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**Measurement of the $\gamma + D^{*\pm}$ Cross Section
in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV**

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**Measurement of the $\gamma + D^{*\pm}$ Cross Section in $\bar{p}p$ Collisions at
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Abstract

We have measured the cross section of $\gamma + D^{*\pm}$ production in $\bar{p}p$ collisions at $\sqrt{s}=1.8$ TeV using the Collider Detector at Fermilab (CDF). From the 45 ± 18 $\gamma + D^{*\pm}$ candidates in a 16.4 pb^{-1} data sample, we have determined the production cross section to be $0.38\pm 0.15(\text{stat})\pm 0.11(\text{syst}) \text{ nb}$ for the rapidity range $|y(D^{*\pm})| < 1.2$ and $|y(\gamma)| < 0.9$, and for the transverse momentum range $p_{\text{T}}(D^{*\pm}) > 6 \text{ GeV}/c$ and $16 < p_{\text{T}}(\gamma) < 40 \text{ GeV}/c$. The measured cross section is compared to a theoretical prediction.

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$\bar{p}p$ collisions producing a charm quark associated with a prompt photon can provide information on the charm quark momentum distribution in a nucleon. Theoretical predictions indicate that the fraction of momentum, x , carried by charm quarks (charm quarks/all quarks) will increase with decreasing x and that in the low x region the Compton scattering process ($gc \rightarrow \gamma c$) is expected to dominate[1]. The charm quark momentum distribution in the proton is an important input to the production cross section estimations for current and future high energy hadron colliders.

In this Letter we report the first measurement of the production cross section for $\gamma + D^{*\pm}$ in $\bar{p}p$ collisions at $\sqrt{s}=1.8$ TeV. This measurement corresponds to a range of fractional momentum of $0.018 < x < 0.044$ for the reaction $\bar{p}p \rightarrow \gamma D^{*\pm} X$. The data used in this analysis were taken with the CDF detector during 1992-1993. Events containing a photon were collected by a trigger that required isolated clusters of electromagnetic energy with a 16 GeV transverse energy, ($E_T = E \sin \theta$), threshold [2][3]. This data sample corresponds to an integrated luminosity, $\mathcal{L} = 16.4 \pm 0.6 \text{ pb}^{-1}$.

The CDF detector is described in detail elsewhere [4]. Only the CDF detector systems relevant to this analysis are described here. Inside a 1.4 T solenoidal magnetic field, the silicon vertex detector (SVX), the vertex time projection chamber (VTX), and the central tracking chamber (CTC) provide the tracking and momentum information for charged particles. The SVX consists of four layers of silicon strip detectors and covers $|z| < 25$ cm. The VTX is used to measure the $\bar{p}p$ interaction vertex position along the z axis. The CTC is a cylindrical drift chamber consisting of 84 layers that are grouped into 5 axial and 4 stereo superlayers [5], and covering the pseudorapidity range $|\eta| < 1.2$. Located outside of the solenoid, the central electromagnetic calorimeter (CEM) has a projective tower

geometry with a segmentation of $\Delta\phi \times \Delta\eta = 15^\circ \times 0.11$ and covers $|\eta| < 1.1$. The central electromagnetic strip chamber (CES) is embedded in the CEM at the shower maximum position to measure electromagnetic shower profiles in both the ϕ and z directions.

Events with isolated photons were selected by the same cuts used in the CDF inclusive photon cross section measurement [2]. These cuts include an isolation requirement of $E_T(0.7) < 2$ GeV, where $E_T(0.7)$ is the E_T sum (excluding the photon) in a cone of radius $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.7$. We used photons within the ranges $|y| < 0.9$ and $16 < p_T < 40$ GeV/ c . The primary vertex of the $\bar{p}p$ interaction was required to be within $|z| < 60$ cm. If there were two or more primary vertices (multiple interactions) in an event, we selected the highest quality vertex by using the number of associated tracks and their fitting qualities [6]. The $D^{*\pm}$ candidates were required to come from this vertex.

