Search for Low-Mass Dark Sector New Physics States at BABAR

Janis McKenna (on behalf of the BABAR Collaboration)

Department of Physics and Astronomy, University of British Columbia,
Vancouver, BC, Canada
E-mail: janis@physics.ubc.ca

Abstract. Recent anomalies observed in astrophysical and terrestrial dark matter search experiments have motivated the proposal of a “dark sector” with GeV-scale gauge boson force carriers and new Higgs bosons. These dark sector bosons would mediate interactions between the dark sector and the Standard Model.

Using the BABAR detector at the PEP-II $e^+e^-$ collider, we have conducted a broad program to search for direct evidence of dark matter via the dark sector. We present four searches for new dark sector particles and find no evidence for dark particles. We set stringent limits on dark sector particle production and coupling strengths. In particular, our limits in each of these four dark sector models essentially exclude values of the dark photon coupling suggested by the dark photon/dark sector interpretation the muon $g_{\mu} - 2$ anomaly.

1. Introduction and Motivation

Indirect astrophysical evidence for dark matter is overwhelming, yet we still have no idea what dark matter is or where it comes from. In the 1930’s Zwicky observed radial velocities of galaxies in the Coma cluster and deduced there was insufficient luminous mass to keep the rotating galaxies from flinging apart[1]. He inferred that there must be unseen non-luminous dark matter in the galaxies.

In the 1970s, Rubin and Ford performed Doppler observations of orbital speeds in spiral galaxies, and determined that stars near the outer edges of galaxies had speeds as fast as the stars closer in, again indicating that there was not enough mass for gravity to hold the stars in orbit. They concluded that about 90% of the mass in galaxies must be in a dark, unseen halo of matter out beyond the luminous mass[2].

More recently, many experiments have been devised to seek, observe and explain the nature of dark matter, but all have yielded null results to date.

2. Dark Sector Models

Observations and anomalies in dark matter searches have motivated new theories beyond the Standard Model which include a “dark sector” containing new particles which couple to the ordinary Standard Model particles via a new dark force. The dark sector could have a rich structure - there may exist more than just one dark matter particle. The lightest particles in the dark sector could have sufficiently low-mass so as to be produced and detected at BABAR PEP-II energies. Searches presented here involve couplings via either a dark photon, $A'$, a dark...
Higgs boson, $h'$, or a dark $Z$ boson, $Z'$. The dark boson width is expected to be below the experimental resolution, and so it could be detected as a narrow resonance in its decay.

3. Searches for the Dark Sector with \textit{BaBar}

We present the results of four different searches for dark sector particles using the \textit{BaBar} detector and dataset. The first three searches were performed using 516 fb$^{-1}$ of data collected with the \textit{BaBar} detector, and the fourth search was performed using 53 fb$^{-1}$. The \textit{BaBar} detector is described elsewhere\cite{3}. For each of the four searches presented here, charged particle tracking, photon calorimetry, and particle identification are performed, and then fiducial and kinematic cuts are applied to these charged and neutral tracks. Full selections and kinematic cuts for each analysis are described in detail in the respective publications\cite{5}\cite{8}\cite{12}\cite{14}. Detector acceptance and reconstruction efficiencies are determined using a GEANT Monte Carlo simulation\cite{4}.

Our searches to date yield null results, which we use to constrain mixing strengths between the Standard Model and the dark sector, as well as the dark sector particle mass.

3.1. Low-Mass Dark Sector Higgs Boson

The first \textit{BaBar} dark sector analysis presented is a search for low mass dark Higgs bosons via the Higgs-strahlung process, $e^{+}e^{-} \rightarrow A'h'$, $h' \rightarrow A'A'$, with each of the three $A'$s decaying to a combination of $e^{+}e^{-}$, $\mu^{+}\mu^{-}$ and $\pi^{+}\pi^{-}$ pairs\cite{5}. The Feynman diagram for this process is shown in Figure 2a). The event topology depends upon the masses of the dark Higgs boson and the dark photon. Events are selected in the fully reconstructed final states $3(\ell^{+}\ell^{-})$, $2(\ell^{+}\ell^{-})\pi^{+}\pi^{-}$, and $\ell^{+}\ell^{-}2(\pi^{+}\pi^{-})$ with $(\ell = e, \mu)$, or in the partially reconstructed final states $2(\mu^{+}\mu^{-}) + X$ and $\mu^{+}\mu^{-}e^{+}e^{-} + X$, where $X$ is any final state other than a pair of leptons or pions. The background to this process is small, and it is only singly suppressed by $\epsilon$, the mixing strength between the Standard Model and the dark sector. The measurement is sensitive to dark photon mass $0.25 < m_{A'} < 4.0$ GeV and dark Higgs mass $0.8 < m_{h'} < 10.0$ GeV with the constraint $m_{h'} > 2m_{A'}$. Our results assume prompt dark Higgs boson and dark photon decays. We see no evidence for a dark sector Higgs boson. Figure 1 shows the resulting 90% CL upper limits on the product $\alpha_{D}\epsilon^2$, where $\alpha_{D} = g_{D}/4\pi$ and $g_{D}$ is the dark sector gauge coupling\cite{6}.

