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Search for Dimuon Decays of a Light Scalar Boson in Radiative Transitions $\Upsilon \to \gamma A^0$

The *BABAR* Collaboration

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Abstract

We search for evidence of a light scalar boson in the radiative decays of the $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances: $\Upsilon(2S,3S) \to \gamma A^0$, $A^0 \to \mu^+\mu^-$. Such a particle appears in extensions of the Standard Model, where a light *CP*-odd Higgs boson naturally couples strongly to b-quarks. We find no evidence for such processes in the mass range $0.212 \le m_{A^0} \le 9.3\,\mathrm{GeV}$ in the samples of 99×10^6 $\Upsilon(2S)$ and 122×10^6 $\Upsilon(3S)$ decays collected by the *BABAR* detector at the PEP-II B-factory and set stringent upper limits on the effective coupling of the b quark to the A^0. We also limit the dimuon branching fraction of the η_b meson: $\mathcal{B}(\eta_b \to \mu^+\mu^-) < 0.9\%$ at 90% confidence level.

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We search for evidence of a light scalar boson in the radiative decays of the $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances: $\Upsilon(2S,3S) \to \gamma A^0$, $A^0 \to \mu^+\mu^-$. Such a particle appears in extensions of the Standard Model, where a light *CP*-odd Higgs boson naturally couples strongly to b-quarks. We find no evidence for such processes in the mass range $0.212 \le m_{A^0} \le 9.3\,\mathrm{GeV}$ in the samples of 99×10^6 $\Upsilon(2S)$ and 122×10^6 $\Upsilon(3S)$ decays collected by the *BABAR* detector at the PEP-II B-factory and set stringent upper limits on the effective coupling of the b quark to the A^0. We also limit the dimuon branching fraction of the η_b meson: $\mathcal{B}(\eta_b \to \mu^+\mu^-) < 0.9\%$ at 90% confidence level.

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The concept of mass is one of the most intuitive ideas in physics since it is present in everyday human experience. Yet the fundamental nature of mass remains one of the great mysteries of science. The Higgs mechanism is a theoretically appealing way to account for the different masses of elementary particles [1]. It implies the existence of at least one new scalar particle, the Higgs boson, which is the only Standard Model (SM) [2] particle yet to be observed. The SM Higgs boson mass is constrained to be of $\mathcal{O}(100-200\,\mathrm{GeV})$ by direct searches [3] and by precision electroweak measurements [4].

A number of theoretical models extend the Higgs sector to include additional Higgs fields, some of them naturally light [5]. Similar light scalar states, *e.g.* axions, appear in models motivated by astrophysical observations and are typically assumed to have Higgs-like couplings [6]. Direct searches typically constrain the mass of such a light particle, A^0, to be below $2m_b$ [7], making it accessible to radiative decays of Υ resonances [8]. Model predictions for the branching fraction (BF) of $\Upsilon \to \gamma A^0$ decays range from 10^{-6} [6, 9] to as high as 10^{-4} [9]. Empirical motivation for a low-mass Higgs search comes from the HyperCP experiment [10], which observed three anomalous events in the $\Sigma^+ \to p\mu^+\mu^-$ final state. These events have been interpreted as production of a scalar boson with the mass of 214.3 MeV decaying into a pair of muons [11, 12]. The large datasets available at *BABAR* allow us to place stringent constraints on such models.

If a light scalar A^0 exists, the pattern of its decays would depend on its mass. Assuming no invisible (neutralino) decays [13], for low masses $m_{A^0} < 2m_\tau$ the BF $\mathcal{B}_{\mu\mu} \equiv \mathcal{B}(A^0 \to \mu^+\mu^-)$, should be sizable. Significantly above the τ threshold, $A^0 \to \tau^+\tau^-$ would dominate, and hadronic decays might also be significant.

This Letter describes a search for a resonance in the dimuon invariant mass distribution for the fully reconstructed final state $\Upsilon(2S,3S) \to \gamma A^0,\ A^0 \to \mu^+\mu^-$. We assume that the decay width of the resonance is negligibly small compared with the experimental resolution, as expected [6, 14] for m_{A^0} sufficiently far from the mass of the η_b [15]. We further assume that the resonance is a scalar (or pseudo-scalar) particle. While the significance of any observation would not depend on this assumption, the signal efficiency and, therefore, the BFs are computed for a spin-0 particle. In addition, following the recent discovery of the η_b meson [15], we look for the leptonic decay of the η_b through $\Upsilon(2S,3S) \to \gamma\eta_b,\ \eta_b \to \mu^+\mu^-$. We use $\Gamma(\eta_b) = 10 \pm 5\,\mathrm{MeV}$, the range expected in most theoretical models and consistent with the *BABAR* results [15].

