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# A Measurement of the Electronic Widths $\Gamma_{ee}$ of the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(4S)$ Resonances, and of the Total Decay Width $\Gamma$ of the $\Upsilon(4S)$

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**Abstract**

The partial decay width into electrons, $\Gamma_{ee}$, of the $\Upsilon(1S)$ and $\Upsilon(2S)$ resonances have been measured with the detector ARGUS at the $e^+e^-$ storage ring DORIS II of DESY. Applying the formula of Kuraev and Fadin for the radiative corrections we find: $\Gamma_{ee}(\Upsilon(1S)) = (1.32 \pm 0.04 \pm 0.03)\,keV$ and $\Gamma_{ee}(\Upsilon(2S)) = (0.52 \pm 0.03 \pm 0.01)\,keV$. The total decay width of the $\Upsilon(4S)$ resonance and its partial width into electrons have been determined as well. Fitting the data with a generalized Breit–Wigner function with an energy dependent decay width $\Gamma(s)$ and a mass shift function $m(s)$, we obtain the following resonance parameters: $\Gamma(M^2) = (10.0 \pm 2.8)\,MeV$, $\Gamma_{ee} = (0.28 \pm 0.05)\,keV$ and $B_{ee} = (2.77 \pm 0.50) \cdot 10^{-5}$

## 1 Introduction

Following the discovery of the $\Upsilon$ resonances in 1977 at Fermilab [1] and the confirmation of their existence in 1978 at DESY [2], the partial decay width into electrons, $\Gamma_{ee}$, was regarded as an important resonance parameter: $\Upsilon$ resonances are interpreted as bound states of a $b\bar{b}$ quark pair, and experimental values of $\Gamma_{ee}$ advocate the assignment of charge $|e_b| = \frac{1}{3}$ for the $b$ quark. Furthermore, comparing $\Gamma_{ee}$ measurements with the theoretical predictions of several potential models [3], the partial decay width into electrons seems to be more suited to discriminate theoretical models than e.g. the resonance mass.

Today's $e^+e^-$ storage rings operating at an c.m.s. energy of $\sqrt{s} \approx 10\,GeV$ have an r.m.s. energy spread of $\Delta \approx 1 - 8\,MeV$; this is considerably larger than the total decay width $\Gamma$ of those $\Upsilon$ states lying below the threshold for the production of $B$ mesons, and makes a direct measurement of the total decay width impossible. If, however, in addition to $\Gamma_{ee}$, the branching ratio of the resonance into electrons, $B_{ee}$, is known, the total decay width of the $\Upsilon$ meson can be derived from the relation $\Gamma = \frac{\Gamma_{ee}}{B_{ee}}$. A direct measurement of the partial width $\Gamma_{ee}$ is possible since $\Gamma_{ee}$ is proportional to the peak value of the $\Upsilon$ resonance production cross section.

The outline of this paper is as follows: In section 2 we describe the parametrization of the $\Upsilon(1S)$ and $\Upsilon(2S)$ resonance curves. Event selection and acceptances are discussed in sections 3 and 4. Section 5 presents the fit of the $\Upsilon(1S)$ and $\Upsilon(2S)$ resonance curves. The parametrization of the $\Upsilon(4S)$ resonance cross section is described in section 6. The fit results are given in sections 7, and we summarize our results in section 8.

## 2 Parametrization of the $\Upsilon(1S)$ and $\Upsilon(2S)$ Resonance Cross Sections

The Born cross section for the production of an $\Upsilon$ meson in $e^+e^-$ annihilation at a c.m.s. energy $\sqrt{s}$ is given by

$$\sigma_0(s) = 12\pi \frac{\Gamma^0_{ee}\,\Gamma}{(s-M^2)^2 + M^2\Gamma^2} \quad , \tag{1}$$

where $\Gamma$ is the total decay width of the $\Upsilon$, $\Gamma^0_{ee}$ is the lowest order partial decay width into $e^+e^-$, and $M$ is the resonance mass. To include all QED corrections of $\mathcal{O}(\alpha^3)$ we follow the formulation of Kuraev and Fadin [4] and write for the total cross section in the soft photon regime:

$$\sigma(s) = \int_0^{\kappa_{max}} \sigma_0(s(1-\kappa))\beta\left(\kappa^{\beta-1}(1+\delta_{vert}+\delta_{vac})\right) d\kappa \; . \tag{2}$$

Here $\kappa = \frac{2E_\gamma}{\sqrt{s}}$ represents the energy of the radiated photon normalized to the beam energy, $\beta = \frac{2\alpha}{\pi}\left(\ln\frac{s}{m_e^2} - 1\right)$ is the equivalent radiator thickness, $\delta_{vert} = \frac{2\alpha}{\pi}\left(\frac{3}{4}\ln\frac{s}{m_e^2} - 1 + \frac{\pi^2}{6}\right)$ is the vertex correction of the $e^+e^-\gamma$–vertex, and $\delta_{vac}$ is the vacuum polarization of the photon propagator.
The lowest order partial decay width $\Gamma^0_{ee}$ entering equations 1 and 2 differs from $\Gamma_{ee}$ defined through the equation $\Gamma_{ee} = B_{ee}\cdot\Gamma$. Since a measurement of $B_{ee}$ includes decays accompanied by an infinite number of soft photons, a definition of $\Gamma_{ee}$ consistent with the above relation has to contain radiated photons as well and cannot be identified with $\Gamma^0_{ee}$. To $\mathcal{O}(\alpha^3)$, the partial widths $\Gamma_{ee}$ and $\Gamma^0_{ee}$ are related by [5]: $\Gamma_{ee} = \Gamma^0_{ee}\left(1+\delta_{vac}+\frac{3}{4}\frac{\alpha}{\pi}\right) \approx \Gamma^0_{ee}\,(1+\delta_{vac})$. Replacing $\Gamma^0_{ee}$ in equation 2 by $\Gamma_{ee}$ yields:

$$\sigma(s) = \int_0^{\kappa_{max}} 12\pi \frac{\Gamma_{ee}\,\Gamma}{(\hat{s}-M^2)^2 + M^2\Gamma^2}\,\beta\left(\kappa^{\beta-1}(1+\delta_{vert})\right) d\kappa \quad , \tag{3}$$

where $\hat{s} = s(1-\kappa)$. To obtain the experimentally observed cross section $\sigma_{exp}(s)$ we convolute $\sigma(s)$ with the Gaussian energy resolution of the storage ring, thereby approximating the Breit–Wigner by a delta function i.e. $12\pi\frac{\Gamma_{ee}\Gamma}{(s-M^2)^2+M^2\Gamma^2} \to 6\pi^2\frac{\Gamma_{ee}}{M^2}\delta(\sqrt{s}-M)$. This procedure is justified since the total width $\Gamma$ of the $\Upsilon(1S)$ or $\Upsilon(2S)$ is in the region of a few $keV$, whereas the FWHM of the storage ring resolution function is about several $MeV$. This leads to:

$$\sigma_{exp}(s) = 6\pi^2\frac{\Gamma_{ee}}{M^2\sqrt{2\pi}\Delta}\,\beta\left(\frac{2\Delta}{\sqrt{s}}\right)^{\beta}(1+\delta_{vert}) \cdot \int_0^{\infty} x^{\beta-1}\exp\left(-\frac{1}{2}(z-x)^2\right) dx \quad , \tag{4}$$



where $\Delta$ is the r.m.s. spread in the c.m.s. energy of the storage ring, and $z = \frac{\sqrt{s}-M}{\Delta}$. In the past, different parametrizations of the observed cross section came into use. Their effect on a $\Gamma_{ee}$ measurement is discussed in great detail in [3, 6] .

## 3 Event Selection

The resonance parameter $\Gamma_{ee}$ is determined through a fit of the theoretical expected resonance shape to the measured excitation curve of the $\Upsilon$ meson. $\Upsilon$ decays are dominated by hadronic channels proceeding via three gluon or $q\bar{q}$ states. The decays into $e^+e^-$ and $\mu^+\mu^-$ interfere with the continuum reaction $e^+e^- \to e^+e^-$ and $e^+e^- \to \mu^+\mu^-$ respectively and distort the shape of the resonance curve. Therefore it is desirable to separate $e^+e^-$ and $\mu^+\mu^-$ events and to measure $\Gamma_{ee}$ solely from the hadronic and tau cross section where interference effects can be neglected due to the large variety of exclusive final states.

In addition, events originating from beam–gas and beam–wall collisions have to be recognized and removed since they may lead to deviations from the pure resonance production cross section.

We preselect hadronic events by requiring either three charged tracks originating from the main vertex or three charged tracks and a measured energy in the shower counters of more than $1.7\,GeV$.
Background from radiative Bhabha events is removed by the following cut: we calculate for each event the angle $\alpha_i$ between each charged or neutral track and its next neighbour and consider the largest of these, $\max(\alpha_i) \equiv \alpha_{max}$. For radiative Bhabha events $\alpha_{max} \approx 180°$, whereas multihadron events have $\alpha_{max} < 90°$. A second quantity to identify Bhabha events is the sum of the energy deposition $E_{12}$ in the shower counters produced by the two charged tracks carrying the highest momenta in the event. The cut in $E_{12}$ and $\alpha_{max}$ is indicated in fig. 1 by the solid line; we accept all events in the upper left half of the plane.
To remove background produced by beam–gas, beam–wall and photon–photon interactions we require for $\sum|\vec{p}\,|$, the sum of all charged and neutral particle momenta, and $\sum p_z$, the sum of their momenta along the beam axis, to fulfil:

$$\frac{\sum|\vec{p}\,|}{\sqrt{s}} > 0.35 + 2.5\left(\frac{\sum p_z}{\sqrt{s}}\right)^2 \quad .$$

This cut is illustrated in fig. 2 by the solid line. After these cuts a residual background contribution of $(1.1 \pm 1.0)\%$ of two–photon background remains, whereas the contamination of beam–gas and beam–wall events is negligible.

## 4 Acceptance

The probability to find an $\Upsilon$ meson after the event selection described in the preceeding section is given by the sum of the acceptances for the different decay modes of the resonance, where each term entering is weighted with the branching ratio of the $\Upsilon$ into this channel. We determine these individual efficiencies through a Monte Carlo simulation of all known $\Upsilon$ decays. Resonance decays into three or two gluons or into $q\bar{q}$ as well as the fragmentation of these partons were modelled using the LUND 6.2 generator [7]; cascade decays like $\Upsilon(2S) \to \Upsilon(1S)\pi\pi$ where the $\Upsilon(1S)$ decays into lepton pairs and the decays $\Upsilon(1S), \Upsilon(2S) \to \tau^+\tau^-$ were generated using the program MOPEK [8]. All Monte Carlo events were passed through a simulation of the ARGUS detector and were processed using the same reconstruction program as the data. Finally, we take into account the trigger acceptances by studying the response of individual trigger components during data taking periods which came to use in this analysis. Table 1 shows the acceptances and their statistical errors for the different decay modes of the $\Upsilon$.

