Comparison of Quark and Gluon Jets Produced in High-Energy e^+e^- Annihilations

Y. K. Kim,[1] P. Auchincloss,[1] D. Blanis,[1] A. Bodek,[1] H. Budd,[1] S. Eno,[1] C. A. Fry,[1,8] H. Harada,[1] Y. H. Ho,[1] T. Kumita,[1] T. Mori,[1] S. L. Olsen,[1,9] N. M. Shaw,[1] A. Sill,[1] E. H. Thorndike,[1] K. Ueno,[1] H. W. Zheng,[1] R. Imlay,[2] P. Kirk,[2] J. Lim,[2] R. R. McNeil,[2] W. Metcalf,[2] S. S. Myung,[2] C. P. Cheng,[3] P. Gu,[3] J. Li,[3] Y. K. Li,[3] Z. P. Mao,[3] Y. T. Xu,[3] Y. C. Zhu,[3] A. Abashian,[4] K. Gotow,[4] K. P. Hu,[4] E. H. Low,[4] M. E. Mattson,[4] L. Piilonen,[4] K. L. Sterner,[4] S. Lusin,[5] C. Rosenfeld,[5] A. T. M. Wang,[5] S. Wilson,[5] M. Frautschi,[6] H. Kagan,[6] R. Kass,[6] C. G. Trahern,[6] R. E. Breedon,[7,8] G. N. Kim,[7,8] Winston Ko,[7] R. L. Lander,[7] K. Maeshima,[7] R. L. Malchow,[7] J. R. Smith,[7] D. Stuart,[7] M. C. S. Williams,[7] K. Abe,[8] Y. Fujii,[8] Y. Higashi,[8] S. K. Kim,[8] Y. Kurihara,[8] A. Maki,[8] T. Nozaki,[8] T. Omori,[8] H. Sagawa,[8] Y. Sakai,[8] Y. Sugimoto,[8] Y. Takaiwa,[8] S. Terada,[8] R. Walker,[1,8] F. Kajino,[10] D. Perticone,[11] R. Poling,[11] T. Thomas,[11] Y. Ishi,[12] K. Miyano,[12] H. Miyata,[12] T. Sasaki,[12] Y. Yamashita,[13] A. Bacala,[14,15] I. H. Park,[14] F. Sannes,[14] S. Schnetzer,[14] R. Stone,[14] J. Vinson,[14] H. Itoh,[16] S. Kobayashi,[16] A. Murakami,[16] K. Toyoshima,[16] J. S. Kang,[17] H. J. Kim,[17] M. H. Lee,[17] D. H. Han,[18] E. J. Kim,[18] D. Son,[18] T. Kojima,[19] S. Matsumoto,[19] R. Tanaka,[19] Y. Yamagishi,[19] T. Yasuda,[19] H. Yokota,[20] T. Ishizuka,[21] and K. Ohta[21]

(The AMY Collaboration)

[1] *University of Rochester, Rochester, New York 14627*
[2] *Louisiana State University, Baton Rouge, Louisiana 70803*
[3] *Institute for High Energy Physics, Beijing*
[4] *Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061*
[5] *University of South Carolina, Columbia, South Carolina 29208*
[6] *Ohio State University, Columbus, Ohio 43210*
[7] *University of California, Davis, California 95616*
[8] *KEK, National Laboratory for High Energy Physics, Ibaraki 305*
[9] *Tsukuba University, Ibaraki 305*
[10] *Konan University, Kobe 658*
[11] *University of Minnesota, Minneapolis, Minnesota 55455*
[12] *Niigata University, Niigata 950-21*
[13] *Nihon Dental College, Niigata 951*
[14] *Rutgers University, Piscataway, New Jersey 08854*
[15] *University of the Philippines, Quezon City, 3004*
[16] *Saga University, Saga 840*
[17] *Korea University, Seoul 136-701*
[18] *Kyungpook National University, Taegu 702-701*
[19] *Chuo University, Tokyo 112*
[20] *Tokyo Insitute of Technology, Tokyo 152*
[21] *Saitama University, Urawa 338*
(Received 19 July 1989)

Three-jet events produced in e^+e^- annihilations are used to provide comparisons between quark and gluon jets. Differences between quark-induced and gluon-induced jets are observed. Quark jets tend to have a more tightly collimated structure than gluon jets, which is reflected in the concentration of a larger fraction of the jet's energy near the jet axis.

