Unparticles and electroweak symmetry breaking

Jong-Phil Lee

Korea Institute for Advanced Study, Seoul 130-722, Korea

Abstract. We investigate a scalar potential inspired by the unparticle sector for the electroweak symmetry breaking. The scalar potential contains the interaction between the standard model fields and unparticle sector. It is described by the non-integral power of fields that originates from the nontrivial scaling dimension of the unparticle operator. It is found that the electroweak symmetry is broken at tree level when the interaction is turned on. The scale invariance of unparticle sector is also broken simultaneously, resulting in a physical Higgs and a new lighter scalar particle.

Keywords: Unparticle, electroweak symmetry breaking

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INTRODUCTION

The start-up of the large hadron collider (LHC) at CERN will shed lights on a long standing puzzle in particle physics, the secret of electroweak symmetry breaking (EWSB). A hidden sector can be a good answer for EWSB. In a minimal extension, the hidden sector scalar couples to the standard model (SM) scalar field in a scale-invariant way [1, 2, 3, 4]. Quantum loop corrections break the scale invariance, and the scalar field achieves the vacuum expectation value (VEV) through the Coleman-Weinberg (CW) mechanism [5].

Recently the hidden sector has received much attention with the possibility of the existence of unparticles [6]. The unparticle is a scale invariant stuff in a hidden sector. Its interactions with the SM particles are well described by an effective theory formalism.

The most striking feature of the unparticle is its unusual phase space with non-integral scaling dimension $d_{\phi}$. For an unparticle operator of scaling dimension $d_{\phi}$, the unparticle appears as a non-integral number $d_{\phi}$ of invisible massless particles. After the Georgi’s suggestion, there have been a lot of phenomenological studies on unparticles [7, 8, 9, 10, 11, 12].

Among other couplings between SM fields and unparticles, Higgs-unparticle interaction is very interesting because its coupling, $\lambda_{\Phi\Phi U}(\Phi^\dagger \Phi)O_{\phi}$, is relevant [9]. Here $\Phi$ is a fundamental Higgs, $O_{\phi}$ is a scalar unparticle operator with scaling dimension $1 < d_{\phi} < 2$, and $\lambda_{\Phi\Phi U}$ is the coupling constant.

This work is motivated by the observation that the scalar unparticle operator $O_{\phi}$ is equivalent to $d_{\phi}$ number of massless particles [13]. This feature of unparticle operator coupled with Higgs sector is already pointed out in the literature [14]. We propose a new type of scalar potential

$$V_{int} \sim \lambda (\Phi^\dagger \Phi)(\phi^* \phi)^{d_{\phi}/2},$$

(1)

where $\phi$ is a massless scalar field with $|\phi| = 1$.

When one considers the scalar potential containing the form of $V_{int}$, it inevitably introduces a mass scale through the dimensionful coupling. One may expect that there is a nontrivial minimum along the radial direction at tree level for $V \supset V_{int}$. The main result of this work is that this is indeed the case. In other words, interactions between the SM fields and unparticle sector themselves break the electroweak symmetry.

After the EWSB occurs one expands the scalar fields around the vacuum. The resulting fluctuations mix up with each other to form two physical scalar states. In this simple setup, it is quite natural to identify a heavy state as Higgs. The other light state has a mass proportional to $\langle 2 - d_{\phi} \rangle$ which vanishes as $d_{\phi} \rightarrow 2$. This is the remnant of the fact that $V_0$ has a massless scalar at tree level as a pseudo Goldstone boson from the conformal symmetry breaking. The unparticle sector thus no longer remains scale-invariant after the EWSB. So the interaction $V_{int}$ induces both EWSB in the SM sector and the scale-invariance breaking in the unparticle sector. We find that all of these things can happen for acceptable values of the parameters of this setup.

In the earlier works of [10], the EWSB with unparticles was considered in the context of deconstruction [11]. But the scalar potential of [10] contains only the usual polynomials of the fields. The unusual scaling behavior of the unparticle was encoded in the deconstructed version of the unparticle decay constant, while in this work it is simplified with the fractional power of the fields. We find that the EWSB conditions on the parameters here are rather stronger, and the predicted new scalar particle is always lighter than the Higgs boson.

Recently it was proposed that the unparticles are gauged to become a Higgs [15]. This ”Unhiggs” can also break EWS and unitarize $WW$ scattering.
SCALAR POTENTIAL AND THE MASS SPECTRUM

The proposed scalar potential has the form of

\[ V(\Phi, \phi) = \lambda_0 (\Phi^4 \phi^2) + \lambda_1 (\phi^4 \phi^2) \]

