PROCEEDINGS OF SCIENCE

Search for Invisible Dark-Photon Decay at BABAR

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We report on a search for single-photon events in 53 fb^{-1} of data collected with the BABAR detector. We look for events consistent with production of a dark photon (A') through the process $e^+e^- \to \gamma A'$, $A' \to$ *invisible*. Such particles are motivated by the possible existence of a $U(1)$ gauge charge for dark matter. We find no evidence for this process and set limits on the A'-photon coupling for a dark photon mass below 8 $\mathrm{GeV/c^2}$. These results greatly improve upon previous bounds, and exclude the range of values suggested by the dark-photon interpretation of the muon $(\mathrm{g}-2)$ anomaly.

The XXXIX International Conference on High-Energy Physics (ICHEP 2018)
4-11 July, 2018
Seoul, South Korea

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†This work was supported by Norwegian Research Council. I would like to thank the BABAR collaboration for the opportunity to present these results, in particular I would like to thank J. McKenna, B. Shuve and F.C. Porter for useful discussions.

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1. Introduction

Different measurements indicate the existence of dark matter. The measured galactic rotation curves differ from the expectation of baryonic mass [1]. Gravitational lenses bend light producing mirror images of galaxies [2] but 80% of the mass is non-baryonic. In the bullet cluster, which consists of two colliding galaxies [3], the center-of-gravity of its mass is separated by 8σ from the center-of-gravity of the baryonic mass. The observed pattern of Cosmic Microwave Background requires most mass to be non-baryonic. [4]. So, what is dark matter? Is it new particles, a gravitational effect, black holes or a combination of all of the above? So far we have seen only gravitational effects of dark matter. We have not observed any new particles yet. Searches at the LHC and in dedicated astro-particle physics experiments are ongoing.

In the past, dark matter (DM) particles have been associated with new heavy particles predicted in extensions of the Standard Model (SM). Since several dedicated WIMP searches have not found any signal, theorists considered light-mass dark-matter scenarios [5] since the low-mass DM scenarios evade conventional WIMP searches. The SM may be connected to the dark sector through so-called portals, links that couple the dark sector to the SM via the lowest-dimensional operators. At low-energy scales, the vector portal is among the most accessible links in which the electromagnetic field tensor $F^{\mu\nu}$ interacts with the corresponding dark photon field tensor $F'_{\mu\nu}$ that is associated with a new $U(1)_{Dark}$ symmetry. Dark photons A' couple to the SM with a mixing strength $\varepsilon^2\alpha$, where α is the electromagnetic coupling constant and ε is the mixing parameter. *BABAR* already searched for dark photons in different visible final states [6].

2. Analysis for Invisible Dark Photons

We have searched for dark photons in the initial-state radiation process $e^+e^- \to \gamma A'$ with decay to invisible neutral particles χ, $A' \to \chi\chi$ [7]. The experimental signature is a single photon plus missing energy and missing momentum in the recoil. The search is based on 53 fb^{-1} of *BABAR* data at the Υ(2S), Υ(3S) and Υ(4S) selected with a special single-photon trigger. We split the search into a low-mass $A' < 5.5$ GeV/c^2 and a high-mass $A' > 5.5$ GeV/c^2 region.

In the low-mass region, the main background originates from $e^+e^- \to \gamma\gamma$ as one photon may escape detection in the *CsI* crystals. For isolated photons with energy $E^*_\gamma > 3$ GeV[1] having no drift chamber tracks with momenta $p^* > 1$GeV/c, we define a multivariate boosted decision tree discriminant trained with 12 discriminating variables. In the high-mass region the main background comes from $e^+e^- \to e^+e^-\gamma$ in which both the e^+ and e^- escape detection. For isolated photons (1.5 GeV $< E^*_\gamma <$3 GeV) having no tracks with $p^* > 0.1$ GeV/c, we train another BDT discriminant. For signal the BDT discriminant peaks at $+1$, while the BDT discriminant is negative for most of the background. We optimize the event selection to minimize the expected upper limit on the $e^+e^- \to \gamma A'$ cross section. We define different selections. For low $m_{A'}$, the tight selection $\mathscr{R}_T$ maximizes ε_S/N_B for large N_B and $\varepsilon_S/2.3$ in the limit $N_B \to 0$ where ε_S is the signal selection efficiency and N_B is the number of background events. An additional loose selection $\mathscr{R}'_L$ maximizes $\varepsilon_S/\sqrt{N_B}$ for events not included in $\mathscr{R}_T$. For high $m_{A'}$, $\mathscr{R}_L$ is a loose selection that maximizes $\varepsilon_S/\sqrt{N_B}$ and $\mathscr{R}_B$ is the background selection for both regions defined by $-0.5 < \mathscr{R}_B < 0$.

