COLLEPS 81/29
November 1981

Some Comments on Jet Structure at LEP Energies.

G. Gustafson, T. Sjöstrand

Dept. of Theoretical Physics
University of Lund
LUND, Sweden

Abstract:

We discuss some of the characteristic event shapes at LEP energies, in particular the three- or four-jet events where two of the jets are very close in angle. In the Lund model, such two-jet systems will show a behaviour different from what would be expected if jets fragmented independently, e.g. the fragmentation functions will be harder. These types of events could also be used to determine the strength of the three-gluon coupling.

The study of jets can be divided into three parts. Firstly, one wishes to prove (or disprove) the validity of perturbative QCD, with massless, spin 1, coloured and hence self-interacting gluons. Secondly, the mechanism of hadronization is still not well understood, and will require much further study. Thirdly, properties that are not directly related to QCD, such as e.g. the Kobayashi-Maskawa matrix of flavour mixing, must be studied with the understanding that quarks, or even hadrons, do not appear in isolation.

We will here present some comments concerning the first two points above. It should from the onset be emphasized that this is only a qualitative survey of some features that could become of interest at LEP energies. For an actual observation and interpretation of such features more quantitative studies will be required.

The two main advantages of jet physics at LEP over the present explorations at PETRA and PEP are the larger jet energies and the higher event rate at the Z^0 pole. Taken together, this means that it will, with various cuts, be possible to study a number of distinct event shape types.

Of these, events with two, three or more narrow and well separated jets, "Mercedes-stars" etc., will of course be the most spectacular ones. They will provide some handle on the relevant matrix elements, since this is the region where perturbative calculations should work well. They will also enable a study of the differences between quark and gluon fragmentation. A gluon fragmentation function could e.g. be obtained as the difference between three-jet and two-jet fragmentation functions (where the energy fraction variable z is normalized independently for each jet).

More typical event shapes will however be the ones with two or three clearly separated jets, but with one or more of these showing a subjet structure. This structure may e.g. provide important information on whether a three-gluon coupling $g \to gg$ exists and has the proper magnitude as predicted by perturbative QCD. If no three-gluon coupling exists, events with two gluon jets close to each other will be rather rare. Normally it is, however, not possible to distinguish quark and gluon jets in the individual events. An exception is if charm and bottom jets can be identified using the electrons and muons produced in semileptonic decays. Note however that both the quark and the antiquark jet have to be identified. Another way out is to observe six-jet events, where the jets are clustered two and two. For such complicated jet geometrics it is however very difficult to envisage a systematic study program at LEP energies.

As a more natural case we propose to study four-jet events where two jets lie very close to each other. Such events have been generated as follows. In a three-jet structure, with the three outgoing partons q, $\bar{q}$ and g separated by 120°, one of the partons is assumed to be off-mass-shell by an amount M^2, where M^2 is distributed according to a spectrum dM^2/M^2. The subsequent decay to two on-mass-shell partons, $q \to qg$ or $g \to gg$, is taken according to the Altarelli-Parisi splitting functions,

where the longitudinal splitting variable z together with M^2 also defines the $p_{\perp}^2$ of the partons produced.

The choice of 120 degrees between the three "original" partons is not critical, so long as the jets are very clearly separated in angle. On the other hand, the cuts made on M are of some importance. We have allowed $5 \text{ GeV} < M < 20 \text{ GeV}$ for 90 GeV events, where the lower cut represents a practical limit on the ability to see a subjet structure and the upper limit borders the region of clearcut four-jet structures. In practice, hadronization effects will play an important rôle. Hence it is realistic to assume that measures are constructed with the intention to find partons primarily in the 10-15 GeV range, which in practice will accept a large fraction of the events in the broader range. Finally, a further cut is made by requiring a minimum energy of 3 GeV for each jet.

The Altarelli-Parisi splitting functions for $q \to qg$ and $g \to gg$ are rather similar in shape for the normal case when the q jet cannot be identified (in our simulations we have used an equal mixture of u and d jets). The energy is shared rather unevenly between the two jets. (However, if the three-gluon coupling should not exist, or have a strength lower than the QCD one, the existence of the decay mode $g \to q\bar{q}$, now assumed to be down by an order of magnitude compared to $g \to gg$, would have to be taken into account. In that case the energy will be more evenly shared between the two subjets.)

