

Hot Topics From *BABAR* Experiment

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Abstract

We search for a new light non-Standard Model CP -odd Higgs boson, A^0 , decaying to $\tau^+\tau^-$, $\mu^+\mu^-$, and invisible in radiative decays of the $\Upsilon(2S)$ and $\Upsilon(3S)$. We search for the light scalar particle produced in single-photon decays of the $\Upsilon(3S)$ resonance through the process $\Upsilon(3S) \rightarrow \gamma A^0$, $A^0 \rightarrow$ invisible. We also search for evidence of an undetectable $\Upsilon(1S)$ decay recoiling against the dipion system. The data samples contain 99×10^6 $\Upsilon(2S)$ and 122×10^6 $\Upsilon(3S)$ decays collected by the *BABAR* detector at the SLAC PEP-II B factory.

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1 Introduction

The search for the origin of mass of fundamental particle is a cornerstone of the Standard Model (SM). The Higgs mechanism is one of the great interests in the particle physics. In recent years many motivations for searching a Higgs boson. Direct searches at the CERN $e^+ - e^-$ Collider (LEP Experiment) via the process $e^+ - e^- \rightarrow ZH$ for the Standard Model Higgs boson, a CP -even scalar, has excluded a lower bound on its mass below 114.4 GeV [1]. The search for the SM Higgs particle is continued at the Tevatron (The CDF and D0 Collaborations) for a Higgs boson decaying to W^+W^- and resulting limits on Higgs boson production exclude a SM Higgs boson in the mass range 162-166 GeV at the 95% C.L [2]. The search is currently continued at Large Hadron Collider (LHC) with the relative increase in charged-particle multiplicity from $\sqrt{s} = 0.9$ to 7 TeV [3, 4].

In recent years a number of theoretical models predicted for the existence of a light CP -odd Higgs boson (A^0) related to the Next-to-Minimal Supersymmetric Model (NMSSM). Direct searches constrain the mass of $m_{A^0} < 2m_b$, where m_b is the b quark and the decay of $A^0 \rightarrow bb$ is forbidden [5]. Of particular interest is to search the lightest CP -odd Higgs boson in Upsilon decays such as $\Upsilon(1S)$ and $\Upsilon(3S)$. In this paper we present a search of the CP -odd Higgs boson decaying to $\tau^+\tau^-$, $\mu^+\mu^-$, and invisible. The large data sets available at *BABAR* experiment allow us to place stringent constraints on such theoretical models.

2 Data Sample

The data used in this paper were collected with the *BABAR* detector at the PEP-II asymmetric-energy $e^+ - e^-$ storage ring at the SLAC National Accelerator Laboratory, operating at $\Upsilon(2S)$

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and $\Upsilon(3S)$. For searching for A^0 decays to either $\tau^+\tau^-$ or $\mu^+\mu^-$, we use a data sample of 122×10^6 $\Upsilon(3S)$ events that corresponds to an integrated luminosity of 28 fb^{-1} . We also used a data sample of 79 fb^{-1} accumulated on the $\Upsilon(4S)$ resonance (ON-resonance) and 8 fb^{-1} 49 MeV below the $\Upsilon(4S)$ resonance (OFF-resonance) for studying the background.

For searching an undetectable $\Upsilon(1S)$ decay recoiling against the dipion system we used the data were taken using an upgraded muon system, instrumented with both resistive plate chambers and the limited streamer tubes between between steel absorbers. The data triggers was modified to substantially increase the pion trigger efficiency. The data sample of 96.5×10^{-6} $\Upsilon(3S)$ were used. The *BABAR* detector is described in detail elsewhere [6].

