EXPECTATIONS FOR ULTRA-HIGH ENERGY INTERACTIONS

R. P. Feynman
California Institute of Technology

I. Introduction

I will talk about expectations for strong interactions and leave to others the discussion of weak interactions. I will concentrate on the hadrons produced in high-energy collisions.

We have a theory called quantum chromodynamics (QCD) that most people think might be right. This theory has a property called asymptotic freedom which means that at very high energies particles appear to be free. That is, the coupling constants in effect go down as the energy or momentum transfers go up. At high energy, we ought to be able to analyze the physics because we think we know how to analyze small-coupling systems.

But in any real experiment, if, for example, you observe a pion, it involves both high and low energies. By the time the quarks and gluons have cascaded down to become real hadrons, the energy of interaction of the parts in the hadron become important, so that the question of how to separate the high and the low energies is one that has not been completely analyzed. My opinion (to summarize my talk) is that in a rather short time, perhaps even before the machines are completed, we will have developed a theory by which we are able to calculate quite accurately the behavior of the high-energy end and will have some way of translating that information into real experimental facts, either by telling what will happen if you sum the momenta of some particles together or hold certain angles fixed or something. How we will separate the low-energy part, which is involved in every experiment, from the high-energy end is not yet known.

II. Quantum Chromodynamics

I would like to discuss first the evidence that QCD might be the right theory and also some estimates of what will happen from the QCD asymptotic-freedom theory. The work I shall discuss was done in collaboration with Field and Fox.[1] All this work is very preliminary. We do not have anything derived correctly from the LaGrangian, or whatever, of the field theory. This is a qualitative discussion and rough estimate of what might happen if QCD is right. A good deal of my talk will be spent in showing that what we have observed so far is not inconsistent with the possibility that QCD is right, but shows no direct evidence that it is right, only that it isn't necessarily wrong.

The idea is that the partons inside nucleons are gluons and quarks. The hard collisions between two quarks, for example, as in Fig. 1(a), can be analyzed in terms of the exchange of a gluon. Or a gluon in one proton and a quark in another interact, as in Fig. 1(b), making a gluon and a quark. Other combinations are possible. All these are to be analyzed by perturbation theory, both in first approximation and with corrections. The coupling constant is given by

$$g^2 = \frac{12\pi}{25\,\ln\left(\frac{Q^2}{\Lambda^2}\right)},$$

where Q is some momentum transfer in the collision and Λ is a parameter that has been evaluated by Politzer from e-p scattering to be in the neighborhood of 0.5 GeV. If that is true, then

$$g^2 \approx \frac{1}{\log_2(2Q)},$$

a simple formula. In a collision at 90° in which there has been a perpendicular momentum transfer $P_\perp$, then

$$g^2 \approx \frac{1}{1.5 + \log_2 P_\perp}.$$

Thus at $P_\perp = 4$, $g^2 = 0.3$ and at $P_\perp = 32$, $g^2 = 0.15$. We expect to be able to do perturbation theory in the $g^2 = 0.15$ case, but maybe not at $g^2 = 0.3$.

We must add to the first-order approximation the effects of higher collisions. Examples of collisions adding to the lowest order of Fig. 1(a) are shown in Figs. 2(a) and 2(b). The first is an analogue of bremsstrahlung. The second is a virtual-gluon correction to the first order. The result of these higher collisions is to yield an effective non-scaling, that is, that the incoming particles appear to have differing momenta depending on Q^2, a non-scaling effect of the parton distribution. I believe these non-scaling effects are caused by trying to combine the effects of higher collisions with those of the first order. The net result is that the parton distributions do not scale perfectly if you use the elementary theory. The fragmentation functions, the distributions of mesons that come out when a quark comes out, also depend on Q^2.

I will give an example of the physics by discussing e-p scattering. This was analyzed by Politzer.[2] Figure 3(a) is a diagram of the elementary process. The incoming proton contains a quark and perhaps another parton or several. The proton is hit by a virtual γ from the electron and knocks the quark off toward the upper right. It was in these terms that the scaling behavior was first understood, by supposing the distribution of the partons in the hadron scaled. But now we realize that there are higher collisions in QCD and that the proton can emit a gluon ahead of the collision, as in Fig. 3(b), or afterward, as in Fig. 3(c), or have a correction to the original diagram from a virtual gluon, as in Fig. 3(d). If the gluon and the quark come out almost in the same direction, we cannot distinguish Figs. 3(b) and 3(c) from Fig. 3(a), because the only thing we can use to distinguish them is kinematics. When the momentum difference is wide enough, the kinematic relations between the momentum of the quark and the energy and momentum of the transfer do not work out because effectively this quark does not have zero mass, but turns into a quark and a gluon which have a relative mass. If this effective mass $m^2 < \Delta^2$, a constant of the order of 1 GeV, one cannot distinguish 3(b) and 3(c) from 3(a). Therefore we integrate the contributions from 3(b) and 3(c) only over those $m^2 > \Delta^2$. Then it turns out, surprisingly (but interesting, that you understand it) that the relative contributions from 3(b) and 3(c) vary as the square of the coupling constant (because there is one extra coupling) and as the square of the logarithm of (Q^2/Δ^2). They go in the typical bremsstrahlung way as dm^2/m^2, with two logarithms, one for the angle and one for the momenta. Thus the relative contributions increase with Q^2, even though g^2 varies inversely with log Q^2. For corrections at transverse momenta that are more than some finite amount, the higher-order corrections rise with Q^2, rather a surprise in view of the dependence of g^2 on Q^2.

Diagram 3(d) has corrections that affect the total cross section σ (more properly σ multiplied by the momentum p of the observed hadron) that also depend on a cutoff in the integration, and the product σp is roughly the same whether or not these effects are included. But the distribution of outgoing momenta, or the apparent parton distribution, appears to change with Q^2. In the diagram of 3(b), the hard quark leaves only a fraction of its momentum to be hit by the electron. The rest coasts out as the gluon and the electron in effect sees a softer quark. Of course, in diagram 3(c) it sees it at full steam, but 3(c) is decreasing, so the hard quarks are decreased in number because the total momentum of the quarks is conserved, but the low end is increased. So as we make corrections and relate them to the elementary theory, we find that we can represent all the effects by the elementary diagram of 3(a), except that the distribution of momentum of the quarks in the proton varies with Q^2. One can transform this idea into a differential equation and find a simple equation for the moments of the distribution and find how the distributions change. So those for any Q^2 can be gotten if they are known for just one "reference momentum."

The same idea works for the disintegration functions, as we can see in production of hadrons by e^+e^-. In Fig. 4(a), we have the simple diagram of two quarks coming out from e^+e^-. In a higher approximation, there can be a correction that cuts it down, as in Fig. 4(b). There can also be the emission of a gluon in addition to the two quarks. If the gluon angle is large enough to give it a finite momentum, this makes the same kind of logarithmic correction as in the total cross section I discussed above. The net result is that the momentum in the hadrons has been split, so that high momenta are cut down and low momenta are enhanced.

I will now present some experimental evidence on apparent scale breaking at larger x in ep and μp scattering. At larger x, the curves of Fig. 5 fall as Q^2 is increased and at smaller x, they appear to rise. There are still questions as to whether various effects have been properly treated and these results should be regarded as preliminary. They do allow us to determine the Λ that appears in g^2 and it is in the neighborhood of 0.4-0.6 GeV. The net result is that the distribution functions for νW_2 varies with Q^2 in a manner predicted by theory, as shown in Fig. 6(a). We must also guess at the gluon distribution at some given reference momentum inside the proton and we have made a reasonable assumption, given the total momentum of the gluons. We show it in Fig. 6(b). It also varies with Q^2 in an analogous way.

Just as the distribution functions of partons vary with Q^2, so do the disintegration functions. Figure 7 (a) is the disintegration function of π^0's produced from quarks. In the same way as above, we must guess the gluon disintegration function. Here we have no information and have explicitly proposed a definite guess for this distribution, shown in Fig. 7(b). In order to agree with experiment, we propose that when gluons turn into hadrons, they turn into generally softer hadrons - higher multiplicity, but lower momentum each - than do quarks.

III. Comparison with Experiment

I will now discuss fitting of the high $P_\perp$ hadron data by QCD. I am trying to show you that it is not impossible that QCD is right. If it is not wrong, it is the most reasonable theory. It has many qualitative features that seem to be right. It is always true in these kinds of talks when a new machine is being built that you can say that anything will happen and you should go ahead and find the marvelous new things that are bound to happen at high energy. But I would like instead to make a conservative best guess as to what is most likely to happen.

