Frascati Physics Series Vol. LVI (2012)
Dark Forces at Accelerators
October 16-19, 2012

SEARCHES FOR DARK PHOTONS AT BABAR

Elisa Guido (on behalf of the *BABAR* Collaboration)
Istituto Nazionale di Fisica Nucleare - Sezione di Genova

Abstract

We present the results of several searches for a narrow resonance, that can be reinterpreted as a dark photon, produced in e^+e^- collisions and decaying into leptons, hadrons, or invisible final states.

1 Introduction

Although the existence of the dark matter is attested by several astrophysical observations, its nature and origin are still not understood. Terrestrial and satellite experiments have recently obtained results motivating the proposal of a hidden gauge sector. This new sector introduces charged WIMP-like dark matter particles [1, 2, 3] with a mass at the TeV scale, and an additional massive photon-like vector - the dark photon A' - responsible for the coupling between this dark sector and the Standard Model (SM), through a kinetic mixing with the SM hypercharge fields [4], in the form $\Delta\mathcal{L}_{mix} = \epsilon F^{\mu\nu} B_{\mu\nu}$, where ϵ represents the mixing angle. The dark photon acquires a charge $e\epsilon$, and, assuming that no light dark fermions exist, it has to decay back to SM particles. The coupling of A' to SM fermions is described by $\alpha' = \epsilon^2\alpha$, and its lifetime is usually small enough so that its decay is prompt. Depending on A' mass, different decays are dominant, either to leptonic or to hadronic final states.

In such a scenario, dark matter particles could annihilate into pairs of dark photons, subsequently decaying to SM fermions. Several astrophysical constraints [5, 6] allows for a small mixing angle between dark sector and SM, thus restricting the possible A' mass to the region of hundreds of MeV to a few GeV.

In a minimal model [7], a dark Higgs boson (h') can also exist, being responsible for the generation of the mass of the dark photon. The mass hierarchy of the two particles is actually not constrained, and the dark Higgs boson could be light as well.

No conclusive proof of the existence of dark forces may come from indirect astrophysical signatures, and only reproducible terrestrial experiments might prove the existence of the dark sector. Actually, these new MeV-GeV scale forces would provide a number of possible new phenomena: high-lepton multiplicity events at the B-factories, high-lepton multiplicity decays of heavy flavors, and even lepton jets at the hadron colliders. In particular, the B-factories, being low-energy and high-luminosity e^+e^- colliders, offer a low background environment for searching for hidden sector signatures at the MeV-GeV scale.

2 Potentialities in searches for the dark sector at e^+e^- colliders.

At low energy e^+e^- colliders several searches for the dark sector are possible:

- searches for a dark photon in events of the type $e^+e^- \to \gamma A'$, with $A' \to e^+e^-$, $\mu^+\mu^-$ or $\pi^+\pi^-$;
- searches for a dark photon in meson decays: $\pi^0 \to \gamma l^+l^-$, $\eta \to \gamma l^+l^-$, $\phi \to \gamma l^+l^-$, etc.;
- searches for dark bosons in events of the type $e^+e^- \to A'^* \to W'W'$, or $e^+e^- \to \gamma A'^* \to W'W''$;

- searches for a dark scalar (s) or a dark pseudoscalar (a) in events of the type $B \to K^{(*)}s \to K^{(*)}l^+l^-$, $B \to K^{(*)}a \to K^{(*)}l^+l^-$, $B \to ss \to 2(l^+l^-)$, $B \to 4(l^+l^-)$;
- searches for a dark Higgs boson in events of the type $e^+e^- \to h'A'$, with $h' \to A'A'$;
- searches for an invisible dark photon in events of the type $e^+e^- \to \gamma A'$, with $A' \to$ invisible final states;
- searches for dark hadrons, such as a dark pion π_D, in events of the type $e^+e^- \to \pi_D X$, with $\pi_D \to e^+e^-$, $\mu^+\mu^-$, and X representing any charged state.

At *BABAR* some of these searches have been already performed [9, 10], or are under study. In this paper, we focus on the *BABAR* searches for a dark photon.

