HADRON FRAGMENTATION FUNCTIONS AND LEADING PARTICLE EFFECTS IN HADRONIC Z^0 DECAYS: NEW RESULTS FROM SLD[*]

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Representing

The SLD Collaboration

Abstract

We have measured the differential cross sections for the production of $\pi^\pm$, $K^\pm$, K^0, $K^*(892)$, $\phi(1020)$, p and Λ in hadronic Z^0 decays and in subsets of flavor-tagged $Z^0 \to$ light quark ($u\bar{u}$, $d\bar{d}$, or $s\bar{s}$) , $Z^0 \to c\bar{c}$ and $Z^0 \to b\bar{b}$ events. Charged hadrons were identified with the SLD Cherenkov ring imaging detector. The vertex detector was employed to select flavor enriched samples and the polarized electron beam from SLC was used to tag quark and anti-quark jets. We observe a flavor dependence in the hadron fragmentation functions. We present evidence for leading particle production in hadronic decays of the Z^0 boson to light-flavor jets and a direct measurement of the strangeness suppression factor γ_s.

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1. Introduction

The production of hadrons in the decay of the Z^0 gauge boson involves the fragmentation stage, that is, the transition of colored partons into colorless hadrons. No theoretical description exists yet for this process. Instead, a variety of phenomenological models has been developed. At the Z^0 energies the two most successful models are the string fragmentation model, incorporated in the JETSET program [1], and the cluster fragmentation scheme that is part of the HERWIG program [2]. The study of the production of identified hadrons has been, and is, an important tool [3] in tests of the fragmentation models because these particles can often be identified with high purity and sufficiently large statistics over a wide momentum range.

In this paper we discuss a measurement of the differential cross sections for the production of $\pi^\pm$, $K^\pm$, K^0, $K^*(892)$, $\phi(1020)$, p and Λ in hadronic Z^0 decays and the first study of leading particle production in light flavor jets in e^+e^- annihilation. The analysis used 150,000 hadronic Z^0 decay events produced by the SLAC Linear Collider (SLC) and recorded in the SLC Large Detector (SLD) from 1993 to 1995.

A description of the SLD detector, trigger, track and hadronic event selection, and Monte Carlo simulation is given in Ref. [4]. Cuts were applied in order to select events well-contained within the detector acceptance, resulting in a sample of approximately 90,000 events. Sub-sets of flavor-tagged $e^+e^- \to Z^0 \to q\bar{q}$, where $q = u, d$, or s, and $e^+e^- \to Z^0 \to Q\bar{Q}$, where $Q = c$ or b were selected by using information from the Vertex Detector (VXD) [5] and applying an impact parameter technique [6].

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) [7]. In each bin 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, identified π, K, and p were counted, and these counts were unfolded using the inverse of the identification efficiency matrix E [8, 9], and corrected for track reconstruction efficiency. The elements E_{ij}, denoting the momentum-dependent probability to identify a true i-type particle as a j-type particle, were measured from the data for $i = \pi$, p and $j = \pi, K$, p using tracks from selected K_S^0, τ and Λ decays. A detailed Monte Carlo simulation was used to derive the remaining elements in terms of these measured ones.

Candidate $K_S^0 \to \pi^+\pi^-$, $\Lambda \to p\pi^-$ 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 [10] on vertex quality and flight distance. Backgrounds from mis-identified Λ and K_S^0 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 in which exactly one track was identified in the CRID as a charged kaon, and the tracks were consistent with intersecting at the interaction point [11].

Candidate $\phi(1020) \rightarrow K^+K^-$ decays were selected by considering all pairs of oppositely-charged tracks in which both tracks were identified in the CRID as charged kaons, and the tracks were consistent with intersecting at the interaction point [11].