We search for two-body transitions $\Upsilon(2S,3S) \to \gamma A^0$, followed by decay $A^0 \to \mu^+\mu^-$ in samples of $(98.6 \pm 0.9) \times 10^6$ $\Upsilon(2S)$ and $(121.8 \pm 1.2) \times 10^6$ $\Upsilon(3S)$ decays collected with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- collider at the SLAC National Accelerator Laboratory. We use a sample of $79\,\mathrm{fb}^{-1}$ accumulated on the $\Upsilon(4S)$ resonance ($\Upsilon(4S)$ sample) for studies of the continuum backgrounds. Since the $\Upsilon(4S)$ is three orders of magnitude broader than the $\Upsilon(2S)$ and $\Upsilon(3S)$, the BF $\mathcal{B}(\Upsilon(4S) \to \gamma A^0)$ is expected to be negligible. For characterization of the background events and selection optimization, we also use a sample of $1.4\,\mathrm{fb}^{-1}$ ($2.4\,\mathrm{fb}^{-1}$) collected 30 MeV below the $\Upsilon(2S)$ ($\Upsilon(3S)$) resonance (off-resonance samples). The *BABAR* detector is described in detail elsewhere [16, 17].

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, while allowing additional photons with CM energies below 0.2 GeV to be present in the event. We assign a muon mass hypothesis to the two tracks (henceforth referred to as muon candidates), and require that at least one is positively identified as a muon [17]. We require that the muon candidates form a geometric vertex with $\chi^2_{\mathrm{vtx}} < 20$ for 1 degree of freedom and displaced transversely by at most 2 cm [18] from the nominal location of the e^+e^- interaction region. We perform a kinematic fit to the Υ candidate formed from the two muon candidates and the energetic photon. The CM energy of the Υ candidate is constrained, within the beam energy spread, to the total beam energy $\sqrt{s}$, and the decay vertex of the Υ is constrained to the beam interaction region. We select events with $-0.2 < \sqrt{s} - m(\Upsilon) < 0.6$ GeV and place a requirement on the kinematic fit $\chi^2_\Upsilon < 30$ (for 6 degrees of freedom). We further require that the momenta of the dimuon candidate A^0 and the photon are back-to-back in the CM frame to within 0.07 rad, and that the cosine of the angle between the muon direction and A^0 direction in the center of mass of the A^0 is less than 0.92. The selection criteria are chosen to maximize $\varepsilon/\sqrt{B}$, where ε is the average selection efficiency for a broad m_{A^0} range and B is the background yield in the off-resonance sample.

The criteria above select 387,546 $\Upsilon(2S)$ and 724,551 $\Upsilon(3S)$ events (mass spectra for $\Upsilon(2S)$ and $\Upsilon(3S)$ datasets are shown in Fig. 3 in [19]). The backgrounds are dominated by two types of QED processes: "continuum" $e^+e^- \to \gamma\mu^+\mu^-$ and the initial-state radiation (ISR) production of ρ^0, ϕ, J/ψ, $\psi(2S)$, and $\Upsilon(1S)$ vector mesons. In order to suppress contributions from the ISR-produced $\rho^0 \to \pi^+\pi^-$ final state in which a pion is misidentified as a muon (probability $\sim$3%/pion), we require that both tracks are positively identified as muons when we search for A^0 candidates in the range $0.5 \leq m_{A^0} < 1.05$ GeV. Finally, when selecting candidate events in the η_b region with dimuon invariant mass $m_{\mu\mu} \sim 9.39$ GeV in the $\Upsilon(2S)$ ($\Upsilon(3S)$) dataset, we suppress the decay chain $\Upsilon(2S) \to \gamma_2\chi_b(1P),\ \chi_b(1P) \to \gamma_1\Upsilon(1S)$ ($\Upsilon(3S) \to \gamma_2\chi_b(2P),\ \chi_b(2P) \to \gamma_1\Upsilon(1S)$) by requiring that no secondary photon γ_2 above a CM energy of $E^*_2 = 0.1$ GeV (0.08 GeV) is present in the event.

We use signal Monte Carlo (MC) samples [20, 21] $\Upsilon(2S) \to \gamma A^0$ and $\Upsilon(3S) \to \gamma A^0$ generated at 20 values of m_{A^0} over a broad range $0.212 \leq m_{A^0} \leq 9.5\,\mathrm{GeV}$ to measure the selection efficiency for the signal events. The efficiency varies between 24–55%, depending m_{A^0}.

