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Search for a dark vector gauge boson decaying to $\pi^+\pi^-$ using $\eta \to \pi^+\pi^-\gamma$ decays

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We report a search for a dark vector gauge boson U' that couples to quarks in the decay chain $D^{*+} \to D^0\pi^+, D^0 \to K_S^0\eta, \eta \to U'\gamma, U' \to \pi^+\pi^-$. No signal is found and we set a mass-dependent limit on the baryonic fine structure constant of $10^{-3} - 10^{-2}$ in the U' mass range of 290 to 520 MeV/c^2. This analysis is based on a data sample of 976 fb^{-1} collected by the Belle experiment at the KEKB asymmetric-energy e^+e^- collider.

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The standard model (SM) of particle physics cannot explain the nature of dark matter that is understood to have mostly gravitational effects on visible matter, radiation, and the large-scale structure of the Universe [1–4]. The dark matter can be naturally explained by the introduction of a

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weakly interacting particle predicted in the supersymmetric extension of the SM [5]. The absence of observation of any supersymmetric particles in hadron collider experiments [6] motivates studies of new classes of models, commonly referred to as dark models, which introduce new gauge symmetries [7] and predict the existence of new particles that couple weakly to SM particles. Most accelerator-based experiments have focused on the dark photon or dark particles coupling to the SM photons [8], though many dark models suggest a new gauge boson that could couple predominantly to quarks [9,10]. This new dark boson (hereafter referred to as the U' boson, instead of B as is originally proposed in Ref. [9], to avoid confusion with the SM B meson) can be produced from light SM meson decays through $P \to U'\gamma$ or $V \to U'P$, where P refers to a pseudoscalar meson (e.g., π^0, η, η') and V to a vector meson (e.g., ω, ϕ). Two recent experimental limits on searches for a dark photon A' via $\pi^0 \to A'\gamma, A' \to e^+e^-$ [11] and $\phi \to A'\gamma, A' \to e^+e^-$ [12] can be applied to the U' boson search in a model-dependent way to constrain the baryonic fine structure constant $\alpha_{U'} \equiv g_{U'}^2/(4\pi)$, where $g_{U'}$ is the universal gauge coupling between the U' boson and the quarks [10]. There are also limits from $\eta \to \pi^0\gamma\gamma$ and $\phi \to \eta\pi^0\gamma$ decays based on their total rate, as well as from the analysis of hadronic $\Upsilon(1S)$ decays [10].

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 $D^{*+} \to D^0\pi^+, D^0 \to K_S^0\eta$ [13]. The kinematics here allows us to suppress the combinatorial background significantly. The decay $U' \to \pi^+\pi^-$ is expected to have a relatively small branching fraction of 2%–4% [10] but nevertheless provides a very clean signature for a possible dark vector gauge boson. The dominant decay modes are $\pi^0\gamma$ at low U' mass and $\pi^+\pi^-\pi^0$ at higher U' mass; however they suffer from higher combinatorial background and therefore are not used in the analysis. We use the decay $\eta \to \pi^+\pi^-\pi^0$ to validate our event reconstruction by measuring the branching fraction of $\eta \to \pi^+\pi^-\gamma$ relative to that of $\eta \to \pi^+\pi^-\pi^0$.

The data used in this analysis were recorded at the $\Upsilon(nS)$ resonances ($n = 1, \ldots, 5$) and 60 MeV below the $\Upsilon(4S)$ resonance with the Belle detector [14] at the e^+e^- asymmetric-energy collider KEKB [15]. The sample corresponds to an integrated luminosity of 976 fb^{-1}. We generated two million Monte Carlo (MC) events [16] each for $\eta \to \pi^+\pi^-\gamma$, $\eta \to \pi^+\pi^-\pi^0$, and $\eta \to U'\gamma \to \pi^+\pi^-\gamma$ at a particular U' mass selected in the range from 280 to 540 MeV$/c^2$ in steps of 10 MeV$/c^2$ (i.e., 58 million events in all). The lifetime of the U' is assumed to be negligible. The U' samples are used to determine the $M(\pi^+\pi^-)$ resolution. The U' signal shape parameters for intermediate U' mass values are determined using spline interpolation.

