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STUDY FOR FERMION DARK MATTER PRODUCTION IN PHOTON-PHOTON COLLISION

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Abstract. Fermion dark matter (FDM) production is investigated via photon-photon collision and the cross section of the FDM production is calculated in detail. Our results are evaluated at different values of the dark matter scale Λ and the light FDM mass.

Keywords: FDM, photon, cross-section.

1. Introduction

The existence of dark matter (DM) is strongly supported by observational evidence at multiple scales through gravitational effects. The DM constitutes about 80% of the matter content of the Universe [1]. The Cosmic Microwave Background (CMB) by the PLANCK collaboration yields the following DM relic abundance [2]

$$\Omega_{DM}h^2 = 0.120 \pm 0.001 \text{ at 90\% C.L.} \quad (1.1)$$

No one knows the nature of dark matter. It is not part of the Standard Model and seems likely that the DM is a neutral and stable weakly interacting massive particle (WIMP) on cosmological time scales. Experiments at the Large Hadron Collider (LHC) and the electron-positron linear collider (LC) will give more information about the DM as a missing energy signature [3]. In 2006, Fayet *et al*. [4] studied the influence of light DM on the core collapse supernova cooling and found that the 1 - 30 MeV mass fermion DM can explain the SN1987A energy loss rate.

Fermion and scalar two-component DM are considered [5] in which the fermion DM is assigned to a singlet fermion and scalar DM is assigned to a single scalar, both stabilized by a single Z_4 symmetry.

The fermion DM production in lepton colliders via photon-dark photon-photon exchange [6] and DM pair production inside supernova [3] had been studied in detail. In this paper, we study the process $\gamma\gamma \to \bar{\chi}\chi$ via the exchange of fermion DM, the effective interaction Lagrangian of photon (γ) and fermion DM (χ) was given by [3]

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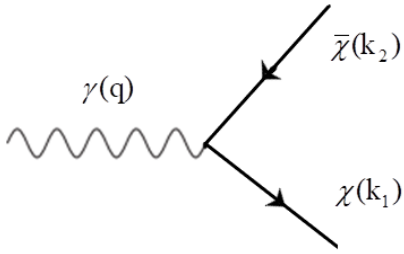
$$L_{\text{int}} = -\frac{i}{2}\bar{\chi}\sigma_{\mu\nu}(\mu_\chi + \gamma_5 \mathrm{d}_\chi)\chi F^{\mu\nu}, \tag{1.2}$$

where $F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$, $\sigma_{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu]$ is the spin tensor, $\mu_\chi = \frac{1}{\Lambda_\mu}, \mathrm{d}_\chi = \frac{1}{\Lambda_d}$ respectively are the magnetic dipole moment and the electric dipole moment of the FDM.

The corresponding Feynman rule has the form



$$-i(\mu_\chi + \gamma_5 d_\chi)(\hat{q}\gamma^\nu - q^\nu)$$

Figure 1. Feynman rule for the photon couplings with FDM

2. Content

The corresponding Feynman diagrams for the pair production of fermion DM in $\gamma\gamma$ collision via DM fermion χ exchange are shown in Figure 2.

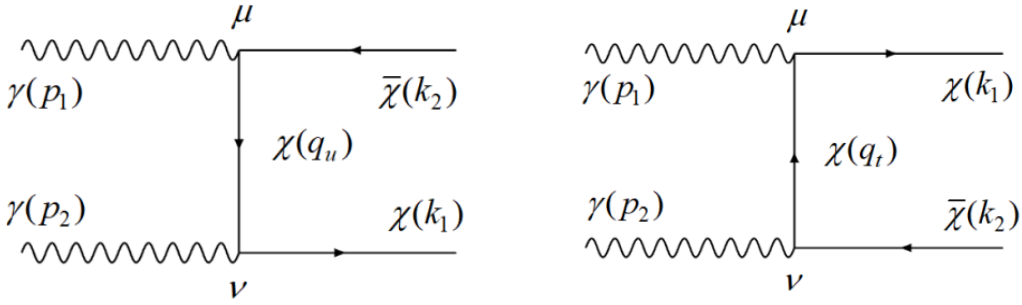


Figure 2. The Feynman diagrams for the process $\gamma\gamma \to \bar{\chi}\chi$ via DM fermion χ exchange

