Lepton universality and lepton flavor violation in $\Upsilon$ decays

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Abstract. The datasets collected at the $\Upsilon(3S)$ and $\Upsilon(2S)$ energies have recently allowed the BABAR experiment to obtain several important results in the precision tests of the Standard Model, as well as in the search for direct and indirect new physics effects. In particular, in this paper we present a test of lepton universality, measuring the ratio of decay widths $\Gamma(\Upsilon(1S) \rightarrow \tau^+\tau^-)/\Gamma(\Upsilon(1S) \rightarrow \mu^+\mu^-)$, and contributing to the search for a light pseudoscalar Higgs boson. We also show new limits on lepton flavor violating decays of the $\Upsilon(3S)$ and $\Upsilon(2S)$.

1. Introduction
The BABAR experiment - which is described in detail elsewhere [1, 2] - has recently obtained several important results beyond its original physics program, mainly related to CP-violation studies. In particular, results in precision tests of the standard model (SM) and in searches for new physics (NP) effects have been achieved, thanks to the large data samples collected by BABAR at an energy in the $e^+e^-$ center-of-mass (CM) frame equal to the mass of the $\Upsilon(3S)$ and the $\Upsilon(2S)$. Samples of data collected 30 MeV below each $\Upsilon$ resonance have been used as well for background studies. The integrated luminosity of the samples employed in the analyses presented in this paper are listed in Table 1.

| $\Upsilon(nS)$ | "on-peak" (fb$^{-1}$) | "off-peak" (fb$^{-1}$) |
|----------------|-----------------------|------------------------|
| $\Upsilon(3S)$ | 28.0                  | 2.6                    |
| $\Upsilon(2S)$ | 13.6                  | 1.4                    |

Here some recent results obtained by BABAR are shown: a test of lepton universality in $\Upsilon(1S)$ decays [3], which could be an indication for the existence of a light pseudoscalar Higgs boson, besides representing the most precise measurement of the ratio $\Gamma(\Upsilon(1S) \rightarrow \tau^+\tau^-)/\Gamma(\Upsilon(1S) \rightarrow \mu^+\mu^-)$; and the search for charged lepton flavor violating decays of the $\Upsilon(3S)$ and the $\Upsilon(2S)$ resonances [4].
With both these analyses the BABAR’s capability of performing precise measurements of the SM, as well as of constraining the NP theoretical models proposed for the different processes, is assessed.

2. Lepton universality test in $\Upsilon(1S)$ decays

A pseudoscalar Higgs boson ($A^0$ hereafter) is expected to exist in several extensions of the SM, such as the Next to Minimal Supersymmetric Standard Model (NMSSM) [5, 6]. $A^0$ could have escaped the current experimental limits [7, 8], and be assigned to a region of the parameter space which should constrain it to be light (with a mass $\sim O(10 \text{ GeV}/c^2)$), and to have a preference for coupling to the $b$-type quarks (due to high $\tan\beta$ values, where $\tan\beta$ is the ratio of the vacuum expectation values of the two Higgs doublets). Therefore the B-factories, like BABAR, are good candidates to be the right environment where to look for $A^0$.

The golden channel for the search of $A^0$ is provided by the radiative decays of the narrow $\Upsilon$ resonances: $\Upsilon(nS) \rightarrow \gamma A^0$, whose predicted branching fractions range up to $\sim O(10^{-4})$ [5, 6]. The following decay of the Higgs boson could lead to a set of different final states ($\mu^+\mu^-$, $\tau^+\tau^-$, or even containing only undetected, i.e. invisible, particles), according to the possible $A^0$ mass and model considered. All these possibilities - which have been recently investigated by BABAR [9, 10, 11, 12] - have in common the basic concept of the photon emitted in the radiative decay of the $\Upsilon$ resonance being energetic and detectable, and therefore the attempt of measuring its energy spectrum.

But the presence of $A^0$ could also be investigated by looking for an ostensible lepton universality violation in $\Upsilon$ decays. This measurement, besides being a precision test of the SM, can be therefore seen as a search for a light CP-odd boson, with an approach complementary to and independent of the previously mentioned analyses.

In the SM, the couplings of the gauge bosons to leptons are independent of the lepton flavor. Aside from small lepton-mass effects, the expression for the decay width $\Upsilon(1S) \rightarrow l^+l^-$ should be identical for all leptons. In the SM, one expects the quantity:

$$R_{\tau\mu}(\Upsilon(1S)) = \frac{\Gamma_{\Upsilon(1S)\rightarrow \tau^+\tau^-}}{\Gamma_{\Upsilon(1S)\rightarrow \mu^+\mu^-}} \quad (1)$$

to be very close to one (in particular, $R_{\tau\mu}(\Upsilon(1S)) \sim 0.992$ [13]).

