

**Measurement of the muonic branching fractions of the  $\Upsilon(1S)$  and  $\Upsilon(3S)$** 

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Using the CLEO detector at the Cornell Electron Storage Ring, we have measured the muonic branching fractions  $B_{\mu\mu}$  of the  $\Upsilon(1S)$  and  $\Upsilon(3S)$  to be  $(2.52 \pm 0.07 \pm 0.07)\%$  and  $(2.02 \pm 0.19 \pm 0.33)\%$ , respectively.

The decay of an  $\Upsilon$  into a lepton pair can be described by the annihilation of the constituent  $b$  and  $\bar{b}$  quarks into a virtual photon which, in turn, materializes into  $e^+e^-$ ,  $\mu^+\mu^-$ , or  $\tau^+\tau^-$ . The measurement of the muonic branching fraction  $B_{\mu\mu}$  is of interest because it can be combined with the partial width of the  $\Upsilon$  into electrons,

$\Gamma_{ee}$ , to obtain the total width of the resonance, which is too narrow to be measured directly.  $B_{\mu\mu}$  also represents the relative strength of the  $\Upsilon$  decay into leptons compared to the decay into three gluons.

In this paper, we report new measurements of  $B_{\mu\mu}$  for the ground and second-excited triplet  $\Upsilon$  states:  $\Upsilon(1S)$  and

$\Upsilon(3S)$ . The data were collected with the upgraded CLEO detector operating at the Cornell Electron Storage Ring (CESR). The data sample includes running at the  $\Upsilon(1S)$ ,  $\Upsilon(3S)$ , and  $\Upsilon(4S)$  center-of-mass energies, as well as nonresonant energies below the  $\Upsilon(4S)$ .

The CLEO detector and hadronic event-selection criteria are described in detail elsewhere.<sup>1</sup> The central detector consists of a three-layer straw-tube vertex detector within a ten-layer vertex drift chamber, surrounded by a 51-layer drift chamber.<sup>2</sup> These chambers are inside a superconducting solenoid of radius 1.0 m which produces a 1.0-T magnetic field. The charged-particle momentum resolution is given by  $(\delta p/p)^2 = (0.23\%p)^2 + (0.7\%)^2$ , where  $p$  is in GeV/c. Outside the solenoid the detector is composed of eight identical octants. Each octant contains a three-layer planar drift chamber, a system of pressurized proportional wire chambers which measure the specific ionization loss ( $dE/dx$ ) of the charged particles with an rms resolution of 6%, twelve time-of-flight counters with an rms resolution of 350 psec, and a 12-radiation-length lead proportional-tube shower counter. The octants are surrounded by 1.0 to 1.5 m of iron and a two-dimensional array of planar drift chambers for muon identification.

Events were classified as muon pairs if they passed the following cuts.

(1) There were exactly two oppositely charged tracks in the event, each of which had a momentum between 60% and 116% of the beam's momentum. The opening angle between the tracks had to be greater than  $170^\circ$ , and each track had to project to within 2 mm of the interaction point in a plane perpendicular to the beam direction.

(2) Each track fired at least one time-of-flight counter, and the flight-time difference between the two tracks was less than 6.0 ns.

(3) At least one track projected to orthogonal hit wires in the outermost muon chambers.

The muon-selection criteria effectively eliminate most backgrounds. These include cosmic rays, which are characterized by a minimum flight time difference of 8 ns, and  $e^+e^-$  pairs, which cannot penetrate the hadron filter. The remaining estimated background from these two sources is less than 0.5%. Other possible backgrounds arise from muons from the decay  $\tau^\pm \rightarrow \mu^\pm \nu\bar{\nu}$ , and, for the  $\Upsilon(3S)$ , from indirect decays to muon pairs. The missing energy carried away by neutrinos causes most of the  $\tau$  events to fail the momentum and collinearity cuts. We estimate the contamination to be less than 0.02%. Indirect

$\Upsilon(3S)$  decays producing muon pairs can occur when the  $\Upsilon(3S)$  decays to the  $\Upsilon(2S)$  or  $\Upsilon(1S)$  plus undetected pions or photons, after which the lower resonance decays to muon pairs. The contribution was estimated from measured branching fractions.<sup>3</sup> Neutral pions and photons were always undetected as we made no cuts on energy deposition in the electromagnetic shower counters. The probability for charged pions to be undetected was estimated from a Monte Carlo detector simulation. The total contamination from indirect decays, estimated in this way, was subtracted from the signal as described below.