We extract the yield of signal events as a function of m_{A^0} in the interval $0.212 \leq m_{A^0} \leq 9.3\,\mathrm{GeV}$ by performing a series of unbinned extended maximum likelihood fits to the distribution of the reduced mass $m_R \equiv \sqrt{m_{\mu\mu}^2 - 4m_\mu^2}$. The likelihood function contains contributions from signal, continuum background, and, where appropriate, peaking backgrounds, as described below. For $0.212 \leq m_{A^0} < 0.5\,\mathrm{GeV}$, we fit over a fixed interval $0.01 < m_R < 0.55\,\mathrm{GeV}$; near the J/ψ resonance, we fit over the interval $2.7 < m_R < 3.5\,\mathrm{GeV}$; and near the $\psi(2S)$ resonance we fit over the range $3.35 < m_R < 4.1\,\mathrm{GeV}$. Elsewhere, we use sliding intervals $\mu - 0.2 < m_R < \mu + 0.1\,\mathrm{GeV}$, where μ is the mean of the signal distribution of m_R. We search for A^0 in fine mass steps $\Delta m_{A^0} = 2$–$5\,\mathrm{MeV}$. We sample a total of 1951 m_{A^0} values. For each m_{A^0} value, we determine the BF products $\mathcal{B}_{nS} \equiv \mathcal{B}(\Upsilon(nS) \to \gamma A^0) \times \mathcal{B}_{\mu\mu}$, where $n = 2, 3$. Both the fitting procedure and the event selection were developed and tested using MC and $\Upsilon(4S)$ samples prior to their application to the $\Upsilon(2S)$ and $\Upsilon(3S)$ data sets.

The signal probability density function (PDF) is described by a sum of two Crystal Ball functions [23] with tail parameters on either side of the maximum. The signal PDFs are centered around the expected values of m_R and have a typical resolution of 2–10 MeV, which increases monotonically with m_{A^0}. We determine the PDF as a function of m_{A^0} using the signal MC samples, and we interpolate PDF parameters and signal efficiency values linearly between the simulated points. We determine the uncertainty in the PDF parameters by comparing the distributions of the simulated and reconstructed $e^+e^- \to \gamma_{\rm ISR} J/\psi,\ J/\psi \to \mu^+\mu^-$ events.

We describe the continuum background below $m_R < 0.23\,\mathrm{GeV}$ with a threshold function $f_{\rm bkg}(m_R) \propto \tanh\left(\sum_{\ell=1}^{3} p_\ell m_R^\ell\right)$. The parameters p_ℓ are fixed to the values determined from the fits to the $e^+e^- \to \gamma\mu^+\mu^-$ MC sample [22] and agree, within statistics, with those determined by fitting the $\Upsilon(2S)$, $\Upsilon(3S)$, and $\Upsilon(4S)$ samples with the signal contribution set to zero. Elsewhere the background is well described in each limited m_R range by a first-order ($m_R < 9.3\,\mathrm{GeV}$) or a second-order ($m_R > 9.3\,\mathrm{GeV}$) polynomial with coefficients determined by the fit.

Events due to known resonances ϕ, J/ψ, $\psi(2S)$, and $\Upsilon(1S)$ are present in our sample in specific m_R intervals, and constitute peaking backgrounds. We include these contributions in the fit where appropriate, and describe the shape of the resonances using the same functional form as for the signal, a sum of two Crystal Ball functions, with parameters determined from fits to the combined $\Upsilon(2S)$ and $\Upsilon(3S)$ dataset. The contribution to the event yield from $\phi \to K^+K^-$, in which one of the kaons is misidentified as a muon, is fixed to 111 ± 24 ($\Upsilon(2S)$) and 198 ± 42 ($\Upsilon(3S)$). We determine this contribution from the event yield of $e^+e^- \to \gamma\phi,\ \phi \to K^+K^-$ in a sample where both kaons are positively identified, corrected for the measured misidentification rate of kaons as muons. We do not search for A^0 candidates in the immediate vicinity of J/ψ and $\psi(2S)$, excluding regions of $\pm 40\,\mathrm{MeV}$ around J/ψ ($\approx \pm 5\sigma$) and $\pm 25\,\mathrm{MeV}$ ($\approx \pm 3\sigma$) around $\psi(2S)$.

We compare the overall selection efficiency between the data and the MC simulation by measuring the absolute cross section $d\sigma/dm_R$ for the radiative QED process $e^+e^- \to \gamma\mu^+\mu^-$ over the broad kinematic range $0 < m_R \leq 9.6\,\mathrm{GeV}$, using the off-resonance sample. We use the ratio of measured to expected [22] cross sections to correct the signal selection efficiency as a function of m_{A^0}. This correction ranges between 4–10%, with a systematic uncertainty of 5%. This uncertainty accounts for effects of selection, reconstruction (for both charged tracks and the photon), and trigger efficiencies.