3.2. Dark Photon to Lepton Pair

A second dark sector search was performed using the \textit{BaBar} detector to search for an initial state radiated (ISR) photon and a dark photon decaying to oppositely charged leptons via the reaction $e^{+}e^{-} \rightarrow \gamma_{ISR} A'$, $A' \rightarrow e^{+}e^{-}$, $\mu^{+}\mu^{-}$\cite{8}. The Feynman diagram for this dark photon production and decay is shown in Figure 2b). The initial state radiated photon is required to have energy $> 0.2$ GeV. Particle identification is used to identify at least one electron or both muons. Backgrounds from radiative Bhabha events and converted photons are greatly reduced using kinematic cuts. The dark photon to dilepton resonance is expected to be narrower than the detector resolution. We probe dark photon masses in the range $0.02 < m'_{A} < 10.2$ GeV. The $e^{+}e^{-} \rightarrow \gamma A'$ cross section for each final state is extracted using the expected dark photon branching fractions $A' \rightarrow \ell^{+}\ell^{-}$ from [6]. These results are then translated [7] into 90% CL upper limits in the mixing strength between the photon and dark photon as a function of the dark photon mass, as shown in Figure 3. \textit{BaBar}, together with NA48\cite{10}, excludes the region which could resolve the discrepancy between the calculated and measured anomalous magnetic moment, $g_{\mu} - 2$, of the muon.

3.3. Dark Sector Muonic Dark Force

Our third dark matter search considers the possibility that Standard Model fields may couple to the $Z'$ dark sector boson, which itself couples preferentially to second and third
Figure 1. 90% CL upper limit on the dark photon coupling [5] (Figures in colour online)
a) as a function of the dark photon mass for selected values of dark Higgs boson masses,
b) as a function of the dark Higgs boson mass for selected values of dark photon masses.

Figure 2. Feynman diagrams for the four dark sector searches in this paper:
a) Dark Higgs boson $h'$:
$e^+e^- \rightarrow A'h', \ h' \rightarrow A'\ A' \ (A' \ decays)$
b) Dark photon to lepton pair:
$e^+e^- \rightarrow \gamma_{ISR} \ A', \ A' \rightarrow \ell^+\ell^-, \ \ell = e, \mu$
c) Muonic dark $Z'$ decay:
$e^+e^- \rightarrow Z'\mu^+\mu^-, \ Z' \rightarrow \mu^+\mu^-$
d) Invisible dark photon decay:
$e^+e^- \rightarrow \gamma_{ISR} \ A', \ A' \rightarrow \chi\chi \ (\chi \ invisible)$

generation leptons[12]. The preferential coupling to the heavier leptons makes this dark sector particle a candidate to resolve the discrepancy in the muon anomalous magnetic moment measurements, and also the proton radius puzzle, which is characterized by discrepancies between Lamb shift measurements in muonic hydrogen as compared to nonmuonic atoms and electron-proton scattering experiments[11]. We search for the dark boson $Z'$ via the reaction $e^+e^- \rightarrow \mu^+\mu^-Z', \ Z' \rightarrow \mu^+\mu^-$, which is shown in Figure 2c). Candidates have two pairs of oppositely charged tracks, with either both positively-charged or both negatively-charged muon tracks identified as muons using particle identification algorithms. To suppress backgrounds, events with electromagnetic calorimeter clusters not associated with charged tracks must sum to less than 200 MeV, and events taken at the $\Upsilon(2S)$ or $\Upsilon(3S)$ energies containing a dimuon pair with invariant mass within 100 MeV of the $\Upsilon(1S)$ mass are rejected. In the
remaining candidate events, no narrow $\mu^+\mu^-$ resonances are observed, other than the $J/\psi$. The $e^+e^-\rightarrow \mu^+\mu^- Z'$, $Z'\rightarrow \mu^+\mu^-$ cross-section is extracted as a function of the $Z'$ mass. No significant signal is observed, yielding a 90% CL upper limit on the cross section, which then permits us to place a 90% CL upper limit on the coupling parameter $g'$ in the scenario in which there are equal magnitude vector couplings to muons, taus and their corresponding neutrinos. This upper limit is shown in Figure 4, along with constraints from neutrino experiments[13]. This analysis is general and provides a model-independent test of theories with new light particles coupling exclusively to muons. All but a sliver of the parameter space preferred by the discrepancy between the calculated and measured anomalous muon magnetic moment has been excluded. Because this search relies only upon the $Z'$ coupling to muons, this is completely general and the result can be interpreted as giving strong constraints on any models with new particles which couple exclusively to muons.

