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Light Quark Fragmentation in Polarized Z^0 Decays at SLD *

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Abstract

We report results on two physics topics from the SLD experiment at the SLAC Linear Collider, using our full sample of 550,000 events of the type $e^+e^- \to Z^0 \to q\bar{q}$. The electron beam was polarized, enabling the quark and antiquark hemispheres to be tagged in each event. One physics topic is the first study of rapidities signed such that positive rapidity is along the quark rather than antiquark direction. Distributions of ordered differences in signed rapidity between pairs of particles are analyzed, providing the first direct observation of baryon number ordering along the $q\bar{q}$ axis. The other topic is the first direct measurement of A_s, the parity-violating coupling of the Z^0 to strange quarks, by measuring the left-right forward-backward production asymmetry in polar angle of the tagged s quark. We obtain $A_s = 0.895 \pm 0.066(stat.) \pm 0.062(syst.)$, which is consistent with the Standard Model and is currently the most precise measurement of this quantity.

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1 Introduction

In this paper we report new results on two physics topics from the SLD experiment at the SLAC Linear Collider, using our full data sample of 550,000 hadronic decays of Z^0 bosons produced in e^+e^- annihilations. A unique feature of the experiment was a highly longitudinally polarized electron beam, with an average magnitude of polarization of 73%.

One physics topic is a study of signed rapidities. The rapidity of a particle is typically defined with an arbitrary sign. If a sign could be given to each measured rapidity such that, for example, positive (negative) rapidity corresponds to the initial quark (antiquark) direction, then one could measure the extent to which a leading particle has higher rapidity than its associated antiparticle, and the extent to which low-momentum particles in jets remember the initial quark/antiquark direction.

The other physics topic in this paper is the first direct measurement of the strange quark asymmetry parameter A_s. 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 bosons to fermions of type f. 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:

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

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 and axial-vector couplings of the Z^0 to fermion f. The Standard Model predictions for the values of the asymmetry parameters, assuming $\sin^2\theta_w = 0.23$, are $A_e = A_\mu = A_\tau = 0.16$, $A_u = A_c = A_t = 0.67$, and $A_d = A_s = A_b = 0.94$. For a given final state $f\bar{f}$, if one measures the polar angle distributions in equal luminosity samples taken with negative and positive beam polarization, then one can derive the left-right forward-backward asymmetry:

$$\tilde{A}^f_{FB} = \frac{3}{4} \mid P_e \mid A_f$$

which is insensitive to the initial state coupling.

A number of previous measurements have been made of the leptonic asymmetries and the heavy-flavor asymmetries, but very few measurements exist for the light quark flavors, due to the difficulty of tagging specific light flavors. We present a direct measurement of the strange quark asymmetry parameter A_s, in which $Z^0 \to s\bar{s}$ 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.

2 Particle Identification

A description of the SLD detector, trigger, track and hadronic event selection, and Monte Carlo simulation is given in Ref. [1]. The identification of $\pi^\pm$, $K^\pm$, p, and $\bar{p}$ was achieved by reconstructing emission angles of individual Cherenkov photons radiated by charged particles passing through liquid and gas radiator systems of the SLD Cherenkov Ring Imaging Detector (CRID) [2]. In each momentum bin, identified π, K, and p were counted, and these were unfolded using the inverse of an identification efficiency matrix [3], and corrected for track reconstruction efficiency. The elements of the identification efficiency matrix were mostly measured from data, using selected K^0_S, τ, and Λ decays. A detailed Monte Carlo simulation was used to derive the unmeasured elements in terms of these measured ones.

$K^0_S \to \pi^+\pi^-$ and $\Lambda^0(\bar{\Lambda}^0) \to p\pi^-(\bar{p}\pi^+)$ decays were reconstructed as described in Ref. [4, 5] by examining appropriate invariant mass distributions.

3 Signed Rapidities

We next tagged the quark (vs. antiquark) direction in each hadronic event by using the electron beam polarization for that event, exploiting the large forward-backward quark production asymmetry in Z^0 decays. If the beam was left(right)-handed, then the thrust axis was signed such that $\cos\theta_T$ was positive (negative). Events with $|\cos\theta_T| < 0.15$ were removed, as the production asymmetry is small in this region. The probability to tag the quark direction correctly in these events was 73%, assuming Standard Model couplings at tree-level.