The existence of the NMSSM pseudoscalar Higgs boson $A^0$ [5, 6] could perturbate this ratio, mediating the decay chain through the processes [14, 15, 16]:

$$\Upsilon(1S) \rightarrow A^0\gamma \rightarrow l^+l^-\gamma \quad (2)$$

or:

$$\Upsilon(1S) \rightarrow \eta_b(1S)\gamma, \eta_b(1S) \leftrightarrow A^0 \rightarrow l^+l^- \quad (3)$$

If the photon remained undetected the lepton pair would be ascribed to the $\Upsilon(1S)$. The proportionality of the coupling of the Higgs boson to the lepton mass would lead to an apparent violation of lepton universality. The deviation of $R_{\tau\mu}$ from the expected SM value depends on $X_d = \cos\theta_A\tan\beta$ (where $\theta_A$ measures the coupling of the $\Upsilon(1S)$ to the $A^0$) and on the mass difference between $A^0$ and $\eta_b(1S)$. Assuming $X_d = 12$, $\Gamma(\eta_b(1S)) = 5 \text{ MeV}$, and the
measured $M_{\eta_b(1S)}$ [17], the deviation of $R_{\tau\mu}(\Upsilon(1S))$ may be as large as $\sim 4\%$, depending on the $A^0$ mass [14, 15, 16].

A measurement of this ratio has been performed by the CLEO Collaboration, with the result $R_{\tau\mu}(\Upsilon(1S)) = 1.02 \pm 0.02(\text{stat.}) \pm 0.05(\text{syst.})$ [18].

This analysis focuses on the measurement of $R_{\tau\mu}(\Upsilon(1S))$ in the decays $\Upsilon(3S) \rightarrow \Upsilon(1S)\pi^+\pi^-$ with $\Upsilon(1S) \rightarrow l^+l^-$ and $l = \mu, \tau$ of the sample of $\Upsilon(3S)$ collected by BaBar. Only $\tau$ decays to a single charged particle (plus unreconstructed neutral particles) are considered, resulting in final states of exactly four detected particles for both the $\mu^+\mu^-$ and the $\tau^+\tau^-$ samples.

The event selection is optimized using Monte Carlo (MC) simulated events. Different selection criteria are used for the $\Upsilon(1S) \rightarrow \mu^+\mu^-$ decays ($D_\mu$) and the $\Upsilon(1S) \rightarrow \tau^+\tau^-$ decays ($D_\tau$), because the presence of neutrinos in the final state of the latter leads to a larger contamination from the background. The main sources of background are given by non-leptonic $\Upsilon(1S)$ decays and $e^+e^- \rightarrow \tau^+\tau^-$ events. The final selection efficiency for the reconstructed decay chains, estimated using a sample of MC simulated events, are $\epsilon_{\mu\mu} \sim 45\%$ and $\epsilon_{\tau\tau} \sim 17\%$ for the $\mu^+\mu^-$ and the $\tau^+\tau^-$ final states, respectively.

An extended unbinned maximum likelihood fit, performed simultaneously on the two disjoint datasets $D_\mu$ and $D_\tau$, is used to extract $R_{\tau\mu} = \frac{N_{\text{sig}\mu}}{N_{\text{sig}\tau}} \cdot \frac{\epsilon_{\mu\mu}}{\epsilon_{\tau\tau}}$, where $N_{\text{sig}\mu}$ ($N_{\text{sig}\tau}$) indicates the number of signal events in the $D_\mu$ ($D_\tau$) sample. For the $D_\mu$ sample, a two-dimensional probability density function (PDF) is used, based on the invariant dimuon mass $M_{\mu^+\mu^-}$ and $M_{\pi^+\pi^-}^\text{reco}$, the invariant mass of the system recoiling against the $\pi$-pair, defined as:

$$M_{\pi^+\pi^-}^\text{reco} = \sqrt{s + M_\pi^2} - 2 \cdot \sqrt{s} \cdot E_{\pi\pi}^s,$$ (4)

where $\sqrt{s}$ is the $e^+e^-$ CM energy and $E_{\pi\pi}^s$ indicates the $\pi$-pair energy calculated in the CM frame. The functional forms of the PDFs describing the signal components are modeled from a dedicated sub-sample consisting approximately of one tenth of the $D_\mu$ sample, and then applied only to the remaining data, in order to avoid a possible bias. The “off-peak” data, i.e. the data collected 30 MeV below the $\Upsilon(3S)$ resonance, are used to model the background shapes. Figure 1 shows the one-dimensional projections of the fit results for the three variables.

