CP-sensitive observables for the process $pp \rightarrow Z^* \rightarrow ZH \rightarrow 2e2\mu$

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Motivation

These days, many intensive searches for physics effects Beyond the Standard Model (BSM) are ongoing. Standard Model (SM) is now under precise experimental validation – research groups are measuring the cross sections of different processes, the branching ratios, trying to find new particles. Any deviations from the SM will highly likely lead us to the new, more general theory. One of the most promising fields for BSM effects is the Higgs boson physics. Spin and CP-parity of the Higgs boson (H) were measured and found to be to 0^+. However, current level of experimental precision allows us to assume, that small mixing of 0^+ and 0^- physical states of H is allowed. If this is the case, then the CP violation, which previously was observed only in the weak decays of some hadrons, is also a physical reality in the Higgs sector. This would be a major discovery, so right now many research groups are trying to probe effect of CP violation in different Higgs boson decay channels [1-3].

In this work, we concentrate on one particular channel, namely $H \rightarrow \mu^+\mu^-$. This channel has lower branching ratio compared to $H \rightarrow b\tilde{b}$ or $H \rightarrow \gamma\gamma$, but the experimental signature is more explicit here. As a production channel the associated Higgs boson production (ZH) was chosen. The main goal of this work is to probe the potential of CP violation searches with $pp \rightarrow Z^* \rightarrow ZH \rightarrow e^+e^-\mu^+\mu^-$ process. Associated Higgs production combined with the dimuon decay allows to efficiently distinguish this process among all the backgrounds.

Theoretical description

For this study, the Effective Field Theory (EFT) approximation has been used. The main idea of the EFT approach is to use the Standard Model Lagrangian enhanced by BSM operators of higher dimension:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(7)}}{\Lambda^3}\mathcal{O}_i^{(7)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots,$$

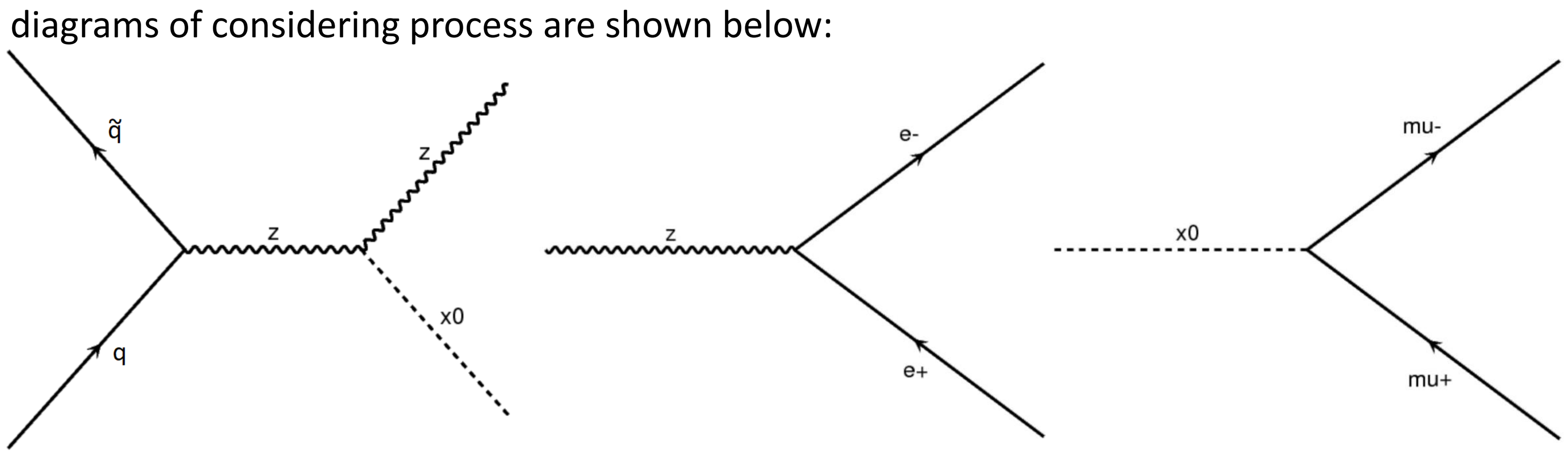
As a particular realization of EFT Lagrangian, the so-called Higgs basis model was chosen [4]. The full Higgs basis Lagrangian describing all the possible interactions can be written as following:

$$\begin{aligned}\mathcal{L}_{\rm EFT} &= \mathcal{L}_{\rm kinetic} + \mathcal{L}_{\rm aff} + \mathcal{L}_{\rm vertex} + \mathcal{L}_{\rm dipole} + \mathcal{L}_{\rm tgc} + \mathcal{L}_{\rm qgc,0} + \mathcal{L}_{\rm qgc,2} \\ &+ \mathcal{L}_{\rm hff} + \mathcal{L}_{\rm hvv} + \mathcal{L}_{hvff} + \mathcal{L}_{hdvff} + \mathcal{L}_{hvvv} + L_{h,\rm self} + \mathcal{L}_{h^2} + \mathcal{L}_{\rm other}.\end{aligned}$$

For $pp \rightarrow Z^* \rightarrow ZH \rightarrow e^+e^-\mu^+\mu^-$ process we are interested to probe the CP violation effects in HZZ vertex, so the following part of the Lagrangian will take into account HZZ as well as the other bosonic interactions:

$$\begin{aligned}\mathcal{L}_{\rm hvv} = \frac{h}{v}\Big[& (1+\delta c_w)\frac{g^2v^2}{2}W^+_\mu W^-_\mu + (1+\delta c_z)\frac{(g^2+g'^2)v^2}{4}Z_\mu Z_\mu \\ & + c_{ww}\frac{g^2}{2}W^+_{\mu\nu}W^-_{\mu\nu} + \tilde{c}_{ww}\frac{g^2}{2}W^+_{\mu\nu}\tilde{W}^-_{\mu\nu} + c_{w\Box}g^2\left(W^-_\mu\partial_\nu W^+_{\mu\nu} + \text{h.c.}\right) \\ & + c_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}G^a_{\mu\nu} + c_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}A_{\mu\nu} + c_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2}Z_{\mu\nu}A_{\mu\nu} + c_{zz}\frac{g^2+g'^2}{4}Z_{\mu\nu}Z_{\mu\nu} \\ & + c_{z\Box}g^2 Z_\mu\partial_\nu Z_{\mu\nu} + c_{\gamma\Box}gg'Z_\mu\partial_\nu A_{\mu\nu} \\ & + \tilde{c}_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}\tilde{G}^a_{\mu\nu} + \tilde{c}_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}\tilde{A}_{\mu\nu} + \tilde{c}_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2}Z_{\mu\nu}\tilde{A}_{\mu\nu} + \tilde{c}_{zz}\frac{g^2+g'^2}{4}Z_{\mu\nu}\tilde{Z}_{\mu\nu}\Big],\end{aligned}$$

For this process genuine CP-observables can be built. Also this process can be a good candidate to measure Higgs boson coupling to leptons of the second generation. Feynman diagrams of considering process are shown below:



Feynman diagrams for the associated Higgs production (left), for decay of Z boson (middle) and decay of the Higgs (right).

Monte Carlo simulation

The Monte Carlo simulation was performed within the MadGraph5 generator with the Higgs Characterisation model included [5]. Right now there is no validated models describing the Higgs basis for MadGraph5, so the Higgs basis couplings was recalculated in terms of the Higgs Characterisation couplings. The Higgs basis couplings for two generated event samples are shown in the table below:

Sample #	δC_Z	C_{ZZ}	$\tilde{C}_{ZZ}$
1	0	0	0
2	0	0	1.3

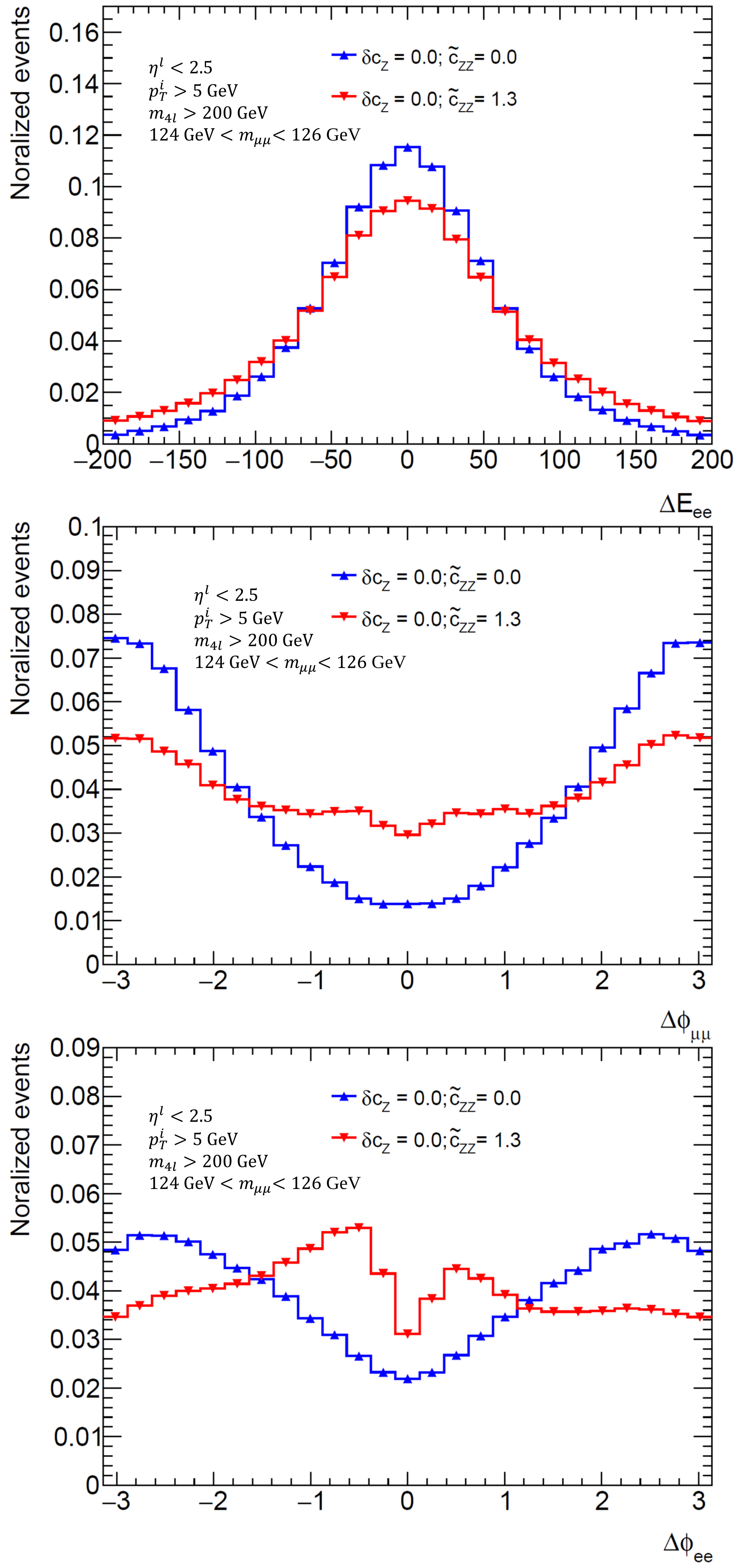
Generated sample #1 corresponds to the Standard Model. Sample #2 is the mixture of the SM and CP-odd Higgs boson states. Both samples contains signal and background processes.

The chosen kinematical variables of interest were the following [6]:

- The azimuthal angle, for which a sign imposes an ordering according to the lepton momentum in the CMS frame ($\Delta\varphi_{ll}$).
- The energy difference between the leptons (ΔE_{ll}).

Results: kinematical distributions

The results of Monte Carlo simulation over the ΔE_{ee}, $\Delta\varphi_{\mu\mu}$and $\Delta\varphi_{ee}$ variables are shown at the plots below. Red lines correspond to sample #1 (SM), while the blue ones correspond to sample #2 (SM + BSM at the level of current experimental limit).



The kinematical distributions over the ΔE_{ee} variable (top), $\Delta\varphi_{\mu\mu}$(middle) and $\Delta\varphi_{ee}$(bottom).

Conclusion

The results of Monte Carlo simulation over the ΔE_{ee}, $\Delta\varphi_{\mu\mu}$ and $\Delta\varphi_{ee}$variables demonstrate the sensitivity of suggested variables to CP-odd BSM contribution. Even at the level of current experimental limits the difference is visible. Thus such approach seems to be effective in terms of CP violation searches. Further studies will be performed to understand how the hadronization and detector effects change the shapes of distributions. The precise measurements of reviewed process can be performed at the HL-LHC.

Bibliography

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