We determine the uncertainty in the signal and peaking background PDFs by comparing the distributions of ≈ 4000 data and MC $e^+e^- \to \gamma_{\rm ISR} J/\psi,\ J/\psi \to \mu^+\mu^-$ events. We correct for the observed difference in the width of the m_R distribution (5.3 MeV in MC versus 6.6 MeV in the data) and use half of the correction to estimate the systematic uncertainty on the signal yield. This is the dominant systematic uncertainty on the signal yield for $m_{A^0} > 0.4$ GeV. We estimate that the uncertainties in the tail parameters of the Crystal Ball PDF contribute less than 1% to the uncertainty in signal yield based on the observed variations in the J/ψ yield. The systematic uncertainties due to the fixed continuum background PDF for $m_R < 0.23$ and the fixed contribution from $e^+e^- \to \gamma\phi$ do not exceed $\sigma_{\rm bkg}(\mathcal{B}_{nS}) = 0.2 \times 10^{-6}$. These are the largest systematic contributions for $0.212 \leq m_{A^0} < 0.4$ GeV.

We test for possible bias in the fitted value of the signal yield with a large ensemble of pseudo-experiments. The bias is consistent with zero for all values of m_{A^0}, and we assign a BF uncertainty of $\sigma_{\rm bias}(\mathcal{B}_{nS}) = 0.05 \times 10^{-6}$ at all values of m_{A^0} to cover the statistical variations in the results of the test.

To estimate the significance of any positive fluctuation, we compute the likelihood ratio variable $\mathcal{S}(m_{A^0}) = \mathrm{sign}(N_{\rm sig})\sqrt{2\log(L_{\rm max}/L_0)}$, where $L_{\rm max}$ is the maximum likelihood value for a fit with a free signal yield centered at m_{A^0}, $N_{\rm sig}$ is that fitted signal yield, and L_0 is the value of the likelihood for the signal yield fixed at zero. Under the null hypothesis $\mathcal{S}$ is expected to be normal-distributed with $\mu = 0$ and $\sigma = 1$ (Fig. 1). Including systematics, the largest $\mathcal{S}$ values are 3.1 ($\Upsilon(2S)$) and 2.8 ($\Upsilon(3S)$), consistent with a null-hypothesis distribution for 1951 m_{A^0} points.

Since we do not observe a significant excess of events above the background in the range $0.212 < m_{A^0} \leq 9.3\,\mathrm{GeV}$, we set upper limits on $\mathcal{B}_{2S}$ and $\mathcal{B}_{3S}$. We add statistical and systematic uncertainties in quadrature. The 90% confidence level (C.L.) Bayesian upper limits, computed with a uniform prior and assuming a Gaussian likelihood function, are shown in Fig. 2 as a function of mass

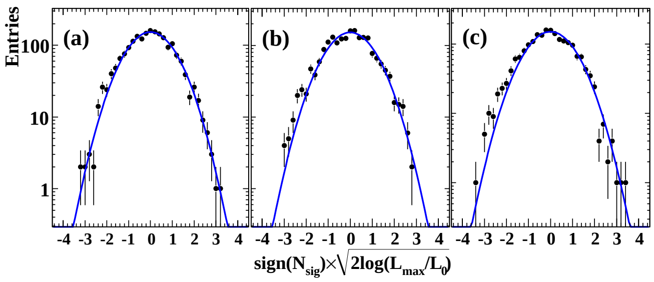

FIG. 1: Distribution of the log-likelihood variable $\mathcal{S}$ with both statistical and systematic uncertainties included for (a) $\Upsilon(2S)$ fit, (b) $\Upsilon(3S)$ fit, and (c) combination of $\Upsilon(2S)$ and $\Upsilon(3S)$ data. There are no points outside of displayed region of $\mathcal{S}$. The solid curve is the standard normal distribution.

m_{A^0}. The limits vary from 0.26×10^{-6} to 8.3×10^{-6} ($\mathcal{B}_{2S}$) and from 0.27×10^{-6} to 5.5×10^{-6} ($\mathcal{B}_{3S}$).

The BFs $\mathcal{B}(\Upsilon(nS)\to\gamma A^0)$ are related to the effective coupling f_Υ of the bound b-quark to the A^0 through [8, 12, 24]:

$$\frac{\mathcal{B}(\Upsilon(nS)\to\gamma A^0)}{\mathcal{B}(\Upsilon(nS)\to l^+l^-)}=\frac{f_\Upsilon^2}{2\pi\alpha}\left(1-\frac{m_{A^0}^2}{m_{\Upsilon(nS)}^2}\right) \qquad (1)$$

