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Measurement of A_c with Charmed Mesons at SLD*

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Abstract

We present a direct measurement of the parity-violation parameter A_c in the coupling of the Z^0 to c-quarks with the SLD detector. The measurement is based on a sample of 530k hadronic Z^0 decays, produced with a mean electron-beam polarization of $|P_e| = 73\%$. The tagging of c-quark events was performed using two methods: the exclusive reconstruction of D^{*+}, D^+, and D^0 mesons, and the inclusive P_T spectrum of soft-pions (π_s) in the decay of $D^{*+} \to D^0\pi_s^+$. The combination of these two methods yields $A_c = 0.687 \pm 0.040$.

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I. INTRODUCTION

In the Standard Model, the Z^0 coupling to fermions has both vector (v) and axial-vector (a) components. Measurements of fermion asymmetries at the Z^0 resonance probe a combination of these components given by

$$A_f = 2v_f a_f/(v_f^2 + a_f^2). \tag{1}$$

The parameter A_f expresses the extent of parity violation at the $Zf\bar{f}$ vertex and its measurement provides a sensitive test of the Standard Model.

At the Born-level, the differential cross section for the reaction $e^+e^- \to Z^0 \to f\bar{f}$ is

$$\sigma_f(z) \equiv d\sigma_f/dz \propto (1 - A_e P_e)(1 + z^2) + 2A_f(A_e - P_e)z, \tag{2}$$

where P_e is the longitudinal polarization of the electron beam ($P_e > 0$ for net right-handed polarization) and $z = \cos\theta$, θ being the polar angle of the outgoing fermion relative to the incident electron. In the absence of electron beam polarization, the parameter A_f can be extracted by isolating the term linear in $z = \cos\theta$ via the forward-backward asymmetry:

$$A_{FB}^f(z) = \frac{[\sigma^f(z) - \sigma^f(-z)]}{[\sigma^f(z) + \sigma^f(-z)]} = A_e A_f \frac{2z}{1 + z^2}, \tag{3}$$

which also depends on the initial state electron parity-violation parameter A_e. At the SLAC Linear Collider (SLC), the ability to manipulate the longitudinal polarization of the electron beam allows the isolation of the parameter A_f in Eq. 2, independent of A_e, using the left-right forward-backward asymmetry:

$$\tilde{A}_{FB}^f(z) = \frac{[\sigma_L^f(z) - \sigma_L^f(-z)] - [\sigma_R^f(z) - \sigma_R^f(-z)]}{[\sigma_L^f(z) + \sigma_L^f(-z)] + [\sigma_R^f(z) + \sigma_R^f(-z)]} = |P_e| A_f \frac{2z}{1 + z^2}, \tag{4}$$

where indices L, R refers to $Z^0 \to f\bar{f}$ decays produced with left-handed or right-handed polarization of the electron beam, respectively. For a highly polarized electron beam with $|P_e|$=73%, $\tilde{A}_{FB}^f$ provides a statistical advantage of $(P_e/A_e)^2 \sim 24$ in the sensitivity to A_f relative to the unpolarized asymmetry.

In this paper, we present a direct measurement of the parity-violation parameter A_c for the $Zc\bar{c}$ coupling. The tagging of c-quarks is performed using exclusively reconstructed D^{*+}, D^+, and D^0 mesons, as well as an inclusive sample of $D^{*+} \to D^0\pi_s^+$ decays identified by the soft-pion (π_s).[1]

The charge of the primary c-quark is determined by the charge of the $D^{(*)}$, K (in the D^0 reconstruction case), or π_s (in the soft-pion analysis case). The direction of the primary quark is estimated from the direction of the exclusively reconstructed $D^{(*)+}$ or D^0 meson, or the jet axis in the soft-pion analysis. The value of A_c is extracted via an unbinned maximum likelihood fit. The fit is performed on two separate data samples: one collected between 1993 and 1995, and the other, with an improved vertex detector, between 1996 and 1998. The data samples associated with these two periods comprise 150k and 380k hadronic Z^0 decays, respectively. The measurement of A_c presented in this paper updates and supersedes our previous publication [1], which was based on a sample of 50k hadronic Z^0 decays from 1993 alone.

II. APPARATUS AND EVENT SELECTION

The measurement described here is based on 530k hadronic Z^0 decays recorded in 1993-98 with the SLC Large Detector (SLD) at the SLC e^+e^- collider at a mean center-of-mass-energy of 91.27 GeV(1993-95) or 91.24 GeV(1996-98). A general description of the SLD can be found elsewhere [2]. Charged-particle tracking for the 1993-95 data sample uses the central drift chamber (CDC) [3] and VXD2 [4] CCD pixel vertex detector. For this system, the measured impact-parameter resolution in the transverse (longitudinal) direction with respect to the beam axis can be approximated by $11 \bigoplus 70/P\sin^{3/2}\theta$ μm ($38 \bigoplus 70/P\sin^{3/2}\theta$ μm), as a function of the track momentum P (in GeV/c) and the polar angle θ. In 1996, we installed the upgraded 307M pixel vertex detector (VXD3) [5], which provides improved

[1] Throughout the paper charge-conjugate states are implicitly included.

impact-parameter resolution of $7.8 \bigoplus 33/P\sin^{3/2}\theta$ μm ($9.7 \bigoplus 33/P\sin^{3/2}\theta$ μm) in the transverse (longitudinal) direction with respect to the beam axis. In addition, VXD3 extended the polar-angle coverage from $|\cos\theta| < 0.75$ to $|\cos\theta| < 0.85$. Combining the CDC and the VXD, a momentum resolution of $\sigma(P_T)/P_T = \sqrt{(.01)^2 + (.0026 P_T/GeV)^2}$ is achieved. The Liquid Argon Calorimeter (LAC) [6] measures the energy of charged and neutral particles and is also used for electron identification. It covers the polar-angle region of $|\cos\theta| < 0.84$, and has energy resolutions of $15\%/\sqrt{E(\mathrm{GeV})}$ and $65\%/\sqrt{E(\mathrm{GeV})}$ for electromagnetic and hadronic showers, respectively. Muon identification is provided by the Warm Iron Calorimeter (WIC) [7]. The Čerenkov Ring Imaging Detector (CRID) [8] provides particle identification. In order to provide particle identification over a wide momentum range, the CRID uses two different radiator systems. Liquid (C_6F_{14}) and gas (C_5F_{12}) radiators provide good $\pi/K/p$ separation in the momentum range from 0.5 to 3.0 GeV/c and up to 35 GeV/c, respectively.

The SLC was operated with a polarized electron beam and an unpolarized positron beam [9]. The average electron polarization measured for the 1993-98 data sample is $|P_e| = 73 \pm 0.5\%$ [9,10]. The SLC interaction-point (IP) size in the xy plane is 2.6 μm $\times$ 0.8 μm and its mean position is reconstructed with a precision of $\sigma_{IP} = 4\mu$m (7μm) using the tracks in sets of $\sim$30 sequential hadronic events for the 1996-98 (1993-95) data sets [11]. The event-by-event median z position of tracks at their point of closest approach to the IP in the xy plane determines the z position of the Z^0 primary vertex (PV) with a precision of $\sim$15 μm (35 μm) for the 1996-98 (1993-95) data.

Hadronic events are selected by requiring at least 5 charged tracks, a total visible energy of at least 20 GeV/c, and a thrust axis calculated from charged tracks satisfying $|\cos\theta_{thrust}| < 0.87$ (0.8 for the 1993-95 data). Tracks were selected by the following criteria for the 1996-98 (1993-95) samples:

1. At least 23 (30 for the 1993-95 data) associated CDC hits (out of a maximum of 80 possible hits);

2. An inner radius of the reconstructed track within 50 cm (39 cm) of the IP;

3. An xy and rz impact parameter with respect to the IP of less than 5cm (10cm);

4. A reconstructed polar angle θ with $|\cos\theta| < 0.87$ (0.80); and

5. A momentum transverse to the beam axis of $P_T > 0.15$ GeV/c.

As $Z^0 \to b\bar{b}$ events are also a copious source of D mesons, they represent a potential background. We reject these events using the invariant mass of the charged tracks associated with reconstructed secondary decay vertices [12]. In particular, we require that there must be no vertex with invariant mass greater than 2.0 GeV/c^2. Monte Carlo (MC) simulations indicate that this cut rejects 57% of $b\bar{b}$ events while preserving 99% of $c\bar{c}$ events.

III. A_C MEASUREMENT WITH EXCLUSIVE CHARMED-MESON RECONSTRUCTION

In this analysis, we reconstruct three different D meson states for c-quark tagging: the pseudo-scalar mesons D^+ and D^0, and the vector meson D^{*+}. This chapter describes the procedure for the reconstruction of the D mesons, as well as the corresponding A_c measurement and a discussion of associated systematic errors.

A. D^{*+} selection

D^{*+} mesons are identified via the decay $D^{*+} \to D^0 \pi_s^+$ followed by:

$$\begin{array}{lll} D^0 \to K^-\pi^+ & & K\pi, \\ D^0 \to K^-\pi^+\pi^0 & & \textit{Satellite}, \\ D^0 \to K^-\pi^+\pi^-\pi^+ & & K\pi\pi\pi, \text{ or} \\ D^0 \to K^- l^+ \nu_l & (l\text{=e or } \mu) & \textit{Semileptonic.} \end{array}$$

In these decays, the charge of the underlying c quark is specified by the charge of the "soft pion" π_s. No attempt is made to reconstruct the π^0 in the satellite mode, nor to estimate the neutrino direction or energy in the semileptonic mode.