For the soft fragmentation part we use the Lund model, in which a stringlike colour flux tube is stretched out between the partons. Starting from the quark it follows the colour of the gluons and ends at the antiquark. This string, stretched between two partons, will get a transverse motion; the transverse velocity is given by $c \cdot \cos \theta/2$ (for massless partons) where θ is the opening angle between the partons. This velocity becomes very large when θ becomes small. Hence in the breakup, fewer low-momenta particles are produced than would be the case if e.g. the jets were allowed to fragment independently and then joined in the center. Such a model will be used for comparison purposes.

In Fig. 1 we show fragmentation functions for gg and qg jet systems, defined with respect to the energy and direction of the off-mass-shell g or q . As a comparison we also show the fragmentation function of a single forward moving g or q . Noteworthy is the fact that for low z the difference between gg and g or qg and q is rather small. This is connected with the fact that in both the gg and the g cases two string pieces are connected to the q and $\bar{q}$ jets, strings which give low-energy particles, while the extra string piece between the two gluons in the gg case will not produce that many low-energy particles. Similarly, both the q and the qg will be connected to the rest of the system by only one string piece.

What happens if instead the jets are allowed to fragment independently is shown in Fig. 2. The spectra for gg and qg jets then become somewhat softer, the difference being most marked for low z . An accurate reconstruction of particles below 1 GeV should be required to study this kind of features.

We return to Fig. 1 and now consider the difference between a gg and a qg jet system. As can be seen, the spectrum of the former is markedly softer, with very few particles above $z > 0.3$. This could be used to determine the strength of the three-gluon coupling as follows. Plot the fragmentation function for all close two-jet systems. Use the large-z tail to determine

the qg contribution and subtract it off. The remaining part will then correspond to the contribution from gg jets. The subtraction of the qg part can be made more or less model independent by using experimentally observed three-jet events where two of the jets lie very close, in the same sense as the jets considered above.

Particles produced in the breakup of a string between two close jets will be boosted forward by the movement of the string piece. This boost will influence heavy particles more than light ones. One result of this can be seen in Figs 3 and 4, where fragmentation functions for pions and kaons are shown for the cases of strings fragmenting and of independent jet fragmentation. For $z > 0.05$, the difference is minor for pions, but the number of kaons differs significantly in the two cases. This result can also be formulated as a prediction that for these z the K/π ratio will be higher for two close-by jets than for a single jet. This should be a very interesting observation, which would require good π/K separation at momenta in the region above 1.5 GeV.

One of the most obvious features of having a gg or qg jet system is that these will define a plane, with momenta in this plane considerably larger than the momenta out of the plane. This behaviour is shown in Fig. 5, where a thrust-oblateness analysis has been made to determine the jet axis and the axis which maximizes $\Sigma|p_{\perp in}|$. The difference between qg and gg events may prove difficult to observe. The difference in $p_{\perp out}$ however reflects a feature already observed by the JADE group: the $p_{\perp}$ of a gluon jet appears to be slightly broader than that of a quark jet. In our model this is mainly related to the softer fragmentation of gluon jets, which makes the determination of the proper jet axis and event plane more unreliable.

The thrust axis together with the minor axis naturally divides a two-jet structure into a hard and a soft side, i.e. the side with largest and with smallest energy. In Fig. 6 fragmentation functions for the two sides are shown (note that z still refers to the fraction of the total energy taken; for some purposes it may however be interesting to normalize only to the energy of the relevant side). It will be noted that although both the hard and the soft side differ between gg and qg events, the largest difference is obtained on the hard side, on which we normally have the q jet in qg events.

The division into a hard and a soft side may also be used to compare $\langle p_{\perp in} \rangle$ on the two sides. This is shown in Fig. 7. For low z, $\langle p_{\perp in} \rangle$ on the soft side is larger than on the hard side. This is again related to the special structure of the Lund model, in which the strings stretched between the partons may have an outward movement conferred to the fragmentation products.

In conclusion, we note that a good both charged and neutral particle detection and momentum determination is preferable in order to study jet phenomena, both with respect to the basic properties and with respect to more general fragmentation properties. Any π^0 reconstruction is however not required; most interesting properties are inherited by and can be studied via the photon decay products. A $\pi/K/p$ separation ability,

also above 1.5 GeV, will offer many interesting prospects for the study of fragmentation properties. Good muon and electron detection efficiency may prove important e.g. to obtain very clean gluon jet samples, although rates may be expected to be correspondingly lower.

