EXPERIMENTAL EVIDENCE FOR DIFFERENCES IN $\langle p_\perp \rangle$ BETWEEN QUARK JETS AND GLUON JETS

JADE Collaboration

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We want to dedicate this work to our friend Peter Dittmann who contributed so much to the JADE experiment and who died on 31.8.1982.

We have studied the transverse momentum $p_\perp$ of particles within jets as a function of jet energy using planar 3-jet final states produced in the reaction $e^+e^- \to$ hadrons at CM energies of 22 GeV and 29–36.4 GeV. At a given jet energy, the mean value $\langle p_\perp \rangle$ of the lowest energy jet is found to be larger than that of the other jets. First order QCD simula-

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tions indicate, rather independently of the fragmentation scheme used, that the lowest energy jet has the largest probability of representing the debris of the gluon. The observed difference in $\langle p_\perp \rangle$ of the jets cannot be reproduced by a model with identical quark and gluon fragmentations. Assuming quark and gluon jets to differ only in the rms transverse momentum σ_q of the secondary quarks, a value of about 300 MeV for quark jets and of about 500 MeV for gluon jets describe the $\langle p_\perp \rangle$ behaviour of the data.

It has recently become apparent that the jetlike structures of hadron final states produced by high energy electron positron annihilation resemble the distributions of quarks and gluons predicted by QCD. In the majority of events, the hadrons show a clear 2-jet structure with an angular distribution of the jet axis as predicted for the process $e^+e^- \to q\bar{q}$. The angle and energy distributions of the 3-jet events suggest that they are due to gluon bremsstrahlung [1] $e^+e^- \to q\bar{q}g$. Furthermore, evidence was recently reported for a 4-jet structure [2] as expected from higher order diagrams.

An important further step in testing the basic QCD assumptions would be to positively identify the jet initiated by the primary gluon. At high energies, gluon jets are predicted [3] to differ from quark jets of the same energy as a result of the 3-gluon coupling and the larger colour charge of the gluon. In a previous publication [4], evidence was reported for differences in the quark and gluon fragmentation in that fragmentation along the colour–anticolour axes reproduces the final state hadron distribution better than fragmentation along the parton directions. This evidence arose mainly from the investigation of particles occurring in the angular regions between the jets.

In this letter we report on a study of particle distributions within jets and present evidence for a broader transverse momentum distribution of gluon jets compared to quark jets. This evidence is based on two assumptions which are well supported by experiment [1]. Firstly, we assume that quarks and gluons are produced as predicted [5] by perturbative QCD. (Our considerations are essentially limited to the lowest order processes $e^+e^- \to q\bar{q}$ and $q\bar{q}g$, though we ascertain that the observed effects cannot be explained by models which include second order terms). The second assumption is that the conversion of quarks and gluons into hadrons can be described by standard fragmentation models [6–8].

The analysis is based on 18424 events of the type $e^+e^- \to$ hadrons measured with the JADE detector at PETRA at centre-of-mass energies between 29 and 36.4 GeV and on 1945 such events at 22 GeV. A description of the detector, the trigger conditions and the selection of hadronic events is given in ref. [9]. The criteria for the selection of 3-jet events, which are the main subject of the present letter, are the same as in ref. [4]. Events are classified according to their shape by using the eigenvalues Q_1, Q_2, Q_3 of the normalized sphericity tensor, ($Q_1 \leqslant Q_2 \leqslant Q_3$, $Q_1 + Q_2 + Q_3 = 1$), where we denote the unit vector of the principal axes by $\boldsymbol{q}_1, \boldsymbol{q}_2, \boldsymbol{q}_3$. Planar events are defined by $Q_1 < 0.06$ and $Q_2 - Q_1 \geqslant 0.07$ and three jets of particles are defined for these events by maximizing the triplicity.

Caution is required in relating kinematic parameters such as total energies and directions of jets to the same parameters of partons. Partons and jets have different rest masses and the "4-vector" of a jet is generally not identical to that of the parton which gave rise to the jet. In the present analysis, two definitions E_j^e and E_j^d of the jet energy are used. E_j^e is defined as the sum of particle energies within jet j, assuming charged particles to be pions and neutral particles to be photons:

$$E_j^e = \sum_{i=1}^{n_j} E_{j,i} \quad (j = 1, 2, 3) \tag{1}$$

(n_j = number of particles in jet j; $E_{j,i}$ = energy of ith particle in jet j).

