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A Measurement of the Total Width, the Electronic Width and the Mass of the $\Upsilon(10580)$ Resonance.

The *BABAR* Collaboration
and
the PEP-II Machine Group

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Abstract

We present a preliminary measurement of the resonance parameters of the $\Upsilon(10580)$ resonance with the *BABAR* detector at the SLAC PEP-II asymmetric B factory. We measure the total width $\Gamma_{\rm tot}$ to be $(20.7 \pm 1.6 \pm 2.5)\,\mathrm{MeV}$, the partial electronic width $\Gamma_{ee} = (0.321 \pm 0.017 \pm 0.029)\,\mathrm{keV}$ and the mass $M = (10.5793 \pm 0.0004 \pm 0.0012)\,\mathrm{GeV}/c^2$.

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1 Introduction

The $\Upsilon(10580)$ resonance is the lowest lying $b\bar{b}$ state above the open bottom threshold. Its strong decay into two B mesons is not suppressed by the OZI rule [1], so that this decay channel is dominant. The total decay width $\Gamma_{\rm tot}$ of the $\Upsilon(10580)$ is therefore much larger than the widths of the lower mass $b\bar{b}$ states, which allows a direct measurement of $\Gamma_{\rm tot}$ at an e^+e^- collider.

Although the state has been known for almost 20 years, its mass and width are still only measured with relatively large uncertainties, and central values from different experiments show substantial variation [2, 3, 4, 5]. We present new measurements of the mass and total and electronic widths of the $\Upsilon(10580)$ at the PEP-II storage ring with errors on the mass and total width much lower than the present world average.

2 The *BABAR* experiment

The data used in this analysis were collected with the *BABAR* detector [6] at the PEP-II storage ring [7]. The data set comprises three energy scans of the $\Upsilon(10580)$ and one scan of the $\Upsilon(3S)$ resonance.

The PEP-II B factory is an asymmetric e^+e^- collider designed to operate at a luminosity of $3\times10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and a center-of-mass (CM) energy around 10.58 GeV. The energy of the electron beam is about 9.0 GeV, that of the positron beam 3.1 GeV, resulting in a Lorentz boost to the $\Upsilon(10580)$ resonance of $\beta\gamma = 0.56$. The energy of the electron beam was varied while the positron beam energy was held constant during the energy scans of the $\Upsilon(3S)$ and $\Upsilon(10580)$ resonances. The intrinsic CM energy spread of PEP-II is about 4.6 MeV.

BABAR is a solenoidal detector optimized for the asymmetric beam configuration at PEP-II. Charged particle momenta are measured in a tracking system consisting of a 5-layer, double-sided readout, silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH) filled with a mixture of helium and isobutane, both operating in a 1.5 T superconducting solenoidal magnet. The electromagnetic calorimeter (EMC) consists of 6580 CsI(Tl) crystals arranged in barrel and forward endcap subdetectors. Muons and long-lived neutral hadrons are identified in the instrumented flux return (IFR), composed of resistive plate chambers and layers of iron. A detector of internally reflected Cherenkov light (DIRC), together with dE/dx information from the DCH and SVT, provides separation of kaons and pions.

3 Parametrization of the $\Upsilon(10580)$ resonance shape

The $\Upsilon(10580)$ resonance is dominantly a $4S$ state, but its shape is modified by interference with the $\Upsilon_1(3D)$ and the $\Upsilon(5S)$ states, and by coupled-channel effects at higher energies where BB^* and B^*B^* production open up. A full spectroscopic fit of the energy region around the $\Upsilon(10580)$ would require both a scan over a much wider region and more detailed theoretical models, which are both unavailable. Fortunately, the $\Upsilon(10580)$ is sufficiently well isolated to be still treated as a simple resonance, which is therefore our approach in this analysis.

