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the cross section for the hard process involving the parton. In the "classic" example of lepton-hadron scattering, illustrated in Fig. 1a, the hard process involves the large angle elastic scattering of a lepton and quark. Originally[1] the distributions of partons within hadrons were assumed to be functions of only the fraction x of the hadron's momentum carried by the parton ($x = p_q/p_H$, the scaling hypothesis) and to be nonzero only for partons collinear with the parent hadron. The parton (quark) distribution F(x) could then be experimentally determined in ep scattering, for example. On the long time scale τ_L, the scattered partons interact and fragment into the observed hadrons. In the naive parton model the resulting hadrons are assumed to be aligned with the parent parton in momentum space and to be described by a fragmentation function D(z), depending only on the ratio z of the hadron's momentum to that of the parent parton ($z = p_H/p_q$). These fragmentation functions can be determined from the analysis of the annihilation of e^+e^- into hadrons as illustrated in Fig. 1b. Again for this process factorization is assumed such that the quark and antiquark fragment independently. Thus a cross section involving such a hard process assumes a general integral form schematically given by

$$d\sigma_{hadron} = \sum_{\substack{i,j \\ (quarks)}} \int dx\, dz\, F_i(x)\, d\sigma_{ij}(x,z,Q^2)\, D_j(z) \quad (3)$$

All of the soft (long-time) physics is now put into the distributions F and D, while $d\sigma_{ij}$ includes all the hard, short-time processes.

While deep inelastic lepton-hadron scattering and the total cross section for e^+e^- annihilation are amenable to more rigorous analyses[2] in terms of the short distance behavior of an operator product expansion, this is not the case for the distribution of hadrons in the final state and the description of this distribution represents a true application of the intuitively simple (naive) physical picture of the parton model. This picture was further extended to describe the hadronic production of massive lepton pairs[3] via quark-antiquark annihilation, as in Fig. 1c, and to large p_T hadron production[4] via quark-quark scattering, as in Fig. 1d. Corrections to the naive picture[4] were presumed to be characterized by the ratio $\langle k_\perp^2\rangle/Q^2$, where $\langle k_\perp^2\rangle$ is the average squared transverse momentum of quarks in hadrons or hadrons in quark jets, assumed originally to be a (few hundred MeV)^2. This quantity essentially characterizes the "size" of hadrons or the time scale τ_L. Hence the corrections were of approximate magnitude τ_S^2/τ_L^2.

Within this parton model framework it is now possible (and necessary) to study the implications of QCD as the theory of the strong interactions. In the context of QCD hadrons are to contain not only quarks but also vector gluons which mediate the interactions between the quarks and, unlike QED, between

[illegible]

[illegible] with the [illegible] are illustrated in Fig. 1. Note that there are not only truly perturbative corrections due to gluon emission and exchange [illegible] of the original diagrams of Fig. 1 [illegible] terms [illegible].

This program is [illegible] very difficult due to the fact that QCD exhibits asymptotic freedom. Simply stated, the effective coupling of the theory decreases with shorter distances and times or larger momenta as

$$[illegible] \qquad (4)$$

This renormalization [illegible] the summation [illegible] perturbative corrections. Furthermore it [illegible] that the remaining [illegible] corrections will be small at large Q^2. However, the theory also exhibits mass [illegible] from the collinear fragmentation of, for example, a quark into a quark and a gluon and from the infrared singularities due to soft gluon emission. This feature of the theory is realized in the perturbation approach as factors of $\ln(Q^2/m_q^2)$ (essentially

[illegible] serve to cancel or overwhelm the logarithmic [illegible] asymptotically small coupling $\alpha_s(Q^2)$, which [illegible] summation of a [illegible] set of $\ln Q^2$ terms. Thus the factorization (Eq. (2)) into long time scale effects and short time scale effects which is central to the initial parton picture is threatened. However, recent work of many physicists[7-11] has led to the realization that even in the presence of the logarithms the soft, long-time, quark mass dependent physics still essentially factors from the hard, short-time physics in a universal fashion. Thus the qualitative structure of the parton model remains basically intact but with certain quantitative modifications.