The jet direction $\boldsymbol{k}_j$ is given by the vector sum of the particle momenta within the jet. E_j^d is the energy of jet j derived from the jet directions, a procedure which is strictly applicable only in the case of three massless jets:

$$E_j^d = \frac{\sin\theta_{k,l}}{\sin\theta_{12} + \sin\theta_{23} + \sin\theta_{31}} E_{\text{cm}} \quad (j, k, l \text{ cyclic}), \tag{2}$$

where $\theta_{k,l}$ is the angle between the jets k and l projected onto the event plane ($\boldsymbol{q}_3, \boldsymbol{q}_2$). Note that, even for an ideal detector, E_j^d and E_j^e do not coincide, since, at present energies, jet masses are not negligible in comparison with jet total energies.

The three jets are ordered according to

$$E_1^d > E_2^d > E_3^d . \quad (3)$$

Events with one or more jets containing less than 4 particles, or having $E_j^e < 2$ GeV, are rejected. 2048 events obtained at CM energies above 29 GeV and 307 events at 22 GeV survive these cuts.

From the bremsstrahlung-like energy spectrum of the gluon in the process $e^+e^- \to q\bar{q}g$, one would expect the lowest energy jet (#3) to have the highest probability of being the gluon jet. This behaviour was quantitatively confirmed by means of model calculations, which were also used to study how differences between quark and gluon fragmentation would manifest themselves in the final hadron distributions.

The model calculations were similar to the ones described in ref. [4]. The partons of the reaction $e^+e^- \to q\bar{q}g$ were generated according to first order QCD (using a quark gluon coupling strength $\alpha_s = 12\pi/23\ln(s/\Lambda^2)$ with $\Lambda = 0.3$ GeV). Three slightly different fragmentation schemes were studied to describe the conversion of quarks and gluons into hadrons. Two schemes are based on the model of Hoyer et al. [7], in which quarks and gluons fragment independently of each other (according to the prescription of Field and Feynman) with a gaussian distribution of the transverse momenta of the secondary quarks relative to the primary quark direction $d\sigma/d^2p_\perp \sim \exp(-p_\perp^2/2\sigma_{q,q}^2)$, where for a gluon fragmentation $\sigma_{q,q}$ is replaced by $\sigma_{q,g}$. Gluons are treated as quark–antiquark pairs but the gluon momentum is carried entirely by one of the quarks, which subsequently fragments either exactly like a primary quark (this is the first scheme, denoted by q = g) or with an average transverse momentum larger than that of a quark jet (denoted q ≠ g). The third scheme is based on the Lund model, in which fragmentation proceeds along the colour flux lines as the primary partons move apart. For $q\bar{q}g$-events, these flux lines do not directly connect quark and antiquark; they rather proceed via the gluon as an intermediary. For details see ref. [8]. In the Lund model, gluons (by construction) fragment differently from quarks. The parameters of the Hoyer et al. [7], and of the Lund [8] models have been adjusted to yield reasonable agreement not only for the 3-jet data, but also for the overall data sample [‡1]. It was found that the experimental data are described better by the Lund model than by the Hoyer et al. (see also refs. [4] and [10]). The present analysis, however, does not depend on the details of this parametrization.

Monte Carlo techniques were used to calculate the four-momenta of the final state particles, including bremsstrahlung from the initial leptons. In a second step, the generated events were passed through a detector simulation with all known imperfections. These simulated data were processed by the same chain of computer programs and cuts as the real data. The model calculations were used to investigate whether the lowest energy jet (#3) is preferentially created by the gluon and, if so, how differences between quark and gluon fragmentation might show up in the distribution of the final state hadrons. A crucial quantity in this context is the angle δ between the parton momentum and the closest reconstructed jet direction $\boldsymbol{k}_j$. The average value of δ was found to follow a universal curve $\sim 1/E_j^e$, ranging from $\langle\delta\rangle \approx 12°$ at $E_j^e = 5$ GeV to $\langle\delta\rangle \approx 6°$ at 12 GeV. At centre-of-mass energies of 33 GeV (22 GeV) the probability for jet #1, #2, and #3 being closest to the gluon direction is 12% (9%), 22% (20%), and 51% (34%), respectively. The probabilities do not add up to 100%; residual $q\bar{q}$-events faking 3-jet structures account for the difference. Figs. 1a and 1b show the probabilities η_j for jet j being closest to the gluon direction as a function of E_j^e and E_j^d, respectively, obtained from model calculations at a fixed CM energy of 33 GeV. These results, which were found to be nearly independent of the assumed gluon fragmentation, confirm the qualitative expectation that the lowest energy jet (#3) is predominantly produced by the gluon. The decrease of η_3 at jet energies below 5 GeV is due to the increasing portion of residual $q\bar{q}$-events. Compared with fig. 1a, fig. 1b shows only a small overlap between E_2^d and E_3^d and within this overlap region only small differences between η_2 and η_3. This behaviour is a consequence of the fact that eq. (2) is used in the determination of E_j^d and in the definition (3) of j, and therefore the condition $E_2^d \approx E_3^d$ preferentially selects events exhibiting 2-fold symmetry about $\boldsymbol{k}_1$, for

