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Discovery searches for light new physics with BaBar

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The *BABAR* experiment collected large samples of events during the last few months of data taking at the $\Upsilon(3S)$ and $\Upsilon(2S)$ resonances, which allowed to obtain several results in the search for new physics like CP-odd scalar bosons or light dark matter candidates. We report the results of searches for $\Upsilon(2S,3S) \to \gamma A^0$ with $A^0 \to \mu\mu$, $\Upsilon(3S) \to \gamma A^0$ with $A^0 \to \tau\tau$, $\Upsilon(1S) \to (\gamma)$ invisible, the indirect search for A^0 by measuring the ratio $\Gamma(\Upsilon(1S) \to \tau^+\tau^-)/\Gamma(\Upsilon(1S) \to \mu^+\mu^-)$ and the direct search for the Dark sector.

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1. Introduction

During the last few monts of data taking in 2008, the *BABAR* experiment collected approximately 122×10^6 $\Upsilon(3S)$ and 99×10^6 $\Upsilon(2S)$ decays. These $b\bar{b}$ states lie below the threshold for B meson pair production, therefore their natural widths are 1 MeV and they can be used to directly search for possible new physics effects at scales below 10 GeV. Several results have been obtained by *BABAR* considering different new physics scenarios and are discussed here: direct searches for a light CP-odd Higgs boson, A^0, in radiative Υ decays, direct search for dark matter candidates in decays of the $\Upsilon(1S)$ to undetected particles, a test of lepton universality in $\Upsilon(1S)$ decays, and a search for the Dark sector in the reaction $e^+e^- \to W'W' \to e^+e^-$.

2. Direct searches for a light CP-odd Higgs

The Next-to-Minimal Supersymmetric (NMSSM) extension of the SM adds an additional singlet Higgs field to the two Higgs doublets of the Minimal Supersymmetric Standard Model (MSSM), resulting in a new CP-odd Higgs boson which mixes with the single CP-odd Higgs of the MSSM. The mass of the physical Higgs boson, A^0, is not required to be large. Direct searches typically constrain m_{A^0} to be below $2m_b$ [1]. Therefore, it can be potentially produced directly in radiative decays of the $\Upsilon(2S,3S)$ resonances.

2.1 $\Upsilon(2S,3S) \to \gamma A^0, A^0 \to \mu\mu$

The *BABAR* experiment reported a search for A^0 in decays of $\Upsilon(nS) \to \gamma A^0, A^0 \to \mu\mu$, with $n = 2$, 3, using a sample which contains 99 x 10^6 $\Upsilon(2S)$ and 122 x 10^6 $\Upsilon(3S)$ candidates [2].

Events with exactly two oppositely charged tracks from a common vertex inside the beampipe and a single energetic photon with a center of mass (CM) energy $E^*_\gamma \geq 0.2$ GeV are selected. A muon mass hypothesis is assigned to the two tracks, along with a kinematic fit to the $\gamma\mu^+\mu^-$ candidate, including beam energy and primary decay vertex constraints, which overall improves the resolution of the di-muon pair.

The signal yield is extracted as a function of m_{A^0} in the interval $0.212 \leq m_{A^0} \leq 9.3$ GeV by performing a series of unbinned extended maximum likelihood fits to the distribution of the reduced mass $m_R \equiv \sqrt{m^2_{\mu\mu} - 4m^2_\mu}$, in steps of 2-5 MeV.

No significant excess of events above the background in the selected mass range was observed in both the $\Upsilon(2S)$ and $\Upsilon(3S)$ data samples. Therefore, 90% confidence level (C.L.) upper limits on the product of branching fractions as a function of m_{A^0} were obtained, as shown in Fig.1. *BABAR* also computed the upper limit $\mathscr{B}\ (\eta_b \to \mu\mu) < 0.9\%$ at 90% C.L.

