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SCIENTIFIC SPOKESMAN:
W. Selove
Physics Department
University of Pennsylvania
Philadelphia, Pa. 19174

FTS/COMMERCIAL:
215-594-8159

SEARCH FOR DIFFERENCE IN PION/PROTON INTERNAL STRUCTURE

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

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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 three, 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.

In the parton model, the pion has a higher probability of having high momentum internal components (i.e., with a large value of the fractional momentum, x) than does the proton. This effect, somewhat analogous to the effect that would result from a 2-quark versus 3-quark structure, would cause the products of a parton-parton collision, from a πp initial state, to carry forward along the π's direction. There would thus exist a forward-backward asymmetry, in the overall πp CM system, for the products of a parton-parton collision. We estimate this asymmetry to be quite large in high-p_T events, which may be dominated by parton-parton collisions; no such strong asymmetry is necessarily to be expected in low-p_T events.

We propose to look for such an asymmetry. It seems likely that its presence, or absence, will constitute important evidence on the validity of the parton model, and could accordingly give important information on the structure of hadrons. Aside from any detailed model of parton distributions and interactions, moreover, the observation of such an asymmetry would constitute direct evidence of a difference in internal structure of the pion and proton.

The form of detector best suited to this study is a calorimeter hodoscope. To study the asymmetry, a pair of calorimeter detectors, on the two sides of the beam, is necessary. To obtain important additional information on the structure and multiplicity of high-p_T clusters, the calorimeters should be hodoscoped more finely than would be required for study of the asymmetry alone. The angular resolution and energy resolution required, the sensitivity required, the beam intensity and target length needed, and other details are described below. For sufficiently sensitive conditions, we estimate that a large asymmetry is expected.

In addition to information on an asymmetry, the detector we propose would be able to give information on many other features of high-p_T events, including the important ratio of event rates with jets of a given p_T compared to single particles of the same p_T, the distribution of multiplicities in jets and correlations in these multiplicities for jet pairs, much additional information on internal jet structure and on jet angular distributions, and some information on particle species in jets. We emphasize, in all this, that the basic asymmetry expected is not in any way dependent on whether multi-particle jets occur or not. Moreover, the asymmetry would occur regardless of the behavior of the parton-parton scattering cross section as a function of s' and t', the parton-pair energy and momentum-transfer variables.

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^o 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 <u>multi</u>-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 different kinds of particles. (We remark, as an aside, that evidence already exists indicating that some clustering <u>does</u> occur in high-p_T events; moreover, some clustering <u>must</u> occur, if only from production of resonances of high p_T.)

(2) In the experiment which we 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 $(\vec{P}_1+\vec{P}_2)_z$

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

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

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

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

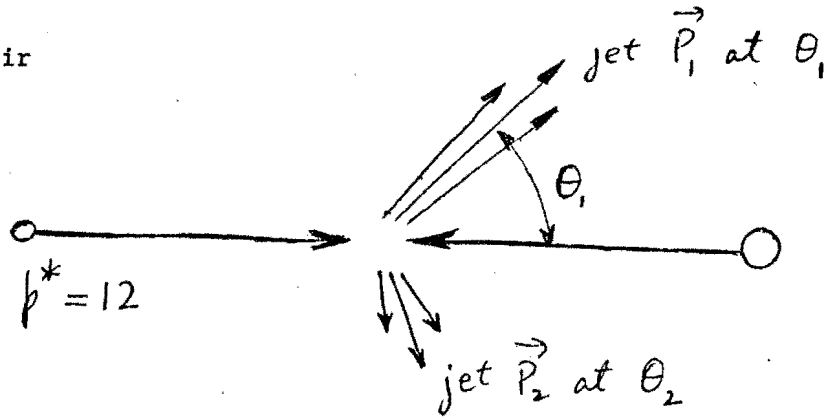
$$= \frac{g_\pi(.78)g_p(.55)}{g_\pi(.55)g_p(.78)} \approx 4 \ .$$

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

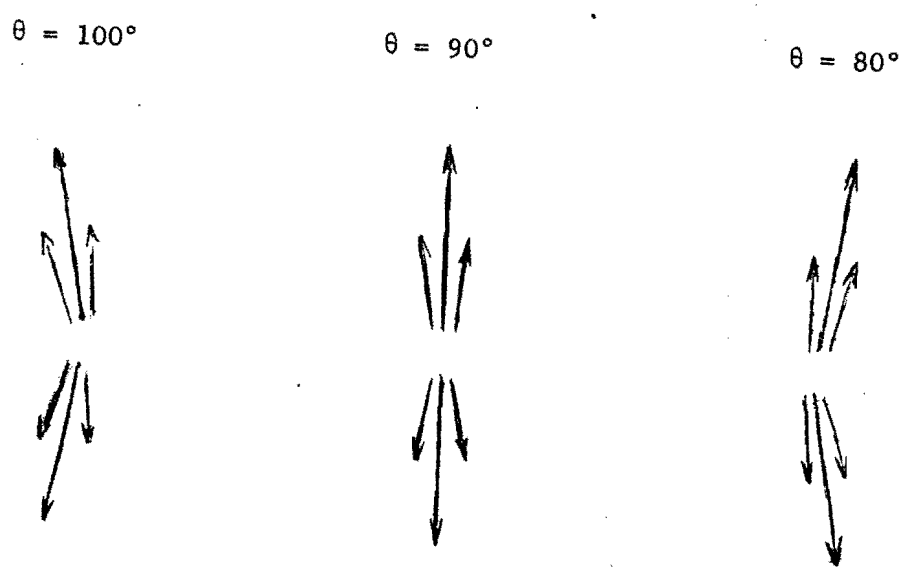
$p^* \approx 12$ GeV

a) General jet pair



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

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



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 single π^o's of that p_T by a factor $\approx \frac{3}{2}(n-1)(n-2)$, 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 multi-particle jets were found this much more frequently than single π^o'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 resoltuion, 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 appears to be somewhat broader for charged π's than for protons. (For π^o's the resolution is considerably narrower than for other particles.) 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.

(g) Detector layout. A schematic representation of a detector layout incorporating the above principles is shown in Figure 1.

COUNTING RATES

Our principal objectives require the highest possible sensitivity. (1) We wish to measure coincidences, and correlated multiplicities, between a pair of high-p_T clusters or particles. (2) We wish to measure the intensity of jets compared to singles. Both of these objectives 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 cycle 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.

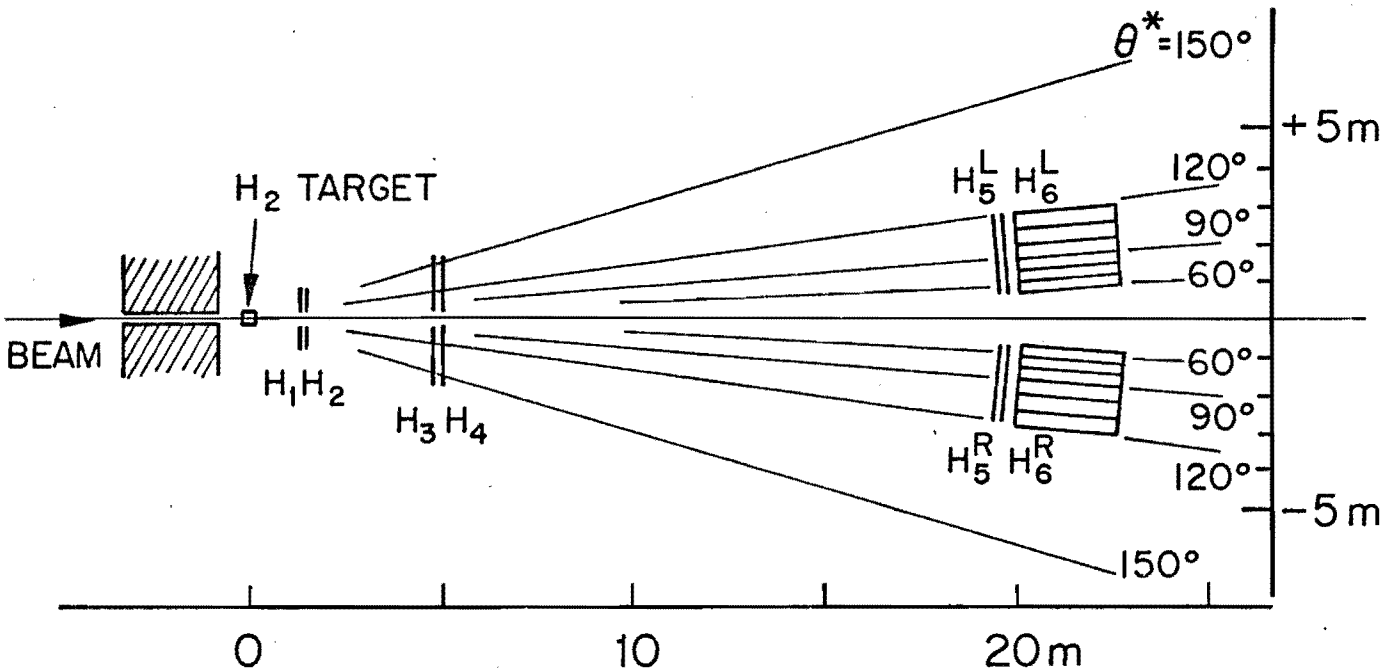
To what p_T will this permit us to go? We first discuss the answer in the case of pp collisions, and single π^o's. On the parton model, the rate for jets of a given p_T will be much higher; and on the parton model, the rate for πp collisions with very large p_T will be higher than for pp.

(a) Singles rates, pp collisions. For π^o's near 90°, made in pp collisions, the CCR data give a cross section:

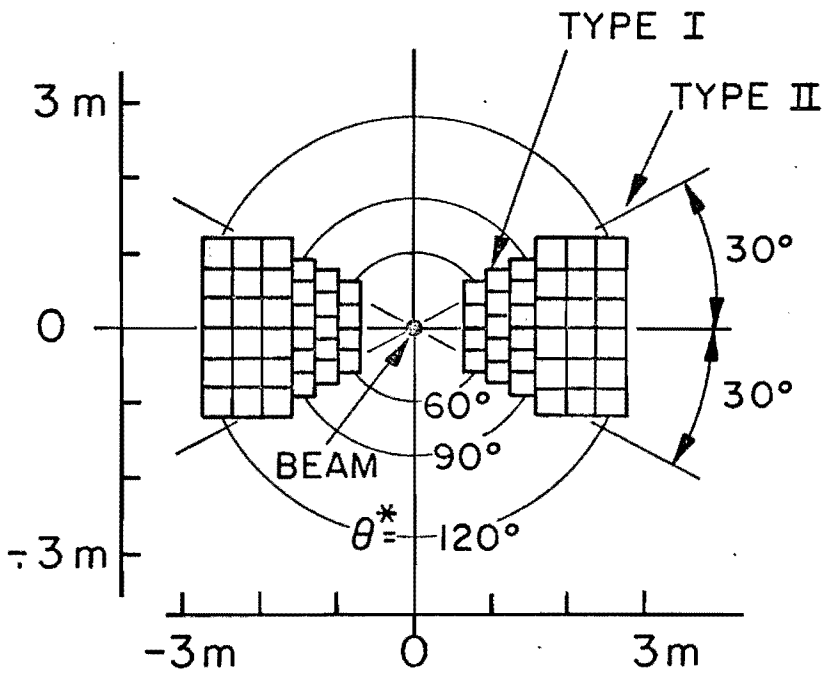
$$\frac{d\sigma}{d^3p/E}(\pi^o) \approx \frac{1.5 \times 10^{-26}}{p_T^{8.24}} \; e^{-26p_T/\sqrt{s}} \; \frac{cm^2}{GeV^2\ sr}$$

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

FIG. 1 SCHEMATIC LAYOUT OF THE EXPERIMENT



BEAM VIEW AT 20m DOWNSTREAM



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 (roughly the fiducial area of our proposed detector on each side of the beam), we have finally $3.5 \times 10^{-34}\ cm^2$ [$\sigma(\pi^o)$, at 90°, above 4.6 GeV, into $\frac{1}{2}$ sr]. 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. Thus one would still get very usable singles rates at $p_T(\pi^o)$ well above 4.6 GeV. It is indeed important to go to higher p_T. 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. These asymmetry values would be reduced slightly by angular smearing due to the unseen members of a jet.

An estimate indicates it is unlikely that we can get to 8 GeV for single π^o's in this proposed experiment. 6 GeV however does seem possible. For 6 GeV an extrapolation of the above cross section gives a rate, into $\frac{1}{2}$ sr, about 30 times less than for 4.6 GeV, or about 10 events per hour. It can be expected that π^+ and π^- will add about twice the π^o intensity, so we conclude that a reasonable estimate for single π's above 6 GeV p_T in our proposed detector (one side of the beam) with the proposed interaction rate is $\sim$ 30 π's per hour, in pp collisions. What <u>coincidence</u> rate can then be expected, for events showing high p_T simultaneously in our detectors on both sides of the beam?

The answer to this question is of course severely model dependent. What we wish to see is whether on a reasonable parton model, with as few assumptions as possible, we can expect a respectable counting rate, and a measurable asymmetry. If so then the presence or absence of such an asymmetry will probably give useful evidence on the validity of a parton model.

(b) Coincidence rates, single-π "trigger", pp collisions. We have estimated above that 6 GeV single π's will occur, as one-sided high-p_T events, at a rate of the order of 30 per hour. (4.6 GeV π's, similarly, would come at about 1000 per hour.) We now ask for the probability, on a parton-parton scattering model, that if one such π is seen on one side that the other "jet" (which could be a single particle, or a multi-particle cluster) go into our detector. For purposes of measuring the asymmetry we have discussed, we are interested in the probability that the second jet be directed at some angle within an interval of about 10° (and also in the probability that if the first jet is at say 80° then the second is between about 60° and 120°).

This angular correlation question has been discussed by Bjorken,[11] and by Ellis and Kislinger.[17] We show below in Figure 2 the results of a calculation using their formulation. In this calculation we have neglected the t'-dependence (and s'-dependence) of the fundamental parton-parton scattering cross section $\frac{d\sigma}{dt'}(s',t')$. As explained above, the asymmetry on which we are seeking evidence does not depend on the s',t' dependence of $\frac{d\sigma}{dt'}$; the detailed curves below would be modified by such a dependence but the ratio of cross sections $\frac{d\sigma}{d\Omega_1 d\Omega_2}(\theta_1=80°, \theta_2=80°)$ to $\frac{d\sigma}{d\Omega_1 d\Omega_2}(\theta_1=100°, \theta_2=100°)$ would not be modified.

