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Symmetry-improved 2PI approach to the Goldstone-boson IR problem of the SM effective potential

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Abstract

The effective potential of the Standard Model (SM), from three loop order and higher, suffers from infrared (IR) divergences arising from quantum effects due to massless would-be Goldstone bosons associated with the longitudinal polarizations of the $W^{\pm}$ and Z bosons. Such IR pathologies also hinder accurate evaluation of the two-loop threshold corrections to electroweak quantities, such as the vacuum expectation value of the Higgs field. However, these divergences are an artifact of perturbation theory, and therefore need to be consistently resummed in order to obtain an IR-safe effective potential. The so-called Two-Particle-Irreducible (2PI) effective action provides a rigorous framework to consistently perform such resummations, without the need to resort to *ad hoc* subtractions or running into the risk of over-counting contributions. By considering the recently proposed symmetry-improved 2PI formalism, we address the problem of the Goldstone-boson IR divergences of the SM effective potential in the gaugeless limit of the theory. In the same limit, we evaluate the IR-safe symmetry-improved 2PI effective potential, after taking into account quantum loops of chiral fermions, as well as the renormalization of spurious custodially breaking effects triggered by fermionic Yukawa interactions. Finally, we compare our results with those obtained with other methods presented in the literature.

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1. Introduction

In Quantum Field Theory (QFT), there are instances where fixed-order perturbative expansions break down and one needs to rely on techniques for resumming higher-order contributions to deal with this problem. A few typical examples are: the IR problem in thermal QFT at high temperatures [1–4], the problem of pinch singularities in non-equilibrium QFT [5,6], the dynamical generation of an effective gluon mass [7,8], the resonant production and mixing of unstable particles [9,10], as the latter occurs, for example, in scenarios of resonant leptogenesis [11–17]. On the other hand, there are cases in which higher-order effects could play an important role, even in scenarios with small perturbative couplings and non-resonant dynamics. For instance, recent studies [18–20] indicate that the profile of the SM effective potential, extrapolated to very high energies, is extremely sensitive to the physics at the electroweak scale. Thus, a formalism to incorporate and resum higher-order effects in a rigorous and self-consistent manner is highly desirable for a number of applications in thermal and non-thermal QFT.

Recently, it was pointed out [21] that the conventional One-Particle-Irreducible (1PI) effective potential [22–24] of the SM is plagued by IR divergences caused by quantum effects due to *massless* would-be Goldstone bosons associated with the longitudinal polarizations of the $W^\pm$ and Z bosons. These divergences start from three-loop order for the effective potential $V_{\rm eff}(\phi)$ itself, but from two loops for its derivative with respect to the Higgs background field ϕ, $dV_{\rm eff}(\phi)/d\phi$, which is required for determining the vacuum expectation value (VEV) of ϕ. The latter is a key quantity, as it enters the state-of-the-art calculations of the matching conditions for the SM effective potential at the electroweak scale.

The IR divergences in the 1PI effective potential pose a serious field-theoretic problem which needs to be addressed for two reasons. First, we expect conceptually that the effective potential $V_{\rm eff}(\phi)$ is a well-behaved analytic function for all values of ϕ. Second, we observe that these IR pathologies formally lower the loop order of the involved contributions, thus causing a breakdown of perturbation theory. Therefore, loop graphs that are naively of higher order can potentially give significant contributions to the threshold corrections to the VEV of ϕ. Since the precise functional form of the effective potential $V_{\rm eff}(\phi)$ for high values of ϕ is very sensitive to the matching conditions at the electroweak scale, this IR problem may affect the stability analyses of the SM potential. Most recently, this problem was addressed [25,26] by devising a procedure for resumming the pathological IR-divergent terms to all orders, albeit in an *ad hoc* manner.

A rigorous framework to study the IR problem of the 1PI effective potential is the formalism introduced by Cornwall, Jackiw and Tomboulis (CJT) [27]. In its simplest version, the Two-Particle-Irreducible (2PI) effective action is a generating functional expressed not only in terms of fields, but also in terms of their dressed propagators. At any given order of its loopwise expansion, the 2PI effective action represents an infinite set of higher-order diagrams induced by partially resummed propagators. Most importantly, in this 2PI approach of selective resummations, one does not run into the danger of over-counting graphs.

There have been numerous applications of the 2PI formalism in the literature, although the main focus of these were within the context of thermal QFT [3,4,28–32]. Nevertheless, one major limitation of the CJT formalism remains its difficulty to describe properly the global and local symmetries of the theory, at any fixed order of a loopwise expansion of the 2PI effective action. In