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HADRON JETS IN PERSPECTIVE

C. Quigg

Fermi National Accelerator Laboratory*
P.O. Box 500
Batavia, Illinois 60510 USA

INTRODUCTION

When the organizers invited me to deliver the summary talk at this workshop, I remarked that since all the other participants were experts who have actually contributed to the subject, this was rather like asking the only student at a summer school to take his final examination in public. Little did I suspect the true depths of my ignorance! After only a short time in Erice, I realized that I was the only person in town not on intimate terms with Geoffrey Fox's COMMON blocks. Therefore, I shall not speak about FORTRAN, but about physics, and that in simple terms.

Although the study of hadron jet phenomena is not a new field - witness the mature experiments and detailed analyses reported here - the very reality of jet phenomena in hadron-hadron collisions has remained a topic of controversy. But no more! The dramatic results presented here by Siegrist[1] (for the UA2 Collaboration) and by Della Negra[2] (for the UA1 Collaboration) show that in 540 GeV $\bar{p}p$ collisions, isolated and well-collimated hadron jets do exist and are evident to the untrained eye, without benefit of arcane event selection procedures. This is highly significant, not only because it promises very incisive studies of hard-scattering phenomena at the new colliders, but also for the moral support it lends to the detailed measurements already undertaken at the CERN ISR and in fixed target experiments.

[Two parenthetical remarks are in order here. First, with regard to the "energy *versus* luminosity" debate, let us note that in

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what has been characterized as the equivalent of 90 seconds of running at (the modest) design luminosity of the $\bar{S}ppS$, decisive results have been obtained. Score one for energy! Let us note as well that in that same minute and a half the UA2 detector has apparently recorded a hard parton-parton collision at a CM energy of 140 GeV, an energy larger than we are likely to see in e^+e^- annihilations until the end of the century. Great things are to be expected in subsequent runs.]

During the course of this workshop, we have heard much about the predictions of quantum chromodynamics, frequently embodied in the output of Monte Carlo simulations, and their comparison with experiment. I will offer a few brief remarks later on the Monte Carlo industry, but I want to devote the first part of my talk to a survey of what QCD has done for us lately. The point of view that I will adopt thereafter is that it is time to rise above worrying about the existence of jets in hadron-hadron collisions, and to get serious about studying the properties of jets and the dynamics of jet formation. I will review the motivation for studying jet phenomena, explore the connection with low-$p_\perp$ physics, and call attention to some exotic possibilities. I shall close with a brief shopping list for future experimentation, and some general impressions of the state of the field.

WHAT ARE (NOT) TRUE TESTS OF QCD?

Much has been said here about the indirectness of tests of QCD and the indecisiveness of comparisons between experiment and theory. In many cases, conclusions are indeed sensitive to apparently arbitrary decisions made in writing computer programs, and one may despair of ever testing the underlying theory. Skepticism is healthy - and surely preferable to the oft-repeated formula that any discrepancy between observation and simplified theory is evidence for higher-twist effects and supports QCD - but one may easily lose sight of the achievements and promise of the theory. Therefore it seems to me worthwhile to invest some of our time in a review of the contributions QCD has already made to our knowledge of hadronic phenomena.

Pleasing as they are in their structure, gauge theories are abstracted from experimental observations and must be subjected to experimental tests. In the case of quantum chromodynamics, this need is frustrated in many cases by the fact that the strong interactions are strong, so that we have not yet learned to make definite predictions. Nevertheless, there are a few circumstances in which the expectations of the theory are unambiguous. For example, I would give up QCD as the theory of strong interactions among pointlike constituents if:

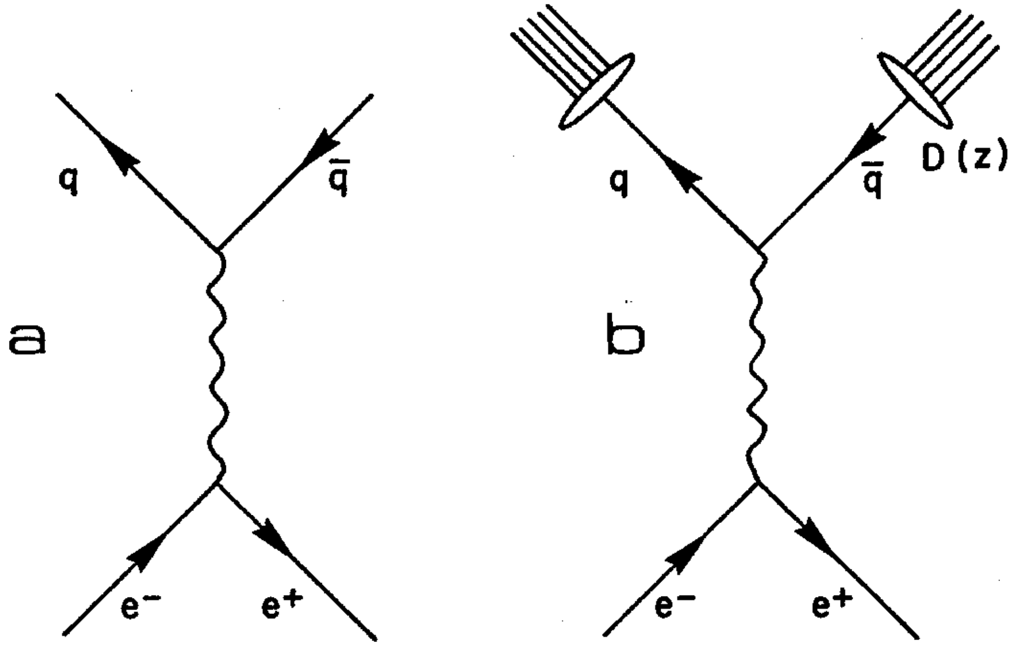


Fig. 1: (a) Parton-model description of electron-positron annihilations into hadrons. (b) Fragmentation of the semifinal-state quarks into hadrons.

- its prediction for $R=\sigma(e^+e^-\to\text{hadrons})/\sigma(e^+e^-\to\mu^+\mu^-)$ failed;

- Bjorken scaling did not hold approximately in deeply inelastic lepton-nucleon scattering;

- a three-jet structure were not observed in electron- positron annihilations into hadrons.

- the photon structure function in the regime ($x\gtrsim0.2$, $Q^2\gtrsim5\ \text{GeV}^2$) were not as predicted.

For essentially all other observables, it would be necessary to revise our understanding of the theory in case of surprises, but not to revise the theory itself.

This is a somewhat short list of tests for what many regard as the ultimate theory of the strong interactions. But in addition, there are many ways in which QCD has advanced our understanding of deeply inelastic processes. Looking at some of these will help to remind us why QCD is taken seriously as a candidate for a final theory, and why rival phenomenological descriptions are not.

