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A Preliminary Direct Measurement of the Parity Violating Coupling of the Z^0 to Strange Quarks, A_s*

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Abstract

We present a preliminary direct measurement of the parity violating coupling of the Z^0 to strange quarks, A_s, derived from a sample of approximately 300,000 hadronic decays of Z^0 bosons produced with a polarized electron beam and recorded by the SLD experiment at SLAC between 1993 and 1997. $Z^0 \to s\bar{s}$ events are tagged by the presence in each event hemisphere of a high-momentum $K^{\pm}$, K_s^0 or $\Lambda^0/\bar{\Lambda}^0$ identified using the Cherenkov Ring Imaging Detector and/or a mass tag. The CCD vertex detector is used to suppress the background from heavy flavor events. The strangeness of the tagged particle is used to sign the event thrust axis in the direction of the initial s quark. The coupling A_s is obtained directly from a measurement of the left-right-forward-backward production asymmetry in polar angle of the tagged s quark. To reduce the model dependence of the measurement, the background from $u\bar{u}$ and $d\bar{d}$ events is measured from the data, as is the analyzing power of the method for $s\bar{s}$ events. We measure:

$$A_s = 0.82 \pm 0.10(stat.) \pm 0.08(syst.)(preliminary).$$

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1. Introduction

Measurements of the fermion production asymmetries in the process $e^+e^- \to Z^0 \to f\bar{f}$ provide information on the extent of parity violation in the coupling of the Z^0 boson to fermions of type f. At Born level, the differential production cross section can be expressed in terms of $x = \cos\theta$, where θ is the polar angle of the final state fermion f with respect to the electron beam direction:

$$\sigma^f(x) = \frac{d\sigma^f}{dx} \propto (1 - A_e P_e)(1 + x^2) + 2A_f(A_e - P_e)x, \tag{1}$$

where P_e is the longitudinal polarization of the electron beam, the positron beam is assumed unpolarized, and the asymmetry parameters $A_f = 2v_f a_f/(v_f^2 + a_f^2)$ are defined in terms of the vector (v_f) and axial-vector (a_f) couplings of the Z^0 to fermion f. If one measures the polar angle distribution for a given final state $f\bar{f}$, one can derive the forward-backward production asymmetry, A^f_{FB}, which depends on both the initial and final state asymmetry parameters as well as on the beam polarization:

$$A^f_{FB}(x) = \frac{\sigma^f(x) - \sigma^f(-x)}{\sigma^f(x) + \sigma^f(-x)} = 2A_f \frac{A_e - P_e}{1 - A_e P_e} \frac{x}{1 + x^2}. \tag{2}$$

For zero polarization, one measures the product of couplings $A_e A_f$. If one measures the distributions in samples taken with negative (L) and positive (R) beam polarization of magnitude P_e, then one can derive the left-right-forward-backward asymmetry, $\tilde{A}^f_{FB}$, which is insensitive to the initial state coupling:

$$\tilde{A}^f_{FB}(x) = \frac{(\sigma^f_L(x) + \sigma^f_R(-x)) - (\sigma^f_R(x) + \sigma^f_L(-x))}{(\sigma^f_L(x) + \sigma^f_R(-x)) + (\sigma^f_R(x) + \sigma^f_L(-x))} = 2|P_e|A_f \frac{x}{1 + x^2}. \tag{3}$$

A number of previous measurements have been made by experiments at LEP and SLC of A_e, A_μ, A_τ, A_c and A_b [1]. In contrast, very few measurements exist for the light flavor quarks, due to the difficulty of tagging specific light flavors. It has recently been demonstrated experimentally [2] that light flavored jets can be tagged by the presence of a high-momentum 'leading' identified particle that has a valence quark of the desired flavor, for example a K^- (K^+) meson could tag an s ($\bar{s}$) jet. However the background from other light flavors (a $\bar{u}$ jet can also produce a leading K^-), decays of B and D hadrons, and nonleading kaons in events of all flavors is large, and neither the signal nor the background has been well measured experimentally.