Several systematic errors cancel in the ratio. The main systematic uncertainties are related to the differences between data and simulation in the efficiency of event selection, the muon identification, and the trigger and background filters. There is also a systematic uncertainty on the signal and background yields due to the imperfect knowledge of the PDFs used in the fit. The total systematic uncertainty, obtained by summing in quadrature all the contributions, is estimated to be 2.2\%.

Including all the systematic corrections, the ratio $R_{\tau\mu}$ is found to be [3]:

$$R_{\tau\mu}(\Upsilon(1S)) = 1.005 \pm 0.013(\text{stat.}) \pm 0.022(\text{syst.}).$$

No significant deviation of the ratio $R_{\tau\mu}$ from the SM expectation is observed. This result improves both the statistical and systematic precision with respect to the previous measurement [18]. Assuming values for $X_d$, $\Gamma(\eta_b(1S))$ and $M_{\eta_b(1S)}$ as previously stated [14, 15, 16], the present measurement excludes an $A^0$ with mass lower than 9 GeV/c$^2$ at 90\% CL.

3. Lepton flavor violating $\Upsilon(3,2S)$ decays

Lepton flavor violation (LFV) can occur via neutrino oscillation, but it has never been observed in charged processes, such as $\Upsilon(nS) \rightarrow l^+l^-$ with $l' \neq l$, because the tree-level contributions
are suppressed by a factor \((\Delta m^2/M_W^2)^2 < \mathcal{O}(10^{-48})\) to rates not achievable by the current experimental sensitivity. In many extensions of the SM, enhancements of these rates are possible, up to a detectable level, with expected branching fractions of \(\mathcal{O}(10^{-8})\). An observation of LFV in charged decays would be a clear signature of NP, and improved limits on the branching fractions of such processes would further constrain the theoretical models proposed.

\(\text{BABAR}\) can search for charged LFV in several typologies of decays. Here we focus on searches for the charged lepton flavor violating decays \(\Upsilon(nS) \rightarrow l^\pm \tau^\mp\), with \(l = e, \mu\) and \(n = 2, 3\), using the \(\Upsilon(3S)\) and \(\Upsilon(2S)\) resonances collected by \(\text{BABAR}\).

The \(\tau\) lepton is required to decay to one charged track (either a lepton or a pion) plus a number of not reconstructed neutral particles (either \(\pi^0\) mesons or neutrinos). Thus the signature of the signal events consists of exactly two oppositely charged particles: a primary lepton, identified as an electron or a muon, with momentum close to the beam energy, and a secondary charged lepton or pion from the \(\tau\) decay. In order to suppress quantum electrodynamics background events, such as Bhabha \((e^+ e^- \rightarrow e^+ e^-)\) and \(\mu\)-pairs events \((e^+ e^- \rightarrow \mu^+ \mu^-)\), if the \(\tau\) decays leptonically, the primary lepton and the \(\tau\)-daughter are required to have different flavors. Thus, for each value of \(n\), four signal channels are defined, consisting of leptonic and hadronic \(\tau\) decay modes, and with an electron or a muon as primary lepton. The main sources of background, besides the already mentioned Bhabha and \(\mu\)-pair events, come from \(\tau\)-pair production and from events containing multiple pions and possible additional photons, where the pion is misidentified as a muon, and the remaining particles satisfy the selection criteria for the \(\tau\) decay products (for this reason, this typology of background is referred to as “\(\pi\)-hadron” background).

The event selection consists of several requirements related to the particle identification and to the kinematics of the \(\tau\)-daughter, which are different in each signal channel. The final selection efficiencies, estimated on samples of MC simulated events, vary in the range (4-6)\% depending on the decay mode considered.
An extended unbinned maximum likelihood fit is performed to the distribution of the variable \( x = |p_1|/E_B \), that is, the momentum of the primary lepton \( p_1 \) normalized to the beam energy \( E_B \). The signal distribution is expected to peak at \( x \approx 0.97 \), while the \( \tau \)-pair background \( x \) distribution is smooth and approaches zero as \( x \to 0.97 \), which is the effective kinematic endpoint for the lepton momentum in the decay \( \tau^\pm \to l^\pm \bar{\nu}_l \nu_\tau \), boosted in the \( \Upsilon \) rest frame. Similarly, the “\( \pi \)-hadron” background is expected to have a distribution which sharply falls off near the endpoint \( x = 0.97 \). Instead, the Bhabha and \( \mu \)-pair events have a peaking behavior at \( x \approx 1 \). PDFs are chosen for each of these components, using samples of data and of MC simulated events. The fit is repeated in each signal channel. In Figure 2 an example of fit is shown, for the \( \Upsilon(3S) \to e\tau \to e\mu(\bar{\nu}_\mu\nu_\tau) \) channel.

