

University of Massachusetts Amherst

ScholarWorks@UMass Amherst

---

Civil and Environmental Engineering Faculty  
Publication Series

Civil and Environmental Engineering

---

2000

## First direct measurement of the parity-violating coupling of the $Z(0)$ to the s quark

The SLD Collaboration

Follow this and additional works at: [https://scholarworks.umass.edu/cee\\_faculty\\_pubs](https://scholarworks.umass.edu/cee_faculty_pubs)

---

### Recommended Citation

The SLD Collaboration, "First direct measurement of the parity-violating coupling of the  $Z(0)$  to the s quark" (2000). *Physical Review Letters*. 486.  
<https://doi.org/10.1103/PhysRevLett.85.5059>

This Article is brought to you for free and open access by the Civil and Environmental Engineering at ScholarWorks@UMass Amherst. It has been accepted for inclusion in Civil and Environmental Engineering Faculty Publication Series by an authorized administrator of ScholarWorks@UMass Amherst. For more information, please contact [scholarworks@library.umass.edu](mailto:scholarworks@library.umass.edu).

# FIRST DIRECT MEASUREMENT OF THE PARITY-VIOLATING COUPLING OF THE $Z^0$ TO THE $s$ -QUARK\*

The SLD Collaboration\*\*

Stanford Linear Accelerator Center  
Stanford University, Stanford, CA 94309

## 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  $\sim 550,000$   $e^+e^- \rightarrow Z^0 \rightarrow \text{hadrons}$  events produced with a polarized electron beam and recorded by the SLD experiment.  $Z^0 \rightarrow s\bar{s}$  events were tagged by the absence of  $B$  or  $D$  hadrons and the presence in each hemisphere of a high-momentum  $K^\pm$  or  $K_s^0$ . From the polar angle distributions of the strangeness-signed thrust axis, we obtained  $A_s = 0.895 \pm 0.066(\text{stat.}) \pm 0.062(\text{syst.})$ . The analyzing power and  $u\bar{u} + d\bar{d}$  background were constrained using the data.

*Submitted to Physical Review Letters.*

\*Work supported in part by Department of Energy contract DE-AC03-76SF00515.

The extent of parity violation in the electroweak coupling of the  $Z^0$  boson to an elementary fermion  $f$  can be specified by the parameter  $A_f = 2v_f a_f / (v_f^2 + a_f^2)$ , 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 e.g.: 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  $\theta_f$ , the polar angle of the outgoing  $f$  with respect to the incoming  $e^-$  beam. At the SLC, the  $e^-$  beam has longitudinal polarization  $P_e$ , the  $e^+$  beam is unpolarized, and the Born-level differential cross-section for the process  $e^+e^- \rightarrow Z^0 \rightarrow f\bar{f}$  is:

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

where the last term is antisymmetric in  $x = \cos\theta_f$ . Using both 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 a particular 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 indirect 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  $K_s^0$  to tag  $Z^0 \rightarrow s\bar{s}$  events, and the  $K^\pm$  charge to separate  $s$  jets from  $\bar{s}$  jets. The heavy flavor ( $c\bar{c} + b\bar{b}$ ) event background was suppressed by identifying  $B$  and  $D$  decay vertices. The  $u\bar{u} + d\bar{d}$  background was suppressed and the  $s\text{-}\bar{s}$  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  $s\text{-}\bar{s}$  separation were constrained using related observables in the data.

