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Measurement of Leptonic Branching Ratios of the $\Upsilon(9.46)$

PLUTO Collaboration

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Abstract. The electronic width Γ_{ee} and the muonic branching ratio $B_{\mu\mu}=\Gamma_{\mu\mu}/\Gamma_{\text{tot}}$ of the $\Upsilon(9.46)$ have been measured as $\Gamma_{ee}=(1.33\pm0.14)\,\text{keV}$ and $B_{\mu\mu}=(2.2\pm2.0)\,\%$. From these values a lower limit of $\Gamma_{\text{tot}}>23\,\text{keV}$ for the total width of the $\Upsilon(9.46)$ is obtained.

1. Introduction

After the discovery of the Υ particles in proton-nucleus interactions [1] their formation in e^+e^- collisions has been reported by several DESY experiments [2–4]. These experiments delivered precise mass values, namely $(9.46\pm0.01)\,\text{GeV}/c$ for the Υ and $(10.02\pm0.02)\,\text{GeV}/c^2$ for the Υ', and also gave the first values of the electronic width Γ_{ee}. The branching fractions and widths for electromagnetic decay into lepton pairs of these new states, commonly interpreted as bound states of new quarks [5], are key parameters for the understanding of their constituents and the binding mechanism [6].

We report the refined analysis of the total hadronic cross section in e^+e^- annihilation in the region of the Υ mass, yielding a more precise value of the electronic width Γ_{ee} of the $\Upsilon(9.46)$. This analysis is described in Sect. 3. From the analysis of the muon pair rate, described in Sect. 4, we obtain the branching fraction of the Υ into muon pairs, $B_{\mu\mu}=\Gamma_{\mu\mu}/\Gamma_{\text{tot}}$. Using $e-\mu$ universality $\Gamma_{\mu\mu}=\Gamma_{ee}$, we obtain a lower limit on the total width of the $\Upsilon(9.46)$.

2. The Experiment

The experiment was performed with the detector PLUTO at DORIS. The double ring multibunch storage ring DORIS has been transformed into a single ring single bunch machine [7], thus extending the range of center of mass energies to about 10 GeV. The detector PLUTO [8] has been supplemented by shower counters. A cylindrical array (barrel) of lead scintillator shower counters (8.6 radiation lengths) and proportional tubes have been installed in the angular region $|\cos\theta|<0.6$ (θ = polar angle between direction from the interaction point and the beam axis), which also supplies a time of flight measurement. The ends of

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the cylindrical detector (end cap) in the angular region $0.6<|\cos\theta|<0.96$ have been covered by a second set of shower counters (10.5 radiation lengths) [9]. With this additional equipment the total photon and electron detection coverage is 94% of 4π. Both counter systems are constructed in 12° azimuthal sectors and provide a further coordinate for the determination of the polar angle θ of the shower or track. 11 cylindrical proportional wire chambers covering 87% of 4π and operating in a field of 1.69 T are used for track recognition and momentum measurements. Muon chambers behind the iron return yoke of average thickness of 68 cm cover 65% of 4π. The detector is triggered either by the presence of tracks in the wire chambers [8], by sufficient energy in the shower counters or by a combination of both. The luminosity is monitored by a set of shower counter telescopes, which record Bhabha scatters at polar angles of about 7°. Good agreement within less than 3% was found between this monitor and the rate of large angle Bhabha scatters observed in the inner detector and the shower counters. Cosmic ray background was reduced during data taking by a time coincidence within 200 ns between the signals in the shower counters and the bunch crossing signal. This time window is reduced in the off-line analysis to 22.5 ns in the barrel region and to 60 ns in the endcap region.

Data have been taken between 9.35 and 9.48 GeV c.m. energy in steps of 5 or 10 MeV, with additional points at 9.2 and 9.3 GeV. The total integrated luminosity used in this analysis is 347.8 nb^{-1}, equally divided between the resonance region and the region below the resonance.

3. The Total Hadronic Cross Section

The published PLUTO results [2] on the hadronic cross section in the Υ region were taken from a preliminary fast analysis used during data taking. In the analysis described here we have selected hadronic e^+e^- annihilation events from the total event sample by applying the following cuts:

i) number of charged prongs $\geqq 2$;

ii) difference in azimuthal angle for 2 prongs $30° < \Delta\phi < 150°$;

iii) detected total energy (charged + neutral) $> 0.6 \times E_{cm}$.