Fig. 1

$\frac{E}{\sigma}\frac{d\sigma}{dp_L} \approx zD(z)$ for all particles

$(\pi^\pm, K^\pm, p, \bar{p}, \gamma, K_L^0, n, \bar{n})$

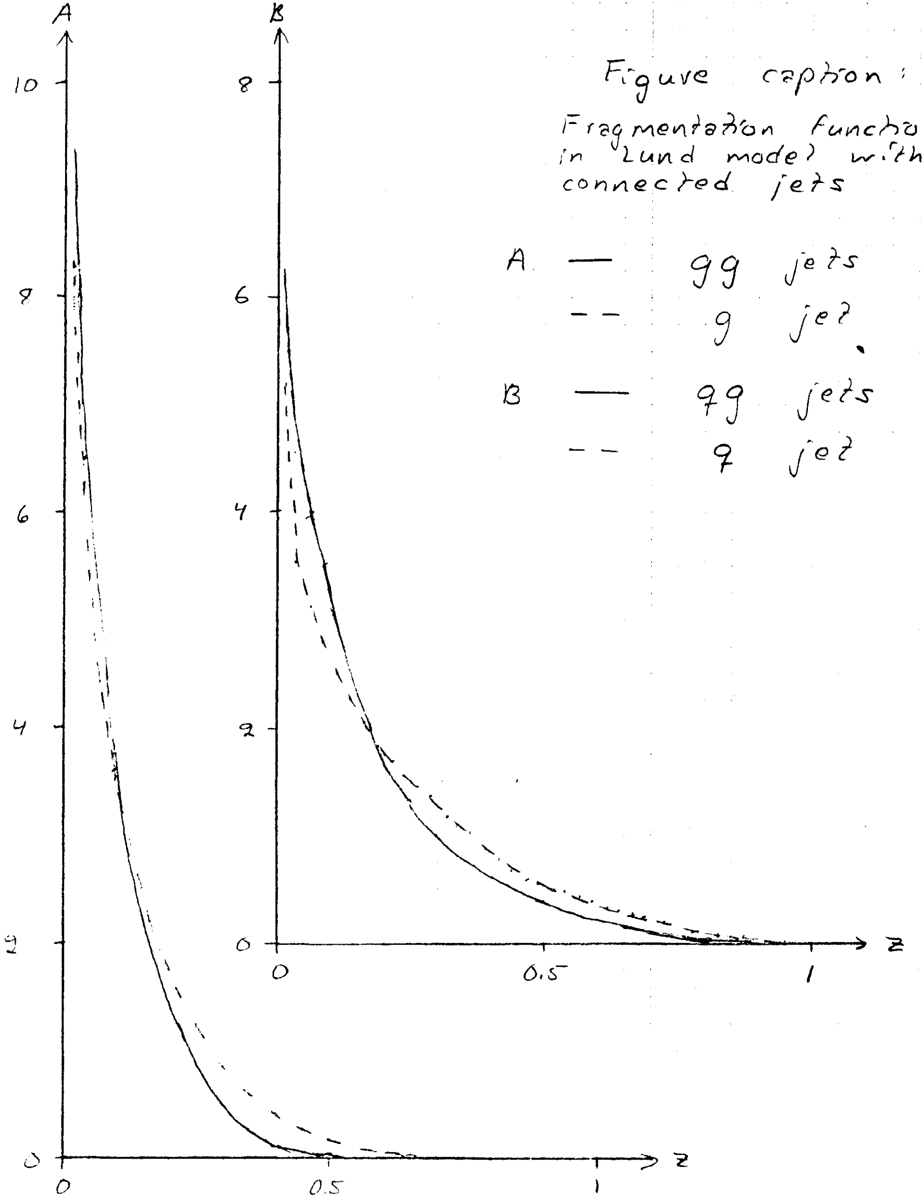

Figure caption:

Fragmentation functions in Lund model with connected jets

(5/11 -81)

