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Inflation, LHC and the Higgs boson

L'inflation, le LHC et le boson de Higgs

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A R T I C L E I N F O

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A B S T R A C T

After the Higgs boson has been discovered, the Standard Model of particle physics became a confirmed theory, potentially valid up to the Planck scale and allowing one to trace the evolution of the Universe from the inflationary stage till the present days. We discuss the relation between the results from the LHC and the inflationary cosmology. We overview the Higgs inflation, and its relation to the possible metastability of the electroweak vacuum. A short overview of the bounds on the metastability of the electroweak vacuum in the models with inflation not related to the Higgs boson is presented.

R É S U M É

Après la découverte du boson de Higgs, le modèle standard de la physique des particules peut être considérée comme une théorie confirmée par l'expérience, potentiellement valable jusquà l'échelle de Planck et permettant de suivre l'évolution de l'univers depuis l'époque inflationnaire jusqu'à aujourdhui. Notre article discute les liens entre les résultats obtenus avec le grand collisionneur de hadrons (LHC) et l'inflation cosmologique. Nous résumons les propriétés des modèles de «Higgs-inflation» et leur relation avec la métastabilité potentielle du vide électrofaible. Une courte revue des limites de cette métastabilité dans les modèles d'inflation ne reposant pas sur le boson de Higgs est aussi présentée.

1. Introduction

During the last several years, a huge progress was achieved in experimental particle physics. The last missing piece of the Standard Model (SM), the Higgs boson with the mass 125–126 GeV, has been discovered. No convincing deviations from the SM have been seen in LHC experiments. The masses of the top quark and of the Higgs boson, which the Nature has chosen, tell us that the SM is a self-consistent effective field theory all the way up to the Planck scale. All this gives us an

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opportunity to describe in terms of known physics the evolution of the Universe from the very early stages till the present days, and, in particular, the inflationary period of its expansion.[1]

The aim of this short review is to discuss the relationship between the LHC findings and inflation. It is divided into two parts. In the first one, we will discuss the hypothesis that it is the Higgs boson of the SM that plays the role of the inflaton. In the second part we will discuss the possibility that the inflaton is something else.

2. Higgs inflation

Since inflation was invented [3–8], one of the most important questions that relates cosmology and particle physics is what particle drives inflation. The best candidate is a spin-zero field—a boson. The equation of state of a bosonic field homogeneous over a sufficiently large portion of space nearly coincides (for flat enough scalar potential) with that of the cosmological constant. This leads to accelerated expansion of the Universe—exactly what is needed for inflation. However, no any fundamental scalar was known before 2012, making the whole approach somewhat speculative. With the discovery of the Higgs boson at the LHC, we got a fundamental scalar, providing a support of the idea of inflation driven by a scalar field. Indeed, as we have got a number of fundamental fermions and vector bosons in the SM, why not to have other scalars with one of them playing the role of the inflaton field? Or, maybe, the Higgs field itself can make the Universe flat, homogeneous and isotropic, and create perturbations necessary for structure formation? Of course, the second option is the most minimal one, potentially providing the maximal number of links between the early Universe and the SM physics.

Let us ignore for the moment all quantum effects and consider the Higgs-gravity sector of the SM in the classical approximation. The Higgs inflation [9] is based on the observation that the Higgs boson field h must have the non-minimal coupling to gravity, i.e.

$$S_G = \int d^4x\sqrt{-g}\left\{ -\frac{M_P^2}{2}R - \frac{\xi h^2}{2}R \right\} \tag{1}$$

where R is the Ricci scalar, $M_P = 2.44\cdot 10^{18}$ GeV is the (reduced) Planck mass. The parameter ξ in this formula cannot be found from available high-energy experiments, and cannot be determined theoretically within the SM and gravity. As other parameters of the SM, it can only be fixed at present from observations, in our case from anisotropies of the Cosmic Microwave Background (CMB).

