

COMPARISON OF QUARK AND GLUON JETS USING THREE-JET EVENTS
FROM e^+e^- ANNIHILATION AT TRISTAN

MINGHAN YE

National Laboratory for High Energy Physics, Tsukuba, Ibaraki, 305 JAPAN

and

Institute of High Energy Physics, Beijing 100039, China

Representing the AMY Collaboration

ABSTRACT

Three-jet events produced in e^+e^- annihilations are used to demonstrate differences between quark-induced and gluon-induced jets. Quark jets tend to have a more tightly collimated structure than gluon jets, which is reflected in a higher concentration of the jet's energy near the jet axis, a higher rapidity relative to the jet direction of the most energetic particle in a jet, and a narrower distribution of the Energy-Energy Correlation.

High-energy e^+e^- annihilations into $q\bar{q}g$ final states, which appear in the laboratory as $e^+e^- \rightarrow$ three jets of hadrons, have a simple underlying parton structure that makes them well-suited for comparisons of the hadronization process for quarks and gluons. In this paper, we report on a comparison of various properties of samples of quark-enriched and gluon-enriched jets extracted from $e^+e^- \rightarrow$ three-jet events observed in the AMY detector at center-of-mass energies between $\sqrt{s} = 50$ GeV and 60.8 GeV. Parts of this work has been reported earlier [1].

Since the discovery of $e^+e^- \rightarrow$ three-jet events, they have been used for many experimental searches for differences between quark jets and gluon jets. The Mark-II collaboration at the PEP storage ring studied the inclusive momentum spectrum of particles and reported a softer fragmentation for gluon jets [2]. This analysis involved extrapolating data from other experiments for quark jets, with the possibility that there may be large systematic errors. A similar study has been done by the TASSO collaboration at the PETRA storage ring using three-jet events at $30 < \sqrt{s} < 38$ GeV and two-jet events at $22 < \sqrt{s} < 25$ GeV [3]. They reported no evidence for any differences, in contradiction with the MARK-II re-

sults, and suggested an explanation of the Mark II results in terms of the selection cuts applied to the different jet samples. The JADE group at PETRA reported a higher average value of transverse momentum relative to the jet axis, $\langle p_t \rangle$, for gluon jets [4]. Averaging over jet energies between 6 and 10 GeV, they found $\langle p_t \rangle_3 / \langle p_t \rangle_2 = 1.16 \pm 0.02$, indicating wider gluon jets. Preliminary results from the TPC group at PEP showed that gluon jets appear to be fatter than quark jets in the average transverse momentum in the event plane, $\langle p_t^{in} \rangle$; they found $\langle p_t^{in} \rangle_3 / \langle p_t^{in} \rangle_2 = 1.08 \pm 0.02$ [5]. The CELLO group at PETRA compared the lowest energy jet in three-jet events at 35 GeV center-of-mass energy with a quark jet at 14 GeV center-of-mass energy. They reported preliminary results that show no evidence for any differences, namely $\langle p_t \rangle_3 / \langle p_t \rangle_2 = 1.03 \pm 0.05$, in contradiction to the JADE results [6]. The HRS group at PEP [7] looked at the charged multiplicities, n_{chg} , of quark and gluon jets using "nearly-symmetric" three-jet events and compared the results with a Monte Carlo (MC) model. Within experimental errors, no strong differences were observed; $\langle n_{chg} \rangle_g / \langle n_{chg} \rangle_q = 1.29^{+0.21}_{-0.41} \pm 0.20$.

The AMY detector and the procedure for selecting multihadron events are described in ref. [8]. Jets are formed by means of the jet-clustering al-

gorithm developed by the JADE group [9] using a cutoff parameter value of $y_{cut} = (9\text{GeV})^2/s$.