Fig. 2 $\frac{E}{\sigma}\frac{d\sigma}{dp_L} \approx zD(z)$ for all particles

$(\pi^\pm, K^\pm, p, \bar{p}, \gamma, K_L^0, n, \bar{n})$

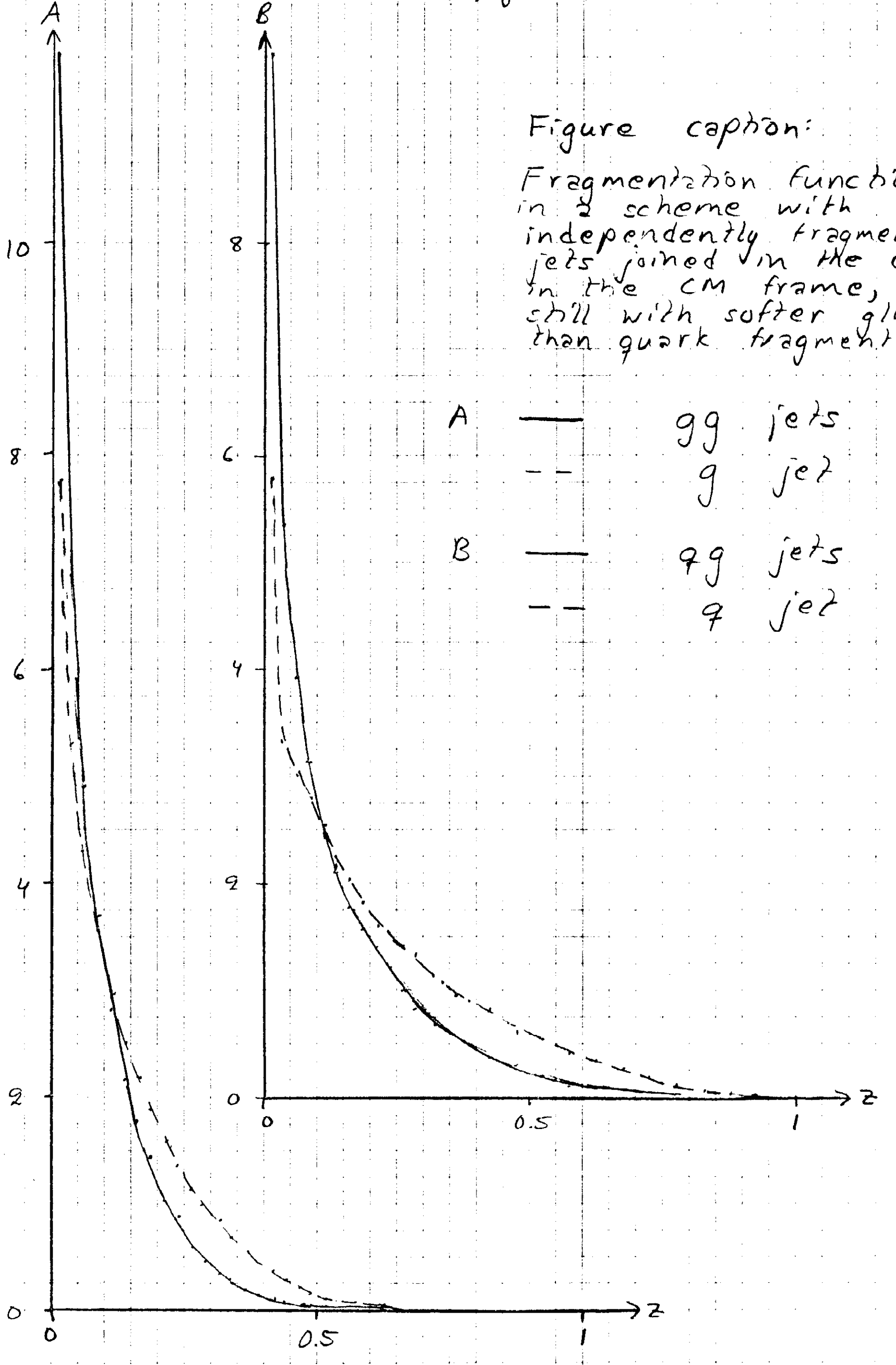

Figure caption:

Fragmentation functions in a scheme with independently fragmenting jets joined in the center in the CM frame, but still with softer gluon than quark fragmentation

(5/11 - 81)

