

Fermi National Accelerator Laboratory

FERMILAB-Conf-94/300-E

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September 1994

Presented at the *XXIXth Rencontre de Moriond on QCD and High Energy Hadronic Interactions*, Savoie, France, March 19-26, 1994

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# INCLUSIVE $B$ PRODUCTION AT CDF AND DØ \*

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## Abstract

We present the latest results on inclusive  $b$  production studies from CDF and DØ collaborations in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8$  TeV at the Fermilab Tevatron Collider. The results are from recently completed analyses of 1988-89 data and preliminary analyses of 1992-93 data. This report includes new  $b$  cross section measurements using semileptonic  $b$  decays to muons,  $J/\psi$  production in dimuon events, and a study of  $b\bar{b}$  correlations in  $e\mu$  events. The new results from CDF and DØ show no major discrepancies between the Tevatron data and the NLO QCD prediction for  $p_t$  values down to 6 GeV.

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\* Presented at the XXIXth Rencontre de Moriond on QCD and High Energy Hadronic Interactions, Savoie, France, March 19-26, 1994.



## I. INTRODUCTION

The study of  $b$  quark production in high energy hadronic collisions is essential for testing the perturbative QCD description of heavy quark production. The fact that the contribution from NLO terms is as large as the LO contribution [1] suggests that even higher order terms may be significant. The comparison of experimental data to the prediction should reveal how reliable the NLO prediction is.

The  $b$  quark integrated  $p_t$  cross section measured at lower energies by UA1 [2] was shown to agree well with the NLO QCD calculation. A summary of the published CDF measurements from 1988-89 data can be found in reference [3]. Compared to the NLO QCD prediction, the data are consistent with the upper bound for large values of  $p_t$  but higher than the prediction by as much as a factor of 4 below 10 GeV. This has been the situation on the  $b$  cross section measurement by last Moriond meeting. New measurements are the subject of this paper.

We will briefly review the upgraded CDF detector and components of DØ detector relevant to  $b$  measurements together with the triggers deployed for these analyses. We will then describe in more details new analyses of inclusive muons,  $J/\psi$  production in dimuon events and the study of  $b\bar{b}$  correlations in  $e\mu$  events. Finally we conclude with a summary of the Tevatron data on  $b$  cross section measurement .

## II. CDF AND DØ DETECTORS

CDF and DØ are large multi-purpose detectors operating at the Tevatron  $\bar{p}p$  Collider, located at Fermi National Accelerator Laboratory. They both feature an inner tracking system, calorimetry for the detection of electrons, jets and missing transverse energy, and a muon system. In addition CDF features a central 1.4 T magnetic field, which provides a momentum resolution of  $\sigma(p_t)/p_t \approx 0.0011p_t \oplus 0.0066$  ( $p_t$  in GeV) for vertex constrained charged tracks.

Several components of CDF detector [5] have been upgraded between the 1988 and 1992 runs. The addition of more muon chambers extends the  $\eta$  coverage from 0.6 to 1.0. The installation of extra steel and chambers behind the first muon chambers increases the number of absorption lengths from 5 to 8. This reduces the hadron punchthrough background in muon events by as much as a factor of 10. The installation of PreRadiator multiwire proportional chambers in front of the central electromagnetic calorimeter allows for better  $e/\pi$  discrimination and therefore improves electron identification. More importantly, the addition of a silicon microstrip detector (SVX) [6] with a typical resolution of about  $35 \mu m$  in the transverse position of primary and secondary vertices provides a more accurate determination of  $b$  decays by confirming that the impact parameter of the displaced vertices is consistent with the  $B$  lifetime.

DØ detector has been described in detail elsewhere [7]. The inner tracking covers a cylindrical region of radius  $75 \text{ cm}$  and  $3 \text{ m}$  in length with wire drift chambers to detect charged tracks in a range of  $|\eta| < 3$ . The calorimeter is a uranium-liquid argon sampling detector with a coverage over the range  $|\eta| < 4.2$ . The hadronic section is  $7 - 9$  interaction lengths ( $\lambda$ ) thick and has a measured fractional energy resolution for pions of  $50\%/\sqrt{E}$  ( $E$  in GeV) [8]. The muon system consists of three layers of chambers, with magnetized iron toroids located between the first and second layers. The magnetic field in the iron toroid is  $1.9 \text{ T}$  and provides a momentum measurement with a modest resolution,  $\sigma(p)/p \approx 0.2(p - 3)/p \oplus 0.006p$  ( $p$  in GeV), for three layer muon tracks. The thickness of the calorimeter plus iron toroids varies from  $14 \lambda$  in the central region to  $19 \lambda$  in the forward region. This reduces the hadron punchthrough background to a negligible level and allows for a good identification of muons inside jets.

