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QCD Studies at SLD: Identified Hadron Production in Jets of Different Flavors*

M. Kalelkar
Rutgers University, Piscataway, NJ 08855

Representing The SLD Collaboration**
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

Abstract

We have measured the differential cross sections for the production of $\pi^{\pm}$, K$^{\pm}$, K^{0}, K*(892), ϕ(1020), p and Λ in hadronic Z^0 decays and in subsets 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. Charged hadrons were identified with the SLD Cherenkov Ring Imaging Detector. A vertex detector was employed to select flavor-enriched samples, and the polarized electron beam from SLC was used to tag quark and antiquark jets. We observe a flavor dependence in the hadron fragmentation functions. We also 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, i.e. 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 energy 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]. Measurements of the differential cross sections of identified particles in flavor-specific samples would be useful for testing the predictions of such models.

A particularly interesting aspect of hadronization is the question of what happens to the quark or antiquark that initiated a jet. Many models assume that the initial quark is contained as a valence constituent of a particular hadron, and that this "leading" hadron has on average a higher momentum than the other particles in the jet. This phenomenon has not been studied in great detail, because it is difficult to identify the sign and flavor of the initial $q/\bar{q}$ on a jet-by-jet basis.

In this paper we report a measurement of the differential cross sections for the production of $\pi^{\pm}$, $\mathrm{K}^{\pm}$, K^0, $\mathrm{K}^*(892)$, $\phi(1020)$, p and Λ in hadronic Z^0 decays, and the first study of leading particle production in light-flavor jets in e^+e^- annihilation. 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 were used in the analysis.

A description of the SLD detector, trigger, track and hadronic event selection, and Monte Carlo simulation is given in Ref. [3]. Cuts were applied in order to select events well-contained within the detector acceptance, resulting in a sample of approximately 90,000 events.

2 Particle Identification

The identification of $\pi^{\pm}$, $\mathrm{K}^{\pm}$, p, and $\bar{\mathrm{p}}$ 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) [4]. In each momentum bin, identified π, K, and p were counted, and these were unfolded using the inverse of an identification efficiency matrix [5], 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 $K^0_S \to \pi^+\pi^-$, $\Lambda \to \mathrm{p}\pi^-$ and $\bar{\Lambda} \to \bar{\mathrm{p}}\pi^+$ 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 [6] 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 [7]. Candidate $\phi(1020) \to K^+K^-$ 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 $\phi(1020)$ 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 $\pi^{\pm}$, $\mathrm{K}^{\pm}$, K^0, $\mathrm{K}^*(892)$, $\phi(1020)$, p and Λ 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 [8] 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 per hadronic event of the seven hadron species as a function of scaled momentum x_p. At low x_p pions are seen to dominate the particles produced in hadronic Z^0 decays. At $x_p \approx 0.03$, pseudoscalar kaons are produced at a rate about ten times lower, vector kaons are suppressed by a factor of 40, and the vector ϕ by a factor of 500. The most commonly produced baryons (protons) are suppressed by a factor of 25, and the strange baryon Λ^0 by a factor of 75. At high x_p, the pion and kaon rates appear to be converging, as do the proton and Λ rates. This convergence could indicate reduced strangeness suppression at high momentum, or that production is becoming dominated by leading particles, such that kaons from $s\bar{s}$ events are as common as pions from $u\bar{u}$ or $d\bar{d}$.

Ratios of rates for various pairs of particles in the light-flavor sample are shown in Fig. 2. The ratios of all the strange mesons to pions are well described over the entire range of x_p by power laws that steepen with increasing strange meson mass. The K^0:$K^{\pm}$ ratio differs significantly from unity, and is not accounted for by our measured ϕ rate. Nor are heavy quark decays an explanation, because this is a light-flavor sample. The K^{*0}:K^0, ϕ:K^{*0}, and Λ^0:K ratios are roughly constant over the entire range. The figure also shows the predictions of the JETSET 7.4 model with default parameters, which qualitatively reproduce the momentum dependence of the ratios, but exhibit a normalization difference.

In Fig. 3 we show the ratios of production in b-flavor to light-flavor events for seven particle species. There is higher production of charged pions in b-flavor events at low momentum, with an approximately constant ratio for $0.02 < x_p < 0.07$. The production of both charged and neutral kaons is approximately equal in the two samples at $x_p = 0.02$, but the relative production in b-flavor events then increases with x_p, peaking at $x_p \approx 0.07$. There is approximately equal production of baryons in b-flavor and light-flavor events below $x_p = 0.15$.

