Charged Hadron Production in e^+e^- Annihilation at 29 GeV

H. Aihara, M. Alston-Garnjost, D. H. Badke, J. A. Bakken, A. Barbaro-Galtieri, A. V. Barnes, B. A. Barnett, B. J. Blumenfeld, A. D. Bross, C. D. Buchanan, O. Chamberlain, C. Chen, J. Chiba, C.-Y. Chien, A. R. Clark, O. I. Dahl, C. T. Day, P. Delpierre, K. A. Derby, P. H. Eberhard, D. L. Fancher, H. Fujii, T. Fujii, B. Gabioud, J. W. Gary, W. Gorn, W. Gu, N. J. Hadley, J. M. Hauptman, H. J. Hilke, W. Hofmann, J. E. Huth, J. Hylen, H. Iwasaki, T. Kamae, R. W. Kenney, L. T. Kerth, R. I. Koda, R. R. Kofler, K. K. Kwong, J. G. Layter, C. S. Lindsey, S. C. Loken, G. W. London, X.-Q. Lu, G. R. Lynch, L. Madansky, R. J. Madaras, R. Majka, J. Mallet, P. S. Martin, K. Maruyama, J. N. Marx, J. A. Matthews, S. O. Melnikoff, W. Moses, P. Nemethy, D. R. Nygren, P. J. Oddone, D. A. Park, A. Pevsner, M. Pripstein, P. R. Robrish, M. T. Ronan, R. R. Ross, F. R. Rouse, R. R. Sauerwein, G. Shapiro, M. D. Shapiro, B. C. Shen, W. E. Slater, M. L. Stevenson, D. H. Stork, H. K. Ticho, N. Toge, M. Urban, R. F. van Daalen Wetters, G. J. VanDalen, R. van Tyen, H. Videau, M. R. Wayne, W. A. Wenzel, H. A. Yamamoto, M. Yamauchi, M. E. Zeller, and W.-M. Zhang

Lawrence Berkeley Laboratory, Berkeley, California 94720, and University of California, Los Angeles, California 90024, and University of California, Riverside, California 92521, and Johns Hopkins University, Baltimore, Maryland 21218, and University of Massachusetts, Amherst, Massachusetts 01003, and University of Tokyo, Tokyo, Japan, and Yale University, New Haven, Connecticut 06520

(Received 28 December 1983)

The inclusive production cross sections and mean multiplicities of $\pi^\pm$, $K^\pm$, p, and $\bar{p}$ in e^+e^- annihilation at a c.m. energy of 29 GeV have been measured with the time-projection chamber at PEP, using ionization energy loss to separate particle types. On average, $10.7 \pm 0.6\ \pi^\pm$, $1.35 \pm 0.13\ K^\pm$, and $0.60 \pm 0.08\ p, \bar{p}$ are contained in an annihilation event. The fraction of pions among final-state particles decreases from over 95% at 0.3 GeV/c momentum to about 60% at high momentum; the kaon and proton fractions rise correspondingly.

PACS numbers: 13.65.+i

Understanding the fragmentation process of quarks and gluons into hadrons requires a knowledge of the production cross sections of charged pions, kaons, and protons in e^+e^- annihilation at high energy. We have measured these cross sections at 29 GeV e^+e^- center-of-mass energy at PEP. The particles were identified by ionization energy loss (dE/dx) over the entire momentum range and over almost the entire solid angle with use of the time-projection chamber (TPC). This results in smaller systematic and statistical errors than previous measurements that used dE/dx at low momentum only,[1] or a combination of different methods such as time of flight or Cherenkov counters with limited acceptance.[2]

The subsystems of the TPC facility include the TPC in a 4-kG magnetic field, drift chambers, electromagnetic calorimeters, and muon detection chambers.[3] In the present analysis, only the information from the tracking of charged particles in the TPC is used. For each track up to fifteen space points are measured with a typical accuracy of 190 μm in the bending plane and 350 μm in z, the beam direction. The momentum resolution typically is $(dp/p)^2 = (0.06)^2 + (0.035p)^2$.

Particles are identified by simultaneous measurement of momentum and ionization energy loss (dE/dx). After a track passes through the TPC its ionization electrons drift axially to the nearest end cap, where they are detected in multiwire proportional chambers (sectors). As many as 183 dE/dx samples per track are obtained from the pulse heights. They are corrected for track length seen by the wire, wire gain, electronic gain, and electron capture along the drift path. The gain calibration is obtained *in situ* at three positions along each wire with ^{55}Fe sources. A gain map is used to interpolate between points. The pulse heights are also corrected for gain variations due to changes in gas density and purity, which are monitored by use of minimum-ionizing pions. The ionization energy loss has a broad spectrum with a long high-energy (Landau) tail. Many samples, therefore, are needed to define an effective dE/dx. In practice we define dE/dx for each track to be the mean of the smallest 65% of the individual samples. For this study, each track is required to have at least 80 dE/dx samples. This condition is met by 65% of the tracks, because of information loss at small polar angles and the requirement that a given dE/dx sample be separated by at least 3 cm in the z direction from ionization produced by an adjacent track in the same TPC sector.