The presence of the non-minimal coupling modifies the λh^4 behavior of the Higgs potential in the Einstein frame, which is derived from the Jordan frame Lagrangian (1) by conformal transformation $g_{\mu\nu} \to \Omega^2 g_{\mu\nu}$, where $\Omega^2 = 1 + \frac{\xi h^2}{M_P^2}$. In terms of the original Higgs field, it has the simple form

$$U_E(h) = \frac{\lambda h^4}{4\Omega^4} \tag{2}$$

which is changed to the exponential at large h if instead of the Higgs field we use the field χ with the standard canonical kinetic term in the Einstein frame,

$$U_E(\chi) = \frac{\lambda M_P^4}{4\xi^2}\left(1 - e^{-\sqrt{2/3}\chi/M_P}\right)^2 \tag{3}$$

The COBE normalization fixes the unknown parameter ξ in terms of the scalar self-coupling as

$$\xi = 49\,000\sqrt{\lambda} \tag{4}$$

whereas the predictions for the scalar spectral index and for the tensor-to-scalar ratio are

$$n_s = 0.97, \quad r = 0.003 \tag{5}$$

consistent with Planck results (see Fig. 1). Moreover, as is the case for most single-field inflationary models, the perturbations are Gaussian, what is also in excellent agreement with Planck observations [10]. After the slow-roll, the Higgs field starts to oscillate and to produce particles of the SM, heating the Universe up to the temperatures $\sim 10^{14}$ GeV [11–13].

3. Vacuum stability, radiative corrections, and Higgs inflation

At the classical level, no link between inflationary cosmology and SM parameters can appear: the only parameter entering in cosmological computations is the combination λ/ξ^2, which is theoretically not known, even if the mass of the Higgs

[1] Of course, we know that the SM is not complete as it cannot explain neutrino masses and oscillations, does not have a candidate for the dark-matter particle, and cannot make the Universe charge asymmetric. However, these problems do not tell us with certainty what is the scale of new physics (for a review, see [1]). In particular, they all can be solved with new feebly interacting particles with masses below the Fermi scale (for a review, see [2]), which do not have any influence on cosmological inflation, in which we are interested in this paper.

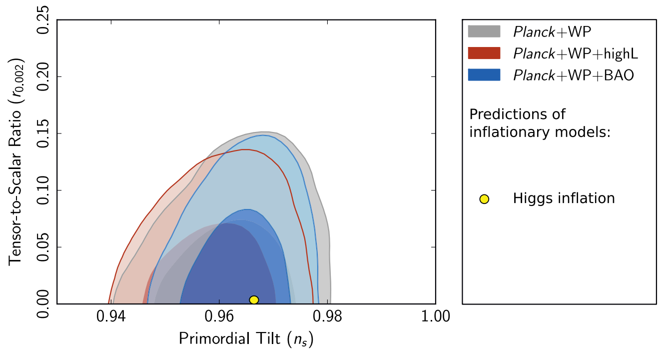

Fig. 1. (Color online.) Predictions of the Higgs inflation, extra non-minimally coupled scalar, and R^2 inflation versus the Planck data.

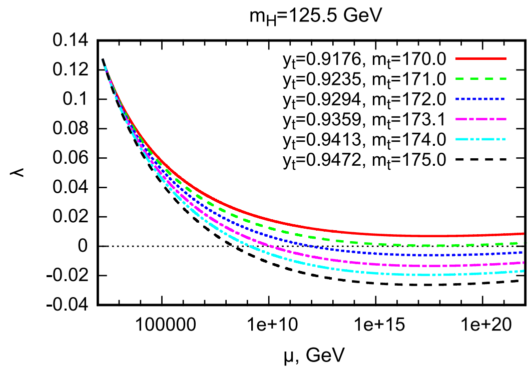

Fig. 2. (Color online.) Renormalization group running of the Higgs self-coupling for several values of the top-quark Yukawa coupling (top pole mass) and fixed to a 125.5 GeV Higgs boson mass.

boson is pinned down by experiment. One would think that this is also the case if quantum corrections are taken into account. Indeed, the most important effect is the running of Higgs' scalar self-coupling constant towards the high-energy scale, where inflation happens [14–17]. Now, just take λ at the inflationary scale, adapt parameter ξ in accordance with (4), and reproduce thus all the predictions of the Higgs inflation discussed above, since the dependence of λ on the energy scale is quite slow (logarithmic).

However, this situation happens to be much more complicated, since the experimentally measured values of the Higgs mass and of the top Yukawa coupling lead to quite a peculiar behavior of the scalar self-coupling λ, see Fig. 2. This constant decreases with energy, reaches its minimum at energies close to the Planck scale, and then increases. Depending on the values of the Higgs mass and top Yukawa coupling (and also, to a smaller extent, on the strong coupling constant) within experimental uncertainties, λ can cross zero at energies as small as 10^{10} GeV and remain negative around the Planck scale, or be positive at any energy, or just touch zero at an energy scale close to the Planck one. Clearly, the analysis of the Higgs inflation should be modified if the scalar self-coupling is negative or very close to zero in the inflationary region.

