First Direct Measurement of the Parity-Violating Coupling of the $\mathbf{Z}^0$ to the s-Quark

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Abstract

We have made the first direct measurement of the parity-violating coupling of the Z^0 boson to the strange quark, A_s, using 550,000 $e^+e^- \to Z^0 \to$hadrons events produced with a polarized electron beam and recorded by the SLD experiment. $Z^0 \to s\bar{s}$ events were tagged by the absence of B or D hadrons and the presence in each hemisphere of a high-momentum $K^\pm$ or K^0_s. From the polar angle distributions of the strangeness-signed thrust axis, we obtained $A_s = 0.895 \pm 0.066(stat.) \pm 0.063(syst.)$. The analyzing power and $u\bar{u} + d\bar{d}$ background were estimated from the data.

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The extent of parity violation in the electroweak coupling of the Z^0 boson to an elementary fermion f can be specified by the observable $A_f = 2v_f a_f/(v_f^2 + a_f^2)$, where v_f (a_f) is the vector (axial-vector) $Zf\bar{f}$ coupling. In the Standard Model (SM), universal couplings are expected for the leptons ($A_e = A_\mu = A_\tau$), the down-type quarks ($A_d = A_s = A_b$) and the up-type quarks ($A_u = A_c = A_t$). Precise measurements of the A_f allow stringent tests of the SM and sensitivity through radiative corrections to the top quark and Higgs boson masses ($A_{e,\mu,\tau}$), new physics that affects primarily the right-handed couplings ($A_{d,s,b}$), and new physics that couples more strongly to heavier quarks (deviations from universality).

All except A_t can be measured in e^+e^- annihilations at the Z^0 resonance, via forward-backward production asymmetries in θ_f, the polar angle of the outgoing f with respect to the incoming e^- beam. For an e^- beam with longitudinal polarization P_e, and an unpolarized e^+ beam, the Born-level differential cross-section for the process $e^+e^- \to Z^0 \to f\bar{f}$ is:

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

where the last term is antisymmetric in $x = \cos\theta_f$. From $d\sigma_f/dx$ in samples with left- ($P_e < 0$) and right-polarized ($P_e > 0$) beams of magnitude $|P_e|$, one can measure both the initial- (A_e) and final-state (A_f) couplings directly [1,2]; for $P_e = 0$ one can measure only their product, or $A_{FB}^f \equiv 3A_e A_f/4$.

The most precisely measured coupling is A_e, with a relative error of 1.3% [1,3], and lepton universality is verified at the 8% level [3]. In the quark sector, several measurements of A_b and A_c that use properties of the leading B and D hadrons can be combined to yield precisions of 2.0% and 4.4%, respectively [3]. However there are few measurements of A_u, A_d or A_s [4,5] because the leading particles in u, d and s jets are more difficult to identify experimentally; they have relatively low energy, are not unique to events of that flavor, and nonleading particles of the same species are produced in hadronic jets of all flavors. Furthermore, these aspects of jet fragmentation are not well measured, and previous measurements either relied on imprecise constraints from their data (OPAL: $A_{FB}^u = 0.040 \pm 0.073$; $A_{FB}^{ds} = 0.068 \pm 0.037$ [4]) or are model-dependent (DELPHI: $A_{FB}^s = 0.101 \pm 0.012$ [5]).

In this Letter we present the first direct measurement of A_s. We used high-momentum $K^\pm$ and K^0_s to tag $Z^0 \to s\bar{s}$ events, and the $K^\pm$ charge to separate s from $\bar{s}$ jets. The heavy flavor ($c\bar{c}+b\bar{b}$) event background was suppressed by identifying secondary vertices. The $u\bar{u}+d\bar{d}$ background was suppressed and the s-$\bar{s}$ separation enhanced by requiring an $s/\bar{s}$-tag in each event hemisphere, reducing any model dependence. The remaining $u\bar{u}+d\bar{d}$ background and the s-$\bar{s}$ separation were constrained using related observables in the data.

