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CP-PARITY OF HIGGS IN $\Phi \to ZZ \to e^+e^-\mu^+\mu^-$ AT CMS*

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This article describes a study of a possible measurement at the CMS detector of the CP-parity of the Higgs boson Φ using angular correlations in the $\Phi \to ZZ \to e^+e^-\mu^+\mu^-$ process, which is a "golden plated channel" for Higgs boson searches at LHC. It will be shown that a measurement of the ξ-parameter describing a generalised ΦZZ coupling, which determines CP-parity of the Higgs boson, will be feasible at CMS. The precision of the measurement is sufficient for determination of CP-parity of the Higgs boson, in particular to distinguish between the scalar and pseudoscalar Higgs bosons.

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1. Introduction

The Standard Model predicts the existence of one scalar Higgs boson, while in more general electroweak theory there could be Higgs particles that have different CP-parity and spin. When such hypothetical particles decay into two vector bosons and then into two fermion pairs, angular correlations of the latter can be used to distinguish between different possible CP-parities and spins.

We study a possible measurement of the CP-parity of the Higgs boson Φ at the LHC, using the CMS detector. We consider a "golden plated channel" $\Phi \to ZZ \to e^+e^-\mu^+\mu^-$ and angular correlations of leptons.

The most general ΦVV coupling ($V = W^{\pm}, Z^0$) for spin-0 Higgs boson Φ (Φ means the Higgs particle with unspecified CP-parity, while H (h) and A mean the scalar and pseudoscalar Higgs particles, respectively) looks as follows [1–4]:

$$\mathcal{C}^{J=0}_{\Phi VV} = \kappa\, g^{\mu\nu} + \frac{\zeta}{m_V^2}\, p^{\mu}p^{\nu} + \frac{\eta}{m_V^2}\, \epsilon^{\mu\nu\rho\sigma}k_{1\rho}k_{2\sigma}\,, \tag{1}$$

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where k_1, k_2 are four-momenta of vector bosons V and $p \equiv k_1+k_2$ is four-momentum of the Higgs boson. In the present analysis a simplified version of above ΦVV coupling (Eq. (1)) is studied with a Standard Model-like scalar and a pseudoscalar contributions (*i.e.* $\kappa, \eta \neq 0$ and $\zeta = 0$). To study deviations from the Standard Model ΦZZ coupling we take $\kappa = 1$[1]. The decay width for the $\Phi \to ZZ \to (\ell_1\bar{\ell}_1)(\ell_2\bar{\ell}_2)$ process consists now of three terms: a scalar one (denoted by H), a pseudoscalar one $\sim\eta^2$ (denoted by A) and the interference term violating CP $\sim\eta$ (denoted by I):

$$d\Gamma(\eta) \sim H + \eta\, I + \eta^2 A\,. \tag{2}$$

This way the Standard Model scalar ($\eta = 0$) and the pseudoscalar (in the limit $|\eta| \to \infty$) contributions could be recovered. It is convenient to introduce a new parameter ξ, defined by $\tan\xi \equiv \eta$, which is finite and has values between $-\pi/2$ and $\pi/2$. Expressions for H, A and I can be found in Ref. [2].

In study of the CP-parity of the Higgs boson two angular distributions were used. The first one is a distribution of the angle φ (called plane or azimuthal angle) between the planes of two decaying Zs in the Higgs boson rest frame. The negatively charged leptons were used to fix plane orientations. The second one is a distribution of the polar angle θ, in the Z rest frame, between momentum of negatively charged lepton and the direction of motion of Z boson in the Higgs boson rest frame (Fig. 1).

The analysis was performed for scalar, pseudoscalar and CP-violating Higgs boson states, the latter for $\tan\xi = \pm0.1$, ±0.4, ±1 and ±4.

A detailed description of the analysis can be found in Ref. [5].

