J. Sanford

September 6, 1973

SEARCH FOR DIFFERENCE IN PION/PROTON INTERNAL STRUCTURE

A Letter of Intent

for a Proposal to NAL

W. Selove, L. Kroger, T. Kondo, W. Kononenko, E. M. O'Neill

University of Pennsylvania

A. R. Erwin, E. Harvey, R. Loveless, M. Thompson

University of Wisconsin

Correspondent: W. Selove
215-594-8159
(also FTS direct)

SEARCH FOR DIFFERENCE IN PION/PROTON INTERNAL STRUCTURE

September 6, 1973

CONTENTS:

1. Introduction

2. Partons and Jet Pairs

3. Magnitude of the Asymmetry

4. Multiplicities in Jets

5. Detector Design

6. Counting Rates

7. Beam Requirements

8. Background

9. Summary

SEARCH FOR DIFFERENCE IN PION/PROTON INTERNAL STRUCTURE

INTRODUCTION

Since the development of the quark model, and in view of its many successes, the question has frequently been examined whether one could find evidence, through study of high energy collisions, that the pion is made essentially of two components, $q\bar{q}$, while the proton is made of 3, qqq. With the development of the parton model[1] this question takes on a new aspect, and a new means of searching for evidence on this question appears.

PARTONS AND JET PAIRS

Bjorken and collaborators[2,3] first suggested that parton-parton collisions might produce (transverse) jet pairs at large angles, distinctly separable from jets along the beam direction. These jet pairs, if found, could give direct evidence on parton-parton collisions, and on the internal momentum distribution of partons in hadrons. The parton model of hadron structure suggests the form of this internal momentum distribution[4,5]. In that model the probability for high-momentum components inside the pion is greater than for high-momentum components inside the proton[6]. This is the parton model's expression of the idea that the pion is made of fewer components than the proton.

How would this effect be detectable? If parton-parton collisions produce jet pairs, then the existence of larger high-momentum components in the pion would show itself, in πp collisions, as a forward-backward asymmetry for the total momentum of the pair of jets, in the πp CM system, $(\vec{P}_1+\vec{P}_2)_z$. The expected magnitude of this asymmetry, on the BBK model[2], is very large. On the BBG model[7,8] (which seems to be in better agreement with large-p_t π^0 data of the CCR group[9]) it appears that the asymmetry would be even larger. This asymmetry would be a very striking effect. Observation of such an asymmetry, or its absence, could give strong evidence on the validity of the parton model of hadron structure--i.e., on the meaningfulness of a picture of hadrons as objects containing point-like components.

We emphasize several points in connection with the idea of searching for jet pairs and for a forward-backward asymmetry.

(1) The idea of an asymmetry does not rest on the notion that multi-particle (transverse) jets must occur. In fact, questions of great interest are: what are the multiplicity distributions in the high-p_T groups, what are the correlations in those distributions in a pair of jets, and how do these distributions vary when one collides with different kinds of particles. (We remark, as an aside, that evidence already exists indicating that some clustering does occur in high-p_T events; moreover, some clustering must occur, if only from production of resonances of high p_T.)

(2) In the experiment which we shall propose, one can hope to study two aspects of hadron structure and interactions which can be studied only in hadron-hadron collisions and which are inaccessible via neutrino or electromagnetic interactions: (a) the internal structure of the pion, as probed by deep inelastic processes, compared to that of the proton, (b) interactions of possible components of hadrons.

(3) If partons exist, and if parton-parton collisions produce jet pairs, then major differences in types of partons and in their fragmentation properties may exist. Such differences for example are suggested by the BBG model. It is important for the equipment to be able to detect such possible differences.

