

A DETERMINATION OF THE TOTAL WIDTH OF THE  $\Upsilon(9.46)$  MESON

H. ALBRECHT, R. CHILDERS<sup>1</sup>, C.W. DARDEN<sup>1</sup>, G. DREWS, H. HASEMANN,  
E. McCLIMENT<sup>2</sup>, W. SCHMIDT-PARZEFALL, H. SCHRÖDER, H.D. SCHULZ,  
F. SELONKE, E. STEINMANN, R. WURTH  
*Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany*

W. HOFMANN, A. MARKEES, D. WEGENER  
*Institut für Physik, Universität Dortmund, Germany*

K.R. SCHUBERT, J. STIEWE, R. WALDI, S. WESELER  
*Institut für Hochenergiephysik, Universität Heidelberg, Germany*

P. BÖCKMANN, L. JÖNSSON  
*Institute of Physics, University of Lund, Sweden*

M. DANILOV, Yu. SEMENOV, I. TICHOMIROV, Yu. ZAITSEV  
*Institute of Theoretical and Experimental Physics, Moscow, USSR*

Received 21 April 1980

Using the DASP detector at the DESY storage ring DORIS we have continued measuring  $e^+e^-$  annihilations near and on the  $\Upsilon(9.46)$  resonance. From the cross sections for  $e^+e^- \rightarrow \mu^+\mu^-$  and  $e^+e^- \rightarrow \text{hadrons}$  we obtain a  $\mu^+\mu^-$  branching ratio for the  $\Upsilon(9.46)$  of  $(2.9 \pm 1.3 \pm 0.5)\%$ , a leptonic width  $\Gamma_{ee} = (1.35 \pm 0.11 \pm 0.22)$  keV and a total width of  $(47_{-15}^{+37})$  keV.

The  $\Upsilon(9.46)$  meson was discovered in hadronic production in its  $\mu^+\mu^-$  decay mode [1] and was subsequently seen in electron-positron annihilations at DORIS [2–4]. A direct determination of its total width  $\Gamma_{\text{tot}}$  is possible neither in hadronic production nor with  $e^+e^-$  storage rings, since  $\Gamma_{\text{tot}}$  is much smaller than the resolutions obtainable with spectrometers and the energy widths of storage ring beams. Therefore, the only practicable method for determining  $\Gamma_{\text{tot}}$  is given by

$$\Gamma_{\text{tot}} = \Gamma_{ee}/B_{\mu\mu}, \quad (1)$$

where  $\Gamma_{ee} = \Gamma(\Upsilon \rightarrow e^+e^-)$  is found from the excitation curve  $e^+e^- \rightarrow \Upsilon \rightarrow \text{hadrons}$  and  $B_{\mu\mu}$  is the muon

pair branching ratio. From lepton universality,  $\Gamma_{ee} = \Gamma_{\mu\mu}$  is assumed in eq. (1).

Using all data from the 1978 DORIS run, the three experimental groups could determine only rough values for the muonic branching ratio  $B_{\mu\mu}$ :  $(2.5 \pm 2.1)\%$  [5],  $(2.2 \pm 2.0)\%$  [6] and  $(1.0_{-1.0}^{+3.4})\%$  [7]. Even the combination of these three results is not sufficiently accurate to give reasonable limits on  $\Gamma_{\text{tot}}$ . It was therefore highly desirable to aim at a more precise value for  $B_{\mu\mu}$ .

From October to December 1979, a new DORIS run in the centre-of-mass energy range from 9.40 to 9.60 GeV allowed us to collect more data for this purpose. We report here on two independent analyses of the  $\mu^+\mu^-$  data, one obtained with the DASP inner detector and the other with the DASP outer detector.

The Double Arm Spectrometer DASP has been de-

<sup>1</sup> On leave from the University of South Carolina, USA.

<sup>2</sup> On leave from the University of Iowa, USA.

scribed before [8]. Its non-magnetic inner detector consists of scintillation counters, lead converters, proportional tube counters and scintillator-lead-sandwich shower counters; it covers a solid angle of about  $0.50 \cdot 4\pi$ . Its last layer of scintillation counters is equipped for a particle time-of-flight determination, with an average distance of 1 m from the interaction point at a time resolution of  $\sigma = 1.1$  ns. The magnetic outer detector consists of two spectrometer arms equipped with spark chambers, Cerenkov counters, scintillators, sandwich shower counters and range counters behind an iron shield for muon identification. Both arms together cover a solid angle of about  $0.05 \cdot 4\pi$ .