3.4. Invisible Decays of the Dark Photon

In the fourth and final dark sector analysis, we search for invisible decays of the dark photon by seeking events with large missing energy and just one single high-energy photon in the final state. The dark photon decays invisibly to particles which we cannot observe[14].

If the lowest mass dark sector state $\chi$ is sufficiently light, with $m_{\chi} < m_{A'}/2$, then the dominant decay mode of the $A'$ will be invisible, decaying via $A' \rightarrow \chi\chi$. The Feynman diagram for this process, $e^+e^-\rightarrow \gamma_{ISR} A'$, $A' \rightarrow \chi\chi$ ($\chi$ invisible), is depicted in Figure 2d). We would expect to see missing energy, missing momentum and a monochromatic photon, and nothing else in the detector. The dataset for this analysis, 53 $fb^{-1}$, is significantly smaller than the dataset used for the previous three searches presented above because a dedicated hardware “single photon” trigger was not implemented in $BABAR$ until the final two years of $BABAR$ running. Additionally, two software level triggers were implemented to reduce the QED backgrounds in the regions of high and low $A'$ mass.

We then measure the cross-section to produce the $A'$ as a function of the $A'$ mass, $m_{A'}$. 

\begin{figure}[h]
\centering
\includegraphics[width=0.49\textwidth]{figure3.png}
\caption{90% CL upper limit on mixing strength $\epsilon$ as a function of the dark photon mass. The (faint/red) line in the upper left excluded region denotes the values required to explain the discrepancy between the calculated and measured anomalous magnetic moment of the muon.[8]}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.49\textwidth]{figure4.png}
\caption{90% CL upper limits in the new gauge coupling $g'$ as a function of the $Z'$ mass.[12]}
\end{figure}
The 90% CL upper limits on the dark sector coupling, $\epsilon^2$, is shown as a function of $m_{A'}$ in Figure 5a). Our measurements place stringent constraints on dark sector models over a broad range of parameter space, and represent a significant improvement over previously available results, as shown in Figure 5b). We completely rule out the entire region preferred by the $g_\mu - 2$ anomaly discrepancy in models in which dark photons decay invisibly.

Figure 5. a) 90% CL upper limits on $A'$ mixing strength squared $\epsilon^2$ as a function of $m_{A'}$. Bayesian limit (red/solid line) and likelihood limit (blue/dashed line). b) Regions of the $A'$ parameter space excluded by this analysis, compared to previous constraints, as well as the region preferred by the $g_\mu - 2$ anomaly[14].

4. Summary and Outlook
The dark sector has emerged as a possible source of dark matter, with models predicting a range of potential dark matter candidates in the GeV-scale mass range. Using the BaBar detector, we have conducted an extensive program searching for direct evidence of dark matter via the dark sector. We find no direct evidence for any dark sector particles and place stringent limits on dark sector production in the accessible mass range. We are continuing dark matter/dark sector particle searches using the BaBar dataset and are in the process of conducting searches for low-mass dark scalar particles and “darkonium” (bound states of a dark matter particle and its anti-particle). Belle II has recently come online and will eventually provide even more stringent limits.

References
[1] Zwicky F 1933 Helv. Phys. Acta. 6 110
[2] Rubin V C and Ford W K 1970 Ap. J. 159 379
[3] Aubert B et al. (BaBar Collaboration) 2002 Nucl. Instrum. Meth. A 479 1
[4] Aubert et al. (GEANT4 Collaboration) 2013 Nucl. Instrum. Meth. A 729 615
[5] Lees J P et al. (BaBar Collaboration) 2012 Phys. Rev. Lett. 108 211801
[6] Batell B, Pospelov M and Ritz A 2009 Phys Rev. D 79 115008
[7] Essig R, Schuster P and Toro N 2009 Phys Rev. D 80 015003
[8] Lees J P et al. (BABAR Collaboration) 2014 Phys. Rev. Lett. 113 201801
[9] Pospelov M 2009 Phys Rev. D 80 095002
[10] Batley R et al. (NA48/2 Collaboration) 2015 Phys. Lett. B 746 178
[11] Hill R. 2017 EPJ Web Conf. 137 01023
[12] Lees J P et al. (BABAR Collaboration) 2016 Phys Rev. D 94 011102
[13] Altmannshofer W, Gori S, Pospelov M and Yavin I 2014 Phys. Rev. Lett. 113 091801
[14] Lees J P et al. (BABAR Collaboration) 2017 Phys. Rev. Lett. 119 131804