\( + 2\lambda_2 \mu^2 \, d_\psi \, (\Phi^4 \phi)(\phi^4 \phi) \, d_\psi / 2 , \)

where \( \lambda_0 \) is assumed to be positive. Here the mass dimension of \( \phi \) is 1 and a dimension-1 parameter \( \mu \) is inserted to make \( \lambda_2 \) dimensionless. The minimum of \( V \) lies along some ray \( \Phi = \rho N_i \) [16], where \( N_i \) is a unit vector in the field space \( \Phi_i = (\Phi, \phi) \). In unitary gauge, the fields are parameterized as

\[ \Phi = \frac{N}{\sqrt{2}} \left( \begin{array}{c} 0 \\ N_0 \end{array} \right), \phi = \frac{N}{\sqrt{2}} N_1 , \]

where \( N_0^2 + N_1^2 = 1 \). The scalar potential becomes

\[ V(\rho, \bar{N}) = \frac{\rho^4}{4} \left[ \lambda_0 N_0^4 + \lambda_1 N_1^4 + \left( \frac{\lambda_2}{2} \right)^2 2\lambda_2 N_0^2 N_1^2 \right] . \]

where \( d_\psi \equiv 2 - 2\epsilon \), and \( \rho \equiv \rho / \mu \).

The stationary condition for \( V \) along the \( \bar{N} \) direction for some specific unit vector \( \bar{N} = \bar{n} \), \( (\partial V / \partial N_i)_\bar{n} = 0 \), combined with the normalization of \( \bar{n} (n_1^2 + n_2^2 = 1) \), gives

\[ n_0^2 = \frac{\sqrt{2\lambda_1}}{\sqrt{d_\psi \lambda_0 + \sqrt{2\lambda_1}}}; \quad n_1^2 = \frac{\sqrt{d_\psi \lambda_0}}{\sqrt{d_\psi \lambda_0 + \sqrt{2\lambda_1}}} . \]

One can easily find that the minimum of \( V(\rho, \bar{n}) \) occurs at

\[ \rho = \rho_0 \equiv \left( -\frac{2\epsilon \lambda_2 n_1^2}{\lambda_0 n_0^2} \right)^{\frac{1}{2}} \mu . \]

It should be noted that when \( d_\psi \to 2 \), \( \rho_0 \) goes to 0 or infinity depending on the values of \( \lambda_{1,2} \) and \( n_0, n_1 \). Since the vacuum expectation value \( \rho \) is directly proportional to the mass scale of the theory (e.g., gauge boson masses, Higgs masses, etc.), it is not desirable if \( \rho_0 \) gets too small or too large for \( d_\psi \to 2 \). We require that \( \rho_0 \) is stable for \( d_\psi \to 2 (\epsilon \to 0) \). A little algebra shows that this requirement is satisfied if

\[ \lambda_2 = -\sqrt{\lambda_0 \lambda_1} \equiv \lambda . \]

When \( \lambda_{1,2} \) are turned on, the potential \( V \) develops the VEV \( v \) at \( \rho = \rho_0 \) and the fields \( \Phi \) and \( \phi \) get fluctuations \( h \) and \( s \) around \( v \). The scalar potential now becomes

\[ V(h, s) = \frac{\lambda_0}{4} (n_0 \rho_0 + h)^4 + \frac{\lambda_1}{4} (n_1 \rho_0 + s)^4 \]

\( + 2^{-d_\psi / 2} \lambda_2 \mu^2 \, d_\psi (n_0 \rho_0 + h)^2 (n_1 \rho_0 + s) d_\psi \).

The mass squared matrix

\[ (M^2)_{ij} = \frac{\partial^2 V}{\partial \psi_i \partial \psi_j} \]

where \( \psi_i = (h, s) \), gives two eigenvalues of \( M^2 \) corresponding to the heavy and light scalar mass squared respectively:

\[ m_{h, l}^2 = \frac{\rho_0^2 \sqrt{2\lambda_0 \lambda_1}}{d_\psi \lambda_0 + \sqrt{2\lambda_1}} \left\{ \sqrt{\lambda_0} \right. \]

\[ + \left( 2 - \frac{d_\psi}{2} \right) \sqrt{\frac{d_\psi}{2} \lambda_1 \pm \sqrt{D}} \right\} , \]

where

\[ D = \lambda_0 + \left( 2 - \frac{d_\psi}{2} \right)^2 \frac{d_\psi}{2} \lambda_1 + \left( \frac{3d_\psi}{2} - 2 \right) \sqrt{2d_\psi \lambda_0 \lambda_1} . \]

When \( d_\psi = 2 \), the light scalar is massless at tree level. The reason is that it corresponds to the pseudo Goldstone boson from the spontaneous symmetry breaking of the conformal symmetry [16, 17].

But for \( \epsilon = 1 - d_\psi / 2 \ll 1 \), we have found that \( m_l^2 / m_h^2 \sim \epsilon \) at tree level. Thus the new light scalar and Higgs boson masses are good probes to the hidden unparticle sector.

