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A 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 $42^{+16}_{-13}(stat)^{+7}_{-7}(syst)$ 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 $\psi \rightarrow \mu\mu$.

13.85. Ni, 13.85. Qk, 13.20. He, 25.40. Ve

B production by pions [1] and protons [2] at Fermilab fixed target energies is interesting both because of insights into the production mechanisms of heavy quarks that can be gained and because B cross sections in this energy range are essential information for the design of future experiments [3]. The E771 spectrometer [4] has been operated in a short run to obtain events in which both B hadrons decayed semimuonically or where a $B \rightarrow J/\psi$+X decay followed by $J/\psi \rightarrow \mu^+\mu^-$ took place. The 800 GeV/c pN$\rightarrow b\bar{b}$ 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 degrees with respect to the horizonal) 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 the E771 dipole analysis magnet (Δp_t=0.821 GeV/c) determined trajectories and momenta. The remaining elements of the E771 spectrometer included a scintillating/Pb glass electromagnetic calorimeter [5] and a muon detector consisting of three planes of scintillation counters and RPC's [6] interspersed between three steel and concrete walls. The muon shield presented 6 GeV/c (10 GeV/c in the central region) of dE/dx to incident μ's.

An integrated luminosity of $(1.48\pm0.04)\times10^{36}$ cm^{-2}, corresponding to $(1.23\pm0.03)\times10^{13}$ protons, was accumulated during the E771 data taking. The average proton beam intensity was approximately 3×10^7 protons per 23 second spill and the average interaction rate was approximately 1.9 MHz. A diμ trigger [7] in which a μ was identified as a triple coincidence of pad signals in the three RPC planes was used to accumulate the data. The diμ trigger rate was 240 Hz, mostly due to π/K$\rightarrow \mu$ decays. Approximately 1.27×10^8 diμ triggers were recorded during the run.

Fig. 1 shows the J/ψ, ψ' and Υ signals in the diμ data. The $J/\psi \rightarrow \mu^+\mu^-$ events and the continuum μ pairs have been used to search for $B \rightarrow J/\psi$+X and double $B \rightarrow \mu$+X decay events. Since the B statistics are largest in the double $B \rightarrow \mu$+X analysis, this analysis is discussed in more detail below. The same general strategies used to analyze the double $B \rightarrow \mu$+X have been used in the $B \rightarrow J/\psi$+X analysis.

Two methods have been used to determine the B cross section using B double semimuonic decays. Method I used a set of physics cuts to isolate a sample of candidate B double semimuonic decay events and minimize other diμ backgrounds. The backgrounds to this B sample were estimated from Monte Carlo and data studies. The cuts imposed on the 1.27×10^8 diμ triggers to isolate the double semimuonic decays and to reduce backgrounds included 1) both μ's have 4 of 5 possible hits in both the x and y silicon planes, 2) both μ momenta be $\geq$ 15 GeV/c, 3) the diμ mass be 2.0<$M_{\mu\mu}$<2.9 GeV/c^2 or $M_{\mu\mu}$>3.3 GeV/c^2, 4) the p_t of leading and non-leading μ's be $\geq$1.5 and 1.0 GeV/c respectively, 5) the primary vertex have a good χ^2 and be within $3\sigma_z$ of one of Si target foils, and 6) the μ impact parameters in the x (bend plane) and y projections be $\geq 10\sigma$ and 3σ respectively. One same-sign and seven opposite-sign diμ events survived reconstruction and these cuts. Independent visual inspections of each of the surviving diμ events rejected two of the opposite-sign events because of bad primary vertices due to secondary interactions.

The acceptances and efficiencies for trigger, reconstruction, and the physics cuts for the final set of B candidates were determined using PYTHIA [8] $b\bar{b} \rightarrow \mu\mu$ events generated with default PYTHIA branching ratios and passed through a GEANT [9] simulation of the E771 spectrometer and the diμ trigger. Measured wire chamber and silicon plane efficiencies applied to each hit of the Monte Carlo μ's that survived. The muon hits were then overlaid with actual diμ triggers in which the real muon hits had been removed. These "overlaid" events were subjected to the same reconstruction process and physics cuts that were applied to the diμ 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} with an estimated 10% error.

