Probing the Electroweak Phase Transition with Exotic Higgs Decays – a Snowmass LOI

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I. MOTIVATION

An important goal of the Higgs physics program at the LHC and proposed future colliders is to explore the nature of the Higgs potential and shed light on the mechanism of electroweak symmetry breaking (EWSB). Given our current understanding of the Higgs boson, we do not yet know how EWSB occurred in the early Universe. The Standard Model (SM) predicts EWSB at a smooth thermodynamic crossover. However, it may well be that new physics beyond the SM (BSM) alters this picture, resulting in a first-order electroweak phase transition (EWPT). A first-order EWPT could have supplied one of the necessary ingredients for generating the observed baryon asymmetry of the Universe through the mechanism of electroweak baryogenesis [1], produced an observable stochastic gravitational wave (GW) background [2, 3], and could have affected the abundance of primordial relics such as dark matter with masses at or above the electroweak scale [4]. Aside from these important cosmological implications, mapping out the phase diagram of the electroweak sector is an important undertaking in its own right, analogous to determining the phase diagram of QCD. For these reasons, and many more, it is important for the high energy physics community to explore the nature of the EWPT as thoroughly and robustly as possible in present-day and future experiments.

Many BSM scenarios predicting a first-order electroweak phase transition are currently being tested at the LHC (see e.g. [5] for a review). An important class of such models are those in which the EWPT is driven first-order by the Higgs coupling to a new *light* particle [6]. As argued in Ref. [7], if the new degree of freedom is below $\sim m_Z$, it must be a singlet-like scalar, which we denote as s. The direct production of such scalars at colliders is governed by the mixing angle with the Higgs boson (h), which can be small or absent entirely if additional symmetries are present. These light new particles can therefore be difficult to detect directly. Despite the potentially small mixing with the Higgs, Refs. [7, 8] recently emphasized that such scalars can still have a dramatic impact on the EWPT, provided the scalar coupling to the SM-like Higgs field is large enough. This coupling also controls the $h \to ss$ branching ratio when $m_s < m_h/2$. Therefore, these scalars provide a compelling target for exotic Higgs decay searches, both at the LHC and future colliders.

Exotic Higgs decays are a cornerstone of the discovery program at both current and future colliders [9–13]. At the HL-LHC, detector upgrades, new trigger and analysis strategies, and increased data sets will steadily increase the sensitivity to small branching ratios, especially in subdominant but cleaner final states (notably $h \to ss \to b\bar{b}\tau\tau$, $h \to$ invisible) [14, 15]. Meanwhile, proposed e^+e^- colliders offer lower integrated luminosities but substantially lower backgrounds, resulting in excellent sensitivity to challenging all-hadronic modes, notably $h \to ss \to 4b$ [16]. The aim of the proposed white paper is to establish how searches for exotic Higgs decays can inform our understanding of the early Universe. It will clearly establish the portions of parameter space that are compatible with both exotic Higgs decays and first-order phase transitions, and provide clear and achievable targets for current and future colliders.

II. CURRENT STATUS AND RECENT RESULTS

Refs. [7, 8] have performed detailed studies of the collider signatures associated with such scenarios. In Ref. [7], analytic and numerical arguments were used to suggest that requiring a strong first-order EWPT together with a small amount of mixing between the Higgs and the new scalar implies a lower bound on the magnitude of the hss coupling, and therefore a lower bound on the Higgs branching ratio for $h \to ss$ provided $m_s < m_h/2$. Ref. [8] studied a wider range of mixing angles in models with a spontaneously-broken Z_2 symmetry, finding qualitatively similar results when restricting to the small-mixing regime. Ref. [8] also investigated the interplay of exotic Higgs decay searches with measurements of the Higgs self-coupling and GW experiments in this scenario. Both studies suggest that searches for exotic Higgs decays at the LHC and future colliders can play a vital role in probing the nature of the EWPT in models with light scalars. Next-generation experiments are likely to either unearth evidence for or concretely rule out this class of scenarios.

III. OBJECTIVES

In light of these results, we propose a Snowmass study on the implications of exotic Higgs decay searches at colliders for the early Universe. We envision the objectives of such a study to include:

- Highlighting and quantifying the extent to which exotic Higgs decay measurements at the LHC and future colliders are sensitive to a first-order EWPT catalyzed by light BSM degrees of freedom. Both scenarios with and without a Z_2 symmetry are of interest.
- Identifying opportunities for future study that will enable current and next generation of collider experiments to harness the full power of the precision Higgs program in exploring the nature of the EWPT.

We welcome the participation of other members of the community who may be interested to join us in this study.

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