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Quarkonia Production, b-Quark Production and $b\bar{b}$ Correlation Studies with CDF

Vaia Papadimitriou

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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1. INTRODUCTION

The high rate of $B\bar{B}$ production at the Tevatron makes it a unique place for the study of B production and decay. Although e^+e^- colliders provide a cleaner environment than hadron colliders for the study of B decays, CDF has shown that exclusive B channels can be succesfully reconstructed in a harsh environment. Our data have been taken in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV with the CDF detector[1] during the 1988-89 and the 1992-93 collider runs. The CDF detector has been upgraded before the start of the 1992-93 run. The upgrades relevant to this presentation are the muon chamber upgrade and the employment of a silicon vertex detector (SVX). The original CDF Central Muon detector, which covers the pseudorapidity region $|\eta| < 0.6$, has been complemented by the addition of four layers of drift tubes behind 2 feet of steel. As a result, hadronic punch-through backgrounds to the muon signal have been reduced by a factor of ~ 10. We have also added layers of drift tubes in the pseudorapidity region of $0.6 < |\eta| < 1.0$ in order to increase our muon coverage. Finally four layers of DC coupled, single sided, silicon detectors with R-ϕ readout have been added around the beam-pipe and provide a very good resolution in the transverse position of primary and secondary vertices. The primary vertex resolution in a typical event is 35 μm, similar to the transverse beam size. The impact parameter resolution is better than 40(15) μm for tracks with $P_T > 1$ (10) GeV/c. We have collected $\sim$21 pb^{-1} of data with this upgraded detector during the 1992-93 run.

2. QUARKONIA PRODUCTION STUDIES

2.1 *1988-89 data*

In the 1988-89 collider run we studied the reactions $p\bar{p} \rightarrow J/\psi(\psi(2S))X \rightarrow \mu^+\mu^- X$ by using 2.6 ± 0.2 pb^{-1} of data. This allowed us to shed some light on the quarkonia production mechanisms at the Tevatron energy. The production mechanisms of the J/ψ's($\psi(2S)$'s) are B decays, direct charmonium production and the recently suggested[2] gluon fragmentation. We obtained the J/ψ and $\psi(2S)$ differential cross sections which are displayed in Fig. 1 as functions of P_T. The number of J/ψ and $\psi(2S)$ events used in the measurement of the cross section was 889 $\pm$ 30 and 35 $\pm$ 8 respectively. Theoretical predictions for the two types of

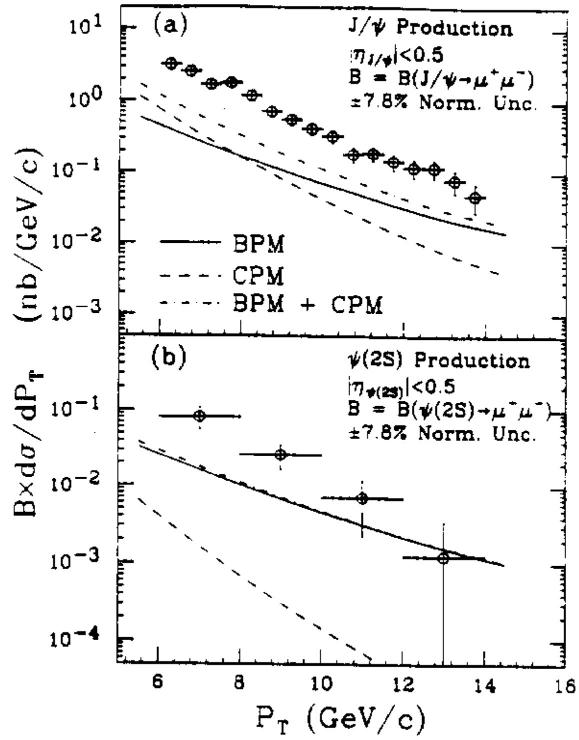

Figure 1: The product $B \times \left(\frac{d\sigma}{dP_T}\right)$ vs. P_T for (a) $J/\psi \rightarrow \mu^+\mu^-$ and (b) $\psi(2S) \rightarrow \mu^+\mu^-$. The circles correspond to the data. The solid curve corresponds to $J/\psi(\psi(2S))$'s produced from B meson decays. The dashed curve corresponds to $J/\psi(\psi(2S))$'s from direct charmonium production. The dot-dashed curve is their sum.

processes expected to dominate J/ψ and $\psi(2S)$ production are also plotted. The solid curve in Fig. 1a (1b) is a next-to-leading-order (NLO) calculation of the production of b-quarks by Nason, Dawson, & Ellis (NDE)[3] leading to B-mesons and subsequent decay to J/ψ ($\psi(2S)$) as discussed in Ref. 4. We refer to this overall calculation as B-production model (BPM). The dashed curve in Fig. 1a (1b) corresponds to J/ψ's ($\psi(2S)$'s) from direct charmonium production[5], that is, either from the decay of a higher charmonium state or from direct production through gluon fusion. We refer to this overall calculation as the charmonium production model (CPM). The sum of these two contributions (BPM and CPM) is also plotted in Fig. 1. In Fig. 1a we fit the theory to the data by summing the two theoretical contributions with independent normalization factors. With no normalization constraints a good fit is obtained with ~69% J/ψ production from CPM and ~31% J/ψ production from BPM. Using additional information which is described in Ref. 4 we found that the 90% C.L. upper limit on the BPM contribution is ~60%; we concluded as well that if future measurements exceed this value, then either at least one of the two models considered above is wrong or there are additional production mechanisms with a significant contribution.

