Upper limits on dark matter annihilation with the teraelectronvolt cosmic ray spectrum of electrons and positrons from DAMPE

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Abstract. We have used teraelectronvolt cosmic ray spectrum of electrons and positrons data from DArk Matter Particle Explorer (DAMPE) to estimate the upper limits on dark matter annihilation. We have created modeled spectrum of electrons and positrons by considering dark matter annihilation into electrons and positrons with different channels. After the production, electrons and positrons can lose their energy by interstellar medium and interstellar radiation field. We have considered loss processes such as inverse Compton scattering, synchrotron radiation and ionization. The upper limits on dark matter annihilation cross-section have been investigated by comparing the model spectrum and observational spectrum. The stringent constraints is from electron-positron channel.

1. Introduction

Dark matter particles may self-annihilate or decay into standard model particles, including electrons and positrons with energies as large as dark matter particle rest mass. The signature of dark matter annihilation can possibly be seen by electrons and positrons in the solar neighborhood.

DAMPE has detected electrons and positrons with unprecedentedly high energy resolution and low background with the energy range between 25 GeV to 4.6 TeV [1]. By using data of high energy cosmic ray electrons and positrons from DAMPE, we are able to investigate properties of dark matter particles such as mass and annihilation cross-section.

In this work, we have adopted the model of dark matter self-annihilation into electrons and positrons from PPPC4DMID [2], including electroweak corrections [3]. We have estimated electron-positron spectrum for all the leptonic channels, as well as for annihilation into top and bottom quarks. During their propagation, high energy electrons and positrons can lose energy quickly by different loss processes, such as inverse-Compton scattering (ICS), synchrotron radiation and ionization. The propagation of electrons and positrons can be determined by a diffusion-loss equation. Upper limits on dark matter annihilation can be estimated by comparison predicted electron-positron fluxes from our model with the observational data from DAMPE.
2. Method

After the production by dark matter annihilation, the high energy electrons and positrons travel through the Galactic interstellar medium (ISM) and the photons of the interstellar radiation field. They can efficiently lose their energy through different processes. Their propagation can be determined by a diffusion-loss equation as in [4]

\[
\frac{\partial}{\partial t} \frac{dn}{d\gamma}(x, \gamma) = \nabla \left[ K(x, \gamma) \nabla \frac{dn}{d\gamma}(x, \gamma) \right] + \frac{\partial}{\partial \gamma} \left[ b(x, \gamma) \frac{dn}{d\gamma}(x, \gamma) \right] + Q(x, \gamma).
\] (1)

The diffusion coefficient is defined as \( K(\gamma) = K_0 \gamma^\delta \). The values of \( K_0 \) and \( \delta \) corresponding to the models discussed by [5]. Since we consider the ISM is mostly neutral hydrogen, we only consider inverse-Compton scattering [6, 7], synchrotron radiation [8] and ionization [9] as energy loss rate \( b(x, \gamma) \), neglecting Coulomb collisions and bremsstrahlung. The particle physics of dark matter annihilation is explained by the source term \( Q(x, \gamma) \) which we estimated by the routines in PPPC4DMID [2] for dark matter annihilation into electron-positron, muon-antimuon, tau-antitau, bottom-antibottom, and top-antitop channels.

The solution of the diffusion-loss equation can be derived by assuming a steady-state distribution and a spherically-symmetric source, then the electron-positron spectrum can be express as

\[
\frac{dn}{d\gamma}(r, \gamma) = \frac{1}{b(\gamma)} \exp\left(-\frac{r^2}{2\Delta \lambda^2}\right)
\]

\[
\times \left\{ \int_\gamma^\infty \frac{dr_s}{r_s} \int_0^\infty dr_s r_s \exp\left(-\frac{r_s^2}{2\Delta \lambda^2}\right) \exp\left(\frac{rr_s}{\Delta \lambda^2}\right) - \exp\left(-\frac{rr_s}{\Delta \lambda^2}\right) \right\} Q(r, \gamma_s),
\] (2)

where the quantity

\[
\Delta \lambda^2 = \lambda^2(\gamma) - \lambda^2(\gamma_s)
\] (3)

is related to the characteristic diffusion length of the electrons and positrons, \( \gamma_s \) denotes their initial energy, and the variable \( \lambda \) is defined as

\[
\lambda^2(\gamma) = \int_\gamma^\infty \frac{2K(\gamma)}{b(\gamma)} d\gamma.
\] (4)