| Decay Channel | Branching Ratio | Acceptance |
|---|---|---|
| $\Upsilon(1S) \to 3g, 2g\gamma$ | $B_g = 0.832 \pm 0.005$ | $0.985 \pm 0.001$ |
| $\Upsilon(2S) \to 3g, 2g\gamma$ | $B'_g = 0.46 \pm 0.03$ | $0.985 \pm 0.001$ |
| $\Upsilon(1S) \to q\bar{q}$ | $B_{q\bar{q}} = 0.090 \pm 0.003$ | $0.949 \pm 0.003$ |
| $\Upsilon(2S) \to q\bar{q}$ | $B'_{q\bar{q}} = 0.048 \pm 0.009$ | $0.949 \pm 0.003$ |
| $\Upsilon(1S) \to \tau\tau$ | $B_{ll} = 0.0258 \pm 0.0006$ | $0.255 \pm 0.007$ |
| $\Upsilon(2S) \to \tau\tau$ | $B'_{ll} = 0.014 \pm 0.003$ | $0.255 \pm 0.007$ |
| $\Upsilon(2S) \to \gamma\chi_{b_{0,1,2}}$ | $B'_{\chi_b} = 0.18 \pm 0.02$ [9] | $0.97 \pm 0.04$ |
| $\Upsilon(2S) \to \Upsilon(1S)\pi\pi$ | $B'_{\Upsilon\pi\pi} = 0.27 \pm 0.01$ [9] | $0.93 \pm 0.04$ |

Table 1: Acceptances

The branching ratios for the decays $\Upsilon(1S) \to 3g, 2g\gamma$ and $\Upsilon(2S) \to 3g, 2g\gamma$ have been calculated using the relations $B_g = 1 - 3B_{ll} - B_{q\bar{q}}$ and $B'_g = 1 - 3B'_{ll} - B'_{q\bar{q}} - B'_{\chi_b} - B'_{\Upsilon\pi\pi}$ where $B_{ll}$ is the weighted mean of the branching ratios $B_{ee}$, $B_{\mu\mu}$, and $B_{\tau\tau}$ [9]; further we used $B_{q\bar{q}} = R \cdot B_{ll}$ and $B'_{q\bar{q}} = R \cdot B'_{ll}$ and $R = 3.515 \pm 0.079$, the weighted average of measurements [10] at c.m.s. energies near 10 $GeV$.

For the average probability to find an $\Upsilon(1S)$ or $\Upsilon(2S)$ we obtain:

$$\eta_{\Upsilon(1S)} = 0.912 \pm 0.002 \pm 0.008$$
$$\eta_{\Upsilon(2S)} = 0.934 \pm 0.007 \pm 0.009,$$



where the first error is statistical and the second is due to systematics. The statistical error is dominated by the uncertainty on the branching ratio $B_{ll}$ for the decays of the $\Upsilon(1S)$ and $\Upsilon(2S)$ into lepton pairs, the relative error from this source on $\eta_{\Upsilon(1S)}$ and $\eta_{\Upsilon(2S)}$ being 0.19% and 0.78%, respectively.
The systematic error includes uncertainties in the hadronization model and in the simulation of the detector response (1% for decays into three gluons, $2g\gamma$, $\chi_b$ and into $\tau^+\tau^-$, 1.5% for decays into $q\bar{q}$).

## 5 Fit of the $\Upsilon(1S)$ and $\Upsilon(2S)$ Resonances

The $\Upsilon(1S)$ data consist of three scans of the hadronic cross section around the resonance mass. For the $\Gamma_{ee}$ measurement of the $\Upsilon(2S)$ we use the scan data of the $\Upsilon(2S)$ mass [11].
A determination of $\Gamma_{ee}$ requires precise knowledge of the energy difference of two adjacent cross section points. At $e^+e^-$ storage rings the absolute energy calibration is usally done with the help of the Sokolov–Ternov effect [12]: the synchrotron radiation polarizes the $e^+e^-$ beams; a weak time dependent magnetic field is used to destroy this polarization. From the frequency of the depolarization field the absolute energy of the storage ring can be inferred.
At DORIS II this method to control the energy of the cross section points has been used for the precise measurement of the $\Upsilon(2S)$ mass. However, at $\Upsilon(1S)$ energies the storage ring inherent resonances hinder the build up of polarization. Here the energy is surveyed by measuring the magnetic field in one of the dipole magnets using an NMR probe. Since in the energy range of our scans the relation between the DORIS II beam energy and the magnetic field measurement of the NMR probe is linear, we use this method to control the point–to–point energy variation of our $\Upsilon(1S)$ scans. The magnetic field is known with an accuracy of $\sigma(B)/B \approx 5 \cdot 10^{-5}$.

In order to compute the experimental cross section at each energy point, we divided the number of events surviving our selection criteria by the integrated luminosity $\mathcal{L}$ of the particular scan point. At ARGUS the luminosity is determined by comparing the number of observed Bhabha events in a specific solid angle with the corresponding QED cross section [13]. The statistical error on the luminosity is determined by the the number of accepted Bhabha events; the systematical uncertainty has been determined to be $\frac{\sigma(\mathcal{L})}{\mathcal{L}} = ^{+1.8}_{-2.5}$ % at the $\Upsilon(1S)$, where the asymmetric error accounts for the contribution of $\Upsilon(1S) \to e^+e^-$ events to the observed Bhabha cross section. In the case of the $\Upsilon(2S)$ and $\Upsilon(4S)$ this decay mode is negligible, here the systematical error on $\mathcal{L}$ is: $\frac{\sigma(\mathcal{L})}{\mathcal{L}} = \pm 1.8\%$. Consequently, the statistical error of each cross section point of the $\Upsilon$ scans receives contributions from the statistical error on the number of accepted multihadron events as well as on the number of Bhabha events.

