IL NUOVO CIMENTO **39 C** (2016) 210
DOI 10.1393/ncc/i2016-16210-5

COLLOQUIA: IFAE 2015

Sensitivity studies based on the EFT parametrization in the double differential cross section for the $H \to ZZ^* \to 4l$ decay channel at LHC

G. MANCINI(1)(2)

(1) *INFN-LNF - Frascati (RM), Italy*
(2) *Università di Roma Tor Vergata - Roma, Italy*

received 7 January 2016

Summary. — After the Higgs boson discovery, great interest was given to the measurements of its properties and studies have been performed to test its nature and probe whether it is the Standard Model (SM) Higgs boson or not. In this scenario, a set of pseudo-observables characterizing the properties of the Higgs decays are defined in generic extensions of the SM with no new particles below the Higgs mass. A phenomenological study is presented in the context of the Effective Field Theory (EFT) approach to the Higgs Physics. The expected sensitivity with the next LHC runs to the EFT parameters has been evaluated using the measurement of the double differential cross section for the $H \to ZZ^* \to 4l$ decay channel.

1. – Introduction

The main idea that lies behind the work is to present a sensitivity study based on the EFT parametrization proposed by G. Isidori, A. Greljo, D. Marzocca and M. González-Alonso [1].

The approach that will be shown is a general EFT approach, and it reflects the importance of investigating the kinematics of the events and the total rate at the same time. To do so, the decay amplitude $H \to 2e2\mu$, defined as a function of 5 pseudo-observables, has been used to extract the parameter values via a binned Likelihood fit.

The pseudo-observables, defined from the on-shell decay amplitude, allow for a systematic inclusion of higher order QED and QCD corrections, including the best up-to-date SM predictions in absence of NP effects and can be computed in any EFT approach to the Higgs physics.

Results will be shown for the statistics available from the LHC RunI and projections will be given for $100\,\mathrm{fb}^{-1}$ at $13\,\mathrm{TeV}$ for the LHC RunII.

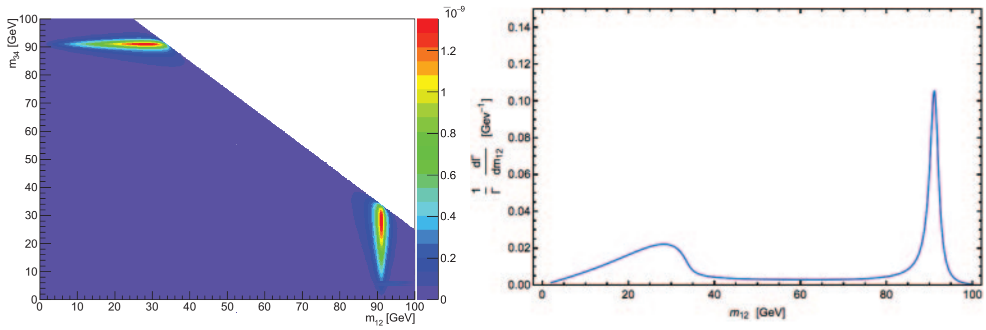

Fig. 1. – Left: Two-dimensional function generated with parameters set to SM values: (k_{ZZ}, ϵ_{ZeL}, $\epsilon_{Z\mu L}$, ϵ_{ZeR}, $\epsilon_{Z\mu R}$) = (1,0,0,0,0). Right: The projection along m_{12} is shown, integrating over m_{34}.

2. – 2D function and extraction of the parameters

In order to extract the contact terms values it is necessary to study the differential decay distributions in q_1^2 and q_2^2.

This work will focus only on the Higgs boson decay to pairs of muons and electrons, which is a particularly clean process with non-trivial kinematics; the double differential rate is a quadratic polynomial function in $k = (k_{ZZ}, \epsilon_{ZeL}, \epsilon_{Z\mu L}, \epsilon_{ZeR}, \epsilon_{Z\mu R})^T$, therefore, the decay amplitude can be written as a function of the parameters as follows:

$$d\Gamma_{H\to 2e2\mu/dm_{12}dm_{34}} = \Sigma_{j\geq i} X_{ij} k_i k_j,$$

where m_{12} and m_{34} are the invariant masses of the $2e$ and 2μ respectively.

Figure 1 shows the $2D$ function generated at SM values and the projection along m_{12} integrating over m_{34}.

