Novel Heavy-Flavor Tagging with 4D-Reconstruction to Measure the Higgs Potential at Future Colliders

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The Higgs Boson self-coupling is one of the last remaining unobserved predictions of the Standard Model. It is also one of the main science drivers of the High-Luminosity LHC (HL-LHC) proton-proton collider physics program and the corresponding Phase 2 upgrade of the CMS detector [1]. By the end of the operational period of the HL-LHC, we expect a first observation and measurement of the Higgs self-coupling from the analysis of a 3000 to 4000 fb^{-1} [2] dataset. This observation requires combination of multiple channels, all exploiting heavy-flavor tagging. Enhanced tracking capabilities made possible by timing detectors will bring new discriminating variables to heavy flavor tagging for selecting Higgs decays to b-quarks, the largest branching fraction of the Higgs Boson. I will develop these, along with other improvements afforded by tracking with precision timing, to ensure the discovery of di-Higgs production at the HL-LHC. Additionally, these developments ensure a rich physics program at the proposed 27 TeV High-Energy LHC [3] (HE-LHC) or 100 TeV Future Circular Hadron Collider [4] (FCC-hh), where this measurement would be carried out with sufficient precision to fully map the Higgs potential shape, and where the experimental environment is expected to be more demanding. I propose to use the computing expertise, silicon detector experience, and facilities available at FNAL to develop the software for achieving these physics goals, and to use this software in simulation to guide the design of future collider detectors, as well as possible post-Phase-2 upgrades to the CMS detector.

At the HL-LHC, only one collision out of 200 occuring simultaneously is usually of interest the rest being ”pile-up”. This problem is made worse at the proposed HE-LHC and FCC-hh colliders where 800-1000 simultaneous proton-proton interactions are expected. Given the large amount of uninteresting collision products, it is important to set apart the particles produced in interesting collisions so as to extract the most relevant physics information. If the relevant content of the event is not adequately filtered, the negative performance impact propagates from reconstruction to high-level analysis, both in terms of physics as well as computing.

For example, when using only 3D information in tracking in HL-LHC conditions there is a 10% reduction in isolated muon identification efficiency at constant background rejection level. This also leads to an increase of 20% on the corresponding high-level trigger rate, and there are similar degradations for heavy-flavor jet tagging coming from the reconstruction of spurious secondary vertices. At the HE-LHC and FCC-hh, the beam crossings are so densely populated with collisions that more fundamental issues arise, such as exponentially large combinatorics hurting tracking performance and the inability to identify low momentum W, Z, or H bosons at the trigger level, which limits the physics program [3, 4]. These issues can be overcome by the use of precision timing detectors with fine spatial granularity.

The essential detector elements for extracting the information about the most interesting collision in high pile-up are the spatial segmentation of tracking detectors [5] and, more recently, the precise time-tagging of minimum-ionizing (charged) particles using a dedicated MIP Timing Detector (MTD) [6]. This, combined with the precise time-tagging of electromagnetic and hadronic showers [7, 8] provides comprehensive information on the fine time structure of the event. This is the first detector in a collider experiment with such fine granularity and exacting timing precision, and improving the spatial segmentation of silicon precision-timing sensors will be critical for future. Using time as an additional dimension, measured both in tracking and calorimetry, eases the identification of interesting collisions products and brings new capabilities to the CMS detector like particle ID for charged particles. This has a positive additional effect on reconstruction and identification of physics objects and, eventually, on all physics analyses.

Global precision timing, such as that brought to the table by the MTD and High-Granularity Calorimeter in CMS, is not yet fully exploited in the highest-level event interpretation. Similarly, there are presently no tracking algorithm implementations that include timing information in the pattern recognition step. Finally, next-generation timing detector hardware, i.e., fully-4D tracking detectors, with enhanced position and timing resolution can significantly improve the quality of charged-particle reconstruction at future colliders.

I pioneered the preliminary explorations into 4D reconstruction described in the MTD Technical Proposal, contributed heavily to developing its physics case, and served as interim project manager during the formation of the international project. Furthermore, Fermilab is well suited as a location for solving these problems and performing the associated analysis due to the lab's sustained involvement in heavy flavor tagging development, silicon detector development, and developing the MTD detector construction project. A 20% improvement in the sensitivity of CMS to the di-Higgs production cross section in HL-LHC is possible using timing. Additionally, tracking and event reconstruction with timing will be critical to executing the physics vision of the future colliders. To achieve these goals I will pursue the following topics in order to reach a more integrated and overarching use of timing information in future detectors:

- Heavy Flavor tagging with timing: For the proposed di-Higgs analysis, I will improve upon the heavy flavor tagging algorithms by including new information that is unique to detectors with charged-particle timing. For instance, time of flight particle ID (TOF-PID) can be used to provide kaon and proton tagging, both being decay products of heavy-flavor mesons.

- 4D Tracking & Particle Flow (PF): I will extend the traditional tracking and PF formalisms that drive the CMS physics reconstruction to fully include timing information, integrating the notion of 4D-tracking being cross referenced with the full, space, energy, timing information of the calorimetry, in addition to measuring particle velocity and providing TOF-PID.

- Silicon Timing Pixel Detector R&D: I will engage in the simulation of next generation of silicon timing devices, beyond those used in the CMS Endcap Timing Layer (ETL) [6], to determine how such a detector and its output would be implemented in the tracking systems of future particle physics experiments.

Given the current LHC performance, leveraging timing detectors and the associated reconstruction techniques will be critical if the HL-LHC operates at higher-than-expected pileup. It also significantly changes the way detector design at future hadron colliders should be evaluated. I propose to engage in the simulation of next-generation silicon precision timing devices and understand how signals from such devices can be digitized for high-speed readout. Based on this understanding, I will develop algorithms as part of this research program to establish the groundwork needed for developing 4D trackers. Added benefits of full-4D tracking include the reduction of spurious tracks and the addition of enhanced reconstruction capabilities, like the time-of-flight particle identification for high-momentum tracks, at the level-one and high-level trigger as well as in offline physics analyses. High-momentum particle identification, for instance, provides tagging of kaons and other open-flavor mesons, improving the jet-flavour tagging purity needed in di-Higgs analyses.

The software technologies that I am proposing to develop pave the way for a hardware development course that provides innovative detector building blocks and which mitigate, or even remove, limitations of particle physics detectors coming from instantaneous luminosity and computing needs. The additional benefits to heavy-flavor tagging that precision timing affords make the identification of Higgs decays to b-quarks significantly better, paving the way for earlier and deeper understanding of di-Higgs production. These new building blocks will enable the HEP community to pursue a more challenging and captivating program of future accelerators and detectors towards understanding the fundamental composition of nature.

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