Search for dark photon and long-lived particles at BABAR

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Abstract: We use the complete large and clean sample of e^+e^- collisions recorded by the BABAR detector at PEP-II at the SLAC National Laboratory to search for a photon-like particle with mass and decaying into an e^+e^- or $\mu^+\mu^-$ pair, which is proposed in some Dark Matter theory models, and to search for a long-lived particle that decays into an oppositely charged fermion pair, predicted in a number of New Physics models. We do not observe a significant signal and we set 90% confidence level upper limits of several production rates and on the parameters of some proposed New Physics models.

Key words: New Physics, Dark Matter, B-Factory

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1 Introduction

Well motivated New Physics (NP) models predict the existence of several new particles that are not yet excluded by experiment. The BABAR experiment has collected large samples of clean e^+e^- collisions with a general purpose full solid-angle detector at and around the $\Upsilon(4S)$ on the PEP-II storage ring at the SLAC National Laboratory. This data sample is well suited to search for kinematically allowed NP particles that are rarely produced and may have escaped previous searches. The results of two recent searches for NP light particles with BABAR are reported in the following.

2 Search for Dark Photon into e^+e^- or $\mu^+\mu^-$

Light NP particles may be loosely coupled with ordinary matter through "portals" [1], which provide interactions between the Standard Model (SM) fields and "dark" fields, which can be scalar, pseudoscalar, vector or spin 1/2 fermions. A model for weakly interacting Dark Matter particles predicts [2] the existence of a "Dark Photon" A' with mass around 1 GeV, which interacts with the SM particles via a "kinetic mixing" term $\Delta\mathcal{L} = (\epsilon/2)F^{Y,\mu\nu}F'_{\mu\nu}$, with a coupling constant $\epsilon \ll 1$.

A search for A' production in the process $e^+e^- \to \gamma A' \to \gamma\ell^+\ell^-$ ($\ell^\pm = e^\pm$ or $\mu^\pm$ (Fig. 1) has been conducted on the whole BABAR data sample of 514 fb^{-1} [3]. The A' branching ratios into $\ell^+\ell^-$ are expected to be sizeable over the whole hypothetical mass range [4] (see also Fig. 2). With respect to the process $e^+e^- \to \gamma\gamma$, the cross-section for this process is reduced by a factor ϵ^2.

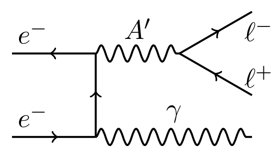

Fig. 1. Diagram for $e^+e^- \to \gamma A' \to \gamma\ell^+\ell^-$.

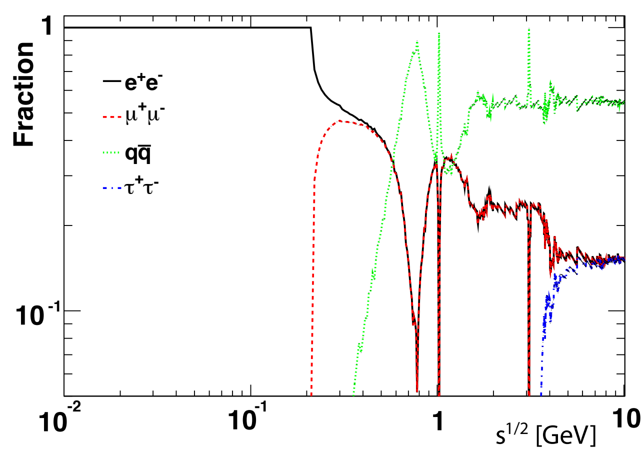

Fig. 2. Branching fraction predictions for $A' \to \ell^+\ell^-$ and $A' \to q\bar{q}$ as a function of $m_{A'}$[4].

We select events with a final state containing two oppositely-charged leptons and a photon and do a kinematic fit of the reconstructed track parameters to match the center-of-mass (CM) energy with the constraint that all three particles come from the interaction point (IP). We suppress background removing events consistent with having an electron conversion and requiring a good-quality photon. According to simulation, which is consistent with the data, the selection efficiency is typically 15% (35%) for the electron pair (muon pair) channel.