### III. B PHYSICS TRIGGERS AT THE TEVATRON

The cross section for producing  $b$  quarks at  $\sqrt{s} = 1.8 \text{ TeV}$  falls steeply with  $p_t$  and is almost flat over several units of rapidity [1]. This indicates the importance of lowering

$p_t$  thresholds and having good  $\eta$  coverage. Despite high trigger rates for low  $p_t$  leptons at the Tevatron, both CDF and DØ managed to set the  $p_t$  thresholds fairly low. It can be seen in Table I that in the case of dimuons for instance, the thresholds almost match the range out energies in the two detectors. While CDF triggers on both electrons and muons for tagging  $b$  quarks, DØ's  $b$  physics program presently relies entirely on muons. The different trigger combinations and the corresponding thresholds are summarized in Table I.

TABLE I.  $p_t$  thresholds for different combinations of muon, electron and jet triggers deployed by CDF and DØ for  $b$  physics analyses. The trigger thresholds in parentheses correspond to prescaled triggers

Combination of Triggers	CDF Experiment	DØ Experiment
$1\mu$	$p_t^\mu > 9.0 (6.0) \text{ GeV}$	$p_t^\mu > (3.5) \text{ GeV}$
$2\mu$	$p_t^{\mu 1} > 2.0 \text{ GeV}, p_t^{\mu 2} > 3.0 \text{ GeV}$	$p_t^{\mu 1, \mu 2} > 3.5 \text{ GeV}$
$1e$	$E_t^e > 9.0 (6.0) \text{ GeV}$	
$2e$	$E_t^{e1, e2} > 5.0 \text{ GeV}$	
$1e + 1\mu$	$E_t^e > 5.0 \text{ GeV}, p_t^\mu > 3.0 \text{ GeV}$	
$1\mu + 1jet$		$p_t^\mu > 3.5 \text{ GeV}, E_t^{jet} > 10.0 \text{ GeV}$

## IV. SEMILEPTONIC $B$ DECAYS TO MUONS

Tagging  $b$  quarks through their semileptonic decays into muons is standard in the study of  $b$  production. For moderately high  $p_t$  (8-25 GeV), muons come primarily from  $b$  quark decays. The following is DØ analysis of an inclusive muon sample to extract a  $b$  cross section measurement.

### A. Inclusive $\mu$ production

This analysis was performed by DØ and corresponds to  $\int \mathcal{L} dt \approx 90 \text{ nb}^{-1}$  of data. The inclusive muon sample required a muon candidate at level 1 trigger and a muon stub at level 2, with  $p_t$  above 3 GeV. Events are then fully reconstructed offline and are retained for further analysis if they contain at least one muon track with a minimum of 1 GeV of energy visible in the calorimeter and a matching track in the central tracking chambers. Using both Monte Carlo and the data itself the total detection efficiency was estimated to be  $25 \pm 3\%$ , independent of  $p_t$ , for  $p_t > 5$  GeV.

The normalized cross section for inclusive muon production, for  $3.5 < p_t < 60$  GeV and  $|\eta| < 0.8$ , is shown in Figure 1. The points are DØ data and the curves represent the expected different sources of muons calculated using ISAJET Monte Carlo [9]. The solid curve, which represents the sum of all expected contributions, reproduces the data fairly well. At low  $p_t$ , where in-flight decays dominate, a steeply falling spectrum is observed. At moderate  $p_t$  values heavy flavor production dominates, and at high  $p_t$  a much flatter spectrum, consistent with W and Z decays, is observed.

