Beam Dump Experiment at Future Electron-Positron Colliders

Shinya Kanemura\(^{(a)}\), Takeo Moroi\(^{(b)}\), Tomohiko Tanabe\(^{(c)}\)

\(^{(a)}\) Department of Physics, University of Toyama, Toyama 930-8555, Japan
\(^{(b)}\) Department of Physics, The University of Tokyo, Tokyo 113-0033, Japan
\(^{(c)}\) ICEPP, The University of Tokyo, Tokyo 113-0033, Japan

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We propose a new beam dump experiment at future colliders with electron (e\(^{-}\)) and positron (e\(^{+}\)) beams, BDec, which will provide a new possibility to search for hidden particles, like hidden photon. If a particle detector is installed behind the beam dump, it can detect the signal of in-flight decay of the hidden particles produced by the scatterings of e\(^{\pm}\) beams off materials for dumping. We show that, compared to past experiments, BDec (in particular BDec at e\(^{+}\)e\(^{-}\) linear collider) significantly enlarges the parameter region where the signal of the hidden particle can be discovered.

High energy colliders with electron (e\(^{-}\)) and positron (e\(^{+}\)) beams, such as the International Linear Collider (ILC) \(^{(1)}\), the Compact Linear Collider (CLIC) \(^{(2)}\), and Future Circular Collider with e\(^{+}\)e\(^{-}\) beams (FCC-ee) \(^{(3)}\), are widely appreciated as prominent candidates of future experiments. One of the reasons is that, with the discovery of Higgs boson at the LHC \(^{(4)}\), detailed studies of Higgs properties at e\(^{+}\)e\(^{-}\) colliders are now very important \(^{(5)}\). In addition, e\(^{+}\)e\(^{-}\) colliders have sensitivity to new particles at TeV scale or below if they have electroweak quantum numbers.

Although e\(^{+}\)e\(^{-}\) colliders have many advantages in studying physics beyond the standard model (BSM), they can hardly probe BSM particles whose interaction is very weak. We call such particles hidden particles, which appear in various BSM models. For example, there may exist a gauge symmetry other than those of the standard model (SM), as is often the case in string theory. If the breaking scale of such a hidden gauge symmetry is lower than the electroweak scale, the associated gauge boson can be regarded as a hidden particle \(^{(6)}\). In string theory, it has also been pointed out that there may exist axion-like particles (ALPs) \(^{(7)}\); they are also candidates of the hidden particle. Sterile neutrino is another example. These particles interact very weakly with SM particles, and are hardly accessed by studying e\(^{+}\)e\(^{-}\) collisions. If e\(^{+}\)e\(^{-}\) colliders will be built in the future, it is desirable to make it possible to study hidden particles as well.

In this letter, we discuss a possibility to detect hidden particles at the e\(^{+}\)e\(^{-}\) facilities. We propose a beam dump experiment at future e\(^{+}\)e\(^{-}\) colliders (BDec), in which the beam after the e\(^{+}\)e\(^{-}\) collision is used for the beam dump experiment. In particular, at the ILC and CLIC, the e\(^{\pm}\) beams will be dumped after each collision, which makes a large number of e\(^{\pm}\) available for the beam dump experiment.

Using the hidden photon, which is the gauge boson associated with a (spontaneously broken) hidden U(1) symmetry, as an example, we show that the BDec can cover a parameter region which has not been explored by past experiments.

Let us first summarize the basic setup of BDec. We simply assume the current design of the beam dump system of the ILC although one may consider other possibilities. The main beam dumps of the ILC will consist of 1.8 m-diameter cylindrical stainless-steel high-pressure (10 bar) water vessels \(^{(1)}\). The e\(^{\pm}\) beams after passing through the interaction point are injected into the dump, which absorbs the energy of the electromagnetic shower in 11 m of water. If there exists a hidden particle, like hidden photon, for example, it is produced by the e\(^{\pm}\)-H\(_{2}\)O scattering process. In this letter, to make our discussion concrete, we consider the case where the target is H\(_{2}\)O, although other materials may be used as a target. The number of the hidden photon produced in the dump is insensitive to the target material.