We used the sample of approximately 550,000 hadronic  $Z^0$  decays recorded by the SLD [6] experiment at the SLAC Linear Collider, with  $\langle |P_e| \rangle = 0.735 \pm 0.005$  [1], from 1993–1998. 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 interaction point, was  $\sigma_d = 11 \oplus 70 / (p \sin^{3/2} \theta) \mu\text{m}$  ( $8 \oplus 29 / (p \sin^{3/2} \theta) \mu\text{m}$ ), where  $p$  is the track momentum in GeV/c and  $\theta$  its polar angle with respect to the beamline. Tracks were identified as  $\pi^\pm$ ,  $K^\pm$  or  $p/\bar{p}$  in the Cherenkov Ring Imaging Detector (CRID) [9], which allowed the identification with high efficiency and purity of  $\pi^\pm$  with  $0.3 < p < 35$  GeV/c,  $K^\pm$  with  $0.75 < p < 6$  GeV/c or  $9 < p < 35$  GeV/c, and  $p/\bar{p}$  with  $0.75 < p < 6$  GeV/c or  $10 < p < 46$  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 well-measured [13] track with  $d/\sigma_d > 2.5$  in the event. The efficiency for selecting light-flavor events with  $|\cos\theta_{thrust}| < 0.71$  and the VXD, CDC and CRID operational was estimated to be over 95%; the selected sample comprised 205,708 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, tuned to reproduce many measured properties of hadronic  $Z^0$  decays, including the momentum-dependent production of  $K^\pm$ ,  $K^0$ ,  $K^*$  and  $\phi$  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  $\mathcal{L}_p$  by at least 3 units. For  $p > 9$  GeV/c, the estimated  $K^\pm$  selection efficiency (purity) was 48% (91.5%).

Candidate  $K_s^0 \rightarrow \pi^+\pi^-$  and  $\Lambda^0/\bar{\Lambda}^0 \rightarrow p\pi^-/\bar{p}\pi^+$  decays 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  $m_{p\pi}$  within two standard deviations of the  $K_s^0$  or  $\Lambda^0$  mass. If CRID information was available for the  $p/\bar{p}$  track in a  $\Lambda^0/\bar{\Lambda}^0$  candidate, we required  $\mathcal{L}_p > \mathcal{L}_\pi$ ; 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  $\Lambda^0/\bar{\Lambda}^0$  reconstruction efficiency (purity) was 12% (90.7%). These  $\Lambda^0/\bar{\Lambda}^0$  were removed from the  $K_s^0$  sample, for an estimated  $K_s^0$  efficiency (purity) of 24% (90.7%).

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 an oppositely charged  $K^\pm$  or a  $K_s^0$ . The  $\Lambda^0/\bar{\Lambda}^0$  tags provided a useful veto in multiply tagged hemispheres and important checks of the simulation; however their inclusion did not improve the total error on  $A_s$ . 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 1 shows the number of events tagged in each mode, along with the predictions of the simulation, which are consistent. 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 pointed into the true  $s$  ( $\bar{s}$ ) hemisphere.

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
$K^+\Lambda^0, K^-\Lambda^0$	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 1: Summary of the selected event sample for the two tagging modes and the three cross-check modes.

Figure 1 shows the distributions of the measured  $s$ -quark polar angle  $\theta_s$  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 similar magnitude to those of the signal, so the measured  $A_s$  is largely insensitive to them; those from  $u\bar{u}+d\bar{d}$  events exhibit asymmetries of opposite sign, and  $A_s$  is more sensitive to the associated uncertainties.

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

$$L = \prod_{k=1}^{N_{data}} \sum_{q=uds\bar{c}b} N_q \{ (1 - A_e P_e)(1 + x_k^2) + 2(A_e - P_e)(1 + \delta)a_q A_q x_k \}. \quad (2)$$

Here, the number of tagged  $q\bar{q}$  events  $N_q = N_{events} R_q \epsilon_q$ ,  $R_q = \Gamma(Z^0 \rightarrow q\bar{q}) / \Gamma(Z^0 \rightarrow \text{hadrons})$ ,  $\epsilon_q$  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  $\epsilon_q$  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  $\epsilon_c$ ,  $\epsilon_b$ ,  $a_c$  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  $\epsilon_u$ ,  $\epsilon_d$  and  $\epsilon_s$  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 a  $u$  ( $d$ ) jet can produce a leading  $K^+$  ( $K^{*0} \rightarrow K^+ \pi^-$ ), giving  $a_u(a_d) < 0$ , but with an associated  $K^-$  or  $\bar{K}^0$ , and a  $K^-$  can be selected with reduced probability, giving  $|a_u|(|a_d|) < |a_s|$ . We scaled the simulated

