CP-sensitive observables for the process

$pp \rightarrow Z \rightarrow ZH \rightarrow 2e2\mu$

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Abstract. After the discovery of the Higgs boson at the LHC, additional precise measurements were performed testing its compatibility with the Standard Model (SM). One of the most important deviations from the SM predictions is the possible CP violation in the Higgs sector that may have implications for the origin of the baryon asymmetry in the early Universe. In this paper, new kinematic observables are suggested to probe the CP properties of the Higgs boson. The Higgs boson associated production with a $Z$ boson with a four-lepton final state is studied at theoretical and Monte Carlo levels. Sensitivity of considered observables to the CP nature of the Higgs boson is demonstrated.

1. Introduction

Since the Large Hadron Collider (LHC) first switched on in 2008, a series of important physics results was obtained. In 2012, the Higgs boson was discovered by the ATLAS and CMS collaborations [1,2]. Later, the signs of tetraquarks and pentaquarks were observed by the LHCb collaboration [3, 4]. Also, the CP violation in rare B-meson decays was observed [5]. For the Higgs boson, the ATLAS and CMS collaborations performed a series of precise measurements of its spin and CP-parity [6–10]. One of the rarest Higgs boson decay modes $H \rightarrow \mu\mu$ was recently observed at the level of three standard deviations [11,12]. No significant deviation from the SM predictions were observed. However, the possible Beyond-the-Standard Model (BSM) effects can still arise as small corrections at current energy scale. The CP violation in the Higgs sector is one of the most promising BSM effects that might appear. Such violation might be directly related to the baryon asymmetry of the Universe. The CP violation in the Higgs sector is considered in many experimental and theoretical papers [13–17].

In this paper, special kinematic observables were used to probe the CP properties of the Higgs boson. The Monte Carlo technique is used to simulate the signal events. Anomalous CP-even and CP-odd Higgs boson interactions are parameterized in the framework of the Effective Field Theory (EFT). The sensitivity of chosen kinematic variables to the CP nature of the Higgs boson was demonstrated. This paper extends the previous work [18].
2. Theoretical description

In $pp$ collisions, one of the possible Higgs boson production modes is the Higgs boson associated production with a $Z$ boson ($ZH$). This mode is the dominant one in case of future $e^+e^-$ colliders. In this study, $2e2\mu$ final state of the $ZH$ system was considered. Despite the fact that $b\bar{b}$ mode of the Higgs boson is the dominant one, the $\mu\mu$ mode has much higher purity and comparable signal to background ratio. The Feynman diagram of the $pp \rightarrow Z \rightarrow ZH \rightarrow 2e2\mu$ process is shown in figure 1.

![Feynman diagram](image)

**Figure 1.** Feynman diagram for the leading-order $pp \rightarrow Z \rightarrow ZH \rightarrow 2e2\mu$ process.

For a large class of BSM models, physics at energies below the mass scale $\Lambda$ of new particles can be parametrized by the EFT where the SM Lagrangian is supplemented by new operators with canonical dimensions $D$ larger than 4 [19]:

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

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 the Wilson coefficients. The part of the full dimension-6 EFT Lagrangian in the Higgs basis [20], describing the $HZZ$ interaction only, can be written as follows:

$$\mathcal{L}_{HZZ}^{D=6} = \frac{H}{v} \left( \frac{M_Z}{v} \right)^2 \left[ (1 + \delta c_Z) v^2 Z_{\mu} Z^{\mu} + c_{ZZ} Z_{\mu \nu} Z^{\mu \nu} + \tilde{c}_{ZZ} Z_{\mu \nu} \tilde{Z}^{\mu \nu} \right], \quad (2)$$

where $\delta c_Z$, $c_{ZZ}$ and $\tilde{c}_{ZZ}$ are the Higgs boson couplings; $v$ 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 $\delta c_Z$ corresponds to the SM term. The $\delta c_Z = 0$ 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.

The differential cross section over the angle between the z-axis and the Higgs boson’s momentum in the center-of-mass frame of the initial quarks corresponding to SM EFT term (coupling $\delta c_Z$) and CP-odd anomalous term (coupling $\tilde{c}_{ZZ}$) can be written as follows:

$$\frac{d\sigma}{dz} = \frac{1}{2\pi} \frac{1}{M_Z^2} \left( \frac{M_Z}{v} \right)^4 \frac{g_\mu^2 + g_a^2}{(1 - M_Z^2/v)^2} \beta \left[ a^2 M_Z^2 \left( \frac{8 M_Z^2}{s} + \beta^2 (1 - z^2) \right) + b^2 \beta^2 (1 + z^2) \right], \quad (3)$$

where $z = \cos \theta^*$, $\beta^2 = \left( 1 + \frac{M_Z^2 - M_Z^2}{s} \right)^2 - 4 \frac{M_Z^2}{s}$, $a = \delta c_Z + 1$ and $b = 2 \left( \frac{M_Z}{v} \right)^2 \tilde{c}_{ZZ}$.

