Standard Model Meets Gravity: Electroweak Symmetry Breaking and Inflation

Mikhail Shaposhnikov,[1,*] Andrey Shkerin,[1,†] and Sebastian Zell[1,‡]

[1] *Institute of Physics, Laboratory for Particle Physics and Cosmology, École Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland*

We propose a model for combining the Standard Model (SM) with gravity. It relies on a non-minimal coupling of the Higgs field to the Ricci scalar and on the Palatini formulation of gravity. Without introducing any new degrees of freedom in addition to those of the SM and the graviton, this scenario achieves two goals. First, it generates the electroweak symmetry breaking by a non-perturbative gravitational effect. In this way, it does not only address the hierarchy problem but opens up the possibility to calculate the Higgs mass. Second, the model incorporates inflation at energies below the onset of strong-coupling of the theory. Provided that corrections due to new physics above the scale of inflation are not unnaturally large, we can relate inflationary parameters to data from collider experiments.

arXiv:2001.09088v1 [hep-th] 24 Jan 2020

Introduction — The results of LHC have been very exciting. First, it has found the last missing particle of the Standard Model (SM), the Higgs boson [1, 2]. Secondly, it has significantly constrained physics beyond the SM. In many scenarios, the existence of new particles close to the electroweak scale is now excluded. This gives a significant motivation to study the proposal that no new degrees of freedom exist anywhere above the weak scale $M_F \sim 10^2$ GeV. Such a situation is self-consistent, since with the measured values of its parameters, the SM is a valid quantum field theory until the Landau poles in the Higgs self-interaction and the hyper-charge gauge interaction, which appear at exponentially large energies, well above another fundamental scale of Nature – the Planck mass $M_P = 2.44 \cdot 10^{18}$ GeV.[1]

Other experimental and observational data that calls for new physics, such as dark matter, neutrino oscillations and baryon asymmetry of the Universe, does not require the presence of any new particle populating the desert between the Fermi and the Planck scales, either.[2] Moreover, the existence of new heavy particles (such as leptoquarks of Grand Unified Theories) leads to the celebrated problem of the stability of the Higgs mass against radiative corrections coming from loops with these superheavy states [10]. If there are no such particles all together, the hierarchy problem as a concern about the sensitivity of low-energy parameters to high-energy physics below the Planck scale disappears [11–13]. Another aspect of the problem, however, remains, and it is centered around the question why the electroweak scale is so much smaller than the Planck scale. This is one of the issues that we shall address in the present work.

If we have only the SM (or νMSM) degrees of freedom all the way up to the Planck scale, the question arises: "How does the SM merge with gravity?" In this Letter we show that the *conformally-invariant* (at the classical level) SM coupled to gravity in the Palatini formulation with non-minimal interaction between the Higgs field and the gravitational Ricci scalar has a number of remarkable properties indicating, perhaps, that this is a step in the right direction. The Lagrangian of the model reads:

$$\mathcal{L} = -\frac{M_P^2}{2} R - \xi H^\dagger H R + \mathcal{L}_{\rm SM}|_{M_H \to 0} \,, \qquad (1)$$

where R is the Ricci scalar, H is the Higgs field, $\xi > 0$ is the strength of its non-minimal coupling to gravity, $\mathcal{L}_{\rm SM}$ is the SM Lagrangian, and M_H is the Higgs mass.

We start from the well known facts about different sectors of this theory. In the Palatini formulation of gravity [14, 15], the metric and the Christoffel connection are treated as independent variables. In spite of the larger number of field components as compared to metric gravity, the number of physical propagating degrees of freedom – two of the massless graviton – is the same in both theories. In the absence of the non-minimal coupling, $\xi = 0$, Palatini gravity is moreover exactly equivalent to the standard metric Einstein gravity.

