Characterising a Higgs-like resonance at the LHC

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We present the implementation of an effective lagrangian via FeynRules, featuring bosons $X(J^P)$ with various assignments of spin/parity $J^P = 0^+, 0^-, 1^+, 1^-$, or $2^+$, that allows one to perform characterisation studies of the boson recently discovered at the LHC, for all the relevant channels and in a consistent, systematic and accurate way.

I. INTRODUCTION

The recent observation of a new boson with a mass of about 125 GeV at the LHC [1] brought us a lot of excitement. While this discovery is a great triumph for theoretical and experimental high energy physics, the detailed study of the new state will require many years of work at the LHC as well as at the ILC. The study includes the determination of its spin and parity quantum numbers and the coupling strength for the interactions, which can tell us if the observed resonance is indeed responsible for the Brout-Englert-Higgs mechanism [2], or involves physics beyond the Standard Model (SM).

We introduce a complete framework, based on an effective field theory approach, that allows one to perform characterisation studies of the recently-discovered boson. Our assumptions are simply that the resonance structure observed in data corresponds to one bosonic state ($X(J^P)$ with $J = 0^+, 0^-, 1^+, 1^-$, or $2^+$, and a mass of about 125 GeV), and that no other new state below the cutoff $\Lambda$ coupled to such a resonance exists. We also follow the principle that any new physics is dominantly described by the lowest dimensional operators. This means, for example, that for the spin-0 CP-even case (which corresponds to the SM scalar) we include all effects coming from the complete set of dimension-six operators relevant to Higgs observables. Given that our goal is that of providing a simulation framework in terms of mass eigenstates, and consistently with the general guidelines outlined above, we construct an effective lagrangian below the EWSB scale, where $SU(2)_L \times U(1)_Y$ reduces to $U(1)_{EM}$; moreover, we do not require CP conservation, and we leave open the possibility that the new boson might be a scalar with no definite CP properties.

Technically, the implementation of the lagrangian is performed in FeynRules [3] extending and completing the earlier version used in ref. [4]. The particle content and the Feynman rules of the model can be exported to any matrix element generator in the UFO format [5]. We dub it Higgs Characterisation model [6] and it can be found on the FeynRules on-line database at http://feynrules.irmp.ucl.ac.be.

There are several advantages in having a first principle implementation in terms of an effective lagrangian which can be automatically interfaced to a matrix element generator (and then to an event generator). First and most important, all relevant production and decay modes can be studied within the same model, from gluon fusion to VBF as well as $VH$ and $ttH$ associated productions can be considered and the corresponding processes automatically generated within minutes. Second, it is straightforward to modify the model implementation to extend it further in case of need, by adding further interactions, for example of higher-dimensions. Finally, higher-order QCD effects can be easily accounted for by multi-parton tree-level or full NLO computations and their matching with parton showers in automatic frameworks, e.g. with MadGraph5 [7] or aMC@NLO [8].

In this report we first write down the effective lagrangian explicitly, and then show mass and angular distributions in the $pp \rightarrow X(\rightarrow ZZ^*/WW^*) \rightarrow 4\ell$ process, comparing with the results by the JHU program [9] which takes the anomalous coupling framework and is employed by both ATLAS and CMS collaborations. See ref. [6] for all the detailed demonstration and analyses.

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II. THE EFFECTIVE LAGRANGIAN

A. Spin 0

The construction of the effective lagrangian for the spin-0 state is obtained by requiring that the parametrisation: i) allows one to recover the SM case easily; ii) includes all possible interactions that are generated by gauge-invariant dimension-six operators above the EW scale; iii) includes 0− state couplings typical of SUSY or of generic two-Higgs-doublet models (2HDM); and iv) allows CP-mixing between 0+ and 0− states (which we parametrise in terms of an angle α).

Let us start with the interaction lagrangian relevant to fermions which, while being extremely simple, illustrates our philosophy well. Such a lagrangian is:

\[ \mathcal{L}_0^F = \sum_{f=t,b,\tau} \bar{\psi}_f \left( c_\alpha \kappa_{Hff} g_{Hff} + i s_\alpha \kappa_{Aff} g_{Aff} \gamma_5 \right) \psi_f X_0, \]  

