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Marcela Carena

Jonathan Kozaczuk

Zhen Liu

Tong Ou

Michael J. Ramsey-Musolf

See next page for additional authors

Authors

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Marcela Carena,[1,2,3] Jonathan Kozaczuk,[4] Zhen Liu,[5] Tong Ou,[6] Michael J. Ramsey-Musolf,[7,8,9] Jessie Shelton,[10] Yikun Wang,[11] and Ke-Pan Xie[12]

[1]*Theoretical Physics Department, Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*
[2]*Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA*
[3]*Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA*
[4]*Department of Physics, University of California, San Diego, La Jolla, CA 92093, USA*
[5]*School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA*
[6]*Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA*
[7]*Tsung-Dao Lee Institute and School of Physics and Astronomy, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai 200240, China*
[8]*Amherst Center for Fundamental Interactions, Department of Physics, University of Massachusetts, Amherst, MA 01003, USA*
[9]*Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, CA 91125, USA*
[10]*Illinois Center for the Advanced Study of the Universe, Department of Physics, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA*
[11]*Walter Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena, CA 91125, USA*
[12]*Department of Physics and Astronomy, University of Nebraska, Lincoln, NE 68588, USA*

Abstract

An essential goal of the Higgs physics program at the LHC and beyond is to explore the nature of the Higgs potential and shed light on the mechanism of electroweak symmetry breaking. An important class of models alter the thermal history of electroweak symmetry breaking from the predictions of the Standard Model (SM). This paper reviews the existence of a region of parameter space where a strong first-order electroweak phase transition is compatible with exotic decays of the SM-like Higgs boson. A dedicated search for exotic Higgs decays can actively explore this framework at the Large Hadron Collider (LHC), while future exotic Higgs decay searches at the high-luminosity LHC and future Higgs factories will be vital to conclusively probe the scenario.

Keywords: electroweak symmetry breaking, electroweak baryogenesis, electroweak phase transition, higgs, exotic decays, large hadron collider, colliders, future collider
DOI: 10.31526/LHEP.2023.432

1. 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 that EWSB proceeds through a smooth thermodynamic crossover. However, new physics beyond the SM (BSM) can modify this picture, enabling the possibility of 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]. In addition, such a process produces a stochastic gravitational-wave (GW) signature that could be observed in future GW probes [2, 3]. A first-order EWPT could have affected the abundance of primordial relics such as dark matter with masses at or above the electroweak scale [4]. Beyond 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. Understanding the nature of the EWPT in our universe will be a profound advance in our understanding of nature, and present and future collider experiments have a crucial role to play in such exploration.

Many BSM scenarios predicting a first-order electroweak phase transition are being tested at the LHC. An important class of such models is that in which the EWPT is driven first-order by the Higgs coupling to a new *light* particle ($m \leq m_h/2$) [5]. As argued in [6], if the new degree of freedom is below $\sim m_Z$, it must be a singlet-like scalar denoted as s. The mixing angle ($\sin\theta$) of this singlet with the SM Higgs boson (h) controls the direct production of such scalars at colliders and can be small or absent entirely if additional symmetries are present. Therefore, these light new particles can be difficult to detect directly. While the excellent agreement of measured Higgs boson properties with SM predictions has eliminated most of the parameter space for first-order EWPTs driven by light scalars, the works in [6, 7] recently emphasized that there are still viable models where such scalars can still have a dramatic impact on the EWPT, provided that there is a sizeable scalar coupling to the SM-like Higgs field. 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 [8, 9, 10, 11, 12, 13]. At the HL-LHC, detector upgrades, new trigger and analysis strategies together with increased datasets will steadily increase the sensitivity to small branching ratios, especially in subdominant but cleaner final states (notably $h \to ss \to bb\tau\tau$,

$h \to$ 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 $h \to ss \to bbbb$ [16]. This brief review paper aims to summarize how searches for exotic Higgs decays can inform our understanding of the early Universe. It will establish parameter space portions that yield both exotic Higgs decays and first-order phase transitions and provide clear and achievable targets for current and future colliders.