The particle physics sector of the theory is the SM with zero Higgs mass. It is well known that the Lagrangian $\mathcal{L}_{\rm SM}|_{M_H \to 0}$ has an extra symmetry – it is invariant under the group of conformal transformations. What is most important for us is that in this theory the Higgs mass is predictable [16–18] (to be more precise, the ratio between the scalar and vector boson mass is computable). The easiest way to see that is to use the minimal subtraction scheme for removing the divergencies. Here the counter-terms are polynomials in the coupling constants [19], and, if $m_H = 0$, no counter-term is needed for the

[1] Depending on the masses of the top quark and of the Higgs boson, the Higgs self-coupling can become negative at energy scales between 10^8 GeV and M_P and thereby give rise to another, deeper minimum of the Higgs potential [3, 4]. Whether this happens or not is an open question, given the uncertainties in the determination of the top quark Yukawa coupling; see [5] for a review. But even if our current vacuum is metastable, the validity of the SM is not spoiled since its lifetime exceeds the age of the Universe by many orders of magnitude [6].

[2] For example, the Neutrino Minimal Standard Model (νMSM) [7, 8], whose particle content is extended compared to that of the SM only by three Majorana neutrinos with masses below M_F, may account for all these phenomena in a unified way (for a review see [9]).

mass renormalization, meaning that m_H can be found in terms of other parameters of the theory. This is true even in the presence of gravity, because perturbative quantum gravity corrections can only contain inverse powers of M_P [20]. To put it in different words, the renormalization group β-function for m_H^2 is zero if $m_H = 0$ [19].

First, we are going to argue that the electroweak symmetry breaking in the theory (1) can be induced by the non-perturbative semiclassical effect related to a singular gravitational-scalar instanton – a solution to classical equations of motion of Euclidean gravity.[3] This effect has been already discussed in [23], but it can be implemented more simply and with fewer ingredients in the model considered here. For large values of the non-minimal coupling ξ, we find that $M_F \propto M_P \exp(-B)$, where B is the instanton action. The observed hierarchy of the Fermi and Planck scales requires $B \sim 30$, which we can easily achieve.

Second, we will show that the very same choice of parameters leads to successful inflation. The role of the inflaton is played by the Higgs field [24]. Due to the non-minimal coupling of the Higgs field to gravity, predictions of Higgs inflation in the Palatini formulation of gravity are different from those in the metric case [25]. The prominent feature of this scenario is the increase of the energy scale Λ, at which tree-level unitarity is violated. In the original Higgs inflation, Λ is of the order of M_P/ξ and lies below inflationary scales [26, 27]. On the one hand, this makes it impossible to determine the inflationary potential from the low-energy SM parameters unless the "jumps" of the coupling constants at the onset of the strong coupling regime happen to be very small [28, 29]. On the other hand, the low value of Λ is expected to lead to a breakdown of perturbation theory during reheating [30, 31]. In contrast, Palatini Higgs inflation gives $\Lambda = M_P/\sqrt{\xi}$ [32], which lies above inflationary energies. As discussed in more detail in [33], this allows us to establish a connection between low- and high-energy parameters of the theory, provided that corrections due to new physics are not unnaturally large. Moreover, no strong coupling is expected to occur during reheating. It is important to recall that in our approach no new particles exist above the weak scale. Consequently, the violation of tree-level unitarity at the scale Λ is due to a strong-coupling regime of the low-energy degrees of freedom.

The model — We are interested in the Higgs-gravity sector of the model (1). The rest of the SM particles manifest themselves through RG running of the Higgs quartic coupling λ, which shapes the effective Higgs potential.[4] When we apply unitary gauge for the Higgs field, $H = (0, h)^T/\sqrt{2}$, the relevant part of the Lagrangian reads

$$\mathcal{L} = -\frac{M_P^2 + \xi h^2}{2} R + \frac{1}{2}(\partial_\mu h)^2 - \frac{\lambda}{4} h^4 \, . \tag{2}$$

In order to make the kinetic term of h canonical, we perform a Weyl transformation of the metric,

$$\hat{g}_{\mu\nu} = \Omega^2 g_{\mu\nu} \, , \quad \Omega^2 = 1 + \frac{\xi h^2}{M_P^2} \, , \tag{3}$$

followed by the field redefinition [25]

$$h = \frac{M_P}{\sqrt{\xi}} \sinh\left(\frac{\sqrt{\xi}\chi}{M_P}\right) . \tag{4}$$

Then Lagrangian (2) becomes

$$\mathcal{L} = -\frac{M_P^2}{2} \hat{R} + \frac{1}{2}(\partial_\mu \chi)^2 - U(\chi) \, , \tag{5}$$

and the scalar potential is given by

$$U(\chi) = \frac{\lambda M_P^4}{4\xi^2} \left(\tanh\left(\frac{\sqrt{\xi}\chi}{M_P}\right)\right)^4 . \tag{6}$$