It is important to stress here, that the k_{ZZ} differs from the usual signal strenght, as reported by the ATLAS and CMS Collaborations, since the latter is linked to a well known kinematical distribution (the SM-like one).

3. – Parametrization in use

The assumptions that lie behind the parametrization in use, can be summarized as follows:

- the Higgs boson, whose mass is 125 GeV is a spin-0 particle
- there are no new particles with mass below 125 GeV able to distort the decay amplitude of the Higgs in SM particles.
- it is not necessary to assume that the Higgs boson is part of an $SU(2)_L$ doublet, neither make assumptions as Lepton Flavor Universality (LFU) nor CP invariance.

Therefore, from the most generic expression of the decay amplitude of an on shell Higgs boson in a $2e2\mu$ final state can be written as a function of several pseudo-observables which contain possible effects of New Physics (NP), can test LFU, CP invariance, etc...: $k_{ZZ}, \epsilon_{ZeL}, \epsilon_{Z\mu L}, \epsilon_{ZeR}, \epsilon_{Z\mu R}, \epsilon_{ZZ}^{CP}, \epsilon_{Z\gamma}^{CP}, \epsilon_{\gamma\gamma}^{CP}$, as follows:

$$A = i\frac{2m_Z^2}{v_F}\Sigma_{e=e_L,e_R}\Sigma_{\mu=\mu_L,\mu_R}(\overline{e}\gamma_\alpha e)(\overline{\mu}\gamma_\beta\mu) \times \Bigg[F_1^{e\mu}(q_1^2,q_2^2)g^{\alpha\beta} + F_3^{e\mu}(q_1^2,q_2^2)\frac{q_1q_2g^{\alpha\beta} - q_2^\alpha q_1^\beta}{m_Z^2} + F_4^{e\mu}(q_1^2,q_2^2)\frac{\epsilon^{\alpha\beta\rho\sigma}q_{2\rho}q_{1\sigma}}{m_Z^2}\Bigg]$$

with $q_1 = m_{12}$ and $q_2 = m_{34}$, while $F_1^{e\mu}(q_1^2,q_2^2)$, $F_3^{e\mu}(q_1^2,q_2^2)$ and $F_4^{e\mu}(q_1^2,q_2^2)$ have the following expressions:

$$F_1^{ff'}(q_1^2,q_2^2) = k_{ZZ}\frac{g_Z^f g_Z^{f'}}{P_Z(q_1^2)P_Z(q_2^2)} + \frac{\epsilon_{Zf}}{m_Z^2}\frac{g_Z^{f'}}{P_Z(q_2^2)} + \frac{\epsilon_{Zf'}}{m_Z^2}\frac{g_Z^{f'}}{P_Z(q_1^2)},$$

$$F_3^{ff'}(q_1^2,q_2^2) = \epsilon_{ZZ}\frac{g_Z^f g_Z^{f'}}{P_Z(q_1^2)P_Z(q_2^2)} + \epsilon_{Z\gamma}\left(\frac{eQ_{f'}g_Z^f}{q_2^2P_Z(q_1^2)} + \frac{eQ_f g_Z^{f'}}{q_1^2P_Z(q_2^2)}\right) + \epsilon_{\gamma\gamma}\frac{e^2Q_fQ_{f'}}{q_1^2q_2^2},$$

$$F_4^{ff'}(q_1^2,q_2^2) = \epsilon_{ZZ}^{CP}\frac{g_Z^f g_Z^{f'}}{P_Z(q_1^2)P_Z(q_2^2)} + \epsilon_{Z\gamma}^{CP}\left(\frac{eQ_{f'}g_Z^f}{q_2^2P_Z(q_1^2)} + \frac{eQ_f g_Z^{f'}}{q_1^2P_Z(q_2^2)}\right) + \epsilon_{\gamma\gamma}^{CP}\frac{e^2Q_fQ_{f'}}{q_1^2q_2^2},$$

where g_Z^f are the effective couplings and $P_Z(q^2) = q^2 - m_Z^2 + im_Z\Gamma_Z$. Imposing the CP invariance, and recalling the Higgs boson to be a CP even state, the term $F_4^{e\mu}(q_1^2,q_2^2)$ cancels out and the most interesting effects can be seen in the $F_1^{e\mu}(q_1^2,q_2^2)$ term; at the end there will be 5 parameters left to fit: k_{ZZ}, ϵ_{ZeL}, $\epsilon_{Z\mu L}$, ϵ_{ZeR}, $\epsilon_{Z\mu R}$.

