# Search for Low-Mass Dark-Sector Higgs Bosons

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Recent astrophysical and terrestrial experiments have motivated the proposal of a dark sector with GeV-scale gauge boson force carriers and new Higgs bosons. We present a search for a dark Higgs boson using 516 $\mathrm{fb}^{-1}$ of data collected with the *BABAR* detector. We do not observe a significant signal and we set 90% confidence level upper limits on the product of the standard model-dark-sector mixing angle and the dark-sector coupling constant.

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While the astrophysical evidence for dark matter is now overwhelming, its precise nature and origin remain elusive. Recent results from terrestrial and satellite experiments have motivated the proposal of a new, hidden gauge sector under which WIMP-like dark matter particles are charged [1–3]. An Abelian gauge field, the dark photon $A'$, couples this dark sector to standard model (SM) particles through its kinetic mixing with the SM hypercharge fields [4]. In this framework dark matter particles can annihilate into pairs of dark photons, which subsequently decay to SM particles. The dark photon mass is constrained to be at most a few GeV to be compatible with astrophysical constraints [5,6]. In a minimal model [7], the dark photon mass is generated via the Higgs mechanism, adding a dark Higgs boson $h'$ to the theory. The mass hierarchy between these two particles is not constrained, and the dark Higgs boson could be light as well.

A consequence of this scenario is the possibility of probing a light dark sector at low-energy $e^+e^-$ colliders [7,8] and fixed-target experiments [9,10]. Searches for dark photon production have yielded negative results, and constraints have been derived on the mixing strength between the SM and the dark sector, $\epsilon$, as a function of the dark photon mass [9].

The Higgs-strahlung process, $e^+e^- \to A'h', h' \to A'A'$, might offer another gateway to a dark sector. This reaction is of particular interest, since it is one of the few process suppressed by a single factor of $\epsilon$, and the background is expected to be small. If observed, this reaction could provide an unambiguous signature of physics beyond the standard model. The event topology depends on the dark Higgs boson and dark photon masses. While Higgs bosons heavier than two dark photons decay promptly, their lifetime becomes large enough to escape undetected for $m_{h'} < m_{A'}$. Moreover, the dark photon width is proportional to $m_{A'}\epsilon^2$, and its decay can be prompt or displaced, depending on the value of these parameters. At *BABAR* energies, the decay length in the detector is $\mathcal{O}(100)$ $\mu$m or less for $m_{A'} > 250$ MeV and $\epsilon \gtrsim 10^{-4}$, and dark photon decays can be considered as prompt in this regime.

We report a search for dark Higgs production in the Higgs-strahlung process. The measurement is performed in the range $0.8 < m_{h'} < 10.0$ GeV and $0.25 < m_{A'} < 3.0$ GeV with the constraint $m_{h'} > 2m_{A'}$. To avoid any experimental bias, the data are not examined before the selection procedure is finalized. The data sample used in this analysis consists of 521 fb$^{-1}$ of data collected mostly at the $\Upsilon(4S)$ resonance, but also including luminosity at the $\Upsilon(3S)$ and $\Upsilon(2S)$ peaks, as well as off-resonance data. A sample corresponding to $\sim$10% of the data (optimization sample) is used to optimize the selection criteria and is discarded from the final data set. This sample is treated entirely as background for optimization and background studies.

The *BABAR* detector is described in detail elsewhere [11]. Charged-particle momenta are measured in a tracking system formed by a five-layer double-sided silicon vertex detector and a 40-layer central drift chamber both immersed in a 1.5 T axial magnetic field. Electron and photon energies are measured in a CsI(Tl) electromagnetic calorimeter. Charged-particle identification (PID) is performed using an internally reflecting ring-imaging Cherenkov detector and the energy loss $dE/dx$ measured by the silicon vertex detector and central drift chamber. Muons are mainly identified by the instrumented magnetic flux return.

Signal events are generated by MADGRAPH [12] for about 40 different hypotheses of dark photon and Higgs boson masses. The hadronization of the $A' \to q\bar{q}$ ($q = u, d, s, c$) decay is performed by JETSET [13]. The detector acceptance is studied using Monte Carlo (MC) simulation based on GEANT4 [14]. Time-dependent detector inefficiencies, as monitored during data taking periods, are included in the simulation.

