COMPARISON OF CHARGED PARTICLE MULTIPLICITIES IN QUARK AND GLUON JETS PRODUCED IN e^+e^- ANNIHILATION AT 29 GeV

M. DERRICK, K.K. GAN, P. KOOIJMAN, J.S. LOOS, B. MUSGRAVE, L.E. PRICE, J. SCHLERETH, K. SUGANO, J.M. WEISS [1], D.E. WOOD [2]

Argonne National Laboratory, Argonne, IL 60439, USA

D. BLOCKUS, B. BRABSON, S.W. GRAY [3], C. JUNG, H. NEAL, H. OGREN, D.R. RUST, M. VALDATA-NAPPI [4]

Indiana University, Bloomington, IN 47405, USA

C. AKERLOF, G. BONVICINI, J. CHAPMAN, D. ERREDE, N. HARNEW [5], P. KESTEN [6], D.I. MEYER, D. NITZ, A.A. SEIDL [2], R. THUN, T. TRINKO [2], M. WILLUTZKY

University of Michigan, Ann Arbor, MI 48109, USA

S. ABACHI, P. BARINGER, I. BELTRAMI [7], B.G. BYLSMA, R. DEBONTE, D. KOLTICK, F.J. LOEFFLER, E.H. LOW, R.L. McILWAIN, D.H. MILLER, C.R. NG, L.K. RANGAN, E.I. SHIBATA

Purdue University, West Lafayette, IN 47907, USA

and

B. CORK

Lawrence Berkeley Laboratory, Berkeley, CA 94720, USA

Received 24 October 1985

The charged particle multiplicities of the quark and gluon jets in the three-fold symmetric $e^+e^- \to q\bar{q}g$ events at $\sqrt{s} = 29$ GeV have been studied using the high resolution spectrometer at PEP. A value of $\langle n \rangle_g = 6.7^{+1.1}_{-2.1} \pm 1.0$ for gluon jets with an energy of $9.7^{+1.5}_{-2.0}$ GeV is measured. The ratio, $\langle n \rangle_g / \langle n \rangle_q$, is $1.29^{+0.21}_{-0.41} \pm 0.20$, which is significantly lower than the value of 9/4 naively expected from the ratio of the gluon-to-quark color charges.

The theory of quantum chromodynamics (QCD) provides a quantitative description of the strong interactions at high Q^2 where perturbative interactions dominate. However, the quarks and gluons are confined by the color force and only the hadronized products of these partons can be observed. Since this hadronization results from non-perturbative interactions, it is necessary to study in detail the properties of the final-state jets in order to infer the interactions

[1] Present address: SRI International, Menlo Park, CA 94025, USA.
[2] Present address: Lockheed Missiles and Space Co., Sunnyvale, CA 94086, USA.
[3] Present address: Laboratory for Nuclear Studies, Cornell University, Ithaca, NY 14853, USA.
[4] Present address: INFN, Pisa, Italy.
[5] Present address: CERN, CH-1211 Geneva 23, Switzerland.
[6] Present address: Brandeis University, Waltham, MA 02254, USA.
[7] Present address: ETH, Zurich, Switzerland.

0370-2693/85/$ 03.30

of the primary partons. High-energy e^+e^- collisions are ideal for studying such transitions because of the simplicity of the parton-level processes. The events can also be selected with low background and much of our knowledge of the properties of jets associated with the different quark flavors comes from these experiments [1].

Because of the higher color charge of the gluon, it is expected that gluon jets will be fatter, softer, and of higher multiplicity [2] than quark jets, although so far it has been difficult to quantitatively check these ideas. In fact, little experimental information is available on gluon fragmentation even though gluons are thought to predominate at the lower transverse momenta in the CERN S$\bar{p}$pS collider jets [3].

In this paper we report a study of the charged particle multiplicity in gluon jets, using a high-statistics data sample corresponding to a total integrated luminosity of $(185 \pm 5)\ \mathrm{pb}^{-1}$ obtained with the high resolution spectrometer (HRS) at PEP. The jet signature becomes clearer as the energy of the primary partons gets larger because each cluster of hadrons forms a relatively narrow cone. At the same time, at the PEP energy of $\sqrt{s} = 29$ GeV, the cone is wide enough so that the tracks can be separated using conventional techniques. The hadronic final states are dominated by events of a clear two-jet topology from quark and antiquark production [4], although about 10% of the events show a three-jet structure resulting from hard gluon radiation.

