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Studies of dark sector particles at Belle

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We show recent results of dark photon and dark-sector particles at Belle. In particular, we present the following searches: for dark photon and dark Higgs via Higgsstrahlung, for a dark gauge boson coupling predominantly to quarks in η decays, and for D^0 decays to invisible final states. The data are produced in e^+e^- collisions at the KEKB asymmetric-energy collider and collected with the Belle detector.

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1. Introduction

1.1 Motivations for the dark sector

Evidences for dark matter inferred from many astrophysical observations certainly lead to speculations for new physics beyond the Standard Model (SM). In particular, observations by PAMELA, AMS, etc. have triggered light dark matter and dark sector scenarios [1]. Moreover, attempts at formulating a unified theoretical framework for explaining all these observations have led to dark sector models where a hidden sector with new gauge interactions may be incorporated [2].

The dark sector can be connected to SM via the so-called *portals*. Possible candidates for such portals include Higgs, vector bosons, neutrinos, and axions. Vector boson portal particle can be the mediator of a hidden-sector $U(1)$ gauge interaction and is often termed as 'dark photon' (denoted as A') [3]. From the observed astrophysical data, the mass of A' is conjectured to be in the range of $(\mathrm{MeV}/c^2 - \mathrm{GeV}/c^2)$. It has been suggested that a vector gauge boson of a hidden sector will mix with the SM photon via the kinetic mixing term $\varepsilon_{\mathrm{m}} F_{\mu\nu} F'^{\mu\nu}$, where ε_{m} is the strength of the kinetic mixing and is supposed to be small. For A' to acquire mass, an extended Higgs sector might be required in order to break this $U(1)$.

1.2 Opportunities at the e^+e^- B-factories

Given the speculations of low-mass (sub-GeV/c^2) and small-coupling with an SM photon of the proposed dark photon, experiments at high-luminosity low-energy machines as well as dedicated beam-dump experiments are ideal places to look for dark photons and other dark-sector particles. In the e^+e^- B-factories such as BaBar and Belle, dark photon and dark Higgs (denoted as h') can be searched for in both initial-state-radiation (ISR) processes and B-meson decays.

In this write-up, we show recent results of dark photon and dark-sector particles at Belle. In particular, we present the following searches: for dark photon and dark Higgs via Higgsstrahlung (section 2), for a dark gauge boson coupling predominantly to quarks in η decays (section 3), and for D^0 decays to invisible final states (section 4).

2. Dark-photon via Higgsstrahlung

Analyzing 977 fb^{-1} data sample of Belle, we search for dark photon and dark Higgs in a Higgsstrahlung process $e^+e^- \to h'(\to A'A')A'$ [5]. In this search we consider only the case $m_{h'} \geq 2m_{A'}$ so that the decay $h' \to A'A'$ is kinematically allowed. Ten exclusive final states are investigated: $3(\ell^+\ell^-)$, $2(\ell^+\ell^-)(\pi^+\pi^-)$, $2(\pi^+\pi^-)(\ell^+\ell^-)$ and $3(\pi^+\pi^-)$ where $\ell^+\ell^-$ is either e^+e^- or $\mu^+\mu^-$ but not $\tau^+\tau^-$. In addition, we also search for three inclusive channels of the type $2(\ell^+\ell^-)X$ for $m_{A'} > 1.1$ GeV/c^2, where X is a dark photon candidate inferred from the missing mass.

For exclusive (inclusive) final states, we require the invariant mass of each $\ell^+\ell^-$ or $\pi^+\pi^-$ pair to be consistent with three (two) distinct dark photon decays to $\ell^+\ell^-$ or $\pi^+\pi^-$. The dark photon candidates are sorted by mass in the order $m^1_{A'_{\mathrm{cand}}} > m^2_{A'_{\mathrm{cand}}} > m^3_{A'_{\mathrm{cand}}}$. The signal region is defined by the mass difference $\Delta m_{A'} \equiv m^1_{A'_{\mathrm{cand}}} - m^3_{A'_{\mathrm{cand}}}$ which must be close to zero. The amount of background events in the signal region is determined by calibrating Monte-Carlo distribution using the same-sign lepton or pion pairs.

