ANL-HEP-CP-79-42
CONF-8010167--1

COMPONENTS OF QCD

by

Dennis Sivers

Prepared for

Topical Workshop
on the
Production of New Particles in
Super-High-Energy Collisions $\sqrt{s}=10^{2}-10^{5}$ GeV

Madison, Wisconsin

October 22-24, 1980

U of C-AUA-USDOE

ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

Operated under Contract W-31-109-Eng-38 for the
U. S. DEPARTMENT OF ENERGY

ANL-HEP-CP-79-42
October, 1979

COMPONENTS OF QCD*

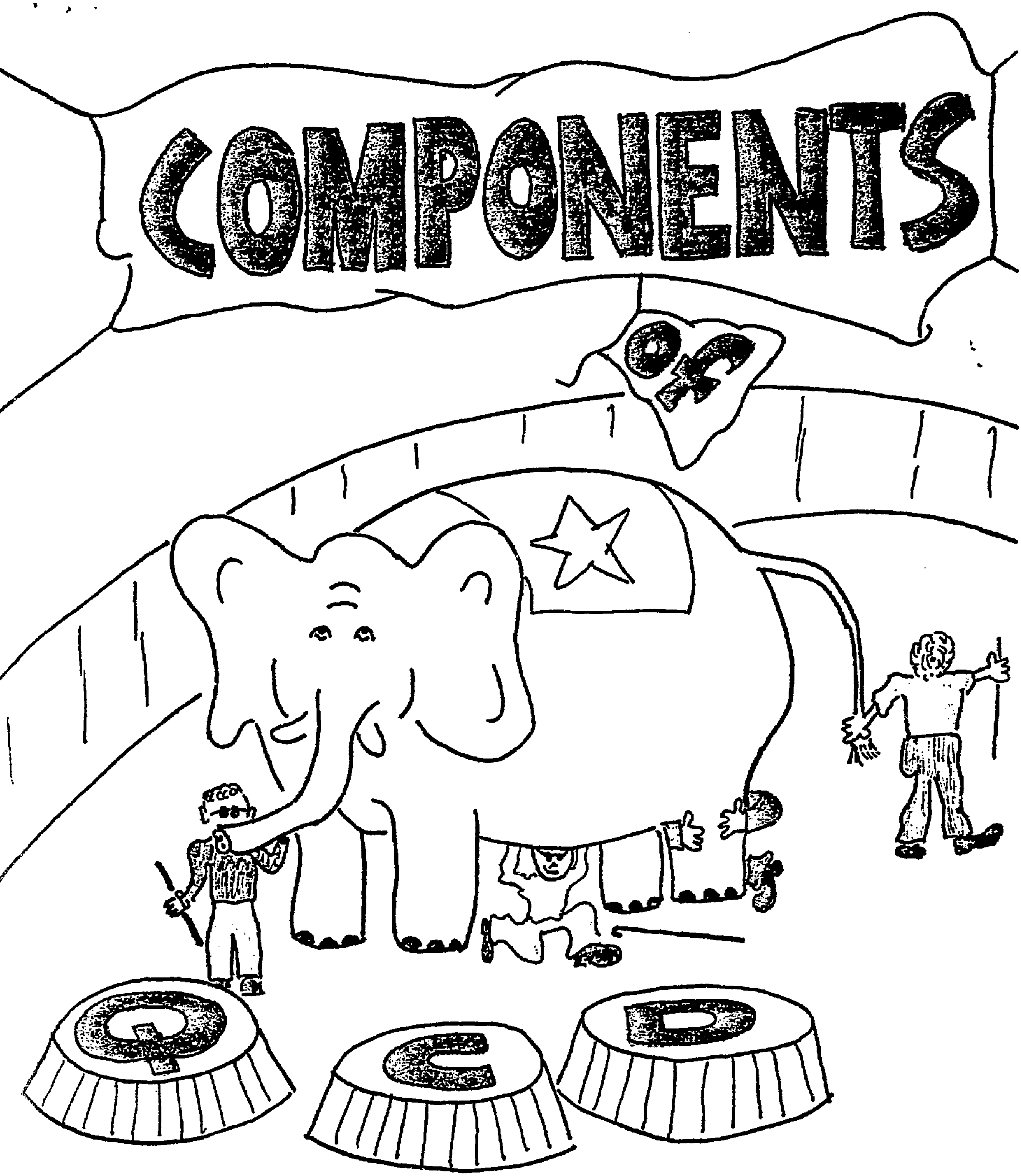
Dennis Sivers
High Energy Physics Division
Argonne National Laboratory
Argonne, Illinois 60439

ABSTRACT

Some aspects of a simple strategy for testing the validity of QCD perturbation theory are examined. The importance of explicit evaluation of higher-order contributions is illustrated by considering Z_0 decays. We discuss briefly the recent progress toward understanding exclusive processes in QCD and give some simple examples of how to isolate and test the separate components of the perturbation expansion in a hypothetical series of jet experiments.

*Work performed under the auspices of the United States Department of Energy.

Talk presented at the Topical Workshop on the Production of New Particles in Super-High-Energy Collisions $\sqrt{s}=10^2-10^5$ GeV Madison, Wisc., Oct.22-24, 1979.


COMPONENTS
OF
Q
C
D

A PARABLE

There is an old parable which appears in the folklore of many cultures concerning four blind men and an elephant. When confronted with this giant beast one man felt the animal's trunk, the second man felt a leg, the third man a side and the fourth the tail. On the basis of these experiences the first man described the elephant as being like a snake; the second man, a tree; the third, a wall; and the fourth, a rope. It is not recorded whether the men were ever asked to speak at a workshop on future applications of elephants.

INTRODUCTION

This workshop has assembled people to contemplate experiments probing the energy scale $\sqrt{s} = 10^2 - 10^5$ GeV. As we move to explore this regime we may hope to encounter new forces and new particles which will, once again, change our perspective and understanding of the physical world. Among the exotica considered here have been very heavy quarks,[1] technicolored forces,[2] unusual leptons[3] and multiple Higgs scalars.[4] By the perverse justice of forecasting we are only excluded from discussing phenomena so unusual they have, as yet, not been imagined. We have also tried here to pin down expectations for the "standard" undiscovered particles, the intermediate vector bosons and the t quark.

In the midst of all this, I have been asked to discuss QCD. What role does the theory of QCD play in the nature of matter at very high energies? Is it merely a well-understood and uninteresting corner of a grand-unification gauge group? Is it a nuisance in the sense that hadronic jets produced in hard collisions will obscure potentially more interesting signals? Will we eventually be able to turn the philosophy of deep inelastic scattering around and use the "well-understood" color force as the probe into a more uncertain realm?

The answers to these questions depend, of course, on just what discoveries await us at super-high energies. They also depend on how well we can test QCD experimentally with the new accelerators that are being designed. Real confidence in a physical theory must be based on something more concrete than the absence of an acceptable alternative. Because of this, it seems certain that among the most important experiments at any new high-energy facility will be tests which extend or confront our understanding of QCD. The most desirable prospect involves the step-by-step confirmation of the elements which make up the perturbation theory. These components can be identified with the pieces (lines and vertices) of the Feynman diagrams displayed in Fig.1.[5] We can follow the procedure advocated by Harari[6] and summarize the steps associated with the "proof" of QCD as:

(q_1) quarks exist — (g_1) gluons exist

(q_2) quarks have spin 1/2 — (g_2) gluons have spin-1

(q_3) quarks are color triplets — (g_3) gluons are color octets

(i_1) the $q\bar{q}g$ coupling exists

(i_2) the three gluon coupling exists

(i_3) the effective coupling runs logarithmically with the momentum scale.

The properties q_1-q_3 and g_1-g_3 are chosen to deal with the fundamental quanta while i_1-i_3 deal with the fundamental interactions. These elements are all part of the gauge theory package and, in that framework, it is artificial to separate them like this. However, if we want to test QCD we must be skeptical and as thorough as possible. Our progress thus far is a matter for debate but my personal views are that the existence and properties of quarks are comparatively well-understood from spectroscopy[7] and various other experiments.[8] We have also made crucial progress toward establishing hypotheses i_1 and g_1 by studying event shapes in e^+e^- annihilation[9] and from observations of the scaling violations in deep inelastic scattering.[10] We still have a long way to go in order to establish the spin and color assignments of the gluon, the triple gluon coupling and the variability of the effective coupling.

There are three areas of theoretical research related to QCD perturbation theory where there has been significant recent progress and which I would like to discuss here. They are:

1. The explicit evaluation of higher-order effects.[11]

2. Techniques to deal with form factors and exlcusive processes.[12]

3. The development of methods to sum all orders in the perturbation expansion to achieve predictions with leading-log accuracy for some observables.[13]

These theoretical developments already point the way toward a strategy for continuing the experimental probe of QCD. I would like to discuss each of them briefly and give some illustrations about how our goal of testing QCD might be achieved. Each of these subjects individually merits a thorough review,[11-13] but that will not be attempted here because of time limitations.

EXPLICIT HIGHER-ORDER CALCULATIONS

The need for calculations of higher-order effects in QCD is quite straightforward. We can indicate crudely the calculation of an arbitrary observable in the form

$$d\sum(p_i;m_i;\alpha_s) = d\sum^0(p_i;m_i;\alpha_s)\left[1+\sum_{n=1}\alpha_s^n d_n(p_i;m_i)\right] \quad (2.1)$$

where the p_i are momenta, the m_i are masses and α_s is the color force analog of the fine structure constant.

$$\alpha_s \equiv g_s^2/4\pi \ . \quad (2.2)$$

For many observables, the coefficients d_n in (2.1) will involve powers of logarithms of large ratios of the kinematic invariants. We will return in Sec.IV to the question of resumming the series (2.1) in such instances with leading log accuracy. For a small number of observables, such as

$$R_{e^+e^-} = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$$

or the ratio of moments of inclusive cross sections at different momenta (scaling violations) all the large logs can be absorbed into a redefinition or renormalization of the parameters.[14] The coefficients in (2.1) can then be shown to be finite. This does not close the question since we don't know if the values for the coefficients of the higher-order terms are large enough that these corrections are important in the comparison of theory and experiment until we evaluate them explicitly.

Several theoretical collaborations have recently reported higher-order QCD calculations of scaling violations in deep inelastic scattering,[15,16] the production of massive lepton pairs[17,18] and $R_{e^+e^-}$.[19,20] For example, the second-order corrections in α_s to $R_{e^+e^-}$ can be written[19] (significantly above quark thresholds)

$$R_{e^+e^-} \cong \sum_{i=1}^{N_f} Q_i^2 \left\{ 1 + \frac{\alpha_s}{\pi}(s) + (1.98 - .116\, N_f)\left(\frac{\alpha_s(s)}{\pi}\right)^2 + \ldots \right\} \quad (2.3)$$

where $\alpha_s(s)$ is given in terms of the QCD effective running coupling defined by a regularization scheme called $\overline{MS}$ (or modified minimal subtraction) by Buras.[11] The number of quark flavors is N_f and the quark charges are Q_i.