Figure 1 shows the distribution of dE/dx versus momentum for tracks in multihadron events. In the low-momentum region, the pion, kaon, and proton bands are well separated; above 1 GeV/c the dE/dx resolution, 3.7%, is comparable to the differences in dE/dx for the various particle types. At 5 GeV/c, e.g., the separation is 3.8 standard deviations for pion-kaon, and 1.9 standard deviations for kaon-proton. Most of the particles in the horizontal electron band in Fig. 1 result from photon conversions in the material before the TPC.

The data used in this analysis correspond to an integrated luminosity of approximately 60 pb^{-1}. For the selection of annihilation events and subsequent analysis, charged tracks with momenta greater than 150 MeV/c are accepted if the extrapolated orbit passes the nominal interaction point within 10 cm in the beam direction and within 6 cm in the plane perpendicular to the beams. An event candidate must have at least five good charged tracks, not including electrons which are identified either by dE/dx or by geometrical reconstruction of the pairs from photon conversions. In order to eliminate two-photon and beam-gas events, the total energy E_{ch} of the charged particles (including electrons) must exceed one-half the beam energy, and the sum of the momentum components along the beam direction must be less than 40% of E_{ch}/c. Three-prong tau decays are removed by requiring that at least one jet in the event has either invariant mass above 2 GeV or more than three nonelectron tracks.

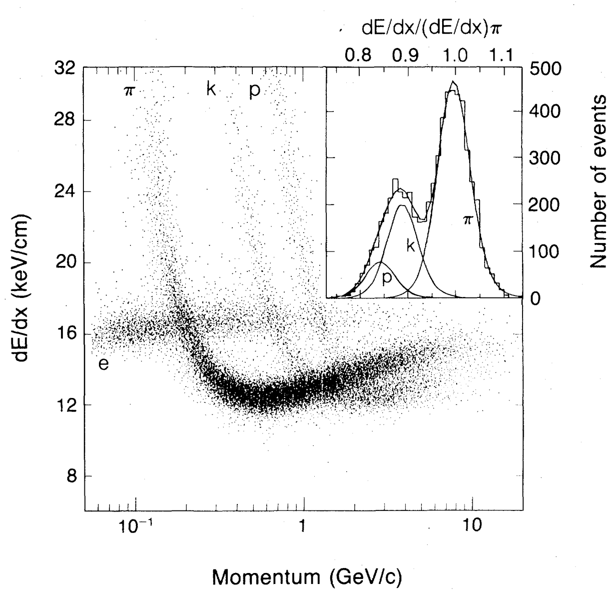

FIG. 1. dE/dx vs momentum for tracks in a sample of hadronic events. The inset shows the distribution of the ratio of measured dE/dx to the expected dE/dx for pions for momenta between 3.5 and 6 GeV/c after electron subtraction. The solid lines represent the contributions of pions, kaons, and protons.

In the 22 300 events passing these cuts, backgrounds are estimated to be $(0.3 \pm 0.1)\%$ from $\tau\bar{\tau}$ events, $(0.8 \pm 0.6)\%$ from two-photon events, and less than 0.1% from beam-gas events and Bhabha scattering. The event acceptance is 77% before radiative corrections.

For the measurement of inclusive cross sections in the low-momentum region, the raw numbers of pions, kaons, and protons are obtained by counting tracks in the bands corresponding to the particle types (see Fig. 1). In regions of ambiguity with electrons, the electron contamination is estimated by use of a smooth fit to the electron density outside the ambiguous region.

In the momentum regions close to and above minimum ionization, a maximum-likelihood fit to the electron-subtracted dE/dx distribution is used. For a given momentum interval, we fit with a sum of three distributions (pions, kaons, and protons) whose relative peak positions and shapes are fixed (see inset in Fig. 1). As input to this fit, we use the velocity dependence of the average dE/dx as determined with an error of less than $\pm 0.3\%$ from independent measurements of cosmic-ray muons and conversion and Bhabha electrons. From the same data the shape of the dE/dx distribution at a given velocity is parametrized. For the particle fractions, we estimate a systematic error of ± 0.017 from the uncertainty in the average dE/dx and ± 0.008 from the uncertainty in the behavior of the dE/dx resolution as a function of velocity. Statistical errors on the cross sections include the effect of the correlation between the variables of the fit.

