Unparticle Physics on Cosmic Ray Photon and $e^{\pm}$

Shao-Xia Chen
School of Space Science and Physics,
Shandong University at Weihai,
Weihai, Shandong 264209, China

Rong Hu
School of Mechanical Engineering,
Beijing Technology and Business University,
Beijing 100048, China

Abstract

We study the effects of unparticle physics on the cosmic ray photon and $e^{\pm}$, including on the pair production (PP) and elastic scattering (ES) of cosmic ray photon off various background radiations, and on the inverse Compton scattering of cosmic ray $e^{\pm}$ with cosmic radiations. We compute the spin-averaged amplitudes squared of three processes and find that the advent of unparticle will never significantly change the interactions of cosmic ray photon and $e^{\pm}$ with various background radiations, although the available papers show that ES which occurs in the tree-level through unparticle exchanges will easily surpass PP in the approximate parameter regions.

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1 Introduction

In convention, it is convinced that the dominant energy loss is PP instead of ES in the Standard Model (SM) for the cosmic ray photon with energy above the PP threshold $E_{\text{th}}$:

$$E_{\text{th}} = \frac{m_e^2}{\epsilon} \simeq 2.6 \times 10^{11}\text{eV} \times \left(\frac{\epsilon}{\text{eV}}\right)^{-1},$$

where $\epsilon$ is the energy of a background photon. However recent research on diphoton interaction reveals that the cross section of unparticle exchange can easily surpass the SM one at high enough energy because unparticle exchanges are also at the tree-level through all $s$-, $t$-, and $u$-channels. It is natural to explore the consequence of unparticle physics on the cosmic ray photon, especially on whether the appearance of unparticle will lead to its dominant energy loss process to change from PP to ES, which will cause nontrivial observational signals in the spectrum of cosmic ray photon.

In the meanwhile, very recently the Pamela collaboration announced their first measurements on the cosmic ray (CR) positron fraction \cite{5} in the energy range $1.5 - 100\text{GeV}$. The positron fraction of Pamela data shows a prominent excess to the background estimation \cite{6} \cite{7} of the conventional CR propagation model in the region $\sim 10 - 100\text{GeV}$. This result is consistent with previous measurements by, e.g., HEAT \cite{8} and AMS \cite{9}. On the other hand, the electron spectrum up to several TeV measured...
by ATIC collaboration also displays an obvious excess in the region around $300 \sim 800\text{GeV}$ \cite{10}, which confirms the measurements of the electron spectrum by PPB-BETS \cite{11}, H.E.S.S. \cite{12,13}, and most recently by Fermi \cite{14}. The mismatch between theory and observations stimulates a lot of interest on the cosmic ray $e^\pm$, and we will reexamine the propagation of cosmic ray $e^\pm$ in the framework of unparticle physics. On particular, we address the dominant loss process for cosmic ray $e^\pm$, inverse Compton scattering, to study the impact of unparticle stuff on $e^\pm$ and further on the observational excess.

The paper is organized as follows. In the next section, we overview the basic property of unparticle physics, including the odd propagator and phase space of unparticle stuff with different Lorentz structures. In Sec.3, we derive the scattering amplitudes for the involved processes, that is, the PP and ES for the photon and the Compton scattering for $e^\pm$. In Sec.4, we apply the results in the previous section to the cosmic ray physics and analyze the specific cases to draw definite results to the propagation of cosmic ray photon and $e^\pm$. In the final section, we present some comments on this manuscript.

## 2 Basic property of Unparticle stuff

Two years ago, Georgi \cite{15} proposed the existence of unparticle, which is a scale invariant sector with a non-trivial infrared fixed-point. He assumed that the very high energy theory contains both the SM fields and the fields of a theory with a nontrivial infrared fixed point, which we will call $BZ$ (for Banks-Zaks \cite{16}) fields. The two sectors interact through the exchange of particles with a large mass scale $M_U$. Below the scale $M_U$, there are nonrenormalizable couplings involving both SM fields and $BZ$ fields suppressed by powers of $M_U$. These have the generic form

\[
\frac{1}{M_U^{d_{BZ}} \theta(P_U)} O_{sm} O_{BZ} \quad (2)
\]

where $O_{sm}$ is an operator with mass dimension $d_{sm}$ built out of SM fields and $O_{BZ}$ is an operator with mass dimension $d_{BZ}$ built out of $BZ$ fields. The renormalizable couplings of the $BZ$ fields then cause dimensional transmutation as scale-invariance in the $BZ$ sector emerges at an energy scale $\Lambda_U$.