3 Analysis Method

3.1 Search for A^0 in the decays of $\Upsilon(3S) \rightarrow \gamma A^0$, $A^0 \rightarrow \tau^+\tau^-$

We search the light CP -odd Higgs boson, A^0 , via the decays $\Upsilon(3S) \rightarrow \gamma\tau^+\tau^-$ for a wider mass range, $4.03 < m_{\tau^+\tau^-} < 10.10 \text{ GeV}/c^2$ [7], over the mass ranges by the CLEO Collaboration [8] and the D0 Collaboration [9], respectively. We exclude the mass region of $9.52 < m_{\tau^+\tau^-} < 9.61 \text{ GeV}/c^2$ because of the irreducible background photons produced in the decays of $\Upsilon(3S) \rightarrow \gamma\chi_{bJ}(2P)$, $\chi_{bJ}(2P) \rightarrow \gamma\Upsilon(1S)$, where $J = 0, 1, 2$. We scan for peaks in the distribution of the photon energy, E_γ , corresponding to peaks in the $\tau\tau$ invariant mass as given by

$$m_{\tau^+\tau^-}^2 = m_{\Upsilon(3S)}^2 - 2m_{\Upsilon(3S)}E_\gamma, \quad (1)$$

where $m_{\Upsilon(3S)}$ is the $\Upsilon(3S)$ mass ($10.355 \text{ GeV}/c^2$) and the E_γ is measured in the $\Upsilon(3S)$ center-of-mass frame.

We select events in which both τ -leptons decay leptonically to either $\tau^+ \rightarrow e^+\nu_e\bar{\nu}_\tau$ or $\tau^+ \rightarrow \mu^+\nu_\mu\bar{\nu}_\tau$. The events are then required exactly two charged tracks to reduce the background and to contain at least one photon with energy $> 100 \text{ MeV}$ in the electromagnetic calorimeter. In addition both charged tracks are required to be identified as leptons either electron or muon. The residual background is mostly due to radiative decays of $e^+e^- \rightarrow \gamma\tau^+\tau^-$ and higher order of QED processes, including two-photon reactions such as $e^+e^- \rightarrow e^+e^-e^+e^-$ and $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$. However this residual background has smaller contributions compared to other $\Upsilon(3S)$ decays and the continuum background from the non-resonance $\Upsilon(3S)$ decays of $e^+e^- \rightarrow \gamma^* \rightarrow q\bar{q}$, where $q = u, d, s, c$.

The events $\Upsilon(3S) \rightarrow \gamma\chi_{bJ}(2P)$, $\chi_{bJ}(2P) \rightarrow \gamma\Upsilon(nS)$, and $\Upsilon(nS)$ decays to $\tau^+\tau^-$, where $J = 0, 1, 2$ and $n = 1, 2$ are expected to peak in the photon energy distribution when the photon comes from the decays of $\chi_{bJ}(2P) \rightarrow \gamma\Upsilon(nS)$ is misidentified as the radiative photon from the $\Upsilon(3S)$ decays. We use a Crystal Ball function (CB) [10] to describes each of the peaks that comes from to the decays of $\chi_{bJ}(2P) \rightarrow \gamma\Upsilon(1S)$ in the photon spectrum. The mean values for the $\chi_{b0}(2P)$ and the $\chi_{b1}(2P)$ CB function are fixed to the PDG values [11], and the width values are fixed to the Monte Carlo (MC) resolution, but the mean and the width of $\chi_{b2}(2P)$ are free parameters. The search for the signal $\Upsilon(3S) \rightarrow \gamma A^0$, $A^0 \rightarrow \tau^+\tau^-$ is performed by scanning for peaks in the photon energy distributions. Figure 1 shows the fits to the photon energy, E_γ , distributions in the different $\tau^+\tau^-$ decay modes fitted in the region $0.2 < E_{\text{gamma}} < 2.0 \text{ GeV}$.

No evidence for a signature of the light Higgs boson decays to τ pairs is observed. We measure the branching fraction of $\mathcal{B}(\Upsilon(3S) \rightarrow \gamma A^0) \times \mathcal{B}(A^0 \rightarrow \tau^+\tau^-) < (1.5 - 16) \times 10^{-5}$ 90% confidence level (C.L.). We also set a 90% C.L. upper limit on the $\tau^+\tau^-$ decays of the η_b at $\mathcal{B}(\eta_b \rightarrow \tau^+\tau^-)$.