where we use the notation \( c_\alpha \equiv \cos \alpha \) and \( s_\alpha \equiv \sin \alpha \), and denote by \( g_{Hff} = m_f/v \) \( (g_{Aff} = m_f/v) \) the strength of the scalar (pseudoscalar) coupling in the SM (in a 2HDM with \( \tan \beta = 1 \)). We point out that the constants \( \kappa_i \) can be taken real without any loss of generality. For simplicity, we have assumed that only the third-generation of fermions couple to the scalar state; extensions to the other families and flavour-changing structures are trivial to implement, which can be directly done by users of FeynRules. The interaction of eq. (1) can also parametrise the effects of a \( \mathcal{L}_{\text{dim}=6}^{\text{trivial}} = (\phi^\dagger \phi) Q_L \partial_R \) operator, which modifies the value of the Yukawa coupling, but not the interaction structure. Note also that all requirements listed above are satisfied at the price of a small redundancy in the number of parameters. The SM is obtained when \( c_\alpha = 1 \) and \( \kappa_{Hff} = 1 \). The pseudoscalar state of a type-II CP-conserving 2HDM or SUSY is obtained by setting \( s_\alpha = 1 \) and \( \kappa_{Aff} = \cot \beta \) or \( \kappa_{Aff} = \tan \beta \) for up or down components of the SU(2) fermion doublet, respectively. The parametrisation of CP mixing is entirely realised in terms of the angle \( \alpha \), i.e. independently of the parameters \( \kappa_i \), so that many interesting cases, such as again CP-violation in generic 2HDM, can be covered.

The effective lagrangian for the interaction of scalar and pseudoscalar states with vector bosons can be written as follows:

\[ \mathcal{L}_0^V = \left\{ c_\alpha \kappa_{\text{SM}} \left[ \frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^\mu - \frac{1}{4} \left[ c_\alpha \kappa_{HZZ} Z_\mu Z^\mu + s_\alpha \kappa_{Azz} Z_\mu \tilde{A}^\mu \right] - \frac{1}{4} \left[ c_\alpha \kappa_{Hgg} g_{Hgg} G^{\alpha \mu} G^{\alpha \nu} + s_\alpha \kappa_{Hgg} g_{Agg} G^{\alpha \mu} \tilde{G}^{\alpha \nu} \right] - \frac{1}{4} \left[ c_\alpha \kappa_{Hgg} g_{Hgg} G^{x a} G^{x a} + s_\alpha \kappa_{Azz} Z_\mu \tilde{Z}^\mu \right] - \frac{1}{2} \left[ c_\alpha \kappa_{HWW} W_\mu^+ W^\mu - \kappa_{Aww} W_\mu^+ \tilde{W}^\mu \right] \right\} X_0, \]  

where the (reduced) field strength tensors are defined as follows:

\[ V_\mu^\nu = \partial_\mu V_\nu - \partial_\nu V_\mu \quad (V = A, Z, W^\pm), \quad G^{\alpha \mu} = \partial_\mu G^{\alpha v} - \partial_\nu G^{\alpha v} + g_s f^{abc} G^{\mu}_v G^{\nu}_v, \]  

and the dual tensor is \( \tilde{V}_\mu^\nu = \frac{1}{2} \kappa_{\mu
u\rho\sigma} V^{\rho\sigma} \). The parametrisation of the couplings to vectors follows the same principles as that of the couplings to fermions. In particular, the mixing angle \( \alpha \) allows for a completely general description of CP-mixed states. We stress here that while in general in a given model CP violation depends on the whole set of possible interactions among the physical states and cannot be established by looking only at a sub sector \( \bar{\mathcal{L}}_0 \), in our parametrisation \( \alpha \neq 0 \) or \( \alpha \neq \pi/2 \) (and non-vanishing \( \kappa_{Hff}, \kappa_{Aff}, \kappa_{HVV}, \kappa_{AVV} \)) implies CP violation. This can be easily understood by first noting that in eq. (1) \( \alpha \neq 0 \) or \( \alpha \neq \pi/2 \) always leads to CP violation and that the corresponding terms in eq. (2) are generated via a fermion loop by the \( X_0 \) interaction. The CP-odd analogues of the operators in the last line of eq. (2) do vanish.

In our implementation, the parameters listed in table 1 can be directly set by the user. The dimensionful couplings \( g_{HY} \) are set as to reproduce a SM Higgs and a pseudoscalar one in a 2HDM with \( \tan \beta = 1 \), e.g. \( g_{HZZ} = 2 m_Z^2/v \) as well as \( g_{Hgg} = -\alpha_s/3\pi v \) and \( g_{Agg} = -\alpha_s/3\pi v \) in the heavy top loop limit.