Consider first the development of our understanding of electron-positron annihilations. The most primitive picture is that of the parton model illustrated in Fig. 1. This is a model, an "as if" description that does not by itself provide a justification or indeed an understanding of the limits of its validity. We simply assert that annihilation into hadrons proceeds through the production (Fig. 1(a)) of a quark-antiquark pair, which fragment independently and with unit probability into the observed hadrons (Fig. 1(b)). Arguments similar to those that motivated Bjorken scaling then suggest that the fragmentation of quarks into hadrons is described by a scaling function of the dimensionless momentum ratio z=p(hadron)/p(quark). This picture is highly successful. It correctly anticipates the prominent two-jet structure observed in this channel and the gross behavior of the total cross section.

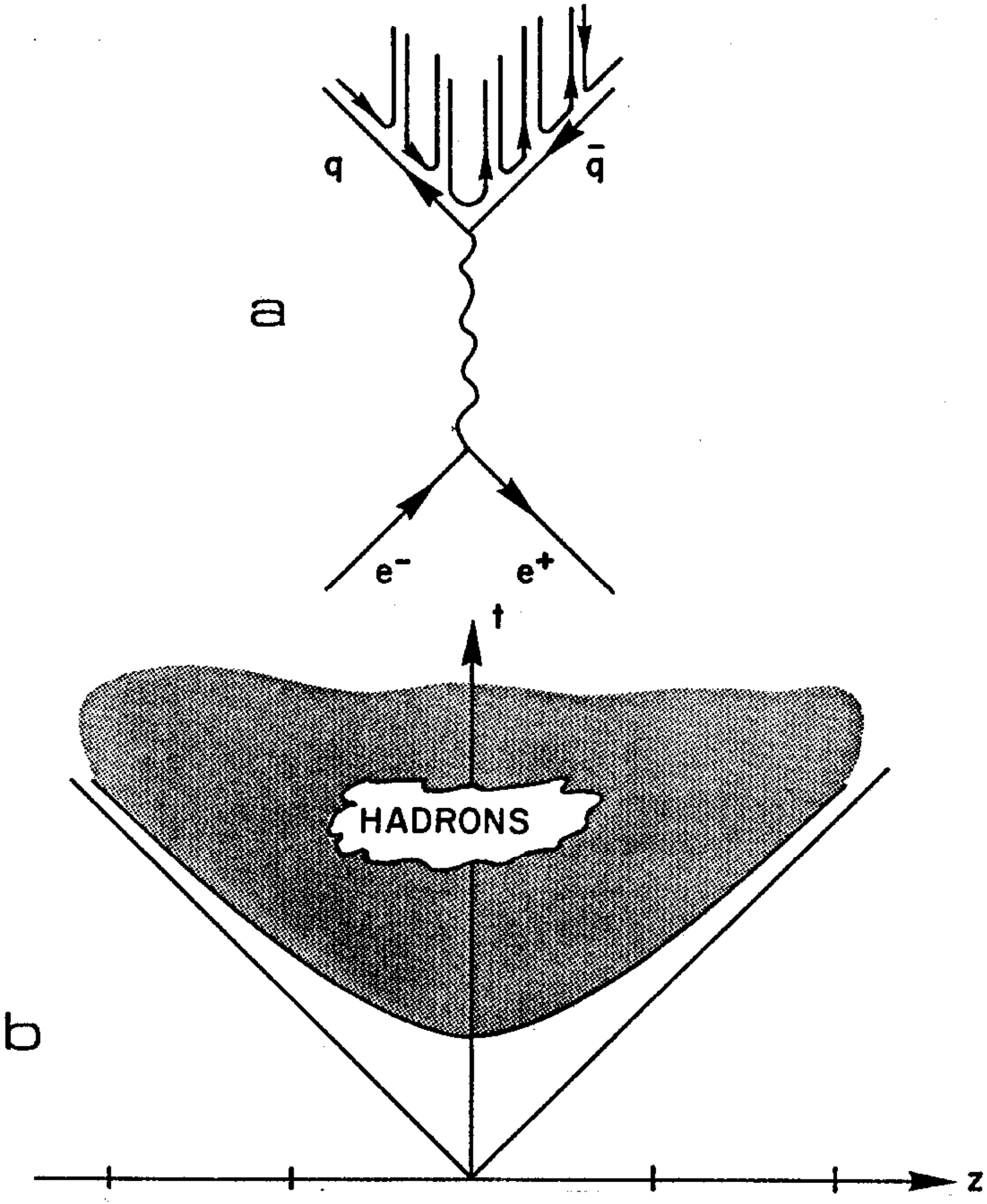
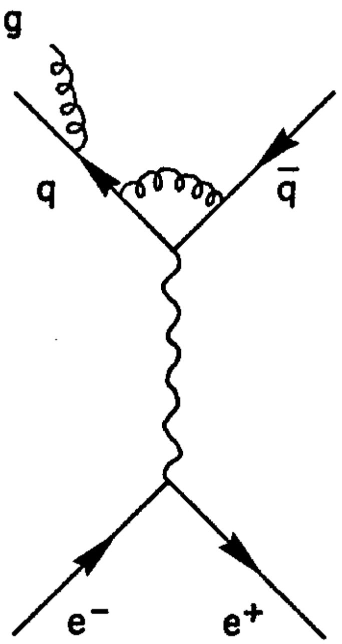


Fig. 2: (a) Quark-pair-creation model of hadron production. (b) Spacetime description of hadron evolution.

Of course, it cannot be literally true that the quark and antiquark fragment with complete independence, for they are isolated color charges which must in some manner be neutralized. Therefore one is motivated to invent mechanisms for communication between the two color sources, and thus for the production of hadrons. One such scheme is depicted in Fig. 2(a), where quark-antiquark pairs are popped out of the vacuum. The same result can be described in the language of strings or of color flux tubes. This gives some understanding of the K/π ratio, charge correlations, etc., and suggests - by virtue of its resemblance to the multiperipheral picture - a relation to particle production in hadron-hadron collisions. Fig. 2(b) gives a view of the spacetime evolution of the process. Hadrons are formed along a surface t^2-z^2=constant, above which direct observations are possible. The region below the surface of hadron production is inaccessible to direct observation.

Enter QCD. The lowest-order strong interaction modifications to the parton model diagram are shown very schematically in Fig. 3(a). These are characterized by the real or virtual emission of gluons. The asymptotic freedom of QCD supports the hope that there will be a regime in which low-order perturbation theory is reliable. This short time and distance region is indicated in Fig. 3(b). Quantum chromodynamics thus justifies and changes quantitatively the predictions of the parton model for the total cross section. In addition, the style of analysis introduced by Sterman and Weinberg[3] confirms and makes more precise the parton model expectations for jet structure, recast in the language of energy flow.