Fig. 3

$\frac{E}{\sigma}\frac{d\sigma}{dp_L}$ for $\pi^\pm$

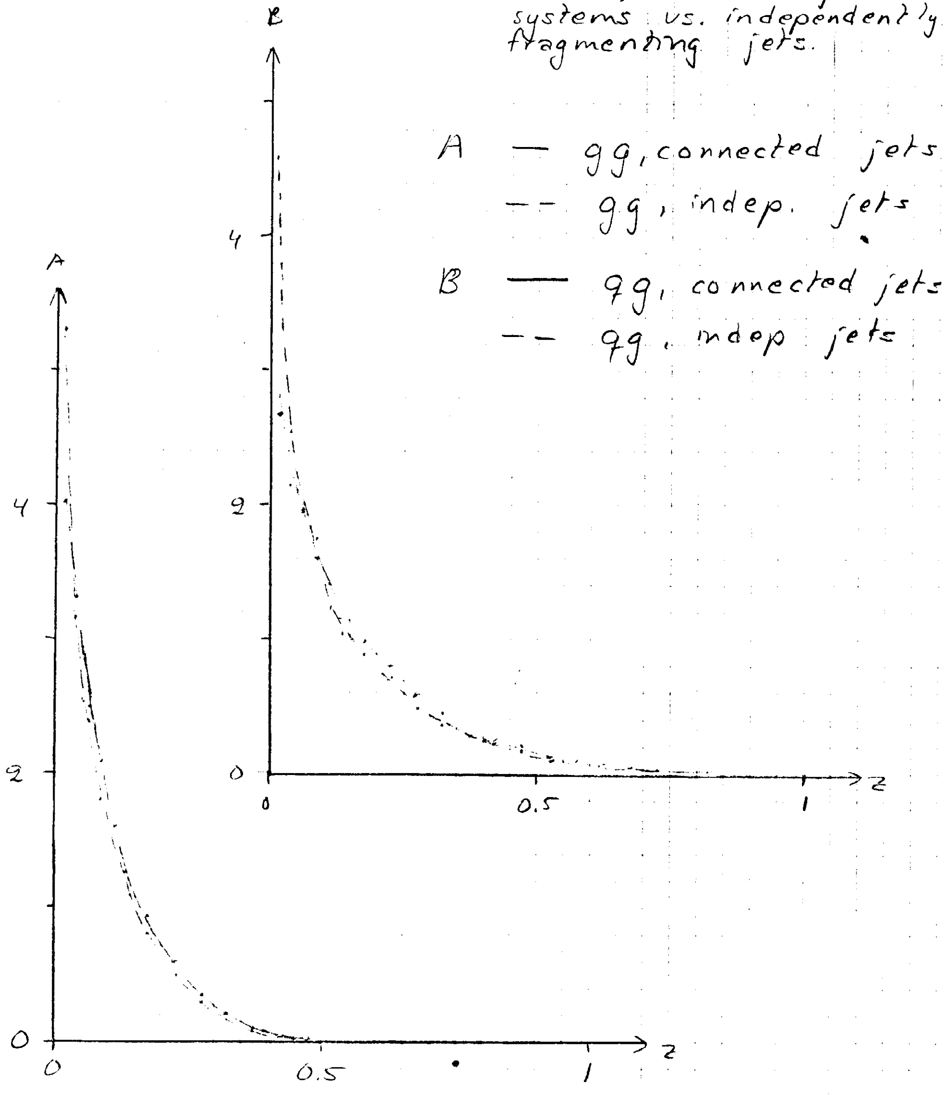

Figure caption:

Fragmentation functions for $\pi^\pm$, connected jet systems vs. independently fragmenting jets.

(5/11 -81)