The behavior of the scalar self-coupling is tightly related to the problem of the stability of the electroweak vacuum. The Higgs field effective potential in the pure SM (no higher dimensional operators are included and all gravity effects are neglected) can be well approximated as

$$V_{\mathrm{eff}}(h) = \frac{\lambda(h)}{4} h^4 \tag{6}$$

where $\lambda(h)$ is a running coupling as a function of the Higgs field. For the top Yukawa couplings smaller than $y_t < y_t^{\mathrm{crit}} - 1.2{\cdot}10^{-6}$, where y_t^{crit} is some critical value (to be specified below), the potential is a growing function of the scalar field for $h > 250$ GeV. For $y_t > y_t^{\mathrm{crit}} - 1.2{\cdot}10^{-6}$, a new minimum of the effective potential develops at large values of the Higgs field, at $y_t = y_t^{\mathrm{crit}}$ our electroweak vacuum is degenerate with the new one, while at $y_t > y_t^{\mathrm{crit}}$ the new minimum is deeper than ours, meaning that our vacuum is metastable. If $y_t > y_t^{\mathrm{crit}} + 0.04$ (this corresponds roughly to the top-quark mass $m_t \gtrsim 178$ GeV) the life-time of our vacuum is smaller than the age of the Universe.

The computations of y_t^{crit} give (for a review see [1] and references therein)

$$y_t^{\mathrm{crit}} = 0.9244 + 0.0012{\cdot}\frac{M_h/\mathrm{GeV} - 125.7}{0.4} + 0.0012{\cdot}\frac{\alpha_s(M_Z) - 0.1184}{0.0007} \tag{7}$$

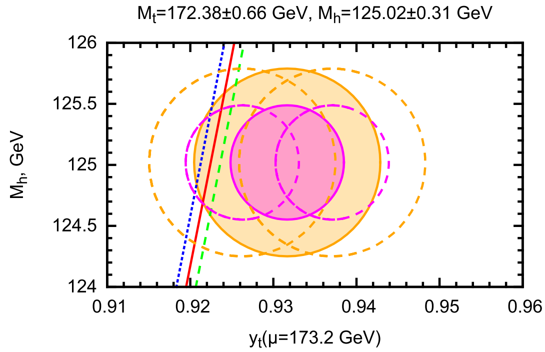

Fig. 3. (Color online.) The figure shows the borderline between the regions of absolute stability and metastability of the SM vacuum on the plane of the Higgs boson mass and top-quark Yukawa coupling in the $\overline{\text{MS}}$ scheme taken at $\mu = 173.2$ GeV. The diagonal line stands for the critical value of the top Yukawa coupling y_t^{crit} as a function of the Higgs mass and the dashed lines account for the uncertainty associated with the error in the strong coupling constant α_s. The SM vacuum is absolutely stable to the left of these lines and metastable to the right. The filled ellipses correspond to experimental values of y_t extracted from the latest CMS determination [18] of the Monte-Carlo top-quark mass $M_t = 172.38 \pm 0.10(\text{stat}) \pm 0.65(\text{syst})$GeV, if this is identified with the pole mass. The Higgs mass $M_h = 125.02 \pm 0.27(\text{stat}) \pm 0.15(\text{syst})$GeV is taken from CMS measurements [19]. Dashed ellipses encode the shifts associated to the ambiguous relation between pole and Monte Carlo masses.

where $\alpha_s(M_Z)$ is the QCD coupling at the Z-boson mass. The experiment does not tell with certainty whether we are below or above y_t^{crit}, see Fig. 3. The more precise determination of the top-quark Yukawa coupling would be needed to resolve the question of stability versus metastability of the SM vacuum and fix the behavior of the Higgs self-coupling, important for the Higgs inflation.

To analyze the possibility and predictions of the Higgs inflation for y_t close to y_t^{crit}, a number of questions should be answered. The main difficulty is that the Lagrangian (2) is essentially non-polynomial and it is therefore non-renormalizable. How can we perform reliable computations of radiative corrections in a non-renormalizable theory? What is the relation between the low-energy parameters of the SM that can be fixed at LHC and other experiments and the high-energy parameters appearing in inflationary computations?