The experimental consequences of (2.3) are easy to see. In the energy range where $\alpha_s(s)/\pi \simeq 0\ 1$ the first nontrivial correction of R represents a 10% effect and the second term a 1% effect or a 10% change in the apparent value of α_s used in the first order expression. The explicit evaluation of higher-order effects to obtain a theoretical number with a decimal point for comparison with experiment has proved to be most effective way of confirming our understanding of QED. For that theory we have a simple way of defining α_e, a value for α_e accurate to one part in a million, as well as several independent measurements with high precision. In using (2.3), however, we have to face the fact that there are experimental problems which may prevent measuring e^+e^- cross sections with significantly better than 1% accuracy in the near future. Current experimental values for $R_{e^+e^-}$ have approximately 10% systematic errors and 2% statistical errors.[6]

There is, perhaps, one place where future e^+e^- facilities may have the power to do truly precision measurements. Because of the high rate of Z_0 production in e^+e^- collisions, measurements at this "resonance" may be a good place to look for small higher order effects. Let's review the usual parton model for the decay of an intermediate vector boson. We parameterize the Z_0-fermion interaction[21]

$$L_Z^{eff} = -M_Z (G_F/\sqrt{2})^{1/2} \, \varepsilon_z^{\mu} \, \bar{u}_f \, \gamma_\mu \left(\frac{v_f - a_f \gamma_5}{\sqrt{2}} \right) u_f \tag{2.4}$$

where v_f and a_f are, respectively, the vector and axial vector couplings. In the standard Weinberg-Salam model these couplings are given in terms of one parameter

$$\sin^2\theta_W = 1 - M_{W_+}^2/M_{Z_0}^2 \tag{2.5}$$

The expressions are (assuming 3 generations of leptons and quarks)

$$\begin{aligned}
&a_e = a_\mu = a_\tau = -1 && v_e = v_\mu = v_\tau = -1 + 4\sin^2\theta_W \\
&a_{\nu_i} = 1 \quad (\text{all } i) && v_{\nu_i} = 1 \quad (\text{all } i) \\
&a_u = a_c = a_t = 1 && v_u = v_c = v_t = 1 - 8/3\sin^2\theta_W \\
&a_d = a_s = a_b = -1 && v_d = v_s = v_b = -1 + 4/3\sin^2\theta_W
\end{aligned} \tag{2.6}$$

With the couplings defined in this way we can write the <u>lowest order</u> expression for the total Z_0 decay width in the form

$$\Gamma^{(0)}(Z^0 \to X) \cong \frac{G M_{Z^0}^3}{24\sqrt{2}\pi}\left\{\sum_{\ell}(v_\ell^2 + a_\ell^2) + 3\sum_q (v_q^2 + a_q^2)\right\} \tag{2.7}$$

This expression is quite similar to the lowest-order expression for $R_{e^+e^-}$ in that it counts the total number of fermions (weighted by the weak charges). Measurement of this decay width has therefore been proposed as a way to determine the number of neutrinos (or other light fermions). It is important to observe that it also provides a good place to test QCD. The same calculations which give (2.3) for the higher-order corrections to $R_{e^+e^-}$ also modify (2.7) by[22]

$$\begin{aligned} v_q^2 &\to v_q^2\left(1 + \frac{\alpha_s(M_{Z^0}^2)}{\pi} + (1.3)\left(\frac{\alpha_s(M_{Z^0}^2)}{\pi}\right)^2 + \ldots\right) \\ a_q^2 &\to a_2^2\left(1 + \frac{\alpha_s(M_{Z^0}^2)}{\pi} + (1.3)\left(\frac{\alpha_s(M_{Z^0}^2)}{\pi}\right)^2 + \ldots\right) \end{aligned} \tag{2.8}$$

where we have assumed six flavors and have ignored mass effects.

The standard version of the Weinberg-Salam model has had resounding phenomenological success and a world average[23]

$$\sin^2\theta_W = 0.23 \pm 0.02 \tag{2.9}$$

for the Weinberg angle has been advertised. The zeroth order expression (2.7) for the total width is plotted in Fig.2 for a range of values of the Weinberg angle. Also shown is the effect of the QCD corrections (2.8) corresponding to values

$$\frac{\alpha_s}{\pi}(M_{Z^0}^2) \in (.04,\ .06) \tag{2.10}$$

These corrections correspond roughly to a range in values for the QCD scale parameter

$$\Lambda \in (0.1, 0.7) \text{ GeV} \tag{2.11}$$

Fig.2 also shows the lowest-order prediction for the Z_0 width under the assumption that it decays into four species of neutrinos. This possibility might signal the existence of a fourth generation of quarks and leptons with the masses of the charged leptons being too heavy to have them produced in Z_0 decays. The QCD corrections are slightly less important than the effect of adding another neutrino!

From Fig.2 it can be seen that measurements of M_{Z_0} and M_{W+} to determine precisely the Weinberg angle can be combined with accurate measurements of the widths to allow a solid test of QCD. This information is shown in Fig.3 in a slightly different way. For $\sin^2\theta_W = 0.23$, the QCD corrections to the total width are plotted as a function of Λ, the QCD scale parameter. Measurements of the Z_0 decay width accurate to 10-20 MeV should be sensitive to the structure of QCD.

We should be able to do slightly better by measuring the ratio of specific hadronic and leptonic branching ratios. These ratios are less sensitive to systematic errors and, in the ideal case of clean channels, only limited by counting rates. Since the counting rates should be quite high at a Z_0 factory, it is possible to obtain precise values by patient measurement. For example, a hadronic channel which has a clean signature, (such as charm?), we can write

$$\frac{B(Z_0 \to c\bar{c}\,X)}{B(Z_0 \to \mu\bar{\mu}\,X)} \cong \frac{3(v_c^2 + a_c^2)\left(1 + \frac{\alpha_s(M_{Z_0}^2)}{\pi} + 1.3\left(\frac{\alpha_s}{\pi}\right)^2 + \frac{4}{9}\,\frac{3}{4}\,\frac{\alpha_e}{\pi}\ldots\right)}{(v_\mu^2 + a_\mu^2)\left(1 + \frac{3}{4}\,\frac{\alpha_e}{\pi} + \ldots\right)} \quad (2.12)$$

$$\cong \frac{B_0^c}{B_0^\mu}\ (1.05187\ldots)\ \text{with}\ (\alpha_s/\pi = .05)$$

where we have also kept the 1st order QED corrections to $Z_0 \to f\bar{f}$ since with

$$\alpha_e(M_{Z_0}^2) \simeq 1/128 \quad (2.13)$$

they can be numerically compared to the second-order corrections from QCD. Measurement of this type of ratio to 1 part in 10^4 may be possible and would constitute a real precision test of QCD perturbation theory. Other effects (such as decays involving Higgs scalars) should be important if the experiments try to do better than 1 part in 10^4, but these can be included when necessary.

We have not shown here the $M_q^2/M_{Z_0}^2$ correction terms to the expressions of order 1 and of order α in (2.13). These can be calculated[24] and are, for heavy quarks, important at the 10^{-4} level. It is <u>assumed</u> that residual "higher-twist" effects are $\propto \Lambda^2/M_{Z_0}^2 \cong 10^{-4}$ but this is not proved. Assumptions like this will ultimately be tested by precision measurements.

Of course, we can also measure event shape variables and other observables in Z_0 decay just as in e^+e^- annihilations off resonance. These will also test QCD effects.

The production of Z_0's just may give the cleanest high-statistics laboratory for testing higher-order corrections in QCD!

High-order calculations in a gauge theory necessarily involve <u>all</u> the components of the perturbation expansion. $(q_1 - i_3)$ Precision numbers are therefore ideally suited to confirming an already well-understood theory. There are limits to how far we can go with this program. There is (at least) an $n!$ explosion of diagrams with order so the amount of theoretical effort increases dramatically. We are restricted to observables which are subject to precise definition and for which the highest-calculated-order corrections are very small (yet measurable).

Since QCD perturbation theory is only valid in the limit of processes involving large momenta we have problems defining observables in scattering experiments. For example, the presence of semi-coherent or "higher-twist" effects in deep inelastic scattering introduces unknown (m^2/Q^2) corrections to the usual treatment of scaling violations which are difficult to untangle from the theoretically calculated logarithmic effects. Abbot and Barnett[25] have done a very thorough treatment of examining the phenomenological consequences of higher-twist effects. Until we have some theoretical calculations about how big higher-twist effects should be, the uncertainty will hamper our progress toward a quantitative comparison with experiment. The advantages of Z_0 decays due to the apparent simplicity of the theoretical concepts involved may turn out to be decisive.

For example, we can parametrize the moments of deep inelastic scattering nonsinglet structure functions in the form

$$M_N(Q^2) = A_N \left(\frac{\ell n Q^2}{\Lambda^2} \right)^{-d_N} \left[1 + \text{h.o.c.} \right] \left[1 + N \frac{m_+^2}{Q^2} + \ldots \right] \tag{2.14}$$

where the second bracket is a crude representation of higher twist effects. With present data we can play off the logarithmic Q^2 behavior against the power behavior of the correction term. The correlation of the parameters Λ^2 and m_T^2 are shown in Fig.4. We are therefore not yet sensitive to the higher-order corrections. However, more clever treatment of the data may be able to remedy this problem in the future and it is certainly important that the calculations have been done.

Let's try now a one-sentence summary of the use of explicit higher order calculations in testing the hypotheses of perturbative QCD listed in the introduction. By the time we are experimentally sensitive to higher-order-effects we will probably have a pretty good idea that q_1-q_3, g_1-g_3 and i_1-i_3 are correct, anyway, but this is the way to really nail things down.

III. EXCLUSIVE PROCESSES AND FORM FACTORS

One of the main attractions of elastic scattering or other exclusive processes has always been their clean experimental signature and their well-defined kinematics. However, unlike inclusive processes in the limit where the impulse approximation is valid, exclusive cross sections and form factors of composite systems depend on coherent effects such as the matching of wave-function phases. They are therefore more difficult to calculate.

Perhaps we should take these arguments seriously and treat the comparison between theory and experiment for exclusive processes as a very strong test of our understanding of the basic theory. We may be beginning to make significant progress. The original step in this direction is the realization that large angle exclusive scattering does probe the short-distance behavior of the theory. Arguments based on the number of hard exchanges necessary to turn around the pointlike constituents lead to[27]

$$\frac{d\sigma}{dt}\,(AB \to CD) \sim \frac{1}{s^{n_A+n_B+n_C+n_D-2}}\, f(t/s) \quad \text{(modulo logs)} \tag{3.1}$$

"constituent counting" power laws. The validity of these rules have been questioned because of possible pinch singularities[28] but they seem to provide a crude guide to the experimentally observed fixed-angle energy behavior of exclusive processes.

For form factors, where the complications of possible pinch singularities do not arise, the counting rules give

$$F(Q^2) \sim \frac{1}{(Q^2)^{n-1}} \quad \text{(modulo logs and helicity flip factors)} \tag{3.2}$$

for an n-quark hadron. The past year has seen these rules for elastic form factors gain in validity in the framework of perturbative QCD.[29,12] The exact asymptotic behavior has been predicted and calculable correction terms have been given. For the pion form factor, the result quoted by Brodsky and Lepage[12] is

$$F_\pi(Q^2) = 16\pi\, f_\pi^2 \frac{\alpha_s(Q^2/4)}{Q^2}\left[1 - C_2(\lambda^2)\left(\frac{\log Q^2/4\Lambda^2}{\log \lambda^2/\Lambda^2}\right)^{-d_2} + C_4(\lambda^2)\left(\frac{\log Q^2/4\Lambda^2}{\log \lambda^2/\Lambda^2}\right)^{-d_4} + \ldots\right] \tag{3.3}$$

where f_π is the pion decay constant, $d_2 \cong 0.62$ and $d_4 \cong 0.90$ are the QCD nonsinglet anomolous dimensions. The scale parameter λ is used to divide the meson wave function arbitrarily into a "soft" component $k^2 < \lambda^2$ and a "hard" component $k^2 > \lambda^2$. The hard component is then calculated perturbatively in terms of the soft component. The comparison of (3.3) with experimental data is sho. ` in Fig.5 where the band represents a range of values for the C's estimated by Brodsky and Lepage by using extreme assumptions about the soft wave functions.