2. HIGGS EXOTIC DECAY TARGET FROM EWPT CONSIDERATIONS

For strong first-order phase transitions driven by *light* degrees of freedom, the most exciting possibility is a singlet scalar s, which can affect the Higgs potential at the tree level. The existence of experimentally viable parameter space where a light singlet-like scalar can drive the EWPT to be strong first-order was recently demonstrated in [7, 6]. It is useful to classify the possibilities according to whether or not the light singlet scalar respects the Z_2 symmetry taking $s \to -s$. Theoretically, this Z_2 symmetry, whether or not it is spontaneously broken, can be a useful proxy for a bigger (gauge or global) symmetry, as can be the case when s is part of a hidden sector, as motivated, e.g., by dark matter model building. Practically, imposing a Z_2 symmetry reduces the number of free parameters. Most consequentially, in models with an unbroken Z_2, s cannot mix with the SM Higgs. At the same time, if the Z_2 is spontaneously broken, the s-h mixing angle $\sin\theta$ is related to the exotic branching fraction $\mathrm{Br}(h \to ss)$. In the absence of the Z_2 symmetry, $\sin\theta$ and $\mathrm{Br}(h \to ss)$ are independent parameters. The work in [7] studies the Z_2 spontaneously-broken scenario, while [6] studies the Z_2 unbroken and nonsymmetric scenarios.

In the viable light scalar scenarios that yield strongly first-order EWPTs, symmetry breaking in the thermal history generically proceeds through a two-step transition, while a one-step transition is feasible in limited regions of parameter space. The step where the electroweak symmetry is first broken is required to be strong first-order. The possibilities are illustrated in Figure 1.[1] Since the SM phase transition is a crossover, if the singlet s is to catalyze a strong first-order phase transition, we expect that its couplings to the Higgs cannot be too small in order to induce a sufficiently large deformation to the scalar potential in the early universe. Thus, we generally expect that the exotic Higgs branching ratio into new scalars compatible with first-order phase transitions is bounded from below. The specific implications for the surviving light scalar parameter space depend on the (non)realization of the Z_2 symmetry, as we now discuss.

In the Z_2-preserving case, a sizeable quartic coupling $s^2|H|^2$ is crucial in generating a two-step phase transition (with the second step being a first-order EWPT). In the general Z_2-explicit breaking scenario, the singlet cubic term s^3 can also be important in providing the tree-level barrier for a first-order EWPT. However, in the spontaneously broken Z_2 case, at the tree-level, the singlet s^3 term is absent, while the only allowed portal coupling, i.e., the quartic term $s^2|H|^2$, is related to the scalar-Higgs mixing angle and thus stringently constrained by Higgs precision tests.

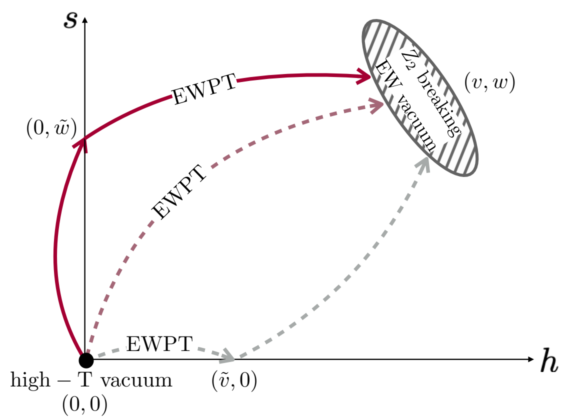
However, the work in [7] demonstrated that the joint scalar sector with a spontaneously broken Z_2 can indeed realize a strong first-order EWPT while satisfying the current constraints on Higgs properties. This analysis includes the full one-loop radiative corrections from zero-temperature and thermal contributions, as well as the daisy resummation. The surviving parameter space exhibits a sharp correlation between the first-order EWPT and the Higgs exotic branching fraction. The region that realizes a strong first-order EWPT parameter space while remaining compatible with Higgs properties features $m_s \lesssim 25\,\mathrm{GeV}$ and gives exotic decay branching ratios $\mathrm{Br}(h \to ss) \sim 10^{-6}$–$10^{-1}$. We extract from [7] the motivated region in such a scenario that is also compatible with the current precision measurement constraints, as shown by the brown shaded region in Figure 4. A finer scan might reveal more tuned parameters, beyond the large scans done in [7], and extend the region of interest.