In these photon candidate events, we reconstructed $D^{*\pm}$ mesons using decays of $D^{*+} \rightarrow D^0 \pi_s^+$ [7], $D^0 \rightarrow K^- \pi^+ (K\pi)$ or $K^- \pi^+ \pi^+ \pi^- (K3\pi)$ and their charge conjugate modes. Hereafter charge conjugate modes are implied. We took all combinations of three ($K-\pi-\pi_s$) or five ($K-\pi-\pi-\pi-\pi_s$) tracks in an event to form a D^{*+} meson, preserving the electric charge correlation between the π_s^+ and K^- mesons. Tracks were required to include hits in 2 or more axial and in 2 or more stereo superlayers. The tracks were assumed to be alternatively a kaon or a pion, and were required to pass the kinematical cuts listed in Table 1. The tracks forming a D^0 were constrained to come from a common point in space. The π_s^+ track was constrained to come from the primary vertex. The D^{*+} system was required to have $p_T > 6$ GeV/ c to reduce the background due to random track combinations (combinatorial background). For each combination, we calculated the mass difference $\Delta m \equiv m(D^0 \pi_s^+) - m(D^0)$. To prevent double counting, we chose the one

D^0 combination whose reconstructed D^0 mass was closest to the world average D^0 mass ($=1864.5 \text{ MeV}/c^2$) [8]. If there were two or more D^{*+} combinations within $\Delta m < 168 \text{ MeV}/c^2$ in an event, we selected the combination which had the highest $D^{*+} p_T$.

Two categories of backgrounds were considered in order to estimate the number of $\gamma + D^{*+}$ candidates: the photon background and the D^{*+} background. The fraction of the photons in the photon candidates was statistically determined by comparing the shower profile, as measured in the CES, with the profile expected from electron test beam data [9]; this is done for each Δm bin separately.

Figure 1 shows the Δm distributions for the two combined D^0 decay channels and for a simulated D^{*+} background before subtracting photon backgrounds. The D^{*+} background was simulated using D^0 side band events within $60 < (m_{D^0} - 1864.5) < 120 \text{ MeV}/c^2$. The number of background events was normalized to the data in $150 < \Delta m < 168 \text{ MeV}/c^2$. A Gaussian distribution plus a simple background function $a \times (\Delta m - m_\pi)^b$ were fitted to the data, where m_π is the pion mass; the result of the fit is shown in the figure. The mean of the fitted Gaussian distribution was $\Delta m = (145.0 \pm 0.3) \text{ MeV}/c^2$, where the error is statistical only. This is consistent with the world average mass difference of $m_{D^{*(2010)+}} - m_{D^0} = (145.42 \pm 0.05) \text{ MeV}/c^2$ [8]. The width, $\sigma_{\Delta m} = (0.7 \pm 0.2) \text{ MeV}/c^2$, is consistent with the expectation from a CDF detector simulation. To determine the $\gamma + D^{*+}$ cross section we define the signal region as $144 < \Delta m < 147 \text{ MeV}/c^2$. The number of D^{*+} background events in this region is determined using the D^0 side band described above under the assumption that the D^{*+} background events have the same Δm distribution as these combinatorial background events. Subtracting the photon background and the D^{*+} background, we observe $(45 \pm 18) \gamma + D^{*+}$ candidates which consist of (22 ± 9) and

(23 ± 16) candidates in the $K\pi$ and $K3\pi$ channels, respectively.

We looked at the proper decay length ($c\tau$) distribution of the D^0 candidates within our sample by selecting the mass difference window $144 < \Delta m < 147 \text{ MeV}/c^2$. From a total of 151 events in this window, we required at least 2 (3) tracks to include SVX information for the $K\pi$ ($K3\pi$) channel, and observed 16 (47) events. The $c\tau$ distribution for these 63 events is shown in Figure 2 together with that for Monte Carlo simulated D^0 mesons originating from prompt c -quark hadronization, b -quark decay, and background events ($150 < \Delta m < 168 \text{ MeV}/c^2$), where the normalization was determined from the Δm distribution. The $c\tau$ distribution observed in the data is consistent with that of the simulated D^0 mesons from the hadronization of directly produced c -quarks.

The contributions to $\gamma + D^{*+}$ production from gluon splitting ($q\bar{q} \rightarrow \gamma g \rightarrow \gamma c\bar{c}$) and b -quark decay ($bg \rightarrow \gamma b \rightarrow \gamma cX$) processes were estimated using two Monte Carlo programs, PYTHIA [10] and HERWIG[11], each followed by a CDF detector simulation. The fraction of our candidates involving gluon splitting is estimated by both PYTHIA and HERWIG to be 7 %. We have made an independent check of this fraction from the inclusive jet data sample in which we reconstructed D^{*+} mesons. Assuming all of the D^{*+} mesons came from gluon splitting, we estimate a $(12 \pm 4)\%$ contribution from gluon splitting in the photon sample, after correcting for the different gluon fractions in the two samples. The fraction of b -quark decay processes that contribute to the $\gamma + D^{*+}$ cross section is expected to be small [12]. Both Monte Carlo programs estimate this fraction to be only 3%.