We used the sample of 550,000 hadronic Z^0 decays recorded by the SLD experiment at the SLAC Linear Collider from 1993–1998, with $\langle |P_e| \rangle = 0.735 \pm 0.005$ [1]. A description of the SLD can be found in [6]. Charged tracks were measured in the Central Drift Chamber (CDC) [7] and the original (upgraded) Vertex Detector (VXD) [8] in 26.5% (73.5%) of the data. The resolution on the impact parameter d in the plane perpendicular to the beam direction, including the uncertainty on the primary interaction point, was $\sigma_d = 11 \oplus 70/(p \sin^{3/2}\theta)$ μm ($8 \oplus 29/(p \sin^{3/2}\theta)$ μm), where p is the track momentum in GeV/c and θ its polar angle with respect to the beamline. Tracks were identified as $\pi^\pm$, $K^\pm$ or p/$\bar{\text{p}}$ in the Cherenkov Ring Imaging Detector (CRID) [9], which allowed the identification of $\pi^\pm$ with high efficiency and purity for $0.3 < p < 35$ GeV/c, $K^\pm$ for $0.75 < p < 6$ GeV/c and $9 < p < 35$ GeV/c, and p/$\bar{\text{p}}$ for $0.75 < p < 6$ GeV/c and $10 < p < 46$ GeV/c [10]. The event thrust axis [11] was calculated using energy clusters measured in the Liquid Argon Calorimeter [12].

After selecting hadronic Z^0 decays [13], we removed $c\bar{c}$ and $b\bar{b}$ events by requiring no more than one high-quality [13] track with $d/\sigma_d > 2.5$ in the event. The efficiency for selecting well-contained light-flavor events with the VXD, CDC and CRID operational was estimated to be over 95%; the selected sample comprised 244,385 events, with an estimated contribution of 14.2% (3.4%) from $c\bar{c}$ ($b\bar{b}$) events. Such performance parameters were estimated from a detailed Monte Carlo (MC) simulation [13,14] of the SLD, based on the JETSET 7.4 [15] event generator, that was tuned to reproduce many measured properties of hadronic Z^0 decays, including the momentum-dependent production of $K^\pm$, K^0, K^* and ϕ mesons.

Each selected event was divided into two hemispheres by the plane perpendicular to the thrust axis, and in each hemisphere we searched for high-momentum strange particles $K^\pm$,

K_s^0 and $\Lambda^0/\bar{\Lambda}^0$. Candidate $K^\pm$ tracks were required to have $p > 9$ GeV/c, $d < 1$ mm, to extrapolate through an active region of the CRID gaseous radiator system, and to have a log-likelihood [10] for the $K^\pm$ hypothesis $\mathcal{L}_K$ that exceeded both $\mathcal{L}_\pi$ and $\mathcal{L}_\mathrm{p}$ by at least 3 units. For $p>9$ GeV/c, the estimated $K^\pm$ selection efficiency (purity) was 50% (91.5%).

Candidate $K_s^0 \to \pi^+\pi^-$ and $\Lambda^0/\bar{\Lambda}^0 \to \mathrm{p}\pi^-/\bar{\mathrm{p}}\pi^+$ were reconstructed as described in [10,16] from tracks not identified as $K^\pm$. We required $p > 5$ GeV/c and a reconstructed invariant mass $m_{\pi\pi}$ or $m_{\mathrm{p}\pi}$ within two standard deviations of the K_s^0 or Λ^0 mass. If CRID information was available for the p/$\bar{\mathrm{p}}$ track in a $\Lambda^0/\bar{\Lambda}^0$ candidate, we required $\mathcal{L}_\mathrm{p} > \mathcal{L}_\pi$; otherwise we required that the $\Lambda^0/\bar{\Lambda}^0$ not be a K_s^0 candidate and that the flight distance exceed 10 times its uncertainty. The estimated $\Lambda^0/\bar{\Lambda}^0 \to \mathrm{p}\pi^-/\bar{\mathrm{p}}\pi^+$ efficiency (purity) was 10% (90.7%). Selected $\Lambda^0/\bar{\Lambda}^0$ were removed from the K_s^0 sample, giving an estimated $K_s^0 \to \pi^+\pi^-$ efficiency (purity) of 20% (90.7%); the 3.0% $\Lambda^0/\bar{\Lambda}^0$ contribution was also a useful $s/\bar{s}$ tag.

