LOW MASS NEW PHYSICS SEARCH FOR A CP-ODD HIGGS BOSON $A^0$
DECAYING TO $s\bar{s}$ OR GLUON GLUON AT BABAR

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We report on the search for the decay $\Upsilon(1S) \to \gamma A^0$, $A^0 \to gg$ or $s\bar{s}$, where $A^0$ is the pseudoscalar light Higgs boson predicted by the next-to-minimal supersymmetric standard model. A sample of $\sim 18 \times 10^6 \Upsilon(1S)$ resonances, produced in the BABAR experiment via $e^+e^- \to \Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$, is used for this search. No significant signal has been found, and upper limits at the 90% of confidence level are set on the product branching fraction of the process.

1 Introduction

The Next to Minimal Supersymmetric Standard Model (NMSSM)\(^1\), one of the several extensions of the Standard Model, predicts a larger Higgs sector, with two charged, three neutral CP-even, and two neutral CP-odd Higgs bosons. In particular, the model includes the possibility that one of the pseudoscalar Higgs bosons, denoted as $A^0$ hereafter, can be lighter than two bottom quarks\(^2\), therefore making its production accessible at the B-factories, via the radiative decay of an $\Upsilon$ resonance.

The $A^0$ is a superposition of a singlet and a non-singlet state, and the value of the branching fraction of the radiative decay $\Upsilon \to \gamma A^0$ actually depends on the non-singlet fraction. The final state to which the $A^0$ decays depends instead on various parameters, such as $\tan\beta$ and the mass of the CP-odd Higgs boson itself\(^3\). In order to be sensitive to as much parameter space as possible, BABAR has performed searches for different final states: $A^0$ decaying into $\mu^+\mu^-$\(^4\), $5$, into $\tau^+\tau^-$\(^6\), into invisible states\(^8\), and into hadrons\(^9\), without seeing any significant signal.

The search presented here\(^10\) focuses on the decays $A^0 \to gg$ or $s\bar{s}$. For an $A^0$ mass smaller than $2m_{\tau}$, the light pseudoscalar Higgs boson is predicted to decay mostly into two gluons if $\tan\beta$ is of order 1, and into $s\bar{s}$ if $\tan\beta$ is of order 10. Despite being motivated by NMSSM, the results of this search can be applied to any CP-odd hadronic resonances produced in the radiative decays of $\Upsilon(1S)$.

2 Experimental technique

This analysis uses the data recorded by the BABAR detector at the PEP-II asymmetric-energy $e^+e^-$ collider at the SLAC National Accelerator Laboratory. The BABAR detector is described in detail elsewhere\(^11,12\). We use $\sim 14$ fb\(^{-1}\) of data taken at the $\Upsilon(2S)$ resonance. Tagging the dipion in the $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ transition allows to significantly reduce the otherwise dominant $e^+e^- \to q\bar{q}$ background, where $q$ is a $u$, $d$, or $s$ quark. We also use $\sim 1.4$ fb\(^{-1}\) of data taken 30 MeV below the $\Upsilon(2S)$ resonance as a background estimate. Simulated signal events with various $A^0$ masses ranging from 0.5 to 9.0 GeV/c\(^2\) are used in this analysis.
Table 1: Decay modes for candidate $A^0 \to gg$ and $s\bar{s}$ decays, sorted by the total mass of the decay products.

| # | Channel | # | Channel |
|---|---|---|---|
| 1 | $\pi^+\pi^-\pi^0$ | 14 | $K^+K^-\pi^+\pi^-$ |
| 2 | $\pi^+\pi^-2\pi^0$ | 15 | $K^+K^-\pi^+\pi^-\pi^0$ |
| 3 | $2\pi^+2\pi^-$ | 16 | $K^+K_S^0\pi^+\pi^+$ |
| 4 | $2\pi^+2\pi^-\pi^0$ | 17 | $K^+K^-\pi^-$ |
| 5 | $\pi^+\pi^-\eta$ | 18 | $K^+K^-2\pi^+2\pi^-$ |
| 6 | $2\pi^+2\pi^-2\pi^0$ | 19 | $K^+K^0_S\pi^+\pi^-2\pi^0$ |
| 7 | $3\pi^+3\pi^-$ | 20 | $K^+K^-2\pi^+2\pi^-\pi^0$ |
| 8 | $2\pi^+2\pi^-\eta$ | 21 | $K^+K^-2\pi^+2\pi^-2\pi^0$ |
| 9 | $3\pi^+3\pi^-2\pi^0$ | 22 | $K^+K^0_S\pi^+2\pi^-\pi^0$ |
| 10 | $4\pi^+4\pi^-$ | 23 | $K^+K^-3\pi^+3\pi^-$ |
| 11 | $K^+K^-\pi^0$ | 24 | $2K^+2K^-$ |
| 12 | $K^+K_S^0\pi^+$ | 25 | $p\bar{p}\eta^0$ |
| 13 | $K^+K^-2\pi^0$ | 26 | $pp\eta^+\pi^-$ |