where $l\equiv e$ or μ and α is a fine structure constant. The effective coupling f_Υ includes the Yukawa coupling of the b-quark and the m_{A^0}-dependent QCD and relativistic corrections to $\mathcal{B}_{nS}$ [24] and the leptonic width of $\Upsilon(nS)$ [25]. To first order in α_S, the corrections range from 0 to 30% [24] but have comparable uncertainties [26]. The ratio of corrections for $\Upsilon(2S)$ and $\Upsilon(3S)$ is within 4% of unity [24] in the relevant range of m_{A^0}. We do not attempt to factorize these contributions, but instead compute the experimentally-accessible quantity $f_\Upsilon^2\mathcal{B}_{\mu\mu}$ and average $\Upsilon(2S)$ and $\Upsilon(3S)$ results, taking into account both correlated and uncorrelated uncertainties. The combined upper limits are shown as a function of m_{A^0} in Fig. 2(c) (plots with expanded mass scales in three ranges of m_{A^0} are available in Fig. 4-6 in [19]) and span the range $(0.44-44)\times10^{-6}$, at 90% C.L. The combined likelihood variable $\langle\mathcal{S}\rangle=(w_{2S}\mathcal{S}_{2S}+w_{3S}\mathcal{S}_{3S})/\sqrt{w_{2S}^2+w_{3S}^2}$ is shown in Fig. 1c, where w_{nS} is the statistical weight of the $\Upsilon(nS)$ dataset in the average. The largest fluctuation is $\langle\mathcal{S}\rangle=3.3$. Our set of 1951 overlapping fit regions corresponds to $\approx$ 1500 independent measurements [27]. We determine the probability to observe a fluctuation of $\langle\mathcal{S}\rangle=3.3$ or larger in such a sample to be at least 45%.

We do not observe any significant signal at $m_{A^0}=0.214$ GeV (Fig. 7 in [19]) and set an upper limit on the coupling $f_\Upsilon^2(m_{A^0}=0.214\,\text{GeV})<1.6\times10^{-6}$ at 90% C.L (assuming $\mathcal{B}_{\mu\mu}=1$), which is significantly smaller than the value required to explain the HyperCP events as light Higgs production [11].

A fit to the η_b region (Fig. 8 in [19]) includes background contributions from the ISR process $e^+e^-\to$

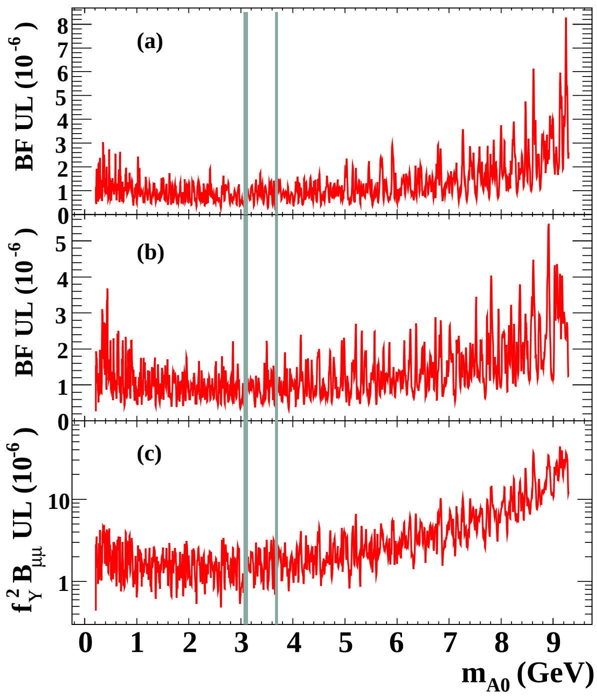

FIG. 2: 90% C.L. upper limits on (a) $\mathcal{B}(\Upsilon(2S)\to\gamma A^0)\times\mathcal{B}_{\mu\mu}$, (b) $\mathcal{B}(\Upsilon(3S)\to\gamma A^0)\times\mathcal{B}_{\mu\mu}$, and (c) effective coupling $f_\Upsilon^2\times\mathcal{B}_{\mu\mu}$ as a function of m_{A^0}. The shaded areas show the regions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

