Gravitational vacuum polarization phenomena due to the Higgs field

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In the standard model the mass of elementary particles is considered as a dynamical property emerging from their interaction with the Higgs field. We show that this assumption implies peculiar deviations from the law of universal gravitation in its distance and mass dependence, as well as from the superposition principle. The experimental observation of the predicted deviations from the law of universal gravitation seems out of reach. However, we argue that a new class of experiments aimed at studying the influence of surrounding masses on the gravitational force - similar to the ones performed by Quirino Majorana almost a century ago - could be performed to test the superposition principle and to give direct limits on the presence of nonminimal couplings between the Higgs field and the spacetime curvature. From the conceptual viewpoint, the violation of the superposition principle for gravitational forces due to the Higgs field creates a conflict with the notion that gravitational potentials, as assumed in Newtonian gravitation or in post-Newtonian parameterizations of metric theories, are well-defined concepts to describe gravity in their non-relativistic limit.

I. INTRODUCTION

The standard model of elementary particle physics has succeeded to partially unify electromagnetic and weak interactions within a consistent, renormalizable framework. However, this is achieved at the price of introducing a new interaction of all massive particles with a scalar field, the Higgs field, which is in turn considered to be responsible for the generation of the mass of all elementary particles constituting matter and mediating interactions. Such a dynamical mechanism for generating mass should ultimately confront the other subfield of fundamental physics in which the concept of mass plays a crucial role, namely gravitation. A first step towards this confrontation has been taken in [1], in which the implications of the Higgs field in proximity of strong sources of gravity have been discussed in the framework of quantum field theory in curved spacetimes [2], leading to the prediction of spectroscopic shifts in principle distinguishable from the usual Doppler, gravitational, or cosmological shifts.

In this work, we continue our analysis of the Higgs interplay with gravitation by describing, still in an elementary fashion, two macroscopic consequences of assuming that the mass of elementary particles is generated by the Higgs field. Similar to [1], the basic idea is that the properties of the Higgs field in flat spacetime are deformed by the presence of masses, and this feeds back on the value of the masses themselves. If the equivalence principle is assumed to be valid, this will lead to corrections to the usual Newton’s law of universal gravitation and to violations of the superposition principle. In particular, in this second case we discuss a potential relationship between such violations and already performed experiments originally aimed at evidencing gravitational screening. We argue that the possible evidence for a detectable signal from this class of experiments could be interpreted as due to the Higgs-mediated influence of surrounding masses, at least if the violation is large enough with respect to the one expected from the nonlinear character of general relativity. In a more general framework, empirical evidences for gravitational polarization of matter have been discussed in [3], and our work discusses in the standard model setting an effect related to the Higgs vacuum which can induce gravitational vacuum polarization phenomena.

The paper is organized as follows. In Section 2, we discuss the mass content of a body from the microscopic point of view in the framework of the standard model of elementary particles. It turns out that, while most of the mass of atoms emerges from QCD vacuum, a nonnegligible part depends instead on the vacuum expectation value (VEV) of the Higgs field. In Section 3 this remark is used to show that the mass of a body is affected by the mass of a surrounding body - provided that a non-null coupling between the Higgs field and the curvature of spacetime exists. This implies deviations from the law of universal gravitation for the force exterted between two bodies. In Section 4 we discuss a more sensitive way to evidence this effect by evaluating deviations from the superposition principle holding in Newtonian gravity. Using the same limits as in the previous section, we show that a window of opportunity for the experimental observation (or to achieve better limits on the Higgs-curvature coupling) is obtained by considering a class of experiments similar to the one pioneered by Quirino Majorana nearly nine decades ago. While these experiments were originally motivated by the search for gravitational ab-

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sorption/shielding, we argue that in our framework they should be considered as the most sensitive to possible changes of inertial and gravitational mass that a test body may experience in the presence of nearby massive objects. This allows us to sketch, in Section 5, two experimental configurations in which a test mass should be maximally coupled to surrounding masses by using a parallel plane geometry. In the conclusions we summarize our discussions, briefly touch the perspectives for generalizations to other extended theories of gravity, and stress their conceptual relevance to the same definition of gravitational potential in a Newtonian or post-Newtonian setting.

