Improved Direct Measurement of the Parity-Violation Parameter $A_b$ Using a Mass Tag and Momentum-Weighted Track Charge


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We present an improved direct measurement of the parity-violation parameter \( A_b \) in the \( Z \) boson–\( b \)-quark coupling using a self-calibrating track-charge technique applied to a sample enriched in \( Z \to b\overline{b} \) events via the topological reconstruction of the \( B \) hadron mass. Manipulation of the Stanford Linear Collider electron-beam polarization permits the measurement of \( A_b \) to be made independently of other \( Z \)-pole coupling parameters. From the 1996–1998 sample of 400 000 hadronic \( Z \) decays, produced with an average beam polarization of 73.4\%, we find \( A_b = 0.906 \pm 0.022(\text{stat}) \pm 0.023(\text{syst}) \). The 1996–1998 run of the SLD detector incorporated the upgraded VXD3 CCD pixel vertex detector [7], which featured a greater coverage in \( \cos \theta \), as well as a larger outer radius and substantially less material per layer, than that of the VXD2 vertex detector [8] in place from 1993–1995.

The SLD measures charged particle tracks with the Central Drift Chamber (CDC), which is immersed in a uniform axial magnetic field of 0.6 T. The VXD3 vertex detector provides an accurate measure of particle trajectories close to the beam axis. For the 1996–1998 data, the combined \( r \phi \) (\( rz \)) impact parameter resolution of the CDC and VXD3 is 7.7 (9.6) \( \mu \)m at high momentum, and 34 (34) \( \mu \)m at \( p_L / \sqrt{\sin \theta} = 1 \) GeV/c, where \( p_L \) is the momentum transverse to the beam direction, and \( r \) (\( z \)) is the coordinate perpendicular (parallel) to the beam axis. The combined momentum resolution in the plane perpendicular to the beam axis is \( \delta p_{L}/p_{L} = \sqrt{(0.01)^{2} + (0.0026 p_{L}/\text{GeV}/c)^{2}} \). The thrust axis is reconstructed using the liquid argon calorimeter, which covers the angular range \( |\cos \theta| < 0.98 \).

The details of the analysis procedure are similar to those of the 1993–1995 sample analysis. Events are classified as hadronic \( Z^0 \) decays if they (i) contain at least seven well-measured tracks (as described in Ref. [5]); (ii) exhibit a visible charged energy of at least 20 GeV; and (iii) have a thrust axis polar angle satisfying \( |\cos \theta_{\text{thrust}}| < 0.7 \). The resulting hadronic sample from the 1996–1998 data consists of 245 048 events with a nonhadronic background estimated to be <0.1%.

We select against multijet events in order to reduce the dependence of the measured value of \( A_b \) on the effects of gluon radiation and interhemisphere correlation. Events are discarded if they are found to have four or more jets by the JADE jet-finding algorithm with \( \gamma_{\text{cut}} = 0.02 \) [9], using reconstructed charged tracks as input. In addition, any event found to have three or more jets with \( \gamma_{\text{cut}} = 0.1 \) is discarded.

To increase the \( Z^0 \to b\overline{b} \) content of the sample, a tagging procedure based on the invariant mass of 3-dimensional topologically reconstructed secondary decay vertices is applied [10]. The mass of the reconstructed vertex is corrected for missing transverse momentum relative to the reconstructed \( B \) hadron flight direction in order to partially account for neutral particles. The requirement that the event contain at least one secondary vertex with mass greater than 2 GeV/c\(^2\) results in a
sample of 36 936 candidate $Z^0 \to b \bar{b}$ decays. The purity (97%) and efficiency (77%) of this sample are calculated from the data by comparing the rates for finding a high mass vertex in either a single or both hemispheres, where the two hemispheres are defined relative to the plane perpendicular to the thrust axis. This procedure assumes a priori knowledge of the small $udsc$ tagging efficiency, as well as the size of interhemisphere correlations, both of which are taken from Monte Carlo (MC) simulation. This procedure also assumes knowledge of the $Z \to c \bar{c}$ and $Z \to b \bar{b}$ branching fractions, which are assigned their standard model values of 0.172 and 0.216, respectively.

We construct a signed thrust axis $\vec{T}$, which provides an estimate of the direction of the negatively charged $b$ quark, as follows. Using all track-charge quality tracks, as defined in Ref. [11], we form the track-direction-signed charge sums $Q^b$ and $Q_{+}$ momentum-weighted track-charge sums

$$Q = - \sum_{\text{tracks}} q_j \cdot \text{sgn}(\vec{p}_j \cdot \vec{T}) |(\vec{p}_j \cdot \vec{T})|^\kappa,$$

$$Q_+ = \sum_{\text{tracks}} q_j |(\vec{p}_j \cdot \vec{T})|^\kappa,$$

where $q_j$ and $\vec{p}_j$ are the charge and momentum of track $j$, respectively. $\vec{T}$ is chosen as the unit vector parallel to the thrust axis that renders $Q > 0$. We use $\kappa = 0.5$ to maximize the analyzing power of the track-charged sum for $Z^0 \to b \bar{b}$ events, resulting in a correct-assignment probability of 70%. Figure 1 shows the $T_z = \cos \theta_{\text{thrust}}$ distribution of the $b$-enriched sample separately for left- and right-handed electron beams. Clear forward-backward asymmetries are observed, with respective signs as expected from the cross-section formula in Eq. (1).

