

# HIGGS TO DIPHOTON DECAY RATE AND THE ANTISYMMETRIC TENSOR UNPARTICLE MEDIATION

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We study the contribution of the antisymmetric tensor unparticle mediation to the diphoton production rate of the Higgs boson and try to explain the discrepancy between the measured value of the decay width of the discovered new resonance and that of the Standard Model Higgs boson. We observe that tree level contribution of the antisymmetric unparticle mediation is a possible candidate to explain the measured value of the diphoton decay rate.

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## 1. Introduction

The Standard Model (SM) electroweak symmetry breaking mechanism is based on the existence of a scalar particle, the Higgs boson  $H_0$ , which is crucial for productions of the masses of fundamental particles. Recently, the ATLAS and CMS collaborations [1, 2] discovered a resonance with the invariant mass 125–126 [GeV]. At this stage, one needs a conformation that the properties of the discovered resonance coincide with that of the SM Higgs boson. Current data shows that there is no significant deviation in the decay widths of the processes  $H_0 \rightarrow W W^*$  and  $H_0 \rightarrow Z Z^*$ , however, in the  $H_0 \rightarrow \gamma\gamma$  channel, there is a deviation from the SM result, namely, the diphoton production rate reaches 1.5 to 2 times that of the SM prediction [1–4]. Even if more data is needed to check whether the excess is based on the statistical fluctuations or not, a possible attempt to explain this excess from the theoretical side would be worthwhile and it has been studied in various models beyond the SM [5–38].

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In the present work, we consider the antisymmetric tensor unparticle mediation in order to explain the excess in the diphoton production and we restrict the free parameters existing in the scenario. Unparticles, being massless, having non-integral scaling dimension  $d_U$ , around the scale  $\Lambda_U \sim 1.0$  TeV, are proposed by [39, 40]. They are new degrees of freedom arising from a hypothetical scale invariant high energy ultraviolet sector with non-trivial infrared fixed point. In the low energy level, the effective interaction of the SM-unparticle sector reads (see, for example [41])

$$\mathcal{L}_{\text{eff}} = \frac{\eta}{\Lambda_U^{d_U+d_{\text{SM}}-n}} O_{\text{SM}} O_U, \tag{1}$$

where  $O_U$  ( $O_{\text{SM}}$ ) is the unparticle (the SM) operator,  $\Lambda_U$  is the energy scale,  $n$  is the space-time dimension and  $\eta$  is the effective coefficient [39, 40, 42]. The antisymmetric tensor unparticle propagator which drives one of the outgoing photon in diphoton production is obtained by the two point function arising from the scale invariance and it becomes

$$\int d^4x e^{ipx} \langle 0|T \left( O_U^{\mu\nu}(x) O_U^{\alpha\beta}(0) \right) |0\rangle = i \frac{A_{d_U}}{2 \sin(d_U \pi)} \Pi^{\mu\nu\alpha\beta} (-p^2 - i\epsilon)^{d_U-2}, \tag{2}$$

with

$$A_{d_U} = \frac{16 \pi^{5/2}}{(2 \pi)^2 d_U} \frac{\Gamma(d_U + \frac{1}{2})}{\Gamma(d_U - 1) \Gamma(2 d_U)}, \tag{3}$$

and the projection operator

$$\Pi_{\mu\nu\alpha\beta} = \frac{1}{2} (g_{\mu\alpha} g_{\nu\beta} - g_{\nu\alpha} g_{\mu\beta}). \tag{4}$$

Notice that the projection operator has the transverse and the longitudinal parts, namely

$$\Pi_{\mu\nu\alpha\beta}^T = \frac{1}{2} (P_{\mu\alpha}^T P_{\nu\beta}^T - P_{\nu\alpha}^T P_{\mu\beta}^T), \quad \Pi_{\mu\nu\alpha\beta}^L = \Pi_{\mu\nu\alpha\beta} - \Pi_{\mu\nu\alpha\beta}^T, \tag{5}$$

where  $P_{\mu\nu}^T = g_{\mu\nu} - p_\mu p_\nu / p^2$  (see [43] and references therein). At this stage we consider that the scale invariance is broken at some scale  $\mu_U$  and we take the antisymmetric tensor unparticle propagator as

$$\int d^4x e^{ipx} \langle 0|T \left( O_U^{\mu\nu}(x) O_U^{\alpha\beta}(0) \right) |0\rangle = i \frac{A_{d_U}}{2 \sin(d_U \pi)} \Pi^{\mu\nu\alpha\beta} \left( -(p^2 - \mu_U^2) - i\epsilon \right)^{d_U-2}, \tag{6}$$

by considering a simple model [44, 45] which provides a rough connection between the unparticle sector and the particle sector.

