# LARGE TRANSVERSE MOMENTUM PHENOMENA

Session organized by

M. Jacob
CERN, Geneva, Switzerland

Abstract The study of large transverse momentum phenomena has provided evidence for hadronic jets at wide angle. These jets are expected to result from direct interactions among hadron constituents. They are therefore of great topical interest. A full day was devoted to the discussion of recent developments in which some of the participants at the Flaine meeting have been involved. The morning session consisted of reviews of new experimental results at Fermilab (Experiment 260) and at the CERN ISR (Experiment 407/408 of the CERN-Collège de France-Heidelberg-Karlsruhe Collaboration, and Experiment 410/413 of the British-French-Scandinavian Collaboration). The afternoon session combined theoretical reports with both overlapping and divergent views. This section of the proceedings contains a short introduction and the write-ups of the different contributions which were presented.

Résumé L'étude des phénomènes à grande impulsion transverse a mis en évidence l'existence de jets hadroniques à grand angle. Ces jets sont supposés résulter de l'interaction primaire entre constituants des hadrons en collision. Ils sont de ce fait l'objet d'un grand intérêt. Un jour entier a été consacré à la discussion de résultats récents auxquels certains des participants à la réunion de Flaine ont été associés. La session du matin a rassemblé des présentations de nouveaux résultats expérimentaux obtenus à Fermilab (Expérience 260) et aux ISR, au CERN (Expérience 407/408 de la Collaboration CERN-Collège de France-Heidelberg-Karlsruhe et Expérience 410/413 de la Collaboration British-French-Scandinavian). La session de l'après-midi a rassemblé des rapports théoriques présentant entre eux convergences et divergences. Cette partie des Comptes-Rendus contient une courte introduction et le texte correspondant aux différentes contributions qui ont été présentées.

## CONTENTS

## 1. INTRODUCTION

Ever since their discovery at the ISR in 1972[1], large transverse momentum phenomena have been under very active study. This is already a mature domain of particle physics and what follows, which focuses on recent results and open questions, is more for the specialist than for the newcomer. The latter should start with reviews of the field as it now stands[2], before being able to appreciate, or assess, the particular relevance of much of what is reported here. As expected, topical questions are overemphasized at the risk of rapid obsolescence. This short introduction merely tries to put the different contributions which were presented into some general perspective.

The discovery of the remarkable properties of deep inelastic lepton-hadron collisions, now associated with Björken scaling, suggested the possible existence of related phenomena in hadron-hadron collisions[3]. This could then be formulated[4] more precisely in the parton model of Feynman[5], and the anomalously large production of secondary particles with large transverse momentum[1] was promptly considered as a possible manifestation of such effects. It took, however, a lot of effort before the first key property, namely the existence of two hadronic jets at wide angle, could be ascertained[6]. Indeed, if the primary interaction corresponds to a wide-angle collision among two proton constituents one would expect all large $p_T$ particles to result from the fragmentation of the scattered constituents. If the looked-for event is signalled by the observation of a (trigger) large $p_T$ particle ($p_T$ > 2 GeV/c say), one would expect that any other large $p_T$ particle seen on the same side as the trigger particle should be almost in the same direction as the two fragments of the same jet. At the same time, large $p_T$ particle(s) observed on the other side should be to a good approximation in the reaction plane defined by the trigger particle and, if more than one, should have almost the same direction as the fragments of a jet. These required properties[7] have now been checked with a reasonable accuracy. The most recent results along these lines have mainly come from two major experiments at the Split Field Magnet (SFM), by the CERN-Collège de France-Heidelberg-Karlsruhe (CCHK) and British-French-Scandinavian (BFS) Collaborations, respectively. The latest available data are reported here in detail by *D. Linglin* and *R. Møller*, in their respective contributions. The reader should assess there for himself (herself) what is meant at present by a two-jet structure. One thus gains confidence for the analysis of large $p_T$ production in terms of a basic process corresponding to the graph of Fig. 1.

As these correlation results were obtained at the ISR [6], inclusive results from Fermilab were also providing further evidence for the relevance of the basic process of Fig. 1. They include charge effects at large $x_T = 2p_T/\sqrt{s}$, the stronger large $p_T$ yields in pion-induced rather than in proton-induced reactions and, finally, peculiar effects associated with production in nuclei[8].