We had done some previous work in which we supposed that the major thing that was happening was collisions between quarks. We had to assume that the cross section varied as $1/E^8$, where E is the energy, because experimentally the cross sections varied as $1/E^8$ if momentum ratios and angles were left fixed and a scaling argument indicated that meant the internal cross section for quarks had to vary the same way. This is not the way that quantum field theory is expected to go. It should give $1/E^4$ with some logarithms. But that was so obviously in disagreement with experiment that we took this ad hoc form, $1/E^8$. We also had to use a $P_\perp$ of 500 MeV for the quarks inside the proton. This model gave good success but with some difficulties. The first was that we needed an arbitrary cross section to fit the data. More important was that the P_{out} that we chose turned out to be too small. Here P_{out} is the transverse momentum of quarks inside, which is easily measured by the outgoing momentum out of the plane of a collision. In addition, if you measured with a target on one side and looked at the particles on the other side, which we supposed were coming from a quark jet, we obtained too large a momentum for these "away" particles. Furthermore, the number of u quarks in the hadron is greater than the number of d quarks and the ratio of π^+/π^- should therefore be greater than unity. We obtained too large a +/- ratio for the away particles.

Our new attempt is based on QCD. It is preliminary in that it uses nonscaling distributions instead of correctly calculating the effects of the higher collisions. It is also necessary to guess the gluon distribution, as I have discussed above. We must also guess how the gluon fragments into hadrons and we have supposed that it fragments into softer hadrons than do quarks.

We chose $\langle P_\perp \rangle$ = 849 to fit the μ^+ and μ^- P_{out} distributions. This is very poor, because these distributions are almost certainly affected strongly by the higher collisions, which we have not treated fairly in our preliminary nonscaling distribution theory. When a quark and an antiquark annihilate to make a μ pair, a gluon is sometimes omitted and therefore the μ pair is moving with a transverse momentum larger than that which comes from the initial transverse momentum of the quarks inside the proton. All this has been summarized in one number in our theory. At any rate, a fit to the data is shown in Fig. 9. The hope is that the effects will be similar in hadron collisions to what they are in the μ collisions, so we can use the transverse momenta we got from the μ experiments.

I should also point out that, since the μ^+ and μ^- are produced in pp collisions, they can also be produced by quark-quark collisions or by quark-gluon collisions. Figure 8(a) is a diagram in which a virtual photon is knocked out and produces a $\mu^+\mu^-$ pair. Figure 8(b) is a diagram in a quark-gluon collision. This second diagram of higher order in g^2 but is not infinitesimal compared with the first [8(a)] in pp collisions because it is more difficult to find an antiquark than to find a gluon. In proton-antiproton, Fig. 8(a) would dominate.

We got as much of our information as we could from non-hadron experiments in trying to compare this QCD model to hadron experiments. First, it turns out that it can be made to fit the cross section, in spite of the $P_\perp^{-8}$. Thus QCD may be all right. If it may be all right, it probably is. In Fig. 10 I show data of cross sections multiplied by $P_\perp^8$. The solid line is QCD theory and we see that we have a not-impossible situation, even though there is some uncertainty (and some skill) in this graph. I emphasize that the absolute cross sections are completely determined by Politzer's coupling constants and that we have no parameters to make a fit. The gluons make relatively important contributions to the cross section and there is some adjustment in that. Second, the transverse-momentum effect that we put in has a large effect. The dotted curves are QCD without the 849 MeV, which is called "smearing" in our work. It is not that with smearing we can predict the result, but that we cannot prove that it is wrong.

The next curve, with a scale with a wider range of $P_\perp$, Fig. 11, is an experiment at very low $x_\perp$ and 90°. The old $P_\perp^{-8}$ extrapolation and the new QCD predict completely different curves by a factor 100. In the next graph, Fig. 12, instead of multiplying by $P_\perp^8$, which we now appreciate is artificial, incidental, and an artifact of the short range of energies covered, we plot it multiplied by $P_\perp^4$, which should give the right behavior at infinity (to within some logarithmic factor) showing how it extrapolates with and without smear up to $P_\perp$ = 20. Note that both curves are getting flatter; the rise at the beginning is caused by other effects, which are not fundamental, we think.

Compared with our earlier attempts, the large P_{out} that we got from the μ experiments shows up in hadron experiments. The solid curve in Fig. 13 is the new prediction of QCD compared with the data of a P_{out} experiment with "away" particles whose momentum is about 65% of the trigger momentum. The old theory is shown as a dashed line. Everyone will appreciate that none of this evidence is very positive or direct, but only shows that nothing is in disagreement.

Some charge ratios are decreased because gluons come out often and gluon jets make as many negatives as positives. But the gluon jets are softer and in a one-particle, one-arm experiment, you are more sensitive to higher momenta and thus to quarks. Because of this bias, the effect is not as large as might be expected, but is still substantial. Figure 14 is a graph of experimental points of the π^+/π^- ratio from pp collisions, with the dashed curve giving our former results and the solid curve our QCD results. The QCD curve is still a little low, so something may still be a little wrong, but at least it is not impossible.

On the other hand, a more dramatic example is the away-side particles with a large fraction Z_p of the trigger momentum. There are many fewer of these particles because the softer gluons are produced most of the time. When you trigger on one side, there is no bias against the gluons on the other side. Because the gluons are assumed to be softer, we get fewer particles of high momentum. Figure 15 shows several examples of data with the old and new predictions.

Finally, I will talk about the charge ratios on the away side. Now, because of the gluons, we should get much closer to equal numbers of positives and negatives, whereas previously we would have predicted more positives than negatives. Figure 16 shows the previous predictions for positives and negatives, both too high compared with the data, shown as circles. The QCD predictions are shown as squares. There is a problem here with the K^-'s, which I will not discuss.

Another change that the new theory makes is that the ratio of jet cross section to single-particle cross section is closer to 1000, instead of the 100 of the previous theory. For the single-particle cross section the new theory is in good agreement with observed data at 53 GeV, but gives a very different prediction from the old theory at 500 GeV, where there are no data as yet (see Fig. 17).

A very serious effect for experiments which are looking for W mesons is illustrated in Fig. 18. Here we have plotted the W meson production expected as analyzed by Quigg[3] (we shall have to reanalyze it in our new model, but it may not be vastly different, although the transverse momenta will be generally higher). These are compared to our old predictions for the number of hadron jets expected as background. You see, as Quigg remarked, they might be observable, but now our hadron predictions are two orders of magnitude higher so the problem of seeing W's in such a background is very severe. (The $\bar{p}p$ production rate for W's is about a factor of 10 greater than the pp rate at this energy which is still significantly below the expected QCD hadronic background.) It is not at all clear how reliable these predictions are, but the orders of magnitude may not be too far off and the new theory has much more physical content than the old phenomenological one.

Thus, in the QCD theory (still to be regarded as preliminary), we find the following new things:

(i) Much larger cross sections at high $P_\perp$.

(ii) Larger values of P_{out}.

(iii) There should occasionally be three-prong jets from two quarks and a gluon, or some other combination. They should be rare, but there is ample phase space available. If you integrate over the momentum of the other jet, then you can get more three-jet than two-jet cases.

(iv) One should be able to see some charm and anticharm particles coming out from gluon-gluon making a quark-antiquark pair, for example. There could also be other kinds of quark-antiquark pairs (t or b). A very crude estimate might show the probability of a charm quark initiated jet to be of the general order of 1.5 to 2% in pp and 4 to 5% in $\bar{p}p$. This does not mean that one will see a few per cent as many charmed as normal hadrons, because in the lower part of the cascade we expect only normal hadrons.

(v) All the effects we expect are nearly the same for pp and $\bar{p}p$, except for the W production and $\mu^+\mu^-$ pairs from a quark-antiquark annihilation, because there are somewhat more $q\bar{q}$ in $p\bar{p}$ than in pp. There is a background effect, a possibility of producing W's from quark-gluon collisions. These contributions, which have not been evaluated, will be the same for pp and $\bar{p}p$. The W will have higher transverse momenta than previously expected. Because of (i) they will have to be observed behind a very large background of hadrons.

IV. A Look into the Future

I would like to illustrate in a qualitative way what will be seen in the future. Instead of the complicated case of two protons making a quark-antiquark pair at high transverse momentum, I'll take the simpler but similar case of e^+e^- making hadrons as a function of energy. I draw in Fig. 19 momentum-space diagrams of where you will find the hadrons. The absolute scale is the beam energy. At a reasonable known energy, say E = 8, the particles will lie in opposite jets as shown in the first sketch. A finite transverse momentum is possible for the hadrons, of order 0.5 GeV or less.

When we go to higher energy (second sketch), we will expect roughly the same thing, stretched out along the jet by our scaling. The transverse momentum will therefore look smaller. But there is the possibility of a small knob sticking out. We have to go to still higher energy to see what it is (third sketch). It is another jet, perhaps another gluon, coming out. As you increase the energy, you get a more structured picture. At "ultra-high" energy (fourth sketch), there are many prongs. It is like looking at a tree in more and more detail and seeing more and more prongs. Such a "tree" is called a "fractal," known from the mathematical problem of subdividing the sides of a triangle into smaller triangles.[4] We may have to deal with fractals at ultra-high energy.

There is a problem of perturbation theory. We should be able to calculate by small-coupling theory, but it isn't low order, because it has so many prongs. If one wants to calculate down to a cutoff of smaller transverse momentum, then the higher-order diagrams become more important. But they ought to be summable or analyzable. If one looks at moments, one gets simple differential equations. But if one wants to discuss more detail, it is necessary to discuss such a "fractal."

