



# Charm and Beauty Production at CDF

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**Abstract.** Using the data samples collected with the CDF Run II detector during 2002 and early 2003, new measurements of the production cross sections of charm and beauty hadrons at  $\sqrt{s} = 1960$  GeV are presented. New measurements of the cross sections of centrally produced  $b$ -hadrons and  $J/\psi$  mesons down to zero transverse momenta have been carried out. The large charm signals made available by the silicon vertex track trigger have enabled the measurement of the cross sections of  $D^0$ ,  $D^*$ ,  $D^\pm$ , and  $D_s$  mesons.

## 1. Introduction

The CDF Run II detector is described in detail in reference [1]. A brief discussion of the CDF Run II triggers which are relevant to the measurement of the heavy flavor cross sections follows. The upgraded CDF II Level 1 muon triggers combine tracks reconstructed in the central-outer tracker drift chamber (COT) with muon track stubs in the central muon systems located outside the calorimeter. The triggered muon transverse momentum threshold is at  $1.5$  GeV/ $c$ , where the Level 1 muon trigger efficiency is 92%. The muon transverse momentum threshold of  $1.5$  GeV/ $c$  is close to one-half of the  $J/\psi$  mass, therefore  $J/\psi \rightarrow \mu\mu$  candidates with zero transverse momenta are accepted by the CDF II di-muon triggers. The muon trigger efficiency is 97% for muons with transverse momentum  $> 2$  GeV/ $c$ .

A large sample of  $J/\psi$  events in the transverse momentum range of  $0 < p_T(J/\psi) < 20$  GeV/ $c$  has been collected using the upgraded di-muon triggers (more than 1 million  $J/\psi$  in the first  $138$  pb $^{-1}$  of data). Using these events, the first measurement of the inclusive central  $J/\psi$  production cross section over the transverse momentum range from zero to  $20$  GeV/ $c$  has been carried out.

A significant fraction of  $J/\psi$  mesons produced at the Tevatron come from the decays of  $b$ -hadrons. The previous Tevatron measurements [2] of the  $b$ -hadron cross section in proton-antiproton collisions at  $\sqrt{s} = 1800$  GeV were substantially larger (by a factor of two to three) than that predicted by next-to-leading order (NLO) QCD calculations [3]. Since the earlier Tevatron results covered only 10-13% of the inclusive  $p_T$  spectrum, it was not evident whether the excess was due to an overall increase in the  $b$ -hadron production rate or a shift in the spectrum toward higher  $p_T$ . In CDF II, an inclusive measurement of the central  $b$ -hadron production over the transverse momentum range from 0 to  $25$  GeV/ $c$  has been performed carried using the low momentum  $J/\psi$  events accessible by the muon triggers.

The Silicon Vertex Tracker (SVT) [4] of CDF II reconstructs two dimensional tracks in 4-5 layers of the inner silicon vertex detector online, thus allowing triggers on detached vertices at Level 2. The SVT impact parameter resolution is measured to be  $48\mu\text{m}$  including a  $30\mu\text{m}$  beam spot. The SVT selects tracks with transverse momenta greater than  $2$  GeV/ $c$  and impact parameter to the beam  $> 120\mu\text{m}$ .

Since January 2002, large samples of  $D$  mesons have been collected using SVT. Approximately 1 million fully reconstructed charm decays were collected in the first  $138 \text{ pb}^{-1}$  of data. In this paper, the CDF Run II measurements of the charm meson production cross sections, including  $D_s$ , from data collected during 2002 and early 2003 with the SVT, are reviewed.