3a



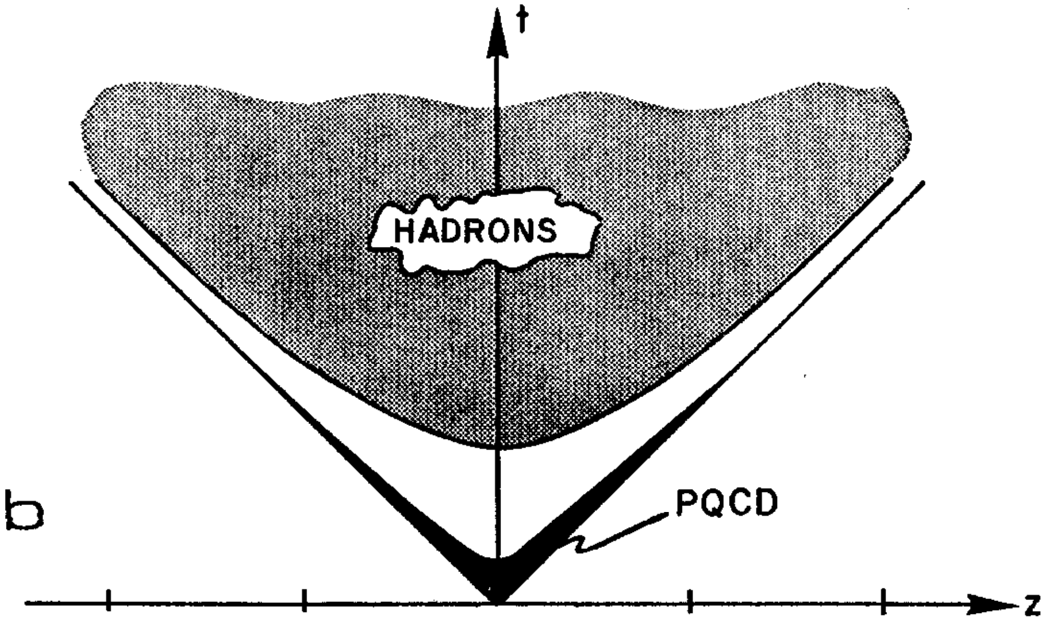


Fig. 3: (a) Real- and virtual-gluon emission corrections to the parton model picture for electron-positron annihilations. (b) Space-time diagram, showing the regime in which perturbative QCD is valid.

For the real-gluon emission diagrams, the incorporation of parton fragmentation into hadrons in the manner of Feynman and Field (as shown in Fig. 4) leads to the qualitative expectation of three-jet events. Quantum chromodynamics replaces the scale-invariant

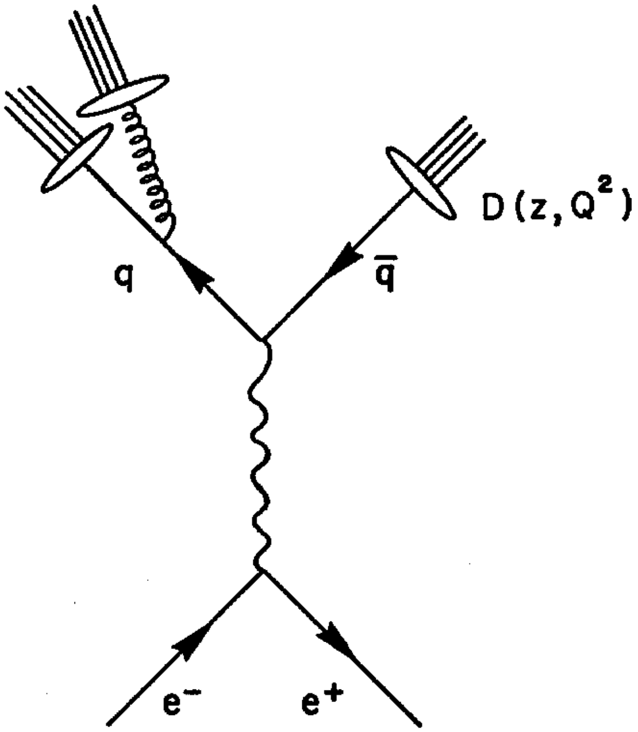


Fig. 4: Fragmentation of quarks and gluons into three jets of hadrons.

fragmentation functions D(z) with fragmentation functions $D(z,Q^2)$ that show systematic deviations from scaling, and replaces the simple expectation of three-jet structure by more general energy-flow predictions. Again one may make specific models for the hadronization, such as the quark-pair creation model indicated in Fig. 5. These may suggest specific differences between quark jets and gluon jets which may provide interesting targets for experiment.

At this meeting, Field[4] and Fox[5] have described attempts to go beyond these images by taking seriously the ideas of perturbative QCD outside the regime in which its validity can be taken for granted. Their view of hadronization is indicated in Fig. 6(a). It consists in the radiation of a large number of soft gluons, which are recombined into the observed hadrons. There are many approximations, idealizations, and acts of faith involved in this scheme, but I regard it as an interesting effort to surpass the parton model and to penetrate the unfamiliar region of space-time indicated in Fig. 6(b).

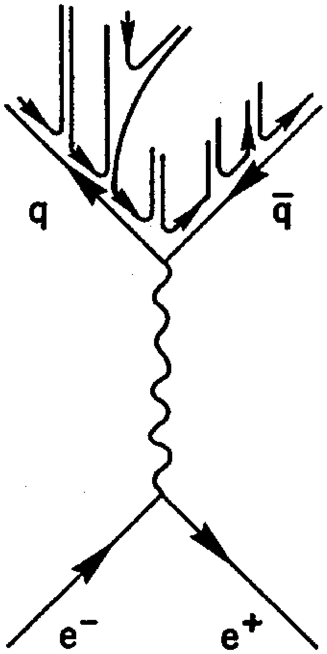


Fig. 5: Quark-pair creation model for hadronization in three-jet events.