To form the D^{*+} candidate, we use all tracks which have VXD hits in one event hemisphere. We divide an event into two hemispheres by the plane which is perpendicular to the thrust axis. In the $K\pi\pi\pi$ mode, we only use tracks which have momentum greater than 0.75 GeV/c. For D^0 candidates, tracks corresponding to the charged multiplicity in each D^0 decay mode are combined assuming one of them is a kaon and the others are pions. Only candidates with the correct charge combinations are selected. In the semileptonic mode, we combine an identified electron or muon track with another track which has opposite charge and assume the track to be a kaon. Electrons are identified based on the momentum measured with the CDC and the energy deposited in the calorimeter [13]. Electrons from γ-conversions are rejected. Muon candidates are identified by the association of extrapolated CDC tracks with hits in the WIC [13].

A vertex fit is performed on the tracks forming a D^0 candidate, and we require that its χ^2 probability be greater than 1%. The invariant mass M of the D^0 candidates is required to lie within the following ranges:

$$
\begin{aligned}
&1.765\mathrm{GeV/c^2} < M_{D^0} < 1.965\mathrm{GeV/c^2} \ \ (K\pi),\\
&1.500\mathrm{GeV/c^2} < M_{D^0} < 1.600\mathrm{GeV/c^2} \ \ (\mathit{Satellite}),\\
&1.795\mathrm{GeV/c^2} < M_{D^0} < 1.935\mathrm{GeV/c^2} \ \ (K\pi\pi\pi),\\
&1.100\mathrm{GeV/c^2} < M_{D^0} < 1.800\mathrm{GeV/c^2} \ \ (\mathit{Semileptonic}).
\end{aligned}
$$

These reconstructed pseudo-scalar meson candidates are then combined with a soft-pion candidate track with charge opposite to that of the kaon candidate, thus forming the D^{*+} candidate.

To reconstruct the D^{*+}, we use two sets of selection criteria. One is based on event kinematics and the other on event topology. The former relies on the fact that D^{*+} mesons in $c\bar{c}$ events have much higher $x_{D^*} \equiv 2E_{D^*}/E_{CM}$, where E_{D^*} is the D^{*+} energy, than those in $b\bar{b}$ events or random combinatoric background (RCBG). The latter relies on the fact that D^0's in $c\bar{c}$ events have a longer 3D decay length (~ 1 mm) than that for RCBG, and originate at the primary vertex, in contrast to those D^0's in $b\bar{b}$ events emerging from B decay vertices. We select the combinations which satisfy either condition.

In the selection based on the event kinematics, we require the candidate to have x_{D^*} greater than 0.4 ($K\pi$, *Satellite*, and *Semileptonic*) or 0.6 ($K\pi\pi\pi$). For a true D^0 candidate, the distribution of $\cos\theta^*$, where θ^* is the opening angle between the direction of the D^0 in the laboratory frame and the kaon in the D^0 rest frame, is expected to be flat. Since background events peak at $\cos\theta^* = \pm 1$, they were further reduced by requiring $|\cos\theta^*| \leq 0.9$ ($K\pi$, *Satellite*, and *Semileptonic*) or 0.8 ($K\pi\pi\pi$). We also require the soft-pion candidate to have momentum greater than 1 GeV/c. In the satellite mode, we apply a 3D decay-length cut of $L/\sigma_L > 1.5$ on the reconstructed D^0 vertices to reduce the RCBG. (The decay-length resolution is $< \sigma_L > \sim 150$ μm.)

In the selection based on the event topologies, we require the reconstructed D^0 vertices to have the 3D decay-length significance $L/\sigma_L > 2.5$, and the xy impact parameter of the D^0 momentum vector to the IP to be less than 20 μm ($K\pi$ and $K\pi\pi\pi$) or 30 μm (*Satellite* and *Semileptonic*). The latter cut is effective in rejecting D decays in $b\bar{b}$ events. Since these D's have significant P_T relative to the parent B flight direction, and the B's themselves have a significant flight length (~ 3.5 mm), many of these D's do not appear to originate from the primary vertex.

Fig. 1 shows the distribution of xy impact parameter of the D^0 relative to the IP for the decay of $D^{*+} \to D^0\pi_s^+$, $D^0 \to K^-\pi^+$. In this figure, we don't reject B-decay candidate events with the invariant mass cut of the reconstructed secondary vertices described above, only for the purpose of showing how the xy-impact-parameter cut is effective to reject the B-decay background. Half of the B-decay background events are rejected by the xy-impact-parameter cut.

Finally, a cut of x_{D^*} greater than 0.3 ($K\pi$, *Satellite*, and *Semileptonic*) or 0.4 ($K\pi\pi\pi$)

is applied. Because the purity of the resulting charm sample is sufficiently high, there is no need to apply $\cos\theta^*$ or momentum cuts on the soft pion. The overlaps of the sets of candidates from the event kinematics and topology analysis are 53% ($K\pi$), 50% (satellite), 28% ($K\pi\pi\pi$), and 36% (semileptonic). In the $K\pi\pi\pi$ sample, there may be multiple D^0 candidates in a single event which pass the above cuts. To avoid double counting and to reduce the background, we select the D^0 candidate with the lowest vertex χ^2.

Having selected a candidate, we form the mass difference $\Delta M = M_{D^*} - M_{D^0}$. We include the candidates in the signal sample provided ΔM is less than 0.148 GeV/c^2 ($K\pi$ and $K\pi\pi\pi$), less than 0.155 GeV/c^2 (*Satellite*), and less than 0.16 GeV/c^2 (*Semileptonic*). The side-band region is defined as $0.16 < \Delta M < 0.20$ GeV/c^2 ($0.17 < \Delta M < 0.20$ GeV/c^2 for the *Semileptonic* mode), and is used to estimate RCBG contamination in the signal region. The mass difference spectra for the four reconstructed D^{*+} decay modes are shown in Fig. 2.

For all decay modes, clear peaks around $\Delta M = 0.14$ GeV/c^2 appear due to the D^{*+} to D^0 transition. In the figure, the MC predictions for the reconstructed D^{*+} (open) and RCBG (hatched) are also presented. For the MC prediction, the relative normalizations of signal and RCBG shapes are adjusted so that the predicted numbers of events match those observed in the data signal and side-band regions. Averaged over the various modes, this procedure requires adding 10% to the MC signal and 5% to the MC RCBG.

B. D^+ and D^0 selection

The D^+ and D^0 mesons are identified via the decay channels

$$D^+ \to K^-\pi^+\pi^+$$
$$D^0 \to K^-\pi^+.$$

These modes are reconstructed by considering all tracks in each hemisphere which have VXD hits. In the D^+ reconstruction, we additionally require each track to have a momentum of greater than 1 GeV/c.

For the D^+ reconstruction, we combine two same-sign pion candidates with an opposite-sign kaon candidate. We require that x_{D^+} be greater than 0.4, and $\cos\theta^*$ be greater than -0.8. To reject D^{*+} decays, the differences between $M_{K^-\pi^+\pi^+}$ and $M_{K^-\pi^+}$ are formed for each of the pions, and both are required to be greater than 0.16 GeV/c^2. To remove RCBG, we require that the χ^2 probability of the good vertex fit be $> 1\%$, and that the 3D decay-length significance L/σ_L be greater than 3.0. To reject D^+'s from $b\bar{b}$ events, the angle between the D^+ momentum vector and the vertex flight direction is required to be less than 5 mrad in xy and less than 20 mrad in rz.

To form the D^0 vertices, kaon-candidate tracks identified with the CRID are combined with an opposite-sign pion candidate. To reject background we require x_{D^0} be greater than 0.4 but do not place a requirement on $\cos\theta^*$ since the resulting signal purity is sufficiently high. We require that the vertex fit have χ^2 probability greater than 1% and apply a 3D decay-length cut of L/σ_L be greater than 3.0. To reject the D^0's from D^{*+} decays, the differences between $M_{K^-\pi^+\pi^+}$ or $M_{K^-\pi^+\pi^-}$ and $M_{K^-\pi^+}$ are formed for all other tracks in the same hemisphere, and these are required to be greater than 0.16 GeV/c^2. Finally, to reject D^0's from $b\bar{b}$ events, we require that the xy impact parameter of the D^0 momentum vector relative to the IP be less than 20 μm.

D^+ and D^0 candidates in the ranges of $1.800 < M_{K^-\pi^+\pi^+} < 1.940$ GeV/c^2 and $1.765 < M_{K^-\pi^+} < 1.965$ GeV/c^2, respectively, are regarded as signal. The side-band regions are defined as $1.640 < M_{K^-\pi^+\pi^+} < 1.740$ GeV/c^2 and $2.000 < M_{K^-\pi^+\pi^+} < 2.100$ GeV/c^2 for D^+, and $2.100 < M_{K^-\pi^+\pi^+} < 2.500$ GeV/c^2 for D^0. In Fig. 3, the invariant mass spectra for the resulting D^+ and D^0 signals are plotted. The backgrounds in the signal regions are estimated from the MC in the same manner as in the D^{*+} analysis.

C. Measurement of A_c

Using the six decay modes, we select 3967 D^{*+}, D^+, and D^0 candidates from 1993-98 SLD data, which, according to the MC, consists of 2829±35 $c \to D$ signal, 281±11 $b \to D$, and 857±19 RCBG. These $c \to D$ signals correspond to a selection efficiency for $c\bar{c}$ events of 3.9%. The results for the number of selected candidates are summarized in Table I.

The charge of the primary c-quark is determined by the charge of the $D^{(*)}$, or K (in the D^0 case). The direction of the primary quark is estimated from the direction of the reconstructed D meson. Then the cosine of the polar angle of the primary c-quark direction relative to the incident electron, $y \equiv q \cos\theta_D$, is estimated. Here, q is the sign of the charge of the primary c-quark and θ_D is the polar angle of the reconstructed D meson. Fig. 4 shows $q\cos\theta_D$ distributions for the selected D meson sample separately for left- and right-handed electron beams. Clear asymmetries are observed.