TABLE I: Model parameters.

| parameter | reference value | description |
|-----------|-----------------|-------------|
| $\Lambda$ [GeV] | $10^3$ | cutoff scale |
| $c_0 (\equiv \cos \alpha)$ | 1 | mixing between 0$^+$ and 0$^-$ |
| $\kappa_1$ | 0, 1 | dimensionless coupling parameter |

B. Spin 1

The interaction Lagrangian for the spin-1 boson with fermions is written as

$$\mathcal{L}_f^I = \sum_{f=q,\ell} \bar{\psi}_f \gamma_\mu (\kappa_{f\nu} a_f - \kappa_{f\nu} b_f \gamma_5) \psi_f X^\mu_I .$$

The $a_f$ and $b_f$ are the SM vector and axial-vector couplings. The most general $X_1WW$ interaction at the lowest dimension can be written as [11]

$$\mathcal{L}_f^W = i\kappa_{w_1} g_{WW} (W_{\mu\nu} W^{-\mu} - W^{-\mu} W^{\mu}) X^{\nu}_1 + i\kappa_{w_2} g_{WW} W_{\mu} W_{\nu} X^{\mu\nu}_1 - \kappa_{w_3} W_{\mu} W_{\nu} (\partial^{\mu} X^{\nu}_1 + \partial^{\nu} X^{\mu}_1)$$

$$+ i\kappa_{w_4} W_{\mu} W_{\nu} \tilde{X}^{\mu\nu}_1 - \kappa_{w_5} \epsilon_{\mu\nu\rho\sigma} [W^{\mu\nu} (\partial^{\rho} W^{\sigma}) - (\partial^{\rho} W^{\mu\nu}) W^{\sigma}] X^\sigma_1 ,$$

where $g_{WW} = -e \cot \theta_W$. Note that our effective field theory description lives at energy scales where EW symmetry $SU(2)_L \times U(1)_Y$ is broken to $U(1)_{EM}$. This approach does not require to specify the transformation properties of $X_1$ with respect to the EW symmetry. In the case of $ZZ$, Bose symmetry implies a reduction of the possible terms and the interaction Lagrangian reduces to [11][12]

$$\mathcal{L}_f^Z = -\kappa_{z_1} Z^{\mu} Z_{\mu} X^{\nu}_1 - \kappa_{z_2} X^{\nu}_1 (\partial^{\nu} Z_{\mu}) Z^{\mu} - \kappa_{z_3} \epsilon_{\mu\nu\rho\sigma} X^{\mu\nu}_{1} Z^{\rho} (\partial^{\sigma} Z^{\nu}).$$

Parity conservation implies that $\kappa_{f_\nu} = \kappa_{V_4} = \kappa_{V_3} = 0$ for $X_1 = 1^-$ while $\kappa_{f_1} = \kappa_{V_1} = \kappa_{V_2} = \kappa_{V_3} = 0$ for $X_1 = 1^+$. 

C. Spin 2

The interaction lagrangian for the spin-2 boson proceeds via the energy-momentum (E-M) tensor of the SM fields and starts at dimension five [13][14];

$$\mathcal{L}_2^f = -\frac{1}{\Lambda} \sum_{f=q,\ell} \kappa_f T^f_{\mu\nu} X^{\mu\nu}_2 \quad \text{and} \quad \mathcal{L}_2^V = -\frac{1}{\Lambda} \sum_{V=W,ZZ} \kappa_V T^V_{\mu\nu} X^{\mu\nu}_2 ,$$

where $T^f,V_{\mu\nu}$ are the E-M tensors; see refs. [14][15] for the explicit forms. The coupling parameters $\kappa_f$ and $\kappa_V$ are introduced [4][16] in full analogy with what has been done in the spin-0 and -1 cases. For $X_2 = 2^+$ in the minimal RS-like graviton scenario, i.e. the universal coupling strength to the matter and gauge fields, the parameters should be chosen as $\kappa_f = \kappa_V \neq 0$.

III. DISTRIBUTIONS IN THE $X \to 4\ell$ ANALYSIS: COMPARISON WITH THE JHU PROGRAM

To validate our FeynRules implementation, we show distributions in $pp \to X \to 4\ell$, comparing with the JHU results in [9]. In table [11] we give the choices of parameters to be made in order to obtain their benchmarks. For all scenarios listed in that table one can see complete agreement in the mass and angular distributions of the $X(J^P)$ decay products in figs. [1][2] and [3] where the LO parton-level events were generated by MadGraph5.