As in the naive model, the asymptotically leading, "scaling," contribution to a given process corresponds to the hard scattering of "on shell" (massless) quarks and gluons. However, in order to actually perform the factorization of the long time scale physics from the hard physics, an arbitrary scale, call it M^2, must be introduced. (Care must be exercised to perform this factorization in an identical fashion for all processes.) The result is then a convolution of distributions for quarks and gluons, evaluated at the scale M^2, with a hard scattering cross section which has a perturbative expansion in terms of $\alpha_s(M^2)$ (for convenience the renormalization point is taken to be also M^2). The hard scattering cross section involves logarithms of both the ratio Q^2/M^2 and the ratios of other large kinematic variables. The schematic form is

$$d\sigma_{hadron} = \sum_{\substack{i,j \\ (quarks,gluons)}} \int dx\, dz\, F_i(x,M^2)\, d\sigma_{ij}(x,z,\alpha_s(M^2),\theta)\, D_j(z,M^2) \tag{5a}$$

where θ represents the ratios of other invariants. To insure the rapid convergence of this expression it is useful to choose $M^2 \simeq Q^2$ (this is equivalent to using the renormalization group) and thus to express the hard scattering cross section as a series in $\alpha_s(Q^2)$. In this case the distributions will be evaluated at scale Q^2, giving

$$d\sigma_{hadron} = \sum_{\substack{i,j \\ (quarks,gluons)}} \int dx \int dz\, F_i(x,Q^2)\, d\sigma_{ij}(x,z,\alpha_s(Q^2),\theta)\, D_j(z,Q^2) \tag{5b}$$

For large Q^2 [$\alpha_s(Q^2) << 1$] the Q^2 dependence (scaling violation) of the distribution and fragmentation functions is predicted by perturbative QCD and the renormalization group to be as a specific inverse power of $\ln(Q^2)$ [the anomalous dimension]. The present lepton-hadron data are suggestive of this behavior but make no decisive statement, as discussed by L. Abbott[3] in this volume.

In the above factorization analysis the actual singularities associated with "on shell" partons have been hidden in the fully renormalized distribution functions which are assumed

to be finite due to nonperturbative confinement physics not calculable by present techniques. It is only the large Q^2 behavior which is amenable to perturbative analysis. It now seems clear that this same noncalculable confinement physics must also induce a nonzero transverse momentum distribution in the functions F and D in addition to that which arises perturbatively[12] from the emission processes illustrated in Fig. 2. Phenomenological studies suggest that the mean of this "primordial" distribution is perhaps as large as 700 MeV/c for quarks in hadrons but more like 300 MeV/c for hadrons resulting from quark fragmentation. Furthermore, applications of this notion, e.g., in μ pair production or large p_T physics, are sensitive to the <u>shape</u> of this noncalculable distribution. The situation is reviewed in the talks of E. L. Berger[4] and J. Owens.[5]

In addition to the power behaved (nonscaling) corrections of the form $\langle k_\perp^2 \rangle/Q^2$ present in the naive parton model, perturbative QCD predicts further corrections essentially of the form $\langle m_q^2 \rangle/Q^2$ which are <u>process dependent</u> and do not factor into a sum of terms of the above $\langle k_\perp^2 \rangle$ form.

Finally, the perturbative QCD improved parton model exhibits infrared finite (i.e., completely calculable) contributions[12] not present in the naive model which are both process dependent and asymptotically significant in the sense that they do not vanish as a power of $1/Q^2$. There are, for example, the gluon emission processes illustrated in Figs. 2c and 2d. For the pair production process (see E. L. Berger[2]) these contributions may be very important for nucleon-nucleon collisions due to their small antiquark content. In the fragmentation process the emission of gluons leads to large $k_\perp$ within a fragmentation jet, Fig. 3a, which on purely dimensional grounds can be understood to behave as

$$\langle k_\perp^2 \rangle_{QCD} \sim \alpha_s(Q^2) \cdot Q^2 \sim Q^2/\ln(Q^2) \quad . \tag{6}$$

In the large angle limit this process presumably leads to two distinct jets as illustrated in Fig. 3b (and 2b). Fig. 3 clearly indicates that the physics is the same in the two cases and one must be careful when using this jet language not to treat "fat jets" and "double jets" as formally distinct objects.