MAGNITUDE OF THE ASYMMETRY IN $(P_1+P_2)_z$

In the Feynman-Bjorken parton model, the internal momentum distribution of the hadron is described by the function

$$\frac{dN}{dx} \equiv f(x) \equiv \frac{1}{x}\, g(x),$$

where f(x) and g(x), in the notation of Feynman[4] and of Bjorken et al[2] respectively, describe the parton fractional momentum distribution. At large

x, the behavior of g(x) is related to the elastic form factor of the hadron, according to the arguments of Drell and Yan,[10] Feynman,[4] and Bjorken and Kogut[5]. We take their result, that for $x \to 1$ one has $g_p(x) \sim (1-x)^3$ for the proton and $g_\pi(x) \sim (1-x)$ for the pion. Then the forward-backward asymmetry, for parton jets made in πp collisions, comes from the fact that for large x the function g_π falls more slowly than g_p. As an example, for collisions with $x_1 \approx x_2 \approx \frac{2}{3}$, one finds the intensity ratio for jet pairs at 80° to that at 100° to be approximately and ideally

$$\frac{I(80°)}{I(100°)} = \frac{g_\pi\left(x_1 \approx \frac{2}{3}\left[1 + .174\right]\right) g_p\left(x_2 \approx \frac{2}{3}\left[1 - .174\right]\right)}{g_\pi\left(x_1 \approx \frac{2}{3}\left[1 - .174\right]\right) g_p\left(x_2 \approx \frac{2}{3}\left[1 + .174\right]\right)}$$

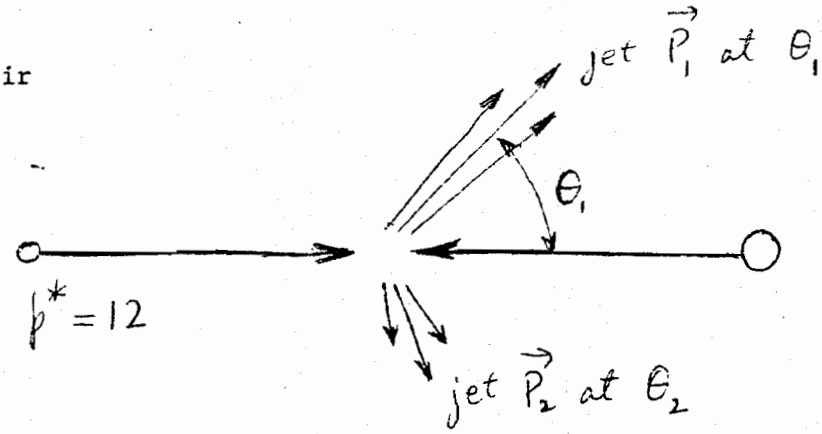
$$= \frac{g_\pi(.78)\ g_p(.55)}{g_\pi(.55)\ g_p(.78)} \approx 4.$$

To describe this result graphically, we consider πp collisions at 300 GeV. The above result can then be represented by the following diagram:

$P_{lab}(\pi) = 300$ GeV

$p^* \approx 12$ GeV

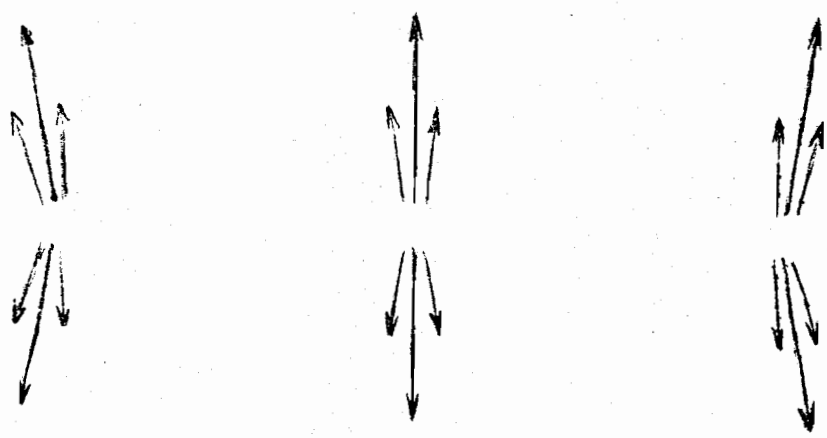
a) General jet pair



b) jets with $\theta_1=\theta_2=\theta$,

and $P_1=P_2=P$, ≈ 8 GeV $\left(\text{i.e., } \frac{x_1 + x_2}{2} = \frac{2}{3}\right)$