To determine $\Gamma_{ee}$ of the $\Upsilon(1S)$ and $\Upsilon(2S)$ , we fit the following theoretical cross section to the data points of our three scans simultaneously:

$$\sigma^{vis}(s) = 6\pi^2 \frac{\Gamma_{ee}}{M^2\sqrt{2\pi}\Delta} \eta_\Upsilon \beta \left(\frac{2\Delta}{\sqrt{s}}\right)^\beta (1+\delta_{vert}) \cdot \int_0^\infty x^{\beta-1} \exp\left(-\frac{1}{2}(z-x)^2\right) dx + R^{vis}\frac{4\pi\alpha^2}{3s} , \quad (5)$$

$$\text{where} \quad z = \frac{\sqrt{s}-M}{\Delta} .$$

Here $\eta_\Upsilon$ is the probability to find an $\Upsilon(1S)$ or $\Upsilon(2S)$ respectively. The free parameters of this fit are: the partial width $\Gamma_{ee}$, the energy resolution $\Delta$ of the DORIS II storage ring, for each scan an individual mass parameter $M$, and the continuum parameter $R^{vis}$. Fig. 3 shows the result of the fit for the $\Upsilon(1S)$ , where the energy scales of all scans where shifted to give $M = 9.4603\,GeV$ [9]. The values of the fit parameters are: $\Gamma_{ee} = (1.32 \pm 0.04)\,keV$, $\Delta = (8.57 \pm 0.27)\,MeV$, and $R^{vis} = 3.98 \pm 0.07$. Together with the systematical uncertainties of the acceptance and of the determination of the integrated luminosity the final value of the partial decay width $\Gamma_{ee}$ of the $\Upsilon(1S)$ is:

$$\Gamma_{ee}(\Upsilon(1S)) = (1.32 \pm 0.04 \pm 0.03)\ keV$$

The equivalent fit to the $\Upsilon(2S)$ resonance data is shown in fig. 4, and the resulting $\Gamma_{ee}$ is:

$$\Gamma_{ee}(\Upsilon(2S)) = (0.52 \pm 0.03 \pm 0.01)\ keV$$

These measurements are in good agreement with those of of the Crystal Ball and MD–1 experiments (Results earlier than 1985 were reevaluated in [3, 6]):

| | |
|---|---|
| Crystal Ball: [14] | $\Gamma_{ee}(\Upsilon(1S)) = (1.34 \pm 0.03 \pm 0.06)\ keV$ |
| MD–1: [15] | $\Gamma_{ee}(\Upsilon(1S)) = (1.286 \pm 0.025 \pm 0.034)\ keV$ |
| Crystal Ball: [14] | $\Gamma_{ee}(\Upsilon(2S)) = (0.56 \pm 0.04 \pm 0.02)\ keV$ |

## 6 Parametrization of the $\Upsilon(4S)$ Resonance Shape

The $\Upsilon(4S)$ resonance lies approximately $20\,MeV$ above the kinematical threshold for the production of two $B$ mesons, its total width being also of the order of $20\,MeV$ [9];



about $20\,MeV$ above the $\Upsilon(4S)$ resonance peak new decay channels into $B\bar{B}^*$ open. In this case a parametrization of the resonance line using the Breit–Wigner function as given in equation 1 is not adequate. This formula is only valid in regions where the decay width $\Gamma$ is small and varies only slowly with $s$ and no new decay channels contribute to the cross section. Therefore we consider a more general ansatz for $\sigma(s)$ [16]:

$$\sigma(s) = 12\pi \frac{\Gamma_{ee}\,\Gamma(s)}{(s - m^2(s))^2 + M^2\Gamma^2(s)} \quad (6)$$

where the imaginary part of the propagator is given by $M\Gamma(s)$ using an energy dependent width. The real part of the propagator is absorbed in a mass shift function $m(s)$ which is related to $\Gamma(s)$ by the dispersion relation:

$$m^2(s) = M^2 + \frac{1}{\pi}\mathcal{P}\int_{s_{thres}}^{\infty} \frac{M\Gamma(s')}{M^2 - s'}ds' - \frac{1}{\pi}\mathcal{P}\int_{s_{thres}}^{\infty} \frac{M\Gamma(s')}{s - s'}ds' \quad (7)$$

Here $\mathcal{P}$ denotes the principal value, and $s_{thres}$ is the square of threshold energy for the $\Upsilon(4S)$ decay. To parametrize $\Gamma(s)$, we exploit the Quark Pair Creation (QPC) model of Le Yaouanc et al. [17] for meson decays allowed by the Okubo–Zweig–Iizuka rule [18]. In this model the matrix element for the decay $\Upsilon(4S) \to B\bar{B}$ is given by the product of a spin dependent amplitude and an overlap integral $I_m(|\vec{k}_B|)$ containing the meson and quark wave functions involved in the decay:

$$I_m(|\vec{k}_B|) = \int Y_1^m(2\vec{k}_B - \vec{Q})\,\psi_{\Upsilon(4S)}(\vec{Q})\,\psi_B(\vec{Q} - h\vec{k}_B)\,\psi_{\bar{B}}(h\vec{k}_{\bar{B}} - \vec{Q})\,d\vec{Q} \quad (8)$$

where $\vec{k}_B$ is the momentum of the $B$ meson and $h = \frac{m_b}{m_b + m_{u,d}}$. The spherical tensor $Y_1^m$ represents the wave function of the created quark antiquark pair, $\psi_{\Upsilon(4S)}$ and $\psi_B$ are the wave functions of the $\Upsilon(4S)$ and the $B$ meson respectively. To facilitate the calculation of this integral, we used harmonic oscillator wave functions whose parameters have been determined so that they minimize the expectation value [19] of a typical $q\bar{q}$ Hamiltonian:

$$H = m_{q_i} + m_{\bar{q}_j} - \frac{\nabla^2}{2\mu} + \kappa r - \frac{4}{3}\frac{\alpha_s}{r} + V_0 \quad , \quad \mu = \frac{m_{q_i} m_{\bar{q}_j}}{m_{q_i} + m_{\bar{q}_j}} .$$

