Characteristics of Proton Production in Jets from e^+e^- Annihilation at 29 GeV

H. Aihara, M. Alston-Garnjost, D. H. Badtke, J. A. Bakken, A. Barbaro-Galtieri, A. V. Barnes, B. A. Barnett, B. J. Blumenfeld, A. D. Bross, C. D. Buchanan, O. Chamberlain, J. Chiba, C.-Y. Chien, A. R. Clark, A. Cordier, O. I. Dahl, C. T. Day, K. A. Derby, P. H. Eberhard, D. L. Fancher, H. Fujii, T. Fujii, B. Gabioud, J. W. Gary, W. Gorn, 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, X.-Q. Lu, G. R. Lynch, L. Madansky, R. J. Madaras, R. M. Majka, P. S. Martin, K. Maruyama, J. N. Marx, J. A. J. 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, R. F. van Daalen Wetters, G. J. VanDalen, R. van Tyen, H. Videau, M. R. Wayne, W. A. Wenzel, H. Yamamoto, M. Yamauchi, and W.-M. Zhang

Lawrence Berkeley Laboratory and University of California, 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

(Received 30 April 1984)

Proton production in e^+e^- annihilation at 29 GeV has been studied with the time projection chamber. Measurements of the dependence of proton fractions on momentum, transverse momentum with respect to the jet axis, hadron multiplicity, and event sphericity are reported. Our results are consistent with the assumption that primary baryons and mesons have similar production spectra, and indicate that protons provide more direct probes of underlying fragmentation phenomena than do pions.

PACS numbers: 13.65.+i, 14.20.Dh

Baryon production in quark and gluon fragmentation provides a valuable test of phenomenological models which aim at a description of color confinement. Whereas the creation of mesons (or meson-like "clusters") from quark-antiquark pairs—produced either in "color strings"[1] or in perturbative "parton showers"[2-6]—is a process common to all models, the implementations of baryon production differ significantly. In addition, for light mesons like pions, the information on the basic production mechanism is diluted because of effects of resonance decays. In contrast, baryons experience little momentum degradation in decays (the momentum of a proton from a Δ decay, e.g., will be similar to the momentum of the Δ) and hence will more closely reflect the distribution of primary fragmentation products. Consequently tests of both color string models and models simulating parton showers in QCD are cleaner for heavy hadrons.[1,6,7]

In this Letter, we present experimental data on inclusive proton production in e^+e^- annihilation at $\sqrt{s} = 29$ GeV, based on the analysis of 29 000 annihilation events (corresponding to $\int L\,dt = 77$ pb^{-1}) recorded with the time-projection-chamber (TPC) detector at the storage ring PEP. We compare the data with model predictions to illuminate the points of view outlined above. A subsequent paper will deal with correlation studies involving baryons.

The TPC detector and the criteria for the event classification and track selection have been described previously.[8] Particles are identified with a dE/dx technique based on simultaneous measurement of momentum and energy loss. The dE/dx analysis, the determination of inclusive spectra, and the acceptance corrections have been discussed in an earlier paper.[8] The term "proton fraction," f_p, will be used to describe the fraction of protons and antiprotons among charged hadrons, including decay products of resonances with lifetimes below 5×10^{-10} sec. To avoid contamination due to protons from nuclear interactions in the material in front of the TPC, the proton plus antiproton rate is represented by twice the antiproton rate for mo-