In each x_p bin, the number of observed $K^0/\overline{K^0}$, $\Lambda/\bar{\Lambda}$, $K^{*0}/\overline{K}^{*0}$ and $\phi(1020)$ was determined from a fit to the appropriate invariant mass distribution. Finally, the signals were corrected for reconstruction efficiencies.
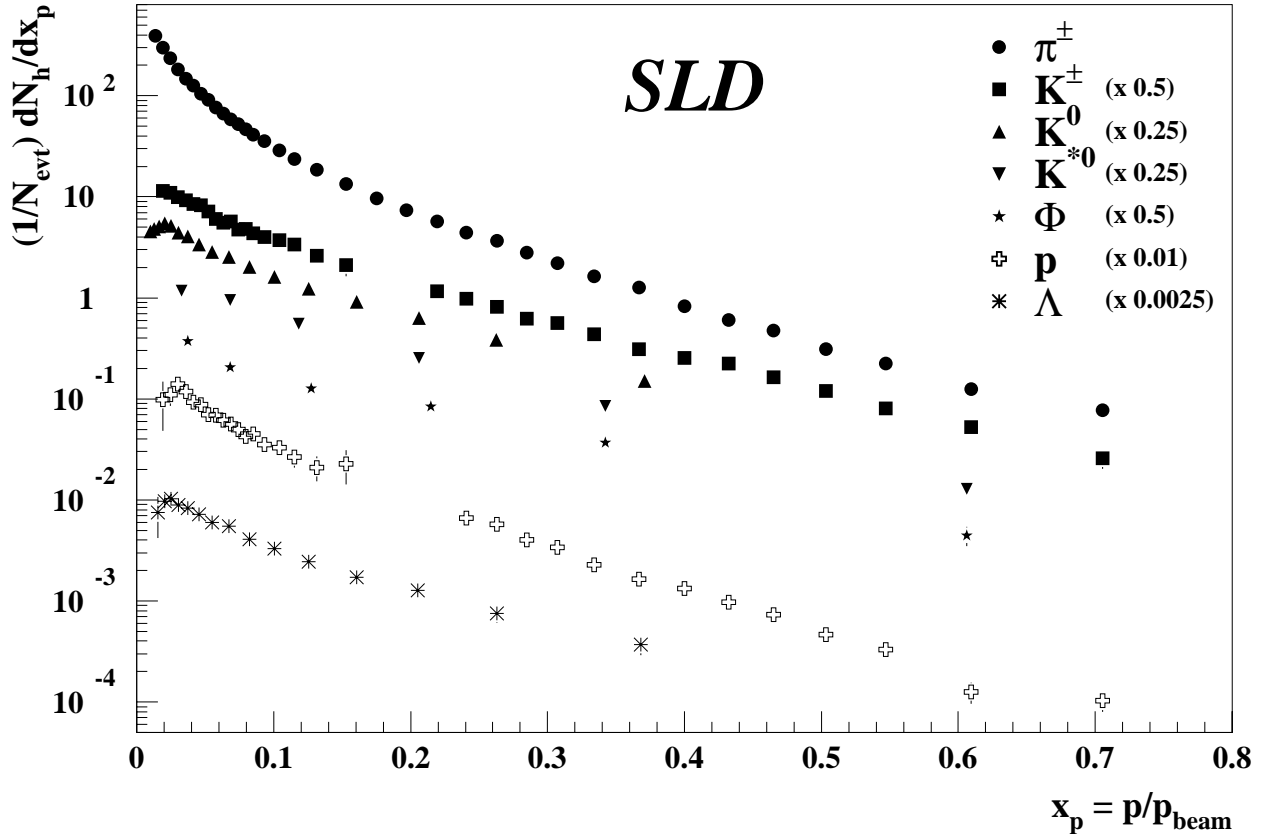

Figure 1: *Differential cross sections in inclusive Z^0 decays as a function of scaled momentum. The errors shown are combined statistical and bin-by-bin systematic uncertainties.*