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 $E_{vis}^{jet} \leq 6\text{ GeV}$, or has $|\cos\theta_{jet}| \geq 0.7$. To select planar events, we require the sum of jet-jet opening angles to be $\geq 358^\circ$. To eliminate events where one of the jets is erroneously formed by clustering a hard photon from initial-state radiation with some random low-momentum particles, we reject events if any jet contains a neutral particle with energy $\geq 0.8E_{vis}^{jet}$. From the original sample of 3230 multi-hadron events, 336 events pass the selection criteria.

We determine the “calculated” energy of each jet, E_{cal}^{jet} , using energy-momentum conservation and the opening angles between the three jets. Here we neglect the jet’s invariant mass. We categorize the jets in each event according to their calculated energy values; jet-1 and jet-2 (the quark-enriched jets) are the highest energy jets and jet-3 (the gluon-enriched jet), the lowest energy jet. To eliminate jets that have many missing or mismeasured particles, we require $\frac{2}{3} \leq (E_{vis}^{jet}/E_{cal}^{jet}) \leq \frac{4}{3}$. This cut, which is applied to individual jets and not to the entire event, eliminates 25% of the jets.

Since the gluon-enriched jet sample corresponds to the jets with the lowest value of E_{cal}^{jet} in each event, there is little energy overlap with jets in the quark-enriched sample over our range of center-of-mass energies. Thus, comparisons are best done using variables that have little variation with E_{cal}^{jet} . It has been shown that quarks and gluons do not hadronize independently in an event [10], which introduces ambiguities into the assignment of particles to jets. These, however, affect mainly the soft particles; the high momentum particles are produced nearly independently of inter-parton correlations [11]. In order to reduce the uncertainties due to soft particles, we prefer to rely on variables that are dominated by high momentum particles

instead of variables that are uniformly weighted by all particles, such as n_{chg} and $\langle p_t \rangle$. Specifically, we define the variables:

- the core-energy fraction, ξ ;

the fraction of E_{vis}^{jet} that is contained in a cone of half angle $\theta_{cone} = 60^\circ/\sqrt{E_{cal}^{jet}}$ that is coaxial with the jet direction.

- the rapidity of the leading particle, η ;

the rapidity of the leading particle in a jet, relative to the jet axis.

- the integrated Energy-Energy Correlation, Σ^{30} ;

the Energy-Energy Correlation *EEC* is the pairwise distribution of opening angles of each pair of particles in the jet weighed by their fractional energies. We define the integrated *EEC* as the integral of the normalized *EEC* between 0° and 30° ;

$$\Sigma^{30} = \int_0^{30^\circ} \frac{d\Sigma}{d\theta} d\theta.$$

Note that the normalization is such that $\Sigma^{180} = 1$.

Since ξ is determined by the energy flow in the core of a jet, η is determined from the most energetic particle in a jet, and Σ^{30} is an energy weighted variable, all of these variables are dominated by high momentum particles in different ways.

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 model [12] with the independent fragmentation scheme of Hoyer et al. [13], subsequently called the $q = g$ model, and the Lund 6.3 Parton Shower model with the string fragmentation [12], subsequently called the PS model. In both cases, samples of generated events are passed through the detector simulation program and are subjected to the

same three-jet analysis that is used for the data. In the $q = g$ model, the same algorithm is used to hadronize quarks and gluons and, thus, we don't 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 artificial differences between quark and gluon jets.

In addition to the above-noted variables, we have also examined the more commonly used variables $\langle p_t \rangle$ and n_{chg} , which are determined using all particles and charged particles, respectively, without any momentum weighting. Figures 1 and 2 show the mean values of $\langle p_t \rangle$ and n_{chg} as a function of E_{cal}^{jet} , respectively. The jet-3 sample appears to favor higher $\langle p_t \rangle$, i.e. wider jets and higher n_{chg} , i.e. softer hadronization at the same jet energies, although these differences are not very dramatic.