Fig. 4

$\frac{E}{\sigma}\frac{d\sigma}{dp_L}$ for $K^\pm$

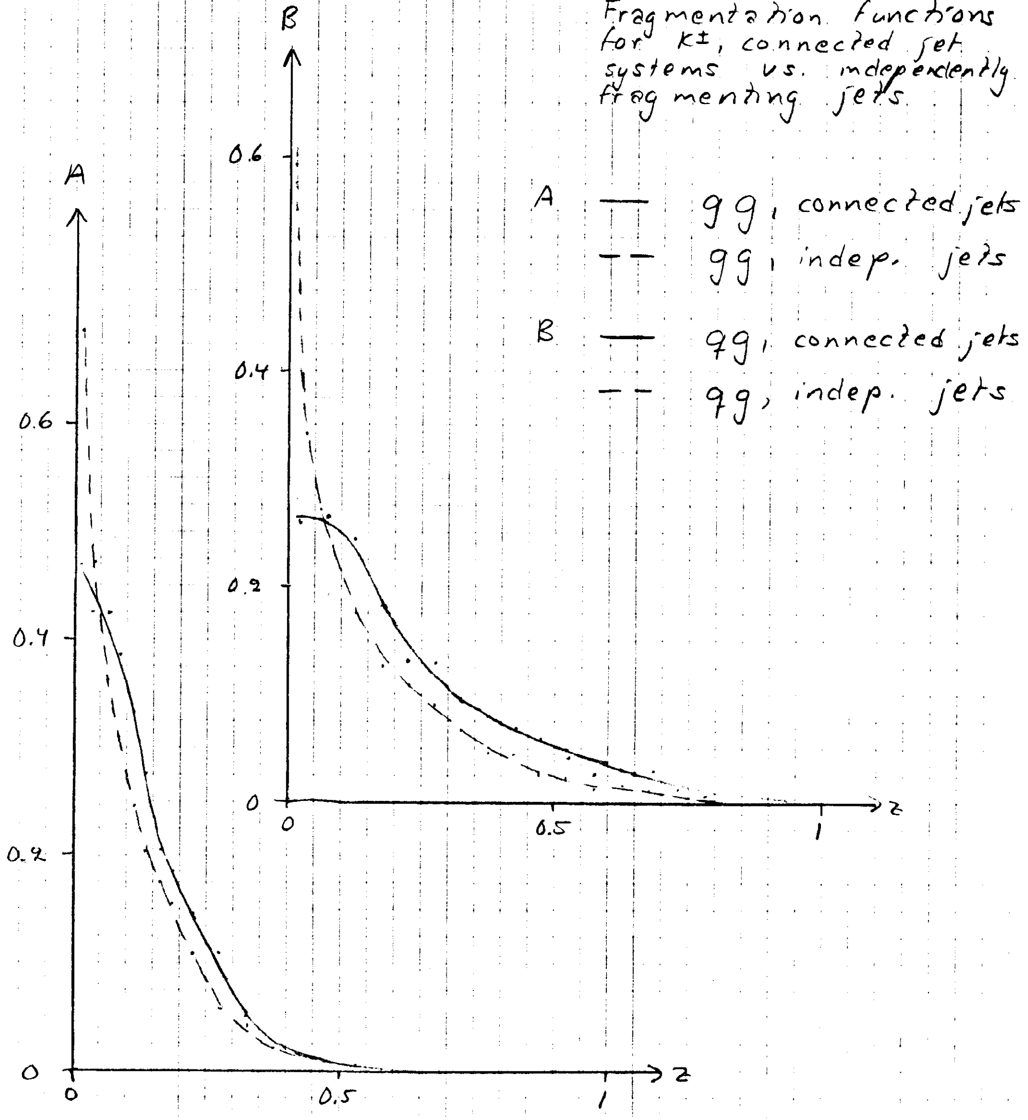

Figure caption:

Fragmentation functions for $K^\pm$, connected jet systems vs. independently fragmenting jets

(5/11 -81)

Fig. 5

$\langle p_{\perp in} \rangle$ and $\langle p_{\perp out} \rangle$ for all particles

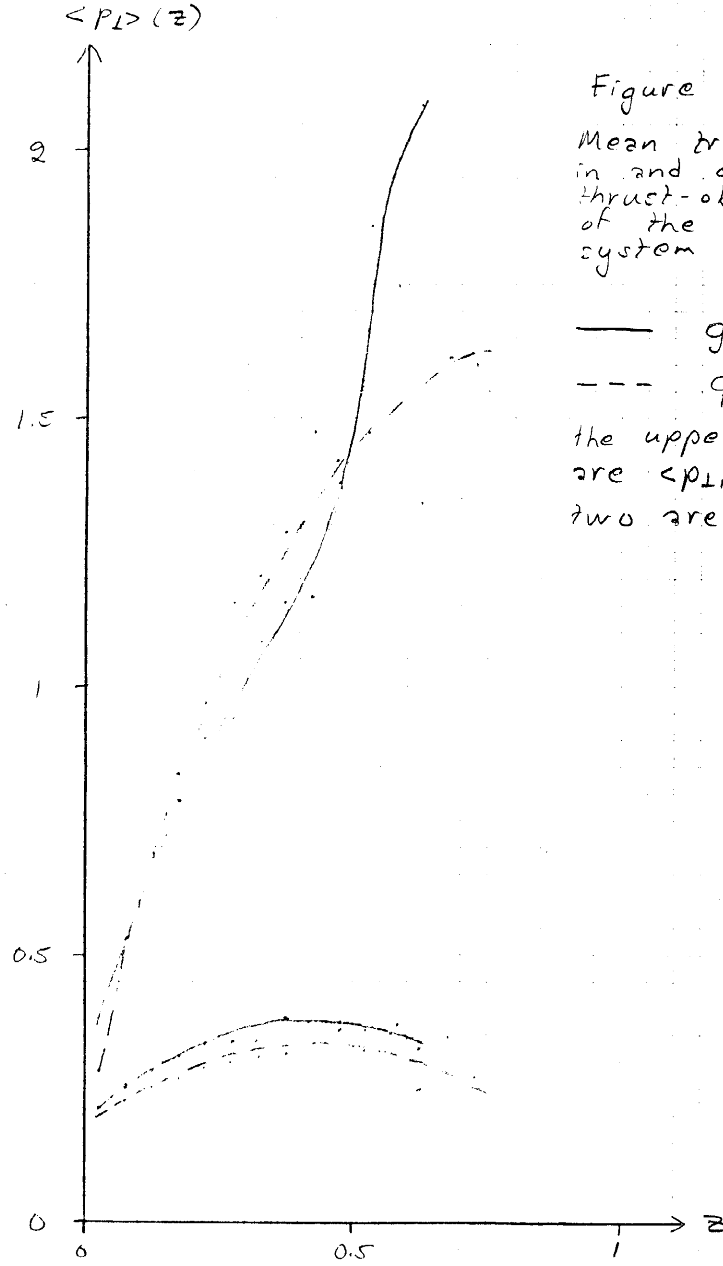

Figure caption

Mean transverse momentum in and out of the thrust-oblateness plane of the forward jet system