$\theta = 100^\circ$ $\theta = 90^\circ$ $\theta = 80^\circ$



relative intensity: 1 2 4

Bjorken has calculated the jet-jet angular correlation for a number of cases[11]. In general, the correlation function involves the parton-parton scattering cross-section $\frac{d\sigma}{dt'}(s',t')$[12]; but for the case that we discuss s' and t' are constant and our result above can be read directly from Bjorken's calculation.

We have not addressed, above, the question of a possible difference in types of partons, nor in parton scattering cross sections, and in g(x), for different parton species. In the parton-interchange model of BBG, one can expect substantial effects of this kind, with possibly even greater asymmetries than occur in the above simplified calculation[8].

Our estimate above represents an idealized calculation, which assumes that one can determine the direction and energy of a jet. In fact, these quantities have an intrinsic uncertainty, because low-energy members of a jet cannot be unambiguously associated with the jet.[13,11]. These uncertainties give in effect an angular resolution smearing. As a result, the forward-backward asymmetry will be reduced. For the example given above, with jets of 8 GeV, the reduction is not a major one. For lower energy jets, however, and even more for lower "x" ($\approx P_{jet}/p^*_{beam}$), the asymmetry to be expected becomes rapidly smaller. To observe a large effect it is therefore necessary to measure jets of high x and large jet energy.

MULTIPLICITIES IN JETS

As remarked above, the idea of a forward-backward asymmetry in jet pairs does not rest on any assumption that high-p_T events occur generally with the total p_T carried by a cluster of particles. However, the question of the mutiplicity distribution in jets is also a highly interesting question. On the BBK model, one can expect to have many more jets of high total p_T than single particles of the same p_T. To make a specific estimate, one must take some model for the fragmentation of scattered partons.

Using a model suggested by Bjorken[11], the intensity of jets of a given p_T might be expected to be higher than the intensity of singles of that p_T by a factor $\frac{3}{2}(n-1)(n-2)$, where n is the (local) power with which the invariant single-particle cross section falls with p_T. From CCR data[9] for pp collisions at equivalent energy 300 GeV, one finds $n \sim 12$ to 15, for $p_T \sim 4$ GeV/c at 90°. This gives $\frac{dN}{dp_T}$(jets) $\sim$ 200 times as large as $\frac{dN}{dp_T}(\pi^o)$, at $\sim$ 4 GeV/c.

If multiparticle jets were found this much more frequently than single π's, it would be spectacular indeed, and would probably constitute very strong support for a parton mechanism of high p_T events. However, there are at least two considerations which prevent the observation of an effect as large as indicated above. One is that the low energy members of a jet can never be unambiguously associated with the jet[13,11]. That gives the result that a jet of "true" energy 4 GeV, say, will <u>appear</u> to be a jet of 2 to 3 GeV. The intensity suggested above will therefore be lost in the far higher <u>single</u>-π intensity at 2 or 3 GeV--at 2 GeV the single π intensity is $\sim$ 1000 times as great as at 4 GeV. Secondly, a jet of 4 GeV "true" energy which appears as say 2.5 GeV observed energy is not a very tightly clustered jet, nor is it likely to have very high observed multiplicity. If one uses for a model the suggestion by Feynman[4] and Bjorken[3] that a parton jet may be expected to fragment with the same kind of rapidity plateau as is observed in beam-direction jets, one finds that the 4 GeV ("true") jet we are discussing is likely to appear as follows: one particle of $\sim$ 1.5 GeV, a second of $\sim$ 1.0 GeV, at an angle of $\sim \frac{1}{2}$ radian from the first, and $\sim$ 1.5 GeV in three more particles which can not be associated with the jet because they are at very distant angles, have quite low p_T with respect to the <u>beam</u> direction, and look just like the other 5 to 10 particles that can come from beam jets in this event.

