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COMPARISON OF QUARK AND GLUON JETS

by

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Abstract

If QCD is the underlying theory of the strong interactions, quark and gluon jets should appear to be rather different in nature. In this talk I shall discuss the (theoretical) roots of this difference and to what extent it has been borne out experimentally.

Invited talk given at the "4th Topical Workshop on Proton Antiproton Collider Physics, Bern, March 5-8, 1984".

1. Introduction

Quarks and gluons play quite a different role in QCD. While quarks are mainly flavour labels and sources of colour perturbation in the vacuum, gluons are largely responsible for confinement, i.e. the QCD vacuum, and dominate the particle production mechanism. This leads us to expect the fragmentation patterns of quark and gluon jets to be rather diverse.

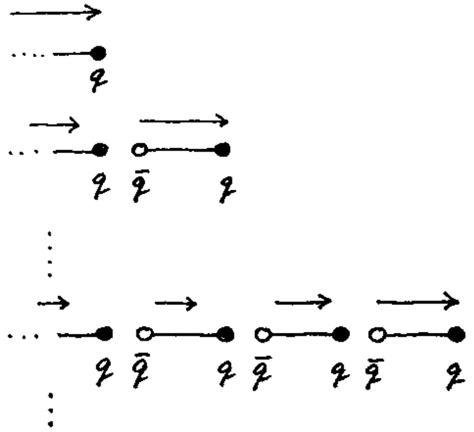
The purpose of my talk is to illuminate this issue. So far we are not able to derive the fragmentation functions from first principles. But in the last years a vast amount of experimental information on the fragmentation mechanisms of quark and gluon jets has accumulated (and I believe there is a lot more to come from the $p\bar{p}$ collider) which will compensate for this weakness.

2. Space-Time Picture of Quark and Gluon Jets

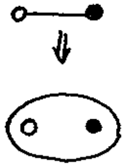
To begin with let me review our current understanding of the process of hadronization in quark and gluon jets.

Quark Jets

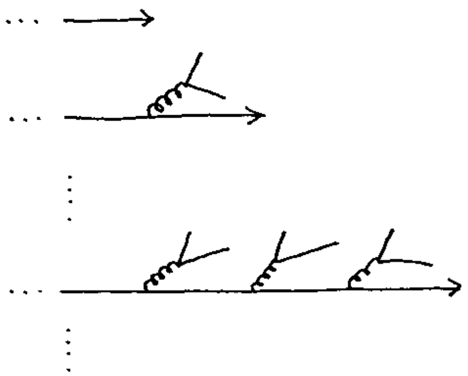
As a quark leaves the interaction region it trails behind it a colour (triplet) flux tube. At some point the gain in diminishing the flux tube length outweighs the cost of exciting a $q\bar{q}$ pair from the vacuum, and the flux tube will break into a string bit of perhaps a mass of $\approx$ 1 GeV (length $\approx$ 1 fermi, given a string tension of 1 GeV/fermi) and a "heavy" string consisting of the original (energetic quark and the newly created antiquark. As the leading quark and the antiquark move apart, the "heavy" string will break repeatedly until eventually the system has totally decayed into string bits of the aforementioned size:



The string bits are strongly ordered in rapidity. The lengths of the arrows represent (pictorially) the velocities of the bits. If not originally so, the string bits will evolve into strongly interacting systems, bags, containing a $q\bar{q}$ pair:



The (Feynman) graphical description of the quark jet evolution



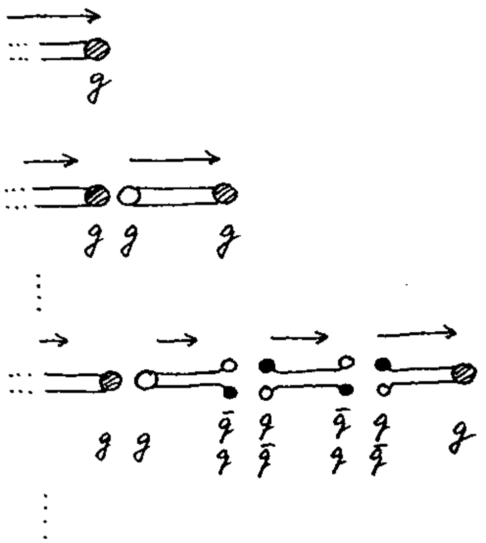
leads in the limit N_c = large to more or less the same strong ordering in rapidity. In the following I shall employ both notations.