Applying Feynman's rule, the matrix element of the process $\gamma\gamma \to \bar{\chi}\chi$ is given by

$$M = \bar{u}(k_1, r)[-i(\mu_\chi + \gamma_5 d_\chi)(\hat{p}_2\gamma^\nu - p_2^\nu)]\varepsilon_\nu(p_2)\frac{-i(\hat{q}_u + m_\chi)}{q_u^2 - m_\chi^2}$$

$$\times\varepsilon_\mu(p_1)[-i(\mu_\chi + \gamma_5 d_\chi)(\hat{p}_1\gamma^\mu - p_1^\mu)]v(k_2, s) + \bar{u}(k_1, r)[-i(\mu_\chi + \gamma_5 d_\chi)(\hat{p}_1\gamma^\mu - p_1^\mu)]$$

$$\times\varepsilon_\mu(p_1)\frac{-i(\hat{q}_t+m_\chi)}{q_t^2-m_\chi^2}\varepsilon_\nu(p_2)[-i(\mu_\chi+\gamma_5 d_\chi)(\hat{p}_2\gamma^\nu-p_2^\nu)]v(k_2,s)\,. \tag{2.1}$$

In the center-of-mass frame, the differential cross section (DCS) for the $\gamma\gamma\to\bar{\chi}\chi$ process is given by

$$\frac{d\sigma}{d\cos\theta}=\frac{1}{32\pi s}\frac{\left|\vec{k}\right|}{\left|\vec{p}\right|}\left|M\right|^2, \tag{2.2}$$

where

$$\begin{aligned}
\left|M\right|^2=&\frac{64}{9(q_u^2-m_\chi^2)^2}\{(\mu_\chi^2-d_\chi^2)^2(p_1k_2)(p_2k_1)[(p_1q_u)(p_2q_u)-(p_1p_2)q_u^2]\\
&+m_\chi^2[(\mu_\chi^2+d_\chi^2)^2+4\mu_\chi^2d_\chi^2][2(p_1p_2)(k_1p_2)-(p_1k_1)p_2^2]\}\\
&+\frac{64}{(q_t^2-m_\chi^2)^2}\{2(\mu_\chi^2-d_\chi^2)^2(p_2k_2)(p_1k_1)[(p_1q_t)(p_2q_t)-(p_1p_2)q_t^2]\\
&+m_\chi^2[(\mu_\chi^2+d_\chi^2)^2+4\mu_\chi^2d_\chi^2](p_2k_2)(p_1p_2)(k_1p_1)\}\\
&+\frac{4}{(q_u^2-m_\chi^2)(q_t^2-m_\chi^2)}\{(\mu_\chi^2-d_\chi^2)^2\{-4\{4(p_1k_2)(p_2q_u)-2(p_1k_2)(2(p_1p_2)-k_2^2)]\\
&\times[(p_1p_2)(q_tk_1)-(p_1q_t)(p_2k_1)+(p_1k_1)(p_2q_t)]\\
&-2(\mathrm{p}_2p_1)(-2(p_1k_1)+k_1^2)[2(k_2p_1)(k_2p_2)-k_2^2(p_1p_2)]\}\\
&-16(q_up_2)(p_1k_1)[(k_2p_1)(k_1p_2)-(k_1k_2)(p_1p_2)+(k_2p_2)(k_1p_1)]\\
&-2[8(k_2p_2)(k_2p_1)-4k_2^2(p_2p_1)]k_1^2(p_2p_1)\\
&-2[8(k_1p_2)(p_1k_1)-4k_1^2(p_1p_2)][(k_2p_1)(k_2p_2)-k_2^2(p_1p_2)]\}\\
&+8m_\chi^2(\mu_\chi^2-d_\chi^2)^2(p_1p_2)[(p_1k_1)(p_2k_2)-(k_1k_2)(p_1p_2)+(k_2p_1)(k_1p_2)]\\
&-8m_\chi^2(\mu_\chi^2+d_\chi^2)^2(p_1p_2)[(k_2p_1)(k_1p_2)-(k_1k_2)(p_1p_2)+(k_2p_2)(k_1p_1)]\\
&-8m_\chi^2(\mu_\chi^2+d_\chi^2)(\mu_\chi^2-d_\chi^2)(p_1k_1)p_2^2(p_1k_2)\}\,.
\end{aligned} \tag{2.3}$$

Here we used $p_1^2=p_2^2=m_\gamma^2=0$, $p_1^\mu(\sqrt{s},\vec{p})$, $p_2^\mu(\sqrt{s},-\vec{p})$, $k_1^\mu(\sqrt{s},\vec{k})$, $k_2^\mu(\sqrt{s},-\vec{k})$ and θ is the angle between $\vec{p}$ and $\vec{k}$.