Now, we are ready to present the low energy effective Lagrangian which drives the new contribution to the diphoton production (see [43])

$$\mathcal{L}_{\text{eff}} = \frac{g' \lambda_B}{\Lambda_U^{d_U-2}} B_{\mu\nu} O_U^{\mu\nu} + \frac{g \lambda_W}{\Lambda_U^{d_U}} \left( H^\dagger \tau_a H \right) W_{\mu\nu}^a O_U^{\mu\nu}, \quad (7)$$

where  $H$  is the Higgs doublet,  $g$  and  $g'$  are weak couplings,  $\lambda_B$  and  $\lambda_W$  are unparticle-field tensor couplings,  $B_{\mu\nu}$  is the field strength tensor of the  $U(1)_Y$  gauge boson  $B_\mu = c_W A_\mu + s_W Z_\mu$  and  $W_{\mu\nu}^a$ ,  $a = 1, 2, 3$ , are the field strength tensors of the  $SU(2)_L$  gauge bosons with  $W_\mu^3 = s_W A_\mu - c_W Z_\mu$ , where  $A_\mu$  and  $Z_\mu$  are photon and  $Z$  boson fields respectively. The gauge invariant amplitude of the  $H_0 \rightarrow \gamma\gamma$  decay is

$$M = C_{\text{eff}} (k_1 \cdot k_2 g^{\mu\nu} - k_1^\nu k_2^\mu) \epsilon_{1\mu} \epsilon_{2\nu}, \quad (8)$$

with the effective coefficient  $C_{\text{eff}}$  and  $i^{\text{th}}$  photon polarization (momentum) four vector  $\epsilon_{i\alpha} (k_{i\beta})$ . In the framework of the SM, this decay appears at least at the one loop level [46, 47] (see Appendix for details). On the other hand, the antisymmetric tensor unparticle mediation results in the contribution to the decay in the tree level, with the transition  $H_0 \rightarrow \gamma O_U \rightarrow \gamma\gamma$  (see Fig.1).

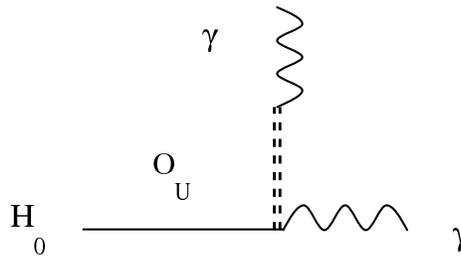


Fig. 1. Tree level diagram contributing to diphoton decay due to the antisymmetric tensor unparticle mediation. Solid (wavy, double-dashed) line represents the Higgs (electromagnetic, antisymmetric tensor unparticle) field.

Here,  $H_0 \rightarrow \gamma O_U$  transition is carried by the vertex

$$i \frac{e v \lambda_W}{\Lambda_U^{d_U}} k_{1\mu} \epsilon_{1\nu} O_U^{\mu\nu} H_0$$

which arises from the second term in Eq. (7). The  $O_U \rightarrow \gamma$  transition appears with the vertex

$$2 i e \left( \frac{\lambda_B}{\Lambda_U^{d_U-2}} - \frac{v^2 \lambda_W}{4 \Lambda_U^{d_U}} \right) k_{2\mu} \epsilon_{2\nu} O_U^{\mu\nu},$$

which is coming from the first term and the second term in Eq. (7). Here,  $v$  is the vacuum expectation value of the SM Higgs  $H_0$  and  $a = 3$  is taken in both vertices. Finally, the effective coefficient  $C_{\text{eff}}$  reads

$$C_{\text{eff}} = C_{\text{SM}} + C_{\text{U}}, \quad (9)$$

where

$$C_{\text{U}} = \frac{-i e^2 \lambda_W v \mu_{\text{U}}^{2(d_{\text{U}}-2)} A_{d_{\text{U}}}}{2 \sin(d_{\text{U}}\pi) \Lambda_{\text{U}}^{2d_{\text{U}}}} \left( \lambda_B \Lambda_{\text{U}}^2 - \frac{v^2 \lambda_W}{4} \right), \quad (10)$$

(see Appendix for  $C_{\text{SM}}$ ).

