SLAC-PUB-7879
July 20, 1998

# An Improved Inclusive Measurement of $A_c$ using the SLD Detector *

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**Abstract**

We report a new measurement of $A_c$ using data obtained by SLD in 1993-97. This measurement uses a vertex tag technique, where the selection of a $c$ hemisphere is based on the reconstructed mass of the charm hadron decay vertex. The method uses the 3D vertexing capabilities of SLD's CCD vertex detector and the small and stable SLC beams to obtain a high $c$-event tagging efficiency and purity of 28% and 81%, respectively. Charged kaons identified by the CRID detector and the charge of the reconstructed vertex provide an efficient quark-antiquark tag. We obtain a preliminary result of $A_c = 0.650 \pm 0.041 \pm 0.033$

*Contributed to the XXIX International Conference on High-Energy Physics,*
*July 23 - 29 1998, Vancouver, Canada*

* Work supported by Department of Energy contract DE-AC03-76SF00515 (SLAC).

# 1 Introduction

Measurements of fermion asymmetries at the $Z^0$ resonance probe a combination of the vector and axial vector couplings of the $Z^0$ to fermions, $A_f = 2v_f a_f/(v_f^2 + a_f^2)$. The parameters $A_f$ express the extent of parity violation at the $Zff$ vertex and provide sensitive tests of the Standard Model.

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

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

where $P_e$ is the longitudinal polarization of the electron beam ($P_e > 0$ for right-handed (R) polarization) and $z = \cos\theta$ is the direction of the outgoing fermion relative to the incident electron. The parameter $A_f$ can be isolated by forming the left-right forward-backward asymmetry $\tilde{A}^f_{FB}(z) = |P_e| A_f\, 2z/(1 + z^2)$, although in this analysis we work directly with the basic cross section.

This note describes the analysis of the data taken during 1996-97 with the newer VXD3 vertex detector. Analysis of the 1993-95 data taken with the original VXD2 vertex detector is described in [1].

# 2 The SLD Detector

The operation of the SLAC Linear Collider with a polarized electron beam has been described in detail elsewhere [2]. During the 1996 run, the SLC Large Detector (SLD) [3] recorded 50k hadronic $Z^0$ decays with a luminosity-weighted electron beam polarization of $|P_e| = 0.765 \pm 0.005$. In 1997 a sample of 100k events with average polarization of $|P_e| = 0.733 \pm 0.008$ was obtained.

Charged particle tracking and momentum analysis are provided by the Central Drift Chamber [4] and the CCD-based vertex detector [5]. The Liquid Argon Calorimeter (LAC) [6] measures the energy of charged and neutral particles and is also used for electron identification. Muon tracking is provided by the Warm Iron Calorimeter (WIC) [7]. The Cherenkov Ring Imaging Detector (CRID) [8] information (limited to the barrel region) provides particle identification. It consists of liquid and gas Cherenkov radiators illuminating large area UV photon detectors. Only the gas information has been included in this analysis, since the liquid covers only marginally the interesting momentum region.

# 3 Event Selection

Hadronic events are selected based on the visible energy and track multiplicity in the event. The visible energy is measured using central drift chamber (CDC) tracks and must exceed 18GeV. There must be at least 7 CDC tracks, 3 that associate to hits in the vertex detector. We also require that the thrust axis, measured from calorimeter clusters, satisfy $|cos\theta_{thr}| < 0.7$. This ensures that the event is contained within the acceptance of the vertex detector. All detector elements are also required to be fully operational. Additionally, we restrict events to 3 jets or less to make sure that we have well defined hemispheres. Jets are defined by the JADE algorithm [9] with $ycut = 0.02$. A total of 117K events pass the above hadronic event selection and jet cut. Background, predominately due to taus, is estimated at $< 0.1\%$.