Next, we evaluated the dependence of the differential cross section (DCS) on the $\cos\theta$ and the center-of-mass energy $\sqrt{s}$ in the supernova SN1987A explosion within the formalism of q-deformed statistics. In the case of the q-undeformed statistics (q = 1), $\Lambda_\mu=\Lambda_d=\Lambda$, when the light FDM mass increases, the bound Λ decreases. Therefore, here we choose m_χ = 10 MeV corresponding to $\Lambda=3.6\times10^6$ TeV and m_χ = 30 MeV corresponding to $\Lambda=3.3\times10^6$ TeV [3]. These results are shown in Figure 3 and Figure 4.

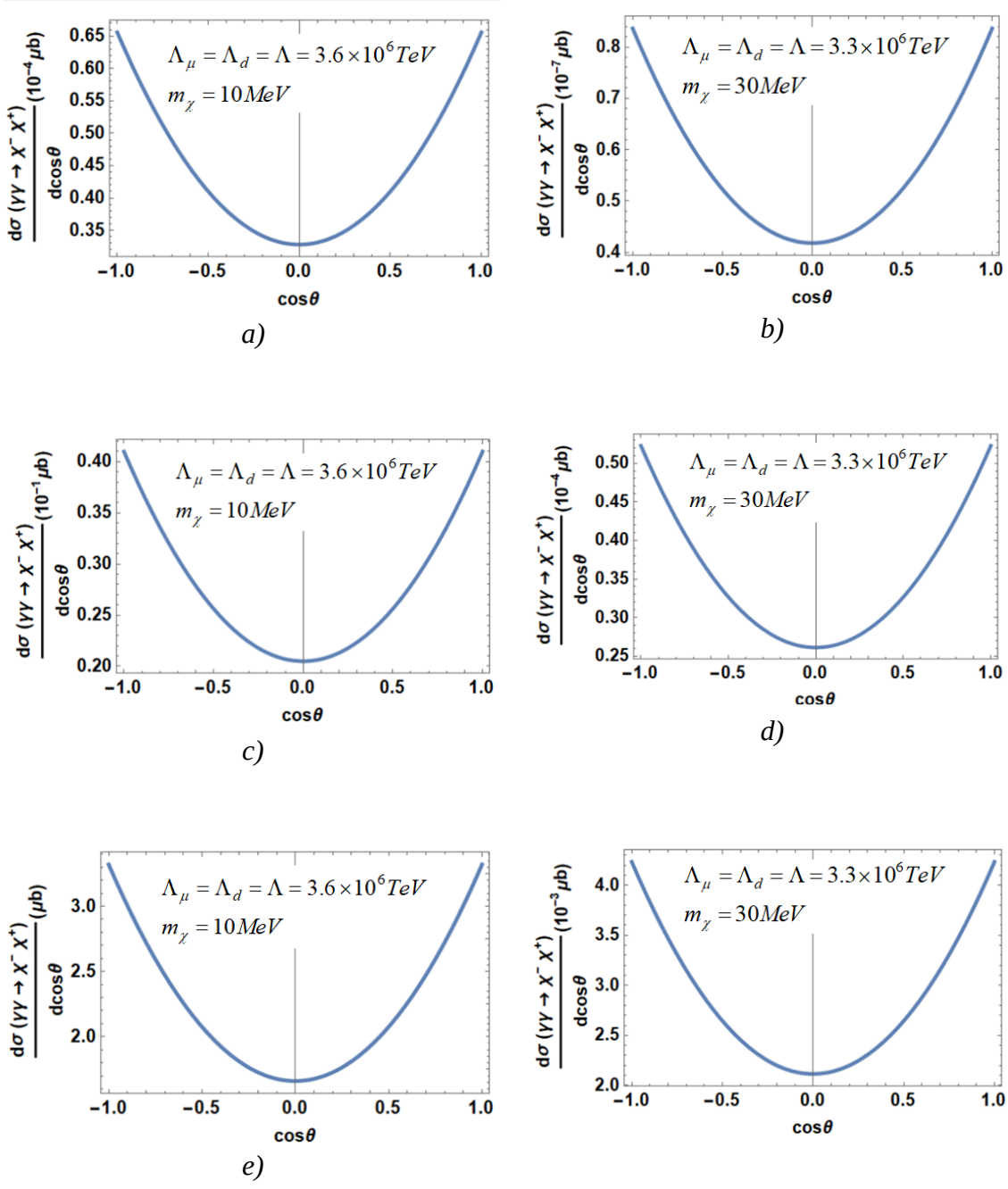
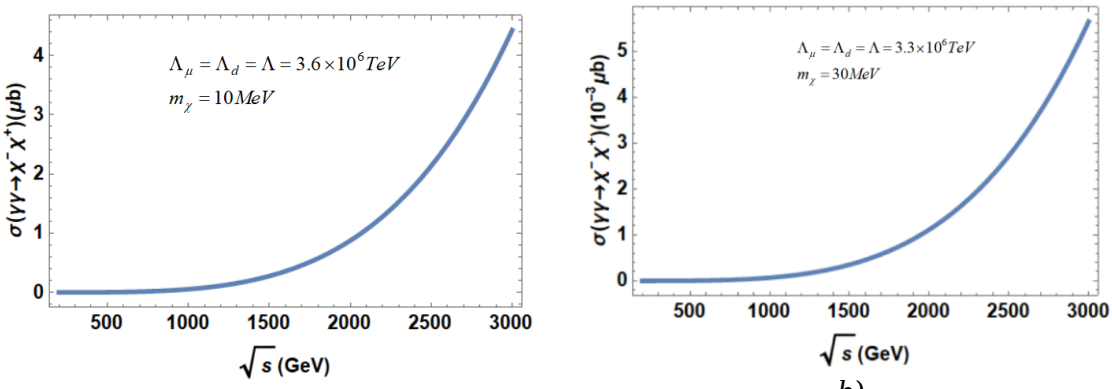


