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PROPERTIES OF LEADING PARTICLES IN HADRONIC Z^0 DECAYS*

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Abstract

We present studies of leading particle production in Z^0 decays into light, c, and b quarks performed with the SLD experiment at SLAC. The SLD precision vertex detector was exploited to tag light-flavor events, to tag charmed meson vertices and separate the prompt and B-decay components, and to reconstruct B-hadrons partially. The relative production of prompt pseudoscalar and vector D-mesons was measured to be $P_V = 0.53 \pm 0.06(stat.) \pm 0.02(syst.)$ (preliminary). The shape of the B-hadron energy spectrum was found to be consistent with the predictions of a number of models, and the average energy fraction was measured to be $< x_E >= 0.697 \pm 0.012(stat.) \pm 0.028(syst.)$ (preliminary). Separation of light quark and antiquark jets was achieved using the highly polarized SLC electron beam, and hadrons were identified using the SLD Cherenkov Ring Imaging Detector. Production of particles and antiparticles in quark jets was compared, allowing the first direct observation of leading particles in $e^+e^- \rightarrow u\bar{u}, d\bar{d}, s\bar{s}$ events. More high momentum baryons and K^-'s than antibaryons and K^+'s were observed, providing evidence for leading baryon and kaon production, as well as for strangeness suppression at high momentum.

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1 Introduction

The process by which partons produced in hard collisions hadronize into observable particles is not understood quantitatively. An aspect of particular interest is the fate of the initial parton in a jet, for example the u or $\bar{u}$ in $e^+e^- \to Z^0 \to u\bar{u}$. That is, does it appear in a specific "leading" final state hadron, and if so, does that hadron have a preferred momentum, baryon number, flavor or spin? This question can be studied in $e^+e^- \to$hadrons if the primary flavor of the event can be tagged, the quark and antiquark hemispheres distinguished, and a particle identified that contains a valence quark or antiquark of the appropriate flavor.

Hadrons containing a heavy (c or b) quark have been observed to carry a large fraction of the beam energy, and to appear at rates consistent with exactly two heavy hadrons per $e^+e^- \to c\bar{c}$ or $b\bar{b}$ event, which presumably contain the heavy quark and antiquark. It is therefore desirable to reconstruct as many heavy particle types as possible, and to study distributions of quantum numbers and momentum in detail. Here we present two such studies, a measurement of the relative production of pseudoscalar and vector D-mesons, and a measurement of the inclusive B-hadron energy distribution.

In light-flavor ($Z^0 \to u\bar{u}, d\bar{d}, s\bar{s}$) events there are few experimental results, due to the difficulty of tagging these events and the large number of particles typically produced in an event that contain light valence quarks. Here we present the first systematic study of leading particle production in light quark jets. We suppress heavy-flavor events using lifetime information and separate the resulting light quark and light antiquark hemispheres using the large forward-backward production asymmetry induced by the high SLC electron beam polarization. Particles are identified in the quark jets and their production rates are compared with those of their antiparticles. Since baryons contain only valence quarks, they provide a clean signature for leading particle effects. Up- and down-type quarks are produced at different rates and with different asymmetries at the Z^0, so that if leading mesons of a particular type are produced equally in jets initiated by the constituent quark and antiquark, then a leading particle signature will cancel if both are d-type (e.g. K^{*0}), and be diluted by $\sim$0.22 if one is u- and the other d-type (e.g. π^-, K^-).

These analyses are based based upon the sample of about 150,000 hadronic Z^0 decays collected by SLD between 1993 and 1995, with an average electron beam polarization of 73%. Charged tracks measured in the Central Drift Chamber [1] and in the Vertex Detector [2] and energy clusters measured in the Liquid Argon Calorimeter [3] were used. Charged particle identification was performed with the Cherenkov Ring Imaging Detector [4]. The track and event selection criteria are described in Ref. [5].

2 The P:V Ratio for Prompt D-mesons

In order to study leading charmed hadron production, we must reconstruct charmed hadrons, suppress combinatoric background, and suppress the background of real charmed hadrons from decays of B-hadrons. We studied [6] the charged vector and pseudoscalar mesons D^{*+} and D^{+}. The former was reconstructed in the decay mode $D^{*+} \rightarrow D^0\pi_s^+$, where D^0 candidates were first reconstructed in the $K^-\pi^+$ and $K^-\pi^+\pi^-\pi^+$ modes. Combinatoric background was suppressed by requiring the tracks to form a good vertex, well separated from the primary interactoin point (IP), with invariant mass near the D^0 mass. D^+ candidates were reconstructed in the $K^-\pi^+\pi^+$ mode, and cuts were applied on vertex quality and separation as well as the helicity angle of the K^-.