We have also reconstructed χ_c mesons through the decay chain $\chi_c \rightarrow J/\psi\gamma$, $J/\psi \rightarrow \mu^+\mu^-$. In the 1988-89 collider run we reconstructed 67 ± 8 χ_c's and we calculated the cross section for the process $p\bar{p} \rightarrow \chi_c X$ to be $\sigma(\chi_c \rightarrow J/\psi\gamma) = 3.2 \pm 0.4(stat) \, {}^{+1.2}_{-1.1} \, (syst)$ nb[6]. We found that the fraction, f_χ, of J/ψ's coming from χ_c decays is $f_\chi = (44.9 \pm 5.5 \, {}^{+15.4}_{-14.1})\%$,

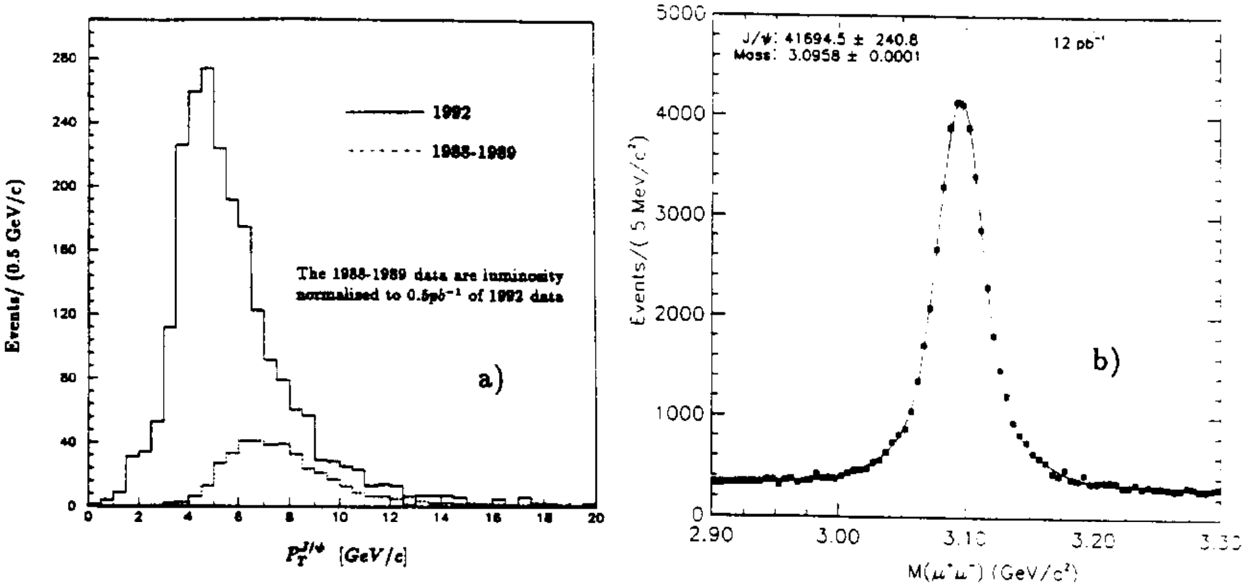

Figure 2: a) J/ψ P_T spectrum in the dimuon channel. b) J/ψ mass spectrum in the dimuon channel from $12pb^{-1}$ of the 1992-93 data.

but we did not have enough statistics to measure this fraction as a function of P_T. Assuming that the only processes for J/ψ production are B decays and χ_c decays, the fraction f_b turns out to be $(63 \pm 17)\%$. This value of f_b was used to derive the b-quark production cross section from the inclusive J/ψ sample (see Fig. 7).

2.2 1992-93 data

Due to improvements in the trigger, in the 1992-93 run we have approximately a factor of 5 more J/ψ's per pb^{-1} than in the previous run (see Fig. 2a)). In Fig. 2b) we show the J/ψ mass spectrum from a 12 pb^{-1} sample which represents $\sim$ 60% of the 1992-93 data. In Fig. 3 we compare the differential J/ψ cross section from the 1988-89 data to the one from 7.5 pb^{-1} of 1992-93 data. In the 1992-93 run we have extended the measurement to both lower and higher P_T values. The agreement with the 1988-89 data is pretty good. In the 1992-93 data, by using the SVX we can measure the fraction of J/ψ's coming from B's directly and without any assumptions. From the measurement[7] of the B lifetime with inlusive J/ψ's we have indications that the fraction of J/ψ's coming from B's is lower than the one we assumed in the previous run. The fraction derived from the lifetime fit is 15%. Although this is the right b fraction in the lifetime sample, it should not be automatically interpreted as the fraction of J/ψ's from b's to be used for the b cross section measurement. The reason is that the applied track quality cuts favor isolated muons and systematically decrease the fraction. This fraction should not be directly compared with the one we derived from the 1988-89 data either, because the fraction is a P_T dependent quantity and the P_T regions for the inclusive J/ψ sample were different in the 1988-89 and 1992-93 collider runs. The measurement of an unbiased fraction f_b from the 1992-93 run is work in progress.

A $\psi(2S)$ mass distribution reconstructed through the decay chain $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$ is shown in Fig. 4 from $\sim$ 11 pb^{-1} of 1992-93 data. All the tracks in the event have been

