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Study of CP violation in the process of associated Higgs boson production with a decay into muon pair

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Abstract. After the Higgs boson discovery at the LHC, a lot of additional measurements should be performed to understand in detail the properties of the observed particle. Searches for CP violation in different physics sectors are one of the most promising and important parts of these measurements. Associated Higgs boson production in *pp* collisions can be a powerful tool for searches for possible CP violation in the Higgs sector. In this paper, the study of CP sensitive observables constructed for a four lepton final state is presented. It is shown that azimuthal angle distributions of leptons in this process demonstrate a strong sensitivity to CP violation at the current limits on Higgs boson coupling parameters and can reveal a genuine mechanism of CP violation.

1. Introduction

After the Higgs boson was discovered by the ATLAS and CMS collaborations at the LHC [1, 2], the particle content of Standard Model (SM) became complete. Searches for physics beyond the Standard Model (BSM) are currently ongoing. Several impressive discoveries based on the LHC data were done in last years, namely the pentaquark observation [3], the observation of CP violation in rare baryon decays [4] and the measurements of the Higgs boson's couplings, spin and mass [5–7].

These days, there are many ongoing theoretical and experimental studies of the Higgs boson [8–12]. Searches for possible CP violation in the Higgs sector are very important part of these studies due to possible consequences in case of discovery of such effect. If CP violation in the Higgs sector exists, it will become the first observation of so-called new physics and might be a key to understanding the baryon asymmetry of the Universe. Searches for CP violation in the Higgs sector can be done in different ways. One can use special asymmetry variables [13], kinematics properties [14] or so-called optimal observables based on matrix elements [15]. In this paper, several kinematic variables sensitive to CP violating effects are suggested for associated Higgs boson production with the four lepton final state.

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2. Higgs boson production

In *pp* collisions, one of the possible Higgs boson production channels is the associated production with the Z boson, or, alternatively speaking, ZH production. Both Z and H bosons further decay into leptons or hadrons. In this paper, the final state with clear signature $2e2\mu$ is considered. The Feynman diagram of the full chain process is shown at figure 1.

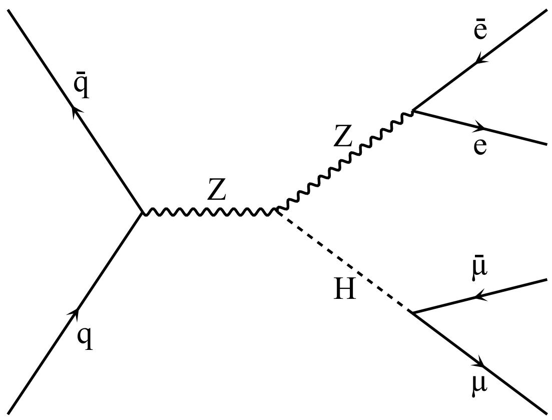


Figure 1. Feynman diagram of the Leading-order $pp \to Z \to ZH \to 2e2\mu$ process.

The $pp \to Z \to ZH \to 2e2\mu$ process involves the same HZZ vertex and four-lepton final state as intensively studying $pp \to H \to ZZ \to 2e2\mu$ process, but the processes features are very different. While in case of ZZ process there are two vector propagators and the angular correlations between the final state leptons are expected, in case of ZH process the situation is much more implicit. Despite the fact that the muon pair is connected to the scalar particle, some special angular correlations are also take place due to their sensitivity to the transverse momentum carried by the scalar particle.

3. Theoretical description

For a large class of models beyond the Standard Model (BSM), physics at energies below the mass scale Λ of new particles can be parametrized by an effective field theory (EFT) where the SM Lagrangian is supplemented by new operators with canonical dimensions D larger than 4 [16]:

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(7)}}{\Lambda^3}\mathcal{O}_i^{(7)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \ldots, \tag{1}$$

where $\mathcal{O}_i^{(D)}$ are the $SU(3)_C \times SU(2)_L \times U(1)_Y$ operators of dimension D and the $c_i^{(D)}$ are called the Wilson coefficients. The part of the full dimension-6 EFT Lagrangian in the Higgs basis [17], describing the HZZ interaction only, can be written as follows:

$$\mathcal{L}_{HZZ}^{D=6} = \frac{H}{v}\frac{g^2+g'^2}{4}\left[(1+\delta c_{zz})v^2 Z_\mu Z^\mu + c_{zz} Z_{\mu\nu}Z^{\mu\nu} + \tilde{c}_{zz} Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right], \tag{2}$$

where δc_z, c_{zz} and $\tilde{c}_{zz}$ are the Higgs boson couplings; g and g' are the $SU(2)_L$ and $U(1)_Y$ couplings, respectively; v is the vacuum expectation value and the field strength tensors are defined as $Z_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu$ and $\tilde{Z}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}Z^{\rho\sigma}$.

Coupling constant δc_z corresponds to the SM term. The value $\delta c_z = 0$ leads to the exact part of the SM Lagrangian describing the HZZ interaction. The coupling c_{zz} corresponds to BSM term with the positive CP parity, while the coupling $\tilde{c}_{zz}$ corresponds to BSM term with negative CP parity. Thus, if $\tilde{c}_{zz} \neq 0$ then the theory contains the CP violating effects in the Higgs sector.