Note that if we had worked in the metric formulation of the theory (1), we would have arrived at the same form (5) of the Lagrangian but with a different potential $U(\chi)$. Thus, the non-equivalence of the Palatini and metric formalisms manifests itself as the difference in the self-interaction of the canonically normalized scalar field.[5]

Fermi scale — Let us discuss how the model (1) can elegantly accommodate the non-perturbative mechanism of generation of the Fermi scale proposed in [23] and developed further in [34, 35]. Our starting point is the expectation value of h in the path integral formalism:

$$\langle h \rangle \sim \int Dh D g_{\mu\nu} \, h \, e^{-S_E} \, , \tag{7}$$

where S_E is the Euclidean action of the theory.[6] We disregarded the rest of the SM degrees of freedom since they can only change the prefactor but not the exponential dependence in our subsequent result (10). Our goal is to study if the path integral (7) possesses saddle points

[3] Note that the Coleman-Weinberg effective potential [16] in the SM cannot lead to electroweak symmetry breaking with the experimental values of the Higgs self-coupling and top quark Yukawa coupling (see, e.g., [21, 22]).

[4] In what follows, we neglect the running of ξ.

[5] It is also possible to arrive at the model (5) in the metric formalism. To this end, one has to add the dimension-six operator $-3\xi^2 h^2 (\partial_\mu h)^2/(M_P^2 \Omega^2)$ to Lagrangian (2) (see [33]).

[6] Note that because of the presence of gravity, the Euclidean path integral in eq. (7) must be taken with caution [36, 37].

besides the trivial one at $\langle h\rangle = 0$. To this end, we notice that by making the change of variable according to eqs. (3), (4), the expectation value can be written as

$$\langle h\rangle \sim \frac{M_P}{\sqrt{\xi}} \int D\chi D\hat{g}_{\mu\nu} J e^{\frac{\sqrt{\xi}\chi}{M_P} - S_E} \; . \tag{8}$$

Here J is the Jacobian of the fields transformation, and we restricted ourselves to the contribution that dominates the path integral for positive χ.

In eq. (8), it is natural to expect the term $\sqrt{\xi}\chi/M_P$ to be included in the determination of the saddle point.[7] As in [23, 34, 35], our subsequent analysis is based on this assumption. If it holds, then the dominant contribution to the path integral is provided by extrema of

$$\mathcal{B} = \int \mathrm{d}^4 x \left(-\frac{\sqrt{\xi}\chi(x)}{M_P} \delta^{(4)}(x) + \sqrt{\hat{g}_E}\, \mathcal{L}_E \right) \; . \tag{9}$$

The subscript E refers to the Euclidean signature. We see that the Lagrangian is supplemented by an instantaneous source and we used translational invariance of the theory to evaluate the latter at the origin. The corresponding saddle-point approximation gives

$$\langle h\rangle \sim \frac{M_P}{\sqrt{\xi}} e^{-B} \; , \tag{10}$$

where B is the value of $\mathcal{B}$, evaluated at a suitable Euclidean classical configuration of the fields χ and $\hat{g}_{\mu\nu}$. The approximation (10) only holds if B is large, since solely in this case fluctuations above the classical background are suppressed. Clearly, the same requirement naturally leads to a hierarchy between the scales M_P and M_F.[8] Now it only remains to show that $\mathcal{B}$ possesses extrema such that the resulting action is large but finite.

It turns out, however, that evaluating $\mathcal{B}$ in the theory (5) leads to an infinite action, caused by a divergent value of $\chi(0)$. At this point, we must remember that our theory enters strong coupling at a finite energy scale. Therefore, its high-energy behavior is sensitive to the existence of higher-dimensional operators. We can use those to remove the unphysical UV-divergence of $\chi(0)$. As we shall show, it suffices to supplement Lagrangian (2) by the operator (in the Lorentz signature)[9]

$$\delta\mathcal{L}_\delta = \frac{\delta}{M_P^8 \Omega^8} (\partial_\mu h)^6 \; , \tag{11}$$

[7] The same approach is used e.g., in the discussion of confinement in gauge theories [38] and of multiparticle production [39].