The quark masses and the parameters of the $q\bar{q}$ potential have the following values [20]: $m_{u,d} = 0.33\,GeV/c^2$, $m_b = 5.17\,GeV/c^2$, $\kappa = 0.186\,GeV^2$, $V_0 = -0.802\,GeV$, $\alpha_s = 0.35$ for the $\Upsilon(4S)$ and $\alpha_s = 0.42$ for the $B$ meson. Considering final states like $B\bar{B}^*$ with thresholds above $10.58\,GeV$ leads to complex mixing with different spectroscopic $b\bar{b}$–states. In the following we will consider the $\Upsilon$ resonance at $10.58\,GeV$ regardless of its spectroscopic composition which implies that those channels do not contribute. In addition to the QPC parametrization, we calculated $\Gamma(s)$ in a simple phase space model where the overlap integral of equation 8 is a constant, and the energy dependence of the width is given by the phase space factor $|\vec{k}_B|s^{-1}$. Fig. 5 shows

the decay width $\Gamma(s)$ of both models in the energy region of our scan data.
The differences of the Breit–Wigner functions given by equation 1 and 6 are illustrated in fig. 6: Here the dotted curve corresponds to equation 1 where the parameters took the values $M = 10.58\,GeV/c^2$, $\Gamma = 10\,MeV$, and $\Gamma_{ee} = 0.28\,keV$. The full curve represents the more general Breit–Wigner function of equation 6 with $\Gamma(s)$ from the QPC model, the dashed curve corresponds to a $\Gamma(s)$ which has a simple phase space behavior. We used the same parameters as for the standard Breit–Wigner function: $M = 10.58\,GeV/c^2$, $\Gamma(M^2) = 10\,MeV$ and $\Gamma_{ee} = 0.28\,keV$.
The standard Breit–Wigner function differs considerably from the more general parametrizations; because of the constant width parameter, it extents even below the kinematically allowed region for $B\bar{B}$ production.

# 7 Fit of the $\Upsilon(4S)$ Resonance

The $\Upsilon(4S)$ data points consist of three scans around the resonance mass. We select hadronic events with the same cuts as for the $\Upsilon(1S)$ and $\Upsilon(2S)$ ; to suppress continuum events we make an additional cut on the second Fox–Wolfram moment $H_2$ and require $H_2 \leq 0.35$. This cut removes about 50% of the continuum events, whereas the acceptance $\eta$ of the $\Upsilon(4S)$ decay into $B$ mesons is still as high as $\eta = 0.945 \pm 0.001 \pm 0.010$.
The resonance parameters $\Gamma_{ee}$ and $\Gamma(M^2_{\Upsilon(4S)})$ of the $\Upsilon(4S)$ are determined in a fit of the theoretical cross section of equation 6, corrected for initial state radiation and convoluted with the energy resolution of the storage ring, to the data points. The fit is shown in fig. 7, the results are: $\Gamma(M^2_{\Upsilon(4S)}) = (10.0 \pm 2.8)\,MeV$ and $\Gamma_{ee} = (0.28 \pm 0.05)\,keV$.
The model dependences of this result have been estimated in a repeated fit to the resonance data assuming a simple phase space behavior of $\Gamma(s)$. The result of this fit is $\Gamma(M^2_{\Upsilon(4S)}) = (12.7 \pm 3.6)\,MeV$ and $\Gamma_{ee} = (0.29 \pm 0.05)\,keV$ and we estimate the systematic error from the parametrization of $\Gamma(s)$ to be $\pm 2.7\,MeV$. Thus, within the QPC model of Le Yaouanc et al. [17] we find the following resonance parameters of the $\Upsilon(4S)$ :

$$\begin{aligned} \Gamma(M^2_{\Upsilon(4S)}) &= (10.0 \pm 2.8 \pm 2.7)\ MeV \\ \Gamma_{ee}(\Upsilon(4S)) &= (0.28 \pm 0.05 \pm 0.01)\ keV \\ B_{ee} = \Gamma_{ee}/\Gamma(M^2_{\Upsilon(4S)}) &= (2.77 \pm 0.50 \pm 0.49) \cdot 10^{-5} \end{aligned}$$

Table 2: $\Upsilon(4S)$ Resonance Parameters



This result may be compared with the world average [9]: $\Gamma_{\Upsilon(4S)} = (23.8 \pm 2.2)\,MeV$, $\Gamma_{ee}(\Upsilon(4S)) = (0.24 \pm 0.05)\,keV$, $B_{ee} = (1.01 \pm 0.21) \cdot 10^{-5}$ which, however, has been obtained using the same ansatz for the resonance cross section as in the case of the $\Upsilon(1S)$ i.e. assuming $\Gamma_{\Upsilon(4S)} \ll \Delta$, where $\Delta$ is the energy resolution of the storage ring. Although we disagree with this assumption, we repeated the fit to the $\Upsilon(4S)$ data using equation 6, the same formula as for the $\Upsilon(1S)$ and conclude that the differences between our results given in table 2 and the world average [9] are due to the different parametrizations of the cross section.
For completeness we finally give the result of a fit with the standard Breit–Wigner function of equation 3, corrected for initial state radiation and convoluted with the energy resolution of the storage ring: $\Gamma_{ee} = (0.31 \pm 0.05)\,keV$, $\Gamma = (13.6 \pm 4.4)\,MeV$ and $B_{ee} = (2.28 \pm 0.27) \cdot 10^{-5}$ which agrees with the more elaborate model we used for the results given in table 2.