The SLC interaction point (IP) has a size of approximately $(1.5 \times 0.5 \times 700)\mu m$ in ($x$,$y$,$z$). The motion of the IP $xy$ position over a short time interval is estimated to be $\sim 6\mu m$. Because this motion is smaller than the $xy$ resolution obtained by fitting tracks to find the primary vertex (PV) in a given event, we use the average IP position for the $x$ and $y$ coordinates of the primary vertex. This average is obtained from tracks with hits in the vertex detector in 30 sequential hadronic events. The $z$ coordinate of the PV is determined event-by-event. This results in a PV uncertainty of $\sim 6\mu m$ transverse and $\sim 25\mu m$ longitudinal to the beam direction.

## 3.1 Track Selection

Reconstruction of the mass of heavy hadrons is initiated by identifying secondary vertices in each hemisphere. Only tracks that are well measured are included in the vertex and mass reconstruction. Tracks are required to have at least 23 CDC hits and start within a radius of 50cm of the IP. The CDC track is also required to extrapolate to within 1.0 cm of the IP in $xy$ and within 1.5 cm of the PV in $z$. At least two vertex detector hits are required, the combined drift chamber + vertex detector fit must satisfy $\chi^2/d.o.f. < 8$, and $|cos\theta| < 0.87$. Tracks with an $xy$ impact parameter $> 3.0$mm or an $xy$ impact parameter error $> 250\mu m$ with respect to the IP are removed from consideration in the vertex reconstruction.

## 3.2 Vertex Mass Reconstruction

Vertex identification is done topologically. [10]. This method searches for space points in 3D where track density functions overlap. Each track is parameterized by a Gaussian probability density tube with a width equal to the uncertainty in the measured track position at the IP. Points in space where there is a large overlap of probability density are considered as possible vertex points. Final selection of vertices is done by clustering maxima in the overlap density distribution into vertices for separate hemispheres. We found secondary vertices in 84% of b, 38% of charm, and 2% of light quark events.

Only vertices that are significantly displaced from the PV are considered to be possible B or D hadron decay vertices. We require a distance between the PV and secondary vertex of at least 1mm.

Due to the cascade nature of the B decay, tracks from the decay may not all originate from the same space point. Therefore, a process of attaching tracks to the secondary vertex has been developed based on the transverse and longitudinal distance of closest approach of the track to the PV-secondary vertex axis.

The mass of the secondary vertex is calculated using the tracks that are associated with the vertex, including the tracks that have been added. Each track is assigned the mass of a charged pion and the invariant mass of the vertex is calculated. The reconstructed mass is corrected to account for neutral particles as follows. Using kinematic information from the vertex flight path and the momentum sum of the tracks associated with the secondary vertex, we add a minimum amount of missing momentum to the invariant mass. This is done by assuming the true quark momentum is aligned with the flight direction of the vertex. The so called $P_t$-corrected mass is given by:

$$M_c = \sqrt{M^2{}_{tk} + {P_t}^2} + |P_t|$$

where $M_{tk}$ is the mass for the tracks associated with the secondary vertex. We restrict the contribution to the invariant mass that the additional transverse momentum adds to be less than the initial mass of the secondary vertex. This cut ensures that poorly measured vertices in *uds* events do not leak into the sample by adding large $P_t$.

## 3.3 Flavor Tag

A bottom tag is defined as a hemisphere with an invariant mass above 2 GeV/$c^2$. The intermediate mass region, between 0.5 and 2 GeV/$c^2$ contains a mixture of $b$ and $c$, with a small *uds* background. We define some additional cuts to reject $b$ and *uds*. A charm tag is defined as follows:

- $0.55 < M_c < 2\text{GeV}/c^2$
- Vertex momentum ($P_V$) greater than 5 GeV/$c$.
- Fragmentation cut: $15M_c - P_V < 10$. This uses the fact that D hadrons from charm have a higher momentum for the same mass than those from $b$ quarks.
- Veto on a tagged $b$ on the opposite hemisphere.

For charm, this tag selects one or both hemisphere in about 28% of the events. The tagged sample has 81% charm purity.

