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A LARGE MASS SCALE IN QCD JETS?*

T. F. Walsh
DESY, Hamburg

and

P. M. Zerwas**
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

ABSTRACT

We argue that jets in QCD involve a large dimensional mass scale $p_{NP}^2 \gg \Lambda^2$. This mass scale is of order the invariant mass of a jet of hadrons at PETRA or PEP energies. Partons with $p^2 < p_{NP}^2$ evolve entirely nonperturbatively into jets. We discuss experiments which might show evidence for such a large mass scale.

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** Kade Fellow, on leave from Technische Hochschule Aachen, West Germany.

1. INTRODUCTION

It is well know that at present energies the hadronic final state in e^+e^- annihilation consists of two and sometimes three jets [1]. Other processes also show jet structure in the final state. For example, one and sometimes two forward jets are seen in lepton-nucleon scattering [2]. This is expected in QCD, where multiple jet events are predicted by perturbation theory [3]. The jets themselves are presumably a nonperturbative phenomenon. The dominant two jet events in e^+e^- annihilation should originate entirely in the long distance (confinement) regime of QCD. This dynamic formation of jets from partons is a theoretically challenging problem. It is less straightforward than the calculation of the hadron spectrum. To solve it we need a better experimental understanding of the problem, which involves a more detailed knowledge of jet structure.

In this paper we examine the transition between perturbatively calculable multijet events and the as yet uncalculable confinement jets. We want to see what can be learned about confinement from this. [For clarity we consider e^+e^- annihilation only.]

The simplest operational discrimination between a two-jet and a three-jet event in e^+e^- annihilation is at the parton level at short distances. A three-jet event arises from production of three partons (quarks and gluons). When the invariant mass of two of them is small, the nonperturbative jet formation will make the resulting event one with two jets, not three. We can speak of a three-parton state or a three-jet event only if all parton-parton invariant masses are large enough. This is the same as demanding that all relevant distances be small. This is what is done in the model of Hoyer et al. [4]. In that model, a three-parton $q\bar{q}G$ state is present if all invariant masses of the parton pairs exceed 5-7 GeV at present energies. Otherwise there are only two partons present, $q\bar{q}$. The argument was that it is not meaningful to refer to a state of several partons if they cannot be resolved as jets. The mass of a typical single jet at PETRA or PEP is of order 5 GeV. The same parameter marks the e^+e^- energy at which $q,\bar{q}$ jets become resolvable at low energies [5]. The cut off in the model is a sharp one (idealized by a step function) at the parton-parton mass we will call p_{NP}^2. [Sharp transitions from perturbative to non-perturbative domains are quite familiar in lattice gauge theories and bag-type models.] To lowest order in the QCD coupling g_s the fraction of $q\bar{q}G$ states is simply given by a perturbative calculation. The fraction of two-jet events follows by conservation of probability, $\sigma(q\bar{q}) + \sigma(q\bar{q}G) = \sigma(TOT)$.[1]

The model of Hoyer et al. describes data reasonably well. The model can be improved [6], but the real question appears to us to be elsewhere. It is, rather, whether or not there is such a large intrinsic mass scale as p_{NP}^2 in QCD jets. It is surprising to encounter such a large dimensional number, $p_{NP}^2 \sim 20\text{-}50\ \mathrm{GeV}^2$. Numbers of order m_ρ^2 might seem more natural.

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[1] To this order the total cross section is $\sigma(TOT) = \sum e_i^2 (1 + \alpha_s/\pi + \text{power corrections})$. Power corrections can arise in principle from the presence of a nonperturbative cut off. However, we expect them to be at worst of order $\sim(\alpha_s/\pi)m_\rho/Q$ and therefore ignorable. (At a time $\gtrsim m_\rho^{-1}$, the connection between the original quark-antiquark pair is disrupted by hadron formation.)