‡1 The following parameters were used for all models: A production ratio of secondary u, d and s quarks of 3 : 3 : 1, equal fraction of pseudoscalar and vector mesons and $\sigma_{q,q} = 330$ MeV. For the Hoyer et al. (Lund) model a fragmentation function $f(z) = 1 - a + 3a(1-z)^2$ [$f(z) = (1-z)^\beta$] with $a = 0.5$ ($\beta = 0.4$) for u, d and s, and $a = 0$ ($\beta = 0.1$) for c and b quarks was taken.

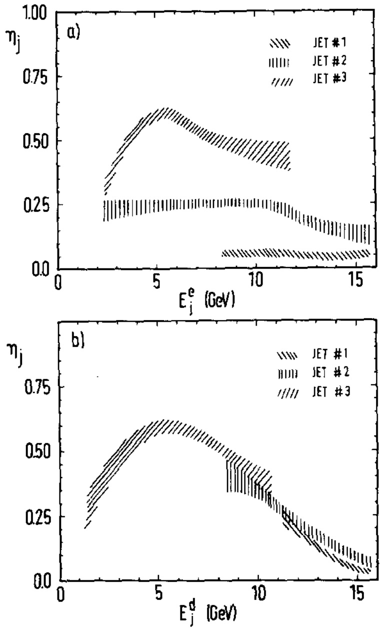

Fig. 1. The probability η_j for jet j being closest to the gluon direction as a function of E_j^e and E_j^d, respectively, obtained from model calculations at a fixed CM energy of 33 GeV. The widths of the shaded areas indicate the statistical errors.

which jets #2 and #3 have equal probability of being a gluon. To enlarge the overlap region and to get different values for η_j, one needs a data sample containing events from different CM energies. The comparison is then made between jet #3 at high E_{cm} and jet #2 at lower E_{cm}. With either definition for E_j we have looked for differences between the particle distribution of quark- and gluon jets of the same energy.

For the experimental data with $E_{\text{cm}} > 29$ GeV, fig. 2a shows the average transverse momentum of the charged and neutral particles within a jet j relative to the jet axis $\boldsymbol{k}_j$ for all three jets as a function of E_j^e. At a given E_j^e, jet #3, the one preferentially created by the gluon, shows a larger $\langle p_\perp \rangle$ than jet #2 and jet #1. As a quantative measure of the effect, the ratio $r_{32} = \langle p_\perp \rangle_{j=3} / \langle p_\perp \rangle_{j=2}$ was determined for each energy bin and then averaged within the range 6 GeV $\leqslant E_j^e \leqslant$ 10 GeV. The value obtained is listed in the first row of table 1. Only statistical errors are quoted there and shown in the figure. Systematic uncertainties in the $\langle p_\perp \rangle_j$ are highly correlated between the jets and are expected to give negligible contributions to $\langle r_{32} \rangle$. To check this, $\langle p_\perp \rangle$ was calculated applying a number of