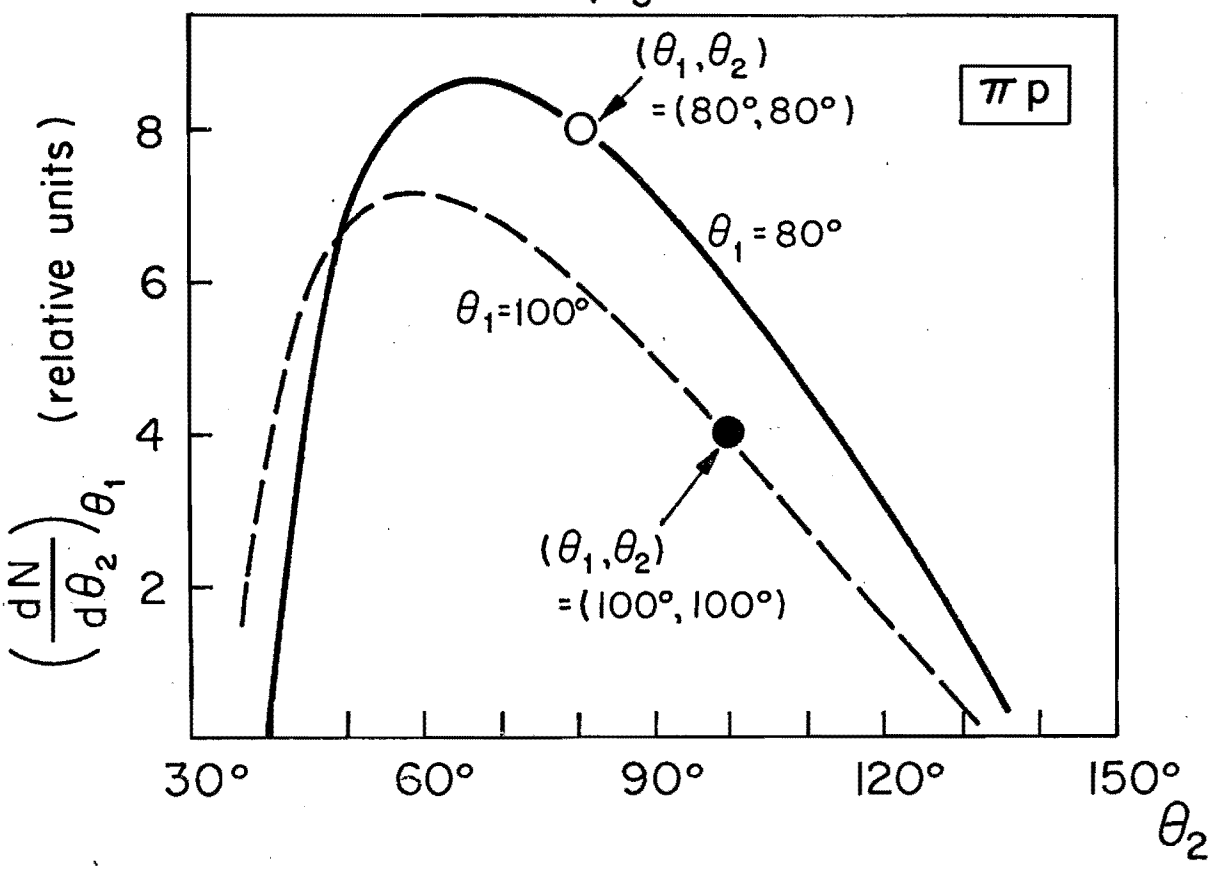
The angular correlation calculation has been made assuming partons, rather than single π's, of 6 GeV p_T. For that case, we find that for pp and πp both, a 10° slice of angle on the "other" side of the beam will show typically a 10% to 15% coincidence rate. (We take the two opposite-side jets to be coplanar.) One also finds that the πp single jet rate is about 50% higher than the pp rate, in this range of p_T and angle.

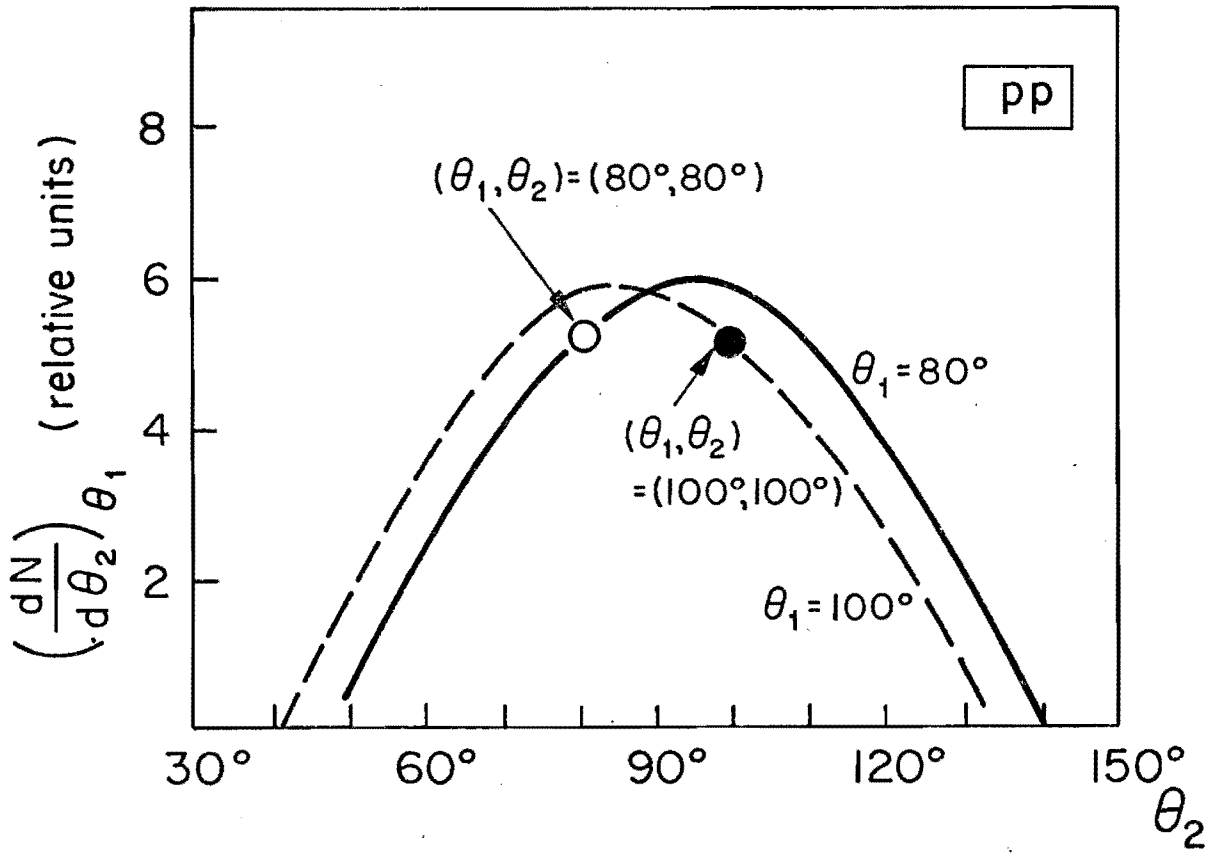
Effects from (a) the probable t'-dependence of $\frac{d\sigma}{dt'}$, and from (b) the unseen members of the jet, work in opposite directions on the coincidence rate. We therefore take 10% as a reasonable estimate for the coincidence rate per 10°.

FIG. 2

ANGULAR CORRELATIONS IN PARTON-PARTON SCATTERING

AT $\frac{2p_T}{\sqrt{S}} = 0.5$





We thus arrive at the following estimate. For an interaction rate in the target of $\sim 10^7$/sec time average, we expect to see about 30 single π's per hour, and about 15 coincidences per hour, in pp collisions, for the $\frac{1}{2}$ sr fiducial area on each side, triggered by single π's above 6 GeV. (15 out of 30 represents the roughly 50% of the time that the coincidence "recoil" high p_T object is detected.) For πp collisions, we expect a slightly higher coincidence rate. But now if we sort these coincidences into the various combinations of angular intervals, taken about 10° wide each, we find for πp collisions, and 6 GeV single π's, about 1 coincidence per hour in each pair of 10° intervals. Thus in several hundred hours, at this rate, we would see for the πp case an intensity ratio, for $(\theta_1,\theta_2) = (80°,80°)$ compared to $(100°,100°)$, of about 2 to 1, with a statistical accuracy of about 7%-10%, so a 5 to 7 standard deviation effect.

This would be a marginal effect. However, one can expect a considerably larger effect, on the parton model, for several reasons. First, the probability for a 6 GeV (detected) multi-particle jet is much greater than for a 6 GeV single π. Secondly, we can expect a larger asymmetry from such <u>jets</u>, because a multi-particle jet with 6 GeV <u>detected</u> corresponds to a "true" jet energy of 7 to 8 GeV, and such jets have a substantially higher asymmetry than for 6 GeV. Finally, we can expect to see a larger asymmetry, by using angles farther apart than 80° and 100°. We also note that the event rate rises rapidly with decreasing p_T--though the asymmetry may also rapidly decrease with decreasing p_T.

We thus conclude that an interaction rate in the target of 20 to 40 MHz is likely to give sufficient sensitivity to observe the asymmetry we wish to look for--and that such a high interaction rate is also necessary.

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 cannot 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 negative π 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^o'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 $\pm 5\%$ would be quite satisfactory, as would be 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 $\sim$ 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 momentum distribution (longitudinal and transverse) in jets, some information on ratios of numbers of π^0's, other neutrals, and charged particles, in jets, and information 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).

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NAL PROPOSAL NO. 246

SUPPLEMENT
October 26, 1973

SEARCH FOR DIFFERENCE IN PION/PROTON INTERNAL STRUCTURE

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

University of Pennsylvania

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

University of Wisconsin

*Spokesman

I. PHYSICS OBJECTIVES

1. Broad objectives. Our broad purpose is to see

   (a) What accompanies a high-p_T particle.

   (b) What balances a high-p_T particle.

   (c) Whether we can study parton-parton scattering.

2. A central objective. The central objective in this proposal is to search for an asymmetry in πp scattering, of the kind suggested by a 2 quark vs. 3 quark model, or suggested by the parton model. For this purpose we need high x_T (= p_T/p_{max}); and we need high p_T. See Section VI below.

3. Study of clusters. It is important for several reasons that the equipment be able to contain clusters of high-p_T particles, and to measure, and trigger on, the total p_T of the cluster.

   (a) The balancing p_T may be carried by a cluster.

   (b) One of our major objectives is to measure the intensity of clusters relative to singles, as a function of total p_T.

   (c) We wish to measure the internal distribution of momentum in clusters.

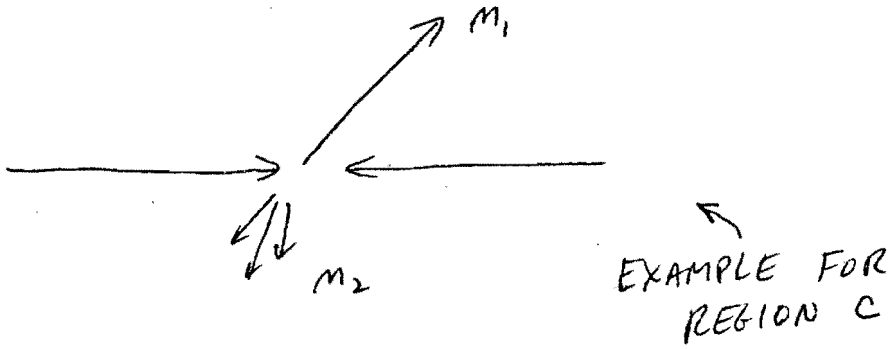
4. Study of multiplicities in high p_T groups.

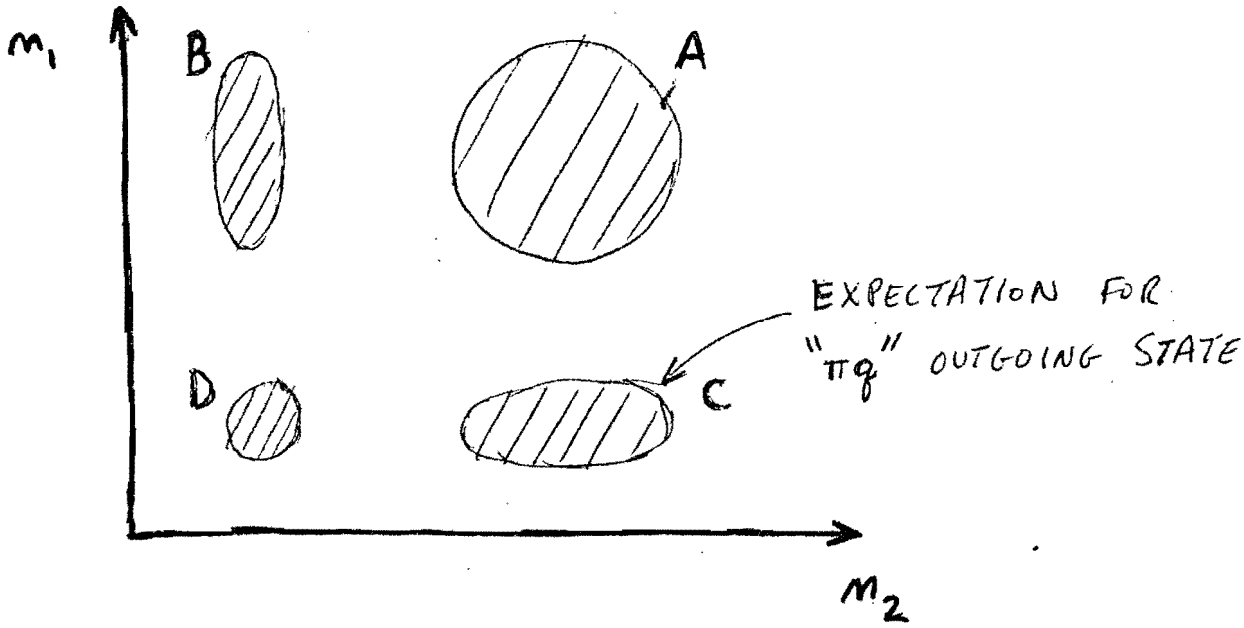
   (a) We wish to be able to "trigger" on the total p_T of a high-p_T group. To "trigger" here means to select for tape readout. The triggering selection requires several features in the calorimeter, because (a) the counting rate is a very steep function of p_T, (b) the calorimeter covers a large range of lab angle (θ_{lab} varies by 3 or 4 to 1) and thus the p_T carried by a given energy depends very much

on the particular particle angle, and (c) π^o's give about 50% more pulse height than charged hadrons. These questions are taken up in Appendix 1, where we conclude that one needs (a) accurate fast pulse height information well identified with individual particle angles--i.e., a calorimeter hodoscope, and (b) accurate fast distinguishing of π^o's from non-π^o's, and appropriate multiplication of the pulse height. In Appendix 1 we also describe the total-p_T trigger arrangement.

(b) The correlation of multiplicities on the two sides of the beam in a high p_T event is a subject of major interest. If the parton interchange model is correct, one can expect to possibly see well defined structure in the plot of multiplicity correlation, n_1 vs. n_2, where the n_i give the multiplicities in the two high-p_T groups. According to the model of Brodsky et. al., it is possible that one might see distinct sets of events corresponding to (a) two "π" outgoing states, (b) a "π" and a "quark" outgoing, (c) two "quark" outgoing states. These might show up in the form indicated in Figure 1, as distinct clusterings in the multiplicity correlation plot. But whether this model applies or not, the question of whether the multiplicities on the two sides of the beam are correlated or not is itself a question of basic interest. In order to study this question, we must be able to study all events in a given p_T band; and when we see a group of particles (expected multiplicity 2 or 3) with a high total p_T we should be able to measure the individual particle p_T values, so as to have a cleaner identification of "high p_T clusters."

FIGURE 1





POSSIBLE STRUCTURE IN MULTIPLICITY CORRELATION

NAL # 246
10/24/73

5. Possible information on parton-parton scattering. This is a somewhat difficult objective. As discussed below in Sections V and VI, it is quite hard in principle to know the "true" total p_T of a cluster, since the low-p_T members can not be unambiguously associated with the cluster. The principal way in which one might hope to make a first test of the consistency of high-p_T events with parton-parton scattering, and a way which avoids this problem of what the "true" cluster energy is, is to study the distribution of pairs of high-p_T groups as a function of the scattering variables, s' and t'. (s' and t' refer to the energy and momentum transfer variables of the pair of high-p_T groups.) Specifically, one can select a subset of events in a given s' interval, and study the t' distribution. If one then changes the beam energy, and selects the same s' interval, and the same CM energy and angle ranges for the clusters, it is then a prime test to see whether the t' distribution remains the same. In order to make such a study, it is important that the high-p_T clusters be clearly identifiable from other tracks in the same event; and this in turn becomes quite difficult if the total p_T of the cluster is not large enough.

One therefore wishes to work at very large p_T. How large? Detailed study (see Section V below) indicates that events of "true" total cluster energy 4 GeV, for example, will be very difficult to recognize and analyze, because they are likely to appear as only $2\frac{1}{2}$ to 3 GeV observed energy. One therefore wishes to be able to measure events, and correlations, for much higher values of cluster energy--say for 5 or 6 GeV <u>observed</u>. This requires the highest possible beam energy, and the highest tolerable beam intensity. (See Section VI.)

II. SOME OBJECTIVES WHICH ARE NOT BASIC OBJECTIVES OF THIS EXPERIMENT

1. To see whether some clusters occur. This is not a basic objective--clusters <u>must</u> occur, because of the emission of resonances.

2. To see whether the balancing momentum opposite a high p_T track

(a) is typically coplanar,

(b) occurs commonly in a small number of particles or in a large numbers.

These are important points, but both will be tested in the presently ongoing ISR experiment by CCR/Saclay; and also in the upcoming Split Field Magnet experiment at ISR.