To measure the cross section for the $\gamma + D^{*+}$ production, the reconstruction efficiency of $\gamma + D^{*+}$ events was determined using the PYTHIA Monte Carlo and the data. Compton

scattering, gluon splitting, and b -quark decay processes were all considered [13]. The trigger efficiency (ϵ_{trig}) for photons in the region of $p_T > 16$ GeV/c and $|y| < 0.9$ is 0.80 ± 0.03 [2][9]. This was obtained from electron events collected with a lower E_T trigger. The photon selection cut efficiency (ϵ_{sel}) is 0.37 ± 0.01 [2]. The D^{*+} detection efficiencies (ϵ_{rec}) are 0.46 ± 0.01 and 0.24 ± 0.01 for the $K\pi$ and $K3\pi$ channels. These were estimated from simulated and real events. Effects such as density of hits in the tracking devices were measured by embedding tracks from simulated D^{*+} mesons in real photon events on the opposite side of photon candidates in azimuthal angle and randomly in $|y| < 1.2$. The overall efficiencies ($\epsilon = \epsilon_{\text{trig}} \times \epsilon_{\text{sel}} \times \epsilon_{\text{rec}}$) were estimated to be $\epsilon_{K\pi} = 0.136 \pm 0.018$ and $\epsilon_{K3\pi} = 0.071 \pm 0.011$ for the $K\pi$ and $K3\pi$ channels, respectively, where the errors quoted include systematic effects which are dominated by the tracking efficiency estimations.

The cross section was calculated using

$$\sigma(\bar{p}p \rightarrow \gamma D^{*+} X) = \frac{N(\gamma + D^{*+})}{B_{D^0\pi_s} \cdot (\epsilon_{K\pi} \cdot B_{K\pi} + \epsilon_{K3\pi} \cdot B_{K3\pi}) \cdot \mathcal{L}} ,$$

where $N(\gamma + D^{*+})$ is the number of the $\gamma + D^{*+}$ candidates, $B_{D^0\pi_s} (= 68.1 \pm 1.6\%)$ denotes the branching ratio of the $D^{*+} \rightarrow D^0\pi_s^+$ decay, $B_{K\pi} (= 3.84 \pm 0.13\%)$ denotes the branching ratio of the $D^0 \rightarrow K^- \pi^+$ decay and $B_{K3\pi} (= 7.5 \pm 0.4\%)$ denotes the branching ratio of the $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$ decay. We used the world average values [8] for the decay branching ratios. The $\gamma + D^{*+}$ production cross section is measured to be $0.38 \pm 0.15 \pm 0.11$ nb for the rapidity range $|y(D^{*+})| < 1.2$ and $|y(\gamma)| < 0.9$ and for the transverse momentum range $p_T(D^{*+}) > 6$ GeV/c and $16 < p_T(\gamma) < 40$ GeV/c, where the first uncertainty is statistical and the second is systematic.

The contributions to the systematic uncertainty are summarized in Table 2. The un-

certainty in subtracting the photon background was determined to be 9% by comparing the measured inclusive photon cross sections obtained by two different background subtraction schemes [2]. The uncertainty associated with the D^{*+} reconstruction includes the following effects: 1) the difference in the track environment around a D^{*+} between real data and simulated data; 2) the D^{*+} p_T spectrum difference due to fragmentation, renormalization scale, relative fraction of the processes involved (Compton scattering, gluon splitting, and b -quark decay), and parton distribution function models. Three different parton distribution functions were used to estimate the model dependence of the D^{*+} p_T spectrum: CTEQ2M [14], MRSD0', and MRSD-' [15]. The largest variation between these acceptance estimates was 4.7% ($K\pi$) and 5.3% ($K3\pi$). The uncertainty on the D^{*+} background subtraction (25%) comes from the variation allowed in the shape of the background Δm distribution and is dominated by the statistics on the D^0 side band events. The total systematic uncertainty is 29% on the measured cross section.

The measured cross section can be compared to a theoretical prediction calculated with PYTHIA including the Compton scattering, the gluon splitting, and the b -quark decay processes. The calculated cross sections with the parton distribution functions CTEQ2M, MRSD0', and MRSD-' were 0.21, 0.22, and 0.18 nb, respectively, where the photon p_T was taken as the renormalization and factorization scales. The measured cross section, $0.38 \pm 0.15(\text{stat.}) \pm 0.11(\text{syst.})$ nb, is higher than, but not inconsistent with, these theoretical predictions.

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Table 1: Kinematic cuts applied to tracks used in the D^{*+} reconstruction.