In the effective theory below the scale $\Lambda_U$ the $BZ$ operators match onto unparticle operators, and the interactions of (2) match onto interactions of the form

\[
\frac{C_U}{M_U^{d_{BZ} - d_U}} O_{sm} O_{ut} \quad ,
\]

where $d_U$ is the scale dimension of the unparticle operator $O_{ut}$ and the constant $C_U$ is a coefficient function.

It was also pointed out \cite{15} that an unparticle stuff with scale dimension $d_U$ looks like a non-integral number $d_U$ of invisible particles. In the same Letter \cite{15}, Georgi derived the peculiar phase space of unparticle from the scale invariance

\[
d\Phi_{ut}(P_U) = A_{d_U} \theta(P_U^2)(P_{ut}^2)^{\frac{d_U}{2} - 2} \quad , \quad A_{d_U} = \frac{16\pi^{5/2}}{(2\pi)^{2d_U}} \frac{\Gamma(d_U + 1/2)}{\Gamma(d_U - 1)\Gamma(2d_U)} .
\]

\[
(4)
\]
Then, he calculated the real emission of unparticle and argued that this kind of peculiar distribution of missing energy may be the signal of unparticle experimentally.

Subsequently, the odd propagators were worked out independently in \cite{17, 18} for scalar, vector and tensor unparticles, respectively,

\[
\Delta_F(P^2) = Z_{d\mu}(\frac{-P^2}{d\mu} - 2) \quad \text{and} \quad Z_{d\mu} := \frac{A_{d\mu}}{2 \sin(d\mu \pi)},
\]

\[
\Delta_F(P^2)_{\mu\nu} = Z_{d\mu}(\frac{-P^2}{d\mu} - 2\pi_{\mu\nu}(P)),
\]

\[
\Delta_F(P^2)_{\mu\nu, \rho\sigma} = Z_{d\mu}(\frac{-P^2}{d\mu} - 2T_{\mu\nu, \rho\sigma}(P)),
\]

where

\[
(-P^2)_{d\mu}^{-2} = \left\{ \begin{array}{ll}
|P^2|_{d\mu}^{-2} & \text{if } P^2 \text{ is negative and real}, \\
|P^2|_{d\mu}^{-2}e^{-i d\mu \pi} & \text{for positive } P^2 \text{ with an infinitesimal } i0^+,
\end{array} \right.
\]

\[
\pi_{\mu\nu}(P) = -g_{\mu\nu} + \frac{P_{\mu}P_{\nu}}{P^2},
\]

\[
T_{\mu\nu, \rho\sigma}(P) = \frac{1}{2} \left[ \pi_{\mu\nu}(P)\pi_{\rho\sigma}(P) + \pi_{\mu\sigma}(P)\pi_{\nu\rho}(P) - \frac{2}{3} \pi_{\mu\mu}(P)\pi_{\rho\rho}(P) \right].
\]

As a direct consequence, the unusual phase in the unparticle propagators would give rise to the interference between s-channel unparticle exchange and SM amplitudes.

In this paper, we focus on the virtual exchange of unparticle at tree-level in the interactions between the cosmic ray photon, $e^\pm$ and background radiations, to examine the significance of unparticle on cosmic ray photon and $e^\pm$.

### 3 Related phenomenology

In this section, we will derive the relevant quantities of the PP and ES for diphoton interaction, and of the Compton scattering for $e^\pm$. Similar processes have been examined in the previous papers \cite{2, 3, 4, 19, 20}, however, there are several significant distinctions in our manuscript

1. There is no prior to reason to presume scalar and tensor unparticles have the same scale dimension, $d_U$, therefore, we drop the subscript $U$ which indicates unparticle stuff and add subscript $s$ and $t$ to the scale dimension of scalar and tensor unparticles to indicate their Lorentz properties, respectively.