To determine  $B_{\mu\mu}$ , we first measure  $\bar{B}_{\mu\mu}$ , which is the ratio of leptonic and hadronic widths

$$\bar{B}_{\mu\mu} = \frac{\Gamma_{\mu\mu}}{\Gamma_h} = \frac{N_{\mu\mu}^r/\epsilon_{\mu\mu}^r}{n_h^r/\epsilon_h^r}$$

where  $N_{\mu\mu}^r$  and  $N_h^r$  are the number of muon pairs and hadronic events produced from the decay of the resonance and  $\epsilon_{\mu\mu}^r$  and  $\epsilon_h^r$  are the respective efficiencies for detection. Assuming lepton universality ( $B_{\mu\mu} = B_{ee} = B_{\tau\tau}$ ), the branching fraction is  $B_{\mu\mu} = \Gamma_{\mu\mu}/(\Gamma_h + 3\Gamma_{\mu\mu}) = \bar{B}_{\mu\mu}/(1 + 3\bar{B}_{\mu\mu})$ . The value of  $N_{\mu\mu}^r$  was determined as

$$N_{\mu\mu}^r = N_{\mu\mu}^{nS} - N_{\mu\mu}^C \frac{\left( \int L^{nS} dt \right) \sigma_{\text{QED}}^n \epsilon_{\mu\mu}^{nS}}{\left( \int L^C dt \right) \sigma_{\text{QED}}^C \epsilon_{\mu\mu}^C} - N_i.$$

Here  $N_{\mu\mu}^{nS}$  is the number of muon pairs observed while running at the  $\Upsilon(1S)$  or  $\Upsilon(3S)$  energy. The second term is the number of nonresonant muon pairs produced from the continuum under the resonance. Since the resonant muon-pair contribution from the  $\Upsilon(4S)$  is negligible,<sup>4</sup> the continuum sample is the number  $N_{\mu\mu}^C$ , observed while running at and just below the  $\Upsilon(4S)$  energies, scaled by luminosity, QED cross section, and efficiency. The third term  $N_i$  is the correction for indirect decays, which we estimate to be  $136 \pm 21$  for the  $\Upsilon(3S)$  and zero for the  $\Upsilon(1S)$ . The number of resonant hadrons is calculated in the same manner, except that there is no indirect decay correction, and the continuum sample is taken exclusively from data taken below the  $\Upsilon(4S)$  energy. Table I shows the integrated luminosity, the detected number of muon and hadronic events, the theoretical QED cross section, and the predicted contamination from indirect muon decays. The cross section was found from the Monte Carlo simulation of Berends and Kleiss,<sup>5</sup> which includes initial- and final-state radiation.

TABLE I. The integrated luminosity, the detected number of muon and hadronic events, the theoretical QED muon-pair cross section, the continuum muon-detection efficiencies, and the predicted contamination from indirect muon decays are shown.

$\sqrt{s}$ (GeV)	$\int L dt$ (pb <sup>-1</sup> )	$N_{\mu\mu}^{nS}$	$N_h^{nS}$	$\sigma_{\text{QED}}$ (nb)	$\epsilon_{\mu\mu}$	$N_i$
9.46 [ $\Upsilon(1S)$ ]	20.8	8 548	484 045	1.12	$0.230 \pm 0.003$	0
10.35 [ $\Upsilon(3S)$ ]	50.9	10 356	375 230	0.937	$0.191 \pm 0.002$	$136 \pm 21$
10.52 (cont)	68.2	13 707	213 875	0.907	$0.219 \pm 0.002$	...
10.58 [ $\Upsilon(4S)$ ]	144.9	28 436	...	0.898	$0.219 \pm 0.002$	...

TABLE II. The number of resonant muonic and hadronic decays, and the detection efficiencies, are given for  $\Upsilon(1S)$  and  $\Upsilon(3S)$ .

Resonance	$N_{\mu\mu}^r$	$\epsilon_{\mu\mu}^r$	$N_h^r$	$\epsilon_h^r$
$\Upsilon(1S)$	$3189 \pm 127$	$0.276 \pm 0.004$	$403\,000 \pm 800$	$0.95 \pm 0.02$
$\Upsilon(3S)$	$1252 \pm 222$	$0.233 \pm 0.003$	$209\,400 \pm 2900$	$0.94 \pm 0.02$

The muon-pair cross section for the data sample is shown in Fig. 1. The curve represents the expected non-resonant QED contribution as calculated from the Monte Carlo simulation of Berends and Kleiss. The data points at  $\Upsilon(1S)$ ,  $\Upsilon(3S)$ , and continuum energies are the observed cross sections corrected by the respective muon-pair efficiencies.

