Abstract

This thesis comprises six papers written during my Ph.D studies and also includes one relevant paper written before the Ph.D. In all these studies, we construct and consider "(Partially) Composite Higgs" ((P)CH) models, a variant of dynamical electroweak (EW) symmetry breaking models that provide a "pseudo-Nambu-Goldstone Boson" (pNGB) composite Higgs which can be as light as that observed at the LHC. This is in contrast to what is expected in the "Technicolor" (TC) framework. All these models alleviate the EW hierarchy problem by replacing the elementary Higgs sector in the Standard Model (SM) with a composite sector.

In the first part, we consider the ability of composite dynamics to provide "Dark Matter" (DM) candidates, both of thermal and non-thermal origin. Firstly, we construct the CH model with minimal number of pNGB states featuring a viable DM candidate. The CH model with a minimal inert sector of two Weyl fermions thermally produces a pNGB DM candidate that is stable due to an $\mathrm{U}(1)_\Lambda$ symmetry. Secondly, we construct two different CH models featuring particle-antiparticle asymmetric DM candidates produced non-thermal via sphalerons. Before this, there existed no such CH models. In the paper "Higgs boson emerging from the dark", we propose a new non-thermal mechanism of DM production based on vacuum misalignment. A global X-charge asymmetry is generated at high temperatures, under which both the would-be Higgs boson and the DM are charged. At lower energies, the vacuum changes alignment and breaks the $\mathrm{U}(1)_\mathrm{X}$, leading to the emergence of the Higgs boson and of a fraction of charge asymmetry stored in the stable DM relic. This mechanism can be present in a wide variety of models based on vacuum misalignment, and we demonstrate it in the $\mathrm{SU}(6)/\mathrm{Sp}(6)$ template CH model. This template model can both alleviate the EW hierarchy problem, feature an asymmetric DM candidate, and may explain the excess in the electron recoil spectrum by the XENON1T experiment. Finally, it gives testable predictions in various phenomena ranging from gravitational waves to future collider signals to kaon physics.

In the second part, we discuss the challenges with generating fermion masses in the CH framework. First, we focus on how the mass hierarchies of the SM-fermions can be established from the composite dynamics. For example, we may explain the smallness of the neutrino masses by considering a novel mechanism, similar in nature to the scotogenic models. This mechanism generates the neutrino masses via loops of $\mathbb{Z}_2$–odd composite scalars. This model can feature $\mathcal{O}(1)$ Yukawa couplings and remain viable with respect to current experimental constraints. The model example studied, based on a $\mathrm{SU}(6)/\mathrm{Sp}(6)$ coset structure, may also (non-)thermally produce the correct DM relic density by the same mechanism as in our "Higgs boson emerging from the dark" model. Next, we consider composite multi-Higgs doublet schemes that may generate the mass hierarchies of the quarks. We start to consider a $\mathrm{SU}(6)/\mathrm{Sp}(6)$ CH template model that can naturally explain the top-bottom mass hierarchy with a single "universal" Higgs-Yukawa coupling, g, which is identified with the top quark, $g \equiv g_t \sim \mathcal{O}(1)$. Furthermore, we discuss the possibility to extend this model example such that the hierarchies of all the SM-quark masses and their mixing may be described by a $\mathrm{SU}(12)/\mathrm{Sp}(12)$ CH model. Finally, we consider the problem that none of the various mechanisms that generate fermion masses in the CH framework are free from fine-tuning problems. Therefore, we end by discussing some ideas of how we can construct a "completely" natural CH model.