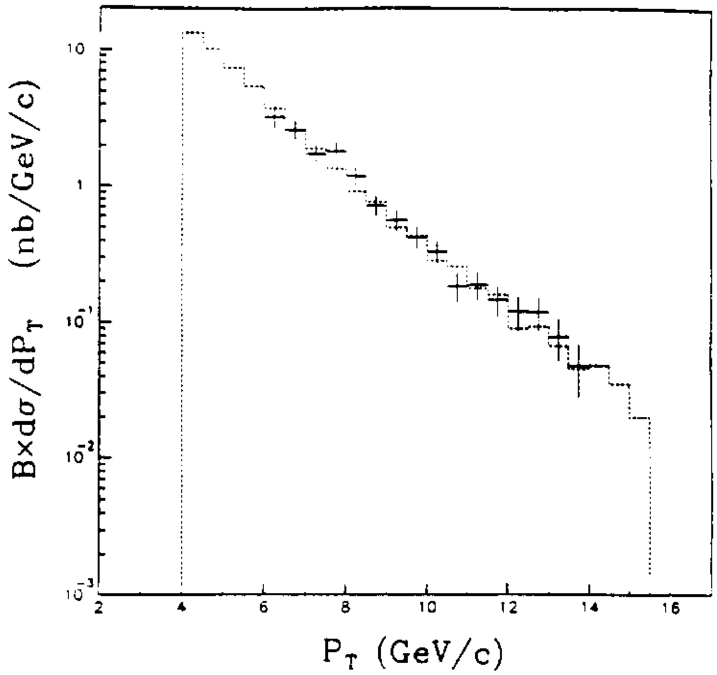

Figure 3: Comparison of the differential J/ψ cross section between the 1988-89 (points with error bars) and the 1992-93 (histogram) data for the region $|\eta_{J/\psi}| < 0.5$.

reconstructed by using the SVX. The use of the SVX in the calculation of the $\psi(2S)$ decay length indicates that the $\psi(2S)$ state has a non negligible prompt component.

With the new data set we are also reconstructing a respectable sample of χ_c decays (see Fig. 5). This sample will be used to measure the fraction f_χ and to cross check the fraction f_b measured with the SVX. Since we can now measure the J/ψ differential cross section from b's and from χ_c's, it will be much easier to disentangle the different J/ψ production mechanisms. By measuring with the SVX the fraction of prompt χ_c's we can also measure the ratio of the inclusive rates of $B \to \chi_c X$ and $B \to J/\psi X$.

Finally in Fig. 6 we show the Υ mass distribution from $\sim 12\ pb^{-1}$ of the 1992-93 data. Since Υ's are not produced from B meson decays but they are produced either directly or from χ_b's, we can use the measurement of $\left(\frac{d\sigma}{dP_T}\right)$ versus P_T in order to check if the direct production spectrum predicted by QCD is correct. Since the $\Upsilon(3S)$ state is produced only directly, it will be especially useful for this comparison. The Υ sample offers also the possibility to check the differential production cross section at P_T values as low as $0.5 - 1.0\ GeV/c$.

3. b-QUARK PRODUCTION STUDIES

3.1 1988-89 data

In Fig. 7 we show the b-quark production cross sections that we derived by studying various b decay channels in the 1988-89 data. The curves in the same figure represent the theoretical predictions based on the NDE calculation. The uncertainty in the predictions arising from choices of the renormalization scale μ, the b-quark mass and the QCD Λ parameter are also shown. The dashed lines correspond to the central value and the upper and

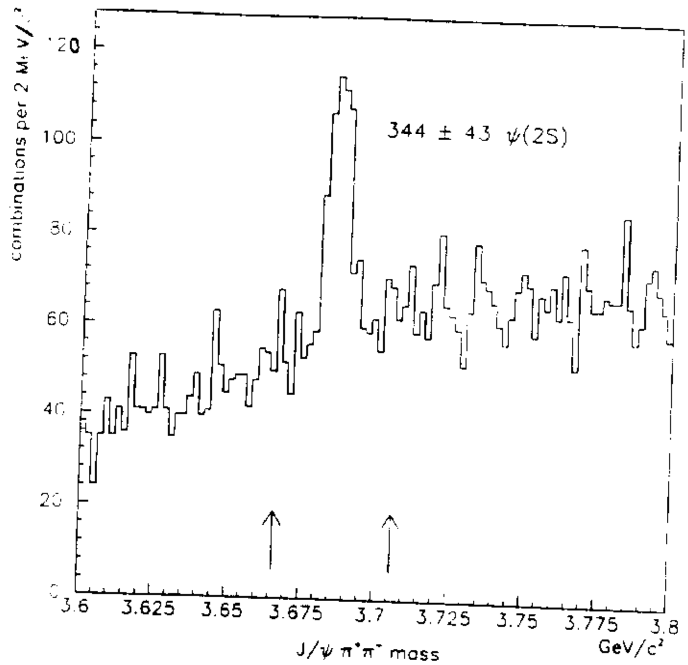

Figure 4: $\psi(2S)$ mass spectrum in the dimuon channel from $\sim 11\ pb^{-1}$ of the 1992-93 data.

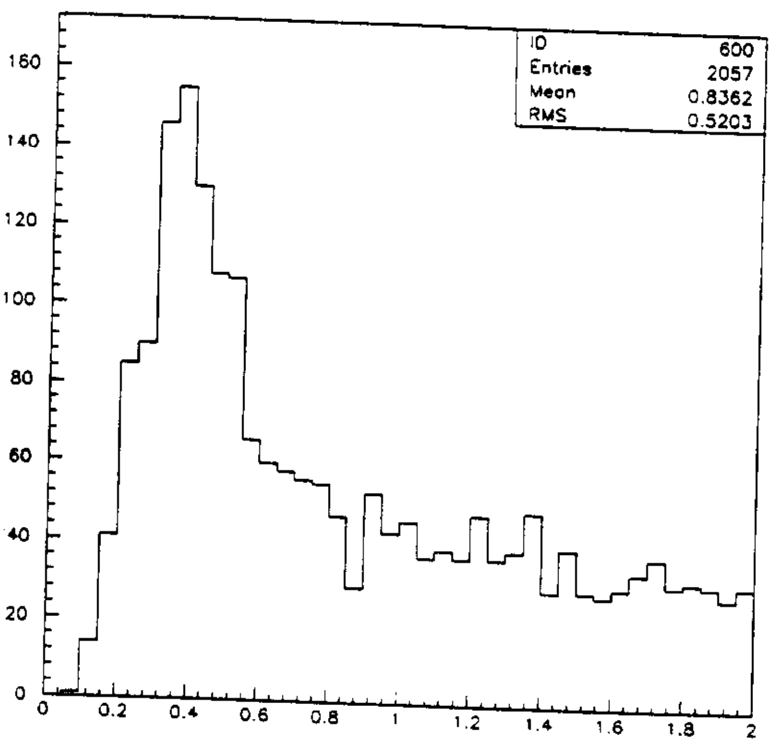

Figure 5: The mass difference ΔM for the χ_c mass region from $\sim 12\ pb^{-1}$ of the 1992-93 data.