For $x_p > 0.10$, production of all particle types falls faster with increasing momentum in b-flavor events. These features are consistent with expectations based on the known properties of $Z^0 \rightarrow b\bar{b}$ 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. 3 are the predictions of JETSET and HERWIG, which reproduce all the features qualitatively, although HERWIG overestimates the pion and kaon ratios by a large factor at low x_p.

In Fig. 4 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. The pion $c : uds$ ratio starts to cut off at a higher value, $x_p \approx 0.3$, than the corresponding $b : uds$ ratio, attributable to the lower average decay multiplicity of D than B hadrons. Also shown in Fig. 4 are the predictions of the two fragmentation models, both of which are consistent with the qualitative features of the data, although HERWIG overestimates the pion ratio at low x_p, as it did for the $b : uds$ ratio.

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 $e^+e^- \to Z^0 \to q\bar{q}$, where $q = u, d$, or s. 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. [9]. We then measured the production rates per light quark jet

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

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

where: q and $\bar{q}$ represent light-flavor quark and antiquark 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 antiparticle. Then, for example, $N(q \to h)$ is the number of hadrons of type h in light quark jets. In every x_p bin, each measured R_h^q and $R_{\bar{h}}^q$ was 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 antiparticle 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 Figure 5, 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.

Since baryons contain no constituent antiquarks, 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 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 Fig. 5. 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 [10] 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 $\gamma_s = 0.26 \pm 0.12$, consistent with values [11] derived from inclusive measurements of the relative production rates of strange and non-strange, pseudoscalar and vector mesons.

5 Conclusions

We have measured the differential cross sections for the production of $\pi^\pm$, $\mathrm{K}^\pm$, K^0, $\mathrm{K}^*(892)$, $\phi(1020)$, p and Λ separately in light-flavor, $c\bar{c}$ and $b\bar{b}$ jets from Z^0 decays. We find the predictions of the JETSET and HERWIG fragmentation models to be in qualitative agreement with our data, but to fail in detail. We find substantial differences in particle production between light- and heavy-flavor events, with the latter producing more mesons overall, but far fewer at high momentum, as expected because of the hard fragmentation and high average decay multiplicity of heavy-flavor hadrons.

By isolating high-purity light-quark and light-antiquark jets, we have made the first comparison of the production of hadrons and their corresponding antihadrons in light-quark jets. Substantial differences are observed for baryons at high momentum, giving direct evidence for leading baryon production. Differences are also observed for vector and pseudoscalar kaons at high momentum, indicating both leading kaon production and strangeness suppression in leading particle production.