In the general nonsymmetric scenario, the work in [6] shows 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 $h \to ss$. The work in [6] considers the leading contributions to the finite-temperature effective potential, keeping terms up to $\mathcal{O}(g^3)$ in Landau gauge, and performs numerical scans for fixed values of $\cos\theta$ that are well below current experimental bounds. The basic results are already evident at $\mathcal{O}(g^2)$, for which the analysis is entirely gauge invariant. The inclusion of the gauge-dependent $\mathcal{O}(g^3)$ terms in the Landau gauge does not appreciably change the result according to the numerical study. The region of parameter space compatible with first-order phase transitions at fixed $\sin\theta = 0.01$ is shown as a blue-shaded region in Figure 4. In particular, global fits to Higgs properties now require $m_s \lesssim 28\,\mathrm{GeV}$ in order to realize a first-order transition. Semianalytical arguments in the small mixing limit, based on an expansion of the finite-temperature effective potential that retains terms up to $\mathcal{O}(g^2)$, can be combined to obtain a simple expression for a lower bound on the value of $\mathrm{Br}(h \to ss)$, as a function of m_s, which is compatible with first-order phase transitions.

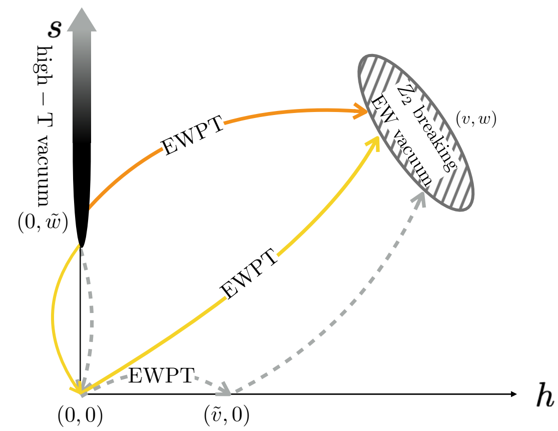
Unlike [7], the work in [6] restricts attention to the region of parameter space with $m_s \gtrsim 5\,\mathrm{GeV}$. This restriction is technical: the region of parameter space realizing first-order phase transitions certainly extends to smaller scalar masses, but the power-counting arguments that justify the approximations made in the finite-temperature potential begin to break down at low scalar masses where smaller values of the mixed quartic coupling must be considered.

The work in [6] also performed a similar analysis for the Z_2-symmetric scenario. In this scenario, purely analytic arguments (again based on an $\mathcal{O}(g^2)$ approximation to the finite-temperature effective potential) can provide a lower bound on the invisible Higgs branching ratio that is in excellent agreement with the results of numerical scans. The identified surviving parameter space of interest is shown in Figure 4 in [6]. In this case, direct LHC searches for $h \to$ invisible, which currently bound $\mathrm{Br}(h \to \text{invisible}) < 15\%$ [17], require $m_s \lesssim 20\,\mathrm{GeV}$.

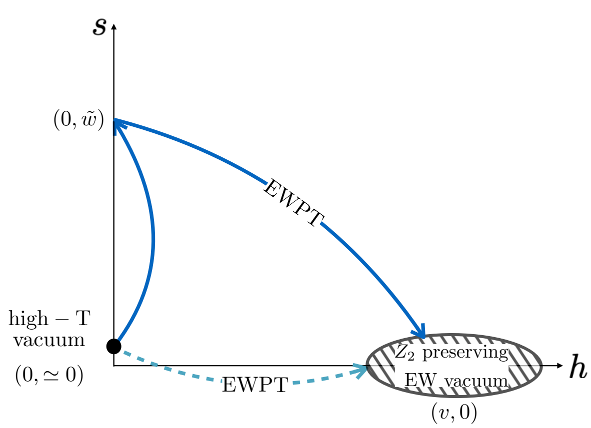
[1] In the general nonsymmetric scenario, one is free to shift the singlet by a constant without changing the physical predictions of the theory. This shift is often used to either remove the tadpole term in the potential or set the singlet vacuum expectation value to zero. We choose the latter.



(a) Z_2 spontaneous breaking scenarios with symmetry restoration.



(b) Z_2 spontaneous breaking scenarios with symmetry nonrestoration.



(c) Z_2 preserving or explicit breaking scenarios.

FIGURE 1: Schematics of EWPT patterns in the singlet-extended SM in different scenarios relevant to exotic Higgs decays [6, 7]. Solid lines correspond to patterns where the EWPT can be strong first-order, while dashed lines correspond to patterns where the EWPT is weakly first-order, second-order, or a crossover. The transition step in which the electroweak symmetry is first broken, thus relevant to baryogenesis, is labeled as "EWPT".