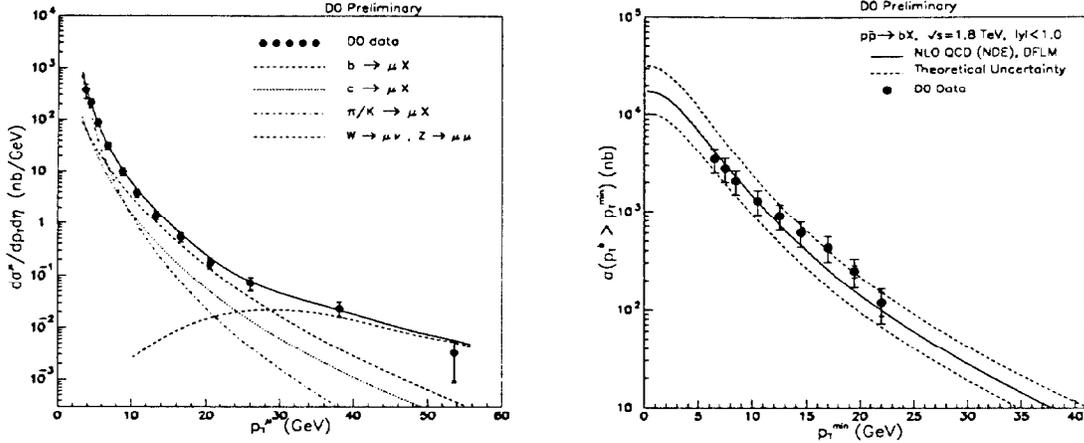


FIG. 1. Comparison between expected and measured inclusive muon cross sections.

FIG. 2.  $b$  quark production cross section compared to the NLO QCD prediction.

### B. $b$ production cross section

The contribution to backgrounds at high  $p_t$  are from  $W$ ,  $Z$  and Drell-Yan events. While  $W$  events are removed on an event by event basis by requiring the missing transverse energy in the event to be less than 20 GeV, others have been estimated and accounted for using Monte Carlo studies. The  $b$  fraction was also determined using the transverse momentum of the muon with respect to the associated jet axis. The derived cross section for  $b$  quark production as a function of the minimum  $p_t$  of the quark,  $p_t^{min}$ , for rapidities less than 1, is shown in Figure 2. The data points are in good agreement, with the NLO QCD prediction over the entire measured  $p_t$  range. The dashed curves represent the band within which the theory is allowed to vary. As for all the QCD predictions shown in this paper, the parton distribution functions used are from reference [10].

### V. $J/\psi$ PRODUCTION

Another tool for tagging  $b$  quarks is through  $J/\psi$  production since a good fraction of  $J/\psi$  events is expected to come from  $b$  decays. Both CDF and DØ have observed an inclusive  $J/\psi$  signal in dimuon events. Using the SVX to reconstruct secondary vertices, CDF is further able to tag whether an event originates from a  $b$  decay and therefore unambiguously determine the  $b$  fraction.

### A. Inclusive $J/\psi$ cross section

At CDF,  $J/\psi$  events are selected by requiring at least two muon candidates at level 1. At level 2 only one stub in the muon chambers is required to match to a hardware track reconstructed in the central tracking chambers in order to increase the acceptance for  $J/\psi$  events in the dimuon trigger. This analysis is based on  $\int \mathcal{L} dt \approx 17 pb^{-1}$  of 1992-93 data. At DØ,  $J/\psi$  events also require at least two muon candidates at level 1. At level 2, at least two muon stubs must be reconstructed and pass some loose quality cuts along with a minimum  $p_t$  cut of 3 GeV on each muon. This analysis includes  $\int \mathcal{L} dt \approx 7.5 pb^{-1}$  of data.

The normalized inclusive  $J/\psi$  cross section times the branching ratio for  $J/\psi \rightarrow \mu^+\mu^-$  from CDF and DØ measurements are shown in Figure 3. The solid curve represents the sum of the expected contributions to  $J/\psi$  production from  $b$  and  $\chi$  decays. The data from the two experiments are consistent with each other. However, as much as half of the  $J/\psi$  events remain unaccounted for. The possible sources of the excess of the  $J/\psi$  rate have been addressed at this conference [4].

