Measurement of the Left-Right Forward-Backward Asymmetry for Charm Quarks with D^{*+} and D^+ Mesons

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We present a direct measurement of $A_c = 2v_c a_c/(v_c^2 + a_c^2)$ from the left-right forward-backward asymmetry of $D^{\star +}$ and D^+ mesons in Z^0 events produced with the longitudinally polarized SLAC Linear Collider beam. These $Z^0 \to c\overline{c}$ events are tagged on the basis of event kinematics and decay topology from a sample of hadronic Z^0 decays recorded by the SLAC Large Detector. We measure $A_c^0 = 0.73 \pm 0.22(\text{stat}) \pm 0.10(\text{syst})$.

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The detailed vertex structure of the electroweak theory is manifest in fermion production asymmetries at the Z^0 pole. The parameter $A_f = 2v_f a_v/(v_f^2 + a_f^2)$, the combination of vector (v_f) and axial vector (a_f) couplings of the Z^0 to fermions of type f, represents the magnitude of parity violation in the Zff coupling and hence the size of the asymmetry in the fermion production cross section.

The Born-level cross section [1] $d\sigma/d\cos\theta$ for producing a final-state fermion at an angle $\cos\theta$ from the electron beam direction in the process $e^+e^- \to Z^0 \to f\overline{f}$ is proportional to $(1 - A_e P_e)(1 + \cos^2\theta) + 2A_f(A_e - P_e)\cos\theta$, where P_e is the longitudinal polarization of the electron beam. At the SLAC Linear Collider (SLC), the ability to manipulate the helicity of the electron beam allows the isolation of the Zff vertex through the formation of the double asymmetry

$$\tilde{A}_{FB} = \frac{\sigma_F^L - \sigma_F^R - \sigma_B^L + \sigma_B^R}{\sigma_F^L + \sigma_F^R + \sigma_B^L + \sigma_B^R} = \frac{3}{4}|P_e|A_f\,,$$

where F (B) refers to fermions produced at angles less (greater) than 90° to the electron beam, and L (R) denotes that the Z^0 was produced with an electron beam of left-handed (right-handed) helicity.

This Letter and a companion document [2] report the first direct measurements of the magnitude of parity violation in the Zcc coupling. We measure A_c, which could be sensitive to new physics contained in various extensions of the standard model [3], by selecting a sample of $Z^0 \to c\overline{c}$ decays. A_c can also be measured in experiments where Z^0 bosons are produced with unpolarized electrons [1], but here the forward-backward asymmetry is $\propto A_e A_c$.

For this analysis, $Z^0 \to c\overline{c}$ events are tagged using fully and partially reconstructed decays of $D^{\star +}$ and D^+ mesons [4]. The charge of the primary charm quark is uniquely determined by the sign of the $D^{(\star)+}$. As $Z^0 \to b\overline{b}$ events are also a copious source of $D^{(\star)+}$ mesons, event kinematics and decay topology are used to reject $D^{(\star)+}$'s originating in B hadron decays.

The measurement reported here is performed with 1.8 pb^{-1} of SLC luminosity taken in 1993 at a mean c.m. energy of 91.26 ± 0.02 GeV. The data were taken with the SLAC Large Detector (SLD), a multipurpose particle detector [5]. The trigger and the event and track selection criteria are as described in Ref. [6], except that the event thrust axis is determined using only charged tracks, reconstructed in the vertex detector (VXD) [7] and the central drift chamber [8], and the polar angle of the thrust axis is allowed to be $|\cos\theta_T| < 0.80$. Tracks are required to have at least one VXD hit to be used in the following analyses.

The SLC was operated with a polarized electron beam and an unpolarized positron beam [9]. The average polarization magnitude measured [10] for the 1993 data sample is $|P_e| = (63.0 \pm 1.1)\%$. The centroid position in the xy plane of the 2.6 μm $\times$ 0.8 μm SLC interaction point (IP) is reconstructed with a measured precision of $\sigma_{\text{IP}} = 7 \pm 2$ μm using the tracks in sets of $\sim$30 sequential hadronic Z^0 decays [11]. The median z position of tracks at their point of closest approach to the IP in the x-y plane determines the z position of the Z^0 primary vertex (PV) with a precision of $\sim$35 μm event by event.