The validity of the string picture has only recently been verified experimentally by comparing the fragmentation properties of charm jets with those of the average jet. According to this picture the two jets should only differ in the leading particle spectrum, and that is exactly what has been found [1].

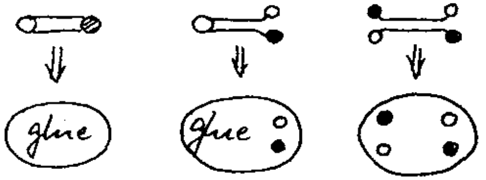
Gluon Jet

An energetic isolated gluon will trail a colour (octet) flux tube behind it. In a world without dynamical triplets of colour the flux tube would break up into a sequence of gluon-string bits in the same way the quark flux tube decays into string bits. The masses of the lowest-lying glueball states range from [2] 0.7 to $\gtrsim$ 2 GeV, and hence the mass of a gluon-string bit is expected to follow some distribution centered on a mean in the range 1.5 to 2 GeV (length $\lesssim$ 1 fermi,

given a string tension more than twice that of the triplet flux). Including dynamical quark triplets is not expected to alter these numbers very much. In the real world with quarks the flux tube may, however, also break by exciting two $q\bar{q}$ pairs (in the octet representation) from the vacuum as shown (e.g.) below:

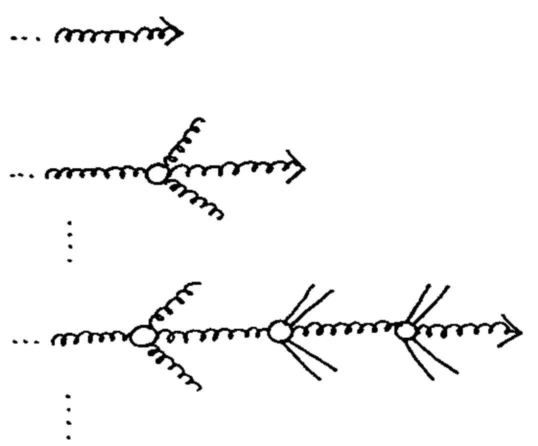


The gluon-, mixed- and diquark-string bits will evolve into three topologically distinct physical systems:



giving rise to glueballs, so-called mixed ($q\bar{q}g$) states and four-quark resonances, respectively. The masses of the lowest-lying mixed states are expected to lie in the range [3] 1.5-2 GeV.

The (Feynman) graphical description of the gluon jet evolution

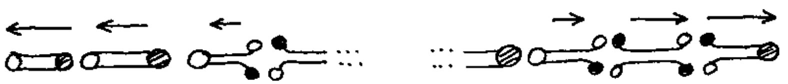


does not obviously agree with the string picture. Presumably this can be achieved to some extent by taking proper care of quantum interference phenomena.

Topological Properties

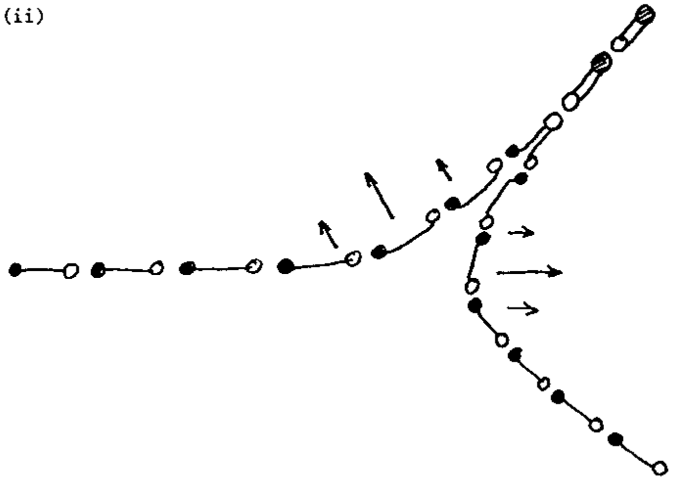
From the discussion so far it is apparent that the gluon jet has a much richer particle spectrum than the quark jet. But more about this later. A further striking difference is that the particle flow in the gluon jet depends crucially on its history, while in the quark jet it appears to be more universal. To give an example consider (i) two back-to-back gluon jets as they arise (e.g.) from heavy para-quarkonium decays or $p\bar{p} \rightarrow gg + X$

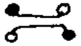
(i)