3.2 Search for A^0 in the decays of $\Upsilon(3S) \rightarrow \gamma A^0$, $A^0 \rightarrow \mu^+\mu^-$

We search for a resonance in the $\mu^+\mu^-$ invariant mass distribution for the fully reconstructed final state $\Upsilon(2S, 3S) \rightarrow \gamma A^0$, $A^0 \rightarrow \mu^+\mu^-$. We assume the A^0 resonance is a scalar (or pseu-

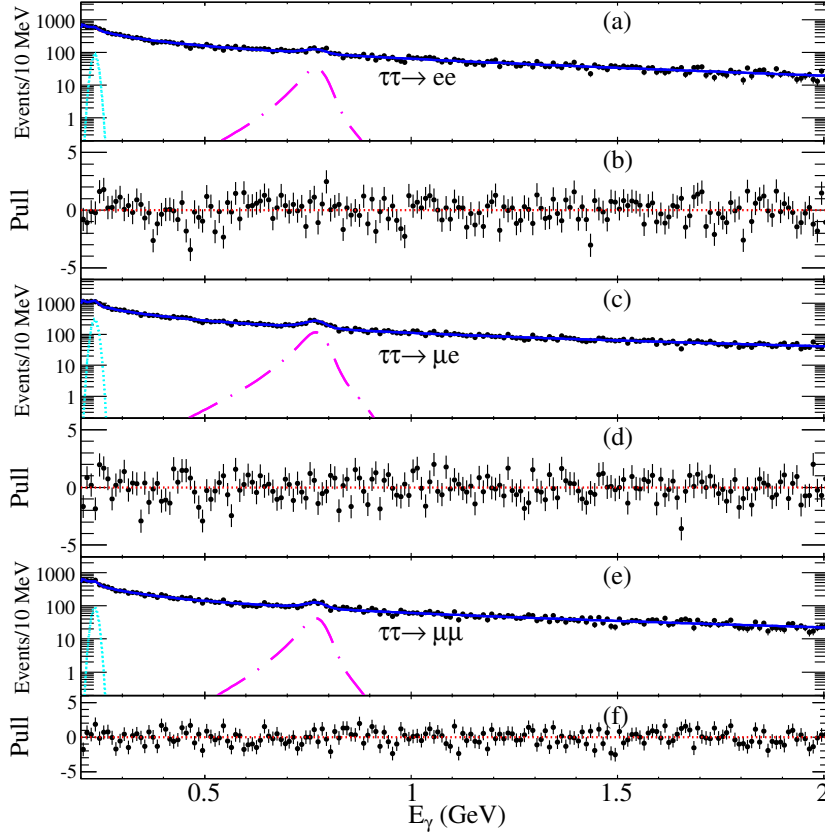


Figure 1: The photon energy distributions for the different $\tau\tau$ -decay modes. The data is shown in filled circles, the dotted lines represent the contributions from $\Upsilon(3S) \rightarrow \gamma\chi_{bJ}(2P), \chi_{bJ}(2P) \rightarrow \gamma\mathcal{T}(2S)$, dotted-dashed lines show the contributions from $\Upsilon(3S) \rightarrow \gamma\chi_{bJ}(2P), \chi_{bJ}(2P) \rightarrow \gamma\mathcal{T}(1S)$, and the solid lines show the total background functions. The different between the background function and the data divided by the uncertainty in the data for each $\tau\tau$ -decay modes is shown in b, c, and d.

doscalar) particle and the width of the resonance is negligibly small compared with the experimental resolution where the mass of light Higgs boson, m_{A^0} , is sufficiently far from the mass of the η_b [12].