[1] The $*$ indicates observables defined in the center-of-mass frame (CM).

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Since the number of peaking $e^+e^- \to \gamma\gamma$ events cannot be estimated reliably for the low m'_A, we extract it from the fit to data. We measure the cross section $\sigma_{A'}$ as a function of $m_{A'}$ by performing a series of extended maximum likelihood fits in which we vary $m_{A'}$ from zero to 8 GeV in 166 steps (half the mass resolution). For low $m_{A'}$ we perform simultaneous fits to the $\Upsilon(2S)$, $\Upsilon(3S)$ and $\Upsilon(4S)$ data sets using selections $\mathscr{R}_T$, $\mathscr{R}'_L$ and $\mathscr{R}_B$. For high $m_{A'}$ we perform simultaneous fits to the $\Upsilon(2S)$ and $\Upsilon(3S)$ data sets using selections $\mathscr{R}_L$ and $\mathscr{R}_B$. The mass resolution decreases with m'_A as $1.5-0.7$ GeV^2. The background probability density function (PDF) consists of peaking background parametrized by a Crystal Ball function and a sum of exponentiated polynomials. The signal efficiencies vary slowly with $m_{A'}$ as $2.4\%-3.1\%$ for $\mathscr{R}_T$ and as $3.4\%(2.0\%)-3.8\%(0.2\%)$ for $\mathscr{R}'_L$ ($\mathscr{R}_L$). The largest systematic uncertainties in the signal yield result from the shapes of signal and background PDFs and errors in the efficiency of signal and trigger selections. The total systematic error of 5% is small with respect to the statistical uncertainty.

3. Results

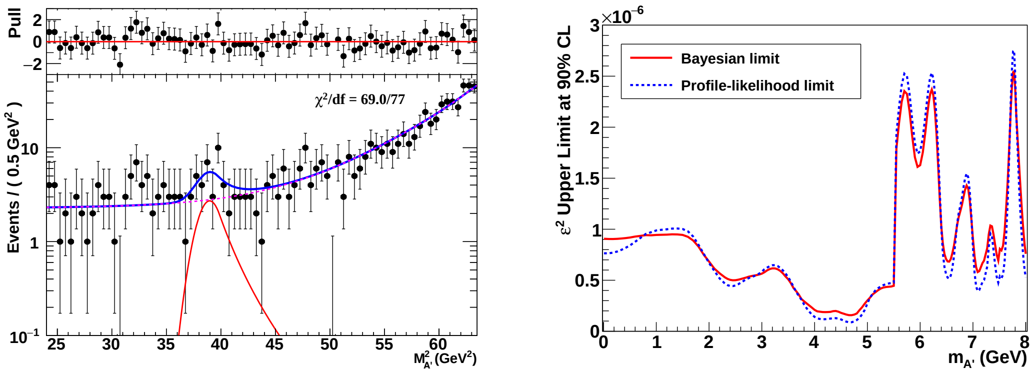

Figure 1: Left: Event yield versus $m_{A'}$ showing the largest observed signal yield at 6.2 GeV (2.6σ global significance) with the fit results (blue line), signal PDF (red line) and background PDF (magenta dashed line) overlaid. Right: Upper limits at 90% CL for ε^2 versus $m_{A'}$ comparing a Bayesian limit computed for a uniform prior for $\varepsilon^2 > 0$ (red solid line) and the profile likelihood limit (blue dashed line).