2. We focus on the high energy photon and $e^\pm$, which permits us reasonably adopt the mass of $e^\pm$ as $m = 0$.

3. We properly write the total amplitude of an interaction as $iM = iM_{SM} + iM_{U}$ and the spin-averaged amplitude squared is given by $|M|^2 = \bar{M}\bar{M}^*$, to explore the total possible interferences.

#### 3.1 Pair Production of diphoton

The diphoton PP carries on via t- and u-channels in the SM, and the amplitude is

\[
iM_{SM} = e^2\epsilon_{\mu}(k_1)\epsilon_{\nu}(k_2)\bar{u}(p_1)\left( \gamma^\mu \frac{i(p_1 - k_1 + m)}{(p_1 - k_1)^2 - m^2} \gamma^\nu + \gamma^\nu \frac{i(p_1 - k_2 + m)}{(p_1 - k_2)^2 - m^2} \gamma^\mu \right) v(p_2).
\]
The diphoton PP can occur via exchanges of scalar and tensor unparticles in s-channel, which gives rise to the interference between unparticle s-channel and SM t-, u-channel amplitudes. The scattering amplitudes through scalar and tensor unparticle exchanges are

\[ iM_{tt} = \frac{4i\lambda_0^2}{\Lambda_{tt}^{2d-1}} \bar{u}(p_1)\epsilon_\mu(k_1)Z_{d_1}(-s)^{d_1-2} (k_1 \cdot k_2 g^{\mu\nu} - k_1^\mu k_2^\nu)\epsilon_\nu(k_2)v(p_2), \]

\[ iM_{ut} = \frac{i\lambda_2^2}{4\Lambda_{ut}^{2d}} \bar{u}(p_1)[\gamma^\alpha(p_1 - p_2)^\beta + \gamma^\beta(p_1 - p_2)^\alpha]v(p_2)\epsilon_\mu(k_1)\epsilon_\nu(k_2)Z_{d_1}(-s)^{d_1-2} \times T_{\alpha\beta,\rho\sigma}(k_1 + k_2)[K^{\mu\nu,\rho\sigma}(k_1^\mu, k_2^\nu) + K^{\mu\nu,\rho\sigma}(k_1^\mu, k_2^\nu)], \]

where \( T_{\alpha\beta,\rho\sigma}(P) \) is defined in (6) and \( K^{\mu\nu,\rho\sigma}(p_1^\mu, p_2^\nu) \) for one photon \( \epsilon_\mu(p_1) \), the other photon \( \epsilon_\nu(p_2) \) and one tensor unparticle with Lorentz indices \( \rho\sigma \) is defined as

\[ K^{\mu\nu,\rho\sigma}(p_1^\mu, p_2^\nu) = -g^{\alpha\beta}p_1^\alpha p_2^\beta - p_1 \cdot p_2 g^{\mu\rho}g^{\nu\sigma} + p_1^\rho p_2^\sigma g^{\mu\nu} + p_2^\rho p_1^\sigma g^{\mu\nu}. \]

The spin-averaged amplitude squared is given by

\[ |\mathcal{M}|^2 = I + II + III + IV, \]

where \( I \) stands for the contribution from the SM, \( II \) is that from scalar unparticle exchange, \( III \) is that from tensor unparticle exchange, and \( IV \) is the interference between the SM and unparticle amplitudes, respectively

\[ I = 2e^4 \left( \frac{t}{u} + \frac{u}{t} \right) \]

\[ II = 4\lambda_0^4 Z_{d_1}^2 \left( \frac{s}{\Lambda_{tt}^2} \right)^{2d_1-1}, \]

\[ III = \frac{\lambda_2^4 Z_{d_1}^2}{2} \left( \frac{s}{\Lambda_{tt}^2} \right)^{2d_1} \frac{tu}{s^2} \left( \frac{t^2}{s^2} + \frac{u^2}{s^2} \right), \]

\[ IV = 2e^2 \lambda_2^4 Z_{d_1}^2 \cos(d_1 \pi) \left( \frac{s}{\Lambda_{tt}^2} \right)^{d_1} \left( \frac{t^2}{s^2} + \frac{u^2}{s^2} \right). \]

It is worth noticing that, due to the phase factor \( \exp(-id_1\pi) \) related to the s-channel from the unparticle sector, there exists interference term \( IV \) between the SM and unparticle amplitudes which is a clear signature of unparticle physics.