We considered only the selected strange particle with the highest momentum in each hemisphere (5.5% of those tagged contained more than one), and tagged the event as $s\bar{s}$ if one hemisphere contained a $K^\pm$ and the other contained either a $K^\pm$ or K_s^0; if both contained a $K^\pm$, the kaons were required to have opposite charge. The thrust axis, signed so as to point into the hemisphere containing (opposite) the K^- (K^+), was used as an estimate of the initial s-quark direction. Table I shows the number of events tagged in the K^+K^- and $K^\pm K_s^0$ modes, along with the predictions of the MC simulation, which are consistent. Events with $\Lambda^0/\bar{\Lambda}^0$ tags are also shown as important checks of the simulation; their inclusion did not improve the total error on A_s, so they were not considered further. Also shown are the simulated $s\bar{s}$ event purities and analyzing powers $a_s \equiv (N_r - N_w)/(N_r + N_w)$, where N_r (N_w) is the number of events in which the signed thrust axis points into the true s ($\bar{s}$) hemisphere.

Figure 1 shows the measured s-quark polar angle distributions for the K^+K^- and $K^\pm K_s^0$ modes. In each case, production asymmetries of opposite sign and different magnitude for left- and right-polarized e^- beams are visible. The content of the largest $|\cos\theta_s|$ bins is reduced by the detector acceptance. The estimated backgrounds (discussed below) are indicated: those from $c\bar{c}+b\bar{b}$ events exhibit asymmetries of the same sign and magnitude similar to those of the signal, so the measured A_s is insensitive to them; those from $u\bar{u}+d\bar{d}$ events exhibit asymmetries of opposite sign, resulting in higher sensitivity to the associated uncertainties.

A simultaneous unbinned maximum likelihood fit to these four distributions was performed using the function:

$$L = \prod_{k=1}^{N_{data}} \{(1-A_e P_e)(1+x_k^2) + 2(A_e - P_e) \sum_{q=u,d,s,c,b} (N_q[1+\delta]a_q A_q x_k)\}. \qquad (2)$$

Here, the number of tagged $q\bar{q}$ events $N_q = N_{events} R_q \epsilon_q$, $R_q = \Gamma(Z^0 \to q\bar{q})/\Gamma(Z^0 \to \text{hadrons})$, ϵ_q is the tagging efficiency, a_q is the analyzing power for tagging the q direction, and the correction for hard gluon radiation $\delta = -0.013$ was derived [17] as in [2]. The values of the ϵ_q and a_q depend on the tagging mode. World average values [3] of A_e, A_c, A_b, R_c and R_b were used, along with SM values of A_u, A_d, R_u, R_d and R_s. Simulated values of ϵ_c, ϵ_b, a_c and a_b were used, as they depend primarily on measured quantities with well defined uncertainties.

