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Complementarity Studies of the Higgs Sector with Colliders and Gravitational Wave Detectors

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

■ (EF01) EW Physics: Higgs Boson properties and couplings
■ (EF02) EW Physics: Higgs Boson as a portal to new physics
■ (TF07) Collider phenomenology
■ (TF9) Astro-particle physics & cosmology
■ (TF08) BSM model building
■ (CF7) Cosmic Probes of Fundamental Physics

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We propose to study the Higgs sector from two complementary directions: (*i*) precision calculations of stochastic gravitational waves coming from phase transitions and (*ii*) collider studies for new resonance searches at the LHC and future colliders, in particular, for di-Higgs production. Our goal is to establish benchmark points for various models that can be used by both communities in the future.

I. INTRODUCTION

Since the first direct detection of gravitational waves (GWs) by the LIGO and Virgo collaborations [1], a new interface has arrived in particle physics – its intersection with GW astronomy. While ground based GW detectors have their best sensitivity at frequencies $\sim \mathcal{O}(100)$ Hertz and their main targets are black hole and neutron star binaries, there is now growing interest in building space-based interferometer detectors for milli-Hertz or deci-Hertz frequencies. Many detectors have been proposed, such as the Laser Interferometer Space Antenna (LISA) [2], the Big Bang Observer (BBO), the DECi-hertz Interferometer Gravitational wave Observatory (DECIGO) [3], Taiji [4] and Tianqin [5]. The physical sources of GWs in this frequency band include supermassive black hole binaries [6], extreme mass ratio inspirals [7] and the stochastic background of primordial GWs produced during first order cosmological phase transitions [8].

This offers tremendous opportunities for theorists, as a new window to the early Universe opens up. Aspects of dark sector physics and baryon asymmetry can now be framed fruitfully in a language that lends itself to data from the GW frontier. The key connection is *phase transitions*, which on the one hand are a primary target of future GW experiments, and on the other are important features of scalar potentials and hence have historically been the target of collider physics.

The purpose of our proposal is to *explore the complementarity of future GW detectors and the LHC (and future particle colliders) in probing phase transitions in the early Universe.* This proposal builds on several papers by the authors where this complementarity was studied in the context of the singlet extended Higgs sector (xSM) [9–12]. In particular, the aspects that were studied include: (*i*) the EWPT patterns admitted by the model, and the proportion of parameter space for each pattern; (*ii*) the regions of parameter space that give detectable GWs at future space-based detectors; (*iii*) the current and future collider measurements of di-Higgs production, as well as searches for a heavy weak diboson resonance, and how these searches interplay with regions of parameter space that exhibit strong GW signals; and (*iv*) the complementarity of collider and GW searches in probing this model.

The purpose of our proposal is to bring together precision calculations of the gravitational wave spectrum in phase transitions with careful analysis of the Higgs sector at the LHC and future colliders. We describe the two aspects below.

II. PRECISION GRAVITATIONAL WAVE CALCULATIONS

In calculating the gravitational wave spectra, we will carefully account for several subtle issues, such as the bubble wall velocity, the super-cooled phase transitions, and the reduction in the gravitational wave production from sound waves outlined in recently conducted numerical simulations [13]. These constitute important ingredients towards a faithful characterization of the gravitational waves signals from the electroweak phase transition and its detection at future gravitational wave detectors.

There are two important advances in recent understandings of these problems:

(*i*) the reduction of the gravitational waves produced from the sound waves obtained in [13], which invalidates the previous naive generalization of these formulae to arbitrary values of v_w and α. We have incorporated this effect by applying a conservative reduction factor of 0.01 in our work; and

(*ii*) Ref. [14] initiated a detailed analysis of stochastic gravitational wave production from cosmological phase transitions in an expanding universe, studying both a standard radiation as well as a matter dominated history. A detailed analysis was performed for the dynamics of the phase transition including the false vacuum fraction, bubble lifetime distribution, bubble number density, mean bubble separation, etc., for an expanding universe. For the amplitude of the gravitational wave spectrum visible today, a suppression factor arising from the finite lifetime of the sound waves was found. This was compared with the commonly used result in the literature, which corresponds to the asymptotic value of the suppression factor. The asymptotic value is only applicable for a very long lifetime of the sound waves, which is highly unlikely due to the onset of shocks, turbulence and other damping processes.

In our complementarity analysis, both these issues will be incorporated into specific models. Currently, we are investigating the suppression factors in SMEFT, xSM, and models of confining hidden sectors, to obtain accurate benchmark predictions for the gravitational wave spectrum.

III. COLLIDER STUDIES FOR THE HIGGS SECTOR

Higgs pair production $pp \to hh$ provides a direct probe of the Higgs potential at colliders. This process is of central importance in measuring the triple Higgs coupling as well as new heavy scalar interactions in the Higgs sector via non-resonant and resonant di-Higgs searches, respectively. Current ATLAS and CMS high-luminosity projections indicate that the triple Higgs coupling will be constrained in the range $0.1 < \lambda_3/\lambda_{3,\mathrm{SM}} < 2.3$ at 95% CL [15, 16]. Resonant searches are also being performed resulting in significant limits. For the latter, the weak boson fusion process provides relevant additional new physics sensitivity [17]. The measurement of the Higgs potential, in particular the Higgs self-interactions, will remain as one of the prime targets for the Large Hadron Collider (LHC) and provides a strong motivation for future colliders.

Future gravitational wave experiments will provide complementary information to collider experiments on the shape of the Higgs potential. The conditions for strong first-order phase transition and generation of observable GW signals are, however, very restrictive to the profile of the Higgs potential. Working in the minimal extension of the SM with a new gauge singlet real scalar, we have shown that the production of signals relevant for future GW experiments, such as LISA, can favor depleted resonant and non-resonant di-Higgs rates at colliders for phenomenologically relevant regimes of scalar mixing angles and masses for the heavy scalar [12]. We performed a comprehensive study on the emergence of these di-Higgs blind spot configurations in GWs and also have shown that di-boson channels, ZZ and WW, can restore the phenomenological complementarities between GW and collider experiments in these parameter space regimes. We will extend this study to additional relevant BSM frameworks, such as the SMEFT and models with hidden sectors.

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