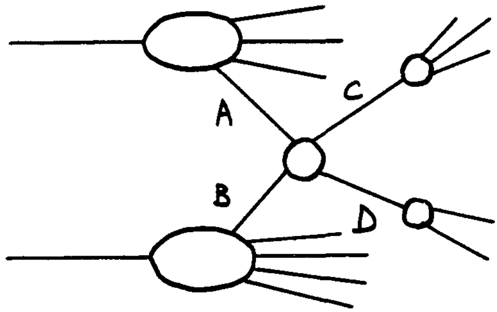


Fig. 1 Constituents A and B with fractions $X_A$ and $X_B$ of the colliding particle momenta ($S' = SX_AX_B$) interact to give C and D, which eventually fragment into hadrons, thus yielding two jets of particles.

Actually, what separates present models from one another is the nature of the constituents which are considered in the subprocess AB → CD, and -- to a large extent a consequence of that -- the energy and angular dependence of the interaction corresponding to the subprocess. All models considered at present to have some claim to success concerning correlation data have, one way or another, the graph of Fig. 1 as the basic process. They are partonic in character. This was, however, not the case two years ago, when non-partonic models could still claim some success with all available data. At the meeting *Clavelli* mentioned that dual models can reproduce the large $p_T$ distribution very well. Our present selected and all-partonic list may well not include models which could be in fashion two years from now. This caveat being given, in all present models, the large $p_T$ particle used as a trigger may come either from the fragmentation of a constituent (the fragments of which define a jet) of much larger momentum, and be one among several large $p_T$ particles, or result from a peculiar fragmentation mode, whereby a constituent of similar momentum would have given almost all its momentum to only one of its daughter particles. The extreme case consists of the observed particle being the constituent itself.

Models differ according to the relative frequency of such fragmentation modes, a property related to a large extent to the nature of the basic constituents considered at the subprocess level.

It turns out that, in view of the rapid fall-off of the production cross-section with $p_T$, the latter mode, where (almost) all the momentum of the constituent is found with the trigger particle, may be dominant at the single-particle trigger level even if it is a minority mode at the parton fragmentation level. This is referred to as trigger bias[9,10]. As a result, one may expect that if one could trigger on a whole jet of hadrons with a global $p_T$, one could get a much larger yield than triggering on a single particle with the same $p_T$ value. Expected enhancement factors are of the order of 100 or more[9,10]. This now seems to be the case experimentally, as reported here by *R. Field*. In a model where the trigger particle could be the scattered constituent, as in the constituent interchange model (CIM)[11], one would have expected the corresponding ratio of yields to be of the order of one. Furthermore, if constituents C and D (Fig. 1) are expected to be of the same nature, one is led to expect that the observed distribution away from the trigger (the fragments of constituent D when the trigger particle would be among those of constituent C) should be the same whether one triggers on a single particle or globally on a jet, provided, of course, provision is made to refer to the same total jet momentum[9,10]. As reported here by *R. Field*, there is now evidence for that. This is, however, against predictions from the CIM, where C and D are of different nature (meson and quark).

*S. Brodsky* courageously faces such difficulties in his report here. He shows how he thinks the CIM may be implemented upon to meet such problems. Such difficulties are worrisome, since the CIM has so far enjoyed a lot of success. It was very successful at predicting inclusive distributions and, in particular, the observed $p_T$ dependences which all depart from what would be expected in a scaling limit which one may *a priori* expect to apply at the constituent level.

Indeed, a scaling behaviour of the type $E(d\sigma/d^3p) \sim (p_T)^{-4}\, F(x_T, \theta)$ was already explicitly considered in the early Berman-Björken-Kogut (BBK) approach[4] and also in later, more detailed, analyses applying the parton model to large $p_T$ data[12]. It is still possible that, at much larger $p_T$, a $p_T^{-4}$ behaviour could prevail[13]. It is, however, certainly not what is seen in data available at present ($p_T < 9$ GeV/c), where one finds a $p_T^{-8}$ rather than a $p_T^{-4}$ (scaling) behaviour. One may also say that the $p_T^{-4}$ yield which one could associate with an asymptotic freedom approach[14] is far below what is measured at present in the $2 < p_T < 9$ GeV/c range where data exist[10].

Present models thus differ much from one another about what to do with the observed $p_T$ dependence. This corresponds to most of the divergences met among the theoretical contributions to be found here. We have already mentioned the CIM, where the basic process for pion production is quark meson → meson quark. This readily implies a $p_T^{-8}$ behaviour for pions and also a very satisfactory $x_T$ dependence.

We already mentioned its shortcomings with respect to recent correlation and jet data. Pion-induced yields are low for quark-antiquark annihilation[15] which is also an *a priori* interesting process considering a two-jet annihilation. This does not mean that these processes are not relevant. They are, however, not dominant as such, as they could once be expected to be.

