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Electroweak symmetry breaking without the μ^2 term

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We demonstrate that from a low-energy perspective a viable breaking of the electroweak symmetry, as present in nature, can be achieved without the (negative sign) μ^2 mass term in the Higgs potential, thereby avoiding completely the appearance of relevant operators, featuring coefficients with a positive mass dimension, in the theory. We show that such a setup is self-consistent and not ruled out by Higgs physics. In particular, we point out that it is the lightness of the Higgs boson that allows for the electroweak symmetry to be broken dynamically via operators of $D \geq 4$, consistent with the power expansion. Beyond that, we entertain how this scenario might even be preferred phenomenologically compared to the ordinary mechanism of electroweak symmetry breaking, as realized in the Standard Model, and argue that it can be fully tested at the LHC. In the Appendix, we classify UV completions that could lead to such a setup, considering also the option of generating all scales dynamically.

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I. INTRODUCTION

We made important progress in understanding nature by uncovering its symmetries. In particular, the very basis of the theories describing our Universe at the most fundamental level, i.e. the Standard Model (SM) of particle physics and general relativity, are symmetries. However, some of these (local) symmetries are not manifest in the vacuum but rather broken spontaneously. This is reflected by the fact that the mediators of the weak force are massive, as are the (chiral) building blocks of matter, which is essential for the existence of the Universe as we see it. A common lore, in particular after the discovery of the Higgs boson at the CERN Large Hadron Collider, is that this electroweak symmetry breaking (EWSB) is triggered by a negative-sign mass term for a scalar Higgs-doublet field, either introduced by hand or generated dynamically. The final ultraviolet (UV) completion of the SM is expected to generate (approximately) a Higgs potential of such a form. However, as we entertain in this article, a more fundamental theory of nature could also have an opposite low-energy ($\gtrsim$ weak scale) limit, where the appearance of relevant operators, such as the negative Higgs-mass squared, is completely avoided. As we show, in such a scenario an 'irrelevant' $D = 6$ operator of the type $\mathcal{O}_6 = |H|^6$ could induce a nontrivial vacuum for the scalar sector.

We point out that it is the lightness of the Higgs boson $m_h^2 \ll v^2$ that allows us to consider this special setup, where the operators in the Higgs potential are not only deformed in a subleading way, as a phenomenologically viable alternative to the SM form, fully trading the ($D = 2$) μ^2-operator for $\mathcal{O}_6$ within a consistent effective field theory (EFT). Entertaining the viability of this limit is of utmost importance as it clarifies the question if a mass term is required in the Higgs-boson potential in order to spontaneously break the symmetries that induce the forces of nature.

After having demonstrated the self-consistency of the setup, we turn to the phenomenology of the model. The most important collider observable is Higgs-pair production, where we show that the LHC is capable of fully testing the pure version of the idea. Beyond that, the model has intriguing consequences for cosmology. We see that it just lies in the correct ballpark such as to allow for a strong first-order phase transition, as required by electroweak baryogenesis. While in the main part of the paper we just treat the $\mu = 0$ Higgs potential as a distinct and interesting boundary condition that a potential UV model could fulfill, thereby opening up a new direction in model building, in the Appendix we present and classify possible ideas for UV completions.

II. THE FORM OF THE HIGGS POTENTIAL

We consider the SM without relevant operators and instead augment the Higgs potential with a dimension-6 term $c_6/\Lambda^2 \mathcal{O}_6$ such that it takes the simple form

$$V(H) = \lambda |H|^4 + \frac{c_6}{\Lambda^2} |H|^6, \tag{1}$$

where all dimensionful parameters are either zero or at the cutoff of the theory.

Inspecting the form of the potential, a first observation is that a stable and nontrivial minimum at $|H|^2 > 0$ should be possible if $\lambda < 0$ and $c_6 > 0$. In the following, we check if

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such a minimum is also viable phenomenologically. For any given cutoff scale Λ, we can first calculate the position of the minimum, i.e., the vacuum expectation value (vev), denoted as $\langle |H|^2 \rangle \equiv v^2/2$, via $\partial V/\partial |H|^2 = 0$. We find

$$v^2 = -\frac{4}{3}\frac{\lambda}{c_6}\Lambda^2. \tag{2}$$

Clearly, the minimization condition only fixes the relative size of the coefficients λ and c_6/Λ^2. In turn, an electroweak-scale vev can be obtained without the need for a large coefficient of the $D = 6$ operator $\mathcal{O}_6$. The size of the latter will however get fixed by the mass of the physical Higgs excitation around the vev, h, where in unitary gauge $H = 1/\sqrt{2}(0, v + h)^T$. This is given as $m_h^2 = \partial^2 V/\partial h^2|_{h=0}$, leading to

$$m_h^2 = 3v^2\lambda + \frac{15}{4}\frac{c_6}{\Lambda^2}v^4. \tag{3}$$

The consequences of these relations are scrutinized in the next section.