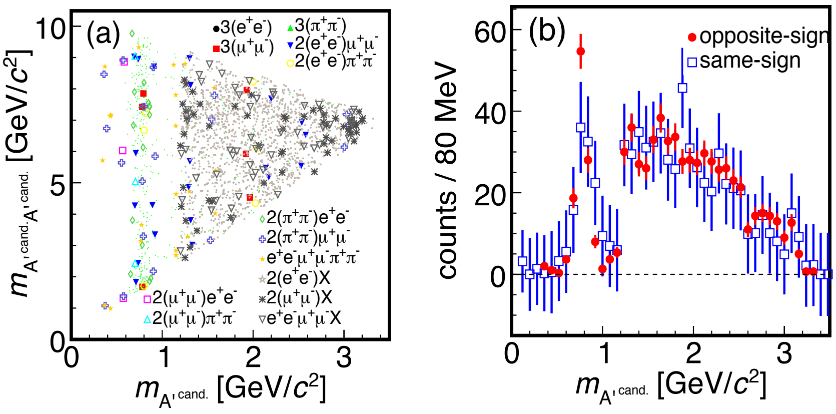

Figure 1: (a) Signal candidates observed for the 13 final states shown in 2-dimensional distributions in dark-photon mass $m_{A'}$ and dark-Higgs mass $m_{A'A'}$. (b) Projection of signal candidates unto $m_{A'}$ (red) overlaid with the projected background (blue) determined by the scaled same-sign distribution.

Figure 1(a) shows two-dimensional distributions, in dark-photon mass $m_{A'}$ and dark-Higgs mass $m_{h'} = m_{A'A'}$, of the signal candidates observed for the 13 final states. 74% of the candidate events are in the inclusive mode $2(\pi^+\pi^-)X$ and 19% are in the exclusive $3(\pi^+\pi^-)$ mode. Figure 1(b) is the projection of signal candidates unto $m_{A'}$ (red) overlaid, for comparison, with the projected background (blue) determined by the scaled same-sign distribution. The discontinuity at 1.1 GeV/c^2 is an artifact due to opening the inclusive modes above this mass point. For exclusive modes, the dominant background is due to ρ, ω mesons from e.g. SM two-photon processes. We find no excess of signal over the expected background in any mode.

We determine upper limits, individually for each final state, on $\mathscr{B}\sigma_{\text{Born}}$ where $\mathscr{B}$ is the branching fraction to each final state and σ_{Born} is the Born cross section which is related to the number of observed events by

$$N_{\text{obs}} = \mathscr{B}\sigma_{\text{Born}}(1+\delta)|1-\Pi|^2\mathscr{L}\varepsilon + N_{\text{bkg}}$$

where $1+\delta$ is the correction for initial-state radiation, $|1-\Pi|$ is for vacuum polarization, $\mathscr{L}$ is the integrated luminosity, and ε is the efficiency. For exclusive modes, the 90% confidence level (CL) upper limits on $\mathscr{B}\sigma_{\text{Born}}$ are in the range $(10-20)$ ab, in the mass region 0.1 GeV/c^2 $< m_{A'} <$ 3.5 GeV/c^2 and 0.2 GeV/c^2 $< m_{h'} <$ 10.5 GeV/c^2, while for inclusive modes the limits are $(20-60)$ ab for 1.1 GeV/c^2 $< m_{A'} <$ 3.5 GeV/c^2. The individual limits are combined for all modes, which is then converted to the limit on $\alpha_{\text{D}}\varepsilon_{\text{m}}^2$. Figure 2 shows the 90% CL upper limits on $\alpha_{\text{D}}\varepsilon_{\text{m}}^2$ vs. $m_{A'}$ (top row) and vs. $m_{h'}$ (bottom row) for Belle (solid red) and BaBar [6] (dashed black). The blue dotted curve which mostly coincides with the solid red shows the expected Belle result. Assuming $\alpha_{\text{D}} = 1/137$, we obtain $\varepsilon_{\text{m}} \lesssim 8\times10^{-4}$ for $m_{h'} <$ 8 GeV/c^2 and $m_{A'} <$ 1 GeV/c^2. The results on $3(\pi^+\pi^-)$ and $2(e^+e^-)X$ modes are first limits by any experiment.