The largest fraction of the effect could then correspond to quark-quark scattering. This is the attitude now followed by most models discussed here. However, models differ in their facing of the actual $p_T$ behaviour, which differs from the scaling one.

One attitude consists in departing from the *a priori* most simple (gluon exchange) interaction among quarks and in choosing a particular form for $d\sigma/dt'$ at the AB → CD level. One should have globally four powers of $s'$ and $t'$ ($s'$, $t'$ and $u'$ are the Mandelstam variables for the two-body subprocess) in order to get the observed $p_T^{-8}$ behaviour. The angular dependence is associated with the powers of $t'/s'$. Feynman and Field[10] have made an extensive study of inclusive distribution, soon to be completed by an extensive study of correlation data. They advocate $d\sigma/dt' \sim (s't'^3)^{-1}$ for the quark-quark interaction and obtain an impressive success. This is described in detail here by *R. Field*. A similar attitude has been taken by the Bielefeld group and by the Leipzig group. Their results are reported here in the contributions of *R. Baier* and *J. Ranft*, respectively. There are, however, people who oppose having an open mind with respect to the form of the quark-quark interaction, which should be simple by essence. In his report, *R. Hwa* advocates that one should start with a scaling interaction which would then give a $p_T^{-4}$ behaviour, but acknowledge the scaling violations observed in deep inelastic muon scattering[16]. Properly parametrized this may provide a large effect and explain the observed distributions.

In the model presented by *D. Linglin*, the $p_T^{-4}$ behaviour initially included disappears in the $p_T$ range so far probed because a large fraction of the relevant transverse momentum is taken by those secondaries which, according to the graph of Fig. 1, one could *a priori* consider as mere spectators. This is no longer true if they are allowed to take a rather large $p_T$ ($p_T \sim 0.6$ GeV/c say).

This question brings us to that of the transverse momentum to be associated with the quarks (partons) in the colliding particles. In the early analyses there was little point in departing from a collinear process. The $p_T$ distribution was anyway expected to be sharply cut off with $\langle p_T \rangle \sim 0.35$ GeV/c. There are, however, already many pieces of data which indicate that a much more detailed study is necessary and that $\langle p_T \rangle$ is likely to be larger (0.5 GeV/c?) than usually assumed. The $p_T$ dependence assumed for the colliding constituent is highly relevant in the calculation of correlations among large $p_T$ particles, in the study of coplanarity effects and, as mentioned already, even for the inclusive yield at medium $p_T$ values. This is a very topical question. It can be related to problems met in the analysis of large mass lepton pair production in terms of a parton model. Almost all the reports put together here are concerned with the parton $p_T$ dependence one way or another. What is clear is that data are already such that the $p_T$ dependence can no longer be neglected. It is also possible that the parton $\langle p_T \rangle$ could be much larger than anticipated. This would then provide several biases which are of much relevance in the $p_T$ range being considered at present in correlation studies ($2 < p_T < 4$ GeV/c say).

If, despite the already itemized problems, quark-quark scattering now enjoys some success as the tentative dominant process, its relative silence with respect to quantum number effects (except of course for charge effects which are easily reproducible) matches a comparable experimental silence. If there has been much progress in the understanding of large $p_T$ phenomena and, if the primary hard scattering among hadron constituents appears as the underlying mechanism, the nature of the constituent is still wide open. There is a relatively large baryon yield (the $\pi^+/p$ ratio at large $p_T$ is of the order of 0.3). There is a relatively large prompt $\gamma$-ray yield (it could be at the 10% level). This should be better studied and understood. The report of *R. Møller* gives quantum number effects as recently obtained. They are not negligible and call for an explanation which present models do not readily provide. Conversely, the comparative study of large $p_T$ phenomena in meson-nucleon and nucleon-nucleon scattering, which is only starting, should eventually be very interesting.

Triggering with a calorimeter should now provide a big step forward in jet analysis, since the reported yields are very much larger than those observed for single particles. With present large lead-glass detectors one may already reach anyway much larger $p_T$ values than so far considered ($p_T \sim 15$ GeV/c at the ISR). One may thus foresee many interesting and rapid developments for which the jet picture is now providing the general framework.

Despite the relative present success of a class of models it remains very important to face new data with as open a mind as possible and select events according to as different criteria as possible. In connection with this, the report of *W. Ochs* proposes a new approach.

