CAN GRAVITY MAKE THE HIGGS PARTICLE DECOUPLE?*

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The spontaneous symmetry breaking theory of gravity is examined, assuming that the vacuum expectation value of the standard model Higgs is also responsible for the generation of the Planck mass. In this model the physical Higgs couples only with gravitational strength to matter. At presently accessible energies the theory is indistinguishable from the standard model without Higgs boson and is in agreement with all existing data. It provides therefore a viable alternative to the standard model coupled to ordinary Einstein gravity. At energies above the Fermi scale new dynamics should occur.

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The standard model is in agreement with existing data. However, it leaves many questions unanswered, in particular with regard to the masses of particles. The mass spectrum of particles is completely understood. In the standard model all masses arise from the coupling to the Higgs sector. It is, therefore, the Higgs sector, where the dynamics of mass generation is hidden. Another problem of the Higgs sector is of a more theoretical but possibly more fundamental nature. It is the so-called naturalness problem. The corrections to the Higgs mass are quadratically divergent. Therefore, one expects the Higgs to be as heavy as the cut-off of the theory, although within the standard model the Higgs mass is supposed to be close to the Fermi scale. Suggested solutions to the naturalness problem are technicolor [1], supersymmetry [2], and heavy quark condensates [3].

In technicolor there is no fundamental Higgs and the only interactions are gauge interactions. Therefore, all radiative corrections are only logarithmically divergent. Unfortunately, no working model has been found so far.

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In supersymmetry there are no quadratic divergences in the theory due to cancellations between boson and fermion loops. A minimal supersymmetric standard model exists which is not in conflict with present data. Unfortunately, the model essentially doubles the present spectrum of particles replacing Bose (Fermi) degrees of freedom with Fermi (Bose) degrees of freedom. About the nature of the Higgs sector itself little is said.

A third attempt is to cancel the quadratic divergences within the standard model itself [4]. This gives rise to relations between top and Higgs mass. However, this cancellation can only be valid at one scale, as the top quark feels QCD corrections and the Higgs not. This leads to the idea that the Higgs is a $\bar{t}t$ condensate. Also here no satisfactory model seems to exist.

In this letter I will consider a fourth logical possibility. Namely, maybe the cut-off of the theory is not so large and of the order of the weak scale, but strong interactions appear. All explanations given above leave gravity out of the picture. While historically it has been emphasized that gravity may not play a role in elementary particle physics because of the large discrepancy between the Fermi scale and the Planck scale, this may be a mistake. To argue that gravity may play a role there are a few points I want to emphasize. First there is the anomaly. There is an anomaly in the gauge currents due to the coupling to gravity, that has to cancel to preserve gauge invariance. This leads to the condition $Tr(Y) = 0$, which is indeed satisfied. Therefore, it appears that gravity is sensitive to the gauge structure of the standard model.

A second point is that the Higgs and the graviton have some similar characteristics. The Higgs is coupled universally to the mass of particles and the graviton to energy-momentum. So, at least at low energy one might conjecture a relation between the Higgs sector and gravity. The fact that the Higgs potential generically generates a cosmological constant may also be an indication for a connection.

As mentioned above the problem establishing such a relation is the large discrepancy between the Fermi scale and the Planck scale. I will try to address this problem in a model with spontaneous symmetry breakdown. Within models of spontaneous symmetry breaking there are essentially two ways to generate a large difference in mass scales. The standard way is to assume that there are several fields having very different vacuum expectation values, but similar values of coupling constants. This way the theory stays perturbative at all scales. The other possibility is to have fields with similar vacuum expectation values, but widely different coupling constants. Models of this type with singlet Higgs fields are considered in [5], giving strong effects in W-boson interactions. Including gravity a model of this type is given by the spontaneous symmetry breaking theory of gravity. In this model the Planck constant is generated through the vacuum expectation value of a Higgs field ϕ that is coupled to gravity via a $\xi\phi^2 R$ term. To my knowledge the first paper of this type is [6]. The subject became popular through the article [7]. A review is given in [8]. In the literature the fields ϕ that have been discussed are typically singlet fields or grand unified fields, with a large vacuum expectation value of the order of the Planck mass, so that the coupling constant ξ is relatively small. Often a bare R term in the action is assumed, so that the non-minimal term is a small correction. At low energies these models are indistinguishable from the standard model.

In this letter I will consider the case that the ϕ field is the Higgs field of the standard model itself. This possibility has been largely ignored in the literature because of the large value of ξ that is needed. The case was discussed by Cheng [9], who was interested in scale invariance and the Weyl vector boson. The scale invariance was used to remove the Higgs from the theory. I will in the following assume the existence of a physical Higgs field with a potential. Scale invariance will play no role. Quantum mechanically scale invariance would be broken anyway. The interactions with matter are determined by the ordinary standard model. The extra Higgs-graviton interaction will be shown to alter the properties of the physical Higgs boson.