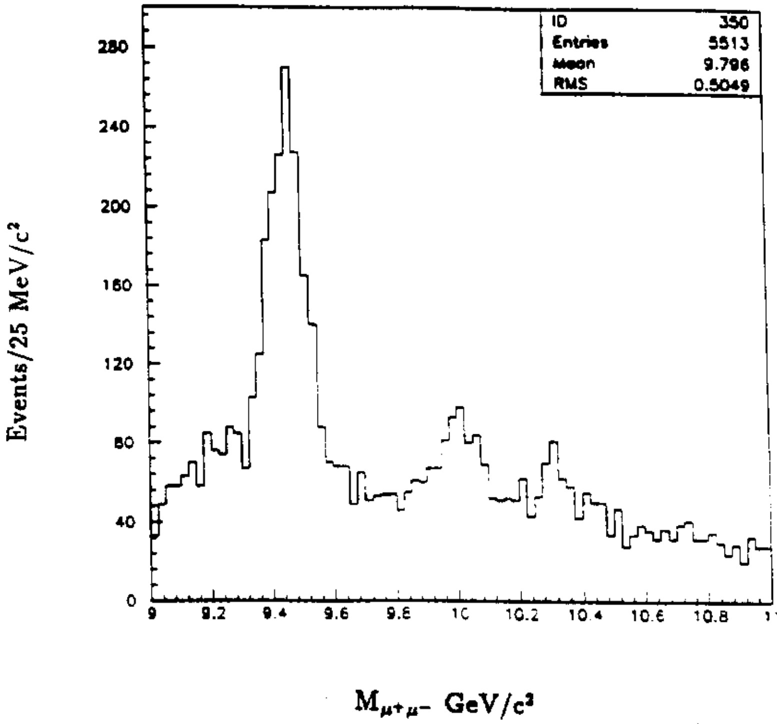

Figure 6: The dimuon mass distribution for the Υ mass region in the 1992-93 data.

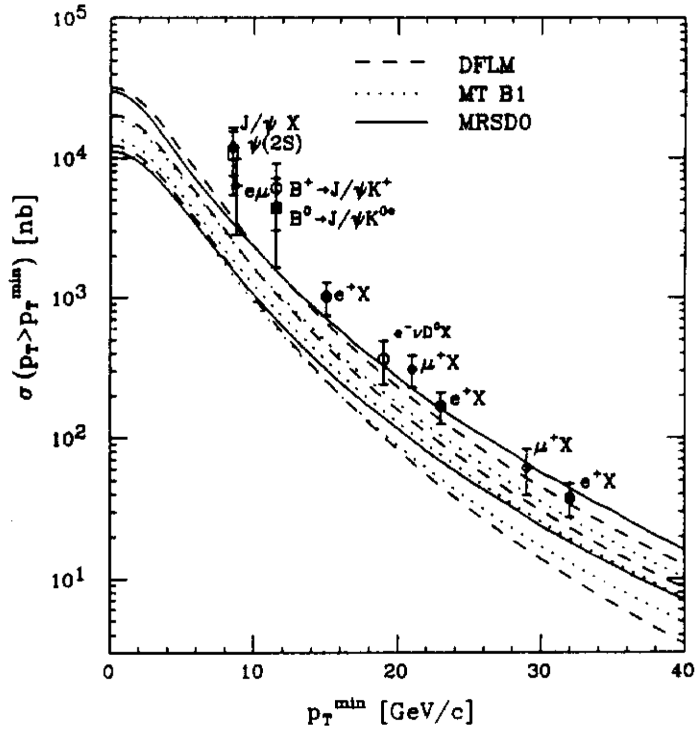

Figure 7: Integrated b P_T distribution at 1.8 TeV: 1988-89 CDF data versus NLO QCD.

lower allowed predictions by using the DFLM structure functions[3]. The dotted lines correspond to similar predictions by using the MT structure functions[8]. Finally the solid lines represent the central value and the upper allowed prediction by using the MRSD0 structure functions[9].

The b-quark production cross section from the inclusive $J/\psi(\psi(2S)) \rightarrow \mu^+\mu^-$ channels was based on the measurement of the integrated $J/\psi(\psi(2S))$ cross section for $P_T > 6\ GeV/c$ (see section 2.1) and on the fraction f_b of $J/\psi(\psi(2S))$'s coming from b's. For the J/ψ's we used the fraction discussed in section 2.1. For the $\psi(2S)$'s we assumed that they all originate from B decays[10]. The b cross section measurement based on the $\psi(2S)$ sample will have a considerably improved statistical error in the 1992-93 data.

The b-quark cross section from the $e\mu$ sample shown in Fig. 7, is a single-b inclusive cross section based on the observation of a correlated lepton pair that originates from the $b\bar{b}$ produced in the event. This measurement has been based on $\sim$ 1000 lepton pairs. It is interesting that although this cross section is measured at a similar P_T^b as the cross section from inclusive J/ψ's and $\psi(2S)$'s, it has a lower central value. This is an indication that there might be something wrong with the assumptions we made to derive f_b from the inclusive J/ψ and $\psi(2S)$ channels.