One can certainly conceive of a situation where confinement processes involve no dimensional numbers larger than, say, m_ρ [7]. Then partons evolve perturbatively down to virtual masses of this order. Confinement only rearranges them slightly inside color neutral clusters of mass $\sim m_\rho$. A large mass scale never appears, and there is nothing beyond the mass spectrum which nonperturbative QCD has to explain. However, we do not think that this can work. It is not clear how one can add perturbative rates rather than amplitudes for "masses" $p^2 < p_{NP}{}^2$. Worse, such a scheme predicts that gluon jets are quite unlike quark jets [8]. This is not supported by experiments at present energies. Gluon and quark jets are hard to tell apart [1]. There are other problems as well [9]. One of the basic notions behind this idea appears to be the view that the smallness of $\alpha_s(p^2)$ is a necessary and sufficient condition to apply perturbation theory to jet formation. We turn now to a space-time view of jet formation which casts doubt on this and appears to us to support the idea that a large dimensional scale appears in QCD jets. We then go on to discuss whether experiments can check the presence of such a mass scale.

2. SPACE-TIME PICTURE

There have been several discussions of the development of perturbative parton showers [10,11] and even nonperturbative jets [12]. We follow Ref. [11] here. We consider the fate of a parton of invariant mass p^2 and energy $E \approx E_B$ (the e^+e^- beam energy). $\sqrt{p^2} \ll E$ is assumed. We drop numerical factors and write the lifetime against decay $q \rightarrow qG$ in the virtual parton rest frame as $\tau \sim 1/\sqrt{p^2}$. The lab frame lifetime or path length before decay is then order E/p^2. This can be very long. Color confinement effects will be present if a parton travels further than some distance $O(m_\rho^{-1})$. This occurs for $p^2 < p_{conf}^2$, where

$$p_{conf}^2 \sim Em_\rho \qquad (1)$$

At this time the quark is surrounded by a strong (confining) color field which the emitted gluon has to pass through to develop a jet of its own. It is intuitively clear that only high energy gluons (large p^2) can escape these forces and generate a new nonperturbative jet. Low energy gluons (small p^2) are expected to suffer subtantial rescattering effects in this field, preventing new jet formation. At present energies p_{conf}^2 is of the same order of magnitude as our empirically arrived at cut off p_{NP}^2. It is natural to assume that <u>at present energies</u> they are the same. This roughly conforms to the intuitive picture of Bjorken for a nonperturbative jet [12]. Beyond a distance $O(m_\rho^{-1})$ strong vacuum polarization effects pop $q\bar{q}$ pairs out of the vacuum, screening the color charge of the leading (heavy virtual) parton. Its virtual mass fluctuates rapidly, so that it is no longer obviously physically meaningful to distinguish the energy and momentum of the parton from the energy and momentum of the strong color fields which it creates.

The argument leading to (1) makes it clear that the smallness of $\alpha_s(p^2)$ may be a necessary condition to apply perturbation theory to jet formation, but it is not a sufficient condition.[2] The distances involved are not small. This makes our choice of p_{NP}^2 as the operational cut off between a short distance two-parton and one-parton state clearer; p_{NP}^2 is the parton mass where the confining color field becomes so strong that a nonperturbative jet is generated. This applies to present PETRA and PEP energies.

What happens at very large energy, $E \to \infty$? Then the mass of a parton arriving at a lab distance $O(m_\rho^{-1})$ becomes arbitrarily large, $p^2 \sim E$. Confinement effects are soft, and it is difficult to see how such a massive parton can give rise to a <u>single</u> jet. In this case it might still be meaningful to consider further perturbative evolution of a parton of such large virtual mass. That this is indeed so becomes clear when we consider the time scale again. The lab frame lifetime of our partons is $\sim E/p^2$; as p^2 cascades down from E to p_{NP}^2, this can become large. However, color screening can take place on all shorter time scales down to $\sim m_\rho^{-1}$. In other words, vacuum polarization effects can screen the color charge of the heavy parton even if its laboratory range before decay to two hard partons is large.

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[2] Other aspects of a possible impact of nonperturbative effects on short-distance processes have been discussed in [13].