[8] Note that if a calculation reveals $B = \mathcal{O}(1)$, this invalidates the saddle-point formula (10) but not the mechanism we advocate. A possible interpretation of having a small instanton action is that in this case quantum gravity effects are strong and rise $\langle h\rangle$ up to $M_P/\sqrt{\xi}$, i.e., no new scale appears.

[9] We choose this operator since the simplest option $\propto -\delta(\partial_\mu h)^4$ (with positive δ) would violate positivity bounds [40, 41].

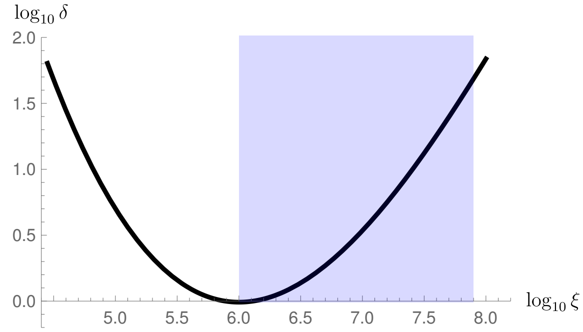

Figure 1. Values of the non-minimal coupling ξ and the sextic derivative coupling δ, for which $B = \ln(M_P/(\sqrt{\xi}M_F))$. Admissible values of ξ are within the blue area, the left bound coming from inflation and the right bound coming from top quark measurements.

where $\delta > 0$ and Ω is defined in eq. (3). Clearly, $\delta\mathcal{L}_\delta$ does not introduce any new degrees of freedom and is suppressed at low energies. Nevertheless, it is important to emphasize that our goal is not to discuss a possible UV-completion of the theory connected to the specific choice of the operator (11). Instead, we want to demonstrate on a simple example how regularization at high energies can be achieved. The operator (11) is not a unique option; other derivative operators produce the same effect on the instanton [23].

In the theory modified by the operator (11), we determine extrema of $\mathcal{B}$ by varying it with respect to χ and $\hat{g}_{\mu\nu}$. This yields Euclidean equations of motion supplemented by the instantaneous source of χ. We specialize to spherically-symmetric solutions centered around the source and choose the ansatz $\mathrm{d}s^2 = f(r)^2\mathrm{d}r^2 + r^2\mathrm{d}\Omega_3^2$ for the metric, where $\mathrm{d}\Omega_3$ is the line element on a unit 3-sphere and f is a function of the radial coordinate r.[10] The equations of motion become

$$\begin{aligned} &\partial_r\left(\frac{r^3\chi'}{f}\right) + \partial_r\left(\frac{6\delta r^3\chi'^5}{M_P^8 f^5}\right) - r^3 f U'(\chi) = -\frac{\sqrt{\xi}}{M_P}\delta(r) \; , \\ &6 - 6f^2 + \frac{2r^2 f^2 U(\chi)}{M_P^2} - \frac{r^2\chi'^2}{M_P^2} - \frac{10\delta r^2\chi'^6}{M_P^{10} f^4} = 0 \; . \end{aligned} \tag{12}$$

We adopt the flat vacuum boundary condition for the instanton. A possible curvature of the background geometry is not important as long as the cosmological length scale exceeds the size of the instanton [34]. The scalar field source provides one more boundary condition for the instanton; together, the two conditions select a unique solution of eqs. (12).

Although we postpone the study of fluctuations around this solution to future work, a necessary condi-

[10] It is believed that a solution of maximal symmetry dominates an instanton action, although the proof is known only for a scalar field theory in flat space background [42, 43].

tions for the validity of our result (10) is that $B \gg 1$. From the analysis of [23] it follows that the strength of the source term determines the instanton profile and eventually appears as a common factor in B. In turn, it is apparent from eq. (12) that the non-minimal coupling ξ controls this strength. Therefore, a value $\xi \gg 1$ automatically gives a large B, unlike in the scenario considered in [23]. Apart from the requirement $\xi \gg 1$, the two parameters ξ and δ are so far unconstrained. But now we can solve eq. (12) and determine δ as a function of ξ in such a way that $\langle h \rangle = M_F$. The result is shown in fig. 1. Note that $\delta \sim 1$ is compatible with the values of ξ admissible for inflation, as we will see shortly.

