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Identified Hadron Production and Light Quark Fragmentation in Z^0 Decays *

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Abstract

We have measured the differential cross sections for the production of π^+, K^+, K^0, K^{*0}, ϕ, p, Λ and their corresponding antiparticles in separate samples of flavor-tagged $Z^0 \to$ light-flavor ($u\bar{u}$, $d\bar{d}$, or $s\bar{s}$), $Z^0 \to c\bar{c}$ and $Z^0 \to b\bar{b}$ events. Clear flavor dependences are observed, and the results are compared with the predictions of three fragmentation models. We have also performed a 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. Our preliminary result is $A_s = 0.82 \pm 0.10(stat.) \pm 0.07(syst.)$.

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1 Introduction

There are several phenomenological models of jet fragmentation in the process $e^+e^- \rightarrow Z^0 \rightarrow q\bar{q}$, followed by the radiation of gluons and the eventual transformation of partons into primary hadrons. The HERWIG [1] model splits gluons into $q\bar{q}$ pairs, and these quarks and antiquarks are then paired up locally to form colorless clusters that decay into hadrons. The JETSET [2] model represents the color field between partons by a string which fragments into several pieces that correspond to primary hadrons. In the UCLA [3] model, whole events are generated according to weights derived from phase space and Clebsch-Gordan coefficients.

In this paper we report a measurement of the differential cross sections for the production of π^+, K^+, K^0, K^{*0}, ϕ, p, Λ and their corresponding antiparticles in separate samples of flavor-tagged $Z^0 \rightarrow$ light-flavor ($u\bar{u}$, $d\bar{d}$, or $s\bar{s}$), $Z^0 \rightarrow c\bar{c}$ and $Z^0 \rightarrow b\bar{b}$ events. We have used the results to test the predictions of the three fragmentation models described above.

Measurements of the fermion production asymmetries in the process $e^+e^- \rightarrow Z^0 \rightarrow f\bar{f}$ 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 (SM) 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 identified strange particles are used to tag s and $\bar{s}$ jets. The ud background is suppressed by requiring a tag in both jets, and the background is measured in the data.

In our experiment, events were produced by the SLAC Linear Collider (SLC) and recorded in the SLC Large Detector (SLD). The SLC delivered an electron beam with an average polarization of 74% and an unpolarized positron beam. A description of the SLD detector, trigger, track and hadronic event selection, and Monte Carlo simulation is given in Ref. [4].

2 Particle Identification

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) [5]. In each momentum bin, identified π, K, and p were counted, and these were unfolded using the inverse of an identification efficiency matrix [6], 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.

Candidate $K^0_S \to \pi^+\pi^-$, $\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\pi^+$ decays were selected by considering all pairs of oppositely charged tracks that were inconsistent with originating at the interaction point and passed a set of cuts [7] on vertex quality and flight distance. Backgrounds from misidentified Λ and K^0_S decays and photon conversions were suppressed by using kinematic cuts.

Candidate $K^{*0} \to K^+\pi^-$, $\overline{K}^{*0} \to K^-\pi^+$ decays were selected by considering all pairs of oppositely-charged tracks that were consistent with intersecting at the interaction point and having one but not both tracks identified in the CRID as a kaon [8]. Candidate $\phi \to K^+K^-$ decays were similarly selected, but with both tracks required to be identified as kaons.

In each momentum bin, the number of observed $K^0/\overline{K}^0$, $\Lambda/\bar{\Lambda}$, $K^{*0}/\overline{K}^{*0}$ and ϕ was determined from a fit to the appropriate invariant mass distributions. Finally, the signals were corrected for reconstruction efficiencies.

3 Production Rates

The differential cross sections for the production of π^+, K^+, K^0, K^{*0}, ϕ, p, Λ and their corresponding antiparticles were measured as a function of the scaled momentum $x_p = 2p/\sqrt{s}$ of the hadron, where p is its magnitude of momentum and $\sqrt{s}$ is the e^+e^- center-of-mass energy. The SLD Vertex Detector [9] was used to select subsamples of events flavor-tagged as light $(u\bar{u}, d\bar{d}, s\bar{s})$, $c\bar{c}$, or $b\bar{b}$. These selections were based on impact parameters of charged tracks with respect to the interaction point in the plane transverse to the beam. All rates were corrected for flavor-tagging purity and bias.