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**List of Authors

K. Abe,[19] K. Abe,[30] T. Akagi,[28] N.J. Allen,[4] W.W. Ash,[28]† D. Aston,[28] K.G. Baird,[24] C. Baltay,[34] H.R. Band,[33] M.B. Barakat,[34] G. Baranko,[9] O. Bardon,[15] T. L. Barklow,[28] G.L. Bashindzhagyan,[18] A.O. Bazarko,[10] R. Ben-David,[34] A.C. Benvenuti,[2] G.M. Bilei,[22] D. Bisello,[21] G. Blaylock,[16] J.R. Bogart,[28] B. Bolen,[17] T. Bolton,[10] G.R. Bower,[28] J.E. Brau,[20] M. Breidenbach,[28] W.M. Bugg,[29] D. Burke,[28] T.H. Burnett,[32] P.N. Burrows,[15] W. Busza,[15] A. Calcaterra,[12] D.O. Caldwell,[5] D. Calloway,[28] B. Camanzi,[11] M. Carpinelli,[23] R. Cassell,[28] R. Castaldi,[23][a] A. Castro,[21] M. Cavalli-Sforza,[6] A. Chou,[28] E. Church,[32] H.O. Cohn,[29] J.A. Coller,[3] V. Cook,[32] R. Cotton,[4] R.F. Cowan,[15] D.G. Coyne,[6] G. Crawford,[28] A. D'Oliveira,[7] C.J.S. Damerell,[25] M. Daoudi,[28] N. de Groot,[28] R. De Sangro,[12] R. Dell'Orso,[23] P.J. Dervan,[4] M. Dima,[8] D.N. Dong,[15] P.Y.C. Du,[29] R. Dubois,[28] B.I. Eisenstein,[13] R. Elia,[28] E. Etzion,[33] S. Fahey,[9] D. Falciai,[22] C. Fan,[9] J.P. Fernandez,[6] M.J. Fero,[15] R. Frey,[20] T. Gillman,[25] G. Gladding,[13] S. Gonzalez,[15] E.L. Hart,[29] J.L. Harton,[8] A. Hasan,[4] Y. Hasegawa,[30] K. Hasuko,[30] S. J. Hedges,[3] S.S. Hertzbach,[16] M.D. Hildreth,[28] J. Huber,[20] M.E. Huffer,[28] E.W. Hughes,[28] H. Hwang,[20] Y. Iwasaki,[30] D.J. Jackson,[25] P. Jacques,[24] J. A. Jaros,[28] Z. Y. Jiang,[28] A.S. Johnson,[3] J.R. Johnson,[33] R.A. Johnson,[7] T. Junk,[28] R. Kajikawa,[19] M. Kalelkar,[24] H. J. Kang,[26] I. Karliner,[13] H. Kawahara,[28] H.W. Kendall,[15] Y. D. Kim,[26] M.E. King,[28] R. King,[28] R.R. Kofler,[16] N.M. Krishna,[9] R.S. Kroeger,[17] J.F. Labs,[28] M. Langston,[20] A. Lath,[15] J.A. Lauber,[9] D.W.G.S. Leith,[28] V. Lia,[15] M.X. Liu,[34] X. Liu,[6] M. Loreti,[21] A. Lu,[5] H.L. Lynch,[28] J. Ma,[32] G. Mancinelli,[24] S. Manly,[34] G. Mantovani,[22] T.W. Markiewicz,[28] T. Maruyama,[28] H. Masuda,[28] E. Mazzucato,[11] A.K. McKemey,[4] B.T. Meadows,[7] R. Messner,[28] P.M. Mockett,[32] K.C. Moffeit,[28] T.B. Moore,[34] D. Muller,[28] T. Nagamine,[28] S. Narita,[30] U. Nauenberg,[9] H. Neal,[28] M. Nussbaum,[7]† Y. Ohnishi,[19] N. Oishi,[19] D. Onoprienko,[29] L.S. Osborne,[15] R.S. Panvini,[31] C.H. Park,[27] H. Park,[20] T.J. Pavel,[28] I. Peruzzi,[12][b] M. Piccolo,[12] L. Piemontese,[11] E. Pieroni,[23] K.T. Pitts,[20] R.J. Plano,[24] R. Prepost,[33] C.Y. Prescott,[28] G.D. Punkar,[28] J. Quigley,[15] B.N. Ratcliff,[28] T.W. Reeves,[31] J. Reidy,[17] P.L. Reinertsen,[6] P.E. Rensing,[28] L.S. Rochester,[28] P.C. Rowson,[10] J.J. Russell,[28] O.H. Saxton,[28] T. Schalk,[6] R.H. Schindler,[28] B.A. Schumm,[6] J. Schwiening,[28] S. Sen,[34] V.V. Serbo,[33] M.H. Shaevitz,[10] J.T. Shank,[3] G. Shapiro,[14] D.J. Sherden,[28] K.D. Shmakov,[29] C. Simopoulos,[28] N.B. Sinev,[20] S.R. Smith,[28] M.B. Smy,[8] J.A. Snyder,[34] H. Staengle,[8] P. Stamer,[24] H. Steiner,[14] R. Steiner,[1] M.G. Strauss,[16] D. Su,[28] F. Suekane,[30] A. Sugiyama,[19] S. Suzuki,[19] M. Swartz,[28] A. Szumilo,[32] T. Takahashi,[28] F.E. Taylor,[15] E. Torrence,[15] A.I. Trandafir,[16] J.D. Turk,[34] T. Usher,[28] J. Va'vra,[28] C. Vannini,[23] E. Vella,[28] J.P. Venuti,[31] R. Verdier,[15] P.G. Verdini,[23] D.L. Wagner,[9] S.R. Wagner,[28] A.P. Waite,[28] S.J. Watts,[4] A.W. Weidemann,[29] E.R. Weiss,[32] J.S. Whitaker,[3] S.L. White,[29] F.J. Wickens,[25] D.C. Williams,[15] S.H. Williams,[28] S. Willocq,[28]