The $\Upsilon(10580)$ lies only about 20 MeV above the kinematic threshold for open bottom production, while the total width is 10–20 MeV [8]. A model derived from a pure spectroscopic $4S$ state together with a relativistic Breit-Wigner function is used to obtain a good approximation of the shape below the opening of new channels. This analysis is therefore restricted to data points taken at CM energies below the BB^* threshold at 10.604 GeV. Systematic effects caused by neglecting interference effects are estimated by a comparison with a simple non relativistic Breit-Wigner function.

The cross section of the process $e^+e^- \to \Upsilon(4S) \to B\overline{B}$ is given as

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

where Γ^0_{ee} is the partial decay width into e^+e^-, $\Gamma_{\rm tot}$ is the total decay width and M is the mass of the resonance. In this equation Γ^0_{ee} is taken as a constant and the approximation $\Gamma_{\rm tot}(s) \approx \Gamma_{\Upsilon(4S)\to B\overline{B}}(s)$ is used.

In this analysis the quark pair creation model (QPCM) [9] is used to describe the energy dependent width $\Gamma_{\rm tot}(s)$. In the QPCM the decay of the bound $b\bar{b}$ state is described by the creation of a light quark-antiquark pair from the vacuum. The b and $\bar{b}$, respectively, each form a B meson with one of the light quarks. The matrix element for this decay is given by a spin dependent amplitude and an overlap integral of the $\Upsilon(4S)$ and B-meson wave functions:

$$I_4(m,\mathbf{q}) = \int Y_1^m(2\mathbf{q}-\mathbf{Q})\psi_{\Upsilon(4S)}(\mathbf{Q})\psi_B(\mathbf{Q}-h\mathbf{q})\psi_{\bar{B}}(-\mathbf{Q}+h\mathbf{q})\,\mathrm{d}^3Q, \tag{2}$$

where $\mathbf{q}$ is the momentum of the B meson, $\mathbf{Q}$ the momentum of the $\Upsilon(4S)$ and $h = 2m_b/(m_b+m_q)$ with the quark masses m_b and m_q. The spherical tensor Y_1^m represents the wave function of the created quark-antiquark pair, and ψ_B and $\psi_{\Upsilon(4S)}$ are the wave functions of the B and the $\Upsilon(4S)$ mesons. The wave functions ψ_B and $\psi_{\Upsilon(4S)}$ are approximated by harmonic oscillator wave functions using the parametrization of the ARGUS collaboration [2].

The resonance shape parametrized by equation (1) is significantly modified by QED corrections [10, 11]. The partial width Γ_{ee} is related to the lowest order partial width Γ^0_{ee} by $\Gamma_{ee} \approx \Gamma^0_{ee}(1+\delta_{\rm vac})$, where $\delta_{\rm vac}$ is the vacuum polarization of the photon propagator [12]. Hence the cross section including radiative corrections of $\mathrm{O}(\alpha^3)$ is given by

$$\tilde{\sigma}(s) = \int_0^{\kappa_{\max}} 12\pi \frac{\Gamma_{ee}\Gamma_{\rm tot}(s')}{(s'-M^2)^2 + M^2\Gamma^2_{\rm tot}} \beta(\kappa^{\beta-1}(1+\delta_{\rm vert}))\,\mathrm{d}\kappa, \tag{3}$$

where $\kappa = \frac{2E_\gamma}{\sqrt{s}}$ is the energy of the radiated photon normalized to the CM energy, $\kappa_{\max} = 1 - \frac{4m_e^2}{s}$, $\beta = \frac{2\alpha}{\pi}(\ln\frac{s}{m_e^2} - 1)$, $\delta_{\rm vert} = \frac{2\alpha}{\pi}(\frac{3}{4}\ln\frac{s}{m_e^2} - 1 + \frac{\pi^2}{6})$ is the vertex correction of the $e^+e^-\gamma$-vertex and $s' = s(1-\kappa)$.

