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Light Higgs and Dark Photon Searches at BABAR

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Several new-physics (NP) models predict the existence of low-mass Higgs states and light dark matter candidates. Previous BABAR searches have given null results for these new states and have excluded large regions of the NP models parameter space. We report on new searches on light Higgs and light dark matter at BABAR using the 516 fb^{-1} of data collected with the BABAR detector at the PEP-II asymmetric-energy e^+e^- collider at the SLAC National Accelerator Laboratory.

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1. Light Higgs searches at *BABAR*

According to the most accepted theories, the fundamental particles acquire mass through the Higgs mechanism [1], which requires the existence of at least one scalar state called the Higgs boson. In the standard model (SM) of particle physics [2] there is only a single Higgs boson, and present experimental evidence by the ATLAS and CMS collaborations at LHC suggest a Higgs-like particle with a mass around 126 GeV/c^2 [3]. The Minimal Super-Symmetric SM (MSSM) solves the hierarchy problem of the SM by extending the Higgs sector, the masses of the Higgs bosons depending on a parameter μ [4]. The MSSM fails to explain why the value of the μ is of the order of the electroweak scale, many order of magnitude below the natural Plank scale. The next-to-minimal super-symmetry SM (NMSSM) [5] solves this so-called "naturalness problem" by adding a singlet chiral super-field to the MSSM. As a result the NMSSM contains two charged Higgs bosons, three neutral CP-even bosons, and two CP-odd bosons. The lightest CP-odd state, A^0, could have a mass smaller that twice the b-quark [5], escaping detection at LEP, but making it detectable via $\Upsilon(nS) \to \gamma A^0$ decays at the B-factories (*BABAR* and Belle) [6]. The branching fraction of $\Upsilon(nS) \to \gamma A^0$ could be as large as 10^{-4} depending of the values of the couplings [5]. All this makes the B-factories experimental environment an ideal place to search for light Higgs bosons. The expected width of this A^0 is expected to be smaller than the current experimental resolution on its mass, so its width is always neglected in the searches performed up to date.

Previous *BABAR* searches for A^0 production in several final states have given null results, including $\Upsilon(2S,3S) \to \gamma A^0(\to \mu^+\mu^-,\ \tau^+\tau^-)$ and $\Upsilon(1S) \to \gamma A^0(\to invisible)$ [7]. Similar searches have been done by CLEO in the di-μ and di-τ with $\Upsilon(1S) \to \gamma A^0$ decays [8], and more recently by BESIII in $J/\psi \to \gamma A^0(\to \mu^+\mu^-)$ [9], and by CMS in $pp \to A^0(\to \mu^+\mu^-)$ [10].

Two datasets of the *BABAR* experiment can be used to search for the A^0 in the radiative decays $\Upsilon(nS) \to \gamma A^0$ of the narrow $\Upsilon(nS)$ resonances, with integrated luminosities of 27.9 fb^{-1} at the centre-of-mass (CM) energy of the $\Upsilon(3S)$ and 13.6 fb^{-1} at the $\Upsilon(2S)$, they contain $N_{3S} = (121.3 \pm 1.2) \times 10^6$ $\Upsilon(3S)$ and $N_{2S} = (98.3 \pm 0.9) \times 10^6$ $\Upsilon(2S)$ mesons, respectively.

1.1 Searches for $\Upsilon(2S,3S) \to \gamma A^0(\to hadrons)$

The searches of A^0 use hadronic events in which the full event energy is reconstructed. In the events with at least two charged tracks, the highest energy photon is assumed to be the photon from the radiative $\Upsilon(nS)$ decay. The A^0 is reconstructed by adding the 4-momenta of the remaining particles, including $K^0_S \to \pi^+\pi^-$, $K^\pm$, $\pi^\pm$, $\pi^0 \to \gamma\gamma$, and any unused photon. The radiative photon energy must be greater than 2.5 GeV ($\Upsilon(3S)$) or 2.2 GeV ($\Upsilon(2S)$). The A^0 mass resolution is improved by constraining the radiative photon and the A^0 decay products to come from the same vertex and the total 4-momentum to be that of the CM system.