DORIS was operated in a single-ring, single-bunch mode and accumulated electron and positron currents of typically 18 mA each with a typical life time of 4 h. The refill time was usually only several minutes. Peak luminosities were about  $10^{30}/\text{cm}^2 \text{ s}$  and average luminosities about 30/nbday. The luminosity was measured by a counter system at scattering angles of  $8^\circ$  to record small angle Bhabha scattering. It was independently determined by large angle Bhabha scattering in the inner detector and also in the outer detector as will be described below.

We start by discussing the outer detector analysis. For an integrated luminosity of 676/nb (410/nb on and 266/nb near the  $\Upsilon$  resonance) we collected a total of 6990 two-arm-triggers. After demanding at least one reconstructed track in each arm and applying cuts for collinearity, vertex position, time of flight, Cerenkov signals, shower counter energies and acceptance region, there remain 252 events. Deviations from collinearity had to be smaller than 80 mrad in the magnetic bending plane and 40 mrad normal to the bending plane; the acceptance region was defined by  $|\cos \theta| < 0.5$  and  $|\tan \phi| < 0.148$ . The 252 events contain 218 identified Bhabha events and 34 identified  $\mu^+\mu^-$  events. By demanding only opposite scintillation counter information and by not requiring reconstructed tracks, one additional  $\mu^+\mu^-$  event was found. The number of muon pair events on the  $\Upsilon$  resonance is  $N_{\mu\mu}^{\text{on}} = 24$  and near the resonance  $N_{\mu\mu}^{\text{off}} = 11$ .

The muonic branching ratio is given by

$$B_{\mu\mu} = \frac{\sigma(e^+e^- \rightarrow \Upsilon \rightarrow \mu^+\mu^-)}{\sigma(e^+e^- \rightarrow \Upsilon \rightarrow \text{hadrons}) + 3\sigma(e^+e^- \rightarrow \Upsilon \rightarrow \mu^+\mu^-)} \quad (2)$$

where the denominator takes into account e,  $\mu$  and  $\tau$

pair decays through lepton universality. A measurement of  $e^+e^- \rightarrow \mu^+\mu^-$  at the peak energy of the resonance yields events from  $\Upsilon$  decay and from the QED continuum. The continuum contribution, apart from its  $1/W^2$  dependence, is equal to the rate near the resonance. To determine  $\sigma(e^+e^- \rightarrow \Upsilon \rightarrow \mu^+\mu^-)$  one may either subtract the *observed* cross section near the resonance or the *expected* QED cross section at the resonance energy. The second method has been applied for this outer detector analysis using the observed number of  $e^+e^-$  events at the resonance energy. There are 135 events identified as  $e^+e^-$  events at the resonance energy in the outer detector. Taking into account the detection efficiency, the radiative corrections, a small  $e^+e^- \rightarrow \Upsilon \rightarrow e^+e^-$  contribution, and multiplying by the QED ratio for muon pairs relative to electron pairs, we expect  $N_{\mu\mu}^{\text{QED}} = 14.3 \pm 2.0$  continuum muon pairs at the resonance energy. This value is compatible with the observed number  $N_{\mu\mu}^{\text{off}}$ .  $L(\text{on})/L(\text{off}) = 16.9 \pm 5.1$ , where  $L$  are the integrated luminosities. We assume unpolarized beams in the storage ring and use the fact that the angular distribution for  $e^+e^- \rightarrow \Upsilon \rightarrow \mu^+\mu^-$  is equal to the corresponding QED distribution to obtain

$$\begin{aligned} \sigma(e^+e^- \rightarrow \Upsilon \rightarrow \mu^+\mu^-) &= \frac{N_{\mu\mu}^{\text{on}} - N_{\mu\mu}^{\text{QED}}}{N_{\mu\mu}^{\text{QED}}} \cdot \sigma_{\mu\mu}^{\text{QED}} \\ &= (0.68 \pm 0.40) \text{ nb} . \end{aligned} \quad (3a)$$

This result includes the DORIS energy resolution and radiative corrections to the resonance height. However, the corresponding hadronic cross section in eq. (2) includes exactly the same factors and we do not need to unfold both for a determination of  $B_{\mu\mu}$ .