II. A MICROSCOPIC VIEW AT THE MASS OF A MACROSCOPIC BODY

In order to study the interplay between the Higgs field and gravitation, the first question we want to answer is the following: How is a macroscopic mass envisioned from the viewpoint of the standard model of elementary particle physics? At the microscopic level, we will have elementary constituents and their binding energies. By neglecting the mutual gravitational and weak binding energies among the elementary constituents, the remaining binding energies originate from the electromagnetic interactions between electrons and nuclei, and from the color interactions among quarks in nucleons. In addition, there are also subleading contributions from the residuals of the electromagnetic interaction among electrons and nuclei of different atoms (also called van der Waals forces) and from the residuals of the color interactions among quarks of different nucleons (also called nuclear force). Unlike quarks and electrons, both photons and gluons are massless and are not expected to interact with the Higgs field at tree level. The mass of nucleons can be then thought as being composed of a Higgs-related mass term, and a term independent on the Higgs field. For instance, assuming mere additivity of the two terms, we may write the masses for protons and neutrons

\[ m_p = (2y_u + y_d)v/(\sqrt{2}c^2) + m_{QCD}, \]
\[ m_n = (y_u + 2y_d)v/(\sqrt{2}c^2) + m_{QCD}, \]

with \( y_u \) and \( y_d \) being the Yukawa couplings of the up and down quarks, \( v \) the VEV of the Higgs field, and \( m_{QCD} \) the mass of the nucleons due to pure gauge interaction of the gluonic fields, with this last component independent upon the VEV of the Higgs field. This approximate constituent model of the nucleons can be made more quantitative by assuming for the up and down quarks the mass values \( m_u = 2.25 \text{ MeV}/c^2 \) and \( m_d = 5.0 \text{ MeV}/c^2 \), respectively. With a VEV for the Higgs field in flat spacetime \( v_0 = 250 \text{ GeV} \) we obtain, in order to fit the proton and neutron masses, \( m_{QCD} = 928.05 \text{ MeV}/c^2 \). This shows that, if we assume only valence quarks, their mass is responsible for a small percentage of the nucleon inertia, of order 1%, whereas the remaining inertia is entirely due to the gluonic field. This model could be refined by considering the sea quarks and partonic density functions, and in this case the gluons will be responsible for a smaller (order of 50%) percentage of inertia, thereby sensibly increasing the percentage of inertia sensitive to the Higgs field. In the spirit of giving simple and conservative estimates, in what follows we will limit our attention to the constituent/valence model. The mass of a body constituted of \( N \) atoms, considered for simplicity homogeneously made of an element of atomic number \( Z \) and atomic mass \( A \), is therefore

\[ M = N[\gamma v/c^2 + A m_{QCD}], \]

where we have again distinguished between the components (electrons and quarks) whose mass linearly depends on the Higgs VEV through a dimensionless coefficient \( \gamma = \gamma(Z, A) = 1/\sqrt{2}[y_u(Z + A) + y_d(2A - Z) + y_eZ] \), and the ones unrelated to the Higgs field. This mass is the one measured for instance in experiments involving deflection of charged particles in magnetic (i.e. non-gravitational) fields, also called inertial mass. We will assume that the Galileian equivalence principle holds also at the microscopic level (see however \([4–7]\) for more detailed discussions). This hypothesis implies that also the gravitational 'charge' (also called gravitational mass) follows exactly the same Higgs content as its inertial counterpart, and that accurate tests of the equivalence principle will be unable to pinpoint the physics discussed in the next sections.