Two parallel analysis are performed: one in which no assumption is made about the CP nature of the A^0, "CP-all"; and one in which the A^0 is assumed to be CP-odd ($A^0 \to \pi^+\pi^-, K^+K^-$ are excluded). The analysis selects 371740 (171136) events for CP-all (CP-odd) in the combined $\Upsilon(2S,3S)$ dataset, with $0.29 < m_{A^0} < 7.1$ GeV/c^2. The left hand plots of figure 1 show the distributions of the reconstructed A^0 mass; a signal would appear as a narrow peak in these spectra. The number of signal events for a particular mass hypothesis of the A^0 is estimated as the number of events within the mass window (a bin in the spectrum) minus the number of background events.

Since the A^0 is narrow, the mass window is chosen according to the A^0 mass resolution, which varies from 3 to 26 MeV/c^2 as m_{A^0} increases from 0.29 to 7 GeV/c^2. The background events are estimated from continuum $\Upsilon(nS)$ events (continuum sample), *i.e.* off-peak $\Upsilon(2S,3S,4S)$ data and on-peak $\Upsilon(4S)$ data. The dominant background is due to $e^+e^- \to q\bar{q}$ (continuum), and consists mostly of initial-state radiation (ISR) production of light mesons and non-resonant hadrons.

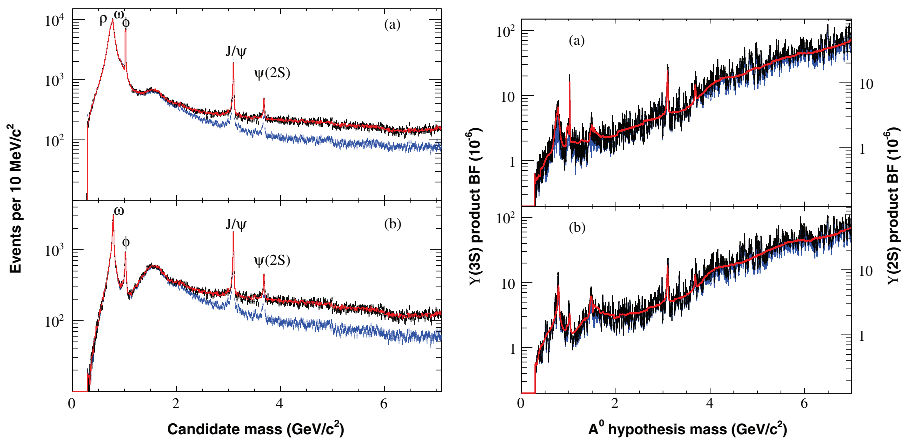

Figure 1: *Left: Candidate mass spectrum in the (a) CP-all and (b) CP-odd analyses. Black dots are on-peak data, blue dots are off-peak scaled data and the red curve is the background fit. The prominent initial-state radiation resonances are labeled. Right: 90% C.L. upper limits on the product of* $B(\Upsilon(3S) \to \gamma A^0)B(A^0 \to hadrons)$ *(left axis) and* $B(\Upsilon(3S) \to \gamma A^0)B(A^0 \to hadrons)$ *(right axis), for (a) CP-all and (b) CP-odd analysis.*

The number of background events is obtained from a fit to the data sample aggregating the properly scaled datasets just mentioned. The A^0 signal is evaluated at masses from 0.291 to 7.000 GeV/c^2 (0.300 to 7.000 GeV/c^2) in 1 MeV/c^2 steps for the CP-all (CP-odd) analysis. The largest upwards fluctuations are 2.8σ (2.2σ) at 3.107 GeV/c^2 (0.772 GeV/c^2) for CP-all (CP-odd) analysis, meaning that no evidence of a signal is found. Therefore, upper limits on the product of branching fractions $B(\Upsilon(nS) \to \gamma A^0)B(A^0 \to hadrons)$ (right hand plot of figure 1) are derived, ranging from 1×10^{-6} at 0.3 GeV/c^2 to 8×10^{-5} at 7 GeV/c^2 at the 90% C.L [11].