Figure 3. The DCS as a function of $\cos\theta$***: (a), (b) at*** $\sqrt{s} = 200$ **GeV; (c), (d) at** $\sqrt{s} = 1000$ **GeV; (e), (f) at** $\sqrt{s} = 3000$ **GeV**



a) *b)*

Figure 4. The total cross section as a function of $\sqrt{s}$ ***: (a) at*** m_χ ***= 10*** **MeV,**

(b) at m_χ ***= 30*** **MeV**

In Figure 3, we plotted the DCS as a function of $\cos\theta$ with $-1\le\cos\theta\le1$ at $\sqrt{s}=200\,\text{GeV}$ for figures a, b; $\sqrt{s}=1000\,\text{GeV}$ for figures c, d and $\sqrt{s}=3000$ GeV for figures e, f. The results show that in all cases, the DCS gets the maximum value at $\cos\theta=\pm1$. When $\Lambda_\mu=\Lambda_d=\Lambda=3.6\times10^6\text{TeV}$, $m_\chi=10\text{MeV}$, the DCS is $0.656\,(10^{-4}\mu\text{b})$, $0.41\,(10^{-1}\mu\text{b})$ and $3.321\,(\mu\text{b})$ at $\sqrt{s}=200\text{GeV}$, $\sqrt{s}=1000\text{GeV}$ and $\sqrt{s}=3000\text{GeV}$ respectively. When $\Lambda_\mu=\Lambda_d=\Lambda=3.3\times10^6\text{TeV}$, $m_\chi=30\text{MeV}$, the DCS is $0.836\,(10^{-7}\mu\text{b})$, $0.523\,(10^{-4}\mu\text{b})$ and $0.4233\,(10^{-3}\mu\text{b})$ at $\sqrt{s}=200\text{GeV}$, $\sqrt{s}=1000\text{GeV}$, $\sqrt{s}=3000\text{GeV}$ respectively. In all cases, the DCS has the smallest value at $\cos\theta=0$. In each case of $\sqrt{s}$, the maximum value of the DCS is about twice as large as the minimum value. Therefore, in the same or opposite direction for the initial photon beams, the missing energy signature is greatest. Besides, at the mass m_χ = 10 MeV, the DCS is larger than at the mass m_χ = 30 MeV (about 100 times). That means DM is maybe observable at low mass than at high mass. The rate of energy loss due to light FDM pair production is proportional to the total cross section [3]. In Figure 4, the cross section increases while $\sqrt{s}$ increases. The total cross section for the mass m_χ = 10 MeV increases faster and larger than that for the mass m_χ = 30 MeV. This indicates that the rate of energy loss for the mass m_χ = 10 MeV DM production is greater than that for the mass m_χ = 30 MeV DM production.

3. Conclusions

The maximum value of the DCS is about twice as large as the minimum value. In the same or opposite direction for the initial photon beams, the missing energy signature is greatest. In addition, the cross section increases when $\sqrt{s}$ increases and the rate of energy loss for the mass m_χ = 10 MeV DM production is greater than that for the mass

m_χ = 30 MeV DM production. That means DM is more observable at low mass than at high mass via the missing energy signature. The cross section is very small, however, we may be searching for light FDM from $\gamma\gamma$ collisions if interactive energy is large enough.

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