In all three scenarios, the parameter space compatible with both exotic Higgs decays and a first-order EWPT predicts exotic branching ratios $\mathrm{Br}(h \to ss)$ that are bounded from below. The branching ratios of interest are in the range of 10^{-6}–10^{-1}, with smaller branching ratios being possible at smaller values of m_s. The resulting parameter space poses an attractive target for both visible and invisible exotic Higgs decay searches at current and future colliders, as discussed in the next section.

In summary, 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.

3. CURRENT STATUS AND RECENT RESULTS IN EXOTIC DECAYS

The studies discussed in the previous section point us toward an intriguing, accessible signal in exotic Higgs decays. The 125 GeV SM-like Higgs boson can decay in pairs of new particles via the portal couplings. As the SM Higgs boson has a very narrow decay width $\Gamma_h = 4.07$ MeV, even very tiny BSM couplings can have appreciable impacts on the decay branching ratios, making exotic Higgs decays a potent probe of beyond-the-SM interactions [8, 13]. This section summarizes the current status and future prospects for Higgs exotic decays that are relevant for the EWPT-motivated $h \to ss$ decays.

Current global fits constrain the Higgs exotic decay branching ratio to be $\leq$16% at 95% C.L. [19]. The $h \to ss$ decay mentioned in the last section can lead to various final states according to the subsequent decay channels of the light scalar state s. In these SM plus singlet models, the s decay is controlled by the s-h mixing and inherits the Higgs-like hierarchical branching fractions following the corresponding fermion masses. The final state is dominated by $h \to ss \to bbbb$ for $m_s > 2m_b \sim 10$ GeV, and by $jjjj$, $jj\tau\tau$, and $\tau\tau\tau\tau$ for $m_s <$ 10 GeV. In Figure 2, we show the singlet decay branching fractions to various final states from [18], building on the work of [20, 21]. In general, the final state arising from $h \to ss$ can be written as $XXYY$, where X and Y represent (possibly) different particles. Beyond these visible decays, if s decays dominantly to dark particles or is stable on collider time scales, the signal would be an invisible Higgs decay. For instance, if the Z_2 symmetry taking $s \to -s$ is unbroken, then the scalar s is stable and hence appears as missing energy (prospects for this case were surveyed in [6]). Other generalizations of Z_2-symmetric SM-singlet extensions could further alter the cosmological history, even achieving electroweak nonrestoration, and leading to invisible Higgs decay phenomenology [22]. Moreover, supersymmetric extensions of the Higgs potential, for example, in the next-to-minimal-supersymmetric-standard model (NMSSM), can give rise to strong first-order phase transitions and induce interesting phenomenology that deserves a detailed study [23].

We summarize existing searches at the LHC for $h \to ss \to XXYY$ final states at the 13 TeV LHC in Table 1. This table lists the final state targeted by a given analysis, together with the utilized production mode and the corresponding integrated luminosity, as well as the intermediate scalar s mass range considered in each search. Except for the $bbbb$ final states, searches for all the other final states at the LHC involve at least a pair

Final state	Production	m_s range [GeV]	$\mathcal{L}$ [fb^{-1}]	Collaboration
$\mu\mu\mu\mu$	gg fusion	$[0.25, 8.5]$	35.9	CMS [24]
		$[4, 8] \cup [11.5, 60]$	137	CMS [25]
		$[1.2, 2] \cup [4.4, 8] \cup [12, 60]$	139	ATLAS [26]
$\mu\mu\tau\tau$	gg fusion	$[3.6, 21]$	35.9	CMS [27]
		$[15, 62.5]$	35.9	CMS [28]
		$[4, 15]$	35.9	CMS [29]
$bb\mu\mu$	gg fusion	$[18, 60]$	139	ATLAS [30]
		$[15, 62.5]$	138	CMS [31]
$bb\tau\tau$	gg fusion	$[15, 60]$	35.9	CMS [32]
$bbbb$	Zh	$[15, 30]$	36.1	ATLAS [33]
	Wh/Zh	$[20, 60]$	36.1	ATLAS [34]
$\gamma\gamma\gamma\gamma$	gg fusion	$[15, 62]$	132	CMS [35]
		$[0.1, 1.2]$	136	CMS [36]
$\gamma\gamma jj$	VBF	$[20, 60]$	36.7	ATLAS [37]

TABLE 1: The existing experimental searches for exotic Higgs decays $h \to ss \to XXYY$ at the 13 TeV LHC. Modified from Table 1 of [13].