To extract A_c, we use an unbinned maximum likelihood fit based on the Born-level cross section for fermion production in Z^0-boson decay. The likelihood function used in this analysis is

$$\begin{aligned}\ln\mathcal{L} = \sum_{i=1}^{n} \ln \{ & P_c^j(x_D^i)\cdot[(1-P_eA_e)(1+y_i^2)+2(A_e-P_e)y_i\cdot A_c^D] \\ & + P_b^j(x_D^i)\cdot[(1-P_eA_e)(1+y_i^2)+2(A_e-P_e)y_i\cdot A_b^D] \\ & + P_{RCBG}^j(x_D^i)\cdot[(1+y_i^2)+2A_{RCBG}y_i]\} \end{aligned} \tag{5}$$

where n is the total number of candidates and the index j indicates each of the six charm decay modes.

A_c^D and A_b^D are the asymmetries from D^{*+}, D^+, and D^0 mesons in $c\bar{c}$ and $b\bar{b}$ events, respectively. We treat A_c^D as a free parameter, while A_b^D is fixed. A_b^D is estimated in a similar manner to Ref. [14]. We start with the Standard Model prediction [15], $A_b = 0.935$, and assign it an error of ± 0.025 from the average value of LEP and SLD measurements of 0.911 ± 0.025 [16]. This b-quark asymmetry is diluted by B^0-$\bar{B}^0$ mixing and the wrong-sign D meson from the W^- in $b \to cW^-$, $W^- \to \bar{c}s$ decay. The effective b asymmetry can be expressed by correcting with two dilution factors:

$$A_b^D = A_b \times (1 - 2\chi_{mix})(1 - 2\chi_{W^- \to \bar{c}s}). \tag{6}$$

The value of χ_{mix} is deduced from the D meson production rates though B decays. We consider two kinds of B decays: 1) There is no preference for $D^{(*)+}$ and D^0 mesons coming from any particular type of B decays (B_u, B_d, B_s, λ_b); and 2) All $D^{(*)+}$ or D^0 mesons come only from B_d or B_u decays, respectively. Here we assume branching fractions of $b \to B_u$ and $b \to B_d$ are the same in the first case. Using the MC, we estimate the fractions of 1) and 2), f_1 and $f_2 = 1 - f_1$, respectively. The estimated fractions are $f_1 = 0.65$, 0.63, and 0.61 for D^{*+}, D^+, and D^0, respectively. Using the fractions, we estimate the χ_{mix} as:

$$\begin{aligned} \chi_{mix} &= f_1 \cdot \bar{\chi} + f_2 \cdot \chi_d \ \text{ for } D^{(*)+} \text{ or,} \\ &= f_1 \cdot \bar{\chi} \qquad\qquad\quad \text{ for } D^0. \end{aligned} \tag{7}$$

We use $\bar{\chi} = 0.1186 \pm 0.0043$ [16], and $\chi_d = 0.156 \pm 0.024$ [17].

The value of the correction for wrong-sign D mesons from the W^- in $b \to cW^-$ decay, $\chi_{W^- \to \bar{c}s}$ is also estimated by MC. We obtain $\chi_{W^- \to \bar{c}s} = 0.023 \pm 0.006$ for the average of D^{*+}, D^+, and D^0 mesons, and 0.021 ± 0.006 for D^{*+} mesons only. Here the errors include the theoretical error of 30% coming from $Br(b \to c\bar{c}s) = 22 \pm 6\%$ [18]. The former and latter $\chi_{W^- \to \bar{c}s}$ values are used for exclusive D reconstruction and inclusive soft-pion analysis, respectively.

By combining these two dilutions, we obtain

$$\begin{aligned} A_b^D &= 0.657 \pm 0.025 \ \text{ for } D^{*+}, \\ &= 0.655 \pm 0.026 \ \text{ for } D^+ \text{ and,} \\ &= 0.762 \pm 0.023 \ \text{ for } D^0. \end{aligned}$$

The errors are taken as experimental systematic errors (see Tables 2 and 3).

To check the A_b^D value, we measured A_b^D for D^{*+} using the 1996-98 experimental data. In this measurement, we selected D^{*+} mesons in the decay, $D^{*+} \to D^0\pi_s^+$ followed by $D^0 \to K^-\pi^+$, $D^0 \to K^-\pi^+\pi^0$, or $D^0 \to K^-\pi^+\pi^-\pi^+$. The $b\bar{b}$ events are selected by requiring that the invariant mass for the reconstructed secondary vertices be greater than 2 GeV/c^2 for at least one of the two event hemispheres. In order to select the D^{*+} mesons, we apply similar cuts to those used to select the D^{*+} mesons from c-quarks, but without any xy impact parameter cut to reject D^{*+}'s from b-quarks. We select 2196 D^* candidates with the fractions of 63% $b \to D$, 2% $c \to D$, and 35% RCBG. Using the sample, we measure $A_b^D = 0.58 \pm 0.10$, which is consistent with our assumed A_b^D value for D^{*+}.

A_{RCBG} is the analog of A_c for the RCBG, and we expect it to be very small. The asymmetry in the side-band region is measured as -0.006 ± 0.003, and is assumed to be zero. For A_e, we have taken $A_e = 0.1513 \pm 0.0022$ from the SLD measurement [10].

P_c^j, P_b^j, and P_{RCBG}^j are the probabilities that a candidate from the jth decay mode is a signal from $c\bar{c}$, $b\bar{b}$, or RCBG. The determination of the function is based on the relative fractions and the x_D distributions for the six decay modes. The functions P are defined as:

$$
\begin{aligned}
P_c(x_D) &= \frac{N_{signal}(x_D)}{N_{total}(x_D)} \cdot \frac{f_c(x_D)}{f_c(x_D) + f_b(x_D)} \\
P_b(x_D) &= \frac{N_{signal}(x_D)}{N_{total}(x_D)} \cdot \frac{f_b(x_D)}{f_c(x_D) + f_b(x_D)} \\
P_{RCBG}(x_D) &= \frac{N_{BG}(x_D)}{N_{total}(x_D)};
\end{aligned}
\tag{8}
$$

where $N_{total}(x_D)$ is the observed number of D mesons, and $N_{BG}(x_D)$ is that of background events, in the x_D bin. Using the x_D distributions for the reconstructed D mesons and side-band events, we determined the ratio N_{BG}/N_{total} in each x_D bin. The ratio N_{signal}/N_{total} is given by the relation $N_{signal}/N_{total} = 1 - N_{BG}/N_{total}$ in each bin. Figs. 5 (a)-(f) show the x_D distributions for six decay modes, which were used in this determination.

The functions $f_c(x_D)$ and $f_b(x_D)$ describe the fraction of D mesons in the c and b decays, respectively. The function is expressed as

$$
f_{c(b)} = \omega_{c(b)} \cdot d_{c(b)}(x_D),
\tag{9}
$$

where $d_{c(b)}(x_D)$ describes the shape of x_D distributions in $c(b) \to D$, and $\omega_{c(b)}$ represents the total fraction of the $c(b) \to D$ in the reconstructed D candidates. We obtain the function $d_{c(b)}(x_D)$ from MC, and the values of ω_c and ω_b are derived from Table I. The ratio $f_{c(b)}/(f_c + f_b)$ gives the probability that D candidate is from a primary $c(b)$ quark.

Performing the maximum likelihood fit to the data sample, we measure $A_c = 0.671 \pm 0.096$ (1993-95) and $A_c = 0.681 \pm 0.047$ (1996-98). As a check, we also determine A_c with a simple binned fit of the type described in Ref. [13]. We find $A_c = 0.731 \pm 0.102$ (1993-95) and $A_c = 0.666 \pm 0.049$ (1996-98); which are consistent with the values above.

D. QCD correction

As a result of hard gluon radiation, the extracted value of $A_{c(b)}$ is somewhat different than its Born-level value in Eq. 1. To account for this, the fit parameter $A_{c(b)}$ in the likelihood function is replaced with the first-order corrected parameter $A_{c(b)}(1 - \Delta^{c(b)}_{QCD}(\cos\theta))$ with $\Delta^{c(b)}_{QCD}(\cos\theta) = C_{c(b)}\Delta^{c(b)}_{QCD,SO}(\cos\theta)$, where $\Delta^{c(b)}_{QCD}$ indicates the magnitude of the leading-order (LO) QCD correction for $c(b)$-quark production, and $\Delta^{c(b)}_{QCD,SO}$ is the LO QCD correction calculated by Stav and Olsen [19]. The factor takes into account the mitigation of the effects of gluon radiation due to the analysis procedure. For example, the requirement that D mesons have high x_D values selects against events containing hard gluon radiation, reducing the overall effect of gluon radiation on the observed asymmetry.

The correction factor $C_{c(b)}$ is estimated with the MC by comparing the effects of QCD radiation, for the JETSET Parton Shower model, with and without the full analysis including detector simulation:

$$C_q = \frac{A^{gen}_{q\bar{q}} - A^{meas}_{PS}}{A^{gen}_{q\bar{q}} - A^{gen}_{PS}} \ (q = c, b), \tag{10}$$

where the superscripts '*gen*' and '*meas*' refer to the MC asymmetry for generator level (Parton Shower Model simulation only) and fully analyzed events, respectively. The MC asymmetries are determined by doing a fit to the form

$$A\frac{2\cos\theta}{1+\cos^2\theta} \tag{11}$$

in bins of $\cos\theta$. We obtain $C_c = 0.22 \pm 0.01(stat.)$. If we use a first-order matrix element instead of the Parton Shower model for the denominator of the expression (A^{gen}_{PS}) for f, we find instead $C_c = 0.29 \pm 0.01(stat.)$. We use this difference as the associated systematic error, and choose a value $C_c = 0.29 \pm 0.07$ for the likelihood function. Due to the limited statistics after the full analysis simulation, the same procedure is only able to set an upper limit $C_b < 0.4$. Thus, for the maximum likelihood function, we again use $C_b = 0.29$, with a large uncertainty (± 0.11). Applying the first-order QCD correction with the correction factors $C_{c(b)}$, leads to a 1.1% increase of A_c.