$\gamma_{\rm ISR}\Upsilon(1S)$, and from the cascade decays $\Upsilon(nS)\to\gamma_2\chi_{bJ}$, $\chi_{bJ}\to\gamma_1\Upsilon(1S)$ with $\Upsilon(1S)\to\mu^+\mu^-$. We measure the rate of the ISR events in the $\Upsilon(4S)$ dataset, scale it to the $\Upsilon(2S)$ and $\Upsilon(3S)$ data, and fix this contribution in the fit. The rate of the cascade decays, the number of signal events, and the continuum background are free in the fits to the $\Upsilon(2S)$ and $\Upsilon(3S)$ data sets. We measure $\mathcal{B}(\Upsilon(2S)\to\gamma\eta_b)\times\mathcal{B}(\eta_b\to\mu^+\mu^-)=(-0.4\pm3.9\pm1.4)\times10^{-6}$ and $\mathcal{B}(\Upsilon(3S)\to\gamma\eta_b)\times\mathcal{B}(\eta_b\to\mu^+\mu^-)=(-1.5\pm2.9\pm1.6)\times10^{-6}$, where the first uncertainty is statistical and the second is systematic, dominated by the uncertainty in $\Gamma(\eta_b)$. Taking into account the *BABAR* measurements of $\mathcal{B}(\Upsilon(2S)\to\gamma\eta_b)$ and $\mathcal{B}(\Upsilon(3S)\to\gamma\eta_b)$ [15], we derive $\mathcal{B}(\eta_b\to\mu^+\mu^-)=(-0.25\pm0.51\pm0.33)\%$ and $\mathcal{B}(\eta_b\to\mu^+\mu^-)<0.9\%$ at 90% C.L. This limit is consistent with the mesonic interpretation of the η_b state.

In summary, we find no evidence for the dimuon decays of a light scalar particle in radiative decays of $\Upsilon(2S)$ and $\Upsilon(3S)$ mesons. We set upper limits on the coupling $f_\Upsilon^2\times\mathcal{B}_{\mu\mu}$ for $0.212\le m_{A^0}\le9.3$ GeV. Assuming $\mathcal{B}_{\mu\mu}\approx1$ in the mass range $2m_\mu\le m_{A^0}\le1$ GeV, our results limit the coupling f_Υ to be at most 12% of the Standard Model coupling of the b quark to the Higgs boson. Our limits rule out much of the parameter space allowed by the light Higgs [9] and axion [6] models. We also set an upper limit on the dimuon branching fraction of the η_b.

We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and for the substantial dedicated effort from the computing organizations that support *BABAR*. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MES (Russia), MEC (Spain), and STFC (United Kingdom). Individuals have received support from the Marie Curie EIF (European Union) and the A. P. Sloan Foundation.

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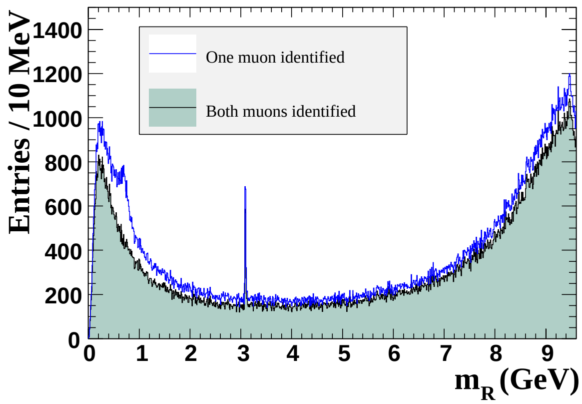
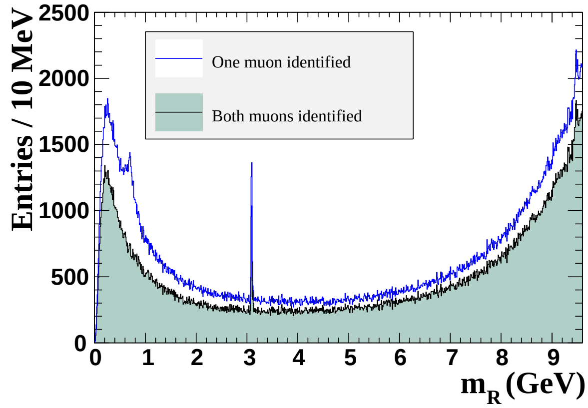
APPENDIX: EPAPS MATERIAL

The following includes supplementary material for the Electronic Physics Auxiliary Publication Service.



(a)



(b)

FIG. 3: Distribution of the reduced mass m_R in (a) the $\Upsilon(2S)$ data and (b) the $\Upsilon(3S)$ data. Blue (open) histogram shows the distribution for the selection in which only one of two muons is required to be positively identified. The peak from $e^+e^- \rightarrow \gamma_{\rm ISR}\rho^0(770)$, $\rho^0 \rightarrow \pi^+\pi^-$, in which one of the pions is misidentified as a muon, is clearly visible. Black (filled) histogram shows the distribution for the selection in which both muons are positively identified (this selection is used in the search for $0.5 \leq m_{A^0} < 1.05$ GeV). The ISR-produced peaks $J/\psi \rightarrow \mu^+\mu^-$ and $\Upsilon(1S) \rightarrow \mu^+\mu^-$ are visible for both selections.

