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Probing dark particles indirectly at the CEPC

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Abstract

When dark matter candidate and its parent particles are nearly degenerate, it would be difficult to probe them at the Large Hadron Collider directly. We propose to explore their quantum loop effects at the CEPC through the golden channel process $e^+e^- \to \mu^+\mu^-$. We use a renormalizable toy model consisting of a new scalar and a fermion to describe new physics beyond the Standard Model. The new scalar and fermion are general multiplets of the $SU(2)_L \times U(1)_Y$ symmetry, and couple to the muon lepton through Yukawa interaction. We calculate their loop contributions to anomalous $\gamma\mu^+\mu^-$ and $Z\mu^+\mu^-$ couplings which can be applied to many new physics models. The prospects of their effects at the CEPC are also examined assuming a 2‰ accuracy in the cross section measurement.

1. Introduction

One of the major tasks of particle physics is to understand the particle nature of dark matter [1–4]. As the dark matter candidate does not register at the detector and induce a large missing transverse momentum ($\not{E}_T$), one usually searches for the dark matter candidate in the signature of a large $\not{E}_T$ together with a bunch of visible particles in the standard model (SM). The method

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is valid only when there is a large mass gap between the dark matter candidate and its parent particle. However, there could be a scenario in which the dark matter candidate (Y) and its parent particle (X) are nearly degenerate, e.g. $X \to Y + a$, where a denotes the SM particles. The energy of a tends to 0 ($E_a \to 0$) in the degenerate limit of X and Y. The particles a (or their decay products if a's are not stable) are very soft and cannot register in the detector. It is hard to directly observe or test such new physics signals at the Large Hadron Collider (LHC), and we name it as a "nightmare" scenario.

On the other hand, the new physics particles affect the SM processes through quantum loop corrections, no matter whether they are degenerate or not. Such quantum corrections, if large enough, could be detected at the electron–positron colliders, e.g. the Circular electron–positron collider (CEPC), FCC-ee or International Linear Collider (ILC). In this work we focus on the "nightmare" scenario and explore the potential of measuring the new physics effects in the scattering of $e^+e^- \to \mu^+\mu^-$ at the CEPC with a center of mass energy of 240 GeV. The $e^+e^- \to \mu^+\mu^-$ channel is known as the golden channel which serves as a precision candle owing to its clean background and high detection efficiency [5]. A relative precision of 2‰ on $\sigma(e^+e^- \to \mu^+\mu^-)$ can be reached at ILC [6,7], and the CEPC [8] is expected to achieve a comparable accuracy.

Dark scalars appear often in various new physics models and have been studied extensively in the literature [2,9–12]. Rather than considering a specific complete model, we use a simple toy model to describe the new physics beyond the SM. The toy model consists of a new complex scalar multiplet (S) and a vector-like fermion (F). We demand that the neutral component of S serves as the dark matter candidate, while the fermion F facilitates the Yukawa coupling of S to μ^-. In practice we require that F be slightly heavier than S such that it can decay into S and muon lepton pairs.[1] Our toy model respects the SM gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$ and is renormalizable. Therefore, it can be viewed as a simplified version of a UV-completion model and can be generalized to many new physics models, e.g., the lepto-philic dark matter models [10,11,14–19]. To ensure the stability of the dark matter candidate, we restrict the mixing of such exotic particles with the SM particles through an exact Z_2 symmetry, under which the SM fields are all even, whereas the new fields are odd. As a result, the SM particles can only interact with a pair of those exotic particles at a time.

We emphasize that the new physics particles in our toy model can be light, say around $\mathcal{O}(100\text{ GeV})$, such that the approach of effective field theory [20–26] no longer works, and the full one loop calculation is necessary to address its effects. We use the dimensional regularization to calculate the loop corrections in the on-shell renormalization scheme [27,28]. The analytical results are written in terms of the Passarino–Veltman scalar functions [29,30].

The paper is organized as follows. In Sec. 2 we first introduce our simplified new physics model with new dark scalar and fermion multiplets. We then calculate the anomalous $\gamma\mu^+\mu^-$ and $Z\mu^+\mu^-$ couplings in the on-shell renormalization scheme. A simple form of those anomalous couplings is also derived in the approximation of large mass expansion. In Sec. 3 we evaluate the numerical effects of those anomalous couplings on the cross section of $e^+e^- \to \mu^+\mu^-$. After taking into account the constraints from dark matter searches at the LHC, we discuss the poten-

[1] Note that the vector-like fermion F, except for a weak gauge singlet, cannot play the role of dark matter candidate as it is constrained severely by the direct detection of the dark matter. However, for the scalar dark matter, it is easy to escape the constraint from LUX data [13] if a small mass splitting is generated between the real and imaginary components of the neutral complex scalar.