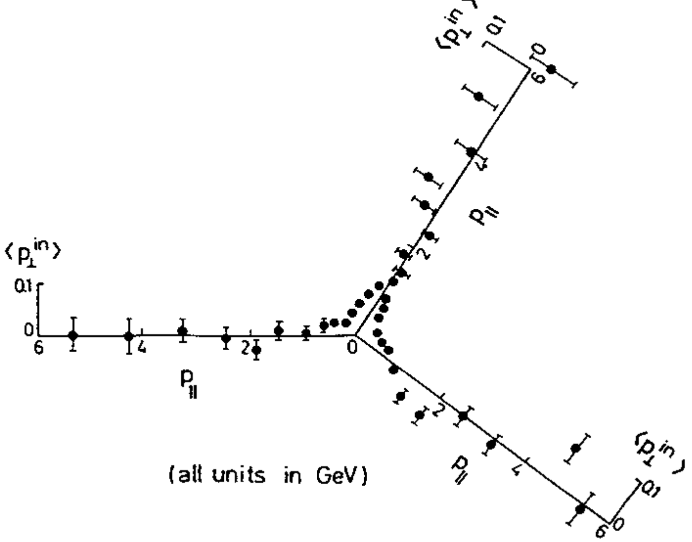
and (ii) a $q\bar{q}g$ three-jet event as it appears (e.g.) in e^+e^- annihilation

(ii)



The three-jet configuration shown is only one of many possible final states. Its particular feature is that the gluon (colour octet) flux tube has broken initially and repeatedly by $q\bar{q}$ pair creation. Furthermore, it assumes that the interaction between overlapping string bits  is small so that the two resulting triplet flux tubes evolve more or less independently (as indicated). Accordingly the gluon jet here will be oblate and much broader (in the event plane) than in case of the back-to-back jet (i).

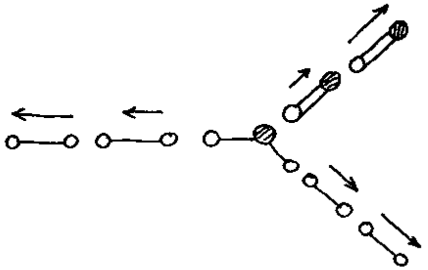
The JADE group has confirmed that the fragmentation proceeds to some extent along the colour flux lines rather than strictly along the parton axes. Below I have transcribed their data [4) into an "event-shape" plot



(all units in GeV)

which clearly shows the effect. (In this plot $\langle p_{\perp}^{in} \rangle$ is zero when the particles fall on the jet axes.)

In general the gluon flux tube may also break by forming gluon-string bits



and the overlapping string bits in (ii) may interact (e.g. to give baryons as I will discuss later on), which then will fragment more or less along the parton axes. How much this is so can only be answered by the experimentalists at the moment. But it is conceivable that the Lund fragmentation model [5], which treats the gluon string as a superposition of two noninteracting quark strings, is as far from the truth as the independent parton fragmentation models.

It is interesting to note that Webber's model [6] for jet fragmentation, which follows the graphical description including some soft-gluon interference, also reproduces the string effects, and I am sure that this will shed some more light on this issue.

3. Longitudinal Evolution

I like to discuss now the single particle distributions in quark and gluon jets. Let me begin (for a change) with the perturbative aspects of it.

(a) Perturbative

The longitudinal development of quark and gluon jets is believed to be governed by the evolution equations [7]:

$$\partial_t D_q^h(z,t) = \frac{6}{33-2N_f} \int_z^1 \frac{dx}{x} \left[P_q^q(x)\, D_q^h\left(\frac{z}{x},t'\right) + P_q^g(x)\, D_g^h\left(\frac{z}{x},t'\right) \right],$$

$$\partial_t D_g^h(z,t) = \frac{6}{33-2N_f} \int_z^1 \frac{dx}{x} \left[P_g^g(x) D_g^h\left(\frac{z}{x},t'\right) + N_f \left(P_g^q(x) D_q^h\left(\frac{z}{x},t'\right) + P_g^{\bar q}(x) D_{\bar q}^h\left(\frac{z}{x},t'\right)\right)\right],$$

where $t = \ln\left[\alpha_s(Q_0^2)/\alpha_s(Q^2)\right]$, $t' = \ln\left[\alpha_s(Q_0^2)/\alpha_s(xQ^2)\right]$.