PACS numbers: 13.87.Fh, 12.38.Qk, 13.65.+i

Quantum chromodynamics (QCD) has been proposed as a theory for the strong interactions.[1] In this theory, the strong force is mediated by the exchange of massless vector gluons between quarks, the fundamental constituents of strongly interacting particles. The coupling of quarks to gluons is expected to decrease with increasing momentum transfer so that in high-Q^2 processes calculations based on perturbation theory are valid. However, in applications of QCD to experimental situations, effects of the transition from the unobservable quarks and gluons to the physically observable hadrons (the so-called hadronization process) are unavoidable. This is a complex sequence of low-Q^2 processes for which the techniques of perturbative QCD are not applicable and phenomenological models must be used. Uncertainties in these models present a major obstacle to the detailed testing of QCD. It is thus important to obtain experimental insight into the hadronization process using reactions where the primary parton dynamics are well understood. High-energy e^+e^- annihilations, because of their basic simplicity, are well suited for these purposes. e^+e^- annihilation into three jets of hadrons, which is most simply interpreted as consisting of two quark jets and one gluon jet, provides an opportunity for direct comparisons of the hadronization process for quarks and gluons.

In QCD, gluons have a larger color factor than quarks[2] and thus should radiate more soft gluons and fragment into more particles than quarks, resulting in softer jets.[3] Despite a considerable amount of experimental effort, unambiguous differences between quark-induced and gluon-induced jets have not yet been established.[4]

We report on an experimental comparison of quark-induced and gluon-induced jets based on an analysis of three-jet events observed in the AMY detector at the KEK e^+e^- storage ring TRISTAN. At the energies provided by TRISTAN, hadron jets are well collimated and the correspondence between particles and jets is less ambiguous than in the case of previous experiments at lower energies. A 27.4-pb^{-1} sample of e^+e^- collisions at c.m. energies between 50 and 60.8 GeV is used for this analysis.

The AMY detector and the procedure for selecting multihadron events are described in Ref. 5. In the analysis reported here we use all detected charged tracks with $|\cos\theta| \leq 0.85$ and momentum above 0.25 GeV/c, and neutral clusters with $|\cos\theta| \leq 0.73$ and energy greater than 0.2 GeV. We assign a pion mass to the charged tracks and treat the neutral clusters as massless particles. The sum of the energies of these particles is defined as the visible energy, E_{vis}.

Jets are formed by means of the jet-clustering algorithm introduced by the JADE group.[6] In this algorithm, the scaled mass squared, defined as $y_{ij} = m_{ij}^2/E_{\text{vis}}^2$ with $m_{ij}^2 = 2E_iE_j(1-\cos\theta_{ij})$, is calculated for each pair of particles in the event. If the smallest of the y_{ij} values is less than a parameter, y_{cut}, the corresponding pair of particles is combined into a cluster by summing the four-momenta. This process is repeated, using all combinations of clusters and remaining particles, until all the y_{ij} values exceed y_{cut}. The clusters remaining at this stage are identified as the jets. We use $y_{\text{cut}} = (9\ \text{GeV})^2/s$.

We apply the following additional selection criteria to those events that contain three jets. An event is rejected if any of the three jets contains less than four particles, or has a visible energy $E_{\text{vis}}^{\text{jet}} \leq 6$ GeV, or has $|\cos\theta_{\text{jet}}| \geq 0.7$. To select planar events, we require the sum of jet-jet opening angles to be $\geq 358°$. To eliminate events where a hard photon from initial-state radiation is clustered with some random low-momentum particles, we reject events if any jet contains a neutral particle with energy $\geq 0.8E_{\text{vis}}^{\text{jet}}$. From the original sample of 3230 multihadron events, 336 events pass the selection criteria.