## 2. Direct charm production cross sections

The secondary vertex trigger immediately provided large samples of fully reconstructed  $D$  mesons during the first few months of data taking in early 2002. From  $5.7 \text{ pb}^{-1}$  of data,  $D$  mesons were reconstructed in the modes  $D^0 \rightarrow K^- \pi^+$ ,  $D^{*+} \rightarrow D^0 \pi^+$ ,  $D^0 \rightarrow K^- \pi^+$ ,  $D^+ \rightarrow K^- \pi^+ \pi^+$ , and  $D_s \rightarrow \phi \pi^+$  as shown in Figure 1. Charm mesons originating from  $B$  meson decays can be

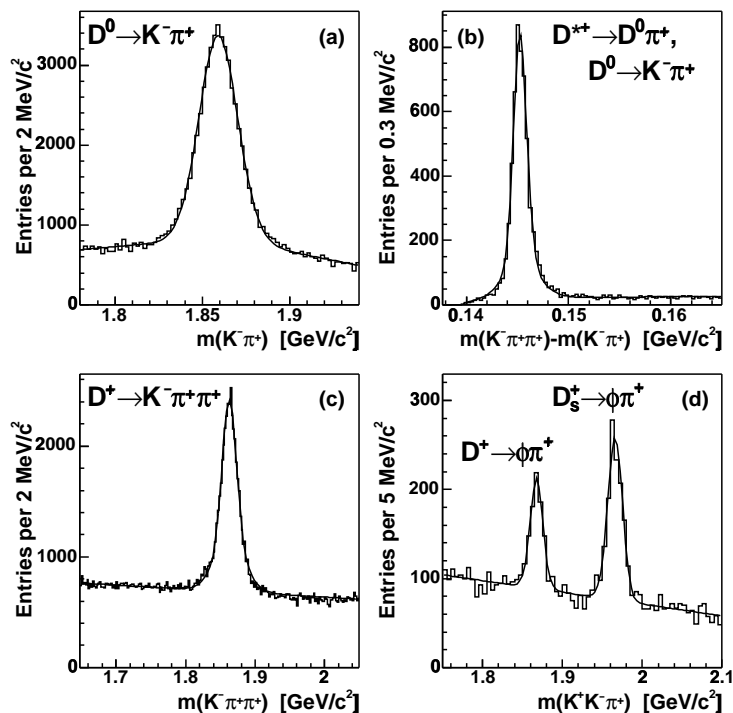
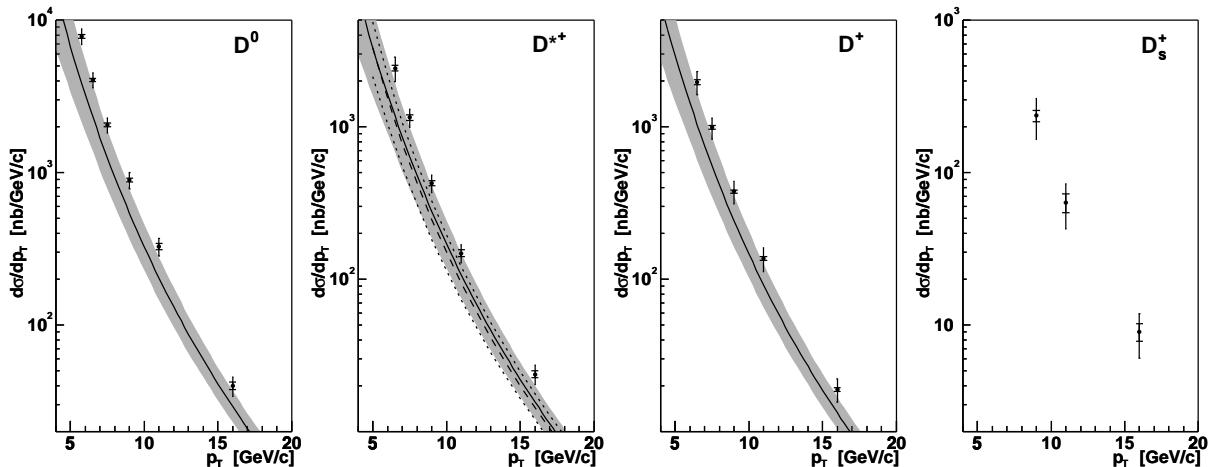


