Composite Higgs: Collider Signals and Electroweak Phase Transition

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Composite Higgs Models in a Nutshell

The idea of the Higgs boson as a pseudo-Nambu-Goldstone boson (pNGB) [1–4] of a strong sector has drawn new interest due to the semi-perturbative scenario based on the holographic perspective on compositeness [5–8]. There are two basic assumptions relevant for the phenomenology: Higgs arises as pNGB from a spontaneously symmetry breaking in the strong sector and the SM fermions obtain their masses from linear mixing with the composite resonances which is denoted as partial compositeness. A widely-studied scenario involves the minimal coset with custodial symmetry $SO(5)/SO(4)$ and the SM Higgs doublet is in the fourplet of $SO(4)$. The electroweak groups are embedded into the $SO(4)$. Partial compositeness indicates that for every SM particle, there is at least a resonance in the strong sector with the same SM quantum numbers. The most-studied case of fermionic resonances are the top partners, which live in the representation of $SO(4)$. In addition, there are also vector resonances, such as the ρ resonances, which can mix with the SM gauge bosons. The interactions between the elementary sector and the strong sector explicitly break the global symmetry protecting the Higgs masses and electroweak symmetry breaking is generated at one loop level due to the vacuum misalignment, mainly from the top quark contribution. Due to their strong interactions with the new sector, the final states involving the longitudinal components of the $W^{\pm}, Z$ bosons and the Higgs boson will provide the most promising channels to probe the new physics.

Phenomenology of CHMs at the HL-LHC and Future Colliders

Due to its strongly interacting with the strong sector, the di-boson (VV, Vh) decay of the spin-1 resonances provide the smoking gun signatures for the composite Higgs models [9]. Recent studies suggest that the light Higgs prefers light top partners [10–12]. The vector-like top partner searches in the pair QCD production or singly electroweak production, followed by the top partner decaying into the top quark plus longitudinal gauge bosons or Higgs boson, are promising channels for making discovery or testing naturalness [13]. In [14], we have systematically constructed the effective Lagrangian and studied the scenario in which there is a mass gap in the spin-1 resonances and top partners. Their strong interactions will strongly affect their phenomenology at the LHC when the cascade decay channels among the heavy resonances will become more relevant. They affect the decay branching ratios and give rise to new signals. In [15], we have systematically categorized the couplings among the resonances and the SM particles according to their expected size by power counting. Furthermore, we have studied the prospects of the searching for the composite resonances at the LHC and future colliders. In [16], we further explored the scenario that the third generation left-handed doublet quarks q_L arise as massless bound states of the strong dynamics in a way that relaxes the bound from $Zb_L\bar{b}_L$. For the Snowmass 21, we plan to study the reach of a set of benchmark models of CHMs at the HL-LHC and future colliders, including FCC [17, 18], CEPC/SppC [19–21], CLIC [22], ILC [23], and the muon collider [24]. Much of the studies we plan to do will go beyond the available results [20, 25].

Cosmological Implications of the Composite Higgs Models

CHMs can also account for the astrophysical/cosmological phenomena beyond the SM. For example, the extra pNGBs in the non-minimal CHMs can serve as dark matter candidate [26], or help to explain the baryon asymmetry of the universe (BAU) [27]. In the latter case, an extensively studied case is the next-to-minimal CHM based on the coset $SO(6)/SO(5)$, whose scalar sector contains one Higgs doublet and one real singlet. In the presence of an extra singlet scalar, the model is able to trigger a strong first-order electroweak phase transition (EWPT), providing the essential cosmic environment for the generation of BAU. In Refs. [28, 29] the authors have considered the fermion embeddings from **6** up to $\mathbf{20'}$ of the $SO(6)$, and provide the detailed analysis about the scalar potential as well as baryogenesis. In the future, we can explore the BAU possibility in different cosets, e.g. $SU(5)/SO(5)$ ("composite Georgi-Machacek model") or $SO(8)/SO(7)$ ("composite 2HDM"). Another research direction is to study the phase transition of the strong dynamics sector itself, rather than the EWPT of the pNGBs. Gravitational wave signal is a good probe of such phase transitions as they tend to be first-order.

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