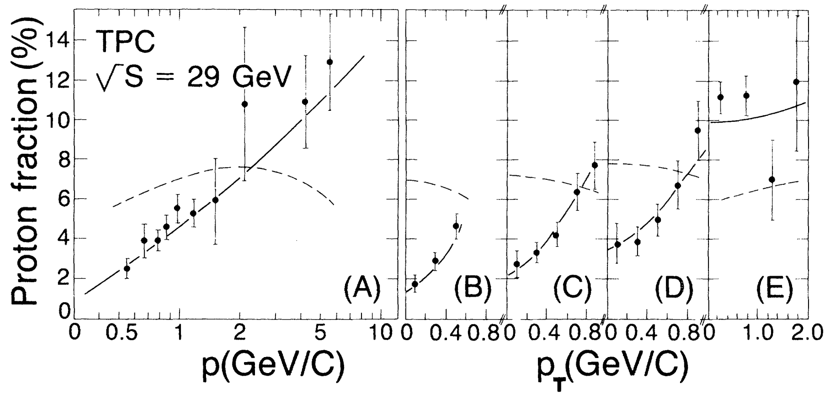

FIG. 1. Fraction f_p of protons and antiprotons among charged hadrons produced in e^+e^- annihilation at $\sqrt{s}=29$ GeV (a) as a function of the momentum p (error bars include systematic uncertainties), and (b)–(e) as a function of transverse momentum p_T with respect to the sphericity axis, for different bins in p: (b) 0.63 to 0.72 GeV/c, (c) 0.83 to 0.95 GeV/c, (d) 1.1 to 1.4 GeV/c, (e) 3.7 to 6.7 GeV/c. There is an additional systematic scale uncertainty of typically $\pm 15\%$ of f_p for each given p. Predictions by the LUND model (Ref. 1) are shown for final stable hadrons (full lines) and for primary hadrons before resonance decays (dashed lines).

menta below 2 GeV/c. All particle fractions quoted here are corrected for detector acceptance and backgrounds.

The proton fraction f_p shows a pronounced dependence on the momentum p as displayed in Fig. 1(a). The dependence of f_p on transverse momentum p_T with respect to the sphericity axis is shown in Figs. 1(b)–1(e) for different ranges of total momentum p. The momentum bins are chosen such that the variation of f_p with p is negligible within a bin. For momenta below 1.5 GeV, a steep increase of f_p with p_T is observed, in agreement with results obtained in deep-inelastic lepton-nucleon scattering.[9] At high momentum, above 3–4 GeV, the p_T dependence flattens out at a high value of f_p.

The high value of f_p at large momentum and the large f_p seen in decays of the Υ meson[10] has stimulated speculations that proton production is related to gluon emission,[11] in which case one expects an increase of f_p with p_T. There exists, however, an alternative explanation for the effects displayed in Fig. 1: If the production of primary baryons and mesons in jets is described by longitudinal phase space, with a constant baryon fraction independent of p and p_T (apart from threshold effects), resonance decays could result in a softer spectrum of final-state mesons as compared to baryons. To illustrate this effect, predictions based on the ("standard") LUND model for quark and gluon fragmentation[1] are included in Fig. 1, both for primary hadrons and for final stable hadrons. For the model calculation the production ratios of (s quarks)/(u quarks), diquarks/quarks, and vector/scalar particles were set to 0.3, 0.075, and 1, respectively. The model gives a very good representation of the data.[12] It is interesting to note that the effects of resonance decays are pronounced enough to create the observed strong dependence of f_p on p and p_T from the almost flat dependence for primary hadrons; only at large momentum, where resonance decay products are suppressed, does the initial flat p_T dependence of f_p survive.

With use of the inclusive proton cross section as a function of p and p_T, the p_T distribution of protons at a fixed rapidity can be derived. The proton cross section $d\sigma/dy\, dp_T^2$ for the central region, $|y|<1$, is displayed in Fig. 2, together with the corresponding cross section for pion production. Because of momentum cutoffs at 150 and 450 MeV for pions and protons, respectively, the entire rapidity range $0<|y|<1$ is not covered for low transverse momenta. These losses have been corrected with the assumption of a flat rapidity distribution for $|y|<1$. The p_T distribution of protons can be represented by $\exp(-p_T^2/\sigma^2)$, with $\sigma = 0.55 \pm 0.04$ GeV. Included in Fig. 2 are predictions of the LUND model, where protons are made of a quark and a diquark, both of which have the same mean p_T (full lines). In the LUND model, primary mesons and baryons have the same $\langle p_T \rangle$. At low p_T, however, the pion rate is strongly enhanced by pions from decays, resulting in a steeper p_T dependence of the cross section as compared to protons. This model, which has been tuned to describe the mean transverse momentum $\langle p_T \rangle$ of observed mesons, reproduces the larger $\langle p_T \rangle$ of baryons with no additional assumptions.

