the important discovery and study channels for the Higgs boson is the decay into two photons, and productions mechanisms relies among others on gluon-gluon; and both these processes are loop-induced). For example, a modification of couplings to the W bosons and the top quark, while modifying tree-level branching ratios and cross sections for the Higgs boson, also affect the loop-level couplings for the Higgs in the gluon-gluon channel or the Higgs into two photons.

2. – One Higgs coupling parameterisation

The parameterisation of the Higgs couplings for one Higgs boson can be found for example in [6-8]. For the tree-level couplings, the same scaling factor appears in front of cross sections and partial decay widths:

$$\sigma_{Wh} = \kappa_W^2 \sigma_{Wh}^{SM}, \qquad \sigma_{Zh} = \kappa_Z^2 \sigma_{Zh}^{SM}, \qquad \sigma_{t\bar{t}h} = \kappa_t^2 \sigma_{t\bar{t}h}^{SM}; \tag{1}$$

$$\Gamma_{WW} = \kappa_W^2 \Gamma_{WW}^{SM}, \quad \Gamma_{ZZ} = \kappa_Z^2 \Gamma_{ZZ}^{SM}, \quad \Gamma_{b\bar{b}} = \kappa_b^2 \Gamma_{b\bar{b}}^{SM}, \quad \Gamma_{\tau^+\tau^-} = \kappa_\tau^2 \Gamma_{\tau^+\tau^-}^{SM}, \dots \tag{2}$$

However for the Vector Boson Fusion (VBF) cross sections, it is imperative to distinguish the two production channels with W or Z fusion:

$$\sigma_{VBF} = \kappa_W^2 \sigma_{WF}^{SM} + \kappa_Z^2 \sigma_{ZF}^{SM}. \tag{3}$$

For loop-induced couplings, we introduce the parameters κ_{gg} and $\kappa_{\gamma\gamma}$, which enter at the level of the amplitude of the loop corrections and not as a multiplicative parameter in front of the branching [6]:

$$\Gamma_{\gamma\gamma} = \frac{G_F \alpha^2 m_H^3}{128\sqrt{2}\pi^3} \left| \kappa_W A_W(\tau_W) + C_t^\gamma 3 \left(\frac{2}{3}\right)^2 A_t(\tau_t)[\kappa_t + \kappa_{\gamma\gamma}] + \ldots \right|^2 , \quad (4)$$

$$\Gamma_{gg} = \frac{G_F \alpha_s^2 m_H^3}{16\sqrt{2}\pi^3} \left| C_t^g \frac{1}{2} A_t(\tau_t)[\kappa_t + \kappa_{gg}] + \ldots \right|^2 , \quad (5)$$

where the dots indicate the small contributions of the light quarks. The coefficients C_t^γ and C_t^g contain the NLO QCD corrections to the SM amplitudes. κ_t and κ_W are respectively the corrections of the tree-level couplings of the Higgs to the top quarks and to WW. A_W and A_t are the well known W and top amplitudes:

$$A_t(\tau) = \frac{2}{\tau^2} \left(\tau + (\tau - 1) f(\tau)\right) , \quad (6)$$

$$A_W(\tau) = -\frac{1}{\tau^2} \left(2\tau^2 + 3\tau + 3(2\tau - 1) f(\tau)\right) , \quad (7)$$

where τ is the ratio $m_H^2/4m^2$ and $f(\tau)$ is the function obtained by the loop calculation and equal to

$$\begin{array}{ll} \arcsin^2 \sqrt{\tau} & \tau \leq 1 \\ -\frac{1}{4}\left[\log \frac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}} - i\pi\right]^2 & \tau > 1 \end{array} . \quad (8)$$

Not the that with the previous choice the contributions of the new physics loops are chased to be normalised to the contribution of the top loop, which is not compulsory but typically a useful choice when discussing effect coming from extensions of the SM.