III. HIGGS FIELD AND NEWTON’S UNIVERSAL GRAVITATION LAW

It is important to realize that in general the VEV of the Higgs field depends, as for any field, on the spacetime point in which it is considered. This leads, in the presence of a specific coupling between the Higgs field and the curvature, to a dependence of the Higgs-dependent gravitational masses of the two bodies upon the specific spacetime point in which they are located. By making explicit the Higgs-related mass contributions, the universal law of gravitation for the amplitude of the force between two homogeneous and spherical bodies spaced by a distance located at positions \( \vec{r}_1, \vec{r}_2 \) will be written in terms of their gravitational masses, based on Eq. 2, as

\[ F_{12}(\vec{r}_1, \vec{r}_2) = G \frac{M_1 M_2}{r^2} = G \frac{N_1 N_2}{r^2} \times \]
\[ [\gamma_1 v(\vec{r}_1)/c^2 + A_1 m_{QCD}][\gamma_2 v(\vec{r}_2)/c^2 + A_2 m_{QCD}], \]

where \( r = |\vec{r}_2 - \vec{r}_1| \). We discuss in the following possible forms of the coupling between the Higgs field and the curvature of spacetime. The simplest coupling is of the form \( L_{\text{Higgs-Curvature}} = -\xi \phi^2 R \), where \( R \) is the Ricci scalar, \( \phi \) the Higgs field, and \( \xi \) their coupling strength \([2]\). Since for spherical masses the Ricci scalar in the outer
volume is zero, a Higgs-curvature coupling like $\xi \phi^2 R$ will not generate any change in the Higgs VEV, ruling out any possible experiment or observation involving symmetrical masses. A coupling of this form is not experimentally observable unless specific geometries with partial spatial symmetry are considered. However, there are gravity models in which a scalar field may couple to the metric also through other curvature invariants, for instance the Einstein-Gauss-Bonnet theory which has been introduced as a promising framework to tame ultraviolet divergences in the quantized counterpart of the theory.\cite{[2]} Experiments with higher degree of spatial symmetry could be sensitive to the Higgs coupling to non-zero curvature scalars such as the Kretschmann invariant $K = R_{\mu \nu \rho \sigma} R^{\mu \nu \rho \sigma}$. The Higgs-Kretschmann coupling becomes expressed in terms of a single free parameter if the Kretschmann invariant contributes to the Lagrangian through its square-root $\mathcal{L}_{\text{Higgs-Curvature}} = -\xi \phi^2 K^{1/2}$ as discussed in a strong-gravity setting (in proximity of a back-hole) in \cite{[2]}. This choice could allow us to conjecture a minimalistic scenario, with $\xi'$ being the only free parameter, but is inconsistent since such a Lagrangian term gives rise to singularities in the $K \to 0$ limit as in a weak-gravity scenario discussed here. A linear coupling to the Kretschmann invariant has a consistent weak-gravity limit but requires instead, for dimensional reasons, the presence of a further parameter in the form of a fundamental length. We then assume, as a natural setting, a Lagrangian term of the form

$$\mathcal{L}_{\text{Higgs-Curvature}} = -\xi \kappa \Lambda_{\text{Pl}}^2 \phi^2 K,$$

where $\Lambda_{\text{Pl}} = (G \hbar / c^3)^{1/2}$ is the Planck length, whose value is $\Lambda_{\text{Pl}} \simeq 10^{-35} \text{ m}$ in conventional quantum gravity models. Of course, any length obtained by multiplying $\Lambda_{\text{Pl}}$ by a reasonably large number could also play its role, or larger values of $\Lambda_{\text{Pl}}$ such as the one corresponding to models with early unifications of gravity to the other fundamental interactions \cite{[2]}. In the latter case the Planck length occurs at the TeV scale via extra dimensions, $\Lambda_{\text{Pl}} \simeq 10^{-19} \text{ m}$. In order to keep an eye open on this arbitrariness, in the following we will consider both these somewhat extreme situations, by evaluating relevant quantities using both values of $\Lambda_{\text{Pl}}$.