The DELPHI collaboration has measured [3] $A^s_{FB} = 0.131 \pm 0.035(stat.) \pm 0.013(syst.)$ and $A^{d,s}_{FB} = 0.112 \pm 0.031(stat.) \pm 0.054(syst.)$, respectively. However the extraction of the asymmetry parameters from the measured production asymmetries is model dependent. The OPAL collaboration has measured [4] $A^u_{FB} = 0.040 \pm 0.067(stat.) \pm 0.028(syst.)$ and $A^{d,s}_{FB} = 0.068 \pm 0.035(stat.) \pm 0.011(syst.)$. In their measurement, most of the background contributions and analyzing powers are determined from double-tagged events in the data. This eliminates most of the model dependence, but results in limited statistical precision.

We present a direct measurement of the asymmetry parameter for strange quarks, A_s, using a sample of 300,000 hadronic Z^0 decays recorded by the SLD experiment at the SLAC Linear Collider between 1993 and 1997, with an average electron beam polarization of 74%. We use identified strange particles to tag s and $\bar{s}$ jets. The analyzing power of the tags for true $s\bar{s}$ events, as well as the relative contribution of $u\bar{u} + d\bar{d}$ events were determined from the data. This procedure removes much of the model dependence, yielding an error that is statistically dominated.

2. Hadronic Event and $s\bar{s}$ Event Selection

A general description of the SLD can be found elsewhere [5]. The trigger and initial selection criteria for hadronic Z^0 decays are described in Ref. [6]. In order to reduce the effects of decays of heavy hadrons, we selected light flavor events ($u\bar{u}$, $d\bar{d}$ and $s\bar{s}$) by requiring each high-quality [7] track in the event to have a transverse impact parameter with respect to the IP of less than three times its estimated error. Finally, the CRID (Cherenkov Ring Imaging Detector) was required to be operational. The selected sample comprised roughly 94,000 events with an estimated background contribution of 11% from $c\bar{c}$ events, 2% from $b\bar{b}$ events, and a non-hadronic background contribution of $0.10 \pm 0.05\%$, dominated by $Z^0 \to \tau^+\tau^-$ events.

For the purpose of estimating the efficiency and purity of the event flavor tagging and the particle identification, we made use of a detailed Monte Carlo (MC) simulation of the detector. The JETSET 7.4 [8] event generator was used, with parameter values tuned to hadronic e^+e^- annihilation data [9], combined with a simulation of B-hadron decays tuned [10] to $\Upsilon(4S)$ data and a simulation of the SLD based on GEANT 3.21 [11].

Then high-momentum strange particles are selected. The CRID allows $K^\pm$ to be separated from $p/\bar{p}$ and $\pi^\pm$ with high purity for tracks with $p > 9$ GeV/c as described in detail in [12]. A track is tagged as a $K^\pm$ if the log-likelihood for this hypothesis exceeds both, the $\pi^\pm$ and the $p/\bar{p}$ log-likelihoods, by at least 3 units. The average purity of the $K^\pm$ sample was estimated using the simulation to be 89%. K^0_s and $\Lambda^0/\bar{\Lambda}^0$ are reconstructed [12] in the modes $K^0_s \to \pi^+\pi^-$ and $\Lambda^0(\bar{\Lambda}^0) \to p(\bar{p})\pi^\mp$ and are identified by their long flight distance, reconstructed mass, and accuracy of pointing back to the primary interaction point, and are required to have $p > 5$ GeV/c. Pairs of tracks with invariant mass $m_{\pi\pi}$ within 12 MeV/c^2 of the nominal K^0_s mass are identified as K^0_s. The simulation predicts that the average purity of the K^0_s sample is 91%. In the case of the $\Lambda^0/\bar{\Lambda}^0$, information from the Cherenkov Ring Imaging Detector is used to identify the $p/\bar{p}$ candidate. $\Lambda^0/\bar{\Lambda}^0$ are identified by requiring the invariant mass of pairs of tracks, $m_{p\pi}$, to be within 5 MeV/c^2 of the nominal $\Lambda^0/\bar{\Lambda}^0$ mass and a combination of K^0_s rejection and particle identification for the high-momentum track. The simulation predicts that the average purity of the $\Lambda^0/\bar{\Lambda}^0$ sample is 84%.