The method of analysis described for the outer detector is independent of a separate luminosity measurement. The luminosity information enters only via the observed number of Bhabha events in the outer detector at the resonance energy. Cross checks with the  $8^\circ$  monitor and with Bhabha events in the inner detector show agreement within the statistical errors of  $\pm 7\%$ .

The inner detector analysis relies on the shower counter and the time-of-flight measurement. Every event with two reconstructed non-showering tracks which are collinear and are determined not to be a single traversing cosmic ray is taken as a  $\mu^+\mu^-$  event. This is justified by the result in the outer detector

that no single hadron pair was found in the sample with 10 events of genuine  $\Upsilon \rightarrow \mu^+\mu^-$  decays.

For an integrated luminosity of 818/nb (300/nb on the resonance and 518/nb at neighbouring energies including the energy range 9.90–10.00 GeV), there were 261 000 pair triggers in the inner detector. The trigger required two roughly collinear scintillator roads to be hit. In the reconstruction, we required two non-showering tracks in the proportional tube chambers with a collinearity deviation  $\cos \alpha < 0.98$ , a shower counter cut  $E < 2.2$  GeV per track and an event time within  $\pm 10$  ns of the DORIS bunch crossing time. For the remaining events, the time-of-flight difference  $\Delta t$  between two opposite scintillators, on the average at a distance of one meter from the interaction point, is shown in fig. 1a. There is a clear peak at  $\Delta t = 0$  from genuine  $\mu^+\mu^-$  events sitting on the tail of the very abundant cosmic rays. A cut  $-1.4 \text{ ns} < \Delta t < 1.8 \text{ ns}$  results in 93 muon pair candidates on the resonance and 132 near the resonance. The numbers of background cosmic rays in these samples are estimated from the  $\Delta t$  distribution of events in a 60 ns wide event time range away from the DORIS bunch crossing time as shown in fig. 1b. There are  $9.0 \pm 1.7$  background events on the resonance and  $23.3 \pm 2.8$  nearby. Using the integrated luminosities from the

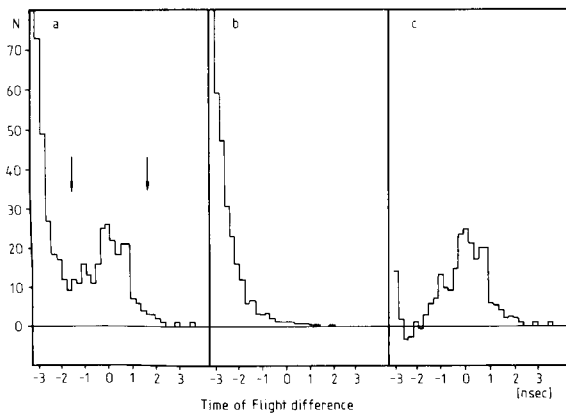


Fig. 1. Distribution of the time-of-flight difference between two opposite scintillation counters for the selected sample of events with two collinear non-showering tracks in the inner detector, (a) for the events within  $\pm 10$  ns of the bunch crossing time, (b) for background events in a 69 ns wide control region away from the bunch crossing time, (c) for muon pair events after subtraction of the background events. The arrows indicate the cuts chosen.

number of reconstructed Bhabha events in the inner detector, the number of observed muon pair events near the resonance and the QED cross section for  $e^+e^- \rightarrow \mu^+\mu^-$ , we obtain an overall acceptance for muon pairs of  $(22.5 \pm 2.4)\%$ . Applying this value to the observed number of events on the resonance, we obtain

$$\sigma(e^+e^- \rightarrow \Upsilon \rightarrow \mu^+\mu^-) = (0.27 \pm 0.20) \text{ nb} . \quad (3b)$$

Fig. 2 shows the  $\cos \theta$  distribution of the observed muon pair events corrected for acceptance as obtained from a Monte Carlo simulation with all trigger and reconstruction criteria. Since the charge of the muons is not determined in the inner detector, the distribution shows only  $|\cos \theta|$ . It compares well with the expected  $(1 + \cos^2 \theta)$  distribution.

