PROCEEDINGS OF SCIENCE

Dark Sector Physics with Belle II

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The Belle II experiment will operate with SuperKEKB e^+e^- energy-asymmetric collider on or near the $\Upsilon(4S)$ resonance energy region, and aims at obtaining an integrated luminosity of 50 ab^{-1}, which is approximately 50 times that of KEKB. The Belle II detector is fully upgraded from the Belle detector for much higher luminosity and contains new trigger system for single photon and low multiplicity events. The new trigger system allows to search for new physics related with hidden portal or axion-like particles. We briefly review the existing dark sector studies by Babar and Belle, and report on the status of Belle II studies of dark sector for vector and axion portals.

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1. Introduction

Dark matter (DM), which constitutes approximately 27% of our universe, is one of the biggest mysteries in nature. There have been many well-discussed candidates of dark matter, for example, WIMP. But in recent days, new possibility of light DM which can interact with the Standard Model (SM) particles through mediators below GeV-scale is proposed. The set of DM particles and the interactions therein is called the dark sector or hidden sector. In many hypotheses, the mediators of dark sector interactions can mix with the SM sector gauge bosons, thus called scalar, pseudo-scalar, or vector portals according to its spin and parity. These mediators can decay into a pair of invisible particles, leptons, or hadrons. In this write-up, existing results of pseudo-scalar and vector portal searches at the e^+e^- B-factories and the prospects for Belle II are discussed.

Because of simple and clean initial state, e^+e^- B-factory experiments such as Belle, Babar and Belle II are sensitive to final states with invisible particles, and therefore can provide great probes to search for the dark sector. The Belle II experiment is fully upgraded from the Belle experiment for various searches for new physics including the dark sector. In the Belle II, where 7 GeV on 4 GeV e^+e^- collisions using SuperKEKB are typically made, the final integrated luminosity goal is 50 ab^{1}, which is almost 50 times that of Belle and KEKB. This higher integrated luminosity can give much more stringent limits of dark sector parameters, if they are not discovered. In addition to luminosity increase, a major upgrade for dark sector studies have been made on the trigger system. New single photon and low multiplicity trigger system allows much improved opportunity to search for various dark sector particles. In the following sections, we review existing results and prospects for Belle II with the new trigger system, for dark photons in the initial state radiation (ISR) processes as well as axion-like particle searches.

2. Dark Photons

More than 30 years ago, B. Holdom proposed that if there is a new U(1) gauge particle A', it can mix with the SM photon with a Lagrangian term $-(\varepsilon/2)F^{\mu\nu}F'_{\mu\nu}$ ("kinetic mixing"), where $F'_{\mu\nu}$ is the field strength tensor of A' [1]. With a kinetic mixing, A' can decay into a pair of leptons or pions. Or, it can decay into a pair of DM particles (invisible decay). We can search for dark photons using an initial state radiation (ISR) process, $e^+e^- \to \gamma_{\mathrm{ISR}}A'$ (Fig. 1). In this process, the energy E_γ of the ISR photon is related to the dark photon mass $m_{A'}$ via $m_{A'} = \sqrt{s - 2E_\gamma\sqrt{s}}$. In the section, we mainly focus on searches with invisible dark photon decays.