These strange particles are then used to tag s and $\bar{s}$ jets as follows. The event is divided into two hemispheres by a plane perpendicular to the thrust axis. We require

each of the two hemispheres to contain at least one identified strange particle ($K^{\pm}$, K_s^0 or $\Lambda^0/\bar{\Lambda}^0$); for hemispheres with multiple strange particles we only consider the one with the highest momentum. We require at least one of the two hemispheres to have definite strangeness (i.e. to contain a $K^{\pm}$ or $\Lambda^0/\bar{\Lambda}^0$). In events with two hemispheres of definite strangeness, the two hemispheres are required to have opposite strangeness (e.g. K^+K^-). This procedure increases the $s\bar{s}$ purity substantially compared with a single tag; thus, for these events, the model dependence of the measurement is reduced.

Table 1 summarizes the composition of the selected event sample for data and simulation for each of the 5 tagging modes used. The number of events for each mode shown is in good agreement with the MC prediction. The $s\bar{s}$ purity and $s\bar{s}$ analyzing power were estimated from the simulation.

Table 1: Summary of selected event sample for 5 modes in data and simulation.

Mode	Data	MC prediction	$s\bar{s}$ purity	$s\bar{s}$ analyzing power
K^+K^-	619	620	0.76	0.94
$K^+\Lambda^0, K^-\Lambda^0$	86	82	0.65	0.86
$\Lambda^0\Lambda^0$	1	6	0.59	
$K^{\pm}K_s^0$	502	531	0.64	0.68
$\Lambda^0K_s^0, \bar{\Lambda}^0K_s^0$	52	52	0.54	0.44
Total:	1260	1291	0.69	0.82

The combined $s\bar{s}$ purity of all modes is 69%, and the predicted background in the selected event sample consists of 10% $u\bar{u}$, 9% $d\bar{d}$, 11% $c\bar{c}$, and 1% $b\bar{b}$ events. The analyzing power is defined as $a_s = \frac{N_s^{right}-N_s^{wrong}}{N_s^{right}+N_s^{wrong}}$ where $N_s^{right}(N_s^{wrong})$ denotes the number of $s\bar{s}$ events in which a particle of negative strangeness is found in the true $s(\bar{s})$ hemisphere. The average analyzing power for all modes is predicted by the simulation to be 0.82. The $K^{\pm}K^{\mp}$ mode has a substantially higher analyzing power and $s\bar{s}$ purity than the other modes. The initial s quark direction is approximated by the thrust axis, $\hat{t}$ of the event, signed to point in the direction of negative strangeness, $x = cos\theta_s = S\frac{\vec{p}\cdot\hat{t}}{|\vec{p}\cdot\hat{t}|}\hat{t}_z$, where S and $\vec{p}$ denote the strangeness and the momentum of the tagging particle.

Figure 1 shows the polar angle distributions, for all 5 tagging modes combined, of the signed thrust axis for left-handed ($P_e < 0$) and right-handed ($P_e > 0$) electron beams. The expected production asymmetries, of opposite sign for the left-handed and the right-handed beams, are clearly visible.