The backgrounds to the six candidate B's come from three sources; 1) charm events in which both charm hadrons decay semimuonically, 2) oppositely charged diμ's from Drell-Yan production or 3) mismeasured $J/\psi \rightarrow \mu^+\mu^-$ decays. To determine the level of the charm background, we used PYTHIA 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 surviving double semimuonic decays from the sample of 5×10^6 events, a $D\overline{D}$ inclusive cross section of 38μb [10] and our integrated luminosity, the charm background to the six B candidates was estimated to be 0.95$\pm$0.26 events.

The Drell-Yan diμ background was generated with the double differential distribution $m^3\ d\sigma/dx_F dm$ measured in 800 GeV/c pN interactions [11]. Chamber efficiencies were applied to the diμ tracks, and the diμ's were inserted into real diμ triggers and subjected to trigger, reconstruction and physics cuts as discussed above. After this process, a Drell-Yan background of 0.15$\pm$0.20 diμ's remained to the six B double semimuonic decay candidates.

The background due to mismeasured $J/\psi \rightarrow \mu\mu$ decays has been 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 B sample is estimated in this way to be $(4\pm1)\times10^{-3}$. Applying the double semimuonic decay cuts to $J/\psi \rightarrow \mu\mu$ data and using the "spillage" fraction, 0.11$\pm$0.03 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 selection procedure were subjected to the same visual inspection rules that were applied to the data. All background events survived the inspection. The final result of this procedure was an estimated background of 1.21$\pm$0.33 events from all sources to the double B semimuonic event sample. After the subtraction of this estimated background, a cross section, $\sigma(\mathrm{pN}\rightarrow b\bar{b}) = 42^{+31}_{-21}$ nb has been obtained for 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 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 likelihood function which depends on the μ kinematic variables has been constructed for B, charm and Drell-Yan μ's generated using PYTHIA. This likelihood function for a sample of N events can be written as

$$L(s,c,d,b) = [\frac{(s+c+d+b)^N e^{-(s+c+d+b)}}{N!}] \bullet [\prod_{i=1}^{N} (\frac{sP_s + cP_c + dP_d + bP_b}{s+c+d+b})] \tag{1}$$

where s is the average number of the B events in this sample, and c, d and b refer respectively to the number of charm, Drell-Yan, and general $\pi/K \rightarrow \mu$ decay background events. The $\pi/K \rightarrow \mu$ decay background distributions are determined from the same sign diμ events in the data sample. The first factor in $L(s,c,d,b)$ incorporates the fluctuations due to Poisson statistics of various components and describes the probability to get 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 diμ mass, diμ opening angle, the p_t and p_z of the leading μ, and the x and y impact parameters of both muons. The P_i distributions of the B decays and backgrounds have been generated using PYTHIA by employing the same techniques as those used in determination of the efficiencies of Method I as described above, i.e. all Monte Carlo events were subjected to the diμ acceptances and trigger requirements, overlaid on on real diμ triggers and 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 s,c,d and b parameters and then subsequently analysing them using *L(s,c,d,b)*. The technique has also been tested by inserting a known number of B events into a sample of the diμ triggers.

L(s,c,d,b) has been maximized as a function of s,c,d and b for a sample of 158 opposite sign diμ events selected to be enriched in $B \to \mu \times B \to \mu$. Fig. 2 shows the variation of *L(s,c,d,b)* as a function of s (converted into the $b\bar{b}$ cross section) when c, d and b are set to their values that maximize L at a given s. At the point of maximum likelihood, s, c, d and b equal approximately 15, 26, 0.28 and 117 events respectively. Fig. 2 also shows the result of a similar likelihood study of $B \to J/\psi$. Since the analysis of the $B \to J/\psi$ mode contained substantially fewer B events than the double semimuonic analysis, the $B \to J/\psi$ peak is broader as shown. As shown in Fig. 2, the two independent likelihoods have been combined into a single likelihood. This resulted in a $b\bar{b}$ cross section of $43^{+27}_{-17}(stat.)$ nb, consistent with the Method I result.