To obtain the experimentally observed cross section, the cross section given by equation (3) has to be averaged over the energy distribution of the colliding beams. The CM energies $\sqrt{s'}$ of the actual e^+e^- collisions have a Gaussian distribution about the mean energy $\sqrt{s}$ with standard deviation Δ. The experimental cross section is therefore given by

$$\sigma(s) = \int \tilde{\sigma}(s')\frac{1}{\sqrt{2\pi}\Delta}\exp\left(-\frac{(\sqrt{s'}-\sqrt{s})^2}{2\Delta^2}\right)\mathrm{d}\sqrt{s'}. \tag{4}$$

4 Analysis method

In order to determine the $\Upsilon(10580)$ resonance parameters, the energy dependence of the cross section $\sigma_{b\bar{b}}$ of the reaction $e^+e^- \to \Upsilon(10580) \to B\bar{B}$ has to be measured in an energy interval around the resonance mass. We determine the shape of the $\Upsilon(10580)$ resonance from three short energy scans where the cross section is measured from small data samples at several CM energies and in the continuum below the $B\overline{B}$ threshold. This is combined with a precise measurement of the peak cross section from a high statistics data set taken close to the peak in the course of B-meson data accumulation. While the scan data provide information mainly on the width and peak position, the high precision cross section gives the absolute normalisation with good accuracy.

The visible hadronic cross section measured from the number of hadronic events N_{had} and the luminosity L is related to $\sigma_{b\bar{b}}$ via

$$\sigma^{\text{vis}}(s) \equiv \frac{N_{\text{had}}}{L} = \varepsilon_{b\bar{b}}\sigma_{b\bar{b}}(s) + \frac{P}{s}, \tag{5}$$

where $\varepsilon_{b\bar{b}}$ is the detection efficiency for $\Upsilon(4S) \to B\overline{B}$ and P a constant, which describes the background level of non-$B\overline{B}$ events. A minimum χ^2 fit of (5) is done to the data points $(\sigma_{\text{i}}^{\text{vis}}, \sqrt{s_i})$. The $b\bar{b}$ cross section is given by the cross section formula (4). The efficiency $\varepsilon_{b\bar{b}}$, which is considered as energy independent, is determined for each scan by the peak cross section measured from the high statistics on-resonance data set.

Any selection of hadronic events will have backgrounds from two classes of sources. Events like $e^+e^- \to e^+e^-(\gamma \to)e^+e^-$ (radiative Bhabhas with converted photon), $e^+e^- \to q\overline{q}(\gamma)$ (continuum) or $e^+e^- \to \tau^+\tau^-(\gamma)$ contribute to the background. These events all have cross sections $\sigma \propto 1/s$, at least on a narrow energy interval, which allows us to describe this background component in a fit to the data. The second class of background originates from two photon processes $\gamma\gamma \to X$ or beam-gas interactions, which do not scale in a simple way with energy changes, and the latter even depend on the vacuum in the beam pipe rather than on the beam energy. This kind of background cannot be taken into account in the fit of the resonance. Therefore the event selection has to reduce this background as much as possible.

The selection of hadronic events is based on two main cuts: A high multiplicity N_{ch} of charged tracks that originate from the beam crossing region and an event shape cut using the normalized second Fox-Wolfram moment R_2, which is smaller for $B\overline{B}$ events than for background events. Additional cuts as given below are applied to the different data samples to reduce the beam-gas and $\gamma\gamma$ background.

The luminosity is measured from $e^+e^- \to \mu^+\mu^-$ events. These events are selected by requiring a track multiplicity $N_{\text{ch}} \geq 2$ and an invariant mass of a pair of tracks greater than $7.5\,\text{GeV}/c^2$. A cut on the cms acolinearity is applied to reject cosmic rays. At least one of the tracks must have associated energy deposited in the calorimeter. Bhabha events are vetoed by requiring that none of the tracks has an associated energy deposited in the calorimeter of more than 1 GeV.

The energy spread Δ of the collider has to be known in order to extract Γ_{tot} from the observed resonance shape. The energy spread is measured from a scan of the narrow $\Upsilon(3S)$ resonance. In addition the $\Upsilon(3S)$ scan provides a calibration of the product of the beam energies, which allows a precise measurement of the $\Upsilon(10580)$ mass.