The D^0 and D^+ candidates were divided into "c-rich" and "b-rich" samples using information from the opposite event hemisphere and the flight path of the candidate. If there were three or more tracks in the opposite hemisphere that were inconsistent with passing through the IP at the 3σ level, the candidate was assigned to the b-rich sample. Otherwise, candidates whose total momentum vector was (not) consistent with passing through the IP were assigned to the c-rich (b-rich) sample.

At this point D^0 candidates were paired with additional tracks to form D^{*+} candidates. In each sample, the numbers of reconstructed D^+ and D^{*+} were extracted from fits to the distributions of $K\pi\pi$ invariant mass and mass difference, $\Delta M = M_{D^0\pi_s} - M_{D^0}$, respectively. The numbers from the c-rich and b-rich samples were unfolded using selection efficiences derived from a detailed Monte Carlo simulation [6], to obtain production rates of prompt and secondary D-mesons.

The ratio $P_V = V/(V+P)$ was calculated from the rates of prompt vector (V) and pseudoscalar (P) production. Averaging over scaled momentum $x_D > 0.4$ we obtained [6]

$$P_V = 0.53 \pm 0.06(\text{stat.}) \pm 0.02(\text{syst.})$$

(preliminary). The systematic error is dominated by the uncertainties in the branching ratios into the measured modes. This result disfavors the naive spin-counting model, which predicts P_V =0.75, but is consistent with other theoretical predictions [7] and previous experimental measurements [8].

3 The B Hadron Energy Spectrum

It is known that the average B hadron energy is high (~70% of the beam energy) in $e^+e^- \rightarrow b\bar{b}$ events, but there is little experimental information on the shape of the spectrum. In order to measure this it is necessary to reconstruct the energies of individual B hadrons, which is problematic due to their high average decay multiplicity. We used semileptonic B-decays in which we also partially reconstruct a D-vertex, so that most of the energy is in charged tracks and the neutrino, the latter appearing as missing energy.

We first selected [9] identified electrons and muons with transverse momentum above 1 GeV/c with respect to the nearest jet. A "D" vertex was defined as the largest set of other tracks in the jet missing the IP by at least 1σ, that passed a set of cuts on vertex quality and mass, closest approach of the vertex axis to the lepton, and separation of the vertex from the IP and, along its axis, from the lepton. This procedure yielded a sample

96.5% pure in B-hadron decays and 84.5% pure in semi-leptonic decays, according to the simulation.

The energies of the remaining tracks in the jet and of calorimeter clusters in the jet not associated with any track were summed to form the "fragmentation" energy. The neutral component was corrected to account for the average neutral energy from B-decays, and the fragmentation energy was subtracted from the jet energy to yield the measured B-hadron energy. The simulation gives an energy resolution of $\delta E_B/E_B$ =10% for 95% of the true B decays in the sample.

In order to study its shape, the raw energy distribution must be corrected for backgrounds, acceptance and resolution. It was found that the correction depends strongly on the shape assumed in the simulation, since the distribution varies rapidly compared with the binning allowed by statistics and resolution. We therefore adopted an iterative procedure to test each of several shapes proposed in the literature, in which the correction was recalculated at each stage of a fit, using the shape in question and current parameter values. We found that all shapes were able to reproduce the data under these conditions. The result is shown in Fig. 1, where the errors from statistics, experimental systematics and the choice of shape are shown separately.

The average value of the energy was [9]:

$$< x_E >_B = 0.697 \pm 0.012(\text{stat.}) \pm 0.028(\text{syst.})$$

(preliminary), where the systematic error is dominated by the variation among assumed shapes. This result is consistent with previous measurements [10].

4 Leading Particles in *uds* Events

In order to study leading particle production in light-flavor events ($Z^0 \rightarrow u\bar{u}, d\bar{d}, s\bar{s}$) we must: i) remove heavy quark events so as to be insensitive to heavy hadron decay products; ii) separate q- and $\bar{q}$-jets; and iii) identify several particle types in the q-jet sample and compare production spectra for particles with those of their antiparticles.