3 *BABAR* searches for a dark photon

The *BABAR* detector is described in detail elsewhere [11]. It collected data mostly at the $\Upsilon(4S)$ resonance, but also at the $\Upsilon(3S)$ and $\Upsilon(2S)$ peaks, as well as off-resonance data. The total integrated luminosity available is of ~ 521 fb^{-1}, of which ~ 28 fb^{-1} (~ 14 fb^{-1}) were collected at the $\Upsilon(3S)$ ($\Upsilon(2S)$). This large data sample allows for several searches in the dark sector.

The *BABAR* experiment has performed several searches for a possible light pseudoscalar Higgs boson (A^0), which is introduced in the Next to Minimal Supersymmetric SM [12]. The reinterpretation of these analyses in terms of dark photon searches is feasible, taking into account a caveat: A^0 is a pseudoscalar, while A' is a vector, therefore any limit should be affected by a change in the efficiency. Despite this, all the searches presented here give a good estimate for the order of magnitude of the corresponding limit in the dark photon search.

3.1 $\Upsilon(3S, 2S) \to \gamma A^0$, $A^0 \to \mu^+\mu^-$

In this search [13], we select events with exactly two oppositely-charged tracks and a single energetic photon with a center-of-mass (CM) energy $E^*_\gamma \geq 0.2$

GeV. At least one of the tracks has to be identified as a muon, and the dimuon candidate and the photon have to be back-to-back in the CM frame. Backgrounds are dominated by QED processes, in the form of "continuum" events $e^+e^- \to \gamma\mu^+\mu^-$, and initial state radiation (ISR) production of light mesons (ρ^0, ϕ, J/ψ, $\Psi(2S)$ and $\Upsilon(1S)$). The signal yield is searched as a function of the A^0 mass in the interval $(0.212-9.3)$ GeV, with a set of unbinned maximum likelihood fits to the reduced mass distribution, defined as: $m_R = \sqrt{m^2_{\mu\mu} - 4m^2_{\mu}}$. The reduced mass spectra for data at the $\Upsilon(2S)$ and at the $\Upsilon(3S)$ are shown in Fig. 1 a) and b), respectively. The scan is performed in steps of 2-5 MeV, for a total of 1951 mass values, while excluding regions in the vicinity of the J/ψ and $\Psi(2S)$ resonances. The typical signal resolution is of 2-10 MeV, increasing with mass. No significant excess of events is observed above the background in the entire mass range. Bayesian upper limits (ULs) at the 90% of confidence level (CL) are set on the product of branching fractions (BFs) of the decay ($\mathcal{B}(\Upsilon(nS) \to \gamma A^0) \times \mathcal{B}(A^0 \to \mu^+\mu^-) = \mathcal{B}(\Upsilon(nS) \to \gamma A^0) \times B_{\mu\mu}$), in the range $(0.3-8.3) \times 10^{-6}$, as shown in Fig. 2. Also, a combined UL on the quantity $f^2_{\Upsilon} B_{\mu\mu}$ is given, with f_{Υ} representing the effective coupling of A^0 to the b-quark.

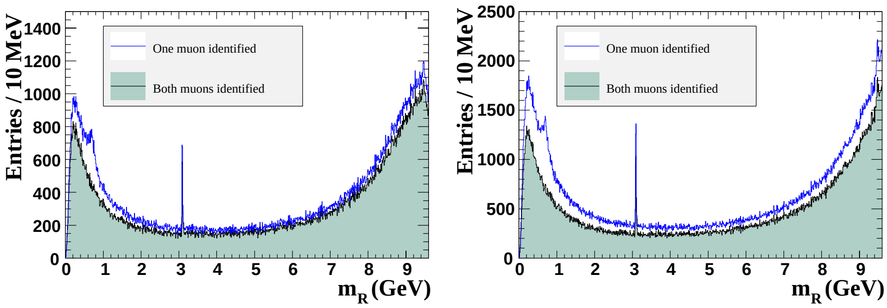

Figure 1: Distribution of the reduced mass m_R in *a)* the $\Upsilon(2S)$ data and *b)* the $\Upsilon(3S)$ data. Open (filled) histograms show the distributions for the selection in which one of (both) the tracks are positively identified as a muon. The ISR-produced J/ψ and $\Upsilon(1S)$ resonances are visible [13].