4.1 $\Upsilon(3S)$ scan

The $\Upsilon(3S)$ scan consists of 10 data points at different CM energies. The visible cross section σ^{vis} is measured for each energy. The $\Upsilon(3S)$ decays dominantly via the three-gluon graph. Therefore the angular distribution of the decay products of the $\Upsilon(3S)$ is more isotropic than the continuum background, which allows us to select $\Upsilon(3S)$ events with cuts similar to the $B\overline{B}$ selection. In particular the cuts $R_2 < 0.4$ and $N_{\mathrm{ch}} \geq 3$ are used to select hadronic events. Additionally the invariant mass of all tracks is required to be greater than 2.2 GeV/c^2.

The branching fraction of the $\Upsilon(3S)$ into $\mu^+\mu^-$ is $(1.81 \pm 0.17)\%$ [8], corresponding to a cross section of roughly 0.1 nb for resonant muon-pair production. Therefore the luminosity is determined from Bhabha events for the data points of the $\Upsilon(3S)$ scan. Figure 1 shows the data points and the result of a fit to these points.

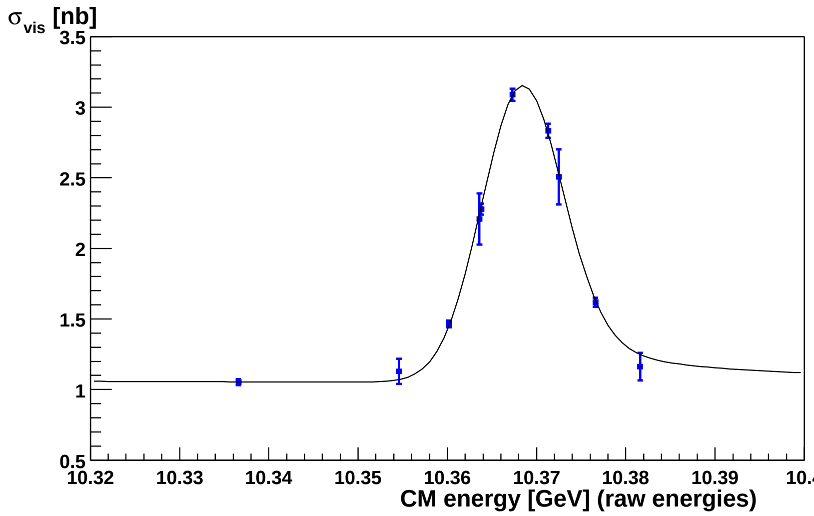

Figure 1: Data points and fit of the $\Upsilon(3S)$ resonance scan.

The Breit-Wigner function (1) of the true $\Upsilon(3S)$ resonance is approximated by a delta function, because the width of the $\Upsilon(3S)$, $\Gamma_{\mathrm{tot}}^{3\mathrm{S}} = (26.3 \pm 3.5)\,\mathrm{keV}$ [8], is very small compared to the energy spread of PEP-II of about 4.6 MeV. Hence the cross section including radiative corrections and averaging over the energy spread Δ is given by

$$\sigma(s) = \frac{6\pi^2}{M^2\Delta\sqrt{2\pi}} \frac{\Gamma_{ee}\Gamma_{\mathrm{had}}}{\Gamma_{\mathrm{tot}}} \beta \left(\frac{2\Delta}{\sqrt{s}}\right)^{\beta} \cdot \int_0^{\infty} x^{\beta-1} \exp\left(-\frac{(z-x)^2}{2}\right) \mathrm{d}x, \tag{6}$$

where $z = \frac{\sqrt{s}-M}{\Delta}$. This cross section is related to the visible cross section via equation (5).