The jets in each event are then ordered according to the angles between jets: By definition, jet 1 is opposite the two jets with the smallest opening angle, and jet 3 is opposite those with the largest opening angle. Since gluon radiation is a bremsstrahlung-like process, the gluon is typically emitted close to one of the primary quarks and is usually the lowest-energy parton. Thus, it is expected that the jet-3 sample will be gluon enriched relative to the jet-1 and jet-2 samples, which are expected to be quark enriched.

We determine the "calculated" energy of each jet, $E_{\text{cal}}^{\text{jet}}$, using energy-momentum conservation and the opening angles between the three jets. Here we neglect the jet's invariant mass. To eliminate jets that have many missing or mismeasured particles, we require $2/3 \leq E_{\text{vis}}^{\text{jet}}/E_{\text{cal}}^{\text{jet}} \leq 4/3$. This cut, which is applied to individual jets and not to the entire event, eliminates 25% of the jets.

We obtain a second sample of quark jets by applying the same selection criteria to a set of two-jet events, except instead of the opening-angle-sum cut we require the two jets to be back-to-back collinear within 10°. This sample is expected to be a very pure set of quark jets with $E_{\text{cal}}^{\text{jet}} \simeq \sqrt{s}/2$.

Since we are trying to compare properties of quarks and gluons, which are unobservable, we are forced to rely on theoretical models for guidance. Two different QCD-motivated Monte Carlo event generators are used: the LUND 6.2 matrix-element (ME) model[7] with the independent-fragmentation scheme of Hoyer *et al.*,[8] and the LUND 6.3 parton-shower (PS) model with string fragmentation.[9] In both cases, samples of generated events are passed through a detector simulation program and are subjected to the same three-jet analysis that is used for the data.

The ME model calculates terms up to second order in the QCD coupling strength, α_s. In the independent-fragmentation scheme, the same algorithm is used to hadronize quarks and gluons and, thus, we do not expect any differences between the resulting jets. These events are used as a "control sample" to verify that the detector acceptance and our analysis procedures are not introducing artifical differences between quark and gluon jets.

The PS model reproduces the general properties of multihadron events in the TRISTAN energy region reasonably well.[10] In this model, the partons are made to branch into other partons of less virtuality via a recursive scheme using a leading-logarithm approximation (LLA). In the showering process hard gluons radiate more gluons than do quarks. In string fragmentation, hadronization occurs via the breaking of color flux tubes that run between color charges; gluons are attached to two flux tubes while quarks are attached to only one. All of these effects can cause differences between quark-induced and gluon-induced jets.

We studied the jet-identification efficiency for the two Monte Carlo (MC) event generators. In the $O(\alpha_s^2)$ ME model, each event has up to four partons. In the case of four-parton events that pass the three-jet selection criteria at the hadron level, we merge the pair of partons that have the smallest invariant mass and associate each jet with the parton (parton cluster) that most closely matches it in direction. In the PS generator, each event has many quarks and gluons and the identification of the parent parton for a given hadron jet has some degree of ambiguity. Here, for the events that pass the three-jet selection, we apply the jet-clustering algorithm at the parton level to form three jets of partons, which we correlate with jets formed at the hadron level by angle matching. The hadron jets that match the parton jets containing the primary quarks (identified as the oppositely flavored $q\bar{q}$ pair with the largest invariant mass) are identified as the quark jets; the other is designated as the gluon jet. Both MC models indicate that approximately two-thirds of the jets in the jet-3 sample that have $E_{\rm cal}^{\rm jet} \geq 13$ GeV are gluon-induced jets. (In tests for differences between quark-induced and gluon-induced jets, the exact value of the parton-identification efficiency is not necessary. We only require that the jet-3 sample is enriched in gluons relative to the jet-1,2 sample.)