2.2 $\Upsilon(3S) \to \gamma A^0, A^0 \to \tau\tau$

BABAR has also studied decays of $\Upsilon(3S) \to \gamma\tau\tau$ to look for A^0 using a sample of 122×10^6 $\Upsilon(3S)$ decays [3]. Although this mode is expected to be the dominant one if kinematically allowed, it is more difficult experimentally because it can not be fully reconstructed. Both τ leptons are selected using the leptonic channels, therefore the events have exactly two tracks identified as e or μ (considering ee, $\mu\mu$ and μe), and a photon exceeding 100 MeV. The dominant background comes from QED sources, such as $e^+e^- \to \gamma\tau^+\tau^-$. In this analysis a scan on the photon energy

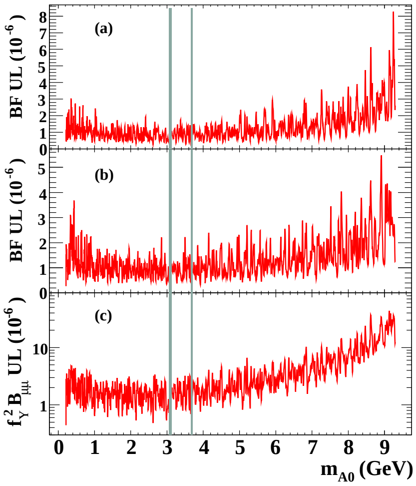

Figure 1: The 90% CL upper limit on the product of branching fractions for $\Upsilon \to \gamma A^0$ and $A^0 \to \mu\mu$ obtained from the $\Upsilon(2S)$ (a) and $\Upsilon(3S)$ (b) samples and (c) effective coupling $f_\Upsilon^2 \times \mathscr{B}$ as a function of the A^0 mass. The shaded areas show the regions around the J/ψ and $\psi(2S)$ resonances which are excluded from the search.

distribution is performed to look for peaks in the range of $4.03 < m_{A^0} < 10.10$ GeV. As no signal is found, we set limits on the product of the branching fraction $(\Upsilon(3S) \to \gamma A^0)(A^0 \to \tau^+\tau^-)$ in the range $[1.5,16] \times 10^{-5}$ as shown in Fig.2.

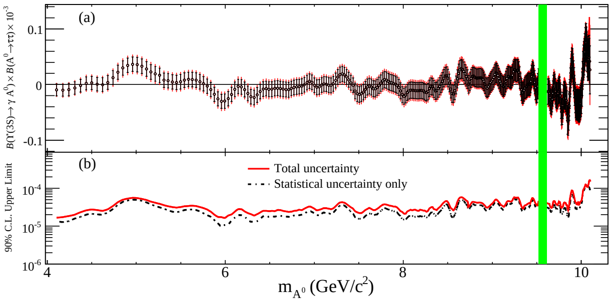

Figure 2: The product of branching fractions (a) and its 90% CL upper limit (b) for $\Upsilon \to \gamma A^0$ and $A^0 \to \tau\tau$ obtained from the $\Upsilon(3S)$.

2.3 $\Upsilon(1S) \to \gamma$ invisible

We search for a light Higgs boson, A^0, in decays of $\Upsilon(1S) \to \gamma$ invisible. The SM process $\Upsilon(1S) \to \gamma\nu\bar{\nu}$ is not observable at the present experimental sensitivity ($\mathscr{B} \approx 10^{-5}$) [4]. The branching fraction of $\Upsilon(1S) \to \gamma A^0$ is predicted to be as large as 5×10^{-4} depending on the mass of the A^0 and the couplings [5]. Therefore an observation of $\Upsilon(1S)$ decays with significant missing energy could be a sign of new physics.

The $\Upsilon(1S)$ candidates are tagged using a dipion transition of $\Upsilon(2S) \to \Upsilon(1S)\pi^-\pi^+$ from a sample of 98×10^6 decays [6]. We search for the resonant two-body decays $\Upsilon(1S) \to \gamma A^0$ and non-resonant three body processes $\Upsilon(1S) \to \gamma\chi\bar{\chi}$. We select events with exactly two oppositely charged tracks and a single energetic photon with $E^*_\gamma \geq 0.15$ GeV plus a large amount of missing energy and momentum. The main background that comes from QED events is reduced using a neural network discriminant by combining several kinematic variables of the dipion system. Other sources of background come from radiative hadronic decays such as $\Upsilon(1S) \to \gamma K^0_L K^0_L$ and two-photon η' production. The signal yield is extracted as a function of $m_{A^0}(m_\chi)$ in the interval $0 \leq m_{A^0} \leq 9.2$ GeV ($0 \leq m_\chi \leq 4.5$ GeV), using two kinematic variables: the dipion recoil mass M_{rec} and the missing mass squared M^2_X. As no significant excess of events above the background is observed we set upper limits on $\mathscr{B}(\Upsilon(1S) \to \gamma A^0) \times \mathscr{B}(A^0 \to \text{invisible})$ in the range (1.9-37)$\times 10^{-6}$ for $0 \leq m_{A^0} \leq 9.2$ GeV.