1.2 Searches for $\Upsilon(1S) \to \gamma A^0(\to \mu^+\mu^-)$

These searches look for a di-muon resonance in the fully reconstructed decay chains $\Upsilon(2S,3S) \to \pi^+\pi^-\Upsilon(1S)(\to \gamma A^0)$, $A^0 \to \mu^+\mu^-$. Events are selected which contain exactly four charged tracks and a single photon with CM energy larger than 200 MeV. All the tracks must be consistent with originating from the collision point, and at least one must be identified as a muon. The two tracks with the highest momenta are assumed to be muons and are constrained to originate from a common A^0 vertex. The $\Upsilon(1S)$ candidate is reconstructed by combining the A^0 candidate and the photon. Finally, the $\Upsilon(2S,3S)$ are formed with the $\Upsilon(1S)$ candidate with the two remaining opposite charged tracks, assumed to be pions. The resolution in the di-muon mass is improved by performing a kinematical fit of the full decay chain, where the $\Upsilon(2S,3S)$ vertex is constrained to the collision point, mass constraints of the $\Upsilon(2S,3S)$ and $\Upsilon(1S)$ candidates are enforced, as well as the requirement that the $\Upsilon(2S,3S)$ energy be consistent with the e^+e^- CM energy.

A total of 11136 $\Upsilon(2S)$ (3857 $\Upsilon(3S)$) candidates are selected. A resonant peak from the A^0 decay is expected in the di-muon reduced mass spectrum ($m_{\rm red} = \sqrt{m^2_{\mu^+\mu^-} - 4m^2_\mu}$). The distribution of $m_{\rm red}$ for the selected candidates is shown on the left hand plots of figure 2. The main backgrounds are dominated by non-resonant di-muon decays. The signal yield is extracted as a function of m_{A^0} in the region $0.212 \leq m_{A^0} \leq 9.20$ GeV/c^2 by performing a series of one-dimensional extended maximum likelihood fits to the $m_{\rm red}$ distribution. The A^0 signal is searched in steps of half the $m_{\rm red}$ resolution, resulting in a total of 4585 points. The largest upward fluctuations are found to be 3.62σ (2.97σ) at $m_{A^0} = 7.87$ GeV/c^2 (3.78 GeV/c^2) for $\Upsilon(2S)$ ($\Upsilon(3S)$) dataset. The probabilities to observe such fluctuation are estimated to be 18.1% (66.2%). Therefore, the distribution of the signal significance is compatible with the null hypothesis.

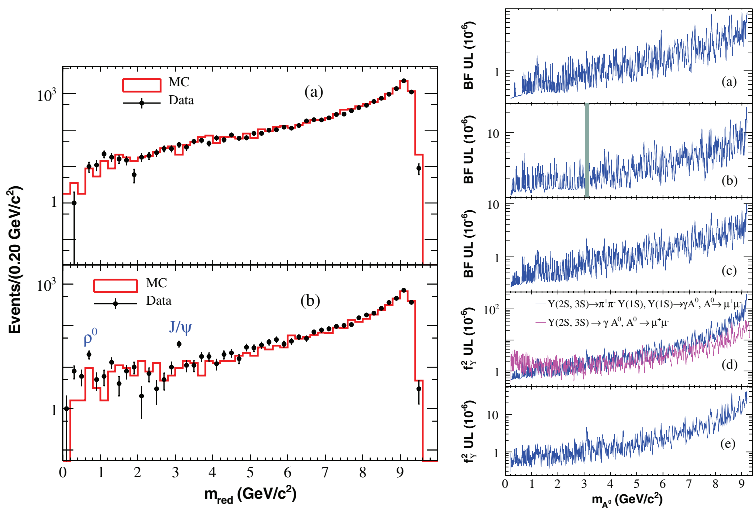

Figure 2: *Left: $m_{\rm red}$ distribution for (a) $\Upsilon(2S)$ and (b) $\Upsilon(3S)$ datasets. Peaking background components can be seen for $\Upsilon(3S)$ data. Right: 90% upper limits on the product of branching fractions $B(\Upsilon(1S) \to \gamma A^0)B(A^0 \to \mu^+\mu^-)$ for (a) $\Upsilon(2S)$, (b) $\Upsilon(3S)$ and (c) combined $\Upsilon(2S,3S)$ datasets; (d) 90% upper limit on $f^2_\Upsilon \times B(A^0 \to \mu^+\mu^-)$ (blue curve), together with previous BaBar measurements (magenta curve), and (e) combined limit.*

