Measurement of the e[superscript +]e[superscript -] -->bb# Cross Section between [sqrt s]=10.54 and 11.20 GeV

Measurement of the $e^+e^- \to b\bar{b}$ Cross Section between $\sqrt{s} = 10.54$ and 11.20 GeV

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We report $e^+e^- \to b\bar{b}$ cross section measurements by the *BABAR* experiment performed during an energy scan in the range of 10.54 to 11.20 GeV at the SLAC PEP-II e^+e^- collider. A total relative error of about 5% is reached in more than 300 center-of-mass energy steps, separated by about 5 MeV. These measurements can be used to derive precise information on the parameters of the $\Upsilon(10860)$ and $\Upsilon(11020)$ resonances. In particular we show that their widths may be smaller than previously measured.

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Recent discoveries of nonbaryonic charmonium states that do not behave as two-quark states [1] call for a search for other resonances belonging to this possible new spectroscopy. Given the charmonium content of these new states, one could infer the presence of similar resonances containing b quark pairs. The observed $J^{PC} = 1^{--}$ exotic states [$Y(4260)$, $Y(4350)$, and $Y(4660)$ [2]] scaled up by the mass difference between the J/ψ and the $\Upsilon(1S)$ ($\Delta M \sim 6360$ MeV$/c^2$) would be exotic bottomonium states with masses above the $\Upsilon(4S)$ and below 11.2 GeV. Moreover, the $\Upsilon(10860)$ and the $\Upsilon(11020)$ states, which are candidate $\Upsilon(5S)$ and $\Upsilon(6S)$, respectively, were observed in the same region [3,4].

Between March 28 and April 7, 2008 the SLAC PEP-II e^+e^- collider [5] delivered colliding beams at a center-of-mass energy ($\sqrt{s}$) in the range of 10.54 to 11.20 GeV. First, an energy scan over the whole range in 5 MeV steps, collecting approximately 25 pb^{-1} per step for a total of about 3.3 fb^{-1}, was performed. It was then followed by a 600 pb^{-1} scan in the range of $\sqrt{s} = 10.96$ to 11.10 GeV, in 8 steps with nonregular energy spacing, performed in order to investigate the $\Upsilon(6S)$ region. This data set outclasses the previous scans [3,4] by a factor >30 in the luminosity and ~ 4 in the size of the energy steps. Across the scan, the energy of the positron beam was kept fixed at 3.12 GeV, while the electron beam energy was varied accordingly, to set the required $\sqrt{s}$. This produced a variation of the boost of the center-of-mass frame during the scan.

In this Letter we present, for each step in $\sqrt{s}$, the measurement of $R_b(s) = \sigma_b(s)/\sigma^0_{\mu\mu}(s)$, where $\sigma^0_{\mu\mu} = 4\pi\alpha^2/3s$ is the lowest-order cross section for $e^+e^- \to \mu^+\mu^-$ and σ_b is the total cross section for $e^+e^- \to b\bar{b}(\gamma)$, including $b\bar{b}$ states produced in initial state radiation (ISR) below the open beauty threshold, i.e., the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ resonances.

The particles produced in the collisions are detected by the *BABAR* detector, described elsewhere [6]. Charged-particle tracking is provided by a five-layer silicon vertex tracker and a 40-layer drift chamber (DCH). In addition to providing precise position information for tracking, the silicon vertex tracker and DCH also measure the specific ionization (dE/dx), which is used for particle identification of low-momentum charged particles. At higher momenta ($p > 0.7$ GeV$/c$) pions and kaons are identified by Cherenkov radiation detected in a ring-imaging device (DIRC). The position and energy of neutral clusters (photons) are measured with an electromagnetic calorimeter consisting of 6580 thallium-doped CsI crystals. These systems are mounted inside a 1.5-T solenoidal superconducting magnet. Muon identification is provided by the magnetic flux return system instrumented with resistive plate chambers and limited streamer tubes. The full detector is simulated, for background and efficiency studies, with a Monte Carlo program (MC) based on GEANT4 [7].

To measure R_b, we count the number of events passing a selection that enriches the sample in events containing B mesons (N_h) and those passing an independent di-muon selection (N_μ) at each energy point and at a reference energy below the open beauty production threshold. Indicating with a prime the quantities at the reference energy, we write

$$N_h(s) = \Big\{[R_b(s)\sigma^0_{\mu\mu}(s) - \sigma_{\rm ISR}(s)]\epsilon_B(s) + \sum_X \sigma_X(s)\epsilon_X(s) + \sigma_{\rm ISR}(s)\epsilon_{\rm ISR}(s)\Big\}\mathcal{L}(s), \quad (1)$$

$$N'_h = \Big(\sum_X \sigma'_X\epsilon'_X + \sigma'_{\rm ISR}\epsilon'_{\rm ISR}\Big)\mathcal{L}', \quad (2)$$