3. To see whether clusters of tracks commonly occur opposite a high p_T track or whether instead there is a general azimuthal spread.

(a) A general spread is not likely kinematically.

(b) Two 4π detectors are now running at the ISR to study this question, the streamer chamber experiment, and the Pisa-Stony Brook experiment.

4. To make a careful study of scaling properties of high-p_T events. This is extremely difficult in principle at present energies. The "true" total energy of a cluster can be expected to have a large uncertainty because the low energy members of a cluster cannot be unambiguously associated with the cluster. This uncertainty, combined with the very steep p_T dependence observed for single particles, makes it very unlikely that scaling behavior can be meaningfully tested at NAL for anything other than single particle inclusive distributions.

We spell out here the nature of the problem. For scaling tests we wish to use fixed $p_T/\sqrt{s}$, and want to test the s dependence. But there is no unambiguous way to determine the total "true" p_T of a high-p_T event, within 1 GeV or $1\frac{1}{2}$ GeV (see Section V below);
a sample calculation indicates that if the invariant cross section is of the form $\frac{1}{p_T^n} f(\frac{p_T}{\sqrt{s}})$, then this 1 GeV or $1\frac{1}{2}$ GeV uncertainty can typically introduce an uncertainty in n of 2 to 4 units.

III. FEASIBLE ADDITIONS TO OUR OBJECTIVES

Several measures are possible, with modest additional resources.

1. Charged particle identification. We can readily add Cherenkov counters, to distinguish π, K, p, masses over a wide range of momentum. The experiment design provides suitable space for the insertion of several layers of these counters, which would run at atmospheric pressure.

2. The sign of the charge of each high-p_T particle detected could be determined. The experiment design provides space for magnets of $\int B d\ell \approx 2$ kg-m and with aperture about one meter by one meter. These magnets would provide charge sign identification, again over a wide range of momentum.

3. Auxiliary hodoscopes to permit operation at higher beam intensity. The present design permits operation at an instantaneous interaction rate of about 0.2×10^7 interactions/sec (beam $\sim 0.5 \times 10^8$/sec instantaneous). We estimate that this beam intensity could be tolerated without serious background problems. With auxiliary hodoscopes we could probably work with a higher beam rate and interaction rate, up by 5 times or perhaps 10 times, background permitting.

IV. SOME PROPERTIES AND REQUIREMENTS OF A CALORIMETER HODOSCOPE

1. The shower size in a calorimeter. To measure energies separately of individual particles in a cluster, particularly if energies of adjacent particles are quite different, we must have the showers separated. This requires that the particles enter the calorimeter farther apart than the resolution distance. Moreover, if we wish to know the total p_T of a cluster, and perhaps to trigger on that total p_T, then we must measure the angle of each particle well enough to determine the associated p_T; if the showers of two particles overlap, it is accordingly necessary that the shower size itself not introduce a large uncertainty in p_T.

For these purposes we must first of all know the approximate size of a shower. In Appendix 2 we show that an optimistic measure of the diameter of a shower is about 2/3 collision length. Two showers must be separated by at least this amount to avoid substantial overlap; more conservatively, the separation should be 1 to $1\frac{1}{3}$ collision lengths. In a calorimeter made with layers of iron and liquid scintillator, with layer thicknesses appropriate to this experiment (about equal thickness), one collision length is about 30 cm.

2. The distance from calorimeter to target. We propose to look initially at particles with laboratory angles of about 40 to 130 mrad. As indicated below in an example, one would like the individual showers in the calorimeter to span an angle range no more than perhaps $1\frac{1}{4}$ to 1 or $1\frac{1}{2}$ to 1. Thus at the smaller angles, say 40-50 mrad, the shower size should correspond to 10-20 mrad lab angle, and thus the target-to-shower distance should be 50 to 100 times the shower diameter. If the shower diameter is 2/3 to 1 collision length, this means the shower maximum should occur at a distance from the target which is 30-100 times as large as a collision length. For a collision length of 30 cm this means the calorimeter should be at 10-30 meters from the target. For example, if the calorimeter were put 4 meters from the target, then at the shower peak (~50 cm farther away) the diameter of the shower would cover the range from 40 mrad lab to about100 mrad lab. In this case, if e.g. two particles enter at 50 and 90 mrad with a total energy of 80 GeV, one would not in general be able to distinguish total p_T values between about $4\frac{1}{2}$ and $6\frac{1}{2}$ GeV. (The intensity for <u>single</u> particles of $p_T = 4\frac{1}{2}$ is ~500 times greater than for $6\frac{1}{2}$, at 90° CM in 300 GeV pp collisions.)

3. Sampling of energy deposition separately for each element of calorimeter area. The hodoscope elements should be entirely separate, and should deliver fast pulse height information on energy (and p_T) deposited in each element. If

several hodoscope elements give a common combined light signal, and if separate area sampling is done only infrequently in depth in the calorimeter, then it will be in effect impossible to isolate true high-p_T events from low-p_T ones which can simulate them because of inadequate sampling. Sampling must occur several times per collision length in depth, since the length of showers for 10 GeV particles is commonly only 2 to 3 collision lengths. Moreover, this sampling should give fast pulse height information, at scintillator speed, so that one can trigger on the total p_T of clusters and thus study questions such as the multiplicity distribution, and multiplicity correlations, as a function of p_T.

4. Fast pulse height signal for π^o's. The π^o-detecting front end of the calorimeter hodoscope must similarly deliver fast pulse height information, hodoscoped, for use in triggering. This π^o front end must also be made with scintillator, like the following part of the calorimeter; hadrons (i.e., other than π^o) will frequently deposit a substantial fraction of their energy in this front section, and it must be possible to combine that signal readily with the signal from the remainder of the calorimeter. In order to "trigger" on a high total p_T of a cluster, π^o's and non-π^o's must be separately identified within the trigger time (on the basis of the deposition of energy vs. depth), and the pulse heights weighted accordingly in order to test the event for total p_T.

V. SOME SPECULATIVE PROPERTIES OF HIGH-p_T CLUSTERS

In this section we discuss some possible or probable properties of clusters, with a view to deciding what angular resolution the calorimeter hodoscope should have. We also discuss the difficulty of testing scaling for high p_T events.

1. Typical angle between tracks. We must make some estimate of the angular spread between tracks in a "high p_T cluster", in order to understand the conditions under which we might be able to identify such clusters, and in order to decide what angular resolution is necessary in the calorimeter hodoscope. As a prototype of a high p_T cluster we consider a ρ meson; we note that the internal transverse momentum in a ρ, with respect to the direction of the ρ as a whole, is of the same 1/3 GeV/c order of magnitude as is expected for "jets" on the parton model.

Consider a ρ of total momentum 6 GeV/c. If it decays symmetrically, it gives two π's of momentum 3 GeV/c each, separated in angle by 0.24 radians. If it decays quite asymmetrically, say into two tracks of longitudinal momentum 1.5 and 4.5 GeV/c, the angle between these two tracks is 0.27 radians, hardly changed. The internal transverse momentum in the two cases is 0.36 and 0.30 GeV/c, respectively.

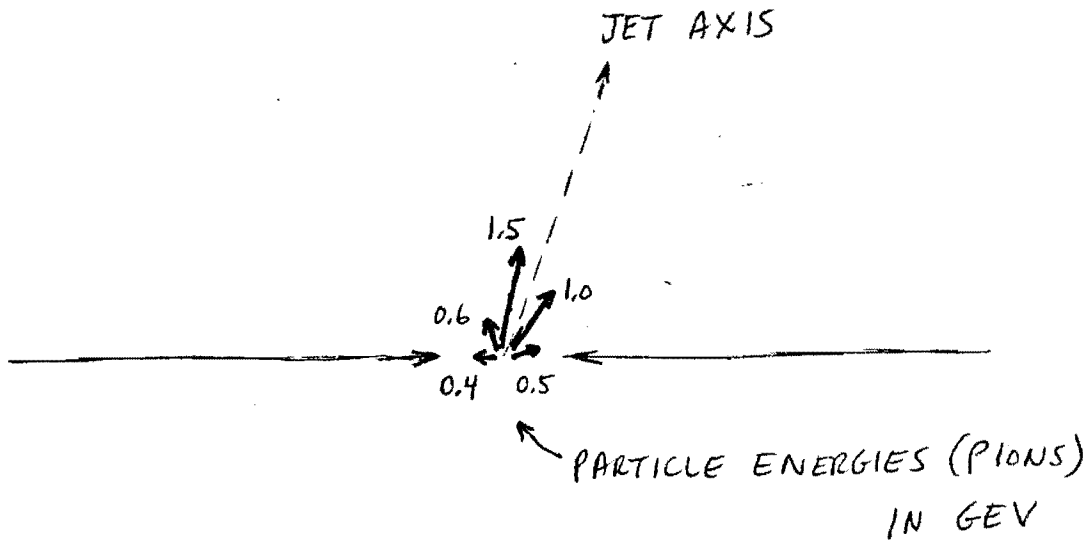
From this example, we see that a pair of high p_T particles, carrying internal transverse momentum of about 1/3 GeV/c each, at a total momentum of 6 GeV/c, will be separated by an angle of about 0.25 radians, as long as the energies of the two particles are no more different than about 3 to 1.

2. Possible structure of multi-particle high-p_T clusters; the rapidity plateau model. Feynman, and Bjorken, have suggested that if high p_T jets occur by a parton mechanism they can be expected to show a flat rapidity distribution, just as is roughly found for jets along the beam direction. (This model has received possibly supporting evidence recently in the work of Berkelman et. al. on hadron states in deep inelastic electron scattering (Cornell preprint CNLS-240, August 1973). They find a roughly logarithmic dependence of hadron multiplicity on total "jet" momentum, thus implying the presence of a rapidity plateau.)

If the internal momentum distribution in a high p_T cluster is described by a rapidity plateau and by a roughly constant internal transverse momentum, then we can construct a picture of a typical multi-particle cluster. First of all, if the height of the rapidity plateau, dN/dy, is written as N', then the rapidity interval between successive members of the cluster is approximately 1/N'. It follows that for the high momentum members of the cluster, the momentum ratio of successive lower-momentum members has the value $p_{n+1}/p_n \approx e^{-1/N'}$. Existing data show that N' for hadron-hadron collisions is about 2; the corresponding value of p_{n+1}/p_n is about 0.6 . If the successively lower momentum members of such a cluster have momentum approximately 0.6 times the momentum of the preceeding member, then the highest momentum member of the cluster carries a fraction (1-0.6), or 0.4, of the total cluster momentum.

We can thus construct a model of such a "jet". For example we consider a jet of total energy 4 GeV. If the fragments of this jet are characterized by a rapidity plateau, then some of them will be at large angles to the jet axis, and the total <u>longitudinal</u> momentum of the group will be appreciably smaller than the total energy. (One can picture that as an outgoing parton "fragments", some of its low energy members have their directions changed by "final state interactions" with the other partons continuing along the beam direction.) Using the model above, and taking the transverse momentum of each member of the jet to be approximately 1/3 GeV/c, we find that this 4 GeV jet would consist of a highest momentum member of ~1.5 GeV, at an angle ~0.2 radians from the jet axis, a second member of ~1.0 GeV, at an angle of ~0.3 radians, a third member ~0.6 GeV, at an angle of ~40° , and two last members with ~0.4 or 0.5 GeV each, at angles of 60° or more from the jet axis. We sketch such a jet in Figure 2.

FIGURE 2



POSSIBLE FORM OF A 4-GEV JET IN A 300 GEV COLLISION

We see that the three lowest energy members of this jet are in no way distinguished from the collection of many particles produced in a typical event, with p_T relative to the beam direction of ~1/3 GeV/c. Moreover the angle of each of the two lowest energy members, or perhaps the lowest three, is so far from the jet axis that those low energy members can not be associated unambiguously with the jet by virtue of angular closeness. Thus the "jet", which may actually carry five particles, would not be cleanly identifiable as a cluster of more than two particles, or perhaps three. Moreover the pair most closely correlated in angle, probably the two highest momentum members, would still have an angle separation probably greater than $\frac{1}{2}$ radian.

Thus this jet, of 4 GeV "true" energy, would be measurable typically only as a pair of particles of total energy 2.5 GeV, or perhaps 3 GeV. Moreover the angle for the total momentum vector of these two highest momentum particles could deviate from the angle of the "true" jet by the order of 1/5 radian or so, or 10°.

This degrading of the apparent energy concentration per unit solid angle which one thinks of a "jet" carrying causes great problems if one tries to study scaling properties of jets. It also causes substantial problems if one wishes to see whether high p_T on one side of the beam is compensated by observed particles with any clear clustering on the other side. Finally, it causes substantial problems if one wishes to study angular correlation effects between two high-p_T groups on opposite sides of the beam.

3. Angular resolution needed in the calorimeter system. The individual members of a cluster will be separated by angles which, statistically, are smaller for jets of higher p_T. The highest p_T at which we can obtain a useful coincidence rate at NAL is of the order of 6 GeV/c, or perhaps 7 GeV/c, measured, based on measured single-particle cross sections.

We thus see that if we wish to measure separately the energy of each particle in a high p_T cluster, in this range of total cluster energy, that we should have angular resolution of at least 0.2 or 0.25 radians for CM angles near 90°, This corresponds to laboratory angular resolution of ~15-20 mrad. For a shower diameter, in the calorimeter, of 20 to 30 cm this in turn shows that we should put the calorimeter at 10 to 20 meters from the target. We have chosen the more conservative value of 20 meters. This corresponds roughly to dividing the CM angular range into intervals of ~0.2 rad each.

4. The ratio of jet intensity to single-particle intensity, for a given total p_T.

The ratio of jet intensity to singles intensity, for a given total p_T, is a highly interesting quantity to measure. It is however a very difficult quantity to measure, particularly at insufficiently high values of p_T. For example, consider jets and singles of "true" energy 4 GeV. Using the method suggested by Bjorken, described in our proposal, one estimates that 4 GeV jets should occur about 100 times as frequently as 4 GeV single π's (all charges included). Suppose however that jets of 4 GeV true energy can be measured only as jets of apparent energy 2.5 GeV, as suggested above. Then the number of such 2.5 GeV jets has to be compared with the number of 2.5 GeV singles; and the number of singles of that energy is ~200 times the number of singles of 4 GeV energy. Therefore the number of 2.5 GeV (measured) "jets" would not be 100 times the number of measured singles of 2.5 GeV, but instead only about equal in number.

If one goes to much higher values of p_T, the problem becomes slightly less severe, at least if one uses the Bjorken method of estimating the number of jets relative to the number of singles. For 7.5 GeV, for example, we find that the number of jets of true energy 7.5 GeV would be about 4 times greater relative to singles, than for 4 GeV. That is, the number of 6 GeV (measured) jets would be several times the number of 6 GeV singles.

Oneshould also note that if the missing energy can be kept to 1.0 GeV instead of 1.5 GeV, the observed ratio of 6.5 GeV (measured) jets to 6.5 GeV singles would be, according to this model, about 5 times greater still, or perhaps 15 to 20. The flat-rapidity model gives for the unobserved energy outside an angle θ the value

$$E\Big]_{>\theta} \approx \frac{N'\langle p_T\rangle}{\tan\theta} .$$

Using $N' \approx 2$ and $\langle p_T\rangle \approx 1/3$ GeV, one finds $E\Big]_{>\theta} \approx 1.0$ GeV for $\theta \approx 0.6$ radian. In principle, one could use for θ, in the experiment, a value as large as the average angle up to the next "random" particle. Since $\frac{dN}{d\Omega} = \frac{1}{2\pi \sin^2\theta} \frac{dN}{dy}$, the next random particle is on the average ~1 radian away, at 90° CM--but of course at a closer angle if one studies high p_T events at CM angles much closer to the beam.

Finally, we note that if "singles" are in fact <u>mostly</u> accompanied by 1 to 1.5 GeV of low energy fellow-travelers, as is suggested by the parton fragmentation model, then the intensity of jets of a given measured total p_T relative to the intensity of singles, could be <u>much</u> larger than the ratio between 1 and 5 indicated above. This point emphasizes the importance of measuring the ratio of jets to singles, and the importance of unambiguous determination of the total p_T of a group of detected particles.

