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Enhancement of $h \to \gamma\gamma$ via spin-0 and spin-1/2 charged unparticle loops

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ABSTRACT

We calculate the spin-0 and spin-1/2 charged unparticle loop contributions to the Higgs diphoton decay within an unparticle gauge model and show that they can significantly enhance or suppress SM predictions for the same. In the SM limits of scalar and fermion conformal dimensions, $d_{\mathcal{U}_s} \to 1$ and $d_{\mathcal{U}_f} \to 3/2$ respectively, our results exactly reproduce the contributions of the spin-0 and spin-1/2 particle cases. Furthermore the decoupling from the Higgs boson occurs only for the spin-0 case in the critical limit $d_{\mathcal{U}_s} \to 2$. Using the recent ATLAS data which reported an excess of diphoton decay rate of SM-like Higgs boson around 125 GeV, and taking into account the vacuum stability and perturbativity conditions, the parameters of the gauge unparticle model are constrained.

With the LHC now colliding hadrons with unprecedented beam energy, a new era of particle physics is being unearthed. Running only for about three years the LHC already met the main challenge it was designed for when both ATLAS and CMS Collaborations announced the discovery of a new particle of mass 125–126 GeV [1,2] having properties for now compatible with those of the long-waited and celebrated standard model (SM) Higgs boson. While confirmation is awaited exploiting current data for beyond standard model (BSM) physics is already in progress.

An important window in this regard is the Higgs diphoton decay channel which is considered one of the most important decay modes in SM precision studies as well as probing for new physics. While a recent update from CMS suggests a suppression of observed events relative to SM predictions in the Higgs decay to diphoton [3], the ATLAS experiment reported an excess of the same [4]. Confirmation of such suppression or excess with larger integrated luminosity would signal various new physics BSM effects contributing to the decay mode $h \to \gamma\gamma$, and strongly constraining the corresponding theoretical models.

Many theoretical frameworks have been developed that could potentially answer major questions still not fully accounted for by the SM and which in the first place motivate BSM studies, and which have thus far not been probed by previous colliders. A candidate model for new physics at the LHC that was proposed some time ago is that of gauged unparticles which couple to the SM through relevant interactions organized in an effective field theory. This model can enhance or diminish the diphoton rate via weak interactions giving rise to new interesting signals in the ATLAS and CMS detectors. More precisely the Higgs diphoton decay $h \to \gamma\gamma$ is a loop-induced process meaning that it could potentially be sensitive to the presence of new charged states that couple to the Higgs boson. As such the phenomenology of charged unparticles carrying SM gauge quantum numbers at the LHC provides a strong constraint for unparticle gauge parameters.

The effects of tree-level gauge-singlet spin-0 unparticles on Higgs decay to diphoton phenomenology have been considered in Ref. [5] where a sizible deviation from SM predictions was found. It is thus expected that charged loop effects would also produce noticeable impact. In this Letter we propose a BSM contribution to the diphoton Higgs decay width, without affecting the Higgs boson production through gluon fusion $gg \to h$ at the LHC, by means of calculating the loop contributions of the weakly-gauged spin-0 and spin-1/2 color-singlet unparticles that depend on the main parameters of the gauge unparticle model. We study the conditions under which these BSM loop contributions can explain the observed excess in $h \to \gamma\gamma$ at the LHC. To the best of our knowledge this work forms a first unparticle loop calculation in the literature. The investigation of spin-1 and spin-2 charged unparticles will be discussed in an other work.

We note that embedding the unparticles into the weak gauge group introduces couplings to the Z boson and yields a correction in $h \to Z\gamma$ decay width and affects electroweak precision tests. In the present work though we only focus on the effect of spin-0 and

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spin-1/2 charged unparticle new physics on the loop-induced process $h \to \gamma\gamma$ which leads to an enhancement or suppression of the Higgs diphoton width with a suitable choice of the gauged unparticle parameters. A detailed analysis of precision measurement constraints and the investigation of the correction to $h \to Z\gamma$ process and its correlations with $h \to \gamma\gamma$ decay rates are left for a future work.

Unparticles, in the original formulation proposed by Georgi [6], are described by local conformal fields "$\mathcal{U}$" with scale dimension $d_{\mathcal{U}}$, weakly coupled to the SM fields through higher dimensional operators in a low-energy effective field theory. For the spin-0 unparticle fields $\mathcal{U}_s$, the free propagator is [7]:

$$\Delta_{\mathcal{U}_s}(p,\mu_s) = \frac{A(d_{\mathcal{U}_s})}{2\sin(\pi d_{\mathcal{U}_s})}\frac{i}{\Sigma_0^s(p)}, \tag{1}$$

where $\Sigma_0^s(p) \equiv (\mu_s^2 - p^2 - i\epsilon)^{2-d_{\mathcal{U}_s}}$, p being the momentum, μ_s is the infrared cutoff incorporating conformal symmetry breaking (CSB) in the spin-0 unparticle sector, and $A(d_{\mathcal{U}_s})$ is expressed as:

