Higgs Boson Decays into Single Photon plus Unparticle

Kingman Cheung\textsuperscript{1,2}, Chong Sheng Li\textsuperscript{3} and Tzu-Chiang Yuan\textsuperscript{2}

\textsuperscript{1}Department of Physics, National Tsing Hua University, Hsinchu 300, Taiwan
\textsuperscript{2}Physics Division, National Center for Theoretical Sciences, Hsinchu 300, Taiwan
\textsuperscript{3}Department of Physics, Peking University, Beijing 100871, China

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Abstract

The decay of the standard model Higgs boson into a single photon and a vector unparticle through a one-loop process is studied. For an intermediate mass Higgs boson, this single photon plus unparticle mode can have a branching ratio comparable with the two-photon discovery mode. The emitted photon has a continuous energy spectrum encoding the nature of the recoil unparticle. It can be measured in precision studies of the Higgs boson after its discovery.

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I. INTRODUCTION

The electroweak-symmetry breaking of the standard model (SM) in particle physics that provides masses to its particle contents will soon be tested at the CERN Large Hadron Collider (LHC), which is scheduled to be online in later part of the year 2008. The simplest version of the electroweak-symmetry breaking consists of an elementary scalar boson known as the Higgs boson $H$. On the theoretical side, the best fit value of electroweak precision data for the Higgs boson mass is $m_H = 89^{+38}_{-28}$ GeV with a 95% CL upper limit of $m_H < 144$ GeV [1], while the direct searches at LEP puts a lower limit on $m_H > 114.5$ GeV [2]. For an intermediate-mass Higgs boson in the mass range of $115 - 140$ GeV, the best hope to search for it at the LHC is the two-photon mode [3] even though the branching ratio for the two-photon decay mode is only $10^{-3}$. The Higgs boson will manifest as a sharp peak standing above the continuum background in the diphoton invariant mass spectrum. The position of the peak indicates the mass of the Higgs boson. In the rest frame of the Higgs boson, the energy of the photon will be exactly one half of the Higgs boson mass. Another rare decay mode of the Higgs boson into a single photon $\gamma$ and the massive neutral gauge boson $Z$ of the SM has a branching ratio of order $10^{-3}$, in which the photon is also mono-energetic in the rest frame of the Higgs boson.

In this work, we point out a possible rare decay mode of the Higgs boson in the scheme of unparticle proposed in [4]. The Higgs boson can decay into a single photon plus a vector unparticle $U$. The salient feature of this decay mode is that the photon energy has a continuous spectrum in the rest frame of the Higgs boson, in contrast to $H \to \gamma\gamma$ and $\gamma Z$. Therefore, by measuring the photon energy spectrum in the Higgs boson decay, one can discriminate the presence of the unparticle or not. Note that we cannot use $H \to \gamma U$ for the discovery of the Higgs boson, because of the missing energy carried away by the unparticle. Therefore, the decay mode that we propose in this work will be in the precision studies of the Higgs boson decay. Perhaps, it can be done at the future International Linear Collider.

The notion of unparticle was introduced in [4] to describe a possible scale-invariant hidden sector that possesses an infrared fixed point at a higher scale $\Lambda_U$ presumably above the Fermi scale. Such a hidden sector is assumed interacting with the visible SM sector weakly enough to be describable by an effective field theory governed by non-renormalizable operators suppressed by inverse powers of $\Lambda_U$. Phenomenological implications of unparticle have since
been studied by many authors \[5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21,
22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44,
45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66\], while
more conceptual aspects of unparticle were explored by others \[67, 68, 69, 70, 71\]. Due
to the exact scale invariance, unparticle does not behave like ordinary particles. It has a
continuous spectral density and behaves like a collection of \(d_U\) massless particles, where \(d_U\)
is the scaling dimension of the unparticle operator \(\mathcal{O}_U\). Thus unparticle does not have a
definite mass and is just like the massless photon that it has no rest frame. This implies that
a real unparticle is stable and cannot decay. Direct signals of unparticle can nevertheless be
detected in the missing energy and momentum distribution carried away by the unparticle
once it was produced in a process \[4\], while virtual unparticle effect can be probed via its
interference with the SM amplitudes \[5, 6\]. Thus, even in the case of 2-body decay like
\(H \rightarrow \gamma U\), the energy spectrum of the photon is no longer a delta function peaked at \(m_H/2\)
but rather a continuous one spreading from zero to \(m_H/2\).