With this assumption, we can mimic the reasoning in \cite{[2]} in which the Higgs-curvature term adds to the metric parameter (introducing explicitly $\hbar$ and $c$) $\mu^2 \mu c^2 / \hbar^2 \to \mu^2 \mu c^2 / \hbar^2 + \xi \kappa \Lambda_{\text{Pl}}^2 K$, which corresponds to renormalize the Higgs mass term such as $\mu^2 \to \mu^2 (1 + \xi \kappa \Lambda_{\text{Pl}}^2 \mu^2 K)$, with $\mu$ the Compton wavelength corresponding to the Higgs mass term, $\lambda_{\mu} = h / (\mu c) \simeq 2 \times 10^{-18} \text{ m}$, choosing $\mu = 160 \text{ GeV}$.

While in flat spacetime and in the spontaneously broken phase the Higgs field develops a VEV $v_0 = (-\mu^2 / \lambda)^{1/2}$, in the presence of curved spacetime the VEV becomes

$$v = \sqrt{-\mu^2 (1 + \xi \kappa \Lambda_{\text{Pl}}^2 \lambda_{\mu}^2 K)} \approx v_0 \left( 1 + \frac{\xi \kappa}{2} \Lambda_{\text{Pl}}^2 \lambda_{\mu}^2 K \right),$$

the latter expression being valid in the weakly coupled regime, i.e. if $\xi \kappa \Lambda_{\text{Pl}}^2 \lambda_{\mu}^2 K \ll 1$. Then, by supposing that two masses are present in locations $\vec{r}_1$ and $\vec{r}_2$, the VEV in $\vec{r}_1$ will be affected by the curvature produced by the mass in $\vec{r}_2$ and vice versa. For the Schwarzschild metric the Kretschmann invariant in position $\vec{r}$ due to the $j$th mass source is $K_j (\vec{r}) = 12 R_s^{2(j)} / r^6$, allowing to write the VEV in location $\vec{r}_i$ as

$$v(\vec{r}_i) \approx v_0 \left( 1 + 6 \xi \kappa \Lambda_{\text{Pl}}^2 \lambda_{\mu}^2 R_s^{2(j)} / r^6 \right),$$

with $i, j = 1, 2$, $R_s^{2(0)} = 2GM_i / c^2$ being the Schwarzschild radius of the $i$th mass. Based on Eq. 2, this allows to write the mass of a body as

$$M_i = M_i^{(0)} \left( 1 + 6 \xi \kappa N_i \gamma v_0 \Lambda_{\text{Pl}}^2 \lambda_{\mu}^2 R_s^{2(0)} / M_i^{(0)} c^2 r^6 \right),$$

where $M_i^{(0)}$ is the bare mass in the presence of flat spacetime, i.e. in the absence of all other $j$th mass sources. The Newton’s universal law will be consequently written as

$$F_{12} (r) = G \frac{M_1^{(0)} M_2^{(0)}}{r^2} \left( 1 + \frac{6 \xi \kappa N_1 \gamma v_0 \Lambda_{\text{Pl}}^2 \lambda_{\mu}^2 R_s^{2(2)} / M_1^{(0)} c^2 M_2^{(0)} c^2 r^6 \right) \times \left( 1 + \frac{6 \xi \kappa N_2 \gamma v_0 \Lambda_{\text{Pl}}^2 \lambda_{\mu}^2 R_s^{2(1)} / M_2^{(0)} c^2 M_1^{(0)} c^2 r^6 \right).$$

Notice the cross-terms in which the two masses appear simultaneously (since the Schwarzschild radius depends on mass), which in principle invalidate the linear dependence of the force on the mass of each body. Also, we will have $r^{-8}$ and $r^{-14}$ distance dependences superimposed to the usual Newtonian $r^{-2}$ scaling. The Higgs correction is expected to be extremely small under practical circumstances so that to the next-to-leading order we can keep only the $r^{-8}$ term. This means that the gravitational force will be written as

$$F_{12} (r) \simeq G \frac{M_1^{(0)} M_2^{(0)}}{r^2} \left[ 1 + \frac{6 \xi \kappa v_0}{c^2} \left( \frac{N_1 \gamma R_s^{2(2)}}{M_1^{(0)} c^2} + \frac{N_2 \gamma R_s^{2(1)}}{M_2^{(0)}} \right) \lambda_{\mu}^2 \frac{\Lambda_{\text{Pl}}^2}{r^6} \right].$$