The $D^{\star +}$ mesons are identified using the decay $D^{\star +} \to \pi_s^+ D^0$, where the D^0 decays via $D^0 \to K^-\pi^+$ or $D^0 \to K^-\pi^+\pi^0$ (satellite resonance) [12]. The π_s^+ in the $D^{\star +}$ decay is known as the spectator pion and carries the sign of the charm quark. Two separate techniques, a kinematic analysis and a decay length analysis, are combined to select the $D^{\star +}$ sample. Since it is not necessary to reconstruct the π^0 in the satellite resonance [12], the analyses for the two decay modes, $D^0 \to K^-\pi^+$ and $D^0 \to K^-\pi^+\pi^0$, are identical except for the mass ranges allowed for the D^0 candidates, which are 1.765 <

$m(K^-\pi^+) < 1.965$ GeV/c^2 and $1.500 < m(K^-\pi^+) <$ 1.700 GeV/c^2, respectively.

All pairs of oppositely charged tracks in a thrust axis hemisphere are combined to form D^0 candidates by assigning the K^- mass to one of the particles and the π^+ mass to the other. If the D^0 candidate mass lies within the ranges specified above, it is then combined with a π_s^+ candidate track having charge opposite to the K^- candidate. In the kinematic analysis, we rely on the fact that $D^{\star+}$ mesons in $c\bar{c}$ events are produced at much higher $x_{D^\star} = 2E_{D^\star}/E_{\text{c.m.}}$, where $E_{D^\star}$ is the $D^{\star+}$ energy, than $D^{\star+}$'s in $b\bar{b}$ events or other random combinatoric background (RCBG). Any $D^{\star+}$ candidate with $x_{D^\star} <$ 0.4 is rejected. The background is further reduced by requiring $|\cos\theta^*| < 0.9$, where θ^* is the opening angle between the direction of the D^0 in the laboratory frame and the K in the D^0 rest frame, and by requiring that the π_s^+ candidate have $p > 1$ GeV/c.

In the complementary decay length analysis, we rely on the fact that D^0's in $c\bar{c}$ events have a long 3D decay length ($\langle L\rangle \sim 1$ mm) and are produced at the Z^0 PV. Since the decay length resolution is $\langle\sigma_L\rangle \sim 200$ μm, a clean separation of these events from RCBG is possible, even at low x_D. A vertex fit is performed on the tracks in a D^0 candidate, and the combination is retained only if the χ^2 probability of both tracks coming from the same vertex is greater than 1%. Next, a decay length significance cut of $L/\sigma_L > 2.5$ is applied to remove RCBG vertices. A cut requiring the xy impact parameter of the D^0 momentum vector to the IP be less than 20 μm (approximately our resolution in this quantity) is also applied. This cut rejects D decays occurring in $b\bar{b}$ events since these D's have significant $\langle p_\perp\rangle$ relative to the parent B flight direction and, with the long average B lifetime, do not appear to originate from the PV. Finally, we require $x_{D^\star} > 0.2$ and make not cuts on $\cos\theta^*$ or minimum π_s^+ momentum, since the charm purity of the remaining sample is sufficiently high.

Once either of the two selection criteria has been satisfied, the mass difference (Δm) between the $D^{\star+}$ and D^0 is formed, and the data are divided into signal ($\Delta m < 0.150$ GeV/c^2) and sideband ($0.160 < \Delta m <$ 0.200 GeV/c^2) regions. The union of the two samples of $D^{\star+}$ candidates is used to perform the asymmetry measurement. The overlap of the sets of candidates from the kinematic and decay length analyses is 28%.