Since the results for the outer and the inner detector, as given in eqs. 3a and 3b, are independent of each other, we average them and obtain

$$\sigma(e^+e^- \rightarrow \Upsilon \rightarrow \mu^+\mu^-) = (0.35 \pm 0.18) \text{ nb} . \quad (3c)$$

The hadronic cross section entering in eq. (2) has been determined from the same sample of events collected in 1979. Fig. 3 shows the observed cross section for  $e^+e^- \rightarrow \text{hadrons}$  with  $\geq 4$  reconstructed particles in the inner detector (charged or converted photons) as a function of the centre-of-mass energy  $W$ . The trigger and reconstruction procedure is essentially the same as in our 1978 experiment. The expected cross section can be expressed in terms of a continuum

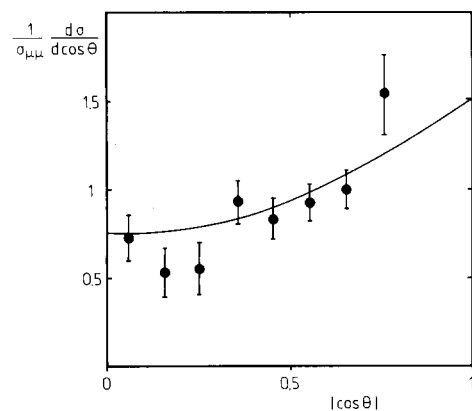


Fig. 2. Distribution of  $|\cos \theta|$  for the selected  $\mu^+\mu^-$  events in the inner detector divided by the overall acceptance. The solid curve shows the  $(1 + \cos^2 \theta)$  expectation.

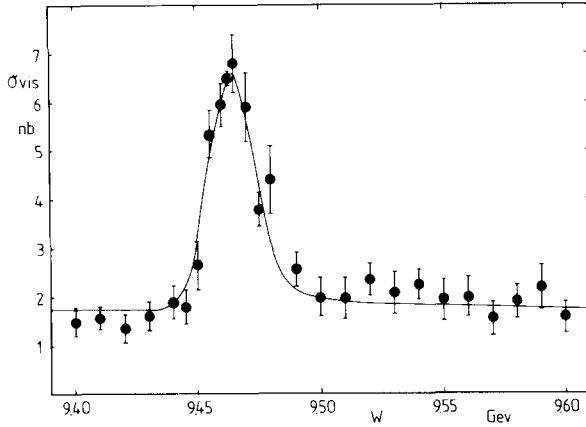


Fig. 3. Visible cross section for the reaction  $e^+e^- \rightarrow$  hadrons with 4 or more charged or converted neutral particles. The data displayed are from the 1979 run alone and statistically independent from the 1978 data in refs. [2] and [5]. The solid curve is the result of a fit.

plus a Breit–Wigner contribution widened by the machine energy spread and radiative corrections [9, 10]. The detector acceptance on and off resonance has been determined with the help of a Monte-Carlo simulation three-jet and two-jet events [11]. A fit of the expected cross section to the data yields

$$\Gamma_{ee}\Gamma_{had}/\Gamma_{tot} = (1.23 \pm 0.09 \pm 0.20) \text{ keV}, \quad (4)$$

where the first error is statistical and the second error is systematic.

From the fit result as shown by the solid curve in fig. 3 we get the peak value for  $\sigma(e^+e^- \rightarrow \Upsilon \rightarrow \text{hadrons})$ :

$$\sigma(e^+e^- \rightarrow \Upsilon \rightarrow \text{hadrons}) = (10.1 \pm 0.7) \text{ nb}. \quad (5)$$

If we insert this value into eq. (2), we obtain

$$B_{\mu\mu} = (3.1 \pm 1.6)\%. \quad (6a)$$

Since this result is independent from our 1978 result [5], we average the two and obtain

$$B_{\mu\mu} = (2.9 \pm 1.3 \pm 0.5)\%, \quad (6b)$$

where the first error is statistical and the second is systematic. The result in eqs. (4) and (6b) may be combined to obtain  $\Gamma_{ee}$  and  $\Gamma_{tot}$  via eq. (1):

$$\Gamma_{ee} = (1.35 \pm 0.11 \pm 0.22) \text{ keV}, \quad (7a)$$

$$\Gamma_{tot} = (47^{+37}_{-15}) \text{ keV}, \quad (7b)$$

where the errors given on  $\Gamma_{tot}$  are one standard deviation statistical errors; the systematic error on  $\Gamma_{tot}$  is much smaller.