We find no significant signal and set 90% C.L. Bayesian upper limits on the product of branching fractions $B(\Upsilon(1S) \to \gamma A^0)B(A^0 \to \mu^+\mu^-)$ in the range of $0.212 \leq m_{A^0} \leq 9.20$ GeV/c^2 (right hand plot of figure 2). The limits range between $(0.37 - 8.97) \times 10^{-6}$ for $\Upsilon(2S)$ data, $(1.13 - 24.2) \times 10^{-6}$ for $\Upsilon(3S)$ data and $(0.28 - 9.7) \times 10^{-6}$ for the combined $\Upsilon(2S,3S)$ datasets [12]. By using the relation $B(\Upsilon(nS) \to \gamma A^0)/B(\Upsilon(nS) \to \ell^+\ell^-) = (f^2_\Upsilon/2\pi\alpha_e)(1 - m^2_{A^0}/m^2_{\Upsilon(nS)})$, where, $n = 1,2,3$, $\ell = e,\mu$, α_e is the fine structure constant and f_Υ the effective Yukawa coupling [12] of the b-quark to A^0, we set 90% upper limits on the product $f^2_\Upsilon \times B(A^0 \to \mu^+\mu^-)$ using the results from the combined $\Upsilon(2S,3S)$ datasets. The upper limit ranges from 0.54×10^{-6} to 3.0×10^{-4} depending upon the A^0 mass. Combining the present results with the previous BaBar results [7] on $\Upsilon(2S,3S) \to \gamma A^0$ we obtain a 90% upper limit on $f^2_\Upsilon \times B(A^0 \to \mu^+\mu^-)$ in the range $(0.29 - 40) \times 10^{-6}$ for $m_{A^0} \leq 9.2$ GeV/c^2 (right hand plot of figure 2).

1.3 Searches for $\Upsilon(1S) \to \gamma A^0(\to \tau^+\tau^-)$

For this search, the $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ transition is used. A signal candidate consist of a photon plus four charged tracks, two associated with the pions of the transition between $\Upsilon(2S)$ and $\Upsilon(1S)$ and two from one-prong decays of each τ-lepton ($\tau^+ \to e^+\overline{\nu}_e\nu_\tau,\mu^+\overline{\nu}_\mu\nu_\tau,\ \pi^+\nu_\tau$). We require that at least one τ decays leptonically, and examine five combinations of daughters: ee, $e\mu$, $\pi\mu$, $\mu\mu$, $\mu\pi$. The masses of the $\Upsilon(1S)$ and A^0 candidates are calculated from the $m^2_{\text{recoil}} = M^2_{\Upsilon(2S,3S)} + m^2_{\pi\pi} - 2M_{\Upsilon(2S,3S)}E^{CM}_{\pi\pi}$ and $m^2_X = (P_{e^+e^-} - P_{\pi\pi} - P_\gamma)^2$ kinematic variables, where the P are the four-momenta of the indicated system.

