SOFT GLUON RADIATION AND A NEW SIMULATION SCHEME FOR QCD JETS*,**

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Initial results of a new Monte Carlo simulation scheme for jet evolution in perturbative QCD, taking into account soft gluon interference effects, are reviewed. When combined with a hadronization model based on the preconfinement and phase-space decay of colour-singlet clusters, the approach is in good agreement with a wide range of data on jet properties in e^+e^- annihilation and hard hadron collisions.

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A Monte Carlo approach to perturbative QCD calculations in leading-logarithmic approximation has been developed by several authors [1–8] over the past few years and has been found to describe quite well many features of the hadronic jets produced in hard processes such as e^+e^- annihilation [9]. As illustrated in Fig. 1, the basic idea is that partons produced far off mass shell in the hard process evolve by successive branching ($q \to qg$, $g \to gg$ or $g \to q\bar{q}$) into jet-like cascades of partons nearer to mass shell [10–13], which subsequently form hadrons by a less well understood but relatively soft mechanism ("hadronization").

Initially, the aim was to include correctly only those leading logarithms in each order which arise from the collinear (mass) divergences of perturbative QCD. Strictly speaking, this limits the approach to those phase-space regions in which all partons carry finite fractions of the jet energy. Owing to the infrared (soft gluon) divergences of the theory, further large logarithms, $\ln x_i$, can arise wherever partons carry small energy fractions,

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x_i. Recent theoretical work [14–21], reviewed in the lecture by G. Marchesini [22], has revealed that leading logarithms of this type can also be summed and that they produce important changes in jet properties at the partonic level. In particular, destructive interference leads to strong suppression of soft gluon emission and a corresponding large reduction in the parton multiplicity. One should emphasize that these effects occur in a phase-space region where perturbation theory should still be reliable: although soft in the sense of carrying a small fraction of the total jet energy, the gluons involved are sufficiently virtual for their effective strong coupling α_s/π to be small.

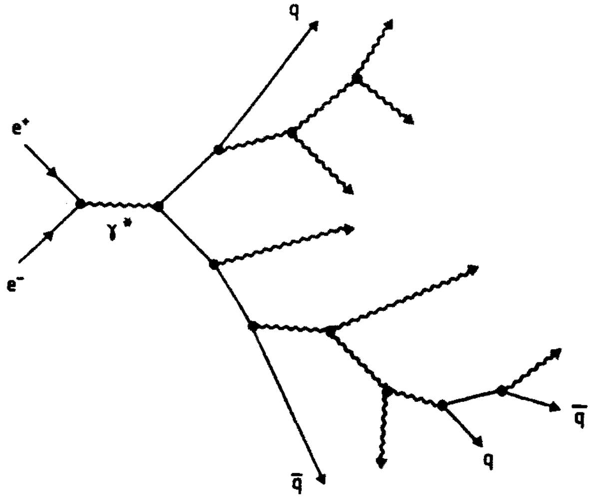

Fig. 1. Perturbative QCD branching process following $e^+e^- \to q\bar{q}$

It is clearly of interest to incorporate these advances in perturbation theory into the Monte Carlo approach. This can be done [23] even though the predominant effect is one of interference, which does not normally have a probabilistic interpretation. It turns out that the interference terms simply cancel the amplitude in certain regions of phase space, namely those in which successive opening angles in the branching process (e.g. Fig. 1) are not uniformly decreasing. Therefore the new Monte Carlo procedure simply has to generate cascades with ordered opening angles. The details of how this may be done are given in Refs. [23–25].

To study the associated changes in observable jet properties one needs a model for the hadronization process. The model should take account of the colour structure of the parton cascade, so that possible difficulties with colour confinement can be investigated. As pointed out by Bjorken [26], soft gluon interference means that fewer gluons are available for transmission of colour between jets, which is essential if they are to become colour singlets. A suitable and appealing hadronization model is of the "QCD cluster" type developed recently by Wolfram, Field and Gottschalk [1, 7, 8, 27, 28], illustrated in Fig. 2. The lines with arrows show the dominant colour structure of the diagram in Fig. 1 (dominant in the sense of a $1/N_c$ expansion, where N_c is the number of colours). The blobs represent colour singlet clusters formed by $q\bar{q}$ pairs that share a colour index. The model supposes that these clusters are formed when the virtualities of the partons in the cascade reach some lower limit, Q_0, beyond which perturbation theory cannot be applied. At this point branching is terminated, except that any gluons in the cascade are forced to split non-perturbatively into $q\bar{q}$ pairs so that their colour indices can form separate colour singlets.