The similar process \( e^- + e^+ \rightarrow \gamma + \gamma \) in unparticle physics has been pursued in Ref. [19], and we can straightforwardly obtain the spin-averaged amplitude squared for \( e^- + e^+ \rightarrow \gamma + \gamma \) as

\[ |\mathcal{M}|^2 = I + II + III + IV, \]

\[ I = 2e^4 \left( \frac{u}{t} + \frac{t}{u} \right), \]

\[ II = \frac{\lambda_0^4 Z_{d_1}^2}{2} \left( \frac{s}{\Lambda_{tt}^2} \right)^{2d_1} \frac{tu}{s^2} \left( \frac{t^2}{s^2} + \frac{u^2}{s^2} \right), \]

\[ III = 4\lambda_2^4 Z_{d_1}^2 \left( \frac{s}{\Lambda_{tt}^2} \right)^{2d_1-1}, \]

\[ IV = -2e^2 Z_{d_1} \lambda_2^4 \left( \frac{s}{\Lambda_{tt}^2} \right)^{d_1} \left( \frac{t^2}{s^2} + \frac{u^2}{s^2} \right) \cos(d_1 \pi), \]

where \( I \) is from the SM, \( II \) is from the tensor unparticle exchange, and the interference between the SM and unparticle amplitudes is provided as \( IV \), which are all consistent with Ref. [19]. The term \( III \) is the contribution from the scalar unparticle exchange, which is absent in Ref. [19]. We investigate further the process in the center-of-momentum system of the two initial photons, and the Mandelstam variables can be written as \( |t| = s(1 - \cos \theta)/2 \) and \( |u| = s(1 + \cos \theta)/2 \), and \( \theta \) is the scattering angle.
Plotting the terms I, II, III, and IV versus \( \theta \) in Fig.1, we find out that contribution III from scalar unparticle exchange to the process \( e^- + e^+ \rightarrow \gamma + \gamma \) is consequential.

![Standard Model](image1.png) ![tensor unparticle](image2.png) ![scalar unparticle](image3.png) ![interference](image4.png)

Fig.1 The terms I, II, III and IV in \( |M|^2 \) of \( e^- + e^+ \rightarrow \gamma + \gamma \) versus \( \theta \) in the case \( d_t = d_s = 1.1, \lambda_0 = \lambda_2 = 1.0 \) and \( \Lambda_U = 1.0 \) TeV at \( \sqrt{s} = 0.5 \) TeV.

### 3.2 Elastic scattering of diphoton

The diphoton can only elastically scatters via the loop-level in the SM and thus is highly suppressed, however, it can take place via scalar and tensor unparticle exchanges in all \( s, t, \) and \( u \)-channels at the tree-level in the unparticle physics. The scattering amplitude through scalar unparticle exchange is [2]

\[
iM_s = -\frac{16i\lambda^2Z_d}{\Lambda^4_U}(M_s + M_t + M_u)^{\mu\nu\rho\sigma} \epsilon_\sigma^*(k_1)\epsilon_\rho^*(k_2)\epsilon_\mu(p_1)\epsilon_\nu(p_2),
\]

\[
M_s^{\mu\nu\rho\sigma} = \left( \frac{-s}{\Lambda^4_U} \right)^{d_s-2} (-k_1 \cdot k_2 \gamma^\sigma + k_1^\rho k_2^\sigma)(-p_1 \cdot p_2 \gamma_\mu + p_1^\mu p_2^\nu),
\]

