PhD Thesis Proposal

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December 17, 2024

Since the discovery of the Higgs boson in 2012 by the ATLAS and CMS collaborations at the Large Hadron Collider (LHC) [1–3], a series of studies have been confirming the predicted values of its Yukawa couplings to fermions in the Standard Model (SM) [4, 5]. Experimental confirmations include the couplings to top quarks through associated production [6,7], to τ leptons [8,9], and to b quarks [10,11]. The amplitudes of the couplings are linearly proportional to the fermion masses, limiting the sensitivity to first and second generation quarks and leptons.

The aim of my thesis is to probe the Higgs couplings to first and second generation quarks. If the observed coupling strengths align with theoretical predictions, it will support the validity of the Standard Model (SM). Deviations, however, could indicate the need for modifications to the electroweak theory. Given the available data within an estimated time frame of my PhD program, it is more realistic to place upper limits on the branching fractions (BR) of the decay channels rather than to expect an observation of an excess of signal.

There are several challenges facing the direct searches for the decays of the Higgs to first and second generation quarks ($\mathrm{H} \to \mathrm{q\overline{q}}$). First, the large QCD background limits the sensitivity in direct searches. While the CMS and ATLAS collaborations have announced results on direct searches for charm quarks ($\mathrm{H} \to \mathrm{c\overline{c}}$) [12,13], the studies rely on the small production cross section of $\mathrm{pp} \to \mathrm{V}(\to \mathrm{ll}, \mathrm{l}\nu_\mathrm{l})\mathrm{H}$ and novel jet flavor identification algorithms to limit the QCD background. Second, the Yukawa couplings of the Higgs boson to lighter quarks decrease proportionally with their masses. As a result, the branching fractions of $\mathrm{H} \to \mathrm{c\overline{c}}$ are 20 times smaller than that of $\mathrm{H} \to \mathrm{b\overline{b}}$, and the branching fractions of $\mathrm{H} \to \mathrm{s\overline{s}}$, $\mathrm{u\overline{u}}$, $\mathrm{d\overline{d}}$ are even less [14]. Finally, the reconstruction of the final states itself is a challenge due to the hadronization of the quarks. Due to these difficulties, alternative search channels have been proposed.

For my thesis research, I propose to analyze two alternative search channels. The first analysis is of the type, $\mathrm{H} \to \mathrm{M}\gamma$, where M is a light-quark meson among one of the following: $\rho(770)^0$, $\phi(1020)$, or $\mathrm{K}^*(892)^0$ [15]. The $\rho(770)^0$ is a bound state of u, d quarks and antiquarks, and the $\phi(1020)$ is a bound state of s quark and antiquark. Hence, the search channel probes the couplings to the u, d, and s quarks. In the flavor-conserving decays to the $\rho(770)^0$ or $\phi(1020)$, there are two processes that interfere destructively. One process involves a direct Higgs Yukawa coupling to the quarks, whereas the other couples indirectly via an off-shell photon or Z boson. It is the direct contribution that is sensitive to modifications of the Yukawa couplings. The $\mathrm{K}^*(892)^0$ is a bound state of $(\mathrm{d}, \overline{\mathrm{s}})$ or $(\overline{\mathrm{d}}, \mathrm{s})$, which is a probe to the flavor-violating coupling of the Higgs. It is included in the analysis because it has the charged di-track final state similar to that of the flavor-conserving probes. The predicted Standard Model branching ratio for the processes $\mathrm{H} \to \phi\gamma$, $\mathrm{H} \to \rho\gamma$, and $\mathrm{H} \to \mathrm{K}^{*0}\gamma$ are $\mathcal{O}(10^{-5})$, $\mathcal{O}(10^{-6})$, and $< \mathcal{O}(10^{-11})$, respectively.

The second analysis probes the couplings to charm quarks via $\mathrm{H} \to \mathrm{J}/\psi + \mathrm{c\overline{c}}$. The Higgs couples to two c quarks, which further produces a total of four intermediary c quarks via the charm-quark fragmentation mechanism. Two are bounded to form a J/ψ meson and two undergo hadronization as jets [16]. The clean decay signature of $\mathrm{J}/\psi \to \mu^+\mu^-$ reduces the QCD background. Unlike the direct search via $\mathrm{H} \to \mathrm{c\overline{c}}$, this channel does not rely on the VH production. Instead, it can take advantage of the ggH production mode, which has a cross section of $\mathcal{O}(10^2)$ times that of the VH mode. The branching fraction of $\mathrm{H} \to \mathrm{J}/\psi + \mathrm{c\overline{c}}$ is about 2×10^{-5}. With the Run 2 integrated luminosity at around 150 fb^{-1} and a projected Run 3 integrated luminosity between 250 and 300 fb^{-1}, it is expected that roughly 25 signal events are produced during the Run 2 and 3 combined data-taking period at the CMS experiment.

The first analysis began in 2021 and was published in 2024 with the full Run 2 data from the CMS experiment [17]. It found exclusive upper limits at 95% CL to the branching fractions of $\mathrm{H} \to \mathrm{M}\gamma$. The limits for $\mathrm{M} = \rho(770)^0$, $\phi(1020)$, and $\mathrm{K}^*(892)^0$ are 3.7×10^{-4}, 3.0×10^{-4}, and 3.1×10^{-4}, which are the most stringent upper limits to date. The paper has been submitted to Physics Review Letters B. Therefore, the remainder of my thesis research will be on the second analysis.