The successes of this perturbative approach suggest the possibility of performing precise tests to establish whether QCD is indeed the correct theory of the strong interactions. Unfortunately, the nonperturbative, noncalculable contributions discussed briefly above guarantee that, in general, the QCD improved parton model will remain largely a phenomenological tool for the near future. At the same time considerable progress[13] has been made in the direction of avoiding these difficulties by a judicious choice of what experimental measure to study as discussed in the talk by L. S. Brown.[2]

To constitute a satisfactory test of QCD such a measure should satisfy the following constraints:

(a) It should exhibit properties characteristic of QCD, e.g., the presence of both quarks and vector gluons.

(b) It should be reliably calculable, which at present means entirely by the methods of perturbation theory. In order to avoid the necessity of nonperturbative renormalization of infrared singularities, the quantity should be free of explicit infrared logarithms when evaluated perturbatively. It should also be insensitive to corrections due to such nonperturbative confinement effects as the "primordial" k_T distribution.

(c) Finally, it should be accessible to experiment. This condition argues against small effects on a large background or measures which are sensitive to missing neutrals. An example of the latter is a measure which requires event by event determination of an axis.

The clear suggestion is to study various inclusive measures of the final state of e^+e^- annihilation into hadrons where there are no initial hadrons and no reference is made to specific final hadrons. The study of calorimetric, i.e., energy weighted, measures appears to avoid the mass singularities from both the collinear and true infrared divergences (the energy-momentum tensor is not renormalized).

Another area of recent and rapid development is the study[14] of methods to actually sum the perturbative expansion of the hard scattering process discussed above. Since the perturbative expansion typically contains logarithms of ratios of various kinematic variables (the remains of the mass singularities which have been eliminated by factorization or by a careful choice of the quantity), there are kinematic regions where the logarithms are divergent and thus where a low order expansion is not useful. Successful techniques for summation would serve to enlarge the region of validity of the perturbative approach. A specific example of this approach is discussed in the presentation of L. S. Brown.[2]

Not discussed in any detail in these proceedings, due simply to lack of time, are the perturbative study of spin effects[15] and the interesting comparisons of the structure of gluon initiated jets versus quark initiated jets.[16]

Overall there has been considerable progress in understanding and implementing perturbative QCD. This trend will undoubtedly continue, accompanied by increasing emphasis on the consideration of those quantities which are readily accessible to both theory and experiment. This will in turn result in the clear confirmation (or refutation) of the role of QCD.

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FIGURE CAPTIONS

1. Processes discussed in the parton model:
    - (a) Lepton-hadron scattering
    - (b) e^+e^- annihilation into hadrons
    - (c) Lepton pair production by hadrons
    - (d) Large $p_\perp$ hadron scattering.
2. Typical QCD corrections to the naive parton model description of the processes in Fig. 1. Individual processes are as labeled in Fig. 1.
3. Two descriptions of the result of energetic gluon emission in the fragmentation process.