Except for tracks from K_S^0 decays, we require that the charged tracks originate from the vicinity of the interaction point (IP) with impact parameters along the beam direction (z axis) and perpendicular to it of less than 4 and 2 cm, respectively. All such charged tracks are required to have at least two associated hits in the silicon vertex detector (SVD), both in the z and perpendicular directions. Such charged tracks are identified as pions or kaons by requiring that the ratio of particle identification likelihoods, $\mathcal{L}_K/(\mathcal{L}_K + \mathcal{L}_\pi)$, constructed using information from the central drift chamber (CDC), time-of-flight scintillation counters, and aerogel threshold Cherenkov counters, be larger or smaller than 0.6, respectively. For both kaons and pions, the efficiencies and misidentification probabilities are 86% and 14%, respectively.

For photon selection, we require the energy of the candidate photon to be greater than 60 MeV (100 MeV) when the candidate photon is reconstructed in the barrel (end cap) calorimeter that covers $32° < \theta < 130°$ ($12° < \theta < 32°$ or $130° < \theta < 157°$) in the polar angle θ with respect to the $+z$ axis. To reject neutral hadrons, the ratio of the energy deposited by a photon candidate in the 3×3 and 5×5 calorimeter arrays centered on the crystal with the largest signal is required to exceed 0.85.

Candidate π^0 mesons are reconstructed from pairs of γ candidates; we require $M_{\gamma\gamma} \in [120, 150]$ MeV$/c^2$ and refit γ momenta with the π^0 mass constraint.

Candidate $K_S^0 \to \pi^+\pi^-$ mesons are reconstructed from two tracks, assumed to be pions, using a neural network technique [17] that uses the following information: the K_S^0 momentum in the laboratory frame; the distance along z between the two track helices at their closest approach; the K_S^0 flight length in the transverse plane; the angle between the K_S^0 momentum and the vector joining the K_S^0 decay vertex to the IP; the angles between the pion momenta and the laboratory-frame direction in the K_S^0 rest frame; the distances of closest approach in the transverse plane between the IP and the two pion helices; and the pion hit information in the SVD and CDC. We also require that the $\pi^+\pi^-$ invariant mass be within ± 9 MeV$/c^2$ (about 3σ in resolution [18]) of the nominal K_S^0 mass [19].

For the $\eta \to \pi^+\pi^-\gamma$ candidates, we require that the photon not be associated with a π^0 candidate and its transverse momentum be greater than 200 MeV$/c$ to remove $D^{*+} \to D^+(\to K_S^0\pi^+\pi^-\pi^+)\gamma$ background. For both $\eta \to \pi^+\pi^-\gamma$ and $\eta \to \pi^+\pi^-\pi^0$ candidates, we perform a vertex fit with the two charged pions and require the reduced χ^2 to be less than 10. The efficiency of this requirement is 94%. We require the reconstructed mass of each η candidate to be in the range $[500, 600]$ MeV$/c^2$ and refit momenta of its daughters with the constraint of the nominal η mass.

Combinations of a K_S^0 candidate and η candidate are fit to a common vertex and their invariant mass is required to be within ± 40 MeV$/c^2$ of the nominal D^0 mass. The D^0 and π^+ combinations are fitted to the IP, and the mass difference

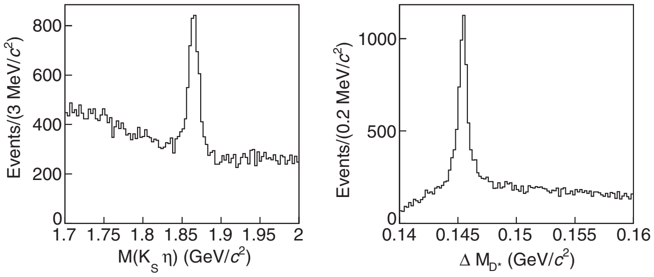

FIG. 1. Invariant mass of the $K_S^0\eta$ combinations (left) and the $D^* - D^0$ mass difference (right) for $\eta \to \pi^+\pi^-\gamma$ decays.