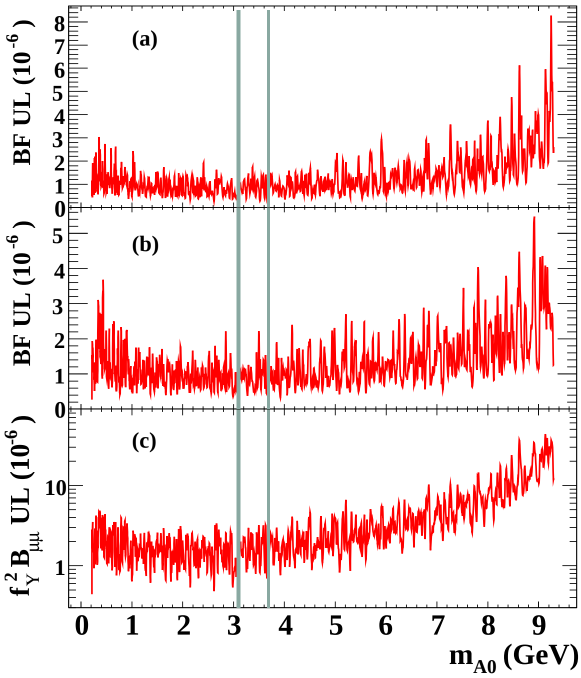

Figure 2: 90% CL ULs on (a) $\mathcal{B}(\Upsilon(2S) \to \gamma A^0) \times B_{\mu\mu}$, (b) $\mathcal{B}(\Upsilon(3S) \to \gamma A^0) \times B_{\mu\mu}$, and (c) effective coupling $f_\Upsilon^2 B_{\mu\mu}$, as a function of A^0 mass. The shaded grey vertical areas are the excluded regions around the J/ψ and $\psi(2S)$ resonances [13].

3.2 $\Upsilon(3S) \to \gamma A^0$, $A^0 \to \tau^+\tau^-$

In this search [14], we select events with exactly two oppositely-charged tracks and a single energetic photon with CM energy $E_\gamma^* \geq 0.1$ GeV. Both the τ leptons are required to decay leptonically, either $\tau \to e\nu_e\bar{\nu_\tau}$ or $\tau \to \mu\nu_\mu\bar{\nu_\tau}$, thus leading to three possible final states. Backgrounds are dominated by $e^+e^- \to \gamma\tau^+\tau^-$ events, and other higher-order QED processes, as well as by $\Upsilon(3S)$ decays and $e^+e^- \to q\bar{q}$ events. Any signal peak in the recoil mass ($m_{\tau\tau}$) would translate to a peak in the photon energy distribution. The signal is actually searched for as an excess in a narrow region of the E_γ spectrum. The photon energy spectra of the three different final states are shown in Fig. 3. The range analyzed corresponds to $4.03 < m_{\tau\tau} < 10.10$ GeV, excluding the region of the decays $\Upsilon(3S) \to \gamma\chi_{bJ}(2P)$, $\chi_{bJ}(2P) \to \gamma\Upsilon(1S)$, where $J = 0, 1, 2$, due to the irreducible photon backgrounds. No evidence for a narrow resonance is found in all the mass range, and 90% CL ULs on the product of BFs of the decay $(\mathcal{B}(\Upsilon(nS) \to \gamma A^0) \times \mathcal{B}(A^0 \to \tau^+\tau^-))$ are set in the range $(1.5 - 16) \times 10^{-6}$, as shown in Fig. 4.