## 3.4 Signal Tag

The determination of the direction of the quark is done in two ways. The first is the vertex charge, $Q_{VTX}$. Charged vertices, coming mostly from $D^{\pm}$ and $D_s$ have a positive charge for $c$ vertices and a negative charge for $\bar{c}$. One would expect that the $b$ background has an opposite sign, but in reality this is diluted significantly. The $b$ vertices that survive the charm tag usually miss some tracks and therefore have lost most of their quark-antiquark charge correlation information.

The second method is the kaon charge, $Q_K$. This is the total charge of the CRID-identified kaons in the vertex. For the kaon charge, the signals for $b \to c \to s$ and $c \to s$ decays have the same sign.

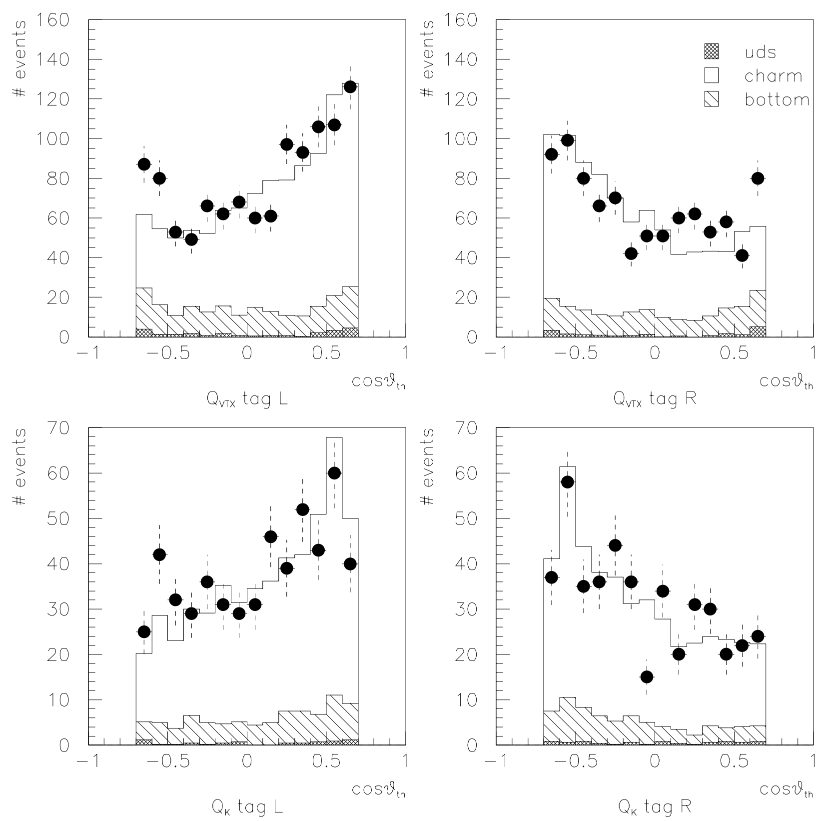


Figure 1: Measured asymmetry in the vertex charge and kaon channel for data (points) and MC (solid). The hatched regions indicate the non-charm backgrounds

MC studies indicate a $\sim 25\%$ efficiency for the kaon tag and $\sim 50\%$ for the vertex charge for both charm and bottom events. For charm events, the correct tag probabilities are

$p_K^{correct} = 91\%$ and $p_{VTX}^{correct} = 90\%$. For bottom events the probabilities are $p_K^{correct} = 79\%$ and $p_{VTX}^{correct} = 54\%$. Both methods show a clear asymmetry signal as seen in figure 1.

# 4 Results

A maximum likelihood fit of all tagged events is used to determine $A_c$. As a likelihood function we use the total cross section.

$$\begin{aligned} \mathcal{L}(P_{VTX}, P_e, z, A_c) \;\propto\; & (1+z^2)(1-A_eP_e) + 2z(A_e - P_e) \\ & \{F_b(P_{VTX}, |z|)(1-2\chi)A_bC_b(tag) + \\ & F_c(P_{VTX}, |z|)A_cC_c(tag) + F_{uds}(P_{VTX}, z)A_{uds}\} \end{aligned} \quad (2)$$