3. Search for a candidate of dark matter in $\Upsilon(1S) \to$ invisible decays

BABAR has performed searches for these decays of the $\Upsilon(1S)$ to invisible by tagging the $\Upsilon(1S)$ using the dipion transition $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$ [7]. The signal events are identified using the recoil mass (m_{rec}) and requiring the absence of significant additional detector activity in the detector apart from that associated with the two pions. Note that this search does not require an identified photon. As said above, the SM branching franction of $\Upsilon(1S) \to \gamma\nu\bar{\nu}$ is 10^{-5}. However, this invisible channel could be enhanced by decays into pairs of low-mass dark matter candidates to the level of 10^{-4} or 10^{-3} [8].

The main source of background comes from combinatorial events which are not $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$ transitions, therefore they exhibit no peaking structure at the $\Upsilon(1S)$ mass. This events are substantially suppressed using a multivariate analysis trained on signal MC events and m_{rec} sideband data.

However, m_{rec} will peak at the $\Upsilon(1S)$ mass for events in which a real $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$ transition occurs but the $\Upsilon(1S)$ final state particles are undetected (peaking background). This include events that pass outside the detector geometrical acceptance, low energy particles or non-interacting neutral hadrons. This peaking components are estimated from MC and then validated on data in a control sample with similar requirements as the signal sample but allowing events with three and four tracks consistent with two-body decays of the $\Upsilon(1S)$ decays. The estimated signal yield for peaking events is 2444 ± 105 events.

The signal yield is extracted from a fit to the m_{rec} distribution (see Fig.3) and the result gives 2326± 105 peaking events. By substracting the estimated peaking background on MC we obtain a signal yield of -118 ± 105 ± 124 events, where the errors are statistical and systematic, respectively. A limit of $\mathscr{B}(\Upsilon(1S) \to \text{invisible}) < 3.0 \times 10^{-4}$ at the 90 % confidence level is obtained.

4. Test of lepton universality using $\Upsilon(1S)$ decays

In the SM the coupling between gauge bosons and leptons are independent of lepton flavor, therefore one expects that the quantity $R_{ll'} = \Gamma_{\Upsilon(nS)\to ll}/\Gamma_{\Upsilon(nS)\to l'l'}$ with $l, l' = e, \mu, \tau$ and $l' \neq l$, to be close to one. In the NMSSM, deviations of $R_{ll'}$ from the SM expectation may arise due to the presence of the A^0 mediating the decay in the following processes:

$$\Upsilon(1S) \to A^0\gamma, A^0 \to l^+l^- \qquad \text{or} \qquad \Upsilon(1S) \to \eta_b(1S)\gamma, \eta_b(1S) \to A^0 \to l^+l^-.$$

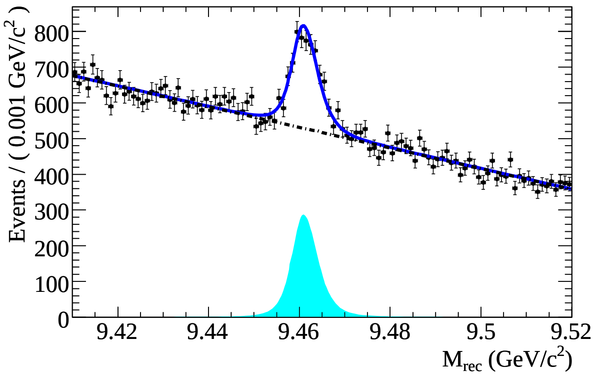

Figure 3: $\pi\pi$ recoil mass distribution, m_{rec}, obtained from the $\Upsilon(1S)\rightarrow$ invisible. Data are shown as points, while the overall fit and non-peaking component are shown as the solid and dashed lines respectively.