The B meson production cross sections from the exclusive decay channels $B^\pm \rightarrow J/\psi K^\pm$ and $B^0 \rightarrow J/\psi K^{0*}$ were based on 14.1±4.3 and 9.6±4.6 events respectively from the 1988-89 data and therefore they were statistically limited. The corresponding b-quark cross sections were $\sigma^b(P_T > 11.5\ GeV/c,\ |y^b| < 1) = 6.1 \pm 3.1\ \mu b$ and $\sigma^b(P_T > 11.5\ GeV/c, |y^b| < 1) = 4.4 \pm 2.8\ \mu b$

From the inclusive electron production rate and the associated electron-D^0 production rate we derived the b-quark cross section for four different ranges of P_T^b; from the inclusive muon production rate in the same data we derived the b-quark cross section for two different ranges of P_T^b. The major systematic uncertainty in these inclusive lepton measurements was the level of the knowledge of the background. This is greatly improved in the 1992-93 run due to the upgrades of the detector.

From the comparison of the data with the theoretical predictions we observe that the experimental b cross section is larger than the theoretical one at the Tevatron energy (see Fig. 7). There is a clear excess in the observed rate at small P_T^b. At larger values of P_T^b, the data are consistent with the upper extreme of the theoretical band. The measurements of b-quark production cross sections from the UA1 experiment in $p\bar{p}$ collisions at $\sqrt{s} = 630\ GeV$ agree much better with the theoretical predictions than the CDF measurements at $\sqrt{s} = 1.8\ TeV$ do[9]. There have been several attempts to explain the difference, such as consideration of higher order corrections to the next-to-leading order theoretical calculation, higher order small-x corrections to the partonic cross sections and modification of the gluon densities[11].

We know that several of the 1988-89 CDF b-quark cross section measurements were statistically limited or were derived under certain assumptions; we expect that the analysis of the data set we collected during the 1992-93 run will shed light onto the problem.

3.2 1992-93 data

Since we know that the measured fraction f_b for both J/ψ's and $\psi(2S)$'s is smaller than the one we assumed in the 1988-89 analyses (see section 2.2), we expect that the b cross sections based on the inclusive quarkonia samples will become more consistent with the theory.

From $(14.3 \pm 1.0)\ pb^{-1}$ of the 1992-93 data we also reconstructed $104 \pm 21\ J/\psi K^\pm$

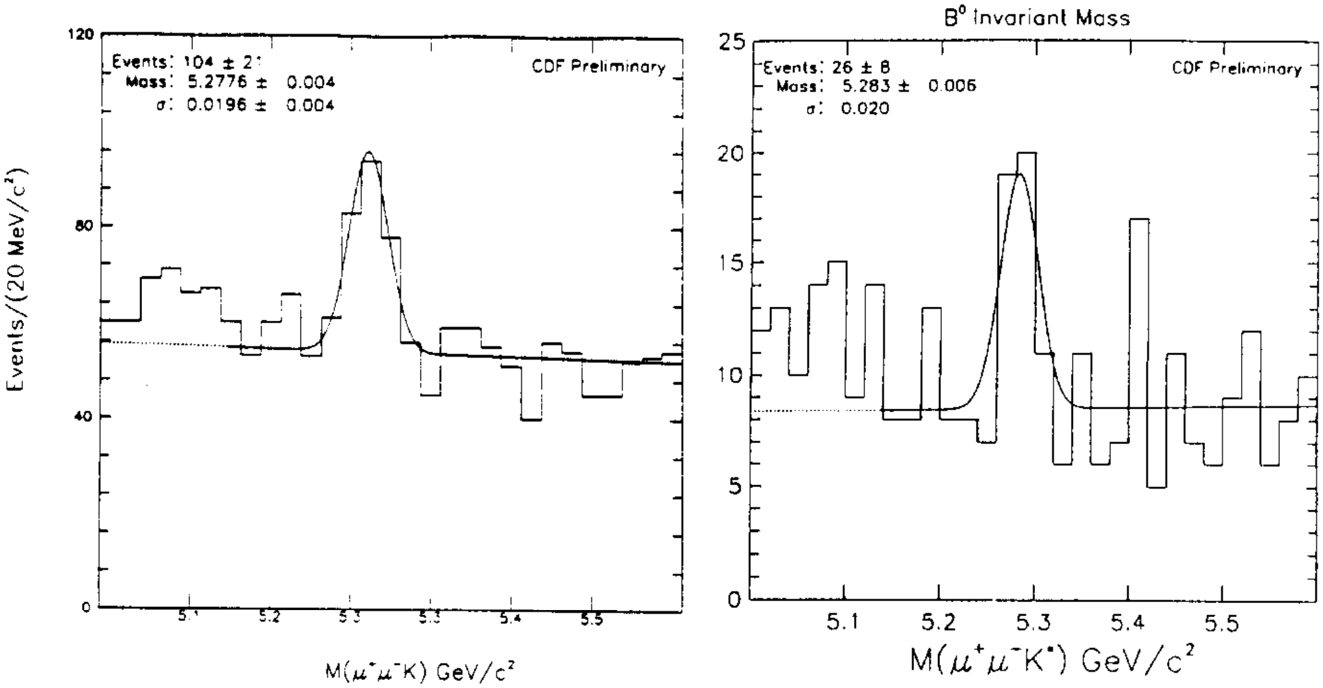

Figure 8: Reconstructed B mass from the decays $B^{\pm} \rightarrow J/\psi K^{\pm}$ and $B^{0} \rightarrow J/\psi K^{0*}$ from 14 pb^{-1} of the 1992-93 data.

