Studying the possibility of FSR suppression in DM decay in dependence of the mass of intermediate particle and vertex

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Abstract. In this proceedings we study possibility of final state radiation (FSR) in the process of dark matter (DM) decay/annihilation. Two possibilities are considered independently: one-cascade annihilation through intermediate particle ($a$), and parameterized interaction vertex. The mass of $a$ and vertex parameters are used to try to suppression FSR. Suppression is necessary to avoid limit from cosmic gamma-radiation preventing DM explanation of positron anomaly in CR. Finally, it may seem that a little suppression can be reached by fine-tuning the mass of $a$, and vertex parameters do not help to do it in the considered cases.

1. Introduction
Many attempts to build Dark Matter (DM) model are undertaken to explain with its help other astrophysical problems. The particle excesses in cosmic rays (CR) are a shining example. There are plenty of models explaining so-called positron anomaly [1] with DM. The recent results of DAMPE[2] experiment on $e^+ + e^-$ flux measurement seem also to show the particle excess, which is often explained with DM (see e.g. [3]).

However, the final-state radiation (FSR) in the process of DM annihilation/decay can lead to contradiction between the gamma-rays from DM and isotropic gamma-ray background (IGRB) [4]. In our previous works [5, 6, 7, 8, 9, 10, 11] we considered the ”dark disk” model to evade this contradiction. In this work we try to follow another approach, studying the possibility to suppress FSR output in the process of DM annihilation itself, and compare with DAMPE data. We apply two ideas how one can try to suppress photons. First one is consider one-cascade annihilation process through some intermediate particle with unknown mass $m_a$. The second one is to take different vertexes of DM interaction with ordinary particles with their parameters. In both cases
2. Cascade annihilation

We assume that Dark Matter particles $X$ can annihilate into $e^+e^-$ pairs through cascade $XX \Rightarrow aa \Rightarrow e^+e^-$. The main goal here is to see how $\gamma$ and $e^+e^-$ spectra change when we take intermediate particle $a$ being heavy ($e^+e^-$ are born ultrarelativistic in their CMS) and light ($e^+e^-$ are non relativistic in CMS).

In this part of work we neglect the influence of matrix element and therefore consider the electron and positron spectra to be determined by kinematics. The electron spectrum can be got from $a$ decay and is described by formula:

$$\frac{dN}{dE_e} = \frac{m_a}{E_ap_e^*} E^+$$

where $E_a = m_x$ is the energy of $a$, $p_e^*$ is the electron momentum in the centre-of-mass system, $E^+ = \frac{E_aE_e^* \pm p_a p_e^*}{m_a}$ are the maximal and minimal energies of electron and $E_e^*$ is the electron energy in the centre-of-mass system.

The FSR spectrum can be estimated [5] as the following:

$$f_{\gamma}(E) = \frac{\alpha}{4\pi} \int_E^{1\text{TeV}} \left( 1 + \left( 1 - \frac{E}{E_0} \right)^2 \right) \left( \ln \left[ \frac{2E_0}{m_e} \right]^2 \left( 1 - \frac{E}{E_0} \right) - 1 \right) \frac{dN}{dE_e}(E_0)dE_0$$

3. Results

In our assumptions, FSR spectrum is uniquely determined by the electron spectrum, and the latter remains unchanged while $m_a \gg m_e$. So, the effects are expected in a narrow area of $m_a \sim 2m_e$. We have chosen the mass of $X$ to be $m_X = 800$ GeV, and several values of $m_a$ from 1 MeV to 10 GeV.

It can be seen that maximal energy of FSR gamma-quanta is smaller in case of "light" intermediate particle. Since the main problem with IGRB lies in the area of high

Figure 1. The spectra are shown for the electrons (a) and FSR (b) for different masses of $a$-particle.
energies, this effect can possibly reduce the contradiction. However, this suppression comes with the cost of strong shift in $e^{-}$ spectrum. Therefore, it is not clear how this difference will affect the final fit.

