Precision Measurement of the Ratio $B(\Upsilon(3S) \to \tau^+ \tau^-)/B(\Upsilon(3S) \to \mu^+ \mu^-)$

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In the standard model (SM) the width of a spin-1 quark-antiquark bound state decaying into a charged lepton-antilepton pair is well known [1]. The ratio of widths to final-state leptons with different flavors is free of hadronic uncertainties, and for heavy spin-1 resonances, such as the family of the $b \bar{b}$ bound-state $\Upsilon(nS)$ mesons, differs from unity only by a small mass correction. Consequently, leptonic decays of the $\Upsilon(nS)$ mesons are excellent candidates to test SM predictions and search for phenomena beyond the SM. For example, the Non-SM Higgs boson $A^0$ proposed in Ref. [2] couples more strongly to heavier fermions and thus a larger value of the ratio $\mathcal{R}_\tau^{\Upsilon(3S)} = \mathcal{B}(\Upsilon(3S) \to \tau^+\tau^-)/\mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-)$ than that predicted by lepton-flavor universality in the SM might be observed. Recent measurements of $\mathcal{B}(B \to D^{(*)}\tau\nu)/\mathcal{B}(B \to D^{(*)}\ell\nu)$ [3] suggest a tension with the SM associated with lepton-flavor universality involving the $\tau$ lepton. It has been remarked [4] that new physics models providing an explanation for that tension also unavoidably affect the $\mathcal{R}_\tau^{\Upsilon(3S)}$ ratio. The only measurement to date of that ratio was made by the CLEO Collaboration, $\mathcal{R}_\tau^{\Upsilon(3S)} = 1.05 \pm 0.08 \pm 0.05$ [5]. A new precise measurement will further constrain new physics models.

We present a precision measurement of the ratio $\mathcal{R}_\tau^{\Upsilon(3S)}$ using a novel technique to discriminate between resonant and nonresonant (i.e., continuum) dimuon production based on differences in the dimuon mass distributions associated with initial-state radiation (ISR). In the resonant process, $e^+e^- \to \Upsilon(3S) \to \mu^+\mu^-$, ISR is heavily suppressed compared to the nonresonant, $e^+e^- \to \mu^+\mu^-$, process. How we estimate the non-$\Upsilon(3S)$ contribution to the dimuon sample using this technique is detailed below.

We report on a precision measurement of the ratio $\mathcal{R}_\tau^{\Upsilon(3S)}$ using data collected with the BABAR detector at the SLAC PEP-II $e^+e^-$ collider. The measurement is based on a 28 fb$^{-1}$ data sample collected at a center-of-mass energy of 10.355 GeV corresponding to a sample of 122 million $\Upsilon(3S)$ mesons. The ratio is measured to be $\mathcal{R}_\tau^{\Upsilon(3S)} = 0.966 \pm 0.008_{\text{stat}} \pm 0.014_{\text{syst}}$ and is in agreement with the standard model prediction of 0.9948 within 2 standard deviations. The uncertainty in $\mathcal{R}_\tau^{\Upsilon(3S)}$ is almost an order of magnitude smaller than the only previous measurement.

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inside a 1.5 T solenoidal magnet. An electromagnetic calorimeter (EMC) is used to identify electrons and photons. A ring-imaging Cherenkov detector is used to identify charged hadrons and provides additional electron identification information. Muons are identified by an instrumented magnetic-flux return (IFR).

The major irreducible background process is continuum dilepton production. The KKMC event generator [9] is used to simulate continuum \( \mu^+\mu^- \) and \( \tau^+\tau^- \) production taking into account radiative effects. For the Bhabha process the BHWIDTH [10] event generator is employed. The EvtGen generator [11] is used to simulate hadronic continuum backgrounds. The KKMC event generator [9] is used to simulate hadronic continuum backgrounds. Particle interactions with the detector systems, whereas the other track must fail the same electron selection requirements. Backgrounds are further suppressed by requiring the angle between the two tracks to be greater than 110° in the center-of-mass frame. The total energy registered in the EMC must be less than 70% of the initial \( e^+e^- \) energy in the laboratory frame. The acollinearity between the two tracks in the azimuthal plane must be greater than 3°. We require \( |M_{\text{miss}}/s| > 0.01 \), where the missing mass, \( M_{\text{miss}} \), is calculated from the tracks and up to the ten most energetic EMC clusters identified as photons. The missing momentum vector must point to the sensitive part of the detector, defined as \( |\cos \theta_{\text{miss}}| < 0.85 \) in the center-of-mass frame. To further suppress the Bhabha background, the acollinearity angle between the nonelectron track and the combination of the identified electron track and the most energetic photon must be greater than 2° in both azimuthal and polar angles in the center-of-mass frame. Two-photon backgrounds are suppressed by applying cuts that exploit correlations between the transverse momenta of the two charged particles. The selected \( \tau^+\tau^- \) sample has 2173122 events with a 98.9% purity, estimated by MC studies.

