Observation of Strangeness Correlations in e^+e^- Annihilation at $\sqrt{s} = 29$ GeV

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Correlations in rapidity space are presented for identified $\pi^\pm$ and $K^\pm$ in e^+e^- annihilation at 29-GeV c.m. energy. Short-range KK correlations indicate local flavor compensation in the hadronization process. Long-range KK and $\pi\pi$ correlations prove that the initial partons carry flavor. In addition, we observe significant $K\pi$ correlations as a result of heavy-quark decays.

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In standard models of hadronization the process $e^+e^- \rightarrow$ hadrons is governed by two distinct time scales. At early times, the production of a parton system is described by perturbative theory. On a much longer time scale, nonperturbative strong interactions transform these partons into hadrons. The large momentum scale involved in the creation of the initial $q\bar{q}$ pair results in a large separation in phase space of hadrons containing those partons. Since the two primary quarks in an annihilation event carry opposite quantum numbers, this process will give rise to long-range flavor correlations (LRC). Such studies by previous experiments have indeed provided evidence that the primary partons are charged.[1,2] On the other hand, the final formation of hadrons is usually assumed to be governed by small-Q^2 phenomena which generate local, short-range correlations (SRC) (see Fig. 1).

In this paper we examine these two regimes by studying flavor correlation in multihadron events, with special emphasis on the investigation of strangeness correlations. As a result of the small number of strange quarks produced in a typical event, strangeness is a much cleaner way to label a specific $q\bar{q}$ pair than, for example, charge.

The data used in this analysis were collected by the time-projection–chamber (TPC) detector at the PEP storage ring and consist of 23 650 annihilation events, representing 68 pb^{-1} at 29-GeV c.m. energy. The PEP4 facility and the multihadronic event selection have been described previously.[3] The TPC provides both tracking information and charged-particle identification. The detector has a

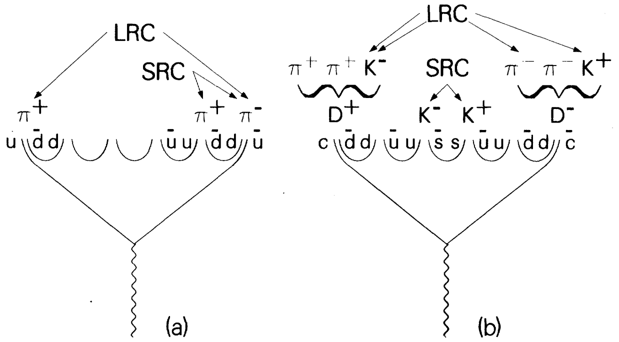

FIG. 1. The mechanisms responsible for long- and short-range flavor correlations (a) among pions and (b) between kaons and pions.

momentum resolution of $(dp/p)^2=(0.06)^2+(0.035p)^2$ where p is the momentum measured in GeV/c. Hadrons are identified by the simultaneous measurement of ionization energy loss (dE/dx) and momentum. For this study, a particle is called a pion (kaon) if at least 70% of the tracks with that dE/dx and momentum are true pions (kaons).[4]

As a consequence of strangeness conservation in strong interactions, there should be an increased number of K^+ in events containing a K^-. Figure 2 demonstrates this effect for high-momentum tracks, where particle identification is most difficult. Figure 2(a) shows the distribution of dE/dx (divided by the predicted value for $\pi^\pm$) for all tracks with at least 80 usable dE/dx samples and a measured momentum between 3.5 and 6 GeV/c. Figures 2(b) and 2(c) show the same distribution for events containing an identified charged K, where 2(b) [2(c)] contains all other tracks with the same [opposite] charge as the tagged K. The crosshatched regions represent those particles accepted by our analysis as pions or kaons. In events with an identified K the rate of oppositely charged kaons among the associated particles is clearly larger than that of kaons with the same charge.

In the rest of this paper we examine the behavior of this strangeness correlation as a function of the separation of the particles in rapidity. We define rapidity in the usual manner:

$$y=\tfrac{1}{2}\ln[(E+p_{\parallel})/(E-p_{\parallel})],$$

where $p_{\parallel}$ is the component of momentum parallel to the sphericity axis found with use of charged particles. To ensure adequate reconstruction of the jet axis, we reject events where the cosine of the angle between the sphericity axis and the beam line is greater than 0.8.