From what has previously been said there are many data being looked for which would be of immediate use in sorting out better models. Concluding, I would only emphasize that there is a particularly important piece of data, which was obtained by the Aachen-CERN-Munich Collaboration at the ISR, for which one would wish to have extensive tests in view of its key relevance to the scaling hypothesis. According to scaling, one expects that the observed $p_T$ dependence should be the same whatever one triggers upon: one pion, two pions, or several pions. There are data showing that the $p_T$ distribution for $2\pi^0$ (there is little dependence on the momentum ratio) is proportional to that for a single $\pi^0$. It would be good to have more precise data and to check this property with other groupings of particles.

## REFERENCES AND FOOTNOTES


1) M. Banner, J.L. Hamel, J.P. Pansart, A.V. Stirling, J. Teiger, H. Zaccone, J. Zsembery, G. Bassompierre, M. Croissiaux, J. Gresser, R. Morand, M. Riedinger and M. Schneegans, Phys. Letters 44B, 537 (1973).
B. Alper, H. Bøggild, G. Jarlskog, G. Lynch, J.M. Weiss, P. Booth, L.J. Carroll, J.N. Jackson, M. Prentice, G. von Dardel, L. Jonsson, G. Damgaard, K.H. Hansen, E. Lohse, F. Bulos, L. Leistam, A. Klovning, E. Lillethun, B. Duff, F. Heymann and D. Quarrie, Phys. Letters 44B, 521 (1973).
F.W. Büsser, L. Camilleri, L. Di Lella, G. Gladding, A. Placci, B.G. Pope, A.M. Smith, J.K. Yoh, E. Zavattini, B.J. Blumenfeld, L.M. Lederman, R.L. Cool, L. Litt and S.L. Segler, Phys. Letters 46B, 471 (1973).

2) D. Sivers, S.J. Brodsky and R. Blankenbecler, Phys. Reports 23, 1 (1975).
P. Darriulat, Rapporteur's talks at the Palermo Conference [Proc. EPS Internat. Conf. on High-Energy Physics, Palermo 1975 (Editrice Compositori, Bologna, 1976), Vol. 2, p. 840] and the Tbilisi Conference (Proc. 18th Internat. Conf. on High-Energy Physics, Tbilisi 1976, to be published) and Phys. Reports, to be published.

3) M. Jacob and S. Berman, Phys. Rev. Letters 25, 1683 (1970).

4) S. Berman, J. Björken and J. Kogut, Phys. Rev. D 4, 3888 (1971).

5) Reviews of the parton model are to be found in R.P. Feynman, Photon hadron interactions (Benjamin, New York, 1972).
J. Kogut and L. Suskind, Phys. Reports 8, 75 (1973).

6) This resulted from a long series of experiments at the ISR, with, in the early stage, major contributions from the CERN SFM Collaboration (412), and also from the Aachen-CERN-Heidelberg-Munich Collaboration and the CERN-Columbia-Rockefeller-Saclay Collaboration. One should also mention the pioneering correlation work of the Pisa-Stony Brook Collaboration. Progress was reported in a long series of ISR discussion meetings (CERN reports, unpublished) which came out between 1972 and 1976.

7) They are spelled out in detail in J.D. Björken, SLAC Summer School 1976, and in M. Jacob and P.V. Landshoff, ISR summary 16, also published *in* Structure of large $p_T$ events , Proc. Conf. on High-Energy Particle Interactions, Smolenica, 1976 (Eds. D. Krupa and J. Pišut, Bratislava). The Rapporteur's talks of P. Darriulat at Palermo, 1975, and Tbilisi, 1976, illustrate beautifully progress along these lines over the past two years.

8) For a review, see: G.F. Fox, Invited paper, APS Brookhaven meeting, 1976, and H. Frisch, *ibid.*

9) S. Ellis, M. Jacob and P.V. Landshoff, Nuclear Phys. B108, 93 (1976).
M. Jacob and P.V. Landshoff, Nuclear Phys. B113, 395 (1976).

10) R. Field and R.P. Feynman, Phys. Rev., to be published.
R.P. Feynman, Invited talk, Coral Gable Conference, 1977.

11) D. Sivers, S.J. Brodsky and R. Blankenbecler, Phys. Reports 23, 1 (1975).

12) S. Ellis and M. Kislinger, Phys. Rev. D 9, 2027 (1974).

13) Recent results from Exp. 702 at the ISR (see ISR summary 21) indicate that events with $p_T \sim 15$ GeV/c are certainly present with a reasonable cross-section. It is, however, much too early to give an actual inclusive distribution.

14) H.D. Politzer, Phys. Reports 14C, 130 (1974).

15) P.V. Landshoff and J.C. Polkinghorne, Phys. Rev. D 8, 927, 4159 (1973).

16) H.L. Anderson et al., Proc. 18th Internat. Conf. on High-Energy Physics, Tbilisi, 1976, to be published.