I believe that it is quite possible that by the time the machine is built, the theory will be worked out and under control. The difficulty is to formulate in more technical detail what part you can calculate and what part you cannot. We know generally that we can calculate the high-momentum part and cannot calculate the low-momentum part. Calculation of moments will not give enough detail of the fractal and we need to be able to calculate more detail of each prong. When we can do these calculations, we will be able to prove all the relationships and theorems and have that end of hadron physics worked out.

References

[1] R. D. Field, Phys. Rev. Lett. 40, 997 (1978); R. P. Feynman, R. D. Field, and G. C. Fox, "A Quantum Chromodynamic Approach for the Large Transverse Momentum Production of Particles and Jets," CALT-68-651 (submitted to Phys. Rev.).

[2] H. D. Politzer, Phys. Reports 14C, 129 (1974); H. Georgi and H. D. Politzer, Phys. Rev. D14, 1829 (1976).

[3] C. Quigg, Rev. Mod. Phys. 49, 297 (1977).

[4] B. Mandelbrot, Fractals (W. H. Freeman and Co., 1977). He says "The nature of self similarity seems tantalizingly close to the physicists' much more recent and still unsystematic nature of scaling and of renormalization groups."

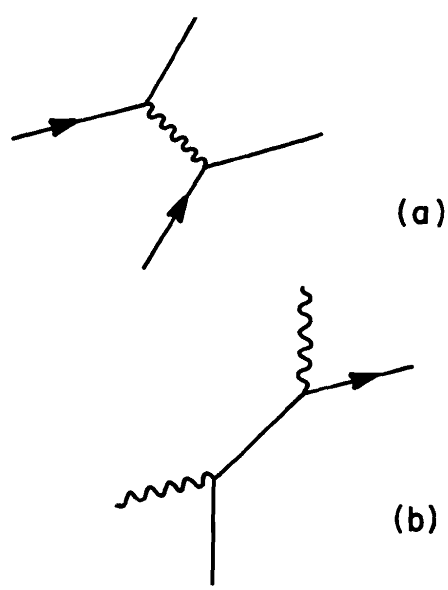


Figure 1

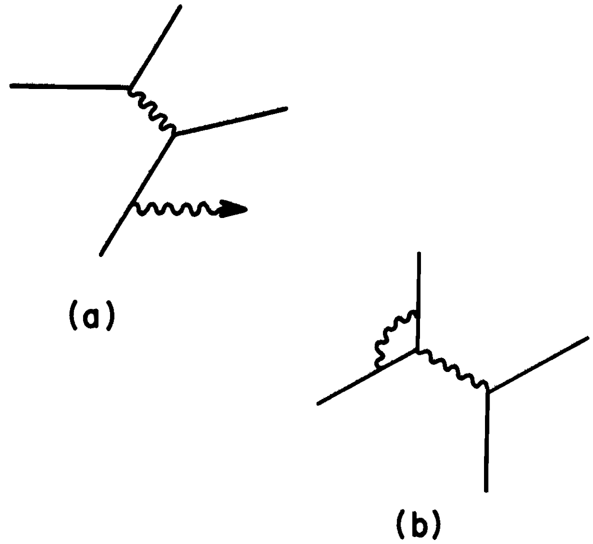


Figure 2

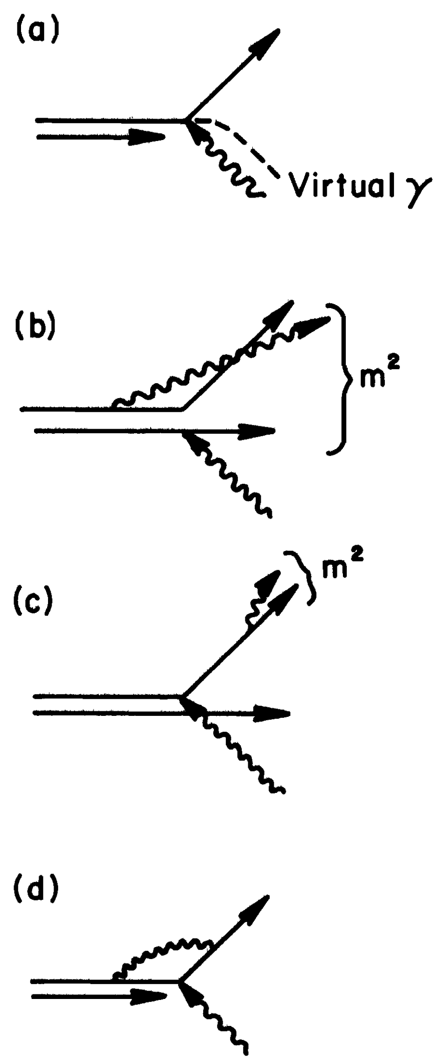


Figure 3

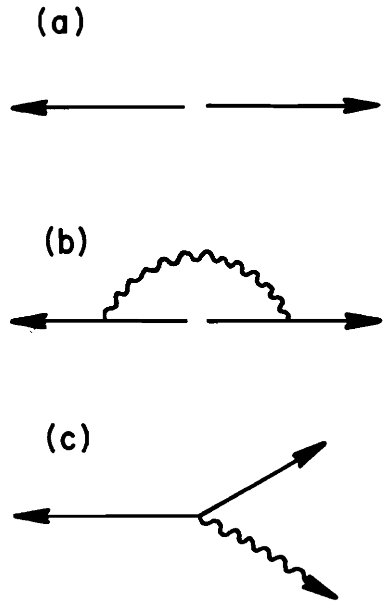
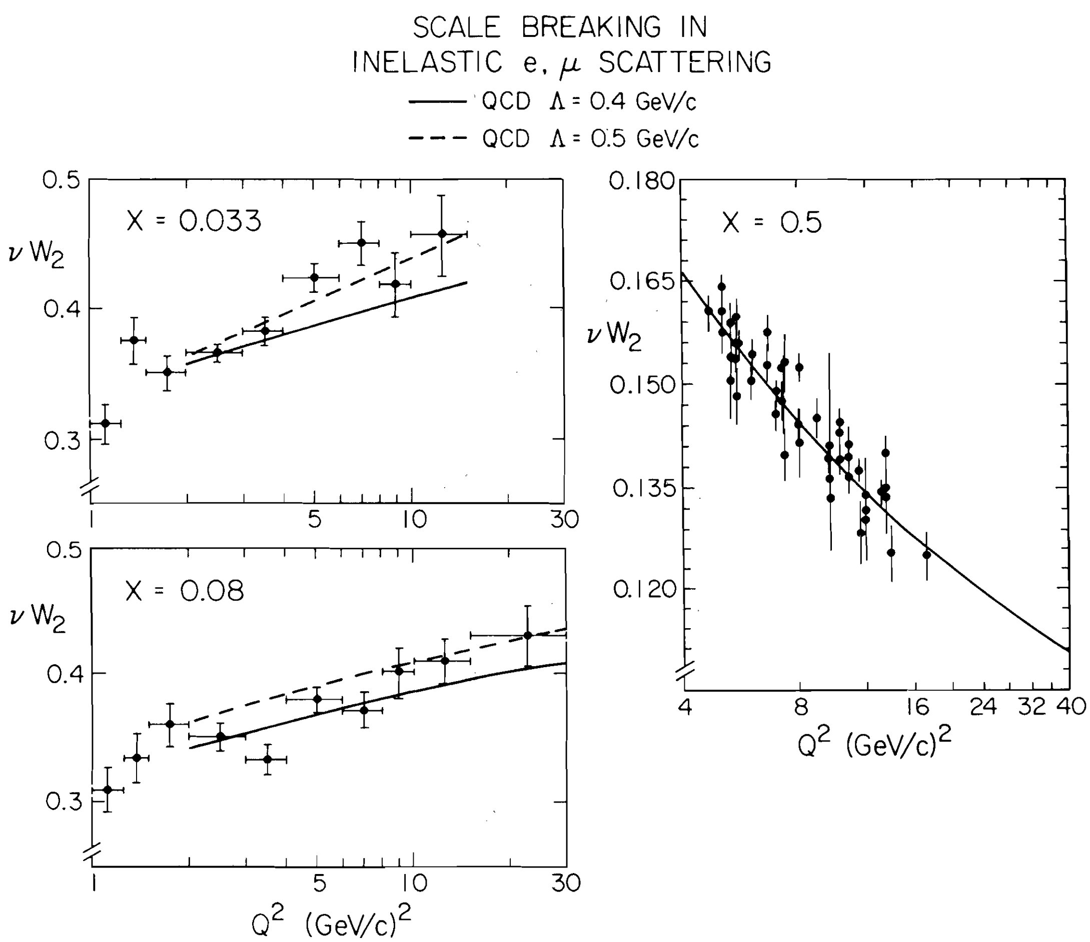