Sections VI through IX, not finished yet, deal with the following topics:

VI. Beam Energy and Intensity Required for the Asymmetry Search

VII. Preliminary Results of our Calorimeter Tests (See Appendix 4, attached herewith)

VIII. Cost Estimate for the Calorimeter System

IX. Auxiliary Equipment, and Overall Costs

THE TOTAL-p_T TRIGGER; CALORIMETER REQUIREMENTS FOR OBTAINING GOOD p_T RESOLUTION

The angle coverage of the calorimeter proposed is shown in Figure 1. In Figure 2 the same calorimeter is shown schematically subdivided in laboratory angle θ, with an output signal weighted from each segment so as to provide a trigger signal proportional to the total p_T of a group of particles reaching the calorimeter.

This subdivision, and p_T- weighting of signals, is essential in order to select the events of high p_T efficiently in the presence of the enormously higher rate of all events. For example, at the interaction rate proposed here of about 10 per microsecond in the target, a 1 sr calorimeter roughly like those shown would have a counting rate of about 3 MHz. It is totally impossible to record events at that rate. Each recorded event requires the ADC processing of about 200 signals. These signals, and the signals from about 1000 more individual track hodoscope elements, are then read out. We estimate that we might be able to record 100 events per burst without much difficulty, with an absolute limit of several hundred events per burst (unless one goes to a much more sophisticated readout system). We must therefore have a trigger system capable of selecting the 1 in 10,000 or so, of all events, that meet the trigger requirement.

The p_T spectrum is very steep. To restrict ourselves to the highest p_T events which occur once in 10,000 times requires that we have a p_T threshhold at $\sim$ 3 GeV/c, according to the single-particle measurements of Cronin et al. With the trigger system of Figure 2, this is straightforward. If we did not have the calorimeter subdivided but instead used only a single calorimeter element as indicated in Figure 1, then we would have to use a 20 GeV <u>energy</u> threshhold.

But in that case we would also be triggered by some signals of ~ 1 GeV/c p_T, at small angles. Integration over the $\Delta\Omega$ of Figure 1 shows that in fact with a 20 GeV trigger threshold one would get trigger signals 200 times as often as with a 3 GeV/c p_T trigger. These could not all be recorded, and hence one would have to raise the threshold energy for the trigger, in order to avoid saturating the readout system. Moreover, without an adequately segmented calorimeter hodoscope structure the p_T thresholds would be strongly angle-dependent. Such an effect would severely interfere with the study of events of fixed p_T as a function of production angle.

To obtain an angle independent p_T trigger we must also identify, for the trigger, whether a particle is a π^o or a non-π^o. The signal size for π^o's is $\sim 50\%$ greater than for non-π^o's. This effect also, if not properly accounted for, would badly distort the triggering threshold for events with π^o's compared to the threshold for events without π^o's.

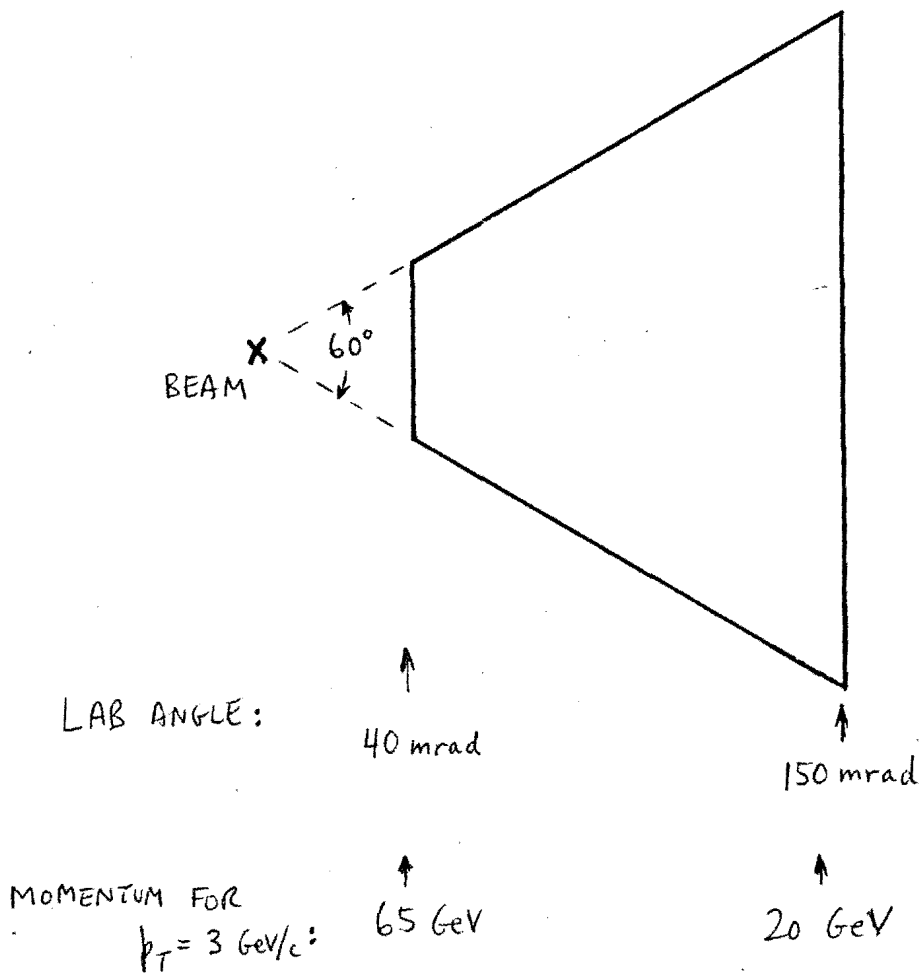
We note that in order to effectively use a total-p_T trigger like that indicated in Figure 2, and in fact to interpret the total p_T of individual multi-particle events and the angle of the total-p_T vector, it is necessary that the showers for individual particles be well resolved and individually well measured, if those particles have appreciably different sin θ values. For example, if the calorimeter segment sampling indicated in Figure 2 is too coarse in depth, then the individual particle energies will not be well known. Such a lack of detailed information could produce large uncertainties--poor "resolution"--in total p_T. In order to give a useful degree of resolution in p_T it is necessary to sample each calorimeter hodoscope element throughout its depth, several times per collision length.

Moreover, the individual particle shower energies must be reasonably well measured in sin θ. This requires that the calorimeter not be too close to the target. Thus if the calorimeter is, e.g., only 4 meters from the target,

and if each particle shower is 20 to 30 cm in diameter, then 2 showers will be resolved only if their laboratory angles are separated by more than 50 mrad or so. Thus if one particle is at say 40 mrad lab angle and the other at 80 mrad, then their individual energies will not in general be well measured but only the sum. This case corresponds to 2 particles with CM angles more than $\frac{1}{2}$ radian apart; and if the particle energies are very different but we do not know which is at 40 mrad and which at 80 mrad then there is a very large uncertainty in total p_T, typically by a factor of $\sim 1\frac{1}{2}$.

We thus see that we require a calorimeter array in which individual calorimeter hodoscope elements give a fast pulse-height signal (a) reasonably accurately measuring the energy deposited at that angle, (b) reasonably accurately measuring sin θ for that element, and (c) distinguishing π^0's from non-π^0's, with appropriate weighting introduced into the signal for determining total p_T.

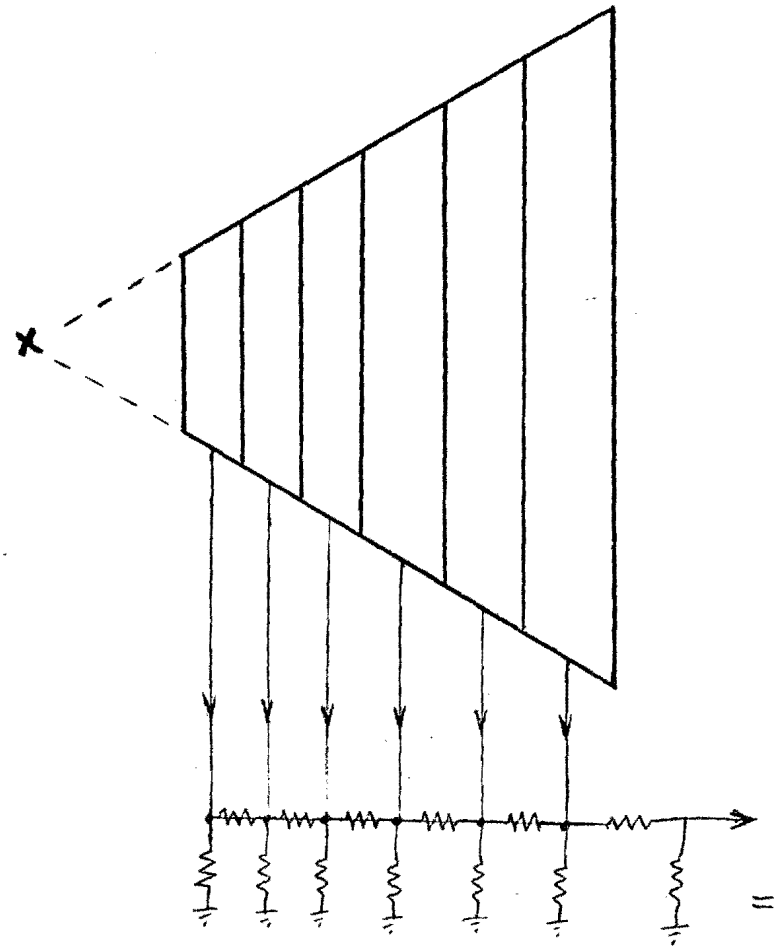
FIG. 1



BEAM VIEW OF CALORIMETER ON ONE SIDE OF BEAM

10-26-73

FIG. 2



$$= \sum_{i=1}^{N} p_i \sin \theta_i$$

$$= p_T \text{ (total)}$$

TOTAL-p_T TRIGGER

10-26-73

AN ESTIMATION OF THE TRANSVERSE DIMENSION OF HADRON SHOWERS IN IRON AT ABOUT 10 GeV/c

(1) We estimate a mean transverse dimension of hadron showers from the two following experimental facts:

(a) Dependence of the pion peak on the location of the beam, as observed at 7 GeV/c in our test runs with the 10-ton calorimeter.[1]

(b) Edge effects observed by Engler, Schopper et. al., with their total absorption spectrometer, for protons.[2]

In order to calculate the mean transverse radius R of the hadron shower, we must make some assumption about the transverse distribution of energy deposited in the hadron shower. The following discussion is based on a very simplified model, with energy deposition uniform inside a circle of radius R, and zero outside.

(2) <u>Estimate of R from the position dependence of the pion peak at 7 GeV/c.</u>

In Figure 1 are shown the relative pulse heights of the calorimeter for π, μ, and e, normalized at the center for each particle. Both muons and electrons give highly localized energy deposition compared with pions, and therefore the dependence of their pulse heights on the location can be taken to give the relative light collection efficiency at different locations. We have interpolated between the measured points in a smooth way, taking into account the geometrical symmetry of the

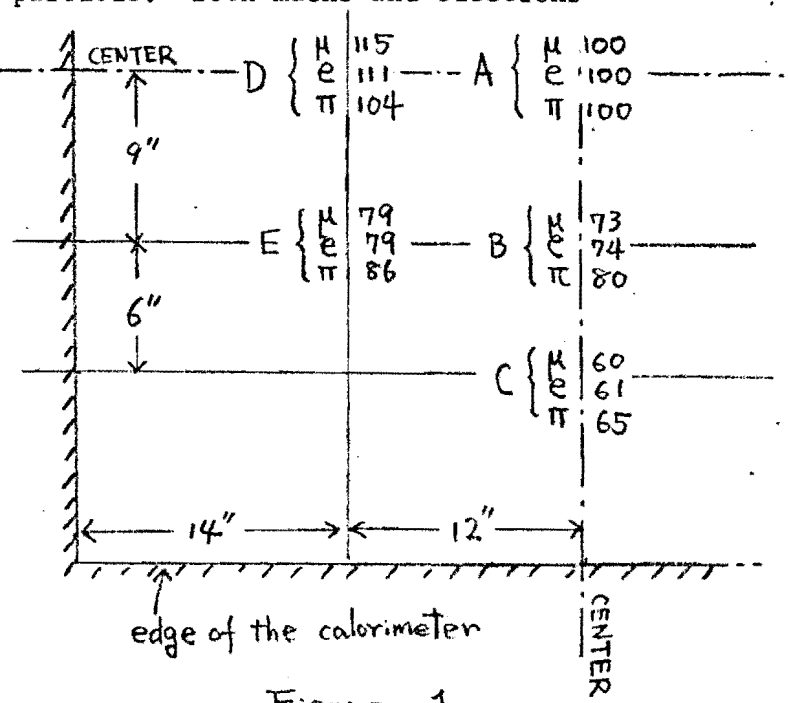


Figure 1.

device, to get the light collection efficiency at positions between the measured points. The pulse height for pions is affected by the non-uniformity of the light collection efficiency, and the pion shower pulse height can be calculated by averaging light collection efficiency inside a circle R. This was done at the positions A and B (see Figure 1) for three different values of R as follows:

R	Averaged Light Collection Efficiency at A	B	Ratio B/A
3"	99.0%	75.5%	0.76
5"	97.8%	77.0%	0.79
7"	95.5%	78.0%	0.82
Observation			0.80

Thus the experimentally observed ratio indicates to us that the mean radius R is between 5" and 7".

(3) Estimate of radius R from the edge effects measured by Engler et. al.

Engler et. al. found the mean pulse height decreased to 85% at a distance of 5 cm from the edge with respect to the one in the center. Using the assumption of uniform energy deposition, we can calculate the radius R of a circle 15% of the area of which is outside their spectrometer, as indicated in Figure 2. R is found to be about 8.5 cm.

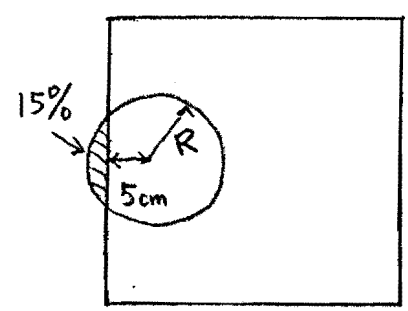


Figure 2.

(4) We examine whether the above crude estimates of R are consistent with each other, by expressing R in units of collision length, as follows.

	Configuration of Matter	Collision Length	R in Collision Length
Our calorimeter	0.5"Fe + 1.5" liq. scintillator	43 cm	0.28 ~ 0.4
Engler et. al.	2cm Fe + 0.7 cm plastic scint. + 0.8cm gap	28 cm	0.3

The collision length of each detector was obtained using 136 g/cm^2 for one interaction length in Fe. As is shown in the last column, the values of R estimated from two different experiments agree reasonably well.

We thus conclude that, using this model of uniform transverse energy deposition inside a radius R, the value of R is about 0.3 collision length. Some of the slow particles made in a cascade could travel considerably larger distances sideways. Therefore, if one wishes to contain a very large fraction of the total energy, say 90%, one should use a larger "effective radius" than the value of 0.3 collision length obtained in this note.

References: (1) BNL-Penn-Wisconsin Collaboration, Internal Report, October 11, 1973.

(2) J. Engler et. al., Nuclear Instruments and Methods 106, 189 (1973).

BACKGROUND EFFECTS, FROM PILEUP, IN A HIGH-p_T CALORIMETER EXPERIMENT

(1). In an inclusive high-p_T and high intensity experiment using a calorimeter, more than one interaction might occur within the resolving time of the apparatus. In such a case transverse momenta observed in the calorimeter could be added up to give a false high-p_T signal.

(2). The probability to have n interactions within the resolving time and unresolved in vertex position in the target is given by

$$P_{int}(n) = \frac{m^n e^{-m}}{n!} \qquad m = Nq \tag{1}$$

where N is the number of incident particles in the resolving time and q is the number of interaction lengths in the resolving length in the target. We assume that q is small enough so that only n = 1 and n = 2 are important. The following example is given for N = 1 and q = 0.04 (or for N = 4 and q = 0.01)

$$P_{int}(1) = e^{-0.04}, \quad P_{int}(2) = 0.02\ e^{-0.04}, \quad P_{int}(3) = 0.0003\ e^{-0.04}$$

and in this case the ratio R_{int} of the double interaction to the single one is

$$R_{int} = \frac{P_{int}(2)}{P_{int}(1)} = 0.02 \tag{2}$$

The quantity R_{int} is plotted in Fig. 1 as a function of the resolving time and of the intensity of the incident beam, for the cases of q = 0.04 and q = 0.01.

