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Searches for Exotic Decays of the $\Upsilon(3S)$ at BABAR

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Abstract. In this paper we present two searches for new physics in $\Upsilon(3S)$ decays collected by the BABAR detector. We search for charged lepton-flavour violating decays of the $\Upsilon(3S)$, which are unobservable in the Standard Model but are predicted to occur in several beyond-the-Standard Model scenarios. We also search for production of a light Higgs or Higgs-like state produced in radiative decays of the $\Upsilon(3S)$ and decaying to muon pairs.

1. Introduction

When the Large Hadron Collider becomes operational, it will probe physics beyond the Standard Model (SM) by searching for direct production of new particles such as those predicted by Supersymmetry and models with extra dimensions. However, it is also possible to search for new physics in data collected at lower collision energies by searching for rare and exotic processes which are forbidden in the SM. In this paper two such searches are presented, which use data collected by the BABAR detector [1] situated at the PEP-II collider at SLAC National Laboratory. PEP-II nominally collides electrons and positrons at a center-of-mass (CM) collision energy $\sqrt{s} = M_{\Upsilon(4S)}$, producing pairs of B mesons which are used to study charge-parity violation. In the searches presented here the collision energy is tuned to the $\Upsilon(3S)$ mass, which is below the threshold for B meson pair production. The width of the $\Upsilon(3S)$ is smaller than that of the $\Upsilon(4S)$ by three orders of magnitude, and the branching fractions for rare $\Upsilon(3S)$ decays are therefore larger by $O(10^3)$. This leads to dramatic enhancement in the sensitivity to rare and exotic processes, motivating the collection of 122×10^6 $\Upsilon(3S)$ decays at the end of PEP-II operations.

2. Search for Lepton-Flavour Violating $\Upsilon(3S)$ Decays

In the SM, the rates for charged lepton-flavour violating (CLFV) processes are suppressed by $(\Delta(m_\nu^2)/M_W^2)^2 \lesssim 10^{-48}$ [2, 3] and are therefore unobservable. Here $\Delta(m_\nu^2)$ is the difference between the squared masses of neutrinos of different flavour and M_W is the charged weak vector boson mass. Several beyond-the-Standard Model (BSM) scenarios, including Supersymmetry and models with leptoquarks or compositeness, predict observable rates for CLFV processes, which would therefore provide a clear signal of new physics. These processes are generally mediated by new particles appearing in loops, whose masses may therefore far exceed the 10.35 GeV CM collision energy. The previous constraints on CLFV $\Upsilon(3S)$ decays come from the CLEO experiment, which placed the 95% confidence level upper limit $BF(\Upsilon(3S) \to \mu^\pm\tau^\mp) < 2.03 \times 10^{-5}$ [4]. In this analysis, documented in [5], upper limits on $BF(\Upsilon(3S) \to e^\pm\tau^\mp)$ and $BF(\Upsilon(3S) \to \mu^\pm\tau^\mp)$ are placed at the 10^{-6} level. These results are used to probe new physics at the TeV mass scale.

The signature of our signal $\Upsilon(3S) \to e^\pm\tau^\mp$ and $\Upsilon(3S) \to \mu^\pm\tau^\mp$ decays consists of a primary high-momentum lepton, either an electron or muon, plus a tau decay in the opposite hemisphere. The tau is required to decay to a single charged particle plus possible additional neutral pions. If the tau decays

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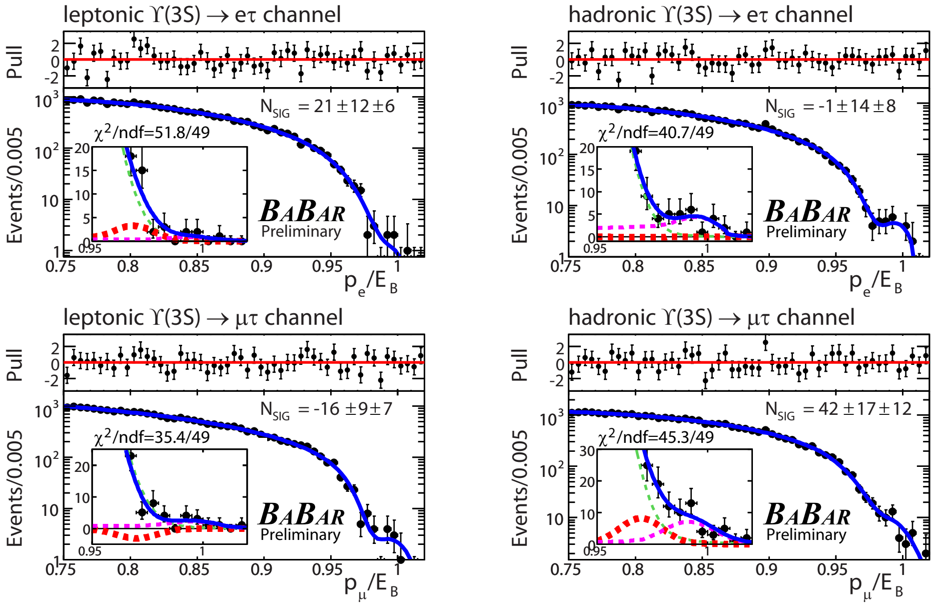