After all analysis cuts, the composition of the remaining events is estimated using a Monte Carlo (MC) simulation [11] to obtain the signal and RCBG Δm shapes. All MC events with three tracks from a correctly signed, three-prong charm decay are taken as the asymmetry-carrying signal; the RCBG shape is taken from all other entries. 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 sideband regions. Figure 1 shows the signal and background shapes superimposed on the data. The unnormalized MC, though not used to predict the fraction of RCBG, predicts the populations of the signal and sideband regions to ~20%, reasonable agreement given data statistics and uncertainties in $D^{(\star)+}$ and background production and decay rates.

Candidates for $D^+ \to K^-\pi^+\pi^+$ are formed by combining two same-sign pion candidates with an opposite-sign kaon candidate. A series of cuts is applied to reject background. We require $x_{D^+} > 0.4$ and $\cos\theta^* >$ -0.8, and the three tracks are each required to have $p > 1$ GeV/c. To reject $D^{\star+}$ 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 0.160 GeV/c^2. To remove RCBG, we require a good vertex fit (> 1% probability) and $L/\sigma_L > 3.0$ for the D^+ decay length. Finally, the colinearity between the D^+ momentum and the vertex flight direction is required to be less than 5 mrad in x-y and less than 20 mrad in r-z to reject D^+'s from $b\bar{b}$ events.

After all selection criteria, $D^+ \to K^-\pi^+\pi^+$ candidates fall in the range $1.800 < m(K^-\pi^+\pi^+) <$ 1.940 GeV/c^2, while sidebands are defined as $1.640 <$ $m < 1.740$ GeV/c^2 and $2.000 < m < 2.100$ GeV/c^2.

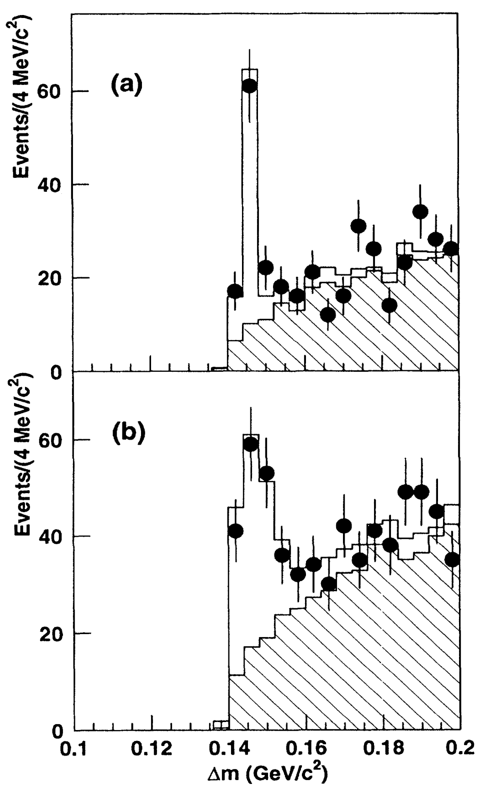

FIG. 1. The Δm distributions from the kinematic and decay length analyses for (a) $D^{\star+} \to D^0\pi_s^+, D^0 \to K^-\pi^+$ (b) $D^{\star+} \to D^0\pi_s^+, D^0 \to K^-\pi^+\pi^0$. The points represent the data, and the solid (hatched) histogram is the estimated signal (background).

The estimate of the background in the signal region is made from the MC in the same manner as in the $D^{\star +}$ analysis. Figure 2 shows the signal and background superimposed on the data.

After cuts, the number of candidates in each sample is 88 for $D^{\star +} \to \pi_s^+(K^-\pi^+)$, 131 for $D^{\star +} \to \pi_s^+(K^-\pi^+\pi^0)$, and 98 for $D^+ \to K^-\pi^+\pi^+$. Monte Carlo estimates for the fractions of $c \to D^{(\star)+}, b \to D^{(\star)+}$, and RCBG in each sample are $(f_c, f_b, f_{\rm RCBG}) =$ (0.52, 0.22, 0.26), (0.50, 0.22, 0.28), and (0.70, 0.14, 0.16), respectively.