$$A(d_{\mathcal{U}_s}) = \frac{16\pi^2\sqrt{\pi}}{(2\pi)^{2d_{\mathcal{U}_s}}}\frac{\Gamma(d_{\mathcal{U}_s}+\frac{1}{2})}{\Gamma(d_{\mathcal{U}_s}-1)\Gamma(2d_{\mathcal{U}_s})}, \tag{2}$$

with $1 < d_{\mathcal{U}_s} < 2$. Spin-1/2 unparticles, $\mathcal{U}_f$, with scale dimension $d_{\mathcal{U}_f}$ are defined in analogy to the spin-0 case, by taking the spin-1/2 unparticle propagator to be:

$$\Delta_{\mathcal{U}_f}(p,\mu_f) = \frac{A(d_{\mathcal{U}_f}-1/2)}{2\cos(\pi d_{\mathcal{U}_f})}\frac{i}{(\not p - \mu_f)\Sigma_0^f(p)}, \tag{3}$$

where $\not p = \gamma^\mu p_\mu$, $\Sigma_0^f(p) \equiv (\mu_f^2 - p^2 - i\epsilon)^{3/2-d_{\mathcal{U}_f}}$, $3/2 \leqslant d_{\mathcal{U}_f} < 5/2$ and μ_f is the infrared cutoff incorporating CSB in the spin-1/2 unparticle sector.

The generalization of the Georgi's unparticle model to a gauge theory has first been achieved in [7], by making Georgi's nonlocal unparticle action corresponding to the unparticle propagator gauge-invariant via the introduction of a Wilson line $W(x,y)$ between the two unparticle fields $\mathcal{U}_i(x)$ and $\mathcal{U}_i(y)$ as follows:

$$S_{\mathcal{U}_i} = \int d^4x\, d^4y\, \mathcal{U}_i^\dagger(x)\widetilde{\Delta}_{\mathcal{U}_i}^{-1}(x-y)W(x,y)\mathcal{U}_i(y), \tag{4}$$

with $\widetilde{\Delta}_{\mathcal{U}_i}^{-1}(x)$ the Fourier transform of $\Delta_{\mathcal{U}_i}^{-1}(p)$ and the Wilson line is $W(x,y) = \exp(-ig_{\mathcal{U}_i}T^a\int_x^y A_\mu^a(w)\,dw^\mu)$, with T^a the generators of the gauge group in the unparticle representation. Here the subscript i refers to the scalar and fermion cases.

The Feynman vertices for one and two gauge bosons coupled to two spin-0 unparticles respectively are [7]:

$$\begin{aligned} &g_{\mathcal{U}_s}\Gamma_s^{a\mu}(p,q) = ig_{\mathcal{U}_s}T^a(2p+q)^\mu\Sigma_1^s(p,q),\\ &ig_{\mathcal{U}_s}^2\Gamma_s^{ab\mu\nu}(p,q_1,q_2)\\ &\quad= ig_{\mathcal{U}_s}^2\big[\{T^a,T^b\}g^{\mu\nu}\Sigma_1^s(p,q_1+q_2)\\ &\qquad+T^aT^b(2p+q_2)^\nu(2p+2q_2+q_1)^\mu\Sigma_2^s(p,q_2,q_1)\\ &\qquad+T^bT^a(2p+q_1)^\mu(2p+2q_1+q_2)^\nu\Sigma_2^s(p,q_1,q_2)\big], \end{aligned} \tag{5}$$

while those for two spin-1/2 unparticles are [8]:

$$\begin{aligned} &ig_{\mathcal{U}_f}\Gamma_f^{a\mu}(p,q)\\ &\quad= i\frac{g_{\mathcal{U}_f}}{2}T^a\big[\gamma^\mu\big(\Sigma_0^f(p+q)+\Sigma_0^f(p+q)\big)\\ &\qquad+(2\not p+\not q-2\mu_f)(2p+q)^\mu\Sigma_1^f(p+q)\big],\\ &ig_{\mathcal{U}_f}^2\Gamma_f^{ab\mu\nu}(p,q_1,q_2)\\ &\quad= i\frac{g_{\mathcal{U}_f}^2}{2}\big[(2\not p+\not q_1+\not q_2-2\mu_f)\Gamma_{s\leftrightarrow f}^{ab\mu\nu}(p,q_1,q_2)\\ &\qquad+\gamma^\mu\Gamma_f^{ab\nu}(p,q_2,q_1)+\gamma^\nu\Gamma_f^{ab\mu}(p,q_1,q_2)\big], \end{aligned} \tag{6}$$

where the spin-0 and spin-1/2 form factors are:

$$\begin{aligned} &\Sigma_1^{s/f}(p,q) = \frac{\Sigma_0^{s/f}(p+q)-\Sigma_0^{s/f}(p)}{(p+q)^2-p^2},\\ &\Sigma_2^{s/f}(p,q_1,q_2) = \frac{\Sigma_1^{s/f}(p,q_1+q_2)-\Sigma_1^{s/f}(p,q_1)}{(p+q_1+q_2)^2-(p+q_1)^2}, \end{aligned} \tag{7}$$

and $\Gamma_f^{ab\mu}$ is given by:

$$\begin{aligned} \Gamma_f^{ab\mu}(p,q_1,q_2) &= T^aT^b\big(2p^\nu+q_1^\nu\big)\Sigma_1^f(p,q_2)\\ &\quad+T^bT^a\big(2p^\nu+2q_2^\nu+q_1^\nu\big)\Sigma_1^f(p+q_2,q_1). \end{aligned} \tag{8}$$

In Eqs. (5) and (6) $g_{\mathcal{U}_i}$ denotes the coupling between unparticle fields $\mathcal{U}_i$ and SM gauge bosons. In our case of $U_{\text{em}}(1)$ external gauge bosons it is sufficient to replace the generators $T^a \to 1$ in the above vertices.

In what follows, and in order to incorporate unparticle loops into the $h \to \gamma\gamma$ process without affecting $gg \to h$ production or $h \to gg$ decay channel, we consider that unparticle fields $\mathcal{U}_i$ are $SU(3)_c$ singlets. We also assume that unparticle loop contributions do not affect the other production rates of the Higgs boson.

The coupling of the Higgs field H to $\mathcal{U}_s$ and $\mathcal{U}_f$ unparticles is described by:

$$\mathcal{L} = \frac{\lambda_{H\mathcal{U}_s}}{\Lambda_{\mathcal{U}}^{2d_{\mathcal{U}_s}-2}}H^\dagger H\mathcal{U}_s^\dagger\mathcal{U}_s + \frac{\lambda_f}{\Lambda_{\mathcal{U}}^{2d_{\mathcal{U}_f}-2}}H^\dagger H\overline{\mathcal{U}}_f\mathcal{U}_f, \tag{9}$$

where $\Lambda_{\mathcal{U}}$ is the cut-off of the theory, which is inserted here for dimensional reasons because of the unusual mass dimension $d_{\mathcal{U}_i}$ of the unparticle fields. $\lambda_{H\mathcal{U}_i}$ are the unknown dimensionless couplings between the Higgs and the charged spin-0 and spin-1/2 unparticles. Upon EWSB where the Higgs field H develops a VEV, $\langle H\rangle = v/\sqrt{2}$ ($v = 246$ GeV), it contributes a universal mass shift of order $(M_{\mathcal{U}_i}^2)^{2-d_{\mathcal{U}_s}} = \lambda_{H\mathcal{U}_i}v^2/2\Lambda_{\mathcal{U}}^{2d_{\mathcal{U}_i}-2}$ to the IR cut-off scale $(\mu_i^2)^{2d_{\mathcal{U}_i}-2}$.

The trilinear couplings between the physical Higgs boson h and the spin-0 and spin-1/2 unparticle fields after the Higgs develops a VEV are given by the relevant terms:

$$\mathcal{L} \supset \frac{2(M_{\mathcal{U}_s}^2)^{2-d_{\mathcal{U}_s}}}{v}h\mathcal{U}_s^\dagger\mathcal{U}_s + \frac{(M_{\mathcal{U}_f}^2)^{2-d_{\mathcal{U}_f}}}{v}h\overline{\mathcal{U}}_f\mathcal{U}_f. \tag{10}$$

From the interaction Lagrangian, Eq. (10), we can obtain the following effective Lagrangian for the $h\gamma\gamma$ coupling:

$$\mathcal{L} = \sum_i \frac{\alpha_{\text{em}}d(r_{\mathcal{U}_i})Q_{\mathcal{U}_i}^2F_{\mathcal{U}_i}}{8\pi v}hF_{\mu\nu}F^{\mu\nu}, \tag{11}$$

where α_{em} is the fine-structure constant, $d(r_{\mathcal{U}_i})$ is the dimension of the unparticle representation $r_{\mathcal{U}_i}$ ($d(r_{\mathcal{U}_i}) = 1$ for color-singlet field), $Q_{\mathcal{U}_i}$ are the electric charges in units of $|e|$, $F_{\mu\nu}$ denotes the photon field strength and $F_{\mathcal{U}_i}$ are the form factors given by:

$$F_{\mathcal{U}_i} = \left(\frac{M_{\mathcal{U}_i}^2}{\mu_i^2}\right)^{2-d_{\mathcal{U}_i}}A_{\mathcal{U}_i}, \tag{12}$$

where $A_{\mathcal{U}_i}$ are unparticle loop functions which will be expressed presently. Finally, from the Lagrangian (11), which represents the