The $e^+e^- \to A'h'$, $h' \to A'A'$ reaction is either fully reconstructed in the $3(l^+l^-)$, $2(l^+l^-)\pi^+\pi^-$ and $l^+l^-2(\pi^+\pi^-)$ final states ($l = e$, $\mu$), or partially reconstructed in the $2(\mu^+\mu^-) + X$ and $\mu^+\mu^-e^+e^- + X$ channels, where $X$ denotes any final state other than a pair of pions or leptons. The $2(e^+e^-) + X$ mode suffers from significantly more background than the other channels and is excluded. The first modes are collectively referred to as ''exclusive modes'', as opposed to ''inclusive modes'' for the $2(l^+l^-) + X$ channels. The inclusive modes are only considered in the region $m_{A'} > 1.2$ GeV, since their contribution is small below this threshold and the background level becomes large.

The event selection proceeds by first reconstructing dark photon candidates from pairs of oppositely-charged tracks identified as electrons, muons or pions by PID algorithms. In addition, the helicity angle of the electron in the dark photon rest frame, $\alpha_e$, must satisfy $\cos\alpha_e < 0.9$. The background from accidental $e^+e^-$ pairs exhibits a peaking component near $\cos\alpha_e \sim 1$, while signal events are broadly distributed. Events are then processed according to the following sequence of hypotheses until a match is found: $6\mu$, $4\mu 2e$, $2\mu 4e$, $6e$, $4\mu 2\pi$, $2\mu 2e 2\pi$, $4e2\pi$, $2\mu 4\pi$, $2e4\pi$, $4\mu + X$, $2\mu 2e + X$. This order is chosen to minimize the cross-feed between channels and the efficiency loss due to misclassification.

Additional criteria are applied to increase the purity of the signal. Exclusive modes must contain exactly six charged tracks, and the invariant mass of the three dark photon system must be larger than 95% of the $e^+e^-$ center-of-mass energy. The dark photons are then fitted, constraining the tracks to originate from the interaction point. The fit probability is required to be larger than $10^{-5}$. Finally, the largest mass difference between the dark photon candidates, $\Delta M$, must be less than 10–240 MeV, depending on the final state and the dark photon masses. The distribution of this variable after all other selection criteria are applied is displayed in Fig. 1 for the $2e4\pi$ final state. The signal peaks near $\Delta M \sim 0$, while the background is concentrated towards higher values.

Inclusive modes are selected by requiring two leptonic dark photon candidates with similar masses. The two dark photons are fitted, constraining the four leptons to originate from the interaction point. Events with a fit probability less than $10^{-5}$ are discarded. The remaining dark photon is then identified as the system recoiling against the two lepton pairs. The cosine of its polar angle in the laboratory frame must be less than 0.99 to remove radiative QED events. Finally, the masses of all dark photons must be compatible within their uncertainties.

A total of six events are selected by these criteria: one $4\mu 2\pi$, two $2\mu 4\pi$, two $2e4\pi$ and one $4\mu + X$ events. No candidate containing six leptons survives the selection. The distribution of the dark photon mass versus the dark Higgs boson mass is shown in Fig. 2. Three entries, corresponding to the possible assignments of the decay $h' \to A'A'$, are considered for each event. Besides the contribution of $\rho \to \pi^+\pi^-$ or $\omega \to \pi^+\pi^-$ decays near $m_{A'} \sim 0.7$–$0.8$GeV, no significant signal is observed. This result is consistent with the two events observed in the optimization sample, assumed to be background. Given these limited

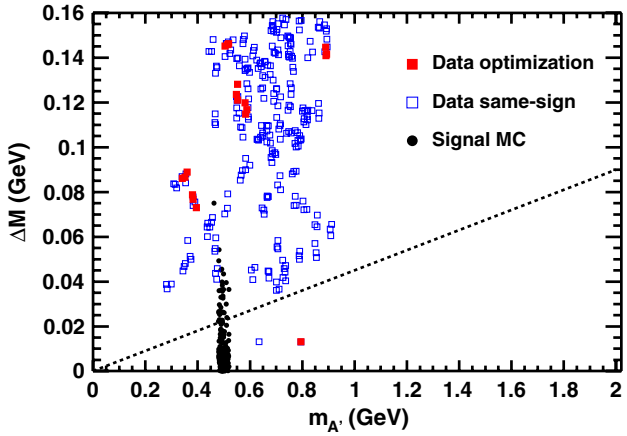


FIG. 1 (color online). Distribution of the largest mass difference between the three dark photon candidates ($\Delta M$) versus the average dark photon mass ($m_{A'}$) after all other selection criteria are applied for the $2e4\pi$ final state. The data are shown for opposite-sign combinations from the optimization sample (plain squares) as well as an additional background estimation, described later, of same-sign combinations from the full data set (open squares). The Monte Carlo predictions for $m_{h'} = 3.0$ GeV and $m_{A'} = 0.5$ GeV are displayed as plain circles. The signal region for the $2e4\pi$ mode is delimited by the dashed line.

statistics, a second background estimation based on the full data set using same-sign combinations, such as $(e^+e^-)(\mu^+\mu^+)(\mu^-\mu^-)$ or $(e^+e^+)(\mu^-\mu^-)X$, is used as a cross-check. Both methods predict background levels consistent within their statistical uncertainties.