and 26 ± 8 $J/\psi K^{0*}$ events for $P_T^B > 6.0\ GeV/c$ and $P_T^B > 9.0\ GeV/c$ respectively (see Fig. 8). The reconstruction of these exclusive channels has not used any decay length or SVX related cuts yet, and therefore the signal to noise ratio is not optimal. Such additional cuts reduce drastically the background as can be seen in Fig. 9. Since there are sufficient statistics in the $B^{\pm} \rightarrow J/\psi K^{\pm}$ decay channel it has been used to determine the differential B meson cross section which is shown in Fig. 10. The measurement suggests that the shape of the theoretical cross section differs from the experimental result since there is an excess in the observed rate at low P_T^B (see Ref. 12). We derived the b-quark cross sections to be $\sigma^b(P_T^b > 7.5\ GeV/c, |y^b| < 1) = 9.43 \pm 3.69\ \mu b$, $\sigma^b(P_T^b > 10.5\ GeV/c, |y^b| < 1) = 2.85 \pm 1.12\ \mu b$, $\sigma^b(P_T^b > 13.5\ GeV/c, |y^b| < 1) = 1.22 \pm 0.51\ \mu b$ from $B^{\pm} \rightarrow J/\psi K^{\pm}$ decays and $\sigma^b(P_T^b > 10.5\ GeV/c, |y^b| < 1) = 2.61 \pm 1.29\ \mu b$ from $B^{\pm} \rightarrow J/\psi K^{0*}$ decays. The error is statistical and systematic combined in quadrature. These new b-quark cross section measurements (see Fig. 11), although statistically consistent with the corresponding ones of the 1988-89 data, they are closer to the theoretical predictions.

Finally we have derived the b-quark cross section for two different ranges of P_T^b from the associated muon-D^0 production rate. These two measurements are based on 8.8 and 4.4 pb^{-1} of 1992-93 data respectively, and they will certainly improve when we use the full data set.

4. $b\bar{b}$ CORRELATION STUDIES

As already mentioned in section 3.1, the NLO QCD prediction is in good agreement with the data at $\sqrt{s} = 630$ GeV but is systematically low when compared to the CDF measurements at $\sqrt{s} = 1.8$ TeV. The process $p\bar{p} \rightarrow b\bar{b}X$ provides further opportunities for comparison between experiment and NLO QCD.

In order to obtain a high enough rate for our studies we chose to tag the $b\bar{b}$ pair by

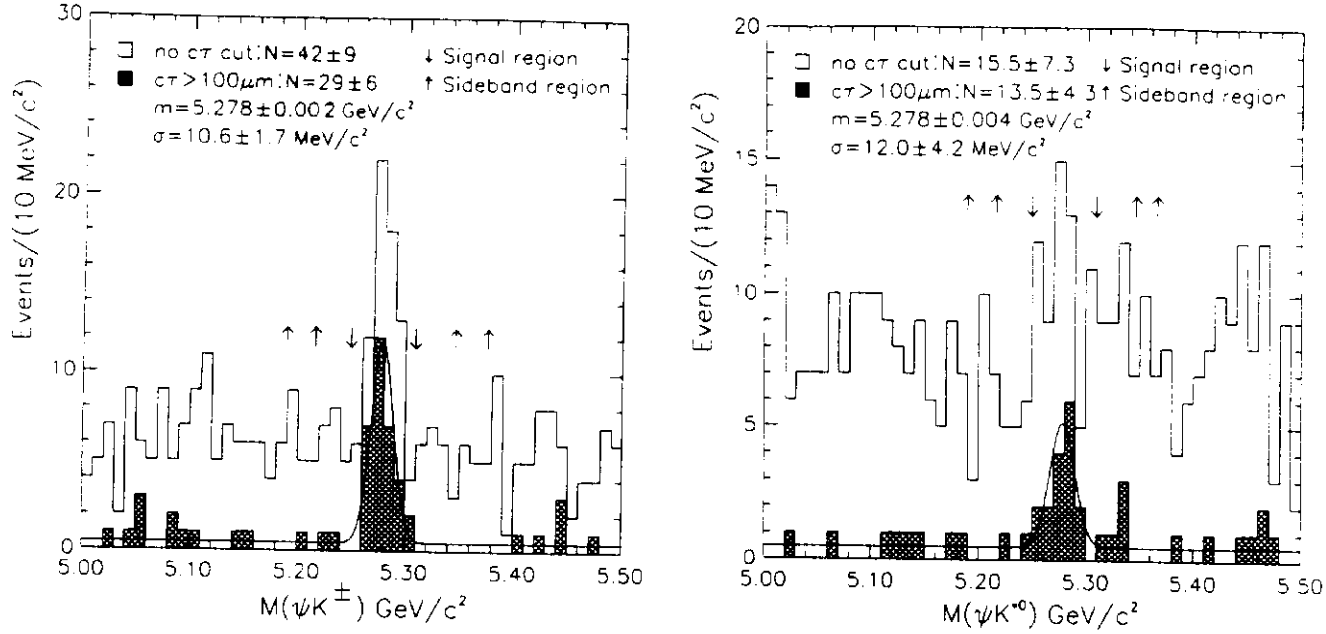

Figure 9: Reconstructed B mass from the decays $B^{\pm} \to J/\psi K^{\pm}$ and $B^{0} \to J/\psi K^{0*}$ using the SVX (9 pb^{-1} of the 1992-93 data).