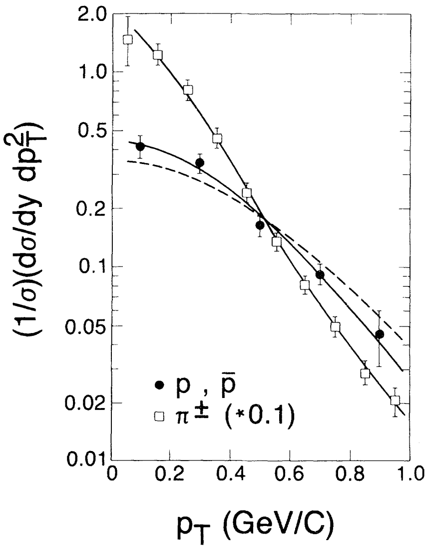

FIG. 2. p_T dependence of proton and pion cross sections for rapidities $|y| < 1$. Full lines: predictions of the LUND model (proton production via diquarks); dashed line: prediction for proton production by recombination of three individual quarks. The model predictions for protons are normalized to the data; the absolute predictions of the LUND model are low by (10–20)% (with diquark/quark = 0.075).

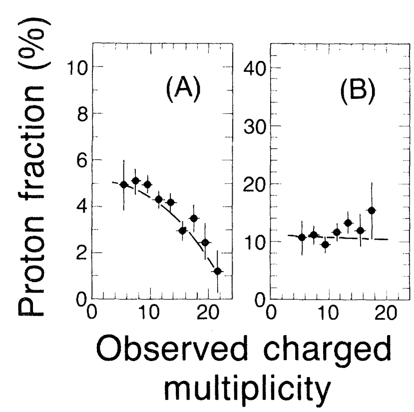

FIG. 3. Proton fraction f_p as a function of the observed multiplicity of charged hadrons in the event. (a) $0.55 < p < 1.0$ GeV/c; (b) $3.7 < p < 6.7$ GeV/c. There is an additional systematic scale uncertainty of ±15%. Full line: prediction of the LUND model.

Also shown is the p_T dependence obtained in a modified version of the model, in which protons are made of three quarks produced independently (dashed line). For such a mechanism, mean transverse momenta of primary baryons are larger than in the diquark scheme.[13] Within the uncertainties involved in the modeling, either one of these mechanisms for baryon production in color flux tubes is consistent with the data, although the diquark model appears favored.

The fraction of protons among charged hadrons as a function of the hadron multiplicity in the event is shown in Fig. 3 for two ranges in hadron momentum. At low momentum, f_p decreases with increasing multiplicity [Fig. 3(a)]. With increasing momentum, the dependence flattens out and f_p is constant for momenta above 3–4 GeV [Fig. 3(b)]. Once again the effects of resonance decays provide a sufficient explanation for these results: High-multiplicity events typically contain a larger fraction of vector mesons, resulting in a strong increase in the number of low-momentum decay pions and a corresponding decrease of f_p. This effect can be modeled quantitatively by use of the LUND generator (full lines).

To investigate a possible correlation between gluon radiation and baryon production, event samples characterized by high (> 0.3) and low (< 0.15) sphericity were selected. Aplanar events (aplanarity > 0.1) were rejected. Monte Carlo studies show that the high-sphericity sample is dominated by events with gluon jets. To account for a possible change in baryon fractions caused by different mean hadron multiplicities in the two samples, the low-sphericity events were weighted such as to reproduce the multiplicity distribution in the high-sphericity sample. Proton fractions for the two event classes are compared in Fig. 4. For momenta above 0.8 GeV/c, f_p for "fat" events is typically 50% larger than in the low-sphericity sample. The effect is not created by the multiplicity weighting; changes in the radio due to the weighting are small compared to the statistical errors.

In some QCD jet models, enhanced baryon production is expected for "fat" or "heavy" jets.[14] However, the observed behavior of f_p is reproduced qualitatively by the LUND model (full line); in this model no corresponding effect is seen for primary hadrons (dashed line). This means that at least part of the effect displayed in Fig. 4 can be attributed to purely kinematical effects caused by resonance decays. Apart from selecting events with gluons, the cuts on high and low sphericity bias towards events with many or few resonances, respectively. Unfortunately, almost any selection criterion for events with hard gluons can be shown to suffer from a similar bias.