We select events with exactly two oppositely charged tracks and a single energetic photon with a center-of-mass energy $E_\gamma^* \leq 0.2$ GeV, while allowing additional photons with the center-of-mass energies below 0.2 GeV. We assign a muon mass hypothesis to the two tracks and require that at least one is positively identified as a muon. We then perform a kinematic fit to the Υ candidate from the two muon candidates and the energetic photon.

The backgrounds are dominated by the QED processes: the continuum background $e^+e^- \rightarrow \gamma\mu^+\mu^-$ and the initial-state-radiation (ISR) production of $\rho^0, \phi, J/\psi, \psi(2S)$, and $\mathcal{T}(1S)$ vector mesons. We suppress the background contributions from the decays of $\rho^0 \rightarrow \pi^+\pi^-$ final state in which the pion is misidentified as a muon by requiring both charged tracks are positively identified as muons in the range $0.5 \leq m_{A^0} < 1.05$ GeV. We also suppress the decays of $\mathcal{T}(2S) \rightarrow \gamma_2\chi_b(1P), \chi_b(1P) \rightarrow \gamma_1\mathcal{T}(1S)$ [$\mathcal{T}(3S) \rightarrow \gamma_2\chi_b(2P), \chi_b(2P) \rightarrow \gamma_1\mathcal{T}(1S)$], where γ_2 is the secondary photon by requiring that no secondary photon above a center-of mass energy of 0.1 GeV [0.008 GeV] is present in the event.

Since we do not observe a significant excess of events in the range of $0.212 < m_{A^0} < 9.3$ GeV, we set upper limits on the branching fractions of $\mathcal{B}(\Upsilon(2S) \rightarrow \gamma A^0) \times \mathcal{B}_{\mu\mu}$ and $\mathcal{B}(\Upsilon(3S) \rightarrow \gamma A^0) \times \mathcal{B}_{\mu\mu}$, where $\mathcal{B}_{\mu\mu}$ is the branching fraction of $A^0 \rightarrow \mu\mu$. The limit vary from $0.26-8.3 \times 10^{-6}$

for \mathcal{B}_{2S} and $0.27 - 5.5 \times 10^{-6}$ for \mathcal{B}_{3S} . The 90% C.L. Bayesian upper limits are computed with a uniform prior and assuming a Gaussian likelihood function. We set an upper limit on the coupling $f_Y^2(m_{A^0} = 0.214 \text{ GeV}) < 1.6 \times 10^{-6}$ at 90% C.L., by assuming $\mathcal{B}_{\mu\mu} = 1$. This result is significantly smaller than the value required to explain the HyperCP events as light Higgs production [13, 14]. Figure 2 shows the upper limits on the branching fractions as a function of the mass m_{A^0} .

