Measurement of the $b\bar{b}$ Cross Section in 800 GeV/c Proton-Silicon Interactions

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The cross section for $b\bar{b}$ production in 800 GeV/c pN interactions has been measured in Fermilab experiment E771 to be $43^{+27}_{-17}(\text{stat})^{+7}_{-7}(\text{syst})$ nb per nucleon from the observation of events in which both the b and the $\bar{b}$ decay semimuonically or a B decays into a J/ψ followed by $J/\psi \to \mu^+\mu^-$. [S0031-9007(98)07987-3]

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The measurement of the production cross sections of mesons containing beauty quarks by pions [1] and protons [2] at fixed target energies is important because the production mechanisms of heavy quarks in this energy range are sensitive to the quark and gluon distributions of the nucleons. Prediction of the $b\bar{b}$ cross section at these energies is a challenge for perturbative QCD [3]. Moreover, the presence of additional nucleons in the target nucleus causes nonperturbative QCD modifications of heavy quark production. Finally, the measurement of $b\bar{b}$ production cross sections in this energy range provides essential information for the design of future experiments [4]. The E771 spectrometer [5] was operated for one month of data taking in which events were collected where both the b and $\bar{b}$ decayed with the emission of a single muon ("semimuonic decay"), or where a $B \to J/\psi + X$ decay followed by $J/\psi \to \mu^+\mu^-$ took place. The 800 GeV/c $pN \to b\bar{b}$ cross section has been determined using these data.

The E771 target consisted of twelve 2 mm Si foils spaced by 4 mm. A 12 plane silicon microvertex detector ($5x$, $5y$ and two u, v planes oriented at $\pm 45°$ with respect to the horizontal) was positioned downstream of the target for measurement of primary and secondary vertices. Additional x and y silicon planes were placed upstream of the target to count the incoming protons and measure their trajectories. A multiwire proportional and drift chamber system and a dipole analysis magnet, which imparted a transverse momentum kick of 0.821 GeV/c, were used to determine charged particle trajectories and momenta. The remaining element of the spectrometer required for this experiment was a muon detector that consisted of three planes of resistive plate counters (RPC's) [6] imbedded in a steel and concrete shield. The muon shield presented 6 GeV (10 GeV in the region near the beam) of energy loss for incident muons. The spectrometer had acceptance for muons from the direct decay of B mesons with $-0.25 \leq x_F \leq 0.50$.

An integrated luminosity of $(1.48 \pm 0.04) \times 10^{36}$ cm^{-2}, corresponding to $(1.23 \pm 0.03) \times 10^{13}$ protons on target, was accumulated during data taking.

The average proton beam intensity was approximately 3.5×10^7 protons per second during a 23 sec spill and the average interaction rate was approximately 1.9 MHz. A dimuon trigger [7] in which a muon was identified as a triple coincidence of pad signals in the three RPC planes was used to collect the data. The dimuon trigger rate was 240 Hz, due mostly to $\pi/K \rightarrow \mu$ decays. Approximately 1.27×10^8 dimuon triggers were recorded during the run.

Events containing $B \rightarrow J/\psi + X \rightarrow \mu\mu$ have been searched for in the $J/\psi \rightarrow \mu^+\mu^-$ data sample. The $b\bar{b} \rightarrow \mu\mu$ double semimuonic decays have been looked for in the events containing continuum muon pairs. Since the largest beauty statistics were obtained using the $b\bar{b} \rightarrow \mu\mu$ decays in the continuum dimuon events, the analysis of these data is discussed in detail below.

Two methods have been used to determine the $b\bar{b}$ cross section using $b\bar{b} \rightarrow \mu\mu$ decays. Method I used a set of physics cuts to isolate a sample of candidate $b\bar{b} \rightarrow \mu\mu$ double semimuonic decay events and minimize other dimuon backgrounds. The backgrounds to the $b\bar{b} \rightarrow \mu\mu$ sample were estimated from Monte Carlo and data studies. The sequence of cuts imposed on the 1.27×10^8 dimuon triggers to isolate the $b\bar{b} \rightarrow \mu\mu$ decays are given in Table I together with numbers of events surviving at each stage. As a final step, physicists visually inspected all surviving events using a computer generated event display which showed hits in the vertex dectector as well as the reconstructed tracks. One same sign and five opposite sign dimuon events survived these requirements. The rationale for the muon p_t, and impact parameter cuts was to eliminate $\pi/K \rightarrow \mu$ and to reduce the charm $\rightarrow \mu$ backgrounds. The $M_{\mu\mu}$ mass cut was made to eliminate the $J/\psi \rightarrow \mu^+\mu^-$ background to the opposite sign $b\bar{b} \rightarrow \mu\mu$ decays. The visual inspection by a physicist was necessary to eliminate events in which an interaction of a secondary or the interaction of a second beam track confused the reconstruction of a primary vertex.