III. SELF-CONSISTENCY OF THE SETUP

We now examine quantitatively if it is possible to generate the vev and the Higgs mass at the correct values in a self-consistent way with $\mu = 0$, keeping the parameters in the range of the validity of the EFT. To that extent, we first solve Eqs. (2) and (3) for the two free parameters in the potential, λ and c_6, expressing them in terms of the vev, fixed by the Fermi constant as $v = 246$ GeV, and the Higgs mass $m_h \approx 125$ GeV. We obtain

$$\lambda = -\frac{m_h^2}{2v^2} \approx -0.13, \qquad c_6 = \frac{2m_h^2}{3v^2}\frac{\Lambda^2}{v^2} \approx 2.8\frac{\Lambda^2}{\mathrm{TeV}^2}. \tag{4}$$

We inspect that, since $m_h^2/v^2 \approx 1/4 \ll 1$, a large cutoff $\Lambda^2 \gg v^2$ is possible while keeping $c_6 \sim \mathcal{O}(1)$. We can thus see explicitly that it is the lightness of the Higgs boson which allows for the mechanism to work naturally. The required c_6 versus the cutoff Λ is visualized in Fig. 1. In particular, setting $\Lambda = 0.8$ TeV ($\Lambda = 1$ TeV) requires only $c_6 = 1.8$ ($c_6 = 2.8$) while even $\Lambda = 2$ TeV is still possible in a rather strongly coupled setup with $c_6 = 11.4$. On the other hand, around $\mathcal{O}$(several) TeV, at the latest, new physics (NP) would be expected. If the new states are uncolored (which we assume in the following), such mass scales clearly introduce no tension with current LHC limits. Moreover, we have checked that for all values of the cutoff considered above, the inclusion of a $D = 8$ operator with $\mathcal{O}(1)$ coefficient alters the numerical results by only a few per cent or less.

We now study more detailed the correlation between the needed size of the coefficient c_6/Λ^2 and the physical

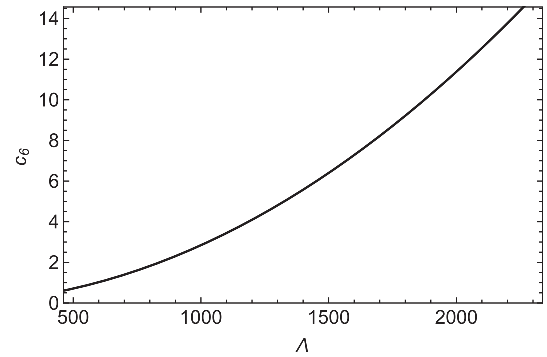

FIG. 1. Required value of the Wilson coefficient c_6 in dependence on the cutoff Λ. See text for details.

parameters in the Higgs sector stressing that only a limited part of the larger parameter space, considered before the discovery of the Higgs boson, is viable in our model.

In Fig. 2 we depict the required value of $\bar{c}_6 \equiv c_6 v^2/\Lambda^2$ (normalized to the weak scale) versus the Higgs-boson mass. While one can already estimate $\bar{c}_6 \sim 1$ as an upper bound on the viable parameter space of the perturbative EFT, this can be made more rigorous by studying the limit following from (perturbative) unitarity, applying the optical theorem. In fact, it is straightforward to show that unitarity in scalar-boson scattering in our model bounds $|a_0^\infty| = 7m_h^2/(8\pi v^2) < 1/2$, which is visualized by the red dashed line, corresponding to $|\bar{c}_6| \lesssim 1.2$.[1] Thus, a heavy Higgs boson of only $m_h \gtrsim 300$ GeV would have already basically invalidated our approach. The same is true for a vev of $v < 100$ GeV (keeping $m_h = 125$ GeV). The experimental values $m_h = 125$ GeV and $v = 246$ GeV, visualized by a green vertical line, are however in perfect agreement with a reasonable value of $\bar{c}_6 \approx 0.17$. The potential (1), employing these values, is plotted as a solid blue line in Fig. 3. It exposes the expected Mexican-hat form with a stable minimum at a nontrivial field value. We conclude that, while it would have been easily possible that the numerical values of the mass scales generated in nature after EWSB would have excluded our setup, the actual values just lie in a range that allows for EWSB to be triggered by a single $D = 6$ operator instead of a negative mass squared term.