Given a negatively charged test particle at rapidity y_{test}, charge conservation requires that total charge of all other particles in the event be +1. Local charge conservation implies that the net positive charge in the rest of the event is distributed at rapidities close to that of the test particle. We define the associated charge density[5] $q(y)$ to be the net compensating charge density at rapidity y:

$$q(y)=\rho^O(y)-\rho^S(y),$$

where $\rho^O(y)$ $[\rho^S(y)]$ is the density, $(1/\sigma_{\text{tot}})d\sigma/dy$, of particles at rapidity y with the opposite [same] charge as the test particle. Charge conservation requires

$$\int q(y)\,dy=1.$$

Analogously, we define the flavor-tagged charge density $q_a^b(y)$ as the net compensating charge density seen in particles of species b when the test particle is of species a. Charge conservation now reads

$$\sum_{b=\text{stable species}}\int q_a^b(y)\,dy=1.$$

In the case where a and b are kaons, $q_K^K(y)$ is equivalent to an associated strangeness density. This density does not integrate to 1, however, because it includes only that fraction of the strangeness carried by charged kaons.

When calculating $q_a^b(y)$, we correct the data for sample purity and detection efficiency by unfolding the measured two-particle π, K, and proton combinations using Monte Carlo–determined misidentification probabilities and acceptances. The Monte Carlo simulation includes the effect of initial-state radiation,[6] pattern recognition, decay in flight, energy loss in the material before the TPC, multiple scattering, nuclear interactions, and loss of dE/dx information due to track overlap. The kaon acceptance varies from 16% to 32% as a function of rapidity and the purity ranges from 70% to 95%. Pion acceptance remains between 50% and 70% with a

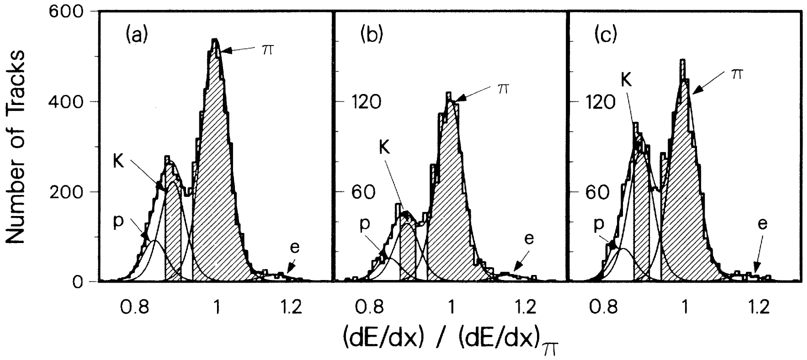

FIG. 2. The distribution of dE/dx divided by the predicted value for pions for tracks with $3.7\leq p<6$ GeV/c (a) for all events and for events with an identified K; (b) for tracks with the same and (c) opposite charge as the K.

purity greater than 90% at all rapidities.[7] The electron contamination in our π and K samples is below 2% everywhere. Our "pion" sample includes about 1% direct muons since the dE/dx method cannot distinguish between $\pi^\pm$ and $\mu^\pm$. Corrections and unfolding are done as functions not only of y and y_{test} but of the angle of the jet axis as well, since for a given angle the loss of tracks down the beam line gives a localized dip in acceptance. Quoted errors include systematic uncertainties in the unfolding procedure.

Figure 3 shows $q_\pi^\pi(y)$, $q_\pi^K(y)$, and $q_K^K(y)$ for two ranges of y_{test}: $0 \leq y_{\text{test}} < 1.5$ and $1.5 \leq y_{\text{test}} < 4$. The first range corresponds to the central region of the rapidity plateau; the second is enriched in hadrons containing primary quarks. The figure also includes the predictions of two rather different hadronization models: the "symmetric" Lund model[8] (solid line) and the Webber QCD Monte Carlo[9] model (dotted line). Both models adequately describe the data. To demonstrate the influence of heavy-quark production on the distributions, we also show the predictions of the Lund model in the absence of b and c quarks (dashed line).

The $\pi\pi$ correlations in Figs. 3(a) and 3(b) are quite similar to the charge-compensation results previously observed in both e^+e^- [1,2] and pp [5] collisions. For small y_{test} [Fig. 3(a)], the dominant feature is a large SRC. Although such behavior is consistent with local charge conservation during hadronization, decays such as $K^0 \rightarrow \pi^+\pi^-$, $\rho^0 \rightarrow \pi^+\pi^-$, and $\omega \rightarrow \pi^+\pi^-\pi^0$ also lead to such SRC. At large y_{test} [Fig. 3(b)] a LRC also becomes evident. This LRC provides evidence for the presence of charged primary partons [see Fig. 1(a)].

The KK correlations [Figs. 3(c) and 3(d)] exhibit a significant SRC. Unlike the $\pi\pi$ case, decay contributions to this SRC are expected to be small. If the primary mesons are produced predominantly in the ground-state scalar and vector nonets, the ϕ should be the only significant resonance component for small y_{test}. In the high-y_{test} region, F-meson decays contribute as well. By use of our measured ϕ cross sections,[4] we determine the ϕ contribution to be approximately 10% of the SRC for the small-y_{test} range [3(c)] and 15% for the large-y_{test} range [3(d)]. We estimate, using the Lund Monte Carlo model, that F mesons (including the $F \rightarrow \phi\pi$ mode) contribute 5% of the SRC signal in Fig. 3(d). It appears, therefore, that for both y_{test} bins the KK SRC is too large to be explained by resonance decays and is evidence for soft hadronization and local compensation of flavor.