The value of $A_b$ is extracted via a maximum likelihood fit to the differential cross section [see Eq. (1)]

$$\rho^{i}(A_b) = (1 - A_e P^i_e)[1 + (T^i)^2] + 2(A_e - P^i_e)T^i[A_e f^i_b(2p^i_b - 1)(1 - \Delta_{QCD,b} f^i) + A_e f^i_c(2p^i_c - 1)(1 - \Delta_{QCD,c})$$

$$+ A_{bckg}(1 - f^i_b - f^i_c)(2p^i_{bckg} - 1)],$$

where $P^i_b$ is the signed polarization of the electron beam for event $i$, $f^i_{bckg}$ is the probability that the event is a $Z^0 \to b \bar{b}(c \bar{c})$ decay (parametrized as a function of the secondary vertex mass), and $\Delta_{QCD,b,c} f^i$ are residual asymmetry of the secondary vertex mass. The $Q_i$, $Q_{sum}$, and $Q_{diff}$ observables are functions of $|Q|$, as well as the secondary vertex mass and $|T_z|$.

As in our previous publication [3], we measure $p_b$ directly from the data [12]. Defining $Q_b (Q_\bar{b})$ to be the track-direction-unsigned momentum-weighted track-charge sum for the thrust hemisphere containing the $b$ ($\bar{b}$) quark, the quantities

$$Q_{sum} = Q_b + Q_{\bar{b}},$$

$$Q_{diff} = Q_b - Q_{\bar{b}},$$

may be related to the experimental observables defined in Eqs. (2) and (3), respectively: $|Q_{diff}| = |Q|$ and $Q_{sum} = Q_+$. Our MC simulation indicates that the $Q_b$ and $Q_\bar{b}$ distributions are approximately Gaussian. In this limit [12],

$$p_b(|Q|) = \frac{1}{1 + e^{-\frac{\alpha_b|Q|}{2}}},$$

with

$$\alpha_b = 2\frac{q_{\text{diff}}}{{\sigma}_{\text{diff}}} = \frac{2\sqrt{\langle |Q_{diff}|^2 \rangle}}{\langle |Q_{diff}|^2 \rangle},$$

where $q_{\text{diff}}$ and $\sigma_{\text{diff}}$ are the mean and width, respectively, of the Gaussian $Q_{diff}$ distribution. The parameter $\alpha_b$, whose magnitude depends upon the separation between the $b$ and $\bar{b}$ track-sum distributions via the observable $\langle |Q_{diff}|^2 \rangle$, provides a measure of the analyzing power of the $b$-quark direction estimator $T_z$. Figure 2 compares the distributions of the observable combinations $|Q_{diff}|$ and $Q_+$ between data and MC.

In the absence of a correlation between $Q_b$ and $Q_\bar{b}$, $\sigma_{\text{diff}} = \sigma_{\text{sum}}$, where $\sigma_{\text{sum}}$ is the observed width of the $Q_+$ distribution. Thus $\alpha_b$ can be derived from experimental

![FIG. 1. Polar angle distributions for track-charge-signed $Z \to b \bar{b}$ candidates, separately for left- and right-handed electron beams. The shaded histogram represents the contribution from a non-$b \bar{b}$ background, estimated as described in the text. The analysis employs a cut of $|\cos \theta| < 0.7$.](image)
lead to a further correction of $-0.2\%$ to the measured value of $A_b$.

While, as described above, the overall tagging efficiency is derived from data, the dependence of the $b$-tagging efficiency upon the secondary vertex mass must be estimated from the MC simulation, as must be the charm correct-signing probability $p_c$. The value of $A_c$ is set to its standard model value of 0.67, with an uncertainty commensurate with that of [16]. The value of $A_{b\mathrm{c}}$ is set to zero, with an uncertainty corresponding to the full physical range $[A_{b\mathrm{c}}] < 1$. The resulting value of $A_b$ extracted from the fit is $A_b = 0.907 \pm 0.022(\mathrm{stat})$. This result is found to be insensitive to the value of the $b$-tag mass cut, and the value of weighting exponent $\kappa$ used in the definition (2) and (3) of the momentum-weighted track-charge sum.