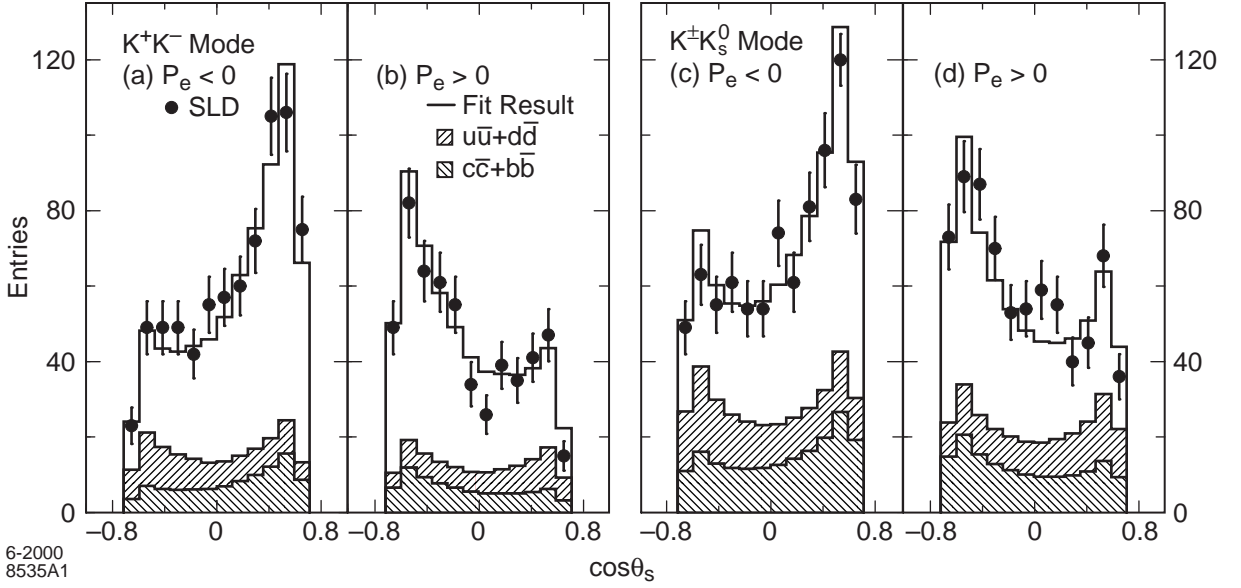


Figure 1: Measured  $s$ -quark polar angle distributions (dots) for selected events in the a,b)  $K^+K^-$  and c,d)  $K^\pm K_s^0$  modes, produced with a,c) left- and b,d) right-polarized electron beams. The histograms represent the result of a simultaneous fit to the four distributions, and the upper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

$a_u$  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 and are consistent with the data; the binned  $\chi^2$  is 42 for 48 bins.

We considered several sources of systematic uncertainty, summarized in table 2. The values of  $R_c$ ,  $R_b$ ,  $A_c$  and  $A_b$  were varied by the uncertainties on their world averages [3]. A large number of quantities in the simulation of heavy flavor events and detector performance were varied as in [14] with negligible effect on the measured value of  $A_s$ . The yield and analyzing power of true  $K^\pm$  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  $\pm 9\%$  to  $\epsilon_c$ ,  $\pm 3.3\%$  to  $\epsilon_b$ ,  $\pm 5\%$  ( $15\%$ ) to  $a_c$  and  $\pm 3.6\%$  ( $4.4\%$ ) to  $a_b$  for the  $K^+K^-$  ( $K^\pm K_s^0$ ) mode. The sum in quadrature of the uncertainties due to heavy flavor background is listed in Table 2; the largest contribution is from  $\delta a_c$ .

