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Cosmological constraint on the mass of Higgs boson in the Standard model

Valery Kiselev[*]
Institute for High Energy Physics, Russia
E-mail: val.kiselev@gmail.com

Sergey Timofeev
Moscow Institute of Physics and Technology, Russia
E-mail: serg_timofeev@list.ru

The excited Higgs boson minimally coupled to the gravity can be consistently treated in the cosmology of early Universe at virtualities below the Planck scale, if only the Higgs particle mass is constrained by the upper bound $m_H < 153 \pm 3$ GeV because the scalar with a super-critical mass would involve arbitrary amplitudes of quantum fluctuations generating unpredictable spatial inhomogeneity of energy density.

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[*] Speaker.

1. Introduction

The Higgs boson field χ of the Standard model considered at high virtualities about the Planckian scale $m_{\rm Pl}$ should satisfy well known constraints on its mass m_H as follows from the consistency of its self-action potential: 129 GeV $< m_H <$ 175 GeV with the accuracy of 1 GeV (see details in review [1]). The upper bound is caused by the Landau pole in the constant of λ in the potential $V = \lambda(\chi^2 - v^2)^2/4$ with the vacuum expectation value v, so that $\lambda(\mu) < \infty$ at virtualities $\mu < m_{\rm Pl}$. The pole leads to arbitrary values of quantum amplitudes involving processes with highly virtual Higgs scalars. The cosmology produces a more strict constraint $\lambda(m_{\rm Pl}) < \lambda_c$ with a finite critical value of λ_c, since the excited scalar field could generate an inflation [2, 3] of Universe with regular fluctuations of spatial inhomogeneity, if the Higgs particle has the sub-critical value of its mass, otherwise, in super-critical case, the Higgsian inflation is forbidden, and amplitudes of inhomogeneity take arbitrary values breaking the consistency and causality of theory.

2. Inflation by the Higgs scalar

The inflation produced by the Higgs field minimally coupled to the gravity can be described as a parametric attractor for scaled values of kinetic and potential energies [4, 5]. The attractor gets a slow driftage with the decreasing Hubble constant H satisfying the criteria of stability for the attractor: $2\pi G H^2 > \lambda$, with $G = 1/m_{\rm Pl}^2$ being the Newton constant. If $\lambda \sim 1$, then the Higgsian inflation is forbidden below the Planckian values of H [3], hence, below the Planckian density of energy, so the field oscillates near the minimum of its potential with arbitrary quantum fluctuations, that breaks the general consistency of theory in cosmology.

In order to fix the critical value of λ we calculate the action of de Sitter spacetime depending on the Hubble rate H: $S = 1/6\pi G H^2$, so the classical approximation for the quantum amplitude $\Psi \sim \exp\{iS\}$ remains valid until $S > 2\pi$, that gives $\lambda_c = 1/6$ [6].

The critical value of λ is transformed to the critical mass of Higgs scalar determining the decoupling of Higgs particle from the inflation by making use of renormalization group at 2 loop accuracy [7]. The decoupling mass essentially depends on the parameters: the scale μ at the end of Higgsian inflation, the coupling constant of strong interactions in QCD α_s taken at the scale of Z-boson mass, and the top quark mass m_t, so that

$$m_H^c = 153 + 0.28 \cdot \ln\frac{10^{18}}{\mu} - 0.19 \cdot \frac{\alpha_s - 0.1187}{0.002} + 2 \cdot \frac{m_t - 173}{2} \pm 2 \text{ GeV},$$

where μ, m_t are taken in GeV, and the uncertainty estimates the accuracy of 2-loop approximation.

If the Higgs boson has got the sub-critical mass $m_H < m_H^c$, then the Higgsian inflation is possible, and it causally determines the definite spectrum of quantum fluctuations of Higgs field producing the spatial inhomogeneity of energy density. However, such the inflation alone would produce a universe different from the observable Universe, so one should consider the case with two scalar fields, at least, in the early stage of Universe evolution: the second field is the inflaton responsible for the formation of visible properties of Universe.

3. New scenario of inflation and the Higgs boson

Observations of the large scale structure of Universe and anisotropy of cosmic microwave background [8] favor for the hilltop scenario of inflation, so that the inflaton with the characteristic mass $m = (1.4 \pm 0.3) \cdot 10^{13}$ GeV slowly rolls down to the minimum of its potential from the plateau $V_{\rm hill} = \Lambda^4$ with $\Lambda \sim 10^{16}$ GeV [5]. Then, the excited Higgs field can determine the Universe evolution at energy densities ρ higher than the altitude of the hill, $\rho > V_{\rm hill}$, that makes the above theoretical consideration actual to the real situation: the super-critical values of Higgs boson mass would destroy the description of very early stages in the Universe history.

4. Constraint excluding the super-critical mass

The cosmological role of Higgs boson is completely predictable, an arbitrary spectrum of spatial inhomogeneity produced by the Higgs boson is excluded, if only the Landau-pole constraint is strengthened by the bound of decoupling

$$\lambda < \lambda(\mu_{\rm pole}) = \infty \quad \mapsto \quad \lambda < \lambda_c(m_{\rm Pl}) = \frac{1}{6},$$

therefore, if the Higgs particle has got the mass within the bounds

$$129 \text{ GeV} < m_H < 153 \text{ GeV}.$$

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