The typical mass spectrum of the resulting clusters is shown in Fig. 3. It peaks at a mass determined by the perturbative cutoff Q_0 and the QCD scale Λ, falls steeply at high mass, and is independent of the hard process scale Q when $Q \gg Q_0, \Lambda$. This is the phenomenon of colour preconfinement [29]. The mass spectrum of the central cluster in Fig. 2 (the

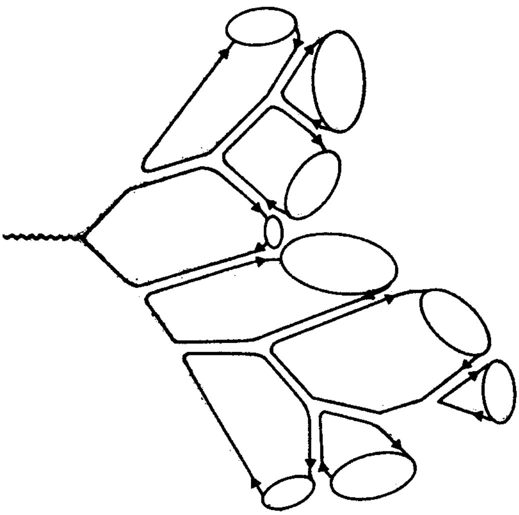

Fig. 2. Dominant colour index structure of Fig. 1. The blobs represent colour singlet clusters to be used as the basis for hadronization

one that neutralizes the colour between the two jets) behaves in a similar way. There are therefore no special difficulties with colour confinement: on the average, enough soft partons are still available to form singlet clusters of moderate, Q^2-independent mass. The neutralization of jet colour is facilitated by the "inside-out" structure of the cascade, in which soft, wider-angle partons tend to be emitted early and are therefore more likely to carry off the colour of the hard partons initiating the jets.

The conversion of the clusters into hadrons is handled in a very simple way: they are assumed to undergo isotropic, quasi-two-body decay into pairs of known resonances, with branching ratios given by density of states (i.e. phase space times spin degeneracy). This approach has the great virtue of introducing no arbitrary parameters, although there are ambiguities about how decays into baryons and heavy flavours should be handled. The prescription followed here is described in more detail in Refs. [24, 25]. It turns out that the observed rates of baryon and strange particle production in jets can be understood quite well in terms of the available phase space for cluster decay into such channels, without invoking any extra dynamical factors.

Occasionally, clusters are produced with masses that are too large for isotropic, quasi--two-body decay to be a reasonable model. Provision was therefore made for a string-like mode of anisotropic fragmentation of clusters above some mass threshold, M_f. Further details may be found in Ref. [25]. The value eventually adopted for M_f was 4 GeV, implying that about 10% of clusters were treated in this way. The effects (compared with setting $M_f = \infty$) were not large, e.g. a 10% increase in the average multiplicity of pions, a 20% decrease in that of baryons, and a 17% decrease in the average transverse momentum.

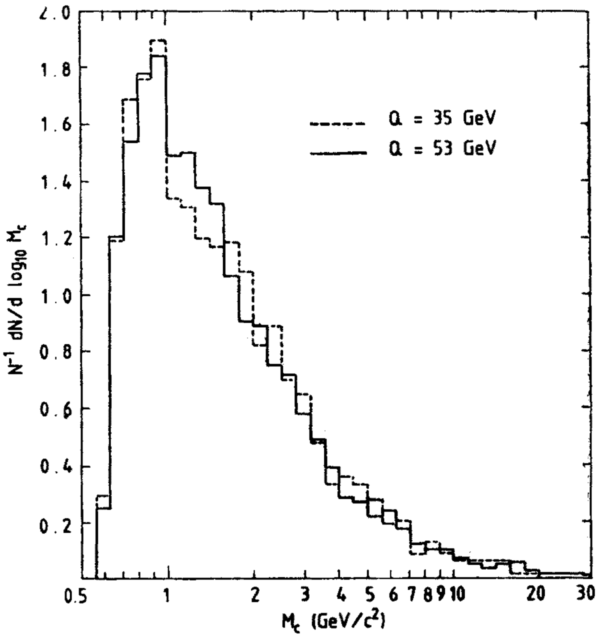

Fig. 3. Distribution of colour singlet cluster mass, M_c, in e^+e^- annihilation at c.m. energies Q = 35 GeV and 53 GeV. Parameter values: Λ = 0.25 GeV, Q_0 = 0.60 GeV

The full development of an e^+e^- final state and the resulting hadron momenta are shown for a typical event in Fig. 4. Actually, the event is not entirely typical: it has a three--jet structure arising from an early hard gluon bremsstrahlung off the initial u quark. The numbering of hadrons makes it possible to see how the parton configuration is reflected in the final hadron momenta and how colour neutralization occurs via relatively soft hadrons between the jets.

A selection of model predictions are compared with e^+e^- annihilation data [30–44] in Figs. 5–14. The parameter values used were:

$$\Lambda = 250 \text{ MeV}, \qquad Q_0 = 600 \text{ MeV}, \qquad M_f = 4 \text{ GeV} \tag{1}$$

Clearly, using QCD perturbation theory down to such a low value of Q_0 is rather bold, but in view of the preconfinement property it is defensible as a model for the early stages of hadronization. In fact, the results are not extremely sensitive to Q_0: for example, doubling it would lead to a decrease in average multiplicity of the order of 10%. Increasing Q_0 decreases the average cluster multiplicity, but it also increases the cluster mass scale and this leads to a partially compensating increase in hadron multiplicity per cluster.