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 [16]. In order to minimize model dependence, we used our data to constrain the largest uncertainties in these parameters within the context of our simulation, which reproduces existing measurements of relevant quantities such as leading particle production and strange-antistrange correlations [16].

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  $\pi^+$  or  $p$  as a  $K^+$ . A true 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 selected  $K^\pm$  and/or  $K_s^0$ ; 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 comparing with the MC prediction for  $(s+\bar{s})$ . 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 any further uncertainties are small compared with 18.5%. Assuming equal production of charged and neutral kaons, this procedure delivers a calibration of  $w_s$  for both tagging modes, which we varied simultaneously by  $\pm 18.5\%$  relative. To account for misidentified particles we varied the production of  $>9$  GeV/c  $p$  and  $\pi^+$  in  $s$  jets by  $\pm 100\%$ , and varied the misidentification probability by its measured relative uncertainty of  $\pm 25\%$  [10]. The sum in quadrature of these three effects is shown in table 2 and is 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, by 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  $K^\pm K_s^0$  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  $\phi$  production in  $s$  jets; and  $N_3$  to these and also the production and misidentification of  $\pi^\pm$  and  $p/\bar{p}$ . 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 limited 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 scaled  $a_u$  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 varying  $A_u$  and  $A_d$  down to half of their SM values and up to well over unity; we considered no additional variation of  $A_u$  or  $A_d$ . The uncertainties listed in table 2 were added in quadrature to yield a total relative systematic error of  $\pm 0.069$ .

Several systematic checks were also performed. Ad hoc corrections [16] 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  $\Lambda^0$  tags, with consistent results. We repeated the analysis using all  $K^\pm$ , and all  $\Lambda^0/\bar{\Lambda}^0$ , hemi-

Source	Systematic variation	$\delta A_s/A_s$	
Heavy flavor background	See text	0.014	
Correction for gluon radiation	$-0.013 \pm 0.006$	0.006	
$\langle  P_e  \rangle$	$0.735 \pm 0.005$	0.006	
MC statistics		0.014	
$a_s$	$K^+K^-$ $K^\pm K_s^0$	$0.949 \pm 0.012$ $0.701 \pm 0.060$	0.032
$(N_u + N_d)/N_s$ (incl. $(R_u + R_d)/R_s$ )	$K^+K^-$ $K^\pm K_s^0$	$0.190 \pm 0.015$ $0.316 \pm 0.026$	0.021
$a_u, a_d$ $A_u, A_d$		$-a_s/2 \pm a_s/\sqrt{12}$ -	0.054
Total			0.069

Table 2: Summary of the systematic uncertainties.

spheres with no tag required in the opposite hemisphere; results were consistent. This  $K^\pm$  analysis is similar to that in [5]; it has a relative statistical precision of 0.03, but of 0.18 systematic.

In conclusion, we have made the first direct measurement of the parity-violating coupling of the  $Z^0$  boson to the strange quark,

$$A_s = 0.895 \pm 0.066(\text{stat.}) \pm 0.062(\text{syst.}),$$

using high-momentum identified  $K^\pm$  and  $K_s^0$  to tag  $Z^0 \rightarrow s\bar{s}$  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 less precise, previous measurements of  $A_{FB}^s$  [4, 5]. It is also consistent with a recent world average  $b$ -quark asymmetry,  $A_b = 0.881 \pm 0.018$  [3], providing a 10% test of down-type quark universality.

We thank the personnel of the SLAC accelerator department and the technical staffs of our collaborating institutions for their outstanding efforts on our behalf. This work was supported by the U.S. Department of Energy, 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); and the Korea Science and Engineering Foundation (Soongsil).