3. – Constraints for BSM Physics

In the following a simple fit, based on the signal strengths will be used for illustrative purposes, even if a more detailed information (sub-channel information, fiducial cross sections, full likelihood, etc) allows to perform more detailed analyses [9]. For each selection channel, the fitted data is represented by a best fit value of the signal strength $\hat{\mu}_i$ as well as its uncertainty σ_i. See for example [10] for comparing the experimental values to the theoretical expectations:

$$\mu_i = \frac{n_s^i}{(n_s^i)^{SM}} = \frac{\sum_p \sigma_p \, \epsilon_p^i}{\sum_p \sigma_p^{SM} \epsilon_p^i} \times \frac{BR_i}{BR_i^{SM}} , \quad (9)$$

where n_s^i is the predicted number of signal events in channel i in a particular model, and $(n_s^i)^{SM}$ that same value in the SM. For each production mode p the efficiency of selection of a channel i is given by ϵ_p^i, considered to stay the same in extensions of the SM physics. This is in agreement with the present parameterisation, including only corrections that do not change the kinematics properties of the event. BR_i and BR_i^{SM} are branching ratios of the Higgs in the decay channel corresponding to the channel i. As an example

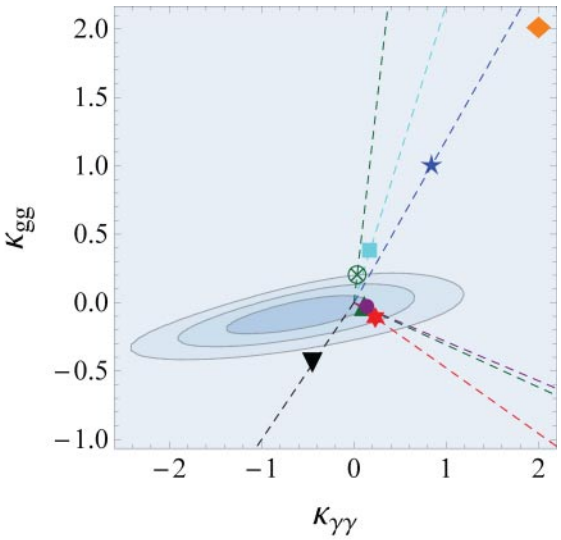

Fig. 1. – $\kappa_{\gamma\gamma}$ and κ_{gg} at the LHC for a Higgs boson with $m_H = 125\,\text{GeV}$. This plot uses CMS and ATLAS data combined. Different points indicate specific BSM models as detailed in the text.

in the following a fit restricted to two parameters shows the typical constraints which can be obtained from different models beyond the SM, by using the CMS and ATLAS data available after the Moriond 2013 conferences. Details about the fit procedure are given in [7]. For reference, in fig. 1, sample points for the following models are indicated: [♦] fourth generation, the result is independent on the masses and Yukawa couplings; [$*$] Littlest Higgs [11], result scales with the scale f, here $f = 500\,\text{GeV}$ for a model with T-parity; [▲] Simplest Little Higgs [12], result scales with the W' mass, set here to $m_{W'} = 500\,\text{GeV}$ for a model with T-parity; [■] colour octet model [13], result is inversely proportional to the mass $m_S = 750\,\text{GeV}$ (and also depends on the couplings set here to $\lambda_1 = 4$, $\lambda_2 = 1$); [$\otimes$] 5D UED model [14], result scales with the size of the extra dimension (here $m_{KK} = 500\,\text{GeV}$); [★] a 6D UED model [15], with $m_{KK} = 600\,\text{GeV}$; [•] Minimal Composite Higgs [16] (Gauge Higgs unification model) with $1/R' = 1\,\text{TeV}$; [▼] a flat (W' at $2\,\text{TeV}$) and [♠] warped ($1/R'$ at $1\,\text{TeV}$) brane Higgs models. In general the conclusion is that the presence of precision Higgs data is and will be very valuable for constraining the possible extensions of the SM.