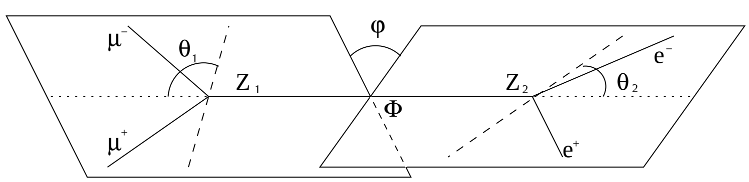

Fig. 1. Definitions of the angles in the $\Phi \to ZZ \to e^+e^-\mu^+\mu^-$ process.

2. Generation and event selections

The production and decay of the scalar, pseudoscalar and CP-violating Higgs boson states were generated using `PYTHIA` [6] for three masses of the Higgs boson, $M_\Phi = 200$, 300 and 400 GeV/c^2. The following background processes were considered:

[1] The ΦVV coupling with $\kappa = 1$ and arbitrary η is implemented in the `PYTHIA` generator.

1. $ZZ \to e^+e^-\mu^+\mu^-$ (irreducible background)
2. $t\bar{t} \to W^+W^-b\bar{b} \to e^+e^-\mu^+\mu^- X$
3. $Zb\bar{b} \to e^+e^-\mu^+\mu^- X$.

Backgrounds and event selections are the same as in the CMS analysis of the Standard Model Higgs boson $H \to ZZ \to e^+e^-\mu^+\mu^-$ described in the CMS Physics TDR [7]. In the selection we require two pairs of isolated opposite-sign leptons $(e^+e^-)(\mu^+\mu^-)$. The mass of each lepton pair has to be compatible with the Z boson mass, while the four lepton mass with the expected Higgs boson mass. After the selection all background contributions, but $ZZ \to e^+e^-\mu^+\mu^-$, are negligible and the signal-to-background ratio is higher than 2. The distribution of four lepton mass before and after the selection for the signal with mass $M_\Phi = 300$ GeV$/c^2$, and for the background are shown in Fig. 2 at 60 fb^{-1}. The reconstructed angular distributions

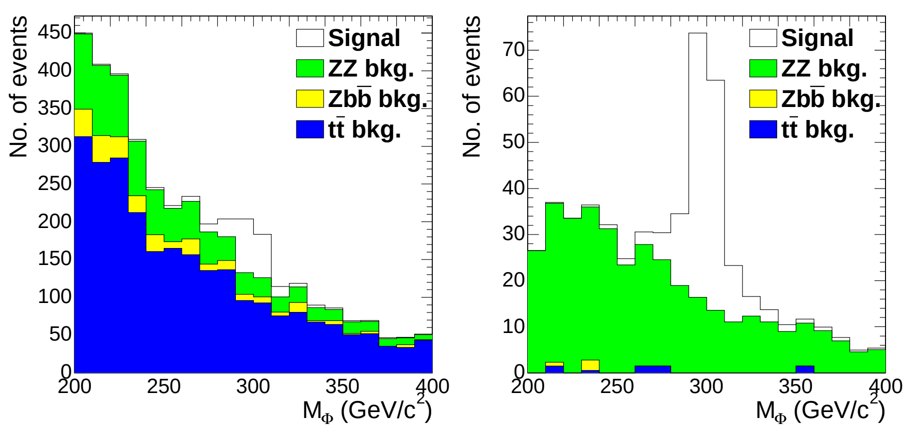

Fig. 2. The four lepton mass distribution before (left) and after (right) selection for at 60 fb^{-1}. Empty histograms — the signal for $M_\Phi = 300$ GeV$/c^2$and; filled histograms — the background.

after all selections for the signal with mass $M_\Phi = 300$ GeV$/c^2$ for various values of the parameter ξ, and for the background are shown in Fig. 3 at 60 fb^{-1}. The Standard Model signal cross-section and branching ratio were used to normalise the signal for each value of parameter ξ in Fig. 3.