For the light flavors, the relevant parameter values were derived where possible from the data. The number of events $N_u + N_d + N_s$ was determined by subtracting the simulated N_c and N_b from the total observed. The values of a_s and the ratio $(N_u + N_d)/N_s$ were constrained (see below) using the data; since the simulation was consistent with the data, the simulated values of a_s were used and the simulated ϵ_u, ϵ_d and ϵ_s were scaled by a common factor to give the measured $N_u + N_d + N_s$. The average $a_{ud} \equiv (N_u a_u + N_d a_d)/(N_u + N_d)$ can also be constrained from the data, however our constraint is less precise than the range $-a_s < a_u, a_d < 0$, obtained by noting that if a u or d jet produces a leading $K^\pm$, then it must be a K^+, and there will be an associated antistrange particle, which, if a K^-, dilutes the analyzing power. We scaled the simulated a_u and a_d by a common factor such that $a_{ud} = -a_s/2$ for each mode. The fit yielded $A_s = 0.895 \pm 0.066$ (stat.). Histograms corresponding to this value are shown in fig. 1 to be consistent with the data; the binned χ^2 is 42 for 48 bins.

Several sources of systematic uncertainty were considered and are summarized in table II. The values of R_c, R_b, A_c and A_b were varied by the uncertainties on their world averages [3], and a large number of quantities in the simulation of heavy flavor events and detector performance were varied as in [14]; all had negligible effect on the measured value of A_s. The yields and analyzing powers of $K^\pm$ from D (B) decays have been derived from SLD data in the context of a measurement [18] of A_c (A_b), and our simulation reproduces them within the measurement errors. We applied corresponding relative variations of $\pm9\%$ to our ϵ_c, $\pm3.2\%$ to ϵ_b, $\pm5\%$ (15%) to a_c and $\pm3.6\%$ (4.3%) to a_b for the K^+K^- ($K^\pm K^0_s$) mode. The sum in quadrature of these uncertainties was taken as the systematic error due to heavy flavor modelling and is listed in Table II; the largest contribution is from δa_c.

The key to this measurement is the understanding of the light-flavor parameters, for which there are few experimental constraints, and these gave rise to the dominant systematic uncertainties. In order to minimize model dependence, we used our data to constrain the largest uncertainties in these parameters [16] within the context of our simulation, which reproduces [16] existing measurements of relevant quantities such as leading particle production and strange-antistrange correlations.

To constrain the analyzing power a_s, we note that to mistag an s jet as an $\bar{s}$ jet we must either identify a true K^+ or misidentify a π^+ or p as a K^+. A high-momentum K^+ in an s jet must be produced in association with an antistrange particle, yielding a jet with three high-momentum particles of nonzero strangeness. In our data we found 61 hemispheres containing three identified $K^\pm$ and/or K^0_s satisfying our selection criteria; the MC prediction of 67 is consistent. We quantified this as a constraint on a_s by subtracting the simulated $c{+}\bar{c}{+}b{+}\bar{b}$ contribution of 9.3, scaling by the simulated ratio $(s{+}\bar{s})/(u{+}\bar{u}{+}d{+}\bar{d}{+}s{+}\bar{s}) = 0.74$, and dividing by the simulated $(s{+}\bar{s})$. Propagating the data and MC statistical errors yielded an 18.5% relative constraint on the wrong-sign fraction, $w_s = (1{-}a_s)/2$, in $s/\bar{s}$ hemispheres. This constraint is not entirely model-independent but we feel that any further uncertainties are small compared with 18.5%. Assuming equal production of charged and neutral kaons, this procedure delivers a simultaneous calibration of w_s for the two tagging modes, which we varied simultaneously by $\pm18.5\%$ relative. To account for misidentified particles we varied the total production of (p$+\pi^+$) with $p > 9$ GeV/c in s jets by $\pm100\%$, and varied the misidentification probability by its measured relative uncertainty of $\pm25\%$ [10]. The sum in quadrature of these three effects is shown in table II and dominated by the 3-kaon calibration.