In Fig. 3 we show the mean value of the core-energy fraction ξ as a function of E_{cal}^{jet} for the jet-1,2 and jet-3 samples. This variable is not too sensitive to the jet energy. 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 $q = g$ MC event sample for the jet-1,2 and jet-3 samples, shown in the figure as solid

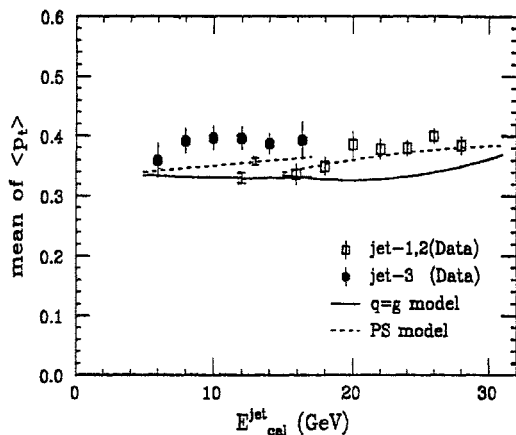


Figure 1: The mean values of the average transverse momentum $\langle p_t \rangle$ as a function of E_{cal}^{jet} for all neutral and charged particles. The solid (open) points are for the gluon-enriched (quark-enriched) jet sample. The solid (dashed) lines are the expectations from the ME + $q = g$ model (PS + string fragmentation model).

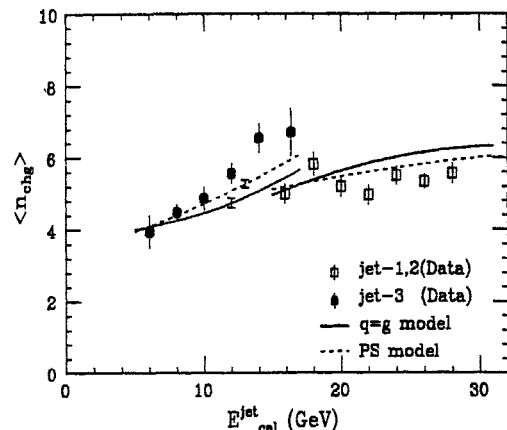


Figure 2: The mean values of the charged-particle multiplicity $\langle n_{chg} \rangle$ as a function of E_{cal}^{jet} .

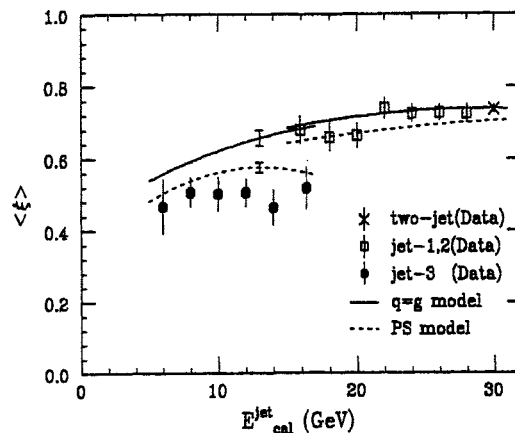


Figure 3: The mean core-energy fraction, ξ , as a function of the calculated jet energy, E_{cal}^{jet} . The cross indicates the result from the two-jet events.

lines, 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.

Figure 4 shows the mean values of the leading particle's rapidity, η , which also indicate 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 $q = g$ MC lie somewhat higher than the jet-1,2 data points but substantially overestimate those from jet-3.

The normalized EEC distribution is shown in Fig. 5 for the lowest energy portion of the jet-1,2 sample ($E_{cal}^{jet} \leq 19$ GeV; average=17.0 GeV)

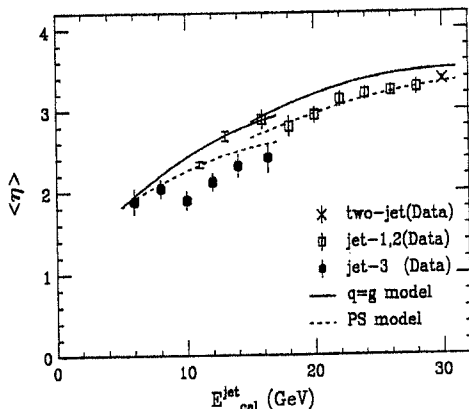


Figure 4: The mean rapidity of the leading particle in the jet, η , as a function of the calculated jet energy, E_{cal}^{jet} .