R.J. Wilson,[8] W.J. Wisniewski,[28] M. Woods,[28] G.B. Word,[24] J. Wyss,[21]
R.K. Yamamoto,[15] J.M. Yamartino,[15] X. Yang,[20] J. Yashima,[30] S.J. Yellin,[5]
C.C. Young,[28] H. Yuta,[30] G. Zapalac,[33] R.W. Zdarko,[28] and J. Zhou[20]

[1]*Adelphi University, Garden City, New York 11530*
[2]*INFN Sezione di Bologna, I-40126 Bologna, Italy*
[3]*Boston University, Boston, Massachusetts 02215*
[4]*Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom*
[5]*University of California at Santa Barbara, Santa Barbara, California 93106*
[6]*University of California at Santa Cruz, Santa Cruz, California 95064*
[7]*University of Cincinnati, Cincinnati, Ohio 45221*
[8]*Colorado State University, Fort Collins, Colorado 80523*
[9]*University of Colorado, Boulder, Colorado 80309*
[10]*Columbia University, New York, New York 10027*
[11]*INFN Sezione di Ferrara and Università di Ferrara, I-44100 Ferrara, Italy*
[12]*INFN Lab. Nazionali di Frascati, I-00044 Frascati, Italy*
[13]*University of Illinois, Urbana, Illinois 61801*
[14]*E.O. Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720*
[15]*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*
[16]*University of Massachusetts, Amherst, Massachusetts 01003*
[17]*University of Mississippi, University, Mississippi 38677*
[18]*Moscow State University, Institute of Nuclear Physics 119899 Moscow, Russia*
[19]*Nagoya University, Chikusa-ku, Nagoya 464 Japan*
[20]*University of Oregon, Eugene, Oregon 97403*
[21]*INFN Sezione di Padova and Università di Padova, I-35100 Padova, Italy*
[22]*INFN Sezione di Perugia and Università di Perugia, I-06100 Perugia, Italy*
[23]*INFN Sezione di Pisa and Università di Pisa, I-56100 Pisa, Italy*
[24]*Rutgers University, Piscataway, New Jersey 08855*
[25]*Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX United Kingdom*
[26]*Sogang University, Seoul, Korea*
[27]*Soongsil University, Seoul, Korea 156-743*
[28]*Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309*
[29]*University of Tennessee, Knoxville, Tennessee 37996*
[30]*Tohoku University, Sendai 980 Japan*
[31]*Vanderbilt University, Nashville, Tennessee 37235*
[32]*University of Washington, Seattle, Washington 98195*
[33]*University of Wisconsin, Madison, Wisconsin 53706*
[34]*Yale University, New Haven, Connecticut 06511*
†*Deceased*
[a]*Also at the Università di Genova*
[b]*Also at the Università di Perugia*