$\Delta M_{D^*} = M(K_S^0\eta\pi^+) - M(K_S^0\eta)$ is required to satisfy $\Delta M_{D^*} \in [143, 148]$ MeV$/c^2$. To remove the combinatorial background, the momentum of the D^{*+} candidates, measured in the center-of-mass system, is required to be greater than 2.5, 2.6, and 3.0 GeV$/c$ for the data taken below, at, and above the $\Upsilon(4S)$ resonance, respectively. Figure 1 shows the invariant mass of the $K_S^0\eta$ combinations (left) and the mass difference (right) for $\eta \to \pi^+\pi^-\gamma$ decays after applying all selection criteria described above, except the mass requirements themselves. Figure 2 shows the invariant mass of the $\pi^+\pi^-\gamma$ combinations after all requirements. There are clear peaks of signal events in all distributions; the increase of the background at low masses in the $M(\pi^+\pi^-\gamma)$ distribution is due to the feed-down from the $\eta \to \pi^+\pi^-\pi^0$ decays when a photon from π^0 is not reconstructed.

To extract the signal yield, we perform a binned maximum likelihood fit to the $M(\pi^+\pi^-\gamma)$ distribution. The fit function is the sum of the signal, the combinatorial background, and the feed-down background components. The signal probability density function (PDF) is the sum of a Gaussian and a bifurcated Gaussian with the ratios of widths fixed from the MC simulation. A linear function is used for the combinatorial background PDF. The feed-down contribution is described by a Gaussian with shape parameters fixed from the MC simulation. The confidence level (p-value) of the fit is 12% and the $\eta \to \pi^+\pi^-\gamma$ signal yield is $N_\eta = 2974 \pm 90$ events. The feed-down yield agrees well with the expectation.

As a cross-check, we measure the ratio of branching fractions $\mathcal{B}(\eta \to \pi^+\pi^-\gamma)/\mathcal{B}(\eta \to \pi^+\pi^-\pi^0)$. The fit to the $\pi^+\pi^-\pi^0$ invariant mass distribution is similar to the one described above, except that the combinatorial background is described by a second-order polynomial and there is no feed-down background. The reconstruction efficiencies, determined from the MC simulation, are $\varepsilon(\pi^+\pi^-\gamma) = 5.1\%$ and $\varepsilon(\pi^+\pi^-\pi^0) = 4.8\%$. The measured ratio of branching fractions, 0.185 ± 0.007, where the uncertainty is statistical only, is in good agreement with the world-average value of 0.184 ± 0.004 [19].

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.

To describe the $M(\pi^+\pi^-)$ distribution, we use an expression of the differential decay rate based on low-energy quantum chromodynamics phenomenology [20,21] using a combination of chiral perturbation theory and dispersive analysis,

$$\frac{d\Gamma}{ds} \propto |P(s)F_V(s)|^2(m_\eta^2 - s)^3 s(1\text{–}4m_\pi^2/s)^{3/2}, \qquad (1)$$

where $s \equiv M(\pi^+\pi^-)^2$, $P(s)$ is a reaction-specific perturbative part, and $F_V(s)$ is the pion vector form factor. We use $|P(s)| = 1 + (1.89 \pm 0.64)s$ [20] and $|F_V(s)| = 1 + (2.12 \pm 0.01)s + (2.13 \pm 0.01)s^2 + (13.80 \pm 0.14)s^3$