The figures show that the model does a good job of accounting for the general features of e^+e^- final states. What about the specific new features associated with the inclusion of

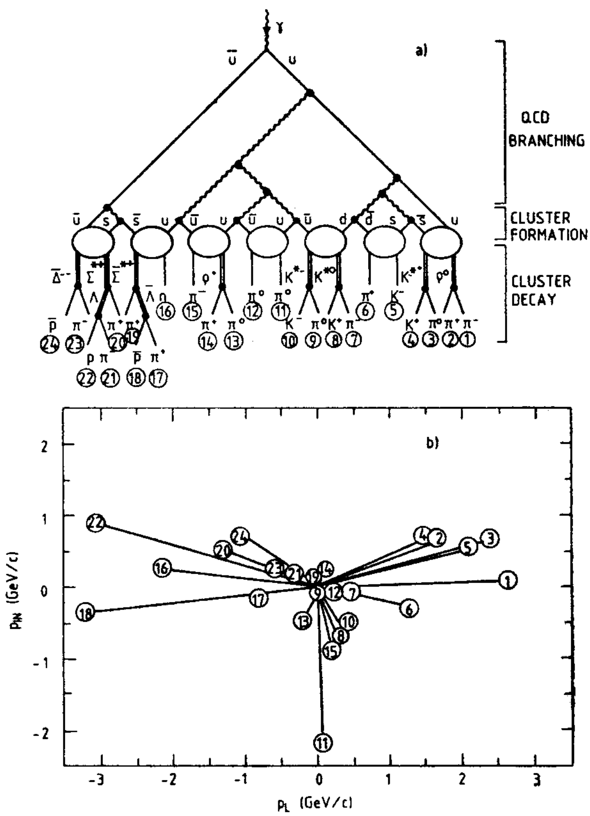

Fig. 4. Monte Carlo event at c.m. energy $Q = 34$ GeV. (a) Schematic time development; (b) Final hadron c.m. momenta in event plane

soft gluon interference? The energy dependence of the average multiplicity above $b\bar{b}$ threshold agrees with the expected asymptotic behaviour including interference [14–19, 25]:

$$\langle n(Q)\rangle \propto \left(\ln \frac{Q}{\Lambda}\right)^{-0.49} \exp\left(6.26 \ln \frac{Q}{\Lambda}\right)^{1/2}, \tag{2}$$

although the normalization of the model prediction may be about 10% too low[1]. In the absence of interference, the exponent would be larger by a factor of $\sqrt{2}$ [13, 45]. The previously-encountered difficulties [7, 8] in reconciling the observed rate of increase of

[1] The latest, unpublished data tend to confirm both the Q^2-dependence (2) and the 10% normalization discrepancy.