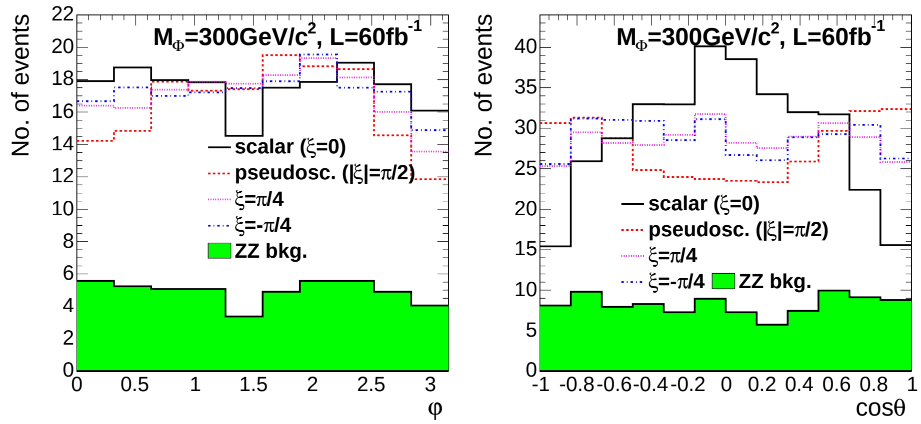

Fig. 3. The φ-distributions (left) and the θ-distributions (right) for various values of the parameter ξ after final selections at 60 fb^{-1}. Empty histograms — the signal for $M_{\varPhi} = 300$ GeV$/c^2$ and $\xi = 0$ (scalar), $\xi = -\pi/4$, $\xi = +\pi/4$ and $|\xi| = \pi/2$ (pseudoscalar). The filled histogram — the ZZ background. The Standard Model signal cross-section and branching ratio were used for the signal normalisation.

3. Determination of the parameter ξ

The parameter ξ was determined by maximisation of the likelihood function $\mathcal{L}(\xi,R)$, which was constructed from angular distributions and invariant mass distribution of four leptons, for the signal and the background. The function depends on two parameters: ξ describing CP property of the signal, and R describing fraction of the signal in the data sample. The function has the following form:

$$\mathcal{L}(\xi, R) \equiv 2 \sum_{x_i \in \mathrm{data}} \log \mathcal{Q}(\xi, R; x_i)\,, \tag{3}$$

where

$$\mathcal{Q}(\xi, R; x_i) \equiv R\,\mathcal{PDF}_{\mathrm{S}}(\xi; x_i) + (1-R)\,\mathcal{PDF}_{\mathrm{B}}(x_i)\,. \tag{4}$$

$\mathcal{PDF}_{\mathrm{B}}(x_i)$ and $\mathcal{PDF}_{\mathrm{S}}(\xi;\ x_i)$ are probability density functions for background and signal respectively; $\{x_i\}$ are values of the measured quantities (angles and invariant mass) in the event i. $\mathcal{PDF}$s are products of probability densities $\mathcal{P}^M$, $\mathcal{P}^{\varphi}$, $\mathcal{P}^{\cos\theta_{1,2}}$ of four leptons invariant mass and angles φ and $\cos\theta_{1,2}$: $\mathcal{PDF} \equiv \mathcal{P}^M\,\mathcal{P}^{\varphi}\,\mathcal{P}^{\cos\theta_1}\mathcal{P}^{\cos\theta_2}$. The $\mathcal{P}^M$, $\mathcal{P}^{\varphi}$, $\mathcal{P}^{\cos\theta_{1,2}}$ are obtained by the Monte Carlo technique, using normalised histograms of given quantities after the final selection. This way we include into $\mathcal{PDF}$s all distortions of the angular distributions caused by detector acceptance and selection cuts.