![Figure 2](image.png)

**Figure 2.** Fit results for the leptonic \( e\tau \) channel in \( \Upsilon(3S) \) data. The inset is a zoom of the region \( 0.95 < x < 1.02 \). The dotted line represents the signal component, the dashed line represents the sum of all background components, and the solid line shows the sum of signal and background, while the points are the data. The top plot shows the normalized residuals of the fit.

The signal yield is extracted and found consistent with the no signal-hypothesis within \( \pm 1.8\sigma \) in all the signal channels. Since no statistically significant signal is observed, the 90% of confidence level (CL) upper limit (UL) on the branching fraction \( B \) of each decay is determined, using a Bayesian technique, in which the prior likelihood is uniform in \( B \) and assumes that \( B > 0 \).

In the UL calculation, the systematic uncertainties affecting the measurement are also taken into account. The dominant contribution to the systematic uncertainty comes from an imperfect knowledge of the PDF shapes. The resulting ULs [4] are summarized in Table 2 and are of \( \mathcal{O}(10^{-6}) \), representing the first constraints on \( B(\Upsilon(nS) \to e^\pm \tau^{\mp}) \), while improving the sensitivity with respect to the previous ULs [19] on \( B(\Upsilon(nS) \to \mu^\pm \tau^{\mp}) \).

The physics of a charged lepton flavor violating \( \Upsilon \) decay can be described by an effective field theory, as a \( bbl^\pm \tau^{\mp} \) contact interaction parameterized by a NP coupling constant \( (\alpha_{b\tau}) \) and by a mass scale \( (\Lambda_{b\tau}^2) \) [20, 21]. In such a scenario, Figure 3 shows the constraint to the allowed parameter space supplied by the \( \mathrm{B}_{\Upsilon} \) result. Assuming \( \alpha_{e\tau} = \alpha_{\mu\tau} = 1 \), these result translate in the 90% CL lower limits \( \Lambda_{e\tau} > 1.6 \) TeV and \( \Lambda_{\mu\tau} > 1.7 \) TeV on the mass scale of NP contributing to the lepton flavor violating decays of the \( \Upsilon \) resonances. These constraints improve upon the previous limits [19].
Table 2. 90% CL ULs on the branching fractions $\mathcal{B}$ for signal decays $\Upsilon(nS) \rightarrow l^\pm \tau^\mp$.

| Mode                               | UL ($\times 10^{-6}$) |
|------------------------------------|------------------------|
| $\mathcal{B}(\Upsilon(2S) \rightarrow e^\pm \tau^\mp)$ | < 3.2                  |
| $\mathcal{B}(\Upsilon(2S) \rightarrow \mu^\pm \tau^\mp)$ | < 3.3                  |
| $\mathcal{B}(\Upsilon(3S) \rightarrow e^\pm \tau^\mp)$ | < 4.2                  |
| $\mathcal{B}(\Upsilon(3S) \rightarrow \mu^\pm \tau^\mp)$ | < 3.1                  |

Figure 3. Excluded regions of effective field theory parameter space given by mass scale $\Lambda_{\ell\tau}$ versus coupling constant $\alpha_{\ell\tau}$. The dotted line is derived from $\Upsilon(2S)$ results only, the dashed line from $\Upsilon(3S)$ results only, and the solid line indicates the combined results, for $l = e$ (left), and $l = \mu$ (right). The shaded regions are excluded at 90% CL.

4. Conclusions

Thanks to the large amount of data collected at the $\Upsilon(2, 3S)$ resonances, BaBar has been able to achieve several important results, like those presented here [3, 4]. In particular, BaBar has performed a test of the SM, improving the precision of the lepton universality measurement in $\Upsilon(1S)$ decays. The results presented in this paper have also demonstrated that BaBar is able to put important constraints on theoretical predictions beyond the SM: the NP effects investigated here are the existence of the NMSSM light pseudoscalar Higgs boson, and the observation of a lepton flavor violating process involving charged leptons.

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