The systematic error in the B cross section arises from the uncertainties in beam flux, in acceptances due to different B and D production models, in the $B \to \mu$ branching ratio, and in silicon efficiency, 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 $D \to \mu$ branching ratio will contribute an additional error to Method I. Studies of each of these give the following systematic errors in the 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 silicon efficiency error, 4) 7% due to uncertainty in the overall acceptance times efficiency for $b\bar{b} \to \mu\mu$ and 5) 7% due to the uncertainty in the $B \to \mu$ branching ratio. As stated above, there is an additional systematic error in the Method I result of 5.7% due to the combination of a 25% uncertainty in the charm cross section and a 30% uncertainty in the BR($D \to \mu$). Combining the errors, an overall systematic uncertainty of 18%(17%) is obtained for the B cross section result for Methods I(II).

In conclusion, we have determined the cross section for B production in 800 GeV/c pN interactions by two different methods which give consistent answers. In order to make the two analyses as independent as possible so we can combine their results, we have excluded the six candidate $B \to \mu \times B \to \mu$ events found using Method I from the data sample and repeated the likelihood analysis. While one might expect the exclusion of the six events found in Method I to result in a lower cross section, the events determined to have the highest likelihood in Method II are not the same as those selected by the set of Method I cuts. Thus, the result obtained from Method II was not affected significantly by the exclusion of the six events found by Method I. We have averaged the likelihood result obtained from the smaller data sample with the Method I result suitably weighted with errors. Our final result is $\sigma(\mathrm{pN} \to b\bar{b}) = 42^{+20}_{-13}(stat.)^{+7}_{-7}(syst.)$. Fig. 3 shows the E771 800 GeV/c pN$\to b\bar{b}$ cross section and other πN and pN $b\bar{b}$ cross sections at similar energies compared to NLO QCD calculations [12]. The E771 pN$\to b\bar{b}$ cross section from pSi interactions is larger by 2.4σ than the 800 GeV/c $b\bar{b}$ cross section obtained in a smaller acceptance experiment [2] using pAu data.

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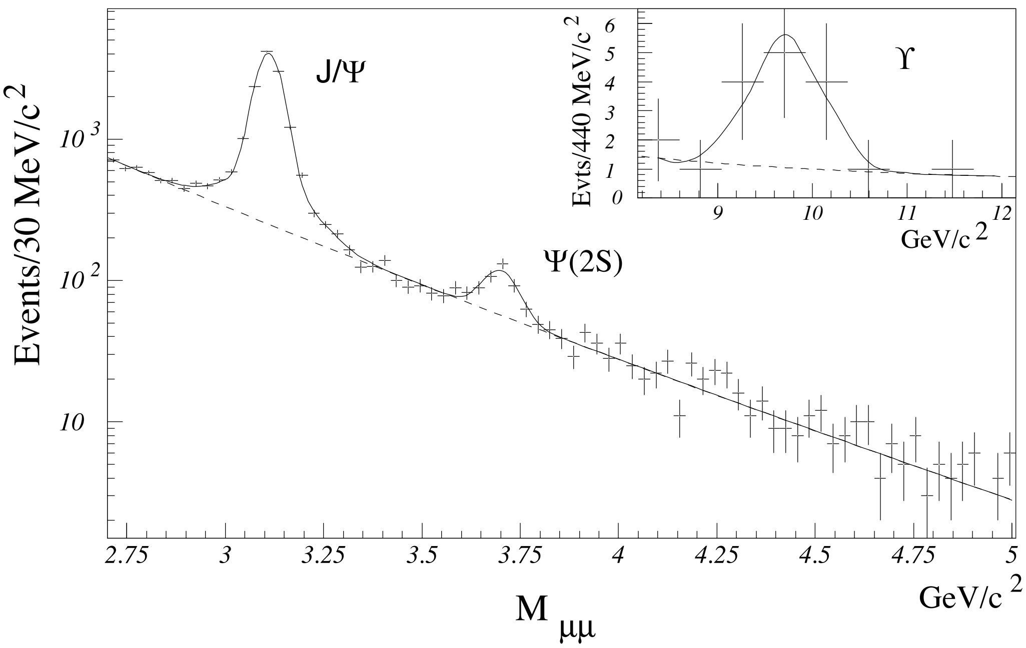