Here $F_{b,c,uds}$ is the probability to be a $b, c$, or $uds$ respectively for an event with vertex momentum $P_{VTX}$ and signed thrust-axis direction $z = -Q\cos\theta_{thr}$. The shape of these functions is taken from Monte Carlo with the overall normalization determined from the data [11]. The factor $C_{(b,c)}(tag) = (2p_{(b,c),tag}^{correct} - 1)$ is the effectiveness of the tag, determined from Monte Carlo. This factor is taken to be independent of $z$ and $P_{VTX}$. The three signs governing the left-right forward-backward asymmetry – beam polarization $P_e$, hemisphere tag charge $Q$, and quark direction $\cos\theta_{thr}$ – are incorporated automatically into the likelihood function.

A correction factor $(1 - 2\chi)$ is applied to all b-quark sources to account for asymmetry dilution due to $B^0\bar{B}^0$ mixing, with $\chi = .125$ taken from LEP measurements of the average mixing in $Z^0 \to b\bar{b}$ events [12]. The light-flavor raw asymmetry $A_{uds}$ is taken from MC simulation.

The QCD corrections to the cross-section are well known [13]. We account for them with a correction term:

$$A^q_{FB|O(\alpha_s)}(\theta) = A^q_{FB|O(0)}(\theta)(1 - \Delta^q_{O(\alpha_s)}(\theta))$$

These QCD correction have to be adjusted for any bias in the analysis method to reject $q\bar{q}g$ events:

$$\Delta^{eff}_{\mathrm{QCD}} = f\Delta_{\mathrm{QCD}}$$

We estimate the analysis bias factor $f$ for $b$ and $c$ from a Monte Carlo simulation at generator level:

$$f = \frac{A_{q\bar{q}}^{gen} - A_{PartonShower}^{analysis}}{A_{q\bar{q}}^{gen} - A_{PartonShower}^{gen}}$$

We found $f_c = 0.25 \pm 0.06$ and $f_b = 0.31 \pm 0.08$.

For 1996-97 we find an efficiency of $\eta_c = 27.5 \pm 1.2\%$ for charm events, with a purity of $\Pi_c = 81.3 \pm 0.9\%$. This agrees well with the Monte Carlo values of $\eta_c^{MC} = 27.3\%$ and $\Pi_c^{MC} = 79.3\%$. The background is made up of 2% *uds* and 17% *b*. From a sample of 3365 selected events we measure $A_c = 0.641 \pm 0.052$. Combining with the previous SLD result for 1993-95 data [1] we obtain:

$$A_c = 0.650 \pm 0.041$$

This includes a QCD correction of $\Delta A_c = +0.009$. The error is statistical only.

# 5 Systematic Errors

The systematic errors for the 1993-97 SLD result can be found in table 1. We give a brief description of the different sources.

The flavor composition normalization is measured from the data [11]. Its statistical error contributes to the systematics, as does the uncertainty on the *uds* fraction from Monte Carlo and the *uds* asymmetry. The *uds* asymmetry was found to be compatible with zero in the Monte Carlo. We vary by the MC statistical error of $\pm 0.15$ to estimate the uncertainty from this source.

The fit systematics include the shape of the flavor composition distributions as functions of $\cos\theta_{thr}$ and $P_{VTX}$. These were estimated by performing fits using flavor distributions independent of each parameter. The full difference was taken as the error.

The error from QCD corrections comes mainly from the uncertainty in the correction factors $f_{b,c}$. Gluon splitting and the error on $\alpha_s$ are also taken into account.

The vertex systematics are built up from detector sources and physics sources. For the detector we considered a 3% effect on the tracking efficiency. The dominant systematic error is the vertex smearing. This accounts for differences between Monte Carlo and data in the vertex charge distribution. These differences can be explained by assuming that there is a charge reconstruction problem. Smearing the charge distribution with a 1% probability of the secondary vertex tracks in the Monte Carlo to be absorbed in the primary vertex produces a good agreement of the charge distribution between data and Monte Carlo. The full difference is taken as the error.