The success demonstrated in Fig.6 for the pion form factor can be balanced against the fact that the prediction for the magnetic form factor of the nucleon is not so good. Perhaps the approximations are still inadequate to deal with the complexity of the nucleon. The overall approach is still very attractive.

One of the immediate consequences of the study into elastic processes and form factors is that it gives us confidence to tackle quasi-exclusive processes. These processes can be used to give specific model estimates of the importance of "higher-twist" effects for inclusive measurements in certain kinematic regions. There has already been a dramatic success for the prediction that as $x_{\text{Feynman}} \to 1$ the virtual photons in $\pi N \to \gamma(Q^2)X$ should have dominately longitudinal polarization.[30] The prediction due to Berger and Brodsky for the parameter α which gives the angular behavior

$$\frac{d\sigma}{dM^2 d\theta} \propto (1 + \alpha \cos^2\theta) \tag{3.4}$$

as a function of Feynman x is compared with data in Fig. 6.

The study of exclusive reactions in QCD has begun. We can hope for several more concrete predictions and the chance to compare these predictions with good data. However, the connection between elastic scattering observables and the simple list of assumptions in the introduction seems pretty remote. To get back to these basics, we'll have to consider the topic of the next section.

IV. JETS AND JET EXPERIMENTS

One of the reasons why the testing of QCD is such a great challenge is that the fundamental quanta of the theory, colored quarks and gluons, have not been experimentally isolated. Indeed, if theoretical conjectures about quark confinement and color screening are correct, we may never see quarks and gluons by themselves. We therefore face the task of confirming our ideas about the theory through analysis of data only indirectly related to the fundamental fields.

We would like, however, to get as close as possible, and one class of observables is quite directly related to the structure of the perturbation theory indicated in Fig.1. These measurements involve the detection of clusters of hadrons which, for historical reasons, are called jets. The experimental definition of a jet, a group of hadrons going roughly the same direction, can be refined to meet specific instrumental criteria and experimentalists seem to think they know what jets are. Theoretically, we would like to identify a jet with one of the "partially dressed" quanta of the perturbation theory--a quark or gluon with virtual $(\text{mass})^2$ large compared to some typical hadronic scale. We make the extra assumption that observables involving jets will not be sensitive to the unknown nonperturbative effects which transform quarks and gluons into hadrons and go off and compare our calculations with what the experimentalists measure.

The problem arises that when we study jet observables, the expansion (2.1) which governs the higher order corrections frequently involves large logarithms. The program which attempts to formally sum this series is currently known as the "jet calculus". Progress in this effort is based on the observation that in "physical" gauges (gauges where the gluons have only transverse polarizations) it is frequently possible to neglect interference effects and still retain leading log accuracy at every stage of the perturbative calculation.[31] The picture that emerges from the study of the theory in this limit is that of a probabilistic branching process.[13,32] As indicated schematically in Fig.7 a QCD jet is branching or fraying as it progresses from being very virtual

$$\mu^2 \simeq Q^2 \quad \text{(momentum scale of high energy process)} \tag{4.1}$$

to being less virtual

$$\mu^2 \simeq \mu_0^2 \quad (\text{several GeV}^2) \gg \Lambda^2 \tag{4.2}$$

At some point, nonperturbative effects take over and transform the clusters or jets into specific hadrons. When this transformation happens, it is assumed to not modify substantially the values of certain "safe" observables.

The branching process bears a formal similarity to structures known as fractals. This connection, which has been pointed out by Veneziano,[13] arises from the observation that the probability for branching in a unit of

$$y = \ln\left(\frac{\alpha_s(\mu^2)}{\alpha_s(Q^2)}\right) \tag{4.3}$$

depends on the resolution. The apparent "lifetime" of a jet in these units with fractional resolution ε can be written

$$\left(\frac{1}{T_i}\right)_\varepsilon = \frac{1}{2}\sum_j \int_\varepsilon^{1-\varepsilon} dz\ P_{j/i}(z) \tag{4.4}$$

where the $P_{j/i}$ are the usual Altarelli and Parisi[32] functions

$$\begin{aligned} P_{q/q}(z) &= \frac{4}{3}\,\frac{1+z^2}{(1-z)} \\ P_{g/q}(z) &= \frac{4}{3}\,\frac{1+(1-z)^2}{z} \\ P_{g/g}(z) &= 6\left[\frac{(1-z)}{z} + \frac{z}{(1-z)} + z(1-z)\right] \\ P_{q/g}(z) &= \frac{1}{2}\left[z^2 + (1-z)^2\right] \quad . \end{aligned} \tag{4.5}$$

The inverse "lifetimes" of quark and gluon jets as given in (4.4) are then,

$$\begin{aligned} \left(\frac{1}{T_q}\right)_\varepsilon &= \frac{4}{3}\left[2\,\ell n\left(\frac{1-\varepsilon}{\varepsilon}\right) - \frac{3}{2} + 3\varepsilon\right] \\ \left(\frac{1}{T_g}\right)_\varepsilon &= 3\left[2\,\ell n\left(\frac{1-\varepsilon}{\varepsilon}\right) + \left(\frac{2n_f-7}{6}\right) + (1-n_f)\,\varepsilon + (1+n_f)\,\varepsilon^2\left(1-\frac{2}{3}\,\varepsilon\right)\right] \end{aligned} \tag{4.6}$$

As in the case of other types of branching processes the "time" development of jets can be dealt with in a generating functional formalism.[33] Among the important topics which have been treated in the jet calculus have been the multiplicity of heavy quark flavors[34] and the transverse spread of QCD jets.[35] The jet calculus has thus been very useful as a method to define a set of goals for jet experiments.

The interpretation of jets and jet observables in QCD has a strong appeal to the tinkerer, the type of person who likes to take clocks apart and see how things fit together. While the rest of us are seduced by the elegance of a local field theory based on the SU_3 gauge group, the tinkerer takes a more pragmatic approach. Based on the many successes of the quark-parton model, he may find it convenient to accept the possibility that the perturbation expansion may be a valuable tool in certain calculations. From this point of view, he would try to imagine a series of jet experiments which test independently each of the hypothesis (q_1--q_3) (g_1--g_3) and (i_1--i_3) of the perturbation theory mentioned earlier.

I would like to illustrate how this tinkerer's proof of QCD might be attempted in terms of a very simple, straightforward set of measurements first discussed by Parisi and Petronzio.[36] The idea is to look for a jet within a jet. Suppose a jet is detected in some detector of solid angle Ω centered around an axis $\hat{x}_i$ and we ask for the conditional probability that some fraction z of the energy is contained in some smaller detector of solid angle ω. The measurement therefore is a specific example of jet correlations discussed by Basham et al.[37] If we assume we are in a kinematic regime where we can neglect higher-order effects (the probability of more than one branching in Fig.7 we have approximately

$$\frac{dJ_i}{dz} = \mathbb{P}^i(z;\Omega,\omega) \cong \left(\frac{\omega}{\Omega}\right)\left|\ell n\left(\frac{\Omega}{\omega}\right)\right|\alpha_s\left(Q^2_{eff}\right)\left[\sum_i P_{j/i}(z)\right]\Bigg| \quad z \neq 0,1 \qquad (4.7)$$

where $Q^2_{eff} \simeq Q^2\Omega/2\pi$ and the $P_{j/i}(z)$ are given in Eq.(4.5). The conditions for this lowest order expression to be a good approximation are roughly

$$\begin{aligned} \alpha_s(Q^2_{eff})\left|\ln\left(\frac{\Omega}{\omega}\right)\right| &<< 1 \\ \left|\ln\left(\frac{\Omega}{\omega}\right)\right| &>> 1 \end{aligned} \tag{4.8}$$

These conditions rule out a simple application of the expression (4.7) to current experiments. However, I am going to use the flexibility granted by the possibility of super-high energies discussed in this conference to deal with imaginary jets of hundreds of GeV total energy where things might be this simple. I am also going to omit here any consideration of nonperturbative effects although they can be important for practical applications. This simple laboratory can then be used to see how the different assumptions of the perturbation expansion might show up experimentally. Much of the same information can be found in thrust, or spherocity measurements or in other event shape observables[38] which should be more suitable to the analysis of practical experiments. However, these jet-within-a-jet experiments are so simple that we can almost see what is supposed to be going on.

The longitudinal momentum profile of a quark jet in the approximation (4.7) is shown in Fig.(8). A region near $z = 0$ and $z = 1$ is blocked off to indicate that higher-order corrections and/or nonperturbative effects are preferentially sensitive to these kinematic regimes. The shape of this distribution can discriminate against other hypotheses for the spin of the gluon and hence test hypothesis (g_2). For example, the decay function for a spin-½ quark and a hypothetical scalar gluon can be written

$$P^{(s)}_{q/q}(z) = c_s\left[(1-z)-\frac{1}{2}\ \delta(1-z)\right]$$
$$P^{(s)}_{s/q}(z) = c_s z \tag{4.9}$$

to lowest order in the quark-scalon coupling. With a scalar-gluon, to this order we would expect

$$\frac{dJ^i}{dz} \sim \text{const} \tag{4.10}$$

instead of the Bremsstrahlung-like spectrum of QCD. It has been frequently reported that the anomalous dimensions extracted from analysis of scaling violations in deep inelastic lepton processes discriminate strongly against this *ad hoc* scalar gluon hypothesis.[21] Since the anomalous dimensions are the moments of the distributions (4.5) it is not surprising that we should be able to easily distinguish the two possibilities in this type of idealized jet experiments. It may be considered more attractive by the tinkerer to directly verify that the spin of the gluon is not zero by observing nontrivial z-dependence of the momentum profile since this is equivalent to the angular dependence in the cluster "rest" frame. However we happen to go about it, determining the spin of the gluon should be considered an interesting (and obtainable) goal for jet experiments.[39]

Abelian Gluons

It is also possible to entertain the idea that the perturbative short-distance interaction between quarks is basically Abelian--like QED. Within this framework we give up ever being able to ask the question of why the hadronic world is so different from QED--i.e. why quarks are evidently confined and electrons are not. But we are (temporarily at least) going to be skeptical about QCD and allow ourselves to ask dumb questions. Perhaps we can eventually put the whole thing back together later with strings.

As can be seen with little effort, the main distinction between an Abelian Theory and a Non-Abelian perturbation theory is whether or not gluons themselves carry charge and self couple. This is not probed directly by looking at quark jets. Scaling violations of non-singlet structure functions or the leading corrections to $\sigma(e^+e^-)$ and the event shapes in $e^+e^- \to$ hadron are also woefully ineffective in proving that the gluons self-couple. The only way to obtain this information in these processes is indirectly. For example, the behavior of $\alpha^{\text{eff}}(Q^2)$, the QCD running coupling, depends on the existence of the triple gluon vertex

$$\begin{aligned} \alpha^{\text{eff}}_{\text{ABELIAN}} &\sim \frac{\alpha(\mu^2)}{1 + \alpha(\mu^2)\left(-\frac{2}{9}N_f\right)\ell n\left(\frac{Q^2}{\mu^2}\right)} \\ \alpha^{\text{eff}}_{\text{QCD}} &\sim \frac{\alpha(\mu^2)}{1 + \frac{(33-2N_f)}{9}\ \ell n\left(\frac{Q^2}{\mu^2}\right)} \end{aligned} \tag{4.11}$$

We can pose the question in a more powerful way and ask how well we can test for the color universality of QCD by asking how we know that the g, coupling, in the triple gluon vertex is identical to that in the $q\bar{q}$ gluon vertex. This can be answered formally once we buy the gauge theory package, but we are looking for an answer at the nuts and bolts level.

