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Probing High Scale Physics via Standard Model Parameters

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Abstract: The discovery of the Standard Model (SM) Higgs and precise measurements of SM parameters have revealed a new *Higgs quartic mass scale* of the SM, a scale far beyond the electroweak scale where the Higgs quartic coupling vanishes. We outline possible new physics at this scale that explains the vanishing quartic coupling, and stress the importance of more precise measurements of SM parameters to accurately determine the Higgs quartic scale. In some of these theories, the scale is correlated with signals for new physics in particle physics or cosmology. In others, the scale is predicted from the consistency of the theory. The pursuit of new physics at the Higgs quartic scale complements the conventional search for new physics around the electroweak scale.

In recent decades, the central issue in particle phenomenology has been the origin of the electroweak scale. Theoretical ideas, such as supersymmetry [1–4] and composite Higgs [5, 6], were put forward, and experimental efforts were made to test those ideas. It was expected that colliders would find new particles around the electroweak scale. So far, no particles beyond the Standard Model (SM) have been discovered. Although we believe that continued efforts, both theoretical and experimental, should be made to understand the origin of the electroweak scale, it is also reasonable to consider complementary directions. This seems particularly important given that the electroweak scale may be determined by the landscape and environmental selections [7–10], without leaving obvious experimental signals.

Assuming that the SM is an effective theory, valid up to high energy scales, the renormalization group running of the Higgs quartic coupling has been computed [11–20]. After the discovery of the SM Higgs [21, 22], it was found that the quartic coupling vanishes at a UV scale μ_λ [20], as shown in Figure 1. Since the running of the quartic coupling is slow at high energy scales, the vanishing quartic requires a quartic coupling of around -0.01 at scales above μ_λ. Instead of embracing such a small value as an accident, we may consider new physics which fixes the quartic to be zero at a scale μ_λ, which we call the Higgs quartic scale. We may then learn about the new physics by measuring SM parameters more precisely and determining μ_λ. In fact, in some theories, μ_λ is restricted from additional theoretical inputs or cosmology, such as coupling unification or dark matter and baryon abundances, thereby predicting SM parameters. In others, μ_λ is correlated with other experimental signals such as the dark matter direct detection rate and the QCD axion mass, providing a connection between SM parameters and new physics searches.

Precise measurements of the top quark mass m_t,[1] the strong coupling constant α_s, and the Higgs mass m_h, are necessary to accurately determine μ_λ and confirm/exclude the predictions of theories explaining the vanishing of the Higgs quartic. As shown in Figure 1, current uncertainties in m_t $(0.4\,\mathrm{GeV})$, $\alpha_s(m_Z)$ (0.0011), and m_h $(0.16\,\mathrm{GeV})$ [27] predict $\mu_\lambda \simeq 10^{12\pm3}\,\mathrm{GeV}$, spanning six decades when all parameters vary within 2σ limits. Future uncertainties in m_t $(0.01\,\mathrm{GeV})$, $\alpha_s(m_Z)$ (0.0001), and m_h $(0.01\,\mathrm{GeV})$ from measurements at future lepton colliders [28–32], improved lattice calculations [33], and high-luminosity LHC [34], will substantially reduce the uncertainty in μ_λ to within about a factor of two. With such a high degree of precision in μ_λ, future colliders and lattice calculations can fix a new scale of physics far beyond the energy scale at which they operate.

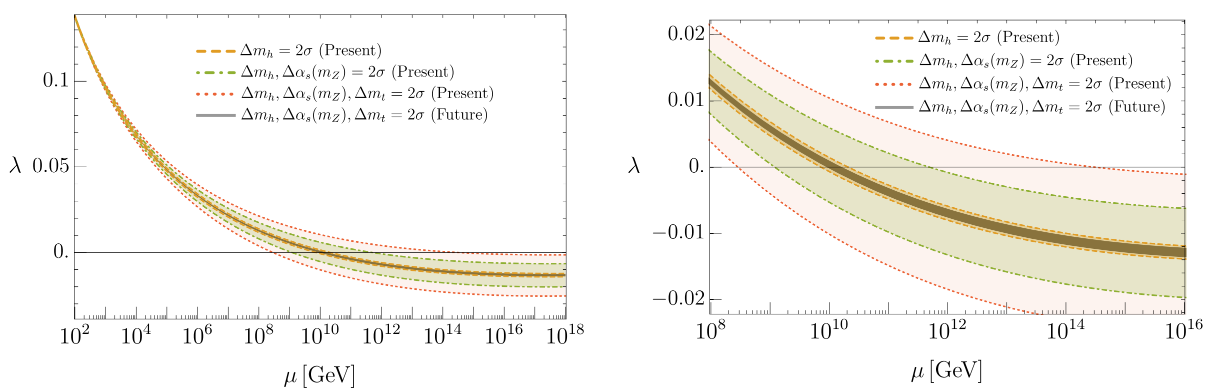

Figure 1: Running of the SM quartic coupling with current and future uncertainties in $m_t, \alpha_s(m_Z)$, and m_h. Their central values are $m_t = 173.0$ GeV, $\alpha_s(m_Z) = 0.1181$, and $m_h = 125.18$ GeV.