The 2.62 fb\(^{-1} \) \( \Upsilon(3S) \) off-resonance and 7.75 fb\(^{-1} \) \( \Upsilon(4S) \) off-resonance samples are used to correct for differences between MC and data \( \tau^+\tau^-/\mu^+\mu^- \) selection efficiency ratios. For the data and their corresponding MC samples, the number of dilepton candidates (MC sample scaled to the data luminosity) and corresponding efficiency corrections are shown in Table I. For the \( \Upsilon(3S) \) and \( \Upsilon(4S) \) off-resonance data samples, the \( N_{\tau\tau}/N_{\mu\mu} \) dilepton candidate ratios are 0.11665 ± 0.00029 and 0.11647 ± 0.00017, respectively. These are in excellent agreement, demonstrating that the efficiency ratio does not depend on the center-of-mass energy or the different boosts. The corresponding MC samples show the same behavior and the average data-driven correction to the MC efficiency ratio is \( C_{\text{MC}} = (\epsilon_{\tau\tau}/\epsilon_{\mu\mu})_{\text{data}}/(\epsilon_{\tau\tau}/\epsilon_{\mu\mu})_{\text{MC}} = 1.0146 ± 0.0016 \).

The method to discriminate between \( \Upsilon(3S) \rightarrow \mu^+\mu^- \) decays and the continuum production \( e^+e^- \rightarrow \mu^+\mu^- \) is based on the fact that the \( \Upsilon(3S) \) resonance is very narrow and thus the ISR effects are highly suppressed for the signal, but not for the continuum background. If the ISR photons have an energy greater than a few MeV (an amount associated with the spread in the PEP-II center-of-mass energy of 4 MeV coming from the spread in beam energies), then the \( e^+e^- \) interaction energy is too low to form the \( bb \) bound state. This effect results in a significant difference in the radiative tail of the \( M_{\mu\mu} \) distribution for the continuum and resonance production processes for reconstructed dileptons.

<table>
<thead>
<tr>
<th>Off-resonance sample</th>
<th>( N_{\mu\mu}^{\text{data}} )</th>
<th>( N_{\mu\mu}^{\text{MC}} )</th>
<th>( N_{\tau\tau}^{\text{data}} )</th>
<th>( N_{\tau\tau}^{\text{MC}} )</th>
<th>( [(N_{\mu\mu}^{\text{data}}/N_{\mu\mu}^{\text{MC}})/(N_{\tau\tau}^{\text{data}}/N_{\tau\tau}^{\text{MC}})] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Upsilon(3S) )</td>
<td>1538 569</td>
<td>1554 208</td>
<td>179 466</td>
<td>178 569</td>
<td>1.015 ± 0.003</td>
</tr>
<tr>
<td>( \Upsilon(4S) )</td>
<td>4422 407</td>
<td>4398 983</td>
<td>515 067</td>
<td>505 133</td>
<td>1.014 ± 0.002</td>
</tr>
</tbody>
</table>
dimuon candidates, as shown in Fig. 1. About 23% of the continuum candidates are in the low-mass radiative tail region ($M_{\mu\mu}/\sqrt{s} < 0.98$), whereas for the resonance decays this number is 7%, and is associated with final-state radiation.

In Fig. 2 the selected events are shown for simulated $\Upsilon(3S)$ decays. For the dimuon events, the $M_{\mu\mu}/\sqrt{s}$ variable is plotted whereas for the $\tau^+\tau^-$ events the total reconstructed event energy scaled to the center-of-mass energy, $E_{\tau\tau}/\sqrt{s}$, is plotted. The total energy is evaluated using the measured momenta of the charged particles and up to the ten most energetic photons not associated with them. In the dimuon events, decays of the $\Upsilon(3S)$ to lower mass $\Upsilon(1S)$ or $\Upsilon(2S)$ resonances via radiative and hadronic transitions, where the $\Upsilon(1S)$ or $\Upsilon(2S)$ then decay into a dimuon pair, are clearly seen and separated. We refer to such processes, including analogous $\tau^+\tau^-$ final-state processes, as “cascade decays.” The $M_{\mu\mu}/\sqrt{s}$ distribution provides not only an estimate of the number of $\Upsilon(3S) \rightarrow \mu^+\mu^-$ events but also a direct evaluation of the contributions from the cascade decays. In the $\tau^+\tau^-$ channel, however, these cascade decay channels are nearly indistinguishable.