$$N_\mu(s) = \sigma_{\mu\mu}(s)\epsilon_\mu(s)\mathcal{L}(s), \quad (3)$$

$$N'_\mu = \sigma'_{\mu\mu}\epsilon'_\mu\mathcal{L}', \quad (4)$$

where ϵ_B is the efficiency for open b production to satisfy the hadronic selection, X represents the different background components described later, σ_i represents the cross sections for the process i, ϵ_i the corresponding efficiency, and $\mathcal{L}$ is the integrated luminosity collected at a given value of $\sqrt{s}$. Measurements of N_μ and N'_μ are needed in order to normalize the hadronic rates to the collected luminosities. As reference we choose the sample collected at $\sqrt{s} = 10.54$ GeV, about 40 MeV below the $\Upsilon(4S)$ mass, taken during 2006–2007. Special mention is made of the ISR sample, the production of $\Upsilon(nS)$ ($n = 1, 2, 3$) mesons via initial state radiation: albeit part of the signal, this process can occur at the reference energy and has an efficiency and an energy dependence of the cross section different from the open beauty production.

Solving the system of equations one obtains

$$R_b = \left(\frac{N_h(s)}{N_\mu(s)} - \frac{N_h'}{N_\mu'}\kappa_{\sigma\epsilon}(s)\right)\frac{\epsilon_\mu(s)\xi_\mu}{\epsilon_B(s)} + R_{\rm ISR}(s), \quad (5)$$

where we defined

$$\kappa_{\sigma\epsilon}(s) = \frac{\epsilon_\mu'}{\epsilon_\mu(s)}\frac{\sum_X R_X(s)\epsilon_X(s) + R_{\rm ISR}(s)\epsilon_{\rm ISR}(s)}{\sum_X R_X'\epsilon_X' + R_{\rm ISR}'\epsilon_{\rm ISR}'}, \quad (6)$$

and $R_i = \sigma_i/\sigma^0_{\mu\mu}$ for each process and $\xi_\mu = \sigma_{\mu\mu}/\sigma^0_{\mu\mu}$, assumed independent of $\sqrt{s}$. It should be noted that these equations assume that the background scales with the integrated luminosity, i.e., that the machine background is negligible, and that the di-muon selection leaves a negligible level of background.

We select the b-enriched sample by requiring at least three tracks in the event, a total visible energy in the event greater than 4.5 GeV, and a vertex reconstructed from the observed charged tracks within 5 mm of the beam crossing point in the plane transverse to the beam axis and 6 cm along the beam axis. These quantities are computed using exclusively tracks in the fiducial volume of the DCH (i.e., forming an angle with the beam axis $0.41 < \theta < 2.54$ rad). A further rejection of the main backgrounds, $e^+e^- \to q\bar{q}$, $q = u, d, s, c$ events (“continuum” events), and $e^+e^- \to \ell^+\ell^-$, $\ell = e, \mu, \tau$ events, is obtained by means of a cut on the ratio of the second and zeroth Fox-Wolfram moments [8], R_2, calculated using only the charged tracks. After optimization of the statistical sensitivity, we require $R_2 < 0.2$. Events that pass this selection at the reference energy comprise 91% continuum, 2% two-photon ($e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-X_h$), and 7% ISR ($e^+e^- \to \Upsilon(nS)\gamma_{\rm ISR}$) events.

To select di-muon events, we require that two tracks have an invariant mass greater than 7.5 GeV/c^2; their angle with the beam axis in the center-of-mass frame, $\theta_{\rm c.m.s.}$, must satisfy $\cos\theta_{\rm c.m.s.} < 0.7485$, and the two muons must be collinear to within 10°. To exploit the fact that muons are minimum ionizing particles, we require that at least one of them leaves a signal in the electromagnetic calorimeter, and neither deposits more than 1 GeV.

In the following we describe the method used to derive the inputs to Eq. (5) and the corresponding errors, separating correlated and uncorrelated errors. The covariance matrix for the measurements of R_b at different energies is $V_{ij} = [\sigma^2_{\rm stat}(s_i) + \sigma^2_{\rm unc}(s_i)]\delta_{ij} + \sigma_{\rm corr}(s_i)\sigma_{\rm corr}(s_j)$, where $\sigma_{\rm stat}(s_i)$, $\sigma_{\rm corr}(s_i)$, and $\sigma_{\rm unc}(s_i)$ are the statistical, correlated, and uncorrelated systematic error, respectively, and δ_{ij} is the Kronecker delta.