Finally, note that although within the low-energy theory discussed here the only physical (suppression) scale Λ can always be factored out of loop integrals and never enters dynamically, the question of the potential full absence of the μ^2 term beyond the tree level should be eventually addressed within a UV completion, providing a reason for its absence (in the best of all cases avoiding tuning). Accordingly, the peculiar setup itself does *not* provide a new solution to the hierarchy problem—in fact the main

[1]This high-energy constraint is approached quickly after the Higgs threshold, within the validity of the EFT considered here.

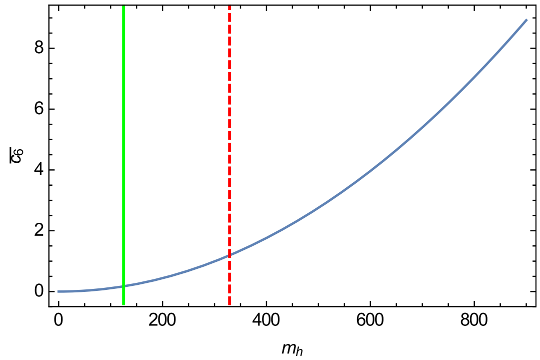

FIG. 2. Required $\bar{c}_6$ in dependence on m_h.

focus of this work is to show its (nontrivial) phenomenological viability and special predictions.

To conclude this section, we show that the inclusion of the SM quantum corrections to the potential, generating a term of the form $|H|^4 \log(H^2/\mu_r^2)$ [1], only corresponds to a small perturbation of our setup. Neglecting the tiny impact of light quarks, the SM contributions to the one-loop Coleman-Weinberg potential are given by (see, e.g., [2])

$$\Delta V = \frac{1}{64\pi^2} \sum_{i=W,Z,h,\chi,t} n_i M_i^4(H) \left[\log \frac{M_i^2(H)}{\mu_r^2} - C_i \right]. \tag{5}$$

Here, the tree-level field-dependent mass terms read

$$m_W^2(H) = \frac{g^2}{2} H^2, \qquad m_Z^2(H) = \frac{g^2 + g'^2}{2} H^2,$$
$$m_h^2(H) = 6\lambda H^2, \qquad m_\chi^2(H) = 2\lambda H^2,$$
$$m_t^2(H) = y_t^2 H^2, \tag{6}$$

where we have dropped contributions suppressed by Λ^2, the numbers of degrees of freedom are $n_W = 6$, $n_Z = 3$, $n_h = 1$, $n_\chi = 3$, $n_t = -12$, and the constants C_i are given by $C_W = C_Z = 5/6$, $C_h = C_\chi = C_t = 3/2$. In the end, the top quark furnishes the dominant correction. Adding (5)

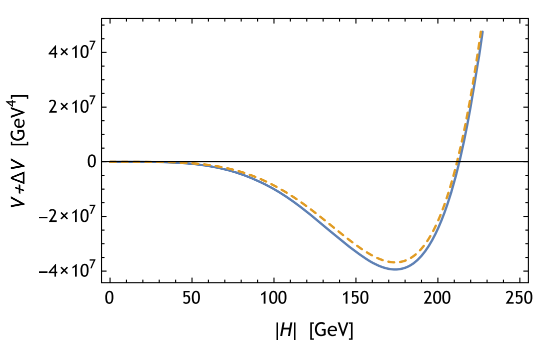

FIG. 3. Blue curve: Higgs potential (1), employing the physical m_h and v. Red dashed curve: Higgs potential, including the SM one-loop corrections (5), leading to the shifts (7).

to (1), setting the renormalization scale to $\mu_r = v/\sqrt{2}$, and solving for c_6 and λ that reproduce correctly v and m_h, leads to the shifts

$$\Delta\lambda \approx -0.033, \qquad \Delta\bar{c}_6 \approx 0.022, \tag{7}$$

which is a $\mathcal{O}(10\%)$ effect. We show the resulting potential as a red dashed line in Fig. 3. It becomes a little bit flatter before the zero of the undisturbed potential and a bit steeper afterwards. Moreover, there arises a tiny maximum at low values of $|H|$, such that the origin is a minimum—which however lies much higher than the global minimum at $|H| = v/\sqrt{2}$.

IV. PHENOMENOLOGY

Beyond the potential direct discovery of new states around the TeV scale, our model offers distinct signatures in Higgs-pair production and cosmology that we discuss in the following.