Considering the dark matter halo as a spherically-symmetric source, we used NFW profile [10] to describe the dark matter density

\[
\rho_{dm}(r) = \frac{\rho_s}{\frac{r}{r_s} \left(1 + \frac{r}{r_s}\right)^2},
\] (5)

where \( r_s \) and \( \rho_s \) are a characteristic density and radius of the Milky Way halo, respectively.

3. DAMPE Data

DAMPE was launched into a sun-synchronous orbit at an altitude of 500 km on December 17, 2015. It is a high energy particle detector optimized for studies of cosmic ray electrons and positrons. The data was recorded between December 27, 2015 and June 8, 2017. We used the data from the direct measurement of high energy cosmic ray electrons and positrons in the energy range 25 GeV to 4.6 TeV.
4. Results and Discussion

By using our model, we have calculated the fermion pair production spectrum for different channels, i.e. electron-positron, muon-antimuon, tau-antitau, bottom-antibottom, and top-antitop channels. We have estimated the upper limits on dark matter annihilation cross-section times the dark matter relative velocity, \( \langle \sigma v \rangle \), by comparing the fermion pair production spectrum from each channel to the data from DAMPE. An upper limit is estimated by imposing that the model spectrum do not exceed the observed values at any energy bin.

The results are shown in figure 1. The stringent constraints are from the electron-positron channel while bottom-antibottom and top-antitop channels provide the highest constraints. Our results are compatible with the result from the other experiment such as AMS-02 [11] which provide \( \langle \sigma v \rangle \) between \( 10^{-24} \) to \( 10^{-23} \) cm\(^3\)s\(^{-1}\). However the upper limits on dark matter annihilation cross-section times the dark matter relative velocity from DAMPE data are much higher than the thermal cross-section \( \langle \sigma v \rangle = 3 \times 10^{-26} \) cm\(^3\)s\(^{-1}\). This might require both particle physics processes and astrophysical boost factors to increase the annihilation rate by more than a factor of 10 with respect to the early universe (see e.g. [12]) or cosmic ray electrons and positrons may be dominated by pulsar-like astrophysical sources as has been suggested in [13, 14].

![Figure 1](image-url)

**Figure 1.** Upper limits on the dark matter annihilation cross-section for different channels which are estimated from the measurement of the cosmic-ray electrons and positron by DAMPE. Black, cyan, green, red and orange lines represent the upper limits from electron-positron, muon-antimuon, tau-antitau, bottom-antibottom, and top-antitop channels respectively. The dash line indicates the value of thermal cross-section \( \langle \sigma v \rangle = 3 \times 10^{-26} \) cm\(^3\)s\(^{-1}\).
5. Conclusions
We have estimated upper limits on the dark matter annihilation cross-section times the dark matter relative velocity $\langle \sigma v \rangle$ by comparing the predictions of an analytic model of electron-positron propagation with a data of high energy cosmic ray electrons and positrons in the energy range 25 GeV to 4.6 TeV obtained from DAMPE.

The propagation can be determined by a diffusion-loss equation in a function of a diffusion coefficient, energy loss rates and a source term. We have considered inverse-Compton scattering, synchrotron radiation and ionization as energy loss rates. The source term is estimated by the dark matter annihilation into electron-positron, muon-antimuon, tau-antitau, bottom-antibottom, and top-antitop channels with NFW profile.

The results indicate that the electron-positron channel provides the stringent constraints while bottom-antibottom and top-antitop channels provide the highest constraints. Since the upper limits are much higher than the thermal cross-section, boost factors or pulsar-like astrophysical sources might be required.

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