Not surprisingly, the best way to look at gluon interactions is to look inside a gluon jet. The momentum profile of a gluon jet (seen, for example, in a heavy onium decay) is shown in Fig. (9) . With the approximations of (4.7) the main difference between a gluon jet and a quark jet is in the normalization--gluons have a higher probability to radiate something as shown by the difference in effective lifetimes of Eq.4.6--but the shapes are similar. With a hypothetical abelian gluon theory, the absence of a gluon self-coupling would change this result dramatically. The shape of the gluon jet momentum profile keeping only the $gq\bar{q}$ coupling is also shown in Fig.(9). Hence, the self coupling of gluons can be revealed in jet experiments.

We haven't yet used the jet calculus in discussing the jet-in-a-jet measurements. The jet calculus allows us to take into account the possibility of repeated independent radiation of a jet. The problem of summing all corrections in Eq(2.1) to this observable with leading log accuracy has been solved by Furmanski and Pokorski.[40] In terms of the variable

$$y(\omega,\Omega) = \ln\left(\frac{\alpha_s\left(Q^2_{eff}(\omega)\right)}{\alpha_s\left(Q^2_{eff}(\Omega)\right)}\right) \tag{4.12}$$

we can sum all corrections to get the curves in Figs.(10) and (12) for a quark jet and a gluon jet respectively. These curves are closer to what might be seen in present jet experiments but they too are subject to nonperturbative and other corrections.

How comfortable should we be with jet calculus results? One of the questions which needs to be answered involves the accuracy of the approximations which neglect interference effects. One simple way to approach this is to look at $2 \to 3$ processes calculated to lowest order in the perturbation expansion but keeping exact control over kinematics and keeping all diagrams and their interference terms. This calculation can be used to check up on the approximations of the jet calculus and, not surprisingly, when the comparison is made, the validity of the probabilistic hypothesis turns out to depend on the observalbe and on the "resolution". For example, the probability of a transition from two jets to three jets in the probabilistic jet calculus picture would depend only on the independent probabilities that one of the two jets split

$$\left(\frac{1}{T}\right)^{\varepsilon}_{ij\to k\ell m} \sim \left(\frac{1}{T}\right)^{\varepsilon}_{i\to k\ell} + \left(\frac{1}{T}\right)^{\varepsilon}_{j\to \ell m}\Bigg|_{\substack{\text{jet}\\ \text{calculus}}} \tag{4.13}$$

and should not depend on how the jets are produced.

We can define a measure of the same quantity in the calculation of the lowest-order expression for the $2 \to 3$ processes by making, for example, a thrust cut to isolate the region of phase space where the three jets can be considered separate entities.[41]

In the limit that the thrust cut $(1-T) \approx \varepsilon$ variable is very small so that the expressions for the $2 \to 3$ amplitudes are dominated by their pole terms, factorization guarantees that we recover (4.13). However, as ε gets bigger we are more sensitive to the exact angular structure of the $2 \to 3$ process and the independent jet hypothesis of (4.13) is not valid.

Fig. (14) compares the dependence on ε of (4.13) for two different processes

$$\frac{\left(\frac{1}{T}\right)^{\varepsilon}_{qq \to qqg}}{\left(\frac{1}{T}\right)^{\varepsilon}_{e^+e^- \to q\bar{q}g}}$$

which would be the same in the leading log approximation of independent jet decays.[41]

For some observables, such as the large angle limit of event-shape variables, it is obviously more important to have the correct angular dependence of the lowest-order process than to sum the independent emission of many quanta. For others, jet calculus results can give 10-20% accuracy.[42] Jet experiments at current and future accelerators will definitely play a role in confirming or refuting our understanding of QCD. Their most probable role will be that of softening up the resistance of skeptics by showing the gross Lorentz structure of the perturbation expansion. The tinkerer's proof of the perturbation expansion is a definite possibility. The more subtle effects--involving higher order calculations and the hadron wave functions--will then provide the knockout punch. We can then use QCD to explore the unknown.

ACKNOWLEDGEMENTS

Much of this work was done in the course of a collaboration with Tom Gottschalk and Evelyn Monsay, who each did a lot to educate me. I'd like to thank Vernon Barger and Francis Halzen for inviting me to speak.

1. Stephen Wolfram, this conference.
2. E. Eichten and S. Dimopoulos, this conference.
3. M. Perl, this conference.
4. E. Ma, G. Kane, R. Oakes, this conference.
5. The diagrams shown follow the conventions of H. D. Politzer, Physics Reports 14C, 131 (1974).
6. H. Harari, Review presented at the 9th International Symposium on Lepton and Photon Interactions at High Energies, Fermilab, August 1979 (to be published).
7. F. E. Close, An Introduction to Quarks and Partons, (Academic Press, N.Y., 1979).
8. See, for example, P. V. Landshoff and H. Osborn, in Electromagnetic Interactions of Hadrons (Plenum Press, N.Y., A. Donnachie and G. Shaw, editors).
9. TASSO Collaboration, R. Brandelite et al., Phys. Lett. 86B, 243 (1979); Mark J Collaboration, D. P. Barber et al., Phys. Rev. Lett 43, 830 (1979); PLUTO Collaboration, Ch. Berger et al., Phys. Lett.
10. See, for example, J. Ellis, Invited talk presented at 1979 Symposium on Lepton and Photon Interaction, Batavia, Ill. and references therein.
11. For a review, see A. Buras, Fermilab preprint PUB-71/17 Thy (1979).
12. See, for example, S. J. Brodsky and P. Lepage SLAC-PUB-2343 (1979) and 2348 (1979).
13. For a review, see A. Konishi, A. Ukawa, G. Veneziano, Rutherford Preprint RL-79-026; Y. L. Dokshitser and D. I. Dyakonov, DESY-L-TRANS-234 (1979), translated from 14th Winter School of Leningrad Institute of Nuclear Phys.

14. H. D. Politzer, Phys. Rev. Lett. 30, 1346 (1973).
D. J. Gross and F. Wilczek, Phys. Rev. Lett. 30, 1343 (1973).

15. E. G. Floratos, et al., Nucl. Phys. B129, 66 (1977) and 139, 545 (1978); W. A. Bardeen et al., Phys. Rev. D18, 3998 (1978).

16. W. A. Bardeen and A. J. Buras, Fermilab-preprint 79/31-THY (1979).

17. G. Altarelli, et al, Nucl. Phys. B143, 521 (1971) and erratum, to be published; A. P. Contogouris and J. Kripfganz, Phys. Rev. D19, 2207 (1979).

18. B. Humpert and W. L. van Neervan, Phys. Lett. 84B, 327 (1979) and 85B, 293 (1979); J. Kubar-Andre and F. E. Page, Phys. Rev. D19, 221 (1978).

19. M. Dine and J. Sapirstein, Phys. Rev. Lett. 43, 668 (1979).

20. K. G. Chetyokin, A. L. Kataev and F. V. Thachov, Phys. Lett. 85B, 277 (1979); W. Celmaster and R. Gonsalves, San Diego Preprints (1979).

21. We are following the treatment of J. Ellis, Proc., 1978 SLAC Summer Institute of Particle Physics.

22. A claim due to O. Nachtmann and W. Wetzel, Phys. Lett. 81B, 211 (1979) and Phys. Lett. 81B, 229 (1979) that v^2 and a^2 get different corrections in perturbation theory has been shown false. See, for example, T. L. Trueman, Brookhaven preprint BNL-26570 (1979).
For *massive* quarks such as b and t there are different (m^2/s) corrections to v_q^2 and a_q^2 not shown here.

23. C. Baltay in, *Proceedings of XIX International Conf.*, Tokyo 1978, edited by S. Homma et al. (Phys. Soc. of Japan, Tokyo, 1979).

24. G. Grunberg, Y. J. Ng and H. Tye, North Carolina preprint 136-UNC.

25. L. Abbot and M. Barnett, SLAC-PUB-2325 (1979).

26. Fits to moments of $xF_3(x,Q^2)$ (BEBC-GGM) using 2 parameters. Attributed by J. Ellis to R. Perkins in Ref.10.

27. S. J. Brodsky and G. Farrar, Phys. Rev. Lett. 31, 1153 (1973) and Phys. Rev. D11, 1309 (1975); V. A. Matveev et al., Lett. Nuovo Cimento 7, 719 (1973).

28. P. V. Landshoff, Phys. Rev. D10, 1024 (1974).

29. D. Sivers, S. B. Brodsky and R. Blankenbecler, Phys. Reports 14C, 1.

30. E. L. Berger and S. B. Brodsky, Phys. Rev. Lett. 42, 440 (1979).

31. C. H. Llewelyn Smith, Schladmung Lectures, 1978, Oxford preprint 47/78.

32. G. Altarelli and G. Parisi, Nucl. Phys. B126, 298 (1977). P. Hoyer, Nordita preprint 79/33.

33. P. Cvitanovic et al., Nordita preprint 79/21; I. V. Andreev, Lebedev preprint (1979).

34. W. Furmanski, et al., preprint TH-2625-CERN (1979). A. Basetto, et al., Pisa preprint SNS 4/1979.

35. T. A. DeGrand et al., Phys. Rev. D16, 516 (1977).

36. G. Parisi and R. Petronzio, CERN preprint 1978.

37. C. L. Basham et al., Phys. Rev. D17, 2298 (1978).

38. See, for example, the very complete study by G. Fox and S. Wolfram, CALT-68-723.

39. Another approach has been suggested by J. Ellis and I. Karliner, Nucl. Phys. B148, 141 (1979).

40. W. Furmanski and S. Pokorski, Ref. TH-2685-CERN.

41. T. Gottschalk and D. Sivers, Phys. Rev., to be published. T. Gottschalk, E. Monsay and D. Sivers ANL-HEP-79-15 and ANL-HEP-79-16.

42. For more discussion, see T. Gottschalk, ANL-HEP-CP-43.

FIGURE CAPTIONS

Fig.1 Rules for Feynman Diagrams in QCD.

Fig.2 Calculation of total width of the neutral vector boson. The lowest order prediction under the hypothesis of 3 neutrinos is shown with QCD corrections according to (2.8). Also shown is the lowest order expression assuming a fourth neutrino.

Fig.3 For $\sin^2\theta_W = 0.230$, the QCD corrections (2.8) are shown as a function of Λ.

Fig.4 Fits to 3rd and 5th moments of xF_3 with the 2-parameter expression (2.14) show that the values of Λ and m_T^2 are highly correlated. The bigger the higher twist effects the smaller the radiative ones and vice versa. Figure from J. Ellis.

Fig.5 The QCD calculation of the pion form factor of Brodsky and Lepage[12] is compared with data. The band represents uncertainty obtained from "extreme" assumptions about the soft wave function.