It follows from the equation (3) that at high energies in case of the SM Higgs boson $d\sigma/dz$ is proportional to $1 - z^2$. Equation (3) also shows in which way the cross section is modified in case of presence of the CP-odd anomalous coupling $\tilde{c}_{ZZ}$. This results is in a good agreement with the results presented in the previous paper [18]. However, the presence of background will modify the $d\sigma/dz$ distribution.
Figure 2. The distributions of the kinematic variables $\Phi_1$ (a); $\cos \theta^*$ (b); $m_{Z_1}$ (c); $\Delta E_{ee}$ (d); $\Delta \phi_{ee}$ (e) and $\Delta \phi_{\mu\mu}$ (f). Blue lines correspond to SM. The red lines correspond to SM + BSM case.
3. Monte Carlo simulation

The Higgs Characterisation model (HC) for the MadGraph5 Monte Carlo generator was used to simulate the signal and background events [21] [22]. The following kinematic cuts were applied to the leptons transverse momenta, multi-lepton masses and leptons pseudorapidity to preserve the signal and reduce the background: $p_T^\ell > 5 \text{ GeV}$, $80 \text{ GeV} < m_{ee} < 100 \text{ GeV}$, $124 \text{ GeV} < m_{\mu\mu} < 126 \text{ GeV}$, $m_4l > 200 \text{ GeV}$ and $\eta^l < 2.5$. Two MC samples were generated to compare the kinematic distributions. The first sample corresponds to the SM case without any BSM contribution. The second sample corresponds to the mixture of the SM and BSM CP-odd terms. The BSM coupling was chosen according to the current experimental limits on the EFT BSM contribution. The second sample corresponds to the mixture of the SM and BSM CP-odd terms. The BSM coupling was chosen according to the current experimental limits on the EFT couplings [23]. The simulated background consists of several SM processes with the $pp$ terms. The $\text{BSM}$ coupling was chosen according to the current experimental limits on the EFT BSM contribution.

As it was done in [18], for each event, three kinematic variables were calculated in the center-of-mass frame of the initial quarks:

- The angle between the Higgs boson decay plane and the beam axis: $\Phi_1$;
- The cosine of an angle between the $H$ boson’s momentum and the beam axis: $\cos \theta^*;
- The mass distribution of the virtual $Z$ boson: $m_{Z1}$;

The distributions of these variables are shown in figure 2(a), (b) and (c). It can be seen that the presence of background modifies the distributions and reduce the sensitivity to the CP violating effects. It is worth mentioning that distributions of $\cos \theta^*$ have maxima around $\pm 1$. This fact is in agreement with equation (3), because in both cases the CP-even states are dominant, for which $d\sigma/d\cos \theta^* \propto C_1 - C_2 \cos^2 \theta^*$, where $C_1$ and $C_2$ are constants.

In paper [16] it was also shown, that variables $\Delta E_\ell^1$ and $\Delta \phi_\ell^1$ are genuine CP-odd observables. For some processes, loop integrals can generate small dispersion parts, which can also cause the CP-violation despite the fact that initial theory Lagrangian is CP-even. The genuine CP-odd variables are not sensitive to such dispersion effects and they are only sensitive to CP-odd terms in Lagrangians. The distributions of these observables are shown in figure 2(d), (e) and (f). Sensitivity of $\Delta \phi_{ee}$ and $\Delta \phi_{\mu\mu}$ variables to the CP-violation effects is visibly higher than $\Phi_1$, $m_{Z1}$, $\cos \theta^*$. Moreover, distribution of $\Delta \phi_{ee}$ has an asymmetry in case of non-zero $\hat{c}_{ZZ}$.

| $\hat{c}_{ZZ}$ | 0.0 | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 | 1.2 | 1.4 | 1.6 | 1.8 |
|----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $\hat{\mu}_3 \cdot 10^2$ | 0.258 | 2.381 | 3.653 | 5.775 | 8.133 | 9.371 | 9.705 | 10.138 | 9.986 | 9.133 |
| $\sigma \cdot 10^2$ [fb] | 1.501 | 1.515 | 1.570 | 1.662 | 1.778 | 1.948 | 2.149 | 2.399 | 2.665 | 2.982 |

Table 1. The skewness $\hat{\mu}_3$, calculated from distributions of $\Delta \phi_{ee}$ for different values of $\hat{c}_{ZZ}$, and the corresponding cross sections $\sigma$. The $\delta c_Z$ coupling is set to 0 in all cases.

The simultaneous presence of CP-even and CP-odd terms in Lagrangian leads to asymmetry in angular distributions. The measure of asymmetry of such distributions can be estimated by using well known coefficient of asymmetry called skewness. The skewness of a distribution is defined as a third standardized moment: $\hat{\mu}_3 = \mu_3/\sigma^3$. The skewnesses of $\Delta \phi_{ee}$ distributions is estimated for several values of $\hat{c}_{ZZ}$, from 0.0 to 1.8, with a step equal to 0.2. The results of these calculation are shown in table 1. It can be seen that the maximum of asymmetry is reached when $\hat{c}_{ZZ}$ is around 1.4.
4. Conclusion
In this paper, the CP-sensitive kinematic observables for the $pp \rightarrow Z \rightarrow ZH \rightarrow 2e2\mu$ process were studied at the generator level, taking into account the relevant background processes. It was found that all considered observables demonstrate the sensitivity to anomalous CP-odd contribution at the level of current experimental constrains on the EFT couplings. The genuine CP-odd variables $\Delta E_{ll}$ and $\Delta \phi_{ll}$ are able to directly reveal the CP-odd term in the Lagrangian. Moreover, distribution of $\Delta \phi_{ee}$ has visible asymmetry in case of presence of BSM CP-odd contribution. The skewness was also estimated considering distribution of $\Delta \phi_{ee}$ for different values of $\tilde{c}_{ZZ}$. The reviewed approach is a promising way to search for possible CP-violation in the Higgs sector at the High Luminosity LHC (HL-LHC).

Acknowledgements
The work of N. Belyaev is supported by the Ministry of Science and Higher Education of the Russian Federation, Project ”Fundamental properties of elementary particles and cosmology” No 0723-2020-0041. The work of R. Konoplich and S. Reese is partially supported by the Kakos Endowed Chair in Science Fellowship. The work of K. Prokofiev is supported by the RGC Hong Kong through GRF grant 16303419 "Structure of Higgs boson interactions with elementary particles”.

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