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We search for a signal peak on top of a smooth background in the lepton pair invariant mass, which is fitted from the sidebands. Therefore, we do not need to accurately simulate the expected SM candidates yield. We nevertheless perform a Monte Carlo (MC) simulation and find that the simulation is reasonably accurate except in the m_{ee} low-mass region, where radiative Bhabha simulation (performed with BHWIDE [5]) is known to be relatively less reliable. Further details are in the *BABAR* publication [3]. In order to get a smoother behaviour at threshold, we consider for muons the reduced mass $m_R = \sqrt{(m^2_{\mu\mu} - 4m^2_\mu)}$ rather than the invariant mass. Figure 3 shows the mass and reduced mass distributions in data and simulation.

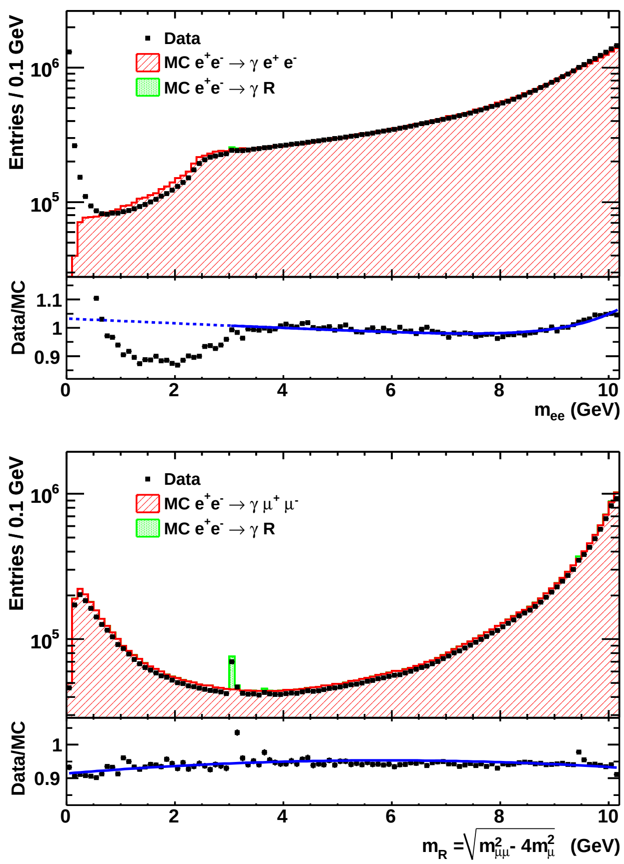

Fig. 3. Electron pair mass spectrum (top) and muon pair reduced mass spectrum (bottom) for data and simulaation. On the bottom the data/simulation ratio is reported.

We fit the signal yield on about 5500 steps in the mass m, with a variable step size close to half the mass resolution, and on mass intervals 20−30 times broader than the mass resolution. We use a likelihood function that includes a signal peak centered on m over a polynomial background. The signal peak shape depends on the mass and is interpolated from simulated events, which are tuned by comparing data and simulation on known resonances.

In the vicinity of known resonances [ω, ϕ, J/ψ, ψ(2S), $\Upsilon(1S, 2S)$], the resonance peaks are escluded from the scan, the resonance is fitted on data, and the resonance tails are added to the likelihood in addition to the signal and non-peaking background components. For the ω and ϕ resonances, their interference with the non-resonant channel is also fitted and used in the maximum likelihood fits of the neighouring masses.

In the fit, the signal component can be negative, but the probability is constrained to be non-negative. We determine the "local" significance of each fit as $S = \sqrt{2 \log{(L/L_0)}}$, where L and L_0 are the maximum likelihood values for fits with and without freely varying signal, respectively. The largest local significance is 3.4σ (2.9σ) for electron pairs (muon pairs). Since we search for signal in many mass hypotheses, we estimate the significance of the whole scan by determining the trial factors with a large sample of simulated Monte Carlo experiments. With this correction, the "global" significance of the two scans is 0.57 (0.94) for electron pairs (muon pairs).