Fig. 1 shows the differential cross sections of the seven hadron species in light-flavor Z^0 decays as a function of scaled momentum x_p. At low x_p pions are seen to dominate over kaons by a factor of 10, and over K^{*0} by a factor of 40. Amongst the baryons at low x_p, protons dominate over the Λ^0 by a factor of 3. However, at high x_p the pion and kaon rates appear to be converging, as are the proton and Λ^0 rates.

Also shown in Fig. 1 are the predictions of the three fragmentation models described in the Introduction. All the models reproduce the shape of each differential cross section qualitatively. The JETSET prediction for charged pions is smaller than the data in the range $x_p < 0.015$, and those for the pseudoscalar kaons are larger than the data for $0.015 < x_p < 0.03$; those for the vector mesons and protons reproduce the x_p dependence but show a larger normalization than the data. The HERWIG prediction for pseudoscalar kaons is also larger

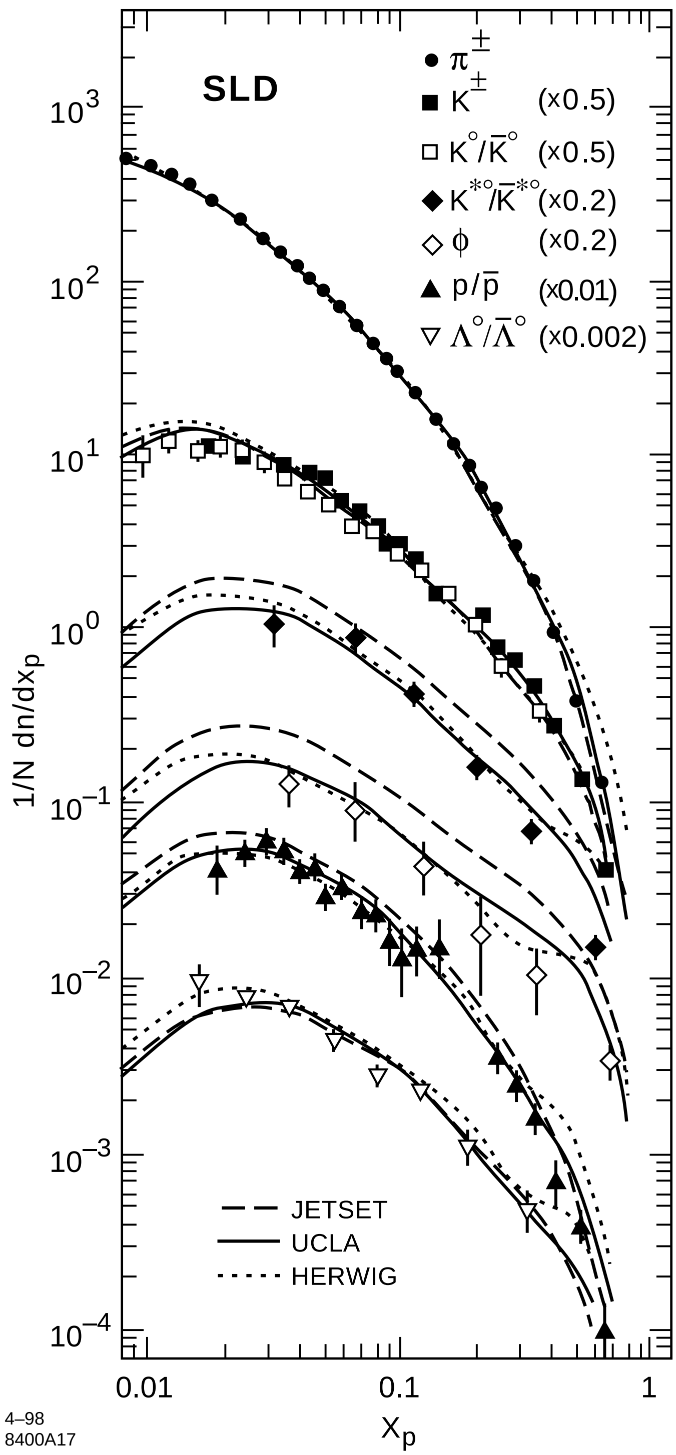

Figure 1: Differential cross sections for the production of identified hadrons in the light-flavor sample, as a function of scaled momentum. Also shown are the predictions of the three fragmentation models discussed in the text.

than the data at low x_p and is slightly smaller than the data in the range $0.15 < x_p < 0.25$. For all hadron species the HERWIG prediction is larger than the data for $x_p > 0.4$, showing a characteristic shoulder structure. The UCLA predictions for the baryons and vector mesons show a similar but less pronounced structure that is inconsistent with the proton and K^{*0} data. Otherwise UCLA reproduces the data except for pseudoscalar kaons in the range $0.15 < x_p < 0.03$.