TABLE I. Method I muon criteria for $b\bar{b} \rightarrow \mu\mu$ double semimuonic decays.

Requirement/cut	No. of events
1. Muon track candidate reconstruction with leading muon $p_t \geq 1.5$ GeV/c, $M_{\mu\mu} \geq 1.0$ GeV/c^2.	4.3×10^6
2. Full track reconstruction with very tight track quality criteria plus primary vertex with $\chi^2_{\text{vert}} \leq 30$ within $3\sigma_z$ of a Si target foil.	3.0×10^5
3. Leading muon momentum ≥ 15 GeV/c, $M_{\mu\mu} \geq 2.0$ GeV/c^2.	2.0×10^4
4. Leading muon impact parameter (ip) $\sqrt{d_x^2 + d_y^2} \geq 10\sigma_{\text{ip}}$.	421
5. Leading muon hit multiplicity requirement on spectrometer and vertex detectors.	96
6. $M_{\mu\mu} \leq 2.9$ GeV/c^2 or $M_{\mu\mu} \geq 3.3$ GeV/c^2.	69
7. Second muon $p_t \geq 1.0$ GeV/c.	20
8. Leading muon x impact parameters $\geq 3\sigma_{\text{xip}}$	8
9. Require primary vertex to pass a visual inspection by physicist.	6

The acceptances and efficiencies for trigger, reconstruction, and the physics cuts for the final set of $b\bar{b} \rightarrow \mu\mu$ candidates were determined using PYTHIA [8], the Lund Monte Carlo generator for hadronic processes. The $b\bar{b} \rightarrow \mu\mu$ events (including neutral B mixing) were generated with default PYTHIA branching ratios and passed through a GEANT [9] simulation of the E771 spectrometer and the dimuon trigger, which included wire chamber and microvertex plane measured efficiencies. The muon hits from these simulated decays were then overlaid with actual dimuon triggers in which the hits belonging to the reconstructed muon track candidates had been removed. These "overlaid" events were subjected to the same reconstruction process and physics cuts that were applied to the dimuon data. The branching ratio times acceptance times efficiency for $b\bar{b} \rightarrow \mu\mu$ events passing through this process was 2.74×10^{-6}.

The backgrounds to the six candidate $b\bar{b}$ events come from three sources: (1) Charm events in which both charm hadrons decay semimuonically, (2) oppositely charged dimuons from Drell-Yan production, or (3) mismeasured $J/\psi \rightarrow \mu^+\mu^-$ decays. To determine the level of the charm background, PYTHIA was used to generate 3.3×10^8 events in which both D's were required to decay semimuonically. These events were subjected to the same procedure as the double semimuonic B decays described above. Using the number of double semimuonic charm decays surviving the full procedure, a $D\overline{D}$ inclusive cross section of 38 μb [10] and the integrated luminosity, the charm background to the six B candidates was estimated to be 0.95 ± 0.26 events.

The Drell-Yan dimuon background events were generated with the double differential distribution $m^3 d^2\sigma/dx_F dm$ measured in 800 GeV/c pN interactions [11], then passed through a GEANT simulation of the spectrometer, which included wire chamber efficiencies, and finally inserted into real dimuon events. The resulting events were subjected to trigger, reconstruction, and physics cuts as discussed above. After this process, a Drell-Yan background of 0.15 ± 0.20 dimuons remained to the six B double semimuonic decay candidates.