The visible cross section of equation (5) is fitted to the data points. The free parameters of the fit are the energy spread Δ, the $\Upsilon(3S)$ mass M_{3S}^{fit}, the parameter P describing the background and the efficiency ε for selecting $\Upsilon(3S)$ decays. The ratio $\frac{\Gamma_{ee}\Gamma_{\mathrm{had}}}{\Gamma_{\mathrm{tot}}}$ is set to 0.45 keV [13]. The result of the fit including the statistical errors is shown in the first two rows of table 1.

Sources of systematic uncertainties to the fit results are potential fluctuations of the detector and trigger performance during the $\Upsilon(3S)$ scan and the precision ($\pm 0.2\,\mathrm{MeV}$) of the determination of the energy differences between the scan points. In total the systematic uncertainty is estimated to be 0.11 MeV and 0.14 MeV/c^2 for the energy spread and $\Upsilon(3S)$ mass, respectively.

A comparison of the fitted $\Upsilon(3S)$ mass $M_{3\mathrm{S}}^{\mathrm{fit}}$ with the world average of (10.3552 ± 0.0005) GeV/c^2 [14] provides a calibration of the product of PEP-II beam energies. The information obtained from the $\Upsilon(3S)$ scan that is essential for the measurement of the $\Upsilon(10580)$ parameters is shown in table 1.

Table 1: Energy spread Δ of PEP-II and $\Upsilon(3S)$ mass at the PEP-II energy scale obtained from a fit to the $\Upsilon(3S)$ scan data including their statistical errors. The value of the energy spread extrapolated to 10.58 GeV and the difference of the fitted $\Upsilon(3S)$ mass to the PDG value are shown as well. The statistical and systematic errors of the latter two quantities are added in quadrature.

Δ	(4.44 ± 0.09) MeV
M_{3S}^{fit}	(10.36798 ± 0.00009) GeV/c^2
Δ extrapolated to $\sqrt{s} = 10.58$ GeV	(4.63 ± 0.15) MeV
$M_{3S}^{\mathrm{PDG}} - M_{3S}^{\mathrm{fit}}$	(12.8 ± 0.5) MeV/c^2

The energy spread measured at the $\Upsilon(3S)$ is extrapolated to 10.58 GeV/c^2 by scaling the spread of the high energy beam with the square of its energy. An extrapolation of the spread of the low energy ring is not necessary, because its energy was always held constant. The extrapolation results in a spread of 4.63 MeV. The energy spread during two of the three $\Upsilon(10580)$ scans was 0.2 MeV larger due to a different magnet configuration of PEP-II.

4.2 Measurement of the peak cross section

The $b\bar{b}$ cross section at the peak of the $\Upsilon(10580)$ resonance is determined from the energy dependence of $\sigma_{b\bar{b}}$ measured from a high statistics data set. The cross section $\sigma_{b\bar{b}}$ is given by

$$\sigma_{b\bar{b}} = \frac{N_{\mathrm{had}} - N_{\mu\mu} \cdot R_{\mathrm{off}} \cdot r}{\varepsilon_{b\bar{b}} L}, \tag{7}$$

where $N_{\mu\mu}$ is the number of muon pairs, R_{off} the ratio of hadronic events to muon pairs below the resonance and $r \approx 1$ a factor estimated from Monte Carlo events to correct variations of cross sections and efficiencies with the CM energy.

A track multiplicity of $N_{\mathrm{ch}} \geq 3$ and a topology cut of $R_2 < 0.5$ is applied to select these hadronic events. Events from $\gamma\gamma$ interactions and beam-gas background are reduced by selecting only events with a total energy greater than 4.5 GeV. Beam-gas interactions are additionally reduced by requiring that the primary vertex of these events lies in the beam collision region. Figure 2 shows the cross section at several CM energies.

A fit of a 3rd order polynomial to the data results in a peak cross section of (1.101 ± 0.005) nb. The systematic error of the peak cross section is 2%, which is dominated by uncertainties of the efficiency $\varepsilon_{b\bar{b}}$ and the luminosity determination.