We consider the energy loss ΔE of a massive parton, $p^2 > p_{conf}^2$ to the creation of $q\bar{q}$ pairs. They fill the rapidity range $\sim \log \Delta E/\langle p_\perp \rangle$ with $q\bar{q}$ mesons. This must be equal to the rapidity of the massive parton if its color is to be screened. Here, $\langle p_\perp \rangle$ is the average transverse momentum of the $q\bar{q}$ mesons, $\langle p_\perp \rangle \sim m_\rho$. Now we get the fractional energy loss of the heavy parton,

$$\frac{\Delta E}{E} \sim \frac{m_\rho}{\sqrt{p^2}} \tag{2}$$

[Unfortunately, this argument is only of logairithmic accuracy, so it is hard to be sure of the scale, m_ρ. It could be, e.g., $O(10m_\rho)$.]

From (2) we see that the situation at very high energies is complex. For $E \to \infty$ and parton masses which scale as does p_{conf}^2 (i.e., $\propto E$), we see that $\Delta E/E \to 0$. Such partons evolve perturbatively, but fast vacuum polarization effects create a spray of hadrons of energy ΔE. This spray travels along the original parton's direction even if it has evolved into, e.g., two hard partons which are seen as two jets. The energy of this spray can scale as $Em_\rho/\sqrt{p^2}$. For partons whose masses scale with p_{conf}^2, this is $\Delta E \sim E^{1/2}$. The spray of hadrons coming from the original parton's hadronic fragmentation can _itself_ become a jet. We do not expect that energies will ever be reached where this effect becomes unambiguous. Nevertheless, it might be quite interesting to study jet topologies at e.g. the Z^0 resonance with this in mind. One could look at three-jet events, and then study the particle distribution as two of the jets get closer and closer in invariant mass. There should be a window of masses of the two-jet bundle (just before it disappears into a single jet) where an excess of hadrons will be seen emerging along the direction of the parent parton which gave rise to the two hard jets. This is optimistically sketched in Fig. 1.

To be concrete, our picture of jet formation is the following. At present energies partons with virtual masses $p^2 < p_{NP}^2 \sim 20\text{-}50$ GeV^2 evolve into single nonperturbative jets, with no perturbative evolution below p_{NP}^2. Partons with $p^2 > p_{NP}^2$ evolve perturbatively by decay to hard partons with smaller virtual mass, $q \to qG$, $G \to GG$. These secondary partons with $p^2 < p_{NP}^2$ give rise to nonperturbative jets.

Unfortunately, we have not been able to give a precise and quantitative form to these ideas.[3] So the burden of our arguments is merely that a purely confining jet involving a large mass scale such as $p_{NP}^2 \sim 20\text{-}50$ GeV^2 is not physically implausible. Perhaps the fact that at present energies gluon jets resemble quark jets points in this direction. We do not know. Is there any way of testing the idea of a large confinement jet mass scale? We now turn to this.

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[3] Something very like the effect shown in Fig. 1 may be present in the Lund model [6]. In our picture nonperturbative jets are entirely dynamical, however, without a physical string which is first produced and then fragments.

3. EXPERIMENTAL MATTERS

For our discussions, we have to assume something about a nonperturbative jet with parton $p^2 < p_{NP}^2$. We take it to have an exponentially falling transverse momentum distribution and a distribution in $z = E_{had}/E$ which scales. By comparison, possible power corrections to the $p_\perp$ distributions or small power scaling violations do not seem so important when we go up in energy from Q = 15 GeV to 30 GeV [14]. We implicitly reject the possibility of perturbative (e.g., leading log) evolution inside such a jet. We regard p_{NP}^2 as an unknown parameter which is most likely of order 20-50 GeV^2.