In the absence of an ultraviolet completion for the SM non-minimally coupled gravity, the answer to these questions can be only based on the *self-consistency* of the procedure—for more details, see [20,21,13]. The minimal approach is to add to the SM with gravity *only necessary counter-terms* that make it finite in every order of perturbation theory and finite terms of the same field structure as counter-terms, all with arbitrary coefficients. The procedure can be constructed in such a way that the symmetries of the original theory, and in particular the scale invariance of it in the Jordan frame at large values of the Higgs field, is kept. Generically, the finite parts of the counter-term depend on the canonically normalized scalar field χ in the exponential manner $\sim e^{-\sqrt{2/3}n\chi/M_P}$ where n is an integer number, and thus do not spoil predictions (5) (an exception is the critical Higgs inflation, discussed below). At the same time, the finite parts of counter-terms change the behavior of the effective potential for the Higgs field near $h \sim M_P/\xi$, and thus the relation between low energy and high energy parameters depends on unknown coefficients. However, if these coefficients are numerically small and have the same hierarchy as the loop corrections producing them, the connection remains, albeit with some uncertainty.

We will discuss below three different possibilities for the Higgs inflation depending on the relation between y_t and y_t^{crit}.

4. Higgs inflation with the stable vacuum

If $y_t < y_t^{\text{crit}}$, the scalar self-coupling is positive in the inflationary region. The radiative corrections do not play any significant role, and we return to the tree analysis of the Higgs inflation of Section 2. Interestingly, since the value λ is small in the inflationary region, the value of the non-minimal coupling can be as low as $\xi \sim 1000$, but still large enough to insure the validity of the tree level analysis of the Higgs inflation (see [20] and references therein).

5. Critical Higgs inflation

Suppose now that we are very close to the critical value of the top Yukawa coupling, $y_t \approx y_t^{\text{crit}}$. In this case, both λ and its β-function are almost zero at the energy scale $\mu \sim M_P$. Let us look in more details at the change of the effective potential in the Einstein frame when y_t is increasing. For y_t somewhat smaller than y_t^{crit}, the potential is a rising function of the field χ, realizing the "tree" Higgs inflation (Fig. 4, blue curve). At $y_t \approx y_t^{\text{crit}}$, a new feature appears: the first and the second derivatives of the potential are equal to zero at some point (Fig. 4, red curve). For $y_t > y_t^{\text{crit}}$, but still close to y_t^{crit}, we get a wiggle on the potential, which is converted into a maximum for somewhat smaller y_t (see Fig. 4, brown line). Increasing y_t even further leads to the unstable electroweak vacuum (Fig. 4, green curve). Clearly, the necessary condition for inflation to happen in the slow-roll regime is to have $dV(\chi)/d\chi > 0$ for all χ, i.e. the absence of a wiggle. For $y_t < y_t^{\text{crit}}$, all the potentials are very much similar, leading to the independence of inflationary indexes on the parameters, while for

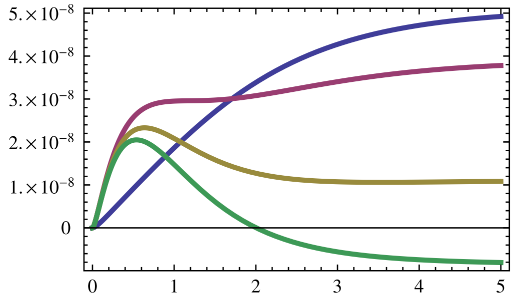

Fig. 4. (Color online.) The schematic change of the form of the effective potential depending on y_t. For better visibility the values of ξ are different for different lines. The horizontal axis corresponds to the canonically normalized field χ, the vertical axis to the effective potential, all in Planck units.

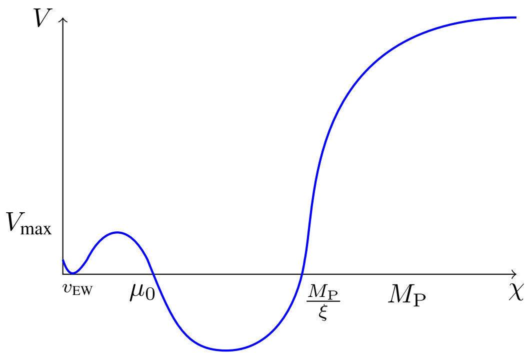

Fig. 5. (Color online.) Sketch of the effective Higgs inflation potential accounting for a *positive* "jump" of the scalar self-coupling. It contains an inflationary plateau at $\chi \gtrsim M_P$ and two minima. The shallowest and narrowest one is the standard electroweak vacuum v_{EW}. The deepest and widest one is generated by the interplay between the instability of the Higgs self-coupling beyond the scale μ_0 and the renormalization effects appearing at the scale M_P/ξ.