(We consider that q = 0.01, which is ~3 inches of liquid hydrogen, is probably reasonably achievable. We also note that when there is an improvement in the microstructure at NAL, one can also profit from the use of sharper time resolution, and can use several times higher beam rate.)

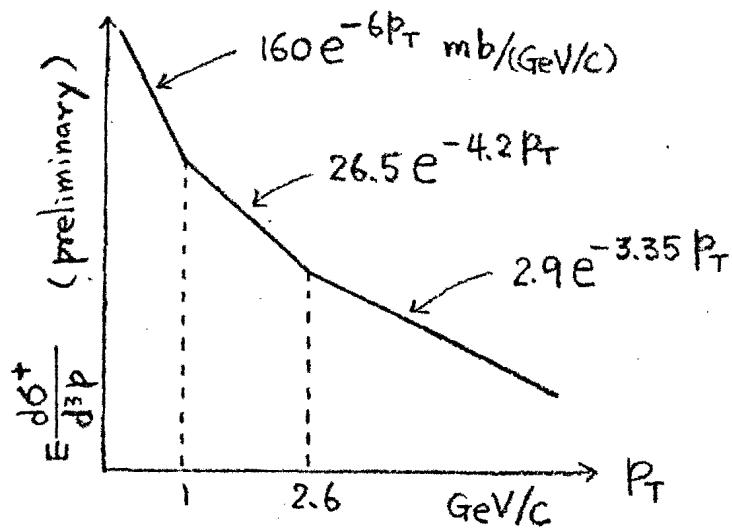
(3). The probability P_1 that one interaction in the target gives a transverse momentum deposit between p_T and $p_T + \Delta p_T$ in the calorimeter of $\Delta\Omega$ sterradian is written as

$$P_1(p_T)\Delta p_T \Delta\Omega = \frac{d\sigma}{dp_T d\Omega} \Delta p_T \Delta\Omega / \sigma_{tot} \tag{3}$$

where $\frac{d\sigma}{dp_T d\Omega}$ is the differential inclusive cross section given by the following approximation at 90°

$$\frac{d\sigma}{dp_T d\Omega} \approx 3 \frac{p_T^2}{E} \frac{d\sigma^+}{d^3p/E} . \tag{4}$$

The invariant inclusive cross section $\frac{d\sigma^+}{d^3p/E}$ for positive particles is taken from the measurement by Cronin et. al. at 300 GeV/c in pp collisions. An approximate representation of these results is shown in the figure. The factor 3 in Eq. (4) is due to the inclusion of negative and neutral particles. The dependence of P_1 on p_T is shown in Fig. 3.



The probability P_2 that two interactions occurring in a resolving time of the apparatus

give a total transverse momentum between p_T and $p_T + \Delta p_T$ into $\Delta\Omega$ steradian is calculated by the formula

$$P_2(p_T)\Delta p_T \Delta\Omega = \Delta p_T (\Delta\Omega)^2 \int_o^{p_T} P_1(p_1) P_1(p_T - p_1)\, dp_1 \tag{5}$$

(4). The overall relative rate to have accidentally coincidenced interations which give a fals high-p_T signal is therefore given by

$$R(p_T) = R_{int} \cdot \frac{P_2(p_T)}{P_1(p_T)} \tag{6}$$

In Fig. 2 we plot $R(p_T)$ against p_T when R_{int} is 0.02 and $\Delta\Omega$ is 1 sr. Note that we have used here the known <u>single</u>-particle p_T distributions in making the calculation. If high-p_T events occur commonly as multi-particle groups, the results shown in Fig. 2 would be modified accordingly.

The relative contributions to the integral in Eq. (5) are plotted against p_1 for several values of p_T in Fig. 4.

FIGURE 1. Probability Ratio of 2 Interactions to Single Interaction

$$R_{int} = \frac{P_{int}(2)}{P_{int}(1)} = \frac{\text{Probability of 2 interactions in resolving time)}}{\text{Probability of 1 interaction in resolving time)}}$$

[Target resolving length = 0.01 collision length (solid)
0.04 collision length (dashed)]

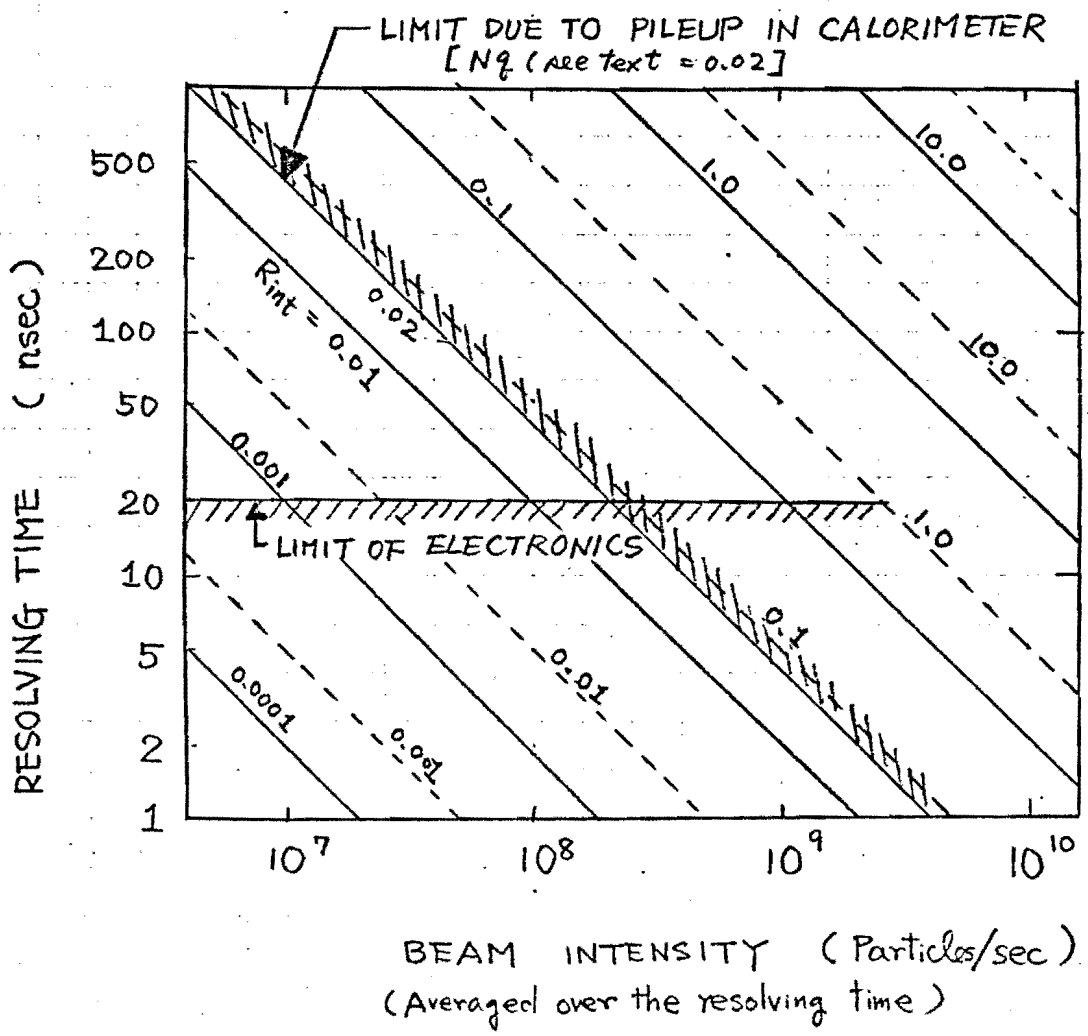


FIG.2 Probability Ratio, $\frac{P_T \text{ by 2 interaction pileup}}{P_T \text{ in single interaction}}$

assuming single-particle inclusive cross-section applies directly.

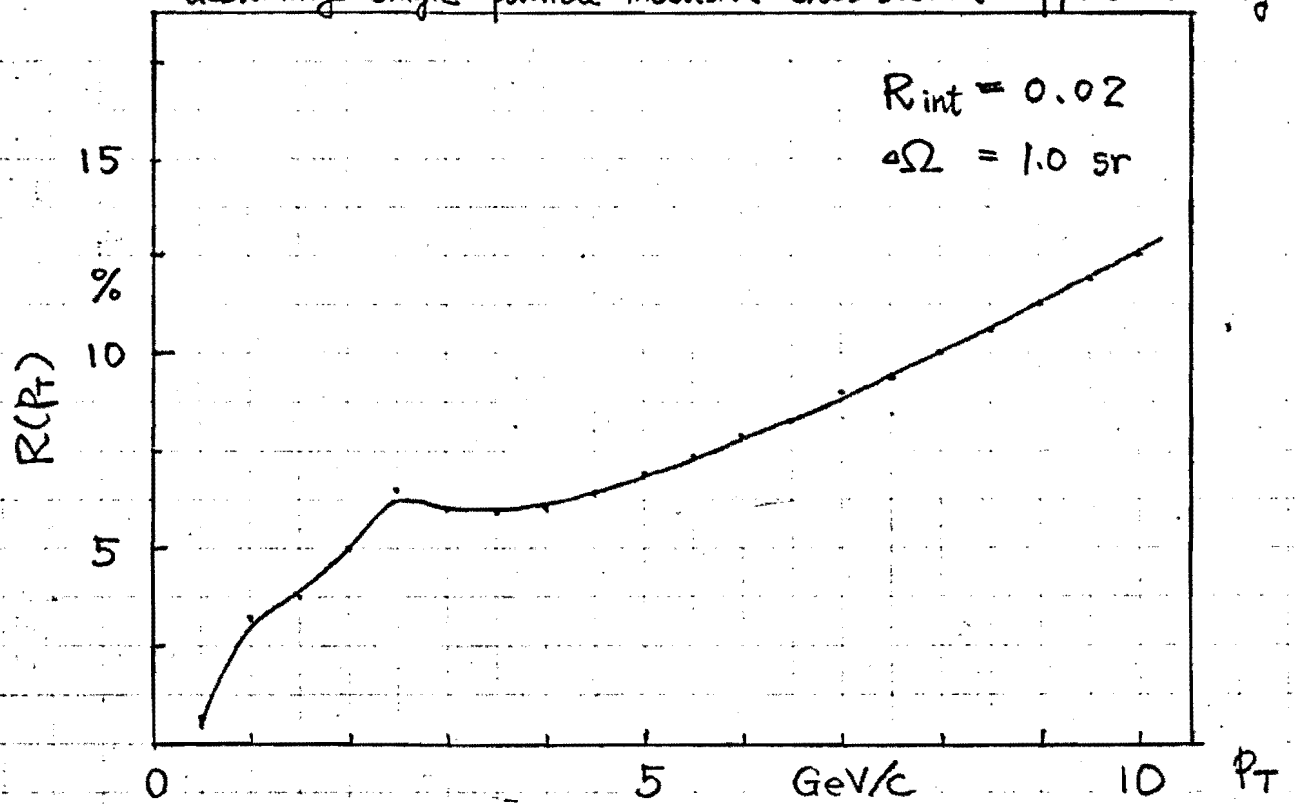
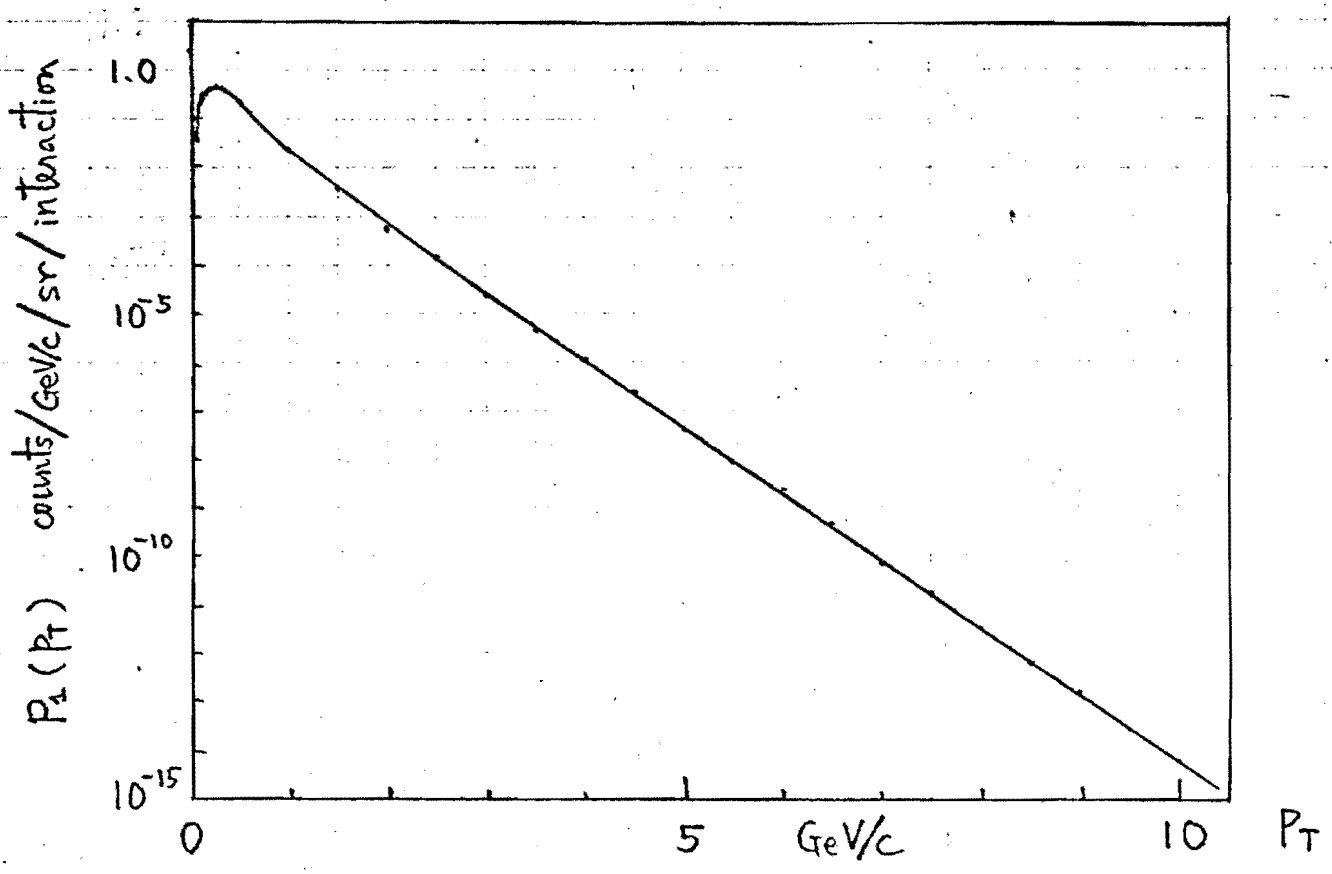


