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Model-independent approach for dark matter phenomenology: Signatures in linear colliders and cosmic positron experiments

SHIGEKI MATSUMOTO* and NOBUCHIKA OKADA
Theory Group, KEK, Oho 1-1, Tsukuba, Ibaraki 305-0801, Japan
*E-mail: smatsu@post.kek.jp

Abstract. We have studied the phenomenology of dark matter at the ILC and cosmic positron experiments based on model-independent approach. We have found a strong correlation between dark matter signatures at the ILC and those in the indirect detection experiments of dark matter. Once the dark matter is discovered in the positron experiments such as the PAMELA, its nature will be investigated in detail at the ILC.

Keywords. Dark matter; collider signature; indirect detection using cosmic positrons.

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1. Introduction

Precise measurements of the cosmological parameters have achieved amazing progress in recent years. Especially, the observation of cosmic microwave background anisotropies by the WMAP has revealed the existence of a non-baryonic cold dark matter (DM) [1]. In order to detect the DM, many experiments have been performed and are now on-going. However, the DM has not been discovered yet and its nature still remains a mystery. On the other hand, the LHC experiment may give a clue for the DM, but it is still difficult to investigate its nature in detail.

On the theoretical side, many candidates of the DM have been proposed so far, for example, the lightest supersymmetric particle in the minimal supersymmetric standard model (MSSM) [2], and the lightest Kaluza–Klein particle in the universal extra-dimension model (UED) [3]. However, all these models have not been confirmed experimentally. Thus we do not know what kind of model provides the DM.

The ILC is expected to be an ultimate experiment to investigate the nature of the DM. Therefore, we consider a signature of the DM at the ILC based on model-independent approach. In particular, we focus on the DM pair production associated with a photon. Furthermore, we point out that there is a strong correlation between the signal in this process and that in the indirect detection of the DM using cosmic positrons. The result of the cosmic experiment will give important information for the DM search at the ILC, e.g. its mass and the typical size of the cross-section for the DM pair production.

In the analysis, we postulate that the DM is a weakly interacting massive particle (WIMP), and its cosmological abundance is determined by the thermal relic scenario. The possibility of coannihilations is ignored. Then, the abundance is given by $\Omega_{\rm DM} h^2 \simeq 2 \times 10^{-26}$ cm^3/s/$\langle \sigma v \rangle$, where $\langle \sigma v \rangle$ is the thermal averaged annihilation cross-section of the DM at the freeze-out temperature, $T \sim m/20$. Since the motion of the DM is non-relativistic at the temperature, the cross-section can be expanded by the relative velocity as $\sigma v = \sigma_0 + \sigma_1 v^2 + \sigma_2 v^4 + \cdots$, where σ_0 receives a contribution from s-wave annihilation. Hence, the approximation $\sigma v \simeq \sigma_0$ can be used unless the s-wave annihilation is highly suppressed [4]. The abundance is precisely determined by the WMAP as $\Omega_{\rm DM} h^2 \simeq 0.112$. Thus the cross-section is estimated as $\sigma_0 \simeq 2 \times 10^{-26}$ cm^3/s.

Following the paper [5], we introduce two parameters for the model-independent analysis. One is the mass of the DM, m, and the other is the annihilation fraction into e^+e^-, which is defined as $\kappa_e \equiv \sigma v(2{\rm DM} \to e^+e^-)/\sigma_0$. For instance, κ_e is 0.2–0.3 for the Kaluza–Klein DM in the UED.

2. DM signature at the ILC

Since the DM cannot be measured directly by the detector, we need at least one detectable particle associated with the DM pair production [6]. Here we consider the γ associated DM pair production at the ILC. In general, there is no model-independent relation between DM pair productions and those associated with γ. However, since emitted γ is either soft or collinear with the beam, we have such a relation. This method has been developed [5] in the context of the model-independent approach.

The differential cross-section for the energy of the signal γ is

$$\frac{{\rm d}\sigma}{{\rm d}E_\gamma} = \frac{(2s_{\rm DM}+1)^2}{8\sqrt{s}} \left(1 - \frac{4m^2}{(1-2E_\gamma/\sqrt{s})s}\right)^{1/2} \times \int {\rm d}c_\gamma H(2E_\gamma/\sqrt{s}, c_\gamma)\ \kappa_e \sigma_0\ , \tag{1}$$

where s is the center-of-mass energy, $s_{\rm DM}$ is the spin of the DM, and c_γ is the angle between the photon and the incoming beam. The function $H(x, \sin\theta)$ is called the dressing function, and defined as $H(x,c) = (\alpha/\pi)\{1 + (1-x)^2\}/x/(1-c^2)$. In figure 1a, some results are shown in cases $m = 150$ GeV with $\sqrt{s} = 500$ GeV and $m = 350$ GeV with $\sqrt{s} = 1$ TeV. We set $s_{\rm DM} = 1$ and $\kappa_e = 0.2$ in both results. In this process, the background comes from $e^+e^- \to \nu\bar{\nu}\gamma$. In figure 1b, the statistical significance for detecting the signal is depicted in the case of 500 fb^{-1} luminosity with $\sqrt{s} = 100$–1000 GeV. From the figure, it seems to be difficult to detect the signal when $\kappa_e < 0.5$. However, if the polarized electron beam is available, the background photon is drastically reduced. Then we will detect the signal even if $\kappa_e \sim 0.1$.