Figure 4



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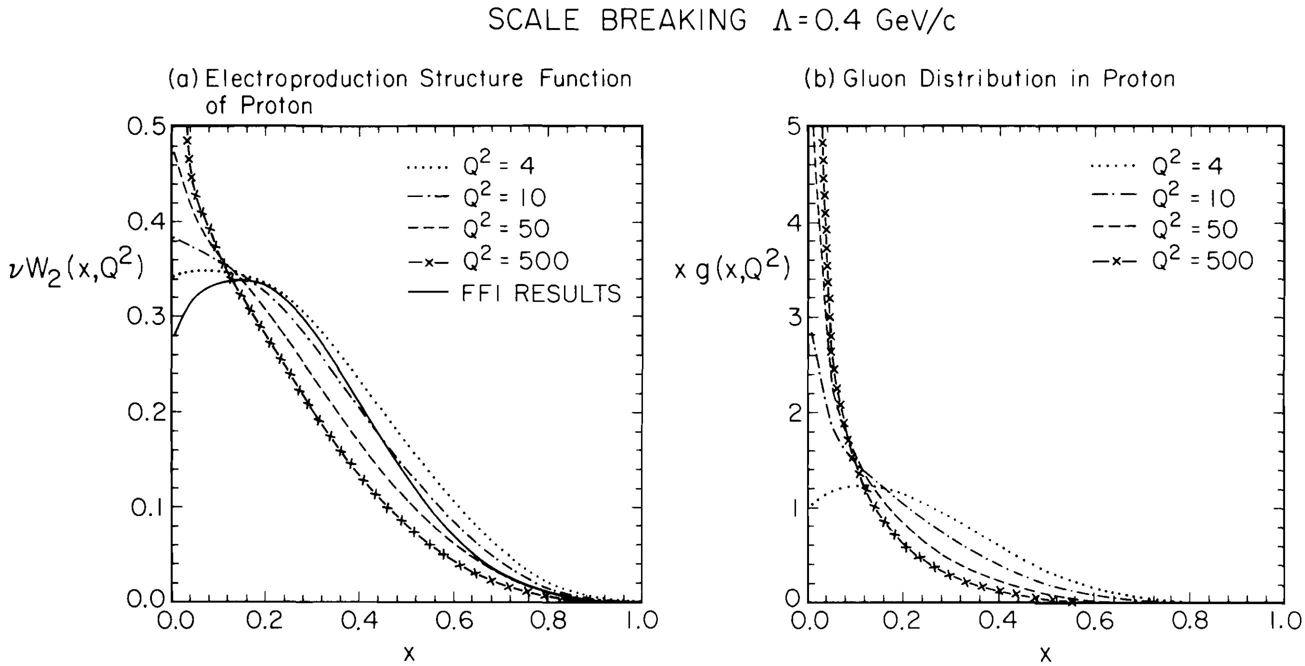

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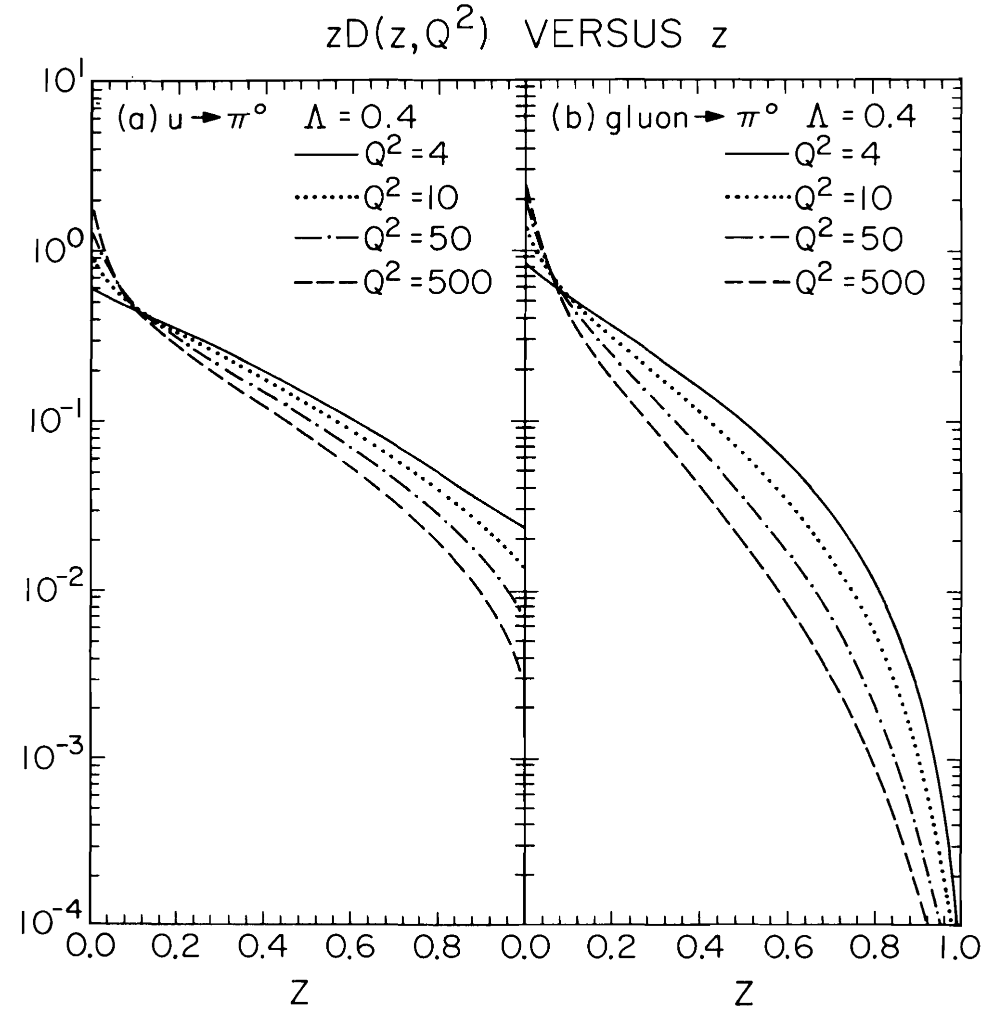