It is now clear that the e^+e^- scaling violations for the hadron spectrum have to be recalculated. They are (apart from remnants of finite $p_\perp$ and mass effects which we neglect in our discussion) due to three-jet events and not leading log parton evolution. Consider the moments of the single particle distribution, $F_n(p_{NP}^2,Q^2)$, where we sum over particle species. Through order g_s^2 we find

$$F_n(p_{NP}^2,Q^2) = 2D^q_n + \frac{\alpha_s(Q^2)}{2\pi}\left[-2D^q_n\, \bar{P}_n{}^q(\epsilon) + D^G_n\, P_n{}^G(\epsilon)\right] \qquad (3)$$

where $D^q{}_n, D^G{}_n$ are moments of quark and gluon fragmentation to purely nonperturbative jets. They are Q^2 independent,

$$D_n = \int_0^1 dz\, z^{n-1}\, D(z) \qquad (4)$$

The moments of quark and gluon distributions are

$$P^G{}_n(\epsilon) = \int_0^1 dx\ x^{n-1}\ P^G(x,\epsilon)$$
$$\bar{P}^q{}_n(\epsilon) = \int_0^1 dx\ [1-x^{n-1}]\ P^q(x,\epsilon) \qquad (5)$$

where $\epsilon = p_{NP}^2/Q^2$ (we cut off all integrals at $1-x = \epsilon$ to get this) and

$$P^G(x,\epsilon) = \frac{8}{3}\ \frac{[1 + (1-x)^2]\ \log(x-\epsilon)/\epsilon + x(2\epsilon-x)}{x}$$
$$P^q(x,\epsilon) = \frac{4}{3}\ \frac{[1+x^2]\ \log x/\epsilon - 2(x-\epsilon) + (x^2-\epsilon^2)/2}{1-x} \qquad (6)$$

Note that we regularized $\bar{P}^q{}_n$ by exploiting the fact that $\sigma(2\text{ jet}) = \sigma(\text{TOT}) - \sigma(3\text{ jet})$ through $O(g_s^2)$. Parenthetically, we might remark that as $Q^2 \to \infty$ we can replace p_{NP}^2 by a purely formal cut off P^2 provided $p_{NP}^2 \ll P^2 \ll Q^2$. Then F_n cannot depend on this formal cut off although the individual quark and gluon fragmentation functions do. (A jet looked at this way is now perturbative in origin, the individual confinement jets being too narrow to resolve.) Differentiating the two sides of (3) with respect to $\log P^2$, we obtain a differential equation which can be used to resum the leading log behavior of (3) as P^2 and $Q^2 \to \infty$. (It is, however, necessary to append a second equation for a gluon source as to get a solution for both D^q and D^G.) This is the limit in which the usual leading log results apply [15].

For a numerical estimate of (4), we set $\alpha_s = 0.16$ and $p_{NP}^2 = 25\ \text{GeV}^2$. Then the n = 3 and n = 5 moments decrease by 10% (23%)

on going from $\sqrt{Q^2}$ = 15 to 30 GeV. In contrast to the leading log result, these scaling violations will be cut off sharply at low energy, because the three-jet rate is near zero there. Similar considerations apply to quark jets in other processes (e.g., leptoproduction) and to gluon jet scaling violations. Following our ideas, however, we still expect signficant scaling violation in gluon jets [16], because the multijet rate is enhanced by the three-gluon vertex. The significance of these results for quark jets may be compromised to some extent by finite mass effects in the case of c and b jets, and remnants of finite $p_\perp$ effects [14]. We hope that it will be possible to check these ideas by measuring scaling violations over a large Q^2 range. (This assumes that a better understanding of c and b fragmentation will be achieved.)

Another possibility presents itself. Since the scaling violations come from three jet events at present energies, we can exploit the event topology. If each event can be divided efficiently into a narrow jet half and a broad jet half such that the narrow jet is from a single parent parton, then we expect all perturbative scaling violations to be in the broad jet half. There will be corrections to this striking asymmetry due to inefficiencies in the procedure and to the small four jet rate (and to finite mass corrections for c and b jets and finite $p_\perp$ corrections). However, a clear observation of large perturbative scale breaking in a single jet would falsify our suggestions. So it may be worthwhile looking for this asymmetry in the scaling violations.

All this will be interesting, but it may not be decisive. Is there a direct way to find the large mass scale p_{NP}^2? We can consider the distribution of jet masses, studied by the PLUTO group [17]. One can plot $\sigma^{-1}\, d\sigma/dM^2$ for the "heavy" jet and the "light" jet. The "heavy" jet distribution is shown in Fig. 2 for the model of Hoyer et al. and different p_{NP}^2 ($\sqrt{Q^2}$ = 30 GeV). An effect is present but it will clearly need high statistics to find it. Many observables have been studied by PETRA and PEP groups, and we recommend examining them for dependences on p_{NP}^2. Unfortunately, one has to use Monte Carlo models in doing this. As compensation, the models can at least be used to study sensitivity to other features of the fragmentation.