Assuming the same atomic composition and, for simplicity, $A = 2Z$ (isoscalar nuclei), this correction is maximal for equal masses $M_1^{(0)} = M_2^{(0)} = M$, therefore we have

$$F_{12} (r) \approx G \frac{M^2}{r^2} \left( 1 + 12 \xi \kappa \frac{\delta M \Lambda_{\text{Pl}}^2 \lambda_{\mu}^2 R_s^{2(1)}}{M c^2 \mu r^6} \right).$$
where we have defined \( \delta M/M = N \gamma \nu_0/(Mc^2) \) as the mass fraction of a body sensitive to the Higgs field through the Yukawa couplings of the elementary constituents, equal to \( \delta M/M \approx 1.2 \times 10^{-2} \) for isoscalar bodies. If we consider \( M=1 \) Kg (leading to \( R_0 = 1.5 \times 10^{-27} \) m), \( \lambda_\mu = 2 \times 10^{-18} \) m, and \( r=10 \) cm, we obtain, for the second term in Eq. 10, the quantity \( 10^{-154} \xi_K \) in the usual quantum gravity scenario with \( \Lambda_{11} \approx 10^{-35} \) m, and \( 10^{-125} \xi_K \) if \( \Lambda_{11} \approx 10^{-19} \) m is instead considered. If any nonminimal coupling is active, it must give rise to tiny deviations from Newtonian gravity, and the fact that the Newton gravitational constant is known with a relative precision of \( 10^{-4} \) gives already upper bounds of \( \xi_K < 10^{150} \) and \( \xi_K < 10^{118} \) for the two choices of \( \Lambda_{11} \), respectively. Lower bounds on the detectable \( \xi_K \) arise from the leading corrections to the universal law of gravitation due to its nonlinear character and quantum gravity effects. These have been evaluated in [10], and the gravitational force between two bodies is then rewritten as

\[
F_{12}(r) = G \frac{M_{1(0)} M_{2(0)}}{r^2} \times \left[ 1 - \frac{2G(M_{1(0)} + M_{2(0)})}{c^2r} - \frac{27}{10\pi^2} \frac{\hbar G}{c^4 r^2} \right]
\]

Plugging in numbers for our case it turns out that the nonlinear term (the second contribution in the square bracket of the above equation) dominates over the quantum gravity correction (the third term linear in \( r \)) and represents a correction of \( \approx 3 \times 10^{-26} \) with respect to unity, forbidding the observation of effects due to \( \xi_K < 2 \times 10^{128} \) for \( \Lambda_{11} \approx 10^{-35} \) (\( \xi_K < 2 \times 10^{96} \) for \( \Lambda_{11} \approx 10^{-19} \)).

The upper bounds of \( \xi_K \) just discussed can be compared to the ones obtainable in dedicated astrophysical surveys near black holes. By repeating the analysis, carried out in [1] for the case of a square-root Kretschmann coupling to the Higgs field, relative frequency shifts in the electronic transitions due to a linear coupling to the Kretschmann invariant are estimated to be

\[
\frac{\delta \nu}{\nu} = \frac{\delta m_e}{m_e} \approx \frac{\xi_K}{2} \Lambda_{11}^2 \lambda_\mu^2 K,
\]

with \( m_e \) the electron mass. For spectroscopic shifts arising from atoms in the innermost stable orbit of a black hole (\( r = 3R_0 \)), this yields \( \delta \nu/\nu \approx 2\xi_K \Lambda_{11}^2 \lambda_\mu^2 /243R_0^6 \). If astrophysical surveys will rule out the presence of anomalous frequency shifts at the \( \delta \nu/\nu \approx 10^{-5} \) level, i.e. the current instrumental sensitivity limit on ammonia surveys [11,12] one will get, for \( \Lambda_{11} = 10^{-35} \) m, the bound \( \xi_K < 2.5 \times 10^{18} \) from the analysis of solar black holes, and \( \xi_K < 1.5 \times 10^{39} \) from the analysis of mini black holes with a mass of \( 10^{14} \) kg, still large enough to survive quantum evaporation up to now (with \( \xi_K < 2.5 \times 10^{96} \) and \( \xi_K < 1.5 \times 10^7 \) if \( \Lambda_{11} = 10^{-19} \) m is instead assumed).