The HRS detector is a solenoidal spectrometer that measures charged particles and electromagnetic energy over 90% of the solid angle [4]. The tracking system consists of a vertex chamber, a central drift chamber, and an outer drift chamber. The central drift chamber has 15 cylindrical layers of drift cells. Eight of the layers have stereo wires (± 60 mrad) in order to measure the z position. The momentum of a 14.5 GeV/c charged particle in the 1.62 T magnetic field can be measured with a resolution of about 3%. A 40-module barrel shower counter system provides electromagnetic calorimetry over 62% of the solid angle with energy resolution below 10 GeV of $\sigma_E/E \simeq 0.16/\sqrt{E}$ (E in GeV). The beam pipe and the inner wall of the central drift chamber are made of beryllium so as to minimize photon conversions; the total material between the interaction point and the central drift chamber is less than 0.02 radiation lengths.

To ensure good tracking efficiency, the thrust axis of the event was selected to be within 30° of the equatorial plane of the detector, and all acceptable tracks were required to have an angle with respect to the e^+e^- beam direction (θ) of more than 24° and to register in more than one-half of the drift chamber layers traversed. Isolated tracks were reconstructed with >99% efficiency, but for a typical annihilation event, with several close tracks, the reconstruction efficiency is lower. For $\theta > 30°$ and $p > 200$ MeV/c, the track reconstruction efficiency is 80% or better and varies slowly with dip angle; for the higher momenta, $p > 2$ GeV/c, this increases to 90%. In addition, ~7% of the found tracks are not valid. Low-momentum tracks are not well reconstructed for any dip angle because of the high magnetic field of the spectrometer; a track with $p < 240$ MeV/c spirals within the central drift chamber.

The events were selected with the number of acceptable charged pracks between 5 and 40. Each track had to pass within 3 cm in (x, y) radius and 15 cm in z from the interaction point. In addition, the scalar sum of the charged momenta, plus the energy registered in the barrel shower counter system, was required to be greater than 12 GeV, with at least 1 GeV in the shower counter and more than 7.5 GeV/c in charged particles. The invariant mass of three-prong jets in six-prong events was required to be greater than the τ lepton mass. These cuts, which effectively removed beam–gas interactions, examples of lepton-pair production, two-photon events, and cosmic rays, produced a data sample of about 34k events.

The events passing these cuts are mixtures of the two-jet and three-jet topologies. The low sphericity region ($0 < S < 0.25$) is dominated by the two-jet events, and contains 82% of the data sample; the higher sphericity region ($S > 0.25$) is strongly enriched in three-jet events. In order to select a clean sample of the latter, a jet-finding algorithm was applied to the hadronic data sample in the kinematic region with $S > 0.15$ and $A < 0.1$, where A is the aplanarity. A and S are determined by the eigenvalues of the momentum tensor. These selections in A and S ensured that the three jets are in a plane. For each event, the values of the variables that maximized the longitudinal momenta along two or three axes were calculated. For a two-jet topology, this is the thrust variable and for a three-jet event, the triplicity variable. The clustering used in calculating the triplicity was done using the charged tracks projected onto the event plane. The three-jet events were then selected by a cut on the normicity variable (C_3) [5], which is the ratio of the triplicity to thrust. For normicity >1.05, 89% of the $q\bar{q}g$ partonic states are selected by the algorithm; the estimated contamination in this three-jet data sample from two-jet events is 16%.

The normalized particle flow of these three-jet events on the event plane is shown in fig. 1a. In this plot ‡1 the jets are ordered according to the angles between neighboring jets; jet 1 is defined as that jet opposite to the smallest angle and, similarly, jet 3 is opposite to the largest angle. The prediction of the Lund Monte Carlo model [8] ‡2, shown by the line, agrees with the data and, in particular, fits the valley between jet 1 and jet 2 well. With our selections, according to the Monte Carlo study, about 56% of the third jets result from gluon fragmentation.