$y_t \approx y_t^{crit}$ the form of the potential is qualitatively different, and the dependence of r and n_s on the top Yukawa coupling and the Higgs boson mass shows up. Qualitatively, the Higgs field spends a lot of time near the inflection point, ensuring the necessary number of e-foldings, whereas the inflationary indexes are related to the form of the potential at some distance from the inflection point. The analysis carried out in [21] showed that both n_s and r depend very strongly on particle-physics parameters (Higgs and top masses), and on the values of unknown coefficients characterizing the counter-terms and may differ considerably from the universal predictions (5). In particular, the tensor to scalar ratio r can be large (see also [22]). The critical Higgs inflation requires rather small values of the parameter $\xi \sim \mathcal{O}(10)$.

6. Higgs inflation with the metastable vacuum

If $y_t > y_t^{crit}$ *and if all finite parts of the counter-terms can be neglected*, the potential for the Higgs field has the form shown by the green line in Fig. 4, making the inflation impossible. It may be shown [13] that the contribution of extra operators can be accounted for by the rapid changes—"jumps" of the different coupling constants at the background Higgs field $h \simeq M_P/\xi$. The amplitudes of these "jumps" cannot be fixed within the SM and requires the knowledge of its ultraviolet completion. If the "jump" $\delta\lambda$ is much smaller than λ at the inflationary scale, then the Higgs inflation requires the absolute stability of the vacuum and provides a clear connection between the properties of the Universe at large scales and the value of the SM Higgs and top-quark masses. However, since the smallness of λ at $\mu \sim M_P$ appears to be the result of a non-trivial cancellation between the fermionic and bosonic contributions, it is conceivable to think that $\delta\lambda$ can be of the order of $\lambda \sim 10^{-2}$. In that case, the "jumps" of the coupling constants open the possibility of having Higgs inflation even in the case of a metastable vacuum by converting a negative scalar self-coupling below M_P/ξ into a positive coupling above that scale. If this indeed happens, the (zero temperature) effective potential will have a form illustrated schematically by Fig. 5. It has an inflationary plateau at large values of the scalar field, and two minima. The first one (the shallowest and narrowest one) corresponds to the standard electroweak vacuum. The second one (the deepest and widest one) is generated by the interplay between the instability of the Higgs self-coupling below M_P/ξ and the jumps at that scale. As in any chaotic inflation scenario [23], the Higgs field will start its evolution from trans-Planckian values, will inflate the Universe (with inflationary indexes given by (5)) and will decay into SM particles after the exponential expansion. It may seem that, at the end of these processes, the universe will end at the deeper and wider vacuum at $\chi \sim M_P/\xi$. However, this is not necessarily the case. The destiny of the Universe strongly depends on the relation between the energy stored in the Higgs field after inflation and the depth of the minimum at large field values. If the first one is much larger than the second one, the reheating of the Universe after inflation may result in a sizeable modification of the effective potential, leading to the

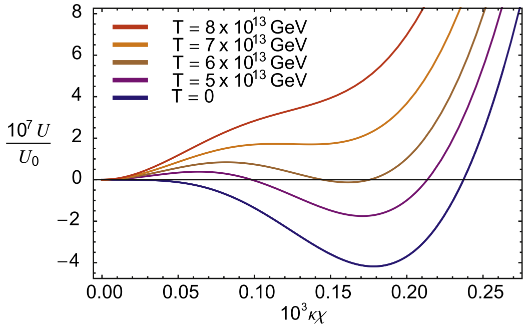

Fig. 6. (Color online.) High-temperature effective potential for non-critical Higgs inflation for $y_t > y_t^{crit}$ corresponding to the parameter choice $m_H = 125.5$ GeV, $m_T = 173.1$ GeV, $\xi = 1500$, $\delta\lambda = 0.0153$.

disappearance of the "dangerous" vacuum at large field values and subsequent evolution of the system towards the "safe" electroweak vacuum. On the contrary, if the two energy scales are comparable, the Universe will end in the "dangerous" vacuum and will inevitably collapse [24].