## 2. Discussion

In this section, we study the discrepancy between the measured value of the decay width of the discovered new resonance, interpreted as the Higgs boson, and that of the SM one, *i.e.*,  $\frac{\Gamma(H_0 \rightarrow \gamma\gamma)_{\text{Measured}}}{\Gamma(H_0 \rightarrow \gamma\gamma)_{\text{SM}}} \sim 1.5$ . We see that the intermediate antisymmetric tensor unparticle mediation (see Fig. 1) can explain the deviation of diphoton production rate from the SM prediction. In the present scenario, the couplings  $\lambda_B$ ,  $\lambda_W$ , the scale  $\Lambda_{\text{U}}$ , the scaling dimension  $d_{\text{U}}$  of the antisymmetric tensor unparticle operator, and the scale  $\mu_{\text{U}}$ , which drives the transition from the unparticle sector to the particle one, are the free parameters. We take  $\lambda_B$  and  $\lambda_W$  as universal and choose  $\lambda_B = \lambda_W = 1$ . For the antisymmetric tensor unparticle scale dimension  $d_{\text{U}}$ , one needs a restriction  $d_{\text{U}} > 2$  not to violate the unitarity (see [48]). However, since we consider that the scale invariance is broken at some scale  $\mu_{\text{U}}$ , we relax the restriction and we choose the range  $1 < d_{\text{U}} < 2$  for the scaling dimension  $d_{\text{U}}$ . Here, we switched on the scale invariance breaking by following the simple model [44, 45] which is based on the redefinition of the unparticle propagator (see Eq. (6)). Notice that the unparticle sector flows to particle sector when  $d_{\text{U}}$  converges to one and the range of  $d_{\text{U}}$  we consider above is appropriate to establish the connection between these two sectors. For the scale  $\mu_{\text{U}}$ , where the scale invariance is broken, we choose different values  $\mu_{\text{U}} = 1\text{--}20$  GeV and we take the scale  $\Lambda_{\text{U}}$  at the order of the magnitude of  $10^4$  GeV. In our numerical calculations, we also consider constraints coming from the Peskin–Takeuchi parameter  $S$ , which is used to restrict the New Physics contribution to the gauge boson self energy (see [43]). Here, the operator  $(H^\dagger \tau^a H) W_{\mu\nu}^a B^{\mu\nu}$  which is induced by the tensor unparticle exchange results in the  $S$  parameter

$$S = \frac{A_{d_U}}{\sin(d_U \pi)} \frac{g^2 g'^2 \lambda_B \lambda_W c_W v^2 \mu^2 (d_U - 2)}{s_W A_U^{2d_U - 2}}. \tag{11}$$

The parameter  $S$  from the electroweak precision data reads  $S = 0.00^{+0.11}_{-0.10}$  [49] which is due to New Physics only. Since the unparticle contribution is negative in our choice of parameters (we choose  $\lambda_B = \lambda_W = 1$ ), we take the lower bound  $S_{LB} = -0.10$  and we plot the contour diagram of the  $S$  parameter with  $1\sigma$  bound in  $\Lambda_U, \mu_U$  plane for different values of  $d_U$ , as shown in figure 2. In this figure, the pair of parameters  $\Lambda_U, \mu_U$  under the curves are excluded.

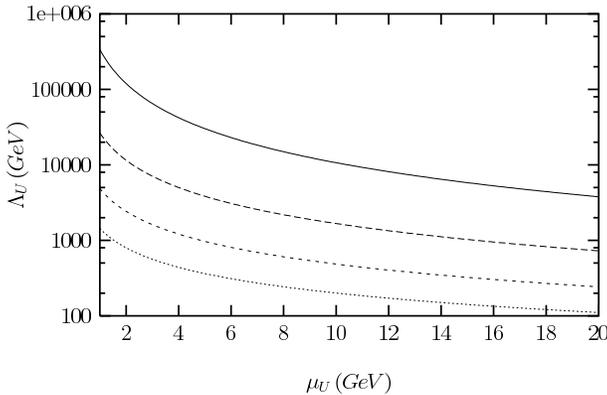


Fig. 2.  $\Lambda_U$  with respect to  $\mu_U$  within  $1\sigma$  bound. Here, the solid (long dashed, dashed, dotted) line represents  $\Lambda_U$  for  $d_U = 1.4$  (1.5, 1.6, 1.7).