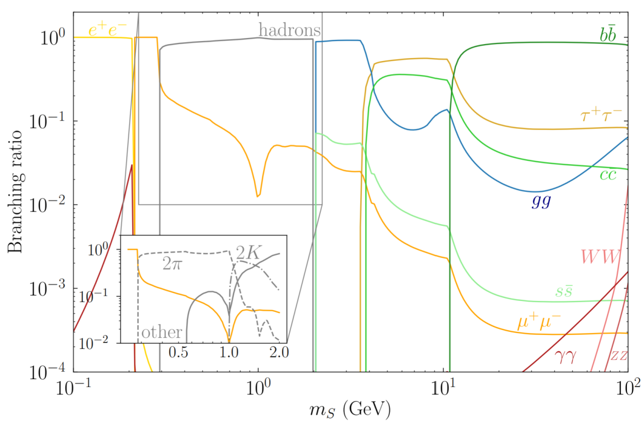


FIGURE 2: Scalar singlet s branching fractions mediated through mixing with the Higgs boson, taken from [18].

of nonhadronic final states, such as photons, muons, or tau leptons.

In Figure 3, we show current LHC constraints and future HL-LHC projections on the branching fraction of $H \to XXYY$ final states as a function of the intermediate scalar mass. The HL-LHC projections are derived using the simple assumption that all uncertainties can be taken to scale as $1/\sqrt{L}$. Searches in these individual final states exclude regions above the lines. We can see that the $\mu\mu\mu\mu$ channel provides a strong limit on Br($h \to ss \to XXYY$) to around 10^{-6}–10^{-5} across the scalar mass. The $\gamma\gamma\gamma\gamma$ channel also yields a stringent $\sim 10^{-5}$ bound. The constraints from $bb\mu\mu$ and $\mu\mu\tau\tau$ channels are a bit weaker, around 10^{-4}–10^{-3}, but still stronger than the $bb\tau\tau$, $\tau\tau\tau\tau$, and $\gamma\gamma jj$ bounds which are around 10^{-2}–10^{-1}. The current $bbbb$ bounds are typically higher than the allowed maximal exotic branching ratio (16%), but the HL-LHC projections for this channel can reach a few percent. On the other hand, the HL-LHC will be able to probe exclusive branching fraction to $\mu\mu\mu\mu$ as low as 10^{-7}.

The bounds on Br($h \to ss$) can be derived from those on Br($h \to ss \to XXYY$) once the $s \to XX/YY$ branching ratios are given. Assuming that the s decay branching ratios are dominated by the h-s mixing (see Figure 2), the bounds on Br($h \to ss$) are given in Figure 4. The Yukawa-weighting of the singlet branching ratios to SM final states means that the relative stringencies of the various channels are significantly affected compared to those in Figure 3. For $m_s \lesssim 10$ GeV, the strongest bounds are still from the $\mu\mu$-relevant channels, e.g., $\mu\mu\mu\mu$ for $m_s \lesssim 3.5$ GeV and $\mu\mu\tau\tau$ for $3.5\,\text{GeV} \lesssim m_s \lesssim 10$ GeV, respectively. For $m_s \gtrsim 10$ GeV, s decays dominantly to bb, making bb-relevant channels most sensitive. As a result, the more stringent bounds for $10\,\text{GeV} \lesssim m_s < 62.5$ GeV come from $bb\mu\mu$ and $bb\tau\tau$.

In Figure 4, we show the projected reach of the $\sim$240 GeV e^+e^- colliders with an integrated luminosity of 5 ab^{-1} for the $\tau\tau\tau\tau$ [38] and $bbbb$ [16] channels. The ILC-related projection for the $bbbb$ channel done by [39], assuming 0.9 ab^{-1} of data at CM energy 250 GeV, finds similar sensitivity. Projected sensitivity in the $qqqq/gggg$ and $cccc$ channels can be found in [16] and is not shown here.