First of all, the sizable coefficient $\bar{c}_6 \approx 0.2$ leads to a notable change in the production cross section of Higgs pairs, since $\mathcal{O}_6$ contributes to the trilinear Higgs-self interaction after EWSB. In fact, it decreases the cross section by $\sim(60-70)\%$. This is in a range that should be possible to exclude at the LHC with a luminosity of $\mathcal{L} \gtrsim 600\ \mathrm{fb}^{-1}$, see [3].[2]

Beyond that, the presence of the operator $\mathcal{O}_6$ also modifies the electroweak phase transition. Without this operator, the phase transition is of second order for $m_h = 125$ GeV (see, e.g., [2]). This excludes the possibility of electroweak baryogenesis within the SM as there is no out-of equilibrium dynamics at the phase transition. On the other hand, a sizable contribution of $\mathcal{O}_6$ changes the Higgs potential such that a first-order phase transition becomes possible for the physical Higgs mass [4], allowing for electroweak baryogenesis (if enough CP violation is present). In Fig. 4 we show again c_6 versus the cutoff Λ, where now the blue region corresponds to a first-order phase transition that leads to a stable $T = 0$ minimum, while in addition sphaleron processes are sufficiently suppressed in the broken phase such as to not wash out the generated baryon asymmetry [4]. The latter requirement leads to the condition $\langle h(T_c)\rangle/T_c \gtrsim 1$ at the critical temperature T_c. Very interestingly, our $\mu^2 = 0$ solution just lies in the middle of the preferred region, while the SM (i.e., $c_6 = 0$) does not allow for electroweak baryogenesis.

We conclude that the required value of $\bar{c}_6$ leads to a very interesting phenomenology, allowing for pronounced effects in Higgs-pair production as well as opening the possibility of the creation of our current Universe via electroweak baryogenesis. This makes the setup avoiding

[2]Note that $\bar{c}_6 \approx 0.2$ corresponds to $c_6 \approx 1.45$ in the conventions used to present the final results in [3].

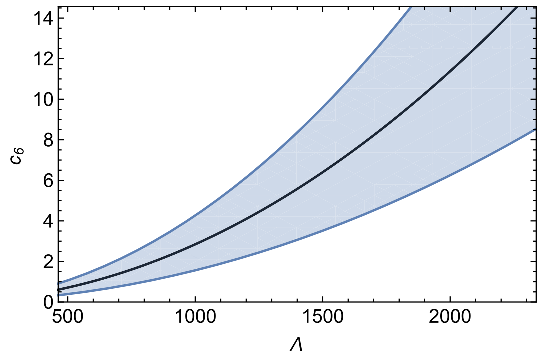

FIG. 4. The solid line depicts the required $c_6(\Lambda)$, while the blue region allows for a first-order electroweak phase transition triggering electroweak baryogenesis. See text for details.

relevant operators attractive on its own. Beyond that, it calls for an examination of how the effective potential (1) could be generated—approximately or exactly—from a UV theory. This will be discussed in the Appendix.

V. CONCLUSIONS

As we know very little about the dynamics of EWSB or how the hierarchy problem is eventually solved in nature, various approaches to EWSB should be examined and tested, in particular, also from the low-energy perspective, even if they might not be the most obvious ones. In this article, we have demonstrated that setting the notorious relevant operator $|H|^2$ in the Higgs potential to zero and adding instead an operator $\mathcal{O}_6 = |H|^6$ can lead to viable electroweak symmetry breaking, thereby opening new directions in model building. We pointed out that it is the lightness of the Higgs-boson that—perhaps unexpectedly—leads to this setup being self-consistent, allowing a natural NP scale of $\Lambda \sim (1-2)$ TeV. Eliminating the μ^2 parameter and adding instead the $D = 6$ coefficient c_6 keeps the theory very predictive, since the number of parameters stays the same. In particular, the setup is fully testable in experiments currently under way, since relatively large changes in the Higgs-pair production cross section are predicted.

As it is a distinct theoretical limit, which also opens the possibility of generating our Universe via baryogenesis at the weak scale and interestingly enough is not excluded by Higgs phenomenology yet, the $\mu^2 \to 0$ model examined here should be considered as an alternative mechanism of breaking electroweak symmetry dynamically.