Figure 1.  $D^0, D^*$ , and  $D_s$  invariant mass signals reconstructed in CDF Run II

distinguished from directly produced charm by studying the impact parameter of the meson to the primary vertex.  $D$  mesons from secondary decays of  $B$  mesons will not point back to the primary vertex. A Monte Carlo simulation is used to model the impact parameter distribution of charm mesons from  $B$  decays. The impact parameter distribution of two-track vertices that originate from the primary vertex is measured using  $K_s \rightarrow \pi\pi$  decays in the same data sample. The fraction of directly produced  $D$  mesons,  $f_D$ , obtained from a binned log-likelihood fit to the impact parameter distribution of reconstructed  $D$  mesons is  $f_D(D^0) = 86.6 \pm 0.4 \pm 3.5\%$ ,  $f_D(D^{*+}) = 88.1 \pm 0.4 \pm 3.5\%$ ,  $f_D(D^+) = 89.1 \pm 0.4 \pm 2.8\%$  and  $f_D(D_s^+) = 77.3 \pm 3.8 \pm 2.1\%$ . The number of observed directly produced  $D$  mesons is corrected for the tracking and secondary vertex trigger efficiencies and detector acceptance. The differential cross section thus obtained for various  $D$  mesons with transverse momentum  $p_T > 5.5 \text{ GeV}/c$ , and rapidity,  $|y| < 1.0$ , is shown in Figure 2 with the theoretical prediction from recent NLO QCD calculations [5] overlaid. The integrated cross sections in the range  $|y| < 1.0$  are [6]  $\sigma(p\bar{p} \rightarrow D^0 X, p_T > 5.5 \text{ GeV}/c) = 13.3 \pm 0.2(stat) \pm 1.5(syst) \mu\text{b}$ ,  $\sigma(p\bar{p} \rightarrow D^+ X, p_T > 6.0 \text{ GeV}/c) = 4.3 \pm 0.1(stat) \pm 0.7(syst) \mu\text{b}$ ,  $\sigma(p\bar{p} \rightarrow D^{*+} X, p_T > 6.0 \text{ GeV}/c) = 5.2 \pm 0.1(stat) \pm 0.8(syst) \mu\text{b}$ , and  $\sigma(p\bar{p} \rightarrow D_s X, p_T > 8.0 \text{ GeV}/c) = 0.75 \pm 0.05(stat) \pm 0.22(syst) \mu\text{b}$ . The central value of the differential cross

sections is found to be 30–70% higher than current theoretical predictions although the results are consistent when data and theoretical uncertainties are considered.



**Figure 2.** The differential  $D^0$ ,  $D^*$ ,  $D^+$ , and  $D_s^+$  cross-section distributions measured in CDF Run II (points with error bars) and the theoretical predictions overlaid as a shaded band.

### 3. Charmonium production

The invariant mass of the  $J/\psi \rightarrow \mu\mu$  candidates reconstructed in the CDF II detector is shown in Figure 3. The sample of  $J/\psi$  candidates is divided into transverse momentum bins and the yield in each bin is determined from a fit to the di-muon invariant mass using a Monte Carlo simulation to model the invariant mass of the  $J/\psi$  signal events. The reconstructed yield of  $J/\psi$  events in each transverse momentum bin is corrected by the detector acceptance and integrated luminosity. The differential cross section of  $J/\psi$  events in the transverse momentum range of 0 to 20 GeV/c is shown in Figure 4 and the integrated cross section is measured to be  $\sigma(p\bar{p} \rightarrow J/\psi X, |y(J/\psi)| < 0.6) = 4.08 \pm 0.02(stat) \pm 0.36(syst)\mu\text{b}$

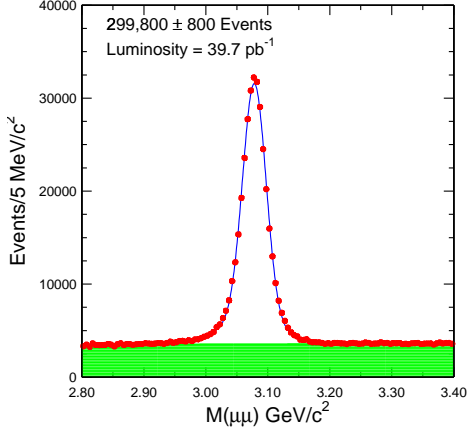
### 4. Measurement of the $b$ -hadron inclusive cross section