The vacuum expectation value \( \rho_0 \) is related to the gauge boson \( (W) \) masses as

\[ (n_0 \rho_0)^2 = \frac{1}{\sqrt{2G_F}} = (246 \text{ GeV})^2 \equiv v_0^2 . \]

From the value of \( \rho_0 \) and \( \lambda_2 \), one has

\[ \hat{v}_0^2 = 2 \left( \frac{d_\psi}{2} \right)^{d_\psi / 2} \lambda_1 \lambda_0 . \]

where \( \hat{v}_0 = v_0 / \mu \). The right-hand-side of Eq. (13) is a slow varying function of \( d_\psi \). If one chooses \( \mu = v_0 \), the ratios of couplings are

\[ \frac{\lambda_1}{\lambda_0} = \frac{1}{4} \left( \frac{2}{d_\psi} \right)^{d_\psi / 2} \to e^{4} / 4 \simeq 0.68 \quad \text{as} \quad d_\psi \to 2 , \]

\[ \frac{\lambda_2}{\lambda_0} = -\sqrt{\frac{\lambda_1}{\lambda_0}} \to -0.82 . \]

When \( d_\psi = 1 \), \( \lambda_1 / \lambda_0 = 0.5 \) and \( \lambda_2 / \lambda_0 \simeq -0.71 \). Since the ratios are of order 1 for all range over \( d_\psi \), the scale of \( \mu \) around the weak scale is a reasonable choice. As given in Fig. 1, \( m_h \) is rather inert with respect to \( d_\psi \) while
FIGURE 1. Scalar masses $m_h$ and $m_\ell$ as a function of $d_U$ for $\lambda_0 = 0.1, 0.2, \cdots, 1.0$, from bottom to top.

$m_\ell$ is not. With the condition of Eq. (14), both $m_{h,\ell}$ are proportional to $\sim \sqrt{\lambda_0}$. One can find that

\begin{equation}
130(149) \text{ GeV} \lesssim m_h \lesssim 411(470) \text{ GeV} ,
66 \text{ GeV} \lesssim m_\ell \lesssim 209 \text{ GeV} ,
\end{equation}

for $d_U = 1(2)$. If the scalar masses turned out to be quite different from Eq. (15), then the value of $\mu$ should be rearranged to fit the data. But in this case one would have to explain why that value of $\mu$ is so different from $v_0$, the electroweak scale.

CONCLUSION

In this talk we suggest a new scalar potential with a fractional power of fields from hidden sector inspired by the scalar unparticle operator. Unlike the usual potential of marginal coupling, the new one develops VEV at tree level. In this picture, the EWSB occurs when the unparticle sector begins to interact with the SM sector. When the scaling dimension $d_{U}$ departs from the value of 2 a new scale (of the order of $\sim 1/\sqrt{G_F}$) is introduced in the scalar potential through the relevant coupling, and the electroweak symmetry is broken at tree level. In other words, the EWSB occurs when the hidden sector enters the regime of scale invariance, i.e., unparticles. In view of the unparticle sector, the new potential also breaks the scale invariance of the hidden sector.

Once the electroweak symmetry is broken, the scalar fields from SM and hidden sector mix together to form two massive physical states. The heavy one is identified as Higgs, while the light one is a new particle of mass around $\lesssim 210$ GeV. It might be that the latter be soon discovered at the LHC.

REFERENCES

1. K. A. Meissner and H. Nicolai, Phys. Lett. B 648, 312 (2007).
2. J. R. Espinosa and M. Quiros, Phys. Rev. D 76, 076004 (2007).
3. W. F. Chang, J. N. Ng and J. M. S. Wu, Phys. Rev. D 75, 115016 (2007).
4. R. Foot, A. Kobakhidze and R. R. Volkas, Phys. Lett. B 655, 156 (2007).
5. S. R. Coleman and E. Weinberg, Phys. Rev. D 7, 1888 (1973).
6. H. Georgi, Phys. Rev. Lett. 98, 221601 (2007); Phys. Lett. B 650, 275 (2007).
7. K. Cheung, W. Y. Keung and T. C. Yuan, Phys. Rev. Lett. 99, 051803 (2007), Phys. Rev. D 76, 055003 (2007); M. Luo and G. Zhu, Phys. Lett. B 659, 341 (2008); Y. Liao, Phys. Rev. D 76, 056006 (2007); T. Kikuchi and N. Okada, arXiv:0707.0893 [hep-ph]; A. Lenz, Phys. Rev. D 76, 065006 (2007); J. R. Mureika, Phys. Lett. B 660, 561 (2008); B. Grinstein, K. Intriligator and I. Z. Rothstein, arXiv:0801.1140 [hep-ph].
8. K. Cheung, W. Y. Keung and T. C. Yuan, this proceeding; arXiv:0809.0995 [hep-ph].
9. P. J. Fox, A. Rajaraman and Y. Shirman, Phys. Rev. D 76, 075004 (2007).
10. A. Delgado, J. R. Espinosa and M. Quiros, JHEP 0710, 094 (2007).
11. M. A. Stephanov, Phys. Rev. D 76, 035008 (2007).
12. J. P. Lee, arXiv:0710.2797 [hep-ph].
13. J. P. Lee, arXiv:0803.0833 [hep-ph].
14. See, for example, Ref. [10].
15. D. Stancato and J. Terning, arXiv:0807.3961 [hep-ph].
16. E. Gildener and S. Weinberg, Phys. Rev. D 13, 3333 (1976).
17. W. D. Goldberger, B. Grinstein and W. Skiba, arXiv:0708.1463 [hep-ph].