## References

- [1] SLD Collab., K. Abe *et al.*, SLAC-PUB-8401, to appear Physical Review Letters (June 26, 2000).
- [2] SLD Collab., K. Abe *et al.*, Phys. Rev. Lett. **83** (1999) 3384.
- [3] The LEP Collabs., the LEP Electroweak Working Group, and the SLD Heavy Flavor and Electroweak Groups, CERN-EP/99-015 (1999).
- [4] OPAL Collab., K. Ackerstaff *et al.*, Z. Phys. **C76** (1997) 387.
- [5] DELPHI Collab., P. Abreu *et al.*, Z. Phys. **C67** (1995) 1; CERN-EP/99-134, submitted to Eur. Phys. J. C.
- [6] SLD Design Report, SLAC-Report 273 (1984).
- [7] M. D. Hildreth *et al.*, Nucl. Instr. Meth. **A367** (1995) 111.
- [8] C.J.S. Damerell *et al.*, Nucl. Instr. Meth. **A288** (1990) 236; Nucl. Instr. Meth. **A400** (1997) 287.
- [9] K. Abe *et al.*, Nucl. Inst. Meth. **A343** (1994) 74.
- [10] SLD Collab., K. Abe *et al.*, Phys. Rev. **D59** (1999) 52001.
- [11] S. Brandt *et al.*, Phys. Lett. **12** (1964) 57.  
E. Farhi, Phys. Rev. Lett. **39** (1977) 1587.
- [12] D. Axen *et al.*, Nucl. Inst. Meth. **A328** (1993) 472.
- [13] SLD Collab., K. Abe *et al.*, Phys. Rev. **D53** (1996) 1023.
- [14] SLD Collab., K. Abe *et al.*, Phys. Rev. Lett. **80** (1998) 660.
- [15] T. Sjöstrand, Comput. Phys. Commun. **82** (1994) 74.
- [16] H. Stängle, Ph.D. Thesis, Colorado State University (1999), SLAC-R-549.
- [17] S. Narita, Ph.D. Thesis, Tohoku University (1998), SLAC-R-520.
- [18] SLD Collab., K. Abe *et al.*, SLAC-PUB-8199, SLAC-PUB-8200, unpublished.