FIG. 3



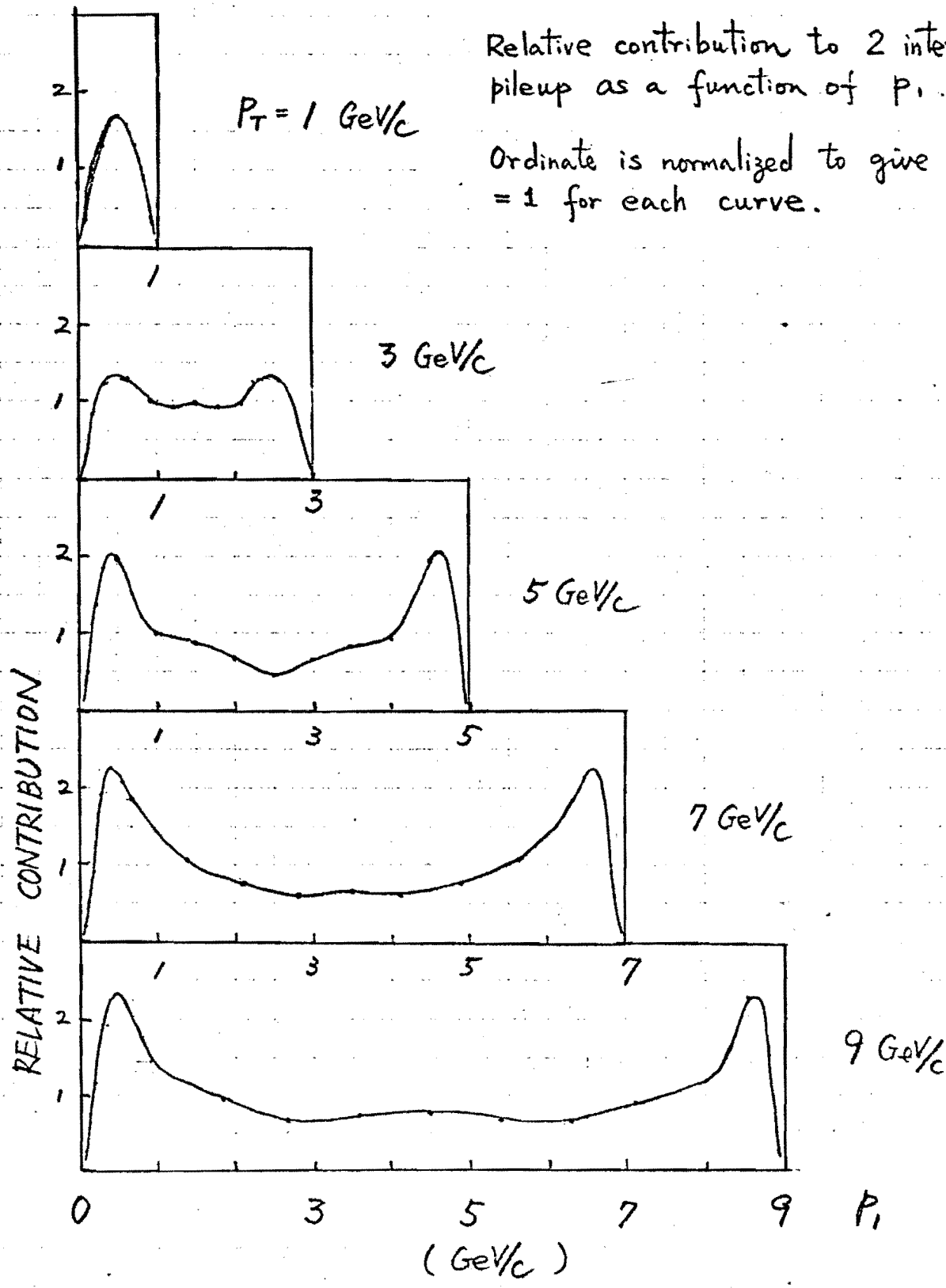

Relative contribution to 2 interaction pileup as a function of p_1.
Ordinate is normalized to give average = 1 for each curve.
P_T = 1 GeV/c
3 GeV/c
5 GeV/c
7 GeV/c
9 GeV/c
RELATIVE CONTRIBUTION
0
3
5
7
9
P_1
(GeV/c)

FIGURE 4

PERFORMANCE OF A SAMPLING CALORIMETER AT 3 TO 17 GeV. A PRELIMINARY REPORT.*

BNL-Penn-Wisconsin**

Abstract: A sampling calorimeter has been built aimed at giving improved resolution in the few GeV range compared to previously obtained results. It has been run in a BNL test beam, with π, p, and e, at momenta from 3 to 17 GeV/c. Runs were taken with 2 different arrangements of plate and scintillator thicknesses.

For energies below 8 or 10 GeV, the fractional energy resolution for π and p becomes roughly constant, at about 50% FWHM. The tail of the resolution curve cuts off relatively sharply, at a pulse height about 50% above the peak of the distribution. These results are little different for the 2 geometries used: I) 0.5 inch Fe and 1.5 inch LS (liquid scintillator), and II) 1.0 inch Fe and 1.5 inch LS.

*Work supported in part by U.S. Atomic Energy Commission.

**BNL: F. Turkot; U. of Pennsylvania: E. Harvey, T. Kondo, W. Kononenko, E. M. O'Neill, W. Selove; U. of Wisconsin: R. Diamond, A. R. Erwin, R. Loveless, M. Thompson.

1. For some experiments aimed at studying high-p_T phenomena, one needs a calorimeter detector for hadrons having individual energies of 2 to 10 GeV. The most complete recently reported work in this energy range was that of Engler et al.[1] They found, with a sampling calorimeter, a FWHM resolution approximately constant at ΔE for protons of about 5 to 20 GeV; the ΔE(FWHM) in their detector was about 5 GeV. For work in the steeply falling momentum spectrum found for single π's near 90° at the ISR, such a resolution is useless below 10 GeV or so, since signals corresponding to a nominal 5 GeV, say, would in fact be totally dominated by signals from particles with a true energy as low as 1 or 2 GeV, which are thousands of times more numerous.

In a study of what resolution might be theoretically obtainable, it was concluded that it might be possible to obtain a resolution of about 50% FWHM, and an end point about 50% beyond the peak, independent of energy.[2] This resolution could in principle be obtained by using a much higher proportion of scintillator than that of Engler et al. A resolution of 50%, and a corresponding end point, would be just about satisfactory for use with a spectrum as steep as that at ISR at 90°. (At angles more forward than 90° less resolution is needed; and for multi-particle groups less resolution is needed.)

2. We have built and tested a calorimeter designed to answer several questions. 1) What resolution can be obtained for this energy range? 2) What does the tail at large pulse heights look like? 3) What effect does plate thickness have in a range of convenient thicknesses?

The calorimeter uses steel plates in liquid scintillator (LS). It has overall dimensions approximately 120 cm square (active area) by 250 cm thick. It is built in the form of 15 cases, each one 15 cm thick with 2 cm of wood between cases. Each case has 1/8 inch thick faces, and was operated with steel plates inserted so as to divide the 15 cm thickness into 3 or 2 compartments. Light is taken from the edges, collected 3 cases at a time into one 5 inch PM (54 AVP) on each side; the 15 cases are thus grouped into 5 triads, looked at by a total of 10 PM's. 1 to 2 per cent of the light reaching the edges was collected by the light pipes going to the PM's.

In "Geometry I", we used steel packages in each case which gave 1/2 inch Fe layers separated by $1\frac{1}{2}$ inch LS. The end faces of two adjacent cases, plus reflecting liners in the cases, plus the wood spacer, constituted approximately 1/2 inch Fe equivalent of nuclear interaction, roughly equivalent in thickness to the inserted 1/2 inch plates. Each case was thus divided into 3 gaps, and each gap was sampled at 3 points by light pipes.

In "Geometry II", the insert consisted of a 1 inch Fe plate in the center, bordered by two $1\frac{1}{2}$ inch LS gaps with 1/4 inch Fe plates outboard. In effect, the light from each of the two $1\frac{1}{2}$ inch gaps was then collected by a set of 3 light pipes, in the light pipe bundles going to the PM's.

The calorimeter could be moved vertically (operating at the reference height or at higher locations), and horizontally. Most of the data were taken with beam defining counters giving a beam 2 inches square entering the calorimeter, acurately aligned parallel to the calorimeter axis.

Figures 1-7 show some details of the physical arrangements.

The case faces, and the plates which were inserted, were lined with FEP teflon, following a technique developed by Cline, Mann, and Rubbia.[3] Extremely good reflection was obtained, as indicated in Figure 8.

3. Data were recorded on magnetic tape, and generally also on a PHA (this is mostly photographically). The PM gains were balanced, to within about ± 10%, by using muons. Each tube's output was amplified 40 times and connected to an individual ADC. The tube outputs, amplified by 10, were also combined into a video sum signal, which was also connected to an ADC. All ADC outputs were recorded on the magnetic tape.

To trigger separately on electrons, or to trigger separately on protons or non-protons, we used a gas Cherenkov counter located about 20 meters upstream. At momenta of 3 GeV/c and lower we used time-of-flight for the beam particles, to separate protons from other particles. For a muon trigger we used a scintillation counter positioned behind 15 feet of concrete following the calorimeter.

Beam rates were in the range of 50 K to 300 K per 800 millisec spill depending on beam momentum and polarity, and on whether we had lead blocks inserted far upstream in the beam. The beam intensity was not always under our control; but for careful measurements of tail effects we were able to take data with relatively low intensity in the beam. We could also, by software processing of the final data, use the first triad of the calorimeter as a veto on signals showing more than one minimum ionizing particle in the first triad, within the ADC time gate of about 200 nsec. (One triad is equivalent to about one collision length,

and about 7 radiation lengths.) With this veto cut we could obtain a purified sample of data for pions and for protons, although not for electrons, which typically deposited about 75% of the total energy into the first triad.

During a major part of the running, the test beam had many occupants simultaneously, and the beam region ahead of the calorimeter had some 20 gm/cm^2 of material distributed in the 20 meters ahead of the calorimeter.

4. A bird's eye view of some major features of the results can be seen in Figures 9 and 10. These were taken in 2 days or preliminary running which we had at the end of May. (Data taking resumed, after an AGS shutdown, in mid August.) These Figures show the following features. (All plots shown below were taken with the entering beam centered in the calorimeter and with no trigger requirements other than beam defining telescope and Cherenkov counter.)

1) For electrons the response is quite linear with energy.
2) The typical FWHM for electrons is about 20% for 5 to 7 GeV/c, and the spectrum shape cuts off sharply at about ± 10% from the peak.
3) For π's, the peak of the pulse height distribution occurs at close to 2/3 of the peak position for e's of the same momentum.
4) The end point of the π spectrum occurs close to where the electron (pure e-m shower) peaks; this is what is to be expected for charged-π events in which almost all of the energy of the π gets converted to π^0's in the first nuclear interaction. Thus the end point of the π spectrum is at about 1.5 times the pulse height of the peak.
5) The shape of the π spectrum, between peak and end point, is approximately linear. Thus the FWHM of the spectrum is also

approximately 50%.

6) The 50% FWHM value, and the 1.5 ratio of end point to peak, hold almost constant for incident energies between 3 and 7 GeV.

5. A few further features of the results are shown in Figures 11 to 14. There the following can be seen:

1) In Figure 11, π^- and e^- are shown for Geometry II. One sees that the resolution is very similar to that for Geometry I (Figures 9 and 10).

2) In Figure 12, the $\pi^\pm$ spectra are shown for 5 to 15 GeV, Geometry II. One sees the end point, say at the level with 1% to 2% of the area remaining, occurring about 50% beyond the peak position, for 5 to 10 GeV, and slightly closer for 15 GeV.

3) In Figure 13, π^+ and proton spectra are shown for 7 GeV/c, for both geometries. These two geometries have respectively Fe thicknesses of 1/2 inch and 1 inch. The resolution curves are almost indistinguishable for these two cases.

4) Finally, in Figure 14, π^+ and proton spectra are shown, this time for 15 GeV/c. At this higher momentum the FWHM is a smaller percentage than for the lower energy range, about 40% or a bit less compared to about 50%. Our preliminary examination of further results at the higher momenta in our data also suggests that the FWHM for protons may decrease a bit faster than for π's, with increasing energy.

6. We have benefited from much assistance given by the University of Pennsylvania machine shop, and by many individuals. We particularly thank M. Hearn and his Staff, and W. Mueller. Discussions with H. Schopper, and calculations he provided for us, were invaluable. A. Mann and C. Rubbia were generous in providing information and assistance. We profited much from discussions with W. Willis, T. A. Gabriel, and R. G. Alsmiller. We thank D. Berley, R. Stafford, and the AGS staff, for much help.

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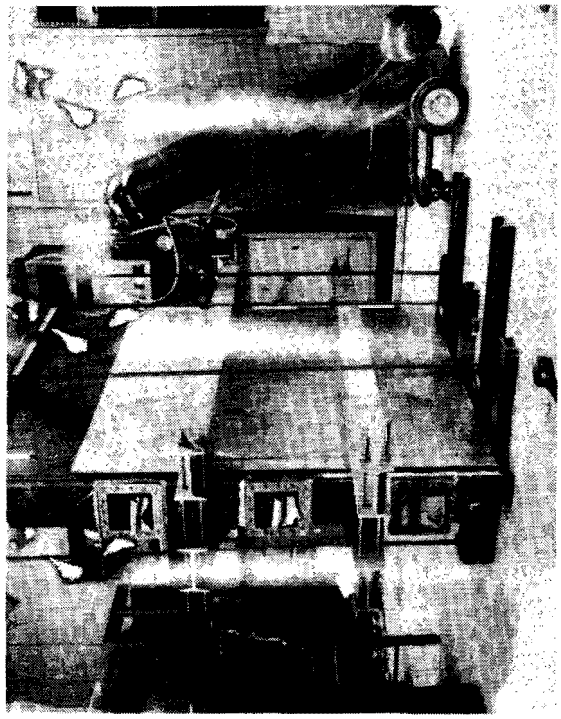
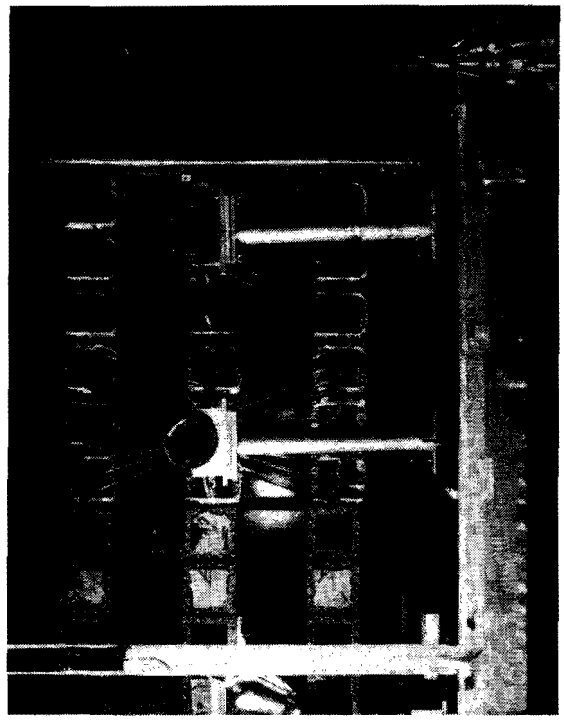
(1) J. Engler et al., Nuclear Instruments and Methods 106, 189 (1973).

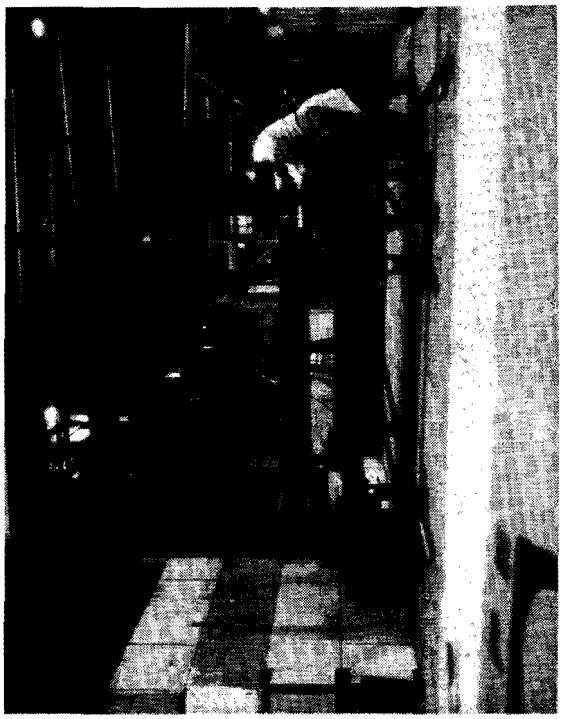
(2) W. Selove, NP Internal Report 72-25, 1972 (CERN).

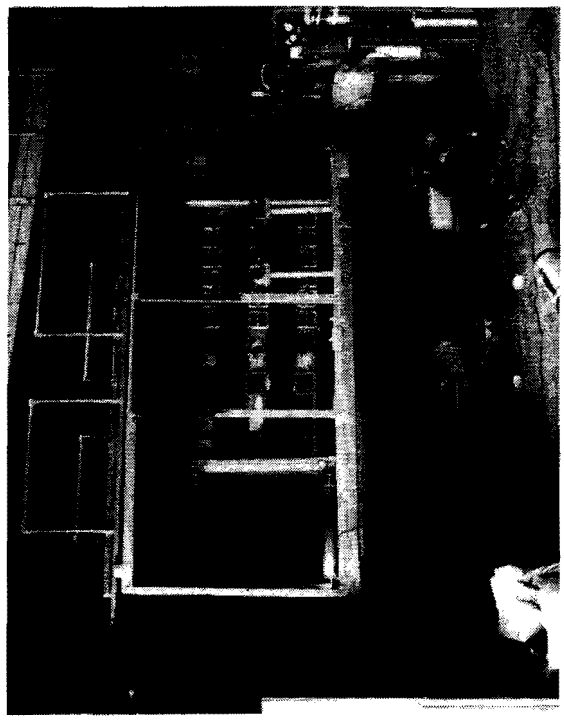
(3) Private communication.