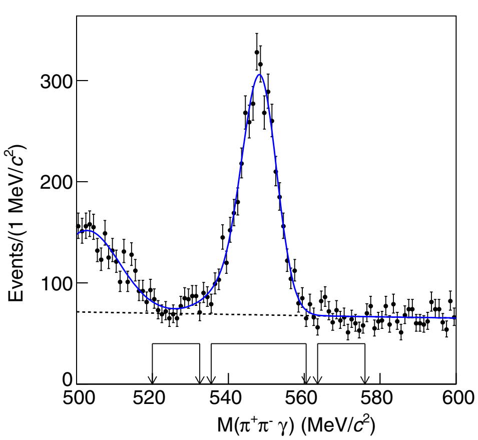

FIG. 2. Invariant mass distribution of the $\pi^+\pi^-\gamma$ combinations (points with error bars), fit result (solid curve), and combinatorial background component (dashed line) of the fit function. Arrows with lines indicate boundaries of the signal and sideband regions.

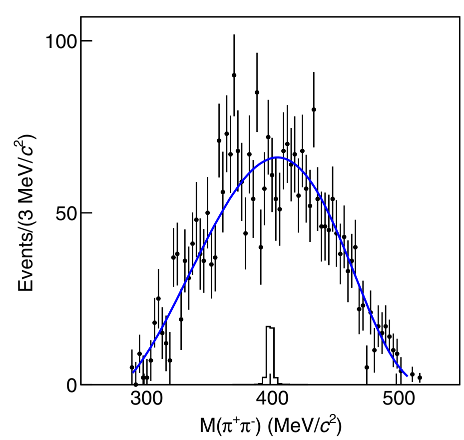

FIG. 3. $\pi^+\pi^-$ invariant mass distribution from the $\eta \to \pi^+\pi^-\gamma$ signal (points with error bars), the fitted differential decay rate described in Eq. (1) (solid curve), and an example U' signal at a mass of 400 MeV$/c^2$ from $\eta \to U'\gamma$, $U' \to \pi^+\pi^-$ (histogram with arbitrary normalization).

[21] (s in GeV^2/c^4). The numerical values and the uncertainties of the expansion coefficients of $|P(s)|$ and $|F_V(s)|$ are taken from fits to data of $\eta^{(\prime)} \to \pi^+\pi^-\gamma$ decays. We multiply the $d\Gamma/ds$ expression from Eq. (1) by the reconstruction efficiency. The efficiency as a function of $M(\pi^+\pi^-)$ is approximately flat but drops to 0 at the kinematic limit of m_η. The fit results are presented in Fig. 3. Equation (1) describes the $M(\pi^+\pi^-)$ distribution well, and the confidence level of the fit is 95%.

We add the U' signal to the above fit function and perform fits while fixing the U' mass at a value between 290 and 520 MeV/c^2 in steps of 1 MeV/c^2. The U' signal is described by the sum of two Gaussians. The signal resolution of the core Gaussian is about 1 MeV/c^2 near the $2m_\pi$ threshold and 2 MeV/c^2 at the m_η kinematic limit. An example of the U' signal with the mass of 400 MeV/c^2 and arbitrary normalization is shown in Fig. 3. We do not find a significant U' signal at any mass value. The typical uncertainty in the U' yield $N_{U'}$ is $\mathcal{O}(1\text{–}10)$ events.

We express the baryonic fine structure constant $\alpha_{U'}$ using the equation for the partial width ratio $\Gamma(\eta \to U'\gamma)/\Gamma(\eta \to \gamma\gamma)$ from Ref. [10] as

$$\alpha_{U'} = \left[\frac{\alpha}{2}\left(1 - \frac{m_{U'}^2}{m_\eta^2}\right)^{-3}\left|\mathcal{F}(m_{U'}^2)\right|^{-2}\frac{1}{\mathcal{B}(U' \to \pi^+\pi^-)}\right] \times \left[\frac{\Gamma(\eta \to \pi^+\pi^-\gamma)}{\Gamma(\eta \to \gamma\gamma)}\right]\left[\frac{\Gamma(\eta \to U'\gamma \to \pi^+\pi^-\gamma)}{\Gamma(\eta \to \pi^+\pi^-\gamma)}\right], \quad (2)$$