The efficiency for the di-muon selection ϵ_μ is extracted from a sample of fully simulated MC events generated with KK2F [9] at several values of $\sqrt{s}$. Because of the change in boost this efficiency is found to change by 1.5% over the whole range, and the MC statistics error we assign to the corresponding correction is 0.2%. The correlated uncertainty on the absolute scale of the efficiency is estimated to be 1% and to come primarily from uncertainties in the simulation of the trigger, of the quantities used in the selection, and of the tracking efficiency. We also account for differences in the trigger configurations between the scan data and the reference data taken during the year 2007 and estimate the efficiency on the reference data to be lower by $(0.5 \pm 0.2)\%$. The same generator is consistently used to extract $\xi_\mu = 1.48 \pm 0.02$, where this correlated error is due to the uncertainty on the cross section.

The efficiency for $e^+e^- \to b\bar{b}$ events is estimated by using EVTGEN [10] as generator, separately for each possible two-body final state including B, B_s, and B_s^* mesons, and at different values of $\sqrt{s}$. Because we ignore the relative composition in terms of final states at each energy we consider the largest and the smallest efficiencies among the allowed final states and take their mean value as the central value and half their difference as uncorrelated error. The correlated error on the absolute scale of ϵ_B is estimated by varying the selection criteria and it is found to amount to 1.3%.

The calculation of the double ratio $\kappa_{\sigma\epsilon}$ requires the dependence on $\sqrt{s}$ of ϵ_μ, which has already been discussed, and the cross sections and efficiencies for the ISR and the background processes.

The ISR cross section is computed to second order according to Ref. [11]. The corresponding efficiency ($\epsilon_{\rm ISR}$) is estimated with MC simulation to be 41% on average. The relative efficiency change across the scan, estimated to be ~5%, is used as a correlated uncertainty and it propagates to an error on R_b of at most 0.7%.

The cross section for two-photon events scales as the square of the logarithm of s, and the corresponding efficiency is considered to be flat. The product of the cross section and the efficiency ($\sigma_{\gamma\gamma}\epsilon_{\gamma\gamma}$) before the R_2 is fitted from the distribution of the direction of the missing momentum and then multiplied by the R_2 cut efficiency. We attribute 50% uncertainty to this estimate, leading to a relative correlated error of at most 0.2%. Finally, the product of the continuum cross section and efficiency is computed by subtracting the ISR and two photon components from N_h' [see Eq. (2)]. The continuum contribution to R ($R_{\rm cont}$) is assumed to be constant with $\sqrt{s}$, while the corresponding efficiency ($\epsilon_{\rm cont}$) was estimated on a sample of MC events generated with JETSET [12]. No correction to account for the fact that the reference data were taken in a different data-taking period was found necessary. The relative change of $\epsilon_{\rm cont}$ over the whole scan range is estimated to be 3%, and a 0.2% systematic error due to MC statistics is assigned to it. We also find that the distribution of R_2 in continuum events is not perfectly reproduced by the MC simulations. We therefore estimate the scaling of $\epsilon_{\rm cont}$ separately with and without the $R_2 < 0.2$

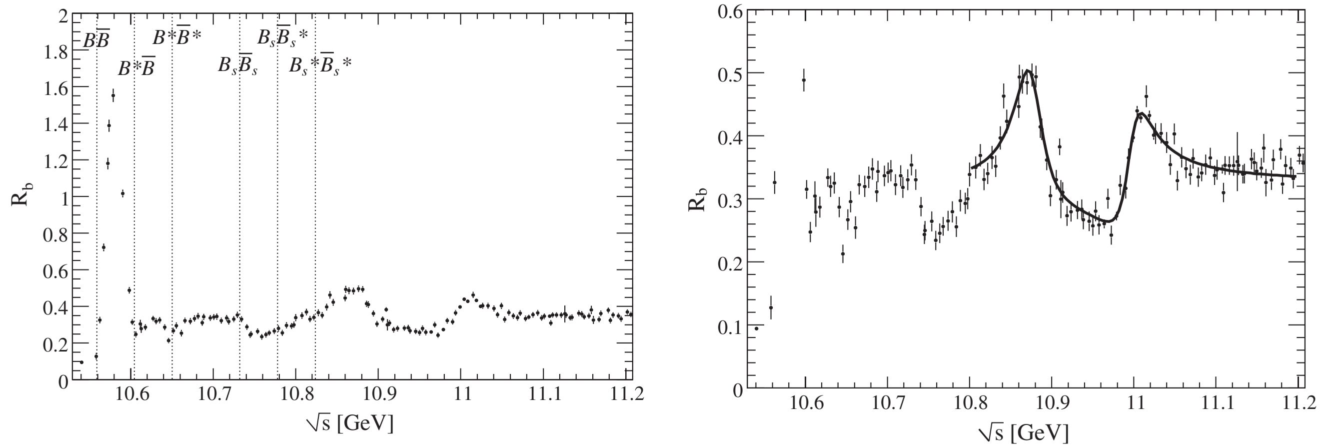

FIG. 1. Left: Measured R_b as a function of $\sqrt{s}$ with the position of the opening thresholds of the $e^+e^- \to B^{(*)}_{(s)}\bar{B}^{(*)}_{(s)}$ processes indicated by dotted lines. Right: A zoom of the same plot with the result of the fit described in the text superimposed. The errors on data represent the statistical and the uncorrelated systematic errors added in quadrature.

requirement and take the difference among the results as a correlated systematic error. Its contribution depends on the value of R_b, and it is at most 2%.