Radiative Bhabha scatters were removed by excluding any 2 or 3 prong events, in which a single track had an associated shower with an energy of more than $0.3 \times E_{beam}$. The distribution of the detected total energy [before cut iii)] is shown in Fig. 1a, the distribution of the reconstructed event vertices along the beam line is shown in Fig. 1b. The 3% background

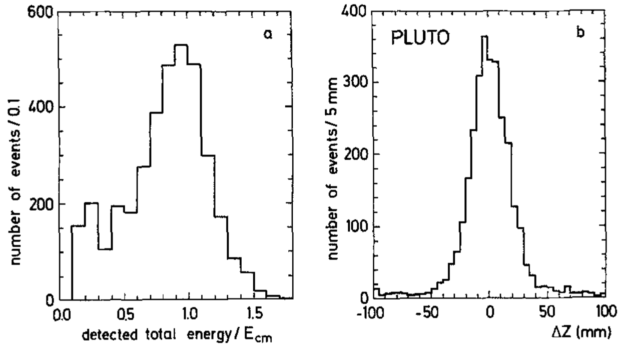

Fig. 1a and b. Distribution of **a** the detected total energy (charged + neutral) divided by E_{cm} and **b** the difference Δz between the z value of the reconstructed event vertex and the mean z value of the interaction point for hadronic event candidates (off and on resonance data)

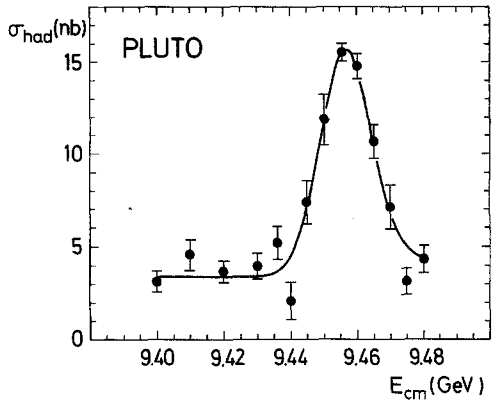

Fig. 2. The total cross section for annihilation of e^+e^- into hadrons in the Υ(9.46) energy region. The data points include 10% of the τ pair events. The curve is described in the text

from beam-gas interactions is subtracted in the following. We obtain 2983 hadronic events compared to 1409 events in the fast analysis.

The resulting cross section after correction for acceptance losses (~20%) is shown in Fig. 2. Acceptance calculations are based on a Monte Carlo simulation of the detector using a multipion phase space model, and were checked using the 2 jet model of Field and Feynman [10]. The two efficiencies agree within 5%. The acceptance after cuts for τ pair events is also calculated from a Monte Carlo simulation. The effect of all cuts has been checked, relaxing the total energy cut from $0.6 \times E_{cm}$ to $0.4 \times E_{cm}$, and the coplanarity cut in $\Delta\phi$ from 30 to 0°. With these loose cuts the acceptance for τ pair events ε_τ increases from 10 to 30%, the rate of the continuum increases by about 20% mainly due to QED processes including τ pair events, the resonant contribution however increases by only 4%.

The parameters of the resonance were obtained by an unfolding procedure accounting for the effects of radiation and for the finite energy resolution of DORIS. Describing the resonant cross section by

$$\sigma_{res}^{had}=\frac{4M^2}{E_{cm}^2}\frac{3\pi\Gamma_{ee}\Gamma_{had}}{(E_{cm}^2-M^2)^2+M^2\Gamma_{tot}^2}$$

with M=mass of the resonance and $\Gamma_{had}=\Gamma_{tot}-(3-\varepsilon_\tau)\Gamma_{ee}$ (assuming $e-\mu-\tau$ universality), the expressions derived by Greco et al. [11] have been used for the radiative effect. The off-resonance data have been fitted with a $1/E_{cm}^2$ behaviour in the interval 9.30–9.43 GeV (not fully shown in Fig. 2) and extrapolated in the resonance region assuming no interference. The curve shown in Fig. 2 is obtained from a fit treating the Υ parameters M, Γ_{ee} and Γ_{tot} and the energy resolution σ as free parameters. The fit is very loosely dependent on the value of Γ_{tot}. The energy resolution $\sigma=(7.3\pm0.1)$ MeV resulting from the fit is in agreement with the expectation from machine parameters. The mass of the resonance was found to be $M=(9456.3\pm0.8)$ MeV/c^2 with a systematic error of 10 MeV from the absolute machine energy calibration.

For the electronic width we obtain from the fit

$$\Gamma_{ee}=(1.33\pm0.14)\,\text{keV},$$

the statistical error being 0.05 keV. The systematic uncertainty comes from the Monte Carlo efficiency calculation and the subtracted contributions (~8%), and from the systematic error of the luminosity monitor (~6%), which influences linearly the Γ_{ee} value.

4. Muon Pair Production

Only a small resonant muon pair signal is expected on the Υ resonance. In order to cancel systematic errors in the efficiency calculation, the QED muon pair cross section measured below the resonance energy is used for normalization.