Light quark events were selected [11] by requiring that no track in the event miss the IP by more than 3σ, yielding a sample of 85% purity. The large forward-backward asymmetry due to the highly polarized electron beam was used to separate quark from antiquark hemispheres. As the primary quarks from Z^0 decays are left handed, they tend to follow the direction of the incident left-handed fermion. The event thrust axis was signed such that its component along the electron beam direction $\hat{t}_z > 0$, and events with $\hat{t}_z > 0.2$ were selected. The quark-tagged hemisphere in events with left-(right-) handed electron beam was defined to be the set of tracks with positive (negative) momentum projection along the thrust axis. The remaining tracks were defined to be the antiquark-tagged hemisphere. The Standard Model at tree level predicts the purity of the quark-tagged sample to be 72% for our average electron beam polarization of 73%.

The particle identification analyses described in Ref. [5] were performed separately for particles and antiparticles in the quark-tagged sample to extract production rates of

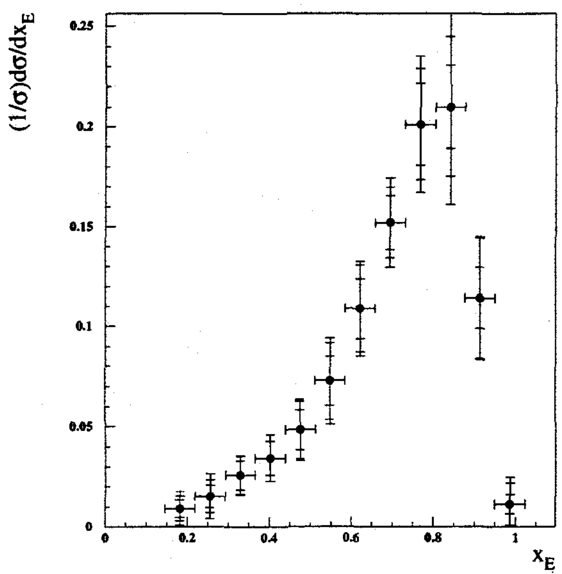

Figure 1: The distribution of B-hadron energies. The inner error bars are statistical, the middle bars include the rms variation among shapes assumed in the correction, and the outer bars include all systematic errors.

$h = \pi^+, \pi^-, K^+, K^-, p, \bar{p}, \Lambda^0$ and $\bar{\Lambda}^0$ as a function of momentum. Antiparticles from the antiquark-tagged sample were included with their respective particles. The contributions to these rates from heavy quark events, estimated from the Monte Carlo simulation, were subtracted. The resulting rates were unfolded for the purity of the quark tag to obtain production rates $R(q \to h)$ in light quark jets.

For each particle type h we considered the difference between h and $\bar{h}$ production rates normalized by their sum:

$$D_h = \frac{R(q \to h) - R(q \to \bar{h})}{R(q \to h) + R(q \to \bar{h})}.$$

The particle identification systematics largely cancel in this observable, and the errors are dominated by statistics. Figure 2 shows these normalized differences as a function of x_p. For each particle type, the differences are consistent with zero at low x_p. For the pions the difference is also consistent with zero at high x_p, whereas significant positive differences are observed for $h = K^-, p$ and Λ^0.

Since baryons contain no constituent antiquarks, we interpret the steep rise in D_p and D_Λ with increasing x_p as evidence that leading baryons are produced and that they prefer high momentum. There is a significant effect for momenta as low as 10 GeV/c, and the