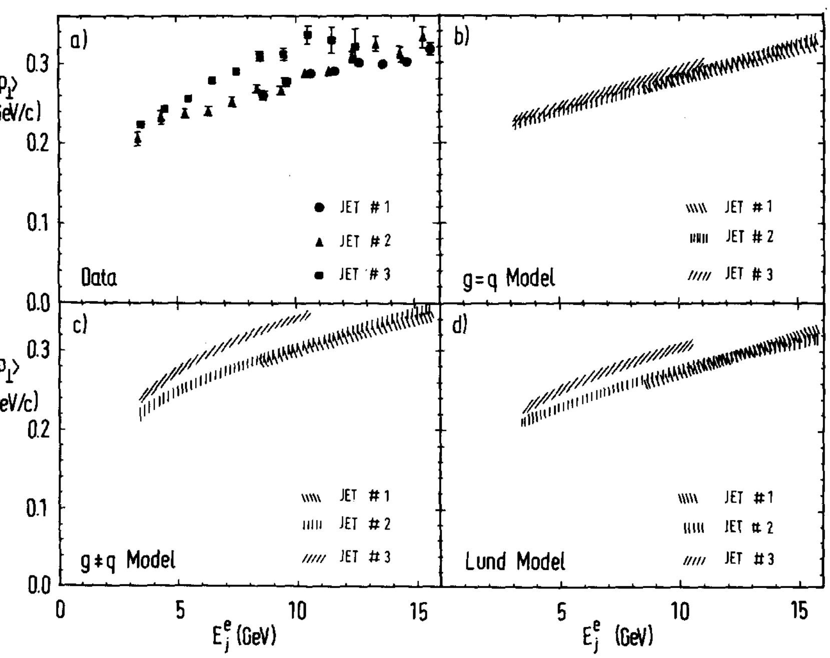

Fig. 2. The average transverse momentum of the charged and neutral particles within a jet relative to the jet axis for the three jets as a function of E_j^e for (a) the experimental data with $E_{\text{cm}} > 29$ GeV, and (b), (c), (d) for the prediction of the q = g model, the q ≠ g model ($\sigma_{q,q}$ = 330 MeV, $\sigma_{q,g}$ = 500 MeV), and the Lund model, respectively.

Table 1
The ratio $\langle r_{32}\rangle$ of $\langle p_t\rangle$ of the lowest energy jet to $\langle p_t\rangle$ of the medium energy jet for different particle and event selection criteria. $\langle r_{32}\rangle$ represents an average of the 4 bins covering the range 6 GeV $\leqslant E_j^e \leqslant$ 10 GeV. Row 1 gives the ratio for the data shown in fig. 2a. Row 2 shows this ratio for charged particles only; row 3 for particles exceeding an energy of 0.5 GeV, row 4 for particles within a 50° cone around the jet axis; and row 5 for particles pointing into the hemisphere towards the highest energy jet. The ratio in rows 6 and 7 include all particles, but include only those events for which the total energy agrees within 20% with E_{cm} (row 6) or for which the angle between q_1 and the beam direction is less than 70° (row 7). The ratios given in rows 8 and 9 are obtained from the data shown in figs. 3a and 4a, respectively. The corresponding ratios are also given for the three model calculations.

Row	Variables used in $\langle r_{32}\rangle$		Further cuts	$\langle r_{32}\rangle = \langle\langle p_t\rangle_{j=3}/\langle p_t\rangle_{j=2}\rangle$ 6 GeV $\leqslant E_j \leqslant$ 10 GeV			
	p_t	E_j		data	Hoyer et al.		Lund
					g = q	g ≠ q	
1	$p_\perp$	E_j^e		1.16 ± 0.02	1.03 ± 0.02	1.13 ± 0.02	1.10 ± 0.02
			particle cut:				
2	$p_\perp$	E_j^e	charged only	1.18 ± 0.02	1.04 ± 0.02	1.15 ± 0.02	1.10 ± 0.02
3	$p_\perp$	E_j^e	$E_{ij} > 0.5$ GeV	1.17 ± 0.02	1.04 ± 0.02	1.12 ± 0.02	1.10 ± 0.02
4	$p_\perp$	E_j^e	$\measuredangle(p_{ij}, k_j) \leqslant 50°$	1.16 ± 0.02	1.03 ± 0.02	1.13 ± 0.02	1.10 ± 0.02
5	$p_\perp$	E_j^e	$\measuredangle(p_{ij}, k_1) < \measuredangle(k_j, k_1)$ (projected onto (q_2, q_3))	1.16 ± 0.02	1.02 ± 0.02	1.14 ± 0.03	1.10 ± 0.03
			event cut:				
6	$p_\perp$	E_j^e	$0.8 \leqslant E_{cm}^{-1} \sum_{j=1}^{3} E_j^e \leqslant 1.2$	1.14 ± 0.03	1.10 ± 0.03	1.13 ± 0.03	1.10 ± 0.03
7	$p_\perp$	E_j^e	$\lvert\cos(q_1, z)\rvert > 0.35$	1.17 ± 0.02	1.04 ± 0.02	1.15 ± 0.02	1.09 ± 0.03
8	$p_\perp$	E_j^d		1.13 ± 0.02	1.01 ± 0.01	1.10 ± 0.02	1.08 ± 0.02
9	$p_\perp^{out}$	E_j^e		1.16 ± 0.02	1.01 ± 0.02	1.12 ± 0.02	1.09 ± 0.02