‡1 These data are very similar to those previously published by the JADE Collaboration [6] who studied in some detail the general problem of separating quark and gluon jets in e^+e^- annihilation. See also the recent results of the TPC group [7].

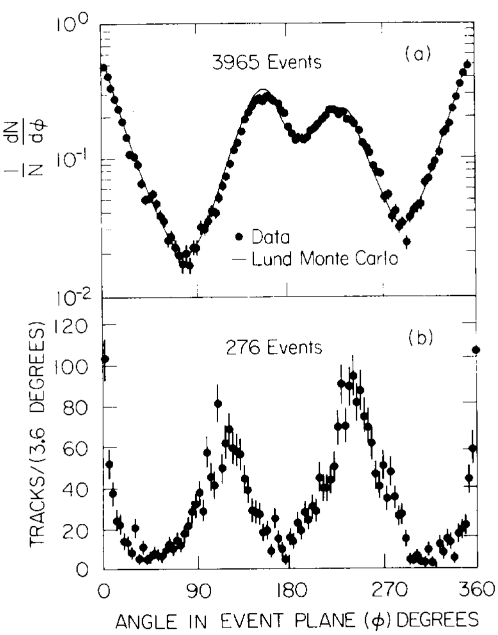

Fig. 1. (a) Particle flow on the event plane for the three-jet events with normicity $C_3 > 1.05$ after the angle ordering. (b) Particle flow on the event plane for the symmetric three-jet events with normicity $C_3 > 1.10$ after the multiplicity ordering. Jet 1 appears narrower than jets 2 and 3 since the angle is measured with respect to the jet 1 axis.

The true multiplicity distribution of the events was calculated from that observed by means of a matrix unfolding technique. If N_m^0 is the number of observed events with m accepted tracks and N_n^T is the true number of events with n tracks, then

$$N_n^T = \sum_m M_{nm} N_m^0 .$$

The matrix M_{nm} was calculated from the Monte Carlo simulation of the experiment and includes the effects of the experimental cuts as well as the tracking inefficiencies discussed earlier. The results, which include the charged particles from K_s^0 and Λ decays, were found to be stable for reasonable variations, both of the cuts and of the definition of a good track. The numbers of events with $m < 5$ were estimated from the data, assuming independent jet fragmentation [9].

The corrected mean multiplicities for the individual jets as a function of their energies ‡3 are shown in

‡2 We use JETSET version 5.3.

‡3 The jet energy is measured by the sum of the energies of all the charged particles, assumed to be pions, plus the electromagnetic energy observed in the shower counters. A correction for the detection efficiency is also applied.

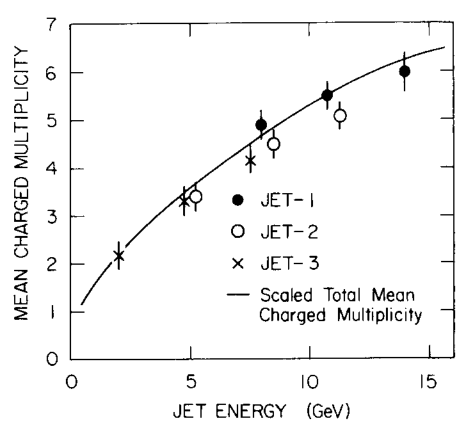

Fig. 2. Mean charged particle multiplicity for the data of fig. 1a as a function of jet energy. The line shows the variation of the single jet multiplicity for $e^+e^- \to$ hadrons as a function of the jet energy ($\sqrt{s}/2$).

fig. 2. The errors are dominated by systematics coming from the contamination from two-jet events, the estimated track-finding efficiency, and the uncertainty of the correction matrix. The solid line is the fit to half of the mean multiplicity for all e^+e^- annihilation events plotted as a function of $\sqrt{s}/2$. Since e^+e^- annihilations in the energy range shown in fig. 2 are dominated by $e^+e^- \to q\bar{q}$, this line shows the expected $\langle n \rangle$ values for quark fragmentation averaged over all flavors. The multiplicities derived from the three-jet events agree with this curve; no evidence is seen for higher $\langle n \rangle$ values even though jet 3 is enriched in gluons.