We observe no significant signal. In the low $m_{A'}$ region the largest fluctuation is less than 2σ. Figure 1 (left) shows the high $m_{A'}$ region for the $\Upsilon(2S)$ and $\Upsilon(3S)$ data sets combined. The most significant deviation from zero occurs at $m_{A'} = 6.21$ GeV/c^2 with a local significance of 3.1σ and a global significance of 2.6σ. A fit to a signal at 6.21 GeV/c^2 plus background is superimposed on the data. We set upper limits on the mixing strength squared ε^2 at 90% confidence level (CL). Figure 1 (right) shows the 90% CL upper limits on ε^2 in the $0 < m_{A'} < 8$ GeV/c^2 mass range using both a Bayesian method with a uniform prior for $\varepsilon^2 > 0$ and a frequentist profile likelihood method. Figure 2 (left) shows the region in ε versus $m_{A'}$ space excluded by this analysis in comparison to previous constraints [8] and the region of parameter space consistent with the $(g-2)_\mu$ anomaly [9]. Our results yield significant improvement over those of previous experiments placing stringent constraints on dark-sector models over a broad range of parameter space. They exclude that the $(g-2)_\mu$ anomaly results from dark photon models with invisible decays.

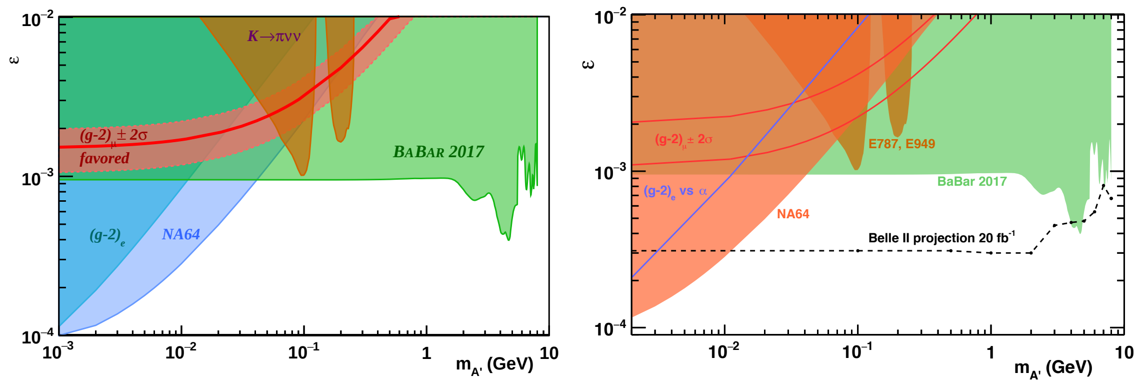

Figure 2: Left: Regions of ε versus $m_{A'}$ excluded by the present analysis (green area) in comparison to previous constraints [8] and the region preferred by the $(g-2)_\mu$ anomaly [9]. Right: Expected Belle II exclusion region in ε versus $m_{A'}$ for an integrated luminosity of 20 fb^{-1} [10] (black dashed line) in comparison to previous constraints.

4. Conclusion

We have searched for invisible decays of dark photons and see no signal. The largest fluctuation at 6.21 GeV/c^2 has a significance of 3.1σ locally and 2.6σ globally. We set 90% CL upper limits on the mixing strength squared ε^2. We exclude that the $(g-2)_\mu$ anomaly originates from dark-photon models with invisible decays. Improvements on the *BABAR* results will come from Belle II [10]. Figure 2 (right) shows the expected exclusion region for 20 fb^{-1} of Belle II data. The improvement at low $m_{A'}$ results from a better calorimeter hermeticity that improves the $e^+e^- \to \gamma\gamma$ suppression. Belle II reaches masses up to 9.1 GeV/c^2 with lower trigger threshold yielding improvements at high $m_{A'}$.

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