3. Search for a dark gauge boson coupling to quarks

While most accelerator-based experiments have focused on dark photon that couples to the SM photon, there are many models suggesting a new gauge boson U' which couples predominantly to

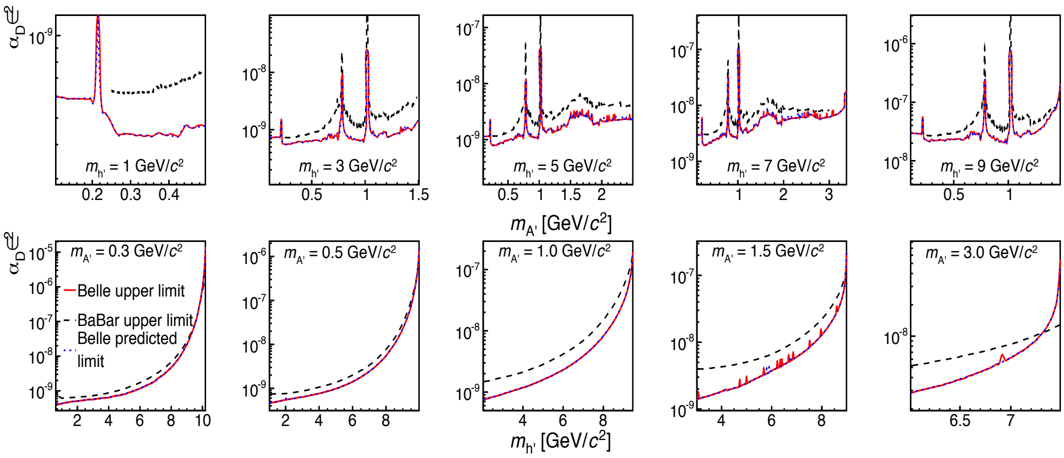

Figure 2: 90% CL upper limits on $\alpha_{\rm D}\varepsilon_{\rm m}^2$ vs. $m_{A'}$ (top row) and vs. $m_{h'}$ (bottom row) for Belle (solid red) and BaBar [6] (dashed black). The blue dotted curve which mostly coincides with the solid red shows the expected Belle result.

quarks [7, 8], e.g. $U' \to \pi^+\pi^-$. The dark boson U' can be produced through SM meson decays $P \to U'\gamma$, where P denotes a pseudoscalar meson such as π^0, η, η'. The coupling of U' to quarks is described by the baryonic fine structure constant $\alpha'_U \equiv g^2_{U'}/4\pi$, where the interaction is given by a Lagrangian term $\mathscr{L} = (1/3)g_{U'}\bar{q}\gamma^\mu q U'_\mu$ [8].

Using the full Belle data sample of 976 fb^{-1}, we search for a U' boson via the process $\eta \to U'(\to \pi^+\pi^-)\gamma$, where η is required, in order to suppress combinatorial background, to originate in the decay chain $D^{*+} \to D^0(\to K^0_S\eta)\pi^+$ [9]. The photons in η decays are selected by requiring $E_\gamma > 60$ (100) MeV in the barrel (endcap) regions and the electromagnetic shower shape be consistent with that of photons. In addition, we require the photon not to be associated with a π^0 when combined with any other photon in the event. The momenta of η daughters are refit by constraining the η mass to the nominal one. Candidate K^0_S mesons are selected using a neural network technique [10]. K^0_S and η mesons are combined and fitted to a common vertex to form a D^0, with the mass constrained to the nominal D^0 mass. This D^0 and a slow π^+ are combined and fitted to the interaction point to find a D^{*+}.

Figure 3(a) shows the $M_{\pi^+\pi^-\gamma}$ distribution from $D^0 \to K^0_S\pi^+\pi^-\gamma$. We obtain $N_\eta = 2974 \pm 90$ events by binned maximum likelihood fit to $M_{\pi^+\pi^-\gamma}$. For a cross-check of the procedure, we measure the ratio of branching fractions $\mathscr{B}(\eta \to \pi^+\pi^-\gamma)/\mathscr{B}(\eta \to \pi^+\pi^-\pi^0) = 0.185 \pm 0.007$, which is consistent with the world-average value. Figure 3(b) displays the $M_{\pi^+\pi^-}$ distribution from $\eta \to \pi^+\pi^-\gamma$, where side-band subtraction has been applied to determine the true η contribution. Overlaid with the distribution is the fit to a differential decay rate based on low-energy QCD phenomena [11]. The U' signal distribution with a mass assumption of 0.4 GeV/c^2 from $\eta \to U'(\pi^+\pi^-)\gamma$ is also displayed with arbitrary normalization. We find no significant U' signal at any mass value. The baryonic fine structure constant is calculated from the measurement:

$$\alpha'_U = \frac{\xi(m^2_{U'})}{\mathscr{B}(U' \to \pi^+\pi^-)} \times \left[\frac{\Gamma(\eta \to \pi^+\pi^-\gamma)}{\Gamma(\eta \to \gamma\gamma)}\right] \times \left[\frac{\Gamma(\eta \to U'\gamma \to \pi^+\pi^-\gamma)}{\Gamma(\eta \to \pi^+\pi^-\gamma)}\right],$$