Our proposal is to install a particle detector behind the dump, with which we can observe signals of hidden particles produced in the dump. The schematic picture of the setup of BDec is shown in Fig. 1. The decay volume is a vacuum vessel with the length of L\(_{\text{dec}}\); the signal of the hidden particle is detected if the hidden particle decays into (visible) SM particles in the decay volume. A tracking detector is used to detect the hidden particle decaying into a pair of charged particles. Additional detectors such as calorimeters and muon detectors may be installed to enrich the physics case. As well as the hidden particles, charged particles are also produced in the dump; rejection of those particles is essential to suppress backgrounds. In particular, a significant amount of muons are produced, as we will discuss in the following. Thus, we expect to install shields and veto counters between the dump and the decay volume. Additional veto counters surrounding the detector serve to reject cosmic rays.

To see the sensitivity of BDec, we consider a model...
with hidden photon (denoted as $X$), which has a small kinetic mixing with ordinary photon. We adopt the following Lagrangian in our analysis

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} F^{(X)}_{\mu\nu} F^{(X)}_{\mu\nu} - \frac{\epsilon}{2} \mathcal{F}^{(em)}_{\mu\nu} F^{(X)}_{\mu\nu} + \frac{m_X^2}{2} X_{\mu} X_{\mu},$$

(1)

where $\mathcal{L}_{SM}$ is the SM Lagrangian, and $F^{(em)}_{\mu\nu}$ and $F^{(X)}_{\mu\nu}$ are field strength tensors of electromagnetic and hidden photons, respectively. In addition, $\epsilon$ is the mixing parameter, which is assumed to be much smaller than 1, while $m_X$ is the mass of the hidden photon.

Once the hidden photon is produced in the dump, it may go through the shield region because the hidden photon is very weakly interacting, and may decay into SM particles in the decay volume. Thus, the SM particles (like a pair of charged particles) originating from the decay volume are the signal of the hidden photon production.

The hidden photon production is dominated by the $t$-channel (ordinary) photon exchange process of $e^\pm N \rightarrow e^\pm X N'$, where $N$ is a nucleus in H$_2$O while $N'$ denotes the hadrons in the final state. Because of the masslessness of the photon, the cross section is enhanced for the configuration in which $t = -q^2$ takes its minimal possible value, where $q \equiv P_N - P_{X'}$ denotes the momentum of the virtual photon, with $P_N$ and $P_{X'}$ being the momenta of $N$ and $N'$, respectively. (The $t$ parameter should not be confused with the length in units of the radiation length, which will be denoted as $t$ in this letter.) Consequently, the hidden photon $X$ is likely to be emitted in (almost) the beam direction, which will be taken to be the $z$-axis. Because we are interested in the case where $E_e \gg m_X$, the decay products of $X$ are also likely to be emitted in (almost) the beam direction. Thus, the particle detector behind the dump can efficiently observe the decay products of $X$.

Using Weizsäcker-Williams approximation, the cross section for $e^\pm N \rightarrow e^\pm X N'$ is estimated as $d\sigma(e^\pm N \rightarrow e^\pm X N')/dx = \epsilon^2 d\sigma_0/dx$, where

$$\frac{d\sigma_0}{dx} = 4\alpha^3 \chi_X \left(1 - x + \frac{1}{3}x^2 \right) \left(\frac{1 - x}{x} m_X^2 + mx^2\right)^{-1}. \quad (2)$$

Here, $\alpha$ is the QED fine structure constant, $m_e$ is the electron mass, $x \equiv E_X/E_e$, $\beta_X \equiv \sqrt{1 - (m_X^2/E_e^2)}$, and $\chi$ is the effective flux of photons. In our numerical analysis, we use

$$\chi = \int_{t_{\min}}^{t_{\max}} \frac{d\tilde{t}}{t^2} G_2(\tilde{t}), \quad (3)$$

where $t_{\min} = (m_X^2/2E_e)^2$, and $t_{\max} = m_X^2$. For a nucleus with the charge $Z$, the electric form factor is given by [9]

$$G_2(\tilde{t}) = \frac{(a^{2}\tilde{t})^2}{1 + a^{2}\tilde{t}} \left(1 \div \frac{1}{1 + \tilde{t}/d}\right)^2 Z^2 + \frac{(a^{2}\tilde{t})^2}{1 + a^{2}\tilde{t}} \left(1 + \frac{\mu_{p}^{2} - 1}{4m_{X}^{2}}\right)^2 \left(1 + \frac{\mu_{p}^{2} - 1}{4m_{X}^{2}}\right)^2 \left(1 + \frac{\mu_{p}^{2} - 1}{4m_{X}^{2}}\right)^2 Z, \quad (4)$$

where $m_p$ is the proton mass, $a = 111Z^{-1/3}/m_e$, $d = 0.146$ GeV$^2$A$^{-2/3}$ (with $A$ being the atomic number), $a' = 773Z^{-2/3}/m_e$, $d' = 0.71$ GeV$^2$, and $\mu_p = 2.79$. (The first and the second terms of the right-hand side of Eq. (4) represent elastic and inelastic components, respectively.)