Inflation — The potential (6) gives rise to inflation at field values $\chi \gtrsim M_P/\sqrt{\xi}$ [25]. The spectral tilt and tensor-to-scalar ratio are readily computed:

$$n_s = 1 - \frac{2}{N+1}\,, \quad r = \frac{2}{\xi(N+1)^2}\,, \tag{13}$$

where N is the number of e-foldings. In what follows, we take $N = 50.9$ corresponding to $\xi \sim 10^7$ [44]. The prediction for n_s is essentially identical to the original scenario of Higgs inflation [24], but r is suppressed by an additional power of ξ [25]. One can use the normalization of the inflationary potential, extracted e.g., from the Planck data [45], to relate ξ and λ:

$$\xi = 1.1 \cdot 10^{10} \lambda\,. \tag{14}$$

At this point, the question arises if the high-energy value of λ, which appears in eq. (14), can be derived from the parameters of the SM measured at collider experiments. The relevant energy for the evaluation of the corresponding RG evolution is of the order of the top quark mass, $\mu = y_t M_P/\sqrt{\xi}$, where $y_t \approx 0.43$ at inflationary energies [33]. It lies below the scale $\Lambda = M_p/\sqrt{\xi}$, at which perturbation theory (defined on top of the low-energy vacuum) breaks down [32].[11] However, the separation of μ and Λ is small and, moreover, λ, as evaluated within the SM, is close to zero and, therefore, susceptible to corrections. For this reason, the connection of low- and high-energy physics may break down if contributions of strongly-coupled physics at Λ are unnaturally large [33]. But if this is not the case, inflationary parameters can be deduced from the low-energy data using the SM running of the relevant couplings.

To a good accuracy the running of λ within the SM can be presented as

$$\lambda(\mu) = \lambda_0 + b \ln^2\left(\frac{\mu}{q M_P}\right)\,. \tag{15}$$

[11] Also in the metric formalism, it is possible to increase Λ by adding higher dimensional operators [46, 47] or new degrees of freedom [48].

Here $q \lesssim 1$, $b \sim 10^{-5}$, and $\lambda_0 \ll 1$ are functions of the parameters of the SM. Today, the largest uncertainty in their determination comes from measurements of y_t [5]. Plugging in $\lambda(\mu)$ in eq. (14), we can determine ξ as a function of m_t measured at the weak scale.[12] For example, taking the conservative lower bound $m_t \gtrsim 170\,\mathrm{GeV}$ [49–52], we get

$$\xi < 7.9 \cdot 10^7\,. \tag{16}$$

Thus, barring the above remark about corrections due to strong coupling at Λ, the lower bound on the top mass inferred from collider experiments leads to an upper bound on ξ. Improving precision in top quark measurements narrows down the window of admissible values of ξ.

Inflation itself provides a lower bound on ξ, as was already noticed in [53]. It is given by [33]:

$$\xi > 1.0 \cdot 10^6\,. \tag{17}$$

Essentially, this constraint comes from the requirement that after plugging in $\lambda(\mu)$ from eq. (15), the potential (6) does not develop a second minimum below μ. If we take the intermediate value $\xi = 10^7$ in between the bounds (16) and (17), we obtain from eqs. (13) that $n_s = 0.961$ and $r = 7.4 \cdot 10^{-11}$. Both values are consistent with recent measurements of the cosmic microwave background [45].

Conclusion — We have considered the Standard Model with a conformally-invariant Higgs potential and proposed a model for how it can be merged with General Relativity. The two key ingredients are the non-minimal coupling of the Higgs field to the Ricci scalar and the Palatini formulation of gravity. No new degrees of freedom are introduced beyond those of the SM and the graviton. We have shown that after regulating the theory with an exemplary higher-dimensional operator, electroweak symmetry breaking can take place due to a singular gravitational-scalar instanton. In this way, an exponential suppression of the weak scale as compared to the Planck mass is naturally achieved. Moreover, such a setup offers the possibility to calculate the value of the former. Finally, the same theory leads to successful inflation with the Higgs boson as inflaton. Since the scale of violation of tree-level unitarity lies above inflationary energies, the Higgs potential during inflation can be determined from the low-energy parameters of the Standard Model, provided that corrections due to the strong-coupling regime at higher scales are not unnaturally large. This makes it possible to test inflationary physics at collider experiments and vice versa.