FIG. 1. E771 diμ mass distribution

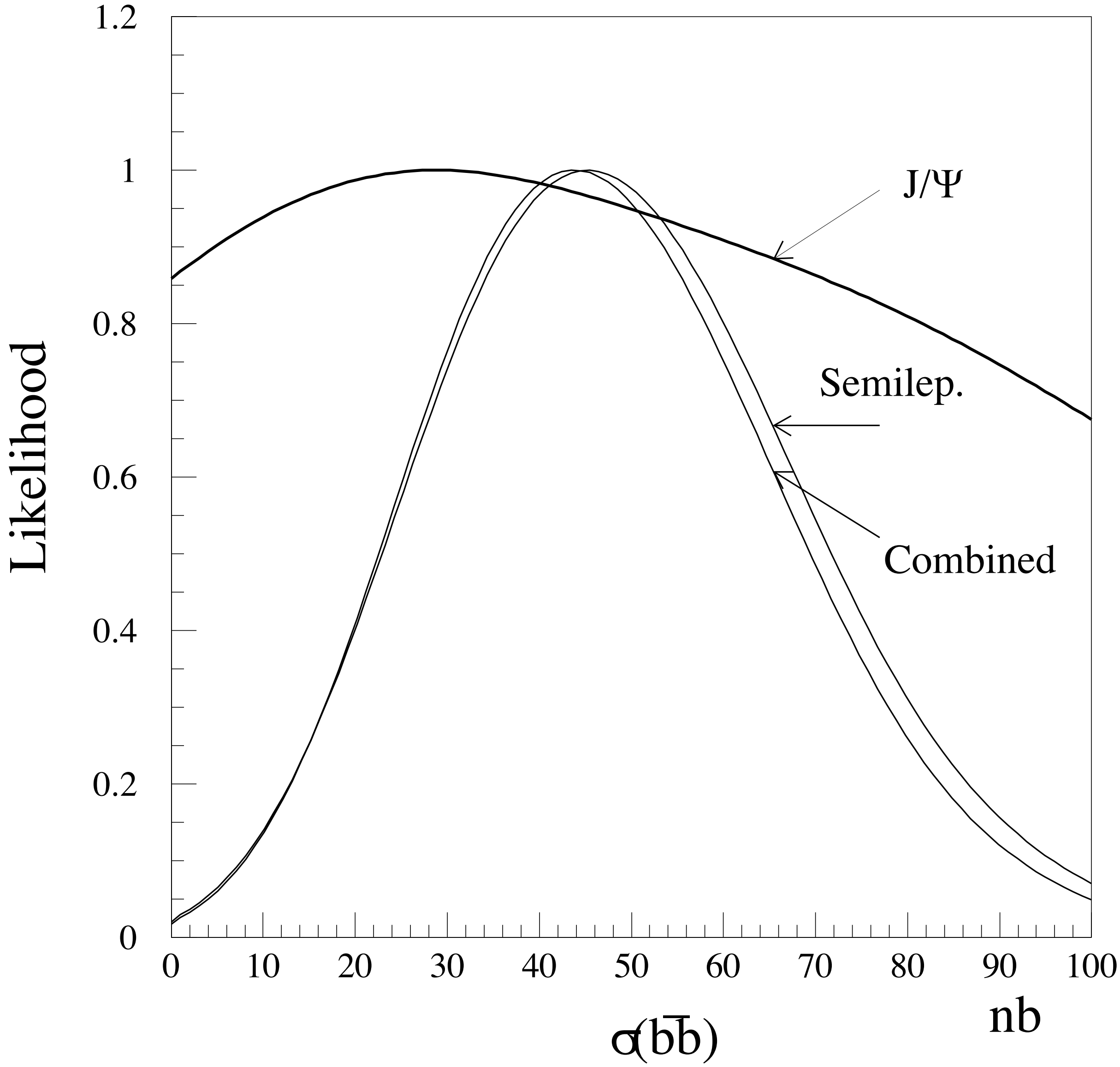

FIG. 2. Likelihood distributions for B cross Sections from $B \rightarrow \mu \times B \rightarrow \mu$ and $B \rightarrow J/\psi$ data.

