WHY DO LOW p_T HADRON JETS LOOK LIKE QUARK JETS IN HARD PROCESSES?*

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Low p_T jets in the hh collisions are discussed from the point of view of their similarity to jets in hard processes (in the e^+e^- annihilation in particular). The question of the relative role of perturbative versus non-perturbative QCD dynamics in low p_T collisions is emphasized.

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Recent progress in strong interactions comes mainly from short distance physics. It seems that hard processes are the best (but still not easy) tests of quantum chromodynamics, at least at the present stage of the theory, based on perturbative methods. The situation remains much more obscure with the main component of hadronic collisions which is soft multiparticle production. Our understanding of low p_T physics in terms of the underlying dynamics of quarks and gluons is far from satisfactory. It may even be that the most economical description is the classical one based on the S-matrix approach and QCD is relevant only indirectly, for instance, by providing us with the spectrum of hadrons. We hope, however, that this fairly pessimistic point of view will turn out to be incorrect.

Over the last few years several QCD inspired models of soft hadronic interactions have been proposed and studied [1]. Most of them seem to have several features in common:

a) Motivated by the striking similarity between the hadronic final states in purely hadronic collisions, in the e^+e^- annihilation and in the deep inelastic lepton-hadron scattering, models for hh collisions refer in one way or another (as far as the process of formation of the final state is concerned) to the parton (QCD) picture for the latter reactions.

b) One can distinguish two steps of model building: the first one deals with the question of the interaction mechanism responsible for a collision at low p_T, the second — with the

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process of formation of the hadronic final state. Different models consider those two problems to different extent and do not necessarily attempt to discuss in detail both of them.

c) Basic physical question and also, in our opinion, the main point of confusion is the relative role of perturbative versus non-perturbative QCD dynamics in low p_T collisions. Perturbative arguments are often used with no theoretical justification and moreover rarely lead to clear, distinctive, testable predictions.

Two steps mentioned in point b) have to be consistent with one another. Points a) and c) are closely related. Reference to hard processes requires special care about its theoretical self-consistency. Correspondence in momentum scales which determines the structure of final states needs justification. Asymptotic predictions (hopefully testable at $p\bar{p}$ collider and at Isabelle) must be formulated clearly in each case since usually they can discriminate between different physical pictures much better than detailed fits to data at present energies.

In the following we briefly review general features of present theoretical approach to the e^+e^- annihilation into hadrons. We try to stress points which may be of relevance for the study of low p_T hadronic physics and to clasify different pictures (not models) of low p_T collisions with mentioned before apparent universality of hadron production in mind. Then, we discuss in some detail a specific model of the low p_T dynamics which has been recently proposed [2].

In processes such as deep inelastic lepton-hadron scattering, high transverse momentum hadron collisions and e^+e^- annihilation into hadrons, partons generated by QCD processes may attain large invariant masses. For instance, the virtual masses of the $q\bar{q}$ produced by the γ^* decay in the e^+e^- annihilation may reach the value of the incoming energy Q^2. In the next stage of the process such off-shell partons dissipate their masses through gluon radiation, as described by the QCD perturbation theory. Perturbative QCD is expected to describe the evolution of the parton jets down to off-shell masses $Q_0 \sim 0(1 \text{ GeV})$, where Q_0 is a fundamental physical parameter, the scale of the non-perturbative hadronization (confinement) effects[1]. Properties of the multiparton state after the perturbative evolution (multiplicity of partons, their transverse momenta etc.) are determined by the *maximal virtuality* $\mu^2_{max} = Q^2$ which can be attained by the quarks coupled to γ^*, and by the value of Q_0^2. (For very large Q the distribution of invariant masses of the $q\bar{q}$ produced by γ^* should take on a "double log" form, giving an average invariant mass

$$\langle\mu^2\rangle \sim (2\alpha_s(Q^2)/3\pi)Q^2. \tag{1}$$

We see therefore that the *average virtuality* $\langle\mu^2\rangle \ll \mu^2_{max}$.) For getting the hadronic final state the perturbative QCD evolution has to be supplemented by the more or less phenomenological model of the transition from partons to hadrons[2]. There are basically two approaches to that hadronization process. One is the parton fragmentation à la Field and Feynman [3] (FF fragmentation) and the second is the colourless cluster (CC) idea [4].