[12] We thank Fedor Bezrukov for kindly providing us with a script to compute the running of λ.

Acknowledgments — The work was supported by ERC-AdG-2015 grant 694896 and by the Swiss National Science Foundation Excellence grant 200020B_182864.

* mikhail.shaposhnikov@epfl.ch
† andrey.shkerin@epfl.ch
‡ sebastian.zell@epfl.ch

[1] Georges Aad *et al.* (ATLAS), "Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC," Phys. Lett. **B716**, 1–29 (2012), arXiv:1207.7214 [hep-ex].

[2] Serguei Chatrchyan *et al.* (CMS), "Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC," Phys. Lett. **B716**, 30–61 (2012), arXiv:1207.7235 [hep-ex].

[3] Giuseppe Degrassi, Stefano Di Vita, Joan Elias-Miro, Jose R. Espinosa, Gian F. Giudice, Gino Isidori, and Alessandro Strumia, "Higgs mass and vacuum stability in the Standard Model at NNLO," JHEP **08**, 098 (2012), arXiv:1205.6497 [hep-ph].

[4] Dario Buttazzo, Giuseppe Degrassi, Pier Paolo Giardino, Gian F. Giudice, Filippo Sala, Alberto Salvio, and Alessandro Strumia, "Investigating the near-criticality of the Higgs boson," JHEP **12**, 089 (2013), arXiv:1307.3536 [hep-ph].

[5] Fedor Bezrukov and Mikhail Shaposhnikov, "Why should we care about the top quark Yukawa coupling?" J. Exp. Theor. Phys. **120**, 335–343 (2015), [Zh. Eksp. Teor. Fiz.147,389(2015)], arXiv:1411.1923 [hep-ph].

[6] Anders Andreassen, William Frost, and Matthew D. Schwartz, "Scale Invariant Instantons and the Complete Lifetime of the Standard Model," Phys. Rev. **D97**, 056006 (2018), arXiv:1707.08124 [hep-ph].

[7] Takehiko Asaka, Steve Blanchet, and Mikhail Shaposhnikov, "The nuMSM, dark matter and neutrino masses," Phys. Lett. **B631**, 151–156 (2005), arXiv:hep-ph/0503065 [hep-ph].

[8] Takehiko Asaka and Mikhail Shaposhnikov, "The νMSM, dark matter and baryon asymmetry of the universe," Phys. Lett. **B620**, 17–26 (2005), arXiv:hep-ph/0505013 [hep-ph].

[9] Alexey Boyarsky, Oleg Ruchayskiy, and Mikhail Shaposhnikov, "The Role of sterile neutrinos in cosmology and astrophysics," Ann. Rev. Nucl. Part. Sci. **59**, 191–214 (2009), arXiv:0901.0011 [hep-ph].

[10] Eldad Gildener, "Gauge Symmetry Hierarchies," Phys. Rev. **D14**, 1667 (1976).

[11] Francesco Vissani, "Do experiments suggest a hierarchy problem?" Phys. Rev. **D57**, 7027–7030 (1998), arXiv:hep-ph/9709409 [hep-ph].

[12] Mikhail Shaposhnikov, "Is there a new physics between electroweak and Planck scales?" in *Astroparticle Physics: Current Issues, 2007 (APCI07) Budapest, Hungary, June 21-23, 2007* (2007) arXiv:0708.3550 [hep-th].

[13] Marco Farina, Duccio Pappadopulo, and Alessandro Strumia, "A modified naturalness principle and its experimental tests," JHEP **08**, 022 (2013), arXiv:1303.7244 [hep-ph].

[14] Attilio Palatini, "Deduzione invariantiva delle equazioni gravitazionali dal principio di hamilton," Rendiconti del Circolo Matematico di Palermo **43**, 203–212 (1919).

[15] A Einstein, "Einheitliche feldtheorie von gravitation und elektrizität," Sitzungsber. Preuss. Akad. Wiss **414** (1925).

[16] Sidney R. Coleman and Erick J. Weinberg, "Radiative Corrections as the Origin of Spontaneous Symmetry Breaking," Phys. Rev. **D7**, 1888–1910 (1973).

