Investigation of the $\mathcal{CP}$ structure of the Higgs bosons Yukawa coupling to the τ-lepton

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Since the discovery of the Higgs boson in 2012 at the LHC at CERN, the full particle spectrum of the Standard Model is established by experiments. Although the Standard Model is extremely successful in the sense that its theoretical predictions fit with great precision to basically every measurement at particle colliders to date, there are observations that cannot be explained without changes to the current Standard Model of particle physics. One of these puzzling observations is the matter–antimatter asymmetry seen in the observable universe.

In order to account for the observed matter–antimatter asymmetry it is well established that the theory of particle physics needs additional sources of $\mathcal{CP}$ violation. So it is of great experimental and theoretical interest to study the possible extensions of the Standard Model that include additional sources of $\mathcal{CP}$ violation. An important sector in the search for additional $\mathcal{CP}$ violation is the Higgs sector. This is partly motivated by the fact that the couplings of the Higgs boson to the other Standard Model particles are, to date, less precisely measured than for example the couplings of the gauge bosons to each other and thus there is more room left for beyond Standard Model (BSM) physics.

For example, should electroweak symmetry breaking be triggered by more than one Higgs doublet, there is the possibility for additional non-vanishing $\mathcal{CP}$ violating couplings. Furthermore it is possible that the discovered Higgs boson is not a $\mathcal{CP}$-eigenstate but a $\mathcal{CP}$-mixture. Such $\mathcal{CP}$ violating effects in the Higgs sector can be studied most directly in production and decay processes of the Higgs boson.

A particularly interesting possibility for additional $\mathcal{CP}$ violation in the Higgs sector is the inclusion of $\mathcal{CP}$-odd Yukawa couplings to the Standard Model fermions. This can be justified by the fact that these terms are the only direct possibility for additional $\mathcal{CP}$ violation by operators of mass-dimension four, and thus might already contribute to observables at tree-level.

Of course the $\mathcal{CP}$ structure of the couplings of the Higgs boson to the gauge bosons could also be affected by BSM physics, however in many BSM Models the $\mathcal{CP}$-odd parts are suppressed since they only contribute to observables beyond tree level.

In my work I focus on the coupling of the Higgs boson to τ leptons. The decay $h \to \tau^+\tau^-$ is of particular interest since the τ lepton, to a certain extent, self-analyses its polarization via its weak decay into leptons and hadrons. In principle, this enables the direct use of the "optimal observable method".

In order to study the possible advantages in applying this method to measure the $\mathcal{CP}$-odd Yukawa coupling, as opposed to the observables used in the past, I have started a phenomenological study. In this study I include the leptonic decay of the τ leptons as well as the $\pi^{\pm}\nu_{\tau}$ and $\pi^{\pm}\pi^{0}\nu_{\tau}$ final states. The hard process as well as the decay of the τ leptons is simulated using the event generator Pythia8. Using these generated events at different Higgs $\mathcal{CP}$ mixing-angles, where the mixing-angle ϕ is defined according to the Yukawa Lagrangian

$$\mathcal{L}_{h\tau\tau} = \kappa g_{h\tau\tau} \bar{\Psi}_{\tau} \left(\cos\phi + \sin\phi \; i\gamma^{5} \right) \Psi_{\tau} h,$$

I estimate the sensitivity of the "optimal observable" in order to compare it against the sensitivity of observables used in the past. In my talk I will present the theory background needed in order to construct the used "optimal observable" as well as the challenges faced in the phenomenological study. Furthermore I will present ideas in order to improve on the current situation and to resolve experimental challenges in using this observable in practise.