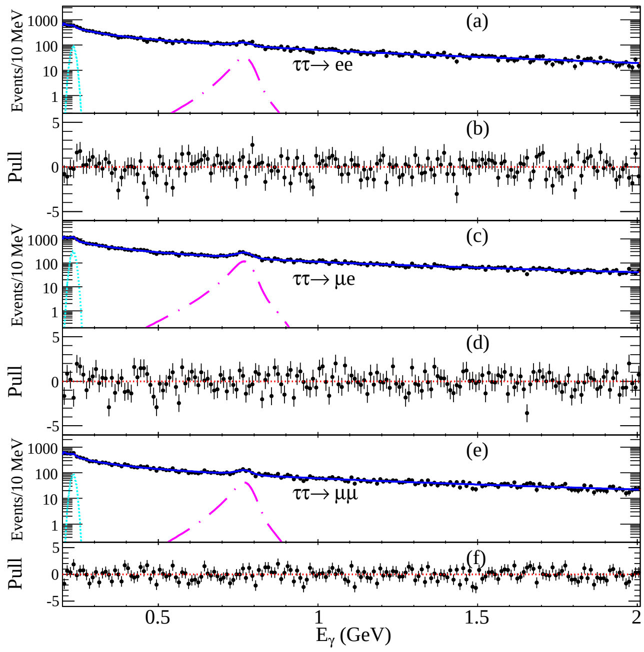

Figure 3: Distribution of the photon energy, E_γ, for each $\tau\tau$-decay modes. Filled circles are data, dotted and dotted-dashed lines represents peaking background contributions, while solid blue lines are the total background functions. Under each plot, the corresponding pull distribution is shown [14].

3.3 $\Upsilon(3S, 2S) \to \gamma A^0$, $A^0 \to$ hadrons

This search [15] looks for hadronic events with the full event energy reconstructed, with at least two charged tracks, and the radiative photon from the $\Upsilon(3S)$ ($\Upsilon(2S)$) with CM energy $E^*_\gamma \geq 2.2(2.5)$ GeV. Background events arise

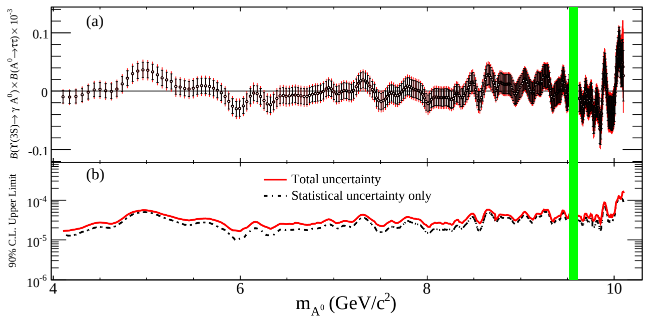

Figure 4: (a) Product BFs and (b) 90% CL ULs on the product of BFs, as a function of A^0 mass. The green vertical region is the excluded range corresponding to the $\chi_{bJ} \to \gamma\Upsilon(1S)$ states [14].

from radiative Bhabha events ($e^+e^- \to \gamma e^+e^-$) or radiative production of muon pairs ($e^+e^- \to \gamma\mu^+\mu^-$), as well as by a light vector meson or a non-resonant hadron, either produced in ISR events or via an $\Upsilon(nS)$ decay. The analysis is performed both in the hypothesis of a CP-odd A^0, and without any specific requirement on the CP values ("CP-all"). A signal would show up as a narrow peak in the candidate mass spectrum, which is analyzed in the range ($2m_\pi$-7 GeV). The candidate mass spectra, before and after the "continuum" background subtraction, are shown in Fig. 5. The signal presence is evaluated in 1 MeV steps, for a total of ~ 6700 mass hypotheses. Being in the absence of a significant signal, 90 % CL ULs on the product of BFs of the decay ($\mathcal{B}(\Upsilon(nS) \to \gamma A^0) \times \mathcal{B}(A^0 \to$ hadrons)) are set in the range $(1 - 80) \times 10^{-6}$, as shown in Fig. 6.

3.4 $\Upsilon(3S) \to \gamma A^0$, $A^0 \to$ invisible final state

The light Higgs boson A^0 could have an invisible decay of the type $A^0 \to \chi^0\bar{\chi}^0$, where χ^0 is the lightest supersymmetric particle, if $m(A^0) > 2m(\chi^0)$. Also the dark photon can decay invisibly in several scenarios, such as light dark matter [16].