3. Hadron Fragmentation Functions

The differential cross sections for $\pi^\pm$, $K^\pm$, K^0, $K^*(892)$, $\phi(1020)$, p and Λ in inclusive hadronic Z^0 decays are shown in Fig. 1 as a function of x_p. There are no $K^\pm$ or $p/\bar{p}$ points in the range $0.12 < x_p < 0.20$ due to the lack of CRID particle separation in this region. We also determined the hadron fragmentation functions in sub-samples of flavor-tagged light quark ($u\bar{u}$, $d\bar{d}$, or $s\bar{s}$), $c\bar{c}$ and $b\bar{b}$ events. The ratios of the differential cross sections in $c\bar{c}$ and $b\bar{b}$ events to light quark events are shown in Fig. 2. A clear flavor dependence can be seen. In particular, the production of the mesons is enhanced in b-jets for momenta below a few GeV/c. At higher momentum, the light hadrons are predominantly produced in $u\bar{u}$, $d\bar{d}$, or $s\bar{s}$ jets. Even though the errors are large, it can be seen that the value of x_p at which the production in light flavor jets becomes dominant is larger for c-quark jets than for bottom events, as expected from the heavy hadron decay properties.
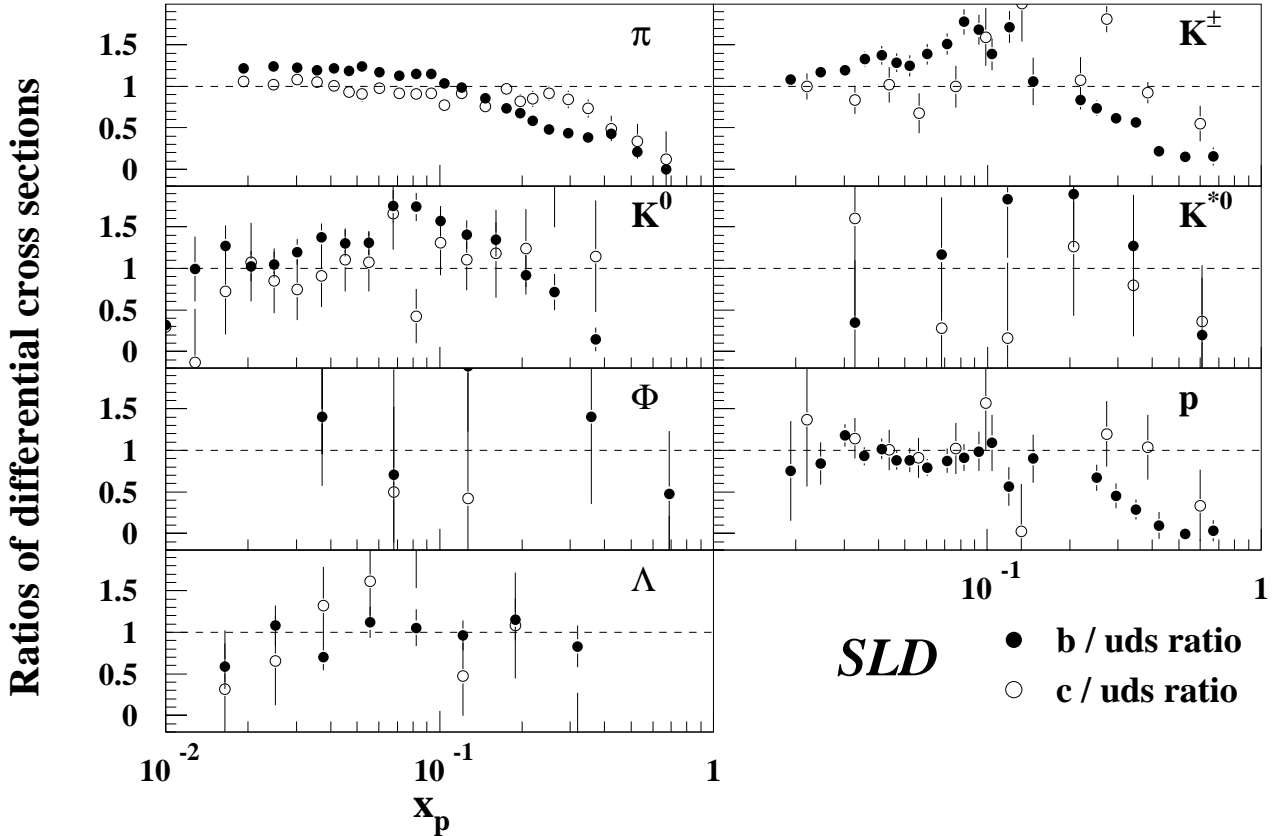
Figure 2: *Ratios of differential cross sections in flavor tagged Z⁰ decays as a function of scaled momentum. The errors shown are combined statistical and bin-by-bin systematic uncertainties.*