[1] Calculations of exclusive parton distributions with off-shell mass Q_0 become exactly gauge invariant only in the limit $Q_0/Q \to 0$.

[2] In view of the comment from the previous footnote the separation between perturbative evolution and non-perturbative hadronization should be also regarded as a phenomenological parton model assumption.

Both approaches have been used in detailed Monte Carlo studies of the e^+e^- annihilation into hadrons [5] with similar success. However, there seems to be a correlation between the hadronization model used and the value of Q_0 (which is a free parameter) necessary to get the correct description of data in the Petra energy range. For the FF fragmentation $Q_0^2 \sim 0(10 \text{ GeV}^2)$ whereas for hadronization by colourless clusters one needs $Q_0^2 \sim 0(1 \text{ GeV}^2)$.

We would like to stress that, in spite of satisfactory fits to e^+e^- data with both models of hadronization, they are physically very much different. In the FF fragmentation it is assumed that each individual parton in the final state (with invariant mass $\lesssim Q_0$) decay independently into hadrons. In addition to the scales Q and Q_0 specifying the perturbative evolution, the non-perturbative phenomenological fragmentation functions involve an additional scale which is the energy of the fragmenting parton. It is relevant, for instance, for the multiplicity of final hadrons (growing like $\log E$ for single parton fragmentation) and in consequence also for other distributions (at least due to phase space limits). Obviously, that additional scale E is not related to the infrared cut-off Q_0. (Actually, in the e^+e^- annihilation $E \sim Q$.) The approximation of independent decays of individual partons fails when many partons with invariant masses $\lesssim Q_0$ are present. In this case pairs of partons can also have small invariant masses $\sim Q_0$, and therefore may act together in forming hadrons. To describe multihadron spectra one has also to specify the multiple fragmentation functions in addition to the single hadron inclusive spectra. This requires a large number of parameters to be determined from experimental data.

In the colourless cluster approach it is assumed that below Q_0 hadronization affects only local sets of partons which form colour singlets. In this approach to hadronization there is only one mass scale Q_0 (cluster masses should, for consistency, be of the same order of magnitude). Therefore, in this case, the structure of the final state is almost fully determined by the perturbative evolution (modulo cluster decay effects). We also mention that often used intuitive picture of two moving colour charges stretching flux tube does not apply to that second approach to hadronization process.

On the basis of the existing Monte Carlo calculations for the e^+e^- hadrons it is difficult to have some preferences for one of the two approaches to hadronization (on the theoretical side the CC idea seems quite appealing; it emphasizes the role of perturbative QCD in the evolution of the final state). This is presumably due to the following fact: in one approach (CC) the final state is essentially determined by the perturbative evolution which depends on Q^2; in the second approach (FF), nonperturbative parton fragmentation plays an important role but it again depends on Q^2. So in both cases the same mass scale Q^2 (the only one we have at our disposal in case of e^+e^- annihilation) is relevant, and in wide energy range we can get similar results by adjusting the free parameter Q_0 properly. The situation is, however, different for deep inelastic lepton-hadron scattering. Here we have two large invariants Q^2 and W^2 which can be varied independently and one may hope that studies of this process similar to those performed for e^+e^- annihilation can shed more light on the nature of the non-perturbative hadronization process. Two models to study are summarized in Fig. 1. In the model of Fig. 1a particle production proceeds by perturbative radiation of partons by the off-shell quark interacting with γ, followed by the CC hadronization.

Two remaining quarks are spectators which in the final stage of the process form one or two clusters by recombining with some of the produced partons.

In the model of Fig. 1b a perturbative evolution (not explicitly shown) is followed by the FF fragmentation of all fast partons including the diquark system.

