Snowmass Letter of Interest

New Heavy Scalars though Pair Production at High-Energy Colliders

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1 Introduction

The large collision energy and Higgs boson h discovery at the LHC [1, 2] bring exciting and relatively new elements into our field which dramatically extend the reach for new physics though the study of multi-boson production. Spin and couplings measurements of h [3–7] are consistent with a SM Higgs boson [8–13] with a mass of 125 GeV [14]. A detailed understanding of the mechanism of electroweak symmetry breaking (EWSB) is a primary goal of the (HL-)LHC. While the Higgs boson discovery and measurements provide insight on EWSB, there is substantial room for new physics to which multi-boson production is sensitive.

Higgs bosons can be pair-produced in the SM via fermion or boson loops (box) or the h self-interaction. Observing the $h \to hh$ process and establishing the strength of the h trilinear self-coupling (λ_{hhh}) will be a definitive test of EWSB and one of the primary physics goals for the HL-LHC and beyond. Although $\sigma(hh)$ is very small in the SM due to destructive interference between the box and h self-interaction diagrams [15, 16] and impossible to measure with current data, in SM extensions $\sigma(hh)$ can be enhanced. Modifications to the top Yukawa coupling or λ_{hhh} can enhance non-resonant hh production. Other theories predict heavy resonances decaying into hh, such as a heavy spin-0 scalar (H) in 2HDM models [17] and spin-2 Kaluza-Klein (KK) excitations of the graviton G^*_{KK} in the bulk Randall-Sundrum model [18, 19]. In SM extensions with an additional real [20] or complex [21] scalar field S, resonant hS and SS production [22–24] can lead to an enhanced hh rate, motivating the *broad search* for pairs of scalar bosons with the same mass (hh or SS) or *different* masses (hS) and this Letter of Interest.

There is increasing interest in hS and SS as promising pathways to early discovery at the (HL-)LHC as compared to restricting searches to only pairs of on-shell 125 GeV Higgs bosons (h). Assuming SM-like couplings, $bbWW$ will be the dominant hS decay mode for $m_S \gtrsim 135$ GeV and will be one of the two dominant SS decay modes for 135 GeV $\lesssim m_S \lesssim 160$ GeV. Theorists are strongly encouraging experimentalists to further explore the rich possibilities of extra scalars, especially to provide a stringent test of the Next-to-Minimal Supersymmetric SM (NMSSM) [25].

2 Opportunities and Outlook

We propose a study as part of Snowmass to will explore the challenges and opportunities of new physics searches in $X \to hS$ and $X \to SS$ production. This should involve a comprehensive phenomenological study to explore the most promising final states and production modes over the m_X and m_S parameter space.

The $bbWW$ channel poses a wide range of final state topologies that can be exploited to maximize sensitivity to hS and SS production. The $S \to WW^{(*)}$ final state can be categorized by the number of final state leptons, 0, 1 and 2. Furthermore, it can be categorized by the angular distributions of the W decay products. For small m_S and small p_{T}^S, the decay products will all be well-separated in the detector (resolved). For $p_{\mathrm{T}}^S \gg m_S$, the decay products will have very small angular separation (boosted). In the limiting case of large m_S and small p_{T}^S, the Ws will be well-separated but individually boosted (split-boosted).

A comprehensive search will require developing and implementing cutting-edge techniques to exploit the entire range of possible final states. These include machine-learning (ML) techniques to identify and reconstruct the 2-lepton decay of S with an unknown mass, novel techniques to identify real leptons overlapping with real boosted hadronically decaying W bosons in the boosted 1-lepton topology, and using advanced ML techniques to identify the very dense 4-prong decays of highly boosted 0-lepton $S \to WW$ decays.

In addition to exploiting the $S \to WW$ decay topologies, there are many opportunities to improve the identification of $h \to b\bar{b}$ and $S \to b\bar{b}$ decays. One of the limiting factors in existing searches that include a resolved $h \to b\bar{b}$ decay is the minimum p_{T} threshold for b-tagged small-R jets. Novel approaches such as using variable-R jets built from charged particle tracks could be used to overcome this limitation. For boosted $S \to b\bar{b}$ decays (necessary for SS searches), ML techniques can be used to develop a mass-agnostic tagger.

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