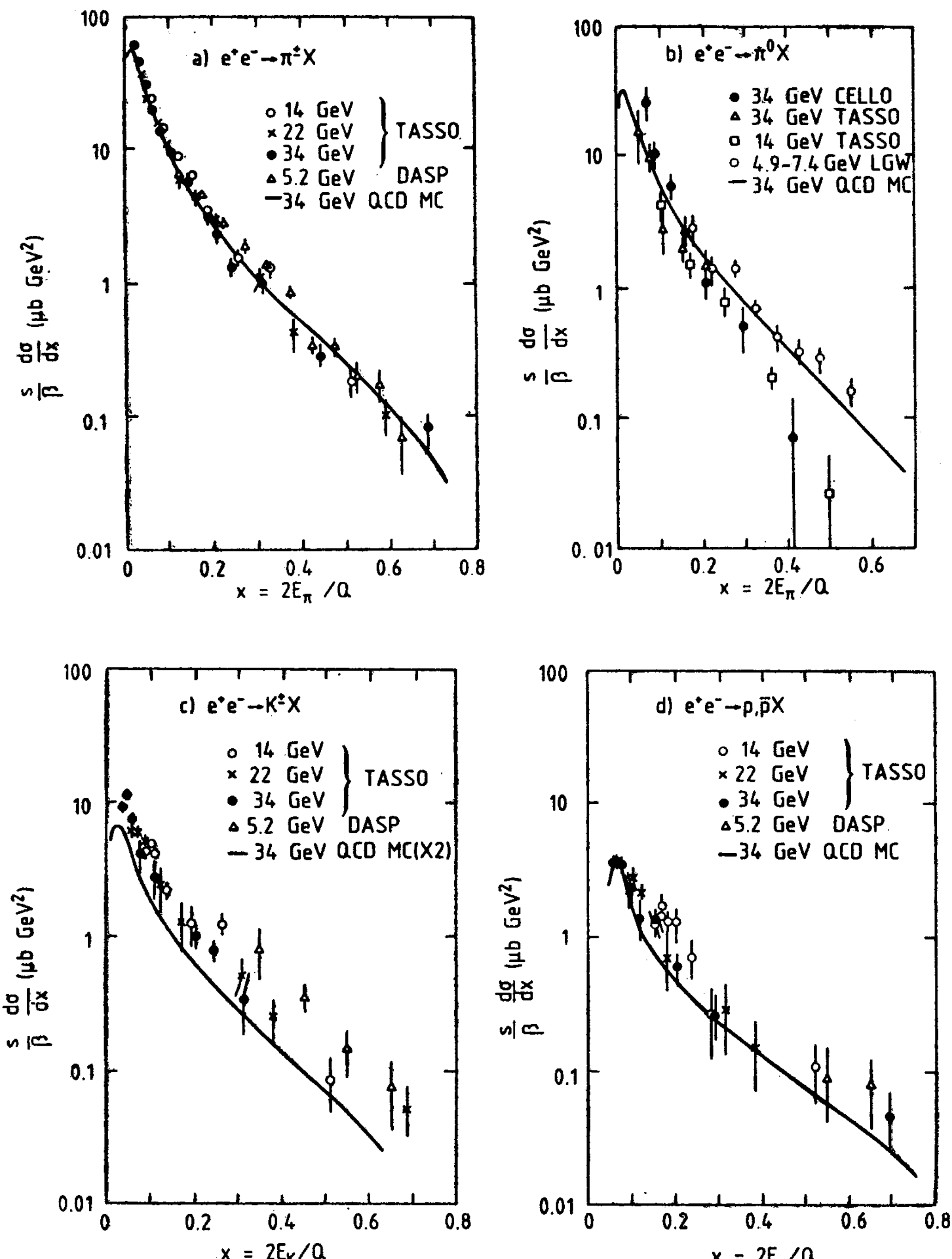

Fig. 5. Single-particle inclusive cross-sections, $e^+e^- \to hX$. Data from Refs. [30–34]. In this and subsequent figures, "QCD MC" refers to the QCD Monte Carlo model prediction with parameter values given by Eq. (1)

transverse momentum (Fig. 9) with the relatively small amount of scaling violation (Fig. 14) are eliminated by the angular ordering due to interference, which tends to suppress gluon bremsstrahlung later in the cascade. On the other hand, there is as yet little direct evidence for a corresponding suppression of soft hadron production. As shown in Fig. 13, the model predicts a modest dip in the central region of the hadron rapidity distribution, which may or may not agree with the trend of the data. Systematic errors are large in this region

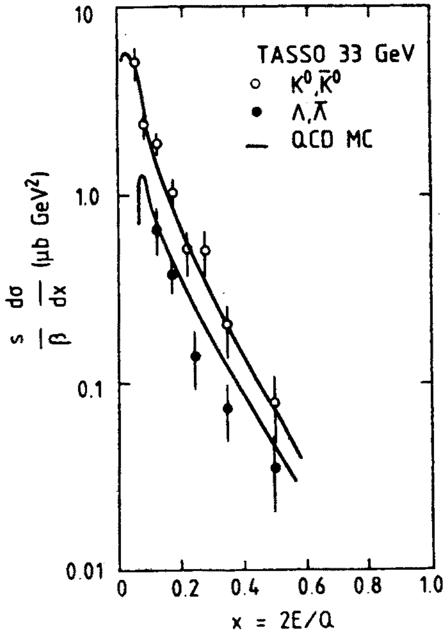

Fig. 6. Inclusive cross-sections for neutral strange particles. Data from Ref. [35]

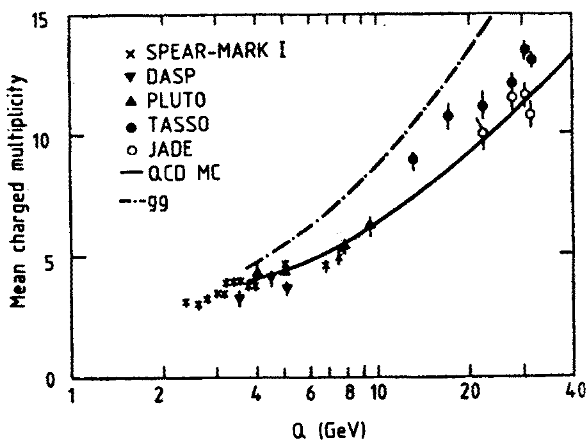

Fig. 7. Overall mean charged multiplicity in $e^+e^- \to$ hadrons. Data from Refs. [32, 36–39]. In this and subsequent figures the dot-dashed curves show the model predictions when quark jets are replaced by gluon jets (i.e. for gg production instead of $q\bar{q}$)