In absence of signal evidence, we compute 90% confidence level (CL) Bayesian upper limits on the cross-section $e^+e^- \to \gamma A'$, combining both channels. The determination uses the *BABAR* luminosity (with ∼0.6% uncertainty), the estimated efficiency (with 0.5−4% uncertainty) and the predicted branching fractions in Ref. [4] (with 0.1%−4% uncertainty) and models the respective uncertainties with Gaussian distributions. The muon pair final state search is significantly more powerful than the electron pair for $m > 212\,\text{MeV}$ because its backgrounds are smaller. From the cross-section limits we derive limits on the Dark Photon coupling constant ϵ as a function of its mass m according to Ref. [4]. Results are shown in Figure 4.

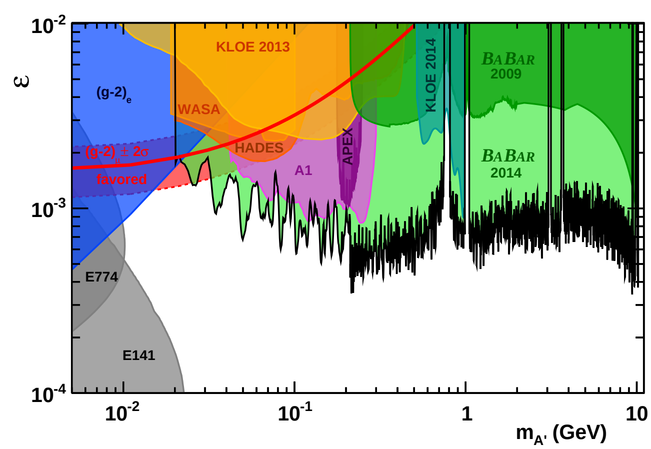

Fig. 4. Upper limit (90% CL) on the mixing strength ϵ as a function of the dark photon mass. The values required to explain the discrepancy

between the calculated and measured anomalous magnetic moment of the muon [6] are displayed as a red line.

Bounds in the range $10^{-4} - 10^{-3}$ for $0.02 < m_{A'} < 10.2\,\text{GeV}$ are set, significantly improving previous constraints derived from beam-dump experiments [7–9], the electron anomalous magnetic moment [10], KLOE [11, 12], WASA-at-COSY [13], HADES [14], A1 at MAMI [15], and the test run from APEX [16].

These results improve and supersede existing constraints obtained from a *BABAR* search for a light *CP*-odd Higgs boson [17, 18] using a smaller dataset. We reduce the experimentally allowed parameter space that could explain with a Dark Photon the discrepancy between the calculated and measured anomalous magnetic moment of the muon [6].

3 Search for Long-Lived Particles in e^+e^- Collisions

When NP particles are weakly coupled to standard matter, they can be long-lived if they are restricted to decay to SM particles [19]. Recent anomalous astrophysical observations have induced the elaboration of several NP models that include low-mass, long-lived hidden-sector states, such as dark photons [19–22], an inflaton [23], supersymmetry [24, 25], a dark Higgs boson [26] and with other dark-sector states [27].

Experiments have mostly searched for such long-lived particles at small masses under 1 GeV [8, 28, 29] and in the multi-GeV mass range [30–34]. The *BABAR* collaboration has completed a search that is sensitive to masses $\mathcal{O}(\text{GeV})$ [35].

At the B factories, a hidden-sector scalar particle may be produced in an Υ radiative decay or in a B penguin decay and, in turn, may decay into a pair of fermions as shown in Fig. 5.