\[
M_t^{\mu\nu\rho\sigma} = \left( \frac{-t}{\Lambda^4_U} \right)^{d_t-2} (k_2 \cdot p_2 \gamma^\sigma - k_2^\rho p_2^\sigma)(k_1 \cdot p_1 \gamma^\mu - k_1^\mu p_1^\nu),
\]

\[
M_u^{\mu\nu\rho\sigma} = \left( \frac{-u}{\Lambda^4_U} \right)^{d_u-2} (k_2 \cdot p_1 \gamma^\rho - k_2^\rho p_1^\rho)(k_1 \cdot p_2 \gamma^\sigma - k_1^\sigma p_2^\nu).
\]

The scattering amplitude through tensor unparticle exchange is

\[
iM_t = iM_{ts} + iM_{tt} + iM_{tu},
\]

(13)
where \( I \) stands for the contribution from the scalar unparticle exchange, \( II \) is that from the tensor unparticle exchange, and \( III \) is the interference between the amplitudes of scalar and tensor unparticle exchanges, respectively. The first two are in good agreement with Ref.\[2\]

\[
\begin{align*}
I &= \frac{16\lambda_2^4 Z_{2d_s}^2}{\Lambda_{4d_s}^4} \left\{ s^{2d_s} + |t|^{2d_s} + |u|^{2d_s} + \cos(d_s \pi) \left[ (s|t|)^{d_s} + (s|u|)^{d_s} \right] + (|t||u|)^{d_s} \right\}, \\
II &= \frac{\lambda_2^4 Z_{2d_s}^2}{2\Lambda_{4d_s}^4} \left\{ s^{2d_s-4}(t^4 + u^4) + |t|^{2d_s-4}(s^4 + u^4) + |u|^{2d_s-4}(s^4 + t^4) + 2 \cos(d_s \pi) s^{d_s-2} |t|^{d_s-2} u^4 + |u|^{d_s-2} t^4 \right\}, \\
III &= 4\lambda_2^4 Z_{2d_s} Z_{4d_t} \left( \frac{s}{\Lambda_{4d_t}^2} \right)^{d_t+d_s} \left\{ \left( \frac{|t|}{s} \right)^{d_s+2} \left( \frac{|u|}{s} \right)^{d_t-2} + \left( \frac{|u|}{s} \right)^{d_s+2} \left( \frac{|t|}{s} \right)^{d_t-2} + \cos(d_s \pi) \left[ \left( \frac{|t|}{s} \right)^{d_s-2} + \left( \frac{|u|}{s} \right)^{d_t-2} \right] \right\}.
\end{align*}
\]

In the Ref.\[2\], the interference \( III \) is not included, thus, we also write the Mandelstam variables as \( |t| = s(1 - \cos \theta)/2 \) and \( |u| = s(1 + \cos \theta)/2 \), and plot Fig.2 to compare the contributions \( I \), \( II \) and \( III \).

![Diagram](image)

Fig.2 The terms \( I \), \( II \) and \( III \) in \( |M|^2 \) of the diphoton ES versus \( \theta \) in the case \( d_t = d_s = 1.1 \), \( \lambda_0 = \lambda_2 = 1.0 \) and \( \Lambda_{4d_t} = 1.0 \text{TeV} \) at \( \sqrt{s} = 0.5 \text{TeV} \).
3.3 Compton scattering

In the SM, Compton scattering can proceed via s- and u-channels, and the scattering amplitude is
\[ iM_{\text{SM}} = -ie^2 \epsilon_\mu^*(k') \epsilon_\nu(k) \bar{u}(p') \left( \gamma^\mu \left[ k \gamma^\nu + 2 \gamma^\rho p^\rho \right] + \frac{-\gamma^\nu k' \gamma^\mu + 2 \gamma^\rho p'^\rho}{2 p \cdot k'} \right) u(p) . \]