In this analysis, we have also considered the effects of next-to-leading order (NLO) gluon radiation. The NLO QCD correction is written as:

$$\Delta_c^{O(\alpha_s^2)} = \left(\frac{\alpha_s}{\pi}\right)^2 \times 4.4 \times C_c + \Delta_{gs}. \tag{12}$$

where first term is from hard gluon emission [20]. We use the same correction factor C_c as in Eq. 10 for the LO QCD correction. The second term Δ_{gs} accounts for the effects of the process $g \to c\bar{c}$ for gluons which arise during the shower and fragmentation processes.

The effects of gluon splitting have been taken into account by analyzing the MC as if it were data, with and without events with gluon splitting. The resulting difference must be scaled to account for the difference between the JETSET gluon splitting rates and the current accepted values for these rates. The rate for gluon splitting to charm quark pairs in JETSET is 0.0136 per hadronic event, and the current LEP average [16] is 0.0319 ± 0.0046, yielding a scale factor of 2.35 ± 0.34.

The second-order QCD correction increases A_c by 0.4%. Applying the first- and second-order QCD corrections, we obtain $A_c = 0.682 \pm 0.097$ (1993-95) and $A_c = 0.691 \pm 0.047$ (1996-98).

E. Systematic error

The following systematic errors have been estimated and are summarized in Table II:

- The largest uncertainties are due to the RCBG, arising from the statistics of the MC and side-band events, which are used to determine the fraction of the RCBG in the signal, and the RCBG x_D distribution which is determined by side-band events. The latter uncertainty is estimated by using the RCBG x_D distribution estimated by MC, instead of using the distribution determined by side-band events.

- There is a difference in acceptance between signal and RCBG event samples. In this analysis, we determine the RCBG probability function as a function of the x_D. This function we determine is correct if the ratio between the signal and RCBG acceptance is constant over the different $\cos\theta$ regions. In order to study this, we compare the RCBG $|\cos\theta|$ distribution obtained from side-band region and that from signal weighted by the RCBG function. These two distributions become significantly different starting at $|cos\theta| \sim 0.65$. Hence, we apply an acceptance cut of $|cos\theta_D| < 0.65$, and determine the signal and background probability functions with this cut. After measuring the A_c value with this cut, we regard the difference as a systematic uncertainty.

- We expect the asymmetry of RCBG is very small, and take a central value of $A_{RCBG} = 0$. Since the asymmetry of the side-band events is measured to be -0.006 ± 0.0003, we take -0.0063 as a lower limit on A_{RCBG}.

- We vary $f_{b\to D}/(f_{b\to D} + f_{c\to D})$, the fraction of D mesons from $Z^0 \to b\bar{b}$, by $\pm 20\%$ to account for differences between our MC and the range of measurements of $D^{(*)+}$ production in Z^0 decay [14,21].

- The effect of the uncertainty of A_b^D is estimated by varying $A_b^D = 0.657 \pm 0.025, 0.655 \pm 0.026$, or 0.762 ± 0.023 for D^{*+}, D^+, or D^0, respectively, by these quoted errors. In Table II We show the resultant error in A_c coming from the uncertainty in A_b (0.935 ± 0.025) separately from the uncertainty in the mixing parameter.

- The systematic errors on the fragmentation function is estimated by modifying the x_D distributions in heavy-quark fragmentation. In our MC sample, we use Peterson fragmentation with $\epsilon_c = 0.06$ and $\epsilon_b = 0.006$. We generated D^{*+}, D^+, and D^0 mesons at $\epsilon_c = 0.045$ and 0.075 and at $\epsilon_b = 0.003$ and 0.009, which correspond to the range of the errors of x_D measurements from the LEP working group [22]. Using these samples, we estimate the effect on A_c from the changes in the x_D distributions.

- Our sensitivity to the RCBG x_D distribution is checked by performing the analysis with P_{RCBG} derived from the MC background instead of the data side-bands.

- The shapes of the x_D distributions in $c(b) \to D$, expressed as $d_{c(b)}(x_D)$ in Eq. 9, are obtained by the fitting to the MC x_D distributions. The sensitivity to this procedure is checked by performing the analysis with the x_D distributions determined by a bin value of the MC x_D distribution instead of the fitting.

- We assume $A_e = 0.1513 \pm 0.0022$, and estimate this systematic error by varying A_e within the error. The precision of the polarization measurements are 1.1% (1996), 0.5% (1994-95), and 0.4%(1996-98) [9,10]. We estimate the systematic error due to polarization uncertainties by varying with these errors.

- We consider two sources for uncertainties on the leading order QCD correction: the uncertainty on α_s and the uncertainty in the estimation of the correction factor due to the analysis bias. The range of α_s chosen for the analysis is 0.118 ± 0.007, while that for the correction factor is 0.29 ± 0.07, as described above.

- In order to estimate the hard-gluon-radiation uncertainty in the second-order QCD correction, we vary the magnitude of the correction by 50% of itself. We use the experimental error for gluon splitting into $c\bar{c}$.

The total systematic errors are 0.032 and 0.019 for 1993-95 and 1996-98 SLD runs, respectively.

F. Results

We obtained the following results for the exclusive channels: $A_c = 0.682 \pm 0.097(stat.) \pm 0.032(sys.)$ (1993-95) and $A_c = 0.691 \pm 0.047(stat.) \pm 0.019(sys.)$ (1996-98). The combined result is:

$$A_c = 0.689 \pm 0.042(stat.) \pm 0.019(sys.)$$

IV. INCLUSIVE SOFT-PION ANALYSIS

In this analysis, c-quarks are identified by the presence of soft pions from the decay $D^{*+} \rightarrow D^0\pi_s^+$. Since this decay has a small Q value of $m_{D^*} - m_{D^0} - m_\pi = 6$ MeV/c^2, the maximum transverse momentum of π_s with respect to the D^{*+} flight direction is only 40 MeV/c.

A. Jet reconstruction and soft-pion selection

We select hadron events and reject $b\bar{b}$ events by using the same criteria described in Section II. The D^{*+} flight direction is approximated by the jet direction, where charged tracks and neutral clusters are clustered into jets, using an invariant-mass algorithm. In the jet clustering, particles are merged together in an iterative way if their invariant mass is less than 4.6 GeV/c^2. We only use the tracks and clusters which have the momentum of greater than 1.2 GeV/c and 1.0 GeV/c, respectively, to form the jet. The tracks are required to satisfy the track quality cuts described in Section II and to have vertex hits. The jets must satisfy the following criteria:

1. At least 3 charged tracks;

2. At least one track with momentum P > 5 GeV/c;

3. The net charge of the jet, Σq, should be $|\Sigma q| \leq 2$;

4. Sum of the largest and second largest 3D impact parameters of the tracks > 2.5 σ; and

5. There is at least one opposite-charged-track pair which has the χ^2 probability of two tracks coming from the same vertex of greater than 1%.

The criteria 2) and 3) are effective to reduce the huge RCBG. The criterion 4) rejects the light flavor events. The criterion 5) relies on the fact that it is likely that the D^0 decays into at least one pair of opposite charged tracks.

After selecting the D^{*+} candidates, we look for the soft-pion candidates which are produced along the D^{*+} jets. We require soft-pion candidates to have a momentum of $1 < P < 3$ GeV/c and an impact parameter of $< 2\sigma$ from the IP. Since soft-pions in $c\bar{c}$ events have much higher momentum than those in $b\bar{b}$ events, the former criterion rejects such soft-pions from $b\bar{b}$ events. The latter criterion is also effective to reduce the soft-pions from $b\bar{b}$, because D decays from $b\bar{b}$ events have significant transverse momentum relative to the parent B flight direction, and they do not appear to originate from the primary vertex due to the B life time.

Using the selected soft-pion candidates, the transverse momenta P_T to the jet axis are calculated. Fig. 6 (a) shows the P_T^2 distribution for the soft-pion candidate tracks. The peak around $P_T^2 = 0$ is from charm signal. We define $P_T^2 < 0.01$ (GeV/c)^2 as the signal region, where a signal-to-background ratio of 1:2 is observed. From 1993-98 data, 12992 soft-pion candidates are selected in the region.

B. BG determination and A_c measurement

To evaluate the number of the $D^{*+} \to D^0\pi_s^+$ decays, a fit to the observed P_T^2 distribution is performed using the signal plus background shape. The signal shape is assumed to be a simple exponential

$$S(P_T^2) = \alpha \exp(-P_T^2/\beta).$$

We obtain $\beta = 0.00471 \pm 0.00007$ by fitting the MC spectrum of $D^{*+} \to D^0\pi_s^+$ decays and fix the value of β. For the background shape, we try two kinds of functions with three free parameters each:

$$F_1(P_T^2) = a/(1 + bP_T^2 + c(P_T^2)^2),$$

$$F_2(P_T^2) = a' + b' \exp(-P_T^2/c').$$

The fit results are illustrated in Fig. 6 (a), where we show the extrapolation of $F_1(P_T^2)$ (dashed line) and $F_2(P_T^2)$ (dotted line).

The observed signal in 1993-98 data is 4291 $\pm$ 147 (χ^2/ndf = 219.0/196) with $S(P_T^2) + F_1(P_T^2)$ and 4032 $\pm$ 124 (χ^2/ndf = 224.0/196) with $S(P_T^2) + F_2(P_T^2)$, where the fit was performed in each case for $P_T^2 < 0.1$ GeV/c. We choose $F_1(P_T^2)$ for the background shape to measure the A_c, because of its smaller χ^2/ndf value. The difference between these two functions is regarded as a systematic error.