Using uniform priors in the cross-section, 90% confidence level (CL) Bayesian upper limits on the production cross-section are derived for each mode separately as a function of the dark Higgs and dark photon masses. The ($m_{h'}$, $m_{A'}$) plane is scanned in steps of 10 MeV in both directions between $0.8 < m_{h'} < 10$ GeV and $0.25 < m_{A'} < 3$ GeV. For each mass hypothesis, the signal region is taken as the interval $m_{h'} - 5\sigma_{m_{h'}} < m_{h'} < m_{h'} + 3\sigma_{m_{h'}}$ and $m_{A'} - 5\sigma_{m_{A'}} < m_{A'} < m_{A'} + 3\sigma_{m_{A'}}$, where $\sigma_{m_{A'}}$ ($\sigma_{m_{h'}}$) denotes the corresponding dark photon (Higgs) mass resolution. An asymmetric range is used to accommodate the non-Gaussian tail of the low-mass side of the signal. The dark photon (Higgs) mass resolution varies between 2–17 MeV (3–55 MeV), depending on the dark photon (Higgs) mass and final state. While setting the limits we adopt the most conservative approach, treating as signal every observed event in the signal region. The systematic uncertainties are included by convolving the likelihood of each final state with Gaussian distributions having variances equal to the systematic uncertainties described below taking correlations into account.

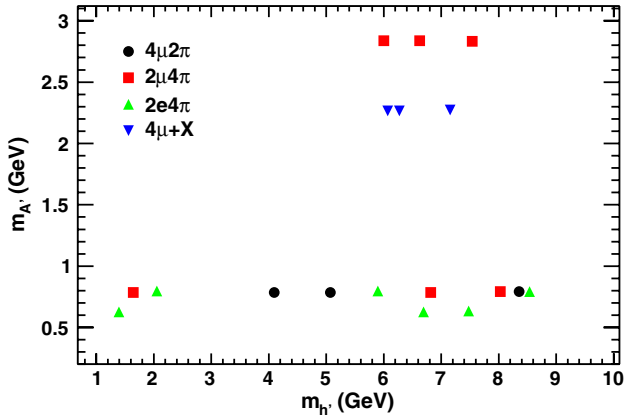


FIG. 2 (color online). Distribution of dark photon mass ($m_{A'}$) versus the dark Higgs mass ($m_{h'}$) for the final data sample. Three entries are plotted for each event, corresponding to the possible assignments of the decay $h' \to A'A'$.

The efficiency is determined for several values of dark photon and Higgs boson masses, and is linearly interpolated between the known points. The efficiency includes acceptance, trigger, selection criteria and the dark photon branching fraction. The branching fractions into leptons and hadrons are given by $BF(A' \to \ell^+\ell^-) = 1/(2 + R)$, $BF(A' \to \text{hadrons}) = R/(2 + R)$ and $BF(A' \to \pi^+\pi^-) = BF(A' \to \text{hadrons})\sigma(e^+e^- \to \pi^+\pi^-)/\sigma(e^+e^- \to \text{hadrons})$, where $R$ denotes the ratio $\sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ [15]. The efficiency increases from a few per mille in regions with small branching fractions to 33% for the six electron mode in the region $m_{A'} < 0.2$ GeV. It drops rapidly in the region $m_{h'} < 0.8$ GeV and $m_{h'} > 10$ GeV, as tracks produced by dark photon decays have a low transverse momentum or are emitted close to the beam and are not reconstructed.

The limits on each channel are then combined to extract 90% CL upper limits on the $e^+e^- \to A'h'$, $h' \to A'A'$ cross