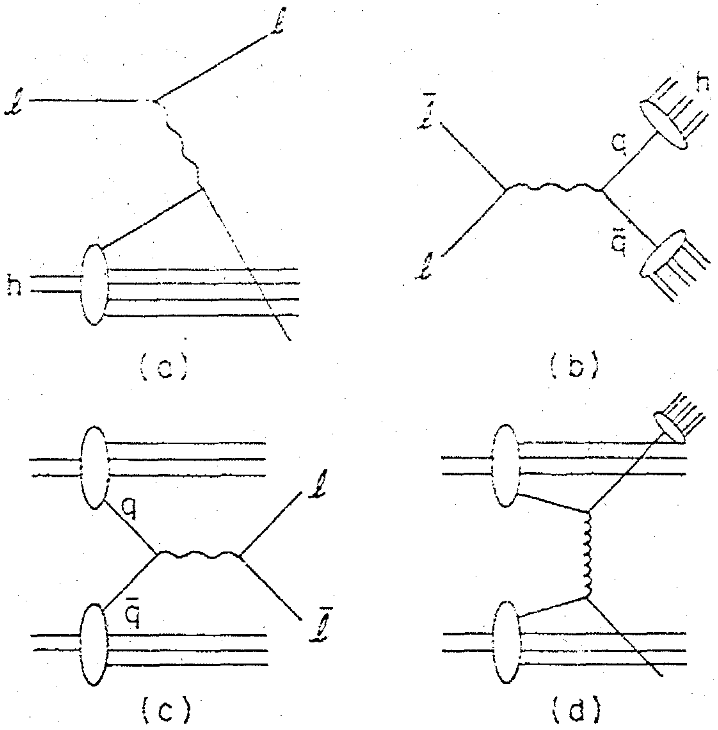

Figure 1

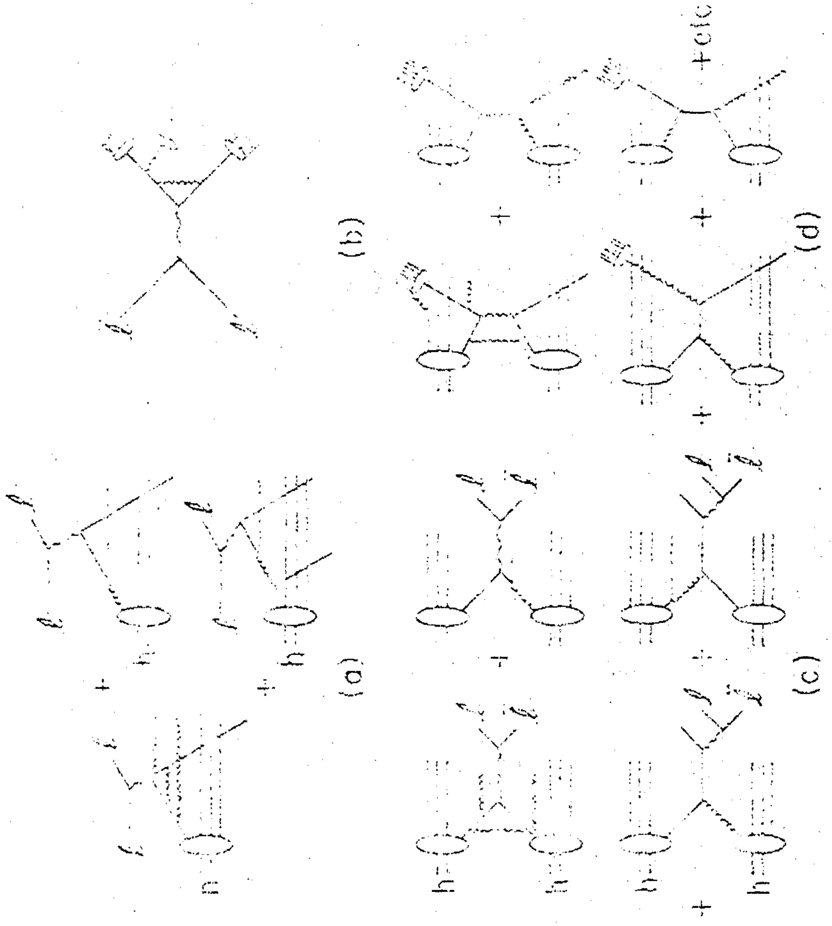

Figure 2

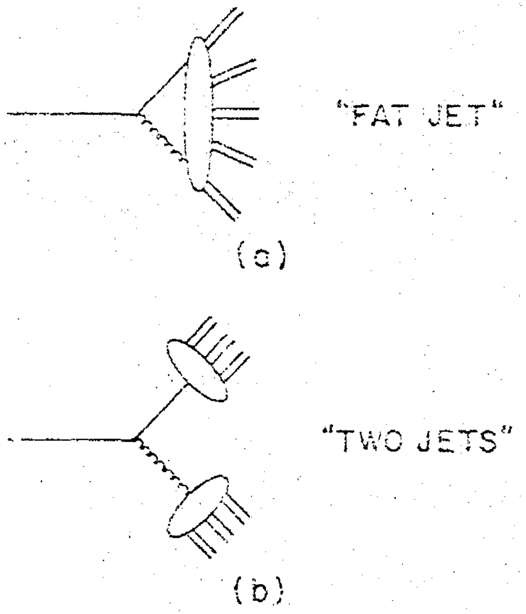

Figure 3