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Thermal phase transition with full 2-loop effective potential

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Abstract

Theories with extended Higgs sectors constructed in view of cosmological ramifications (gravitational wave signal, baryogenesis, dark matter) are often faced with conflicting requirements for their couplings; in particular those influencing the strength of a phase transition may be large. Large couplings compromise perturbative studies, as well as the high-temperature expansion that is invoked in dimensionally reduced lattice investigations. With the example of the inert doublet extension of the Standard Model (IDM), we show how a resummed 2-loop effective potential can be computed without a high-T expansion, and use the result to scrutinize its accuracy. With the exception of T_c, which is sensitive to contributions from heavy modes, the high-T expansion is found to perform well. 2-loop corrections weaken the transition in IDM, but they are moderate, whereby a strong transition remains an option.

1. Introduction

With the upcoming years of the LHC probing the Higgs mechanism, and the continued direct, indirect and collider searches for dark matter, together with the prospect of LISA probing gravitational wave backgrounds related to particle physics, it has become popular to search for a framework which may play a role in all contexts. Surprisingly, the Standard Model supplemented

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by an additional scalar field, for instance in the singlet, doublet, triplet, or higher representation, cannot easily be excluded from these considerations. We focus here on the doublet case, simplified further by an additional Z(2) symmetry, a framework that is generally referred to as the Inert Doublet Model (IDM) [1–3].

The original interest in the IDM came largely from the dark matter context [4–13], which remains a viable option today (cf. e.g. refs. [14–21] and references therein). Many theoretical (cf. e.g. refs. [22–26]) and collider (cf. e.g. refs. [27–43]) constraints on the model have been considered. Furthermore, following early suggestions [44–48], a strong phase transition appears possible [49–51]. However the issue of large couplings emerges, for instance in some of the benchmarks of ref. [50] certain scalar couplings attain the magnitude $\lambda_3 \simeq 3$ in a normalization in which the Standard Model Higgs self-coupling is $\lambda_1 \simeq 0.15$.

There is a clear reason for the need for large couplings if a strong phase transition is to be present. Without any additional particles, the theory has no thermal phase transition at all (for a review, see ref. [52]). If degrees of freedom are added which are weakly coupled and massive, they can be integrated out, resulting in the same "dimensionally reduced" effective theory [53, 54] as for the Standard Model [55], and thereby with the same conclusion concerning the phase transition. To change the conclusion, we either need to add new degrees of freedom which are light around the transition point, or which come with large couplings, so that the effective couplings of the low-energy theory change by a significant amount. Light degrees of freedom could experience a transition of their own and thereby indeed influence the dynamics substantially [56, 57]; this is an interesting option but will not be considered here, given that it requires a degree of fine tuning. Thereby we are left with large couplings as the remaining avenue. It is difficult to exclude the existence of such couplings phenomenologically, given that Higgs physics does not easily avail itself to precision inspection and that constraints from fermionic processes are largely missing for the inert doublet. Large couplings do imply the presence of a nearby Landau pole and, conversely, could originate as a low-energy description of some sort of composite dynamics.

In the context of electroweak baryogenesis, a strong phase transition refers to a discontinuity $\Delta v \sim T$, where v is a gauge-fixed Higgs expectation value ($v \simeq 246$ GeV at $T = 0$), and T is the temperature [58]. In the Higgs phase, gauge boson masses are then of order $m_W \sim gv/2 \ll \pi T$, where $g \sim 2/3$ is the $\mathrm{SU_L}(2)$ gauge coupling. In this situation a high-T expansion in $m_W^2/(\pi T)^2$ works well.[1] The high-T expansion is an ingredient for instance in non-perturbative studies based on dimensional reduction (cf. e.g. refs. [59–63] and references therein). However, new degrees of freedom which get a mass through a large coupling $\lambda_3^{1/2} \sim 2$ may become heavy in the broken phase, $\lambda_3^{1/2} v \sim \pi T$. Given that the high-$T$ expansion is an asymptotic series, it is not clear whether it is numerically accurate in such a situation.

In order to test the convergence of the high-T expansion, and of the perturbative treatment in general, a sufficient loop order is needed. Here we go to 2-loop level for the effective potential. Earlier results probing the validity of the high-T expansion at 2-loop level, associated however with large vacuum masses rather than with large couplings, can be found in ref. [64]. Another related investigation, albeit restricted to an Abelian theory and without a detailed exposition of the "master" sum-integrals that appear, was presented in ref. [65].

[1] For bosonic degrees of freedom the high-T expansion also includes non-analytic terms, such as $(m_W^2)^{3/2}/(\pi T)^3$; however any sum-integral only generates a finite number of such terms, associated with Matsubara zero-mode contributions, so that they do not affect the convergence of the infinite series.