Figure 3 shows the $-q\,\mathrm{sgn}(P_e)\cos\theta_D$ distribution, where θ_D is the polar angle of the $D^{(\star)+}$ meson momentum and q is its charge; the data show a large asymmetry. 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 similar to that used in Ref. [13]. The likelihood function has the form

$$\begin{aligned}\ln\mathcal{L} = \sum_{i=1}^{n} \ln\{&P_c^j(x_D^i)[(1 - P_eA_e)(1 + y_i^2) + 2(A_e - P_e)y_iA_c^D(1 - \Delta^c)] \\ &+ P_b^j(x_D^i)[(1 - P_eA_e)(1 + y_i^2) + 2(A_e - P_e)y_iA_b^D(1 - \Delta^b)] \\ &+ P_{\rm RCBG}^j(x_D^i)[(1 + y_i^2) + 2A_{\rm RCBG}y_i]\},\end{aligned}$$

where $y = q\cos\theta_D$, n is the total number of candidates, and A_c^D and A_b^D are the asymmetries from $D^{(\star)+}$ decays in tagged $c\bar{c}$ and $b\bar{b}$ events, respectively. Since the measured asymmetry in the sideband regions is expected to be small and is consistent with zero, we take $A_{\rm RCBG} = 0$ for the central value. The functions $\Delta^f(y)$ are the $\mathcal{O}(\alpha_s)$ QCD radiative corrections to the asymmetry, including quark mass effects [14]. The terms P_c^j, P_b^j, and $P_{\rm RCBG}^j$ are the probabilities that a candidate from the jth decay mode is either signal from $c\bar{c}$ or $b\bar{b}$ events, or RCBG, calculated from the relative fractions and x_D distributions. The x_D distributions used for $c\bar{c}$ and $b\bar{b}$ (RCBG) are taken from the MC (sidebands); the shapes are parametrized as in Ref. [15].

In this analysis, we take A_b^D to be fixed and fit only for $A_c^D = A_c$. We estimate A_b^D in a similar manner to Refs. [13] and [16]. We start with the standard model prediction [17], $A_b = 0.935$, and assign it an error of ± 0.105 to cover the range of measurements from LEP and SLD [18]. To arrive at the mixing-corrected value A_b^D, the fraction of $D^{(\star)+}$ coming from the spectator part of B_d decays is taken halfway between its two extrema: all $D^{(\star)+}$'s in B decays come only from B_d decays, or $D^{(\star)+}$'s come equally from all types of B decays $(B_u, B_d, B_s, \Lambda_b)$. For these two assumptions, the mixing parameters [19] $\chi_d = 0.16 \pm 0.02$ or $\overline{\chi} = 0.12 \pm 0.01$, respectively, are then applied to arrive at an average mixing dilution factor $1 - 2\chi_{\rm mix} = 0.72 \pm 0.09$. The correction for wrong-sign $D^{(\star)+}$ from the W^- in $b \to cW^-$ is the same as in Ref. [13]. These combine to $A_b^D = 0.64 \pm 0.11$, where the error is taken as an experimental systematic error. We have taken A_e^0 to be 0.162 ± 0.012 [20]. Performing the maximum likelihood fit to the data sample, we obtain $A_c = 0.71 \pm 0.20(\rm stat)$. As a check, a simple binned fit of the type described in Ref. [2] yields $A_c = 0.74 \pm 0.24$.

Possible systematic errors have been estimated and are summarized in Table I. The largest uncertainties result

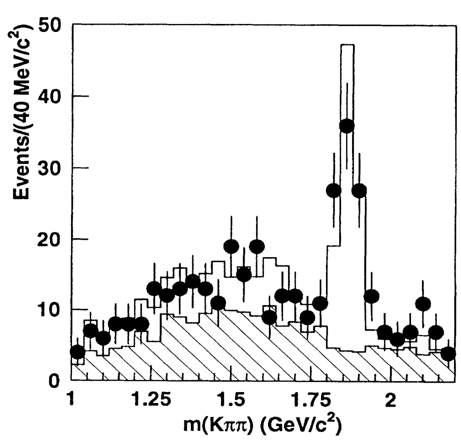

FIG. 2. The mass distribution for $D^+ \to K^-\pi^+\pi^+$. The signal and background are shown as in Fig. 1.