# 8 Summary

In summary we have measured the partial decay width into electrons, $\Gamma_{ee}$ of the $\Upsilon(1S)$ and $\Upsilon(2S)$ resonances. We find:

$$\begin{aligned} \Gamma_{ee}(\Upsilon(1S)) &= (1.32 \pm 0.04 \pm 0.03)\ keV \\ \Gamma_{ee}(\Upsilon(2S)) &= (0.52 \pm 0.03 \pm 0.01)\ keV \end{aligned}$$

For the $\Upsilon(4S)$ the partial decay width $\Gamma_{ee}$ and the total decay width $\Gamma(M^2_{\Upsilon(4S)})$ have been determined as well. Using a model of Le Yaouanc et al. [17] for the parametrization of the energy dependence of $\Gamma(s)$ we find the following resonance parameters:

$$\begin{aligned} \Gamma(M^2_{\Upsilon(4S)}) &= (10.0 \pm 2.8 \pm 2.7)\ MeV \\ \Gamma_{ee}(\Upsilon(4S)) &= (0.28 \pm 0.05 \pm 0.01)\ keV \\ B_{ee} = \Gamma_{ee}/\Gamma(M^2_{\Upsilon(4S)}) &= (2.77 \pm 0.50 \pm 0.49) \cdot 10^{-5} \end{aligned}$$

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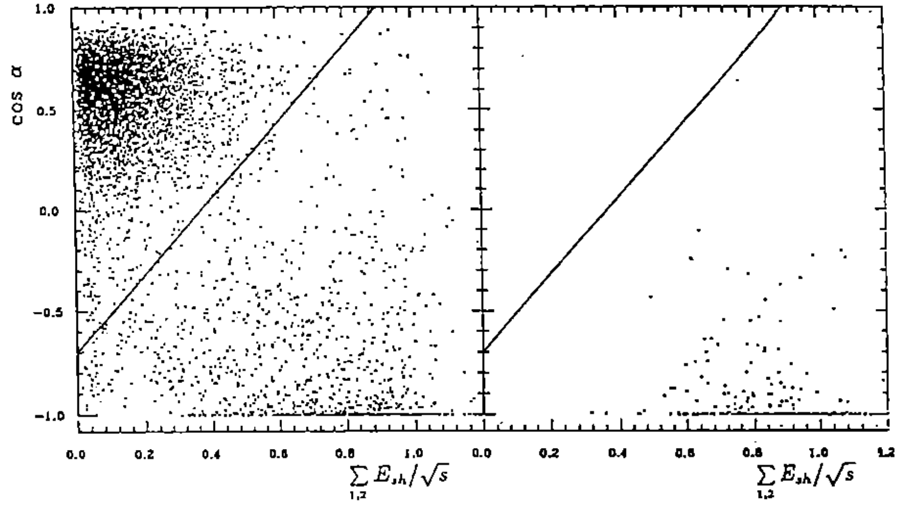


Figure 1: Scatterplot of $\cos\alpha_{max}$ versus the scaled sum of the observed shower energy of the two particles with largest momenta $E_{12}/\sqrt{s}$ where $\alpha$ is the isolated track angle described in the text. The left part of the figure shows the distribution in the data, the right part shows the distribution of a Bhabha Monte Carlo sample.

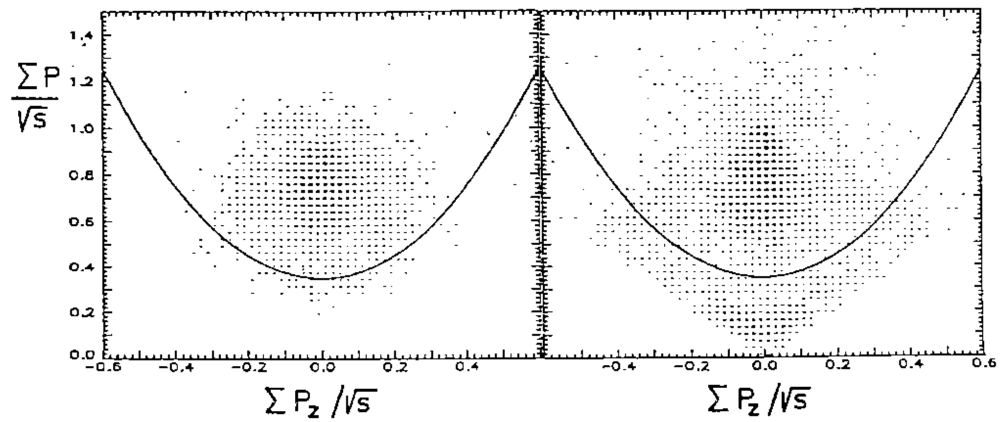


Figure 2: Scatterplot of the total momentum sum $\sum|\vec{p}|/\sqrt{s}$ versus the sum of the particle momenta along the beam axis $\sum P_z/\sqrt{s}$. The left plot represents Monte Carlo data simulating the 3-gluon decays of the $\Upsilon(1S)$ . The right plot shows the distribution of our data.