The computations performed in [13] demonstrated that for the non-critical Higgs inflation, the temperature after reheating exceeds the temperature of symmetry restoration, at which the extra minimum of the effective potential with large value of the Higgs field disappears, see Fig. 6. The system relaxes to the SM vacuum. In the subsequent evolution of the Universe, the temperature decreases and the second minimum reappears at large field values, first as a local minimum, then as the global one. However, there is always a barrier separating these two minima (not really visible on the plot due to the overall χ^4 behavior at low field values). This barrier prevents the direct decay of the Fermi vacuum. The decay of the SM vacuum can still happen via tunneling, but the probability of this process turns out to be rather small [25–28].

On the contrary, for the critical Higgs inflation, the mechanism does not seem to work: the height of the potential barrier separating different minima is comparable with the energy of the Higgs field after slow-roll, and the system is trapped in the deeper vacuum with a large value of the Higgs field. In other words the critical Higgs inflation requires the stability of the SM vacuum.

7. Inflation as a manifestation of new physics and stability bounds

Let us turn to less "minimal" scenarios, where additional new physics drives the inflationary expansion of the Universe. Let us assume first that this new physics *does not* modify the Higgs potential up to the Planck scale (i.e. the inflaton is not coupled with the Higgs boson, or the coupling is negligible for the analysis). Examples of such inflationary models are R^2 inflation [7] and chaotic ϕ^2 inflation [23] (with the inflaton not coupled with the Higgs boson directly).

For the stable SM electroweak vacuum, $y_t < y_t^{crit}$, these models work well. The only subtlety that one should have in mind is the reheating of the Universe after inflation, which prevents the complete decoupling of the inflationary and SM sectors.

The fate of the metastable world with $y_t > y_t^{crit}$ is not certain and is model dependent. Indeed, even if the Higgs field turns out to be near the electroweak minimum in a large patch of the Universe, it can decay. Let us see at what stage of the Universe evolution this can happen.

At the present epoch, this can happen only by tunneling via the creation of a bubble of true (Planck scale) vacuum. The probability of this process is negligible for all allowed top and Higgs masses, with the typical timescale of the decay greatly exceeding the age of the Universe [25].[2] Numerically, the lifetime of the vacuum would become shorter than the age of the Universe for $y_t \gtrsim y_t^{crit} + 0.04$, which is about 5σ away from the current top-quark mass measurements.

Let us turn now to the earlier period of evolution probing higher energies—the reheating after inflation. At high temperature, thermal fluctuations may trigger the decay of the SM vacuum [27,25], providing an upper bound on the reheating temperature for a given value of the top and Higgs masses. The bound again turns out to be not very strong—extrapolating the results of [25] to the current value of the Higgs mass, we get that only at top-quark masses exceeding $m_t \gtrsim 175$ GeV, the upper bound on the temperature becomes as small as 10^{15} GeV, which is the highest reheating temperature still compatible with inflationary observations. Basically, this means that thermal tunneling also does not lead to the decay of the metastable SM vacuum.

Going further back in time (and higher in energies), we arrive to the inflationary stage. Quantum fluctuations of the Higgs field in the quasi-de-Sitter space may lead to the decay of the metastable vacuum.

A simple estimate of whether this decay happens can be made by comparing the typical momentum of the perturbations during inflation, which is equal to the inflationary Hubble H_{inf} and the height of the barrier $V_{max}^{1/4}$. If $H_{inf} > V_{max}^{1/4}$, we should

[2] Let us emphasize, that a crucial assumption here is the absence of Planck scale suppressed higher order operators. Their presence may change the fate of the EW vacuum in any direction, making it live very long or making it decay in an instant [29].

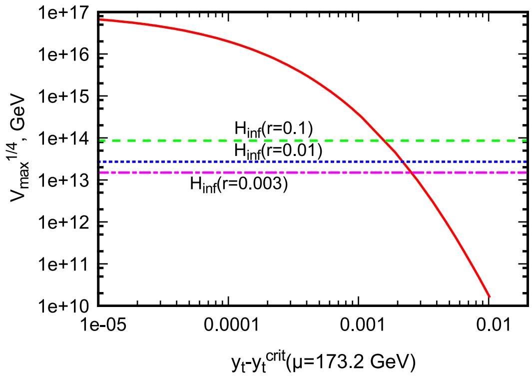

Fig. 7. (Color online.) Estimate of the height of the Higgs effective potential barrier between the electroweak and high scale vacua, cf. [1]. Lines of the Hubble scale during inflation leading to the tensor scalar ratio values $r = 0.1$, 0.01, 0.003 are given for reference.