One distribution which much attention has been paid to, is the asymmetry in the energy-energy correlation [18],

$$AS(\theta) \;=\; F(\pi-\theta) - F(\theta) \qquad (7)$$

where F is defined as

$$F(\theta) = \sigma_{TOT}^{-1} \int dz_1\, dz_2\, z_1\, z_2\, \frac{d\sigma}{d\cos\theta\, dz_1\, dz_2} \qquad (8)$$

This asymmetry gets a nonvanishing contribution from two-jet events. The shape of this contribution even resembles that due to unfragmented $q\bar{q}G$ events. (Actually, it falls off somewhat faster with θ.) In the model of Hoyer et al. we expect that at small θ, $\theta \lesssim \sqrt{p_{NP}^2/Q^2}$,

$$AS(\theta) \;\approx\; [\sigma(2\ \text{jet})/\sigma_{TOT}]\, AS_{2jet}(\theta) \qquad (9)$$

at larger θ, however,

$$AS(\theta) = AS_{q\bar{q}G}(\theta)\ [1 + \text{finite } p_\perp \text{ etc. corrections}] \qquad (10)$$

This behavior is due to the p^2 cut off in the model. The transition between (9) and (10) depends on p_{NP}^2 and Q^2. This asymmetry has been measured by the PLUTO [19] and CELLO [20] groups at PETRA and MARK II [21] at PEP. In Fig. 3 we show the model expectation as compared with the data by CELLO. The low θ data and the model are near (9). We think that this quantity may enable one to extract p_{NP}^2 once the statistical and systematic errors are small enough. Again, this has to be checked against models of the fragmentation process to see if one can get out p_{NP}^2 independent of other parameters.

Our preceding suggestions suffer from their dependence on fragmentation. The process of hard photon radiation in a quark jet [22]

$$e^+e^- \to \gamma^* \to q\bar{q} \to \gamma + \text{hadrons} \tag{11}$$

is free of this difficulty. The direct photon comes directly from the short and intermediate distance range which interests us. In the leading log approximation there is a direct correspondence between the transverse momentum of the photon relative to the opposite side jet and the virtual mass of the parton which radiated it, $p_\perp \sim \sqrt{p^2}/2$. In Born approximation the $p_\perp$ and fractional momentum distribution ($z = 2E_\gamma/\sqrt{Q^2}$) of the photon from a quark of charge e_q is

$$\left.\frac{1}{\sigma}\,\frac{d\sigma}{dz\,dp_\perp^2}\right|_{\text{Born}} = \frac{\alpha}{\pi}\,e_q^2\,\frac{1+(1-z)^2}{z}\,\frac{1}{p_\perp^2} \tag{12}$$

Gluon radiation will somewhat soften the z spectrum. However, we still expect hard photons out at large z, which will not happen for hadrons. The transverse momentum spectrum should also be less steep at low $p_\perp^2$ than the Born approximation. This modification will be a slowly varying function of $p_\perp^2$. The situation is dramatically different in the region where confinement effects are important. There will be few photons at low $p_\perp^2$ and large z. This is because they are radiated at long times or by small p^2 quarks. We expect this radiation to be like that in the vector meson dominance model - namely, steeply falling in z as for hadrons. We think that direct photon radiation offers the best insight into the space-time dynamics of jet formation and the transition region from the perturbative to the nonperturbative domain of QCD. From a theoretical point of view the best place to do this would be on the Z^0 resonance in e^+e^- annihilation.

4. CONCLUSIONS

In this paper we have argued that a large jet mass as a nonperturbative cut off between one and two (or more) parton states [4] is a real physical effect. There is a large mass scale in QCD jets. We cannot rigorously derive this from QCD. Rather, we offer it as an incitement to experimentalists to study the issue more closely. Can one confirm (or refute) the presence of such a mass scale?