A part of the function $\mathcal{Q}$ which describes angular distributions of signal depends on the parameter ξ, namely from Eq. (2) we obtain:

$$\begin{aligned} \mathcal{P}(\xi) &\equiv \mathcal{P}_S^{\varphi}(\xi)\,\mathcal{P}_S^{\cos\theta_1}(\xi)\,\mathcal{P}_S^{\cos\theta_2}(\xi) \\ &\equiv \frac{\mathcal{H} + \tan\xi\,\mathcal{I} + \tan^2\xi\,a^2\mathcal{A}}{1 + a^2\tan^2\xi}\,, \end{aligned} \tag{5}$$

where: $\mathcal{H} \equiv \mathcal{P}_H^{\varphi}\,\mathcal{P}_H^{\cos\theta_1}\mathcal{P}_H^{\cos\theta_2}$ and $\mathcal{A} \equiv \mathcal{P}_A^{\varphi}\,\mathcal{P}_A^{\cos\theta_1}\mathcal{P}_A^{\cos\theta_2}$ are probability densities obtained by the Monte Carlo technique for the scalar (H) and the pseudoscalar (A) Higgs boson, respectively. The parameter a^2 is a (mass dependent) relative strength of the pseudoscalar and scalar couplings. For example $a^2 = 0.51,\ 1.65,\ 1.79$ for $M_\Phi = 200, 300, 400$ GeV/c^2, respectively. The $\mathcal{I}$ is a normalised product of angular distributions for the CP-violating term. The $\mathcal{I}$ is not always positive, and its integral is equal to zero, so it is not possible to simulate it separately. The $\mathcal{I}$ contribution can be obtained indirectly from the combined probability density for the signal with non-zero value of the parameter ξ. For example by introducing

$$\begin{aligned} \mathcal{P}_+ &\equiv \mathcal{P}(+\pi/4) = \frac{\mathcal{H} + \mathcal{I} + a^2\mathcal{A}}{1 + a^2}\,, \\ \mathcal{P}_- &\equiv \mathcal{P}(-\pi/4) = \frac{\mathcal{H} - \mathcal{I} + a^2\mathcal{A}}{1 + a^2} \end{aligned} \tag{6}$$

we have

$$\mathcal{I} = \frac{(1 + a^2)}{2}\,(\mathcal{P}_+ - \mathcal{P}_-)\,. \tag{7}$$

Finally we obtain:

$$\mathcal{P}(\xi) \equiv [\mathcal{H} + \tan\xi\,\frac{1 + a^2}{2}\,(\mathcal{P}_+ - \mathcal{P}_-) + \tan^2\xi\,a^2\mathcal{A}]/(1 + a^2\tan^2\xi)\,. \tag{8}$$

4. Results

After selection all background contributions, but $ZZ \to e^+e^-\mu^+\mu^-$, are negligible, therefore only these events were used to construct probability density function for the background. Signal probability density functions were constructed using samples of scalar Higgs boson (H), pseudoscalar (A) and $\mathcal{P}_+$, $\mathcal{P}_-$ samples ($\xi = \pm\pi/4$).

For each value of the parameter ξ and for each Higgs-boson mass we performed 200 pseudo-experiments for the integrated luminosity $\mathcal{L} = 60\ \ \mathrm{fb}^{-1}$. For each pseudo-experiment we randomly selected events from the signal and background samples to form a test sample. The number of selected events was given by a Poisson probability distribution with mean defined by the process cross-section, selection efficiency and the examined luminosity. Then we performed a maximisation of the likelihood function $\mathcal{L}(\xi,R)$ for the test sample to obtain a value of the parameter ξ. The generated and reconstructed values of the parameter ξ with its uncertainty, obtained for three masses of the Higgs boson are shown in Fig. 4. The Standard Model signal cross-section and branching ratio were used to normalise signal for each value of the parameter ξ.