Figures 1-4

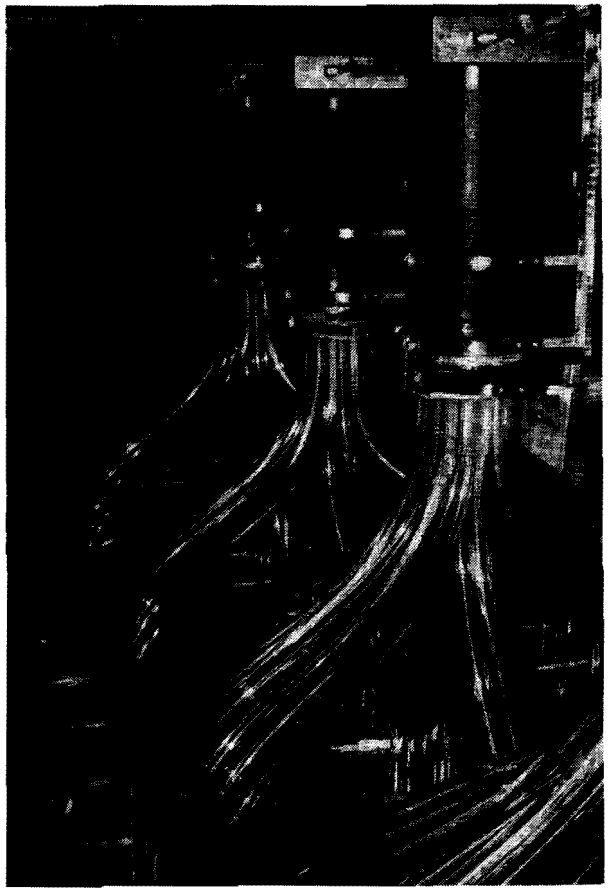


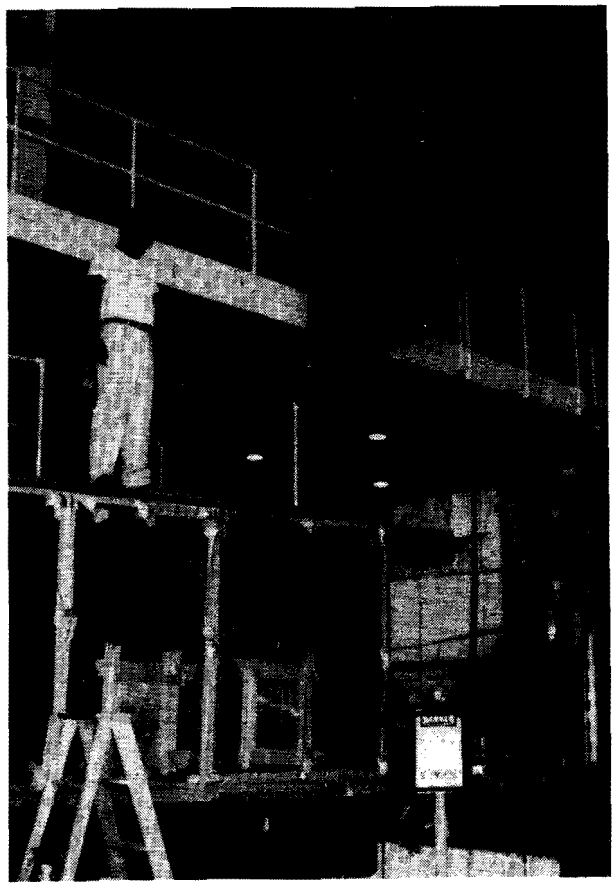


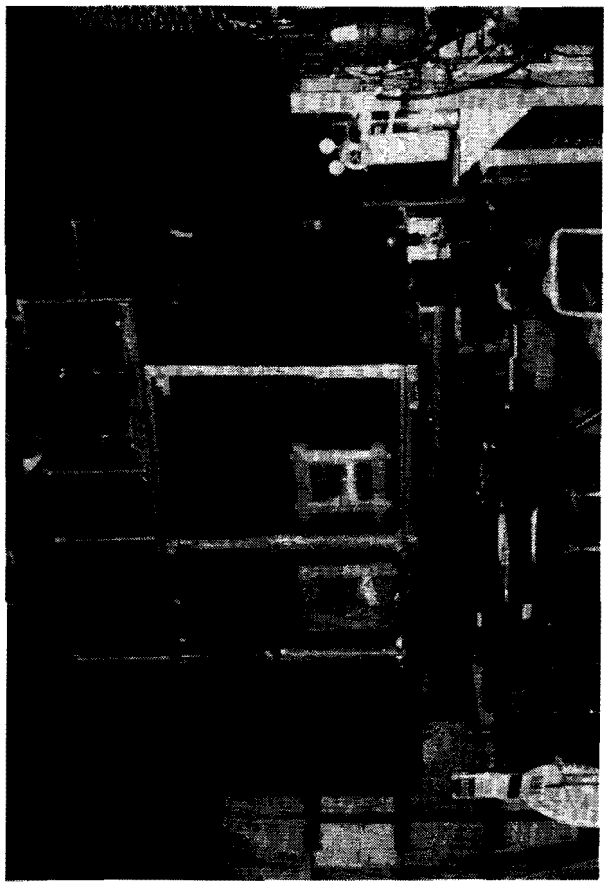




Figures 5-8







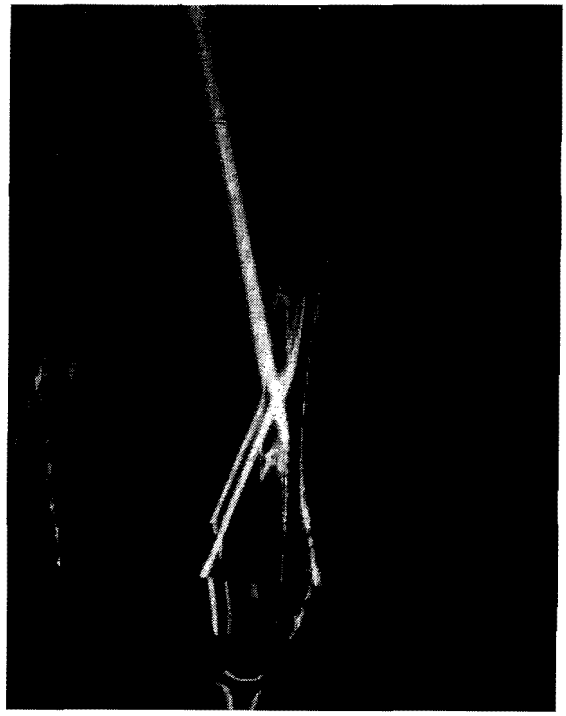
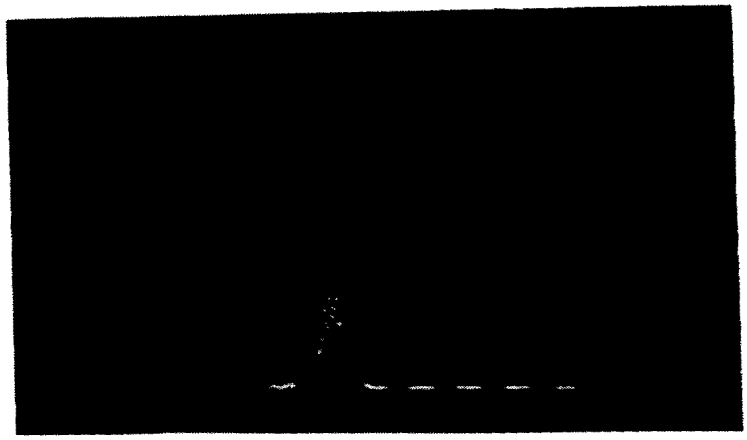


Figure 9

e^-

2.5 GeV



5 GeV

7 GeV

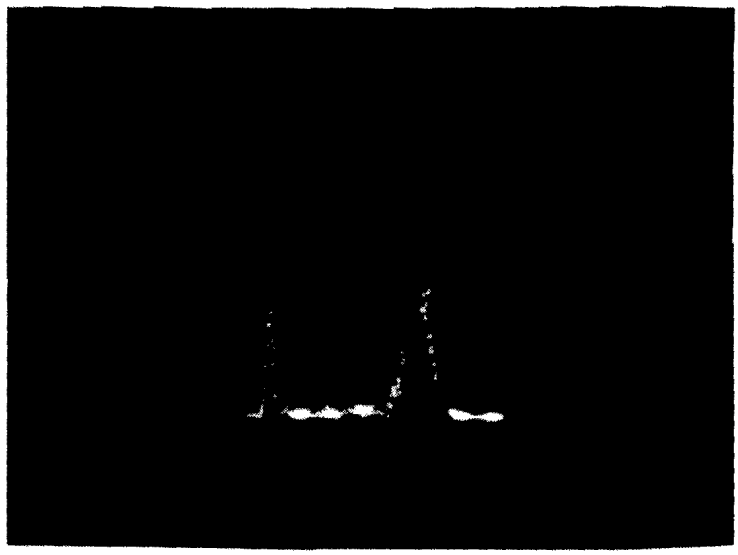
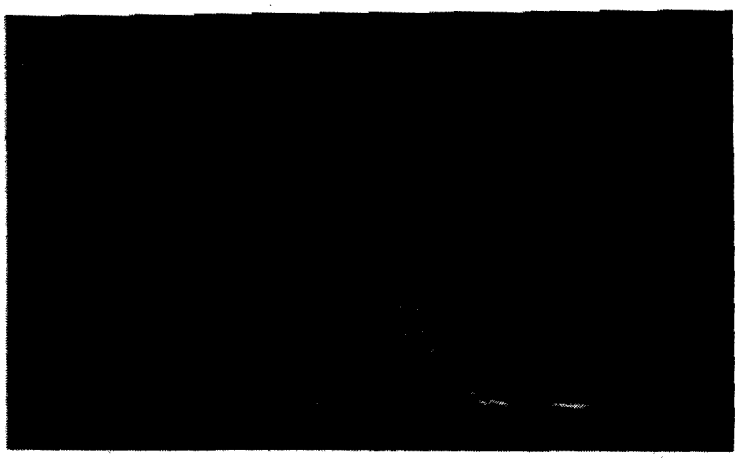


Figure 10

π^+

3 GeV



5 GeV

7 GeV

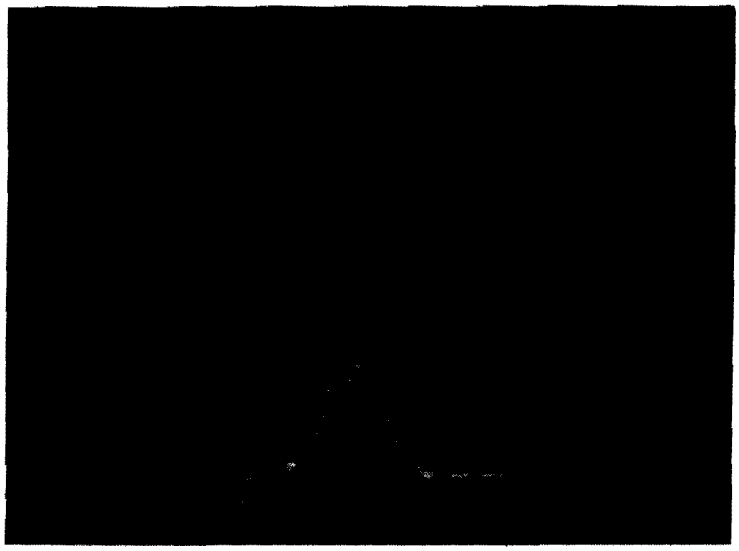
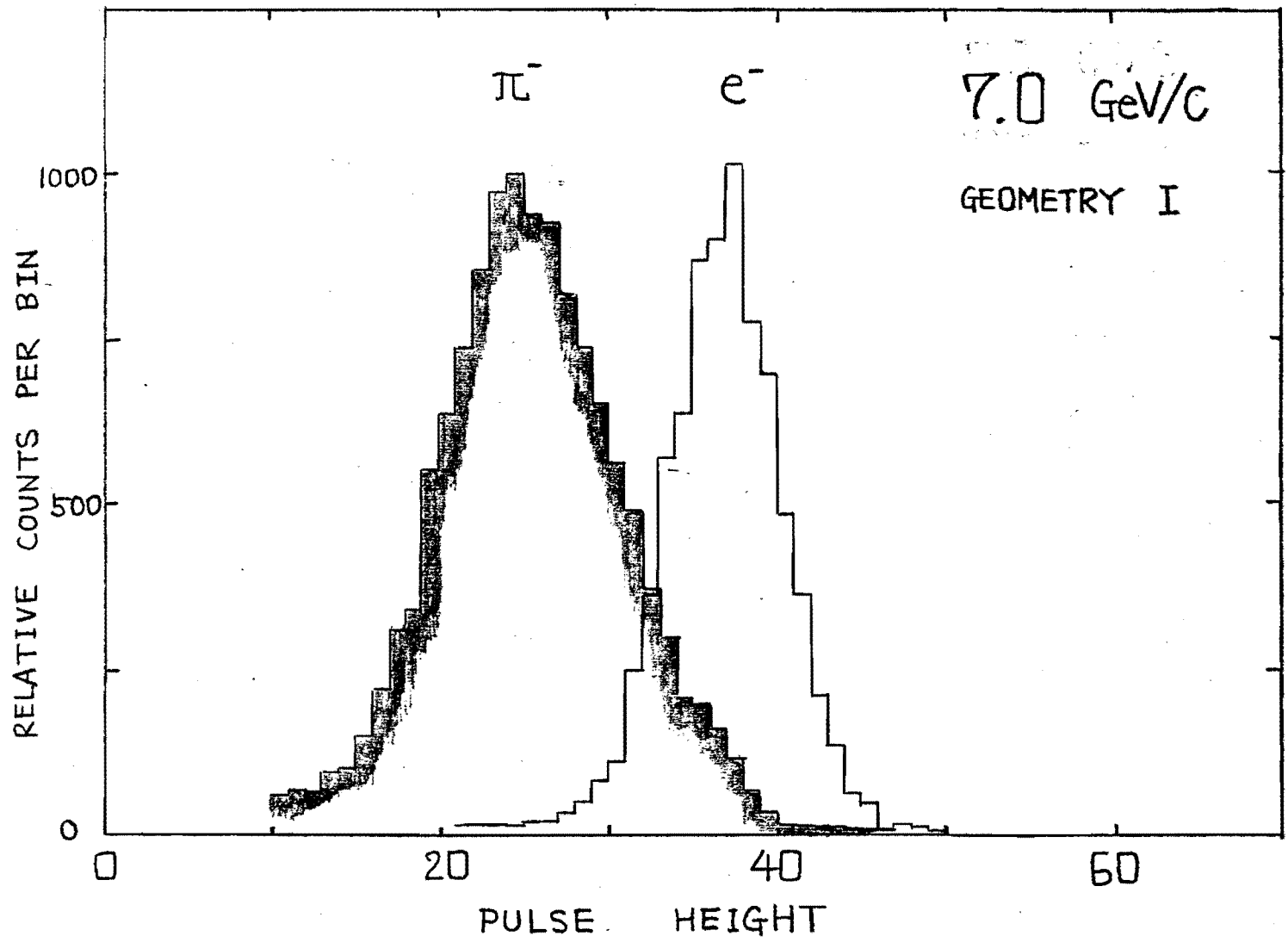