There are larger issues involved. For one, it is important to know from experiment what a nonperturbative calculation of jet properties should set out to do. Perhaps a first problem is to calculate p_{NP}^2. Secondly, the existence of such a cut off from the space-time development has implications for the calculation of higher order radiative corrections. These corrections involve the cancellation of infrared and collinear divergences. These divergences appear for parton $p^2 \to 0$ or for long distance spatial propagation. However, free partons cannot propagate for long distances because of confinement. The divergences which one cancels in a perturbative calculation do not in fact exist in the real physical system. Here also we need more information on confinement, and looking for p_{NP}^2 seems to be one place to start.

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FIGURE CAPTIONS

Fig. 1 (a) $q\bar{q}G$ with two partons having a low invariant mass. (b) The corresponding hadronic final state at very high energies, with an excess of hadrons between the two nearby jets. (c) Rapidity distribution at low and high energy.

Fig. 2 Plot of $d\sigma/dM^2$ for the "heavy" jet in e^+e^-. At large M^2 this is resolved into two jets. At low M^2, $d\sigma/dM^2$ is a fluctuation in a two-jet event. Curves drawn through 5000 Monte Carlo events for two values of p_{NP}^2.

Fig. 3 The energy flow asymmetry $AS(\theta)$. At low θ, this is due principally to hadronization of $q\bar{q}$. At large θ it is due to hadronization of $q\bar{q}G$. The solid line is the model of Hoyer et al. as compared with the data by CELLO [20].