One more remark before we come to the details of the calculation is that \(H \rightarrow \gamma U\) is
a one-loop process, in analogous to \(H \rightarrow \gamma Z\), but with only SM fermions flowing in the
loop. The major contribution comes from the top-quark loop. The vector coupling of the
top quark to the unparticle can be parameterized by \((\lambda_1^t/\Lambda_U^{d_U-1}) t \gamma \mu t \mathcal{O}_{U}^\mu\). As long as the
coupling is flavor dependent, the constraint coming from the top quark physics \(^1\) is rather
loose, even though the constraints for other fermions (e.g. electron) are very stringent \[6\].
Therefore, we are allowed to use \(\lambda_1^t \sim 1\) and \(\Lambda_U \sim 1\) TeV for the top quark without upsetting
existing constraints.

II. UNPARTICLE CALCULATION

The interaction of a vector unparticle \(U\) with a standard model fermion \(f\) is given by
\[\text{4, 6}\]
\[\mathcal{L}_{\text{eff}} \ni \frac{1}{\Lambda_U^{d_U-1}} f \left(\lambda_1^f \gamma_\mu + \lambda_{1f}^f \gamma_\mu \gamma_5\right) f \mathcal{O}_{U}^\mu\]  
\(1\)

\(^1\) We note that strong constraints for flavor independent couplings between SM fermions and unparticle
operators have been obtained in \[33\] using the \(t\bar{t}\) production cross section from the Tevatron.
where \( \lambda_1^f \) and \( \lambda_1^{f'} \) are the unknown vector and axial vector couplings. The process \( H \to \gamma\mathcal{U} \) can be induced at one-loop level with the standard model fermions circling the loop. The most dominant contribution comes from the top-quark loop. We note that the \( W \) boson loop that contributes significantly in the two-photon mode does not contribute in the unparticle case. The Lorentz-invariant decay amplitude \( \mathcal{M} \) for \( H \to \gamma(k) + \mathcal{U}(P_\mathcal{U}) \) is dictated by gauge invariance of electromagnetism and can be written as

\[
\mathcal{M} = 
\epsilon_\mu^*(k, \lambda) \epsilon_\nu^*(P_\mathcal{U}, \lambda') \mathcal{M}^{\mu\nu}
\]

with

\[
\mathcal{M}^{\mu\nu} = (P_\mu^\mathcal{U} k^\nu - g^{\mu\nu} P_\mathcal{U} \cdot k) A .
\]

The loop-induced amplitude \( A \) can be extracted from previous \( H\gamma Z \) calculations \([72, 73, 74, 75, 76]\) by the following substitutions

\[
-g \cos \theta_w \left( \frac{1}{2} T_f^{3L} - Q_f \sin^2 \theta_w \right) \rightarrow \frac{\lambda_1^f}{\Lambda_{dU}^{d-1}} ,
\]

\[
m_Z^2 \rightarrow P_{dU}^2 .
\]

As in the \( H\gamma Z \) case, the axial vector coupling \( \lambda_1^{f'} \) does not contribute to \( A \) as it is forbidden by charge conjugation. Thus

\[
A = \frac{\alpha}{\pi m_W \Lambda_{dU}^{d-1}} A_F
\]

where

\[
A_F = \sum_f N_f \frac{\lambda_1^f Q_f}{\sin \theta_w} \left( I (x_f, y_f) - J (x_f, y_f) \right)
\]

with \( x_f = 4m_f^2/m_H^2 \), \( y_f = 4m_f^2/P_{dU}^2 \) and \( m_f \) is a fermion mass. The loop functions \( I(x, y) \) and \( J(x, y) \) are given by

\[
I (x, y) = \frac{xy}{(x - y)} \left[ \frac{1}{2} - J (x, y) + \frac{x}{(x - y)} \left[ g(x) - g(y) \right] \right] ,
\]