Figure 7

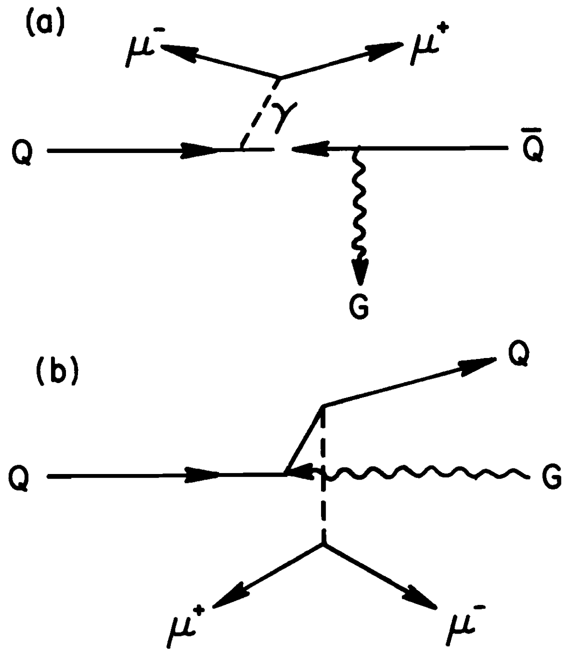


Figure 8

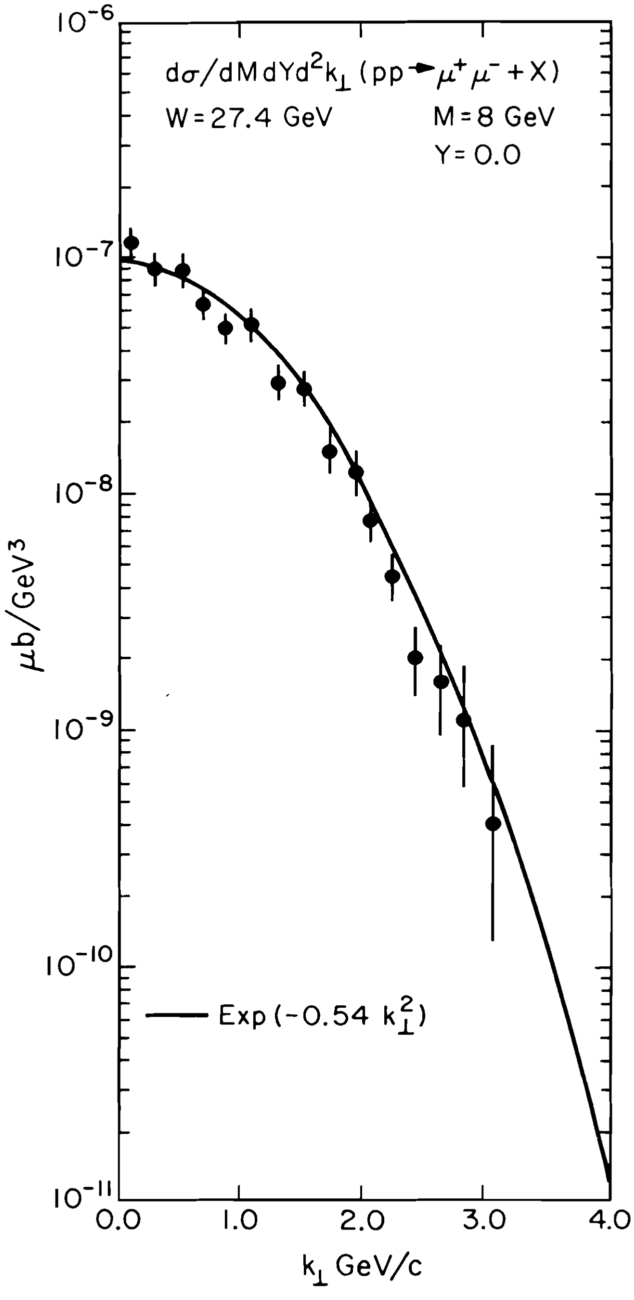
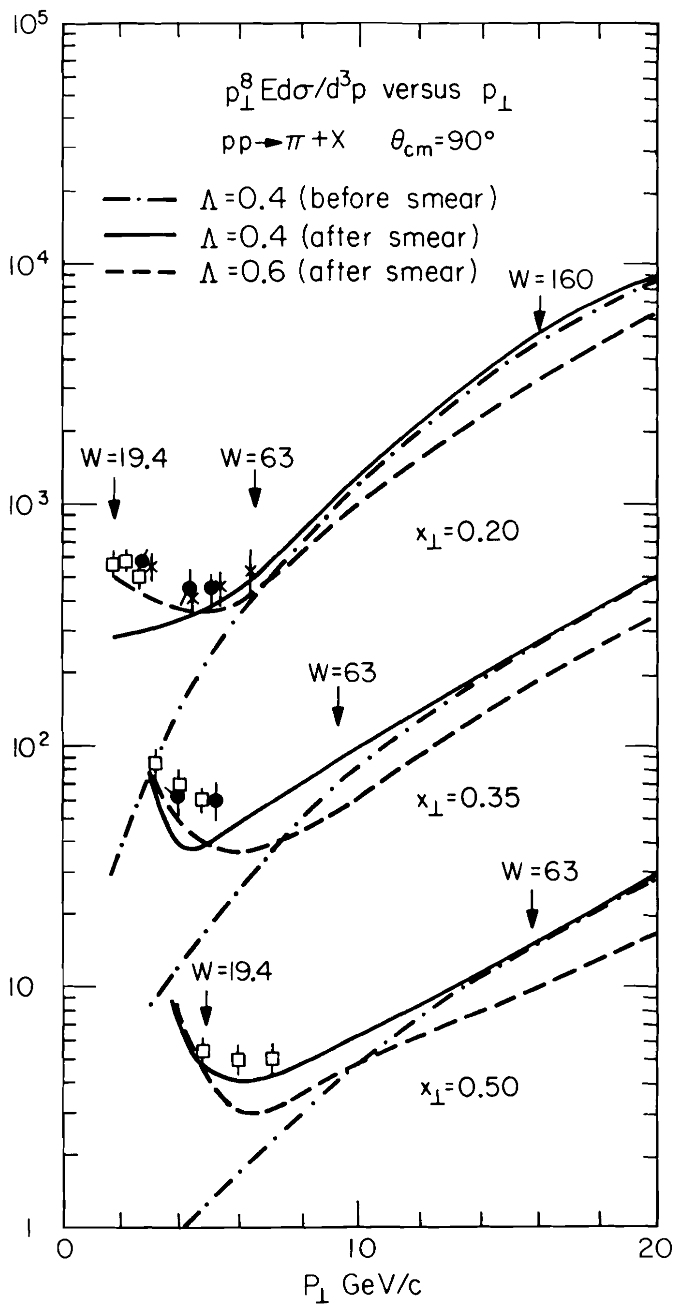


Figure 9



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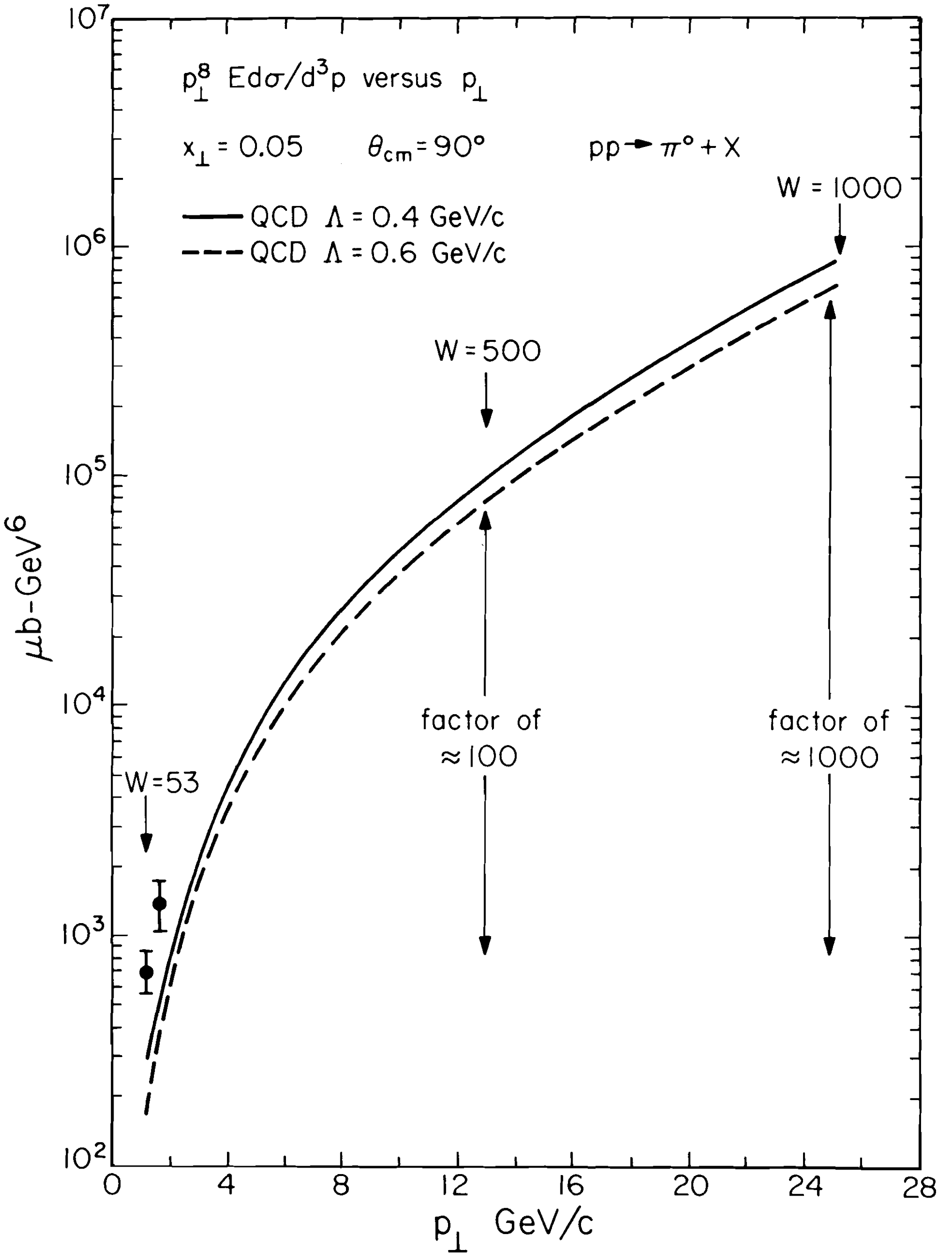