We notice first that *both* models predict similar particle production in the forward and the backward hemispheres. This is due to the fact that in the perturbative QCD the struck quark can radiate gluons before and after interaction with the γ, and the former gives particle production in the backward hemisphere (in the leading log approximation both radiation processes are identical; symmetry is broken by non-leading effects). So the

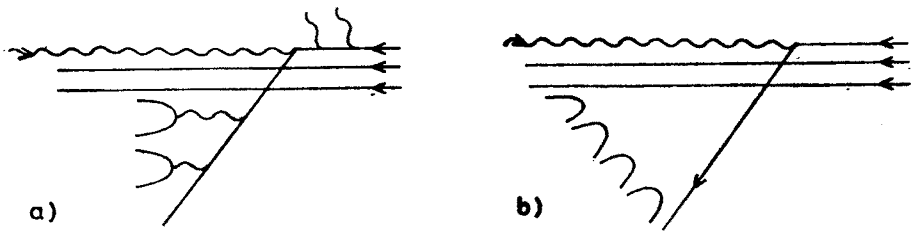

Fig. 1a, b

arguments in favour of the model of Fig. 1b based on a similarity of particle production in both hemispheres [1] are not strong enough. We note also that both models predict dependence of the multiparticle production on W^2 at fixed Q^2. Variable W^2 is directly the scale of the FF fragmentation of Fig. 1b, and the perturbative effects depend on the virtuality of the interacting quark which is a function of W^2 and Q^2. Again, merely the existence of W^2 dependence in data cannot yet discriminate between the two models. Finally, the FF fragmentation of Fig. 1b depends only on W^2, so in the region of the dominance of the non-perturbative mechanism (determined by the value $Q_0^2 \sim 0(10\ \mathrm{GeV}^2)$ taken from the e^+e^- annihilation) the model of Fig. 1b predicts negligible Q^2 dependence for fixed W^2. In the model of Fig. 1a the Q^2 dependence is in principle more explicit but it also requires a quantitative study to know how conclusive the weak Q^2 dependence observed in data is[3]. Although we share the opinion that investigations of the 1h particle production should constrain non-perturbative hadronization models, we see that a reliable conclusion can only be reached on a basis of a quantitative study. It should include perturbative and non--perturbative effects in both models and also kinematical constraints which may be relevant, particularly at relatively low energies we deal with at present.

With basic features of the present picture of the e^+e^- annihilation in mind we turn now our attention to hadronic collisions. Let us begin with asking the following questions:

1. Do quarks of the colliding hadrons attain virtual masses larger than the fundamental scale parameter Q_0 in low p_T collisions?

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[3] The data are hard to understand qualitatively in any of the two models. There is some Q^2 dependence of the $\langle p_T \rangle$ in the forward hemisphere, very weak in the backward one and also very little of Q^2 dependence in the average multiplicity.

2. Is the virtuality of quarks any function of incoming energy s (which is the only obvious large momentum scale in low p_T collisions)?

The answer to those questions depends on the interaction mechanism causing collisions at low p_T which remains unknown. So the answer is model dependent and we have to discuss different possibilities. Let us first assume that the answer to both questions is negative. It means that multihadron production in low p_T collisions is purely a non-perturbative effect and any use of perturbative jet evolution is unjustified. Reference to e^+e^- (and also to universality of non-perturbative hadronization in different processes) then requires the FF approach to be phenomenologically correct. In this case we expect similar structure of final states in hh collisions and in e^+e^- annihilation at $Q^2 \sim 0(s)$[4] as long as non-perturbative jet evolution dominates the latter reaction (perturbative effects become visible in the Petra energy range [5]). Asymptotic properties of multihadron final states in both processes should be, however, totally different. This is because e^+e^- annihilation will be dominated by perturbative features whereas energy dependence in hh collisions provides only simple rescaling of FF distributions. In particular, for e^+e^- we expect the $\frac{1}{\sigma}\frac{d\sigma}{dy}$ distribution and the $\langle p_T^2 \rangle$ to rise with Q^2, and also the hadron multiplicity should rise faster than any power of logarithm. For hh collisions we should have asymptotic Feynman scaling, logarithmically rising multiplicity, energy independent $\langle p_T^2 \rangle$.

