Vacuum Stability in the Standard Model and Beyond
A guide for BSM Model Building

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In this talk, I will discuss the stability of the electroweak vacuum in the Standard Model (SM) and its implications for Beyond Standard Model (BSM) physics. The discovery of the Higgs boson with a mass around 125 GeV has profound consequences for the stability of our universe. Current measurements suggest that we are in a metastable state, where the vacuum could potentially decay to a lower energy state, albeit with a lifetime much longer than the age of the universe. This metastability relies on the precise measurements, particularly of the top quark mass, and the strong coupling constant which is therefore prone to uncertainties. Furthermore, I will discuss the relevance of vacuum stability for BSM model building by the example of a simple scalar singlet extension of the SM.

1 Vacuum Stability in the Standard Model

On a classical level, the Higgs potential of the SM is given by

$$V(\phi) = -m^2(\phi^\dagger\phi) + \lambda(\phi^\dagger\phi)^2, \tag{1}$$

where ϕ is the $SU(2)_L$ Higgs field, m^2 is the mass parameter, and λ is the quartic coupling. The potential has a minimum at a non-zero value of ϕ for $m^2 > 0$. This field value at the minimum is known as the vacuum expectation value (VEV), measured to be $v \approx 246$ GeV. The physical Higgs boson mass m_h is related to the quartic coupling λ and the VEV by $m_h^2 = 2\lambda v^2$. Due to the measurement of the Higgs boson mass $m_h \approx 125$ GeV, the quartic coupling λ can be inferred at the electroweak scale. Now, on the classical level, it is sufficient to demand $\lambda > 0$ to ensure that the potential is bounded from below and has a stable vacuum. However, quantum corrections modify the potential, leading to the effective potential $V_{\text{eff}}(\phi)$, which includes loop corrections. The process of choosing a renormalization scheme, mostly the $\overline{\text{MS}}$ scheme, introduces the ambiguity of a renormalization scale μ. This suggests that the parameters of the theory are not directly physical but change with μ to fit observables at different energy scales. This scale dependence is captured within a set of differential equations, called renormalization group equations (RGEs). The scale dependence of λ is particularly interesting. If the quartic λ becomes negative at some scale $\tilde{\mu}$, the potential develops a second minimum at large field values, which can be deeper than the electroweak minimum. This situation is depicted in Fig. 1 (left) for current PDG central values, where λ becomes negative at around 10^{11} GeV. The exact scale at which λ turns negative is particularly sensitive to the top quark mass m_t and the strong coupling constant α_s. This dependence is illustrated in the phase diagram in Fig. 1 (right) which shows regions of absolute stability

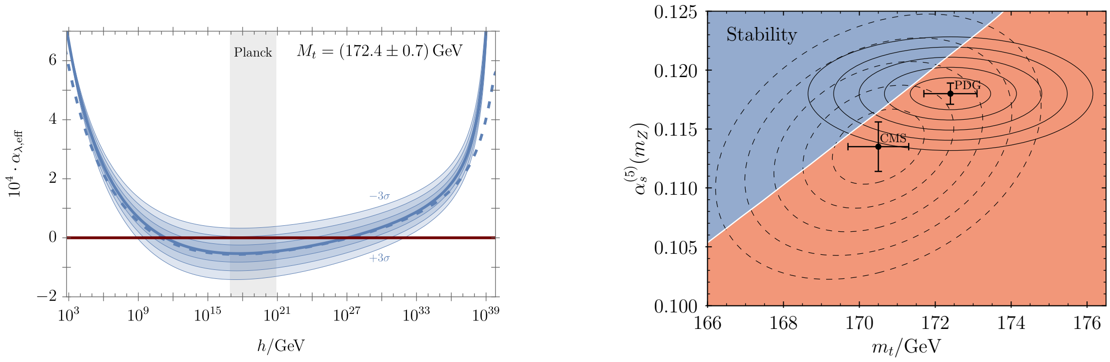

Abbildung 1: Left: Shown is the running of $\alpha_\lambda = \frac{\lambda}{(4\pi)^2}$ (blue dashed line) depending on the field value $\phi \equiv h$. Right: Shown is the SM stability phase space depending on m_t and α_s. Blue denotes absolute stability, red metastability and instability combined.

(blue), metastability and instability combined (red) in the α_s-m_t plane. The current experimental values place us in the metastable region, but close to the boundary with absolute stability. The proximity to this boundary is intriguing and has led to various speculations about its significance, including the possibility of new physics at high scales that could stabilize the vacuum.

2 Guide for BSM Model Building

The metastability of the SM vacuum has important implications for BSM physics. Many extensions of the SM can significantly affect the running of λ and the stability of the vacuum. For instance, consider a simple extension of the SM by a real scalar singlet S with a Z_2 symmetry. The potential reads

$$V(\phi, S) = -m^2\phi^2 + \lambda\phi^4 - \frac{m_S^2}{2}S^2 + \frac{v}{4}S^4 + \frac{\delta}{2}\phi^2 S^2, \tag{2}$$

where v is its quartic coupling, and δ the portal coupling between the Higgs and the singlet. Now within this theory the RGEs are modified (at one-loop)

$$\beta_\lambda \equiv \frac{\mathrm{d}\lambda}{\mathrm{d}\log\mu} \sim \beta_\lambda^{\mathrm{SM}} + \frac{1}{16\pi^2}\,2\delta^2. \tag{3}$$

So a non-zero portal coupling δ can have a stabilizing effect on the running of λ and thus the vacuum stability. Such a theory can be probed experimentally, for instance, via direct searches for the new scalar at colliders, or indirectly through its effects on Higgs boson properties and electroweak precision observables. In my thesis, I study the effects of different types of scalar extensions on vacuum stability and its dynamics regarding cosmology.