$z \to 1$

This set of coupled equations can be solved for $z \approx 1$, and we obtain [8]

$$D_q^h(z,t) \underset{z\to 1}{\simeq} \text{const.} \left[\alpha_s(Q^2)\right]^{-\left(\frac{3}{4}-\gamma_E\right)\frac{16}{33-2N_f}} (1-z)^{c_q(t)},$$

$$c_q(t) = c_q(0) + \frac{16}{33-2N_f}\, t$$

for the fragmentation function of the quark and

$$D_g^h(z,t) \underset{z\to 1}{\simeq} \text{const.} \left[\alpha_s(Q^2)\right]^{-\left(\frac{11}{12}-\frac{N_f}{8}-\gamma_E\right)\frac{9}{4}\frac{16}{33-2N_f}} (1-z)^{c_g(t)},$$

$$c_g(t) = c_g(0) + \frac{9}{4}\,\frac{16}{33-2N_f}\, t$$

for the fragmentation function of the gluon (γ_E is Euler's constant). The derivation assumes that $c_q < c_g - 1$ which, if not originally so, will become true at least at large t.

Because quark and gluon jets lose momentum by gluon bremsstrahlung, the single particle distribution in the jets becomes softer as Q^2 increases. Moreover, we see that the ratio between the rate of softening of gluon and quark jets is $9/4 = N_c/C_F$, which is a consequence of the higher colour charge of the gluon. For $Q_o = 10$ GeV, $Q = 100$ GeV and $N_f = 5$ we obtain ($\Lambda_{\overline{MS}} = 200$ MeV)

$$c_q(t) = c_q(o) + 0.30,$$

$$c_g(t) = c_g(o) + 0.68$$

which might be just enough of a change to be detectable experimentally. To draw any firm conclusions one will, however, have to know $c_q(o)$, $c_g(o)$ (e.g. from measurements on and off the Υ resonance) rather accurately.

I shall discuss the experimental situation after I have presented the nonperturbative aspects of the longitudinal distributions at the end of this section.

Multiplicities

The zeroth moments of the quark and gluon fragmentation functions give the mean multiplicities in quark and gluon jets

$$n_q^h(t) = \int_0^1 dz\, D_q^h(z,t),$$

$$n_g^h(t) = \int_0^1 dz\, D_g^h(z,t).$$

The evolution equations for the zeroth moments develop, as they stand, some divergences associated with the emission of a divergent number of soft gluons. But if the gluon is very soft it cannot fragment into hadrons. So we integrate only over those gluons $t' \geqslant t_o$ which are capable of fragmenting 8). This gives

$$\partial_t\, n_q^h(t) \simeq \frac{16}{33-2N_f}\, e^t \int_{t_o}^{t} dt'\, e^{-t'}\, n_g^h(t'),$$

$$\partial_t\, n_g^h(t) \simeq \frac{9}{4}\, \frac{16}{33-2N_f}\, e^t \int_{t_o}^{t} dt'\, e^{-t'}\, n_g^h(t'),$$

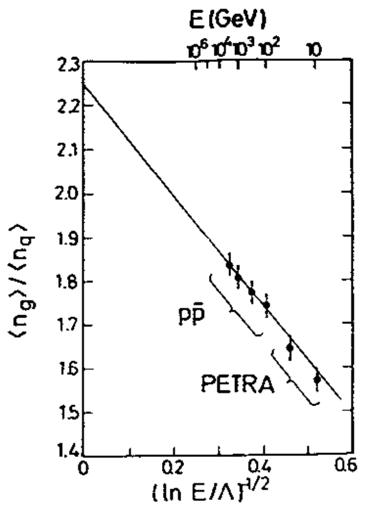
which has the asymptotic solution

$$n_g^h(t) \simeq \frac{9}{4}\, n_q^h(t),$$

$$n_g^h(t) \simeq \text{const.}\; e^{-2\sqrt{\frac{36}{33-2N_f}\ln Q^2/\Lambda^2}}\,.$$

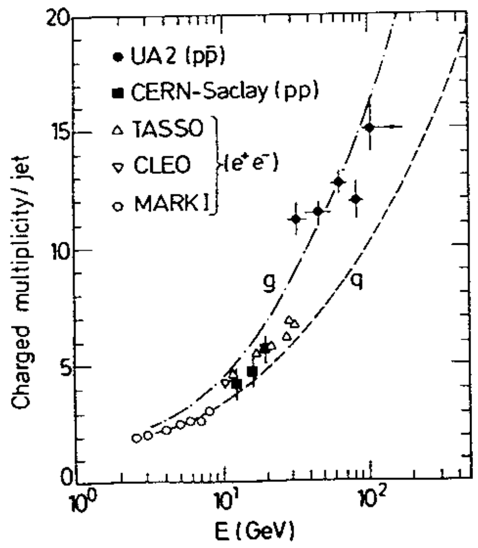
Again there is a factor 9/4 between the asymptotic multiplicities in gluon and quark jets due to the greater colour charge of the gluon.