For each identified particle the rapidity $y = 0.5\ln((E+p_{||})/(E-p_{||}))$ was calculated using the measured momentum and its projection $p_{||}$ along the thrust axis, and the appropriate hadron mass. The rapidity with respect to the signed thrust axis is naturally signed such that positive rapidity corresponds to the hemisphere in the tagged direction of the initial quark, and negative rapidity corresponds to the tagged antiquark hemisphere. The signed rapidity distributions for identified K^+ and K^- are shown in Fig. 1.

There is a clear difference between the two, with more K^- than K^+ in the quark hemisphere, as expected due to leading K^- produced in s-quark jets [4, 6]. The difference between the two distributions is also shown in the figure and is compared with the prediction of the JETSET [7] simulation, which is consistent with the data.

For pairs of identified particles, one can define an ordered rapidity difference. For particle-antiparticle pairs, we define $\Delta y^{+-} = y_+ - y_-$ as the difference between the signed rapidities of the positively charged particle and the negatively charged particle. In Fig. 2 we show the distribution of Δy^{+-} for $\pi^+\pi^-$, K^+K^- and $p\bar{p}$ pairs. Asymmetries in these distributions are indications of ordering along the event axis, and the differences between the positive and negative sides of these distributions are also shown. The predictions of the simulation are also shown and are consistent with the data at high $|\Delta y^{+-}|$.

The negative difference at high $|\Delta y^{+-}|$ for the K^+K^- pairs can be attributed to the fact that leading kaons are produced predominantly in $s\bar{s}$ events. For $\pi^+\pi^-$ pairs we observe a large positive difference at high $|\Delta y^{+-}|$ rather than the expected small negative difference, and we have confirmed that this effect is due entirely to $c\bar{c}$ events. Our sample of uds-tagged events does show the expected small negative difference.

The positive difference in the lowest $|\Delta y^{+-}|$ bins for the $p\bar{p}$ pairs indicates that the baryon in an associated baryon-antibaryon pair follows the quark direction more closely than the