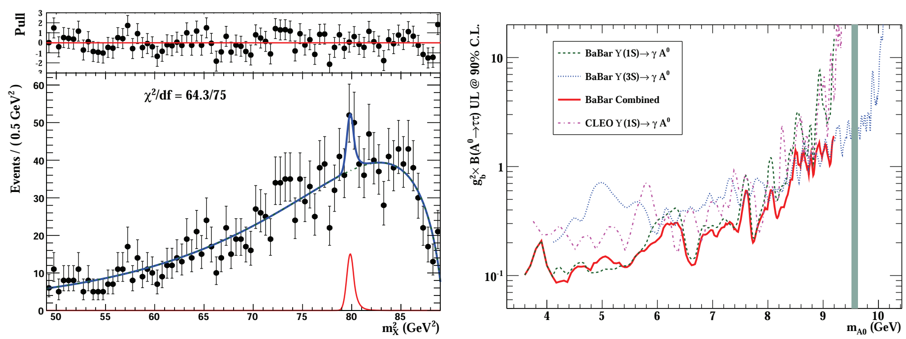

Figure 3: *Left: Fit to m_X^2 distribution for the m_{A^0} point that return the largest upward fluctuation (see text). Right: 90% C.L. upper limits for $g_b^2 \times B(A^0 \to \tau^+\tau^-)$. Shown are the present results (dashed green), the previous BABAR results from $\Upsilon(3S)$ radiative decays (dotted blue), the combination (red); and results from CLEO experiment (dashed magenta).*

A resonant peak from the A^0 decay would manifest in the m_X^2 spectrum. We extract the signal yields as a function of the m_{A^0} in the interval $3.6 \leq m_{A^0} \leq 9.2$ GeV/c^2 by performing a series of maximum-likelihood fits to m_X^2. The fit model contains contributions from signal, which is expected to peak near the light Higgs mass squared, and a smooth background function, arising from continuum and radiative leptonic $\Upsilon(1S)$ backgrounds. We search for the A^0 in varying mass steps that correspond to approximately half of the expected resolution on m_{A^0}. A total of 201 mass points are sampled. The most significant upward fluctuations occurs with 2.7σ at $m_{A^0} = 6.36$ GeV/c^2 (left hand plot of figure 3). Estimations reveal that such fluctuations are expected with a probability of 7.5%, therefore, we conclude that no significant A^0 signal is found and set Bayesian 90% C.L. upper limits on the product $B(\Upsilon(1S) \to \gamma A^0)B(A^0 \to \tau^+\tau^-)$, computed with a uniform prior. The limits range between $(0.9 - 13.0) \times 10^{-5}$ [13]. Using the relation $B(\Upsilon(nS) \to \gamma A^0)/B(\Upsilon(nS) \to \ell^+\ell^-) = (g_b^2 G_F m_b^2/\sqrt{2}\pi\alpha_e)\mathscr{F}_{QCD}(1 - m^2_{A^0}/m^2_{\Upsilon(nS)})$, where g_b^2 is the Yukawa coupling of the b-quark to the A^0, G_F the Fermi constant, and $\mathscr{F}_{QCD}$ includes QCD corrections [13]; we can set a constrain on the product $g_b^2 \times B(A^0 \to \tau^+\tau^-)$, and combine the present results with previous BABAR measurements on $B(\Upsilon(3S) \to \gamma A^0) \times B(A^0 \to \tau^+\tau^-)$ [7]. We set a 90% C.L. upper limits on the product $g_b^2 \times B(A^0 \to \tau^+\tau^-)$ in the range $0.09 - 1.9$ for $m_{A^0} \leq 9.2$ GeV/c^2 (right hand plot of figure 3). Our limits place significant constraints on NMSSM parameter space.

2. Dark Higgs and dark photon searches at *BABAR*

There is overwhelming evidence for dark matter from terrestrial and satellite astrophysical observations, but its precise nature and origin remain unknown. To try to explain this observational evidence many models [14] introduce a new hidden dark sector under which WIMP-like dark matter particles are charged. In these models, the WIMP-like particle can annihilate into pairs of dark bosons, which subsequently annihilate into leptons (protons are kinematically forbidden). In one of these models [14] there is a new dark sector that couples to the SM particles with a dark photon, A', through a small kinetic term. Astrophysical data constrains the A' mass to be a few GeV. The A' acquire its mass via the Higgs mechanism, adding a dark Higgs, h', to the theory. The mass hierarchy is not constrained, and the h' could be light as well. The high collision rate and the relatively clean experimental environment of B-factories is an ideal place to probe for MeV – GeV dark matter, complementing the searches performed at LHC.