where $\xi(m^2_{U'}) = (\alpha/2)(1-m^2_{U'}/m^2_\eta)^{-3}|\mathscr{F}(m^2_{U'})|^{-2}$ with $\mathscr{F}$ being the form-factor [8]. As we don't see any signal for U', we set 95% CL upper limit on α'_U using the Feldman-Cousins method [12]. Figure 3(c) shows the upper limit on α'_U as a function of $m_{U'}$. In the region 0.29 GeV/$c^2 < m_{U'} <$ 0.52 GeV/c^2, α'_U is limited to below $10^{-3} - 10^{-2}$ at 95% CL. This is the first search for U' in the $\pi^+\pi^-$ mode.

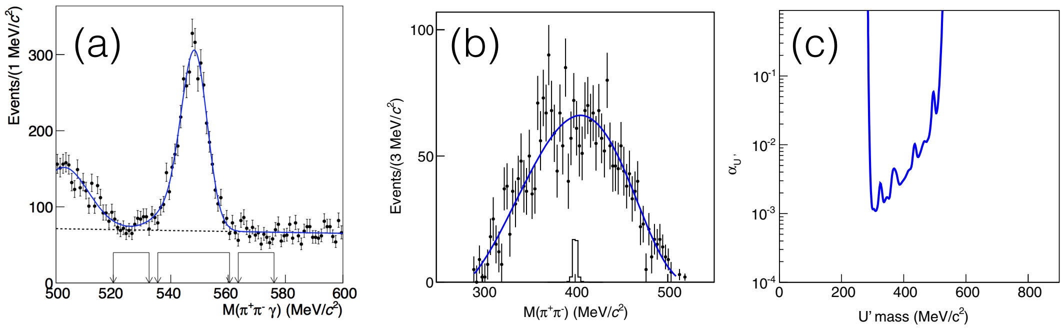

Figure 3: (a) $M_{\pi^+\pi^-\gamma}$ distribution from $D^0 \to K^0_S\pi^+\pi^-\gamma$, overlaid with the fit result. Vertical arrows show the boundaries of signal and sideband regions. (b) $M_{\pi^+\pi^-}$ distribution from $\eta \to \pi^+\pi^-\gamma$, overlaid with the fitted differential decay rate. The U' signal distribution with a mass of 0.4 GeV/c^2 from $\eta \to U'(\pi^+\pi^-)\gamma$ is also displayed with arbitrary normalization. (c) The 95% CL limit of the baryonice fine structure constant α'_U as a function of the assumed U' mass.

4. Search for D^0 decays to invisible final states

The $D^0 \to \nu\bar{\nu}$ decay exemplifies a meson decay to an invisible final state. In the SM, this decay is helicity-suppressed with an expected branching fraction $\mathscr{B}(D^0 \to \nu\bar{\nu}) = 1.1 \times 10^{-30}$ [13]. But the rate could be much enhanced with dark matter (DM) particles in the final state via non-SM mechanisms.

Using the nearly full data sample of Belle with an integrated luminosity of 924 fb^{-1}, we search for D^0 decays to invisible final states [14]. To utilize a few million D^0 mesons produced in the $e^+e^- \to c\bar{c}$ continuum process, we use a 'charm-tagger' and collect an inclusive sample of D^0. The process $e^+e^- \to c\bar{c} \to D^{(*)}_{\rm tag}X_{\rm frag}\overline{D}^{*-}_{\rm sig}$ with $\overline{D}^{*-}_{\rm sig} \to \overline{D}^0_{\rm sig}\pi^-_s$ is identified by reconstructing everything except for $\overline{D}^0_{\rm sig}$. The inclusive $\overline{D}^0_{\rm sig}$ sample is identified by the recoil mass, M_{D^0}, against $D^{(*)}_{\rm tag}X_{\rm frag}\pi^-_s$. Figure 4(a) shows the M_{D^0} distribution of the approximately 7 million inclusive D^0 events collected by the charm-tagger. Candidates for D^0 decays to invisible final states are selected by requiring no remaining final state particles associated with $\overline{D}^0_{\rm sig}$. Figures 4(b) and (c) show the M_{D^0} and $E_{\rm ECL}$ distributions, respectively, of the $D^0 \to$ invisible decay candidates. Overlaid with Fig. 4(b) and (c) are the fit projections to 2-dimensional observables M_{D^0} and $E_{\rm ECL}$. The fitted yield of $D^0 \to$ invisible final states is $-6.3^{+22.5}_{-21.0}$ events. The corresponding upper limit for the branching fraction is $\mathscr{B}(D^0 \to \text{invisible}) < 9.4 \times 10^{-5}$ at 90% CL.