## \*\*List of Authors

Koya Abe,<sup>(24)</sup> Kenji Abe,<sup>(15)</sup> T. Abe,<sup>(21)</sup> I. Adam,<sup>(21)</sup> H. Akimoto,<sup>(21)</sup> D. Aston,<sup>(21)</sup>  
K.G. Baird,<sup>(11)</sup> C. Baltay,<sup>(30)</sup> H.R. Band,<sup>(29)</sup> T.L. Barklow,<sup>(21)</sup> J.M. Bauer,<sup>(12)</sup>  
G. Bellodi,<sup>(17)</sup> R. Berger,<sup>(21)</sup> G. Blaylock,<sup>(11)</sup> J.R. Bogart,<sup>(21)</sup> G.R. Bower,<sup>(21)</sup>  
J.E. Brau,<sup>(16)</sup> M. Breidenbach,<sup>(21)</sup> W.M. Bugg,<sup>(23)</sup> D. Burke,<sup>(21)</sup> T.H. Burnett,<sup>(28)</sup>  
P.N. Burrows,<sup>(17)</sup> A. Calcaterra,<sup>(8)</sup> R. Cassell,<sup>(21)</sup> A. Chou,<sup>(21)</sup> H.O. Cohn,<sup>(23)</sup>  
J.A. Coller,<sup>(4)</sup> M.R. Convery,<sup>(21)</sup> V. Cook,<sup>(28)</sup> R.F. Cowan,<sup>(13)</sup> G. Crawford,<sup>(21)</sup>  
C.J.S. Damerell,<sup>(19)</sup> M. Daoudi,<sup>(21)</sup> S. Dasu,<sup>(29)</sup> N. de Groot,<sup>(2)</sup> R. de Sangro,<sup>(8)</sup>  
D.N. Dong,<sup>(13)</sup> M. Doser,<sup>(21)</sup> R. Dubois, I. Erofeeva,<sup>(14)</sup> V. Eschenburg,<sup>(12)</sup> E. Etzion,<sup>(29)</sup>  
S. Fahey,<sup>(5)</sup> D. Falciari,<sup>(8)</sup> J.P. Fernandez,<sup>(26)</sup> K. Flood,<sup>(11)</sup> R. Frey,<sup>(16)</sup> E.L. Hart,<sup>(23)</sup>  
K. Hasuko,<sup>(24)</sup> S.S. Hertzbach,<sup>(11)</sup> M.E. Huffer,<sup>(21)</sup> X. Huynh,<sup>(21)</sup> M. Iwasaki,<sup>(16)</sup>  
D.J. Jackson,<sup>(19)</sup> P. Jacques,<sup>(20)</sup> J.A. Jaros,<sup>(21)</sup> Z.Y. Jiang,<sup>(21)</sup> A.S. Johnson,<sup>(21)</sup>  
J.R. Johnson,<sup>(29)</sup> R. Kajikawa,<sup>(15)</sup> M. Kalelkar,<sup>(20)</sup> H.J. Kang,<sup>(20)</sup> R.R. Kofler,<sup>(11)</sup>  
R.S. Kroeger,<sup>(12)</sup> M. Langston,<sup>(16)</sup> D.W.G. Leith,<sup>(21)</sup> V. Lia,<sup>(13)</sup> C. Lin,<sup>(11)</sup>  
G. Mancinelli,<sup>(20)</sup> S. Manly,<sup>(30)</sup> G. Mantovani,<sup>(18)</sup> T.W. Markiewicz,<sup>(21)</sup>  
T. Maruyama,<sup>(21)</sup> A.K. McKemey,<sup>(3)</sup> R. Messner,<sup>(21)</sup> K.C. Moffeit,<sup>(21)</sup> T.B. Moore,<sup>(30)</sup>  
M. Morii,<sup>(21)</sup> D. Muller,<sup>(21)</sup> V. Murzin,<sup>(14)</sup> S. Narita,<sup>(24)</sup> U. Nauenberg,<sup>(5)</sup> H. Neal,<sup>(30)</sup>  
G. Nesom,<sup>(17)</sup> N. Oishi,<sup>(15)</sup> D. Onoprienko,<sup>(23)</sup> L.S. Osborne,<sup>(13)</sup> R.S. Panvini,<sup>(27)</sup>  
C.H. Park,<sup>(22)</sup> I. Peruzzi,<sup>(8)</sup> M. Piccolo,<sup>(8)</sup> L. Piemontese,<sup>(7)</sup> R.J. Plano,<sup>(20)</sup>  
R. Prepost,<sup>(29)</sup> C.Y. Prescott,<sup>(21)</sup> B.N. Ratcliff,<sup>(21)</sup> J. Reidy,<sup>(12)</sup> P.L. Reinertsen,<sup>(26)</sup>  
L.S. Rochester,<sup>(21)</sup> P.C. Rowson,<sup>(21)</sup> J.J. Russell,<sup>(21)</sup> O.H. Saxton,<sup>(21)</sup> T. Schalk,<sup>(26)</sup>  
B.A. Schumm,<sup>(26)</sup> J. Schwiening,<sup>(21)</sup> V.V. Serbo,<sup>(21)</sup> G. Shapiro,<sup>(10)</sup> N.B. Sinev,<sup>(16)</sup>  
J.A. Snyder,<sup>(30)</sup> H. Staengle,<sup>(6)</sup> A. Stahl,<sup>(21)</sup> P. Stamer,<sup>(20)</sup> H. Steiner,<sup>(10)</sup> D. Su,<sup>(21)</sup>  
F. Suekane,<sup>(24)</sup> A. Sugiyama,<sup>(15)</sup> A. Suzuki,<sup>(15)</sup> M. Swartz,<sup>(9)</sup> F.E. Taylor,<sup>(13)</sup>  
J. Thom,<sup>(21)</sup> E. Torrence,<sup>(13)</sup> T. Usher,<sup>(21)</sup> J. Va'vra,<sup>(21)</sup> R. Verdier,<sup>(13)</sup> D.L. Wagner,<sup>(5)</sup>  
A.P. Waite,<sup>(21)</sup> S. Walston,<sup>(16)</sup> A.W. Weidemann,<sup>(23)</sup> E.R. Weiss,<sup>(28)</sup> J.S. Whitaker,<sup>(4)</sup>  
S.H. Williams,<sup>(21)</sup> S. Willocq,<sup>(11)</sup> R.J. Wilson,<sup>(6)</sup> W.J. Wisniewski,<sup>(21)</sup> J.L. Wittlin,<sup>(11)</sup>  
M. Woods,<sup>(21)</sup> T.R. Wright,<sup>(29)</sup> R.K. Yamamoto,<sup>(13)</sup> J. Yashima,<sup>(24)</sup> S.J. Yellin,<sup>(25)</sup>  
C.C. Young,<sup>(21)</sup> H. Yuta.<sup>(1)</sup>