After corrections for the different nuclear in-

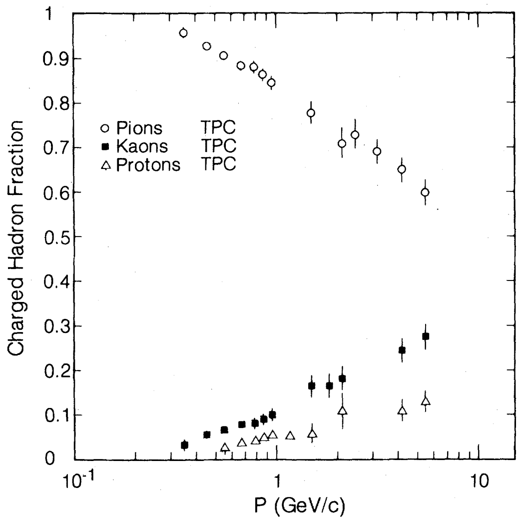

FIG. 2. Particle fractions vs momentum for pions, kaons, and protons. For the lowest two momentum points the proton fraction was assumed to be 1%.

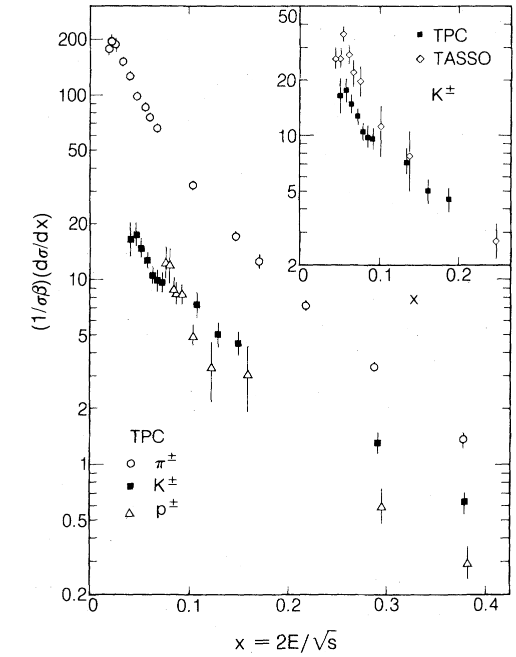

FIG. 3. Differential cross section vs $x = 2E_{\text{hadron}}/\sqrt{s}$, for pions, kaons, and protons. The inset shows the kaon distribution for this experiment and TASSO (Ref. 2).

teraction probabilities in the material before the TPC, the positive-to-negative charge ratios for pions and kaons are statistically consistent with unity. For momenta less than 2 GeV/c the number of protons is greater than the number of antiprotons because of secondary protons from nuclear interactions. In this region we have used twice the observed number of antiprotons to represent the number of p's plus $\bar{p}$'s.

The number of hadrons observed in each momentum bin is corrected for geometrical acceptance, efficiency of the track selection cuts, decay loss of charged pions and kaons, contamination of the pion sample by direct muons, nuclear interactions and energy loss in the material before the TPC, effects of finite momentum resolution, and finally the effects of event selection and initial-state radiation.[4] The detection efficiencies are evaluated with use of a Monte Carlo simulation of the detector, and an analysis procedure identical to that used for the data. Typical efficiencies are about 45%, and are dominated by the geometrical acceptance (85%) and the requirement of at least 80 usable dE/dx samples (65%). The effect of the latter cut can be derived directly from the data, yielding good agreement with the Monte Carlo method. The efficiencies show little variation with momentum and particle type, and are insensitive to details of the event generator for a wide range of parameters. Within the quoted uncertainties the results are also insensitive to different cuts in event selection and track definition.

All results reported here on inclusive cross sections are normalized to the total annihilation cross section into hadrons. The normalized cross section corresponds to the fragmentation function.[5] The measured hadron ratios and cross sections, which include decay products of particles with lifetimes less than 5×10^{-10} sec, are given in Table I. Figure 2 shows the fraction of pions, kaons, and protons among charged hadrons as a function of their momenta. The normalized production cross sections $(1/\sigma\beta)(d\sigma/dx)$ for pions, kaons, and protons are shown in Fig. 3. The error bars given are dominated by systematic errors, which include the effect of the limited momentum resolution. The latter is calculated with the assumption that the inclusive spectra are smooth functions of momentum. Without this assumption, the errors would increase by roughly 50%.