For the analysis of the muon pair production

$$e^+e^-\rightarrow\mu^+\mu^-$$

events are selected in the whole energy region having two tracks with an acoplanarity angle less than 60 mrad. Bhaba scatteres are removed by requiring a pulse height in the shower counters corresponding to minimum ionizing tracks. The analysis is restricted to the region $|\cos\theta|<0.75$, where the inner detector has a large detection efficiency. 10% of the azimuth had to be excluded, because part of the shower counters, already installed for experiments at PETRA, could not be activated at DORIS because of space limitations. The accepted angular region corresponds to 60% of 4π, or to 53.4% of the cross section for a $(1+\cos^2\theta)$ distribution. The muon chambers are not used in the event selection, but they serve for a check of the final result.

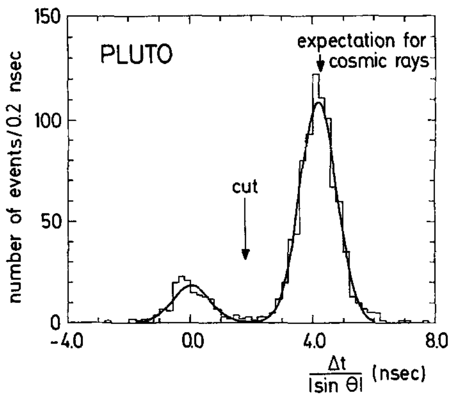

Fig. 3. Distribution of the time difference between signals from opposite barrel shower counter segments hit by the tracks. The large peak is due to cosmic rays

The selected events are fitted simultaneously to geometrical and kinematical constraints. The two geometrical constraints are a common origin of both tracks in the z direction (parallel to the beam axis) and in the $r-\phi$ plane perpendicular to the beam axis. Kinematically the events are constrained by momentum conservation in the $r-\phi$ plane, thus allowing for undetected photons radiated in the beam direction. A cut is applied to the fitted photon momentum in the beam direction at 0.4 GeV/c.

Cosmic ray background is reduced by a cut in the minimum distance d_{min} of the two tracks from the interaction point in the $r-\phi$ plane at 1.5 mm. The remaining background due to cosmic rays is suppressed in the barrel region using the measured time difference between the signals from opposite counter segments hit by the tracks. For cosmic rays perpendicular to the beam axis the time difference is 4.25 ns with an rms error of 0.6 ns. Figure 3 shows the measured time difference divided by $|\sin\theta|$. Events with a time difference of more than 1.8 ns are rejected.

The remaining events show clear peaks in the distribution of the difference Δz between the z value of the track vertex and the mean z value of the interaction point, and in the distribution of the muon momentum p_μ divided by the beam energy E_{beam}. Muon pair events are selected by simultaneous cuts in Δz at ±35 mm and in the relative muon momentum p_μ/E_{beam} at 1.0 ± 0.2. The distributions in the two variables p_μ/E_{beam} and Δz are shown in Fig. 4a and b, respectively, after the cut has been applied in the other variable. The observed widths of the peaks are as expected, the width of the peak in p_μ/E_{beam} corresponds to a rms momentum resolution of (6.0 ± 0.4)%. 155 events are found within the cuts, of which 142 have at least one track hitting a muon chamber behind ~68 cm of iron, while 141.0 ± 3.3 events (91%) are expected for muonic tracks from the

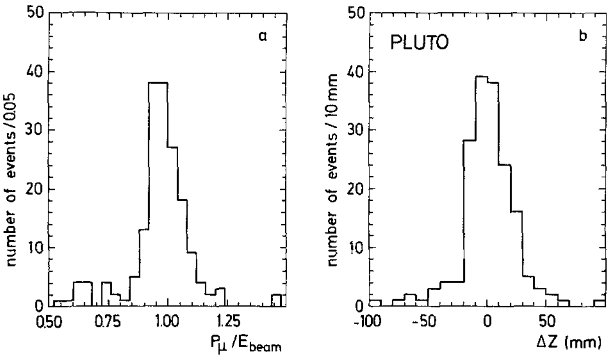

Fig. 4a and b. Distribution of **a** the measured muon momentum p_μ divided by beam energy E_{beam} (after a cut in Δz at ± 35 mm) and of **b** the difference Δz between the z value of the track vertex and the mean z value of the interaction point (after a cut in p_μ/E_{beam} at (1 ± 0.2) for muon pair candidates