If the photon remains undetected, the lepton pair would be ascribed to the $\Upsilon(1S)$ and due to the proportionality of the coupling of the Higgs to the lepton mass, an apparent violation of lepton universality may be observed. This effect should be larger for decays to $\tau\tau$ pairs and enhanced for higher mass $\Upsilon(nS)$ and $\eta_b(nS)$ resonances. Deviations of $R_{ll'}$ from 1 could be as large as 4% depending on the A^0 mass. *BABAR* has reported a measurement of $R_{\tau\mu}(\Upsilon(1S)) = \Gamma\Upsilon(1S)\rightarrow\tau^+\tau^-/\Gamma\Upsilon(1S)\rightarrow\mu^+\mu^-$ using a sample of $122{\times}\text{x}10^6$ $\Upsilon(3S)$ decays, where $\Upsilon(3S)\rightarrow\Upsilon(1S)\pi^+\pi^-$ [9]. Only τ decays to a single charged particle are considered, therefore the signature consists of four charged particles for both the $\tau\tau$ and the $\mu\mu$ mode. The selection is optimized using simulated samples, separately for these two modes given the different levels of backgrounds. The signal is extracted performing an unbinned extended maximum-likelihood fit (see Fig.4) simultaneously to the two disjoint datasets using the invariant mass of the system recoiling against the dipion pair $M^{reco}_{\pi\pi}$ for the $\tau\tau$ sample, and $M^{reco}_{\pi\pi}$ and the dimuon invariant mass for the $\mu\mu$ sample. We obtain, including all the systematic corrections, the ratio $R_{\tau\mu}(\Upsilon(1S)) = 1.005\pm0.013$(stat.) $\pm$ 0.022(syst.). No significant deviation of the ratio $R_{\tau\mu}$ from the SM is observed. This result improves both the statistical and systematic precision with respect to the previous measurement [10].

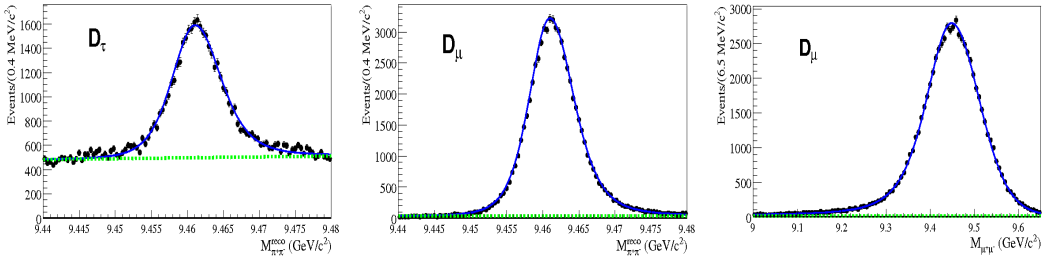

Figure 4: 1-D fit projections for $M^{reco}_{\pi\pi}$ for the τ sample (left), $M^{reco}_{\pi\pi}$ (middle) and $M_{\mu\mu}$ (right) for the $\mu\mu$ sample. In each plot the dashed line represents the background shape, while the solid line is the sum of signal and background contributions to the fit, and the points are the data.

5. Direct search for Dark sector

Arkani-Hamed et al. [11] have introduced a class of theories containing a new dark force and a light hidden sector. In these theories, there are at least three dark particles in play, denoted by A' which mixes with the photon, another gauge boson W', and the dark Higgs h'. Depending on the considered scenario the signature at *BABAR* could have cross sections as large as a few femtobarns. *BABAR* performed a search for the W' in the process $e^+e^- \to W'W' \to l^+l^-l^+l^-$ using the full *BABAR* dataset ($\mathscr{L}$ = 536 fb^{-1}) [12]. Events are selected containing 4 leptons with zero total charge carrying the full beam momentum, where the two dilepton invariant masses are equal. The main background comes from the 4-lepton QED process and is estimated from MC simulated events. The signal is extracted performing a cut-and-count analysis in bins of $\bar{m} = (m_1 + m_2)/2$ in the $\bar{m}$ range from 0.24 to 5.3 GeV, where m_1 and m_2 are the dilepton invariant masses. As no significant signal is obtained, a combined upper limit is set to $\sigma(e^+e^- \to W'W' \to l^+l^-l^+l^-) < (25-60)$ ab.

6. Conclusions

Using the datasets collected at $\Upsilon(2S)$ and $\Upsilon(3S)$ *BABAR* performed several searches for a light Higgs, A^0. No evidence is found, which strongly constrains the available parameter space of the NMSSM. In addition, we have reported the result of a search for invisible decays of the $\Upsilon(1S)$ to look for light dark matter candidates, and a direct search for Dark sector.

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