We find the muon-pair efficiencies by determining separately the geometric, trigger, and muon-chamber efficiencies:

$$\epsilon_{\mu\mu} = \epsilon_{\text{geo}} \epsilon_{\text{trig}} \epsilon_{\text{mu}}.$$

The geometric efficiency  $\epsilon_{\text{geo}}$  is obtained by applying the event-selection cuts to events from the Monte Carlo detector simulation. This efficiency is determined primarily by the time-of-flight-counter fiducial volume and is roughly 28% for continuum muon pairs and 32% for resonance muon pairs. To determine the trigger efficiency  $\epsilon_{\text{trig}}$ , we use Bhabha events which trigger the detector in a completely independent way as a result of their deposition of energy in the electromagnetic shower counters. By counting the fraction of these events that also satisfy the muon trigger requirements, we determine a relative muon trigger efficiency. The trigger efficiency depends upon running conditions: it is 92% for the  $\Upsilon(1S)$  and continuum data samples and 79% for the  $\Upsilon(3S)$  data sample. The muon-chamber efficiency  $\epsilon_{\text{mu}}$  is obtained from a

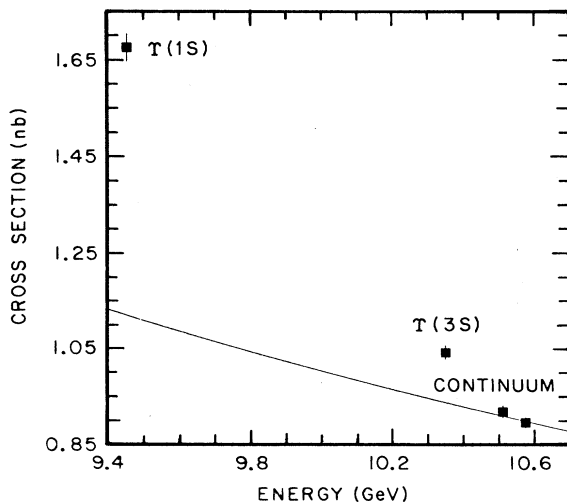


FIG. 1. The efficiency-corrected muon-pair cross section as a function of center-of-mass energy. The curve represents the expected nonresonant QED contribution.

high-purity sample of muon pairs identified by strict minimum-ionization requirements in the electromagnetic shower counter. The fraction of these muon pairs in which at least one track projects to orthogonal hit wires in the outermost muon chambers is identified as the muon-chamber efficiency, and is roughly 93%. The hadronic efficiencies are obtained from the LUND event simulator and the Monte Carlo detector simulation.

Our overall muon efficiencies, as determined by the above procedures, are given in Table I for muon pairs produced from the continuum for various center-of-mass energies. In general, the muon pairs from the resonance have a higher efficiency than those from the continuum due to the absence of initial-state radiation. Table II shows the calculated number of resonant muonic and hadronic decays and the detection efficiencies for the  $\Upsilon(1S)$  and  $\Upsilon(3S)$ .

From the above results, the branching fractions are

$$B_{\mu\mu}(1S) = (2.52 \pm 0.07 \pm 0.07)\%,$$

$$B_{\mu\mu}(3S) = (2.02 \pm 0.19 \pm 0.33)\%,$$

where the first error is statistical and the second is systematic. These values are in good agreement with previous measurements as shown in Table III.

The systematic errors account for the uncertainties in luminosity ratios [0.4% for  $\Upsilon(1S)$ , 1.7% for  $\Upsilon(3S)$ ], hadronic efficiencies (2%), continuum muon efficiencies (1%), and the difference between the continuum muon-pair cross section observed and that expected from QED (1%). Our value for the  $\Upsilon(3S)$  is particularly sensitive to the uncertainty in scaling factors such as the luminosity because the number of resonance muons is only 12% of the continuum background.

To calculate the total width, we use published values of

 TABLE III. Recent measurements of  $B_{\mu\mu}$  for the  $\Upsilon(1S)$  and  $\Upsilon(3S)$  resonances.