where α is the electromagnetic fine structure constant. The first factor in Eq. (2), which is purely theoretical, contains the phase space, the form factor $\mathcal{F}(m_{U'}^2)$, and the branching fraction of $U' \to \pi^+\pi^-$ decay. The branching fraction is about 2%–4%, as computed from formulas provided in Ref. [10] and references therein. The second factor is obtained from the latest measurements [19]. The third factor is determined from the η and U' yields and reconstruction efficiencies $(N_{U'}/\varepsilon(\eta \to U'\gamma \to \pi^+\pi^-\gamma))/(N_\eta/\varepsilon(\eta \to \pi^+\pi^-\gamma))$.

To estimate the systematic uncertainties in the $\eta \to \pi^+\pi^-\gamma$ and $\eta \to U'\gamma \to \pi^+\pi^-\gamma$ yields, we change the parametrization of the combinatorial background in the $M(\pi^+\pi^-\gamma)$ fit from a first- to a second-order polynomial and account for the background nonlinearity while subtracting the sidebands. The change in the η yield is at the 1% level, while the change in the U' yield is negligible. The systematic effect due to the uncertainties of the expansion coefficients in $|P(s)|$ and $|F_V(s)|$ is negligible in the U' yield. The systematic uncertainty in the ratio of the reconstruction efficiencies $\varepsilon(\eta \to U'\gamma \to \pi^+\pi^-\gamma)/\varepsilon(\eta \to \pi^+\pi^-\gamma)$ is conservatively estimated to be 4% (1% per track and 3% per photon). The total systematic uncertainties are estimated by adding the above contributions in quadrature.

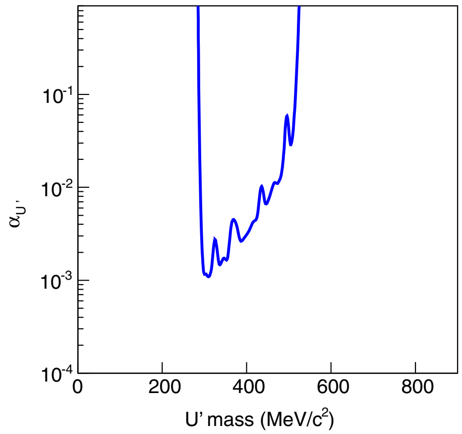

FIG. 4. Computed 95% upper limit on the baryonic fine structure constant $\alpha_{U'}$ as a function of the unknown U' mass (solid curve).

Using Eq. (2), we set a 95% confidence level upper limit on $\alpha_{U'}$ using the Feldman-Cousins approach [22], adding the statistical and systematic uncertainties in quadrature. The upper limit as a function of the U' boson mass is shown in Fig. 4. Considering other results in this mass region, we find that our limit is stronger than that from a model-dependent analysis [10] of the $\phi \to e^+e^-\gamma$ decays [12] for $m_{U'} > 450$ MeV/c^2, but weaker than the limit based on the $\eta \to \pi^0\gamma\gamma$ total rate [10]. Recently, we learned that the data set in Ref. [23] contains many more $\eta \to \pi^+\pi^-\gamma$ decays and can provide a more stringent limit on $\alpha_{U'}$ in future.

To conclude, we perform a search for a dark vector gauge boson U' that couples to quarks [10], using the decay chain $D^{*+} \to D^0\pi^+$, $D^0 \to K_S^0\eta$, $\eta \to U'\gamma$, $U' \to \pi^+\pi^-$. Our results limit the baryonic fine structure constant $\alpha_{U'}$ to below 10^{-3}–10^{-2} at 95% confidence level over the U' mass range 290 to 520 MeV/c^2. This is the first search for U' in the $\pi^+\pi^-$ mode. We find that our limit is stronger than that from a model-dependent analysis [10] of the $\phi \to e^+e^-\gamma$ decays [12] for $m_{U'} > 450$ MeV/c^2, but weaker than the limit based on the $\eta \to \pi^0\gamma\gamma$ total rate [10].

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