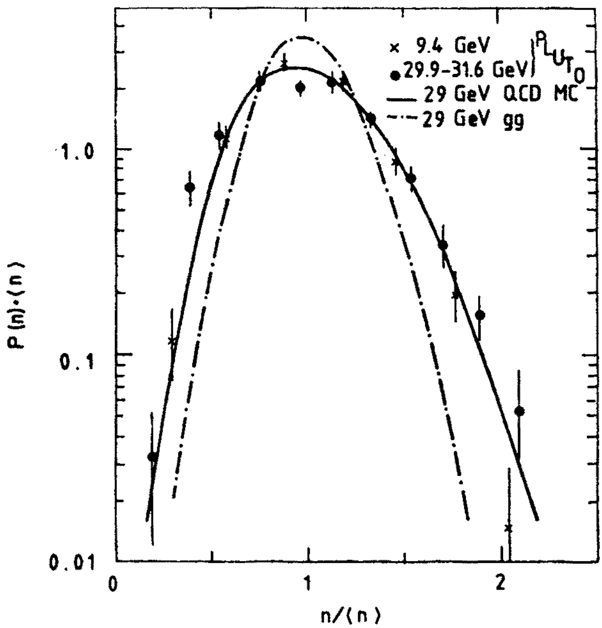

Fig. 8. KNO-scaled charged multiplicity distribution. Data from Ref. [40]

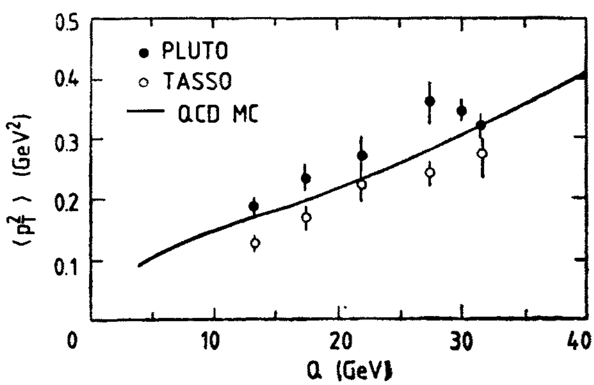

Fig. 9. Mean square transverse momentum, relative to the sphericity axis, as a function of c.m. energy. Data from Refs. [41, 42]

and more accurate data on low-momentum ($|p| \lesssim 600$ MeV/c) hadron production are required.

Probably the best place to look for clear evidence of interference would be in hadronic $\ln(1/x_p)$ distributions, where x_p is the momentum fraction $2|p|/Q$. As shown in Figs. 15 and 16, one expects to find an approximately gaussian peak whose position is given asymptotically by

$$\left(\ln \frac{1}{x_p}\right)_{\text{peak}} \simeq \left\langle \ln \frac{1}{x_p} \right\rangle \sim \tfrac{1}{2} \ln (Q/Q_h), \tag{3}$$

where Q_h is a constant that depends on the type of hadron h being observed. Empirically, the model suggests that Q_h is about half the hadron mass. This puts the interference peak for pions at very low x_p and the characteristic behaviour (3) is masked by threshold effects until very high Q^2 (Fig. 16). However, for kaons and protons the possibility of observing a peak with the behaviour (3) appears much more encouraging (Fig. 16 and Refs. [16, 25]). This is because the heavier hadrons have momentum spectra that reflect more accurately that of the QCD clusters from which they originate.

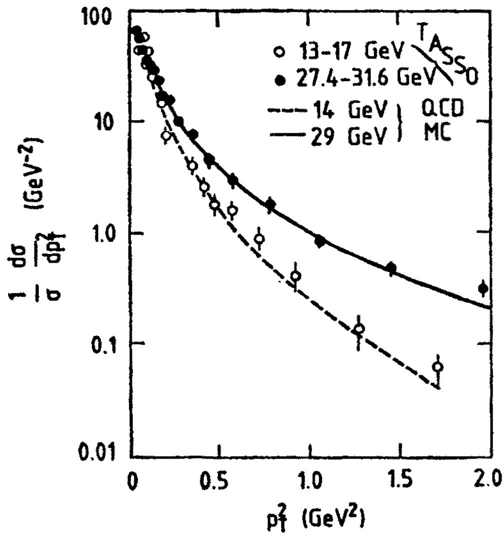

Fig. 10

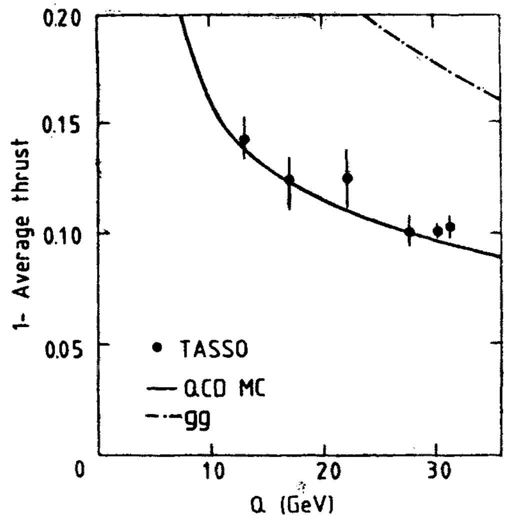

Fig. 11

Fig. 10. Transverse momentum distribution, relative to the sphericity axis. Data from Ref. [41]
Fig. 11. Average value of (1-thrust) versus c.m. energy. Data from Ref. [43]