The analysis of the search for $\mathrm{H} \to \mathrm{J}/\psi + \mathrm{c\bar{c}}$ began in 2024. As of now, we are studying the Monte Carlo (MC) simulation samples for signal and background with the conditions for 2018, the final year of Run 2. The major background events come from an inclusive J/ψ production in association with light g, q jets, $\mathrm{b} \to \mathrm{J}/\psi(\to \mu^+\mu^-) + X$ decays with a displaced di-muon vertex, and contamination from the $\mathrm{H} \to \mathrm{J}/\psi + \mathrm{b\bar{b}}$ decays. The progress which we have made in our analysis so far consists of reconstructing the signal events and reducing the background through optimization of selection cuts. The cuts on the variables include the displacement of the di-muon vertex in the signal as well as the angular distribution of the final states. However, the invariant mass of the reconstructed Higgs candidate has a poor resolution. As a first step to resolving this problem, we have removed from the charm jets the muons which originate from the J/ψ. In 2025, we plan to recalibrate the charm-tagging algorithm and recalculate the jet energy scale correction (JEC). These steps are necessary in order to ensure sensitivity that is comparable to the direct search. As of now, the existing charm-tagging algorithm is optimized to find a charm jet of higher momentum, and does not provide any meaningful discrimination between signal and background events in our analysis. While it is possible to reconstruct the signal events without the usage of any charm-tagger, a detailed study into the optimization of a charm-tagger can potentially lead to a greater sensitivity. The performance of the charm-tagger can be calibrated with the WW samples, where one W decays leptonically and the other decays to a pair of q $(\mathrm{u}, \mathrm{d}, \mathrm{s}, \mathrm{c}, \mathrm{b})$ jets. It is projected that a majority of the analysis effort will be spent on the optimization of the charm-tagger.

I plan to relocate to CERN in June, 2025 for my thesis research. The primary benefit is that I have immediate access to the collaborators involved in the $\mathrm{H} \to \mathrm{J}/\psi + \mathrm{c\bar{c}}$ analysis. I will stay there until my graduation, which will be possible once the analysis successfully undergoes the collaboration-wide review process. The approximate date of the publication depends on many factors, among which is the amount of data from Run 3 the collaboration deems necessary for the analysis. The Run 3 period of data-taking is scheduled to be finished by May 2026 for p-p collisions. Hence, it is possible, or even likely, that my graduate will not take place until after the Fall Semester of 2026.

My thesis research will contribute to further advancing our knowledge of the Higgs Yukawa couplings to first and second generation quarks. This area of knowledge is essential to completing our verification of the electroweak theory of the Standard Model, and is challenging due to the rarity of the decays. The searches via Higgs radiative decays and charm-fragmentation will either complement the direct searches or compensate for the lack thereof. With the available data from the CMS experiment at the LHC, we expect to place stringent limits on the branching fractions of these decays, and by extension, on the Yukawa coupling modifiers.

References

[1] ATLAS Collaboration. Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. *Phys. Lett. B* **716**, 1–29 (2012).

[2] CMS Collaboration. Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC. *Phys. Lett. B* **716**, 30–61 (2012).

[3] CMS Collaboration. Observation of a new boson with mass near 125 GeV in pp collisions at $\sqrt{s} = 7$ and 8 TeV. *J. High Energ. Phys.* **2013**, 30–61 (2012).

[4] ATLAS Collaboration. A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery. *Nature* **607**, 52–59 (2022).

[5] CMS Collaboration. A portrait of the Higgs boson by the CMS experiment ten years after the discovery. *Nature* **607**, 60–68 (2022).

[6] ATLAS Collaboration. Observation of Higgs boson production in association with a top quark pair at the LHC with the ATLAS detector. *Phys. Lett. B* **784**, 173–191 (2018).

[7] CMS Collaboration. Observation of $t\bar{t}H$ Production. *Phys. Rev. Lett.* **120**, 231801 (2018).

[8] CMS Collaboration. Observation of the Higgs boson decay to a pair of τ leptons with the CMS detector. *Phys. Lett. B* **779**, 283–316 (2018).

[9] ATLAS Collaboration. Cross-section measurements of the Higgs boson decaying into a pair of τ-leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector. *Phys. Rev. D* **99**, 072001 (2019).

[10] ATLAS Collaboration. Observation of $H \to b\bar{b}$ decays and VH production with the ATLAS detector. *Phys. Lett. B* **786**, 59–86 (2018).

[11] CMS Collaboration. Observation of Higgs Boson Decay to Bottom Quarks. *Phys. Rev. Lett.* **121**, 121801 (2018).

[12] ATLAS Collaboration. Direct constraint on the Higgs–charm coupling from a search for Higgs boson decays into charm quarks with the ATLAS detector. *Eur. Phys. J. C* **82**, 717 (2022).

[13] CMS Collaboration. Search for Higgs Boson Decay to a Charm Quark-Antiquark Pair in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV. *Phys. Rev. Lett.* **131**, 061801 (2023).

[14] CERN. CERN Yellow Reports: Monographs, Vol 2 (2017): Handbook of LHC Higgs cross sections: 4. Deciphering the nature of the Higgs sector. 2017. 10.23731/CYRM-2017-002.

[15] M. König and M. Neubert. Exclusive radiative Higgs decays as probes of light-quark Yukawa couplings. *J. High Energ. Phys.* **2015**, 12 (2015).

[16] T. Han, A.K. Leibovich, Y. Ma et al.. Higgs boson decay to charmonia via c-quark fragmentation. *J. High Energ. Phys.* **2022**, 73 (2022).

[17] CMS Collaboration. Search for the Higgs boson decays to a ρ^0, ϕ, or K^{*0} meson and a photon in proton-proton collisions at $\sqrt{s} = 13$ TeV. 2024. 10.48550/arXiv.2410.18289.