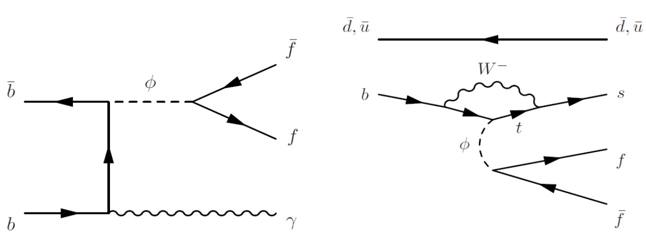

Fig. 5. Lowest-order diagrams for the production of a long-lived dark scalar particle in radiative Υ decays (left) and in penguin decays of B mesons (right).

We completed a model-independent search for inclusive production of a long-lived particle L in the process $e^+e^- \to LX$, where L decays at a displaced vertex into any of six different final states, $e^+e^-, \mu^+\mu^-, e^\pm\mu^\mp, \pi^+\pi^-, K^+K^-$ and $K^\pm\pi^\mp$. Except for 20 fb^{-1} taken at the $\Upsilon(4S)$, which where used to test the analysis, we use the entire *BABAR* data collected at the $\Upsilon(4S)$, 40 MeV below the $\Upsilon(4S)$ peak, at the $\Upsilon(2S)$, and $\Upsilon(3S)$, corresponding to a luminosity of 489.1 fb^{-1}.

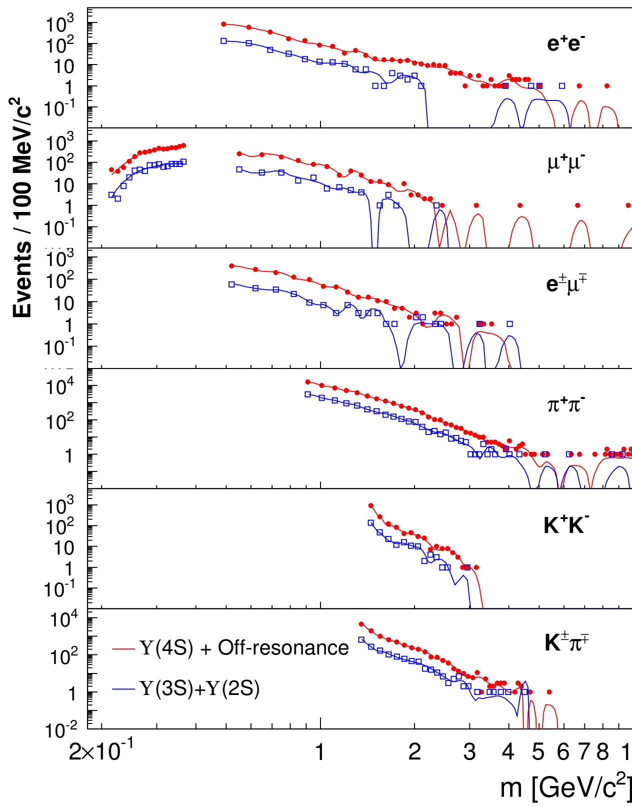

Fig. 6. Observed mass distribution for $\Upsilon(4S)+$ off-resonance data (red solid points), for $\Upsilon(3S) + \Upsilon(2S)$ data (blue open squares) as a function of mass m for each final state with the background PDF P_B overlaid (red, blue solid lines).

We reconstruct L from two oppositely-charged tracks that originate from a common vertex with distance to the beam line in the transverse plane from 1 to 50 cm. The resolution on the radial distance of the fitted vertex must be smaller than 0.2 cm. We require that both tracks have impact parameters with respect to the beam line larger than 3 times the resolution. We reject background from K_S^0 and Λ decays, and we skip searching for signal in several low-mass regions with problematic structures in the mass distribution by requiring, depending on the final state, that $m_{e^+e^-} > 0.44\,\text{GeV}$, $m_{\mu^+\mu^-} < 0.37\,\text{GeV}$ or $m_{\mu^+\mu^-} > 0.5\,\text{GeV}$, $m_{e^\pm\mu^\mp} > 0.48\,\text{GeV}$, $m_{\pi^+\pi^-} > 0.86\,\text{GeV}$, $m_{K^+K^-} > 1.35\,\text{GeV}$, and $m_{K^\pm\pi^\mp} > 1.05\,\text{GeV}$. According to a Monte Carlo simulation, surviving background consists primarily of hadronic events with high track multiplicity, where large-d_0 tracks originate mostly from K_S^0, Λ, $K^\pm$, and $\pi^\pm$ decays, as well as particle interactions with detector material. Random overlaps of such tracks comprise the majority of the background candidates.