The Compton scattering through the scalar and tensor unparticle exchanges are via t-channel, and the scattering amplitude is
\[ iM_{tt} = -\frac{4i\lambda_0^2}{\Lambda_{tt}^2} \bar{u}(p')u(p)Z_d((-t)^{d_s-2}((k' \cdot g)\gamma^\mu - k'^\mu k^\mu))\epsilon^*_\mu(k')\epsilon_\nu(k) , \]
\[ iM_{tt} = \frac{i\lambda_0^2}{4\Lambda_{tt}^2} \bar{u}(p')\left[ \gamma^\alpha(p + p')^\beta + \gamma^\beta(p + p')^\alpha \right]u(p)Z_d((-t)^{d_t-2}T_{\alpha\beta\rho\sigma}(p' - p) \right. \]
\[ \times \left. (K^{\mu\nu\rho\sigma}(k^\nu, k^\mu) + K^{\mu\nu\rho\sigma}(k^\nu, k^\mu))\epsilon^*_\mu(k')\epsilon_\nu(k) . \]

The spin-averaged amplitude squared has the form
\[ |M|^2 = \text{I} + \text{II} + \text{III} + \text{IV} , \]
\[ \text{I} = -2e^4 \left( \frac{u}{s} + \frac{s}{u} \right) , \]
\[ \text{II} = 4\lambda_0^4 Z_d^2 \left( \frac{|t|}{\Lambda_{tt}^2} \right)^{2d_t-1} , \]
\[ \text{III} = -\frac{\lambda_0^4 Z_d^2}{2} \left( \frac{|t|}{\Lambda_{tt}^2} \right)^{2d_s} \frac{us}{t^2} \left( \frac{u^2}{t^2} + \frac{s^2}{t^2} \right) , \]
\[ \text{IV} = 2e^2 \lambda_0^2 Z_d \left( \frac{|t|}{\Lambda_{tt}^2} \right)^{d_t} \left( \frac{u^2}{t^2} + \frac{s^2}{t^2} \right) , \]

where \( \text{I} \) is the SM contribution, \( \text{II} \) is the contribution from the scalar unparticle exchange, \( \text{III} \) is that from tensor unparticle exchange, and \( \text{IV} \) is the interference between the amplitudes of SM and unparticle stuff.

Ref.[20] derived the contribution from scalar unparticle exchange to the Compton scattering, and we complete the derivation by replenishing \( \text{III} \) and \( \text{IV} \). Similarly we write the Mandelstam variables as \( |t| = s(1 - \cos \theta)/2 \) and \( |u| = s(1 + \cos \theta)/2 \), then contrast the contributions \( \text{I}, \text{II}, \text{III}, \) and \( \text{IV} \) in the Fig.3, and it is clear that the terms \( \text{II} \) and \( \text{IV} \) are vital and innegligible.

![Fig.3](image)

The terms \( \text{I}, \text{II}, \text{III} \) and \( \text{IV} \) in \( |M|^2 \) of the Compton scattering versus \( \theta \) in the case \( d_t = d_s = 1.1, \lambda_0 = \lambda_2 = 1.0 \) and \( \Lambda_{tt} = 1.0\text{TeV} \) at \( \sqrt{s} = 200\text{GeV} \).
3.4 Brief Summary

In the SM, the ES cross section of photon-photon interaction is nearly negligible compared to the PP one for the reason that ES can only proceed at loop-level while PP can take place at tree-level. However, previous analysis indicate that ES can also proceed at tree-level in the presence of unparticle physics. In order to contrast the probabilities of ES and PP for interacting diphoton, we plot their $|M|^2$s in Fig.4. It is evident that in the framework of unparticle physics ES can easily exceed PP in some parameter regions, such as that in Fig.4.

Fig.4 The $|M|^2$s of ES and PP of interacting diphoton versus $\theta$ in the case $d_i = d_s = 1.1$, $\lambda_0 = \lambda_2 = 1.0$ and $\Lambda_U = 1.0$TeV at $\sqrt{s} = 0.5$TeV.

In addition, as shown in Fig.5, while $d_i = d_s = d$ increases, the $|M|^2$s of the ES, PP and Compton scattering all have a sharp decline. Moreover, the decrease of PP $|M|^2$ is much slower than Compton scattering one, which is also much slower than ES one, with the increase of scale dimension $d$.