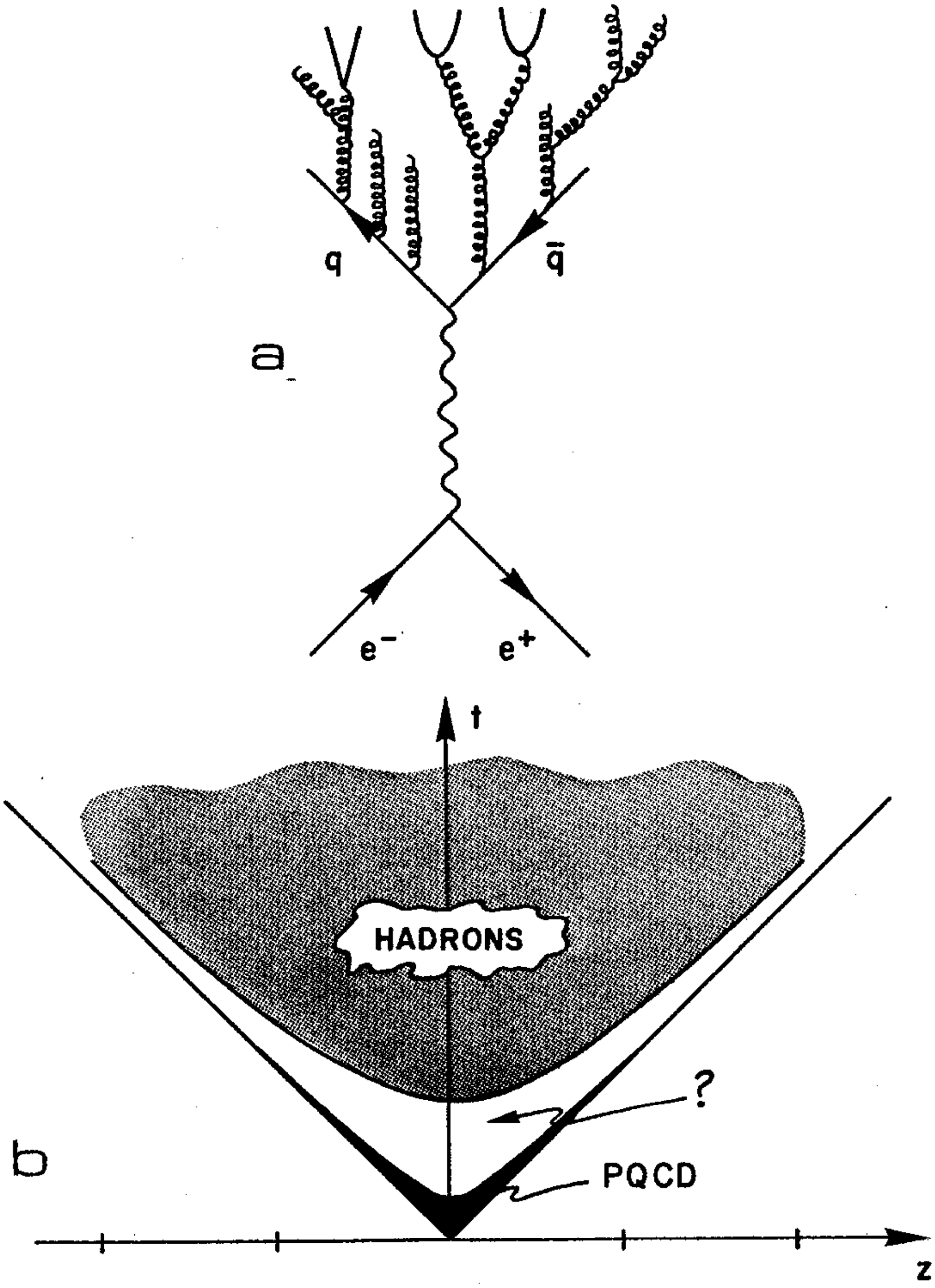


Fig. 6: (a) QCD-inspired microscopic picture of hadronization in electron-positron annihilations. (b) Regions of spacetime accessible to observation, speculation, and calculation.

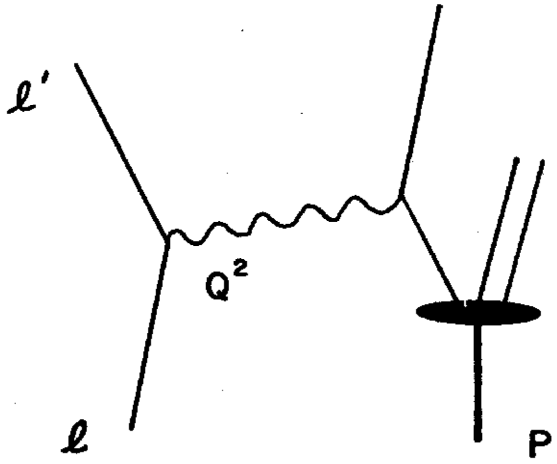


Fig. 7: Parton-model description of deeply inelastic lepton-nucleon scattering.

Let us turn now to deeply inelastic lepton scattering, the process for which the parton picture was invented. The parton model itself is sketched in Fig. 7. According to this picture, the hadron structure is probed by a current with (virtual) $\text{mass}^2 = -Q^2$, which interacts with a single pointlike constituent. The struck parton and the erstwhile nucleon target do not interact but, as shown in Fig. 8, fragment separately. This simple model accounts for Bjorken scaling, and correctly relates the properties of hadron jets observed in e^+e^- annihilations, in deeply inelastic $\ell^\pm N$ collisions, and in the charged- and neutral- current interactions of neutrinos with nucleons.

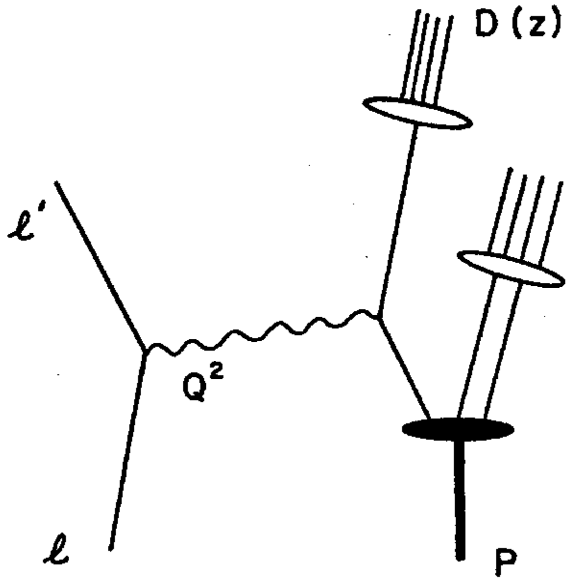


Fig. 8: Fragmentation of the struck quark and spectator diquark into hadrons in the parton picture of deeply inelastic scattering.

Again, these successes are those of an "as if" model, without secure theoretical underpinnings. QCD makes the predictions of the parton model somewhat more secure. While QCD by no means justifies all the assumptions of parton picture (there are, for example, no hadrons in perturbative QCD), asymptotic freedom and diagrams like those of Fig. 9 make plausible approximate Bjorken scaling and yield definite predictions for the Q^2-evolution of (moments of) structure functions and fragmentation functions. Predictions for jet-broadening akin to those derived for e^+e^- annihilations are also available.

