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On electroweak metastability and Higgs inflation

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Abstract

For the central values of the relevant experimental inputs, that is the strong coupling constant and the top quark and Higgs masses, the effective Higgs potential displays two minima, one at the electroweak scale and a deeper one at high energies. We review the phenomenology of the Higgs inflation model, extending the Standard Model to include a non-minimal coupling to gravity; as recently shown [1], even configurations that would be metastable in the Standard Model, become viable for inflation if the non-minimal coupling is large enough to flatten the Higgs potential at field values below the barrier between the minima.

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1 Introduction

In the Standard Model (SM), the central values of the relevant experimental inputs – the strong coupling constant with five flavors, $\alpha_s^{(5)}$, the top quark pole mass, m_t, and the Higgs mass, m_H – suggest that the electroweak vacuum is likely to be metastable rather than stable. The shape of the Higgs effective potential at high energy is relevant in view of the possible role of the Higgs field as the inflaton; for this sake, a region where the Higgs potential becomes sufficiently flat, for large enough values of the Higgs field, to meet the slow-roll conditions would be required.

By introducing a non-minimal coupling to gravity, ξ, that flattens the Higgs potential at field values larger than about $M_P/\sqrt{\xi}$, where M_P is the reduced Planck scale, the Higgs might successfully play the role of the inflaton [2]. In this contribution, based on [1], we review the phenomenology of Higgs inflation, including would-be metastable configurations.

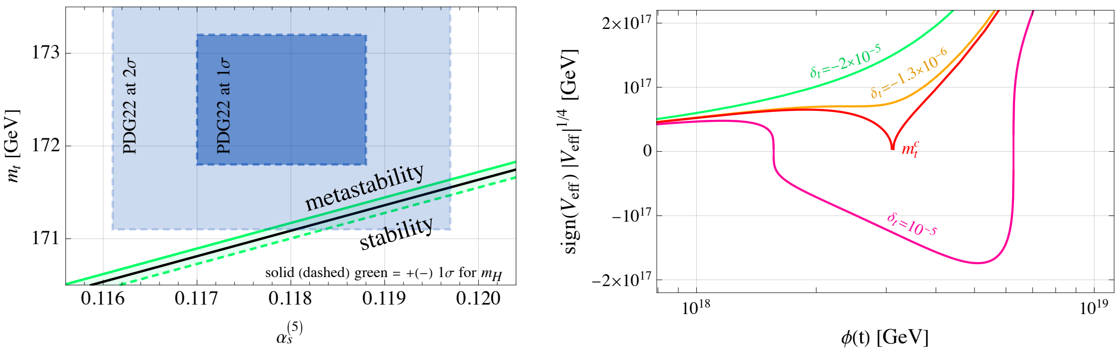

Figure 1: Left: the black line separates the regions of stability and metastability; the green solid and dashed lines display the effect of a positive and negative 1 σ variation in m_H; the shaded blue rectangles display the 1 σ and 2 σ allowed ranges for $\alpha_s^{(5)}$ and m_t [13]. Right: Higgs effective potential configurations near criticality. From [1].

2 Metastability of the Standard Model Higgs potential

Consider the SM Higgs doublet, $H = (0, \phi + v)^T/\sqrt{2}$, where v is the electroweak vev. Via the Renormalization Group Equations, it is possible to extrapolate the SM Higgs effective potential, $V_{\rm eff}$, at high energies. The most relevant experimental inputs to determine the shape of the Higgs potential are m_t, m_H and $\alpha_s^{(5)}$. According to their values, three scenarios can be found: instability, metastability and stability.

The program of discriminating these scenarios started in the fall of the '70s [3–6], after the prediction of the top quark in 1973, but much before its discovery in 1995. The 2012 discovery of the Higgs boson by LHC triggered theoretical improvements, and the extrapolation reached the NNLO accuracy: 2-loop in the effective potential and matching conditions, and 3-loop in running. Still, the ambiguity was left among stability and metastability, the latter being slightly favored (see *e.g.* [7–11]); the difference between instability and metastability requires an analysis of the tunneling probability from the false to the true minima. Even in the future, it will be difficult to exclude stability [12].

Taking central values for $\alpha_s^{(5)}$ and m_H [13], the (critical) value of the top mass for which the NNLO Higgs effective potential displays two degenerate minima is $m_t^c \approx 171.0588$ GeV, as discussed *e.g.* in Ref. [1]. The left plot in Fig. 1 shows the regions where the electroweak vacuum is stable or metastable.