2.1 Searches for $e^+e^- \to A'h'(\to A'A')$; with $A' \to e^+e^-,\ \mu^+\mu^-,\ \pi^+\pi^-$

We search for dark Higgs and dark photons via *Higgsstrahlung* production $e^+e^- \to A'^* \to A'h'(\to A'A')$ [15]. This interaction is very interesting because it is singly suppressed by the mixing strength between the SM and the dark sector, ε. If observed, it could provide an unambiguous signature of NP. The event topology depends on the A' and h' masses. This measurement is performed in the range $0.8 < m_{h'} < 10.0$ GeV/c^3 and $0.25 < m_{A'} < 3.0$ GeV/c^3 with the constrain $m_{h'} > 2m_{A'}$. The data sample used consists of 521 fb^{-1} collected mainly at the $\Upsilon(4S)$ peak, but also includes data collected at the $\Upsilon(2S)$ and $\Upsilon(3S)$ peaks, as well as off-peak data.

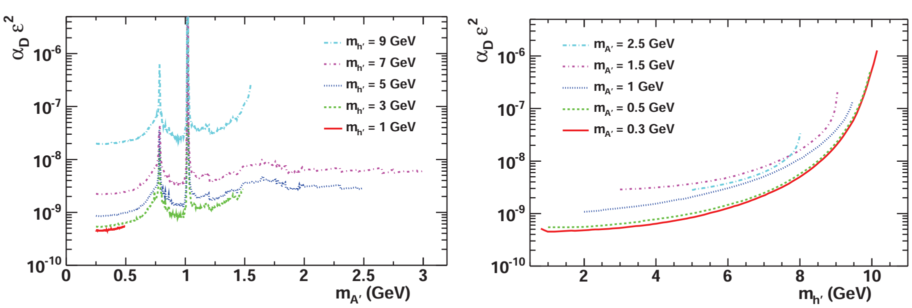

Figure 4: *90% C.L. upper limits on $\alpha_D\varepsilon^2$ (see text). Left: limits as a function of $m_{A'}$ for selected values of $m_{h'}$; Right: limits as a function of $m_{h'}$ for selected values of $m_{A'}$.*

The process $e^+e^- \to A'^* \to A'h'(\to A'A')$ is either fully reconstructed in $3(\ell^+\ell^-)$, $2(\ell^+\ell^-)\pi^+\pi^-$ and $\ell^+\ell^- 2(\pi^+\pi^-)$ ($\ell = e,\mu$); or partially reconstructed in $2(\mu^+\mu^-)+X$ and $(\mu^+\mu^-)(e^+e^-)+X$, where X denotes any final state other than a pair of leptons or pions. A total of six events where selected: one $4\mu 2\pi$, two $2\mu 4\pi$, two $2e4\pi$ and one $4\mu + X$. No candidate with six leptons survives the selection. The selected events are very likely to come from $\rho \to \pi^+\pi^-$ or $\omega \to \pi^+\pi^-$ decays near $m_{A'} \sim 0.7 - 0.8$ GeV/c^2, and it is concluded that no significant signal is observed.

Using a Bayesian method, upper limits on the $e^+e^- \to A'^* \to A'h'(\to A'A')$ cross-section are obtained as a function of $m_{h'}$ and $m_{A'}$. These limits can be translated into 90% upper limit on the coupling $\alpha_D\varepsilon^2$ (see figure 4), where $\alpha_D = g_D^2/4\pi$, with g_D the dark sector gauge coupling. Values as low as $10^{-10} - 10^{-8}$ are excluded for a large range of $m_{A'}$ and $m_{h'}$, assuming prompt decay. Under the assumption that $\alpha_D \approx \alpha_e$, the current measurement can also be translated into limits on the mixing strength ε which range $10^{-4} - 10^{-3}$, an order of magnitude smaller that current experimental bounds from direct photon production in this mass range.

3. Conclusion

We performed several searches for evidence of dark sector candidates and CP-odd light Higgs in the $\Upsilon(2S, 3S, 4S)$ *BABAR* data sample. The data show no evidence of such signals but enable to improve the limits within the parameter space of various NP models.

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