In order to extract the ratio $R_{\mu\mu}^{\Upsilon(3S)}$ a binned maximum-likelihood fit procedure based on the $M_{\mu\mu}/\sqrt{s}$ and $E_{\tau\tau}/\sqrt{s}$ distributions is employed using the method of Ref. [14]. The $\Upsilon(3S) \rightarrow \mu^+\mu^-$ and $\Upsilon(3S) \rightarrow \tau^+\tau^-$ templates are taken from the KKMC-based MC simulation without ISR. The templates for $\Upsilon(2S) \rightarrow \ell^+\ell^-$ and $\Upsilon(1S) \rightarrow \ell^+\ell^-$ via cascade decays, as well as the remaining small contributions from $\Upsilon(nS)$ hadronic decays, are taken from the EvtGen-based MC simulation. The continuum templates use data control samples, as described in the following paragraph.

The amount of BABAR data collected on-resonance is about 10 times larger than off-resonance. Consequently, when the continuum template is based only on the off-resonance data, the small size of that sample dominates the statistical uncertainty of the ratio. To overcome this limitation, $\Upsilon(4S)$ on-resonance Run-6 data, with an integrated luminosity of 78.3 fb$^{-1}$ and the same detector configuration as Run-7, is used for the continuum template in the fit. The leptonic width of the $\Upsilon(4S)$ is $1.57 \times 10^{-5}$ of its total width, which results in a negligible number of resonance-produced dilepton events being present in the sample compared to the number of continuum events. However, other $\Upsilon(nS) \rightarrow \ell^+\ell^-$ decays appear in the data continuum template via ISR. The radiative return processes have been extensively studied by BABAR (see, e.g., Ref. [15]) and based on this approach, the amount of ISR-produced $\Upsilon(nS)$ mesons is estimated and subtracted from the continuum template.

The number of $\Upsilon(3S) \rightarrow \mu^+\mu^-$ events $N_{\mu\mu}$ and the raw ratio $R_{\mu\mu} = N_{\tau\tau}/N_{\mu\mu}$ are free parameters of the fit. In the nonsignal templates, this ratio is fixed either as in data for the continuum background or to the simulation prediction for the other templates.

A graphical representation of the fit result is shown in Figs. 3 and 4. The fit yields a raw ratio of $R_{\mu\mu} = N_{\tau\tau}/N_{\mu\mu} = 0.10778 \pm 0.00091$ and $N_{\mu\mu} = (2.014 \pm 0.015) \times 10^6$.
events. The MC-based selection efficiencies and their ratio, required to obtain the ratio $R_{\tau\tau}$, are shown in Table II.

Low multiplicity $\Upsilon(4S) \rightarrow B\bar{B}$ decays can mimic $\tau^+\tau^-$ events and pass the selection criteria. According to MC studies, the $B\bar{B}$ contribution to the muon template is negligible whereas the $B\bar{B}$ background in the $\tau^+\tau^-$ template translates into a correction of $\delta_{B\bar{B}} = 0.42\%$ to the expected number of $\Upsilon(3S) \rightarrow \tau^+\tau^-$ candidates and is applied to the ratio $R_{\tau\tau}$.

Combining the fit result $\tilde{R}_{\tau\tau}$, the ratio of MC efficiencies $\epsilon_{\mu\mu}/\epsilon_{\tau\tau}$, the data/MC correction $C_{MC}$, and the correction from $B\bar{B}$ events $\delta_{B\bar{B}}$, the ratio is

$$R_{\tau\tau}^{\Upsilon(3S)} = \tilde{R}_{\tau\tau} \frac{\epsilon_{\mu\mu}}{C_{MC} \epsilon_{\tau\tau}} (1 + \delta_{B\bar{B}}) = 0.9662 \pm 0.0084,$$

where uncertainties from the data/MC correction and MC efficiencies are included in the statistical uncertainty.