expect that the quantum fluctuations force the Higgs field value away from the electroweak vacuum [30,31]. Evidently, the constraint on the top-quark Yukawa depends on the (yet unknown) inflationary expansion rate, which is related to the tensor-to-scalar ratio r as

$$H_{\rm inf} \sim 8.6\cdot 10^{13}\,\mathrm{GeV}\left(\frac{r}{0.1}\right)^{1/2}$$

The bound on the top Yukawa can be read from Fig. 7, where the height of the barrier in the Higgs effective potential (6) is plotted together with $H_{\rm inf}$ for several typical values of r. The current constraint on the tensor-to-scalar ratio from CMB observation is $r < 0.11$ [10] (see also [32]). Thus, if the corresponding limit $y_{\rm t} < y_{\rm t}^{\rm crit} + 0.0015$ is satisfied, the decay of the metastable SM vacuum is not dangerous. Let us note that for R^2 inflation, $H \sim 1.5\cdot 10^{13}$ GeV ($r \sim 0.003$), the bound weakens only by a little, $y_{\rm t} < y_{\rm t}^{\rm crit} + 0.0025$. For extremely low-scale inflationary models, the limit weakens even further.

One can further argue that the tunneling process in the inflationary quasi-de-Sitter space is always suppressed as compared to the decay by quantum fluctuations of the field [33,30,31].

To summarize, in the models where inflation is completely decoupled from the Higgs physics, the bound on the stability of the EW vacuum is also present and depends on the tensor-to-scalar ratio. If the tensor-to-scalar ratio is observed in near-future experiments, the bound on the top-quark mass in such models is about 0.2–0.6 GeV weaker than for the critical Higgs inflation in Section 5. However, for very low-scale inflation ($r \ll 10^{-3}$), the bound can effectively disappear.

7.1. Meta-stability and non-minimal coupling

The bounds on the top-quark mass can be changed if the dynamics of the Higgs field is modified during inflation. A natural example is the non-minimal coupling to gravity (1). Note that such term is generated by radiative corrections, so ξ cannot be zero at all energy scales.

If we consider the evolution of the Higgs field in the external gravitational background, this term acts as a mass of the Higgs field. For the uniform background (neglecting the spacial curvature contribution) we have for the Ricci scalar

$$R = -12H^2 - 6\dot{H}$$

where dot means the time derivative. During inflation, $R = -12H^2$, at matter-dominated stages $R = -3H^2$, and $R = 0$ at radiative expansion. Thus, for *negative* values of ξ, the non-minimal coupling in (1) provides effectively a *positive* quadratic term to the Higgs potential throughout the evolution of the Universe, thus stabilizing the potential [25,34]. The competing terms of the potential are $\xi R h^2$ and λh^4, with everything being estimated at inflationary scales $h, R^{1/2} \sim H$. The Higgs coupling constant is small at high scales, $|\lambda| \lesssim 0.02$, so small negative $\xi < -10^{-2}$ is enough to make the potential positive.

The RG evolution of the non-minimal coupling was taken into account in [34], with the conclusion that if the non-minimal coupling at electroweak scale is such that $\xi_{\rm EW} \lesssim -6\cdot 10^{-2}$ the vacuum is stabilized, while for $\xi_{\rm EW} \gtrsim -2\cdot 10^{-2}$ the RG evolution drives ξ to positive values during inflation and leads to the destabilization of the potential.

Note, that $\xi = -1/6$, corresponding to the conformal coupling, also stabilizes the potential during inflation [35].

There are also problems that can arise in presence of a negative value of ξ. If ξ is negative and the Higgs field background is sufficiently large, the coefficient in front of R in the action (1) changes sign. This may lead to severe gravitational instabilities. This complication can be evaded by considering a more general case, replacing $\xi\phi^2$ by a function of the Higgs field that never exceeds $M_{\rm P}^2/2$ [36].

8. Higgs interacting with the inflaton

Let us finally depart from both assumptions that the Higgs field drives inflation and that it does not interact with the inflationary sector. As can be expected, this situation has large freedom and, depending on the concrete model, leads to very different phenomenologies. Without going into a full analysis, we provide here two examples of models with and without limits on the stability of the EW vacuum.