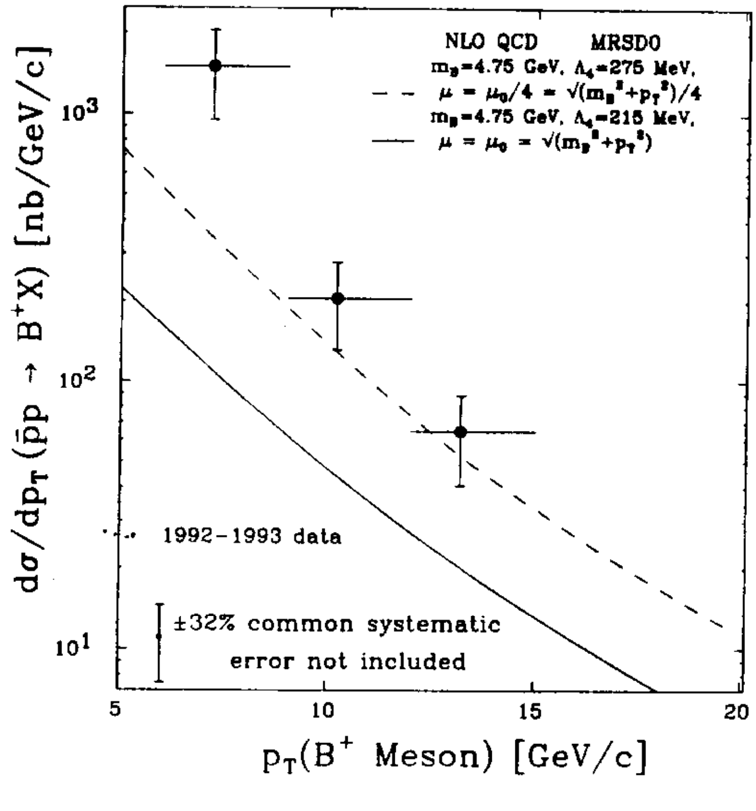

Figure 10: B meson differential cross section.

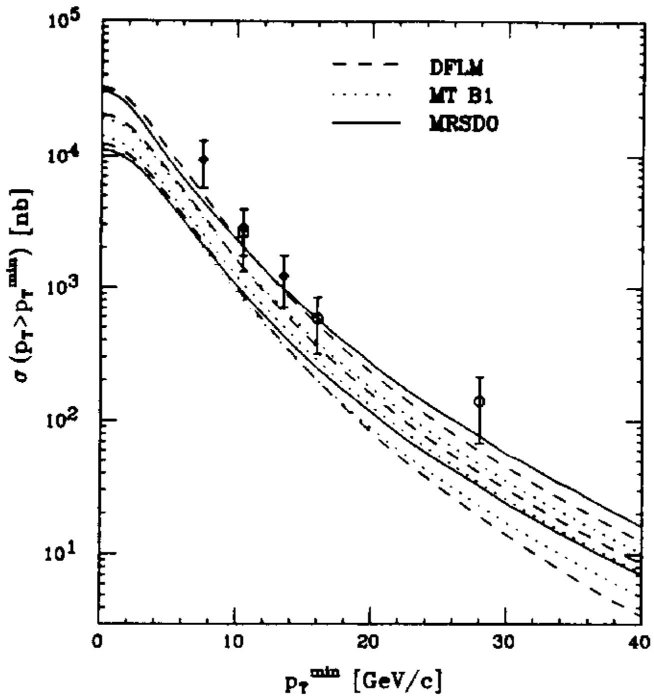

Figure 11: Integrated b P_T distribution at 1.8 TeV: 1992-93 CDF data versus NLO QCD. The diamonds correspond to the decay $B^{\pm}\rightarrow J/\psi K^{\pm}$, the square to $B^0\rightarrow J/\psi K^{0*}$ and the circles to $B\rightarrow \mu D^0 \nu X$.

the semileptonic decay of the b and $\bar{b}$ quarks. More specifically, we chose to look for events in which one b decayed to an electron and the other to a muon, thus avoiding potential backgrounds such as Drell Yan and leptonic decays of the J/ψ, $\psi(2S)$, Υ and Z. We made this study using (2.65 ± 0.17) pb^{-1} of the 1988-89 collider run data. The data were collected with the dilepton trigger which requires an electron in the Central Electromagnetic calorimeter with minimum E_T of 5 GeV and a muon in the Central muon chambers with a minimum P_T of 3 GeV/c. Events with electron-muon pairs in the final state come from $b\bar{b}$ production, $c\bar{c}$ production, a cascade decay of a single bottom quark and "fakes", that is events with misidentified particles. To determine the number of $e\mu$ events due to $b\bar{b}$ production, we separated the data into events with leptons of same sign (SS) or opposite sign (OS). The $b\bar{b}$ production, although it produces mainly opposite sign pairs, it contributes to the SS sample as well due to $B^0\bar{B}^0$ mixing. The $c\bar{c}$ production contributes only to the OS sample since the mixing is negligible. We get rid of lepton pairs from the decay of a single B by requiring that $m_{e\mu} > 5$ GeV/c^2. Fakes contribute equally to the SS and OS samples and they are removed by subtracting the SS $e\mu$ pairs from the OS. The fraction, $f_{b\bar{b}}$, of the sign subtracted events due to $b\bar{b}$ production is determined by examining the distribution of the component of the lepton momentum transverse to the direction of the associated jet, P_T^{rel}. The P_T^{rel} distribution for leptons from b decays is stiffer than the corresponding one from c decays. We obtain $f_{b\bar{b}}$ by fitting the difference of the P_T^{rel} distribution for the SS and OS samples (see Fig. 12) to the sum of the normalized b and c distributions. It turns out that $f_{b\bar{b}} = 1.0\,^{+0.0}_{-0.1}$. The electron and muon acceptances are calculated using the full NLO calculation of $b\bar{b}$ production by Mangano, Nason and Ridolfi (MNR)[13]. In Fig. 13 we show our measured cross section for the process $p\bar{p}\rightarrow b\bar{b}X$ versus the P_T^{min} of the second b given the P_T^{min} of the first b (see Ref. 14). The inner error bars correspond to the statistical uncertainty and the outer error