In the following, we outline ideas that explain the small quartic coupling at high energy scales, and how the determination of μ_λ impacts these theories and the new physics signals that they generate.

[1] In this letter, m_t is the pole mass, and we use the perturbative relation between the pole mass and the $\overline{\mathrm{MS}}$ top quark Yukawa coupling in [20]. This relation, as well as the experimental determination of m_t, suffers from an ambiguity of $O(100)$ MeV in m_t [23–26]. Eventually, one should directly measure the well-defined $\overline{\mathrm{MS}}$ top quark mass to determine μ_λ.

Discrete symmetry: Higgs Parity The SM is extended by a Z_2 symmetry which exchanges the SM Higgs H with its partner H', and the weak $SU(2)$ with $SU(2)'$. The discrete symmetry, called Higgs Parity, is spontaneously broken by a condensation of H'. In the limit where the electroweak scale is far below the Higgs Parity symmetry breaking scale, the Higgs quartic coupling is found to vanish at the symmetry breaking scale, and hence $\langle H' \rangle \simeq \mu_\lambda$ [35]. This can be understood by an accidental global symmetry of the scalar potential of H and H'. Higgs Parity can be realized in various ways, which mainly differ by the choice of the gauge group. In various realizations experimental signals of new physics are correlated with μ_λ: proton decay [36], dark matter direct detection [37], dark radiation and gravitational waves [38], and warmness of dark matter and the neutrino mass hierarchy [39]. If Higgs Parity involves space-time parity, the strong CP problem can be solved along the line of [40, 41]. When Higgs Parity is identified with the Left-Right symmetry arising from $SO(10)$ unification, precise gauge coupling unification predicts a range of μ_λ [35, 36].

Pseudo Nambo-Goldstone Higgs and Peccei-Quinn symmetry If the SM Higgs is a pseudo-Nambu-Goldstone boson arising from spontaneous breaking of a global symmetry, the quartic coupling vanishes around the global symmetry breaking scale. Usually, significant positive threshold corrections to the quartic coupling are introduced, so that there is not much hierarchy between the global symmetry breaking scale and the electroweak scale. [42] considers the possibility that these threshold corrections are small, allowing the global symmetry breaking scale to be around μ_λ. The same dynamics may simultaneously break Peccei-Quinn symmetry [43] at μ_λ, solving the strong CP problem. In this theory, μ_λ is the Peccei-Quinn symmetry breaking scale, and hence correlated with QCD axion searches.

Intermediate scale supersymmetry In the minimal supersymmetric SM, two Higgs doublets are introduced. If the mass terms of the two doublets are close with each other (i.e. $\tan\beta \simeq 1$), the quartic coupling vanishes around the mass scale of scalar supersymmetric particles [44–46]. (See [47] for earlier work on a heavy scalar scenario.) The near degeneracy of the two Higgs mass terms may arise from universal soft masses at a mediation scale, or the supersymmetric mass of the Higgs being larger than the soft masses. Precise gauge coupling unification holds under reasonable assumptions on the mass spectrum [48, 49]. In a certain string setup, large threshold corrections to the gauge coupling constants at the unification scale are present, but are determined by the string coupling constant [46, 50]; hence, μ_λ is correlated with the string coupling constant. In other theories. μ_λ may be correlated with proton decay [49] or with the Peccei-Quinn symmetry breaking scale [46, 49].

Gauge-Higgs unification The Higgs field may originate from an extra dimensional component of a gauge field [51]. The Higgs quartic coupling is predicted to vanish at the compactification scale because of the gauge symmetry. Precise measurements of SM parameters thus fix the compactification scale [52], and will help further theoretical developments. By further assuming the unification of the top Yukawa and the $SU(2)$ gauge interaction, the compactification scale is fixed and hence SM parameters are predicted [52]. Confirmation of the prediction will elucidate the origin of the top Yukawa coupling and of the size of the new extra spatial dimension.

Landscape The Higgs quartic coupling becomes negative at high energy scales. Consequently, our universe resides in a false vacuum and may eventually tunnel out of the electroweak vacuum [53, 54]. It is remarkable that the observed values of m_t, m_h, and α_s correspond to electroweak vacuum metastability: an unstable vacuum with a lifetime longer than 10^{10} years. This situation only results for a very narrow range of m_t, m_h, and α_s. This apparent fine tuning of SM parameters may point to the Landscape [55]. More precise measurements of SM parameters are necessary to accurately determine just how close the SM resides to this catastrophic metastablity boundary, affecting the significance of the Landscape interpretation. Also, further theoretical calculations are important to understand the sensitivity of the metastability boundary to UV completions of the SM.

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