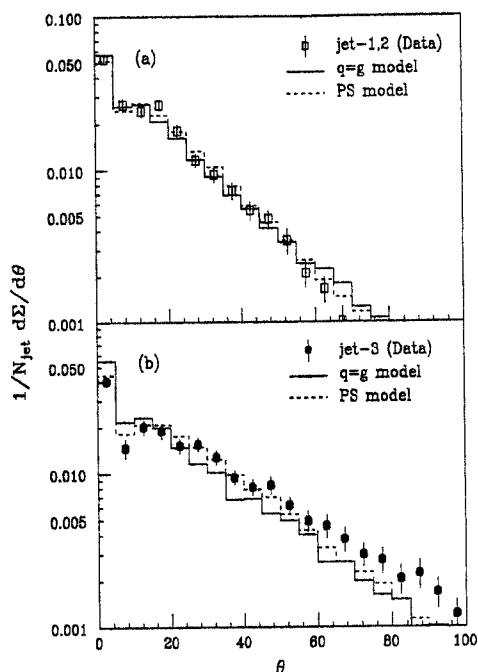


Figure 5: The normalized Energy-Energy Correlation, $d\Sigma/d\theta$, for the (a) quark-enriched jets with $E_{cal}^{jet} < 19$ GeV and (b) gluon-enriched jets with $E_{cal}^{jet} > 13$ GeV. All distributions are normalized to have unit integral.

and the highest energy portion of the jet-3 sample ($E_{cal}^{jet} \geq 13$ GeV; average=14.7 GeV), respectively. The peak in the first bin is the particles' self correlation (i.e., when $i = j$). The $q = g$ MC event sample gives reasonable agreement with our data for jet-1,2 sample while the jet-3 distribution for the data sample is wider than that of $q = g$ MC

sample. Figure 6 shows the mean values of Σ^{30} , the integral of the EEC distribution between 0° and 30° , as a function of E_{cal}^{jet} , for the jet-1,2 and jet-3 samples. This also indicates some distinctions between the different jet samples.

The predictions of the PS model are shown as dashed lines in Figs. 1, 2, 3, 4, 5, and 6. The agreement with the jet-1,2 data sample is reasonably good and the model's different treatment of quarks and gluons results in a different predicted behavior for the jet-3 sample. This difference, while evident in all four figures, is not as strong as the differences observed in the data.

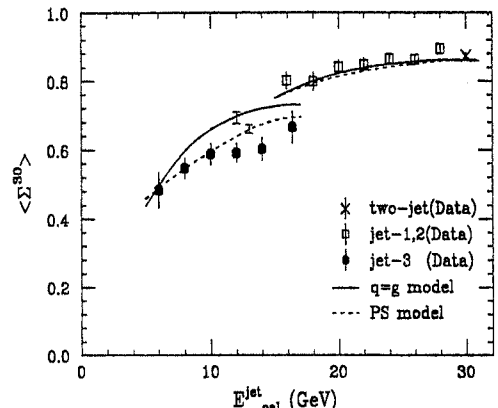


Figure 6: The mean of Σ^{30} as a function of the calculated jet energy, E_{cal}^{jet} .

In Figs.7 (a) and (b), we show distributions in ξ for the lowest energy portion of the jet-1,2 sample ($E_{cal}^{jet} \leq 19$ GeV; average=17.0 GeV) and the highest energy portion of the jet-3 sample ($E_{cal}^{jet} \geq 13$ 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 $\xi = 1$, corresponding to 100% of the visible energy in the core, while the gluon-enriched sample favors smaller values of ξ , corresponding to little of the visible energy in the core. The solid-line histograms are the results from the $q = g$ 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 ($\chi^2 = 19.4$).