different cuts and particle selection criteria. The resulting $\langle r_{32}\rangle$ values, some of which are listed in table 1, rows 2–7, were found to be the same within the statistical errors. It was also verified that the larger $\langle p_\perp\rangle$ of jet #3 is due to different shapes of the differential $p_\perp$-distribution. These observations suggest a broader distribution of the gluon jet.

To ensure that the observed effect is not caused by possible biasses of the jet selection procedure we show in fig. 2b–2d and table 1 the $\langle p_\perp\rangle$ distributions and $\langle r_{32}\rangle$ values predicted by the 3 models studied. The model results should contain any possible biasses as well. For the q = g model ($\sigma_{q,g} = \sigma_{q,q}$ = 330 MeV was chosen) $\langle p_\perp\rangle$ of all three jets follows nearly a universal curve (fig. 2b) and $\langle r_{32}\rangle$ is found to be close to 1. The observed behaviour of jet #3, however, is at least qualitatively reproduced if we enlarge $\sigma_{q,g}$ to 500 MeV [‡2] (q ≠ g in fig. 2c and table) or if we use the Lund model.

In a plot of $\langle p_\perp\rangle$ versus E_j^d instead of E_j^e one gets a different gluon content $\eta_3 > \eta_2$ in the region of overlap only, if the data cover a wide range of CM energies. In fig. 3a data down to E_{cm} = 22 GeV are included. Again the higher $\langle p_\perp\rangle$ of jet #3 cannot be reproduced by the q = g model (fig. 3b) but by the q ≠ g model and the Lund model, as evident from the $\langle r_{32}\rangle$ given in row 8 of table 1.

For fragmentation along the colour flux lines, jet broadening of the q$\bar{\text{q}}$q-events is expected to occur mainly in the plane containing the primary partons. The data, however, also show that $\langle p_\perp^{out}\rangle$, the average momentum normal to the event plane (q_2, q_3), is

[‡2] This description is not at all unique, and there exist other ways of describing the different behaviour of quark and gluon jets. Our aim is to demonstrate, how large the difference between $\sigma_{q,q}$ and $\sigma_{q,g}$ has to be in order to account for the data, if all other parameters are kept constant.

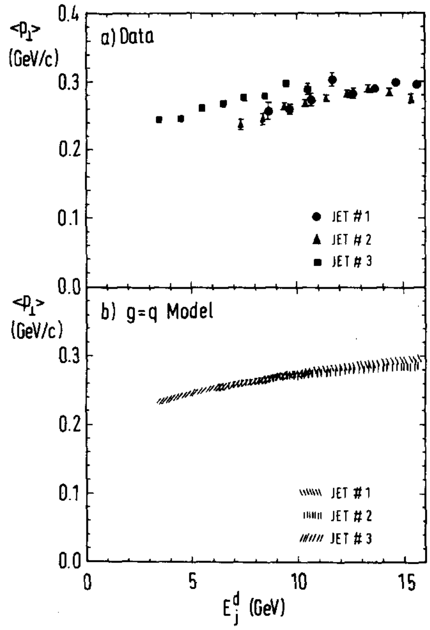

Fig. 3. (a) The average transverse momentum of charged and neutral particles within a jet for all three jets as a function of E_j^d including all data at E_{cm} = 22 GeV and E_{cm} > 29 GeV; (b) the same for the prediction of the q = g model.

largest for jet #3. Fig. 4 shows $\langle p_\perp^{out} \rangle$ for the three jets versus E_j^e, together with the results from the two versions of the model of Hoyer et al. Again, the observed behaviour is not reproduced by the q = g version, while the version with increased $\sigma_{q,g}$ reproduces the above effect. The Lund model also shows $\langle p_\perp^{out} \rangle$ of jet #3 larger than that of jets #2 and #1 of similar energy [‡3]. The last row of table 1 shows the resulting values of $\langle r_{32} \rangle$.