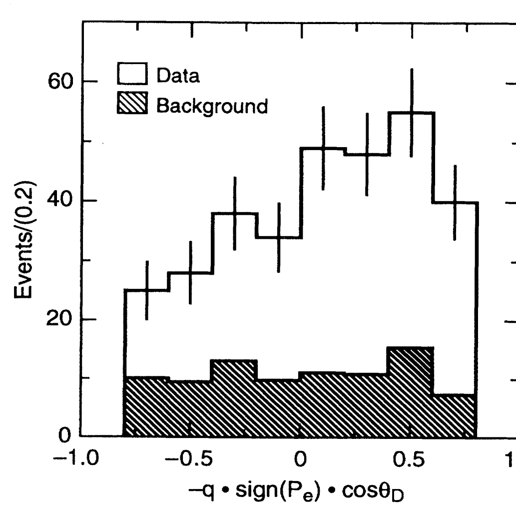

FIG. 3. The distribution of $-q\,\mathrm{sgn}(P_e)\cos(\theta_D)$ for the 317 signal events. The background shown is the scaled signal-subtracted sideband asymmetry.

from our lack of knowledge of the RCBG due to limited statistics. After subtracting the residual signal in the sideband region, we obtain a net sideband asymmetry of $+0.05 \pm 0.10$. We therefore take 0.15 as an upper limit on A_{RCBG}. The uncertainty in f_{RCBG} is a combination of the statistical error on the relative fractions of signal and background from data and MC and an average of the variation in f_{RCBG} allowed by the following: matching the signal and background shapes in the intermediate region between the signal and sideband regions, using wrong-sign combinations for the background shape, and adjusting the sideband signal content to produce the observed sideband asymmetry. Our sensitivity to the RCBG x_D distribution was checked by performing the analysis with P_{RCBG} derived from the MC background instead of the data sidebands. The error due to nonuniform $\cos\theta_D$ acceptance between signal and RCBG is estimated using the one standard deviation limit allowed by data signal and sideband entries. We varied $f_b/(f_b + f_c)$, the fraction of signal events from $Z^0 \to b\bar{b}$, by $\pm 30\%$ to account for differences between our MC and the range of measurements of $D^{(*)+}$ production in Z^0 decay [13,16,21]. Modifying $\langle x_f \rangle$ in heavy quark fragmentation [18] and the exact shape of fragmentation functions gave estimates of our sensitivity to these effects. An uncertainty of ± 0.02 in the value [20] of $\alpha_s(M_Z^2)$ used to calculate the $\mathcal{O}(\alpha_s)$ correction is also included.

To obtain A_c^0, the charm asymmetry parameter at the Z^0 pole, we applied the following: electroweak corrections [17,22] for initial- and final-state radiation, vertex corrections, γ exchange, and γ-Z^0 interference totaling 0.8%; and final-state, $\mathcal{O}(\alpha_s)$ QCD corrections for massive quarks [23] totaling $(2.3 \pm 1.0)\%$. The final result is

$$A_c^0 = 0.73 \pm 0.22(\text{stat}) \pm 0.10(\text{syst})\,.$$

When combined with our other measurement [2] using a lepton tag, this yields $A_c^0 = 0.59 \pm 0.19$. This is in good agreement with the LEP average [18] of $A_c^0 = 0.698 \pm 0.087$, and the standard model prediction [22] of $A_c^0 = 0.67$ for $\sin^2\theta_W^{\mathrm{eff}} = 0.23$.

TABLE I. Contributions to the estimated systematic error.

Source	Error
A_{RCBG}	0.044
f_{RCBG}	0.038
RCBG x distribution	0.039
RCBG $\cos\theta$ acceptance	0.045
A_b^D	0.020
$f_b/(f_b + f_c)$	0.005
c and b fragmentation	0.035
A_e	0.003
P_e	0.013
QCD correction	0.009
Total	0.095

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