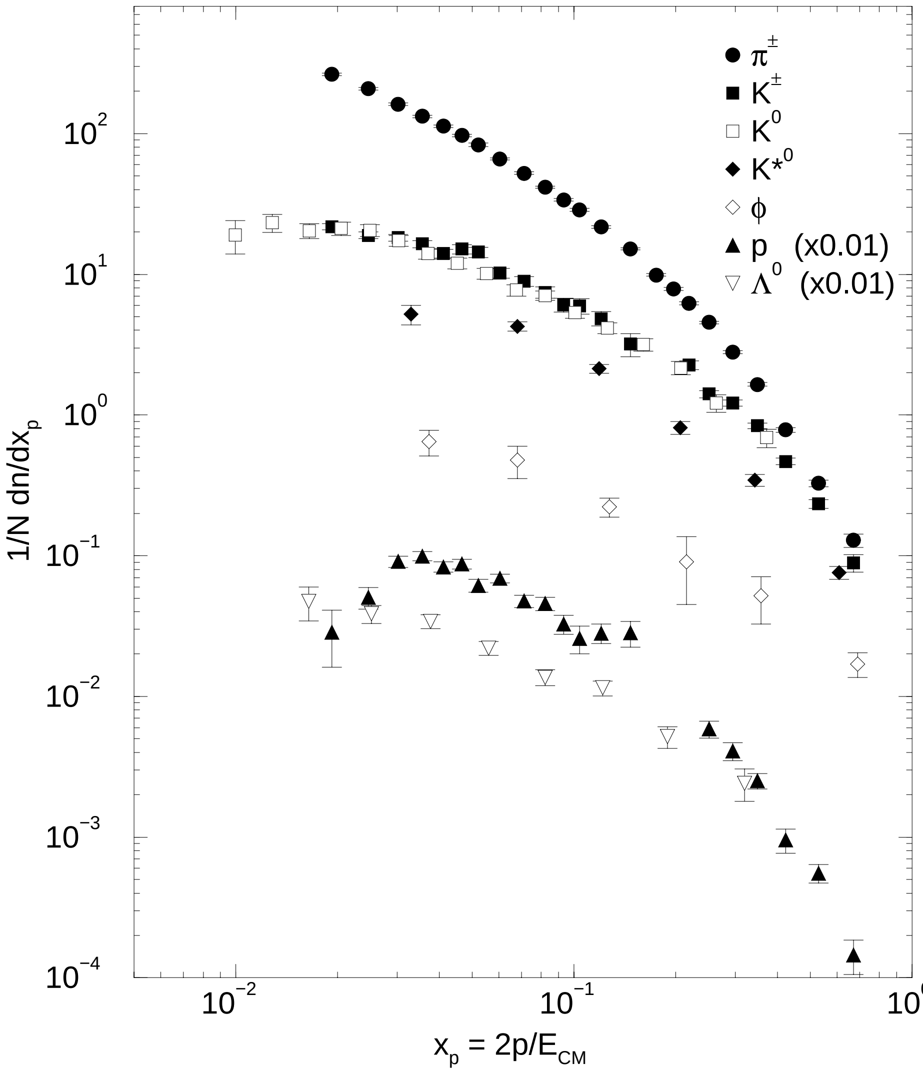

Figure 1: Differential cross sections for the production of identified hadrons in the light-flavor sample, as a function of scaled momentum.