Figure 1. Fit results for the four signal channels, where 'leptonic' and 'hadronic' refer to the τ decay mode. The thin green dashed line is the τ-pair background PDF, the medium magenta dashed line is the Bhabha/μ-pair background PDF, the thick red line is the signal PDF, and the solid blue line is the sum of these components. The inset shows a close-up of the region $0.95 < \mathrm{p}_\ell/\mathrm{E}_\mathrm{B} < 1.02$. The extracted signal yield N_SIG is displayed with its statistical and systematic uncertainties.

leptonically, we require that the tau daughter and primary leptons are of different flavour, while if the tau decays hadronically we require one or two additional neutral pions from this decay. This leads to four signal channels, consisting of leptonic and hadronic tau decay modes for the $\Upsilon(3S) \to e^\pm\tau^\mp$ and $\Upsilon(3S) \to \mu^\pm\tau^\mp$ searches. The beam-energy-normalized primary lepton CM momentum $x = p_1/E_B$ is used to discriminate between the signal and background processes. The signal x distribution is peaked at $x \approx 0.97$ since the momentum of the primary lepton from the $\Upsilon(3S) \to \ell^\pm\tau^\mp$ decay is fixed by the two-body decay kinematics. The background is dominated by τ-pair production, which constitutes an irreducible background. The τ-pair x distribution is smooth and approaches zero as $x \to x_{MAX}$, where $x_{MAX} \approx 0.97$ is the kinematic endpoint of the lepton momentum in the decay $\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau$, boosted into the $\Upsilon(3S)$ rest-frame. There is also a contribution to the $\Upsilon(3S) \to e^\pm\tau^\mp$ search from Bhabha events and to the $\Upsilon(3S) \to \mu^\pm\tau^\mp$ search from μ-pair events. The x distributions of these reducible backgrounds have a peaking component near $x = 1$.

All events are required to pass a set of preselection criteria which suppress Bhabha, μ-pair and two-photon processes, as well as beam-gas interactions. Events are then classified into one of the four signal channels based on the identified particle types and their CM momenta, and additional kinematic selection criteria are applied to further suppress the Bhabha and μ-pair backgrounds. After selection, an unbinned, extended maximum likelihood fit is performed using the x distributions for the four signal channels individually. Probability density functions (PDFs) for the signal, Bhabha/μ-pair and τ-pair processes are determined using simulated events and $\Upsilon(4S)$ data, which is not expected to contain signal events. A global PDF consisting of the sum of these three components is fitted to the x distributions, and the yield of each component is extracted by the fit as shown in Fig. 1. The resulting signal yields are all consistent with zero within $\pm 2.1\sigma$ after including statistical and systematic uncertainties, where the systematic uncertainties are dominated by uncertainties in the PDF shapes. To extract the branching fraction upper limits, the likelihood as a function of the branching fractions is determined for the four signal channels individually. The likelihood functions for the two $\Upsilon(3S) \to e^\pm\tau^\mp$ channels are multiplied to give the combined $\Upsilon(3S) \to e^\pm\tau^\mp$ likelihood function, and likewise for the two $\Upsilon(3S) \to \mu^\pm\tau^\mp$ channels. The 90% confidence level uppers limits are determined by integrating the likelihood functions L and finding UL such that $\int_0^{UL} L\, d(BF)/\int_0^{\infty} L\, d(BF) = 0.9$. The extracted upper limits are $BF(\Upsilon(3S) \rightarrow e^{\pm}\tau^{\mp}) < 5.0 \times 10^{-6}$, which represents the first upper limit on this process, and $BF(\Upsilon(3S) \rightarrow \mu^{\pm}\tau^{\mp}) < 4.1 \times 10^{-6}$, which represents a sensitivity improvement of more than a factor of four with respect to the previous upper limit from the CLEO experiment. These upper limits can be used to constrain new physics using effective field theory. Parameterizing the $\Upsilon(3S) \rightarrow \ell^{\pm}\tau^{\mp}$ process ($\ell = e, \mu$) as a generic $b\bar{b}\ell\tau$ contact interaction with coupling constant $\alpha_{\ell\tau}$ and mass scale $\Lambda_{\ell\tau}$, the branching fraction $BF(\Upsilon(3S) \rightarrow \ell^{\pm}\tau^{\mp})$ is proportional to the quantity $\alpha_{\ell\tau}^2/\Lambda_{\ell\tau}^4$, assuming vector coupling of the $b\bar{b}\ell\tau$ interaction term [6, 7]. The upper limits on $BF(\Upsilon(3S) \rightarrow \ell^{\pm}\tau^{\mp})$ therefore translate to upper limits on $\alpha_{\ell\tau}^2/\Lambda_{\ell\tau}^4$, which can be used to exclude a region of the $\Lambda_{\ell\tau}$ vs. $\alpha_{\ell\tau}$ plane. In the strong coupling limit ($\alpha_{e\tau} = \alpha_{\mu\tau} = 1$), these results translate to the 90% confidence level lower limits $\Lambda_{e\tau} > 1.4$ TeV and $\Lambda_{\mu\tau} > 1.5$ TeV on the mass scale of new physics contributing to CLFV $\Upsilon(3S)$ decays.