The strong first-order EWPT parameter space for the spontaneous Z_2-breaking model [7] and general singlet scalar extension of the SM with mixing angle $\sin\theta = 0.01$ [6] is indicated by the brown and light blue-shaded regions in the Br($h \to ss$)-m_s plane in Figure 4, respectively. Combined with the current bounds at the LHC, we see that exotic Higgs decay searches have already probed a notable fraction of the EWPT parameter space, especially for the low-mass region $m_s \lesssim 10$ GeV. For the high mass region $m_s > 10$ GeV, the direct constraints from the bb-relevant channels are slightly weaker than the indirect bound Br($h \to ss$) < 16% that arises from a global fit to Higgs properties [41]. At the HL-LHC, the Br($h \to ss$) reach in both the low and high mass regions is significantly improved, while the expected reach from direct searches at high masses is still comparable with the expected indirect bounds (4% [40]).

Future Higgs factories can greatly improve the coverage of EWPT parameter space, as shown by the dashed lines in the right panel of Figure 4. Combining the $\tau\tau\tau\tau$ and $bbbb$ channels, future Higgs factories will be able to cover almost all the EWPT parameter space for the general singlet scalar extension with mixing angle $\sin\theta = 0.01$ [6]. Advances in analysis techniques at HL-LHC may also provide further improvement in sensitivity beyond existing projections, e.g., by using machine

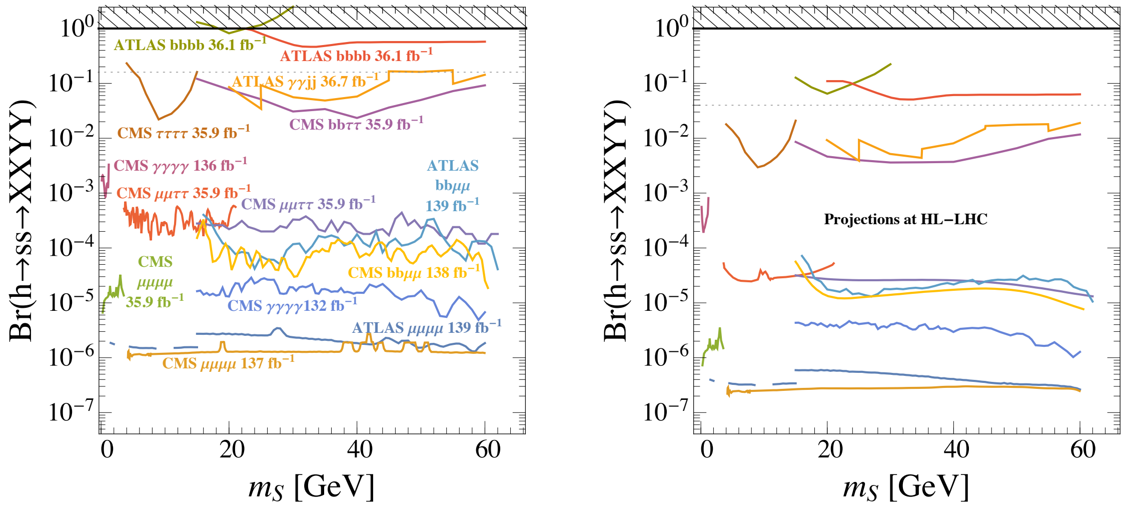


FIGURE 3: Current bounds (left panel) on exotic Higgs decays $h \to ss \to XXYY$ and corresponding projections (right panel) at the HL-LHC. The horizontal dotted line in the left (right) panel shows the current (future projected) upper limit for the exotic Higgs branching ratio from global fits to Higgs properties (16% and 4%, respectively).