To tell how far we are from asymptotic one has to go beyond the presentation given here. Webber has done this and he finds for the ratio $\langle n_g\rangle/\langle n_q\rangle$ (which is of most interest to us here) the following energy dependence 6):



(the points show the Monte Carlo results and the line is a linear fit). The outcome is that the asymptotic predictions are so asymptotic as to be useless. But the difference of quark and gluon jet multiplicities is still big enough to be conclusive.

The experimental data and the (Monte Carlo) predictions are summarized in the figure below



where E is the c.m. energy of the two-jet system. The dashed line is the prediction for the quark jet multiplicities, the dashed-dotted line that for the gluon jet multiplicities [6]. The TASSO data [9], which proceed dominantly from quark jets, fall (at their highest energies) close to the quark curve while the UA2 data [10], which are dominated by gluon jets, fall on the gluon curve. This nicely confirms the predictions. One can also say that the QCD prediction of a rapidly increasing multiplicity is in accord with the data.

(b)Nonperturbative

According to the string picture the fragmentation function of the quark is given by the iterative equation

$$D_q^h(z) = \int_0^{1-z} dy \frac{dP}{dy} \left[\frac{1}{1-y} D_q^h\left(\frac{z}{1-y}\right) + \delta(y+z-1) \right],$$

where dP/dy is the probability to find a meson containing the original quark at 1-y. The most natural choice for the probability function is $dP/dy = 1$, apart from may be the boundaries. This implies the large-z behaviour $D_q^h(z) \simeq$ const. For the fragmentation function of the gluon we find analogously

$$D_g^h(z) = \int_0^{\frac{1}{2}} dy_1 \int_0^{\frac{1}{2}} dy_2 \frac{d^2P}{dy_1 dy_2} \left[\frac{\Theta(\frac{1}{2}-y_1-z)}{\frac{1}{2}-y_1} D_g^h\left(\frac{z}{\frac{1}{2}-y_1}\right) + \frac{\Theta(\frac{1}{2}-y_2-z)}{\frac{1}{2}-y_2} D_g^h\left(\frac{z}{\frac{1}{2}-y_2}\right) + \delta(y_1+y_2-z) \right].$$

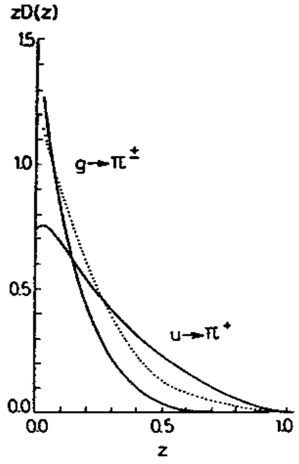
In case the gluon flux tube breaks into a sequence of noninteracting (triplet) string bits

we expect, except perhaps for $y_1, y_2 \approx 0$,

$$\frac{d^2P}{dy_1 dy_2} = \frac{dP}{dy_1} \frac{dP}{dy_2} = 1.$$

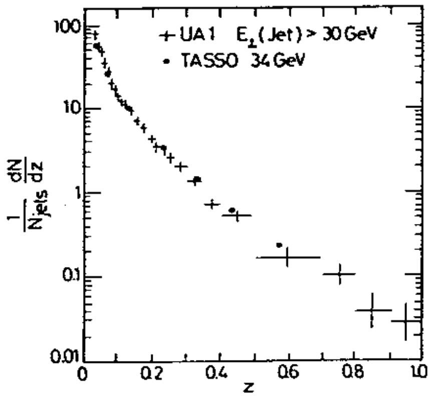
At large z this gives $D_g^h(z) \sim (1-z)$, which has an extra power of $(1-z)$. Note also that $\langle n_g \rangle \approx 2 \langle n_q \rangle$ in this picture.

The Lund group has studied the quark and gluon fragmentation functions in the context of this simplified model in great details. The result of their calculation is given below [5]



We see that the gluon fragmentation function comes out to be very much softer than that of the quark.