*(The SLD Collaboration)*

<sup>(1)</sup> *Aomori University, Aomori, 030 Japan,*

<sup>(2)</sup> *University of Bristol, Bristol, United Kingdom,*

<sup>(3)</sup> *Brunel University, Uxbridge, Middlesex, UB8 3PH United Kingdom,*

<sup>(4)</sup> *Boston University, Boston, Massachusetts 02215,*

<sup>(5)</sup> *University of Colorado, Boulder, Colorado 80309,*

<sup>(6)</sup> *Colorado State University, Ft. Collins, Colorado 80523,*

<sup>(7)</sup> *INFN Sezione di Ferrara and Università di Ferrara, I-44100 Ferrara, Italy,*

<sup>(8)</sup> *INFN Laboratori Nazionali di Frascati, I-00044 Frascati, Italy,*

<sup>(9)</sup> *Johns Hopkins University, Baltimore, Maryland 21218-2686,*

<sup>(10)</sup> *Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720,*

<sup>(11)</sup> *University of Massachusetts, Amherst, Massachusetts 01003,*

- (<sup>12</sup>) *University of Mississippi, University, Mississippi 38677,*  
(<sup>13</sup>) *Massachusetts Institute of Technology, Cambridge, Massachusetts 02139,*  
(<sup>14</sup>) *Institute of Nuclear Physics, Moscow State University, 119899 Moscow, Russia,*  
(<sup>15</sup>) *Nagoya University, Chikusa-ku, Nagoya, 464 Japan,*  
(<sup>16</sup>) *University of Oregon, Eugene, Oregon 97403,*  
(<sup>17</sup>) *Oxford University, Oxford, OX1 3RH, United Kingdom,*  
(<sup>18</sup>) *INFN Sezione di Perugia and Università di Perugia, I-06100 Perugia, Italy,*  
(<sup>19</sup>) *Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX United Kingdom,*  
(<sup>20</sup>) *Rutgers University, Piscataway, New Jersey 08855,*  
(<sup>21</sup>) *Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309,*  
(<sup>22</sup>) *Soongsil University, Seoul, Korea 156-743,*  
(<sup>23</sup>) *University of Tennessee, Knoxville, Tennessee 37996,*  
(<sup>24</sup>) *Tohoku University, Sendai, 980 Japan,*  
(<sup>25</sup>) *University of California at Santa Barbara, Santa Barbara, California 93106,*  
(<sup>26</sup>) *University of California at Santa Cruz, Santa Cruz, California 95064,*  
(<sup>27</sup>) *Vanderbilt University, Nashville, Tennessee 37235,*  
(<sup>28</sup>) *University of Washington, Seattle, Washington 98105,*  
(<sup>29</sup>) *University of Wisconsin, Madison, Wisconsin 53706,*  
(<sup>30</sup>) *Yale University, New Haven, Connecticut 06511.*