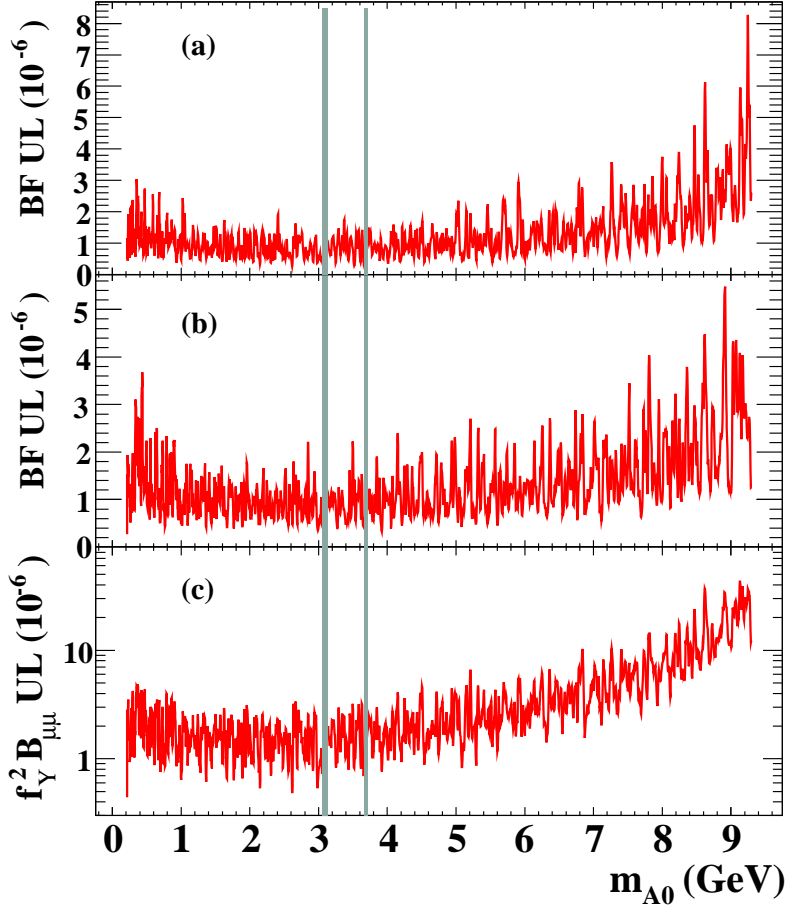


Figure 2: The 90% C.L. upper limits on the branching fractions of (a) $\mathcal{B}(\Upsilon(2S) \rightarrow \gamma A^0) \times \mathcal{B}_{\mu\mu}$, (b) $\mathcal{B}(\Upsilon(3S) \rightarrow \gamma A^0) \times \mathcal{B}_{\mu\mu}$, and (c) effective coupling $f_Y^2 \times \mathcal{B}_{\mu\mu}$ as a function of m_{A^0} (color online). The shaded areas show the regions around the J/ψ and $\psi(2S)$ resonances excluded from the search.

We also measure the branching fractions of $\mathcal{B}(\Upsilon(2S) \rightarrow \gamma \eta_b) \times \mathcal{B}(\eta_b \rightarrow \mu^+ \mu^-) = (-0.4 \pm 3.9 \pm 1.4) \times 10^{-6}$ and $\mathcal{B}(\Upsilon(3S) \rightarrow \gamma \eta_b) \times \mathcal{B}(\eta_b \rightarrow \mu^+ \mu^-) = (-1.5 \pm 2.9 \pm 1.6) \times 10^{-6}$, where the first uncertainty is statistical and the second is systematic, dominated by the uncertainty in $\Gamma(\eta_b)$. Using the *BABAR* measurement of $\mathcal{B}(\Upsilon(2S) \rightarrow \gamma \eta_b)$ and $\mathcal{B}(\Upsilon(3S) \rightarrow \gamma \eta_b)$ [12], we derive $\mathcal{B}(\eta_b \rightarrow \mu^+ \mu^-) = (-0.25 \pm 0.51 \pm 0.33)\%$ and $\mathcal{B}(\eta_b \rightarrow \mu^+ \mu^-) < 0.9\%$ at 90% C.L. This limit is consistent with the mesonic interpretation of the η_b state [15].

3.3 Search for $\Upsilon(3S) \rightarrow \gamma A^0$, $A^0 \rightarrow$ Invisible

We search for the light scalar particle produced in single-photon decays of the $\Upsilon(3S)$ resonance through the process $\Upsilon(3S) \rightarrow \gamma A^0$, $A^0 \rightarrow$ invisible. We split the data sets into two broad energy ranges based on the energy of the highest-energy in the center-of-mass in our electromagnetic calorimeter cluster. The high-energy region is $3.2 < E_\gamma^* < 5.5 \text{ GeV}$, where $E_\gamma^* = E_{com}/2$. The backgrounds in the high-energy region are dominated by the QED process such as $e^+e^- \rightarrow$

$\gamma\gamma$, where the photon energy distribution for this process peaks. The low-energy region is $2.2 < E_\gamma^* < 3.7$. The backgrounds in this region are dominated by the radiative Bhabha events $e^+e^- \rightarrow \gamma e^+e^- \rightarrow$ in which both electron and positron are misidentified.