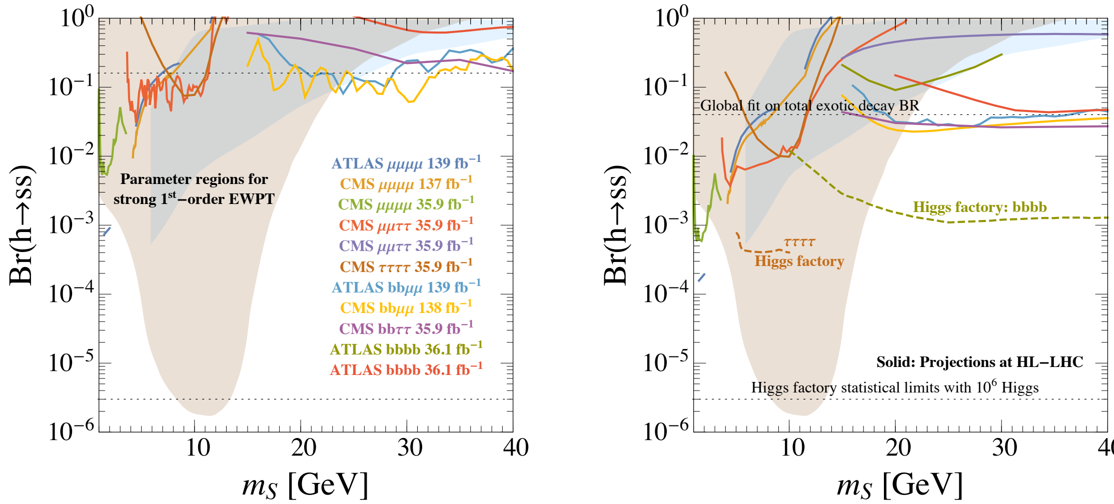


FIGURE 4: The current bounds on Higgs exotic decay $h \to ss$ and the projections at the HL-LHC, assuming that the s decays to SM particles are mediated by the mixing, and the corresponding branching ratios are taken from [18]. The upper and lower horizontal dotted lines are the expected upper limit for Higgs exotic decay branching ratio at the HL-LHC (4% [40]) and statistical limit of 10^6 Higgs at future lepton colliders, respectively. The brown and light blue shaded regions are the strong first-order EWPT regions from [6, 7]; see text for details. Projections of the reach of future lepton colliders are shown in dashed lines.

learning to better separate signals from backgrounds in the decay $h \to 4b$ [42].

For tiny mixing angles $\sin\theta$, which render the singlet scalar long-lived, both long-lived particle searches [43, 13, 44, 45] and searches for dark Higgs bosons in intensity frontier machines [46, 47, 48, 49, 50, 51, 52] can become important probes. Note that a typical Higgs factory producing a sample of 10^6 Higgs bosons is statistically limited to probing branching ratios larger than 3×10^{-6}. Given the clean, low-background environments at future lepton colliders, we conclude that there is ample scope for future discovery in exotic Higgs decays.

4. SUMMARY AND OUTLOOK

Determining the true nature of the electroweak phase transition is a fundamental question in particle physics that connects searches at energy frontier facilities to the thermal history of the early universe. While much study has been devoted to discovery prospects for theories where heavy ($m > m_h$) new physics drives the electroweak phase transition strongly first-order, we emphasize that there exists an experimentally viable region of parameter space where *light* new states can accomplish the same goal. Following the studies in [6, 7], we describe the frameworks where the simple singlet scalar extension of the SM can realize a strong first-order EWPT along with allowing for exotic Higgs decays, $h \to ss$. Such new physics targets are an interesting and accessible target for both the LHC and future Higgs factories.

At the LHC, we find that direct searches in the $bbbb$, $bb\mu\mu$, and $\mu\mu\mu\mu$ final states provide the leading sensitivity to singlets with masses below 10–15 GeV, where constraints on exotic Higgs branching ratios reach as low as 10^{-2}, as shown in the left panel of Figure 4. The full run of the HL-LHC and future lepton collider Higgs factories can access most of the relevant parameter space for light singlet SM extensions that enable a strong first-order EWPT, with the current projections being shown in the right panel of Figure 4. The $bbbb$ and $\tau\tau\tau\tau$ (similarly, $bb\tau\tau$) channels have the best sensitivities at future lepton colliders. The sensitivity projections shown are based on studies of the signal $e^+e^- \to hZ$ in various exclusive final states and assuming leptonic decays of the Z. There is ample room for improvement by including more final states for the Higgs decay, especially in the low-mass regions, and by considering hadronic Z decays. Altogether a combination of future lepton and hadron colliders offer excellent prospects for full coverage of the strong first-order EWPT-motivated region of relevance for electroweak baryogenesis models.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

ACKNOWLEDGMENTS

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics. Z. Liu is supported in part by the U.S. Department of Energy (DOE) under grant No. DE-SC0022345. J. Shelton is supported in part by U.S. DOE grants DE-SC0017840 and DE-SC0023365. K.-P. Xie is supported by the University of Nebraska-Lincoln. M. J. Ramsey-Musolf was supported in part under U.S. DOE Contract No. DE-SC0011095 and National Natural Science Foundation of China, Grant No. 19Z103010239. Y. Wang is supported by the Walter Burke Institute for Theoretical Physics. T. Ou is supported by the Visiting Scholars Program of Universities Research Association.

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