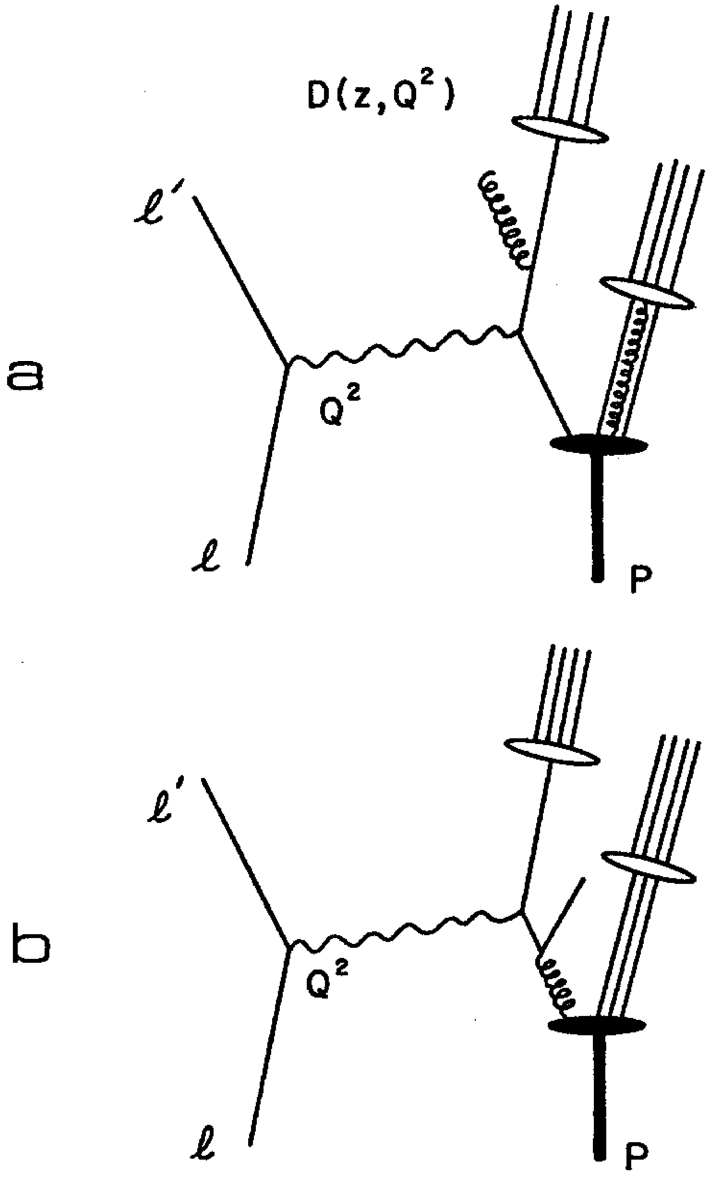


Fig. 9: (a) "Radiative" corrections to deeply inelastic lepton-nucleon scattering. (b) Dissociation of a gluonic parton into a quark-antiquark pair which is seen by the probe.

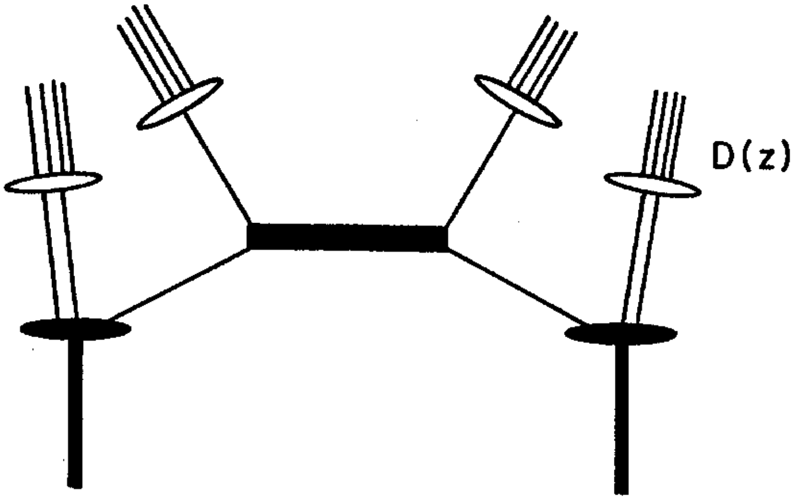


Fig. 10: Parton model description of high-$p_\perp$ events in hadron-hadron collisions.

Finally let us examine the development of our description of hadron-hadron collisions. At the most elementary parton model level, we have the picture shown in Fig. 10 in which a parton from the beam interacts in unspecified fashion with a parton from the target. The outgoing partons fragment independently, as do the spectator diquarks. This very fruitful approach is represented by the early work of Berman, Bjorken, and Kogut,[6] of Drell and Yan,[7] and of Feynman and Field.[8] With QCD comes the idea of colored gluons and the suggestion of specific mechanisms for parton-parton scattering at large transverse momenta. Some of these are indicated in Fig. 11. Experiment has not yet responded decisively. The idea of factorization, i.e. that parton distributions measured in one kind of interaction may be relied upon for the description of other processes, has been examined in QCD and seems likely to be correct in at least some circumstances.

A fuller implementation of QCD, represented in Fig. 12, brings with it deviations from scaling in both the parton distributions and fragmentation functions, as well as perturbative corrections to parton model predictions. While the latter may not all be small, we may hope that the tools to study them theoretically lie within reach.

The point of this brief series of cartoons has been to emphasize that QCD has given some support and some clarification to parton model ideas. Many things which are merely attractive *ad hoc* assumptions in the parton model are justified or seen to be reasonable approximations within perturbative QCD. There are, in addition, some explicit and testable predictions of the theory.

