SLAC-PUB-8199
Revised July 1999

Direct Measurement of A_c using Inclusive Charm Tagging at the SLD Detector*

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Abstract

We report a new measurement of A_c using data obtained by SLD in 1993-98. 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 82%, respectively. Charged kaons identified by the CRID detector and the charge of the reconstructed vertex provide an efficient quark-antiquark tag, with the analyzing power calibrated from the data. We obtain a preliminary result of $A_c = 0.603 \pm 0.028 \pm 0.023$

Contributed to the International Europhysics Conference on High Energy Physics, July 15-21 1999, Tampere, Finland; Ref 6-474, and to the XIXth International Symposium on Lepton Photon Interactions, August 9-14 1999, Stanford, USA.

*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 1996-98 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 100k events with a luminosity-weighted electron beam polarization of $|P_e| = 0.765 \pm 0.005$. In 1997-98 a sample of 350k 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 18 GeV. There must be at least 7 CDC tracks, 3 with 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 290k 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 $(1.5 \times 0.5 \times 700)$ μm in (x,y,z). The motion of the IP xy position over a short time interval is estimated to be ~ 6 μm. 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 ~ 6 μm transverse and ~ 25 μm 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 50 cm 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 μm 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 bottom, 38% of charm, and 2% of light quark events.

The mass of the secondary vertex is calculated using the tracks that are associated with the vertex. 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:

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

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:

- $0.55 < M_{VTX} < 2$ GeV/c^2
- Vertex momentum (P_{VTX}) greater than 5 GeV/c.
- Fragmentation cut: $15M_{VTX} - P_{VTX} < 10$. This uses the fact that D hadrons from direct charm have a higher momentum than those from B hadron decays.

These tags are calibrated against the data as described in [11]. The efficiencies η_c (for the charm tag) and ϵ_b (for the bottom tag), and partial widths R_c and R_b are found by comparing the single- vs. double-tagged event rates for the two tags. In addition, the b mis-tag efficiency η_b can be found from the fraction of events with a charm tag in one hemisphere and a bottom tag in the other (mixed tag). The light-flavor efficiencies and ϵ_c are taken from Monte Carlo.

A charm event is defined to be one with at least one charm-tagged hemisphere and no bottom-tagged hemispheres. This is found to be $\sim 28\%$ efficient for charm events. With the calibrated efficiencies and partial widths the charm purity of these events is calculated to be $f_c = 82.1 \pm 0.5\%$. This is in good agreement with the Monte Carlo value 82.6%. The b background fraction is 15.5% with uds making up the remainder.

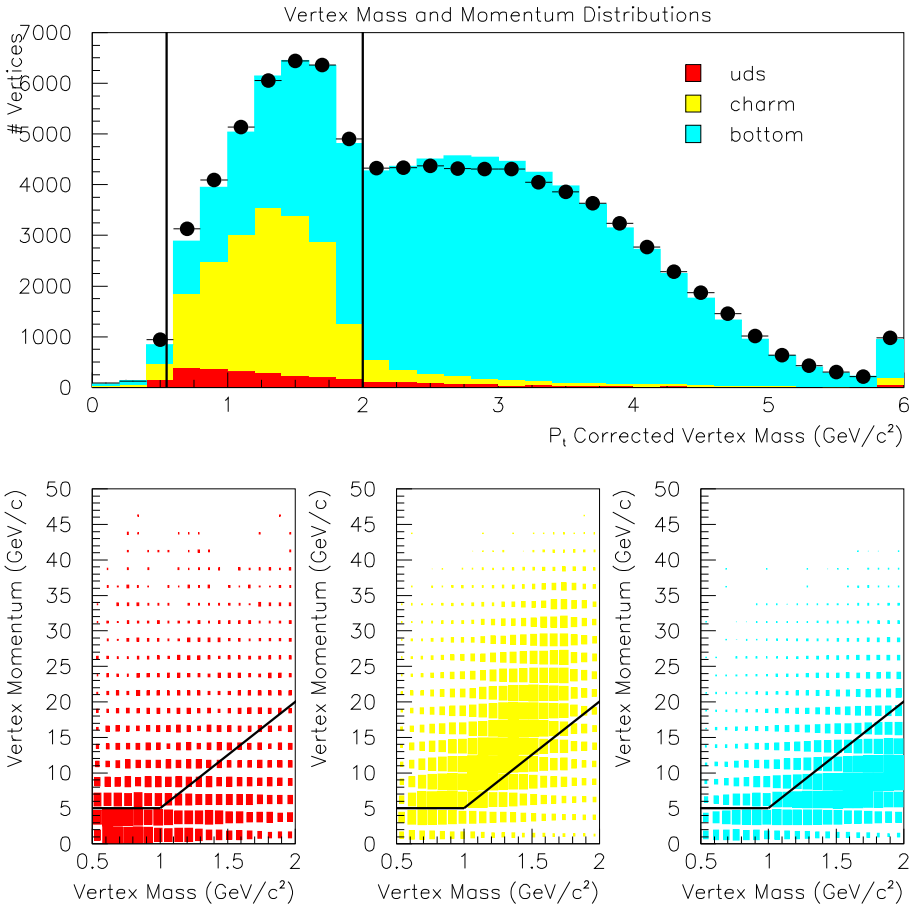

Figure 1: Distributions of M_{VTX} and P_{VTX} vs. M_{VTX} for uds, c, and b hemispheres. The lines represent the cuts described in the text. The points on the M_{VTX} plot are the data.