Now, we start to study the discrepancy between the measured value of the decay width of the discovered new resonance and the SM Higgs boson by considering the restriction region coming from the  $S$  parameter. Figure 3 represents  $d_U$  dependence of the ratio  $r = \frac{\Gamma(H_0 \rightarrow \gamma\gamma)_{SM+U}}{\Gamma(H_0 \rightarrow \gamma\gamma)_{SM}}$  for different values of the scales  $\Lambda_U$  and  $\mu_U$ . Here<sup>1</sup>, the upper-intermediate-lower solid (dashed) line represents  $r$  for  $\mu_U = 1-10-20$  [GeV],  $\Lambda_U = 5000$  (10000) [GeV]. The ratio is strongly sensitive to the scale dimension  $d_U$  for the values far from 1.9 and the decrease in the scale  $d_U$  results in the increase in the unparticle contribution which makes it possible to overcome the discrepancy between the measured value and the SM result. We observe that the measured value is reached if the scaling dimension is in the range  $1.48 < d_U < 1.68$  for the given numerical values of  $\Lambda_U$  and  $\mu_U$ . In the case of  $\Lambda_U = 10000$  (5000) [GeV]

<sup>1</sup> The solid straight line represents the ratio  $\frac{\Gamma(H_0 \rightarrow \gamma\gamma)_{Measured}}{\Gamma(H_0 \rightarrow \gamma\gamma)_{SM}} \sim 1.5$  in each figure.

and  $\mu_U = 1$  [GeV], the measured decay rate is obtained for  $d_U \sim 1.63$  (1.68). For  $\mu_U = 20$  [GeV], the measured value is reached for  $d_U \sim (1, 49) 1.54$ .

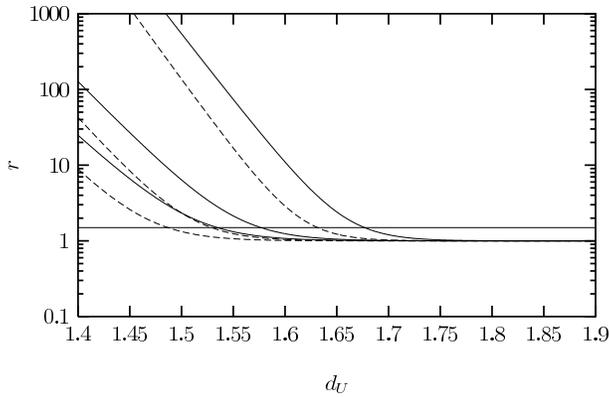


Fig. 3.  $r$  with respect to  $d_U$ . Here, the upper-intermediate-lower solid (dashed) line represents  $r$  for  $\mu_U = 1-10-20$  [GeV],  $\Lambda_U = 5000$  (10000) [GeV].

Figure 4 is devoted to  $\mu_U$  dependence of the ratio  $r$  for  $\Lambda_U = 10000$  [GeV] and different values  $d_U$ . Here, the solid (long dashed, dashed, dotted) line represents  $r$  for  $d_U = 1.4$  (1.5, 1.6, 1.7). The ratio is sensitive to the scale  $\mu_U$  and increases with its decreasing value. One can reach the measured decay rate for  $2.3$  [GeV]  $< \mu_U < 16$  [GeV] if  $d_U$  is in the range of  $d_U \sim 1.50-1.60$ .

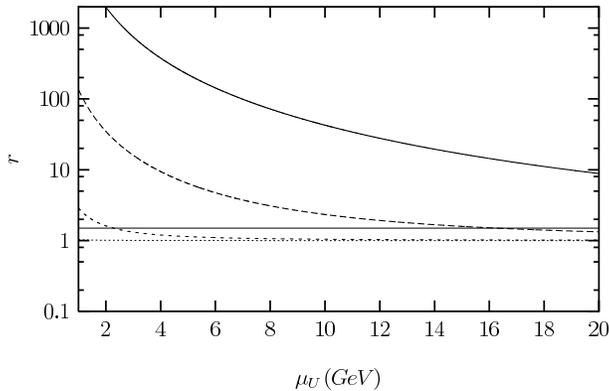


Fig. 4.  $r$  with respect to  $\mu_U$  for  $\Lambda_U = 10000$  [GeV]. Here, the solid (long dashed, dashed, dotted) line represents  $r$  for  $d_U = 1.4$  (1.5, 1.6, 1.7).