Fig. 2 shows the ratios of production in b-flavor to light flavor events for the seven species. The systematic errors on the hadron reconstruction and identification largely cancel in these ratios, and the total errors are predominantly statistical. There is higher production of charged pions in b-flavor events than in light-flavor events at low x_p, with the ratio rising slowly until $x_p = 0.06$, and falling rapidly thereafter. The production of both charged and neutral kaons is approximately equal in the two samples for $x_p < 0.03$, but the relative production in b-flavor events increases in the range $0.03 < x_p < 0.09$, and then decreases sharply for higher x_p. There is approximately equal production of baryons in the two samples for $x_p < 0.15$, followed by a decline in the ratio at higher x_p. These features are consistent with expectations based on the known properties of $e^+e^- \to b\bar{b}$ events, namely that a large fraction of the event energy is carried by the leading B- and $\bar{B}$-hadrons, which decay into a large number of lighter particles.

Also shown in Fig. 2 are the predictions of the three fragmentation models, all of which reproduce these features qualitatively, although HERWIG overestimates the ratio for pions in the range $x_p < 0.5$ and that for kaons for $x_p < 0.3$. In the right half of the figure are shown the ratios of production in c-flavor to light-flavor events for the seven species. Features similar to those in the b:uds comparison are observed. There is higher kaon production in c-flavor events than in light-flavor events at $x_p \approx 0.1$, reflecting the tendency of c-jets to produce a fairly hard charmed hadron whose decay products include a kaon carrying a large fraction of its momentum. Also shown are the c:uds ratios predicted by the fragmentation models. All models are consistent with the data, except that HERWIG overestimates the pion ratio for $0.03 < x_p < 0.15$.

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. Each event was divided into two hemispheres by a plane perpendicular to the thrust axis. We required each hemisphere to contain at least one identified strange ($K^\pm$, K^0_s or $\Lambda^0/\bar{\Lambda}^0$) particle, and the strange particle of highest momentum was used to tag the strangeness of the hemisphere. At least one of the tagging particles was required to possess definite strangeness (note that K^0_s does not have definite strangeness), and if both particles had definite strangeness, their strangeness was required to be opposite. This procedure resulted in an overall $s\bar{s}$ purity of 69% for the selected sample.

The initial s quark direction was approximated by the thrust axis of the event, signed to point in the direction of negative strangeness. Fig. 3 shows the polar angle distributions 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