It is also interesting to study the shape of the Higgs potential around criticality, as shown in the right plot of Fig. 1. The critical configuration is shown in red, and one can see that the high energy vacuum is located at field values $\phi(t)$ which are close to the Planck energy scale. It is useful to define

$$\delta_t = m_t/m_t^c - 1\,, \tag{1}$$

and explore possible shapes close to the critical one, as for instance the inflection point configuration (in orange), achieved with $\delta_t = -1.3\times10^{-6}$, and the configurations corresponding to $\delta_t = -2\times10^{-5}$ and $\delta_t = 10^{-5}$.

3 Inflation, new physics, and the Higgs field

The basic idea of inflation is to introduce a homogeneous scalar field, called inflaton. If, for some reason, there has been a period in which the Hubble rate $H(t)$ was dominated by a

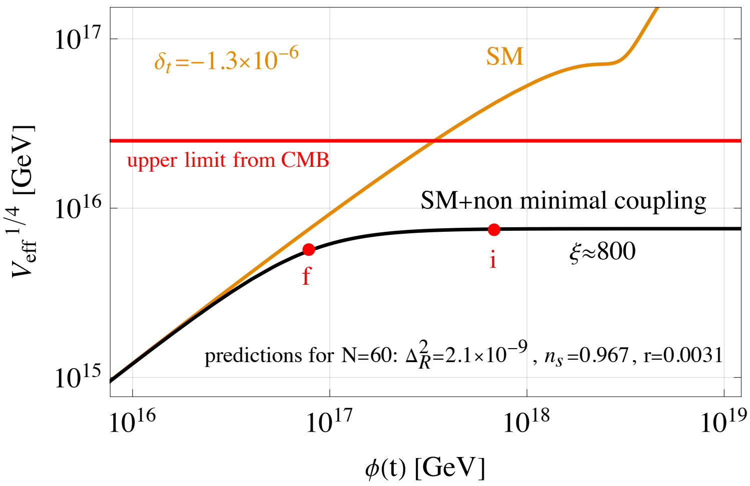

Figure 2: The upper curve is the SM inflection point configuration. The lower (black) curve shows how the same configuration gets modified by including $\xi \approx 800$; the cosmological predictions agree with CMB data [13], and the red dots signal the beginning (i) and end (f) of inflation. Adapted from [1].

positive nearly constant potential $V(\phi)$, then

$$\left(\frac{\dot{a}(t)}{a(t)}\right)^2 = H^2(t) \approx \frac{8\pi V(\phi)}{3M_P^2}, \tag{2}$$

where $a(t)$ is the scale factor; a period of exponential expansion is thus achieved, $a(t) \propto e^{Ht}$. The latter might address issues like the Universe flatness, isotropy and homogeneity, etc. If the potential $V(\phi)$ is sufficiently flat, the slow-roll conditions are met,

$$\epsilon \equiv \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1, \qquad |\eta| \equiv M_P^2 \frac{|V''|}{V} \ll 1, \tag{3}$$

and the cosmological observables are:

$$\Delta_R^2 \simeq V/(24\pi^2 M_P^4 \epsilon) \simeq 2.1 \times 10^{-9}, \quad n_s \simeq 1 + 2\eta - 4\epsilon, \qquad r = 16\epsilon, \tag{4}$$

where Δ_R^2 is the amplitude of density perturbations, n_s the inflaton spectral index, and r the tensor-to-scalar ratio. The inflationary period should end after about $N = 60$ e-folds, leading to matter production via the so-called reheating process.

As the Higgs is the only elementary scalar found, could it be involved in primordial inflation? Let us start from top to bottom in the right plot of Fig. 1, that is from stable to metastable configurations: i) If the Higgs potential is ever increasing, it is also too steep and slow-roll cannot take place; ii) In the case of an inflection point, a bit of slow roll is found, but not for enough e-folds [14]; iii) Critical and metastable configurations clearly do not work.

As a variation of i), one might envisage the possibility that the Higgs is trapped in a shallow vacuum (old inflation type), and another field acts as inflaton. This scenario cannot account for the observed cosmological parameters [15, 16]: as shown in Fig. 2, the value of the Higgs effective potential at the stationary point exceeds the upper limit $V_{\rm eff}^{1/4} \lesssim 2.5 \times 10^{16}$ GeV [1], derived from CMB data by combining, via Eq. (4), the observed value of Δ_R^2 with the upper bound on $r \lesssim 0.036$ [13].