Fig.6 The angular dependence of μ-pairs in πN collisions compared with the model calculation of Berger and Brodsky.[30]

Fig.7 Schematic sketch of the branching of a QCD jet.

Fig.8 Longitudinal momentum profile of jets within a quark jet to lowest order (4.7). The existence of a scalar gluon would mean this curve should be constant.

Fig.9 Longitudinal momentum profile of jets within a QCD gluon jet. Also shown is the curve for an abelian "photon-like" jet.

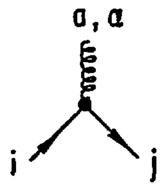
Fig.10 The probability $zdJq/dz$ calculated in the jet calculus. Curves due to Furmanski and Pokorski, Ref.40.

Fig.11 The probability $zdJg/dz$ in the jet calculus. Curves due to Furmanski and Pokorski, Ref.40.

Fig.12 The importance of interference effects in the angular distribution of $2 \to 3$ processes is demonstrated by comparing $d\sigma(e^+e^- \to q\bar{q}g)$ and $d\sigma(qq \to q\bar{q}g)$ with a thrust cut $\varepsilon = (1 - T)$.

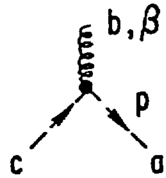
VERTICES

(1) (FFV)



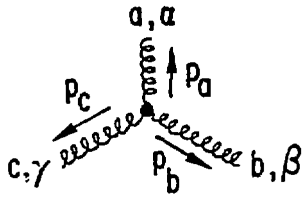
$-ig\,\gamma^{\alpha}\,T^{a}_{ij}$

(2) (GGV)



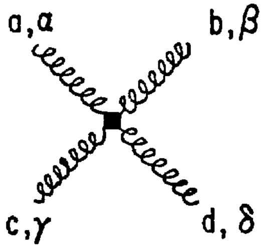
$gf^{abc}\,p^{\beta}$

(3) (V^3)



$-gf^{abc}\,V^{\alpha\beta\gamma}\,(p_a, p_b, p_c)$

(4) (V^4)



$-ig^2\,f^{xab}\,f^{xcd}\quad K(\alpha\beta,\gamma\delta)$

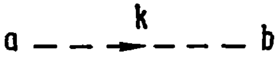
$-ig^2\,f^{xac}\,f^{xdb}\quad K(\alpha\gamma,\delta\beta)$

$-ig^2\,f^{xad}\,f^{xbc}\quad K(\alpha\delta,\beta\gamma)$

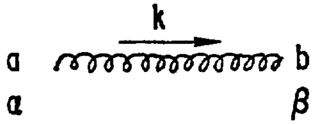
PROPAGATORS

$i\,P/k^2$

$P_F = +\,\delta^{ij}\,\not{k}$



$P_G = -\,\delta^{ab}$



$P_V = +\,\delta^{ab}\left[-g^{\alpha\beta} + (1-a_G)\,k^{\alpha}k^{3}/k^{2}\right]$

a_G = GAUGE PARAMETER

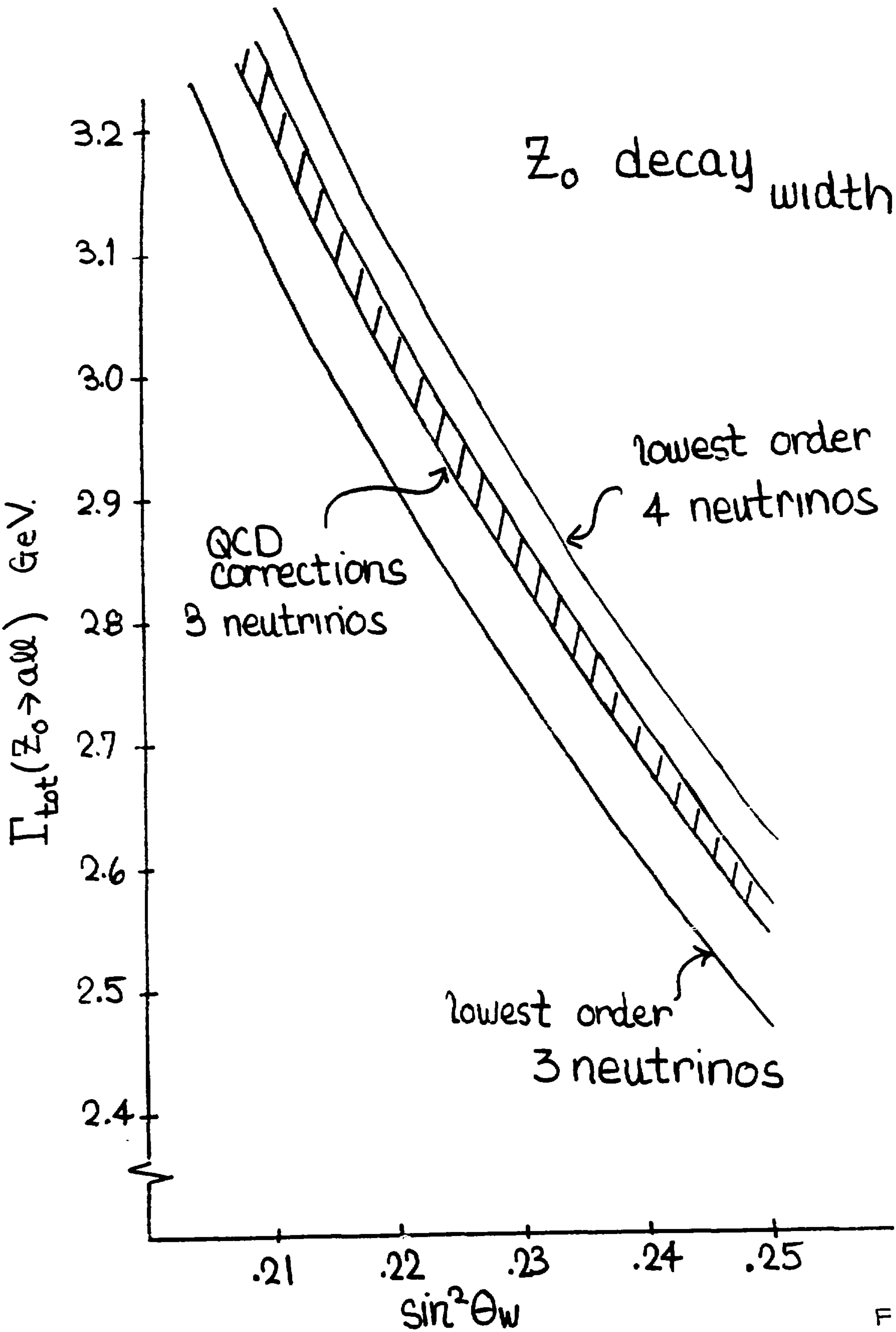

Z₀ decay width
lowest order
4 neutrinos
QCD
corrections
3 neutrinos
lowest order
3 neutrinos
Γtot(Z₀→all) GeV.
3.2
3.1
3.0
2.9
2.8
2.7
2.6
2.5
2.4
.21
.22
.23
.24
.25
sin²θW