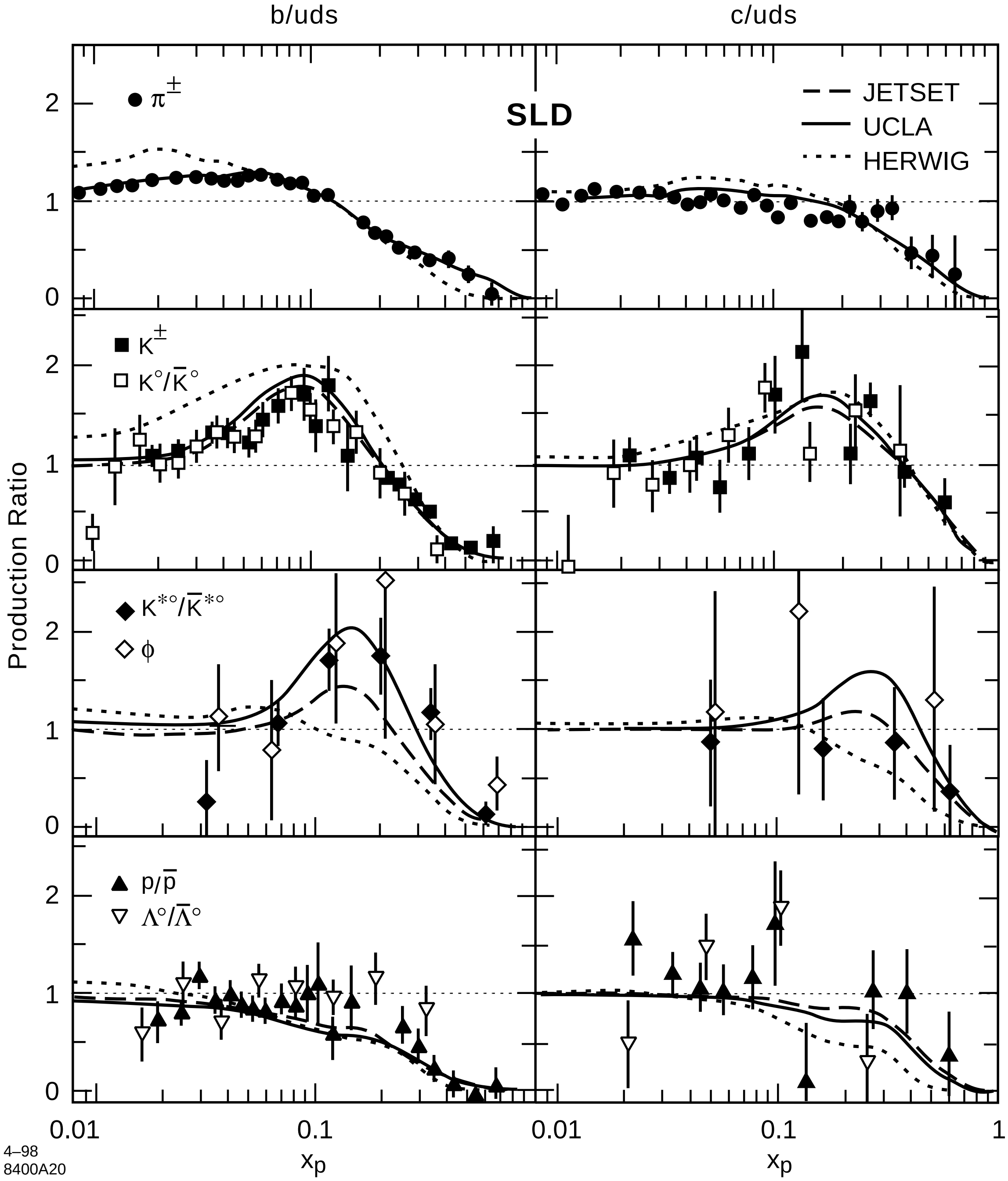

Figure 2: Ratios of production of each hadron species in b-flavor events to that in light-flavor events (left) and in c-flavor:light-flavor events (right). Also shown are the predictions of the three fragmentation models.

handed beams, are clearly visible.

A_s was extracted from these distributions by a binned 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 12.9 for 24 bins. Also shown in the figure are our estimates of the non-$s\bar{s}$ backgrounds. The cross-hatched histograms indicate $c\bar{c} + b\bar{b}$ backgrounds which show asymmetries of the same sign and similar slope as the total distribution. These backgrounds are understood experimentally and were evaluated using a detailed Monte Carlo simulation. Standard systematic variations of the simulation [4] were considered. The hatched histograms indicate $u\bar{u} + d\bar{d}$ backgrounds, showing asymmetries of the opposite sign and slope to the total distribution. This background is not well-understood experimentally, and we are especially sensitive to both its size and slope. Furthermore, the analyzing power in $s\bar{s}$ events has not been measured. Our Monte Carlo was used to evaluate the parameters used in the fit, but was calibrated using the data:MC ratios of the number of hemispheres with an identified K^+K^- pair, the number of hemispheres with three identified kaons, and the number of events with a $K^\pm$ tag of the same sign in both hemispheres. The uncertainties on these measured ratios were taken as systematic variations. Our preliminary result is

$$A_s = 0.82 \pm 0.10(stat.) \pm 0.07(syst.)$$

This result is consistent with the Standard Model expectation of 0.94 for A_s. Two of the LEP experiments have measured forward-backward asymmetries from which A_s can be derived by assuming a value for A_e. Using $A_e = 0.155$, the DELPHI [10] measurements translate into $A_s = 1.13 \pm 0.30(stat.) \pm 0.11(syst.)$ and $A_{d,s} = 0.96 \pm 0.27(stat.) \pm 0.46(syst.)$. The OPAL [11] measurements yield $A_{d,s} = 0.58 \pm 0.30(stat.) \pm 0.09(syst.)$. Our measurement is consistent with these and represents a substantial improvement in precision.

5 Conclusions

We have measured the differential cross sections as a function of scaled momentum x_p for the production of π^+, K^+, K^0, K^{*0}, ϕ, p, Λ and their corresponding antiparticles separately in light-flavor, $c\bar{c}$ and $b\bar{b}$ jets from Z^0 decays. Significant differences between flavors were found, consistent with expectations based on the known properties of B and D hadron production and decay. Our data were used to test the predictions of three fragmentation models with default parameters. In most cases these simulations reproduced the data to within a few percent. Each model, however, did disagree with some features of the data in isolated regions of x_p.