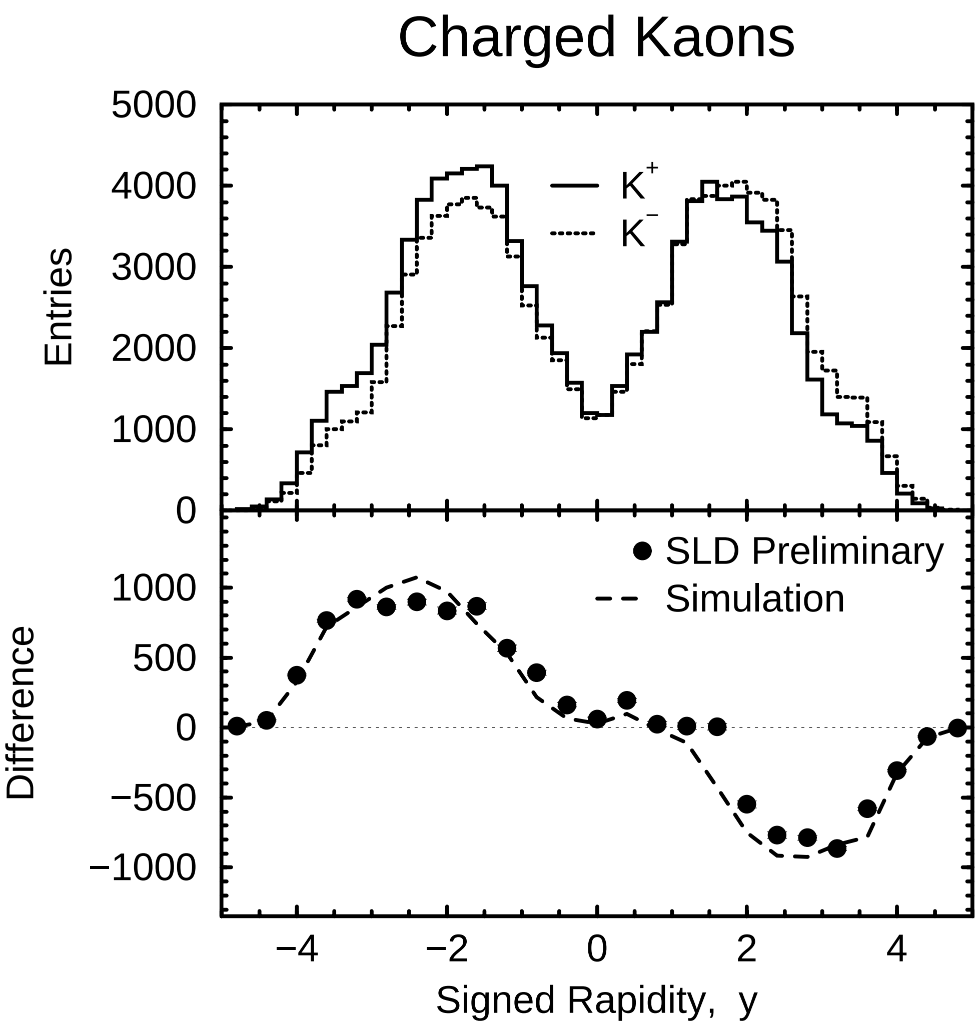

Figure 1: Top: Distributions of the rapidity with respect to the signed thrust axis for positively (solid histogram) and negatively (dashed) charged kaons. Bottom: The difference between these two distributions compared with the prediction of the Monte Carlo simulation.