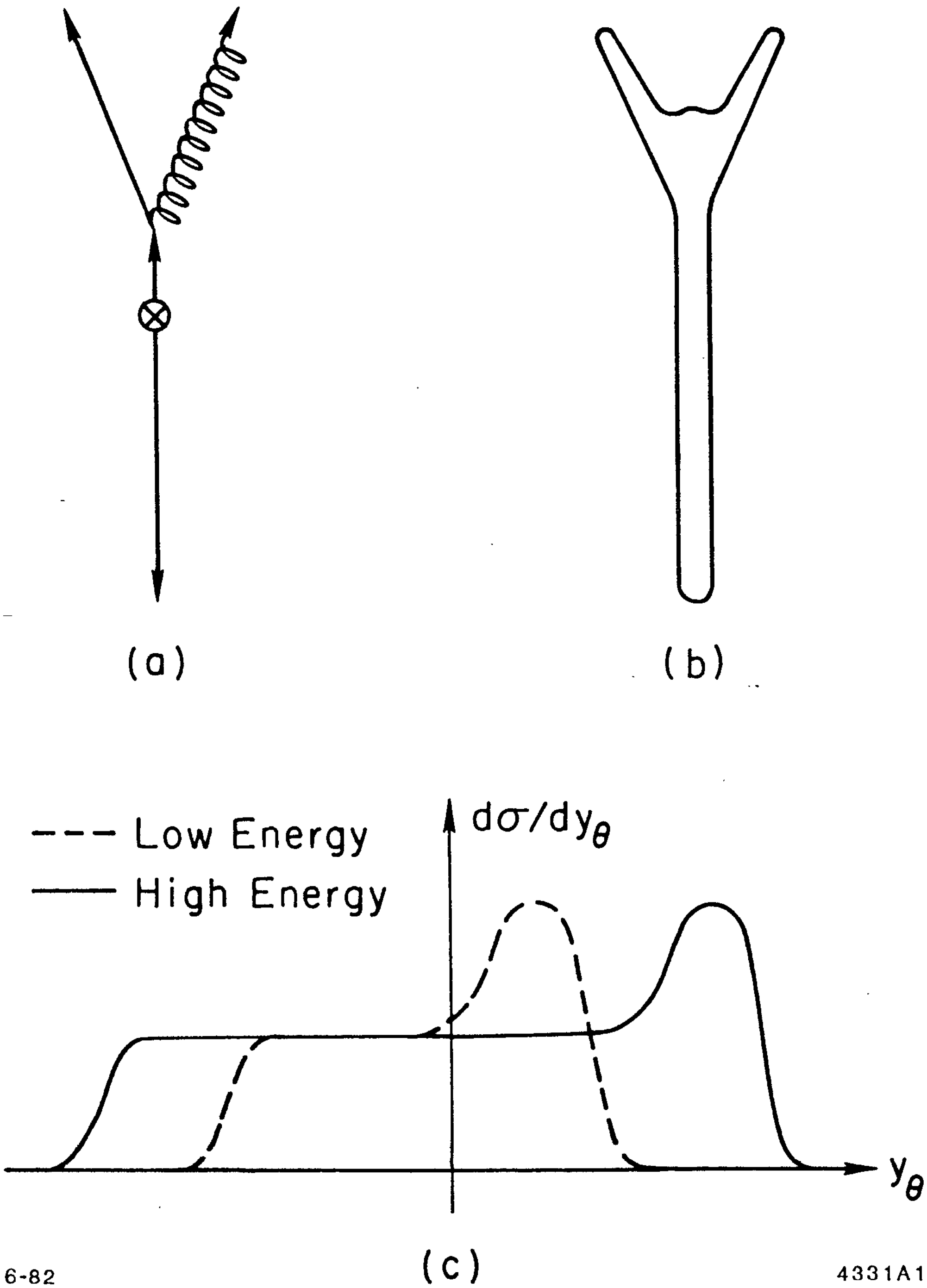

Fig. 1

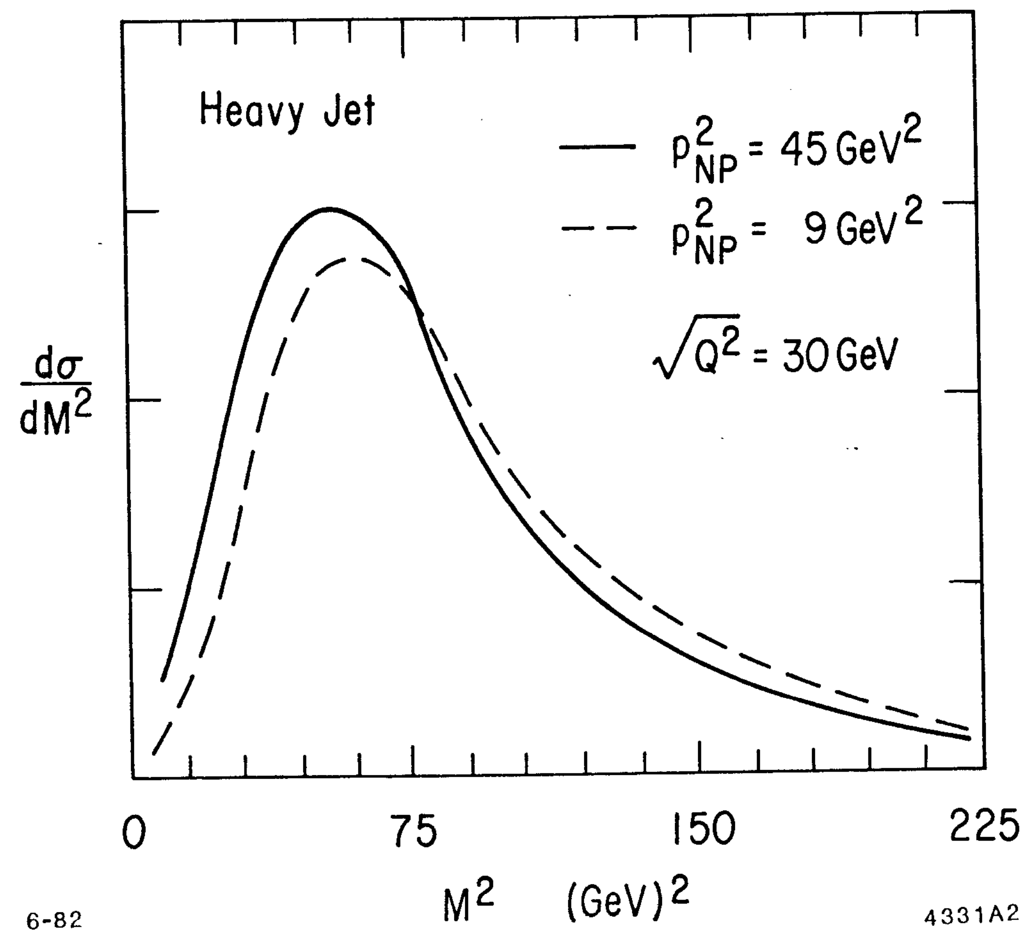
Heavy Jet
$p^2_{NP} = 45\,GeV^2$
$p^2_{NP} = 9\,GeV^2$
$\sqrt{Q^2} = 30\,GeV$
$\frac{d\sigma}{dM^2}$
0
75
150
225
M^2 $(GeV)^2$
6-82
4331A2