Table 1: Systematic errors for the maximum likelihood analysis

| source | $\delta A_c$ |
|---|---|
| **Tag Composition** | |
| $b$, $c$, $uds$ ratio | 0.009 |
| $uds$ asymmetry | 0.004 |
| **Fit Systematics** | |
| $F_{c,b,uds}$ shape vs. $P_{VTX}$ | 0.009 |
| $F_{c,b,uds}$ shape vs. $\cos\theta_{thr}$ | 0.011 |
| MC Statistics | 0.003 |
| **QCD corrections** | |
| Correction factor | 0.002 |
| $\alpha_s$ | 0.001 |
| $g \to c\bar{c}$ | 0.002 |
| **Vertex Charge** | |
| Tracking efficiency 3% | 0.015 |
| Charge Smearing 7% | 0.015 |
| **Kaon Systematics** | |
| K mis-id | 0.005 |
| $D^{+/-}$ wrong sign K (0.81 $\pm$ 0.05) | 0.002 |
| $D^0$ wrong sign K (0.940 $\pm$ 0.013) | 0.004 |
| **Physics Systematics** | |
| $D^+$ ratio $0.230 \pm 0.028$ | 0.007 |
| $D_s$ ratio $0.115 \pm 0.037$ | 0.005 |
| $\lambda_c$ ratio $0.074 \pm 0.029$ | 0.001 |
| $A_b(1-2\chi)$ $(0.64 \pm 0.11)$ | 0.007 |
| **Polarization Systematics** | |
| $\delta P_e$ | 0.006 |
| $A_e = 0.152 \pm 0.008$ | 0.001 |
| **total** | 0.033 |

The kaon related systematic errors come from two sources. The uncertainty in the kaon production ratios, and the actual kaon identification from the CRID detector. For the first we use the variations from [14] and for the second we vary the background misidentification level by $1\sigma$. The misidenfication of pions as kaons is measured from data in $K_S^0$ decays.

Another source of errors is the uncertainty in the production rates of the charmed hadrons. We vary them within the recommendations of the LEP Electroweak Working Group [15].

# 6 Conclusions

We have performed a measurement of $A_c$ using a method that takes advantage of some of the unique features of the SLD detector. Our preliminary result based on 300K hadronic $Z^0$ decays is:

$$A_c = 0.650 \pm 0.041 \pm 0.033 \qquad \textbf{Preliminary}$$

This result is consistent with the SM expectation of 0.67 and other measurements at SLD and LEP. Due to the efficient tag and high analyzing power inclusive quark-antiquark discrimination, the statistical power of this analysis is significantly improved compared to more conventional techniques. This result is still statistically limited and the systematic errors are small and mostly uncorrelated with those from other analyses. With the remaining data from the 1997-8 run of SLD, we expect a further reduction of the errors.

# Acknowledgements

This work was supported by Department of Energy contracts: DE-FG02-91ER40676 (BU), DE-FG03-92ER40701 (CIT), DE-FG03-91ER40618 (UCSB), DE-FG03-92ER40689 (UCSC), DE-FG03-93ER40788 (CSU), DE-FG02-91ER40672 (Colorado), DE-FG02-91ER40677 (Illinois), DE-AC03-76SF00098 (LBL), DE-FG02-92ER40715 (Massachusetts), DE-AC02-76ER03069 (MIT), DE-FG06-85ER40224 (Oregon), DE-AC03-76SF00515 (SLAC), DE-FG05-91ER40627 (Tennessee), DE-AC02-76ER00881 (Wisconsin), DE-FG02-92ER40704 (Yale); National Science Foundation grants: PHY-91-13428 (UCSC), PHY-89-21320 (Columbia), PHY-92-04239 (Cincinnati), PHY-88-17930 (Rutgers), PHY-88-19316 (Vanderbilt), PHY-92-03212 (Washington); the UK Science and Engineering Research Council (Brunel and RAL); the Istituto Nazionale di Fisica Nucleare of Italy (Bologna, Ferrara, Frascati, Pisa, Padova, Perugia); and the Japan-US Cooperative Research Project on High Energy Physics (Nagoya, Tohoku).

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