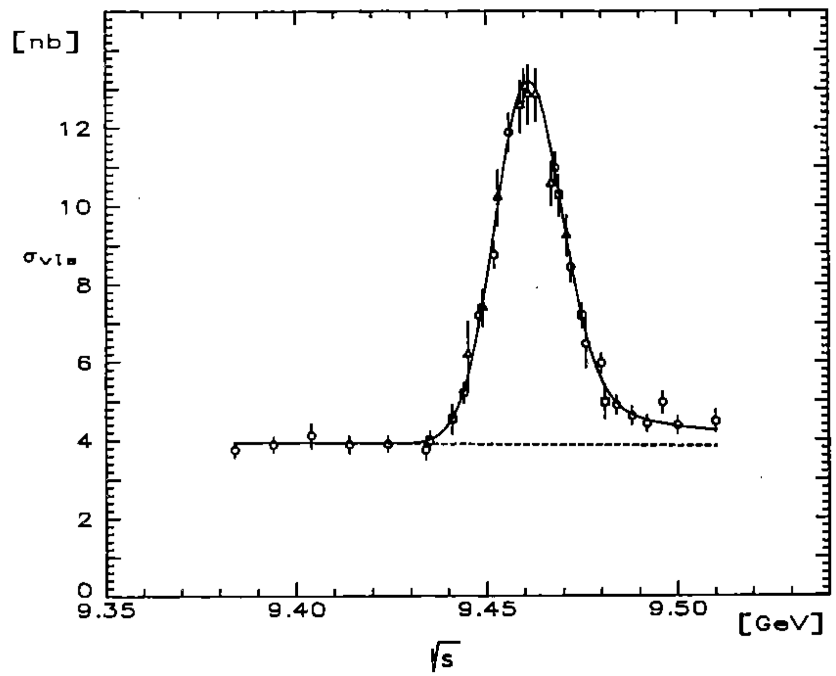


Figure 3: Fit of the $\Upsilon(1S)$ resonance cross section. The different symbols represent different scans.

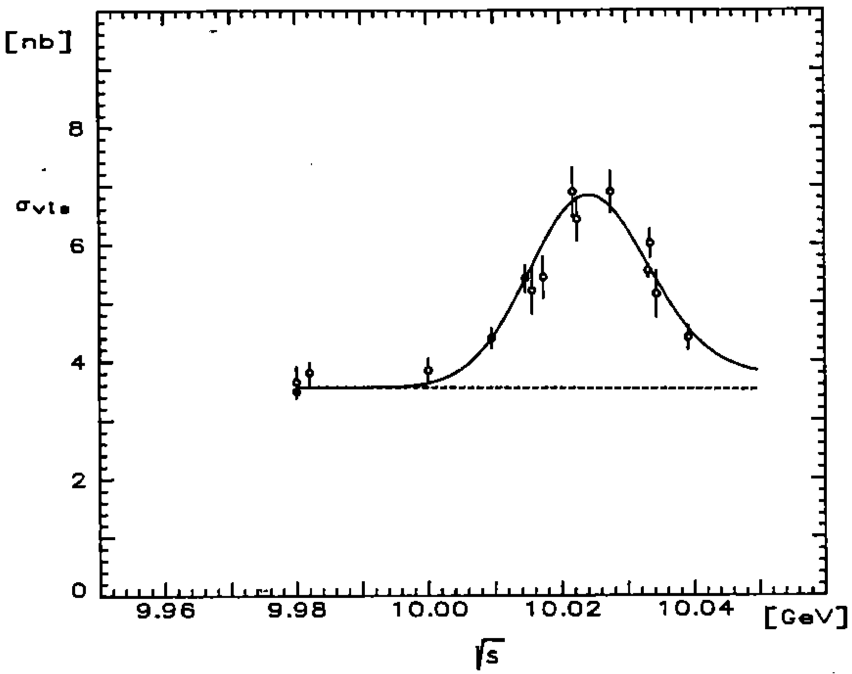


Figure 4: Fit of the $\Upsilon(2S)$ resonance cross section.