Despite what I regard as very impressive progress, many aspects of the theoretical description remain incomplete or idealized

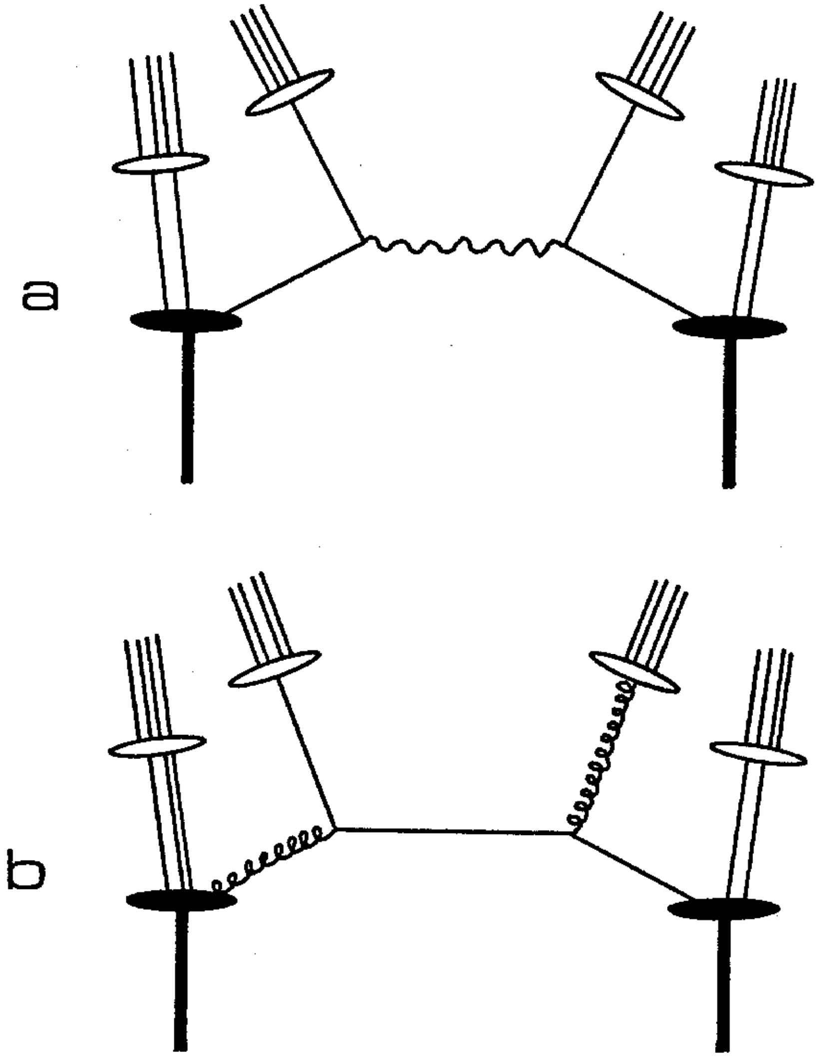


Fig. 11: Some mechanisms for parton-parton scattering in QCD.
(a) Quark-(anti)quark scattering by gluon exchange.
(b) "Compton scattering" of a gluon and quark.

or conjectural. It is worthwhile to list a few of these:

- Many predictions rely on the impulse approximation, or assumption of incoherence. This amounts to summing probabilities rather than amplitudes, and cannot always be trustworthy. When is it misleading?

- The phenomenon of color confinement, presumed to occur both in QCD and in Nature, is not understood in perturbative terms. Both the hadron spectrum and some aspects of hadronization must therefore lie outside the domain of perturbative QCD which appears so fruitful for the description of hard-scattering processes. How can we do better?

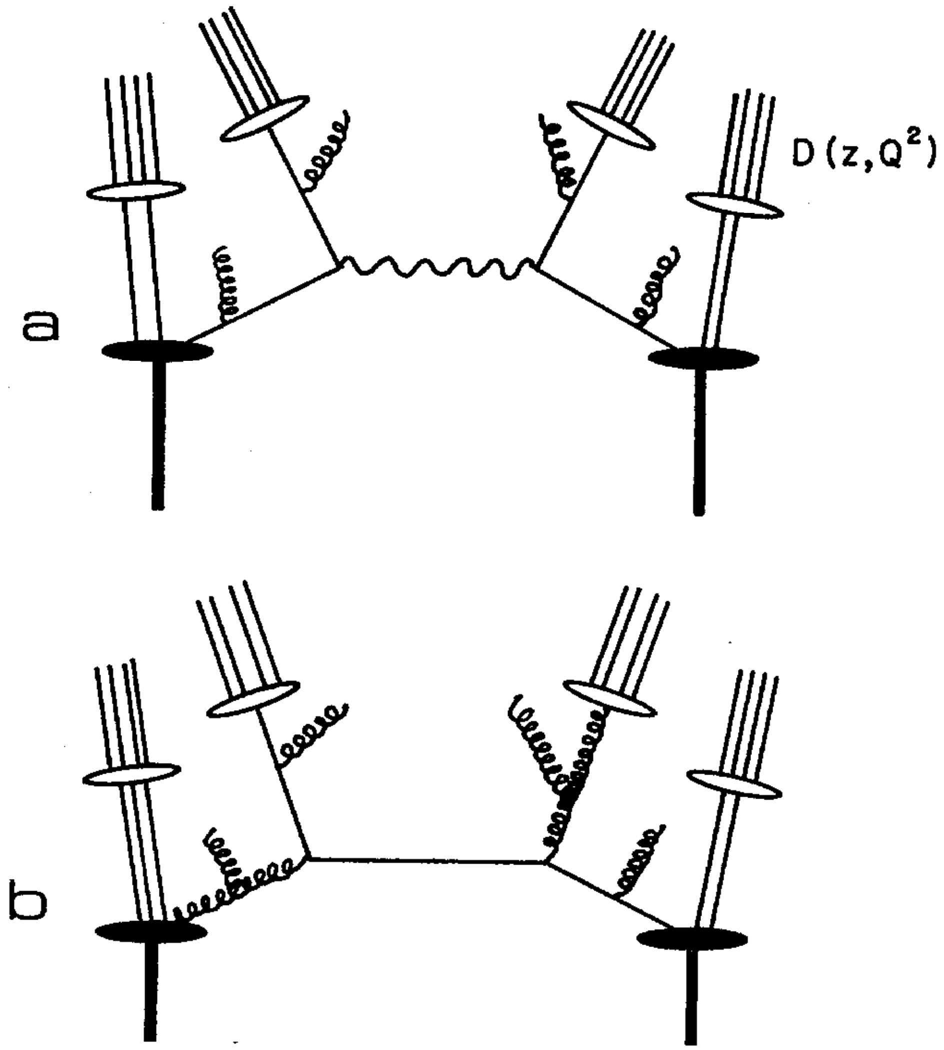


Fig. 12: Examples of "radiative" corrections to hadron-hadron scattering.

• Indeed, all soft processes - for which the strong interactions are strong - have resisted the incisive application of constituent concepts. Despite a laudable and extensive effort[9] to translate the old verities into the parton language, I am unaware of any really new insights or connections which have emerged.

• Another technical matter in QCD calculations arises in problems with two mass scales, in which $\Lambda^2<Q^2<M^2$, as is the case for heavy quark contributions to the photon structure function. How may we advance from plausible prescription to true calculation?

• Many of the remaining uncertainties may be placed under the rubric of infrared issues and nonperturbative effects. Some call only for attention to detail, but others would seem to require new computational inventions.