		$K\pi$	$K3\pi$	
p_T of K	>	1.0	1.7	GeV/ c
Leading pion p_T	>	0.7	1.2	GeV/ c
p_T of π 's	>	–	0.6	GeV/ c
p_T of π_s^+	>	0.4	0.45	GeV/ c
$ m_{D^0} - 1864.5 $	<	30	30	MeV/ c^2

Table 2: Systematic uncertainties on the cross section.

Source	Contribution
Luminosity	3.6%
γ background subtraction	9%
D^{*+} background subtraction	25%
Branching ratio of the D^{*+} decay	2.4%
Branching ratio of the D^0 decays	3.4%
Reconstruction efficiency	11%
Total systematic uncertainty	29%

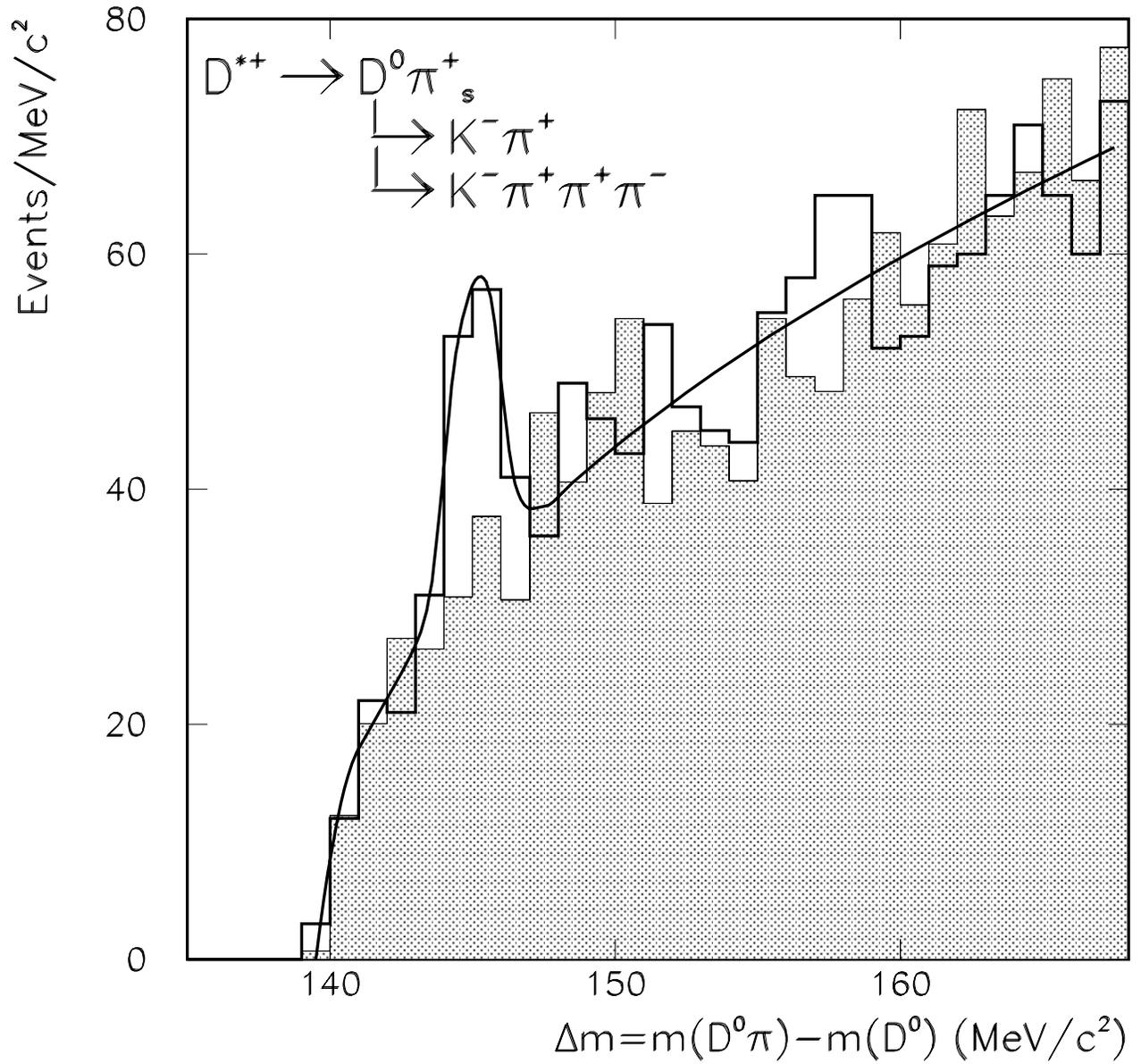


Figure 1: The mass difference (Δm) distributions using the D^0 reconstructions of $D^0 \rightarrow K^- \pi^+$ and $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$. The open histogram shows the data, and the shaded histogram shows the D^{*+} background using the D^0 side band events. The solid line is the fit to the data described in the text.