FIG. 2

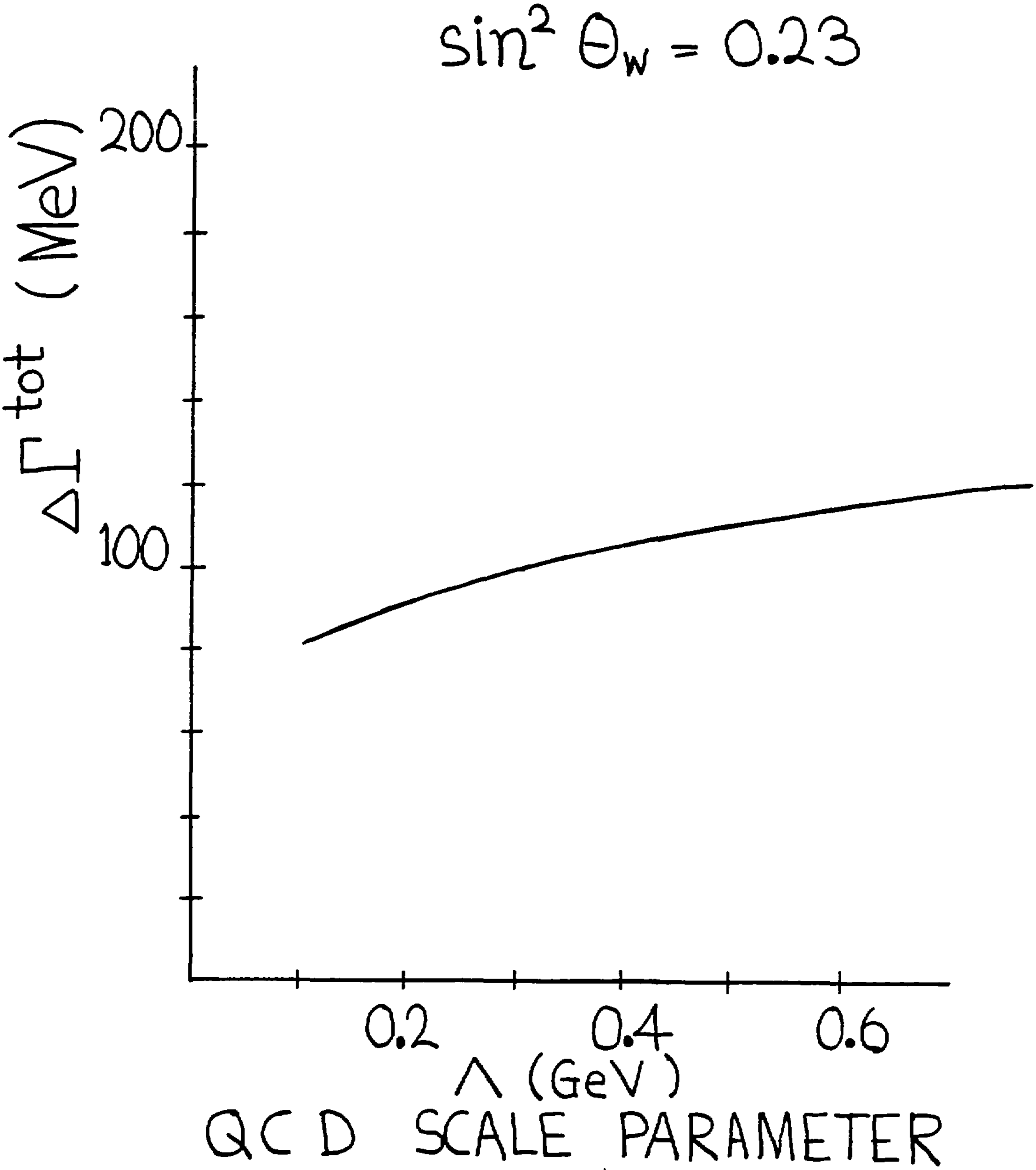

sin² θ_W = 0.23
ΔΓ tot (MeV)
200
100
0.2
0.4
0.6
Λ (GeV)
QCD SCALE PARAMETER

FIG.3

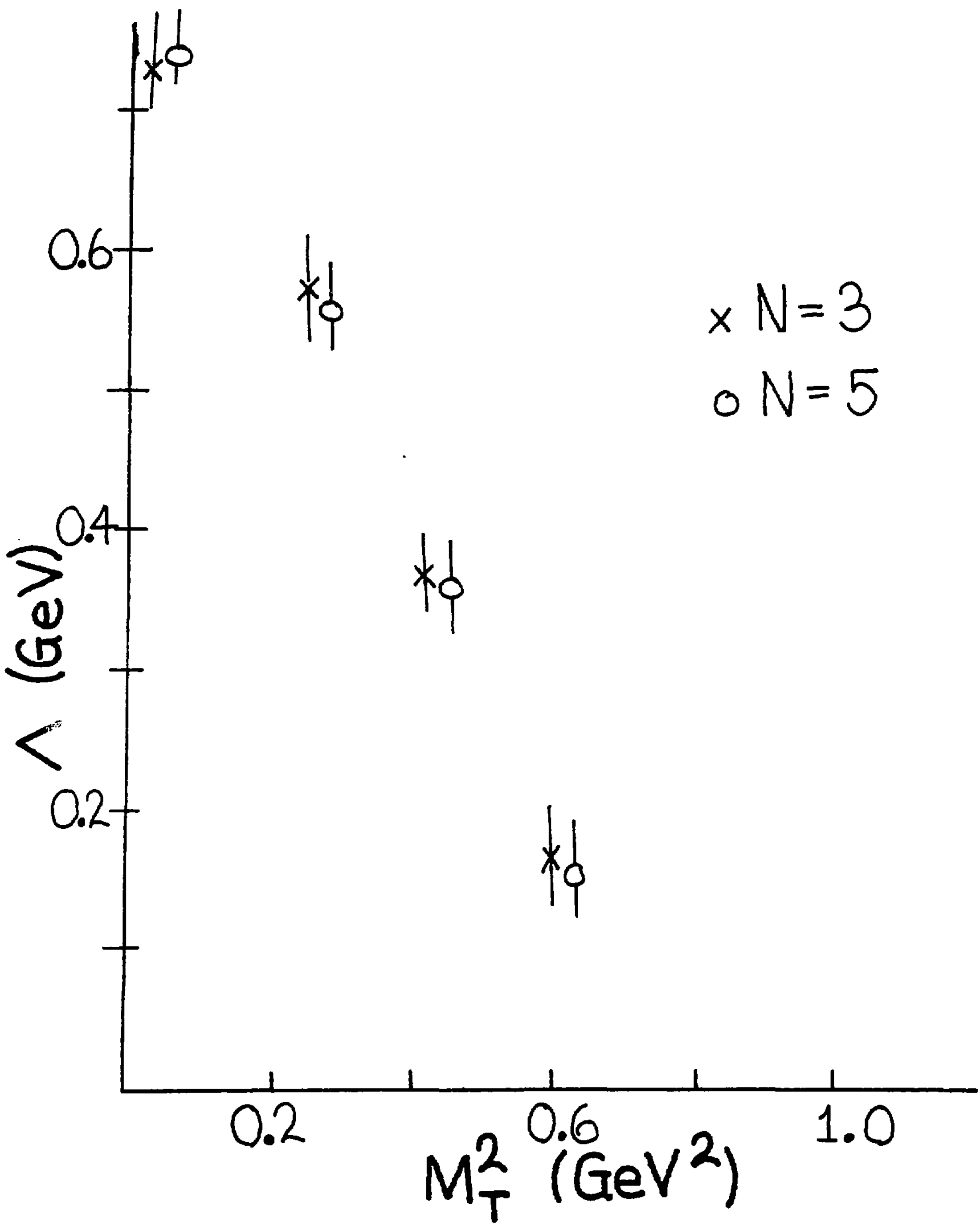


FIG.4

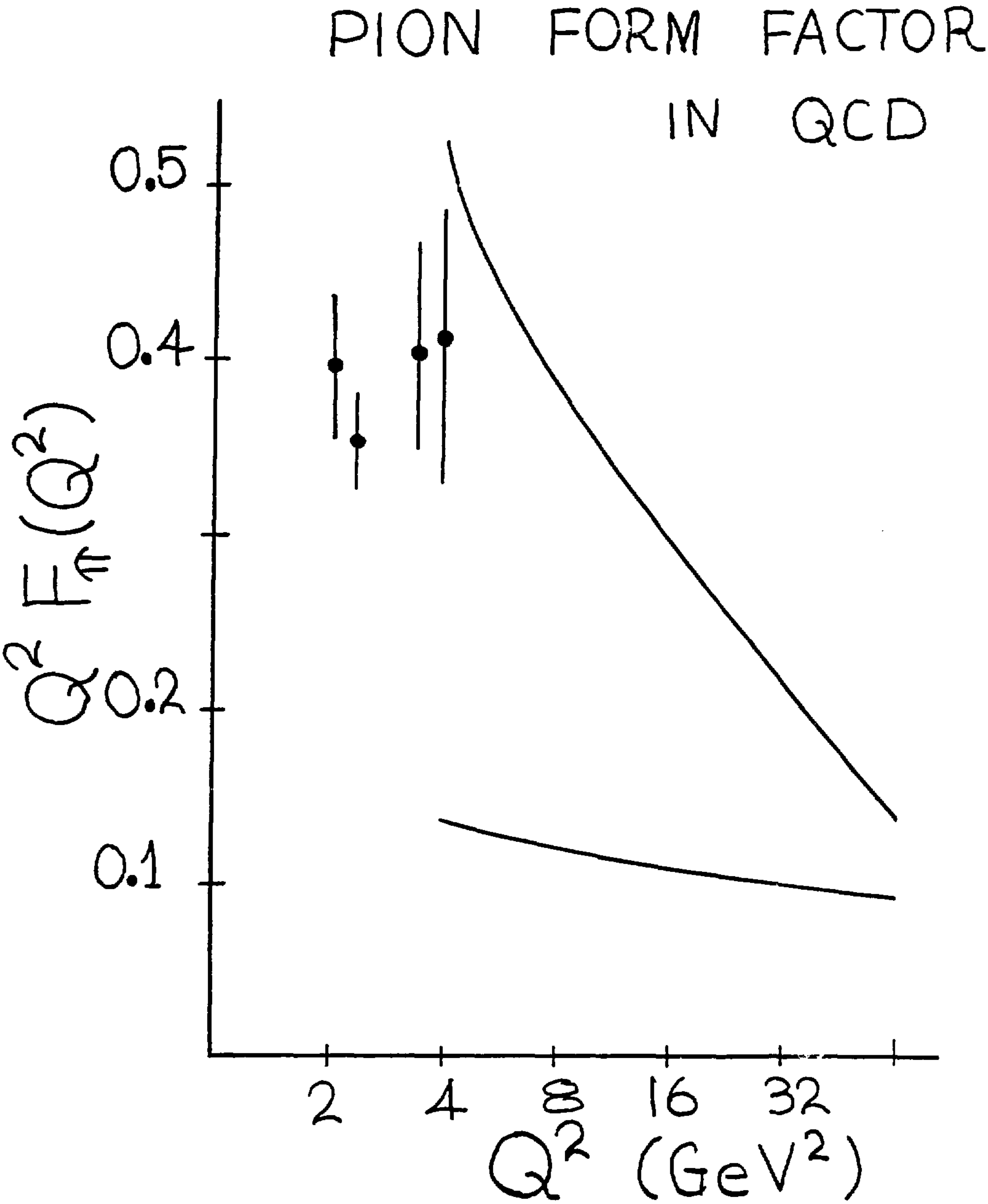
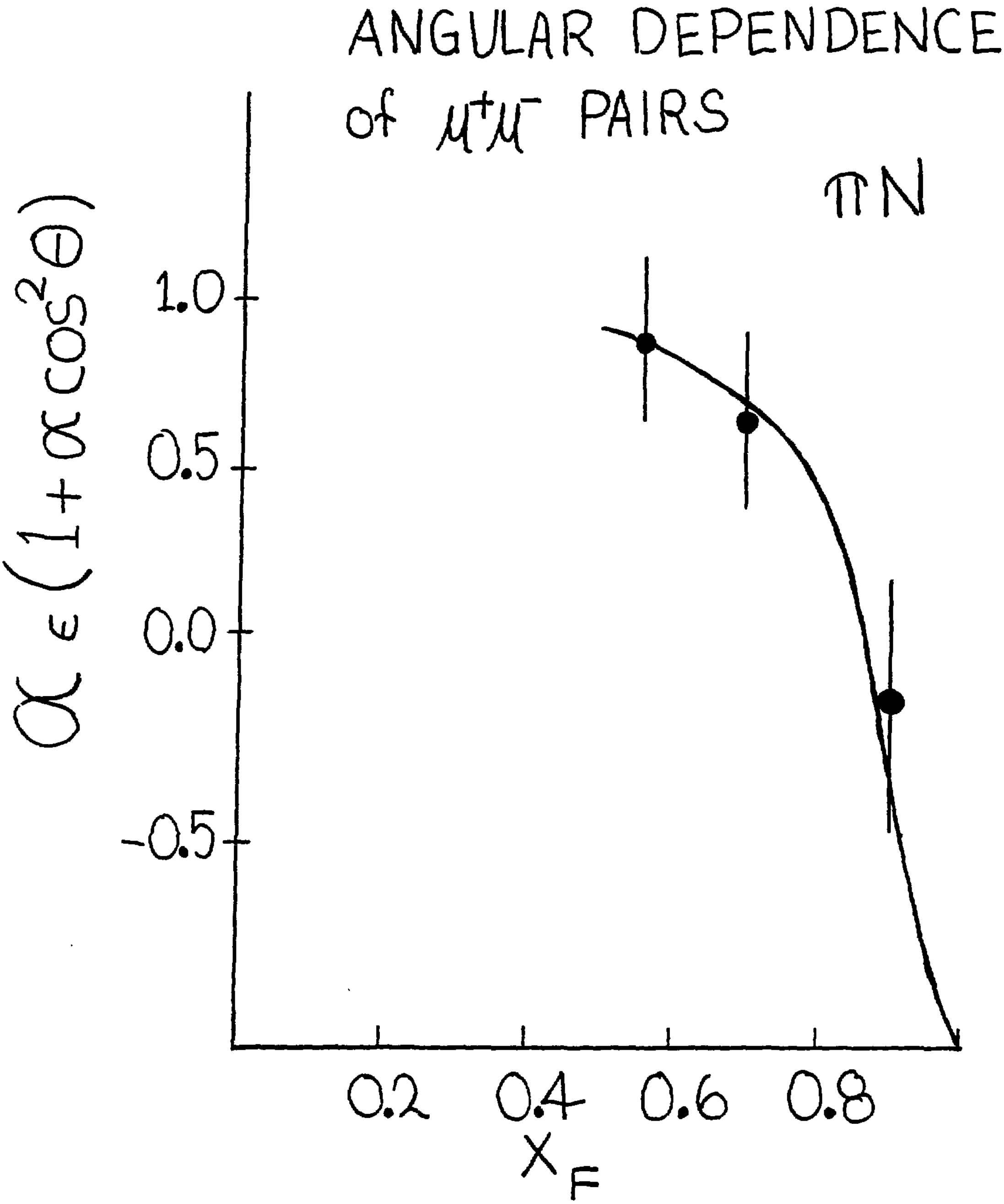


FIG.5



ANGULAR DEPENDENCE
of $\mu^+\mu^-$ PAIRS
πN
$\alpha \in (1+\alpha\cos^2\theta)$
1.0
0.5
0.0
-0.5
0.2
0.4
0.6
0.8
X_F