[17] Steven Weinberg, "Mass of the Higgs Boson," Phys. Rev. Lett. **36**, 294–296 (1976).

[18] Andrei D. Linde, "On the Vacuum Instability and the Higgs Meson Mass," Phys. Lett. **70B**, 306–308 (1977).

[19] Gerard 't Hooft, "Dimensional regularization and the renormalization group," Nucl. Phys. **B61**, 455–468 (1973).

[20] Gerard 't Hooft and M. J. G. Veltman, "One loop divergencies in the theory of gravitation," Ann. Inst. H. Poincare Phys. Theor. **A20**, 69–94 (1974).

[21] Edward Witten, "Cosmological Consequences of a Light Higgs Boson," Nucl. Phys. **B177**, 477–488 (1981).

[22] C. D. Froggatt and Holger Bech Nielsen, "Standard model criticality prediction: Top mass 173 +- 5-GeV and Higgs mass 135 +- 9-GeV," Phys. Lett. **B368**, 96–102 (1996), arXiv:hep-ph/9511371 [hep-ph].

[23] Mikhail Shaposhnikov and Andrey Shkerin, "Conformal symmetry: towards the link between the Fermi and the Planck scales," Phys. Lett. **B783**, 253–262 (2018), arXiv:1803.08907 [hep-th].

[24] Fedor L. Bezrukov and Mikhail Shaposhnikov, "The Standard Model Higgs boson as the inflaton," Phys. Lett. **B659**, 703–706 (2008), arXiv:0710.3755 [hep-th].

[25] Florian Bauer and Durmus A. Demir, "Inflation with Non-Minimal Coupling: Metric versus Palatini Formulations," Phys. Lett. **B665**, 222–226 (2008), arXiv:0803.2664 [hep-ph].

[26] J. L. F. Barbon and J. R. Espinosa, "On the Naturalness of Higgs Inflation," Phys. Rev. **D79**, 081302 (2009), arXiv:0903.0355 [hep-ph].

[27] C. P. Burgess, Hyun Min Lee, and Michael Trott, "Power-counting and the Validity of the Classical Approximation During Inflation," JHEP **09**, 103 (2009), arXiv:0902.4465 [hep-ph].

[28] F. Bezrukov, A. Magnin, M. Shaposhnikov, and S. Sibiryakov, "Higgs inflation: consistency and generalisations," JHEP **01**, 016 (2011), arXiv:1008.5157 [hep-ph].

[29] Fedor Bezrukov, Javier Rubio, and Mikhail Shaposhnikov, "Living beyond the edge: Higgs inflation and vacuum metastability," Phys. Rev. **D92**, 083512 (2015), arXiv:1412.3811 [hep-ph].

[30] Yohei Ema, Ryusuke Jinno, Kyohei Mukaida, and Kazunori Nakayama, "Violent Preheating in Inflation with Nonminimal Coupling," JCAP **1702**, 045 (2017), arXiv:1609.05209 [hep-ph].

[31] Matthew P. DeCross, David I. Kaiser, Anirudh Prabhu, Chanda Prescod-Weinstein, and Evangelos I. Sfakianakis, "Preheating after multifield inflation with nonminimal couplings, III: Dynamical spacetime results," Phys. Rev. **D97**, 023528 (2018), arXiv:1610.08916 [astro-ph.CO].

[32] Florian Bauer and Durmus A. Demir, "Higgs-Palatini Inflation and Unitarity," Phys. Lett. **B698**, 425–429 (2011), arXiv:1012.2900 [hep-ph].

[33] Mikhail Shaposhnikov, Andrey Shkerin, and Sebastian Zell, *in preparation*.