As the normicity cut is increased, the three separate peaks of fig. 1a become more pronounced, the gluon jet becomes harder, and the shape of the events becomes more three-fold symmetric. For such symmetric events, the probability of identifying the gluon jet is lower; naively speaking about one-third. However, one can test if one of the jets has a significantly larger multiplicity than the other two.

The three-fold-symmetric three-jet events were selected by the three-jet finding algorithm with cuts: $S > 0.15$, $A < 0.1$, $C_3 > 1.10$, and the angle between the jet axes in the range 100° to 140° [‡4]. The sample of 276 events passing these cuts has a total mean multiplicity of $\langle n \rangle = 16.3 \pm 0.3 \pm 0.7$ and dispersion $D = (\langle n^2 \rangle - \langle n \rangle^2)^{1/2}$ of $4.2 \pm 0.5 \pm 0.3$. The first error is statistical and the second systematic. According to the Monte Carlo simulation, the energy of each jet is 9.7 GeV with a width of +1.5 GeV and −2.0 GeV measured at the half maximum value. We note that the line on fig. 2 gives $\langle n \rangle = 5.2$ for a quark jet of this energy. The estimated background from the process $e^+e^- \to q\bar{q}\gamma$, where the photon converts to simulate a third jet, is 0.2%.

The three jets are now ordered according to their charged particle multiplicities, with jet 1 defined as the jet with the lowest number of charged particles and jet 3 with the highest multiplicity. Fig. 1b shows the particle flow on the event plane with this ordering. The angle is now measured with respect to the axis of jet 1 in the direction of jet 2. The areas in the three peaks are then proportional to the mean particle multiplicities. The overlapping of the peaks is about 8%.

The ratio of the mean multiplicity of jet 3 to that of the average of jet 1 and jet 2 is $2\langle n_3 \rangle / \langle n_1 + n_2 \rangle = 1.71 \pm 0.06 \pm 0.05$. The systematic error of ± 0.05 is estimated from the 8% jet overlap. Because of the multiplicity ordering, we expect this ratio to be greater than one even if the multiplicity of the gluon jet is the same as that of the quark jet.

In order to compare this ratio with the values expected for different multiplicities of the gluon jet, we made a simple simulation of the experiment in which each 9.7 GeV with $\langle n \rangle = 5.2$ particles was allowed to independently fragment with a Poisson distribution adjusted to fit the observed single-jet multiplicity distributions [9]. This model predicts $2\langle n_3 \rangle / \langle n_1 + n_2 \rangle = 1.69$ for $\langle n \rangle_g = \langle n \rangle_q = 5.2$ and $2\langle n_3 \rangle / \langle n_1 + n_2 \rangle = 2.31$ for $\langle n \rangle_g = (9/4)\langle n \rangle_q = 11.7$. The corrected multiplicity distribution for the jet 3 sample is shown in fig. 3. The solid line, which agrees reasonably well with the data, shows the expectation from this simple Poisson model with $\langle n \rangle_g = \langle n \rangle_q = 5.2$, and the dashed line corresponds to that with $\langle n \rangle_g = (9/4)\langle n \rangle_q = 11.7$. If $\langle n \rangle_g$ is allowed to vary, then a value of $\langle n \rangle_g = 6.7^{+1.1}_{-2.1} \pm 1.0$ at a jet energy of $9.7^{+1.5}_{-2.0}$ GeV is found to best

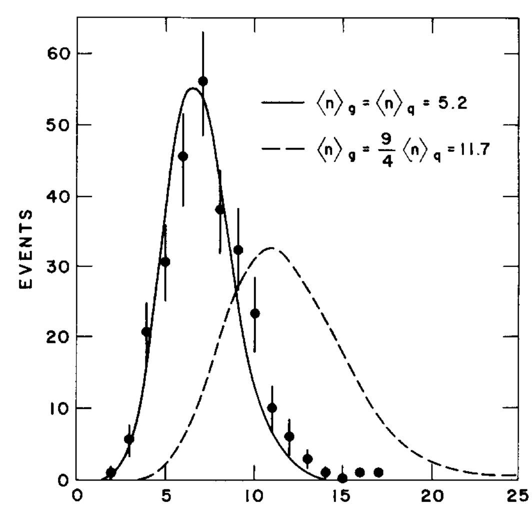

Fig. 3. Charged particle multiplicity distribution of jet 3 compared to two assumptions for the mean multiplicity of gluon jet in a simple Poisson model.