The MC event samples are also used to estimate the deviations between the calculated energy ($E_{\rm cal}^{\rm jet}$) and the measured direction of the detected hadron jet and the energy and direction of the parent parton (or parton jet). The results from the ME model indicate that for $E_{\rm cal}^{\rm jet} = 16$ GeV, the energy resolution is $\sigma(\rm rms) \simeq 2.6$ GeV and the angular resolution is $\sigma(\rm rms) \simeq 8.5°$. These resolutions are about the same for quark-enriched and gluon-enriched jets with the same energy.

Since the gluon-enriched jet sample corresponds to the jets with the lowest value of $E_{\rm cal}^{\rm jet}$ in each event, there is little energy overlap with jets in the quark-enriched sample. Thus, comparisons are best done using variables that have little variation with $E_{\rm cal}^{\rm jet}$. Also, since the particle-jet correspondence is most reliable for the higher-energy particles in a jet, we choose variables that are dominated by them. Specifically, we define the core energy fraction, ξ, as the fraction of $E_{\rm vis}^{\rm jet}$ that is contained in a cone of half angle $60°/(E_{\rm cal}^{\rm jet})^{1/2}$ ($E_{\rm cal}^{\rm jet}$ in GeV) that is coaxial with the jet direction,[11] where the $(E_{\rm cal}^{\rm jet})^{1/2}$ denominator is motivated by the expectation that the widths of hadron jets decrease with the jet energy.[12] In addition, we examine the behavior of the rapidity relative to the jet axis of the most energetic particle (leading particle) in each jet, $\eta = \frac{1}{2}\ln[(E+p_\parallel)/(E-p_\parallel)]$, where E is the leading particle's energy and $p_\parallel$ is its momentum component parallel to the jet direction.

In Fig. 1(a) we show the mean value of ξ as a function of $E_{\rm cal}^{\rm jet}$ for the jet-1,2 and jet-3 samples. The data indicate that in quark jets the energy is concentrated near the jet axis while in gluon jets it tends to be diffuse. The results for the ME+independent-fragmentation MC event sample for the jet-1,2 and jet-3 samples are shown in the figure as solid lines. This model shows no significant discontinuity between the different jet samples; it agrees reasonably well with the jet-1,2 data points and lies considerably above those from the jet-3 sample. Included in the figure is the mean value of ξ for the jets from the two-jet data sample, which agrees well with the results from the jet-1,2 data sample.