Measurement	Experiment	Value (%)
$B_{\mu\mu}(1S)$	CLEO (this paper)	$2.52 \pm 0.07 \pm 0.07$
	ARGUS (Ref. 6)	$2.30 \pm 0.25 \pm 0.13$
	CLEO (Ref. 7)	$2.84 \pm 0.18 \pm 0.20$
	CUSB (Ref. 8)	$2.7 \pm 0.3 \pm 0.3$
	CLEO (Ref. 9)	$2.7 \pm 0.3 \pm 0.3$
$B_{\mu\mu}(3S)$	CLEO (this paper)	$2.02 \pm 0.19 \pm 0.33$
	CUSB (Ref. 10)	$1.53 \pm 0.33 \pm 0.21$
	CLEO (Ref. 9)	$3.3 \pm 1.3 \pm 0.7$

the leptonic width,<sup>11</sup>

$$\Gamma_{ee}(1S) = 1.35 \pm 0.04 \text{ keV}, \quad \Gamma_{ee}(3S) = 0.44 \pm 0.02 \text{ keV}.$$

We then find the total widths ( $\Gamma_{\text{tot}} = \Gamma_{ee}/B_{\mu\mu}$ ) to be

$$\Gamma_{\text{tot}}(1S) = 53.6 \pm 2.2 \pm 2.1 \text{ keV},$$

$$\Gamma_{\text{tot}}(3S) = 21.8 \pm 2.3 \pm 3.7 \text{ keV}.$$

The ratio of the partial widths for any of the  $\Upsilon$  resonances to decay into three gluons to the corresponding partial decay width into muons ( $\Gamma_{ggg}/\Gamma_{\mu\mu}$ ) can be used as a measurement of the strong coupling constant  $\alpha_s$ .<sup>12</sup> However, it has been shown<sup>13</sup> that this calculation has a very unreliable perturbative expansion, making the value of  $\alpha_s$  obtained from this procedure suspect.

In conclusion, we have measured  $B_{\mu\mu}$  for  $\Upsilon(1S)$  and

$\Upsilon(3S)$ . Using these values we have calculated the total width for each resonance.

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<sup>1</sup>D. Andrews *et al.*, Nucl. Instrum. Methods **211**, 47 (1983); S. Behrends *et al.*, Phys. Rev. D **31**, 2161 (1985).

<sup>2</sup>D. G. Cassel *et al.*, Nucl. Instrum Methods A **252**, 325 (1986).

<sup>3</sup>T. Bowcock *et al.*, Phys. Rev. Lett. **58**, 307 (1987); J. Lee-Franzini, in *Lepton and Photon Interactions*, proceedings of the International Symposium on Lepton Photon Interactions at High Energies, Hamburg, West Germany, 1987, edited by W. Bartel and R. Rückl [Nucl. Phys. B, Proc. Suppl. **3** (1988)].

<sup>4</sup>D. Besson *et al.*, Phys. Rev. Lett. **54**, 381 (1985).  $B_{\mu\mu}(4S) \approx 10^{-5}$  is estimated from the measured total width.

<sup>5</sup>F. A. Berends and R. Kleiss, Nucl. Phys. **B177**, 237 (1981). The value of the cross section at the average continuum center-of-mass energy,  $\sigma_{\text{QED}} = 0.901 \text{ nb}$ , was used the scale the continuum.

<sup>6</sup>H. Albrecht *et al.*, Z. Phys. C **35**, 283 (1987).

<sup>7</sup>D. Besson *et al.*, Phys. Rev. D **30**, 1433 (1984).

<sup>8</sup>P. Michael Tuts, in *Proceedings of the 1983 International Symposium on Lepton and Photon Interactions at High Energies, Ithaca, New York, 1983*, edited by D. G. Cassel and D. L. Kreinick (Newman Laboratory of Nuclear Studies, Cornell University, Ithaca, 1983).

<sup>9</sup>D. Andrews *et al.*, Phys. Rev. Lett. **50**, 807 (1983).

<sup>10</sup>T. Kaarsberg *et al.*, Phys. Rev. D **35**, 2265 (1987).

<sup>11</sup>W. Buchmüller and S. Cooper, in *High Energy Electron-Positron Physics*, edited by A. Ali and P. Söding (World Scientific, Singapore, 1988); J. P. Alexander *et al.*, Report No. SLAC-PUB-4501, 1988 (unpublished).

<sup>12</sup>W. Kwong *et al.*, Phys. Rev. D **37**, 3210 (1988).

<sup>13</sup>S. J. Brodsky *et al.*, Phys. Rev. D **28**, 228 (1983).