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Strong phase transition, dark matter and vacuum stability from simple hidden sectors

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Abstract

Motivated by the possibility to explain dark matter abundance and strong electroweak phase transition, we consider simple extensions of the Standard Model containing singlet fields coupled with the Standard Model via a scalar portal. Concretely, we consider a basic portal model consisting of a singlet scalar with Z_2 symmetry and a model containing a singlet fermion connected with the Standard Model fields via a singlet scalar portal. We perform a Monte Carlo analysis of the parameter space of each model, and we find that in both cases the dark matter abundance can be produced either via freeze-out or freeze-in mechanisms, but only in the latter model one can obtain also a strong electroweak phase transition required by the successful electroweak baryogenesis. We impose the direct search limits and consider systematically the possibility that the model produces only a subdominant portion of the dark matter abundance. We also study the renormalization group evolution of the couplings of the model to determine if the scalar sector of the model remains stable and perturbative up to high scales. With explicit examples of benchmark values of the couplings at weak scale, we show that this is possible. Models of this type are further motivated by the possibility that the excursions of the Higgs field at the end of inflation are large and could directly probe the instability region of the Standard Model.

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1. Introduction

Extensions of the Standard Model (SM) of elementary particle interactions have been put under severe tests [1–4] after the discovery of the Higgs boson with mass $m_h = 126$ GeV at the ATLAS and CMS experiments in the CERN Large Hadron Collider [5,6]. The requirement of a light Higgs scalar boson and no other obviously accessible states at the energy scales probed so far presents a challenge for traditional model paradigms like supersymmetry and technicolor which predict an extended spectrum beyond the SM. On the other hand, the cosmological observations on the dark matter abundance and matter–antimatter asymmetry clearly require, in the elementary particle physics context, the existence of new degrees of freedom not present in the SM.

One possible framework to address these aspects is to take the SM according to the current collider data and extend it with singlet fields communicating with the SM fields only through the scalar or vector portals. The singlet sector can consist of a single scalar [7,8], more complex scalar multiplets [9,10], fermions [11–13] or vectors [14,15]. The resulting spectrum can contain particles stable over the timescales of the age of the universe and contribute to the observed abundance of the dark matter. Moreover, the extended scalar potential can modify the properties of the phase transitions in the early universe with respect to the results obtained in the SM. A strong first-order electroweak transition is a prerequisite for successful electroweak baryogenesis [16], and it is well known that the electroweak phase transition in the SM is not of first order but a smooth crossover [17,18]. If the electroweak sector of the SM were fully perturbative, a first-order phase transition would arise from a cubic term generated in the Higgs effective one-loop potential by the thermal effects of fields coupled to the Higgs. However, addition of a singlet scalar can sufficiently modify the picture already by tree level effects due to the presence of T-independent dimensional parameters appearing in the scalar potential and lead to a strong first-order transition [19,20]. Consequently, the ratio $v(T_c)/T_c$ which controls the sphaleron erasure of the baryon asymmetry can be large and lead to successful electroweak baryogenesis.

The phenomenologically interesting scenario would, thus, be the one where the strong electroweak phase transition is accompanied by an explanation of the dark matter relic density by a weakly coupled massive particle (WIMP). As a concrete model paradigm in this paper, we consider simple scalar portals between the hidden sector and the visible one. In addition to the Standard Model Higgs field, the scalar sector contains a real singlet scalar S.

As a simple limiting case, we consider a model where the singlet sector is solely constituted by S with a discrete Z_2 symmetry [7,21–23]. Then S can also act as a dark matter candidate provided that the global minimum of the potential at zero temperature does not spontaneously break this Z_2 symmetry. However, in this model it is not possible to simultaneously explain the strong electroweak phase transition and the observed dark matter relic abundance. Therefore, as a second example we consider a model where the scalar S is not assumed to have any discrete symmetries, but the singlet sector also contains a Dirac fermion [11,12,24]. We find that in this model it is possible to realize simultaneously strong electroweak phase transition and the observed dark matter relic abundance.

To establish our results, we perform a Monte Carlo analysis of the parameter space to search for viable models. We impose the constraints from LHC data and precision electroweak measurements, and from the dark matter direct searches [25,26]. To improve the earlier work on models of this type [22,12], we also require that the couplings remain perturbative up to scales of $\mathcal{O}$(TeV). As a special case, we consider the possibility that the model could remain perturbative up to the Planck scale. This happens only on very specific couplings and allows to single out