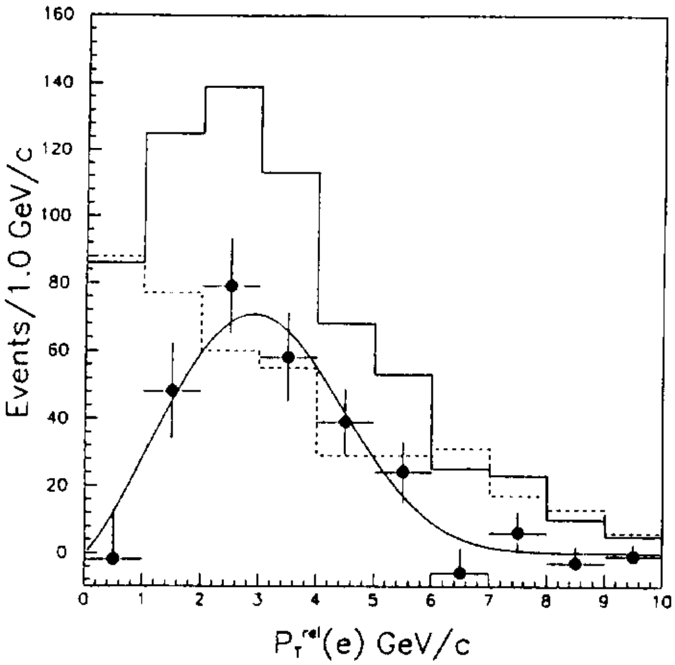

Figure 12: P_T^{rel} for electrons from the data. OS (SS) events are shown in solid (dashed) lines. The difference of the OS and SS distributions is shown with points. The curve is a fit of the sum of the normalized b and c distributions to the subtracted data.

bars represent the combined statistical and systematic uncertainty. In the same plot we also show the MNR theoretical prediction using the DFLM structure functions. The upper and lower uncertainty bands correspond to variations in the mass of the b-quark, in Λ_4 and in the normalization scale μ. In Fig. 14 we show the sign-subtracted distribution of the angle between the electron and the muon in the transverse plane for events passing all the analysis cuts, and we compare it with the MNR prediction.

The data is seen to be consistent with the shape of the $b\bar{b}X$ cross section as predicted by NLO QCD. The absolute normalization though is found to be lower than the data by a factor of 4. The shape of the $\Delta\phi_{e\mu}$ distribution from $b\bar{b}$ production is seen to be in good agreement with the theory.

1. SUMMARY

During the 1988-89 collider run CDF has shown that one can study quarkonia physics and b physics even in a harsh $p\bar{p}$ collider environment. The 21 pb^{-1} we collected with the upgraded CDF detector during the 1992-93 run are leading us to a rich program which focuses on the production and decay of quarkonia and b-quarks, and which will answer many of the questions posed during the 1988-89 collider run.

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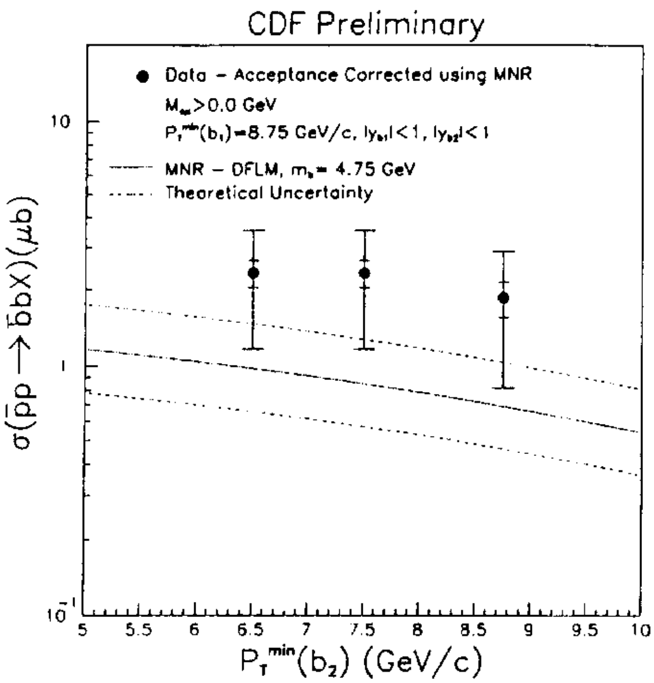

Figure 13: The cross section for $p\bar{p}\rightarrow b\bar{b}X$. The theoretical prediction and associated uncertainty are represented by the solid and dashed lines respectively.

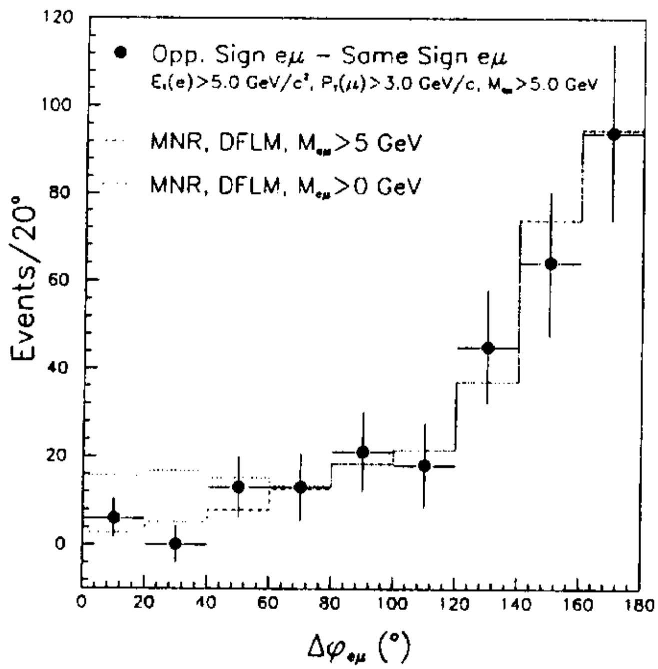

Figure 14: The opening angle between the electron and the muon in the transverse plane.

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