The relative $u\bar{u}$+$d\bar{d}$ background $B_{ud} = (N_u+N_d)/N_s$ was constrained in a similar manner, exploiting the fact that an even number of particles with nonzero strangeness must be produced in a u or d jet. The three quantities, the number $N_1 = 1262$ of hemispheres in the data containing an identified K^+K^- pair, $N_2 = 983$ hemispheres containing a $K^\pm K^0_s$ pair, and $N_3 = 503$ events with an identified $K^\pm$ of the same charge in both hemispheres, constrain B_{ud} in complementary ways: N_1 and N_2 are primarily sensitive to $K\bar{K}$ production in u/d jets; $(N_1 - N_2)$ to ϕ production in s jets; and N_3 to these and also the production and misidentification of $\pi^\pm$ and p/$\bar{\text{p}}$. Furthermore, all are sensitive to deviations from the assumed values of R_u, R_d and R_s. The MC predictions of $N_1 = 1218$, $N_2 = 1002$ and $N_3 = 559$ are consistent, and relative constraints on B_{ud} of 4.6%, 5.1% and 8.1%, respectively, were derived. Since N_3 constrains the sum of all contributions, we varied B_{ud} by $\pm$8.1%.

These quantities are also sensitive to a_u and a_d, however our present event sample did not allow us to obtain a useful constraint. We therefore took $-a_s < a_u, a_d < 0$ as hard limits and varied a_u and a_d simultaneously such that $a_{ud} = -a_s/2 \pm a_s/\sqrt{12}$. This yielded the dominant systematic error on A_s and is a quantity that must be understood experimentally before a more precise measurement can be made. Since the product $A_q a_q$ appears in Eqn. 2, this is equivalent to a variation of $A_u + A_d$ down to half of its SM value and up to well over unity; we considered no additional variation of A_u or A_d. The uncertainties listed in table II were added in quadrature to yield a total relative systematic error of ± 0.07.

Several systematic checks were also performed. Ad hoc corrections to the simulation of the kaon momentum distributions and identification efficiencies, and the charged track reconstruction efficiency and impact parameter resolution were removed and the analysis repeated; changes in the measured value of A_s were much smaller than the systematic error. We fitted each tagging mode separately, including those involving Λ^0 tags, with consistent results. We repeated the analysis using all $K^\pm$ or $\Lambda^0/\bar{\Lambda}^0$ hemispheres, with no tag required in the opposite hemisphere; results were consistent. The $K^\pm$ analysis is similar to that in

[5]; it has a relative statistical precision of 0.03 but a systematic error of 0.19.

In conclusion, we have made a precise first direct measurement of the parity-violating coupling of the Z^0 to strange quarks,

$$A_s = 0.895 \pm 0.066(stat.) \pm 0.063(syst.),$$

using high-momentum identified $K^{\pm}$ and K_s^0 to tag $Z^0 \to s\bar{s}$ decays and determine the s-quark direction. Our high $K^{\pm}$ identification efficiency allowed the use of a relatively high-purity, double-tagged event sample, and the extraction from the data of constraints on the analyzing power of the method and the $u\bar{u}+d\bar{d}$ background, using events with same-charge double tags and jets with two or three identified kaons. This result is consistent with the Standard Model expectation, $A_s = 0.935$, and with a recent world average $A_b = 0.881 \pm 0.018$ [3], providing a 10% test of down-type quark universality. Our measurement is consistent with previous measurements of A_{FB}^s [4,5] and is more precise.

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TABLES

Mode	# Events in Data	MC Prediction	$s\bar{s}$ Purity	Analyzing Power
K^+K^-	1290	1312	0.73	0.95
$K^{\pm}K_s^0$	1580	1617	0.60	0.70
$K^+\Lambda^0, K^-\bar{\Lambda}^0$	219	213	0.66	0.89
$\Lambda^0\bar{\Lambda}^0$	17	14	0.57	0.70
$\Lambda^0 K_s^0, \bar{\Lambda}^0 K_s^0$	193	194	0.50	0.32

TABLE I. Summary of the selected event sample for five tagging modes.