4. Leading Particle Effects

We define a particle to be leading if it carries a primary quark or antiquark, namely the q or $\bar{q}$ in $e^+e^- \to Z^0 \to q\bar{q}$. We separated jets initiated by primary quarks from those initiated by primary antiquarks by utilizing the electroweak forward-backward production asymmetry in the polar angle, enhanced by the high SLC electron beam polarization. We considered all events to consist of one jet in each of the two hemispheres separated by the plane perpendicular to the thrust axis. Defining the forward direction to be along the electron beam, the quark jet was defined to comprise the set of tracks in the forward (backward) hemisphere for events recorded with left-(right-) handed electron beam. The opposite jet in each event was defined to be the antiquark jet. For details on the tagging procedure, see Ref. [6]. In our sample of approximately 41,000 light quark events we measured the differential production rates per light quark jet (as opposed to light anti-quark jet)

$$R_h^q = \frac{1}{2N_{evts}} \frac{d}{dx_p} \left[N(q \to h) + N(\bar{q} \to \bar{h}) \right],$$

$$R_{\bar{h}}^q = \frac{1}{2N_{evts}} \frac{d}{dx_p} \left[N(q \to \bar{h}) + N(\bar{q} \to h) \right],$$

where: q and $\bar{q}$ represent light-flavor quark and anti-quark jets respectively; N_{evts} is the total number of events in the sample; h represents any of the identified hadrons π^-, K^-, $\overline{K}^{*0}$, p, and Λ, and $\bar{h}$ indicates the corresponding anti-particle; Then, for example, $N(q \to h)$ is the

number of hadrons of type h in light quark jets. In every x_p bin, R_h^q and $R_{\bar{h}}^q$ were corrected for the contribution from residual heavy-flavor events, estimated from our Monte Carlo simulation. Finally, the corrected R_h^q and $R_{\bar{h}}^q$ were unfolded for the purity of the quark jet tag.

We define the difference between each particle and anti-particle production rate, normalized by the sum:

$$D_h = \frac{R_h^q - R_{\bar{h}}^q}{R_h^q + R_{\bar{h}}^q},$$

for which the common systematic uncertainties cancel. As shown in Fig. 3, for each hadron h, D_h is consistent with zero for $x_p < 0.1$. D_{π^-} is also consistent with zero for $x_p > 0.1$, but for the other hadrons $D_h > 0$ for $x_p \gtrsim 0.2$. The JETSET 7.4 [1] and HERWIG 5.8 [2] fragmentation models were found to reproduce these features qualitatively.
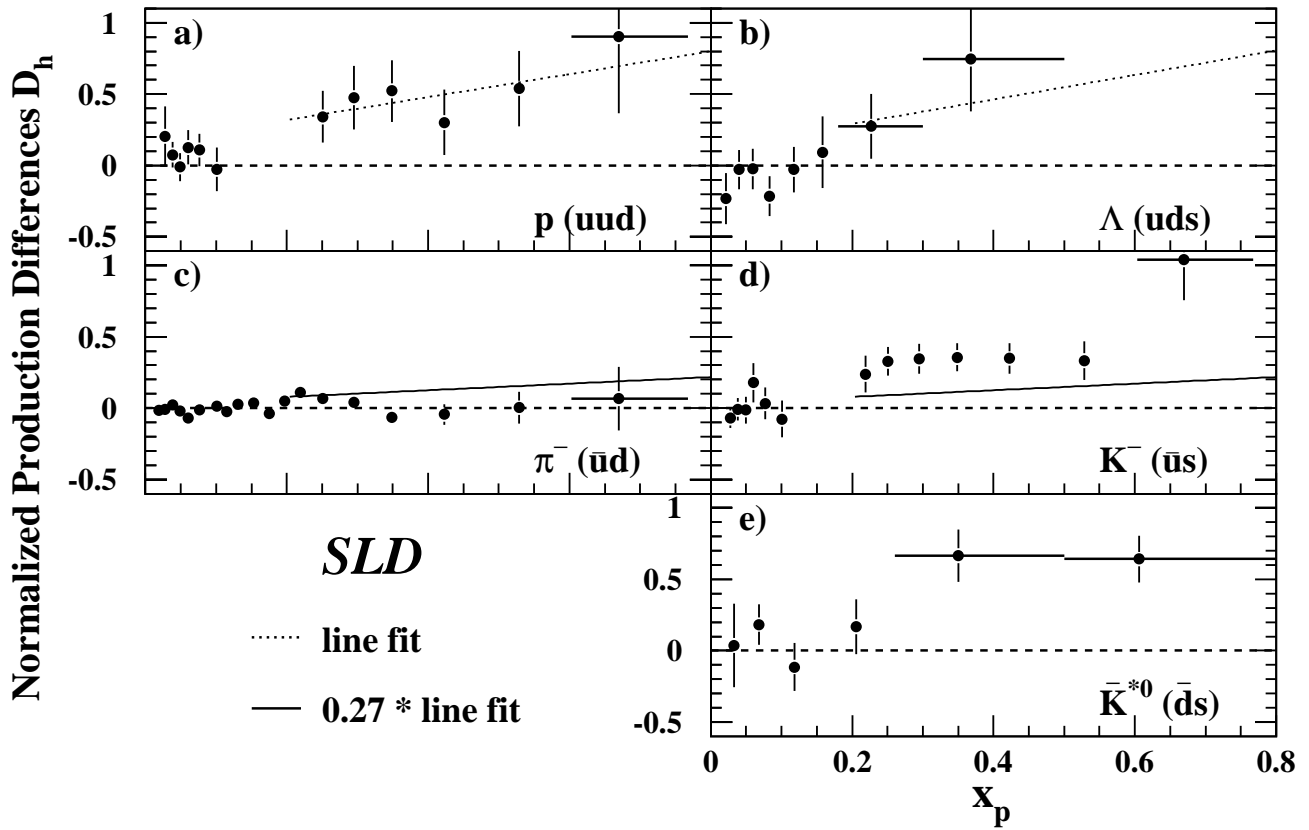