5. Conclusion

The e^+e^- B-factory experiments have made great achievements on the CP violation and CKM

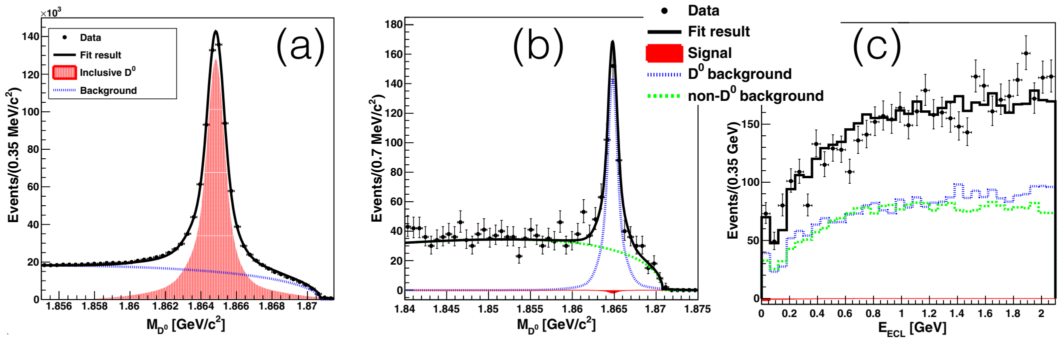

Figure 4: (a) The M_{D^0} distribution of the inclusive D^0 sample. (b) M_{D^0} distribution and the fit result for $D^0 \to$ invisible decays, and (c) E_{ECL} distribution and the fit result for $D^0 \to$ invisible decays.

structure in B and charm meson systems. At the same time they can probe much wider range of elementary particle physics including exotic hadron states, heavy invisible particles as well as dark sector particles. Several dark photon searches at BaBar and Belle have been made. In this talk we have reported recent studies of dark sector and related subjects from the Belle experiment. But there are many other modes which have yet to be explored. With the expectation of 50 times more data at Belle II, we look forward to more stringent searches for the dark sector particles.

References

[1] O. Adriani *et al.* (PAMELA Collab.), Nature (London) **458**, 607 (2009); M. Ackermann *et al.* (Fermi LAT. Collab.), Phys. Rev. **D 82**, 092004 (2010); M. Aguilar *et al.* (AMS Collab.), Phys. Rev. Lett. **110**, 141102 (2013).

[2] N. Arkani-Hamded, D. P. Finkbeiner, T. R. Slatyer and N. Weinder, Phys. Rev. **D 79**, 015014 (2009).

[3] P. Fayet, Phys. Lett. **B 95**, 285 (1980).

[4] B. Holdom, Phys. Lett. **B 166**, 196 (1986).

[5] I. Jaegle *et al.* (Belle Collab.), Phys. Rev. Lett. **114**, 211801 (2015).

[6] J.P. Lees *et al.* (BaBar Collab.), Phys. Rev. Lett. **108**, 211801 (2012).

[7] A.E. Nelson and N. Tetradis, Phys. Lett. **B 221**, 80 (1989).

[8] S. Tulin, Phys. Rev. **D 89**, 114008 (2014).

[9] E. Won *et al.* (Belle Collab.), Phys. Rev. **D 94**, 092006 (2016).

[10] M. Feindt and U. Kerzel, Nucl. Inst. Meth. Phys. Res. **A 559**, 190 (2006).

[11] P. Alderson *et al.* (WASA-at-COSY Collab.), Phys. Lett. **B 707**, 243 (2012); F. Stollenwerk, C. Hanhart, A. Kupsc, U.-G. Meißner, and A. Wirzba, Phys. Lett. **B 707**, 184 (2012).

[12] G.J. Feldman and R.D. Cousins, Phys. Rev. **D 57**, 3873 (1998).

[13] A. Badin and A.A. Petrov, Phys. Rev. **D 82**, 034005 (2010).

[14] Y.-T. Lai *et al.* (Belle Collab.), Phys. Rev. **D 95**, 011102(R) (2017).