— gg jets

- - - qg jets

the upper two curves are $\langle p_{\perp in} \rangle$, the lower two are $\langle p_{\perp out} \rangle$

(6/11 -81)

Fig. 6

$\frac{E}{\sigma} \frac{d\sigma}{dp_L} \approx z D(z)$, hard and soft side,
for all particles

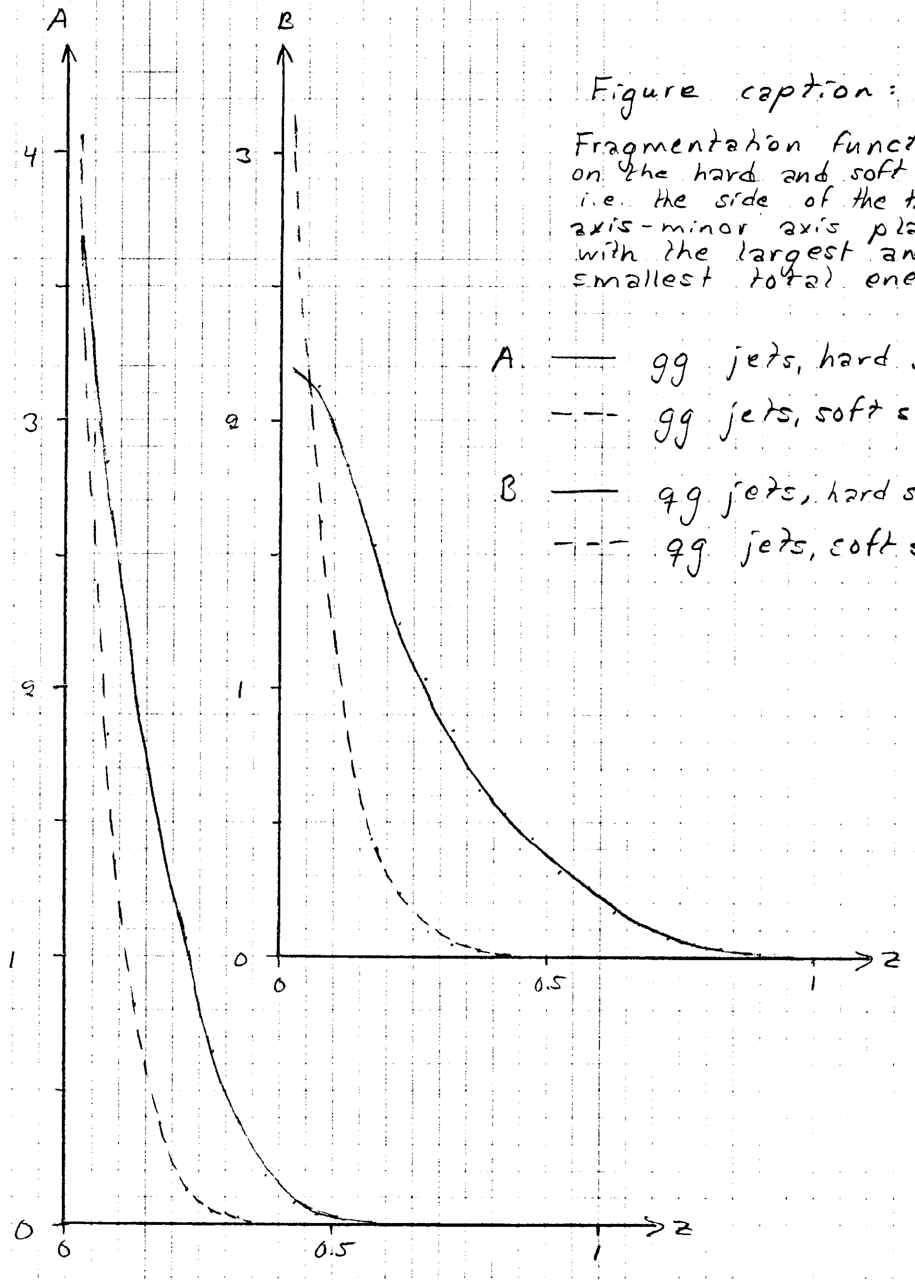

Figure caption:

Fragmentation functions on the hard and soft side i.e. the side of the thrust axis-minor axis plane with the largest and smallest total energy

A. — gg jets, hard side
- - - gg jets, soft side

B. — qg jets, hard side
- - - qg jets, soft side

(6/11 -81)

Fig. 7

$\langle p_{\perp in} \rangle$, hard and soft side, for all particles

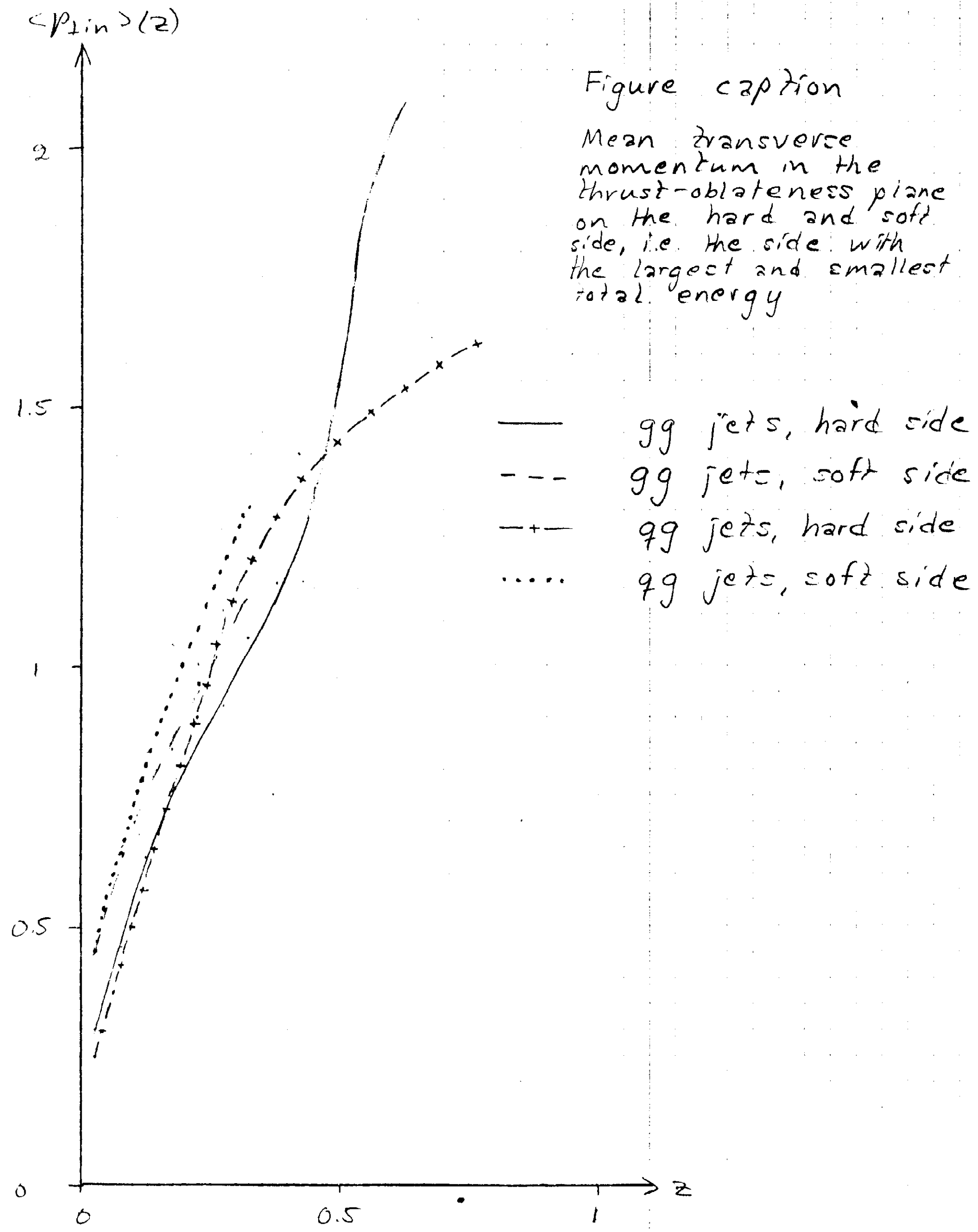

Figure caption

Mean transverse momentum in the thrust-oblateness plane on the hard and soft side, i.e. the side with the largest and smallest total energy