For this search [17], we select events with a single energetic photon: two regions are defined, high- and low-energy, with the requirement $E^*_\gamma \geq$ 3.0 GeV and $\geq$ 1.5 GeV, respectively. No tracks originating from the e^+e^-

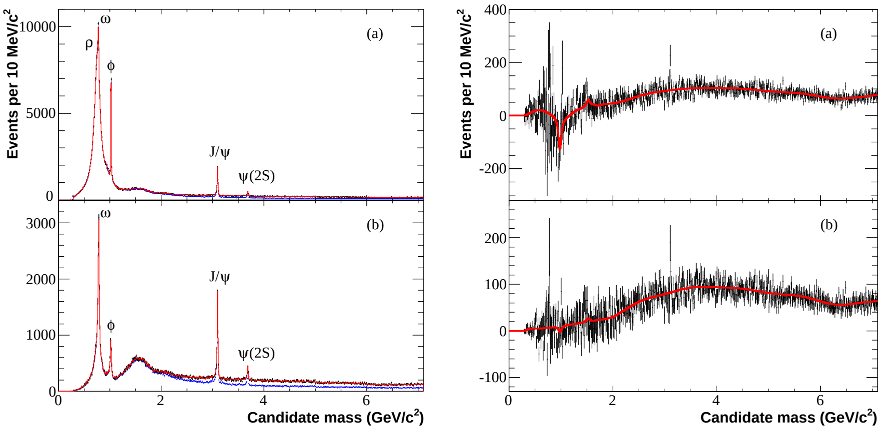

Figure 5: Candidate mass spectrum (left) before, (right) after the "continuum" background subtraction, (a) in the "CP-all" and (b) "CP-odd" hypothesis [15]. The data are shown in black, the background fit function in red, and the "continuum" component in blue.

interaction region must be present in the event. The dominant background in the high-energy region arise from the QED processes $e^+e^- \to \gamma\gamma$, and from the radiative Bhabha events $e^+e^- \to \gamma e^+e^-$ in the low-energy region. We search for a monochromatic peak in the squared missing mass distribution, defined as $m_X^2 = m(\Upsilon(3S))^2 - 2E_\gamma^* m(\Upsilon(3S))$. Two examples of this distribution for the high-energy and the low-energy regions are shown in Fig. 7. A set of maximum likelihood fits to the mass distribution is performed, without finding any evidence for a signal in the range (0-7.8) GeV. Bayesian ULs on the product of BFs of the decay $(\mathcal{B}(\Upsilon(nS) \to \gamma A^0) \times \mathcal{B}(A^0 \to \text{invisible}))$ are set at the 90% CL, in the range $(0.7 - 31) \times 10^{-6}$, as shown in Fig. 8.

4 Conclusions

Several searches performed by the *BABAR* experiment and presented here can be reinterpreted as searches for a dark photon. Until now, only the $\Upsilon(3S) \to \gamma A^0$, $A^0 \to \mu^+\mu^-$ analysis has been reinterpreted for this purpose [8]. Extending to all the *BABAR* data sample, and analyzing all the possible final

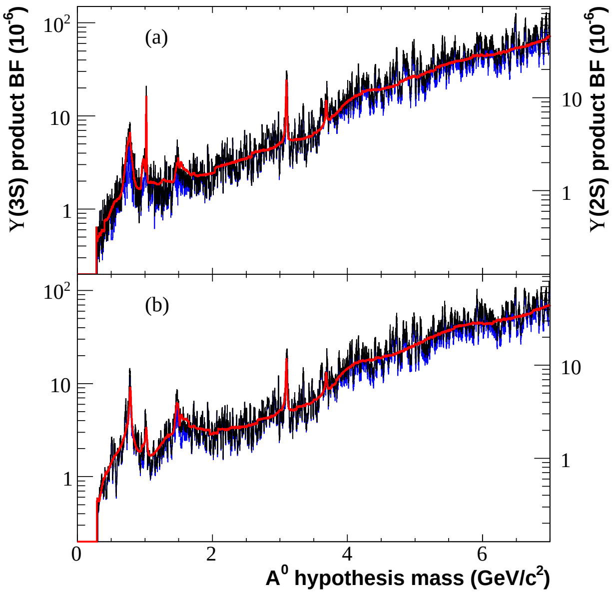

Figure 6: 90% CL ULs on product BFs for (a) "CP-all", and (b) "CP-odd" analysis [15]. The expected ULs are shown in red, while the observed ULs in blue.

states would lead to tighter constraints on the mixing strength between the dark sector and the SM.

