PROCEEDINGS OF SCIENCE

Search for Dark Particles and Dark Sector at Belle

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We search for dark photon A' and the dark Higgs boson h' particles that are suggested in number of recently proposed dark sector models. We present our search results in the production of $e^+e^- \to A'h'$ with the decay mod of $h' \to A'A'$. The search was carried out in both inclusive and exclusive modes. We also discuss a search for new dark vector gauge boson that couples to light quark predominantly.

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1. Introduction

The dark particles, can be a candidate for dark matter were originally considered as a new spin-1 boson for new physics [1] beyond the Standard Model [2, 3]. The dark boson A' can be produced in a radiative e^+e^- collision via kinetic mixing of a virtual photon with the kinetic mixing parameter ε and is illustrated in the left diagram of Fig. 1. This new dark boson requires an extended Higgs sector to break the new $U(1)'$ symmetry and is commonly referred as the dark Higgs h'. In this presentation, we search for the dark boson and the dark Higgs in both exclusive and inclusive modes.

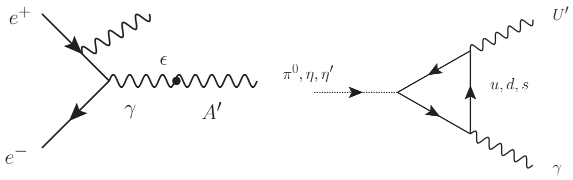

Figure 1: Example Feynman diagrams that illustrate production of the dark photon A' in e^+e^- collision and of the dark boson U' from light mesons.

Also, recently there is a proposal of a new dark gauge boson that couples predominantly to light quarks [4], its production example is shown in Fig. 1, and we also discuss a search for the new dark gauge boson U'.

2. Experimental facility and the data set

We use data collected with the Belle detector [5] at the KEKB e^+e collider [6] , amounting to 977 fb^{-1} at center-of-mass energies corresponding to the $\Upsilon(1S)$ to $\Upsilon(5S)$ resonances and in the nearby continuum. We optimize the selection criteria and determine the $e^+e \to A'h'$ signal detection efficiency using a Monte Carlo (MC) simulation where the interaction kinematics and detector response are simulated with the packages MadGraph [7] and GEANT3 [8], respectively.

2.1 Search for dark photon analysis

We study the Higgs-strahlung channel, $e^+e^- \to A'h'$. The dark photon A' can decay into lepton pairs, hadrons, or invisible particles while the dark Higgs boson h' can decay into either A', $A'^{(*)}$, leptons pairs, or hadrons, where A'^{*} is a virtual dark photon [9]. In total there are 10 exclusive channels: $3(\ell^+\ell^-)$, $2(\ell^+\ell^-)(\pi^+\pi^-)$, $(\ell^+\ell^-)\ 2\ \pi^+\pi^-)$, and $3(\pi^+\pi^-)$. We also look at 3 inclusive modes for $m_{A'} > 1.1$ GeV/c^2: $2(\ell^+\ell^-)X$ where X is the missing mass from the dark photon candidate.

For the background estimation, we use the same esign events from $e^+e^- \to (\ell^+\ell^+)\ (\ell^-\ell^-)\ (\ell^+\ell^-)$, order masses of lepton (or hadron) pairs as $m^1_{\ell\ell} > m^2_{\ell\ell} > m^3_{\ell\ell}$, and plot $m^1_{\ell\ell} - m^3_{\ell\ell}$ vs. $m^1_{\ell\ell}$. The background estimation from MC events and real data agree each other and no significant access of signal events is seen in the data.

The upper limit on the $\alpha_D \times \varepsilon^2$ are computed based on equations described in Ref [9]. Figure 2 shows the 90 % credibility level (CL) upper limits on $\alpha_D \times \varepsilon^2$ for Belle, expected and measured, and for BaBar, for five different mass hypotheses for the dark Higs boson (top row) and dark photon (bottom row) masses.