We determine the relative normalizations of signal and background for the MC prediction using the above fit to the data. Fig. 6 (b) shows the detailed P_T^2 distribution from the MC prediction with this normalization. We also overlay the background shape extrapolated by the fitting with $S(P_T^2) + F_1(P_T^2)$ (dashed line). Using the MC, we estimate the contributions of $c \to D^{*+}$ and $b \to D^{*+}$ as 3791$\pm$39 and 500$\pm$14, respectively, in 1993-98 data.

The direction of the primary quark is estimated from the jet axis, and the charge of the primary c-quark is determined by the charge of the π_s. Fig. 7 shows the $q \cos\theta_D$ distributions, where q is the sign of the primary c-quark, and θ_D is the polar angle of the jet axis, for the selected D^{*+} sample separately for left- and right-handed electron beams. Clear asymmetries are shown.

To extract A_c, we use an unbinned maximum likelihood fit, using a likelihood function similar to the exclusive D reconstruction analysis (Eq. 5). We regard the A_c as a free parameter, and fix the asymmetry of D^{*+} as $A_b^D = 0.660 \pm 0.025$. This value is obtained from Eq. 6 by substituting $\chi_{mix} = 0.65 \cdot \bar{\chi} + 0.35 \cdot \chi_d$, (which is determined for D^{*+} in Eq. 7) and $\chi_{W^- \to \bar{c}s} = 0.021 \pm 0.006$ (which is determined by MC for D^{*+}, as described in Section III C).

We expect the asymmetry for the BG, A_{BG}, to be very small and assume it to be zero. Using the MC, we measure the asymmetry of the background to be 0.009 ± 0.017.

For the probabilities of P_c, P_b, and P_{RCBG} in Eq. 5, we used the following functions:

$$
\begin{aligned}
P_c(P, P_T^2) &= \frac{N_{signal}(P, P_T^2)}{N_{total}(P, P_T^2)} \cdot \frac{f_c(P)}{f_c(P) + f_b(P)} \\
P_b(P, P_T^2) &= \frac{N_{signal}(P, P_T^2)}{N_{total}(P, P_T^2)} \cdot \frac{f_b(P)}{f_c(P) + f_b(P)} \\
P_{RCBG}(P, P_T^2) &= \frac{N_{BG}(P, P_T^2)}{N_{total}(P, P_T^2)};
\end{aligned}
\tag{13}
$$

where P and P_T^2 indicate the momentum and the squared transverse momentum to the D^* jet axis for soft-pion tracks, respectively. N_{total} and N_{BG} are the observed number of soft-pion candidates and that of background in each P and P_T^2 bin, respectively. We estimate N_{BG} from MC, and the relation $N_{signal}/N_{total} = 1 - N_{BG}/N_{total}$ gives the ratio N_{signal}/N_{total}. Fig. 8 shows the momentum distributions for experimental data and MC predictions. Figs. 6 and 8 are used for this estimation.

The function $f_{c(b)}$ in Eq. 13 describes the fractions of D mesons in the $c(b)$ decays, and the ratio $f_{c(b)}/(f_c + f_b)$ gives the probability that D candidate is from a primary $c(b)$ quark. We regard $f_{c(b)}$ as a function of soft-pion momentum, P. The function is expressed as $f_{c(b)} = \omega_{c(b)} \cdot d_{c(b)}(P)$. Here $d_c(b)$ is determined by the shape of MC soft-pion momentum distributions in $c(b) \to D$ and $\omega_{c(b)}$ is the estimated total fraction of the $c(b) \to D$ among the selected candidates.

Performing the maximum likelihood fit to the data sample, we measure $A_c = 0.654 \pm 0.125$ (1993-95) and $A_c = 0.673 \pm 0.056$ (1996-98). As a check, we also measure A_c with a simple binned fit as $A_c = 0.520 \pm 0.164$ (1993-95) and $A_c = 0.665 \pm 0.085$ (1996-98), which are consistent with the above values.

The first- and second-order QCD correction are applied with the same method as in the exclusive D reconstruction analysis. The correction factor due to the analysis bias is estimated as 0.35 ± 0.09. Using this factor, and applying the first- and second-order QCD corrections, we obtain $A_c = 0.667 \pm 0.127$ (1993-95) and $A_c = 0.687 \pm 0.057$ (1996-98).

C. Systematic error

The estimated uncertainties in this analysis are summarized in Table III, where we show average systematic errors for the 1993-98 data.

- The largest uncertainties are due to the imperfect knowledge of the background fraction and its shape. Here the background is determined by using the fitting to the P_T^2 distribution of the experimental data, and we try the two kind of functions F_1 and F_2 described above. In order to estimate the former uncertainty, we fix the background shape as F_1, and change its height so as to cover the possible range of the background fraction. The latter uncertainty is estimated by using the two kinds of background shapes, F_1 and F_2, while keeping the integrated number of the background events in the signal region ($P_T^2 < 0.1$ (GeV/c)^2) constant.

- In order to estimate the systematic error due to the difference of the acceptance between signal and background, we apply the same method as in the exclusive D reconstruction: apply an acceptance cut of $|cos\theta_D| < 0.65$; determine the signal and background probability functions with this cut; then measure the A_c with this cut. The difference is regarded as a systematic error.

- Using the MC, we measured the asymmetry of the background to be 0.009 ± 0.017. We therefore take 0.018 as a upper limit on A_{BG}.

- The shape of the soft-pion momentum distributions in $b \to D^*$ or $c \to D^*$ is determined by the fitting to the MC distributions. The uncertainty concerning this distribution is estimated by performing the analysis using a bin value of the momentum distribution instead of the fitting.

- We follow the same procedure as in the exclusive D reconstruction to estimate the uncertainties on the fraction of $f_{b\to D}/(f_{b\to D} + f_{c\to D})$, and the fraction of D mesons from $Z^0 \to b\bar{b}$, A_b^D. We vary the fraction $f_{b\to D}/(f_{b\to D}+f_{c\to D})$ by $\pm 20\%$, and $A_b^D = 0.660 \pm 0.025$.

- The systematic errors on the fragmentation function is estimated by modifying the momentum distributions in heavy-quark fragmentation. We use the same range as in the exclusive D reconstruction analysis, $\epsilon_c = 0.045 - 0.075$ and $\epsilon_b = 0.003 - 0.009$, then modify the shape of the momentum distributions.

- In order to estimate the uncertainties on polarization and A_e, we vary these values with the same error ranges as described in the exclusive D reconstruction analysis.

- The systematic errors from first-order QCD correction are estimated by taking α_s to be 0.118 ± 0.007 and the correction factor which is determined as described above, to be 0.35 ± 0.09. The second-order QCD correction is studied by varying half of the magnitude of the hard gluon radiation and using the experimental error for gluon splitting into $c\bar{c}$.

The total systematic errors are obtained to be ± 0.065 and ± 0.052 for 1993-95 and 1996-98, respectively.

D. Results

The A_c values obtained in the inclusive soft-pion analysis are $A_c = 0.667 \pm 0.127(stat.) \pm 0.065(sys.)$ (1993-95) and $A_c = 0.687 \pm 0.057(stat.) \pm 0.052(sys.)$ (1996-98). The combined result is

$$A_c = 0.683 \pm 0.052(stat.) \pm 0.036(sys.)$$

V. CONCLUSION

Using the 1993-98 experimental data collected by the SLD experiment, we measure the parity-violation parameter A_c using two different c-quark tagging methods:

$$A_c = 0.689 \pm 0.042(stat.) \pm 0.019(sys.) \text{ and}$$

$$A_c = 0.683 \pm 0.052(stat.) \pm 0.036(sys.),$$

from exclusive charmed-meson reconstruction and inclusive soft-pion analysis, respectively.

To combine them, we must avoid double counting signal events from both samples. We find that 1182 events are common to the two analyses. These events are taking into account by increasing the statistical error for soft-pion analysis to 0.061. The combined result is

$$A_c = 0.687 \pm 0.040,$$

where we have treated the systematic errors as correlated.