Thus multi-particle jets of true energy 4 GeV will probably be almost impossible to observe clearly; and it will be equally impossible to measure the intensity of such jets in a meaningful way. One finds that when the total energy of the jet increases, it becomes rapidly very much easier to observe the jet as a cluster; and the estimate of the intensity of jets of a given observed total p_T also leads to a rather sharply increasing ratio of jets to singles. We can therefore hope to get important information on the ratio of (multi-particle) jets to singles, at sufficiently high jet momentum.

In order to be able to observe in a meaningful way the ratio of jets to singles, it is not only important to detect jets of higher energy, but it is equally important to have a sufficiently large angular acceptance. This is necessary because one wishes (a) to contain as large as possible a fraction of the true jet energy, and (b) to be able to see the jet as standing distinctly separated from the general distribution of other, low p_T , particles in a given event. Estimates of the kind indicated above, if applied to a jet of observed energy 6 GeV in a cone of half-angle 30° or 45°, respectively, indicate that at 300 GeV in pp collisions one might expect to observe 10 or 50 times as many jets as single π^o's.

Whatever the true intensity ratio will prove to be, it is clear that it is likely to be of high importance (1) to be able to measure jets of the highest possible energy--i.e., to build a detecting system which can detect (and can trigger on) the smallest possible cross section, and (2) to be able to measure the intensity of jets as a function of p_T, and to be able to compare it with the intensity for singles. The second requirement also calls for very high sensitivity; and the requirement of measuring $\frac{dN}{dp}$ (jet) dictates a calorimeter as the basic detector element.

It is important to note that the multiplicity distribution in jets--or more generally, the multiplicity distribution in high-p_T clusters--is likely also to be a very powerful tool in elucidating the mechanism of high p_T processes. For example, in the parton interchange model of BBG one might expect that collisions of different kinds of partons might produce strikingly different multiplicity distributions, and different multiplicity correlations (i.e., between two jets). We remark that in the BBG model the internal momentum distribution of partons in pions and in protons, and the fragmentation properties of different kinds of partons emerging in πp and pp collisions, may be very different, more different even than in the BBK model. In any event, to investigate the possible presence of different components in high-p_T events, and to look for the expected high ratio of jet intensity to singles intensity, it is very important to have, in a single apparatus, the ability to see and distinguish high p_T events of various multiplicities, including low multiplicity jets and singles.

DETECTOR DESIGN

For the objectives we have discussed, it is clear that the principal detector system must be a calorimeter array or hodoscope. Most of this section deals with the properties of such a calorimeter hodoscope. An auxiliary charged particle detector is also needed, and we comment on it at the end of this section.

(a) Calorimeter detection compared to magnetic analysis. An essential part of the study we propose is the measurement of the cross-section for jets of a given p_T, independent of the multiplicity within the jet, and independent of whether the members of the jet are charged or neutral. A magnetic analysis system without a calorimeter cannot accomplish these purposes.

(b) Jet energies and composition. Above, we gave an example of a "jet structure" for a jet of 4 GeV (true) in the CM. The internal transverse momentum in a jet is taken to be $\sim \frac{1}{3}$ GeV/c. If the internal longitudinal momentum distribution corresponds to a flat rapidity plateau, as suggested by Feynman and Bjorken, then transverse jets will look similar to beam jets. This picture leads, as in the example above, to a jet of CM momentum 4 to 8 GeV/c as having 2 to 4 fast particles and 3 or so slow particles (which can not be associated with the jet).