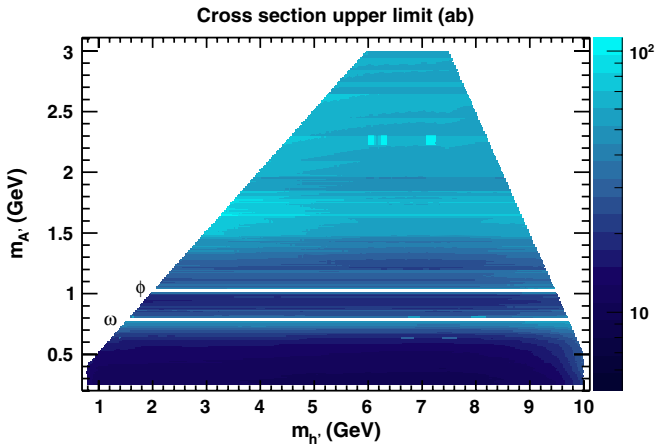


FIG. 3 (color online). Upper limit (90% CL) on the $e^+e^- \to A'h'$, $h' \to A'A'$ cross-section as a function of the dark photon and dark Higgs masses. The limits in the $\omega$- and $\phi$-mesons regions are orders of magnitude larger than the average limits and the corresponding regions (horizontal bands centered around $m_{A'} \sim 0.78$ GeV and $m_{A'} \sim 1.04$ GeV) are masked to avoid overflow.

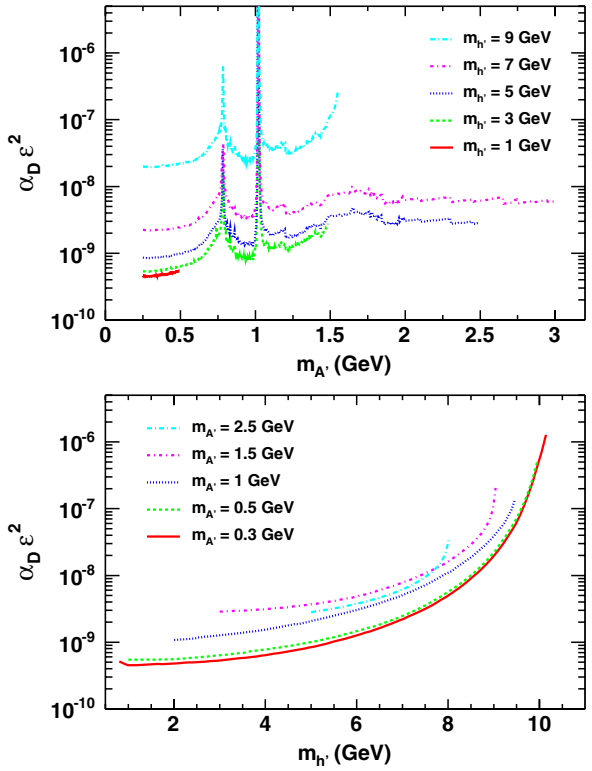


FIG. 4 (color online). Upper limit (90% CL) on the product $\alpha_D \epsilon^2$ as a function of the dark photon mass for selected values of dark Higgs boson masses (top) and as a function of the dark Higgs boson mass for selected values of dark photon masses (bottom).

section. The results are displayed in Fig. 3. The limits are typically at the level of 10–100 ab.

The major contribution to the systematic uncertainty arises from the extrapolation procedure used to determine the efficiency, which is estimated by comparing the extrapolated value to the nearest known point. This uncertainty increases from 1% to 8% in some corners of the phase space. The uncertainty on the branching fractions ranges from a few per mille to 4%. The uncertainty due to the modeling of $A' \to$ hadron decays in inclusive modes is estimated by comparing different fragmentation models. This systematic is found to be 4% reflecting the limited sensitivity of the selection procedure to the hadronic system produced by the dark photon decay. The uncertainty due to PID algorithms varies between 1.5% and 4.5%, assessed using high-purity samples of leptons and pions. Additional uncertainties include the determination of the track reconstruction efficiency (1.2%), luminosity (0.6%), and the limited Monte Carlo statistics (0.5%–2.4%).

The limits on the $e^+e^- \to A'h'$, $h' \to A'A'$ cross section are finally translated into 90% CL upper limits on the product $\alpha_D \epsilon^2$, where $\alpha_D = g_D^2/4\pi$ and $g_D$ is the dark-sector gauge coupling [7]. The results are displayed in Fig. 4 as a function of the dark photon (Higgs) mass for selected values of the dark Higgs boson (photon) mass. Values down to $10^{-10}$–$10^{-8}$ are excluded for a large range of dark photon and dark Higgs masses. These results assume prompt dark Higgs boson and dark photon decays.

In conclusion, a search for dark Higgs boson production has been performed in the range $0.25 < m_{A'} < 3$ GeV and $0.8 < m_{h'} < 10$ GeV for $m_{h'} > 2m_{A'}$. No signal has been observed and upper limits on the product of the mixing angle and the dark coupling constant in the case of a hidden sector with an Abelian Higgs boson have been set at the level of $10^{-10}$–$10^{-8}$. Assuming $\alpha_D = \alpha$, these measurements translate into limits on the mixing strength in the range $10^{-4}$–$10^{-3}$, an order of magnitude smaller than the current bounds.

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