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FIGURES

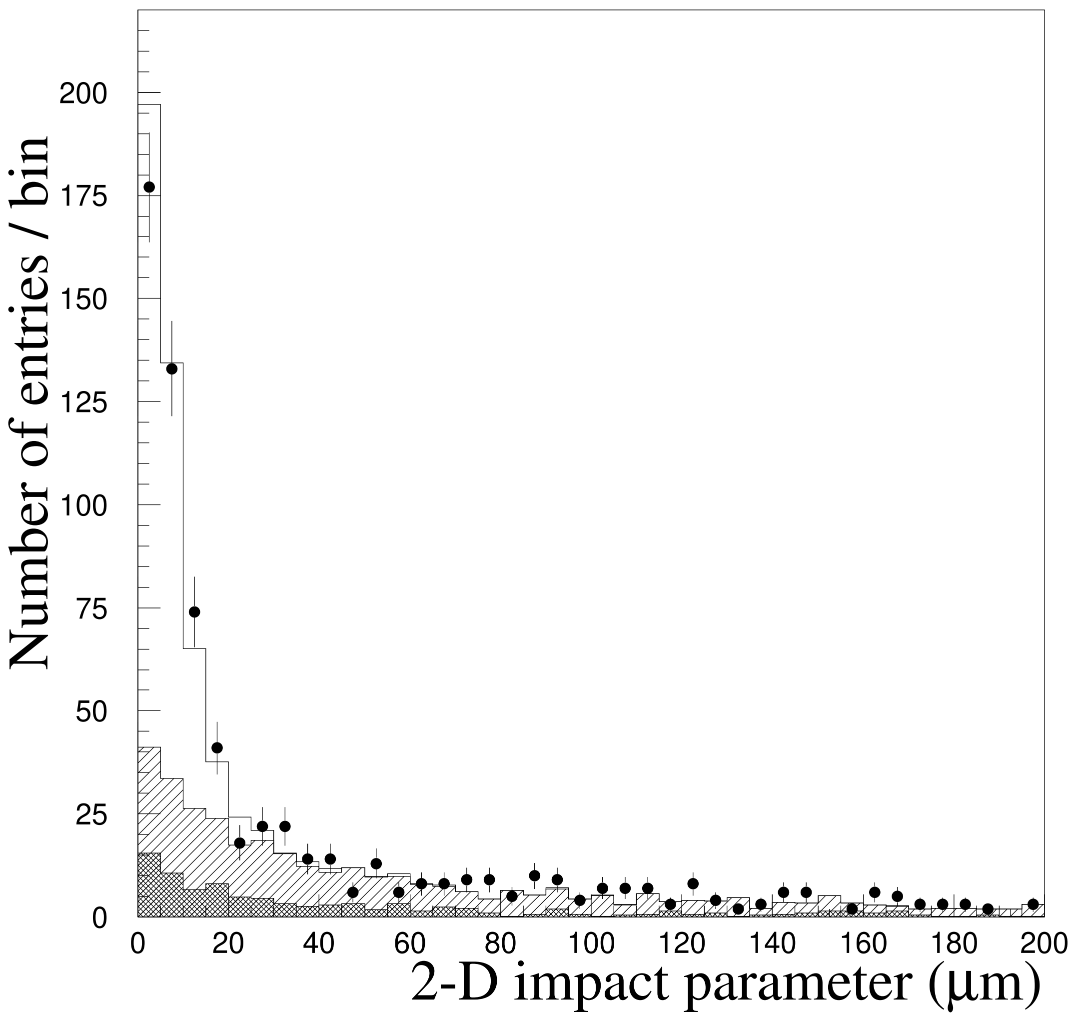

FIG. 1. The distribution of 2-D impact parameter of the D^0 momentum vector to the IP for the decay of $D^{*+} \to D^0\pi_s^+$, $D^0 \to K^-\pi^+$. The solid circles indicate the experimental data, and histograms are MC of D^{*+} from c-quark (open), from b-quark (single hatched), and RCBG (double hatched).

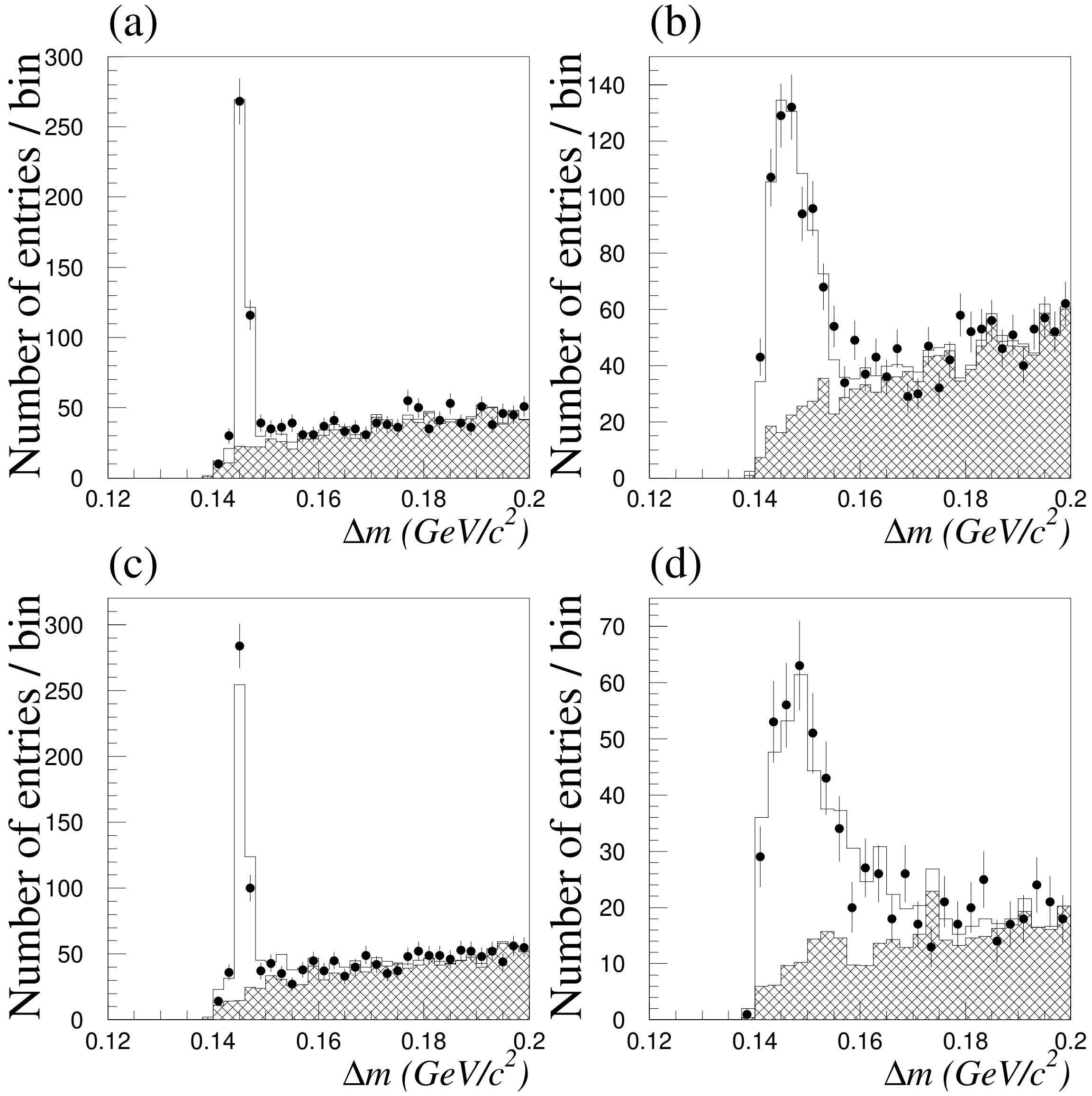

FIG. 2. The mass-difference distributions for the decay of (a)$D^{*+} \to D^0\pi_s^+$, $D^0 \to K^-\pi^+$, (b)$D^0 \to K^-\pi^+\pi^0$, (c)$D^0 \to K^-\pi^+\pi^+\pi^-$, and (d)$D^0 \to K^-l^+\nu_l$ (l =e or μ). The solid circles indicate the exp. data, and histograms are MC of signal (open) and RCBG (double hatched).

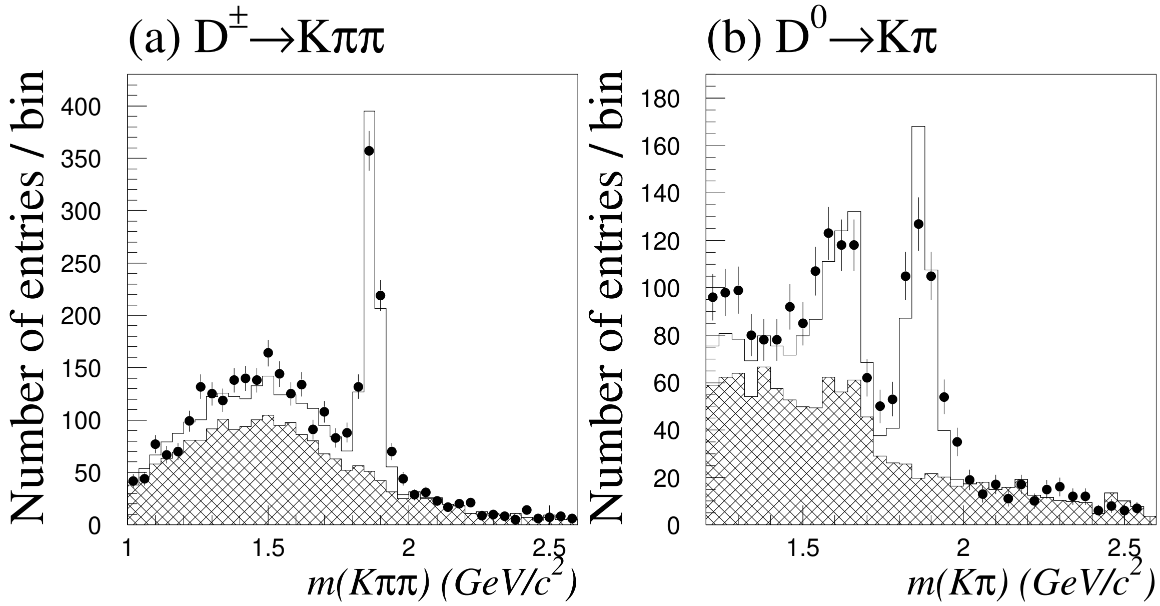

FIG. 3. The mass distributions for (a)D^+ and (b)D^0 mesons. The solid circles indicate the exp. data, and histograms are the MC of signal (open) and RCBG (double hatched). The peaks around $m(K\pi) \sim 1.6$ GeV/c^2 in figure (b) comes from the decay $D^0 \to K\pi\pi^0$.