We note that existing data indicate that to at least some extent high-p_T events show some clustering--jet-like--character. Data of the CCR and PSB groups show an increasing clustering effect (associated multiplicity in a $\Delta\Omega$ of ½ sr or so) with increasing p_T. Such an effect is in qualitative agreement with the model suggested above. We note also that high-p_T resonances will have a similar appearance--i.e., a cluster of 2 or more particles each with high p_T and having an angular spread which decreases with increasing total jet momentum.

We expect to concentrate our initial attention on jets (or single particles) of CM momentum 4 to 8 GeV, at angles of about 70° to 110°. Such a jet, as seen in the laboratory for a beam energy of 300 GeV, will have a total energy of about 40 to 100 GeV. An individual 60 GeV jet might consist of 3 particles, with energies of 30, 20, and 10 GeV, with angle separation of about 0.2 rad CM and 10 to 20 mr lab.

We wish to be able to detect two such jets, to obtain information on the energy of each member of the jet, to see that each member has "unusually high" p_T, and to see if the jet stands alone, with momentum vectors clearly distinct from other particles produced in the same event. This requires a calorimeter hodoscope.

(c) Calorimeter hodoscope. The calorimeter hodoscope should have individual elements of the desired angular resolution, and should cover a large enough total solid angle to (a) contain the jet, (b) see whether the jet is a group of particles distinctly separated in momentum space from other particles. This requires a solid angle of about 1 steradian CM[13], subdivided into perhaps 20 separate elements in angle. The physical size of each element will be approximately the diameter of a cascade shower (~ 8" to 16" depending on the inner construction), and the calorimeter will be located at such a distance as to give the desired angular resolution per element. These considerations indicate a calorimeter with elements of area from ~ 8" square to 16" square, with some 20 to 30 such elements located about 20 meters from the target.

(d) Energy resolution. We consider a calorimeter made of steel plates, and scintillator. For particle energies of 10 to 30 GeV, published work[14] indicates resolution of ±20 or 25% to ±10% or so is obtainable for protons in this energy range. We have constructed and tested a calorimeter (steel and liquid scintillator) designed to work in this energy range and below. We find (a) we can readily get resolution of about ±25% down to a few GeV, and (b) the resolution at higher energies in this range is broader for π's than for protons. The physical mechanism which produces the broader resolution appears to be fluctuations in the fraction of the energy going into π^o's[13] in the course of the cascade. From calculations by T. A. Gabriel and R. G. Alsmiller[15] it appears that the resolution can accordingly be improved by simultaneous measurement of a Cerenkov pulse height signal from the cascade, together with a scintillator signal, as suggested by Brody.[16]

One can thus expect that for a 60 GeV jet one can obtain resolution of about ±10%. This resolution is adequate to work with the single-π^o spectrum

at 90° CM, as measured by the Columbia-CERN-Rockefeller group[9]. That is, the "effective" energy of a π^{o}, or a group of particles, measured at 60 GeV lab and about 6 GeV CM, with a momentum spectrum extrapolated slightly from the 4.5 GeV/c or so measured by CCR, would be about 10% less than 6 GeV--so the spectrum unfolding problem would not be a serious one. We remark that for jets the momentum spectrum can be expected to be less steep than for singles, so that the resolution problem is even less troublesome.

The front part of the calorimeter would be built of lead, and scintillator, to give preferential detection of π^{o}'s. This is necessary because the signal size for π^{o}'s of a given energy is substantially higher than for non-e-m showers of that energy (50% higher, for 10 GeV or so). This construction also permits obtaining information on the number of non-π^{o} neutrals (K_L^{o} and neutrons) compared to the number of π^{o}'s.

(e) Time resolution. As we have emphasized, we wish to measure very high p_T events, and this requires very high sensitivity. We wish therefore to run at very high "luminosity", with the highest possible event rate. One ultimate limitation will be the detector resolving time. Accordingly, we wish to make the resolving time as short as possible. We expect to have a resolving time in the calorimeter of 10 to 20 nanoseconds, using liquid scintillator. We wish to have a comparable resolving time in the auxiliary charged particle detector.