Fig.5 The $|M|^2$s of ES and PP for interacting diphoton, and of the Compton scattering versus $\theta$ in the case $d_i = d_s = d$, $\lambda_0 = \lambda_2 = 1.0$ and $\Lambda_U = 1.0$TeV at $\sqrt{s} = 1.0$TeV. The left column displays those with $d = 1.1$ and the right one does those with $d = 1.9$; from top to bottom, every row deals with that of ES, PP, and Compton scattering, respectively.
4 Unparticle physics on cosmic ray photon and $e^\pm$

In this section, we specially investigate the previous processes in the cosmic ray physics, that is, the ES, PP and inverse Compton scattering in the energy scope of relevance to the cosmic ray photon and $e^\pm$ interacting with various background radiations. As is well known, ultra high energy cosmic rays are the highest energy events we have observed in our earth laboratory frame. However, it is worth clarifying that, because the typical energies of background radiations are tiny, about or below $\sim$eV, the invariant $\sqrt{s}$ in the interactions between cosmic rays, even for the highest energy cosmic ray event, and various background radiations are small compared to those related to the colliders. Due to the different $s$ in collider and cosmic ray physics, we will prudently deal with the previous processes in the cosmic ray physics instead of applying the previous results immediately.

Fig.6 The $|\mathcal{M}|^2$ s of ES and PP for interacting diphoton versus $\theta$ in the case $d_t = d_s = 1.1$, $\lambda_0 = \lambda_2 = 1.0$ and $\Lambda_{U} = 1.0$ TeV. The left column exhibits ES $|\mathcal{M}|^2$ s and the right one does PP ones; from top to bottom, every row is that at $\sqrt{s} = 1000$ GeV, $\sqrt{s} = 10$ GeV, $\sqrt{s} = 0.1$ GeV, and $\sqrt{s} = 10^{-3}$ GeV, respectively.
4.1 Cosmic ray photon

The cosmic ray photon spectrum can extend from $10^8$eV to the highest $10^{21}$eV and the typical energies $\epsilon$ of different background radiations vary from $10^{-8}$eV to $10^{-1}$eV. Thus, roughly speaking, the variable $\sqrt{s} = \sqrt{4E\epsilon}$ of the interaction between a cosmic ray photon and a background photon is in the range $(2.0\text{eV}, 20\text{GeV})$ where $E$ is energy of the cosmic ray photon. Allowing for the existence of threshold $E_{\text{th}}$ for PP, we plot Fig.6 to describe the variation of the $|\mathcal{M}|^2$ of ES and PP for interacting diphoton.

Fig.6 shows that the contributions of unparticle exchange to ES and PP decrease quickly with decrease of $\sqrt{s}$. As is discussed below Fig.4, it is obvious that in some regions of parameter space, that is, $\sqrt{s}$ is $\sim$TeV and $d_1$, $d_4$ are near above 1.0, ES is really dominant on PP. However, for cosmic ray photons interacting with various background radiations, the $s$s are much smaller than TeV scale, which makes the probability of ES much smaller than PP one as shown in Fig.6. In result, in the case of cosmic ray photon propagation, unparticle physics plays a minute role and the dominant energy loss process of cosmic ray photon with energy above PP threshold $E_{\text{th}}$ will never convert into ES.

4.2 Cosmic ray $e^{\pm}$

Similarly $\sqrt{s} \sim \sqrt{4Ee}$ of inverse Compton scattering between cosmic ray $e^{\pm}$ and various background radiations are also in the rough range $(2.0\text{eV}, 20\text{GeV})$ where $E$ is the energy of cosmic ray $e^{\pm}$. We plot Fig.7 to describe the variation of the $|\mathcal{M}|^2$ of inverse Compton scattering with variable $\sqrt{s}$.

![Fig.7](image-url)

Fig.7 The $|\mathcal{M}|^2$ of the inverse Compton scattering versus $\theta$ in the case $d_1 = d_4 = 1.1$, $\lambda_0 = \lambda_2 = 1.0$ and $\Lambda_U = 1.0\text{TeV}$ with different $\sqrt{s}$.