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 kaon tracks in the vertex. For the kaon charge, the signals for $b \to c \to s$ and $c \to s$ decays have the same sign.

We have $\sim 25\%$ efficiency for the kaon tag and $\sim 50\%$ for the vertex charge for both

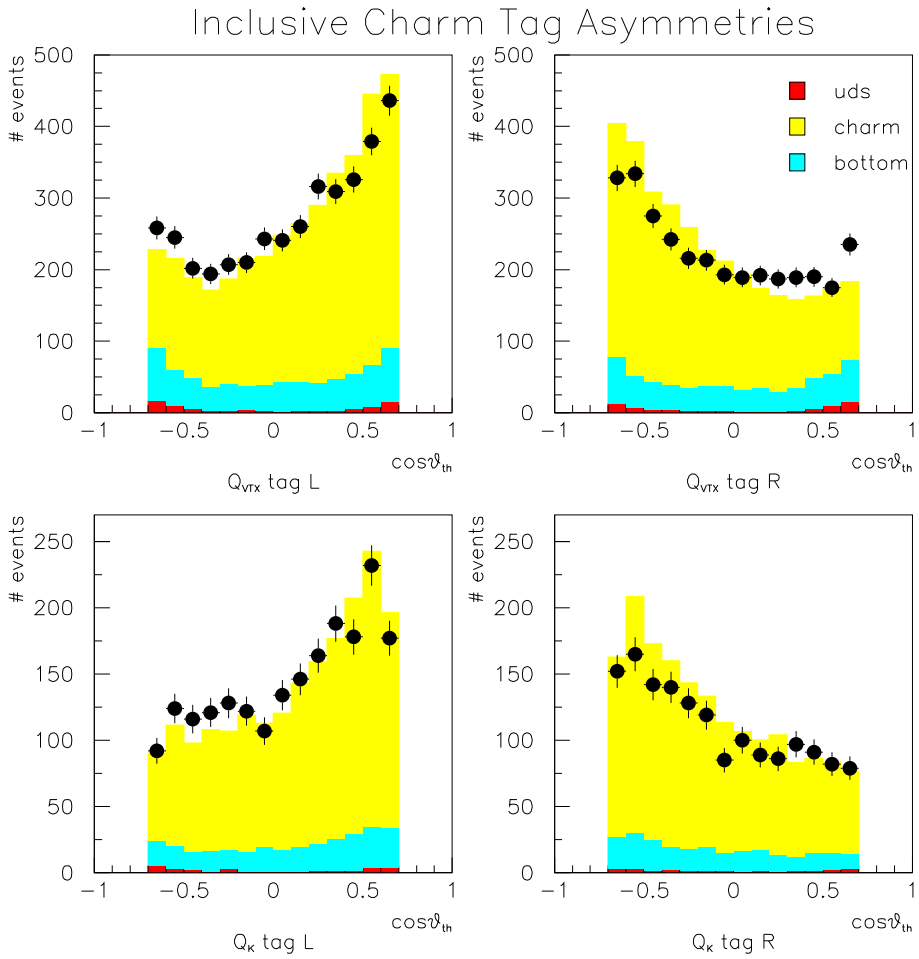

Figure 2: Measured asymmetry in the vertex charge and kaon channel for data (points) and MC (solid). Left side shows left-polarized electrons and similarly for right side.

charm and bottom events. A hemisphere is considered charged if it has either tag nonzero, but hemispheres with the two tags in disagreement are considered uncharged.

The probability to correctly discrimate between quark/antiquark for these tags can be calibrated from the data. The sample used is the events with both hemispheres charm-tagged and with nonzero charge in each hemisphere. The fraction of these events that are in agreement (opposite charges) can be written as $r_{agree} = p^2_{correct} + (1 - p_{correct})^2$. This simply says the hemispheres must either be both right or both wrong. After making a correction for the b contamination we find $p_c^{correct} = 94.2 \pm 1.2\%$. The Monte Carlo gives 92.1%.

The mixed tag events defined above that also have double charge are used to calibrate the b background in a similar way. We find $p_b^{correct} = 60.5 \pm 3.6\%$ (the Monte Carlo value is 57.7%). Because this procedure calibrates the quark/antiquark flavor at production the B-mixing dilution is automatically included in $p_b^{correct}$.