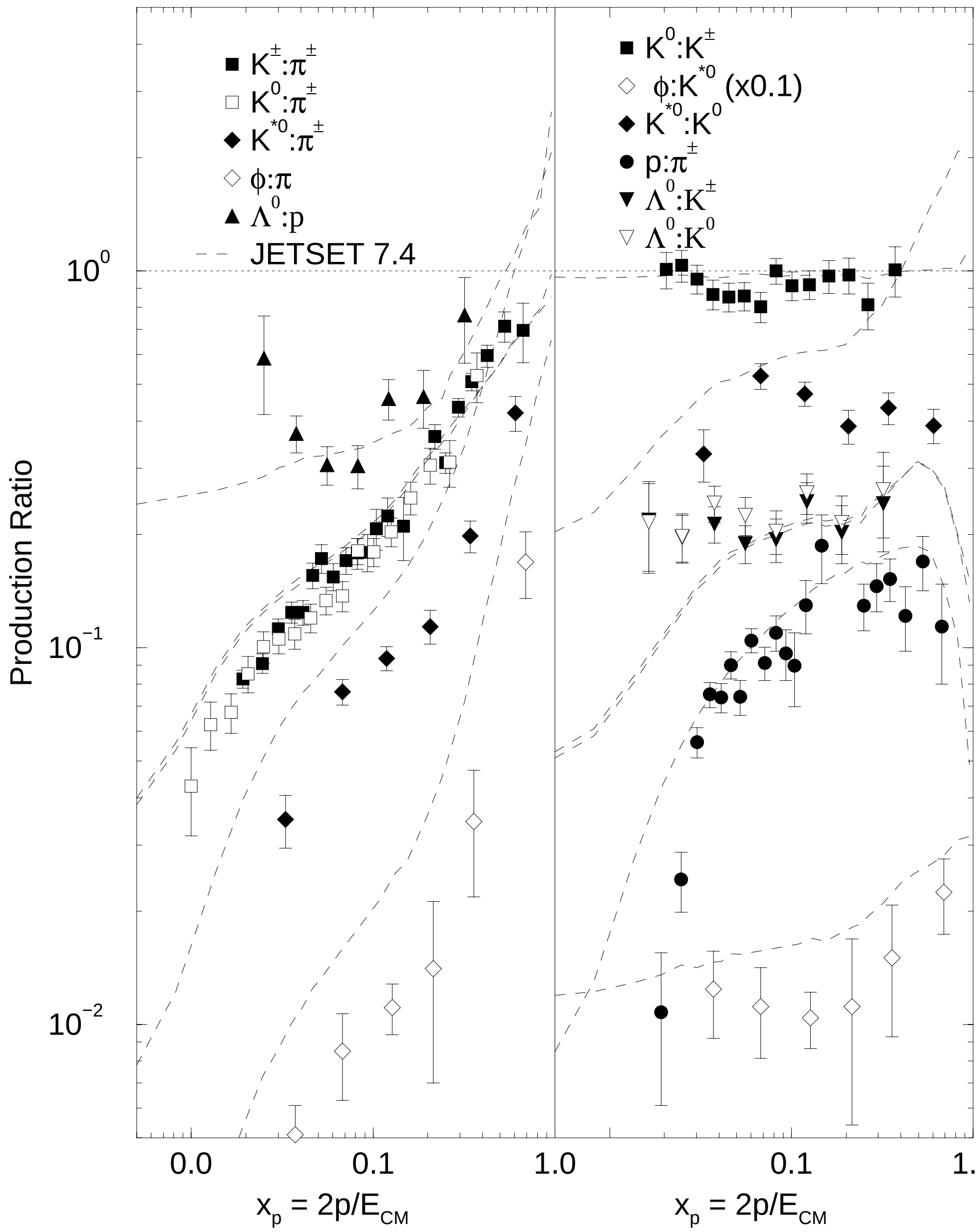

Figure 2: Ratios of production rates for various pairs of particles in the light-flavor sample. The curves represent the predictions of the JETSET model with default parameters.