4.3 Fit of the $\Upsilon(10580)$ resonance

The $\Upsilon(10580)$ scan comprises three scans around the resonance mass. Hadronic events are selected by requiring $N_{\mathrm{ch}} \geq 4$ and $R_2 < 0.3$. The background from beam-gas and $\gamma\gamma$ interactions is reduced by the cut $E_{\mathrm{tot}} - |P_z| > 0.2\sqrt{s}$, where E_{tot} is the total CM energy calculated from all charged tracks and P_z is the component of the total momentum of all charged tracks along the beam axis. The data points, $(\sigma_i^{\mathrm{vis}}, \sqrt{s_i})$, are shown in figure 3.

The visible cross section of equation (5), with the $b\bar{b}$ cross section given by (4), is fitted to the data points. The CM energies of the $\Upsilon(10580)$ scans are corrected using the shift obtained from the $\Upsilon(3S)$ fit. The free parameters are the total width Γ_{tot}, the electronic width Γ_{ee}, the mass

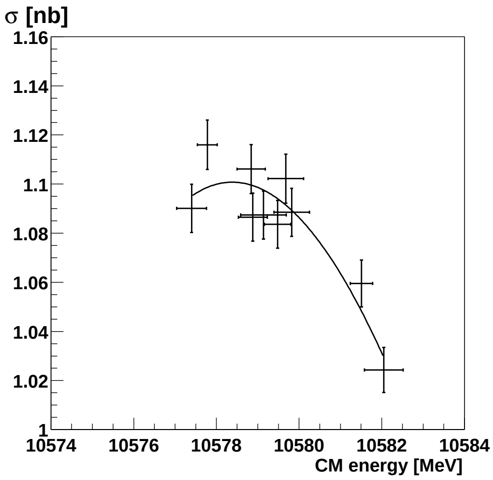

Figure 2: $\sigma_{b\bar{b}}$ vs. CM energy.

M of the $\Upsilon(10580)$, the background parameter P and the efficiency $\varepsilon_{b\bar{b}}$. The energy spread of the collider is fixed to 4.63 MeV. The result of the fit is shown in table 2. Alternatively the electronic branching fraction

$$B_{ee} = \frac{\Gamma_{ee}}{\Gamma_{\text{tot}}}$$

can be used as a free fit parameter instead of Γ_{ee} or Γ_{tot}. The fit results of these three quantities are highly correlated as can be seen from table 3. We therefore quote the results of all three parameters.

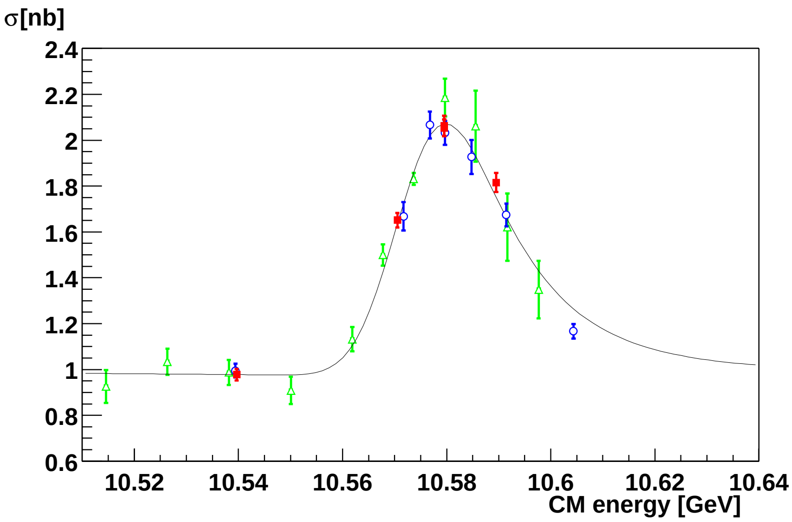

Figure 3: Data points and fit of the $\Upsilon(10580)$ resonance scan. Different symbols represent different scans. The small efficiency variations between the different scans are corrected.

Table 2: $\Upsilon(10580)$ resonance parameters and their statistical errors obtained from a fit to the scan data.