The background due to mismeasured $J/\psi \rightarrow \mu^+\mu^-$ decays was estimated by using fits to the J/ψ peak in the mass region $2.90 < M_{\mu\mu} < 3.3$ GeV/c^2 to determine the leakage out of the region into the adjacent mass bins. The fraction of the J/ψ events falling outside the mass cut and contaminating the opposite sign $b\bar{b} \rightarrow \mu\mu$ sample is estimated in this way to be $(4 \pm 1) \times 10^{-3}$. Applying the double semimuonic decay cuts to $J/\psi \rightarrow \mu^+\mu^-$ data and using the "spillage" fraction, 0.11 ± 0.03 opposite sign background events are estimated to be due to mismeasured $J/\psi \rightarrow \mu^+\mu^-$.

All background events in the three categories that survived the $b\bar{b} \rightarrow \mu\mu$ selection procedure were subjected to the same inspection by physicists that was applied to the data. All background events survived the inspection. The final result of this procedure was an estimated background of 1.21 ± 0.33 events from all sources to the double B semimuonic event sample. After the subtraction of this estimated background, a cross section per nucleon of $\sigma(pN \rightarrow b\bar{b}) = 42^{+31}_{-21}$ nb has been obtained for $b\bar{b}$ production in 800 GeV/c pN interactions, assuming an atomic weight dependence of A^1.

Method I does not allow for the ambiguities that arise between background events and $b\bar{b} \rightarrow \mu\mu$ candidate events selected by a given set of cuts. No matter how selective the cuts are, some features of the selected events overlap the background. In addition, the severity of the cuts that must be imposed lowers the statistical significance of the data. For these two reasons, a second method has been employed to extract the beauty cross section. In method II a likelihood fit has been performed using a likelihood function which depends on the muon kinematic distributions for B and charm semimuonic decays and Drell-Yan process muons generated using PYTHIA. This likelihood function for a sample of N events can be written as

$$L(b,c,d,o) = \left[\frac{(b+c+d+o)^N e^{-(b+c+d+o)}}{N!}\right] \times \left[\prod_{i=1}^{N}\left(\frac{bP_b + cP_c + dP_d + oP_o}{b+c+d+o}\right)\right],$$

where b is the number of the $b\bar{b} \rightarrow \mu\mu$ events in this sample, and c, d, and o refer, respectively, to the number of charm, Drell-Yan, and "other" backgrounds (mainly residual $\pi/K \rightarrow \mu$ decays). The other background distributions were determined from the same sign dimuon events in the data. The first factor in $L(b,c,d,o)$ incorporates the fluctuations due to Poisson statistics of various components and describes the probability of getting N events in general. The second factor is the product of probability functions, P_i, describing the expected distributions of the B decays and the backgrounds in dimuon mass, dimuon opening angle, the p_t and p_z of the leading muon, and the x and y impact parameters of both muons. The P_i distributions of the B decays and charm and Drell-Yan backgrounds have been generated using the same techniques as were used in determination of the efficiencies of method I as described above, i.e., all Monte Carlo events were subjected to the dimuon acceptances and trigger requirements, inserted into real dimuon triggers, required to undergo the track reconstruction process, and, finally, required to pass some of the same physics cuts as were used in method I. The likelihood technique has been successfully tested by generating events according to the probability distributions P with a wide range of b, c, d, and o parameters and then subsequently analyzing them using $L(b,c,d,o)$. The technique has also been tested by inserting a known number of B events into a sample of the dimuon triggers.

$L(b,c,d,o)$ has been maximized as a function of b, c, d, and o for a sample of 158 opposite sign dimuon events selected to be enriched in $b\bar{b} \rightarrow \mu\mu$. The cuts that were used to select the 158 event sample were the same as requirements 1–4 and 6 of Table I except that the second muon was also subjected to the impact parameter cut of requirement 4, in order to make the muon criteria similar for both muons. Figure 1 shows the variation of $L(b,c,d,o)$ as a function of $b\bar{b}$ cross section (as derived from b, the number of $b\bar{b} \rightarrow \mu\mu$ events in the data sample from the likelihood fit) when c, d, and o are set to the values that maximize L at a given b. At the point of maximum likelihood, b, c, d, and o equal approximately 15, 26, 0.28, and 117 events, respectively, resulting in a $b\bar{b}$ cross section of 45^{+27}_{-19}(stat), consistent with the result of method I. Figure 1 also shows the result of a similar likelihood study of $B \rightarrow J/\psi \rightarrow \mu^+\mu^-$ where the data set was chosen to select the $B \rightarrow J/\psi \rightarrow \mu^+\mu^-$ decays. Since the analysis of the $B \rightarrow J/\psi \rightarrow \mu^+\mu^-$ mode yielded substantially fewer B events than the double semimuonic analysis, the $B \rightarrow J/\psi$ likelihood distribution is considerably broader than the $b\bar{b} \rightarrow \mu\mu$ distribution as shown in Fig. 1. The two independent likelihoods have been combined in a single likelihood fit. This resulted in a $b\bar{b}$ cross section of 43^{+27}_{-17}(stat) nb.