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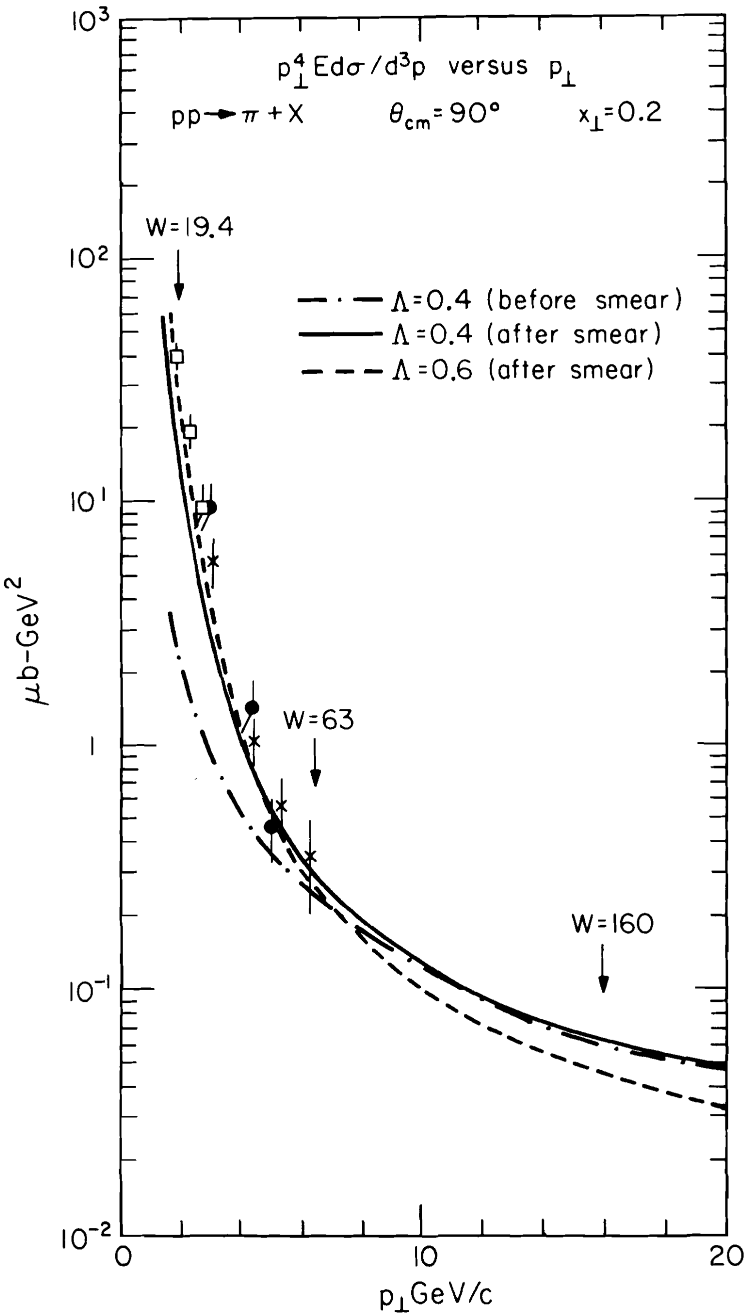


Figure 12

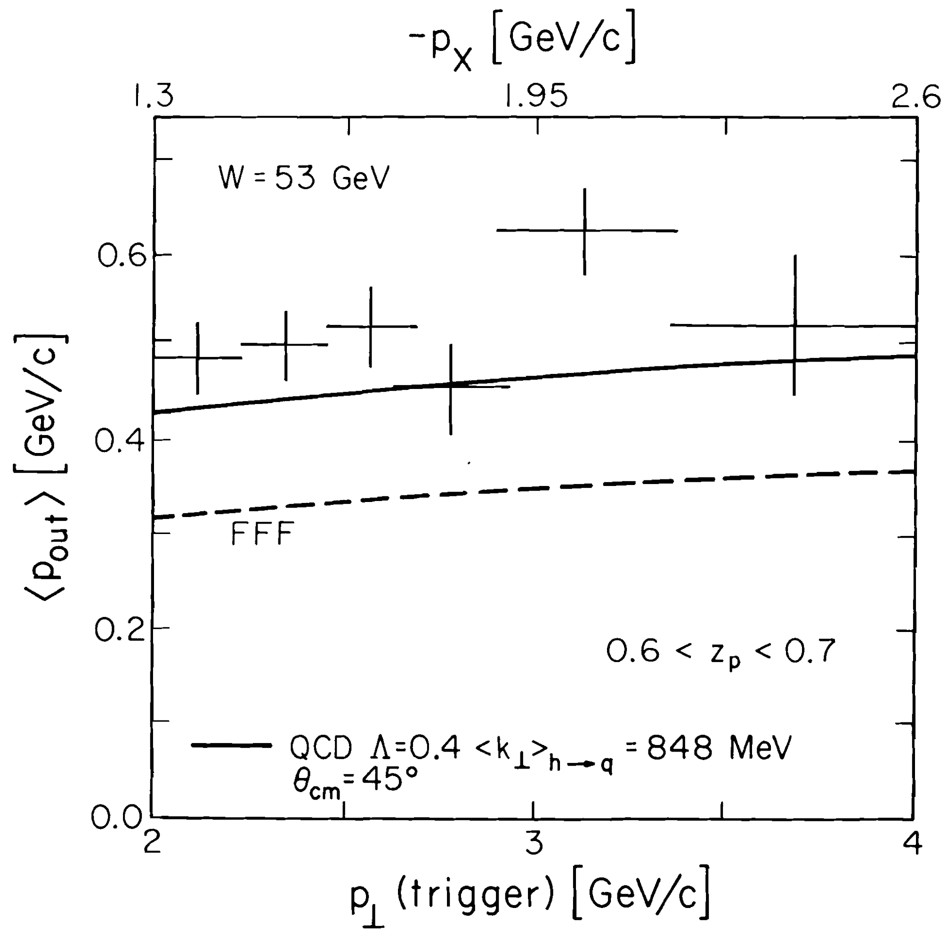
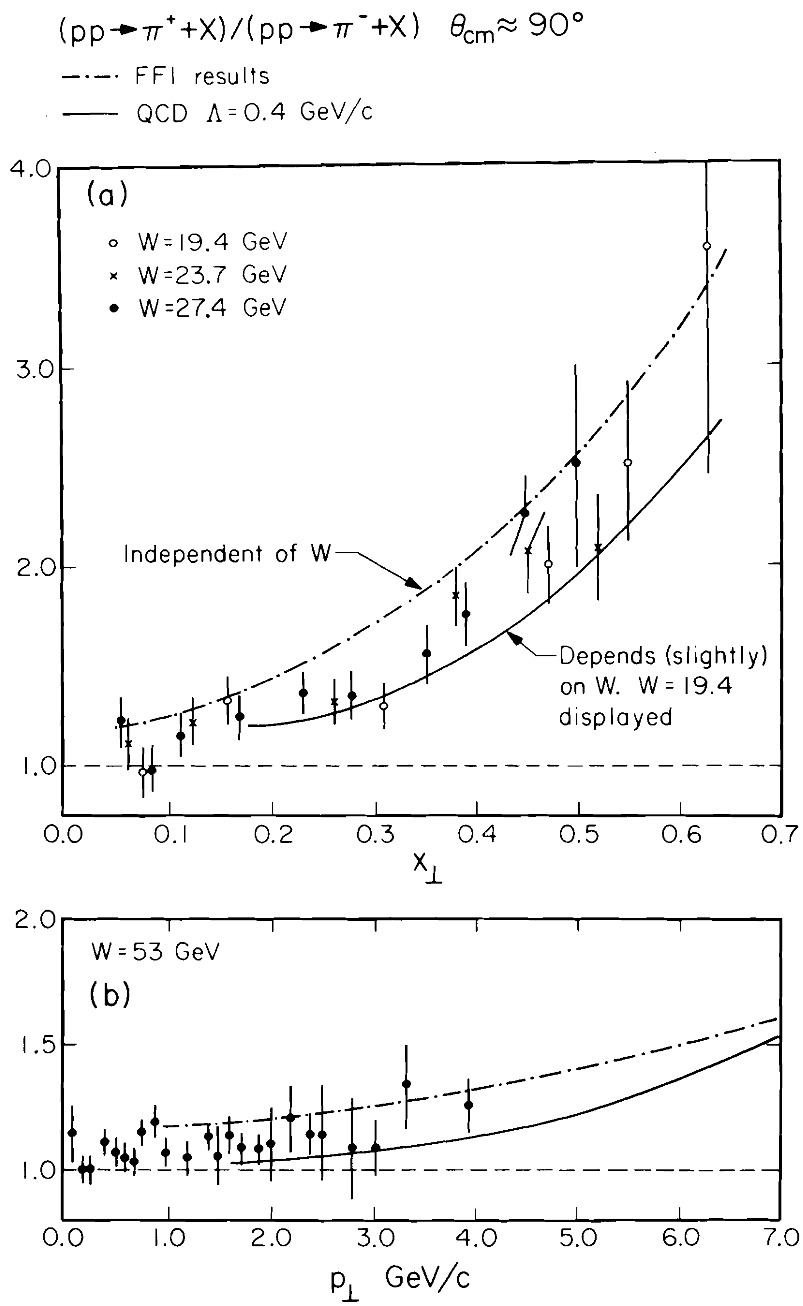


Figure 13



(pp→π⁺+X)/(pp→π⁻+X) θcm≈ 90°
FFI results
QCD Λ=0.4 GeV/c
(a)
W=19.4 GeV
W=23.7 GeV
W=27.4 GeV
Independent of W
Depends (slightly) on W. W = 19.4 displayed
x⊥
W=53 GeV
(b)
p⊥ GeV/c