A significant fraction of  $J/\psi$  mesons produced at the Tevatron come from the decays of  $b$ -hadrons ( $H_b$ ). In this experiment, the large sample of  $H_b \rightarrow J/\psi X$  events is used to measure the inclusive  $b$ -hadron cross section. Bottom hadrons have long lifetimes, on the order of picoseconds [7], which correspond to flight distances of several hundred microns at CDF. The measured distance between the  $J/\psi$  decay point and the beamline is used to separate prompt production of charmonium from  $b$ -hadron decays.

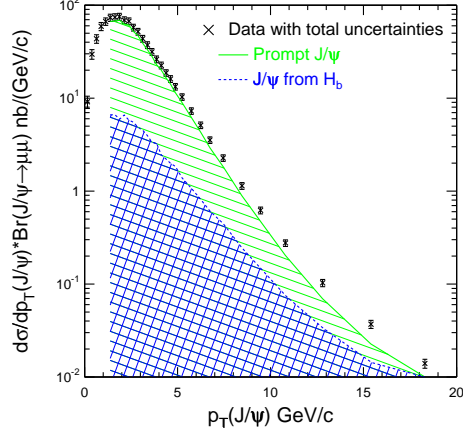
The single  $b$ -hadron cross section is then extracted from the measurement of the cross section of  $J/\psi$  mesons from long-lived  $b$ -hadrons and is found to be  $17.6 \pm 0.4(stat)_{-2.3}^{+2.5}(syst)\mu\text{b}$ . In Figure 5, the  $H_b$  cross-section measurement is compared to a QCD calculation by Cacciari *et al.* [8]. The  $b$ -hadron cross section from this calculation is found to be in good agreement with the CDF II measurement.

### 5. Conclusion

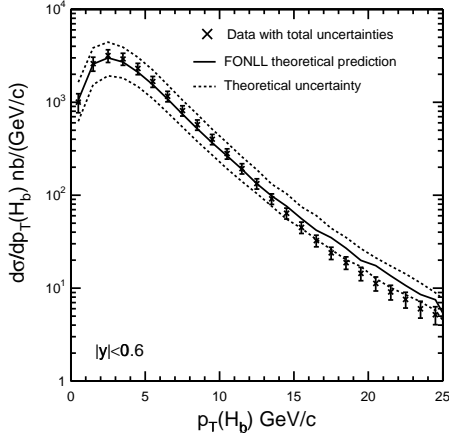
CDF Run II has produced new measurements of charm and beauty cross sections at  $\sqrt{s} = 1960$  GeV using the data sample collected during the first year of running. These measurements exploit the high yields of triggered displaced charm mesons and  $J/\psi$  from the secondary vertex track trigger and upgraded di-muon triggers respectively. The central  $J/\psi$  and  $b$ -hadron



**Figure 3.** The invariant mass distribution of triggered  $J/\psi$  events reconstructed in  $37 \text{ pb}^{-1}$  of Run-II data.



**Figure 4.** The inclusive production cross section of  $J/\psi$  mesons and the contribution from the decays of  $b$ -hadrons.



**Figure 5.** The differential cross section for  $H_b \rightarrow J/\psi$  with  $|y| < 0.6$ . The solid line is the central theoretical values using the FONLL calculations outlined in [8], the dashed line is the theoretical uncertainty.

cross sections have been measured in the transverse momentum range of 0-20  $\text{GeV}/c$  for the first time. The charm meson cross sections of  $D^0$ ,  $D^*$ ,  $D^\pm$ , and  $D_s$  have been measured for  $p_T(D) > 5.5 \text{ GeV}/c$ . A comparison between some recent theoretical calculations and the measured charm meson and  $b$ -hadron cross sections show reasonable agreement within measurement and theoretical uncertainties, although the central values of the charm meson cross sections are 30% to 70% higher than theoretical predictions.

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