Fig. 2

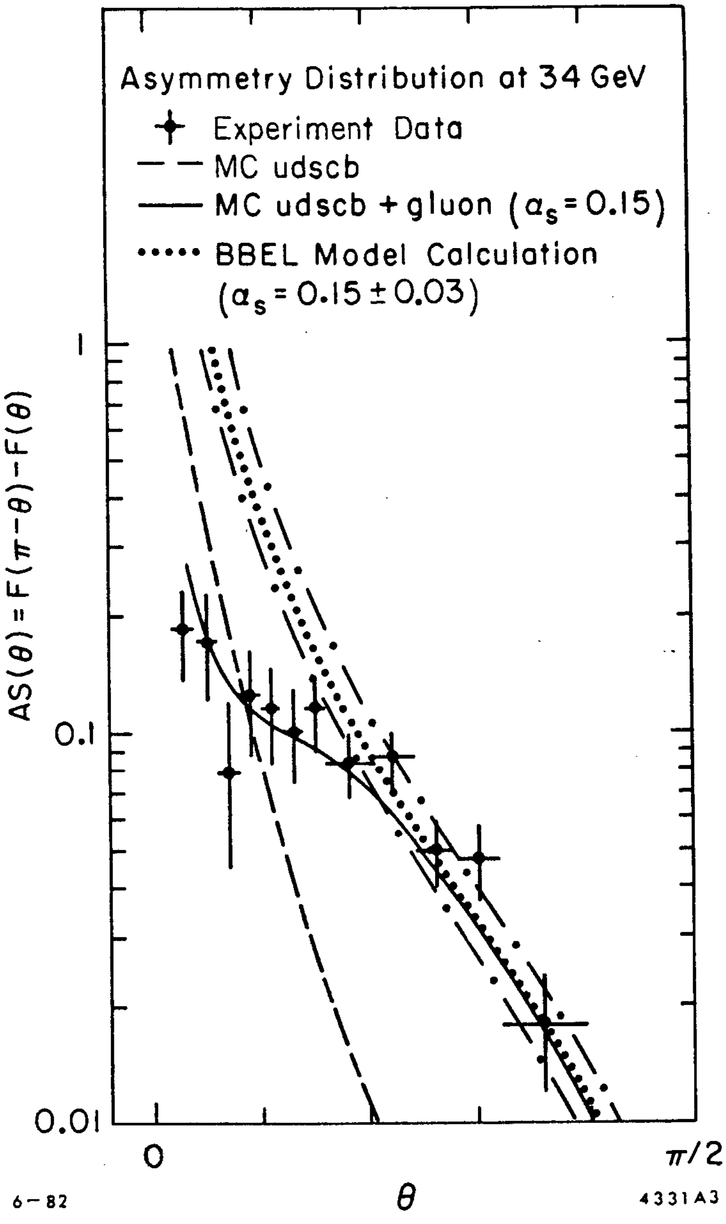
Asymmetry Distribution at 34 GeV
Experiment Data
MC udscb
MC udscb + gluon (α_s = 0.15)
BBEL Model Calculation
(α_s = 0.15 ± 0.03)
AS(θ) = F($\pi-\theta$) − F(θ)
1
0.1
0.01
0
$\pi/2$
θ
6−82
4331A3

Fig. 3