IV. HIGGS FIELD AND THE SUPERPOSITION PRINCIPLE FOR GRAVITATION

A more sensitive framework to constrain possible non-minimal couplings related to the Higgs field is provided by experiments in which the superposition principle for Newtonian forces is tested. This allows for the usually more controllable and reproducible environment characteristic of tabletop experiments. However, there are intrinsic limitations since the superposition principle for gravitational forces is approximately valid only within the linearized, weak-gravity limit, but it is expected to fail if a sufficient degree of precision is achieved, due to the underlying nonlinear character of general relativity. As we will discuss below, this will translate into a lower bound on the minimum detectable value of \( \xi_K \).

Let us consider two bodies 1 and 2 separated by a distance \( r \), gravitationally attracting each other in the presence of a third body 3. This last is put in proximity of body 2, at a distance \( R_0 \) such that the line passing along 2 and 3 is orthogonal to the line passing along 1 and 2. In this way the force component along the direction joining bodies 1 and 2 is not affected by the force exerted between bodies 2 and 3. The Higgs vacuum polarization will induce a change of the masses, and if we focus on body 2, the force exerted on it due to body 1 will change by an amount \[\delta F_{12} = 6\xi_K \frac{G M_{1(0)}^2}{r^2} \left( 1 + 6\xi_K \frac{N_2 \gamma \nu_0^0 A_{11}^2 \lambda_\mu^2 R_0^2}{r^6} \right) \times \left( 1 + 6\xi_K \frac{N_2 \gamma \nu_0^0 A_{11}^2 \lambda_\mu^2 R_0^2}{r^6} \right) \]

The relative force change is therefore, in the weak limit

\[
\frac{\delta F_{12}}{F_{12}} \simeq 6\xi_K \frac{N_2 \gamma \nu_0^0 A_{11}^2 \lambda_\mu^2 R_0^2}{M_{1(0)} c^2} \frac{R_3}{R_0^6}.
\]

This implies a violation of the superposition principle linear in the coefficient \( \xi_K \), independent upon the distance between the two bodies 1 and 2 and, as before, depending on the percentage of the Higgs-related mass in a nucleon. By considering again an element with \( A = 2Z \) and a mass \( M_3=1 \) Kg at a distance of 10 cm, we obtain \( \delta F_{12}/F_{12} \approx \delta \xi_K < 6 \times 10^{-155} \xi_K \). Even in this case the expected shift is minute unless large values of \( \xi_K \) are assumed.

This has to be confronted with the deviation from the superposition principle expected in post-Newtonian parameterizations of general relativity. In the configuration discussed above, this becomes \[\delta F_{12} = G \frac{M_1 M_2}{r^2} \left( 1 + \frac{R_3}{R} \right).
\]

Therefore, we have genuine general relativity corrections directly proportional to \( R_s(3)/R \). In the same example discussed above, this leads to force shifts \( \delta F/F_{\text{GR}} \approx \)
10^{-26}$, and then values of $\xi_K \leq 10^{128}$ cannot be discriminated from this background due to general relativity corrections.