(f) Charged particle detector. To obtain a short resolving time, we plan to use a scintillator hodoscope. To observe events with a typical multiplicity of perhaps 10 to 20, to cover essentially all solid angle up to about 150° CM, and to obtain a more accurate measurement of the angles of particles entering the calorimeter, we plan to build a scintillator hodoscope with 300 to 600 elements of solid angle.

COUNTING RATES

One of our principal objectives is the measurement of the jet intensity compared to the intensity of single π's. Another is the measurement of correlated multiplicities. Both of these require that we be sensitive to single particle cross sections, at very high p_T. We propose to use such a combination of beam flux and target length as to give an interaction rate close to the saturation rate for our detector. Thus we would like an interaction rate of some 20 to 40 MHz instantaneous. Assuming an effective duty angle of 30% (a year or so from now), this gives a rate of 10 MHz average, or $\sim 3 \times 10^{10}$ interactions per hour.

To what p_T will this permit us to go? The CCR data give for π^o's near 90° made in pp collisions a cross section:

$$\frac{d\sigma}{d^3p/E}(\pi^o) \approx \frac{1.5 \times 10^{-26}}{p_T^{8.24}} e^{-26\, p_T/\sqrt{s}}$$

which fits data near 90° over a wide range of p_T and s. At 300 GeV equivalent their last data point, at $p_T = 4.6$ GeV, gives a measurement in reasonable agreement with this expression, which gives $4.5 \times 10^{-34} \frac{cm^2}{GeV^2 sr}$. The CCR data would indicate an integrated cross section, above 4.6 GeV, of $\sim 7 \times 10^{-34}\ \Delta\Omega\ cm^2$. For $\Delta\Omega$ of $\sim \frac{1}{2}$ sr, we have finally $3.5\ 10^{-34}\ cm^2$ $\left[\sigma\ (\pi^o)\right.$, at 90°, above 4.6 GeV, into $\left.\frac{1}{2}\ sr\right]$. This is about 10^{-8} of the total pp cross section--so one would get about 300 single π^o/hr, above 4.6 GeV, with the interaction rate described above. One could thus go to much higher p_T. It is indeed important to do so. The discussion of the asymmetry, above, indicates an asymmetry of about 4:1 for jets (or singles) of 8 GeV each; for 6 GeV a similar calculation gives only 2:1--and even that is smeared by the unseen members of a jet. We do not

attempt to extrapolate rates to 6 GeV, much less to 8. Nevertheless, it is clear from this discussion that we need an interaction rate near 30 MHz instantaneous, and not 1 MHz.

We remark here that on the parton model higher rates for high p_T events are to be expected for the πp collisions than for pp; but we have given as examples only rates for the pp case, which can be estimated with little uncertainty from known cross sections.

BEAM REQUIREMENTS

For 30 MHz interaction rate we need a beam flux of 100 to 300 MHz or more. In fact, as we discuss in the next section, one can not use a very long target, and consequently we need a beam flux at the upper end of this range. We would like to obtain a beam of $\sim 10^9$ particles per burst.

The beam energy must be as high as possible. Only if the jet energy is high enough will the jets we expect to see look like jets, be analyzable in a simple way, and give a relatively uncomplicated interpretation in terms of the "true" energy spectrum of jets. We estimate that with a beam of 10^9 protons at 300 GeV, we will be able to see single π^0's up to about 6 GeV, and jets up to perhaps 7 GeV observed ($\sim$ 8 GeV true), at a few events per hour. If the beam is appreciably lower in energy or in intensity, we will not be able to go this high in p_T, and the problem of detecting the asymmetry we search for, and of determining the properties of jets in general, will become much more difficult.

Except for energy and intensity, beam requirements are not particularly severe. We do also need protons available at high intensity, for comparison. But otherwise the momentum spread, and the size and emittance of the beam, are not critical. A momentum spread of ±5% would be quite satisfactory, as is an angular divergence even as large as a few mrad.