We note that our $CP$-even spin-0 parametrisation also includes the so-called “derivative operators”, that are absent in the parametrisation of ref. [9], and that give non-trivial contributions to $X_0 \to VV$ decays [6]. For spin 1 the $X_1VV$ interactions defined in ref. [9] have one-to-one correspondence with the $\kappa_{V_5}$ and $\kappa_{V_3}$ terms for both the $X_1WW$ and $X_1ZZ$ cases. We also note that a spin-2 state with non-universal couplings to SM particles might have a very different behaviour with respect to that of an RS-graviton, especially at high energies. See more details and non-trivial phenomenological implications due to the NLO QCD effects in ref. [6].
TABLE II: Parameter correspondence to the benchmark scenarios defined in Table I of ref. [9]. In each scenario, the \( \kappa \) couplings that are not explicitly mentioned are understood to be equal to zero.

| JHU scenario | HC parameter choice |
|--------------|---------------------|
| \( 0_{m}^{+} \) | \( \kappa_{Hg} \neq 0 \), \( \kappa_{SM} \neq 0 \) (\( c_{a} = 1 \)) |
| \( 0_{m}^{-} \) | \( \kappa_{Hg} \neq 0 \), \( \kappa_{H_{\gamma \gamma}, H_{ZZ}, H_{WW}} \neq 0 \) (\( c_{a} = 1 \)) |
| \( 0^{-} \) | \( \kappa_{A_{g g}} \neq 0 \), \( \kappa_{A_{\gamma \gamma}, A_{ZZ}, A_{WW}} \neq 0 \) (\( c_{a} = 0 \)) |
| \( 1^{+} \) | \( \kappa_{f_{a}, f_{b}} \neq 0 \), \( \kappa_{Z_{a}, Z_{b}} \neq 0 \) |
| \( 1^{-} \) | \( \kappa_{f_{a}, f_{b}} \neq 0 \), \( \kappa_{Z_{a}, Z_{b}} \neq 0 \) |
| \( 2^{+} \) | \( \kappa_{Z} \neq 0 \), \( \kappa_{\gamma_{Z}, \gamma_{W}} \neq 0 \) |

[1] ATLAS: G. Aad et al., Phys.Lett. B716 (2012) 1; CMS: S. Chatrchyan et al., Phys.Lett. B716 (2012) 30.
[2] F. Englert and R. Brout, Phys.Rev.Lett. 13 (1964) 321; P. W. Higgs, Phys.Rev.Lett. 13 (1964) 508.
[3] N. D. Christensen and C. Duhr, Comput.Phys.Commun. 180 (2009) 1614.
[4] C. Englert, D. Goncalves-Netto, K. Mawatari, and T. Plehn, JHEP 1301 (2013) 148.
[5] C. Degrande, C. Duhr, B. Fuks, D. Grellscheid, O. Mattelaer, et al., Comput.Phys.Commun. 183 (2012) 1201.
[6] P. Artoisenet, P. de Aquino, F. Demartin, R. Frederix, S. Frixione, F. Maltoni, M. K. Mandal, P. Mathews, K. Mawatari, V. Ravindran, S. Seth, P. Torrielli, and M. Zaro, arXiv:1306.6464 [hep-ph].
[7] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, and T. Stelzer, JHEP 1106 (2011) 128.
[8] R. Frederix, S. Frixione, F. Maltoni, and T. Stelzer, JHEP 10 (2009) 003; V. Hirschi et al., JHEP 05 (2011) 044.
[9] S. Bolognesi, Y. Gao, A. V. Gritsan, K. Melnikov, M. Schulze, et al., Phys.Rev. D86 (2012) 095031.
[10] G. C. Branco, L. Lavour, and J. P. Silva, CP violation. Oxford Univ. Press, 1999.
[11] K. Hagiwara, R. Peccei, D. Zeppenfeld, and K. Hikasa, Nucl.Phys. B282 (1987) 253.
[12] W.-Y. Keung, I. Low, and J. Shu, Phys.Rev.Lett. 101 (2008) 091802.
[13] G. F. Giudice, R. Rattazzi, and J. D. Wells, Nucl.Phys. B544 (1999) 3.
[14] T. Han, J. D. Lykken and R. -J. Zhang, Phys. Rev. D 59 (1999) 105006.
[15] K. Hagiwara, J. Kanzaki, Q. Li, and K. Mawatari, Eur.Phys.J. C56 (2008) 435.
[16] J. Ellis, R. Fok, D. S. Hwang, V. Sanz, and T. You, arXiv:1210.5229 [hep-ph].

FIG. 1: Normalised distributions of the lepton invariant masses in the \( X \rightarrow ZZ \) analysis (cf. fig. 11 in the JHU paper [9]).
FIG. 2: Angular distributions in the $X \to ZZ$ analysis (cf. fig. 12 in the JHU paper [9]).
FIG. 3: Mass and angular distributions in the $X \rightarrow WW$ analysis (cf. fig. 13 in the JHU paper [9]).