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:

$$\begin{aligned} \mathcal{L} \;\propto\; & (1+z^2)(1-A_eP_e) + 2z(A_e - P_e) \\ & \Big\{ f_c(2p_c^{correct}-1)A_c + \\ & f_b(2p_b^{correct}-1)A_b + f_{uds}A_{uds} \Big\} \end{aligned} \tag{2}$$

where $z = -Q\cos\theta_{thr}$, the thrust axis signed by the tagging method described earlier, is an estimate of the quark direction, $f_{c,b,uds}$ is the probability for an event to be c, b, or uds respectively, and the factor $(2p^{correct}-1)$ is the effectiveness of the quark/antiquark tag. The shape of these functions in z and P_{VTX} is taken from Monte Carlo with the overall normalizations determined from the data. The light-flavor raw asymmetry A_{uds} is taken from the MC simulation. 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.

The QCD corrections to the cross-section are well known [12]. 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 corrections have to be adjusted for any bias in the analysis method against $q\bar{q}g$ events:

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

We estimated the analysis bias factor f^{QCD} for b and c from a generator-level Monte Carlo study:

$$f^{QCD} = \frac{A^{gen}_{q\bar{q}} - A^{analysis}_{q\bar{q}+q\bar{q}g}}{A^{gen}_{q\bar{q}} - A^{gen}_{q\bar{q}+q\bar{q}g}}$$

We found $f_c^{QCD} = 0.25 \pm 0.06$ and $f_b^{QCD} = 0.31 \pm 0.08$.

From the sample of selected events we measure $A_c = 0.589 \pm 0.031$. Combining with the previous SLD result for 1993-95 data [1] we obtain:

$$A_c = 0.603 \pm 0.028$$

Table 1: Systematic errors for the maximum likelihood analysis

Source	δA_c
Tag Composition	
f_b, f_c	0.002
uds efficiency	0.004
uds asymmetry	0.001
Analyzing Power	
$p_c^{correct}$	0.016
$p_b^{correct}$	0.015
Tracking efficiency 3%	0.003
MC Statistics	0.003
Fit Systematics	
$f, p^{correct}$ shape	0.006
δP_e	0.007
A_b (0.935 ± 0.040)	0.002
QCD corrections	
analysis bias	0.002
$\alpha_s(0.118 \pm 0.007)$	0.003
$g \to c\bar{c}$	0.001
Total	0.025

The error is statistical only.

5 Systematic Errors

The systematic errors for the 1996-98 SLD result can be found in Table 1. We give a brief description of the different sources.

The flavor composition error includes the statistical error associated with the calibration procedure. Also included is the uncertainty on the uds efficiency from Monte Carlo. The uds asymmetry was found to be compatible with zero in the Monte Carlo. We vary by the MC statistical error of ± 0.15 to estimate the uncertainty from this source.

The analyzing power error comes mostly from calibration statistics. Also included here are the tracking efficiency uncertainties and MC statistics which impact the inter-hemisphere correlation.

The fit systematics include the shape of f and p as functions of $\cos\theta_{thr}$ and P_{VTX}. These shapes are taken from the Monte Carlo and normalized by the calibrated values. The error is estimated by fitting with and without these shapes. Also included in this category are the

b quark asymmetry and beam polarization which are needed in the fit.

The error from QCD corrections comes mainly from the conservative uncertainty on α_s. Also contributing are the correction factors $f_{c,b}^{QCD}$ and dilution from events with gluon splitting.

6 Conclusions

We have performed a measurement of A_c using a method that takes advantage of some of the unique features of the SLC/SLD experimental program. Our preliminary result based on 450k hadronic Z^0 decays is:

$$A_c = 0.603 \pm 0.028 \pm 0.023 \qquad \textbf{Preliminary}$$

This result is consistent with the SM expectation of 0.67 and other measurements at SLD and LEP. Due to the efficient charm tag and high analyzing power quark-antiquark discrimination, the statistical power of this analysis is significantly improved compared to more conventional techniques. Because the systematic errors are dominated by calibration statistics this result is largely uncorrelated with other measurements.

Acknowledgements

We thank the personnel of the SLAC accelerator department and the technical staffs of our collaborating institutions for their outstanding efforts on our behalf.

*Work supported by Department of Energy contracts: DE-FG02-91ER40676 (BU), 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-FC02-94ER40818 (MIT), DE-FG03-96ER40969 (Oregon), DE-AC03-76SF00515 (SLAC), DE-FG05-91ER40627 (Tennessee), DE-FG02-95ER40896 (Wisconsin), DE-FG02-92ER40704 (Yale); National Science Foundation grants: PHY-91-13428 (UCSC), PHY-89-21320 (Columbia), PHY-92-04239 (Cincinnati), PHY-95-10439 (Rutgers), PHY-88-19316 (Vanderbilt), PHY-92-03212 (Washington); The UK Particle Physics and Astronomy Research Council (Brunel, Oxford and RAL); The Istituto Nazionale di Fisica Nucleare of Italy (Bologna, Ferrara, Frascati, Pisa, Padova, Perugia); The Japan-US Cooperative Research Project on High Energy Physics (Nagoya, Tohoku); The Korea Research Foundation (Soongsil, 1997).

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