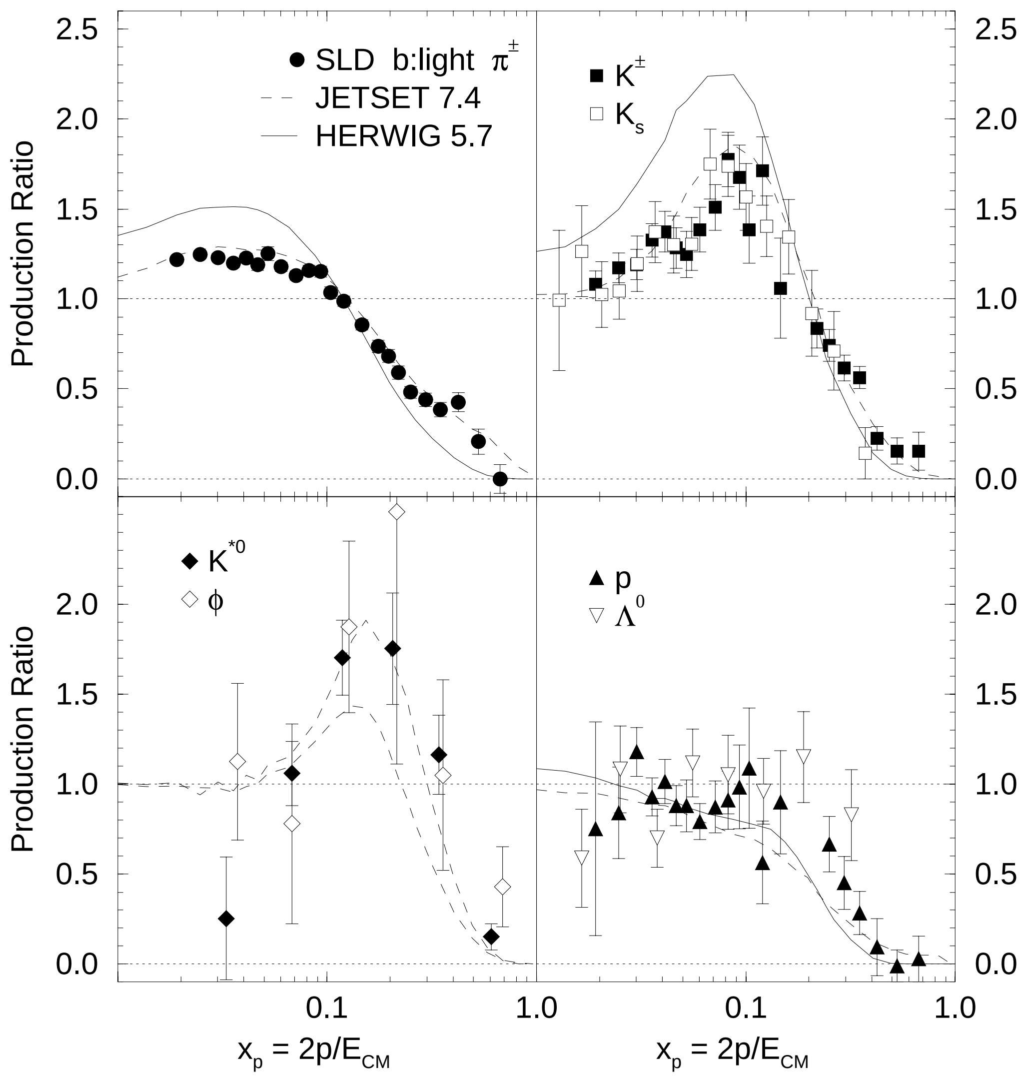

Figure 3: Ratios of production rates in b-flavor events to those in light-flavor events.

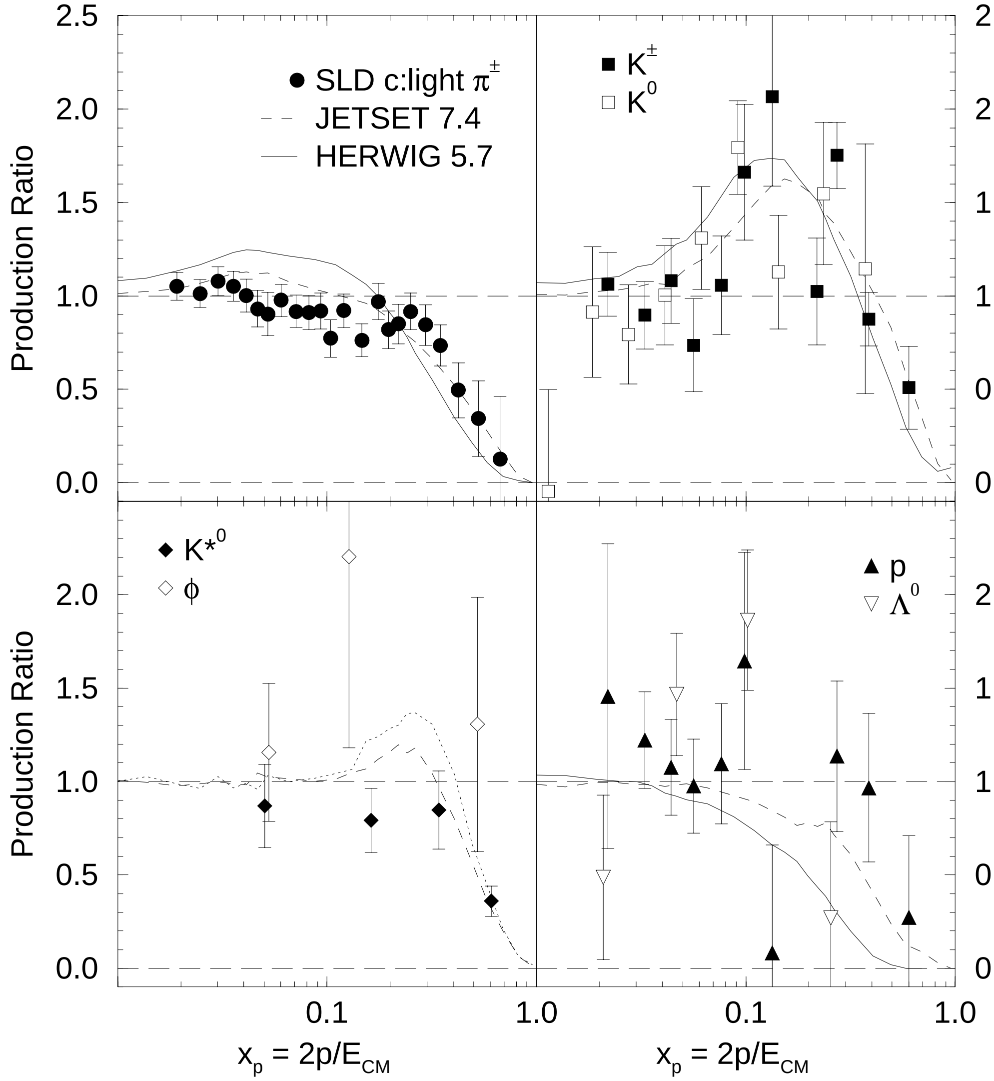

Figure 4: Ratios of production rates in c-flavor events to those in light-flavor events.