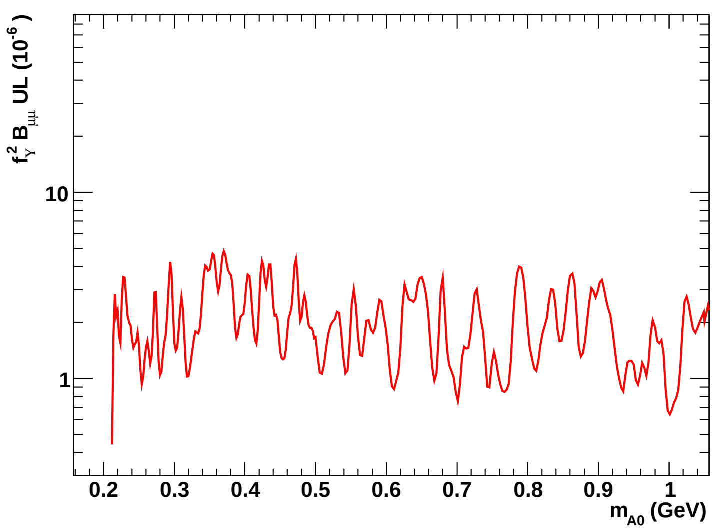


FIG. 4: 90% C.L. upper limits on the effective Yukawa coupling $f^2_\Upsilon \times \mathcal{B}_{\mu\mu}$ as a function of m_{A^0} in the range $0.212 \leq m_{A^0} \leq 1.05$ GeV.

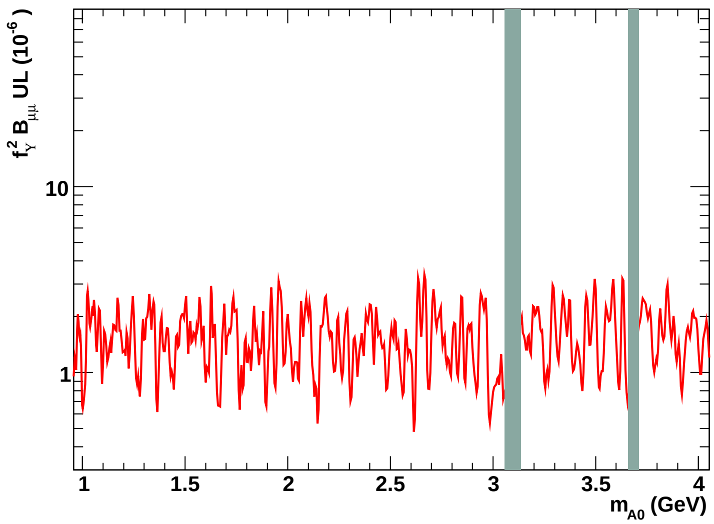


FIG. 5: Upper limits on the effective Yukawa coupling $f^2_\Upsilon \times \mathcal{B}_{\mu\mu}$ as a function of m_{A^0} in the range $1 \leq m_{A^0} \leq 4$ GeV. The shaded areas show the regions around the J/ψ and $\psi(2S)$ resonances excluded from the search.

