Polarization Effects in the Search for Dark Vector Boson at $e^+e^-$ Colliders\#

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Abstract—We argue that the search for dark vector boson through $e^+e^-\rightarrow Z_d\gamma$ can determine the Lorentz structure of $Z_d^{\pm}\gamma$ couplings with the detection of leptonic decays $Z_d\rightarrow l^+l^-$. We assume a general framework that the dark vector boson interacts with ordinary fermions through vector and axial-vector couplings. Taking $l^\pm\equiv\mu^\pm$, we study the correlation between $Z_d$ angle relative to $e^-$ beam direction in $e^+e^-$ CM frame and $\mu^-$ angle relative to the boost direction of $Z_d$ in $Z_d$ rest frame. This correlation is useful for probing the Lorentz structure of $Z_d^{\pm}\gamma$ couplings. We discuss the measurement of such correlation in Belle II detector.

Keywords: $e^+e^-$ colliders, dark vector boson, dark matter

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1. INTRODUCTION

Recently there are growing interests to search for DM related phenomena with huge statistics and high precision measurements. These phenomena involve the hidden sector [1–6], which is assumed to interact with Standard Model (SM) particles through certain messengers. A popular messenger particle proposed is the so called dark photon, which mixes with the $U(1)$ hypercharge field $B_\mu$ in SM,

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{\varepsilon_{\gamma}}{2\cos\theta_W}B_{\mu\nu}A'_{\mu\nu} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu},$$

where $A'_\mu$ is the dark photon field, and $A'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$. The above mixing induces electromagnetic couplings, $\mathcal{L}_{\text{em}} = \varepsilon_{\gamma}\varepsilon f_{\text{em}} A'_{\mu\nu}$, between the dark photon and SM fermions while the neutral current couplings between the same set of particles are further suppressed by the factor $m_{A'}/m_Z^2$ for $m_{A'} \ll m_Z$ with $m_{A'}$ the dark photon mass. However, independent neutral current couplings can be generated through mass mixing between the messenger particle and the Z boson [7–9]. In this case, the messenger particle is often referred to as $Z'$ boson. The mass mixing term $\delta m^2 Z'_{\mu}Z_{\mu}$ can induce neutral current couplings $\mathcal{L}_{\text{NC}} = (\varepsilon_Z/\cos\theta_W) J_{\text{NC}}^\mu Z_{\mu}$ with $\varepsilon_Z \equiv \delta m^2/m_Z^2$. For a general scenario that both kinetic and mass mixings are present, the interactions between dark boson and SM fermions are given by

$$\mathcal{L}_{\text{int}} = \left(\varepsilon_{\gamma}\varepsilon f_{\text{em}} + \varepsilon_Z g_{\cos\theta_W} J_{\text{NC}}^\mu\right) Z_{d,\mu},$$

with $Z_d$ the dark boson, which is the generalization of $A'$ and $Z'$. We can conveniently rewrite the above interaction as $\mathcal{L}_{\text{int}} = \varepsilon f_{\gamma\gamma} f_{Z'\gamma} + f_{Z'\gamma} f_{Z'\gamma} f_{Z_d\gamma} \gamma_5 f Z_{d,\mu}$ with $g^2_{\gamma,\gamma} + g^2_{Z',\gamma} = 1$. Due to the presence of both vector and axial vector couplings, parity violation effect is expected in the search for $Z_d$ and it can be quantified by the parameter $\rho \equiv 4g_{\gamma\gamma}g_{Z'\gamma}$. The maximum parity violation case corresponds to $\rho = \pm 2$ ($V = A$). In this talk we discuss the prospect of detecting $Z_d$ and possibly measuring $\rho$ in Belle II detector [10, 11].

2. RESULTS

We propose to search for $Z_d$ in Belle II detector through the process $e^+e^-\rightarrow Z_d\gamma \rightarrow \mu^+\mu^-\gamma$ with the

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\#Talk presented by G.-L. Lin.
muon pair arising from $Z_d$ decay. Following Ward–Takahashi identity [12, 13], the vector boson $Z_d$ must be in one of the transversely polarized states (left- or right-handed) in the limit $m_{Z_d} \ll \sqrt{s}$ [14]. The longitudinal $Z_d$ appears in the final state when $m_{Z_d}$ is no longer suppressed compared to $\sqrt{s}$. The appearance of longitudinal $Z_d$ weakens parity violation effects in the dark boson production. To probe parity violation effects, we bin the signal events according to the sign of $J \equiv \cos \theta \times \cos \theta_d$ where $\theta$ is the angle of $Z_d$ with respect to the $e^-$ direction in $e^+e^-$ CM frame while $\theta_d$ is the helicity angle of $\mu^-$ arising from $Z_d$ decay. Such an event binning allows one to measure the asymmetry parameter $A_{PN} \equiv (S(J > 0) - S(J < 0))/(S(J > 0) + S(J < 0))$ with $S$ the number of signal events. Under the assumption of 5$\sigma$ detection of the dark boson, i.e., $S/\sqrt{B} = 5$, with Belle II full integrated luminosity 50 ab$^{-1}$, the expected measurement of $A_{PN}$ is shown in Fig. 1 for $\rho = 0.5, 1.0, 1.5$, and 2.0, respectively [14]. In Fig. 1, we present results for $\rho = 0.5, 1.0, 1.5$, and 2.0, respectively. It is seen that $A_{PN}$ is consistent with zero for $\rho = 0.5$ and 1, since the 1$\sigma$ error bars in these cases reach $A_{PN} < 0$ regime. On the other hand, for $\rho = 2$, $A_{PN}$ is non-vanishing at more than 2$\sigma$ for $m_{Z_d}/\sqrt{s} \leq 0.3$. In general, the central value of $A_{PN}$ decreases when $m_{Z_d}/\sqrt{s}$ increases. This is due to the growing fraction of longitudinal $Z_d$ boson in the final state of $e^+e^- \rightarrow Z_d\gamma$, as we have just commented.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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