The systematic error in the $b\bar{b}$ cross section arises from the uncertainties in beam flux, in acceptances due to different B and D production models, in the $b \rightarrow \mu$ branching ratio, and in microvertex detector efficiencies, all of which apply equally to methods I and II. In addition, since method I depends on the subtraction of background, the error in the D cross section and in the $D \rightarrow \mu$ branching ratio will contribute an additional error to method I. Since method II depends on the shapes of the Monte Carlo distributions which are model dependent, an extra systematic error in method II is due to the uncertainty in these distributions. Various studies give

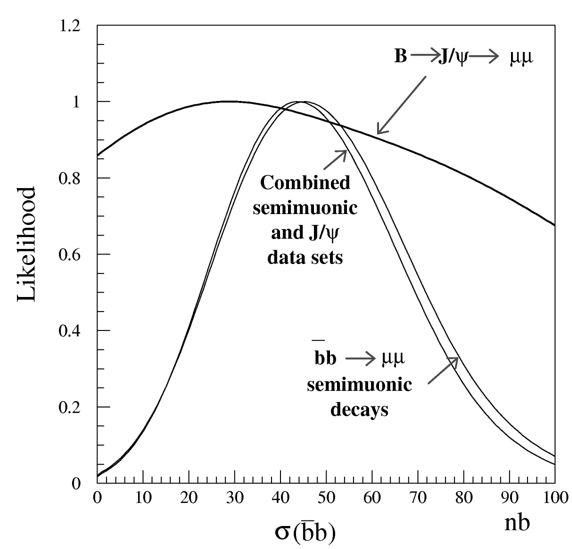

FIG. 1. Likelihood fits for the $b\bar{b}$ cross section using $b\bar{b} \rightarrow \mu\mu$ double semimuonic and $B \rightarrow J/\psi \rightarrow \mu^+\mu^-$ candidate events.

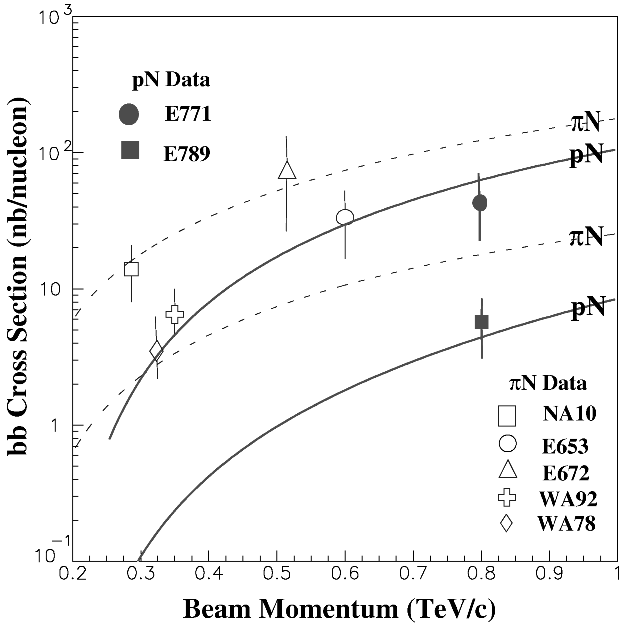

FIG. 2. The $b\bar{b}$ cross section from the E771 $b\bar{b} \rightarrow \mu\mu$ double semimuonic decay and $b \rightarrow J/\psi$ data as compared to other experiments and to the latest QCD calculations by Nason *et al.* [12]. The dashed (solid) curves represent the theoretical uncertainty in $\pi N(pN)$ $b\bar{b}$ cross section due to the uncertainty in α_s.