4. – An extra lighter neutral scalar boson

A scalar particle lighter than the 126 GeV Higgs boson is actively searched by ATLAS and CMS, as this possibility may hint to an extended Higgs sector, typical of many extensions of the standard model, or constrain it if this mass window is fully excluded. The interactions of both scalars can be altered in a similar way to what discussed for a single Higgs boson, by defining two sets of parameters:

$$
\begin{aligned}
&g_{h_i bb} = \kappa_{b,i}\, g^{SM}_{hbb}, && g_{h_i tt} = \kappa_{t,i}\, g^{SM}_{htt},\\
&g_{h_i \tau^+\tau^-} = \kappa_{l,i}\, g^{SM}_{h\tau^+\tau^-}, && g_{h_i ZZ,WW} = \kappa_{V,i}\, g^{SM}_{hZZ,WW},
\end{aligned}
\tag{10}
$$

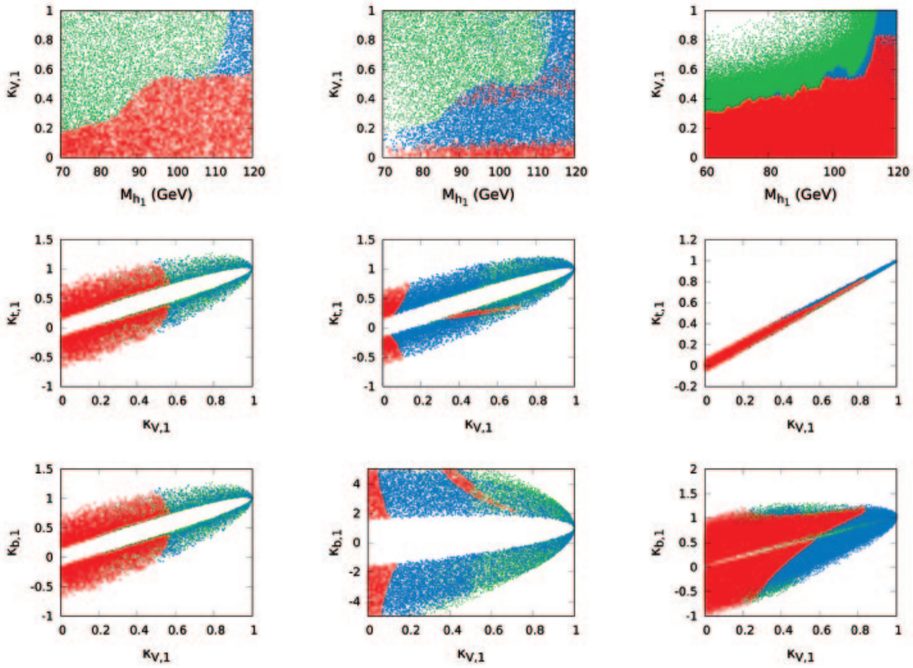

Fig. 2. – Correlations between $\kappa_{V,1}, \kappa_{t,1}, \kappa_{b,1}$ and m_{h_1}. The left column is 2HDM(I), the middle one 2HDM(II) and right one NMSSM. The colours are: green (light grey) all points passing flavour and theoretical constraints, blue (grey) those which also pass LEP constraints on h_1 and red (dark grey) pass in addition the LHC couplings constraint on h_2.

where $i = 1, 2$ are the two Higgs bosons $h_{1,2}$ (with h_2 the 126 GeV Higgs boson). Custodial symmetry implies that the couplings to the W and Z bosons are multiplied by the same modifiers $\kappa_{V,i}$. Assuming universality, the couplings of the light generations are scaled as the top, bottom and tau. For couplings arising only at loop level, we follow again a procedure similar to the one used for a single Higgs boson. For example the coupling to photons is modified by $\kappa_{\gamma\gamma,i}$ parameters, defined as

$$\begin{aligned}\Gamma_{h_i\to\gamma\gamma} &\propto |\mathcal{A}_{W^\pm} + \mathcal{A}_t + \mathcal{A}_b + \mathcal{A}_{NP}|^2 \\ &\propto |\kappa_{V,i}\mathcal{A}^{SM}_{W^\pm} + \kappa_{b,i}\mathcal{A}^{SM}_b + (\kappa_{t,i} + \kappa_{\gamma\gamma,i})\mathcal{A}^{SM}_t|^2,\end{aligned} \quad (11)$$