In Fig. 5, we present  $\Lambda_U$  dependence of the ratio  $r$  for different values of  $d_U$  and  $\mu_U$ . Here, the solid (long dashed, dashed, dotted) line represents  $r$  for  $d_U = 1.5$ ;  $\mu_U = 1.0$  [GeV] ( $d_U = 1.5$ ;  $\mu_U = 10$  [GeV],  $d_U = 1.6$ ;  $\mu_U = 1.0$

[GeV],  $d_U = 1.6$ ;  $\mu_U = 10$  [GeV]). The measured decay rate is reached for  $d_U = 1.6$ ;  $\mu_U = 1.0$  [GeV] if the energy scale reads  $\Lambda_U \sim 17000$  [GeV].

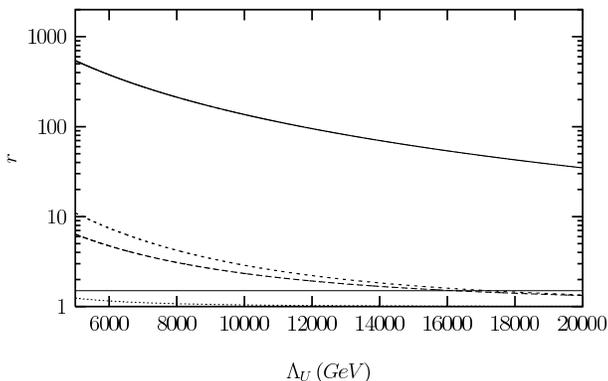


Fig. 5.  $r$  with respect to  $\Lambda_U$ . Here, the solid (long dashed, dashed, dotted) line represents  $r$  for  $d_U = 1.5$ ;  $\mu_U = 1.0$  [GeV] ( $d_U = 1.5$ ;  $\mu_U = 10$  [GeV],  $d_U = 1.6$ ;  $\mu_U = 1.0$  [GeV],  $d_U = 1.6$ ;  $\mu_U = 10$  [GeV]).

As a summary, we show that the intermediate antisymmetric tensor unparticle mediation is a possible candidate to overcome the deviation of diphoton production rate from the SM prediction. We study the ratio  $r = \frac{\Gamma(H_0 \rightarrow \gamma\gamma)_{SM+U}}{\Gamma(H_0 \rightarrow \gamma\gamma)_{SM}}$  and see that  $r \sim 1.5$  is reached if the scaling dimension is almost in the range of  $1.48 < d_U < 1.68$  for the given numerical values of  $5000$  [GeV]  $< \Lambda_U < 17000$  [GeV] and  $1.0$  [GeV]  $< \mu_U < 20$  [GeV]. This result makes it possible to explain the discrepancy between the measured value of the decay width of the discovered new resonance and that of the SM Higgs boson. In addition, it also gives an opportunity to understand the role and the type of the unparticle scenario and to determine the existing free parameters.

### Appendix

In the framework of the SM, the  $H_0 \rightarrow \gamma\gamma$  decay appears at least in the loop level with the internal  $W$  boson and fermions, where the top quark gives the main contribution. The gauge invariant amplitude reads

$$M = C_{SM} \left( k_1 \cdot k_2 g^{\mu\nu} - k_1^\nu k_2^\mu \right) \epsilon_{1\mu} \epsilon_{2\nu}, \tag{12}$$

where  $C_{SM} = \frac{\alpha_{EM} g}{4\pi m_W} F(x_W, x_f)$  and

$$F(x_W, x_f) = F_1(x_W) + \sum_f N_C Q_f^2 F_2(x_f), \tag{13}$$

with

$$\begin{aligned} F_1(x) &= 2 + 3x + 3x(2-x)g(x), \\ F_2(x) &= -2(1 + (1-x)g(x)). \end{aligned} \quad (14)$$

Here,

$$g(x) = \begin{cases} \arcsin^2(x^{-1/2}), & x \geq 1; \\ \frac{-1}{4} \left( \ln \frac{1+\sqrt{1-x}}{1-\sqrt{1-x}} - i\pi \right)^2, & x < 1, \end{cases} \quad (15)$$

and  $Q_f$  is the charge of the fermion  $f$ ,  $N_C = 1(3)$  for lepton (quark),  $x_i = \frac{4m_i^2}{m_{H_0}^2}$ ,  $i = W, f$ . Finally, the decay width  $\Gamma(H_0 \rightarrow \gamma\gamma)$  is obtained as

$$\Gamma(H_0 \rightarrow \gamma\gamma) = \frac{m_{H_0}^3 |C_{SM}|^2}{64\pi}. \quad (16)$$

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