Similar to the case of cosmic ray photon, $s$ of the inverse Compton scattering of a cosmic ray $e^{\pm}$ is also small compared to those in the colliders, which results in the impact of unparticle physics on cosmic ray $e^{\pm}$ is almost negligible as Fig.7 indicates.

Now let us turn to the hot topic, observed cosmic ray $e^{\pm}$ excess about the energy 100GeV, where cosmic ray $e^{\pm}$ mainly interacts with optical background radiation of energy $\sim$eV. We can obtain
figures similar to that at the bottom right corner in Fig.7, so, the same conclusion can be drawn for cosmic ray $e^\pm$ excess: the influence of unparticle physics on cosmic ray $e^\pm$ excess can nearly be neglected.

In fact, as have been pointed out in papers [21, 22], the low energy experiments will never be able to observe unparticle physics. The coupling $\sim H^2 O_U$ between scalar unparticle operator and SM Higgs boson will cause the breaking of conformal symmetry of unparticle sector at some scale $\Lambda_U$, thus, the experimental probes of the conformal hidden sector must probe energies in the conformal window $\Lambda_U < \sqrt{s_{\text{exp}}} < \Lambda_U$. In general, $\Lambda_U$ has the scale $\gtrsim 10\text{GeV}$, and below this scale the unparticle sector becomes a traditional particle sector. Comparably, the typical energy $\sqrt{s} = (\sim)\sqrt{4E_\epsilon}$ of interaction between a cosmic ray photon ($e^\pm$) and a background photon is in the scope ($2.0\text{eV}$, $20\text{GeV}$). The incoming photon ($e^\pm$) couples unparticle operators if and only if it satisfies

$$\sqrt{4E_\epsilon} > \Lambda_U = \left[ \left( \frac{\Lambda_U}{M_U} \right)^{d_{uZ} - d_t} \right. \left. \frac{M_U^2 - d_t \nu^2}{v^2} \right]^{1/4},$$

(18)

where $v = \langle H \rangle = 246\text{GeV}$ is the vacuum expectation value (VEV) of Higgs boson [21]. Deviating from the kinematic conditions (18) for unparticle exchange, cosmic ray photon ($e^\pm$) decouples rapidly from unparticle sector, which makes unparticle physics inaccessible for most cosmic ray events. In the particular case of observed cosmic ray $e^\pm$ excess, $\sqrt{s} \sim \sqrt{4E_\epsilon} \sim 10^6\text{eV}$ is far below the characteristic scale $\Lambda_U \gtrsim 10\text{GeV}$, thus, unparticle physics should be irrelevant to the issue. The conclusions drawn here more precisely qualify the above negative results obtained from Fig.6 and Fig.7.

5 Results and Comments

We compute the amplitudes of PP and ES for diphoton interaction and the amplitude of inverse Compton scattering in the framework of unparticle physics, and we find that unparticle physics plays a negligible role in the cosmic ray photon and $e^\pm$ propagation.

Let us close with several comments.

• In some regions of parameter space of interacting diphoton, ES will dominate PP while in some other regions PP is dominant on ES, which though has a trivial influence on the cosmic ray physics but may play roles to different extents in other photon phenomena, such as the gamma-ray bursts and supernovae, etc.

• In the discussion, we firstly set the scalar and tensor unparticles have the different scale dimensions $d_s$ and $d_t$. In the following, when plotting the figures we adopted $d_s = d_t$ in order to simplify the case and have a general but rough results. In fact, there seemingly exists no reason to impose $d_t = d_s$ except simplicity. However, due to the crucial influence of $d_U$ on the $|M|^2$ s of the three processes, there will appear interesting but more complicated signals in the case $d_t \neq d_s$.

• The advent of unparticle physics results in new angular distributions in the $|M|^2$ s of three processes discussed above and will further give rise to the angular distributions in the cross
sections which are very different from those in the SM cross sections, which is a distinct signal in the related phenomena, such as $e^+e^-$ collider.

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