We have also performed a measurement of A_s, the parity-violating coupling of the Z^0 to strange quarks, obtained directly from the left-right-forward-backward production asymmetry in polar angle of the tagged s quark. Our preliminary result is $A_s = 0.82 \pm 0.10(stat.) \pm 0.07(syst.)$, which is consistent with the Standard Model expectation. It is also consistent with previous measurements of A_s, but with significantly smaller uncertainties.

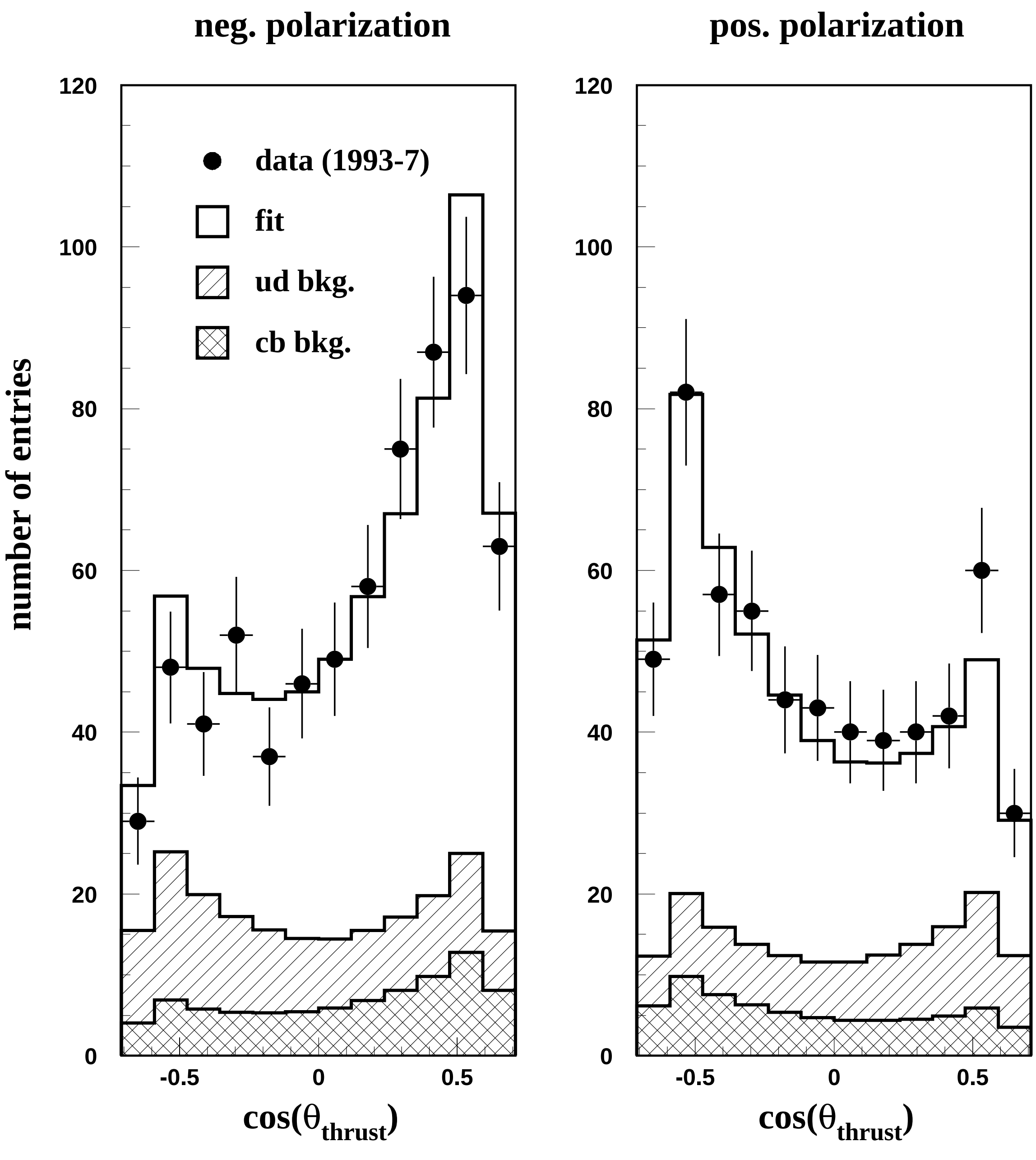

Figure 3: Polar angle distributions of the thrust axis, signed with the strangeness of the tagged strange particle, for negative (left) and positive (right) beam polarization. The dots show data and the histograms show our estimates of the non-$s\bar{s}$ background and the result of the fit to the data.

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