Source		Systematic variation	$\delta A_s/A_s$
Heavy Flavor Background		See text	0.012
Correction for gluon radiation		-0.013 ± 0.006	0.006
$\langle \lvert P_e \rvert \rangle$		0.735 ± 0.005	0.006
MC statistics			0.013
a_s	K^+K^- $K^{\pm}K_s^0$	0.949 ± 0.012 0.701 ± 0.060	0.032
$(N_u + N_d)/N_s$ (incl. $(R_u + R_d)/R_s$)	K^+K^- $K^{\pm}K_s^0$	0.190 ± 0.015 0.316 ± 0.026	0.026
a_u, a_d A_u, A_d		$-a_s/2 \pm a_s/\sqrt{12}$	0.054 –
Total			0.070

TABLE II. Summary of systematic uncertainties.

FIGURES

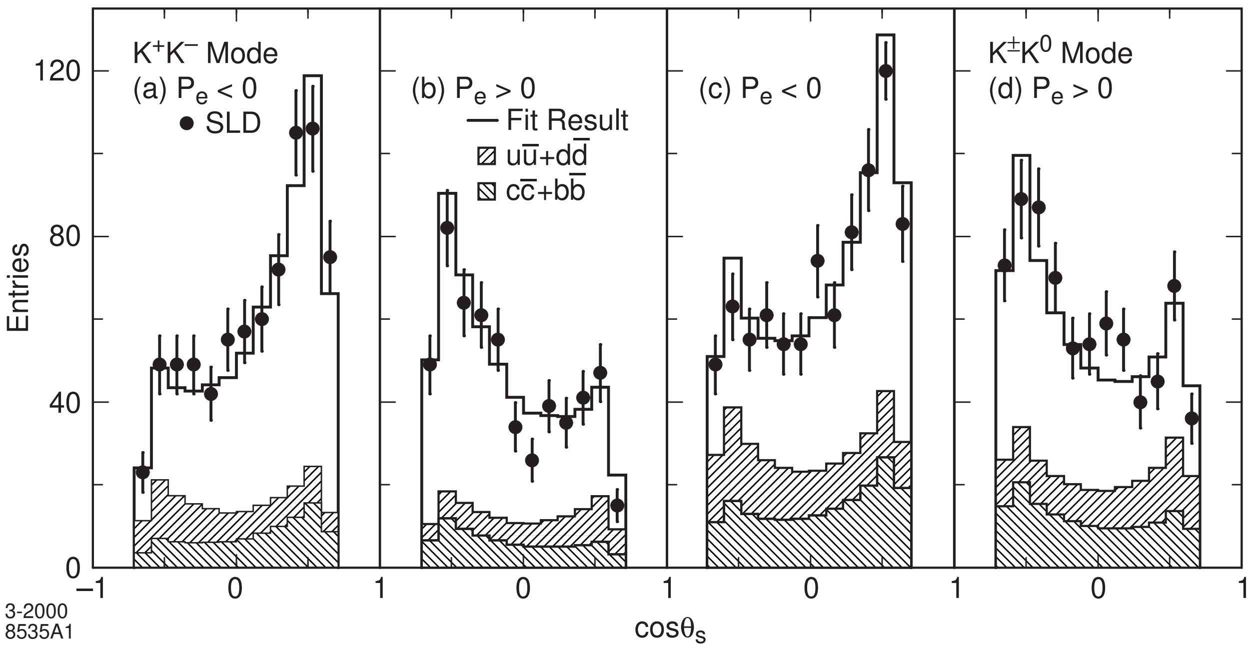

FIG. 1. Measured s-quark polar angle distributions (dots) for selected events in the a,b) K^+K^- and c,d) $K^{\pm}K^0_s$ mode, produced with a,c) left- and b,d) right-polarized electron beam. The histogram represents the result of a simultaneous fit to the four distributions, and the upper (lower) hatched areas indicate the estimated $u\bar{u}+d\bar{d}$ ($c\bar{c}+b\bar{b}$) backgrounds.

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