3. Search for a Low-Mass Scalar in Radiative $\Upsilon(3S)$ Decays

We search for a low-mass scalar particle A^0 in decays of the $\Upsilon(3S)$ as documented in [8]. This search is motivated by theoretical models including the Next-to-Minimal Supersymmetric Model (NMSSM), which introduces a Higgs singlet state in additional to the two Higgs doublets of the MSSM [9, 10], and a recent model which introduces a light axion [11]. These particles may be produced in the radiative decay $\Upsilon(3S) \rightarrow \gamma A^0$, and the branching fraction for this decay is predicted to be in the range $10^{-6} - 10^{-4}$ for the given models. The branching fraction for the decay $A^0 \rightarrow \mu^+\mu^-$ is predicted to be large if $M_{A^0} < 2m_{\tau}$, leading to a clean final state signature consisting of a muon pair and a photon. This search is complementary to the Higgs searches performed at the LEP2 and Tevatron experiments. The searches performed at LEP2 are not sensitive to a Higgs state whose mass is below $2m_b$, since these experiments searched for the Higgs decaying to two b jets. The most stringent constraints on the signal process come from the CLEO experiment, which placed the upper limit $BF_{EFF} = BF(\Upsilon(1S) \rightarrow \gamma A^0) \times BF(A^0 \rightarrow \mu^+\mu^-) < (1-20) \times 10^{-6}$ for $M_{A^0} < 3.6\ \mathrm{GeV/c^2}$ [12] on the effective signal branching fraction. Further motivation for this search comes from evidence of a resonance structure in the dimuon invariant mass distribution of the decay $\Sigma \rightarrow p\mu^+\mu^-$ observed by the HyperCP experiment [13]. Three events were observed at $M_{\mu\mu} = 214\ \mathrm{MeV/c^2}$, which may be interpreted as a light scalar decaying to a muon pair. Furthermore, in this analysis we investigate the nature of the $b\bar{b}$ ground state η_b recently discovered at *BABAR* [14] by searching for the decay $\eta_b \rightarrow \mu^+\mu^-$. The branching for this decay is not predicted to be sizable if the η_b is a $q\bar{q}$ meson state.

The signature of our events consists of two oppositely-charged tracks, back-to-back with a photon in the CM frame. The photon energy is required to satisfy $E_{\gamma} > 0.5$ GeV and the total recorded energy must be consistent with $\sqrt{s}$. The main background is due to $e^+e^- \rightarrow \mu^+\mu^-\gamma$ production, which leads to a smooth dimuon invariant mass distribution as shown in Fig. 2a. The processes $e^+e^- \rightarrow \gamma_{ISR}\rho^0,\ \rho^0 \rightarrow \pi^+\pi^-$, in which one of the charged pions is misidentified as a muon, and $e^+e^- \rightarrow \gamma_{ISR}X,\ X \rightarrow \mu^+\mu^-$, where $X = J/\psi,\ \psi(2S),\ \Upsilon(1S)$, contribute additional peaking backgrounds. The strategy used in this analysis is to perform a series of maximum likelihood fits to the distribution of reduced mass defined by $m_R = \sqrt{M_{\mu\mu}^2 - 4m_{\mu}^2}$. This variable is used instead of the dimuon mass because its distribution is smoother at low mass. Using a sliding window of width $\sim 300\ \mathrm{MeV/c^2}$, ~ 2000 fits are performed in the range of reduced mass corresponding to $0.212\ \mathrm{GeV/c^2} \leq M_{A^0} \leq 9.3\ \mathrm{GeV/c^2}$. For each fit, the signal is modeled by a peaking function consisting of the sum of two Crystal Ball functions [15] with low- and high-energy tails. The radiative dimuon background is modeled by a threshold function of the form $\tanh(\mathrm{poly}(m_R))$ in the range $m_R < 230\ \mathrm{MeV/c^2}$ and by a first- or second-order polynomial for $m_R > 230\ \mathrm{MeV/c^2}$. For the ~ 2000 fits, the signal significance S is determined according to $S = \mathrm{sign}(N_{SIG})\sqrt{2\log(L_{MAX}/L_0)}$, where N_{SIG} is the extracted signal yield, L_{MAX} is the value of the maximized likelihood function, and L_0 is the value of the likelihood function when the signal yield is fixed to zero. The distribution of S for the ~ 2000 fits is found to be well-described by a Gaussian with a mean consistent with zero and