$\mathcal{A}^{SM}_X$ is the loop amplitude for particle X calculated with SM couplings for a Higgs with mass of h_i. More details can be found in [17]. As an example I show here some constraints on few types of BSM models allowing a lighter Higgs boson, namely two doublet Higgs models (2HDM) and the Next-to-Minimal Supersymmetric Standard model (NMSSM) The correlations between $\kappa_{V,1}$ and $\kappa_{t,1}$ differ significantly between the two classes of models: in the NMSSM they have the same behaviour while in the 2HDM, $\kappa_{t,1}$ can reach high values (see fig. 2). A more detailed analysis of the possible constraints is given in [17].

5. – Conclusion

I have discussed a simple parameterisation both for studying the properties of a single Higgs boson and two neutral Higgs bosons, particularly suited for general analyses of BSM physics. The parameterisation allows a simple recasting of experimental results by the ATLAS and CMS Collaborations for the study of classes of models with the use of a limited set of parameters.

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REFERENCES

[1] Englert F. and Brout R., *Phys. Rev. Lett.*, **13** (1964) 321.
[2] Higgs P. W., *Phys. Rev. Lett.*, **13** (1964) 508.
[3] Aad G. *et al.* (ATLAS Collaboration), *Phys. Lett. B*, **716** (2012) 1; *Science*, **338** (2012) 1576.
[4] Chatrchyan S. *et al.* (CMS Collaboration), *Phys. Lett. B*, **716** (2012) 30; *Science*, **338** (2012) 1569.
[5] David A., Denner A., Duehrssen M., Grazzini M., Grojean C., Passarino G., Schumacher M. *et al.* (LHC Higgs Cross Section Working Group), arXiv:1209.0040 [hep-ph].
[6] Cacciapaglia G., Deandrea A. and Llodra-Perez J., *JHEP*, **06** (2009) 054 [arXiv:0901.0927 [hep-ph]].
[7] Cacciapaglia G., Deandrea A., La Rochelle G. D. and Flament J.-B., *JHEP*, **03** (2013) 029 [arXiv:1210.8120 [hep-ph]].
[8] Belanger G., Dumont B., Ellwanger U., Gunion J. F. and Kraml S., *JHEP*, **02** (2013) 053 [arXiv:1212.5244 [hep-ph]].
[9] Boudjema F., Cacciapaglia G., Cranmer K., Dissertori G., Deandrea A., Drieu la Rochelle G., Dumont B., Ellwanger U. *et al.*, arXiv:1307.5865 [hep-ph].
[10] Azatov A., Contino R. and Galloway J., *JHEP*, **04** (2012) 127; **04** (2013) 140(E) [arXiv:1202.3415 [hep-ph]].
[11] Arkani-Hamed N., Cohen A. G., Katz E. and Nelson A. E., *JHEP*, **07** (2002) 034 [arXiv:hep-ph/0206021].
[12] Schmaltz M., *JHEP*, **08** (2004) 056 [arXiv:hep-ph/0407143].
[13] Manohar A. V. and Wise M. B., *Phys. Rev. D*, **74** (2006) 035009 [arXiv:hep-ph/0606172].
[14] Appelquist T., Cheng H. C. and Dobrescu B. A., *Phys. Rev. D*, **64** (2001) 035002 [arXiv:hep-ph/0012100].
[15] Cacciapaglia G., Deandrea A. and Llodra-Perez J., *JHEP*, **03** (2010) 083 [arXiv:0907.4993 [hep-ph]]; Arbey A., Cacciapaglia G., Deandrea A. and Kubik B., *JHEP*, **01** (2013) 147 [arXiv:1210.0384 [hep-ph]].
[16] Agashe K., Contino R. and Pomarol A., *Nucl. Phys. B*, **719** (2005) 165 [arXiv:hep-ph/0412089]; Agashe K. and Contino R., *Nucl. Phys. B*, **742** (2006) 59 [arXiv:hep-ph/0510164].
[17] Cacciapaglia G., Deandrea A., La Rochelle G. D. and Flament J.-B., arXiv:1311.5132 [hep-ph].