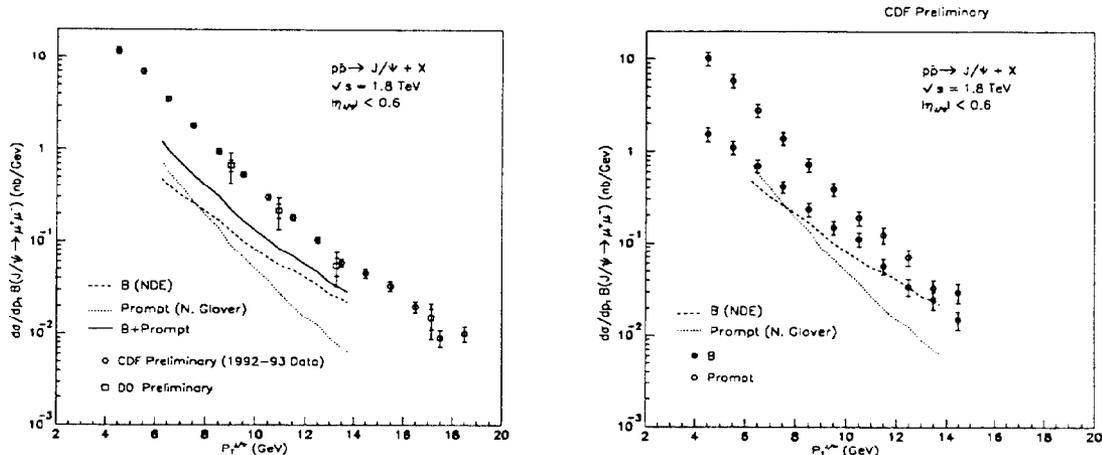


FIG. 3. Measurements of inclusive  $J/\psi$  differential cross section from CDF and  $D\bar{O}$  compared to QCD predictions.

FIG. 4. Separation of the  $J/\psi$  cross section into  $b$  and prompt sources using the SVX detector at CDF.

### B. $J/\psi$ cross section from $b$ decays

By requiring both muon tracks to be reconstructed in the SVX, the relative contributions of  $b$  and prompt decays are determined in the case of CDF analysis. This analysis proceeds by constraining the two muon tracks to come from a common vertex, where the impact parameter is calculated and converted to a proper lifetime [11]. The lifetime distribution is then fit to parametrizations representing  $J/\psi$  events from  $b$  decays, prompt charmonium production and background. This yields a  $b$  fraction which varies with  $p_t$  and is of the order of 15-30%. This is much lower than the 63% fraction obtained, in the analysis of the 1988-89 data [12], using the assumption that  $J/\psi$  production is dominated by  $b$  and  $\chi$  decays. The resulting  $J/\psi$  production cross sections for  $b$  and prompt decays are shown in Figure 4. While the rate for  $b$  production is now in better agreement with the NLO QCD prediction [13],  $\chi$  production [14] alone does not explain the prompt part. The preliminary  $b$  cross section, extracted from this analysis, is shown in Figure 7. The data points are consistent with the upper bound of the prediction.

## VI. STUDY OF $b\bar{b}$ CORRELATIONS

The calculation of the correlations between a pair of  $b\bar{b}$  quarks was performed to next to leading order perturbative QCD [15]. The comparison of measurements of the spatial,  $\Delta\phi$ , and  $p_t$  correlations, with the calculation provides a further opportunity to test the NLO QCD prediction. The investigation of the  $\Delta\phi$  correlations by UA1 [16] shows a good qualitative agreement with the calculation. The following section describes a CDF study of  $b\bar{b}$  correlations in  $e\mu$  events.

### A. $p_t$ Correlations

This analysis [17] is based on 1988-89 data. The data consisted of events collected with a dilepton trigger, which required an electron with a minimum  $E_t$  of 5 GeV and a muon with a minimum  $p_t$  of 3 GeV. To determine the number of  $e\mu$  events due to  $b\bar{b}$  production, the difference in number of same sign to opposite sign is formed, then corrected for events lost due to mixing. The fraction of sign subtracted events due to  $b\bar{b}$  as opposed to  $c\bar{c}$  is measured from examining the transverse momentum of the electron with respect to the associated jet. The result of this analysis for the  $b\bar{b}$  cross section is shown in Figure 5. The data points seem to be systematically higher than the theoretical prediction but the two agree fairly well in shape.