Within errors, the proton fractions and inclusive cross sections agree with earlier measurements from TASSO.[2] The kaon fractions and cross sections below 1 GeV/c are significantly lower than the TASSO data; at higher momenta the two experiments agree (see inset in Fig. 3). The inclusive pion cross sections agree within errors although the TPC data tend to be some-

TABLE I. Charged hadron fractions and normalized cross sections. Here $x = E/E_{\text{beam}}$ and β is the velocity of the particle.

		$e^+e^- \to \pi^\pm + X$			$e^+e^- \to k^\pm + X$			$e^+e^- \to p^\pm + X$		
p (GeV/c)	<p> (GeV/c)	Fraction (%)	<x>	$\frac{1}{\sigma\beta}\frac{d\sigma}{dx}$	Fraction (%)	<x>	$\frac{1}{\sigma\beta}\frac{d\sigma}{dx}$	Fraction (%)	<x>	$\frac{1}{\sigma\beta}\frac{d\sigma}{dx}$
0.20–0.25	0.23	–	0.018	176.±11.	–	–	–	–	–	–
0.25–0.30	0.27	–	0.021	192.±14.	–	–	–	–	–	–
0.30–0.41	0.35	95.7±1.2	0.026	181.±13.	3.3±1.2	0.042	16.2±3.0	–	–	–
0.41–0.50	0.45	93.0±0.8	0.032	147.± 7.	5.5±0.9	0.046	17.5±2.6	–	–	–
0.50–0.61	0.55	91.0±0.6	0.039	122.± 5.	6.5±0.6	0.051	14.7±1.2	2.5±0.5	0.075	12.4±2.4
0.61–0.74	0.67	88.3±1.0	0.047	97.4±4.2	7.8±0.6	0.057	12.7±0.9	3.9±0.8	0.080	12.1±2.6
0.74–0.82	0.78	88.0±1.3	0.055	84.1±4.0	8.1±1.2	0.064	10.5±1.5	3.9±0.5	0.084	9.0±1.2
0.82–0.90	0.86	86.4±1.4	0.060	73.1±3.5	9.0±1.3	0.068	9.8±1.4	4.6±0.6	0.088	8.4±1.1
0.90–1.00	0.95	84.5±1.6	0.066	65.5±3.2	10.0±1.4	0.074	9.6±1.4	5.5±0.7	0.092	8.3±1.0
1.00–1.35	1.18	–	–	–	–	–	–	5.3±0.7	0.103	5.0±0.6
1.35–1.65	1.50	77.7±2.5	0.103	31.7±1.7	16.3±2.4	0.108	7.3±1.1	5.9±2.1	0.122	3.4±1.2
1.65–2.01	1.83	–	–	–	16.5±2.7	0.130	5.0±0.7	–	–	–
2.01–2.23	2.12	71.0±3.4	0.146	16.8±1.0	18.2±2.6	0.150	4.5±0.7	10.8±3.8	0.160	3.1±1.2
2.23–2.72	2.46	73.0±3.3	0.170	12.4±0.7	–	–	–	–	–	–
2.72–3.67	3.16	69.1±2.7	0.218	7.14±.41	–	–	–	–	–	–
3.67–4.95	4.18	64.8±2.7	0.288	3.40±.21	24.3±2.7	0.290	1.29±.15	10.9±2.3	0.295	0.60±.13
4.95–6.69	5.47	59.7±2.9	0.378	1.36±.09	27.4±2.8	0.379	0.63±.07	12.9±2.4	0.383	0.30±.06

what higher. The mean hadron multiplicity has been determined with use of a fit to the production cross section by a sum of exponentials to extrapolate to momentum regions where no measurements are available. On the average an event contains $10.7 \pm 0.6\ \pi^\pm$, $1.35 \pm 0.13\ K^\pm$, and $0.60 \pm 0.08\ p, \bar{p}$. The quoted uncertainties include systematic errors.

We would like to thank the PEP staff and the Lawrence Berkeley Laboratory engineers, programmers, and technicians who made these results possible. This work was supported by the U. S. Department of Energy under Contracts No. DE-AC03-76SF00098 and No. DE-AM03-76SF-00034, the National Science Foundation, and the Joint Japan–U. S. Collaboration in High Energy Physics.

[1]W. Bartel *et al.*, Phys. Lett. 104B, 325 (1981).

[2]M. Althoff *et al.*, Z. Phys. C 17, 5 (1983).

[3]H. Aihara *et al.* (TPC), IEEE Trans. Nucl. Sci. 30, 63, 67, 76, 117, 153 (1983). Also N. J. Hadley, Lawrence Berkeley Laboratory Report No. LBL-16116, 1983 (unpublished).

[4]F. A. Berends and R. Kleiss, Nucl. Phys. B178, 141 (1981).

[5]S. D. Drell, D. J. Levy, and T. M. Yan, Phys. Rev. D 1, 1617 (1970).