Fig. 6 shows the mass distributions of the signal candidates (with uniform mass bins) together with the respective background PDFs.

We scan for a signal mass peak over a smooth background with an extended unbinned maximum likelihood fit with a polynomial background and a signal peak corresponding to a mass m whose shape and width we determine from a Monte Carlo simulation for 11 mass hypotheses. We repeat the fit in steps of 2 MeV. We determine the significance of the signal yield as $S = \sqrt{2\log(L/L_0)}$, where L and L_0 are the maximum likelihood values for fits with and without freely varying signal, respectively.

For each final state mass scan, we determine the background-only hypothesis p-values of the largest found signal significances with positive signal yields using a large amount of background-only toy Monte Carlo simulations. No evidence of signal was found, hence we compute upper limits on the product $\sigma(e^+e^- \to LX)\,\mathrm{BF}(L \to f)\ \epsilon(f)$ using the signal yield and the estimated *BABAR* integrated luminosity. We determine the signal yield profile likelihood using convolutions with Gaussians to account for systematic uncertainties on the signal efficiency (obtained from a Monte Carlo simulation) and on the background likelihood term. We obtain Bayesian 90% CL upper limits using a flat prior, shown in Figure 7.

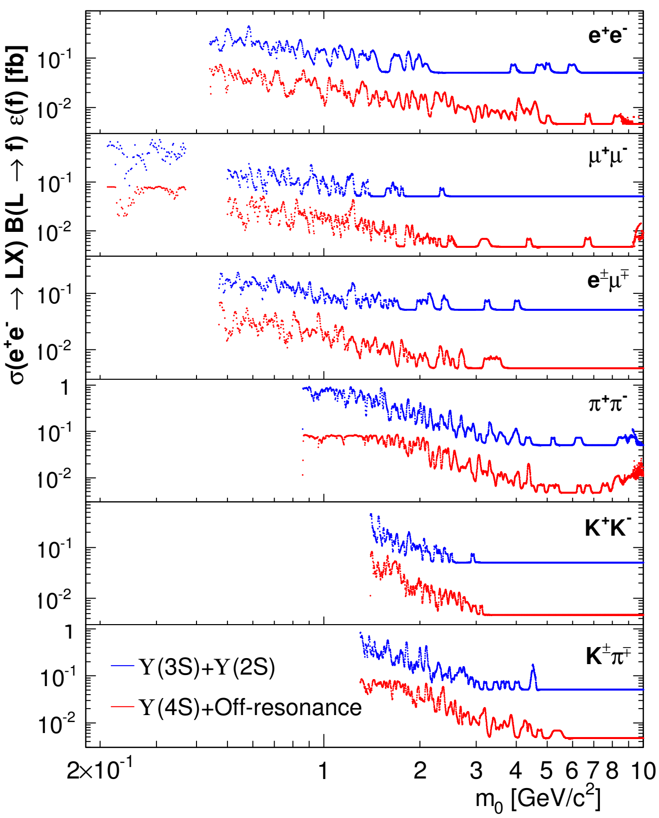

Fig. 7. Upper limits on the cross section σ_f as a function of L mass for each final state (left) for $\Upsilon(4S)$ data (lower red curves) and for $\Upsilon(3S)+\Upsilon(2S)$ data (upper blue curves) and on the product branching fraction $\mathcal{B}_{Lf}$ (right) for different decay lengths.