The total width of the  $\Upsilon(9.46)$  meson is found to be very close to the width of the  $J/\psi$  meson which is  $(67 \pm 12)$  keV. This indicates that the nature of the two mesons is indeed very similar and that their decays are governed by the same mechanism. The dominant decay mode of both is the direct hadronic decay. Its width is obtained by subtracting  $(N_1 + R)\Gamma_{ee}$  from  $\Gamma_{tot}$ , where  $N_1$  is the number of lepton decay modes and  $R$  takes into account the hadronic decay through a virtual photon. For the  $J/\psi$ ,  $\Gamma_{had,dir}$  is about  $(48 \pm 12)$  keV, and we obtain  $(38^{+37}_{-15})$  keV for the  $\Upsilon(9.46)$ .

The direct hadronic decay of  $1^- Q\bar{Q}$  states has often been interpreted as a decay into three massless gluons which subsequently fragment into hadrons. In lowest order quantum chromodynamics [12], this rate is given by

$$\Gamma(Q\bar{Q} \rightarrow ggg) = \frac{10(\pi^2 - 9)\alpha_s^3}{81\pi e^2 \alpha^2} \Gamma(Q\bar{Q} \rightarrow e^+e^-). \quad (8)$$

Although the size of corrections to this expression due to higher orders and due to fragmentation is still unknown, we have nevertheless used it in order to see if its application to  $J/\psi$  and  $\Upsilon$  decays leads to consistent values of the QCD coupling constant  $\alpha_s$ . By inserting the experimental values of  $\Gamma_{had,dir}$  as mentioned above into eq. (8) without any corrections, we find

$$\alpha_s(J/\psi) = 0.19 \pm 0.02, \quad (9a)$$

$$\alpha_s(\Upsilon) = 0.17^{+0.04}_{-0.03}. \quad (9b)$$

We express our thanks to Dr. K. Wille and the DORIS group for their excellent work in operating the storage ring and to Professors E. Lohrmann, H. Schopper and G.A. Voss for their support. We wish to thank A. Krolzig and all members of the F 51 group for the skilful technical help during the runs, and B. Hildebrandt for his help in data processing. The non-DESY members of the collaboration want to thank the DESY directorate for their hospitality. This work was supported in part by the Bundesministerium für Forschung und Technologie.

*References*

- [1] S.W. Herb et al., Phys. Rev. Letters 39 (1977) 252.
- [2] C.W. Darden et al., Phys. Letters 76B (1978) 246.
- [3] Ch. Berger et al., Phys. Letters 76B (1978) 243.
- [4] J.K. Bienlien et al., Phys. Letters 78B (1978) 360.
- [5] C.W. Darden et al., Phys. Letters 80B (1979) 419.
- [6] Ch. Berger et al., Zeits. f. Physik C1 (1979) 343, DESY 80/15 (Bee)(1980).
- [7] G. Heinzlmann, Proc. 19th Intern. Conf. on High energy physics (Tokyo, 1978) p. 263.
- [8] R. Brandelik et al., Phys. Letters 56B (1976) 491 and 67B (1977) 243.
- [9] J.D. Jackson and D.L. Scharre, Nucl. Instr. Meth. 128 (1975) 13.
- [10] M. Greco et al., Nucl. Phys. B101 (1975) 234.
- [11] T. Nakada, Heidelberg reports IHEP-HD/79-1/ARGUS and IHEP-HD/79-2/ARGUS, unpublished.
- [12] T. Appelquist and H.D. Politzer, Phys. Rev. Lett. 34 (1975) 43;  
V.A. Novikov et al., Physics Reports 41 (1978) 1.