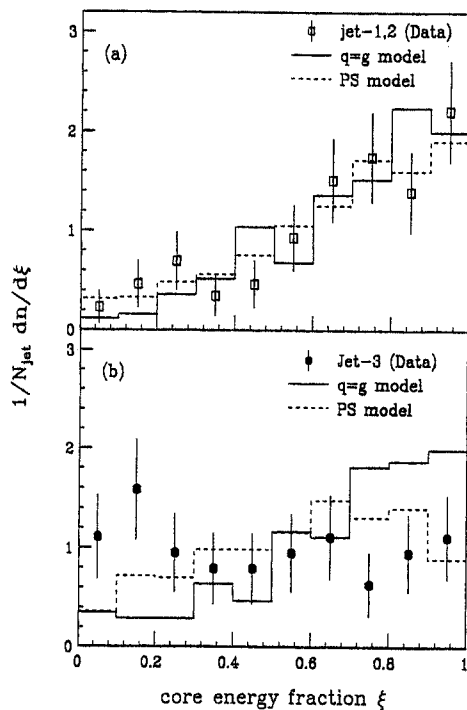


Figure 7: The core-energy fraction distributions (ξ) for the (a) quark-enriched jets with $E_{cal}^{jet} < 19$ GeV and (b) gluon-enriched jets with $E_{cal}^{jet} > 13$ GeV.

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. The differences reported here are not very sensitive to our choice of selection criteria [11].

References

- [1] Y.K. Kim (AMY Collaboration), Phys. Rev. Lett. **63**, 1772 (1989).
- [2] A. Petersen *et al.* (Mark II Collaboration), Phys. Rev. Lett. **55**, 1954 (1985).
- [3] W. Braunschweig *et al.* (TASSO Collaboration), Z. Phys. **C45**, 1 (1989).
- [4] W. Bartel *et al.* (JADE Collaboration), Phys. Lett. **123B**, 460 (1983).
- [5] R.J. Madaras *et al.* (TPC Collaboration), Rencontre de Moriond on Strong Interactions and Gauge Theories, Les Arcs (1986).
- [6] Cello Collaboration, contributed paper at the International Symp. on Lepton and Photon Interactions at High Energies, Hamburg (1987).
- [7] M. Derrick *et al.* (HRS Collaboration), Phys. Lett. **165B**, 449 (1985); K. Sugano, Int. J. Mod. Phys. **A3**, 2249 (1988).
- [8] T. Kumita *et al.* (AMY Collaboration) KEK preprint 89-188, submitted to Physical Review D.
- [9] S. Bethke, LBL-25247, March 1988. Presented at XXII Rencontre de Moriond, March 1988.
- [10] W. Bartel *et al.* (Jade Collaboration), Z. Phys. **C21** (1983); Phys. Lett. **134B**, 275 (1984); **157B**, 340 (1985); M. Aihara *et al.* (TPC Collaboration), Z. Phys. **C28**, 31 (1985); M. Althoff *et al.* (TASSO Collaboration), Z. Phys. **C29**, 29 (1985).
- [11] Y.K. Kim (AMY Collaboration), Ph.D. Thesis, University of Rochester (1990), unpublished.
- [12] M. Bengtsson, T. Sjöstrand, Phys. Lett. **185B**, 435 (1987). M. Bengtsson, T. Sjöstrand, Nucl. Phys. **B289**, 810 (1987).
- [13] P. Hoyer, P. Osland, H.G. Sander, T.F. Walsh, P.M. Zerwas, Nucl. Phys. **B161**, 349 (1979).

DISCUSSION

Q. R. Blair (ANL): Are there plans to run at lower \sqrt{s} to provide quark jet data that better overlaps the gluon jet data?

A. M. H. Ye: The data are limited by the energy range of the accelerator. There is an overlap, but it is only over a narrow range of jet energies.