At high y_{test}, $q_K^K(y)$ shows a LRC that is compar-

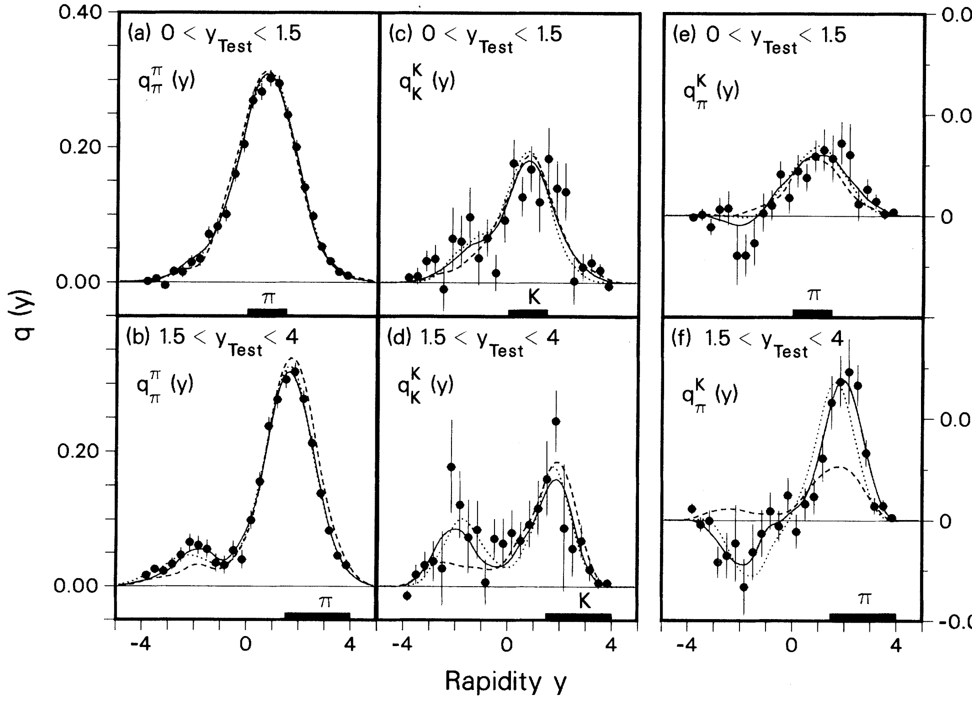

FIG. 3. The associated charge densities (a),(b) $q_\pi^\pi(y)$, (c),(d) $q_K^K(y)$, and (e),(f) $q_\pi^K(y)$ for the rapidity ranges $0 \leq y_{\text{test}} < 1.5$ and $1.5 \leq y_{\text{test}} < 4$. The solid and dotted curves show the predictions of the Lund (Ref. 8) and Webber (Ref. 9) models. Dashed curves give the Lund prediction without heavy quarks.

able in size to the SRC [3(d)]. This distribution has significantly different shape than $q_\pi^\pi(y)$, where the SRC is about a factor of 6 larger than the LRC. These results indicate that for this test range a large fraction of kaons are direct descendents of the primary quarks. Comparison of the Monte Carlo predictions with and without heavy quark indicates that c and b events are an important source of such $K^\pm$. Also, the predicted LRC is greatly reduced in a Monte Carlo model that conserves charge but not flavor.

The size of the $K\pi$ correlation displayed in Figs. 3(e) and 3(f) is much smaller than either the $\pi\pi$ or KK correlations. The observed SRC is due to a combination of local charge conservation during hadronization and decays such as $K^{*0} \rightarrow K^+\pi^-$. The πK correlations in Fig. 3(f) demonstrate the impact of heavy-quark decays. While the SRC remains comparable in size to that of Fig. 3(e), $q_\pi^K(y)$ shows a significant same-charge LRC. This correlation between a kaon in one jet and a pion of the same charge in the opposite jet can be explained by the decays $c \rightarrow \pi^+K^-X$ and $\bar{c} \rightarrow \pi^-K^+X$ [see Fig. 1(b)] where the c quarks have been produced either from the initial virtual-photon or from b-quark decays. The effect is reproduced by both the Lund and Webber models. If heavy quarks are eliminated from the model the LRC changes sign and is quite small.

In conclusion, we have observed both short- and long-range flavor correlations in high-energy e^+e^- annihilation. Short range correlations support the hypothesis that quantum numbers are locally conserved during hadronization.[10] Long-range correlations provide additional evidence that jets are produced by flavor-carrying particles (quarks).

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