Figure 14

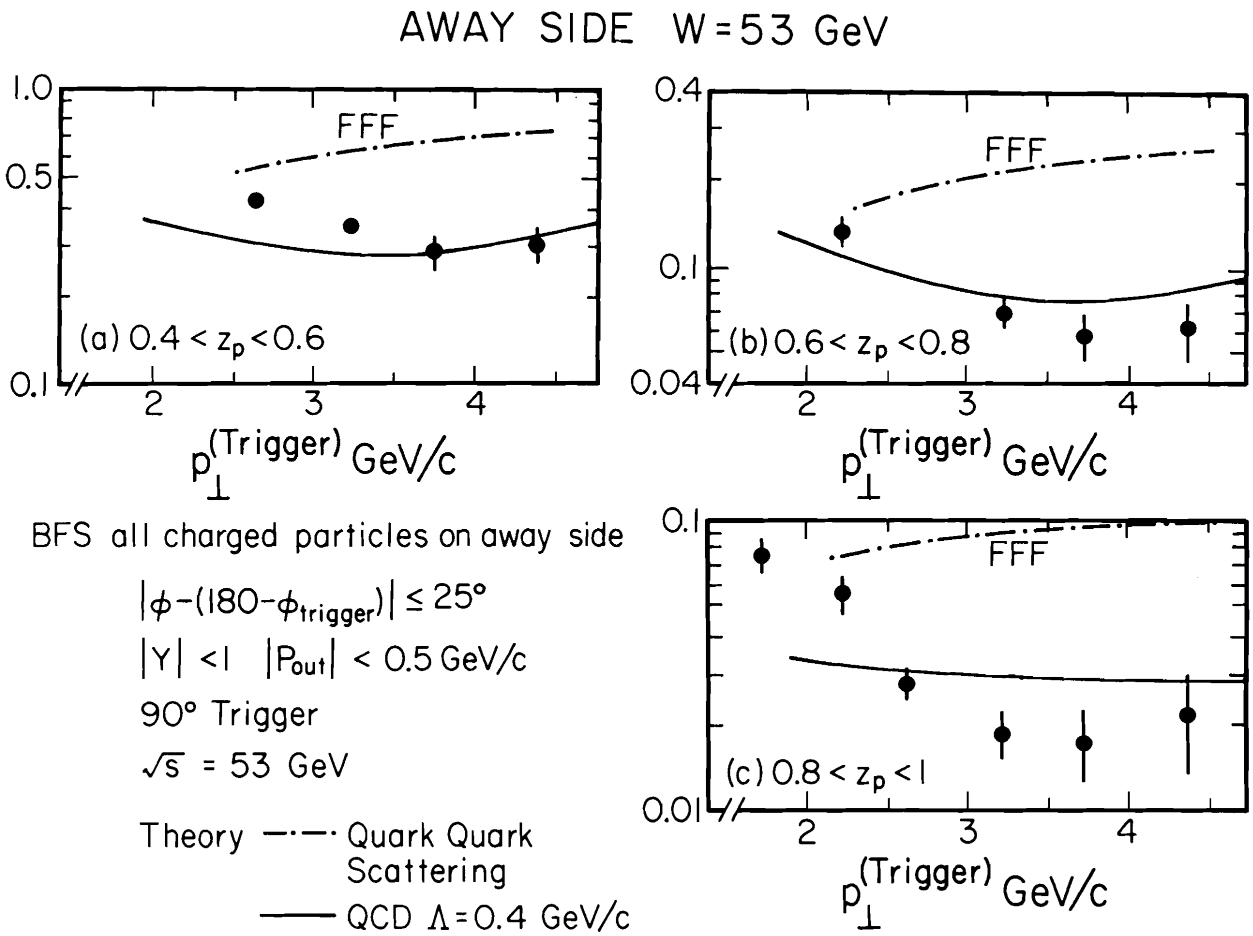
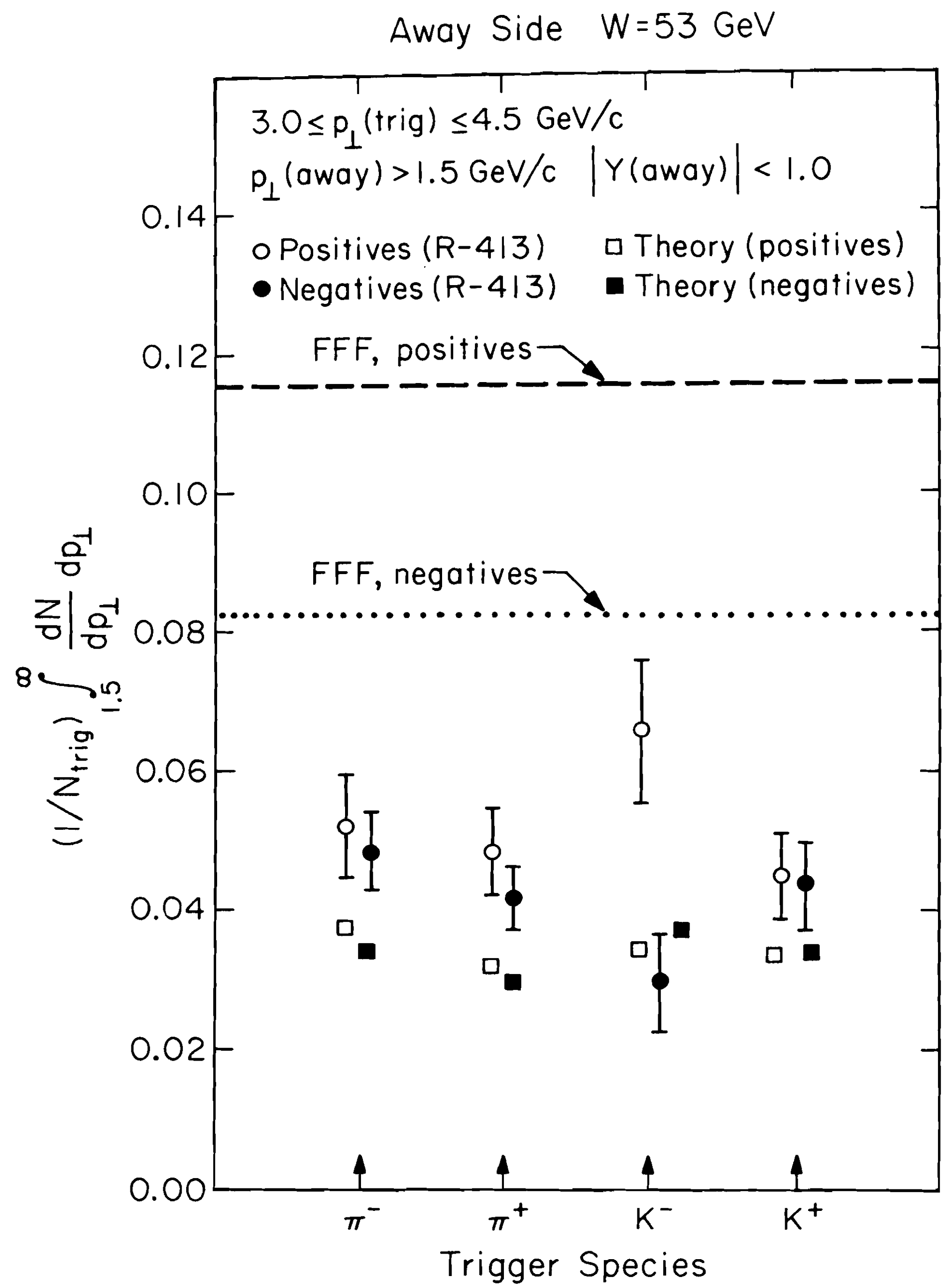

AWAY SIDE W=53 GeV
FFF
(a) 0.4 < z_p < 0.6
(b) 0.6 < z_p < 0.8
(c) 0.8 < z_p < 1
1.0
0.5
0.1
0.4
0.04
0.01
2
3
4
p⊥(Trigger) GeV/c
BFS all charged particles on away side
|φ−(180−φtrigger)| ≤ 25°
|Y| < 1 |Pout| < 0.5 GeV/c
90° Trigger
√s = 53 GeV
Theory —·— Quark Quark Scattering
—— QCD Λ=0.4 GeV/c

Figure 15



Away Side W=53 GeV
3.0 ≤ p⊥(trig) ≤ 4.5 GeV/c
p⊥(away) > 1.5 GeV/c |Y(away)| < 1.0
o Positives (R-413)
● Negatives (R-413)
□ Theory (positives)
■ Theory (negatives)
FFF, positives
FFF, negatives
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
(1/N_trig) ∫_1.5^∞ dN/dp⊥ dp⊥
π⁻
π⁺
K⁻
K⁺
Trigger Species