After the injection into the dump, the beam loses its energy. We use the following energy distribution of $e^-$ after passing through a medium of the radiation length $t$ [11]:

$$I_e(E_{\text{beam}}, E_e, t) = \frac{1}{E_{\text{beam}}} \left[\ln(E_{\text{beam}}/E_e)\right]^{bt-1}, \quad (5)$$

where $E_{\text{beam}}$ is the energy of the electron beam just before the injection into the dump, and $b = \frac{1}{4}$.

The total number of the signal is given by

$$N_{\text{sig}} = N_e \frac{N_{\text{AvO}} X_0}{A} e^2 B_{\text{sig}} \int_{m_X}^{E_{\text{beam}} - m_e} dE_X \int_{E_X + m_e}^{E_{\text{beam}}} dE_e \int_0^T \frac{dt}{E_e} \frac{d\sigma_0}{dx} \bigg|_{x = E_X/E_e} P_{\text{dec}}, \quad (6)$$

where $N_e$ is the total number of electron injected into the dump, $N_{\text{AvO}}$ is the Avogadro constant, $X_0 \approx 716.4A/[Z(Z + 1) \ln(287/\sqrt{Z})]$ g/cm$^2$ is the radiation length, $T = \rho L_{\text{dump}}/X_0$ with $\rho$ being the density of water, and $B_{\text{sig}}$ is the branching ratio of $X$ into the signal channel. (Hereafter, for simplicity, we take $B_{\text{sig}} = 1$.) In addition, $P_{\text{dec}}$ is the probability of the decay of $X$ in the decay volume. With the present setup, $L_{\text{dump}}$ is so long that the hidden photon production mostly occurs near the edge of the dump. Thus, we approximate

$$P_{\text{dec}} = e^{-(L_{\text{dump}} + L_{\text{sh}})/l_X} \left(1 - e^{-L_{\text{dec}}/l_X}\right), \quad (7)$$

where $l_X$ is the decay length of $X$ with energy $E_X$. Using $R \equiv \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$, we evaluate
with $m$ being the mass of the lepton $\ell$.

The number of events is proportional to the total number of injected electrons which depends on collider parameters. First, we consider the case of the ILC, at which electron and positron beams are dumped immediately after passing thought the interaction point. (We call such a case “BDeeLC.”) In the current design of the ILC, the bunch train consists of 1312 bunches, each of which contains $2 \times 10^{10}$ electrons, and is dumped with the frequency of 5 Hz [1]. Thus, with one-year (i.e., $3 \times 10^7$ sec) operation, about $4 \times 10^{21}$ electrons are injected into the dump. While we take this value as the basis for our calculation, luminosity upgrades are foreseen in the later stage of the ILC operation, which doubles the number of bunches [13]. In the case of CLIC, a similar calculation yields $(2 - 4) \times 10^{21}$ electrons using the parameters given in [2]. Since these numbers are similar in order of magnitude, in the following discussion, we take the ILC number and scale the beam energy up to the CLIC energy range.

We numerically integrate Eq. (6) to evaluate the number of events. Taking $N_e = 4 \times 10^{21}$, $L_{\text{dump}} = 11$ m, $L_{\text{sh}} = 50$ m, and $L_{\text{dec}} = 50$ m, we calculate $N_{\text{sig}}$ for $E_{\text{beam}} = 250$, 500, and 1500 GeV. In Fig. 2, we plot the contours of constant $N_{\text{sig}}$ on the $m_X$ vs. $\epsilon$ plane. The number of signal is suppressed for both large and small values of $\epsilon$. When $\epsilon$ is too small, the production cross section as well as the number of the decay inside the decay volume are suppressed. On the contrary, with too large $\epsilon$, most of the hidden photons decay before reaching the decay volume.