We conclude that in the considered case any similarity between the formation of the hadronic state in the e^+e^- annihilation and in hh collisions can only be limited to low Q^2 and low s values, and based on an universal non-perturbative hadronization process of the FF type. This conclusions could be avoided by assuming that the radiation of the two separating on-shell colour charges is responsible for hadron production in e^+e^- annihilation at any Q^2. Such a picture, unattractive from the theoretical point of view, assumes that the perturbative QCD is not applicable to the formation of the final state, irrespectively of the range of Q^2. It would justify the similarity of hadron production in e.g. e^+e^- annihilation at Q^2 and the hh scattering at $s \sim Q^2$ but does not explain any of them.

We shall now discuss the possibility that in the low p_T collisions quarks do attain large invariant masses μ^2 which rise with incoming energy s[5]. (In the following we shall discuss a specific model of this type). Firstly, it is extremely unlikely that $\mu^2_{\max} = s$, so one should not expect a naive correspondence $Q^2 = s$ between large momentum scales in e^+e^- and hh collisions[6] (the statement remains true also if we interpret s as the energy per qq collision) but rather $Q^2 = f(s)$, where the shape of function f depends on details of the interaction mechanism. Secondly, in the present case some correspondence with the e^+e^- annihila-

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[4] We do not discuss here such details as e.g. the number of tubes in hh collisions (two in dual models) or the difference between quark and diquark fragmentation which are important for quantitative comparison of those reactions.

[5] The case of $\mu^2 > Q_0^2$ but energy independent is not very different from the one already discussed and in addition seems to be physically unattractive to us.

[6] We assume here that the properties of the final state depend only on the maximal possible virtuality of quarks and are independent of the process the quarks were produced. This is exactly true in the leading log approximation to the perturbative QCD.

tion should exist independently of the nature of the non-perturbative hadronization mechanism. Asymptotic predictions (for large s) are very similar to those for the e^+e^- i.e. no Feynman scaling of the $\frac{1}{\sigma}\frac{d\sigma}{dy}$ distribution, rise of the $\langle p_T^2 \rangle$ with s, faster than logarithmic rise of the average multiplicity.

The model we would like to discuss in some detail is the following one [2]. To a first approximation, we take the incoming hadrons to consist only of "valence" quarks carrying fixed fractions of the total hadron c.m. energy $E = \sqrt{s}/2$. The interaction is assumed to occur by exchange of a *small* (energy independent) average momentum Δ between quarks from the two hadrons. (The detailed mechanism for the momentum transfer is not considered: we consider merely an "effective interaction".) An important assumption is that scattering should occur by independent and incoherent interaction of one quark from each hadron. This "additivity" assumption formed the basis of several successful previous phenomenological investigations of the dynamical quark model [6]. We should like to mention further evidence for this assumption coming from the hadron-nucleus scattering, and specifically, from the attenuation of fast particles (in the projectile hemisphere) traversing the nucleus [7].

As a result of the momentum transfer Δ, the interacting quarks attain in the $2 \to 2$ scattering process some invariant masses μ_i^2. In the limit that c.m. momenta of incoming quarks $|\vec{p}| \gg |\vec{\Delta}|$, there is a definite relation between the components of Δ and the μ_i^2 ($\|$ denotes component along $\vec{p}$):

$$\Delta_{\|} = \frac{1}{4|\vec{p}|}((\mu_3^2+\mu_4^2)-(\mu_1^2+\mu_2^2)),$$

$$\Delta_0 = \frac{1}{4|\vec{p}|}((\mu_3^2+\mu_1^2)-(\mu_2^2+\mu_4^2)). \tag{2}$$

Eq. (2) demonstrates that even if no energy were transfered ($\Delta_0 = 0$), transfer of momentum parallel to $\vec{p}$ is sufficient to effect the acceleration necessary to generate $\mu_i^2 \neq 0$. Note that radiation of real or timelike invariant particles from initial or final quarks must give μ_1^2, $\mu_2^2 \leqslant 0$ and μ_3^2, $\mu_4^2 \geqslant 0$. Typically, the average invariant mass attained by incoming or outgoing quarks is $\langle |\mu_i^2| \rangle \sim \Delta_{\|}|\vec{p}|$ and, rising with energy, it causes the quarks to emit gluon radiation.