FIG. 6

QCD
JETS & BRANCHING PROCESSES

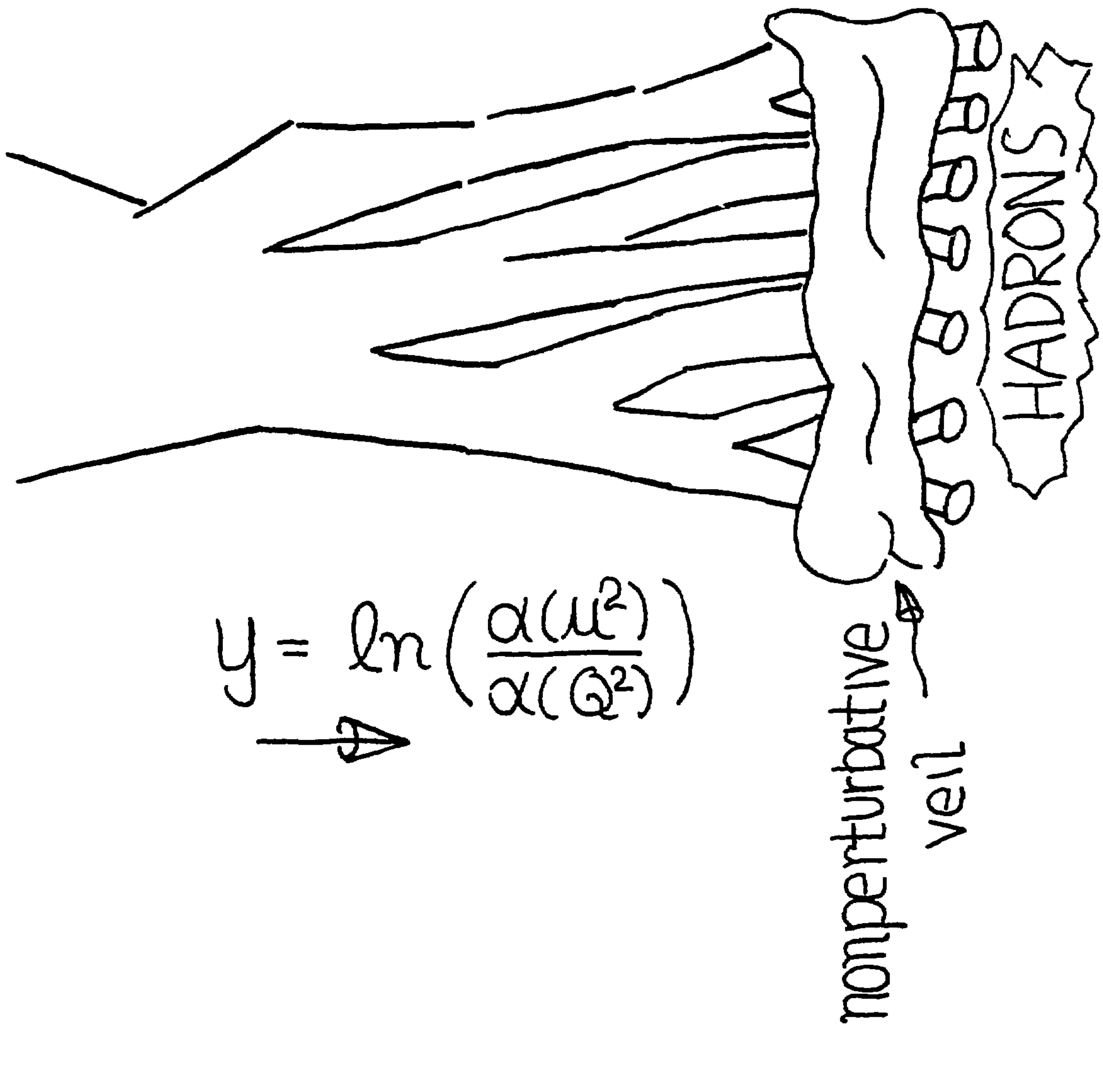
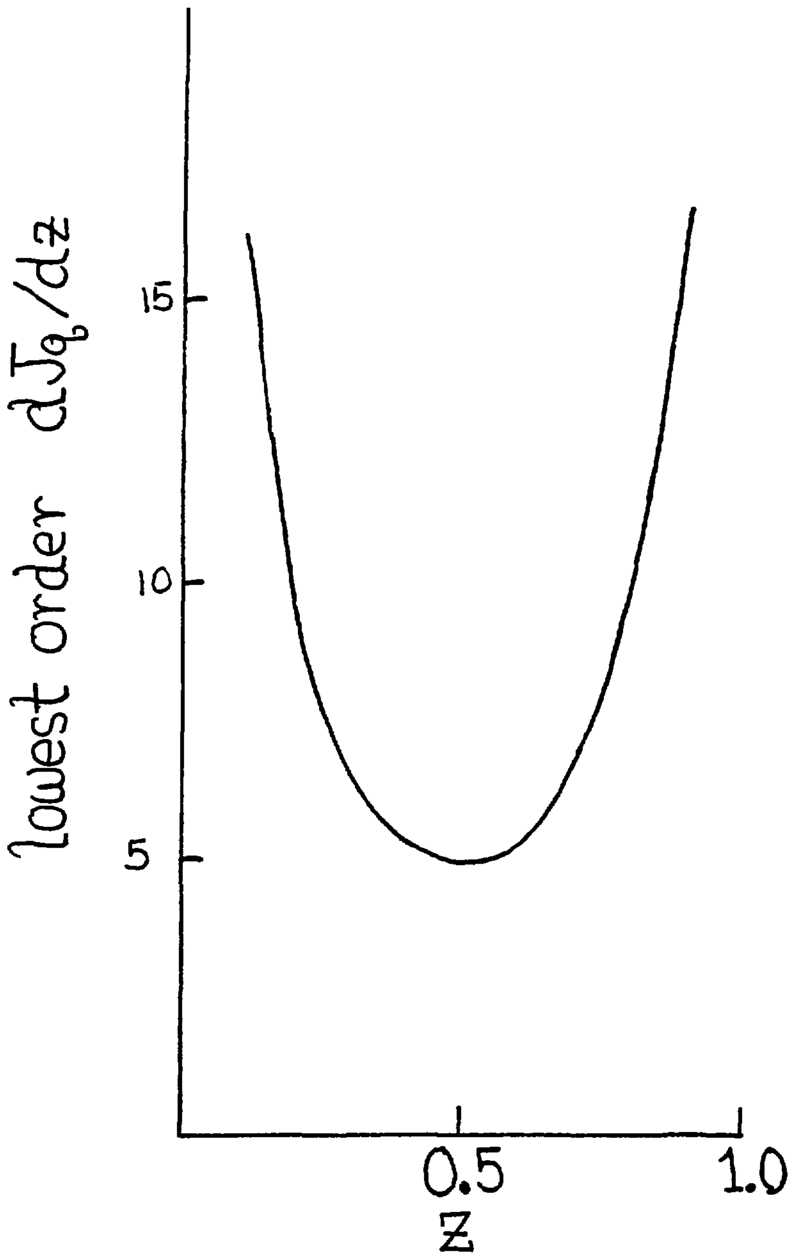
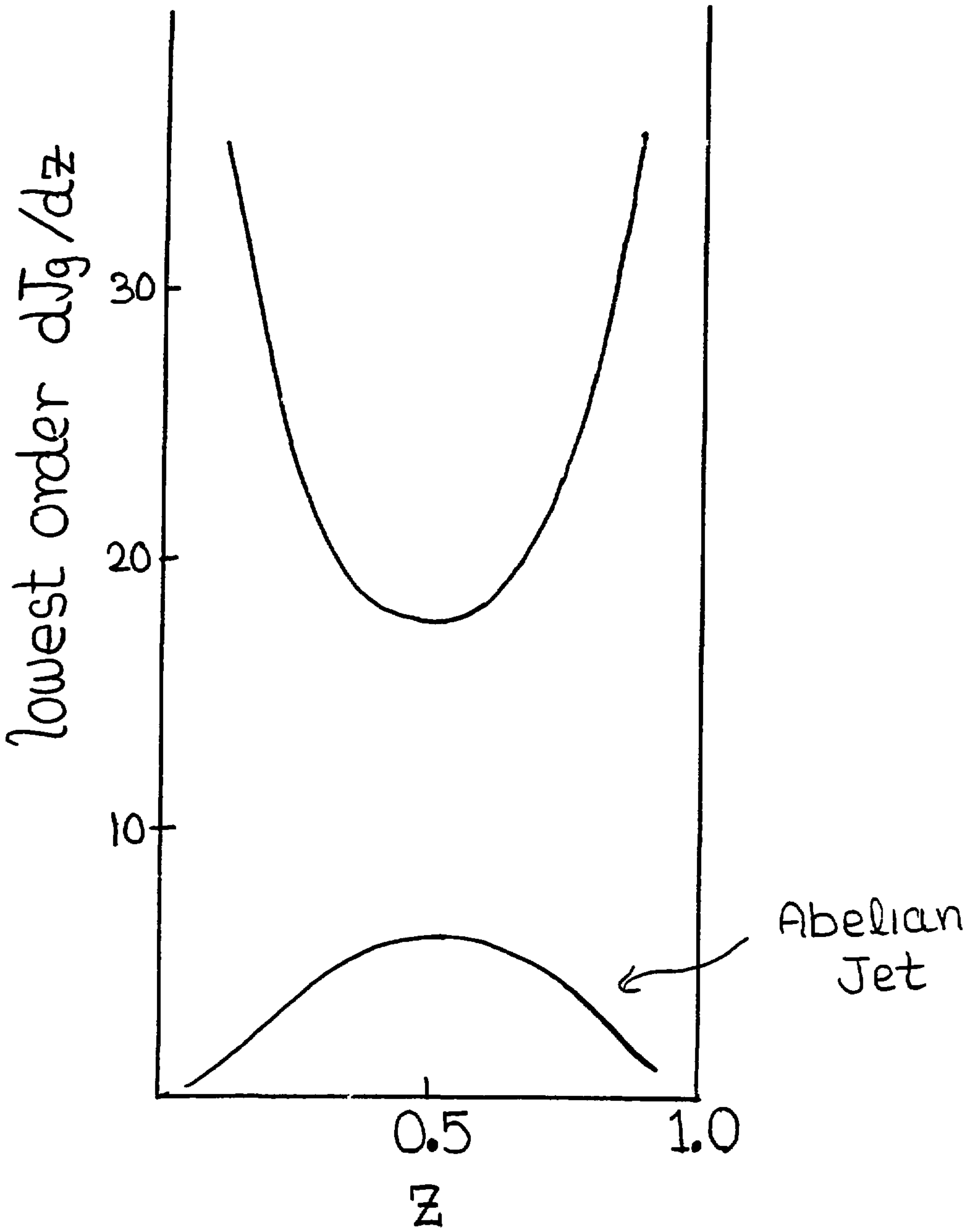


