Probing Higgs-Tau Interactions: Precision Measurements and CP Studies in Electron-Positron Collisions at FCC-ee and Proton-Proton Collisions at $\sqrt{s} = 13.6$ TeV with CMS

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The discovery of the Higgs boson in 2012 opened the way to a rich experimental program aimed at pinning down the boson's properties, in an effort to understand the nature of the Electroweak Symmetry Breaking (EWSB) mechanism and, in turn, the Standard Model (SM). In particular, the precise measurement of the Yukawa couplings to the SM particles could shed light on small deviations leading to new physics beyond the SM. In this sense, the Higgs coupling to taus is of considerable interest, given that the branching ratio of the channel is the highest among the leptons, and further studies on the Higgs J^{PC} quantum numbers are favored in this channel by effects appearing at tree level in an accessible topology. In this thesis, the capabilities of two different colliders are explored in the $H \rightarrow \tau\tau$ channel.

The first part of the project starts with the investigation of future colliders, in particular, the Future Circular Collider (FCC), which stands at the forefront of the European Strategy for Particle Physics as the future Higgs factory. We concentrated on the electron-positron stage, which provides a clean environment with unprecedented luminosity, enabling accurate tau decay reconstruction - unlike hadron colliders, where high event multiplicity can obscure critical information. This facilitates precision studies of processes involving tau leptons. The work analyzed Monte Carlo generated events with a comprehensive study of the possible backgrounds. A fast simulation of the IDEA detector concept, one of the main designs proposed for FCC-ee based on a short-drift wire chamber and a dual-readout calorimeter, is also performed.

Precise tau lepton reconstruction is critical. We evaluated and developed various methods for tau reconstruction at FCC-ee, utilizing available software and modern machine learning techniques by identifying visible decay products and reconstructing tau neutrinos, by exploiting the missing energy in the events. Our focus was primarily on hadronic tau decays, beginning with the initial reconstruction of jets, as leptonic tau decays can be reconstructed directly from isolated electrons and muons.

This allowed us to estimate the achievable relative uncertainty on the cross-section of the Higgs decay into a pair of taus in the ZH production channel at FCC-ee, at $\sqrt{s} = 240$ GeV and $\sqrt{s}$ =365 GeV, and from the vector boson fusion (VBF) channel at the top threshold. The current measurements by CMS and ATLAS for these channels on the product $\sigma \cdot BR(H \rightarrow \tau\tau)$, normalised to the SM predictions, are respectively $\mu_{ZH} = 1.00^{+0.62}_{-0.59}$ and $\mu_{ZH} = 1.33^{+0.61}_{-0.57}$ for ZH and $\mu_{VBF} = 1.00^{+0.21}_{-0.18}$ and $\mu_{VBF} = 0.86^{+0.17}_{-0.16}$ for VBF, resulting in circa 60% relative uncertainty from ZH production and 20% for VBF. We studied how FCC-ee will be able to achieve sub-per-cent precision in the ZH channel, improving the current knowledge by two orders of magnitude. In the VBF channel, the improvement is of a factor 2 given the low cross-section expected at $\sqrt{s}$ =365 GeV compared to the $\sqrt{s} = 13.6$ TeV runs at the LHC, while still being able to show how a dedicated Higgs factory can give powerful insight into the Higgs sector.

Building from this, we estimate the achievable constraints on Standard Model Effective Field Theory (SMEFT) operators responsible for a CP-odd Higgs in the ZH channel at $\sqrt{s} = 240$ GeV. To extract the Higgs boson spin information, we use the charged prongs in the one-prong decays or the pion with the same sign as the tau, identified as coming from the ρ^0 resonance by finding the pair that matches the invariant mass, in three-prong decays to define a zero-momentum frame to represent the Higgs rest frame. We then need to consider additional discrimination to avoid destructive interference between differently polarised states of the meson to finally construct an angular variable with the tau prongs in this frame in the range $[-\pi, \pi]$ where the periodicity is directly related to the Higgs boson spin. We considered up to dimension-6 operators and included all relevant tau decays, accounting for circa 70% of all possible tau pair decays, in conjunction with $Z \to ee$, $Z \to \mu\mu$ and $Z \to qq$. A comparison with the more common anomalous coupling method to introduce a CP-odd Higgs boson is performed to have a direct comparison to existing studies for both current and future experiments.

The second part of the project concerns measurements of the $H \to \tau\tau$ cross-section at the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC) at CERN, using the data from Run 3 taken between 2022 to 2024, with a total integrated luminosity of about 170 fb^{-1} at $\sqrt{s} = 13.6$ TeV. Hadronic tau reconstruction in CMS is handled by DeepTau 2.5, a deep convolutional neural network. The methods used follow the Simplified Template Cross Section (STXS) framework, devised by LHC experiments to minimize the theoretical uncertainties that are directly incorporated into the measurements as much as possible, while also allowing for the combination of measurements between different decay channels and experiments. Using the Run 3 extensive dataset allows the current measurement to be improved on account of the luminosity achieved. This part of the project has just begun in recent months, proposing one of the first analyses making use of the 2024 dataset.