The sources of the systematic uncertainty in $R_{\tau\tau}^{\Upsilon(3S)}$ are summarized in Table III. The PID uncertainty is assessed by studying three additional $\tau^+\tau^-$ classifiers. The first used tighter electron selectors for both the $\tau$ to electron and the $\tau$ to nonelectron selection. The second applied a tighter electron selector only for the $\tau$ to nonelectron selection. The third replaced the $\tau$ to nonelectron selection with an explicit requirement that the nonelectron particle be identified as a muon or a pion. Even though the data-driven corrections associated with each of these separate $\tau^+\tau^-$ classifiers were applied, and despite the highly correlated statistics in these samples, there remains a $0.9\%$ difference between one of these test classifiers and the default classifier, which we assign as the PID systematic uncertainty.

The ratio of the number of dimuon and $\tau^+\tau^-$ events from the cascade decays in the MC fit templates is fixed according to lepton-flavor universality. This ratio was varied according to the current experimental uncertainties in branching fractions for $\Upsilon(1S)$ and $\Upsilon(2S)$ to dimuon and $\tau^+\tau^-$ final states, resulting in a maximum difference in $R_{\tau\tau}$ of $0.6\%$, which is taken as the systematic uncertainty.

### Table II. MC selection efficiencies in percent for $\Upsilon(3S) \rightarrow \tau^+\tau^-$. The quoted uncertainties reflect MC statistics.

<table>
<thead>
<tr>
<th>Source</th>
<th>$\epsilon_{\mu\mu}$ (%)</th>
<th>$\epsilon_{\tau\tau}$ (%)</th>
<th>$\epsilon_{\tau\tau}/\epsilon_{\mu\mu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>69.951 ± 0.018</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>7.723 ± 0.010</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>0.11041 ± 0.00015</strong></td>
</tr>
</tbody>
</table>

### Table III. The summary of systematic uncertainties.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle identification</td>
<td>0.9</td>
</tr>
<tr>
<td>Cascade decays</td>
<td>0.6</td>
</tr>
<tr>
<td>Two-photon production</td>
<td>0.5</td>
</tr>
<tr>
<td>$\Upsilon(3S) \rightarrow$ hadrons</td>
<td>0.4</td>
</tr>
<tr>
<td>MC shape</td>
<td>0.4</td>
</tr>
<tr>
<td>$B\bar{B}$ contribution</td>
<td>0.2</td>
</tr>
<tr>
<td>ISR subtraction</td>
<td>0.2</td>
</tr>
<tr>
<td>Total</td>
<td>1.4</td>
</tr>
</tbody>
</table>
The systematic uncertainty associated with two-photon background is estimated by varying the selection on the transverse momenta to reduce the $\tau^+\tau^-$ selection efficiency to almost half its nominal value. These variations result in a maximal deviation in $R_{\gamma\mu}$ of 0.5%.

The simulation of other generic $\Upsilon(3S)$ decays shows that a small fraction of background events (about 0.1% of dimuon and 1% of $\tau^+\tau^-$ samples) still pass the selection criteria. The amount of this background is fixed to the MC prediction in the fit and a 0.4% systematic uncertainty assessed by varying these backgrounds by $\pm 50\%$.

The systematic uncertainty from the MC template shape modeling associated with the radiative and resolution effects is estimated to be 0.4% based on varying the $M_{\mu\mu}$ resolution and from changing the templates based on KKMC with those using EvtGen with PHOTOS.

A systematic uncertainty of 0.2% is associated with the $B\bar{B}$ background in the continuum template, estimated by varying the expected amount of the background by $\pm 50\%$.

The systematic uncertainty associated with $\Upsilon(nS)$ mesons produced by the radiative return process in the continuum template is estimated by accounting for experimental uncertainties of total widths and leptonic branching fractions of these mesons and by varying the overall amount of these produced mesons by 10% in order to conservatively account for radiator function uncertainties. We assign a value of 0.2% as the associated systematic uncertainty.

Systematic uncertainties described in the preceding paragraphs are combined in quadrature, giving a total systematic uncertainty of 1.4%.

In conclusion, based on the data collected by the BABAR detector near the $\Upsilon(3S)$ and $\Upsilon(4S)$ resonances, the ratio of the leptonic branching fractions of the $\Upsilon(3S)$ meson is measured to be

$$R_{\gamma\mu}^{\Upsilon(3S)} = 0.966 \pm 0.008_{\text{stat}} \pm 0.014_{\text{syst}}.$$  

This is 6 times more precise than the only previous measurement [5] and is within 2 standard deviations of the SM prediction of 0.9948 [4].

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