Snowmass2021 - Letter of Interest

Complementarity between collider and gravitational wave signatures of a first-order electroweak phase transition

Thematic Areas: (check all that apply □/■)

□ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
□ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
■ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
■ (EF02) Higgs as a Probe of New Physics
■ (EF09) BSM: General Explorations
■ (TF09) Astro-particle physics and cosmology

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Abstract:
We investigate the complementarity between collider and gravitational-wave probes of beyond-standard model physics that can induce a first-order phase transition in the Higgs condensate. We will identify where, in the parameter space of various representative scenarios, there is overlap between LISA and other future gravitational-wave probes compared to the high-luminosity LHC, high-energy LHC, a 100 TeV pp collider, and prospective e^+e^- colliders (CEPC, FCC-ee, ILC, CLIC).

Keywords: electroweak phase transition, scalar fields, gravitational waves, bubble nucleation.

1 Motivation and Background

Determining the thermal history of electroweak symmetry breaking (EWSB) is an important challenge for particle physics and cosmology. Lattice simulations indicate that EWSB in the Standard Model (SM) occurs through a crossover transition, while the presence of new physics beyond the SM (BSM) could alter this thermal history. The occurrence of a first order EWSB transition would be particularly interesting, providing the needed pre-conditions for generation of the cosmic matter-antimatter asymmetry via electroweak baryogenesis[1] and sources for potentially observable gravitational radiation. Generic arguments have been made[2] that if such an alternate thermal history exists, the new particles involved cannot be too heavy with respect to the SM electroweak temperature ($T_{\rm EW} \sim 140$ GeV), nor can they interact too feebly with the SM Higgs boson. These arguments apply while the new bosons are present in the thermal bath and thermal equilibrium with the SM Higgs boson. Corresponding quantitative expectations have been calculated[2] for masses and interaction strengths which imply that their effects could in principle be observed (or ruled out) by prospective next generation high energy colliders. These arguments provide a quantitative, parametric understanding of results obtained in a wide range of explicit model studies. Relationships have been derived between BSM model parameters and the electroweak temperature, and broad contours of collider phenomenology pertaining to a non-standard history of EWSB have been obtained[2]. Results from a plethora of detailed model studies with extended scalar sectors are broadly consistent with these general arguments and quantitative expectations.

While collider studies provide an indirect probe of a possible first order electroweak phase transition (EWPT), future gravitation wave (GW) missions can provide direct access to the primordial gravitational waves produced in such a transition. Initial studies of the reach of the LISA mission have been reviewed in Ref.[3], where representative model predictions for benchmark parameter choices have been compared with the LISA sensitivity. For a related recent general study, see Ref.[4]. In addition, there exist several additional projects under consideration, including the Taiji[5], Tianqin[6], Big Bang Observer[7], and the Deci-Hertz Interferometer Gravitational wave Observatory (DECIGO)[8,9].

In this context, it is of interest to determine (a) to what extent the next generation GW probes will probe the landscape of first order EWPT-viable scenarios and (b) what level of synergy and complementarity exists between GW and collider probes. While several recent studies have explored these questions in model-specific studies[10–15], one would like to obtain a more comprehensive picture, in the spirit of the EWPT-collider connection given in Ref.[2]. Indeed, while it appears promising for future colliders to provide a comprehensive indirect probe the first order EWPT landscape, it is also important to determine under what general conditions (scenarios, regions of parameter space) GW detectors could yield conclusive evidence for such an EWSB transition.

To that end, the first end-to-end nonperturbative analysis of the gravitational wave power spectrum from first-order EWPT, using the framework of dimensionally reduced effective field theory and preexisting nonperturbative simulation results, has been published[16]. This analysis shows that when the new scalars are sufficiently heavy that a low-energy, SM-like effective field theory applies, one may expect a first order EWPT with gravitational wave signatures too weak to be observed at existing and planned detectors. This implies that for this regime, colliders are likely to provide the best chance of exploring the phase structure of such theories. Transitions strong enough to be detected at gravitational wave experiments require dedicated nonperturbative studies of the corresponding BSM models. It is, thus, of interest to determine the important collider signatures most relevant to these different regimes.

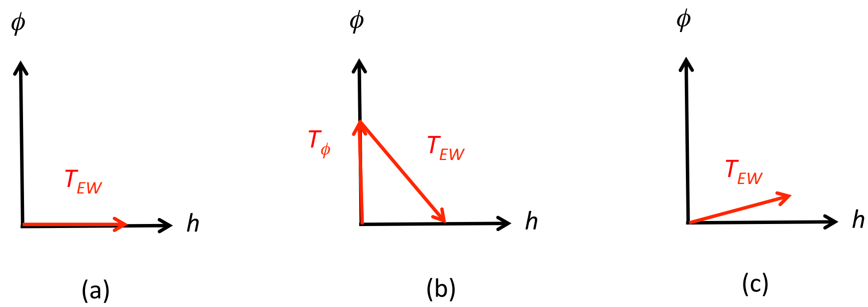

Figure 1: Representative thermal histories of EWSB in the presence of the Higgs field h and additional neutral scalar ϕ. (a) A one-step transition to the pure Higgs phase at temperature $T_{\rm EW}$; (b) a two-step transition, with a first step to the ϕ-vacuum at $T_\phi > T_{\rm EW}$ followed by a second step to the pure Higgs phase; (c) a one-step transition at temperature $T_{\rm EW}$ to the a mixed phase in which both h and ϕ have non-zero vacuum expectation values.. Figure taken from Ref.[2] (to appear in JHEP).

2 Objectives

We plan to study the prospects for exploring the electroweak phase diagram through a combination of collider and gravitational wave experiments, using well-motivated BSM scenarios with additional scalar fields. We consider the sensitivity to such physics at the high-luminosity LHC, a high-energy LHC and a 100 TeV pp collider, as well as the ILC, FCC-ee and CEPC, and CLIC e^+e^- colliders. Specifically:

- In the plane of parameters α and β/H_* relevant to GW generation, identify the reach of various future collider probes and compare with (a) LISA and other (prospective) future GW signal to noise sensitivity curves; (b) the region of applicability for effective field theory.
- Delineate the different classes of collider observables and their sensitivity in the (α, β/H_*) plane.
- Carry out the foregoing analysis for representative scalar sector extensions and thermal histories as outlined in Fig. 1.

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