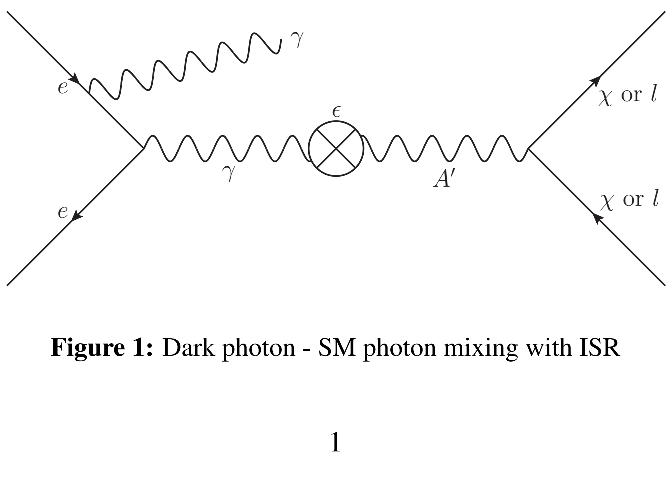

Figure 1: Dark photon - SM photon mixing with ISR

For invisible dark photon search, a trigger system sensitive to single-photon events is needed. The Belle did not have such a trigger while Babar has accumulated 53 fb^{-1} of data at $\Upsilon(2S)$, $\Upsilon(3S)$ and $\Upsilon(4S)$ energy regions with a single-photon trigger. In the Babar analysis, the signal events are required to satisfy the following conditions; an electromagnetic calorimeter (ECL) cluster with $E^{\mathrm{CM}} > 1.0$ GeV, where E^{CM} is the energy in the center-of-mass (CM) frame, no other ECL cluster with $E^{\mathrm{CM}} > 0.1$ GeV, and no track with $p_{\mathrm{T}}^{\mathrm{CM}} > 0.2$ GeV. After the event selection, the following backgrounds are expected: $e^+e^- \to 2(3)\gamma$ with the missing photons at the low $m_{A'}$ region and $e^+e^- \to e^+e^-\gamma$ with missing $e^\pm$ at the high $m_{A'}$ region. Photons can escape through the ECL gap at forward, backward and 90°. Each background makes specific structures on E^{CM} vs. θ^{lab} space (Fig. 2).

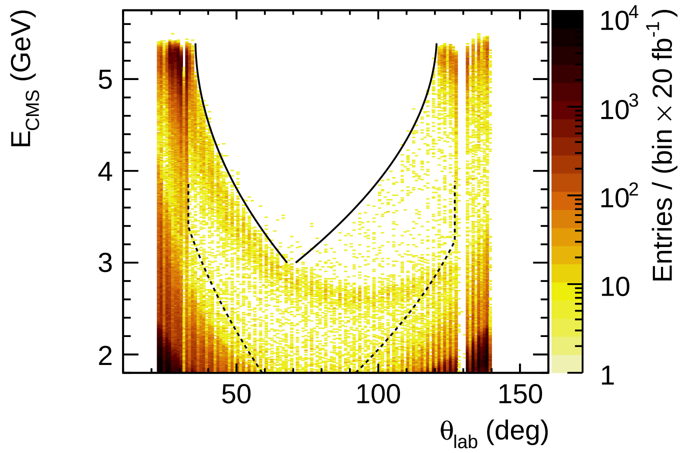

Figure 2: E^{CM} vs. θ_{lab} for background events after selection [2]

The Babar collaboration published results on dark photon searches in both invisible [3] and visible final states [4]. But we expect much more stringent constraints on ε, the kinetic mixing parameter, by using improved beam and detector at Belle II. For invisible dark photon search, Belle II expects obtaining better constraint with just 20 fb^{-1} integrated luminosity especially at low $m_{A'}$ region (Fig. 3). For dark photon search in the visible mode, Belle II result is expected to be competitive with Babar at 500 fb^{-1}. With the target luminosity of 50 ab^{-1}, Belle II expects to constrain ε down to $\mathscr{O}(10^{-4})$ (Fig. 4).

3. Axion-like Particles

The e^+e^- B-factories can also be used to search for other types of dark sector portals, e.g. pseudo-scalar portals such as axion-like particles (ALPs). ALP can couple with two SM photons: $a \to \gamma\gamma$, where a is the ALP. A possible process is $e^+e^- \to \gamma a$, the ALP-strahlung process. The process has not been studied but it is one of important searches that shall be performed by Belle II.

The signal events have three different event shapes depending on the feature of the ALP. If it does not decay inside the detector, only a single photon is detected. In this case, the event looks almost identical to those of the invisible dark photon search. If the ALP decays into a photon pair,

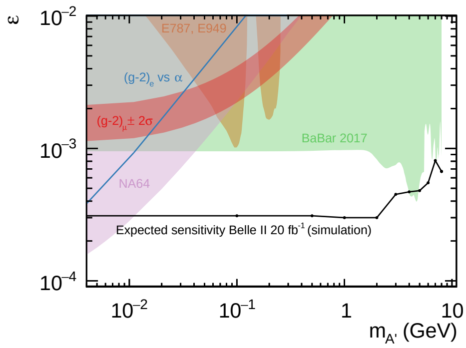

Figure 3: Expected sensitivity projection of mixing strength for invisible dark photon [2]

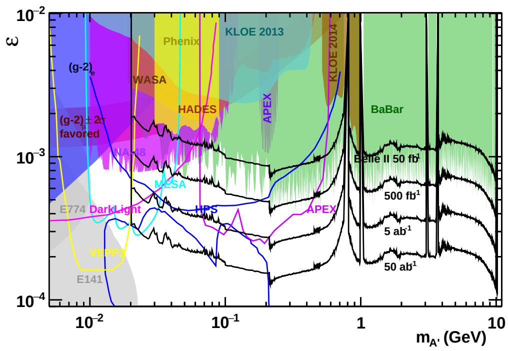

Figure 4: Expected sensitivity projection of mixing strength for visible dark photon [2]