FIG. 7



JET IN A JET

FIG.8



Gluon Jet

FIG. 9

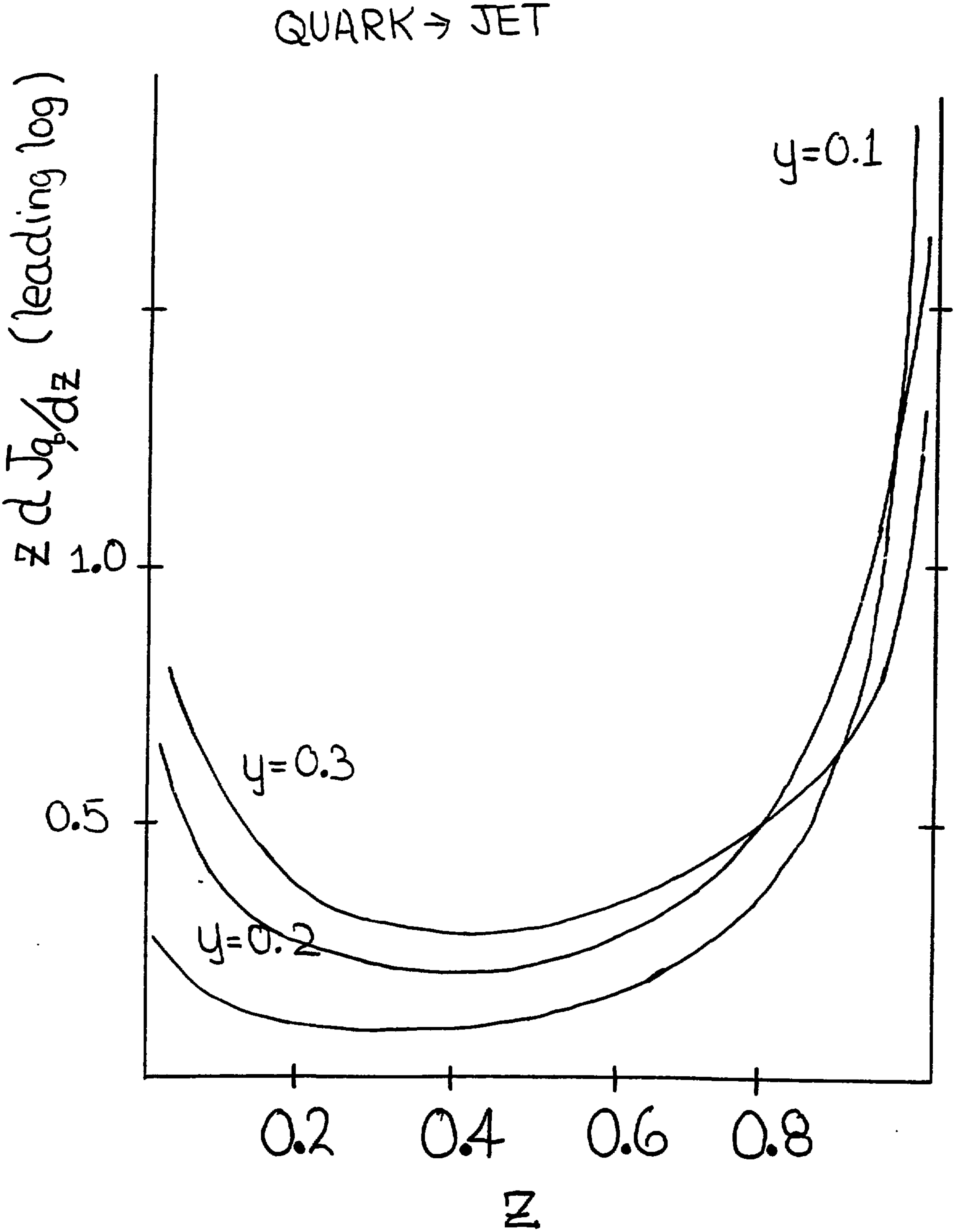


FIG. 10

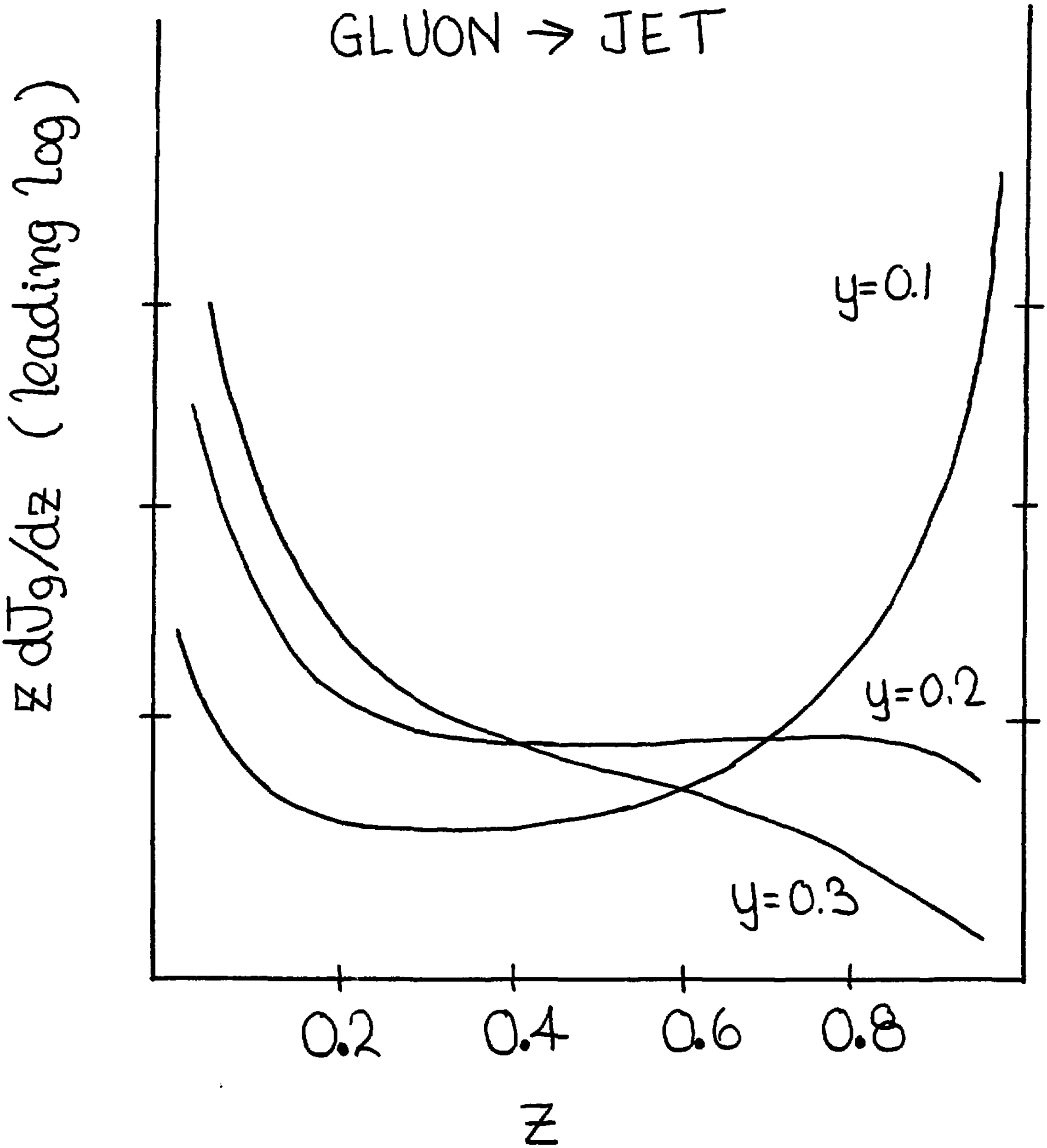
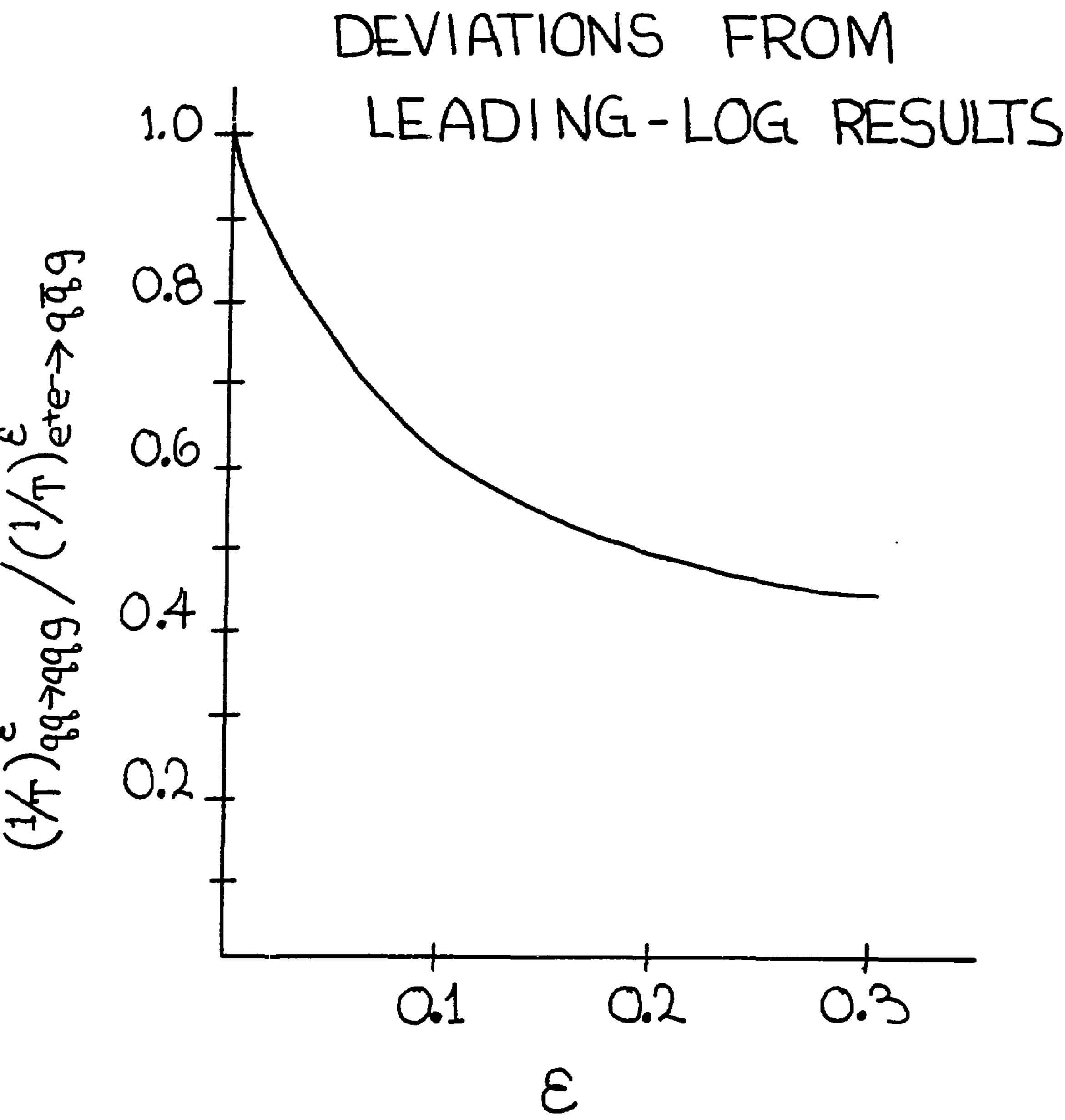


FIG. 1



DEVIATIONS FROM
LEADING-LOG RESULTS
1.0
0.8
0.6
0.4
0.2
0.1
0.2
0.3
ε
$(1/T)^{\varepsilon}_{qq\to qqg} / (1/T)^{\varepsilon}_{e^+e^-\to q\bar{q}g}$

FIG. 12