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APPENDIX: POSSIBLE UV COMPLETIONS

So far, the form of the Higgs potential (1) was considered as a matching condition on the unspecified UV completion. Now, we discuss UV setups that could generate such a potential at the tree level. The general picture is that the SM-like theory (featuring $\mu^2 = 0$) possesses no scale at the classical level and is then coupled to a sector that breaks scale invariance. Such an additional breaking is needed in the first place, since the breaking of scale invariance within the SM by dimensional transmutation is not sufficient to generate the Higgs mass of $m_h = 125$ GeV (see, e.g., [5,6]). The NP might itself respect scale invariance at the classical level, generating all masses dynamically.

Let us however stress a difference compared to the usual approach, often used in models employing classical scale invariance (CSI) as a building principle. In the latter, the μ^2 term is forbidden at the tree level, but then regenerated spontaneously, usually via the (loop-induced) vev of an additional scalar singlet in a Higgs portal term, mimicking the usual SM Higgs potential (see, e.g., [5,6], as well as [7,8] on general models that generate all scales dynamically). In our approach, however, no relevant operator needs to be generated in the electroweak-scale theory at all. The breaking of scale invariance is induced in an orthogonal—possibly also spontaneous/dynamical—way, via an *irrelevant* operator, introduced by integrating out a heavy field that couples to the SM. This leads to a distinct low-energy phenomenology and full testability of our setup. It provides a new minimal way of allowing for viable EWSB in the presence of the scale-invariant tree-level SM Lagrangian, that interestingly features $m_h \to 0$ in the decoupling limit $\Lambda \to \infty$.[3]

We consider a scalar field S, singlet of $SU(2)_L$ with mass M_S, to generate the operator $\mathcal{O}_6$ at the tree level via the interactions $M_S \lambda_S S |H|^2$ and $\lambda_p S^2 |H|^2$, see Fig. 5, leading to $c_6/\Lambda^2 \sim \lambda_p |\lambda_S|^2 / M_S^2$. This allows the NP to be not too light, while a potential contribution to the $|H|^2$ operator could be deferred to the loop level (or beyond, in the presence of additional structures). To generate all scales dynamically, the dimensionful coefficient in front of λ_S could be thought of as a vev of a new field, or arise from a compositeness scale, see below. Since at tree level only $\mathcal{O}_6$ is generated, one could entertain the possibility that quadratically cutoff-dependent quantum corrections to μ^2 are canceled in an extended NP sector, e.g., by invoking (partial) supersymmetry or a twin Higgs mechanism, such as to approximate, or even fully satisfy, (1) in the full quantum theory. A

[3]Also, a combination, generating a very small (potentially even positive) μ^2, while assisting with $\mathcal{O}_6$ to trigger EWSB in a theory respecting scale invariance at the tree level, might be interesting.

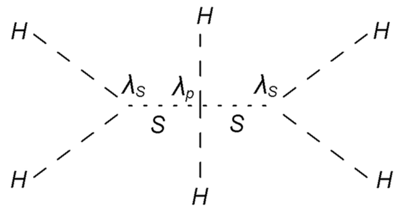

FIG. 5. Generation of $\mathcal{O}_6$ by integrating out the singlet S.

related discussion on a complete cancellation of UV effects on the $|H|^2$ operator—which however there is generated again spontaneously—is given in [6] (see also [5]). Alternatively, the interaction terms might be cut off by a rapidly vanishing form factor $\lambda_i(p)$, taming loops but not preventing a sizable tree-level contribution to $\mathcal{O}_6$ via integrating out S at zero momentum. Finally, one could just set the (renormalized) relevant operator to zero at the matching scale. In any case, the scalar S allows one to entertain UV completions where EWSB could be driven by $\mathcal{O}_6$ and not by a negative sign μ^2 term. If $\langle S \rangle = 0$ and $M_S \gg v$, with a significant fraction not stemming from the SM-Higgs sector, it should also be save from current limits. For an overview of constraints on scalar extensions of the SM see, e.g., [9]. Finally, extension of the vector-boson sector could also induce $\mathcal{O}_6$ at the tree level, see [10].

Note that all scales in the UV completion could be generated dynamically, avoiding relevant operators not only in the IR limit $E \sim v$ but also in the shortest-distance UV theory, via considering the heavy fields to be composites of a new strong interaction, or via the Coleman-Weinberg mechanism. For the latter, a further scalar singlet could obtain a dynamical vev as explained before (see also [6]), inducing the mass of S via a portal interaction (while direct portals to the SM Higgs could be suppressed, e.g., via geometrical sequestering [11]).

Finally, nature might have chosen a completely different way to generate $\mathcal{O}_6$, while avoiding the μ^2 term, still to be found. A further analysis of the potential UV completions, including the examination of dark matter candidates, will be deferred to future work.

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