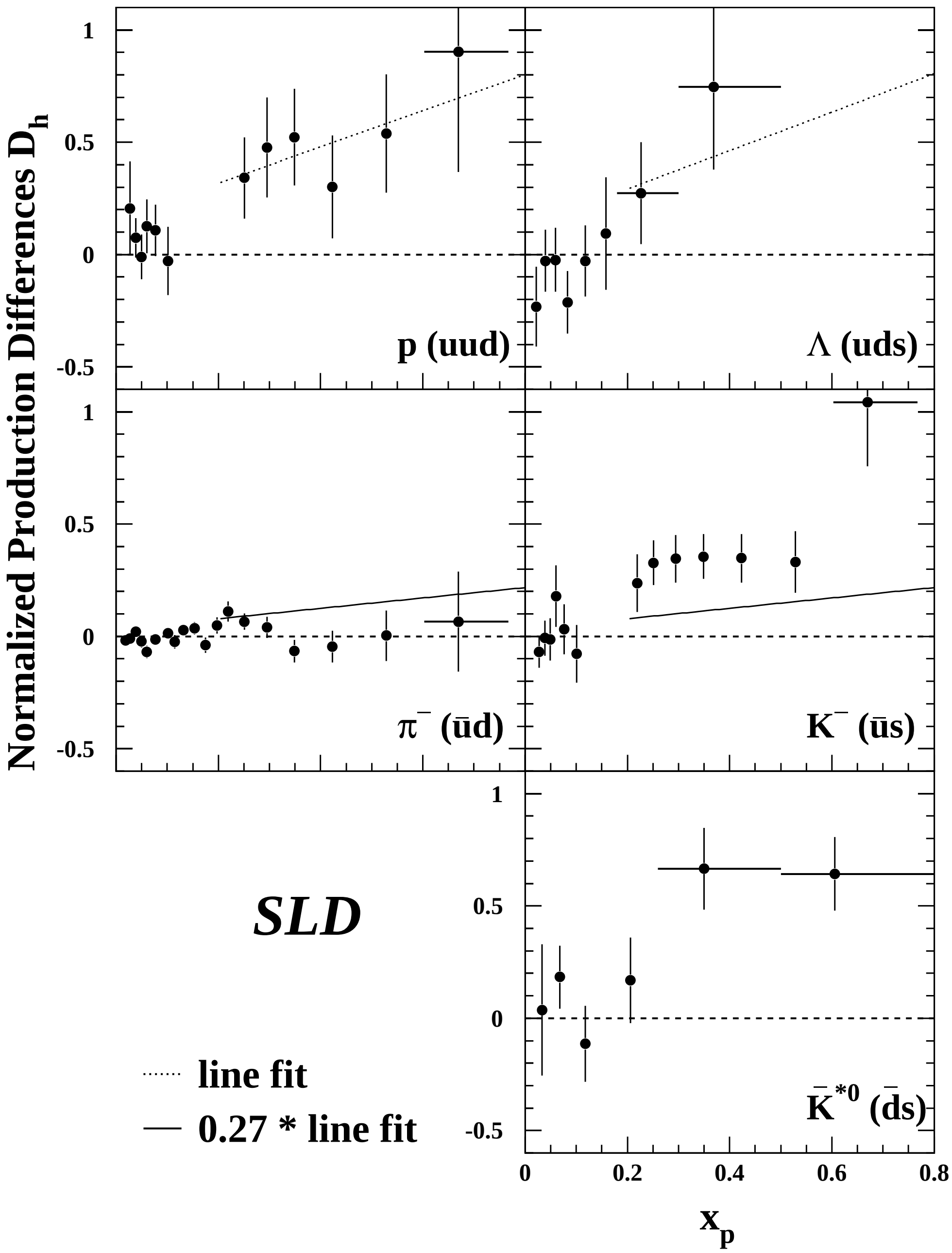

Figure 5: Normalized production differences between light quark and antiquark jets (dots) as a function of scaled momentum. The dotted lines represent a linear fit to the D_p and D_Λ points for $x_p > 0.2$, and the solid lines are this fit scaled by the factor 0.27 discussed in the text.