BACKGROUND

The most severe background we anticipate is that coming from secondary scattering in the target or nearby downstream material. A rough calculation shows that for a target of say 10% interaction length (i.e., a target length of ~ 60 cm) about 20% of the high p_T events observed in the calorimeter (with particles of 1 to 4 GeV/c p_T) would come from double scattering rather than single beam-interactions. This is a large number, and would very much confuse the interpretation of multiplicity distributions in high p_T events. We therefore propose to use a target length of about 5% (~ 30 cm), and perhaps run part of the time with a longer target, to see if we can detect the effect of these secondary scatterings. In any event, this effect limits the target length we feel is acceptable, and leads us to request a beam flux of 10^9.

SUMMARY

We propose to study "jet pairs", pairs of high-p_T clusters (or single particles), in πp and pp collisions. Prime objectives are

(1) to look for an asymmetry in the production of forward pairs compared to backward pairs, which would indicate a greater probability of high momentum components in the pion than in the proton;

(2) to measure the ratio of event rates with jets of a given p_T compared to single particles of the same p_T; a large ratio would probably represent support for a parton model;

(3) to study the distribution of multiplicities in jets, and correlations in these multiplicities for jet pairs; these distributions and correlations might show structure indicating a multiple component mechanism for high-p_T events.

In addition, we expect to obtain information on the internal constitution in jets (the internal longitudinal and transverse momentum distribution), and

on the angular distribution of jets and of possible parton-parton scattering.

The asymmetry effect is estimated to be a very large one, on the parton model. Using the Berman, Bjorken and Kogut model, with partons scattering via gluon exchange and with differences from different parton species neglected, the cross section for jet pairs 10° forward of 90°, in πp collisions, is estimated to be 4 times larger than for jet pairs 10° backward of 90°, for jets of 6-7 GeV observed (300 GeV π beam). On the parton interchange model, of Blankenbecler, Brodsky and Gunion, different parton species may give quite different results, and it appears that the asymmetry would be even larger. An asymmetry of the magnitude predicted by these models would be a very striking effect; it seems likely that it would be strongly suggestive of a model of hadron structure with point-like components, and with fewer such components in the pion than in the proton.

To see this asymmetry (or lack of it!) clearly, and to study the other matters listed, a pair of calorimeter hodoscopes, of the best time resolution, is required, and a beam of the highest possible energy (300 GeV) and very high flux (10^9 pions per burst). The considerations leading to these conclusions, and other details, are given in the preceding sections.

REFERENCES AND FOOTNOTES

1. R. P. Feynman, Phys. Rev. Letters 23, 1415 (1969).
2. Berman, Bjorken and Kogut, Phys. Rev. D4, 3388 (1971).
3. J. Bjorken, Proceedings of the 1971 Electron-Photon Conferences, Cornell University, 1972.
4. R. P. Feynman, Photon-Hadron Interactions, W. A. Benjamin, Inc. 1972.
5. Bjorken and Kogut, Phys. Rev. D8, 1341, (1973).
6. The parton momentum distribution function, g(x), is greater for the pion than for the proton, for x near 1, because of the connection between g(x) and the elastic form factor. See references 4, 5, and 10.
7. Blankenbecler, Brodsky and Gunion, Physics Letters 42B, 461 (1972).
8. S. Brodsky, private communication.
9. F. W. Büsser et al (CERN-Columbia-Rockefeller Collaboration(, submitted to Physics Letters, August 1973.
10. Drell and Yan, Phys. Rev. Letters 24, 181 (1970).
11. J. Bjorken, private communication, and forthcoming SLAC report.
12. s' and t' describe the parton pair.
13. W. Selove, Notes on Calorimeters for High-p_T Events at ISR, CERN, NP Internal Report 72-25, 1972.
14. J. Engler et al, Nuc. Instr. and Methods 106, 189 (1973).
15. T. Gabriel and R. G. Alsmiller, private communication.
16. H. Brody, private communication.