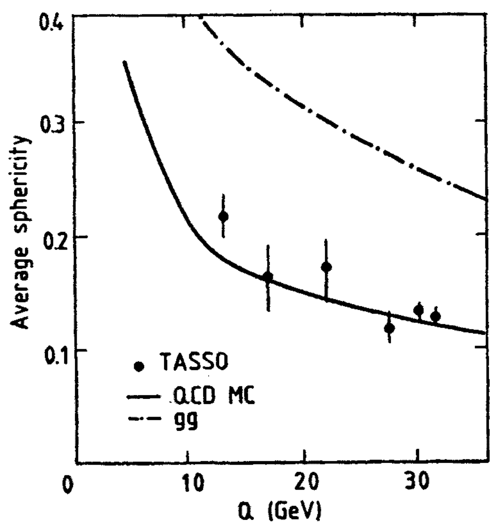

Fig. 12. Average sphericity versus c.m. energy. Data from Ref. [43]

An important question to address in any discussion of jet properties is the following: What characteristic differences are expected between jets initiated by quarks and those initiated by gluons? This question is particularly relevant now that large amounts of data on jets in hard hadron-hadron collisions are becoming available from the CERN $p\bar{p}$ Collider [46–49]. Calculations of $p\bar{p}$ jet production cross sections [50] show that gluon jets should predominate in the transverse momentum region currently being studied. Any differences

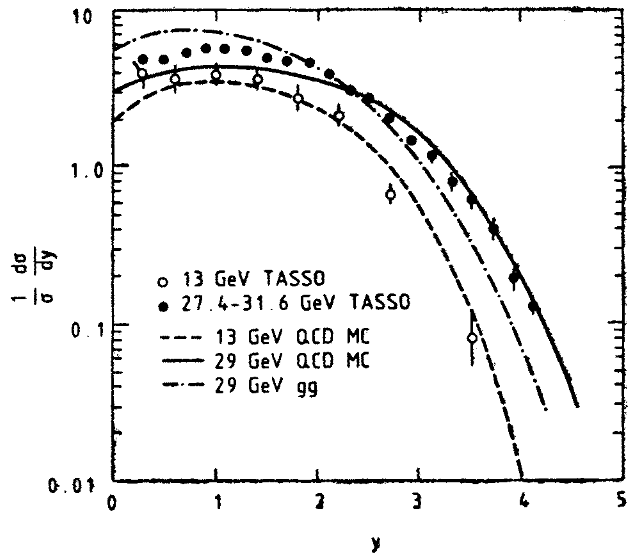

Fig. 13. Charged particle rapidity distribution, relative to the thrust axis. Data from Ref. [39]

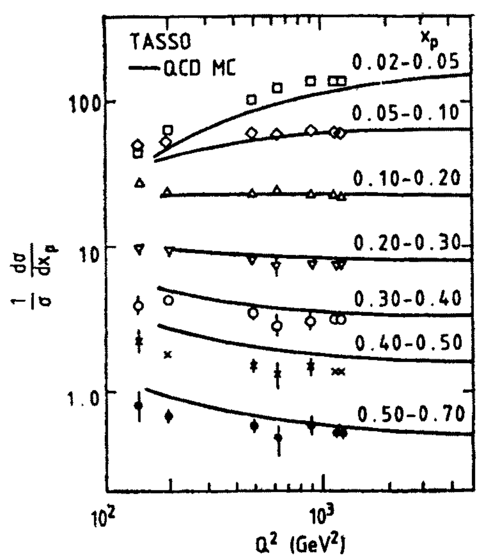

Fig. 14. Dependence on c.m. energy-squared of the charged particle momentum fraction distribution ($x_p = 2|p_{cm}|/Q$). Data from Ref. [44]

between the fragmentation properties of Collider jets and the quark jets that predominate in e^+e^- final states would therefore help to confirm the existence of gluons as a distinct parton species.

To investigate the predicted differences between quark and gluon jets, final states initiated by two gluons were generated and compared with e^+e^- final states initiated by quark-antiquark pairs at the same c.m. energy. An attractive feature of the model is that no new parameters are available to describe gluon jet fragmentation: everything is already