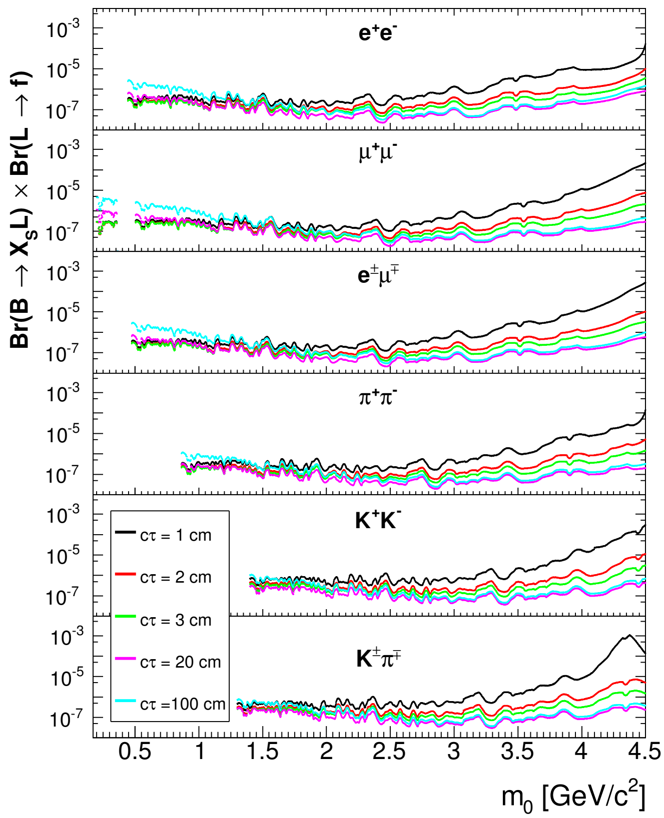

Fig. 8. Upper limits on $\mathcal{B}_{Lf} = \mathcal{B}(B \to LX_s)\cdot\mathcal{B}(L \to f)$ as a function of the L mass for a selection of lifetimes.

For the purpose of testing specific NP models, the signal efficiency has been estimated with a Monte Carlo simulation using 11 L masses. The simulation used lifetime large enough to populate the acceptance in the radial distance of the displaced vertex. With appropriate weighting, shorter signal lifetimes are then properly simulated. The estimated signal efficiencies as a function of the mass, the lifetime and the transverse momentum are provided to allow model testing [35].

We used the results to set constraints on a specific model where L is produced in B decays via $B \to LX_s$ where X_s is a hadronic state with strangeness S=-1 as in Higgs portal [23–26] and axion-portal [36] models of dark matter. By simulating the detection efficiency with this production model, we obtained limits on the product branching fraction $\mathcal{B}_{Lf} = \mathcal{B}(B \to LX_s) \cdot \mathcal{B}(L \to f)$, shown in Figure 8. These limits exclude a significant region of the parameter space of the inflaton model [23].

4 Conclusion and Outlook

The e^+e^- collision data recorded by *BaBar* have been used to search for new particles that are predicted by several New Physiscs models. We did not find evidence for any signal beyond the Standard Model and we obtained significant experimental constraints to present and future theory models.

No dark photon has been found in the 0.02−10.2 GeV mass region, constraining the kinetic mixing parameter ϵ to be less than 10^{-4} to 10^{-3} depending on the dark photon mass.

We do not find evidence of non-SM long-lived particle in the $0.2 < m < 10\,\mathrm{GeV}$ mass range and proper decay lengths of $0.5 < c\tau < 100$ cm and we publish appropriate 90% CL upper limits on the product $\sigma(e^+e^- \to LX) \cdot \mathcal{B}(L \to f) \cdot \epsilon_f$.

Belle has collected about twice the amount of *BaBar* events, and has good prospects of improving part of the above measurements. BelleII with 50 ab^{-1} and an improved trigger for light New Physics searches will be able to ameliorate all the presented limits by one order of magnitude or more.

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