We extract the yield of signal events using a likelihood fits to the distribution of the observable missing mass squared in the mass interval $0 < m_{A^0} < 6$ GeV:

$$m_X^2 = m_{\Upsilon(3S)}^2 - 2E_\gamma^* m_{\Upsilon(3S)}, \quad (2)$$

where m_X is the missing mass squared, $m_{\Upsilon(3S)}$ is the $\Upsilon(3S)$ mass, and E_γ^* is the photon energy in the Υ center-off-mass system. The E_γ^* is given by

$$E_\gamma^* = \frac{m_\Upsilon^2 - m_{A^0}^2}{2m_\gamma} \quad (3)$$

The current precise limit on the measurement of the branching fraction of $\mathcal{B}(\Upsilon \rightarrow \gamma X)$ with $X \rightarrow$ invisible is given by CLEO collaboration on $\Upsilon(1S)$ [16].

In the high-energy range, the selection efficiency for signal is 10–11% depending on the mass m_{A^0} , and it is below 10^{-5} for $e^+e^- \rightarrow \gamma\gamma$ events, whereas in the low-energy range the selection efficiency for signal is about 20%. The signal PDF is described by the Crystal Ball function [10] that centered around the expected value of $m_X^2 = m_{A^0}^2$. We compare the distributions of the simulated and reconstructed $e^+e^- \rightarrow \gamma\gamma$ events to determine the uncertainty of the PDF parameters.

We determine the PDF as a function of mass m_{A^0} . In the low-statistics simulated samples of signal events, we exclude $6 < m_{A^0} < 7.8$ GeV and in the high-statistics simulated samples of signal events, we excluding the values of $m_{A^0} < 6$ GeV due to low statistics. The fit results give us signal yields of $N_{sig} = 119 \pm 71$ (1.7σ) and $N_{sig} = 37 \pm 15$ (2.6σ) for the low-energy dataset and the high-energy dataset, respectively. The fit results on the low-energy range ($m_{A^0} = 7.275$ GeV) and the high-energy ($m_{A^0} = 5.2$ GeV) are shown in Fig. 3.

We do not observe a significant excess of events above the background in the mass range of $0 < m_{A^0} < 7.8$ GeV., and we set 90% C.L. upper limit on the branching fraction of $\mathcal{B}(\Upsilon(3S) \rightarrow \gamma A^0) \times \mathcal{B}(A^0 \rightarrow \text{invisible})$ at $(0.7 - 31) \times 10^{-6}$ in the mass range of $m_{A^0} \leq 7.8$ GeV [17]. These results are preliminary.

3.4 Search for $\Upsilon(1S) \rightarrow$ Invisible

The nature of dark matter is one of the most challenging issues in the elementary particle physics. Observation of the SM particles coupling to undetectable (invisible) particles might provide information on dark matter candidates. The dark matter couples to the SM through the mediating boson. This particle is expected to be a vector, scalar, or pseudoscalar. The dark matter to show up dominantly in interactions with heavy fermions such as b quarks [18, 19].

We select events in the invisible subsample by requiring exactly two tracks originating from the interaction point (IP) with opposite charge. These track have a center-off-mass momentum of $p^* < 0.8$ GeV/c and they are consistent with pions from dipion transition with the invariant mass of $0.25 < M_{\pi\pi} < 0.95$ GeV/ c^2 . The dipion recoil mass is given by

$$M_{rec}^2 = s + M_{\pi\pi}^2 - 2\sqrt{(s)}E_{\pi\pi}^*, \quad (4)$$

where M_{rec} is the reconstructed dipion recoil mass, $E_{\pi\pi}^*$ is the center-off-mass energy of the dipion system, and $\sqrt{(s)} = 10.3552$ GeV/ c^2 . The overall efficiency of the selection events is about 64%.