Among precision experiments able to further constraint nonminimal coupling coefficients, it is worth to point out that Quirino Majorana nine decades ago [13] (see also [14] for former attempts) provided tests of the superposition principle for gravitational forces, with a dynamical version of the experiment being subsequently performed at about the same level of precision [15]. More specifically, in Majorana’s experiments a reduction of the weight of a spherical mass symmetrically surrounded by another mass in close proximity was observed at the $10^{-9}$ level. In a first series of experiments using a 1.274 Kg mass of lead surrounded by 115 Kg of mercury, Majorana observed a decrease in weight of $9.7 \times 10^{-10}$ Kg [16] corresponding to a relative decrease of $7.7 \times 10^{-10}$. In a second version of the experiment he surrounded the same lead mass with 9.603 Kg of lead, obtaining a decrease in weight of $2.01 \times 10^{-9}$ Kg [17], translating into a relative decrease of $1.578 \times 10^{-9}$. Majorana interpreted these results in the framework of gravitational screening, obtaining in the first class of experiments with mercury a gravitational permeability coefficient about twice bigger than the one obtained in the second class. Objections to this interpretation soon arose, with current stronger limits coming from the study of solar eclipses and tides [18, 20] (see also [21] for a discussion of shielding of dynamical gravitational fields such as gravitational waves).

An alternative view in which the observed effect is due to a mass reduction coming from proximity masses was suggested in Ref. [18]. Incidentally, in this view the larger effectiveness, relatively to the involved masses, in decreasing the weight of the lead mass by the mercury mass with respect to the more massive lead mass could be tentatively justified due to the closeness of the former mass to the lead sphere, as it seems corroborated by a detailed scrutiny of the experimental setup drawings reported in Majorana’s papers [16, 17]. In our setting, by rejecting the hypothesis that mass shifts were effectively observed, and claiming that the superposition principle is valid at the $10^{-9}$ accuracy level implies, based on Eq. 13, an upper bound on the Kretschmann coupling $\xi_K < 2 \times 10^{145}$.

More recent experiments such as the one described in [22, 23], while yielding stronger limits on gravitational absorption than the Majorana’s ones as discussed in [24], do not necessarily correspond to stronger constraints on the influence of surrounding masses as the test mass and the surrounding bodies were significantly more spaced apart than in Majorana’s experiments [39], with a similar relative precision for mass measurements. Experiments using rotating torsional balances as in [25] designed for test of the equivalence principle would be extremely sensitive to possible differences induced by the Higgs field between inertial and gravitational mass, assumed in this paper to be rigorously proportional to each other. However, they are not sensitive enough to look for the influence of surrounding bodies on the gravitational force, as shown by the fact that the upper limit on other than purely gravitational force for an Yukawa interaction range of 4 cm could be achieved with dedicated tabletop experiments, as we will briefly suggest in the following section.

| $\Lambda_{Pl}$ | $10^{-35}$ m | $10^{-19}$ m |
|---------------|----------------|----------------|
| (a) 2-body gravitational force | $10^{150}$ | $10^{118}$ |
| (b) 3-body superposition test | $2 \times 10^{145}$ | $2 \times 10^{113}$ |
| (c) Higgs-shifts 1 M⊙ BH | $2.5 \times 10^{118}$ | $2.5 \times 10^{86}$ |
| (d) Higgs-shifts mini-BH | $1.5 \times 10^{39}$ | $1.5 \times 10^{7}$ |

TABLE I: Summary of the possible upper bounds on Kretschmann-Higgs couplings $\xi_K$ from tabletop experiments (first two rows) and astrophysical surveys (second two rows). We assume current instrumental sensitivities equivalent to a gravitational force measurement measured at $10^{-4}$ precision level in (a) and superposition principle tested at $10^{-9}$ precision level in (b), both with test masses of 1 Kg at distances of 10 cm and made of an isoscalar element. For the cases of (c) and (d) we assume a minimum detectable relative frequency shifts of $\delta \nu/\nu = 10^{-4}$. In (d) we assume the optimal situation of the lightest minihole, with a similar mass $M = 10^{11}$ kg. Upper bounds have been evaluated, as discussed in the text, for two different values of the Planck length, the standard one and one assuming early unification of gravity at the Fermi scale.