We have tried to fit the DAMPE results using the method from our previous works and these spectra. The $e^{+}e^{-}$ background was taken from [12]. First, we have fitted the $e^{+}e^{-}$ data only, and then, using the found parameters, evaluated the $\chi^2$ taking into account the IGRB data.

|Table 1. $\chi^2$ values, |  |
|---|---|---|---|---|---|
 Mode | $\chi^2$ | $\chi^2_{\gamma\gamma}$ | $\chi^2_{N_{\text{deg}}}$ | $\chi^2_{N_{\gamma\gamma}^{\text{deg}}}$ |
|Heavy | 124 | 145 | 5.17 | 6.05 |
|Light | 173 | 175 | 7.22 | 7.29 |

### 4. Vertex effect

Suppression of photon yield in ($X \rightarrow e^{+}e^{-}\gamma$) decays of DM particle can be achieved by considering the physics of the DM interactions with ordinary matter. The cases of scalar, pseudo-scalar, vector and axial-vector dark matter particles $X$ are considered. The corresponding interaction lagrangians are given below

\[
\mathcal{L}_s = aX\bar{\psi}\psi, \quad \mathcal{L}_{ps} = bX\bar{\psi}\gamma^5\psi, \quad \mathcal{L}_v = a\bar{\psi}\gamma^\mu\psi X_\mu, \quad \mathcal{L}_{pv} = b\bar{\psi}\gamma^\mu\gamma^5\psi X_\mu, \tag{1}
\]

where $a$ and $b$ - some arbitrary factors, and $\psi$ - electron field. The Feynman diagrams of two-particle ($X \rightarrow e^{+}e^{-}$) and three-particle ($X \rightarrow e^{+}e^{-}\gamma$) decays are shown in Figure 2 a) and b), respectively.

For scalar $X$ particle one takes the sum $\mathcal{L}_s + \mathcal{L}_{ps}$. In this case squares of matrix elements for two-particle and three-particle decays of DM particle $X$ are equal to:

\[
|M|^2 = 4(a^2 + b^2)(l_1l_2) \tag{2}
\]

\[
|M|^2 = 16(a^2 + b^2)\left[\frac{(l_1k)(l_2k)}{(l_1 + l)^4} - 2\frac{(l_1l_2 + l_1k)(l_1l_2 + l_2k)}{(l_1 + k)^2(l_2 + k)^2}\right] + \frac{(l_1k)(l_2k)}{(l_2 + k)^4} \tag{3}
\]

respectively.

In case of vector $X$ particle $\mathcal{L}_v + \mathcal{L}_{pv}$ interaction lagrangian was investigated. Corresponding squares of matrix elements for two-particle and three-particle decays are as follows

\[
|M|^2 = \frac{4(a^2 + b^2)(m^2(l_1l_2) + 2(p_l_1)(p_l_2))}{m^2} \tag{4}
\]

Figure 2. a) Two-particle and b) three-particle decays of DM.
\[ |M|^2 = \frac{16(a^2 + b^2)}{m^2} \left[ \frac{(l_1 k)(m^2(l_2 k) + 2(l_2 p)(k p))}{(l_1 + k)^4} + \frac{(l_2 k)(m^2(l_1 k) + 2(l_1 p)(k p))}{(l_2 + k)^4} \right. \\
- \frac{2(m^2(l_1 l_2)^2 + (l_1 l_2)(m^2(l_1 k) + (l_2 k)) + (k p)((l_1 p) + (l_2 p)) + 2((l_1 p)(l_2 p))}{(l_1 + k)^2(l_2 + k)^2} \\
- \left. \frac{((l_1 p) - (l_2 p))(l_1 p)(l_2 k) - (l_1 k)(l_2 p))}{(l_1 + k)^2(l_2 + k)^2} \right] \] (5)

It can be seen that the ratio of the decay widths \( \frac{\Gamma(X \rightarrow e^+ e^- \gamma)}{\Gamma(X \rightarrow e^+ e^-)} \) does not depend on the parameters \( a \) and \( b \). Thus, for chosen scalar (vector) DM particle interaction there is no choice of the parameters \( a \) and \( b \) for suppressing the photon yield in the final state.

5. Conclusion

We obtained that it seems to be possible to achieve the FSR suppression due to light intermediate particle even in the considered simplistic case of DM annihilation. However, it turns out, that at taken initial parameters the case with the light intermediate particle, which provides FSR suppression, is worse than the case with the heavy intermediate particle due to deteriorating \( e^+ e^- \) data description. Therefore we intend to continue our work in two directions: the first one is to make the complex analysis with a wide range of initial parameters and the second one is to try using more accurate techniques for our calculations.

As to possible suppression due to Lagrangian, it is also should be analyzed on more deep level, and new model cases should be involved.

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