We collect the invisible subsample by selecting tree-track and four-track events using the dipion system. We search high-momentum tracks from $\Upsilon(1S)$ decays by requiring only one or two additional tracks originating from the IP point, each with momentum $p^* > 2.0$ GeV/ c^2 . We

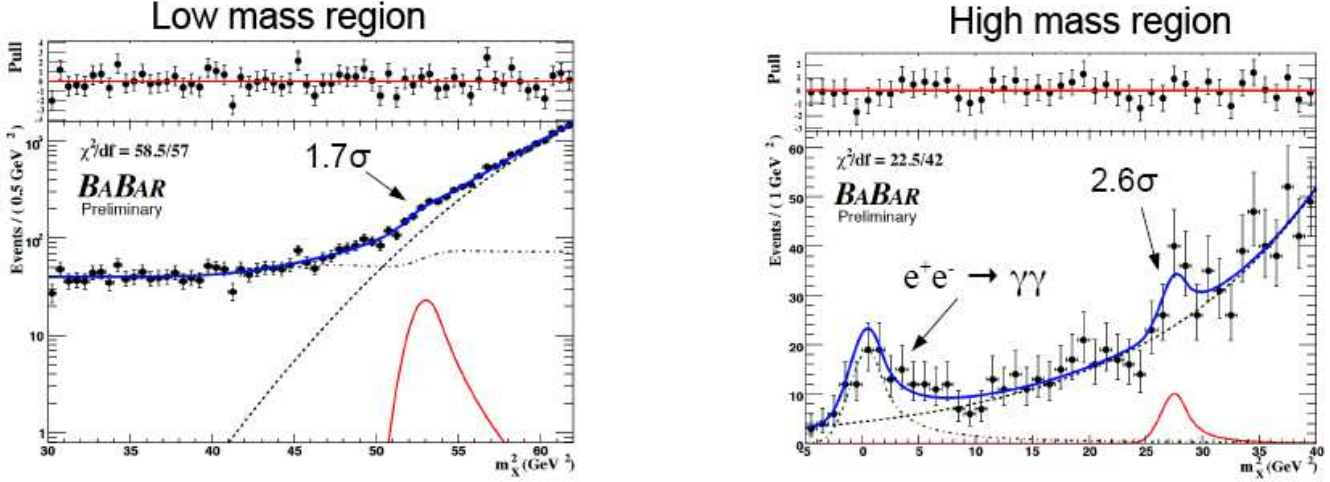


Figure 3: [Left] Sample fit to the low-energy dataset ($83 \times 10^6 \Upsilon(3S)$) decays. The bottom plot shows the data (solid points) overlaid by the full PDF curve (solid blue line), signal contribution with $m_{A^0} = 7.275$ GeV (solid red line). [Right] Sample fit the high-energy dataset ($122 \times 10^6 \Upsilon(3S)$) decays. The bottom plot shows the data (solid points) overlaid by the full PDF curve (solid blue line), signal contribution with $m_{A^0} = 5.2$ GeV, $e^+e^- \rightarrow \gamma\gamma$ (dot-dashed green line), and the continuum background (black dashed line).

then use our lepton identification to treat these tracks. If either both tracks passing electron-identification criteria the both tracks are treated as electron candidates; otherwise, both are treated as muon candidates. Figure 4 shows the M_{rec} distribution from our invisible subsample.

We determine the parameters of the PDF by fitting the M_{rec} distribution in the four-track data subsample. We extract the peaking contribution by using an extended unbinned maximum likelihood fit and the non-peaking contribution using a first-order polynomial function. The peaking background is estimated using Monte Carlo subsamples of 1019 $\Upsilon(1S) \rightarrow e^+e^-$ events, 1007 $\Upsilon(1S) \rightarrow \mu^+\mu^-$ events, 92 $\Upsilon(1S) \rightarrow \tau^+\tau^-$ events, and $2.9 \pm 1.3 \Upsilon(1S) \rightarrow$ hadrons events.