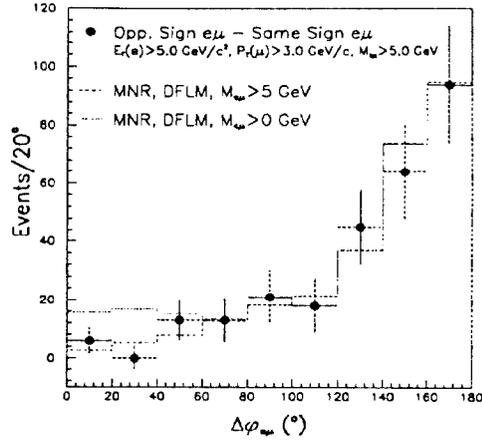
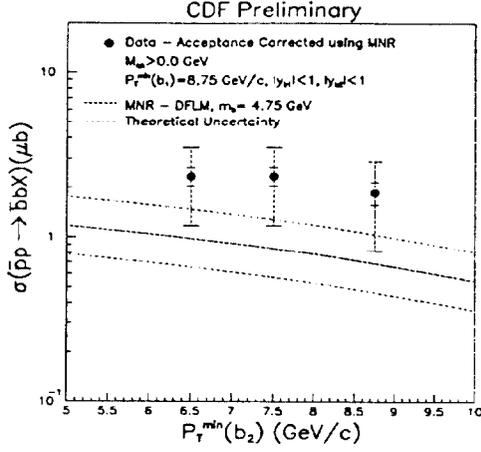


FIG. 5. The cross section for  $p\bar{p} \rightarrow b\bar{b}X$  as a function of the  $p_t^{\min}$  of one of the  $b$  quarks given

$p_t^{\min}$  of the other  $b$ .

FIG. 6. Distribution of the opening angle,  $\Delta\phi_{e\mu}$ , between the electron and the muon in the

transverse plane.

## B. $\Delta\phi$ Correlations

To investigate the spatial  $b\bar{b}$  correlations, the opening angle,  $\Delta\phi_{e\mu}$ , between the electron and muon in the transverse plane is examined. A comparison of data with the expected correlation is shown in Figure 6. The shape of the data is in agreement with the calculation over the entire range of  $\Delta\phi_{e\mu}$  indicating a good qualitative description of LO and NLO processes by the theory. The absence of the expected excess of events due to gluon splitting at low values of  $\Delta\phi_{e\mu}$  is consistent with the  $e\mu$  invariant mass cut of 5 GeV, and is illustrated in the figure.

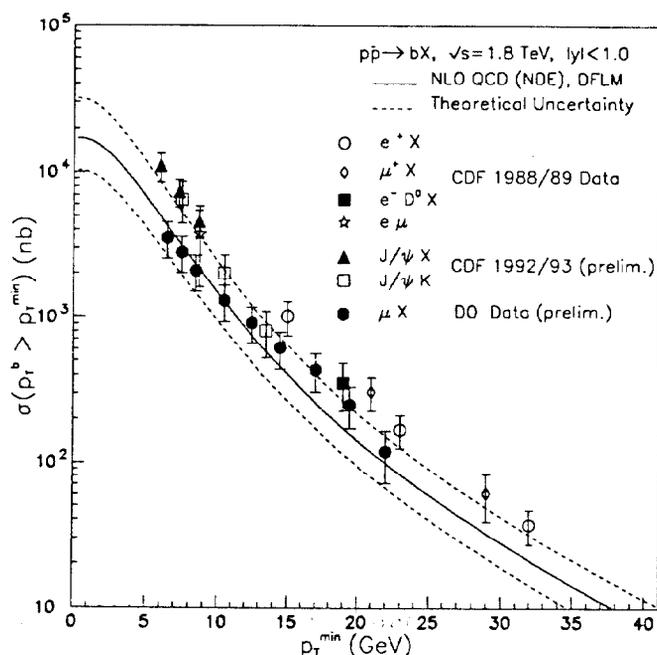


FIG. 7. The Tevatron data on  $b$  cross section measurement compared to the NLO QCD prediction.

## VII. CONCLUSIONS

CDF and DØ experiments have demonstrated an ability to study  $b$  production in hadronic collisions with reasonable efficiency and background rejection. Although we could not review all new CDF and DØ results on inclusive  $b$  production, we felt it was important to present new results on the cross section measurement since earlier data were not completely described by the NLO prediction. The Tevatron data on  $b$  cross section measurement are compared to the QCD prediction in Figure 7. No worrisome discrepancy is observed and the new data indicate that the NLO calculation for  $b$  production cross section at the Tevatron energy is indeed reliable. Several analyses, by CDF and DØ collaborations, are in progress and should further our understanding of  $b$  production at the Tevatron. With more data we hope to constrain the theory more tightly and provide more reliable extrapolations to higher energies.

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