the following systematic errors in the $b\bar{b}$ cross section: (1) 10% geometric and trigger acceptance uncertainties due to production model uncertainties, (2) 5% due to beam flux uncertainty, (3) 9% due to microvertex detector efficiency error, (4) 7% due to uncertainty in the overall acceptance times efficiency for $b\bar{b} \rightarrow \mu\mu$, and (5) 7% due to the uncertainty in the $b \rightarrow \mu$ branching ratio. The extra systematic error in method I due to the combination of a 25% uncertainty in the charm cross section and a 30% uncertainty in the $B(D \rightarrow \mu)$ is 5.7%. The extra systematic error in method II due to variations in the shapes of the Monte Carlo distributions is 7.7%. Combining all systematic errors, an overall systematic uncertainty of 18%(19%) is obtained for the $b\bar{b}$ cross section result for methods I(II).

In conclusion, we have determined the cross section for $b\bar{b}$ production in 800 GeV/c pN interactions by two quite different methods which give consistent answers. Our final result is $\sigma(pN \rightarrow b\bar{b}) = 42^{+31}_{-21}(\text{stat})^{+7}_{-7}(\text{syst})$ for method I and $43^{+27}_{-17}(\text{stat})^{+7}_{-7}(\text{syst})$ for method II. Figure 2 shows the E771 800 GeV/c $pN \rightarrow b\bar{b}$ cross section for the method II likelihood approach together with the other measurements of πN and pN $b\bar{b}$ cross sections at similar energies. We also show in Fig. 2 the most recent next-to-leading-order QCD calculations [12] where the variations of the predictions for pN and πN cross sections are due to the uncertainty in α_s. We find the 800 GeV/c $pN \rightarrow b\bar{b}$ cross section obtained using pSi interactions differs by 2.3 σ from the 800 GeV/c $pN \rightarrow b\bar{b}$ cross section [2] obtained using pAu data.

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[1] M. Adamovich *et al.*, Nucl. Phys. **B519**, 19 (1998); R. Jesik *et al.*, Phys. Rev. Lett. **74**, 495 (1995); K. Kodama *et al.*, Phys. Lett. B **303**, 359 (1993); M. Catanesi *et al.*, Phys. Lett. B **231**, 328 (1989); P. Bordalo *et al.*, Z. Phys. C **39**, 7 (1988).
[2] D. M. Jansen *et al.*, Phys. Rev. Lett. **74**, 3118 (1995).
[3] S. Frixione *et al.*, Nucl. Phys. **B431**, 453 (1994); M. L. Mangano *et al.*, Nucl. Phys. **B373**, 295 (1992); **B405**, 507 (1993); P. Nason *et al.*, Nucl. Phys. **B303**, 607 (1988); **B327**, 49(E) (1989); **B335**, 260 (1990); E. L. Berger, Phys. Rev. D **37**, 1810 (1988).
[4] HERA-B Technical Design Report No. DESY-PRC 95/01; HERA-B Proposal No. DESY-PRC 94/02.
[5] T. Alexopoulos *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **376**, 375 (1996).
[6] L. Antoniazzi *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **315**, 92 (1992); G. Cataldi *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **337**, 350 (1993)
[7] L. Antoniazzi *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **360**, 334 (1995); L. Antoniazzi *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **355**, 320 (1995).
[8] T. Sjöstrand, CERN-TH 6488/92 (1992); Particle Data Group, K. Hikasa *et al.*, Phys. Rev. D **45**, 51 (1992).
[9] R. Brun *et al.*, Int. J. Phys. A **3**, 731 (1988).
[10] K. Kodama *et al.*, Phys. Lett. B **263**, 573 (1991); S. Frixione *et al.*, Nucl. Phys. **B431**, 453 (1994).
[11] P. McGaughey *et al.*, Phys. Rev. D **50**, 3038 (1994).
[12] P. Nason *et al.*, CERN-TH/97-16, hep-ph/9702287, in *Heavy Flavors II*, edited by A. J. Buras and M. Lindner, Advanced Series on Directions in High Energy Physics (World Scientific, Singapore, to be published).