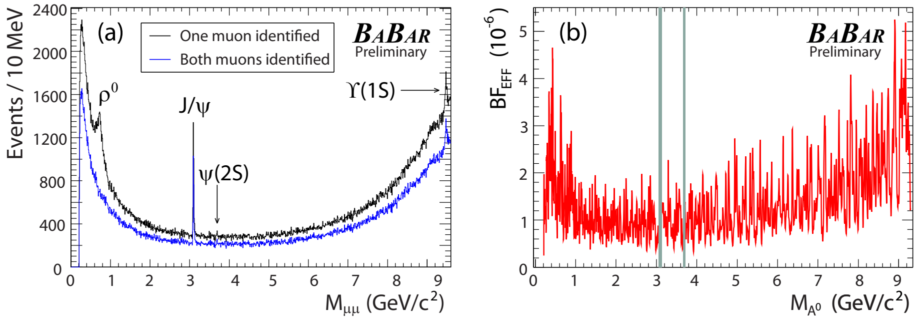

Figure 2. (a) Dimuon invariant mass distribution for events passing selection and (b) 90% confidence level upper limits on the effective branching fraction $BF_{EFF} = BF(\Upsilon(3S) \to \gamma A^0) \times BF(A^0 \to \mu^+\mu^-)$ as a function of the A^0 mass.

width consistent with one, with no outliers at high significance values. We therefore conclude that no statistically significant signal is observed, and the results are used to place the 90% confidence level upper limits $BF_{EFF} = BF(\Upsilon(3S) \to \gamma A^0) \times BF(A^0 \to \mu^+\mu^-) < (0.25 - 5.2) \times 10^{-6}$ as shown in Fig. 2b. These results represent the best upper limits to date on the process $\Upsilon(3S) \to \gamma A^0, A^0 \to \mu^+\mu^-$.

We investigate the HyperCP anomaly by examining the extracted signal yield at the reduced mass corresponding to $M_{\mu\mu} = 214\ \mathrm{MeV/c^2}$. The extracted effective branching fraction is $BF_{EFF} = (1.2 \pm 4.3 \pm 1.7) \times 10^{-7}$, where the first error is statistical and the second is systematic, which is consistent with zero and corresponds to the 90% confidence level upper limit $BF_{EFF} < 8 \times 10^{-7}$. We also search for dimuon decays of the η_b using the extracted signal yield at $M_{\mu\mu} = M_{\eta_b} = 9.38\ \mathrm{GeV/c^2}$. We find $BF(\Upsilon(3S) \to \gamma\eta_b) \times BF(\eta_b \to \mu^+\mu^-) = (0.2 \pm 3.0 \pm 0.9) \times 10^{-7}$, which is consistent with zero. Using the result from the BABAR experiment $BF(\Upsilon(3S) \to \gamma\eta_b) = (4.8 \pm 0.5 \pm 1.2) \times 10^{-4}$ [14], we determine $BF(\eta_b \to \mu^+\mu^-) = (0.0 \pm 0.6 \pm 0.2)\ \% < 0.8\ \%$ at 90% confidence level.

4. Conclusions and Outlook

Decays of the narrow Υ resonances provide an excellent laboratory for searches for rare and exotic processes. We have performed a search for lepton-flavour violation in $\Upsilon(3S)$ decays and placed the best upper limits to date, $BF(\Upsilon(3S) \to e^{\pm}\tau^{\mp}) < 5.0 \times 10^{-6}$ and $BF(\Upsilon(3S) \to \mu^{\pm}\tau^{\mp}) < 4.1 \times 10^{-6}$. These results are used to probe TeV-scale physics using effective field theory. We have also performed a search for a light scalar in radiative decays of the $\Upsilon(3S)$, and placed the best upper limit to date $BF_{EFF} = BF(\Upsilon(3S) \to \gamma A^0) \times BF(A^0 \to \mu^+\mu^-) < (0.25 - 5.2) \times 10^{-6}$. We find no evidence to substantiate the evidence for a light scalar decaying to muon pairs observed by the HyperCP experiment. We place the upper limit $BF(\eta_b \to \mu^+\mu^-) < 0.8\ \%$ on the dimuon branching fraction of the η_b. All upper limits are at 90% confidence level. These results will be improved by extending the search to $99 \times 10^6\ \Upsilon(2S)$ decays collected with the BABAR detector.

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