References

1. P. Fayet, Phys. Rev. D **75**, 115017 (2007).
2. M. Pospelov, A. Ritz, and M. B. Voloshin, Phys. Lett. B **662**, 53 (2008).
3. N. Arkani-Hamed *et al.*, Phys. Rev. D **79**, 015014 (2009).
4. B Holdom, Phys. Lett. B **166**, 196 (1986).
5. O. Adriani *et al.* [PAMELA Collaboration], Nature **458**, 607 (2009).

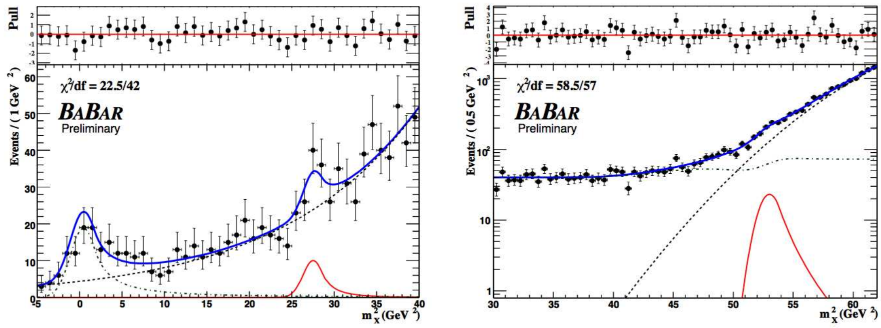

Figure 7: Sample fits to (left) the high-energy and (right) the low-energy region datasets [17]. Data are shown by black points, the signal function in solid red, and the total fit function in solid blue, while the green dotted-dashed line represents the QED processes contributing to the background.

6. M. Ackermann *et al.* [Fermi LAT Collaboration], Phys. Rev. D **82**, 092004 (2010).
7. B. Batell, M. Pospelov, and A. Ritz, Phys. Rev. D **79**, 115008 (2009).
8. J. D. Bjorken *et al.*, Phys. Rev. D **80**, 075018 (2009).
9. B. Aubert *et al.* [BABAR Collaboration], arXiv:0908.2821 [hep-ex].
10. J. P. Lees *et al.* [BABAR Collaboration], Phys. Rev. Lett. **108**, 211801 (2012).
11. B. Aubert *et al.* [BABAR Collaboration], Nucl. Instrum. Methods Phys. Res. Sect. A **479**, 1 (2002).
12. R. Dermisek, J. F. Gunion and B. McElrath, Phys. Rev. D **76**, 051105 (2007).
13. B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **103**, 081803 (2009).
14. B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **103**, 181801 (2009).

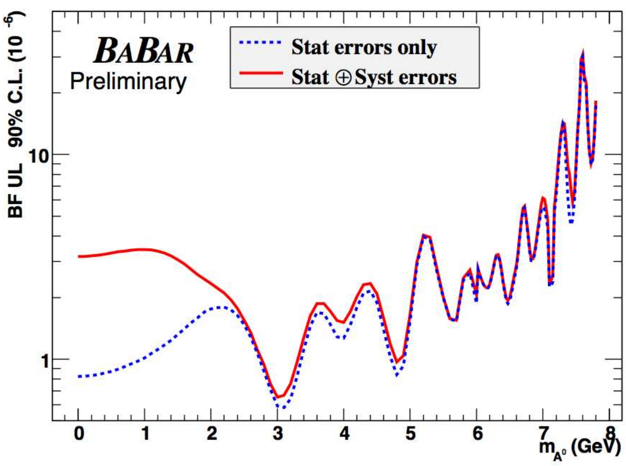

Figure 8: 90% CL ULs on the product BFs, either (dashed blue line) with the statistical uncertainties only, or (solid red line) when considering also systematic uncertainties [17].

15. B. Aubert *et al.* [BABAR Collaboration], arXiv:0808.0017 [hep-ex].

16. J. M. Cline and A. R. Frey, Phys. Rev. D **84**, 075003 (2011).

17. J. P. Lees *et al.* [BABAR Collaboration], Phys. Rev. Lett. **107**, 221803 (2011).