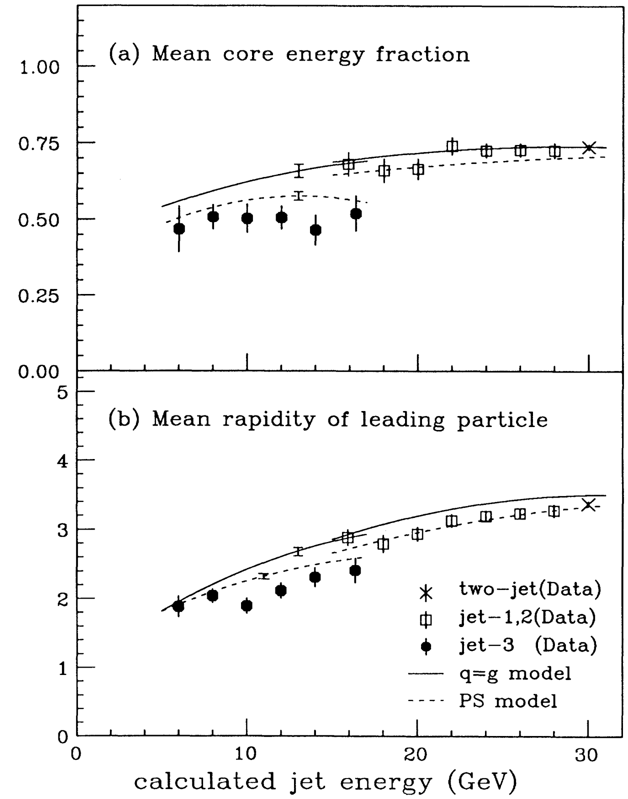

FIG. 1. (a) The mean energy fraction in a cone of half angle $60°/(E_{\rm cal}^{\rm jet})^{1/2}$ coaxial with the jet axis, ξ, and (b) the mean rapidity of the leading particle in the jet, η, as a function of the calculated jet energy, $E_{\rm cal}^{\rm jet}$. The solid points are for the gluon-enriched jet sample; the open points for the quark-enriched sample. The crosses indicate the results from the two-jet events. The solid curves (labeled $q = g$) indicate the results from the $O(\alpha_s^2)$ matrix-element model with independent fragmentation; the dashed curves (labeled PS) are the results from the parton-shower model with string fragmentation. Error bars are statistical errors only; the error bar centered on each curve indicates the statistical uncertainty of the Monte Carlo simulation.

Figure 1(b) shows the mean value of η, which also indicates some distinction between the different jet samples. The leading particles tend to have a higher rapidity in quark jets than in gluon jets. Here, the results of the ME+independent-fragmentation MC lie somewhat higher than the jet-1,2 data points but substantially overestimate those from jet 3. The data point from the two-jet event sample is consistent with those from the jet-1,2 data sample.

The predictions of the PS model are shown in Figs. 1(a) and 1(b) as dashed lines. The agreement with the jet-1,2 data sample is reasonably good and the model's different treatment of quarks and gluons results in different predicted behavior for the jet-3 sample. This difference, while it is evident in both figures, is not as

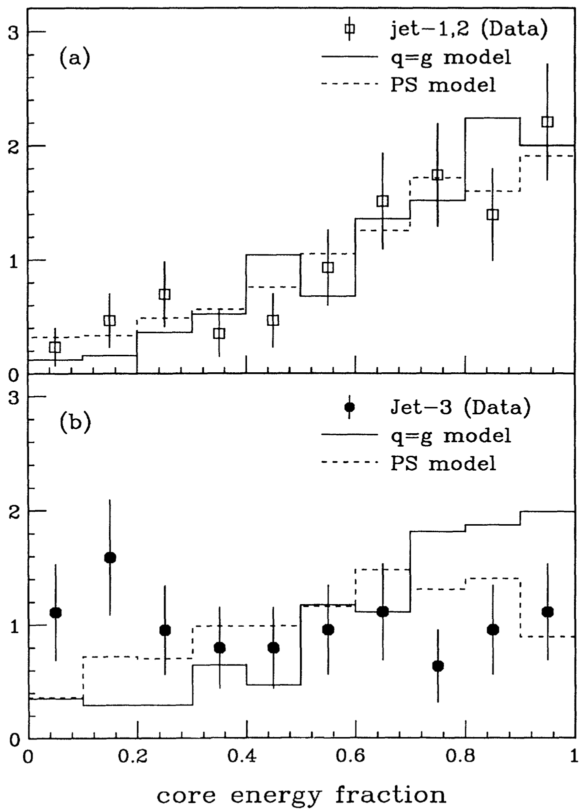

FIG. 2. The distribution of the core energy fraction ξ for the (a) quark-enriched jets with $E_{\text{cal}}^{\text{jet}} \leq 19$ GeV and (b) gluon-enriched jets with $E_{\text{cal}}^{\text{jet}} \geq 13$ GeV. The solid lines are the expectations from the ME+independent-fragmentation model; the dashed lines are the expectations from the PS+string-fragmentation model. All distributions are normalized to have unit integral.

strong as the differences observed in the data.

In Figs. 2(a) and 2(b), we show distributions in ξ for the lowest-energy portion of the jet-1,2 sample ($E_{\text{cal}}^{\text{jet}} \leq 19$ GeV, average = 17.0 GeV) and the highest-energy portion of the jet-3 sample ($E_{\text{cal}}^{\text{jet}} \geq 13$ GeV, average = 14.7 GeV), respectively. The distributions for the jet-1,2 and jet-3 samples show a strikingly different character. The quark-enriched sample peaks at $\xi = 1$, while the gluon-enriched sample favors smaller values of ξ. The solid-line histograms are the results for the ME+independent-fragmentation MC events. These give very similar distributions in both cases, showing reasonable agreement with the quark-enriched data sample ($\chi^2 = 11.9$ for 9 degrees of freedom) and clear disagreement with the gluon-enriched data sample ($\chi^2 = 49.6$). The PS model (dashed lines) predicts some distinction between the different jet samples, although not as much as is observed in the data. The PS model gives good agreement with the jet-1,2 sample ($\chi^2 = 3.9$); the agreement with the jet-3 data is worse ($\chi^2 = 19.4$).