Let us consider the quartic Higgs-inflaton coupling

$$\mathcal{L}_{\rm int} = \frac{\alpha}{2}\phi^2 h^2 \tag{8}$$

where ϕ is the inflaton field. If the coupling constant α is negative, then during inflation the Higgs field gets additional mass term $-\alpha\phi^2$, which can stabilize the Higgs potential. Moreover, for large-field inflation models, $\phi \gg M_{\rm P}$, so quite small values of α suffice in this task. In the case of, e.g., the quadratic inflaton potential, the value of $|\alpha|$ exceeding 10^{-10} is enough to stabilize the Higgs potential [37]. Note that for $|\alpha| < 10^{-6}$, the inflationary potential is not significantly modified by radiative corrections, so the analysis is consistent. This is the example of the model, where no bounds on the SM vacuum stability follow from inflation.

Another simple model proposed in [38,39] leads to the requirement of the stable EW vacuum. In this model, a positive $\alpha > 0$ was chosen. Specifically, the Higgs-inflaton scalar potential of the model is

$$V = \frac{\lambda}{4}\left(h^2 - \frac{2\alpha}{\lambda}\phi^2\right)^2 + \frac{\beta}{4}\left(\phi^2 - v_\phi^2\right)^2$$

with typical values of the constants $\beta \sim 10^{-13}$, $10^{-7} \gtrsim \alpha \gtrsim 10^{-11}$, $\lambda \sim 0.1$. The potential of this form is inspired by the idea of having only one energy scale in the theory related to v_ϕ, with the inflaton serving as a messenger of the dilational symmetry breaking. Inflation here is supported by the quartic term $\beta\phi^4/4$, while a relatively large value of λ guarantees that inflation proceeds along the valley $h^2 = \frac{2\alpha}{\lambda}\phi^2$, where the first term does not contribute to the inflationary energy density. For the typical Planck scale values of inflationary field ϕ, the Higgs field gets to values of about 10^{13} GeV, so at least up to this scale the Higgs potential should be positive. As far as the behavior of λ is very shallow at high scale, cf. Fig. 2, the model requires absolutely stable SM vacuum, i.e. $y_{\rm t} < y_{\rm t}^{\rm crit}$.

We should mention that even more complicated scenarios of the Higgs interplay with the inflation were studied in the literature, with various predictions for the Higgs mass. An example is the model where the inflationary energy density is provided by the *positive* energy density in the Planck scale vacuum, and the graceful exit is realized by the evolution of an additional scalar field. This model predicts a very precise value of $y_{\rm t}$ just *above* $y_{\rm t}^{\rm crit}$, so that the second vacuum at high scale is present, but is the false vacuum itself [40–42].

9. Conclusions

The results from LHC experiments are very important for cosmology. They have already established that the SM is a valid effective field theory all the way up to inflationary scale, providing us with an opportunity to follow the evolution of the Universe within the SM.

The Higgs boson of the SM, besides its particle physics “obligations” to break the electroweak symmetry and generate the masses of quarks, leptons, and intermediate vector bosons, can inflate the Universe, producing primordial fluctuations needed for structure formation and making the Hot Big Bang. The Higgs inflation can take place both for absolutely stable and metastable vacuum, with universal predictions $n_{\rm s} = 0.97$, $r = 0.003$ for a wide range of parameters. For the critical Higgs inflation corresponding to $y_{\rm t} \approx y_{\rm t}^{\rm crit}$, the inflationary parameters $n_{\rm s}$ and r can be substantially different from these values.

If inflation is realized by a mechanism separate from the Higgs boson, it can provide bounds on the value of $y_{\rm t}$ due to the possibility of decay of the SM vacuum at an inflationary stage of evolution. These bounds depend both on the inflationary parameters and on the details of the interaction between the Higgs boson and inflationary and gravity sectors. In particular, if the Higgs is completely separate from the inflationary and gravity sector, then the metastable SM vacuum is prone to decay during inflation. The higher the inflationary scale is, the stronger the bound becomes. For small r it becomes weaker, but even for $r \sim 0.003$, predicted by R^2 inflation, it is relaxed only by half a GeV for the top-quark mass.

The presence of interaction between the Higgs boson and inflaton or gravity can change the requirements on the stability of the EW vacuum. While the stable EW vacuum is always compatible with inflation, the unstable vacuum can be both stabilized or further destabilized by new physics, such as Higgs-inflaton interactions or small Higgs boson non-minimal gravity coupling.

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