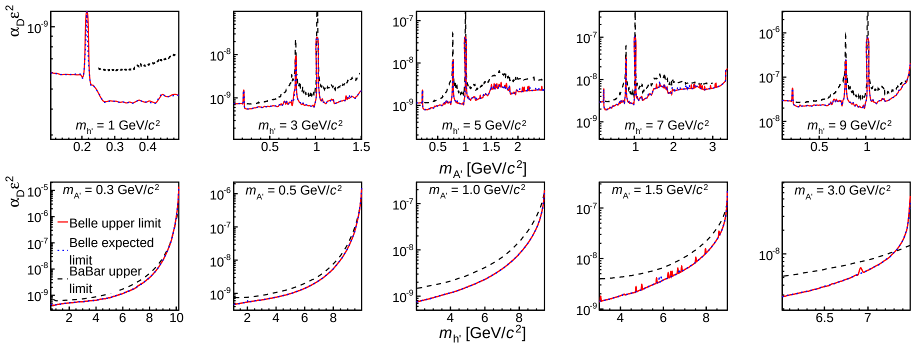

Figure 2: 90 % CL level on the product $\alpha_D \times \varepsilon^2$ versus dark photon mass (top row) and dark Higgs boson mass (bottom row) for Belle (solid red curve) and BaBar [11] (dashed black curve). The blue dotted curve, which coincides more or less with the solid red curve, shows the expected Belle limit. The figure is taken from [10].

2.2 Search for dark boson analysis

We search for U' bosons decaying to $\pi^+\pi^-$ pairs using $\eta \to \pi^+\pi^-\gamma$ decays where η is produced in the decay chain $D^{*+} \to D^0\pi^+, D^0 \to K_S^0\eta$. The decay, $U' \to \pi^+\pi^-$, is expected to have a relatively small branching ratio down to 10^{-2} [4] but nevertheless provides a very clean environment to look for a possible dark vector gauge boson.

After reconstructing all needed final-state particles, we define the η signal region as $M(\pi^+\pi^-\gamma) \in [535.5, 560.5]$ MeV/c^2, and the sideband regions used for background subtraction as $M(\pi^+\pi^-\gamma) \in [520.0, 532.5]$ or $[563.5, 576.0]$ MeV/c^2. The $M(\pi^+\pi^-)$ distribution for the background-subtracted η signal is shown in Fig. 3.

We set a 95% confidence level upper limits on $\alpha_{U'}$ using the Feldman-Cousins approach [12], adding the statistical and systematic uncertainties in quadrature. The upper limit as a function of the U' boson mass is shown in Fig. 3 . Considering other results in this mass region, we find that our limit is stronger than that from a model-dependent analysis [4] of the $\phi \to e^+e^-\gamma$ decays [13] for $m_{U'} > 450$ MeV/c^2, but weaker than the limit based on the $\eta \to \pi^0\gamma\gamma$ total rate [4].

2.3 Other Ongoing Analyses

We are also working on a long lived dark photon search where $c\tau$ can be as long as 1-10 cm. Since it is low multiplicity final state (two charged tracks and one photon), the efficiencies are low in general in Belle and one analysis is ongoing. Another analysis is a search for invisible decays when the dark photon decays to a pair of dark matter particles [14]. Since this is a final state with a single photon only, the Belle analysis relies on the photon conversion technique.

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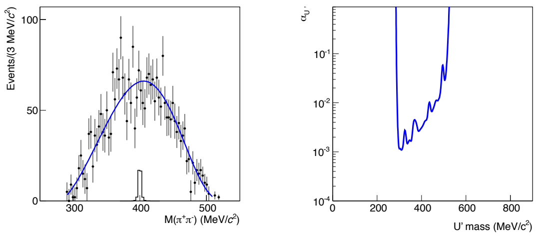

Figure 3: Left: $\pi^+\pi^-$ invariant mass distribution from the $\eta \to \pi^+\pi^-\gamma$ signal (points with error bars), the fitted differential decay rate (solid curve), and an example U' signal at a mass of 400 MeV/c^2 from $\eta \to U'\gamma, U' \to \pi^+\pi^-$ (histogram with arbitrary normalization). Right: Computed 95% upper limit on the baryonic fine structure constant $\alpha_{U'}$ as a function of the unknown U' mass (solid curve).

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