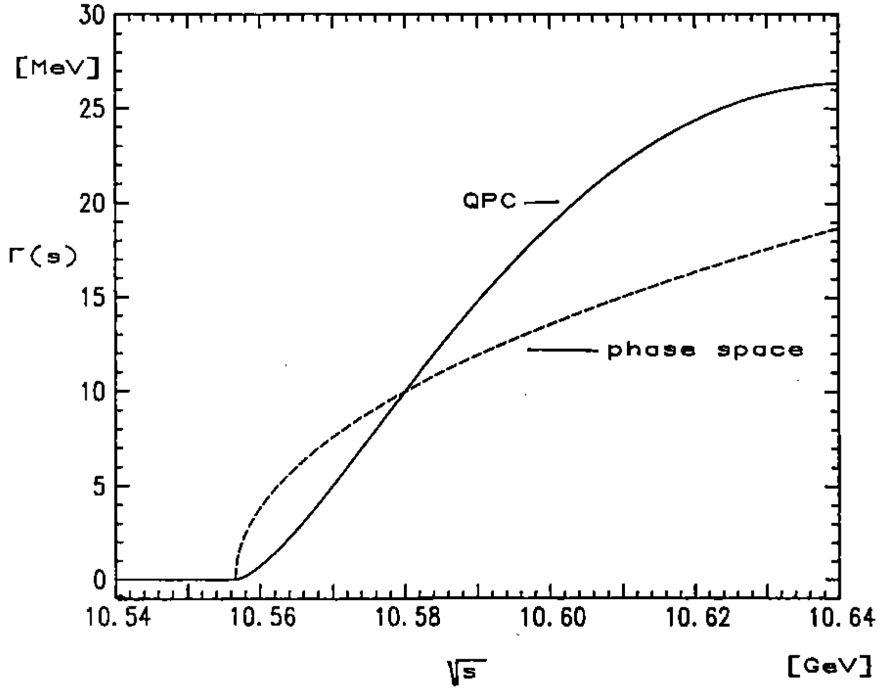


Figure 5: Full line: $\Gamma(s)$ of the decay $\Upsilon(4S) \to B\bar{B}$ in the QPC-model. The dashed curve represents $\Gamma(s)$ in the phase space model. Both parametrizations are normalized to $\Gamma(M^2_{\Upsilon(4S)}) = 10\,MeV$.

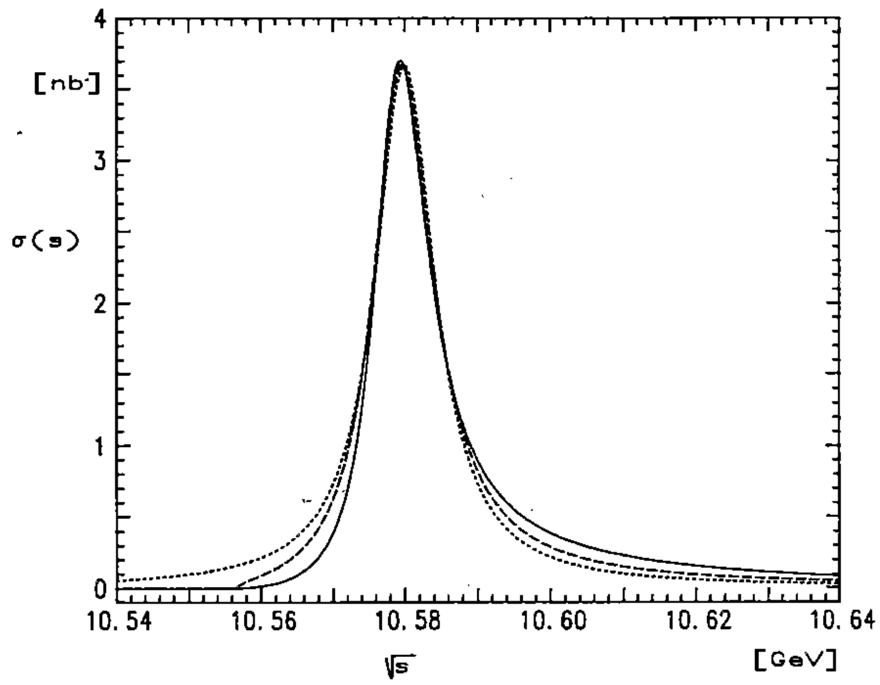


Figure 6: Dotted line: Standard Breit–Wigner function of equation 1. Full line: generalized Breit–Wigner function of equation 5 where $\Gamma(s)$ has been calculated from the QPC model. For the dashed line $\Gamma(s)$ varies according to the two body phase space. The resonance parameters for all curves are the same: $M = 10.58\,GeV$, $\Gamma(M^2) = 10\,MeV$ and $\Gamma_{ee} = 0.28\,keV$.



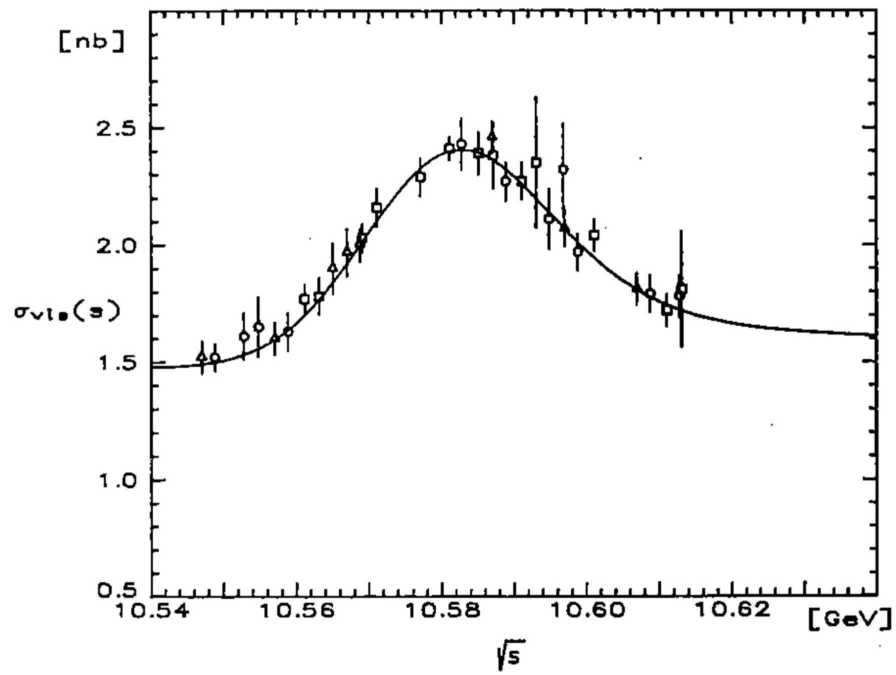


Figure 7: Fit of the $\Upsilon(4S)$ resonance cross section. The different symbols represent different scans.