V. POSSIBLE UPGRADES FOR HIGH PRECISION TESTS OF THE SUPERPOSITION PRINCIPLE

Dedicated configurations in which violations to the superposition principle for gravitational forces could be evidenced or ruled out at the highest level of precision may be designed. Since we expect the sought effect to be proportional to the surface-to-mass ratio, the basic idea behind these optimized configurations is to take into account the geometrical shape of a body, and use slabs instead of the usual spherical geometry. Two different configurations can be envisaged to find out or give upper bounds to a possible Kretschmann coupling between the Higgs field and gravitation. One consists in using a Cavendish balance with test masses designed as plates, for instance of a rectangular shape rather than the usual spherical shape (Fig. 1a). Two plates are also added on each side of the test mass in a parallel plate configuration, at approximately the same distance to compensate for the added gravitational force. The requirements on the distance are not stringent since the gravitational force between parallel plates is independent on distance, apart
The force between the gravitational source of the gravitational field, with a highly sensitive test mass (T), the source mass (S), and a removable fork-shaped mass (F), with masses symmetrically centered around the test mass. (b) Majorana-like balance with an horizontal geometry, in which the source mass is the Earth. The direction of the Earth's gravitational field is also evidenced. The fork-shaped mass may be replaced with a variable-density rotating chopper in order to have a time-modulation of the effect, similarly to the scheme used in Fig. 1b.

The second scheme, more in the spirit of Majorana's experiments, could alternatively exploit the Earth as a source of the gravitational field, with a highly sensitive balance and test masses still of planar shape but now lying along the vertical axis, in order to cancel any contribution due to the Earth's gravitational field. This closely resembles the scheme proposed in [26] for the study of submillimeter short-range non-Newtonian components of the gravitational force.

VI. CONCLUSIONS

In conclusion, we have discussed gravitational vacuum polarization effects induced by the Higgs field, which imply distinctive changes in Newton's gravitational law and the superposition principle for gravitational forces. Even considering the current precision level in the determination of the universal gravitational constant \(G\) [30], a direct measurement of deviations from Newton's law is experimentally precluded. Nevertheless, we believe that experiments aimed at evidencing deviations from the superposition principle using modern balance techniques are feasible and could shed light on possible nonminimal couplings between the Higgs (or a Higgs-like field) and spacetime, complementary or in alternative to dedicated astrophysical surveys as suggested in [1]. We have also discussed explicit experimental configurations which seem the most promising to evidence the presence of gravitational effects due to proximity masses.

The phenomenological platform has been developed assuming a linear coupling of the Higgs field to the Kretschmann invariant, however other forms of coupling could be considered, as for instance the scalar of 3-curvature (3)\(R\) or the trace of the extrinsic curvature [31] in the framework of the recently proposed Hořava-Lifshitz gravity [32]. An even more general scenario left open in this analysis is the one in which the Higgs field couples also to invariants related to torsion. For \(f(R)\)-gravity models, this has intriguing implications as it naturally leads to weak-like, chiral interactions acting at an energy scale close or coincident with the Fermi scale [33,35], paving the road to a possible unification of gravitation and weak interactions. While a comprehensive analysis of phenomenological bounds on curvature-torsion models is beyond the scope of this paper, this shows again that our discussion relative to a specific, model-dependent Higgs-curvature coupling through the Kretschmann invariant provides an operative setting in which extensions of general relativity may confront possible experiments/observations. Although partially related to our consideration, we mention recent work discussing the possible mass shifts of heavy elementary particles due to a Higgs self-polarization phenomenon, supposed to be observable near pair production threshold at high energy accelerators, most notably for the top quark [36].

Any possible matching between quantum vacuum and gravitation has been so far frustrated by the difficulty for successful experimental observation of predicted effects, as in the well-known example of Hawking radiation, due to the combined smallness of the universal constant of gravitation and Planck’s constant, and the discussion in this work confirms this state of affairs in terms of experimental observability of the investigated effects. It is at least comforting to point out that, at a more conceptual level, our findings also show a conflict between Higgs field physics and the notion that gravitational potentials, as assumed in Newtonian gravitation or in post-Newtonian parameterizations of metric theories, are meaningful concepts to describe gravity in their non-relativistic limit, providing a further source of concern for any future hypothetical unification between quantum physics and gravitation.
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\[ \text{Refs. [16][17].} \]