4. – Analysis description

The extraction of the events has been done from the double differential rate and an Asimov dataset has been used for our purpose, normalized to the statistics recorded by both ATLAS and CMS in the LHC RunI. The total amount of events recorded by the two experiments is ~ 15 events in the $2e2\mu$ channel in the mass window [120–130] GeV [2,3].

A binned Likelihood then has been built and a scan over the parameter of interest as been performed; studies were carried out following several configurations and will be given for the statistics available in the LHC RunI (ATLAS + CMS); in addition, projections for $100\,\text{fb}^{-1}$ at 13 TeV for the RunII of LHC will be given accordingly.

5. – Results

Different combinations of the parameters have been chosen to be studied since they were showing interesting features in investigating possible deviations from the SM values of the pseudo-observables. In order to do so, among the 5, some of them have been fixed to their SM values, fitting the others.

The most interesting cases found are the following:

A: scan over (k_{ZZ}, ϵ_{ZeR}), fixing $\epsilon_{Z\mu L}, \epsilon_{ZeL}$ and $\epsilon_{Z\mu R}$ to their SM expectations. This test is interesting in order to give an estimate of the sensitivity on the contact terms which have never been considered before.

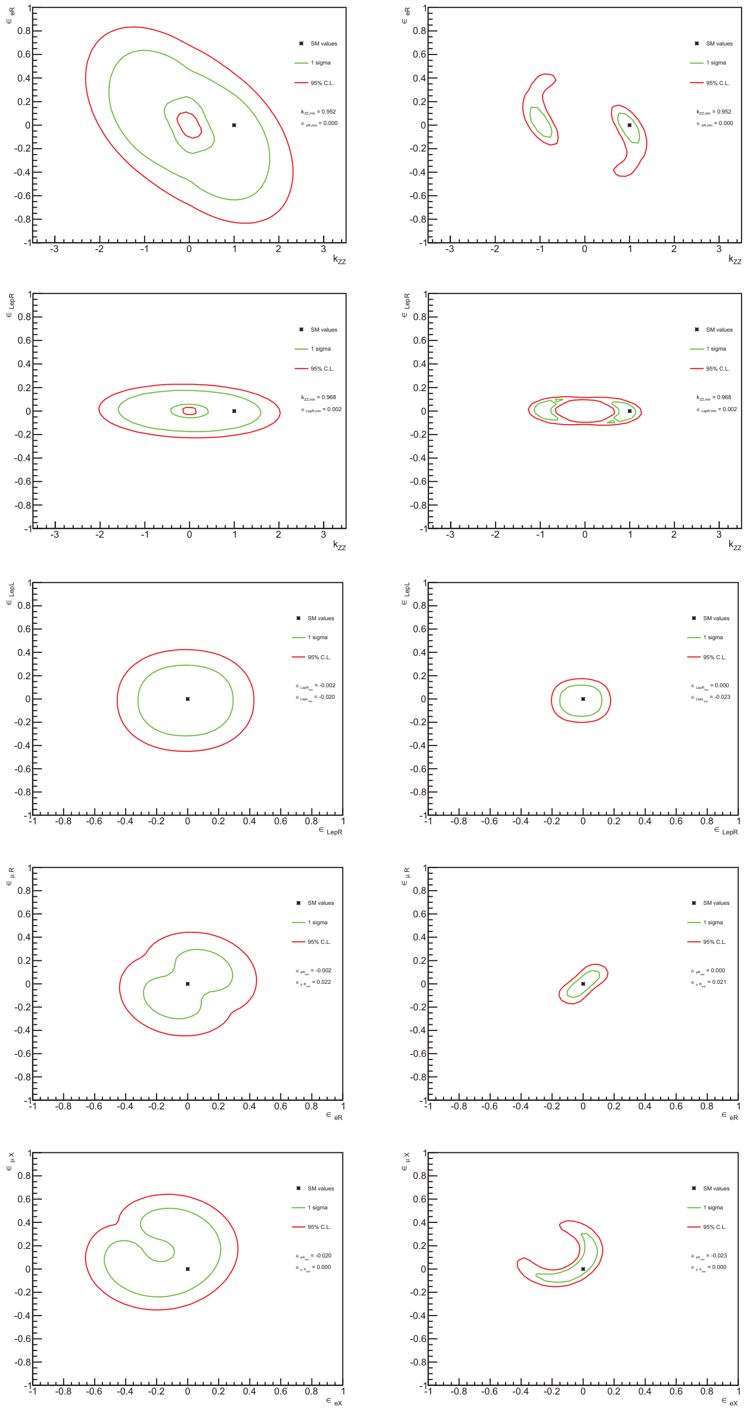

Fig. 2. – Each row corresponds to the tests mentioned in the text: from the top to the bottom, respectively, cases A, B, C, D and E are shown. The left column reflects what expected for the statistics available in the LHC RunI, the right column is what is expected for $100\,\mathrm{fb}^{-1}$ at 13 TeV. The green contour and the red contour reflects respectively the 1σ and the 95% confidence level (CL). The value of the pseudo-observables obtained from the fit are also shown in each plot.

B: scan over $(k_{ZZ}, \epsilon_{ZLepR})$, being $\epsilon_{ZLepL} = 2. * \epsilon_{ZLepR}$ and $\epsilon_{Z\mu X} = \epsilon_{ZeX}$. In this case the LFU is imposed and the assumption of the Higgs being part of an $SU(2)_L$ doublet is made, therefore comes the relation between ϵ_{ZLepL} and ϵ_{ZLepR}.

C: scan over $(\epsilon_{ZLepR}, \epsilon_{ZLepL})$, fixing k_{ZZ} and imposing LFU, *i.e.* $\epsilon_{ZeX} = \epsilon_{Z\mu X}$. This case is mainly made to test LFU.