To measure $\sqrt{s}$ of each point we fit the distribution of the invariant mass of the two muons in the selected di-muon sample with a function made of a Gaussian with an exponential tail on the side below the peak mass. We then use the mean of the Gaussian as estimator of $\sqrt{s}$ and we determine a bias of (20.9 ± 1.5) MeV for this quantity by comparing the $\Upsilon(3S)$ mass measured on the data taken during the ~ 100 pb^{-1} scan performed by PEP-II at the beginning of the last data-taking period with the resonant depolarization result [13]. We correct for this bias, that comes from the (strongly) nonlinear impact of the momentum resolution in the invariant mass, and verify on simulated events that it does not depend on $\sqrt{s}$.

The resulting measurements of R_b as a function of $\sqrt{s}$ are shown in Fig. 1, where the error bars represent the sum of the statistical and uncorrelated systematic errors and dotted lines show the different B meson production thresholds. The relative correlated systematic errors on R_b are summarized in Table I. The numerical results for each energy point, together with the estimated ISR cross section, can be found in Ref. [14]. It is important to stress that radiative corrections have not been applied since they would require an *a priori* knowledge of the resonant region. The measured R_b therefore includes all final- or initial-state radiation processes.

The large statistics and the small energy steps of this scan make it possible to observe clear structures corresponding to the opening of new thresholds: dips corresponding to the $B^{(*)}B^*$ and $B_sB_s^*$ openings and a plateau close to the $B_s^*B_s^*$ one. It is also evident that the $\Upsilon(10860)$ and $\Upsilon(11020)$ behave differently above and below the corresponding peaks. Finally, the plateau above the $\Upsilon(11020)$ is clearly visible.

We fit the following simple model to our data between 10.80 and 11.20 GeV: a flat component representing $b\bar{b}$-continuum states not interfering with resonance decays, added incoherently to a second flat component interfering with two relativistic Breit-Wigner (BW) resonances, i.e., $\sigma = |A_{nr}|^2 + |A_r + A_{10860}e^{i\phi_{10860}}\mathrm{BW}(M_{10860}, \Gamma_{10860}) + A_{11020}e^{i\phi_{11020}}\mathrm{BW}(M_{11020}, \Gamma_{11020})|^2$, with $\mathrm{BW}(M, \Gamma) = 1/[(s - M^2) + iM\Gamma]$. The results summarized in Table II and Fig. 1 differ substantially from the PDG values [15]. In particular, the $B_s^*B_s$ and $B_s^*B_s^*$ thresholds have a very large impact on the determination of the $\Upsilon(10860)$ width.

TABLE I. Contributions to the relative correlated systematic error on R_b. The last three contributions depend on the energy point and only the largest value is reported.

Contribution	Relative error (%)
$\mu\mu$ MC statistics	0.2
$\mu\mu$ radiative corrections	1.4
ϵ_μ	1.3
ϵ_B	1.3
ϵ_{cont}	<2.0
ϵ_{ISR}	<0.7
$\sigma_{\gamma\gamma}\epsilon_{\gamma\gamma}$	<0.2

TABLE II. Fit results for the $\Upsilon(10860)$ and $\Upsilon(11020)$ resonances resulting from the fit described in the text. The ϕ phases are relative to the interfering continuum. The corresponding world averages [15] are also reported.

	$\Upsilon(10860)$	$\Upsilon(11020)$
Mass (GeV)	10.876 ± 0.002	10.996 ± 0.002
Width (MeV)	43 ± 4	37 ± 3
ϕ (rad)	2.11 ± 0.12	0.12 ± 0.07
PDG mass (GeV)	10.865 ± 0.008	11.019 ± 0.008
PDG width (MeV)	110 ± 13	79 ± 16

The number of states is, *a priori*, unknown as are their energy dependencies. Therefore, a proper coupled channel approach [16,17] including the effects of the various thresholds outlined earlier would be likely to modify the results obtained from our simple fit. As an illustration of the systematic uncertainties arising from the assumptions in our fit, a simple modification is to replace the flat non-resonant term by a threshold function at $\sqrt{s} = 2m_B$. This leads to a larger width (74 ± 4 MeV) and a lower mass ($10\,869 \pm 2$ MeV) for the $\Upsilon(10860)$.

In summary, we have performed an accurate measurement of R_b in fine grained center-of-mass energy steps and have shown that these measurements have the potential to yield information on the bottomonium spectrum and possible exotic extensions.

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