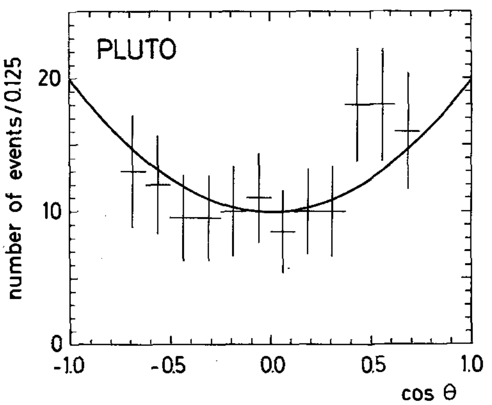

Fig. 5. Distribution in $\cos\theta$ for muon pair production for $9.2 < E_{\text{cm}} < 9.465$ GeV (off and on resonance data). The curve shown is proportional to $(1+\cos^2\theta)$

angular coverage of the muon chambers (the detection efficiency is above 99.9%). This result corresponds to a measurement of zero events with hadronic tracks. The remaining background in our event sample due to cosmic rays was estimated to be 9.5 events using the adjacent regions in Δz and p_μ/E_{beam} and was subtracted. The $\cos\theta$ distribution of the muon pair events is shown in Fig. 5 and is consistent with the curve proportional to $(1+\cos^2\theta)$. The ϕ distribution is isotropic within statistical errors.

The observed muon pairs correspond to seen (uncorrected) cross sections of (0.35 ± 0.05) nb for the energy region below the resonance (9.20–9.445 GeV c.m. energy) and to (0.43 ± 0.05) nb for the resonance region (9.450–9.465 GeV). In order to check that the number of muon pairs observed outside the resonance is in agreement with the theoretical expectation we next correct for cuts and radiative effects.

The correction factor for the angular cuts is 1/0.534. The total loss of events caused by the different cuts (cuts in the χ^2 of the fit, in $d_{\min}$, time difference, Δz and p_μ/E_{beam}) is estimated to be 9.3%. Radiative corrections are calculated from a Monte Carlo sample of $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \mu^+\mu^-\gamma$ events, where terms up to α^3 are included [12]. Folding these events with the experimental resolution in θ (average $\sigma = 9$ mrad) and applying the same cuts as in the experimental data including the cut in photon momentum at 400 MeV/c, a radiative loss of 14% relative to the lowest order QED cross section is obtained, which is reduced to 11% by the hadron and τ vacuum polarisation contribution [12]. Applying the above corrections to the data in the energy region below the resonance, a corrected cross section of $\sigma_{\exp} = (0.83 \pm 0.11)$ nb is obtained, to be compared with the lowest order QED cross section of $\sigma_{\text{QED}} = 0.986$ nb. The ratio of these two values measures the efficiency of the detector including the trigger and the whole track recognition and filter chain. The resulting value of (83 ± 11)% is consistent with the expectation from a Monte Carlo study and the systematic uncertainty of the luminosity monitor.

In the following we have used the muon pair data below the resonance energy for normalization. Using data in the angular region $-0.75 < \cos\theta < 0.75$ we obtain an average muon pair cross section in the Υ(9.46) region of 1.22 ± 0.22, whereas the QED cross section is 0.97 nb. If instead we restrict the angular region to $-0.5 < \cos\theta < 0.5$, an average muon pair cross section of (1.36 ± 0.32) nb is obtained. We conclude that the excess of muon pairs at the resonance does not come from misidentification of events in the large $|\cos\theta|$ region, where a small excess of events is observed above the $(1+\cos^2\theta)$ distribution (see Fig. 5).

Comparing the excess of the muon pair cross section above the QED cross section with the corresponding hadronic cross section (taking into account the different geometric effects of radiative corrections in presence of a resonance), we obtain a branching ratio of the Υ(9.46) of

$$B_{\mu\mu} = \frac{\Gamma_{\mu\mu}}{\Gamma_{\text{tot}}} = (2.2 \pm 2.0)\,\%,$$

where Γ_{tot} includes the leptonic widths; the error is almost completely statistical.

In principle the total width Γ_{tot} can be obtained from $B_{\mu\mu}$ assuming $\Gamma_{ee} = \Gamma_{\mu\mu}$ from $e-\mu$ universality. Due to the large error of $B_{\mu\mu}$, at the 95% C.L. only a lower limit

$$\Gamma_{\text{tot}} > 23\ \text{keV}$$

can be obtained. From the DORIS energy spread the upper limit is $\Gamma_{\text{tot}} < 18$ MeV.

5. Summary and Conclusions

We have measured the electronic width Γ_{ee} and the muonic branching ratio $B_{\mu\mu}$ of the Υ(9.46). The results are $\Gamma_{ee}=(1.33\pm0.14)$ keV, where the error is mainly systematic and $B_{\mu\mu}=(2.2\pm2.0)$%. From these two values a lower limit of $\Gamma_{tot}>23$ keV for the total width has been derived. All results are in qualitative agreement with expectations from QCD [5, 6, 13], assuming that the resonance is a $b\bar{b}$ bound state with a new heavy quark of charge 1/3. Moreover the measured value of Γ_{ee} agrees quantitatively with predictions [14] from duality arguments. Our results also agree within errors with previously published data on Γ_{ee} and $B_{\mu\mu}$ [2–4, 15].

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