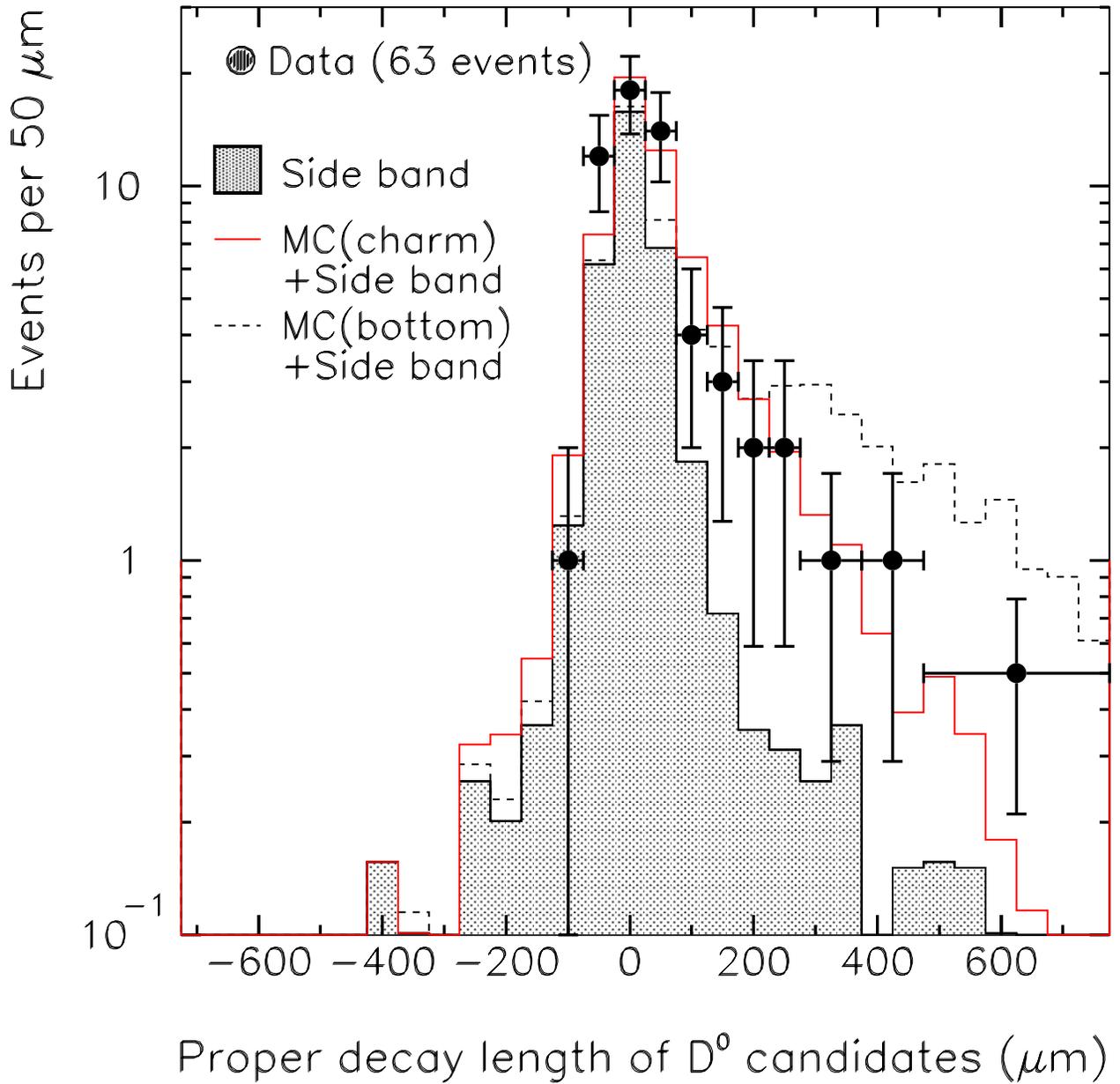


Figure 2: The proper decay length distribution of the D^0 candidates in the $\gamma + D^{*+}$ events. The dots show the data, where the errors on the data are statistical only. The shaded histogram shows the background simulated by the side band events, and the solid and dashed lines show the distributions of the background plus Monte Carlo D^0 mesons originating from prompt c -quark hadronization and from b -quark decay, respectively.