Figure 3: *Normalized production differences (dots) as a function of scaled momentum. The vertical error bars shown are combined statistical and bin-by-bin systematic uncertainties. The horizontal error bars on selected points indicate their bin widths. The dotted lines represent a linear fit to the D_p and D_Λ points for $x_p > 0.2$, and the solid lines are this fit scaled by the factor 0.27 discussed in the text.*

Since baryons contain no constituent anti-quarks, we interpret the positive D_p and D_Λ as evidence for leading baryon production in light-flavor jets. If pions and kaons exhibited similar leading effects, then, due to the larger asymmetry parameter for u-type than d-type quarks, one would expect $D_{\pi^-} \approx D_{K^-} \approx 0.27 D_{baryon}$, and $D_{\overline{K}^{*0}} = 0$, assuming Standard Model quark couplings to the Z^0. For purposes of illustration, the result of a linear fit to the D_p and D_Λ points above $x_p = 0.2$ was scaled by 0.27 and is shown in Figs. 3(c) and 3(d). The observed D_{π^-}

are below this line, and are consistent with zero at all x_p, suggesting that either there is little production of leading pions, or there is substantial background from non-leading pions or pions from decays of resonances such as the ρ and K^*. For $x_p > 0.2$, we observe $D_{K^-} > 0.27 D_{baryon}$ and $D_{\overline{K}^{*0}} > 0$. This indicates both substantial production of leading K and K^* mesons at high momentum, and a depletion of leading kaon production in $u\bar{u}$ and $d\bar{d}$ events relative to $s\bar{s}$ events.

Assuming these high-momentum kaons to be directly produced in the fragmentation process, this amounts to a direct observation of a suppression of $s\bar{s}$ production from the vacuum with respect to $u\bar{u}$ or $d\bar{d}$ production. In the case of K^{*0} mesons it has been suggested [12] that this effect can be used to measure the "strangeness suppression parameter" γ_s, that is an important component of models of hadronization, see e.g. Ref. [1]. Assuming *all* K^{*0} and $\overline{K}^{*0}$ in the range $x_p > 0.5$ to be leading, we calculate $\gamma_s = 0.26 \pm 0.12$, where the error is predominantly statistical, consistent with values [3] derived from inclusive measurements of the relative production rates of strange and non-strange, pseudoscalar and vector mesons.

Acknowledgments

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