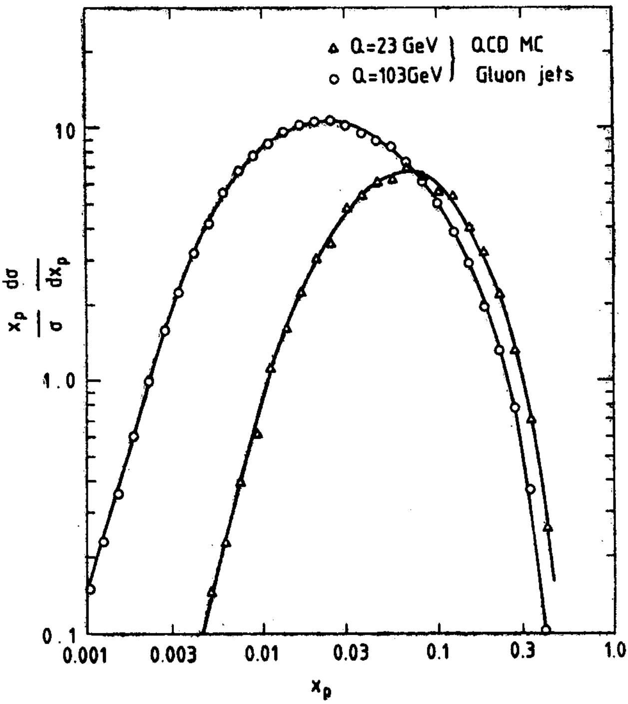

Fig. 15. Model predictions of the charged particle momentum fraction distribution in gluon jets, showing the interference peak

prescribed by the same three parameter values (1) used for e^+e^- jets. The most striking differences between the pairs of gluon and quark jets generated occur in the average multiplicity, thrust and sphericity (Figs. 7, 11, 12) and in the multiplicity and rapidity distributions (Figs. 8, 13), as indicated by the dot-dashed curves in the relevant figures. These model predictions reflect QCD expectations [51] that gluon jets should have higher multiplicities, softer momentum spectra and broader angular distributions than quark jets.

For a more direct comparison with the CERN Collider jet data, two-gluon and $q\bar{q}$ dijet systems were generated with the jet axis and transverse energy distributions expected for the process $\bar{p}p \to$ (2 jets + anything) via parton hard scattering. The resulting multihadron configurations did not of course contain any background of low-p_T hadrons unassociated with the jets, which arises in real Collider events from soft spectator parton interactions and initial-state gluon bremsstrahlung. However, the simulated jets were subjected as far as possible to the selection cuts used experimentally to remove hadrons unassociated with the jets and so they may be compared with the data after cuts.

Figure 17(a) shows the resulting mean charged multiplicities per jet, compared with the data of the UA2 Collaboration [48] and with quark jet data [36, 39, 52, 53] at lower energies. Unfortunately, the selection cuts preferentially remove the soft region, in which the difference between quark and gluon jets is expected to be greatest and in which interference effects are important. An attempt to correct for the effect of cuts (see Ref. [48]) is

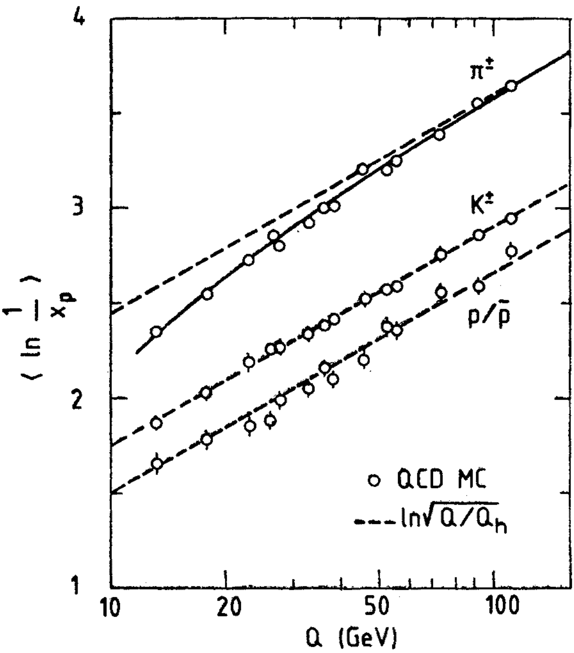

Fig. 16. Predicted mean values of $\ln 1/x_p$ for different types of charged hadrons in e^+e^- final states. The dashed lines show the expected asymptotic behaviour (3) [$Q_h \simeq 0.075, 0.30$ and 0.50 GeV for $\pi^\pm$, $K^\pm$ and $p/\bar{p}$ respectively]

shown in Fig. 17(b). Figures 18 and 19 show comparisons with the UA1 data [49] on jet fragmentation into charged hadrons. Here again one sees that the expected differences between quark and gluon jets after cuts are significant but not enormous.

The conclusion to be drawn from Figs. 17–19 is that the model, with parameter values (1) fixed by comparisons with e^+e^- data at much lower Q^2, gives a qualitatively sound description of available Collider jet data and suggests that a substantial fraction of jets could indeed have the properties expected for gluon jets. More quantitative statements must await more careful model computations and analysis of the copious data from 1983 Collider running.

In summary, a simple angular ordering algorithm permits the Monte Carlo simulation of QCD jets with correct treatment of both collinear and infrared leading logarithms.