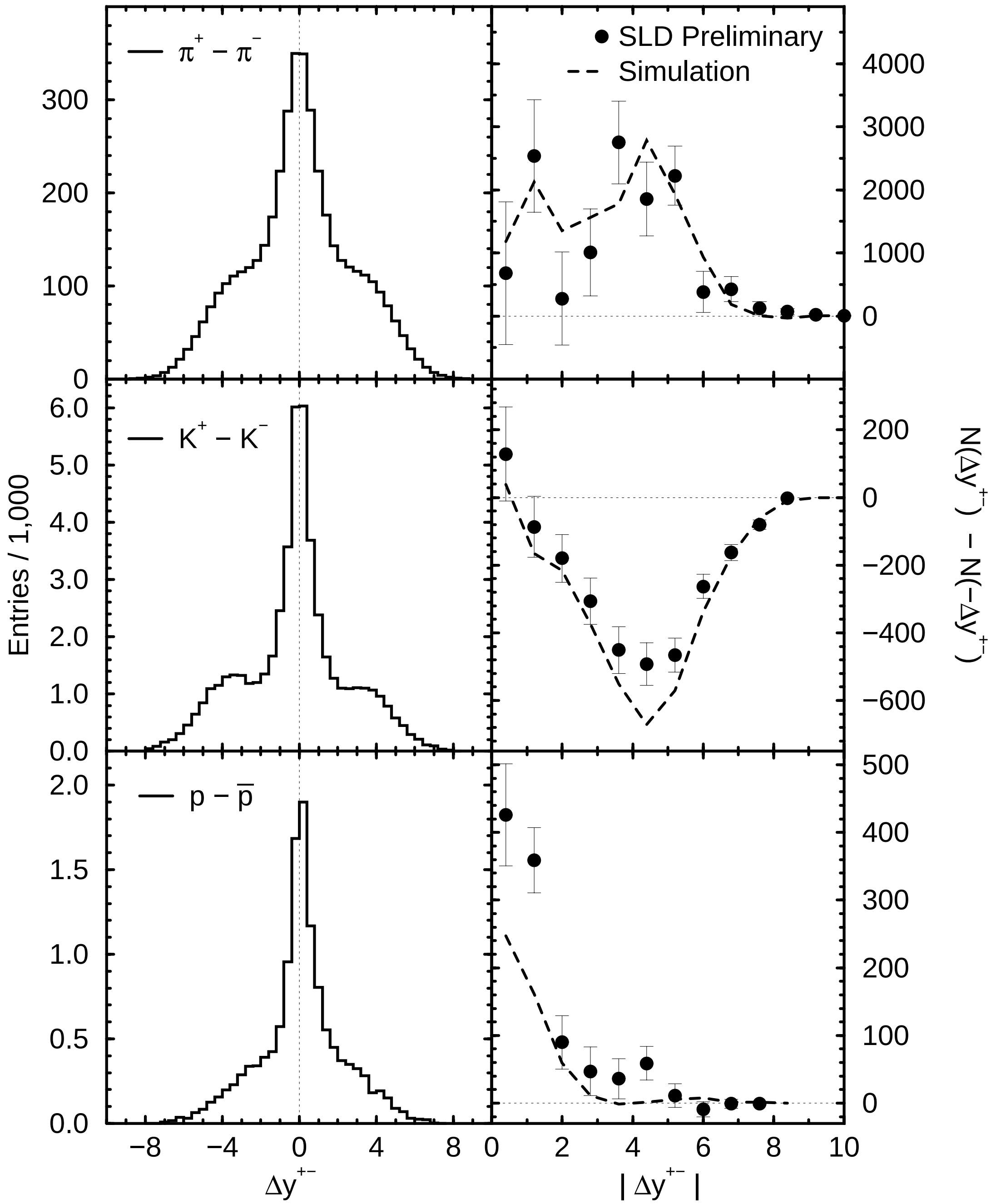

Figure 2: Left: Distributions of the difference between the signed rapidities of positively and negatively charged hadrons of the same type. Right: Differences between the right and left sides of the distributions, compared with the prediction of the Monte Carlo simulation.

antibaryon. This could be due to leading baryon production and/or to baryon numbering ordering along the entire fragmentation chain. We find a significant effect in all of our momentum bins, and the bulk of the observed difference occurs at low momentum. We therefore conclude that both of these effects contribute; this is the first direct observation of baryon number ordering along the entire chain. The prediction of the simulation is low by a factor of two at low $|\Delta y^{+-}|$.

4 Strange Quark Asymmetry

For the measurement of the strange quark asymmetry parameter A_s, the first step was to select $s\bar{s}$ events and tag the s and $\bar{s}$ jets. We used the SLD Vertex Detector [8] to measure each track's impact parameter d in the plane perpendicular to the beam direction. We then removed $c\bar{c}$ and $b\bar{b}$ events by requiring no more than one well-measured track with d larger than 2.5 times its uncertainty.

Each remaining event was divided into two hemispheres by the plane perpendicular to the thrust axis. In each hemisphere we searched for the strange particle with the highest momentum. If it was a charged kaon, we required it to have $p > 9$ GeV/c, while if it was a K^0_S or $\Lambda^0/\bar{\Lambda}^0$ it was required to have $p > 5$ GeV/c. An event was tagged as $s\bar{s}$ if one hemisphere contained a $K^\pm$ selected as just described, and the other contained either an oppositely charged $K^\pm$ or a K^0_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.

Fig. 3 shows the distributions of the measured s-quark polar angle θ_s for the K^+K^- and $K^\pm K^0_S$ modes. In each case, production asymmetries of opposite sign and different magnitude for left- and right-polarized e^- beams are visible.

A_s was extracted from these distributions by a simultaneous maximum likelihood fit, the result of which is shown as a histogram in the figure. The fit quality was good, with a χ^2 of 42 for 48 bins. Also shown in the figure are our estimates [5] of the non-$s\bar{s}$ backgrounds, which were mostly determined from data. Our final result is $A_s = 0.895 \pm 0.066(stat.) \pm 0.062(syst.)$. This result is consistent with the Standard Model expectation of 0.935 for A_s, and with less precise previous measurements [9, 10].

5 Conclusions

We have presented results from a sample of 550,000 $e^+e^- \to Z^0 \to q\bar{q}$ events produced with a longitudinally polarized electron beam. Polarization enables us to give a sign to rapidities so that positive rapidity corresponds to the quark (rather than antiquark) direction. The distribution of the difference between the signed rapidities of K^+ and K^- shows a large asymmetry at large values of the absolute rapidity difference, a direct indication that the long-range correlated KK pairs are dominated by $s\bar{s}$ events. There is a large asymmetry at small rapidity difference for $p\bar{p}$ pairs, a clear indication of ordering of baryons along the event axis.