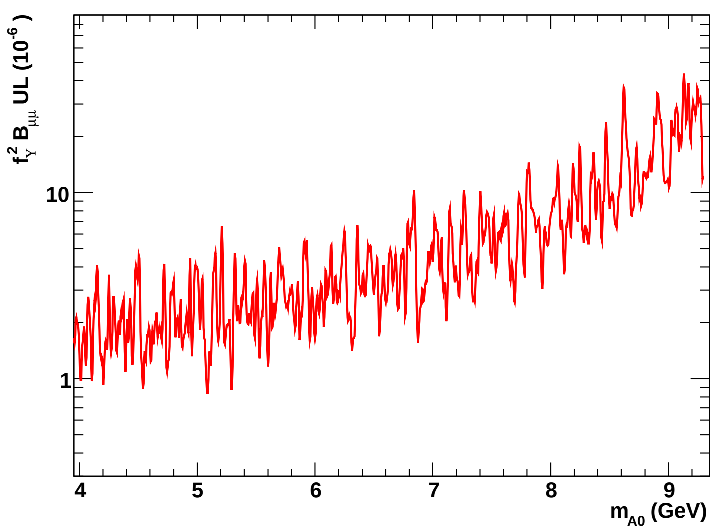
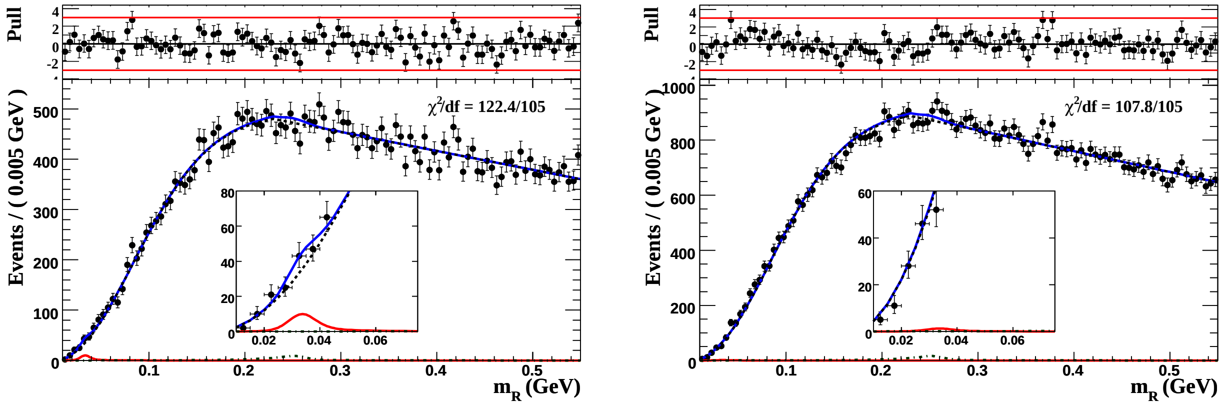
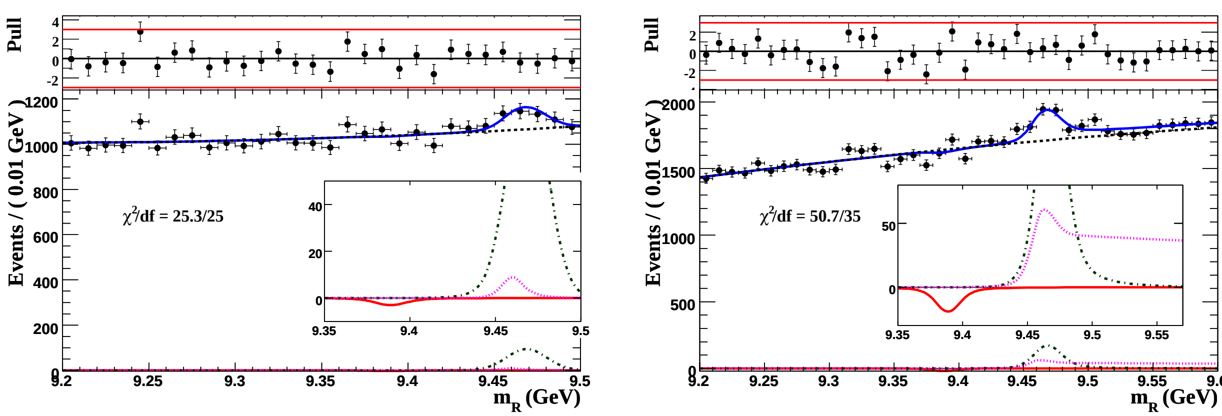


FIG. 6: Upper limits on the effective Yukawa coupling $f^2_\Upsilon \times \mathcal{B}_{\mu\mu}$ as a function of m_{A^0} in the range $4 \leq m_{A^0} \leq 9.3$ GeV.



(a) (b)

FIG. 7: Fits to the HyperCP region $m_{A^0} = 0.214$ GeV in (a) $\Upsilon(2S)$ dataset and (b) $\Upsilon(3S)$ dataset. The bottom graph shows the m_R distribution (solid points), overlaid by the full fit (solid blue line). Also shown are the contributions from the signal at $m_{A^0} = 0.214$ GeV (solid red line) and the continuum background (dashed black line). The inset zooms in on the signal region. The top plot shows the normalized residuals $p = (\text{data} - \text{fit})/\sigma(\text{data})$ with unit error bars. The individual fits correspond to the log-likelihood ratios of $\mathcal{S} = 2.0$ ($\Upsilon(2S)$) and $\mathcal{S} = 0.2$ ($\Upsilon(3S)$), and the combined significance $\langle \mathcal{S} \rangle = 1.4$.



(a) (b)

FIG. 8: Fits to the η_b region in (a) $\Upsilon(2S)$ dataset and (b) $\Upsilon(3S)$ dataset. The bottom graph shows the m_R distribution (solid points), overlaid by the full fit (solid blue line). Also shown are the contributions from the signal at at $m_{\eta_b} = 9.389$ GeV (solid red line), background from the $e^+e^- \to \gamma_{\text{ISR}}\Upsilon(1S)$ (dot-dashed green line), background from $\Upsilon(3S) \to \gamma\chi_b(2P)$, $\chi_b(2P) \to \gamma\Upsilon(1S)$ (dotted magenta line), and the continuum background (dashed black line). The inset zooms in on the signal region. The top plot shows the normalized residuals $p = (\text{data} - \text{fit})/\sigma(\text{data})$ with unit error bars.