The model calculations used so far are based on perturbative QCD and limited to first order terms in the quark gluon coupling strength α_s. We also considered whether the observed broadening of jet #3 might be explained by including 2nd order QCD diagrams. For this purpose, 4-parton final states were generated [11] (requiring the masses of all possible parton pairs to exceed 5 GeV), which subsequently fragment. Subjecting only these "4-parton" model events to the above 3-jet analysis, we find a small increase of $\langle p_\perp \rangle$ for all three jets, but the enhancement

[‡3] In the present version of the Lund model this behaviour has its more technical origin in the special treatment of the leading meson of the gluon jet.

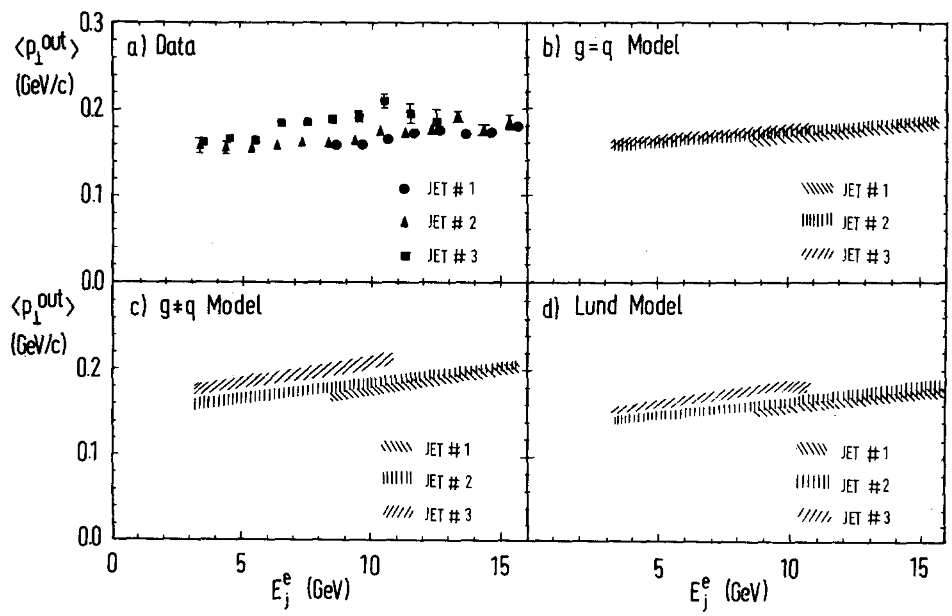

Fig. 4. (a) The average momentum of the particles normal to the event plane (q_2, q_3) as a function of E_j^e for the data with E_{cm} > 29 GeV; (b), (c), (d) for the prediction of the q = g model, the q ≠ g model ($\sigma_{q,q}$ = 330 MeV, $\sigma_{q,g}$ = 500 MeV) and the Lund model, respectively.

of jet #3 relative to jet #2 and #1 is less than for example that in fig. 2d. The resulting value of $\langle r_{32} \rangle$ for these "4-parton"-events alone is 1.07 ± 0.03. Furthermore, we expect at most 20% of our 3-jet event sample to be due to these "4-parton" events. Combining these facts, the larger $\langle p_\perp \rangle$ of jet #3 in the data cannot be described by including 2nd order diagrams in the q = g model.

In summary, at a given jet energy the average transverse momentum $\langle p_\perp \rangle$ of particles within the lowest energy jet of a 3-jet event is observed to be larger than the $\langle p_\perp \rangle$ of the other jets. For jet energies between 6 and 10 GeV, an excess in $\langle p_\perp \rangle$ of the lowest energy jet relative to the medium energy jet of about 15% is found. To describe this observation within the framework of perturbative QCD and the standard fragmentation models, the gluon fragmentation has to be broader than the quark fragmentation. For independent parton fragmentation, parametrized according to Field and Feynman one needs a σ_q of about 300 MeV for quark jets and of about 500 MeV for gluon jets to explain the data, if the remaining fragmentation parameters are kept constant.

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