We search for evidence of the decays of $\Upsilon(1S)$ into undetectable final states recoiling against the dipion system in the $\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(1S)$, using a sample of $9.14 \times 10^6 \Upsilon(3S)$ mesons. We find no evidence for the decays of $\Upsilon(1S) \rightarrow$ invisible. We set an upper limit on the branching fraction of $\mathcal{B}(\Upsilon(1S) \rightarrow \text{invisible}) < 3.0 \times 10^{-4}$ at the 90% C.L. [20].

4 Summary

We search for a new light non-Standard Model CP -odd Higgs boson in the $\Upsilon(3S)$, $\Upsilon(2S)$, and $\Upsilon(1S)$ systems. We also search for invisible decays of the $\Upsilon(1S)$ system. *BABAR* recent measurements are important input to rule out much of the parameter space allowed by the light non-Standard Model CP -odd Higgs and other models. These measurements also provide new and stringent constraints on the light CP -odd Higgs boson. In addition the measurement of the branching fraction of $\Upsilon(1S) \rightarrow$ invisible is extremely important as a sensitive probe of dark matter.

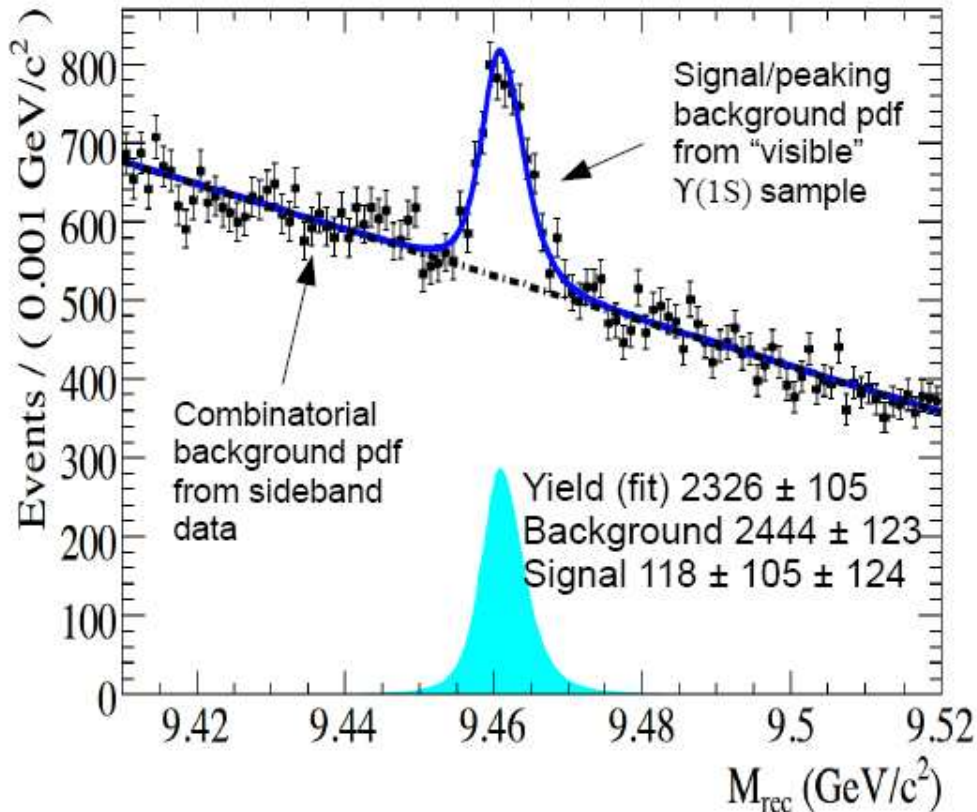


Figure 4: The maximum likelihood fit to the dipion recoil mass for data in the invisible sub-sample. Dash-dotted line is the nonpeaking background and the solid fitted-line is the peaking background. The solid line is the total fit function.

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