Next, we discuss several issues related to the backgrounds. First, the muons produced by $e^\pm - H_2O$ scattering may become serious background. We estimate the spectrum of the muons produced in the dump as

\[
\frac{dN_{\mu^+\mu^-}}{dp_z} = 2N_e N_{\text{Axo}} X_0 \frac{d\sigma_0}{dx} \left. \int \frac{dt}{E_{\text{beam}} E_{\ell}} \frac{d\sigma_0}{dx} \left. \int \frac{dE_{\ell}}{E_{\ell} \gamma^*} \right|_{x=E_{\ell}/E_{\ell}} \int \frac{dm^2_{\ell\gamma}}{\pi} \int dt \int E_{\ell} \, \frac{d\Gamma(\gamma^* \rightarrow \mu^+\mu^-)}{dp_z},
\]

where $p_z$ is the $z$-component of the momentum of the muon. In addition, $d\Gamma(\gamma^* \rightarrow \mu^+\mu^-)/dp_z$ is the differential decay rate of the “virtual photon” with its energy of $E_{\ell\gamma}$ and the invariant mass of $m_{\gamma\ell}$. We found that $O(10^6)$ muon pairs are produced with the injection of one bunch train, and that the energy of the produced muons are typically of the order of $E_{\text{beam}}$. A significant reduction of the flux of these muons is mandatory. One possibility of shielding these muons is to bend them out from the aperture of the vacuum vessel of the decay volume using magnetic field. A total field of $B_{\perp} \sim O(10)$ Tm is required to bend out $O(100)$ GeV muons, if the aperture of the vacuum vessel is $O(1)$ m. Assuming that the magnetic field of $O(1)$ T is available in the shield region, $L_{\text{sh}}$ should be of $O(10)$ m. The muon shield using the magnetic field was studied for SHiP experiment [15, 10], which is a new fixed target experiment proposed in CERN; it was pointed out that the return fields of a long sequence of magnets may bend back the muons which have been once bent out. Thus, detailed study of the configuration of the magnets for the muon shield is necessary; we leave the detailed studies of shield and detector designs for future consideration. The SHiP collaboration claims that the muons can be removed using a carefully designed configuration of magnetic field with $L_{\text{sh}} \sim 50$ m [10]. Here, we use $L_{\text{sh}} = 50$ m in our study, and assume that muon reduction is possible with magnetic fields between the dump and the decay volume.

Neutrino- and muon-induced backgrounds may also exist. Neutrinos and muons produced in the dump, as well as cosmic rays, may interact inelastically with the materials surrounding the decay volume, resulting in the production of long-lived $V^0$ particles, like $K^0_L$. Their decay products may mimic the charged particles produced by the decay of the hidden photon. The amount of $V^0$ particles produced in such a process depends on the experimental design.

Assuming no background and requiring a few events to claim the discovery of the signal of hidden photon, the discovery reach is significantly enlarged by BDeeLC, as shown in Fig. 2 dark photon with its mass of $O(1)$ GeV or smaller may be accessed by BDeeLC. Thus, BDeeLC will provide a new possibility to find a signal of hidden particles.

Next, we shortly comment on the beam dump experiment at FCC-ee (which we call “BDeeCC.”) Adopting the current design of FCC-ee [1], the number of electrons available for BDeeCC is $O(10^{10})$ per second, which is $3 - 4$ orders of magnitude smaller than that for BDeeLC. Even so, BDeeCC can enlarge the discovery reach of hidden particles compared to past experiments. (See Fig. 2.)
Finally, we compare BDee with another possible hidden particle search in the future, SHiP experiment [10]. The expected discovery reach of SHiP is also shown in Fig. 2 for the hidden photon model. We can see that, if approved, SHiP will also cover the parameter region on which BDee has a sensitivity. It should be noted that SHiP is a fixed target experiment with proton beam, so the fundamental processes producing hidden particles are different. If signals of a hidden particle are discovered, discrimination of various possibilities of hidden particles may become possible by combining the results of BDee and SHiP.

In summary, given the fact that a large number of $e^\pm$ will become available for beam dump experiment once $e^+e^-$ collider starts its operation, we propose to install a particle detector behind its dump. Using the hidden photon model as an example, we have shown that the beam dump experiment at $e^+e^-$ colliders, BDee, significantly enlarges the discovery reach of hidden particles. To understand the potential of BDee, case studies for other hidden particles, like ALPs and sterile neutrinos, should be performed. In doing so, the full capabilities of the machine, such as the use of positrons which yield annihilation processes, and, in the case of linear colliders, the use of beam polarization, should be explored. In addition, the discovery reach depends on the details of the configurations of detectors and shields. As we have discussed, the muons produced in the dump are potential serious background and hence careful designs of detectors and shields are needed. These issues will be discussed elsewhere [17]. BDee will provide a new possibility to probe hidden particles, and hence is worth being considered seriously as an important addition to future $e^+e^-$ facilities.

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