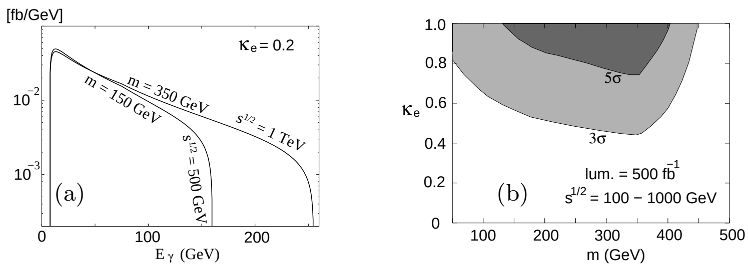

Figure 1. (**a**) Cross-section for the process $e^+e^- \to 2\mathrm{DM}+\gamma$ as a function of the photon energy E_γ. (**b**) The statistical significance for detecting the signal.

3. DM signature in cosmic positron experiments

In the present Universe, the DM makes up a halo associated with a galaxy. In the halo, the DM often annihilates and produces high energy positrons. In indirect detection measurement of DM using anti-particles, people try to observe such positrons to explore the nature of DM. In this measurement, main background comes from the cosmic ray (CR). As a result, the signal of DM in the measurement is expected to be observed as the anomalous excess of positrons in CR measurements.

Since the inverse process of the dark matter pair production at the ILC is nothing but the DM annihilation into positrons, we can expect a strong correlation between these signals. Using model-independent parameters, the flux of signal positrons is given by

$$\frac{\mathrm{d}\Phi^{(S)}_{e^+}}{\mathrm{d}E} = \mathrm{BF}\int \mathrm{d}E' G(E,E')\kappa_e\sigma_0. \tag{2}$$

All information for the modification of the positron spectrum due to the propagation in the galaxy is encoded in the function $G(E,E')$ [8]. As a result, it depends on several astrophysical parameters such as the strength of the magnetic field. Since the positron is absorbed and loses its energy through the propagation in the galaxy, the flux at the earth mostly originates within a few kpc. Hence, the function depends only on the parameters near the solar system, and its ambiguity is small. On the other hand, a relatively large ambiguity comes from the DM density around the solar system. Recent N-body simulations show that the DM is clustered at the local scale, and it leads to an enhancement of the flux. This effect is represented in the boost factor, BF, and its value is expected to be 2–5 [9].

In figure 2a, the cosmic positron fractions are shown in cases of $m = 150$ GeV and 350 GeV with BF = 5. The fraction is defined as the ratio of the positron flux (signal + background) to the combined electron and positron fluxes. We find the clear signature of the DM annihilation at the threshold ($E \sim m$) in this figure. In fact, in the PAMELA [11] (on-going experiment) and the AMS-02 [12] (future experiment), the signal can be discriminated from the background unless κ_e is tiny (see figure 2b).

In realistic cases, high energy positrons from the DM annihilation are also produced through cascade processes, e.g. 2DM$\to b\bar{b} \to e^+$s in addition to the direct

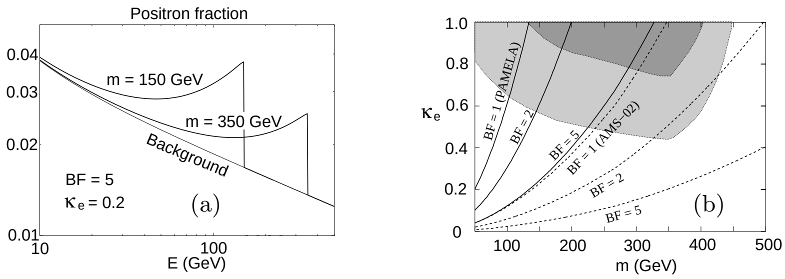

Figure 2. (**a**) Positron fraction as a function of the positron energy. (**b**) The statistical significance for detecting the signal in the PAMELA and the AMS-02 experiments in several cases of BF. In the region above a line, the signal can be discriminated from the background at the 5σ level.

production 2DM$\rightarrow e^+e^-$. One might think that these contributions smear the clear signature in figure 2. However, the spectrum of positrons from these cascade decays are very soft, and does not contribute to the signal at the threshold region unless $\kappa_e \ll 1$.

4. Summary

We have performed the model-independent analysis for the DM signatures at the ILC and cosmic positron experiments, and shown that there is a strong correlation between signals in these experiments. Cosmic experiments such as the PAMELA and the AMS-02 will give important information for the DM production at the ILC through the observation of the 'dip' at the threshold region.

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