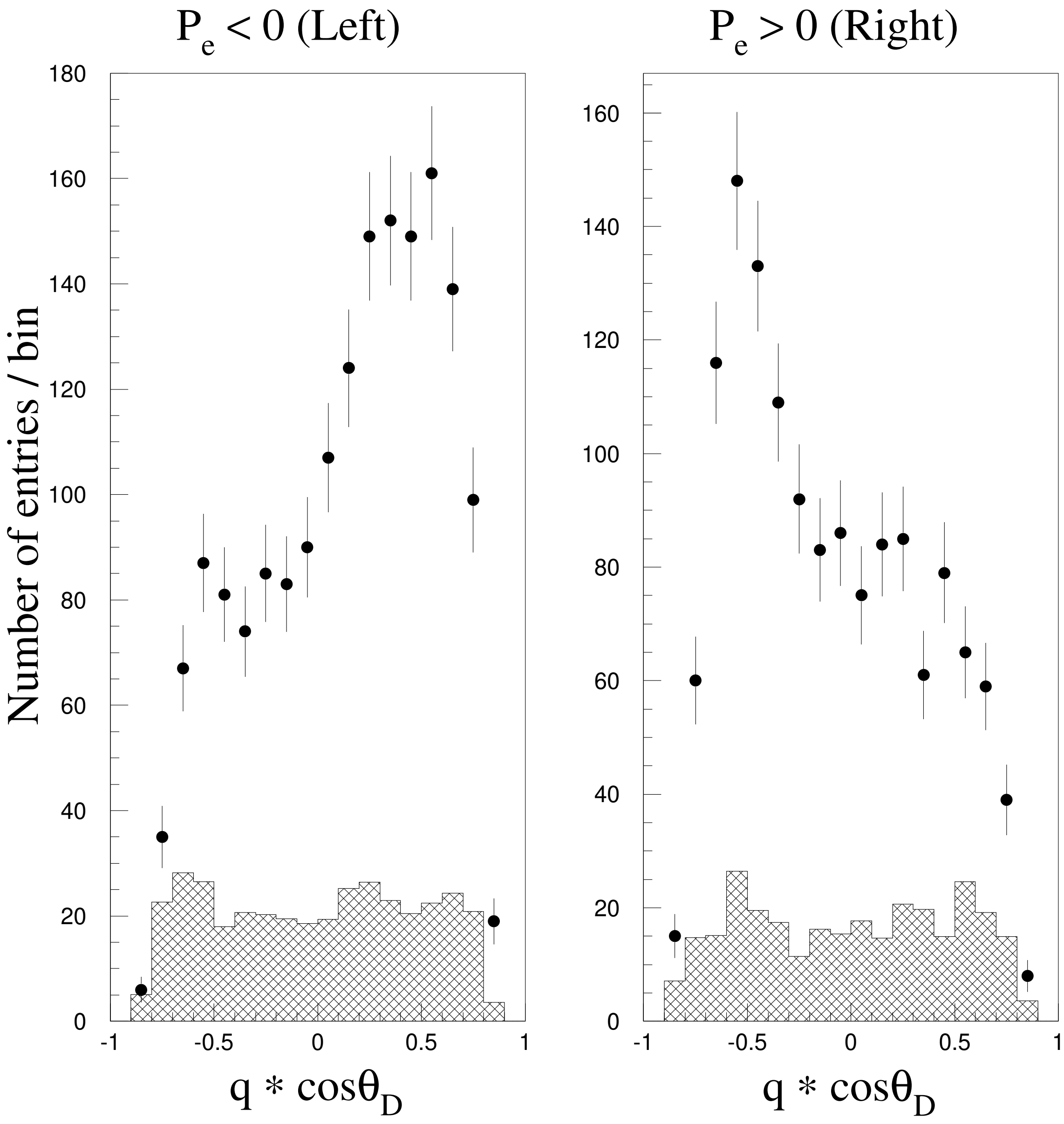

FIG. 4. The distributions of the $q \cdot \cos\theta_D$ for the selected D meson sample for (a) left- and (b) right- handed electron beams. The solid circles are exp. data, and double hatched histograms are RCBG estimated from side-band regions.

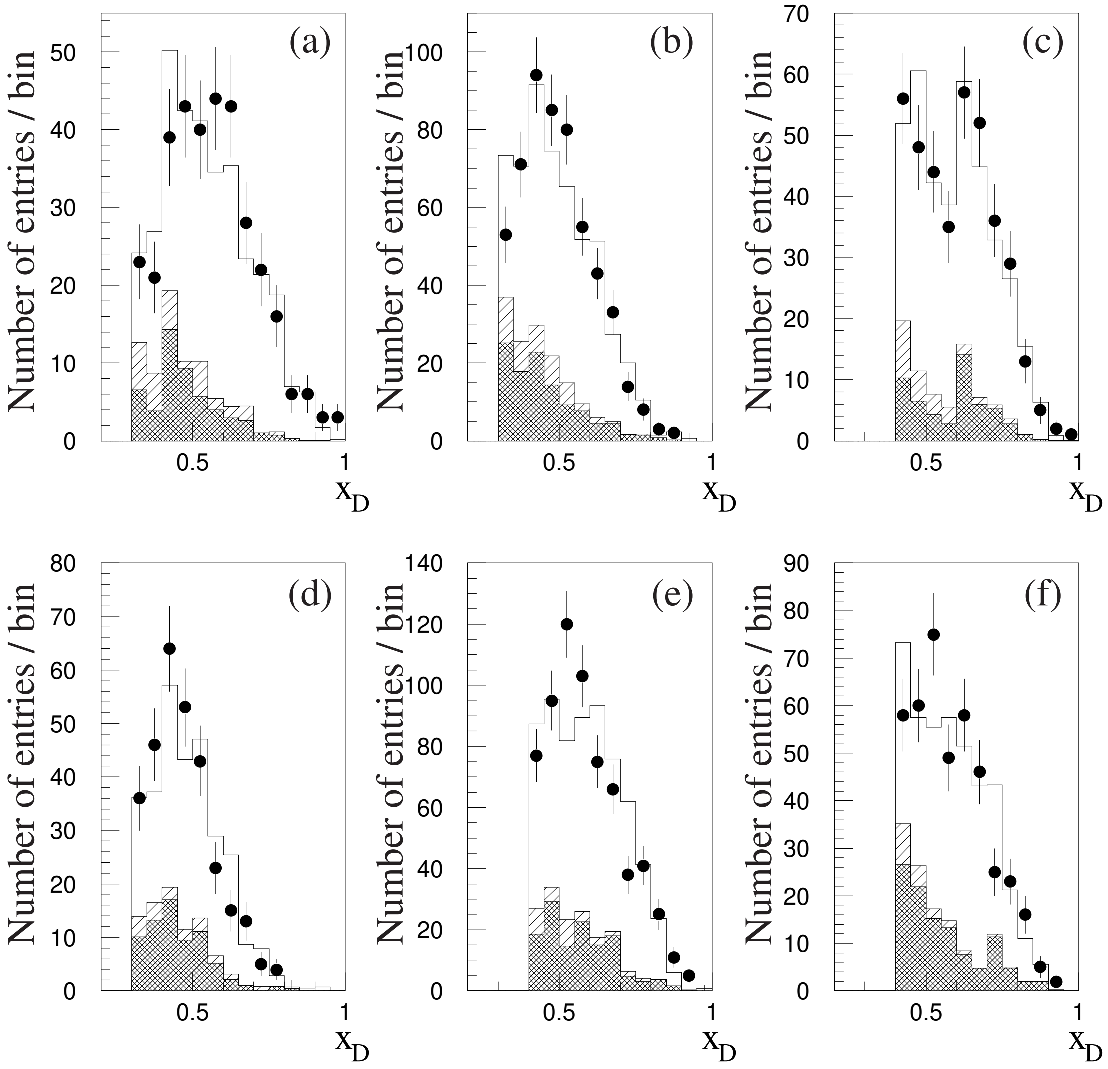

FIG. 5. The x_D distributions for (a)$D^{*+} \to D^0\pi_s^+$, $D^0 \to K^-\pi^+$, (b)$D^0 \to K^-\pi^+\pi^0$, (c)$D^0 \to K^-\pi^+\pi^+\pi^-$, (d)$D^0 \to K^-l^+\nu_l$ (l =e or μ) (e)$D^+ \to K^-\pi^+\pi^+$, and (f)$D^0 \to K^-\pi^+$. The solid circles are exp. data and hatched histograms are background estimated from side-band events. MC prediction of D mesons from c-decay (open histograms) and b-decay (single hatched histogram) are also shown.

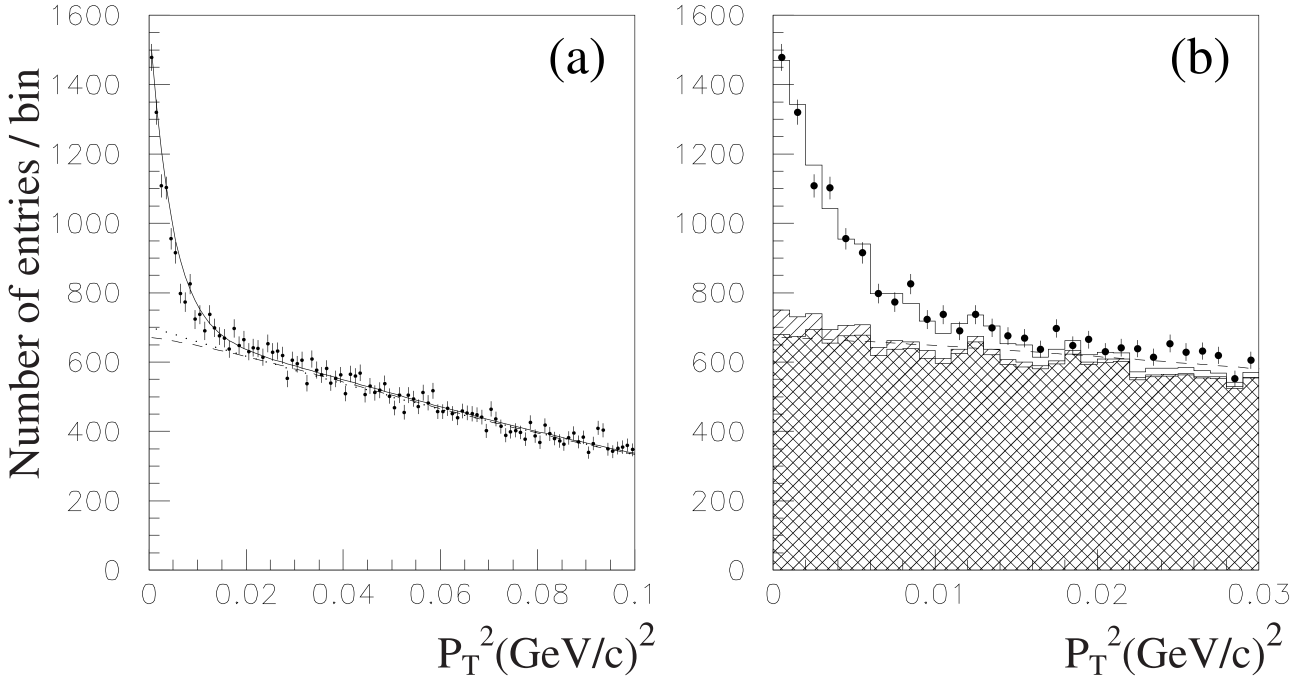

FIG. 6. The P_T^2 distributions for soft-pion candidate tracks. (a) The solid circles indicate the exp. data. The curves are the result of the a fit $S(P_T^2) + F_1(P_T^2)$ performed for $P_T^2 < 0.1$ GeV/c (solid line), and the extrapolations of $F_1(P_T^2)$ (dashed line) and $F_2(P_T^2)$ (dotted line). The definition of the functions are described in the text. (b) The solid circles are the exp. data, and histograms are MC prediction of D mesons from c-decay (open), D mesons from b-decay (single hatched), and background (double hatched). The extrapolation of $F_1(P_T^2)$ is also shown as dashed line.