This difference (if true) should become visible if we compare the jet fragmentation at PETRA (mostly quark jets) to that of the $p\bar{p}$ collider (mostly gluon jets) what I have done below



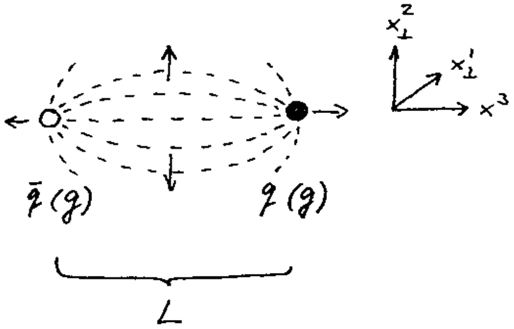
It looks as if the quark and gluon fragmentation functions are almost the same contrary to the model. This appearance is, however, deceptive. In the UA2 data events with $z \leqslant 0.05$ have been discarded. If one applies the same cut to the

Lund gluon fragmentation function (and rescales) one obtains the dotted curve in the figure before [12], and a lot of the difference has gone away. This will be further washed out by also including charm quark jets (which at PETRA energies are much softer than u and d quark jets [1]) in the model calculations. But there is also the possibility, as I said before, that the gluon flux tube decays into glueballs and that the overlapping (triplet) string bits interact which will obviously modify the predictions for the quark and gluon fragmentation functions.

4. Transversal Evolution

The intrinsic transverse momenta in jets are proportional to Λ, the only scale parameter in QCD (in the chiral limit), and hence they are nonperturbative in origin.

Let us consider now (e.g.) two back-to-back quark-antiquark and gluon jets, respectively. As the quark and antiquark (the two gluons) separate the transversal width of the field energy distribution (flux tube) increases due to quantum fluctuations [13]:



(It increases without bound when the $q\bar{q}$ (gg) separation goes to infinity.) The chromo-electric field energy density above the vacuum is [13]

$$\mathcal{E}_{q(g)}(x) \sim e^{-\sigma_{q(g)}\frac{\pi x_\perp^2}{\ln L/\lambda}} ,$$

where $\sigma_{q(g)}$ is the string tension and λ is some constant. In momentum space this gives

$$\mathcal{E}_{q(g)}(p_\perp) = \int d^2x_\perp\, e^{ip_\perp x_\perp}\, \mathcal{E}_{q(g)}(x) \sim e^{-\frac{\ln L/\lambda}{\pi\sigma_{q(g)}} p_\perp^2} .$$

The partons that break the flux tube (while expanding) will now be created with an intrinsic transverse momentum

$$\langle p_\perp q(g)\rangle = \int d p_\perp\, p_\perp\, \mathcal{E}_{q(g)}(p_\perp) ,$$

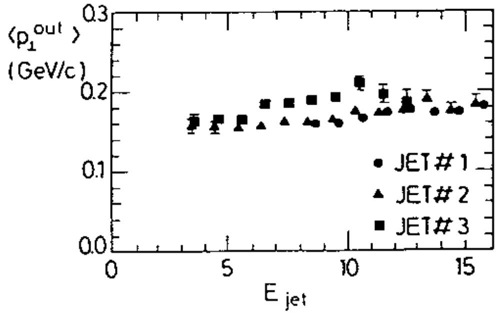
so that the mean transverse momentum of hadrons in quark and gluon jets is

$$\overset{4}{\langle} p_\perp q(g)\rangle \cong \frac{4}{3}\langle p_\perp q(g)\rangle \sim \sigma_{q(g)} .$$

The string tensions σ_q and σ_g can and have been calculated on the lattice. What will interest us here is only the ratio σ_g/σ_q. By dimensional reduction techniques [15] (which have been verified in SU(2) by lattice Monte Carlo calculations [15]) we arrive at $\sigma_g/\sigma_q = 9/4$, so that

$$\overset{4}{\langle} p_\perp g\rangle / \overset{4}{\langle} p_\perp q\rangle = 9/4 .$$

The JADE group finds a significant difference in the mean transverse momentum out of the three-jet plane [4]:



The probability that the fastest jet (# 1) is the quark or antiquark is 88 % and that the least energetic jet (# 3) is the gluon is 51 %. Taking this into account I obtain (at $E_{jet} = 10$ GeV)

$$\langle p_{\perp q}^{out} \rangle \approx 130 \text{ MeV}, \quad \langle p_{\perp g}^{out} \rangle \approx 260 \text{ MeV},$$

which gives for the ratio

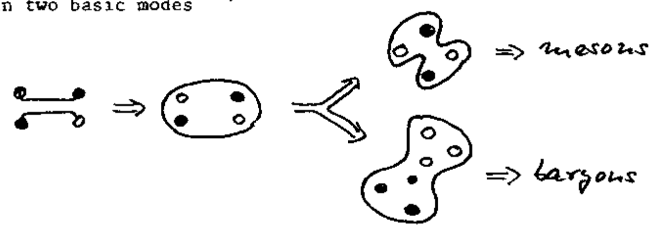
$$\langle p_{\perp g}^{out} \rangle / \langle p_{\perp q}^{out} \rangle \approx 2,$$

which is close to what one expects.

5. Particle Yields

In the gluon jet (at least) the leading string bits should remember that they are fragments of a (iso-singlet) gluon. This is to say that we expect glueballs, mixed ($q\bar{q}g$) states, η, η', ω, ϕ, etc. to be produced abundantly (for a model calculation involving the conventional mesons see (e.g.) ref. 16). So far the JADE group has found some evidence [17] that the η yield is larger for three-jet events than for two-jet events supporting this picture. For a further test and for our further understanding of the fragmentation mechanism it is important now to also trace the glueballs and mixed states.

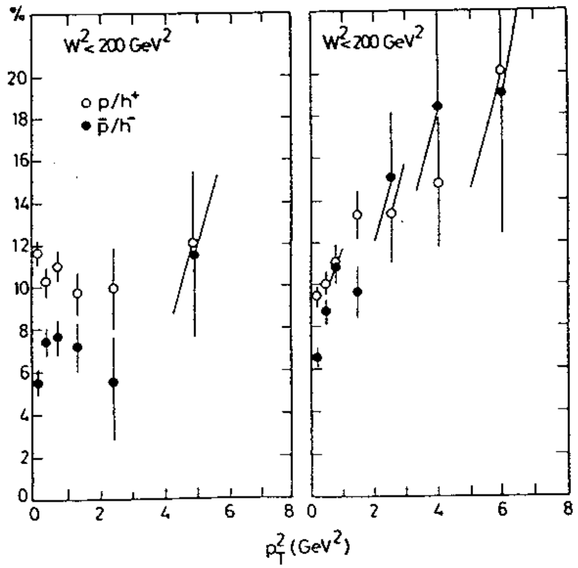
The four-quark states in the gluon jet, having a mean mass of O(2 GeV), may decay in two basic modes [18]



In case the two (triplet) string bits would not interact (Lund model) only the top mode would be present. To gain some insight into the dynamics of the decay one may look at low energy $p\bar{p}$ annihilations. At $\sqrt{s} \approx 2$ GeV the relative kinetic energy is low enough that the intermediate state will at some point consist of

two quarks and two antiquarks mixed together in a strongly interacting region of total mass ≈ 2 GeV. The annihilations correspond to the case when this system decays into mesons. The cross section is 77 ± 3 mb [19]. The cross section for producing a baryon-antibaryon pair may be estimated by taking $p\bar{p} \to p\bar{p}$ or $n\bar{n}$ and subtracting the pp value. This gives ≈ 38 mb [19]. Thus there appears to be no particular suppression of this mode, and our best guess is that the decay of the gluon flux tube into baryon, antibaryon will also not exhibit any marked dynamical suppression. This contradicts obviously the (naive) Lund model to the extent that we observe abundant baryon production in gluon jets. (But at present we can also not totally deny that there are other mechanisms within the context of QCD that might lead to substantial baryon production in jets. For a further discussion see ref. 18).

Let me now turn to the data. The DASP II group has found that antiprotons on the Υ (presumably three gluon jets) are produced at a rate about six times higher than on the neighbouring continuum [20]. At PETRA [21] the $\bar{p}$/meson and Λ/meson ratios increase with x and become large. In deep inelastic processes, and in particular the EMC data [22], the ratio of protons to mesons increases with increasing $p_\perp$ (three-jettiness) as shown below:



We conclude that the recent high-energy data does not only reveal substantial baryon production but also indicates that the (dominant) source of all these baryons is glue.

6. Miscellaneous

In this last section I like to mention very briefly a couple of other features that further mark the different nature of quark and gluon jets.