D: scan over $(\epsilon_{ZeR}, \epsilon_{Z\mu R})$, fixing k_{ZZ} and assuming an axial coupling of a Z' with a couple of leptons, *i.e.* $\epsilon_{ZeR} = -\epsilon_{ZeL}$ and $\epsilon_{Z\mu R} = -\epsilon_{Z\mu L}$.

E: scan over $(\epsilon_{ZeR}, \epsilon_{Z\mu R})$, fixing k_{ZZ} and assuming a vectorial coupling of a Z' with a couple of leptons, *i.e.* $\epsilon_{ZeR} = \epsilon_{ZeL}$ and $\epsilon_{Z\mu R} = \epsilon_{Z\mu L}$.

In the last two cases, the contact terms are assumed to be different for muons and electrons, reflecting the case of a flavor simmetry violation.

From the plots shown in fig. 2 it can be seen that the sensitivity on the contact term that we have with the statistics available from RunI is not sufficient to exclude some EFTs, but $100\,\text{fb}^{-1}$ at $13\,\text{TeV}$ would be enough to start discriminating between EFTs due to the typical values of the contact terms which goes around 0.2.

6. – Conclusions

The (spin-averaged) double differential distribution has been used to perform a sensitivity study to extract the pseudo-observables previously defined by the momentum expansion of the on-shell Higgs boson decay amplitudes.

Therefore, the framework of Higgs pseudo-observables can capture all the physics accessible in Higgs decays if no new light state is coupled to the Higgs boson and can be efficiently used to test possible NP effects.

To investigate possible deviations from the SM it is necessary, as already stressed before, to consider both normalization and shape effects.

From the sensitivity study presented, which has been performed on the contact terms and k_{ZZ} given from the EFT parametrization described; has been shown that with the actual statistics, the bounds on each parameter are still lightly stringent but, even at the end of the LHC RunII ($100\,\text{fb}^{-1}$ at $13\,\text{TeV}$), the constraints on each contact terms becomes to be interesting to exclude possible EFTs.

REFERENCES

[1] González-Alonso Martin, Greljo Admir, Isidori Gino and Marzocca David, *Pseudo-observables in Higgs decays* (arXiv:1412.6038v1).

[2] The ATLAS Collaboration, *Measurements of the properties of the Higgs-like boson in the four lepton decay channel with the ATLAS detector using* 25 *fb*$^{-1}$ *of proton-proton collision data* (ATLAS-CONF-2013-013, 06 March 2013).

[3] The CMS Collaboration, *Measurement of the properties of a Higgs boson in the four-lepton final state* (arXiv:1312.5353v3).