‡4 The cuts on S, C_3, and the angle span were varied, and the results were found to be the same within the statistical errors. A loose energy requirement for each jet of 3 to 17 GeV was also applied to eliminate backgrounds from mistracking and "jets" that consisted of a single isolated track.

reproduce the jet 3 multiplicity data and the measured ratio of $2\langle n_3\rangle/\langle n_1 + n_2\rangle$. This value gives a ratio $\langle n\rangle_g/\langle n\rangle_q$ of $1.29^{+0.21}_{-0.41} \pm 0.20$. We conclude, therefore, that in the energy range of our experiment, the mean multiplicity of the gluon jet, for the particles with $x = p/p_{beam} \gtrsim 0.01$, is consistent with being equal to that of the quark jet, and significantly different from the value of 9/4 coming from the color factor ratio.

There are several uncertainties that cloud these comparisons of quark and gluon jet multiplicities. First, some of the charged particles in the quark jets result from the decay of the mesons containing the heavy quarks (c and b). The multiplicity measurements of jets resulting from heavy quark fragmentation [1] gives an increase of ~ 0.5 particles per quark jet from this effect. Second, the next-to-leading order QCD corrections to the ratio of quark-to-gluon multiplicities gives a reduction of about 10% [10,11]. At high jet energies these calculations, therefore, predict a $\langle n\rangle_g/\langle n\rangle_q$ ratio of two. Third, the very low momentum particles are difficult to assign to a specific jet. However, in the Gottschalk cluster model [12], the total multiplicity for the symmetric three-jet events is about 30% higher than we measure.

The simulation of e^+e^- annihilation, with our experimental selections, based on the Lund string model [8], predicts a total mean multiplicity of 16.7 and $2\langle n_3\rangle/\langle n_1 + n_2\rangle = 1.64$ in agreement with the data. In this approach, the gluon is considered to be a kink in the string joining the q and $\bar{q}$, and so the 9/4 color factor does not explicitly enter. At infinite energy, the dual string topology at the gluon kink leads to a rapidity density which is twice that at the quark ends of the string. The difference between these expectations and the agreement of our data with the Lund simulation reflects the kinematic constraints coming from the low energy of the experiment.

This work was supported in part by the US Department of Energy, under Contracts W-31-109-Eng-38, DE-AC02-76ER01112, DE-AC03-76SF00098, DE-AC02-76ER01428, and DE-AC02-84ER40125. We thank the PEP operations group for providing the luminosity on which these results are based.

References

[1] Tasso Collab., M. Althoff et al., Phys. Lett. 135B (1984) 243;
Delco Collab., M. Sakuda et al., Phys. Lett. 152B (1985) 399;
P. Kesten et al., Phys. Lett. 161B (1985) 412.
[2] S.J. Brodsky and J.F. Gunion, Phys. Rev. Lett. 37 (1976) 402.
[3] UA2 Collab., P. Bagnaia et al., Phys. Lett. 144B (1984) 291.
[4] D. Bender et al., Phys. Rev. D31 (1985) 1.
[5] A. Bäcker, Z. Phys. C12 (1982) 161.
[6] JADE Collab., W. Bartel et al., Z. Phys. C21 (1983) 37.
[7] TPC Collab., H. Aihara et al., Z. Phys. C28 (1985) 31.
[8] B. Andersson et al., Phys. Rep. 97 (1983) 31.
[9] M. Althoff et al., Z. Phys. C22 (1984) 307;
M. Derrick et al., Study of quark fragmentation in e^+e^- annihilations at 29 GeV: Charged particle multiplicity distributions, ANL-HEP-CP-85-60 (1985), to be submitted to Phys. Rev. D.
[10] Yu.L. Dokshitzer, V.S. Fadin and V.A. Khoze, Z. Phys. C15 (1982) 325.
[11] A.H. Muller, Nucl. Phys. B241 (1984) 141;
E.D. Malaza and B.R. Webber, Phys. Lett. 145B (1984) 501; Cambridge preprint HEP 85/4.
[12] T. Gottschalk, Nucl. Phys. B239 (1984) 349.