KNO Scaling

We expect the shape of the KNO scaling curve $\langle n_{ch}\rangle P(n_{ch})$ versus $n_{ch}/\langle n_{ch}\rangle$ for gluon jets at large $n_{ch}/\langle n_{ch}\rangle$ to be much flatter than for quark jets. This follows naturally from the (simplified) Lund model and should be true in general, though maybe in a weaker form. Experimentally there are some indications that this is indeed the case.

Prompt Photons

The QCD vacuum is a highly nontrivial setup of fluctuating colour fields. Nachtmann and Reiter have put forward the idea that energetic quarks traversing these fields will produce soft photons [23] (and soft gluons) similar to synchrotron radiation of energetic electrons passing through a magnetic field. This would lead us to expect more prompt photons in quark jets than in gluon jets.

Charge Retention

Measurements of the net charges of quark jets in neutrino and antineutrino interactions have appeared recently [24]. It has been found that the net charge of the jet closely reflects the charge of the parent quark. Moreover, it has been shown that the energy dependence of the net charge of the quark jets bears some information about the charge exchange properties of "isolated" quarks [25]. It will be important now to repeat the analysis for gluon jets at the $p\bar{p}$ collider.

7. Conclusions

Quark and gluon jets, that seems to be established, are different. As far as one can tell, the differences are in qualitative (and in some cases even semi-quantitative) agreement with our theoretical expectations based on QCD. However, we cannot make precise tests of QCD yet because of substantial uncertainties in the theoretical calculations.

References

1. TASSO Collaboration, M. Althoff et al.: DESY preprint 83-114 (1983).
2. K. Ishikawa, A. Sato, G. Schierholz, M. Teper: Zeitschr. f. Physik C21, 167 (1983); B. Berg: DESY preprint 84-012 (1984).
3. F. Close in Few Body Problems in Physics, Proceedings of the Tenth International Conference on Few Body Problems in Physics, 1983, ed. B. Zeitnitz, Vol. 1, p. 55c (North-Holland, 1984).
4. JADE Collaboration, W. Bartel et al.: Zeitschr. f. Physik C21, 37 (1983).
5. B. Andersson, G. Gustafson, G. Ingelman, T. Sjöstrand: Phys. Reports 97, 31 (1983).
6. B.R. Webber: CERN preprint TH.3713 (1983).
7. J.F. Owens: Phys. Lett. 76B, 85 (1978); T. Uematsu: Phys. Lett. 79B, 97 (1978).
8. E.g. B.R. Webber: Phys. Scripta 25, 198 (1982).
9. TASSO Collaboration, R. Brandelik et al.: Phys. Lett. 89B, 418 (1980).
10. UA2 Collaboration, P. Bagnaia et al.: CERN preprint EP/83-94 (1983).
11. UA1 Collaboration, G. Arnison et al.: Phys. Lett. 132B, 223 (1983).
12. T. Sjöstrand, private communication.
13. M. Lüscher, K. Symanzik, P. Weisz: Nucl. Phys. B173, 365 (1980).
14. M. Lüscher, G. Münster, P. Weisz: Nucl. Phys. B180, 1 (1981).
15. J. Ambjørn, P. Olesen, C. Peterson: Niels Bohr Institute preprint NBI-HE-84-06 (1984).
16. C. Peterson, T.F. Walsh: Phys. Lett. 91B, 455 (1980).
17. JADE Collaboration, W. Bartel et al.: DESY preprint 83-063 (1983).
18. G. Schierholz, M. Teper: Zeitschr. f. Physik C13, 53 (1982).
19. V. Flaminia et al.: CERN-HERA 79-03 (1979); O. Benary et al.: UCRL-20000 NN (1970).
20. DASP II Collaboration, H. Albrecht et al.: Phys. Lett. 102B, 291 (1981).
21. TASSO Collaboration, R. Brandelik et al.: Phys. Lett. 94B, 444 (1980); JADE Collaboration, W. Bartel et al.: Phys. Lett. 104B, 325 (1981).
22. European Muon Collaboration, J.J. Aubert et al.: CERN preprint EP/83-164 (1983).
23. O. Nachtmann, A. Reiter: Heidelberg preprint THEP-83-28 (1983).
24. J.P. Berge et al.: Phys. Lett. 91B, 311 (1980); N. Schmitz: Lectures at the XX Krakow School, Zakopane, 1980.
25. M. Teper: DESY preprint 81-007 (1981).