$\Gamma_{\rm tot}$	(20.7 ± 1.6) MeV
Γ_{ee}	(0.321 ± 0.017) keV
B_{ee}	$(1.55 \pm 0.04) \cdot 10^{-5}$
M	(10.5793 ± 0.0004) GeV/c^2
χ^2/DoF	18.3/14

Table 3: Correlation coefficients of the fit to the $\Upsilon(10580)$ scans. Any combination of two of the three parameters $\Gamma_{\rm tot}$, Γ_{ee} and B_{ee} can be used as free parameters in the fit.

	Γ_{ee}	B_{ee}	M
$\Gamma_{\rm tot}$	0.996	-0.980	0.206
Γ_{ee}		-0.961	0.186
B_{ee}			-0.226

5 Systematic studies

The systematic error induced by the assumptions in the quark pair creation model, e.g., neglecting interference effects with other spectroscopic states, is estimated by fitting a non relativistic Breit-Wigner function with a constant decay width $\Gamma_{\rm tot}$ to the scan data. Half of the deviation between the results of this fit and the fit using the QPCM is taken as an estimation of the systematic uncertainty due to the resonance parametrization. The systematic errors assigned to each parameter are listed in table 4.

A systematic bias on the fit results could be caused by detector instabilities or a incorrect energy measurement during a scan. This effect is estimated by excluding single data points from the fit. The maximum shift for each fit parameter is taken as a systematic error.

The $\Upsilon(3S)$ scan and the $\Upsilon(10580)$ scans were spread over a period of three years. A systematic error of 1.0 MeV is assigned to the mass measurement due to drifts in the beam energy determination between the $\Upsilon(10580)$ scans and the $\Upsilon(3S)$ scan that are not reflected in the beam energy corrections. Another contribution to the uncertainty of the mass measurement is caused by the precision of the $\Upsilon(3S)$ mass knowledge. The systematic error caused by the uncertainty of the energy spread of the collider is estimated by varying the energy spread used in the fit procedure for all three $\Upsilon(10580)$ scans by its uncertainty of ± 0.15 MeV. Long term fluctuation of the energy spread are taken into account by varying the energy spread of single scans in the fit by ± 0.1 MeV from its nominal value. The quadratic sum of both contributions is listed in table 4. In addition the systematic error due to the uncertainty of the peak cross section is included. The systematic uncertainties caused by potential energy dependences of the event selection efficiencies are found to be negligible.

Table 4: Summary of systematic uncertainties

	$\delta\Gamma_{\rm tot}$ [MeV]	$\delta\Gamma_{ee}$ [keV]	$\delta B_{ee}/10^{-5}$	δM [MeV/c^2]
model uncertainty	1.4	0.017	0.03	0.1
systematic bias by single data point	2.0	0.022	0.04	0.3
uncertainty of energy spread	0.4	0.0019	0.03	< 0.1
uncertainty of peak cross section	< 0.1	0.006	0.03	< 0.1
long term drift of energy scale	-	-	-	1.0
error on $M_{\Upsilon(3S)}$	-	-	-	0.5
total error	2.5	0.029	0.07	1.2

6 Results

In summary we have preliminarily measured the total decay width $\Gamma_{\rm tot}$, the partial decay width into electrons Γ_{ee} and the mass of the $\Upsilon(10580)$ resonance and find

$$\begin{aligned}
\Gamma_{\rm tot} &= (20.7 \pm 1.6 \pm 2.5)\,\mathrm{MeV}, \\
\Gamma_{ee} &= (0.321 \pm 0.017 \pm 0.029)\,\mathrm{keV}, \\
B_{ee} &= (1.55 \pm 0.04 \pm 0.07) \cdot 10^{-5}, \\
M &= (10.5793 \pm 0.0004 \pm 0.0012)\,\mathrm{GeV}/c^2.
\end{aligned}$$

The measurement of the total width and mass are an improvement in precision compared to the present world average.

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