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CP-mixing measurement in $H \to ZZ^* \to 4l$ channel

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Summary. — In this note, the prospects for experimental studies of the general HVV tensor coupling using the $H \to ZZ^* \to 4l$ decay are presented. The sensitivity of the ATLAS experiment to non-Standard Model contributions to the HZZ vertex is estimated for $300\,\text{fb}^{-1}$ and $3000\,\text{fb}^{-1}$ of LHC data at $\sqrt{s} = 14\,\text{TeV}$. The exclusion limits on the non-Standard Model CP-even coupling g_2 and CP-odd coupling g_4 are established for individual components of g_2 and g_4 : $|g_2|/g_1$, $|g_4|/g_1$, $\text{Re}(g_2)/g_1$, $\text{Im}(g_2)/g_1$, $\text{Re}(g_4)/g_1$ and $\text{Im}(g_4)/g_1$.

PACS `13.75.Cs` – Proton-proton interactions.
PACS `13.38.Be` – Decays of Z bosons.
PACS `14.80.Bn` – Standard-model Higgs bosons.
PACS `11.30.Er` – Charge conjugation, parity, time reversal, and other discrete symmetries.

With the statistics collected at LHC during 2011 and 2012, corresponding to an integrated luminosity of $25\,\text{fb}^{-1}$, the ATLAS and CMS experiments have proven the existence of a new boson. Both signal strength and the spin measurements for this new particle point to identify it with the Standard Model Higgs Boson. In particular, the quantum numbers (J^P) agree with the 0^+ hypothesis, excluding with 99% of confidence level alternative values (0^-, 1^-, 1^+, 2^+). Some anomalous odd components of the Spin/CP can be still present, although small and in the following I describe how to measure them. Writing the most general vertex for a spin-0 boson X, coupled to two vector bosons VV, we get the following expression:

$$A(X \to VV) \sim (a_1 M_x^2 g_{\mu\nu} + a_2(q_1+q_2)_\mu(q_1+q_2)_\nu + a_3\epsilon_{\mu\nu\alpha\beta})\epsilon_1^{*\mu}\epsilon_2^{*\nu}, \quad (1)$$

where the coefficients a_1, a_2 represent the even and a_3 the odd contributions to the process amplitude A. They are in general complex numbers and can be expressed in terms of momentum-dependent form factors g_1, g_2, g_3 and g_4:

$$a_1 = g_1^{(0)}\frac{m_v^2}{m_x^2} + \frac{s}{m_x^2}\left(2g_2^{(0)} + g_3^{(0)}\frac{s}{\Lambda^2}\right), \quad a_2 = -\left(g_2^{(0)} + g_3^{(0)}\frac{s}{\Lambda^2}\right), \quad a_3 = -2g_4^{(0)}. \quad (2)$$

Table I. – *Definitions of observables sensitive to the presence and structure of* g_2 *and* g_4 *considered in the current analysis. The direction in which each observable has the strongest sensitivity is listed.*

Observable	Sensitivity
$\ln \frac{\|ME(g_1=1,g_2=0,g4=0)\|^2}{\|ME(g_1=0,g_2=0,g4=1)\|^2}$	$\|g_4\|/g_1$
$\ln \frac{\|ME(g_1=1,g_2=0,g4=-2+2i)\|^2}{\|ME(g_1=1,g_2=0,g4=2+2i)\|^2}$	$\mathrm{Re}(g_4)/g_1$
$\ln \frac{\|ME(g_1=1,g_2=0,g4=2-2i)\|^2}{\|ME(g_1=1,g_2=0,g4=2+2i)\|^2}$	$\mathrm{Im}(g_4)/g_1$
$\ln \frac{\|ME(g_1=1,g_2=0,g4=0)\|^2}{\|ME(g_1=1,g_2=1,g4=0)\|^2}$	$\|g_2\|/g_1$
$\ln \frac{\|ME(g_1=1,g_2=-1+i,g4=0)\|^2}{\|ME(g_1=1,g_2=1+i,g4=0)\|^2}$	$\mathrm{Re}(g_2)/g_1$
$\ln \frac{\|ME(g_1=1,g_2=1-i,g4=0)\|^2}{\|ME(g_1=1,g_2=1+i,g4=0)\|^2}$	$\mathrm{Im}(g_2)/g_1$

Table II. – *Results of the ME-observable fit to the Standard Model signal: the* 95% *CL exclusion limits for* g_4 *and* g_2 *coupling constants at* $300\,fb^{-1}$ *and* $3000\,fb^{-1}$*.*

Luminosity	$\|g_4\|/g_1$	$\mathrm{Re}(g_4)/g_1$	$\mathrm{Im}(g_4)/g_1$	$\|g_2\|/g_1$	$\mathrm{Re}(g_2)/g_1$	$\mathrm{Im}(g_2)/g_1$
$300\,\mathrm{fb}^{-1}$	1.03	$(-1.01, 1.01)$	$(-1.02, 1.02)$	1.39	$(-0.88, 0.38)$	$(-1.13, 1.13)$
$3000\,\mathrm{fb}^{-1}$	0.49	$(-0.34, 0.26)$	$(-0.34, 0.48)$	0.81	$(-0.33, 0.11)$	$(-0.73, 0.75)$

The goal of this analysis is to measure the ratio of the couplings pairs (g_1, g_2), (g_1, g_4). In order to this, a possible approach is to use the Optimal Observables method. The method consists in the following: using the masses of the intermediate vector bosons m_1 and m_2 and the three decay angles ϕ, θ_1, θ_2, one can calculate observables that are sensitive to the absolute value of the ratios (g_1, g_2), (g_1, g_4) or their real and imaginary parts. The optimal observables are defined in the table I. ME represent the matrix element for a given value of the g_i.

The measured observable is then compared with the values of the same quantity, calculated from Monte Carlo samples with different configurations of the g_i values. Defining a plane $(\mathrm{Im}(g_i/g_1),\ \mathrm{Re}(g_i/g_1))$, one can make a likelihood fit to data in each point of the 2D plane and obtain a global minimum in the 2D distributions. An important point of the analysis is to generate Monte Carlo samples with different values of the couplings g_i. The samples are obtained with a re-weighting technique, using the JHU Generator.

The comparison of test data to the Monte Carlo distribution in each bin of the $(\mathrm{Re}(g_i/g_1),\ \mathrm{Im}(g_i/g_1))$ plane is performed by a likelihood fit, with corresponding likelihood function, defined as follows:

$$L(\mu, N_{sig}, N_{bckg}, syst) = \sum_{FS} \prod_{Bins} (\mu N_{sig} pdf_{sig} + N_{bckg} pdf_{bckg}) \tag{3}$$

For the final result of the analysis, the exclusion of the non-Standard Model contributions given the Standard Model data is estimated for $300\,\mathrm{fb}^{-1}$ and $3000\,\mathrm{fb}^{-1}$. The results of the likelihood fits for g_4 and g_2 sensitive observables are presented in table II.