We have also performed a measurement of A_s, the parity-violating coupling of the Z^0 to

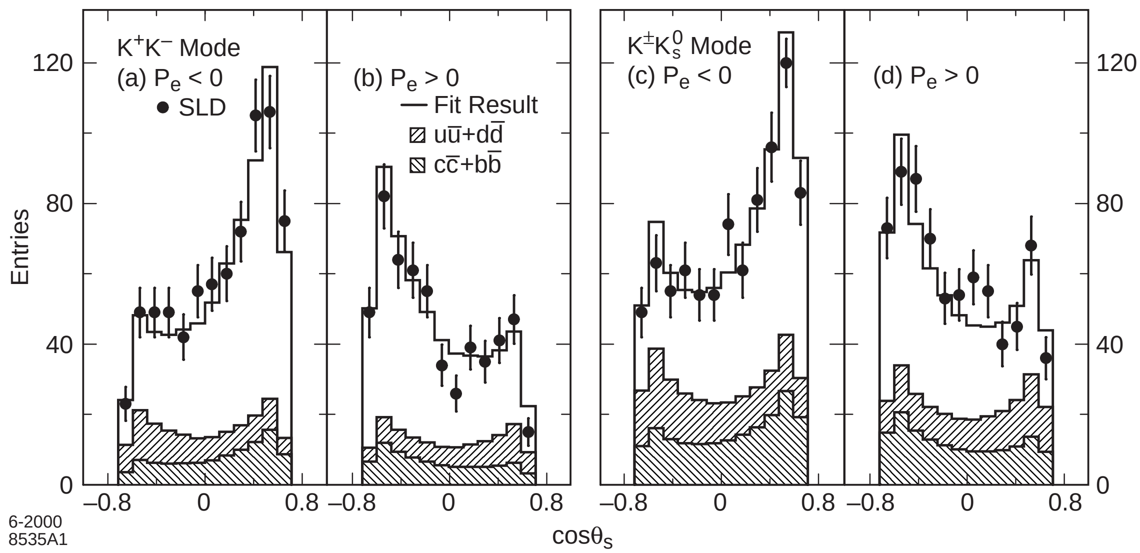

Figure 3: Measured s-quark polar angle distributions (dots) for events in the (a,b) K^+K^- and (c,d) $K^\pm K^0_S$ modes, produced with (a,c) left- and (b,d) right-polarized electron beams. The histograms represent the result of a simultaneous fit to the four distributions, and the upper (lower) hatched areas indicate the estimated $u\bar{u} + d\bar{d}$ ($c\bar{c} + b\bar{b}$) backgrounds.

strange quarks, obtained directly from the left-right forward-backward production asymmetry in polar angle of the tagged s quark. Our result is $A_s = 0.895 \pm 0.066(stat.) \pm 0.062(syst.)$, which is consistent with the Standard Model expectation, and with less precise previous measurements.

6 Questions and Answers

Question (from M. Boutemeur, Munich): How do the $\pi^\pm$, $K^\pm$, and $p/\bar{p}$ rates compare in quark and gluon jets?

Answer: My graduate student Hyejoo Kang is working on this very topic for her Ph.D. thesis. We expect to have results ready in time for the Moriond Conference in early 2001.

References

[1] SLD Collab.: K. Abe *et al.*, Phys. Rev. D **53** (1996) 1023.

[2] K. Abe *et al.*, Nucl. Inst. Meth. **A343** (1994) 74.

[3] T.J. Pavel, Ph.D. Thesis, Stanford University, 1996, SLAC-R-491 (1996).

[4] SLD Collab.: K. Abe *et al.*, Phys. Rev. D **59** (1999) 52001.

[5] H. Staengle, Ph.D. Thesis, Colorado State University (1999), SLAC-R-549.

[6] SLD Collab.: K. Abe *et al.*, Phys. Rev. Lett. **78** (1997) 3442.

[7] T. Sjöstrand, Comp. Phys. Comm. **82** (1994) 74.

[8] C.J.S. Damerell *et al.*, Nucl. Inst. Meth. **A288** (1990) 236.

[9] P. Abreu *et al.*, Eur. Phys. J. **C14** (2000) 613.

[10] K. Ackerstaff *et al.*, Z. Phys. **C76** (1997) 387.

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