WHY STUDY JETS?

Before proceeding to some specific comments on jet physics, it may be prudent to review what it is we hope to learn from the study of hadron jets in e^+e^-, ℓN, or NN collisions. At bottom lies the hope that jets provide us with a window on the hard scattering of pointlike constituents, by providing a tag for interesting events. We expect that the strongly interacting partons can be identified as quarks and gluons. It may therefore be possible to investigate elementary reaction mechanisms. For this purpose, a hadron is to be regarded as an unseparated beam of partons. Here we are relying on the applicability of perturbation theory ideas in order to make sense of observations, but the program of study is rather well defined and easy to describe, if not to carry out.

We may also try to seek clues for the understanding of nonperturbative phenomena such as hadronization by examining the development of the jets themselves. Nuclear targets have repeatedly been advocated as "detectors" sensitive to short time-scale phenomena, and I am persuaded that for beam energies of $\gtrsim 1$ TeV, they may be very useful indeed. Finally, by seeking regularities and systematics we define norms that may enable us to recognize new conditions of matter.

JETS AND LOW TRANSVERSE MOMENTUM PHENOMENA

The rough correspondence between parton fragmentation and hadronic multiple production has been known for nearly a decade. As Palmonari[10] has shown us, the data sets are now greatly expanded, but the analysis is not much more penetrating than it was in the early days. It would be relatively easy to make the comparisons more incisively, and I believe there is considerable value in doing so.

One reason detailed comparisons may be of interest is that it is not at all evident that there must be a single, universal pattern to particle production in all circumstances. The deviations from universal behavior may be quite instructive.

For example, the case for color separation in soft collisions is not nearly so obvious as it seems in hard scattering. In spite of this, we resort to a color flux argument to understand the apparent equality of the slopes of meson and baryon Regge trajectories.

Within soft collisions, many similarities have been established between distributions in hadron-hadron and Pomeron-hadron collisions, but some questions persist. Is there, one may ask,[11] a leading particle effect associated with the Pomeron? What is the character of Pomeron-Pomeron collisions, which should be truly accessible for the first time at S$\bar{p}$pS energies?

Because of the rise in the pp total cross section and the increase in the central density of produced hadrons, it is natural to anticipate changes in the character of multiparticle events between ISR and S$\bar{p}$pS energies. The short-range correlation picture of multiple production which applied so generally[12] between $\sqrt{s}$=20 and 60 GeV may well be supplanted by a picture in which long-range correlations are preëminent. If so, there must be limits to universality.

As many have observed, heavy quarks are produced far more copiously in e^+e^- annihilations than in soft collisions. It is reasonable to suppose that this must have some effect upon the inclusive distributions.

What I am urging is that one take the similarity of multiplicity distributions, etc., observed in different processes seriously enough to inspire a microscopic comparison, with attention to two-particle corrections and possibly distinct components of the cross section. This has been talked about, for example, for the annihilation and nonannihilation contributions to $\bar{p}$p collisions but, to my knowledge, has not yet been carried out in any circumstances.

ANALYZING JETS

It is easy to be specific about observables which are more differential than those in common use, and which may therefore be more revealing.

- What are the multiplicity distributions for single-jet systems of definite invariant mass, or for two-jet systems of definite effective mass W=$\sqrt{s}$? Perhaps these can be labeled by the leading particle in each jet.

- Define a rapidity variable y along the axis of a jet. What is the shape of the one-particle inclusive distribution $d\sigma/dy$? How does it depend on the species of parton from which the jet evolved?

- Two-particle correlations for particles within jets may be studied through the correlation function

$$C_2(y_1,y_2) \equiv \rho_2(y_1,y_2) - \rho_1(y_1)\rho_1(y_2)$$

and by rapidity-interval methods.[13] Such measurements were decisive in the development of an understanding of soft collisions. Moreover, they may yield explicit tests of assumptions about strings, branching processes, etc. that go into simulations. For soft collisions, it was possible to build apparently reasonable models that did not correctly reproduce such observables. Thus some discrimination was achieved.

- A number of variables related to two-particle correlations and rapidity gap distributions bear on specific questions such as the locality of electric charge compensation. These are of interest both for precise checks of models and for detailed comparison with soft hadron-hadron collisions. The latter were found, in the Fermilab-SPS-ISR energy range, to be well represented by the independent emission of clusters carrying less than two units of charge, decaying on the average into approximately 3 pions, and with masses between about 1 and 2 GeV/c^2.

- A long-standing dream[14,15] has been to measure parton-parton cross sections in hadron-hadron collisions. This is to be achieved as follows. Select a two-jet event. Boost to the CM frame of the parton-parton collision, and examine the two-body differential cross section[16] $d\sigma(\hat{s},\hat{t})/d\hat{t}$. Potential quark-quark, quark-gluon, or gluon-gluon collisions may perhaps be selected by exploiting kinematical prejudices, as in the "back-to-back" or "back-to-antiback" selections made in ISR experiments. This exercise now appears (to me at least) to be relatively straightforward at collider energies, and may well be practical at ISR energies, though probably with less control over systematic uncertainties. One should not be put off by the fact that the expected angular distributions are not dramatically different or by the contention that Monte Carlo calculations based on the expected elementary interactions reproduce the data. The point here is that reasonably direct measurements of elementary cross sections have become thinkable, and that it is worthwhile to expend the effort needed to carry out such measurements.

MONTE CARLO CALCULATIONS

Having already proclaimed my ignorance of the inner workings of Monte Carlo representations of jet events, I shall not make detailed remarks about them. I would, however, like to add my voice to those already raised at this meeting on the connection between such programs and QCD. It is sometimes said that what can be calculated in perturbative QCD cannot be measured, and what can be measured cannot reliably be computed. This is a mild exaggeration, but a good introduction to the need for simulations. There are many things we can't yet calculate - the hadronization process for example. In such cases it is possible (and necessary) to make reasonable models, consistent with known phenomenology and with the general properties of the theory, and to incorporate these into Monte Carlo programs. Such models are inevitably somewhat arbitrary and oversimplified. This has two implications: first, that the internal parameters need not have a transparent interpretation in terms of PQCD, and second that meticulous checks of the predictions of the programs are both necessary and worthwhile. These may not directly test the underlying theory which inspired a particular program, but they can help to make the simulations ever more reliable representations of reality. Thus, while Grindhammer's conclusion[17] that determinations of α_s in three-jet events are uncertain is unsurprising, the efforts he reported to understand why different programs yield different answers seem quite valuable.

BEYOND THE IMPULSE APPROXIMATION

According to the usual picture of a hard collision, as indicated in Fig. 13(a), the partons propagate as "free" particles, in a perturbative vacuum. This is not derived in QCD. Could it happen instead, as represented in Fig. 13(b), that the outgoing partons must traverse a medium in which their interaction length is finite?