To check for possible systematic sources for the observed differences between the jet-1,2 and jet-3 samples, we made the comparison for a variety of selection criteria. For example, if we increase y_{cut} to $(12\text{ GeV})^2/s$, or eliminate the cut on $E_{\text{vis}}^{\text{jet}}/E_{\text{cal}}^{\text{jet}}$, or use only the charged tracks to compute ξ and η, or use $E_{\text{vis}}^{\text{jet}}$ rather than $E_{\text{cal}}^{\text{jet}}$, the observed differences persist.

We observe differences in the concentration of energy near the jet core and in the rapidity of the leading particles for quark and gluon jets. Studies with a QCD-motivated event generator that uses the same fragmentation procedure for quarks and gluons indicate that the observed differences are not introduced by the effects of detector acceptance or by our analysis procedures, but are reflections of basic differences in the fragmentation processes of the partons.

We wish to thank L. M. Jones and T. Sjöstrand for helpful discussions. We thank the TRISTAN staff for the excellent operation of the storage ring and the staffs of our home institutions for their strong support. This work has been supported by the Japan Ministry of Education, Science and Culture (Monbusho) and Society for the Promotion of Science, the U.S. Department of Energy and National Science Foundation, the Korean Science and Engineering Foundation and Ministry of Education, and the Academia Sinica of the People's Republic of China.

[1]H. Fritzsch, M. Gell-Mann, and H. Leutwyler, Phys. Lett. **47B**, 365 (1973); D. J. Gross and F. Wilczek, Phys. Rev. Lett. **30**, 1343 (1973); H. D. Politzer, Phys. Rev. Lett. **30**, 1346 (1973).

[2]J. Ellis and I. Karliner, Nucl. Phys. **B148**, 141 (1979).

[3]S. J. Brodsky, T. DeGrand, and R. Schwitters, Phys. Lett. **79B**, 1585 (1978).

[4]HRS Collaboration, M. Derrick *et al.*, Phys. Lett. **165B**, 449 (1985); Mark II Collaboration, A. Peterson *et al.*, Phys. Rev. Lett. **55**, 1954 (1985); JADE Collaboration, W. Bartel *et al.*, Phys. Lett. **123B**, 460 (1983); TPC Collaboration, R. J. Madaras, in *Strong Interactions and Gauge Theories*, edited by J. Tran Thanh Van (Editions Frontieres, Gif-sur-Yvette, France, 1986); TASSO Collaboration, W. Braunschweig *et al.*, Weizmann Institute of Science Report No. WIS-89/7/89-PH (to be published).

[5]AMY Collaboration, H. Sagawa *et al.*, Phys. Rev. Lett. **60**, 93 (1988).

[6]JADE Collaboration, W. Bartel *et al.*, Z. Phys. C **33**, 23 (1986).

[7]T. Sjöstrand, Comput. Phys. Commun. **39**, 347 (1986).

[8]P. Hoyer *et al.*, Nucl. Phys. **B161**, 349 (1979).

[9]T. Sjöstrand and M. Bengtsson, Comput. Phys. Commun. **43**, 367 (1987); M. Bengtsson and T. Sjöstrand, Phys. Lett. B **185**, 435 (1987).

[10]AMY Collaboration, Y. K. Li *et al.*, KEK Report No. 89-34 (unpublished).

[11]L. M. Jones, Phys. Rev. D **39**, 2550 (1989).

[12]Yu. L. Dokshitzer, V. A. Khoze, and S. I. Troyan, in *Perturbative QCD*, edited by A. Mueller, World Scientific Series on Directions in High Energy Physics Vol. 5 (World Scientific, Singapore, 1989).