[34] Mikhail Shaposhnikov and Andrey Shkerin, "Gravity, Scale Invariance and the Hierarchy Problem," JHEP **10**, 024 (2018), arXiv:1804.06376 [hep-th].
[35] Andrey Shkerin, "Dilaton-assisted generation of the Fermi scale from the Planck scale," Phys. Rev. **D99**, 115018 (2019), arXiv:1903.11317 [hep-th].
[36] G. W. Gibbons, "The Einstein Action of Riemannian Metrics and Its Relation to Quantum Gravity and Thermodynamics," Phys. Lett. **A61**, 3–5 (1977).
[37] Steven Gratton and Neil Turok, "Cosmological perturbations from the no boundary Euclidean path integral," Phys. Rev. **D60**, 123507 (1999), arXiv:astro-ph/9902265 [astro-ph].
[38] Alexander M. Polyakov, "Thermal Properties of Gauge Fields and Quark Liberation," Phys. Lett. **72B**, 477–480 (1978).
[39] S. Yu. Khlebnikov, V. A. Rubakov, and P. G. Tinyakov, "Instanton induced cross-sections below the sphaleron," Nucl. Phys. **B350**, 441–473 (1991).
[40] Allan Adams, Nima Arkani-Hamed, Sergei Dubovsky, Alberto Nicolis, and Riccardo Rattazzi, "Causality, analyticity and an IR obstruction to UV completion," JHEP **10**, 014 (2006), arXiv:hep-th/0602178 [hep-th].
[41] Mario Herrero-Valea, Inar Timiryasov, and Anna Tokareva, "To Positivity and Beyond, where Higgs-Dilaton Inflation has never gone before," (2019), 10.1088/1475-7516/2019/11/042, arXiv:1905.08816 [hep-ph].
[42] Sidney R. Coleman, V. Glaser, and Andre Martin, "Action Minima Among Solutions to a Class of Euclidean Scalar Field Equations," Commun. Math. Phys. **58**, 211–221 (1978).
[43] Kfir Blum, Masazumi Honda, Ryosuke Sato, Masahiro Takimoto, and Kohsaku Tobioka, "O(N) Invariance of the Multi-Field Bounce," JHEP **05**, 109 (2017), [Erratum: JHEP06,060(2017)], arXiv:1611.04570 [hep-th].
[44] Javier Rubio and Eemeli S. Tomberg, "Preheating in Palatini Higgs inflation," JCAP **1904**, 021 (2019), arXiv:1902.10148 [hep-ph].
[45] Y. Akrami *et al.* (Planck), "Planck 2018 results. X. Constraints on inflation," (2018), arXiv:1807.06211 [astro-ph.CO].
[46] Cristiano Germani and Alex Kehagias, "New Model of Inflation with Non-minimal Derivative Coupling of Standard Model Higgs Boson to Gravity," Phys. Rev. Lett. **105**, 011302 (2010), arXiv:1003.2635 [hep-ph].
[47] Rose N. Lerner and John McDonald, "A Unitarity-Conserving Higgs Inflation Model," Phys. Rev. **D82**, 103525 (2010), arXiv:1005.2978 [hep-ph].
[48] Gian F. Giudice and Hyun Min Lee, "Unitarizing Higgs Inflation," Phys. Lett. **B694**, 294–300 (2011), arXiv:1010.1417 [hep-ph].
[49] André H. Hoang, "The Top Mass: Interpretation and Theoretical Uncertainties," in *Proceedings, 7th International Workshop on Top Quark Physics (TOP2014): Cannes, France, September 28-October 3, 2014* (2014) arXiv:1412.3649 [hep-ph].
[50] Vardan Khachatryan *et al.* (CMS), "Measurement of the top quark mass using proton-proton data at $\sqrt{(s)}$ = 7 and 8 TeV," Phys. Rev. **D93**, 072004 (2016), arXiv:1509.04044 [hep-ex].
[51] Silvia Ferrario Ravasio, Tomáš Ježo, Paolo Nason, and Carlo Oleari, "A theoretical study of top-mass measurements at the LHC using NLO+PS generators of increasing accuracy," Eur. Phys. J. **C78**, 458 (2018), arXiv:1801.03944 [hep-ph].
[52] Morad Aaboud *et al.* (ATLAS), "Measurement of the top quark mass in the $t\bar{t} \rightarrow$ lepton+jets channel from $\sqrt{s} = 8$ TeV ATLAS data and combination with previous results," Eur. Phys. J. **C79**, 290 (2019), arXiv:1810.01772 [hep-ex].
[53] Syksy Rasanen and Pyry Wahlman, "Higgs inflation with loop corrections in the Palatini formulation," JCAP **1711**, 047 (2017), arXiv:1709.07853 [astro-ph.CO].