There has been considerable speculation that a quark-gluon plasma with temperature $T \sim 200$ MeV may form in nucleus-nucleus collisions, or even in very energetic e^+e^- or pp collisions.[18] In any particular case, formation of such a plasma depends upon a number of parameters, some of which are incompletely known: the collision volume, the transparency of hadronic matter, the total energy, and others. I have my doubts that the necessary initial conditions are ever fulfilled, but doubts do not make a firm conviction. It is anyway of interest to suppose that a plasma is formed, and to ask whether there follow any interesting consequences for jet physics. This question has been examined recently by Bjorken,[19] who reasons as follows.

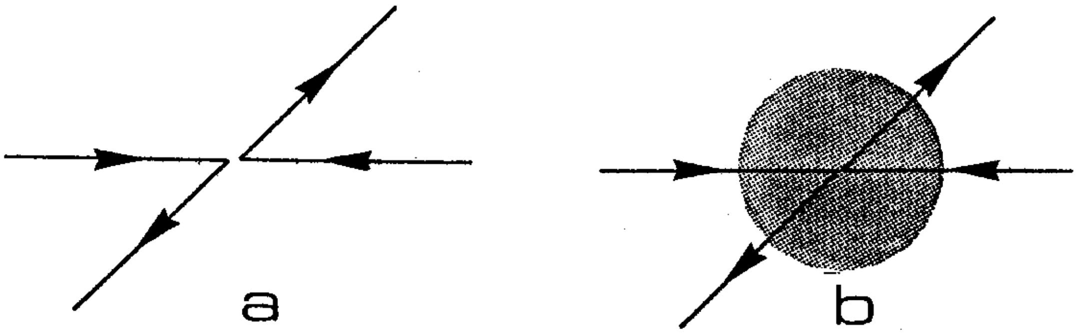


Fig. 13: (a) Parton-parton collision in a perturbative vacuum. (b) Parton-parton collision in a strongly-interacting medium.

In the hypothesized plasma of temperature T, the density of quarks, antiquarks, and gluons is known. So too is the cross section

$$\frac{d\sigma}{dt} \simeq \frac{2\pi\alpha_s^2}{t^2} \times (\text{Clebsch})$$

for the small angle elastic scattering of an emerging parton. Therefore, if perturbative QCD applies to the plasma-outgoing parton interactions (and if there is nothing exceptional about the interactions of an extremely virtual parton), the energy loss due to multiple scattering may be computed in familiar fashion. The energy loss per unit length for an emerging parton traversing the plasma is very roughly given by

$$\frac{dE}{dx} \sim \left(\frac{\varepsilon}{1\ \text{GeV/fm}^3}\right)^{1/2} \log\left(\frac{4ET}{1\ \text{GeV}^2}\right) \frac{\text{GeV}}{\text{fm}} \quad ,$$

where $\varepsilon \propto T^4$ is the energy density in the plasma, E is the parton energy, and the strong coupling constant has been taken as $\alpha_s \simeq 1/4$.

From an expression of this kind one may calculate the degradation in transverse momentum of a parton emerging at 90° in the CM. The precise result depends of course of the parton species and upon details of the assumed plasma properties, as represented by the associated (isotropic) transverse energy. However, it is plausible that the transverse momentum of a parton emerging at 90° may be degraded, on the average, by 3-30 GeV/c, if $dE_T/dy \sim 10$ GeV, and by 30-60 GeV/c if $dE_T/dy \sim 100$ GeV.

This raises the possibility of jet extinction, with an accompanying large multiplicity of relatively low-$p_\perp$ particles. The most spectacular case would be that in which the hard collision occurs near the edge of the plasma, so that one parton traverses the full diameter of the fireball while the other traverses almost no plasma. In this event, one jet might be totally absorbed, while the other survives unaltered. This speculative outcome is uncertain, but would be interesting. This suggests[19] studying the transverse-momentum imbalance for well-defined two-jet events as a function of transverse energy and multiplicity. On the theoretical side, one is led to ask whether any other mechanisms might yield similar exotic events. The multiple bremsstrahlung model described by Fox[5] and Field[4] comes to mind as a candidate. We are left with two interesting questions: do such events exist, and - if so - what are they telling us?

FUTURE EXPERIMENTATION

Chiefly as a stimulant to further thought and discussion, I offer here a few half-baked remarks on new initiatives. It seems to me that variation of the CERN Collider energy is of high interest for the study of jet production mechanisms. The search for intermediate bosons and other new phenomena of course argues for running at the highest possible energies, but as the program matures the opportunity to separate $p_\perp$ and $x_\perp$ dependences should not be neglected.

With regard to $\alpha\alpha$ collisions in the ISR, I consider the principal interest to lie in the search for "zoo events" qualitatively different from what is familiar in nucleon- nucleon collisions. Very detailed comparison with pp events seems to me much less likely to lead to new insights in the short program now contemplated.

Seeing the apparent ease with which high transverse momentum jets have been observed at the CERN Collider, I am prompted to ask whether fixed-target studies of hadron-induced jets remain worthwhile. (They have always been extremely challenging.) I am less equivocal in my assessment of the value of the harder to interpret single-particle inclusive cross section measurements, which certainly benefit from the higher fixed-target luminosities. It seems to me also that prompt-photon and dimuon measurements in open geometries will be of considerable importance.

Finally, what are the new instruments we should be dreaming of for the second half of this decade? The high energy (as opposed to high Q^2) possibilities of an ep collider have not, I think, been sufficiently explored. Similarly, exotic possibilities such as heavy-ion - heavy-ion or electron - heavy-ion storage rings deserve to be worked out in greater detail, both with respect to physics possibilities and insofar as machine performance is concerned. Multi-TeV $\bar{p}p$ colliders seem a rather straightforward extrapolation from current accelerator practice. The question here is, how much of a step in energy is enough?

CONCLUSIONS

The subject of hadron jet studies, to judge by the work presented at this workshop, is a maturing field which is still gathering steam. The very detailed work being done in lepton-lepton and lepton-hadron collisions, the second-generation measurements being carried out at Fermilab, the CERN SPS, and the ISR, and the very high energy hard scatterings being observed at the CERN Collider all show enormous promise for increased understanding. Perhaps we shall yet reach that long-sought nirvana in which high-$p_\perp$ collisions become truly simple.

It is my pleasure to thank the organizers of this workshop, Giorgio Bellettini and Hannu Miettinen for assembling a stimulating cast of characters, and to express my appreciation to the staff of the Majorana Centre for their warm hospitality in Erice.

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