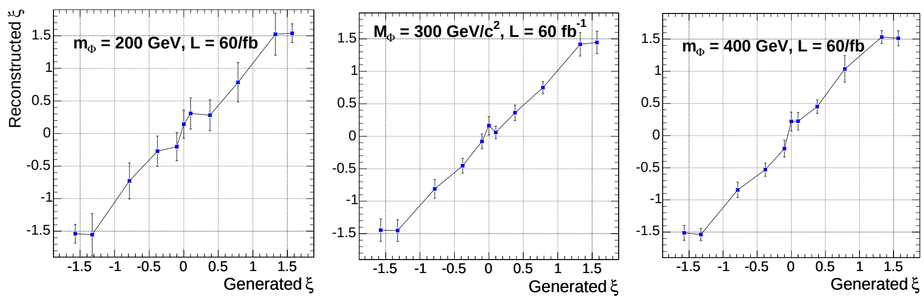

Fig. 4. Reconstructed value of the parameter ξ as function of the generated value of the parameter ξ for $\mathcal{L} = 60$ fb^{-1} and Higgs boson masses $M_\Phi = 200$, 300, 400 GeV/c^2. Uncertainties correspond to one standard deviation. The Standard Model signal cross-section and branching ratio were used.

In our analysis the Standard Model signal cross-section and branching ratio were used as a reference for each value of the parameter ξ. However, both of them may change for other Higgs models. An influence of enhancement (or suppression) factor C^2 of the Higgs boson production cross section times branching ratio, in respect to the Standard Model

$$C^2 = \frac{\sigma \times \mathrm{Br}}{\sigma_{\mathrm{SM}} \times \mathrm{Br}_{\mathrm{SM}}} \tag{9}$$

on the accuracy of the ξ measurement and thus, on possibility to exclude the Standard Model, scalar Higgs boson was studied. It was found that the precision of ξ measurement is approximately proportional to $1/C$ (*i.e.* it depends on square-root of number of events, as one can expect):

$$\Delta\xi(\xi, C^2) \equiv \frac{\Delta\xi_{\mathrm{SM}}(\xi)}{\sqrt{C^2}}\,. \tag{10}$$

A value of $\Delta\xi_{\mathrm{SM}}(\xi)$ corresponds to the precision of the parameter ξ measurement assuming the Standard Model Higgs boson production cross section times branching ratio. It is shown as the error bars in Fig. 4. Fig. 5 shows the minimal value of the factor C^2 needed to exclude the SM Higgs boson at $N\sigma$ level ($N = 1, 3$), where $N = \xi/\Delta\xi$, as a function of the parameter ξ.

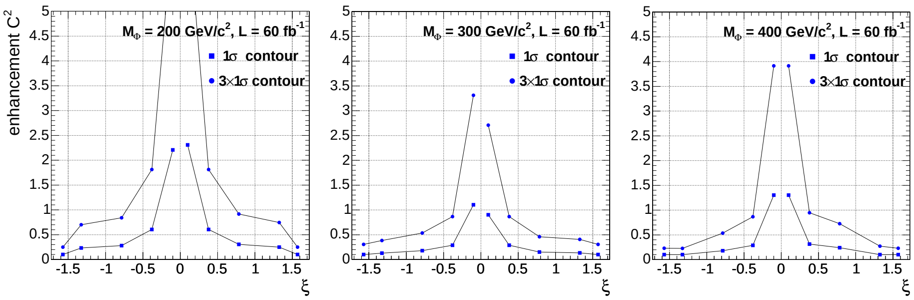

Fig. 5. The minimal value of the factor C^2 needed to exclude the Standard Model, scalar Higgs boson at $N\sigma$ level ($N = 1, 3$) as a function of the parameter ξ for the Higgs boson masses M_Φ = 200, 300 and 400 GeV/c^2 (from left to right) at 60 fb^{-1}.

5. Summary

The measurement of the CP-properties of the Higgs boson Φ in the $\Phi \to ZZ \to e^+e^-\mu^+\mu^-$ process at LHC with the CMS detector was studied. It was shown that using angular correlations of the Higgs boson decay products (leptons) the measurement of the parameter ξ, describing a general ΦZZ coupling, will be feasible. The precision of this measurement is sufficient for determination of the CP-parity of the Higgs boson, and in particular it is sufficient to distinguish scalar from pseudoscalar coupling.

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