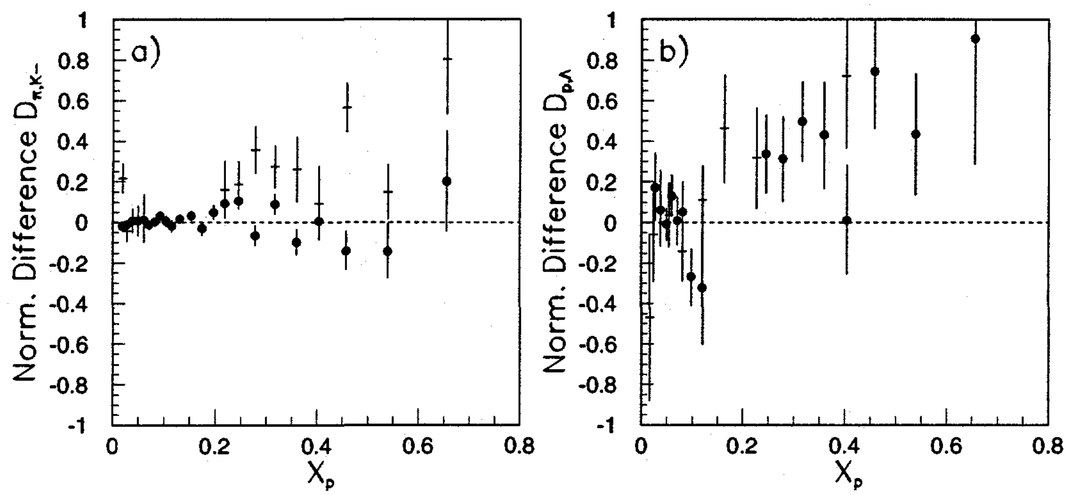

Figure 2: Normalized production differences as a function of scaled momentum for (a) charged pions (circles) and kaons (crosses), and (b) protons (circles) and Λ's (crosses).

data are consistent with complete dominance of leading baryon production as $x_p \to 1$.

If the production of $\pi^{\pm}(K^{\pm})$ mesons were completely dominated by leading meson production, *and* $\pi^-(K^-)$ were produced equally in jets initiated by $\bar{u}$ and $d(s)$ quarks, then we would expect to observe $D_h \sim 0.22$ for these mesons, due to the different rates and asymmetries for u- and d-type quark production at the Z^0. Our data are more consistent with $D_\pi = 0$ than $D_\pi = 0.22$ over the entire measured x_p range, suggesting either no production of leading pions, substantial dilution from decays of resonances such as the ρ^0, or simply a very soft leading pion spectrum. We measure $D_K \geq 0.22$ for $x_p \geq 0.2$, indicating both that *i*) there is leading kaon production at high momentum, and *ii*) leading kaons are produced more often in $s\bar{s}$ events than in $u\bar{u}$ events. Thus we observe directly that strangeness suppression is substantial for particles produced with a large fraction of the 46 GeV beam energy.

5 Summary

We have presented three preliminary measurements that exploit the capabilities of the SLC and SLD programs to expand our understanding of the hadronization process. By separating D-meson candidates that do and do not originate from B-decays, we measured $P_V = 0.53 \pm 0.06(\text{stat.}) \pm 0.02$ (syst.) for prompt charmed mesons with no assumptions on the ratio in B-decays. By reconstructing a large fraction of the energy in semileptonic B-hadron decays, we obtained a relatively efficient and precise measure of individual B-hadron energies, and measured their distribution. We found the average scaled energy to be $< x_E >_B = 0.697 \pm 0.012$(stat.)$\pm 0.028$(syst.). By tagging light-flavor events and separating the quark and antiquark hemispheres, we observed clear evidence for production of leading baryons and K-mesons in these events, as well as for strangeness suppression in hadronization at high momentum fraction.

References

[1] M.D. Hildreth et al., Nucl. Inst. Meth. **A367** (1995) 111.

[2] C. J. S. Damerell et al., Nucl. Inst. Meth. **A288** (1990) 288.

[3] D. Axen et al., Nucl. Inst. Meth. **A328** (1993) 472.

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

[5] K. Abe et al., SLAC-PUB-7199; contributed to this conference (PA04-045).

[6] K. Abe et al., SLAC-PUB-7200; contributed to this conference (PA04-046).

[7] M. Suzuki, Phys. Rev. **D33** (1986) 676;
K. Cheung and T.C. Yuan, Phys. Rev. **D50** (1994) 3181;
E. Braaten et al., Phys. Rev. **D51** (1995) 4819.

[8] P. Abreu et al., Z. Phys. **C59** (1993) 533;
D. Buskulic et al., Z. Phys. **C62** (1994) 1.

[9] K. Abe et al., SLAC-PUB-7198; contributed to this conference (PA04-044).

[10] D. Buskulic et al., Phys. Lett. **B357** (1995) 699;
P. Abreu et al., CERN-PPE/95-076 (1995);
P.D. Acton et al., CERN-PPE/95-122 (1995).

[11] K. Abe et al., SLAC-PUB-7197; contributed to this conference (PA04-043).

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