\[
J (x, y) = -\frac{xy}{2(x - y)} \left[ f(x) - f(y) \right]
\]

with

\[
f(x) = \begin{cases} 
\left[ \sin^{-1} \left( \frac{1}{\sqrt{x}} \right) \right]^2 & \text{if } x \geq 1 \\
-\frac{1}{4} \left[ \ln \left( \frac{1 + \sqrt{1-x}}{1 - \sqrt{1-x}} \right) - i\pi \right]^2 & \text{if } x < 1
\end{cases}
\]

\[
g(x) = \begin{cases} 
\sqrt{x-1} \sin^{-1} \left( \frac{1}{\sqrt{x}} \right) & \text{if } x \geq 1 \\
\frac{1}{2} \sqrt{1-x} \left[ \ln \left( \frac{1 + \sqrt{1-x}}{1 - \sqrt{1-x}} \right) - i\pi \right] & \text{if } x < 1
\end{cases}
\]
FIG. 1: Normalized photon energy spectrum for different values of $d_U = 1.001, 1.1, 1.2, 1.3, 1.5$ and 2.

The energy distribution of the emitted photon for this process can be easily derived as

$$\frac{d\Gamma}{dE_\gamma} = \frac{\alpha^2}{4\pi^4m_W^2} A_{d_U} m_H E_\gamma^3 \frac{1}{\Lambda_{U}^2} \left( \frac{P_{U}^2}{\Lambda_{U}^2} \right)^{d_U-2} |A_F|^2$$

(12)

with $P_{U}^2 = m_H^2 - 2m_H E_\gamma$ and $E_\gamma$ lies in the range $[0, m_H/2]$. $A_{d_U}$ is the normalization for the unparticle phase space $\mathcal{U}$

$$A_{d_U} = \frac{16\pi^\frac{5}{2}}{(2\pi)^{2d_U}} \frac{\Gamma(d_U + \frac{1}{2})}{\Gamma(d_U - 1) \Gamma(2d_U)}.$$  

(13)

III. RESULTS

In Fig. 1 we plot the normalized energy spectrum of the emitted photon from $H \to \gamma\mathcal{U}$ for various values of the scaling dimension $d_U = 1.001, 1.1, 1.2, 1.3, 1.5$ and 2 with a Higgs boson mass of 140 GeV. As the scaling dimension approaches unity, the distribution becomes a delta function peaked at one half of the Higgs boson mass. As $d_U$ moves away from unity, the energy spectrum begins to flatten out gradually. For simplicity, we have only included the top quark in the loop, because it is the most dominant and the size of the coupling that we used is consistent with the top quark physics. Even if we include all SM fermions in the loop, there is hardly any visible change to the figure.
In Fig. 2, we compare the decay rate of the single photon mode $H \rightarrow \gamma U$ with that of the two-photon mode $H \rightarrow \gamma \gamma$. One can see that for $d_U = 1.1$ and $50 \text{ GeV} < m_H < 100 \text{ GeV}$, both modes can have the same branching ratio.

In Fig. 3, the branching ratios of various Higgs boson decay modes are plotted as a function of the Higgs boson mass including the process that we study in this paper. We have used the running masses for all the fermions to account for the QCD radiative corrections as well as the off-shell decay formulae in the $WW$, $ZZ$ and $t\bar{t}$ modes. It is clear from the figure that the $\gamma U$ mode is comparable to the $\gamma\gamma$ mode and larger than the $\gamma Z$ mode for all the Higgs boson mass range up to 130 GeV.

In summary, we have studied the Higgs boson decay mode into a single photon plus a vector unparticle. This mode can be used to probe the hidden unparticle sector since the emitted energy of the single photon is encoded with the information of missing energy of the recoil unparticle. This mode is particularly useful for an intermediate mass Higgs boson since it may have comparable branching ratio with the two-photon discovery mode of the Higgs boson decay. Finally, it should be of interest to extend the present study to the case of the tensor unparticle operator as well as the $HZU$ vertex.
FIG. 3: Branching ratios of various decay modes of the Higgs boson versus the mass of the Higgs boson for $\lambda_t = 1$, $\Lambda_U = 1$ TeV and $d_U = 1.1$.

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