We have investigated a number of systematic effects which can change the measured value of $A_b$; these are summarized in Table I. The uncertainty in $\alpha_b$ due to the statistical uncertainties in $(|Q_{\mathrm{sum}}|)_{\mathrm{stat}}$ and $\sigma_{\mathrm{stat}}$ corresponds to a $1.6\%$ uncertainty in $A_b$. The uncertainty in the hemisphere correlation parameter $\lambda$ is estimated by varying fragmentation parameters within JETSET 7.4, and by comparison with the HERWIG 5.7 [18] fragmentation model. The resulting uncertainty in $A_b$ is $1.4\%$. The sensitivity of the result to the shape of the underlying $Q_b$ distribution is tested by generating various triangular distributions as well as double Gaussian distributions with offset means. The test distributions are constrained to yield a $Q_{\mathrm{sum}}$ distribution consistent with data, and the total uncertainty is found to be $0.8\%$. In addition, while the mean value of the self-calibration parameter $\alpha_b$ is constrained by the data, it has a $\cos\theta$ dependence due to the falloff of the tracking efficiency at high $|\cos\theta|$ which must be

<p>| TABLE I. Relative systematic errors on the measurement of $A_b$. |
|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Error source</th>
<th>Variation</th>
<th>$\delta A_b/A_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_b$ statistics</td>
<td>$\pm 1\sigma$</td>
<td>1.6%</td>
</tr>
<tr>
<td>$\lambda_b$ correlation</td>
<td>JETSET, HERWIG</td>
<td>1.4%</td>
</tr>
<tr>
<td>$P(Q_b)$ shape</td>
<td>Different shapes</td>
<td>0.8%</td>
</tr>
<tr>
<td>$\cos\theta$ shape of $\alpha_b$</td>
<td>MC shape vs flat</td>
<td>0.4%</td>
</tr>
<tr>
<td>Light flavor</td>
<td>50% of correction</td>
<td>0.2%</td>
</tr>
<tr>
<td>Analyzer</td>
<td>Tag composition</td>
<td>Procedure from [17]</td>
</tr>
<tr>
<td>Detector modeling</td>
<td>Compare tracking efficiency corrections</td>
<td>0.8%</td>
</tr>
<tr>
<td>Beam polarization</td>
<td>Full correction QCD</td>
<td>$\pm 0.5%$</td>
</tr>
<tr>
<td>Gluon splitting</td>
<td>Full correction $A_c$</td>
<td>$0.67 \pm 0.04$</td>
</tr>
<tr>
<td>$A_{b\mathrm{c}}$</td>
<td>$0 \pm 0.50$</td>
<td>0.2%</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>2.6%</td>
</tr>
</tbody>
</table>
estimated using the simulation, leading to a 0.4\% uncertainty in \(A_b\).

The extracted value of \(A_b\) is sensitive to our estimate of the \(Z^0 \rightarrow c \bar{c}\) background, which tends to reduce the observed asymmetry due to the positive charge of the underlying \(c\) quark. The uncertainty in the purity estimate of 96.9\% ± 0.3\% is dominated by the uncertainties in the charm tagging efficiency (\(\epsilon_c = 0.0218 \pm 0.0004\)) and the statistical uncertainty of the bottom tagging efficiency determined from data, leading to a 0.5\% uncertainty in \(A_b\). An outline of the charmed quark efficiency uncertainty determination can be found in Ref. [17]; the uncertainty is dominated by empirical constraints on charmed hadron production rates and on \(K^0\) production in the decay of charmed mesons. Uncertainties in the measured values of \(R_b\) and \(R_c\) contribute, through the tag purity, to uncertainties in \(A_b\) of 0.1\% and 0.0\%, respectively.

Agreement between the data and MC simulation charged track multiplicity distributions is obtained only after the inclusion of additional ad hoc tracking inefficiency. This random inefficiency was parametrized as a function of total track momentum, and averages 0.4 charged tracks per event, leading to an overall change of +1.3\% in \(A_b\). As a check, we employ an alternative approach, matching the efficiency of the linking of the independent CDC and VXD3 track segments between data and MC simulation. This yields a change of +0.5\% in \(A_b\); we take the difference of 0.8\% as an estimate of the systematic error on the modeling of the tracking efficiency. Combining all systematic uncertainties in quadrature yields a total relative systematic uncertainty of 2.6\%.

The extracted value of \(A_b\) depends on a number of model parameters, as follows. Increases by 0.01 in the values of \(A_c, R_b, R_c\), and the per-event rate of \(b\bar{b}\) production via gluon splitting lead to changes in \(A_b\) of +0.0002, −0.0055, +0.0002, and +0.0110, respectively.

In conclusion, we have exploited the highly polarized SLC electron beam and precise vertexing capabilities of the SLD detector to perform a direct measurement of \(A_b = 0.906 \pm 0.022\) (stat) ± 0.023 (syst), from the 1996–1998 SLD data sample. Combined with our previously published result [3] based on the 1993–1995 data sample, we find

\[A_b = 0.907 \pm 0.020\) (stat) ± 0.024 (syst), \]

for the full 1993–1998 data sample. This result is in good agreement with the standard model prediction of 0.935, and represents an improvement of over a factor of 2 in the precision of the determination of \(A_b\) via the use of momentum-weighted track charge.

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