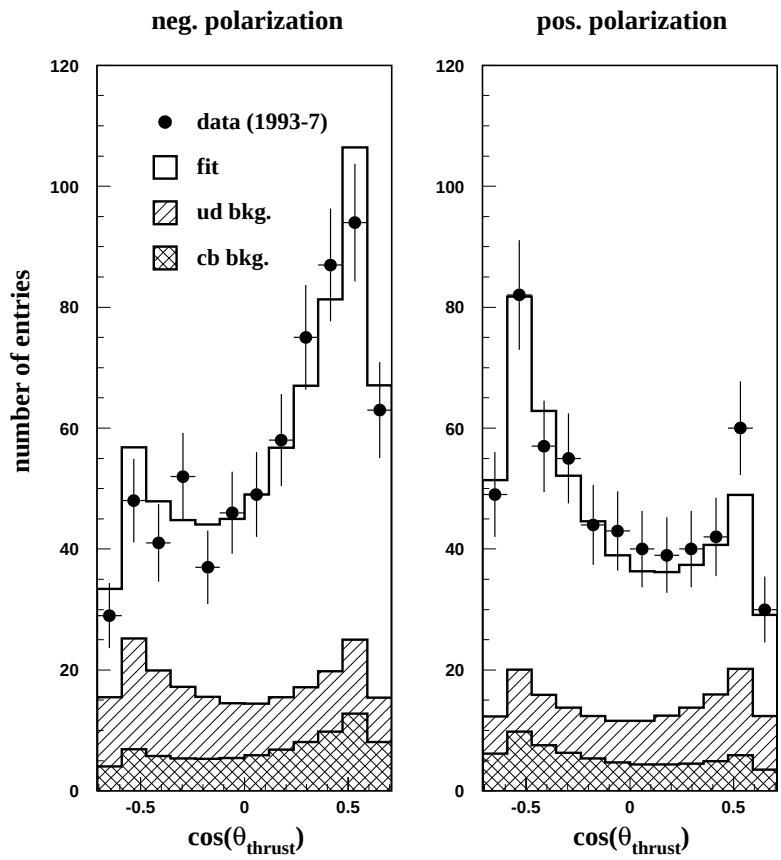

Figure 1: Polar angle distributions of the thrust axis, signed to point in the direction of negative strangeness, of the tagged strange particle, for negative (left) and positive (right) beam polarization. The dots show data and the histogram shows our fit to the data. Our estimates of the non-$s\bar{s}$ backgrounds are indicated by the hatched histograms.

3. Extraction of A_s and Systematic Uncertainties

A_s is extracted from these distributions by a binned maximum likelihood fit. The fitting function is given by:

$$P(x) = D(x) \sum_f N_f (1 + x^2 + 2(1+\delta) a_f A_f A_Z x). \tag{4}$$

The function $D(x)$ describes the acceptance and the strange particle identification efficiencies. $N_f = N_{events} R_f \epsilon_f$ denotes the number of events in the sample of flavor f ($f = u, d, s, c, b$) in terms of the number of selected hadronic events N_{events}, $R_f = \Gamma(Z^0 \to f\bar{f})/\Gamma(Z^0 \to hadrons)$ and the tagging efficiencies ϵ_f; $\delta = -0.013$ corrects for the effects of hard gluon radiation [13]; a_f denotes the analyzing power for tagging the f rather than the

$\bar{f}$ direction; A_f is the asymmetry parameter for flavor f; and $A_Z = (A_e - P_e)/(1 - A_e P_e)$. The function $D(x)$ was calculated from the simulation and verified by comparing data and simulated x-distributions of identified $K^{\pm}$, K^0_s, and $\Lambda^0/\bar{\Lambda}^0$. The parameters ϵ_c, ϵ_b, and a_c, a_b for the heavy flavors are taken from the MC simulation [10]. The world average experimental measurements of the parameters A_c, A_b, R_c, R_b [1] were used. For the light flavors, the relevant parameters in the fitting function are derived where possible from the data as described below. The total number of light flavor events, N_{uds}, is determined by subtracting the simulated number of heavy flavor events from the entire event sample. The ratio N_{ud}/N_s is 0.27 ± 0.03. The asymmetry parameters A_u and A_d are set to the Standard Model values. The $s\bar{s}$ analyzing power, a_s, is 0.82 ± 0.03 (averaged over all modes). The combined $(u\bar{u} + d\bar{d})$ analyzing power, a_{ud}, is estimated to be -0.41 ± 0.24. The result of the fit is shown as a histogram in Figure 1. The fit quality is good with a χ^2 of 12.9 for 24 bins. Also included are our estimates of non-$s\bar{s}$ background. The cross-hatched histograms indicate $c\bar{c} + b\bar{b}$ backgrounds which are seen to show asymmetries of the same sign and similar slope to the total distribution. The hatched histograms indicate $u\bar{u} + d\bar{d}$ backgrounds showing asymmetries of the opposite sign and slope to the total distribution. The A_s value extracted from the fit is $A_s = 0.82 \pm 0.10(stat.)$.