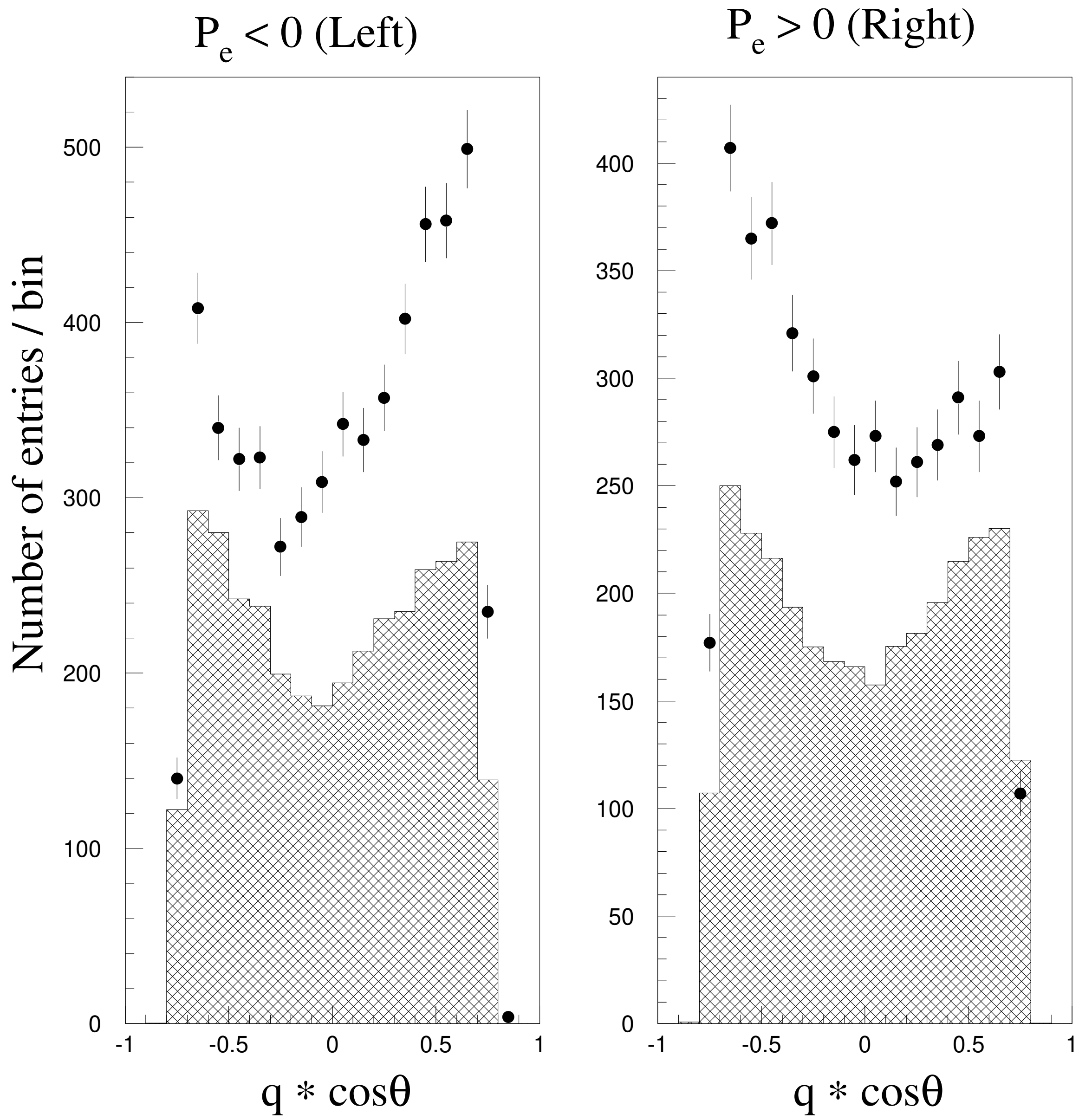

FIG. 7. The distributions of the $q \cdot \cos\theta_D$ for the selected D^{*+} meson sample for (a) left- and (b) right- handed electron beams. The solid circles are exp. data, and hatched histograms are RCBG estimated from side-band regions.

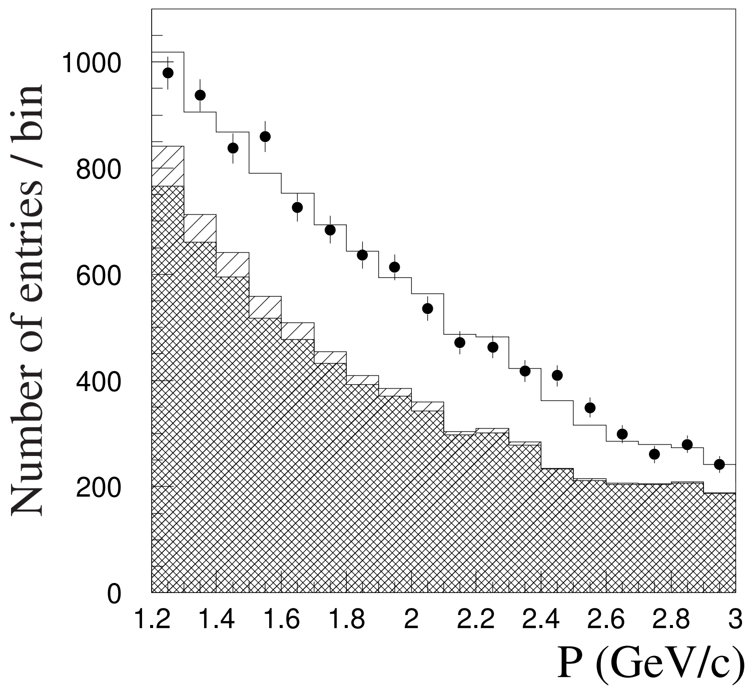

FIG. 8. The momentum distribution for soft-pion candidate tracks. The points are exp. data.The histograms are MC predictions of D's from c decays (open), D's from b decays (single hatched), and background (double-hatched).

TABLES

TABLE I. The number of selected candidates from 1993-98 SLD experimental data, and contributions from $c \to D$, $b \to D$, and RCBG estimated by MC.

Channel	Candidates	$c \to D$	$b \to D$	RCBG
$D^{*+} \to D^0 \pi_s^+$,				
$D^0 \to K^- \pi^+$	561	413 (74%)	59 (10%)	89 (16%)
$D^0 \to K^- \pi^+$	896	601 (67%)	83 (9%)	212 (24%)
$D^0 \to K^- \pi^+ \pi^0$	537	418 (78%)	36 (7%)	83 (15%)
$D^0 \to K^- \pi^+ \pi^+ \pi^-$	433	296 (68%)	31 (7%)	106 (24%)
$D^+ \to K^- \pi^+ \pi^+$	957	698 (73%)	45 (5%)	214 (22%)
$D^0 \to K^- \pi^+$	583	403 (69%)	27 (5%)	153 (26%)
Total	3967	2829 (71%)	281 (7%)	857 (22%)

TABLE II. 1993-98 average contributions to the estimated systematic error for exclusive D meson reconstruction analysis.

Source	δA_c
f_{RCBG}	0.0111
RCBG x_D distribution	0.0112
RCBG acceptance	0.0087
A_{RCBG}	0.0028
$f_{b\to D}/(f_{b\to D}+f_{c\to D})$	0.0011
$A_{b\to D}$ (A_b)	0.0017
$A_{b\to D}$ (Mixing)	0.0016
c fragmentation	0.0003
b fragmentation	0.0003
D meson x_D shape	0.0040
A_e	0.0002
Polarization	0.0035
α_s	0.0004
Correction factor for first order QCD correction	0.0018
Second order QCD correction	0.0006
Gluon splitting	0.0002
Total	0.0193

TABLE III. Contributions to the estimated systematic error for the inclusive soft-pion analysis (combined averages for 1993-98 data sets).

Source	δA_c
f_{BG}	0.0324
BG P_T^2 distribution	0.0018
BG acceptance	0.0122
A_{BG}	0.0093
$f_{b\to D}/(f_{b\to D} + f_{c\to D})$	0.0018
$A_{b\to D}$ (A_b)	0.0021
$A_{b\to D}$ (Mixing)	0.0021
c fragmentation	0.0010
b fragmentation	0.0005
Soft-pion momentum shape	0.0003
A_e	0.0005
Polarization	0.0033
α_s	0.0005
Correction factor for first order QCD correction	0.0024
Second order QCD correction	0.0008
Gluon splitting	0.0005
Total	0.0363