Note that the qq interaction assumed above is different from the often discussed multiperipheral approach in which the interacting states are produced virtually over a long time prior to the actual collisions and which is characterized by the short range order in rapidity. Owing to the latter property, in a *multiperipheral* qq collision at large s and fixed Δ quarks stay essentially on the mass-shell (all the nearest neighbour two-body subenergies are small). The qq interaction, we have in mind, is a genuine long range interaction.

The momentum transfer Δ has been estimated empirically from the inclusive distributions in the ISR energy range with the result $|\Delta_\mu| \sim 1$ GeV. It is interesting to note that a similar magnitude of the momentum transfer between the two hemispheres follows from the analysis of the cosmic ray data [8] (in the framework of the two fireball model).

With $|\Delta_\mu| \sim 1$ GeV we expect an average "struck" quark invariant mass $\mu \sim 3$ GeV at $\sqrt{s} \sim 60$ GeV and $\mu \sim 10$ GeV at $\sqrt{s} \sim 600$ GeV. Hadron jets resulting from the "struck" quark in low momentum transfer hadronic collisions should be similar to jets produced in other processes by quarks with similar invariant masses. Taking e^+e^- annihilation we can use Eq. (1) to get

$$\sqrt{s} \sim \alpha_s(Q^2)Q^2/\Delta_{||} \tag{3}$$

as the relation (for large s and Q^2) between the c.m. energies in the hh collisions and the e^+e^- annihilation at which similar structure of the final states should be observed[7]. From Eq. (3), $\sqrt{s} \sim 500$ GeV gives $Q \sim 100$ GeV and at $p\bar{p}$ collider we should observe several distinctive effects expected for e^+e^- at LEP [5] such as rise of $\langle p_T^2 \rangle$ by factor 2 (as compared to ISR energies), rise of $\left.\frac{1}{\sigma}\frac{d\sigma}{dy}\right|_{y=0}$ by factor 1.5–2 and clear departure from the logarithmic law for the average multiplicity. There are persistent indications from cosmic ray data [8] that those effects may indeed be observed.

In summary, it seems that the nature of the non-perturbative hadronization process can be further investigated by studying hadronic final state in the deep inelastic lh scattering (as a function of W^2 and Q^2) in a way similar to Monte Carlo studies for e^+e^- annihilation [5]. Universality of low p_T jets in hh collisions may be limited to the non-perturbative region (low s and low Q^2) but it may also extend to higher energies. The latter case would require an important role to be played by the perturbative QCD dynamics in low p_T collisions. A specific model of this type has been discussed. It relates s to Q^2 at which similar structure of final states should be observed in the hh and in the e^+e^- collisions. Data at $p\bar{p}$ collider and Isabelle will be able to distinguish between different pictures of low p_T collisions.

REFERENCES

[1] For a recent review see e.g. J. F. Gunion, *Quarks and Gluons in Low p_T Physics*, SLAC-PUB-2607 (1980).

[2] S. Pokorski, S. Wolfram, *QCD Expectations for High Energy Hadronic Collisions*, CALT-68-795 (1980).

[3] R. D. Field, R. P. Feynman, *Nucl. Phys.* **B136**, 1 (1978).

[4] D. Amati, G. Veneziano, *Phys. Lett.* **83B**, 87 (1979); G. C. Fox, S. Wolfram, *Nucl. Phys.* **B168**, 285 (1980).

[5] S. Wolfram, *Parton and Hadron Production in e^+e^- Annihilation*, CALT-68-778 (1980); P. Mazzanti, R. Odorico, *Z. Phys.* **C7**, 61 (1980).

[6] E. M. Levin, L. L. Frankfurt, *JETP Lett.* **2**, 65 (1965); H. J. Lipkin, F. Scheck, *Phys. Rev. Lett.* **16**, 71 (1966); H. Satz, *Phys. Lett.* **25B**, 220 (1967).

[7] N. N. Nikolaev, S. Pokorski, *Phys. Lett.* **80B**, 290 (1979); J. Nassalski, private communication.

[8] C. M. G. Lattes, Y. Fujimoto, S. Hasegawa, *Phys. Rep.* **65**, 151 (1980).

[7] Of course, in a quantitative analysis one should remember about spectator quarks.