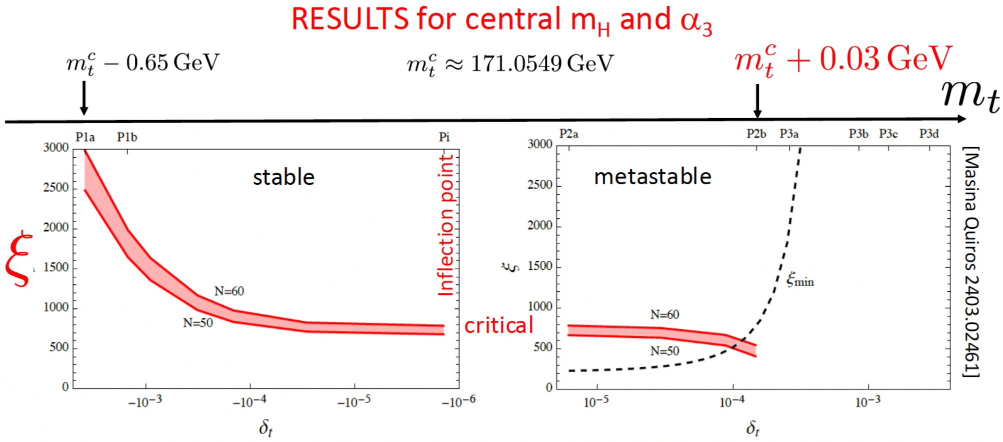

Figure 3: The values of ξ providing successful Higgs inflation. Adapted from [1].

The general lesson is that new physics beyond the SM is needed. For instance: something that flattens the Higgs potential at some ϕ, so that the Higgs itself is the inflaton. Bezrukov and Shaposhnikov [2] showed that is precisely what happens to $V_{\rm eff}$ by adding to the SM Lagrangian, $\mathcal{L}_{\rm SM}$, a non-minimal gravitational coupling ξ between the SM Higgs doublet H and the Ricci scalar R. The classical action for such Higgs inflation model is

$$\mathcal{S} = \int d^4x\,\sqrt{-g}\left[\mathcal{L}_{\rm SM} - \frac{M_P^2}{2}R - \xi\,|H|^2 R\right], \tag{5}$$

where g is the determinant of the FLRW metric. The effect of the introduction of the non-minimal coupling to gravity, ξ, is to flatten the Higgs potential at field values larger than about $M_P/\sqrt{\xi}$, so that slow-roll conditions are met, and the Higgs successfully plays the role of the inflaton. In the metric formulation and for $N = 60$ e-folds, the cosmological predictions are: $n_s - 1 \approx -2/N = -0.033$, $r \approx 12/N^2 = 0.0033$. Substituting the latter predictions in (4), one gets a numerical value for the Higgs potential at the beginning of inflation, $V_i^{1/4} \approx 7.6 \times 10^{15}$ GeV; the value of ξ is determined from the requirement of matching such a value.

The previous literature focused on ever increasing stable configurations. However, thanks to the flattening mechanism, even configurations that in the SM would display two minima – like a shallow vacuum or slightly metastable configurations – become viable for inflation [1]. For instance, as shown in Fig. 2 for the metric formalism, for the same input parameters that would lead to an inflection point configuration in the SM, the inclusion of a non-minimal coupling, $\xi \approx 800$, suitably flattens the Higgs effective potential, leading to viable cosmological predictions for Δ_R^2, n_s and r [13].

4 Conclusions and perspectives

Fig. 3 summarizes the results of our analysis, by showing the values of ξ providing successful Higgs inflation as a function of δ_t, hence of the top quark mass. Notice that ξ decreases as m_t increases, and that for configurations close to metastability ξ can be as small as about 500.

There are no roses without a thorn. In this context, the debated issues of unitarity and which formalism to adopt attracted much interest; for a dedicated discussion about those aspects, we refer to [1]. Here we just mention that with ξ as small as 500, unitarity issues should not apply, and the inflationary dynamics is expected to be reliable.

To conclude, a future better experimental determination of the top quark mass value would be extremely relevant and helpful for Higgs inflation models.

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