The Lagrangian of the model is given by:

$$\mathcal{L} = \sqrt{g}\big(\xi\Phi^+\Phi R - \tfrac{1}{2}g^{\mu\nu}(D_\mu\Phi)^+(D_\nu\Phi) - V(\Phi^+\Phi) - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu}\big)\,. \qquad (1)$$

If we take Φ to be the standard model Higgs field the coupling constant ξ is very large. In order to obtain the Einstein Lagrangian after spontaneous symmetry breakdown one needs $\xi = \frac{\kappa^2}{v^2} = \frac{1}{16\pi G_N v^2} \approx O\big(\frac{m^2_{\rm Pl}}{v^2}\big)$. Due to this very large value of ξ the physical content of the theory is not quite manifest. The physical content can be made manifest by the Weyl rescaling $g_{\mu\nu} \to \frac{\kappa^2}{\xi v^2}g_{\mu\nu}$. Keeping only the Higgs and the gravity part the Lagrangian becomes:

$$\mathcal{L} = \sqrt{g}\Big(\kappa^2 R - \frac{3}{2}\frac{\xi v^2}{|\Phi|^4}(\partial_\mu|\Phi|^2)(\partial^\mu|\Phi|^2) - \frac{1}{2}\frac{v^2}{|\Phi|^2}(D_\mu\Phi^+)(D^\mu\Phi) - \frac{v^4}{|\Phi|^4}V(|\Phi|^2)\Big). \qquad (2)$$

The gravity part of the Lagrangian has now become of the canonical form. The Higgs part is a modified form of the standard model. As potential we take $V(\Phi) = \frac{1}{8}\lambda(\Phi^+\Phi - v^2)^2$. To analyze the physical content of the theory one takes the unitary gauge $\Phi = \binom{0}{v+\sigma}$. Expanding around the minimum one gets for the quadratic part of the Higgs Lagrangian

$$\mathcal{L}_{\rm Higgs} = -\tfrac{1}{2}(1 + 12\xi)(\partial_\mu\sigma)(\partial^\mu\sigma) - \tfrac{1}{2}\lambda v^2\sigma^2\,. \qquad (3)$$

Therefore, there is a wave function renormalization of the Higgs field by a factor $1/\sqrt{1+12\xi}$. As a result the effective coupling of the Higgs field to matter becomes of gravitational strength $O(m/m_{\rm Pl})$. The mass of the Higgs particle itself is given by $m_H^2 = \frac{\lambda v^2}{1+12\xi}$. Because the coupling of the Higgs to matter is of gravitational strength the Higgs becomes essentially a stable particle. This could have some cosmological consequences and remnant Higgs particles could still be present. For $\lambda \approx O(1)$ m_H becomes very small and this will result in a contribution to the gravitational force with a range of 1.9 cm$/\sqrt{\lambda}$. The coupling strength to matter is given by

$$\left(\frac{1}{1+12\xi}\right)^{1/2}\left(g_q\bar{q}q + \frac{\alpha_s}{2\pi}G_{\mu\nu}G^{\mu\nu}\right). \tag{4}$$

In this range the Higgs particle behaves similar to the cosmon [10]. This range may already be ruled out by fifth force experiments.

When one assumes that $\lambda \approx O(\xi)$, m_H becomes of the order of the electroweak scale. Because the Higgs coupling has been reduced to gravitational strength, the Higgs particle effectively decouples from the theory and one is left with the massive Yang–Mills theory. The massive Yang–Mills theory is in agreement with present experiments even though it is non renormalizable, because the cut-off dependence is only logarithmic (Veltman's theorem) [11]. Therefore, if the cut-off of the theory is around the Fermi scale, the present experiments at LEP are not sensitive to such effects.

The way the Higgs is removed from the theory here by making its coupling to matter small is to be contrasted with the usual way where the mass of the Higgs is taken to be large. As is well known in such a limit the theory becomes equivalent to a gauged non-linear σ model. The longitudinal W-bosons correspond to the pions of the theory. The scattering amplitude of the pions should go to zero at low energy. This is indeed the case for the Lagrangian [2]. As an example one has for the 4-point scattering amplitude the following formula in lowest order

$$\mathcal{M} = \frac{1}{v^2}\left[\frac{(12\xi k^2 + \lambda v^2)^2}{(1+12\xi)k^2 + \lambda v^2} - (12\xi k^2 + \lambda v^2)\right]\delta_{\rm ab}\delta_{\rm cd} + \text{permutations}, \tag{5}$$

which behaves as $-\frac{k^2}{v^2}\delta_{\rm ab}\delta_{\rm cd}$ for $k \to 0$, so that indeed an Adler zero is present.

Therefore, it has been shown that at energies below the Fermi scale the model is equivalent with the standard model without Higgs particle. This leaves open the question what happens at energies above the Fermi scale. At these energies the non-renormalizability of the theory plays a role and strong interactions should be present. What the nature of these strong interactions should be is not clear. As a first approximation one would expect some form of chiral perturbation theory to be valid. One might even conjecture that gravity could play a role. The model makes clear that the method of mass generation and the question of renormalizability are two separate issues. The necessary strong interactions should give interesting physics at the planned future colliders, like the SSC, LHC and NLC.

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