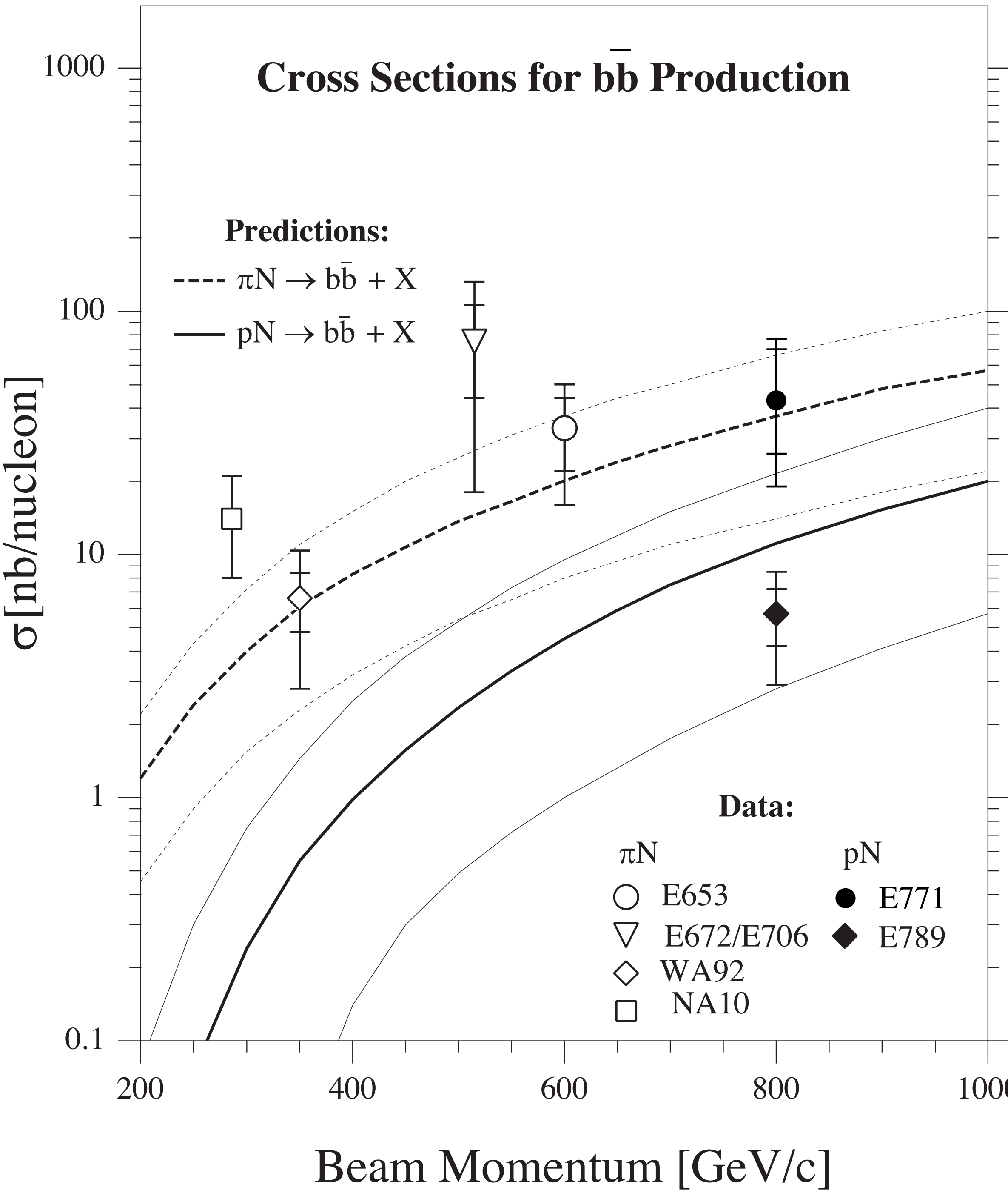

FIG. 3. B Cross Section from E771 $B \to \mu \times B \to \mu$ and $B \to J/\psi$ data compared to other experiments and the QCD calculations by Nason, Dawson and Ellis. The dashed (solid) curves are the πN(pN) B cross section. The lighter dashed and solid curves represent the theoretical uncertainties of the calculated cross sections.