The final states analyzed must contain: two charged tracks as the dipion system candidate, a radiative photon with an energy greater than 200 MeV when calculated in its center-of-mass frame, and a hadronic system. An exclusive reconstruction of $A^0 \to gg$ is performed, using 26 channels as listed in Table 1, while disregarding two-body decay channels because a CP-odd Higgs boson cannot decay into two pseudoscalar mesons. The $A^0 \to s\bar{s}$ sample is defined as the subset of the 26 $A^0 \to gg$ decay channels that include two or four kaons (channels 11-24 in Table 1). Charged kaons, pions, and protons are required to be positively identified.

The $A^0$ mass resolution is improved by constraining the $A^0$ candidate and the photon to have an invariant mass equal to the $\Upsilon(1S)$ one, and a decay vertex at the beam spot. The main backgrounds to this search are:

- $\Upsilon(1S) \to \gamma gg$ events, with gluons hadronizing to more than one daughter; it is dominant at low masses, i.e. between 2 and 4 GeV/$c^2$;
- $\Upsilon(1S) \to ggg$ events, with a $\pi^0$ mistaken as a photon; it is dominant at higher masses, i.e. between 7 and 9 GeV/$c^2$.

This search relies on the hadronization modelling used in simulations; the agreement between data and Monte Carlo samples is checked on $\Upsilon(1S) \to \gamma gg$ events, resulting in a scaling factor and a global systematic uncertainty of 50% to be applied to the efficiency. This is the dominant contribution to the systematic uncertainties of this analysis.

3 Results

The candidate mass spectrum is shown in Fig. 1. The $A^0$ would appear as a narrow peak in the distribution. A scan of the mass spectrum has been performed in 10 MeV/$c^2$-steps, from 0.5 to 9 GeV/$c^2$, without finding any significant signal through the entire mass range analyzed. Bayesian upper limits at the 90% of confidence level are then set on the product of branching fractions $B(\Upsilon(1S) \to \gamma A^0) \times B(A^0 \to gg)$ and $B(\Upsilon(1S) \to \gamma A^0) \times B(A^0 \to s\bar{s})$, ranging between $10^{-6}$ and $10^{-2}$, and between $10^{-5}$ and $10^{-3}$ for the two final states, respectively, as shown in Fig. 2. As a result, the low mass region for $A^0$ is excluded, and no evidence either for a light pseudoscalar Higgs boson, or for any narrow hadronic resonance is found through the entire mass spectrum.
Figure 1: $A^0$ candidate mass spectra after applying all selection criteria. We reconstruct $A^0 \to gg$ using the 26 channels listed in Table 1 and $A^0 \to s\bar{s}$ using the subset of the same 26 channels that includes two or four kaons. The $A^0$ candidate mass is the invariant mass of the reconstructed hadrons in each channel. The black points with error bars are on-resonance data for $A^0 \to gg$. The red squares with error bars are on-resonance data for $A^0 \to s\bar{s}$. The thick blue histogram is $A^0 \to gg$ in off-resonance data normalized to the on-resonance integrated luminosity. The thin magenta histogram is $A^0 \to s\bar{s}$ in off-resonance data normalized to the on-resonance integrated luminosity.

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Figure 2: The 90% confidence level upper limits (thin solid line) on the product branching fractions $\mathcal{B}(\Upsilon(1S) \rightarrow \gamma A^0) \times \mathcal{B}(A^0 \rightarrow gg)$ (top) and $\mathcal{B}(\Upsilon(1S) \rightarrow \gamma A^0) \times \mathcal{B}(A^0 \rightarrow s\bar{s})$ (bottom). We overlay limits calculated using statistical uncertainties only (thin dashed line). The inner band is the expected region of upper limits in 68% of simulated experiments. The inner band plus the outer band is the expected region of upper limits in 95% of simulated experiments. The bands are calculated using all uncertainties. The thick line in the center of the inner band is the expected upper limits calculated using simulated experiments.