Figure 16

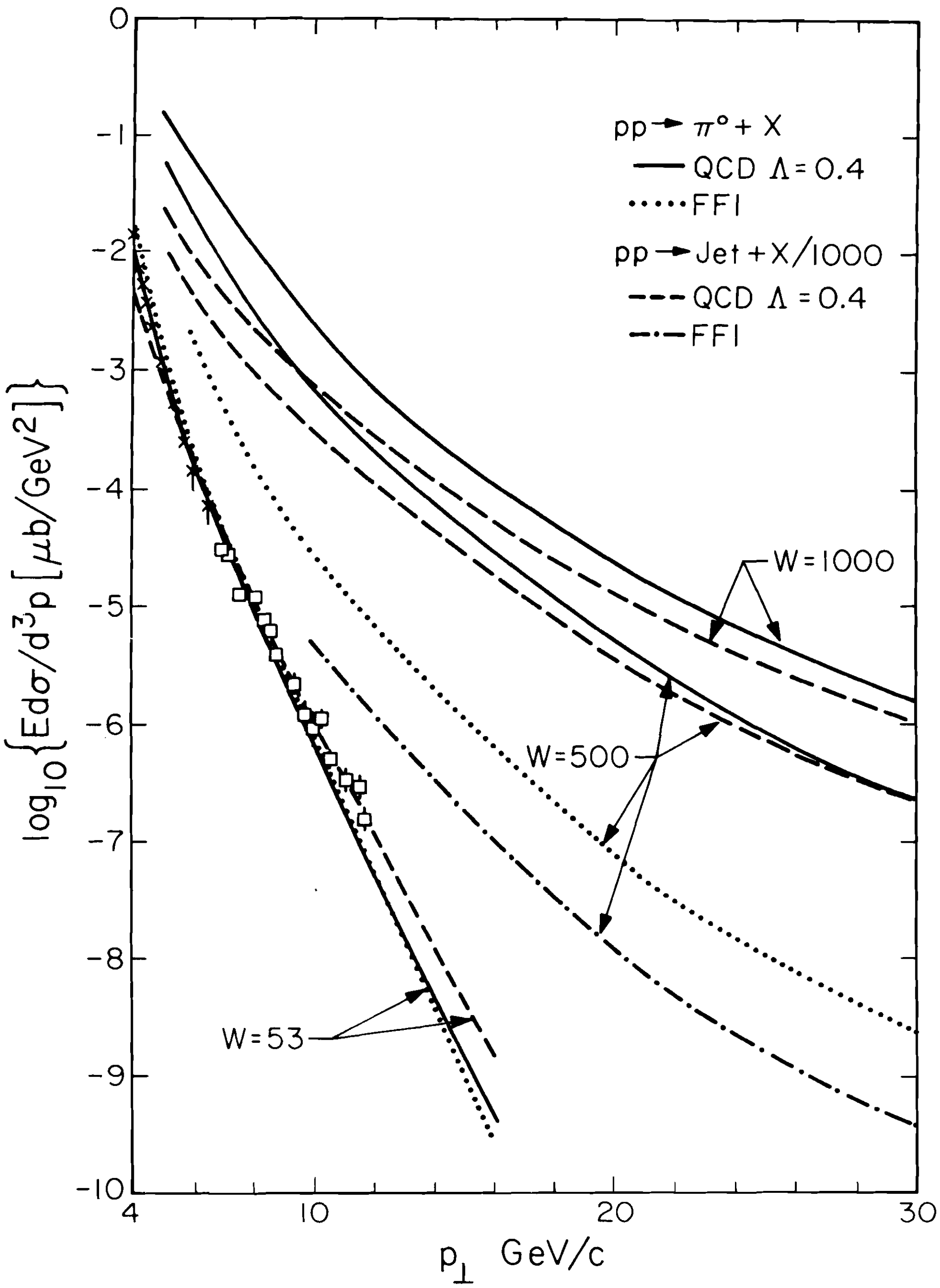

pp → π° + X
QCD Λ = 0.4
FFI
pp → Jet + X/1000
QCD Λ = 0.4
FFI
W=1000
W=500
W=53
log10{Edσ/d3p [μb/GeV2]}
pT GeV/c
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
4
10
20
30

Figure 17

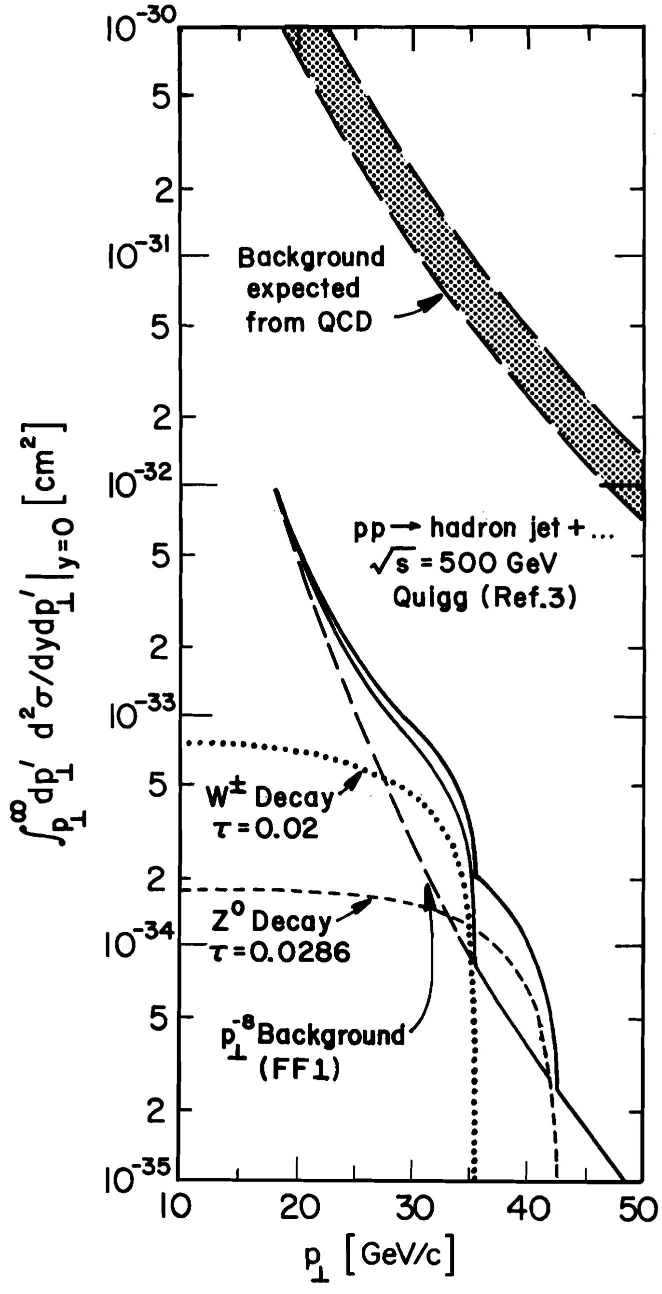
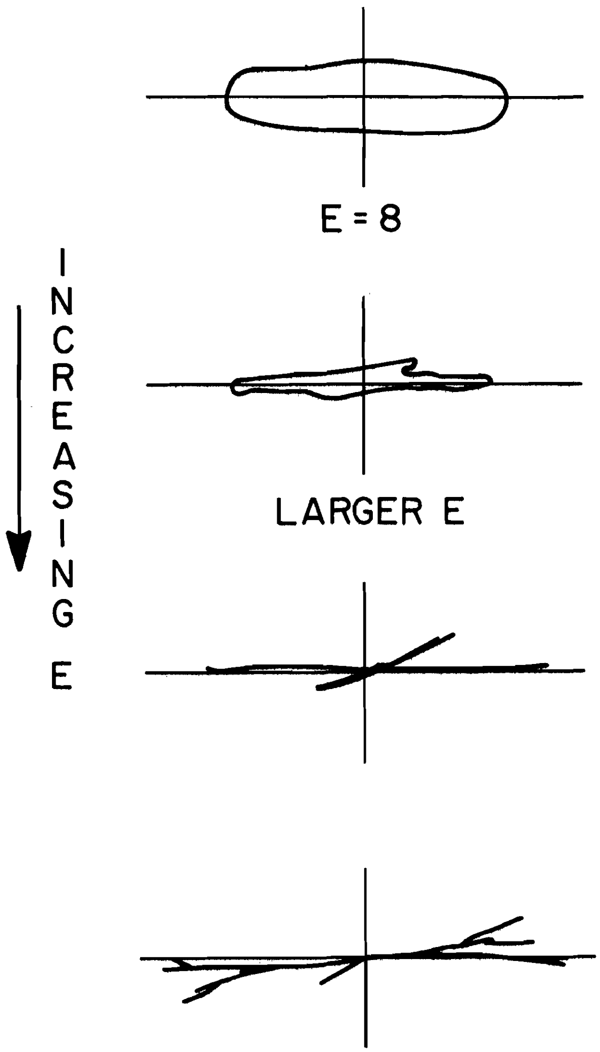

Background
expected
from QCD
pp → hadron jet + ...
√s = 500 GeV
Quigg (Ref.3)
W± Decay
τ = 0.02
Z⁰ Decay
τ = 0.0286
p⊥⁻⁸ Background
(FF1)
∫ dp⊥' d²σ/dydp⊥' |y=0 [cm²]
p⊥ [GeV/c]
10⁻³⁰
5
2
10⁻³¹
5
2
10⁻³²
5
2
10⁻³³
5
2
10⁻³⁴
5
2
10⁻³⁵
10
20
30
40
50

Figure 18

$e^+e^- \rightarrow$ HADRONS VS. ENERGY

(Drawings Scaled to Beam Energy - Momentum Space, Final Hadrons)



Calculations via
"Pert." Theory
(Trees)

Figure 19