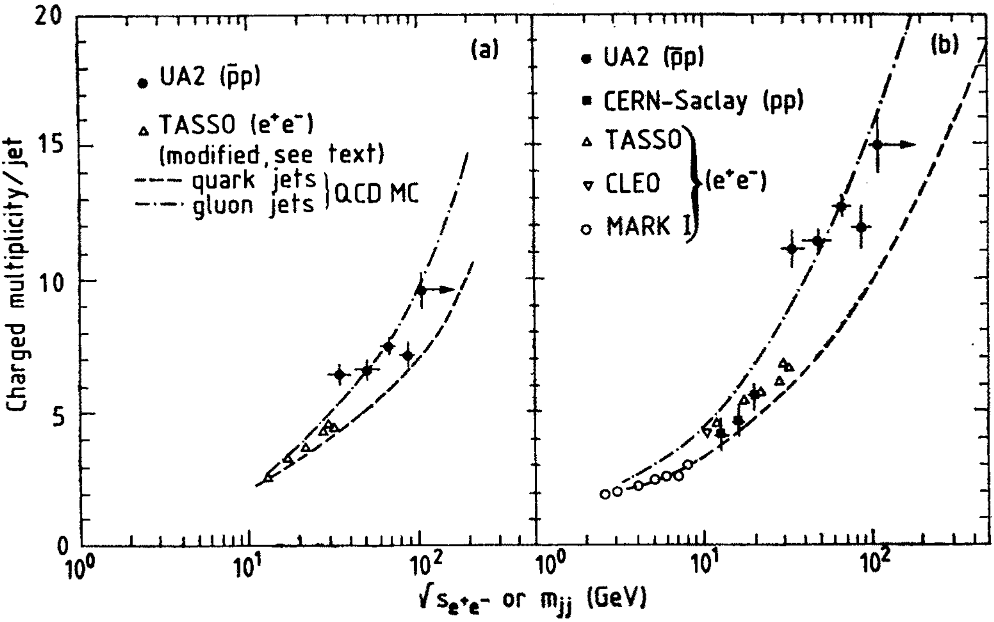

Fig. 17. Mean charged particle multiplicities in jets. Data from Refs. [36, 39, 48, 52, 53]. (a) Data and predictions after cuts to eliminated unassociated particles [see text and Ref. 48]; (b) Corrected UA2 data, compared with model predictions and lower-energy data

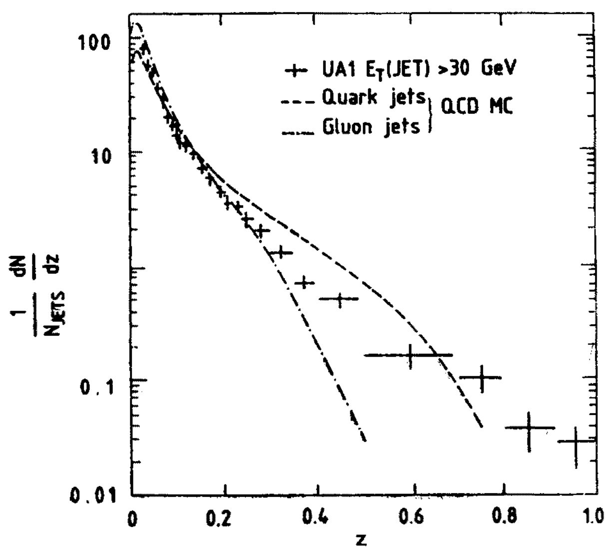

Fig. 18. Distribution of the longitudinal momentum fraction, z, for charged particles in $p\bar{p}$ collider jets with $E_T > 30$ GeV. z is defined as the component of the momentum along the jet axis, divided by the energy of the jet. Data from Ref. [49]

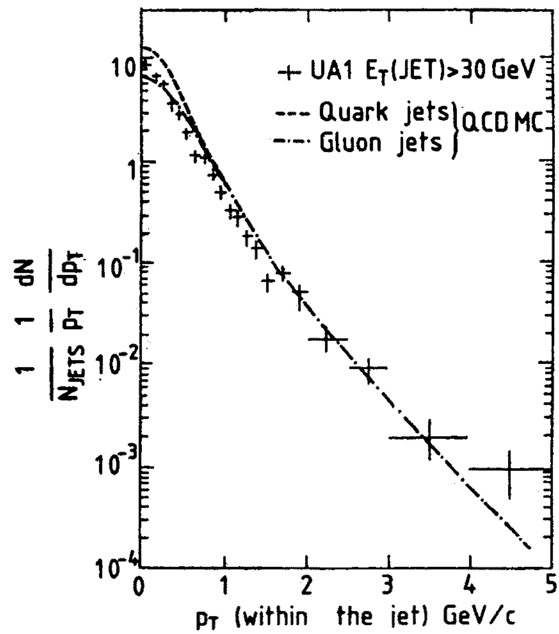

Fig. 19. Transverse momentum distribution relative to the jet axis for $z > 0.1$ charged particles in $p\bar{p}$ collider jets with $E_T > 30$ GeV. Data from Ref. [49]

Combined with the QCD-cluster type of hadronization model, this approach provides a rather natural interpretation of existing e^+e^- annihilation data in terms of very few parameters. The soft gluon interference effects incorporated have some beneficial indirect consequences and should be more directly visible in the spectra of heavy hadrons. Prospects are good for the identification of characteristic features of gluon jets in hard hadron-hadron collisions.

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