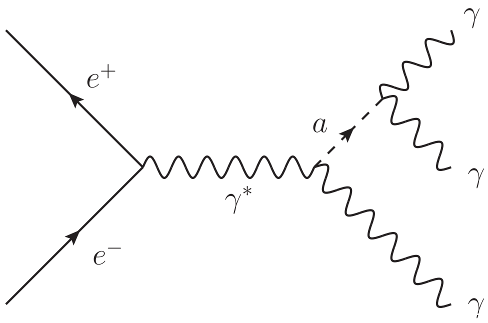

Figure 5: ALP-strahlung

with $m_a \lesssim 150$ MeV, the two photons are not well resolved. Therefore, the event shape looks like $e^+e^- \to \gamma\gamma$ and is difficult to analyze. If the ALP decays into a photon pair and m_a is moderately high, we can see three photons in final state. Then the event is selected by requiring three detected photons with $E^{\mathrm{CM}} < 0.25$ GeV and we seek for a bump in $m_{\gamma\gamma}$. The most dominant background comes from a QED process, $e^+e^- \to \gamma\gamma\gamma$, which is irreducible. The process $e^+e^- \to \gamma\gamma$ can also be background candidates. First, a third photon can come from beam-induced background, but it can be reduced by timing information from ECL. Second, one of the photons can convert into e^+e^- outside the tracking detector, thus both electron and positron are identified as photons. The e^+e^- pair production background can be reduced by angular distribution between γ, e^+, and e^-. The SM processes such as $e^+e^- \to \pi^0\gamma$, $\eta\gamma$, and $\eta'\gamma$, where the meson decays into $\gamma\gamma$ can also become backgrounds. To remove these backgrounds, events are excluded if the $\gamma\gamma$ invariant mass is within -50 MeV to $+75$ MeV with respect to their reference masses. Expected sensitivities of the coupling strength $g_{a\gamma\gamma}$ vs. m_a are shown in Fig. 7. The final 50 ab^{-1} Belle II data may give constraints from $10^{-4} \sim 10^{-5}$. It is notable that the three photon final state result can cover beyond the reach of SHiP experiment. There is a narrow region that is not covered either by 3γ or γ plus invisible. It is due to the merging the two photons from $a \to \gamma\gamma$ decay at low m_a.

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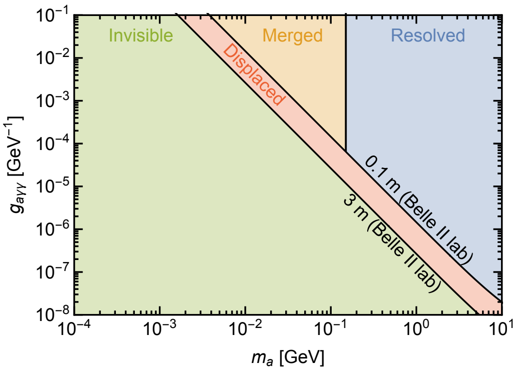

Figure 6: ALP signature in detector for ALP-γ-γ coupling strength and mass of ALP [5]

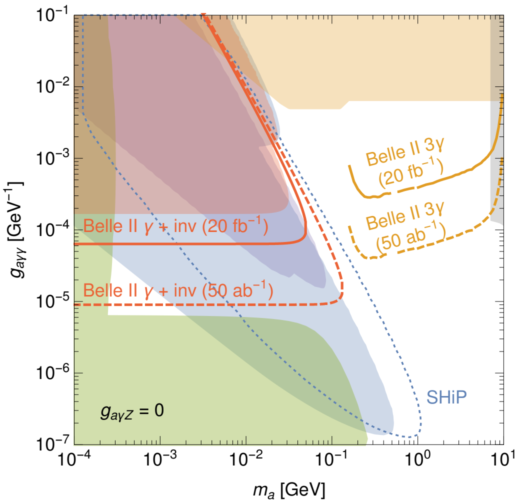

Figure 7: Expected sensitivity projection of ALP-γ-γ coupling strength [5]

4. Conclusion

There have been searches for dark sector by Belle and Babar. Especially, Babar had the single photon trigger partially, for only 53 fb^{-1} integrated luminosity, and produce notable constraints for kinetic mixing of dark photon to SM photon. The Belle II detector is capable to cope with 40 times increase of the peak luminosity and 50 times for integrated luminosity (50 ab^{-1}) in comparison to Belle. Moreover new trigger menus, e.g. a single-photon trigger, are being prepared. The Belle II invisible dark photon search with ISR may give more stringent constraint for mixing parameter between SM photon and dark photon than Babar even with the initial Phase-2 data set. Visible dark photon search may give competitive constraint on the mixing parameter at 500 fb^{-1} integrated luminosity. New axion-like particle mediator can also be searched for. The analysis has not been done and Belle II can exclude a region of parameter space beyond what is expected of the SHiP experiment.

References

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