To summarize: A pronounced dependence of proton fractions on total momentum, transverse momentum, hadron multiplicity in the event, and event sphericity is observed in e^+e^- annihilation events at 29 GeV. Protons show a broader distribu-

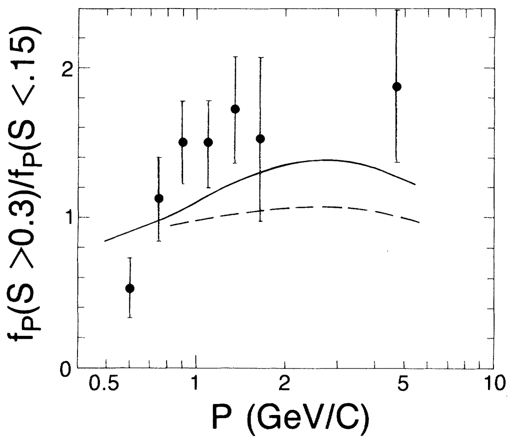

FIG. 4. Ratio of proton fractions in events with high (> 0.3) and low (< 0.15) sphericity, as a function of momentum. Full and dashed lines: prediction of the LUND model for final-state hadrons and for primary hadrons, respectively.

tion in transverse momentum than pions. Though these effects might seem to indicate different production dynamics for baryons and mesons, it is demonstrated that the observed behavior in fact is consistent with similar production spectra for primary mesons and baryons, provided that a significant fraction of the primary hadrons are resonances. Resonance decays then lead to an increased multiplicity and to a softening of both longitudinal and transverse spectra of light mesons as compared to baryons. Only in the sphericity dependence of proton fractions is an effect seen which is not fully explained by resonance decays alone, leaving room for a possible enhancement of proton production in events with hard gluons. In conclusion, it appears that baryons are more direct probes of fragmentation phenomena than light mesons.

We acknowledge the efforts of the PEP staff, and the engineers, programmers, and technicians of the collaborating institutions who made this work possible. This work was supported by the U. S. Department of Energy under Contracts No. DE-AC03-76SF00098, No. DE-AM03-76SF00034, and No. DE-AC02-76ER03330, the National Science Foundation, and the Joint Japan–U. S. Collaboration in High Energy Physics.

---

[1]B. Andersson *et al.*, Phys. Rep. **97**, 31 (1983).

[2]R. D. Field and S. Wolfram, Nucl. Phys. **B213**, 65 (1983).

[3]T. D. Gottschalk, Nucl. Phys. **B214**, 201 (1983).

[4]T. D. Gottschalk, California Institute of Technology Report No. CALT-68-1052, 1983 (unpublished).

[5]P. Mazzanti and R. Odorico, Z. Phys. C **7**, 61 (1980).

[6]B. Webber, CERN Report No. CERN-TH-3713, 1983 (unpublished).

[7]Yu. L. Dokshitzer, V. S. Fadin, and V. A. Khoze, Z. Phys. C **15**, 325 (1982).

[8]H. Aihara *et al.* (PEP4-TPC Collaboration), Phys. Rev. Lett. **52**, 577 (1984).

[9]J. J. Aubert *et al.* (EMC Collaboration), Phys. Lett. **135B**, 225 (1984).

[10]H. Albrecht *et al.* (DASP Collaboration), Phys. Lett. **102B**, 291 (1981); CLEO Collaboration, to be published; see also J. Dorfan, in *Proceedings of the International Symposium on Lepton and Photon Interactions at High Energies, Ithaca, New York, 1983,* edited by D. G. Cassel and D. L. Kreinick (Cornell Univ. Press, Ithaca, 1983), p. 686.

[11]G. Schierholz and M. Teper, Z. Phys. C **13**, 53 (1982).

[12]A similarly good agreement is obtained for independent-fragmentation schemes of the Feynman-Field type; the LUND model has simply been used as a representative of a wide class of models in which fragmentation distributions are essentially governed by longitudinal phase space for the directly produced objects, followed by resonance decays.

[13]In the modified model, a "diquark" was considered as being composed of two quarks produced independently, each having a certian p_T. The p_T of the diquark is calculated as the sum of the p_T's of its quarks, yielding $\langle p_T\rangle_{qq}=\sqrt{2}\langle p_T\rangle_q$, as opposed to $\langle p_T\rangle_{qq}=\langle p_T\rangle_q$ in the normal LUND model. This modification should be understood mainly as a means to demonstrate the sensitivity of inclusive p_T spectra to the input assumptions; more sophisticated implementations of a three-quark mechanism yield different results, especially if effects of color screening are taken into account, since then the three quarks are no longer independent (T. Sjöstrand, private communication).

[14]R. D. Field, in *Proceedings of the International Symposium on Lepton and Photon Interactions at High Energies, Ithaca, New York, 1983,* edited by D. G. Cassel and D. L. Kreinick (Cornell Univ. Press, Ithaca, 1983), p. 593.