The understanding of the parameters used as inputs to the fitting function and of their uncertainties is crucial to this analysis. The characteristics of heavy flavor events relevant to this analysis have been measured experimentally, and our simulation [8, 9, 11] has been tuned [10] to reproduce these results. Standard systematic variations of the heavy flavor simulation were considered, and the resulting uncertainties are a small contribution to the total systematic error. Other small contributions to the systematic error include those from the 0.6% uncertainty in the correction for the effect of hard gluon radiation, and the 0.8% uncertainty in the beam polarization. For the light flavors, there are few experimental constraints on the relevant input parameters. Qualitative features such as leading particle production [2], short range rapidity correlations between high-momentum KK and baryon-antibaryon pairs [14] and long-range correlations between several particle species [14] have been observed experimentally, but these results are not sufficient to quantify the analyzing power of the strange-particle tag or the $u\bar{u}$ and $d\bar{d}$ background. Our MC simulation provides a reasonable description of the above observations and was used to evaluate the parameters used in the fit, but was calibrated using data. For the analyzing power in $s\bar{s}$ events, we investigated the rate of production of wrong-sign kaons by counting events in which we find three identified $K^{\pm}$ and/or K^0_s. Since we found that the MC prediction for the number of 3-kaon jets is consistent with the data, we used the simulated $a_s = 0.82$ as our central value for the analyzing power in $s\bar{s}$ events and the statistical error on the data-MC comparison as uncertainty. We also counted hemispheres containing a K^+K^+ or K^-K^- pair, obtaining consistent but less precise constraints.

For the calibration of the relative $u\bar{u} + d\bar{d}$ background level, N_{ud}/N_s, we counted the number of hemispheres containing an identified K^+-K^- pair or an identified $K^{\pm}$-K^0 pair. The MC prediction is consistent with the data and was used as the central value. Another, less precise contraint was obtained from events that were tagged by kaons of the same

Table 2: Summary of systematic uncertainties.

Source	Comments	Systematic variation	$\delta A_s/A_s$
heavy flavor modelling	MC/world averages	Ref. [1, 9, 10]	0.008
hard gluon radiation	Stav-Olsen with bias correction	$(1.3 \pm 0.6)\%$	0.006
beam polarization	data	$(73.7 \pm 0.8)\%$	0.008
a_s	MC constrained by 3-K jets in data	0.82 ± 0.03	0.038
a_{ud}	$-a_s < a_{ud} < 0$	-0.41 ± 0.24	0.071
A_{ud}	Standard Model	–	–
N_{ud}/N_s	MC constrained by 2-K jets in data	0.27 ± 0.03	0.046
MC statistics			0.021
Total:			0.096

sign in both hemispheres. The above checks are also sensitive to the analyzing power of $u\bar{u} + d\bar{d}$ events, a_{ud}. However, with the present event statistics we cannot obtain a tight constraint on this quantity. We therefore assume that a_{ud} must be negative, since u and d jets must produce a leading K^+ rather than K^-, and that $|a_{ud}|$ must be less than a_s, since there is always a companion particle of opposite strangeness in a u or d jet that will tend to dilute the analyzing power. We take these as hard limits, $-0.82 < a_{ud} < 0$, use the middle of the range for our central value and assign an uncertainty equal to the range divided by $\sqrt{12}$. The simulation predicts a value of $a_{ud} = -0.38$, consistent with our estimate. Table 2 summarizes the systematic uncertainties. The total systematic uncertainty is $\delta A_s = 0.08$.

4. Summary and Conclusion

We have presented a preliminary direct measurement of the parity violating coupling of the Z^0 to strange quarks, A_s, derived from a sample of approximately 300,000 hadronic decays of Z^0 bosons produced with a polarized electron beam and recorded by the SLD experiment at SLAC between 1993 and 1997. The coupling A_s is obtained directly from a measurement of the left-right-forward-backward production asymmetry in polar angle of the tagged s quark. The background from $u\bar{u}$ and $d\bar{d}$ events is measured from the data, as is the analyzing power of the method for $s\bar{s}$ events. A binned maximum likelihood fit is used to obtain the result:

$$A_s = 0.82 \pm 0.10(stat.) \pm 0.08(syst.)(preliminary). \tag{5}$$

This result is consistent with the Standard Model expectation for A_s. Our measurement can be used to test the universality of the coupling constants by comparing it with the world average value for A_b [1]. The two measurements are consistent.

In order to compare with previous measurements of A^s_{FB} and $A^{d,s}_{FB}$ (see section 1), we must assume a value of A_e. Using $A_e = 0.1499$ [1] and neglecting the small uncertainty on A_e, the DELPHI measurements translate into $A_s = 1.165 \pm 0.311(stat.) \pm 0.116(syst.)$ and $A_{d,s} = 0.996 \pm 0.276(stat.) \pm 0.480(syst.)$. Similarly, the OPAL measurement yields $A_{d,s} = 0.605 \pm 0.311(stat.) \pm 0.098(syst.)$. Our measurement is consistent with these and represents a substantial improvement in precision.

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