4. Monte Carlo simulations

In order to probe possible CP violating effects, two Monte Carlo samples were generated using the MadGraph5 generator [18]. One of the most validated and widely used MadGraph5 models is the Higgs Characterisation model [19]. The Higgs Characterisation (HC) model is based on different Lagrangian than the Higgs basis (HB), but the direct translation in case of HZZ interaction from the Higgs basis to the Higgs Characterisation is possible. It can be done by direct calculation or, for example, by using Rosetta [17]. The mapping between HB and HC in the case of HZZ interaction is given by the following equations:

$$k_{SM} = \frac{1+\delta c_z}{\cos\alpha}, \qquad k_{AZZ} = -\frac{\Lambda(g^2+g'^2)}{v\sin\alpha}\tilde{c}_{zz}, \qquad k_{AWW} = -\frac{\Lambda g^2}{v\sin\alpha}\tilde{c}_{zz}. \tag{3}$$

Here α is the mixing angle between CP-even and CP-odd Higgs boson states. The coupling constants for each sample are shown in table 1.

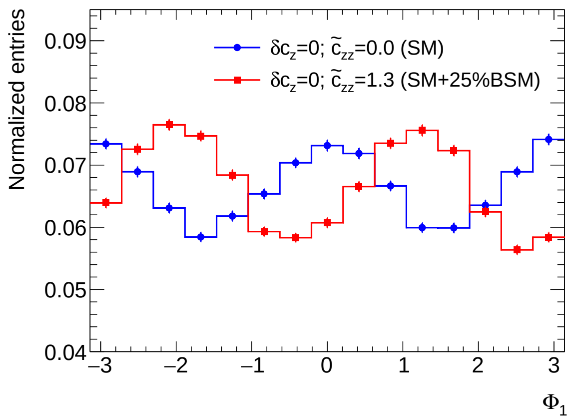
Table 1. List of generated Monte Carlo samples.

Sample number	Higgs basis couplings	Related Higgs Characterisation couplings
1	$\delta c_z = 0$; $\tilde{c}_{zz} = 0.0$	$k_{SM} = \sqrt{2}$; $k_{AZZ} = 0.000$; $k_{AWW} = 0.000$;
2	$\delta c_z = 0$; $\tilde{c}_{zz} = 1.3$	$k_{SM} = \sqrt{2}$; $k_{AZZ} = -4.097$; $k_{AWW} = -3.139$;

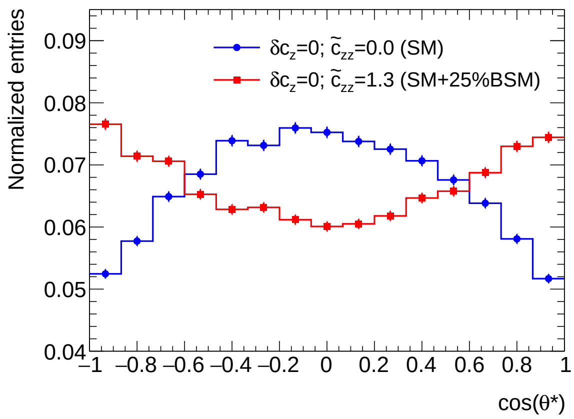
Sample 1 corresponds to the SM case without any BSM contribution. Sample 2 corresponds to the mixture of the SM and BSM CP-odd terms. Value of the BSM coupling was chosen according to the condition $\sigma_{SM+BSM} = 1.25\sigma_{SM}$, which approximately represents the current experimental limit on the cross section [20].

For each event, three kinematic variables were calculated in the rest system of a virtual Z:

- The angle between the Higgs boson decay plane and the plane which contains both Higgs momentum vector and the beam axis: Φ_1;
- The cosine of an angle between the H boson's momentum and the beam axis: $\cos\theta^*$;
- The distribution over the mass of a virtual Z boson: m_{Z_1};



(a)



(b)

Figure 2. The distributions over the kinematic variables Φ_1 (a) and $\cos\theta^*$ (b). Blue lines correspond to SM case, while the red ones correspond to SM+25%BSM case.

Both MC samples contain 100k events generated with $\alpha = 45^o$ and $\Lambda = 1$ TeV. The resulted distributions are presented in figures 2 and 3.

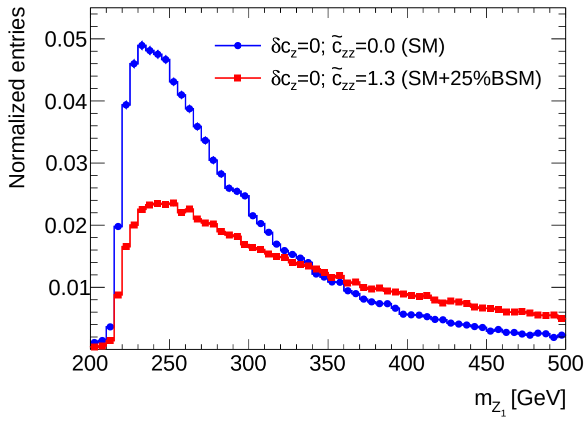


Figure 3. The distribution over the variable m_{Z_1}. Blue line corresponds to SM case, while the red one corresponds to SM+25%BSM case.

5. Conclusion

In this paper, the study of CP sensitive observables constructed for a four lepton final state in ZH channel was presented. Distributions over the kinematic variables Φ_1, $\cos\theta^*$ and m_{Z_1} demonstrate different shapes for SM and SM+BSM cases within the current experimental limits on the cross section. The reviewed approach is a promising way to search for possible CP violation in the Higgs sector at the High Luminosity LHC (HL-LHC).

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