FIGURE 11


π⁻
e⁻
7.0 GeV/c
GEOMETRY I
1000
500
0
RELATIVE COUNTS PER BIN
0
20
40
60
PULSE HEIGHT

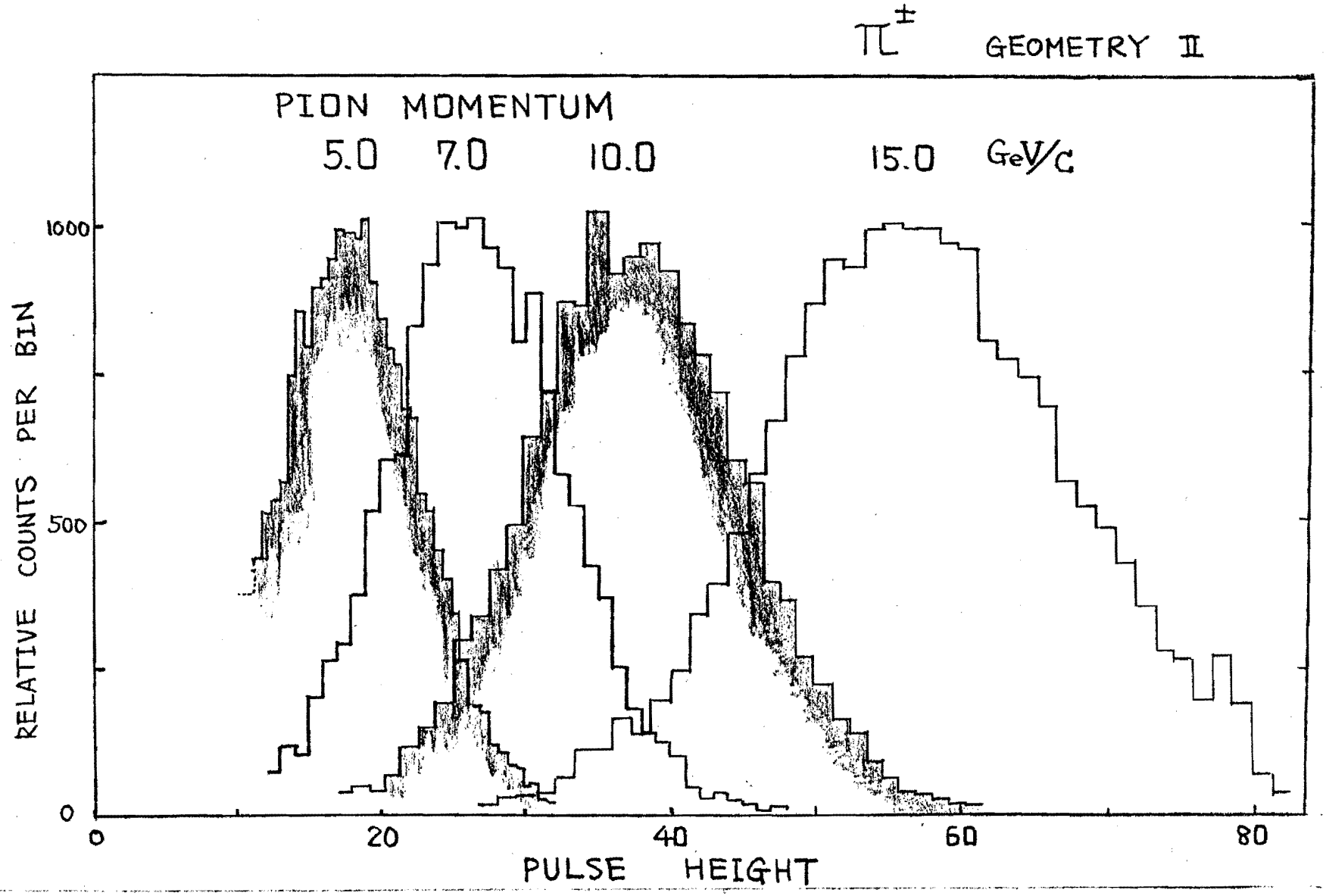
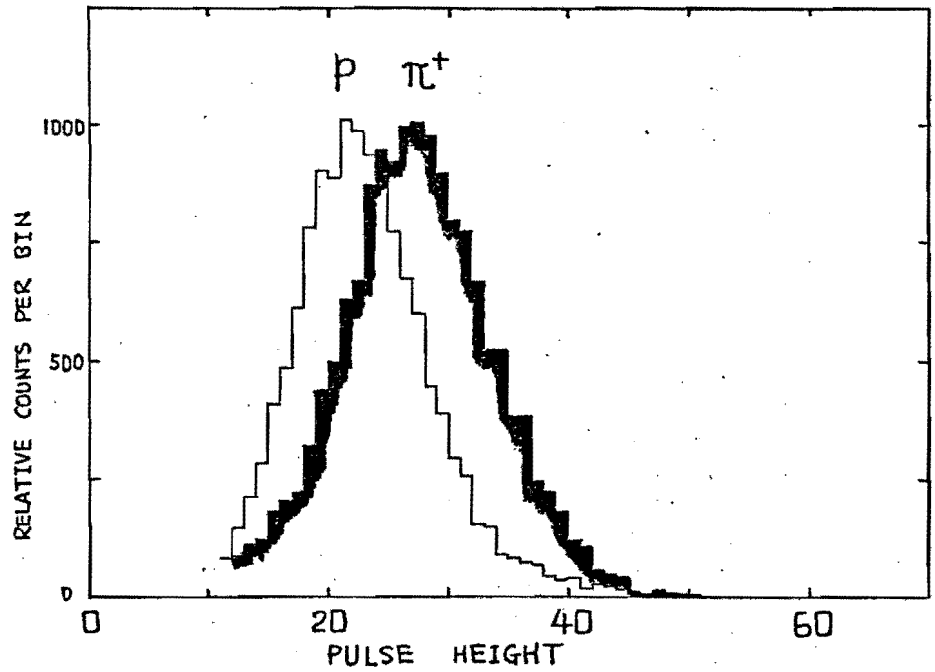

π±
GEOMETRY II
PION MOMENTUM
5.0
7.0
10.0
15.0
GeV/c
1000
500
0
RELATIVE COUNTS PER BIN
0
20
40
60
80
PULSE HEIGHT

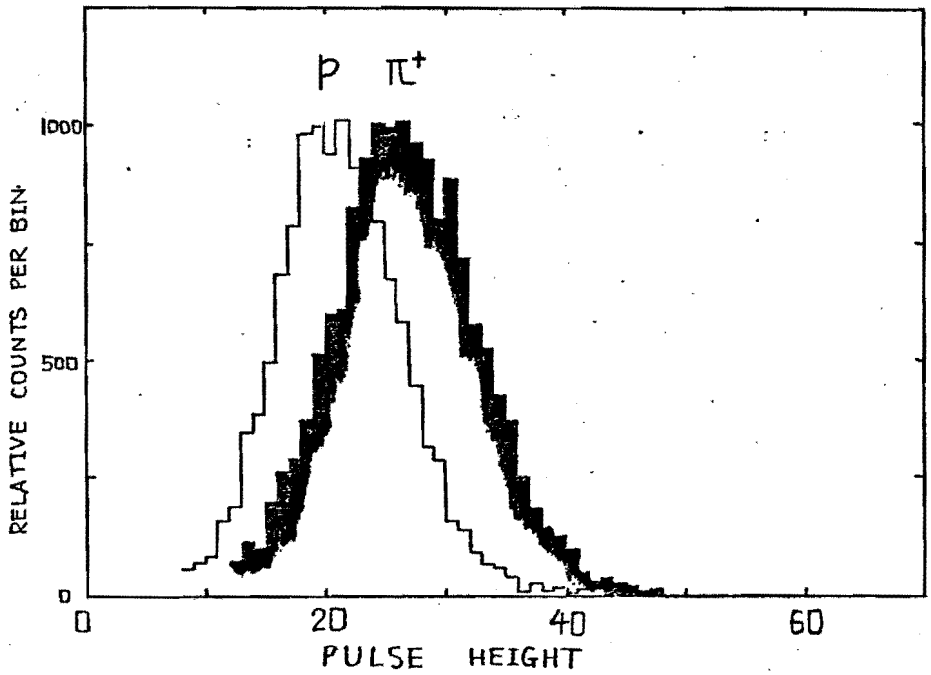
Figure 12

FIGURE 13

7.0 GeV/c



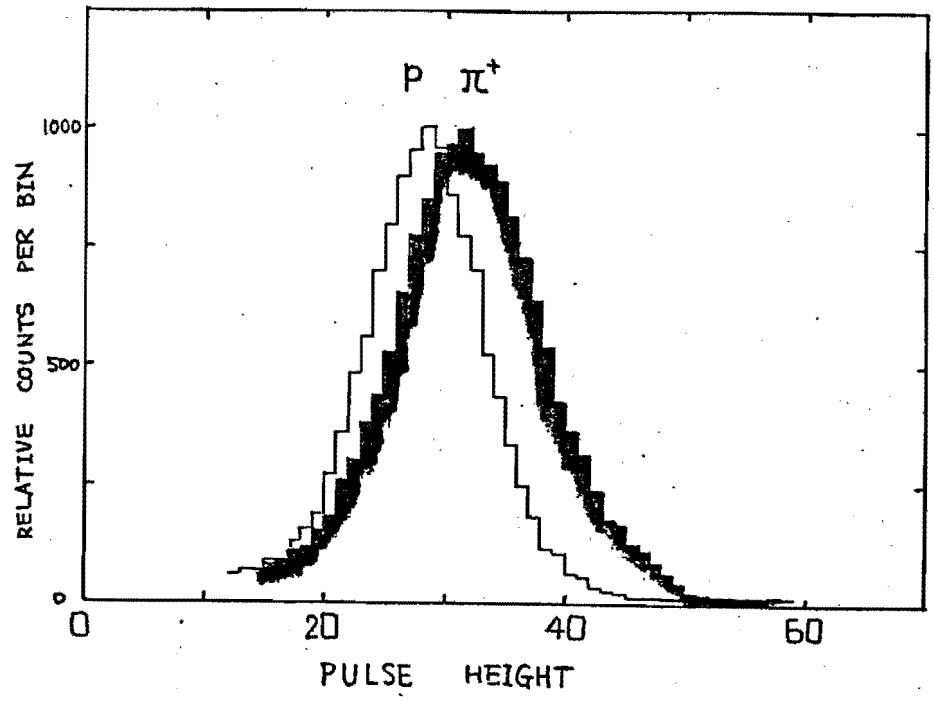
GEOMETRY I



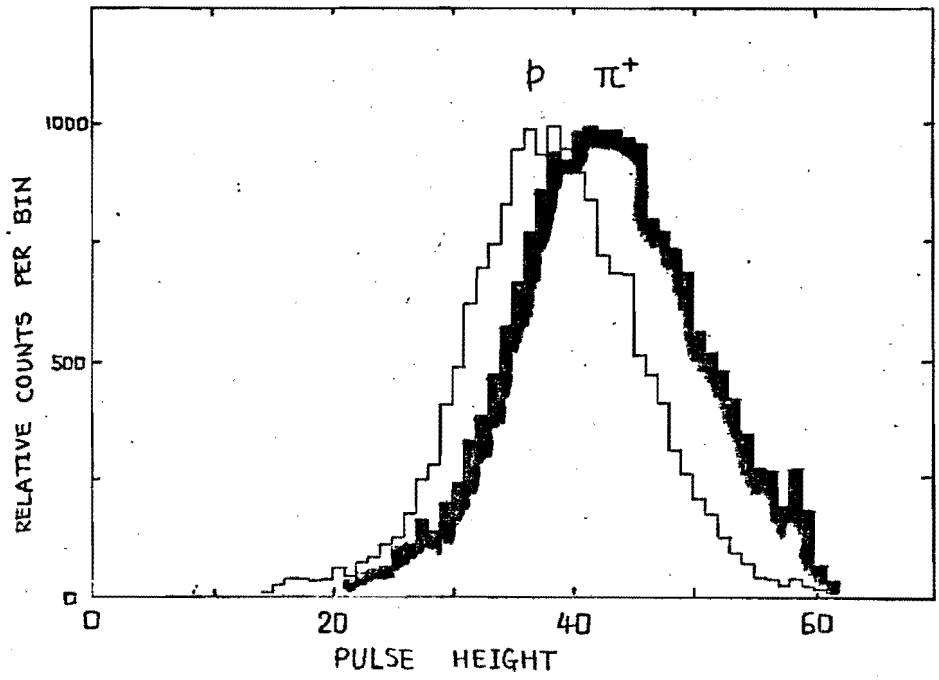
GEOMETRY II

FIGURE 14

15.0 GeV/c



GEOMETRY I



GEOMETRY II

T. Kondo
10/22/73

AN ESTIMATION OF THE TRANSVERSE DIMENSION OF HADRON SHOWERS IN IRON AT ABOUT 10 GeV/c

(1) We estimate a mean transverse dimension of hadron showers from the two following experimental facts:

(a) Dependence of the pion peak on the location of the beam, as observed at 7 GeV/c in our test runs with the 10-ton calorimeter.[1]

(b) Edge effects observed by Engler, Schopper et. al., with their total absorption spectrometer, for protons.[2]

In order to calculate the mean transverse radius R of the hadron shower, we must make some assumption about the transverse distribution of energy deposited in the hadron shower. The following discussion is based on a very simplified model, with energy deposition uniform inside a circle of radius R, and zero outside.

(2) <u>Estimate of R from the position dependence of the pion peak at 7 GeV/c.</u>

In Figure 1 are shown the relative pulse heights of the calorimeter for π, μ, and e, normalized at the center for each particle. Both muons and electrons give highly localized energy deposition compared with pions, and therefore the dependence of their pulse heights on the location can be taken to give the relative light collection efficiency at different locations. We have interpolated between the measured points in a smooth way, taking into account the geometrical symmetry of the

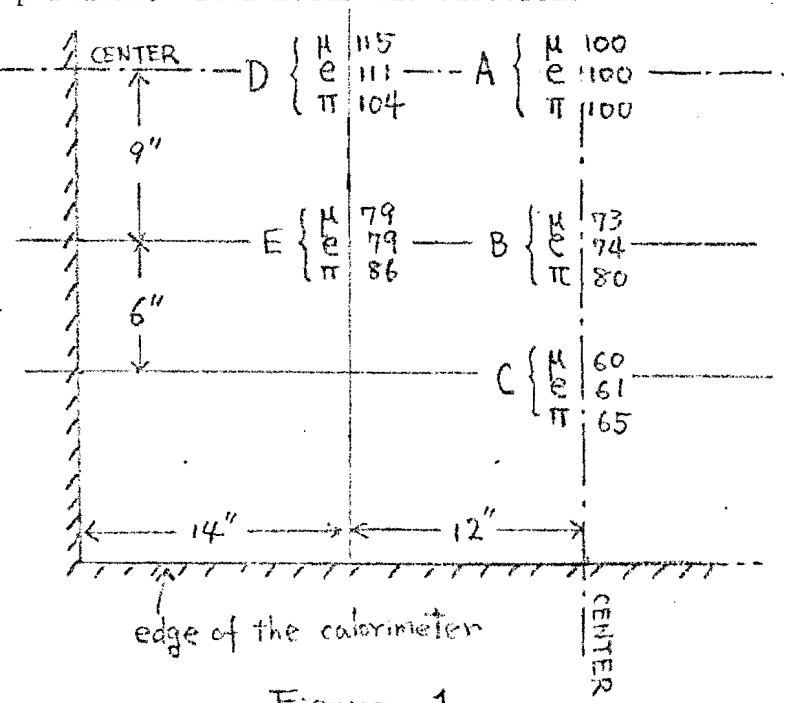


Figure 1.

device, to get the light collection efficiency at positions between the measured points. The pulse height for pions is affected by the non-uniformity of the light collection efficiency, and the pion shower pulse height can be calculated by averaging light collection efficiency inside a circle R. This was done at the positions A and B (see Figure 1) for three different values of R as follows:

R	Averaged Light Collection Efficiency at A	B	Ratio B/A
3"	99.0%	75.5%	0.76
5"	97.8%	77.0%	0.79
7"	95.5%	78.0%	0.82
Observation			0.80

Thus the experimentally observed ratio indicates to us that the mean radius R is between 5" and 7".

(3) Estimate of radius R from the edge effects measured by Engler et. al.

Engler et. al. found the mean pulse height decreased to 85% at a distance of 5 cm from the edge with respect to the one in the center. Using the assumption of uniform energy deposition, we can calculate the radius R of a circle 15% of the area of which is outside their spectrometer, as indicated in Figure 2. R is found to be about 8.5 cm.

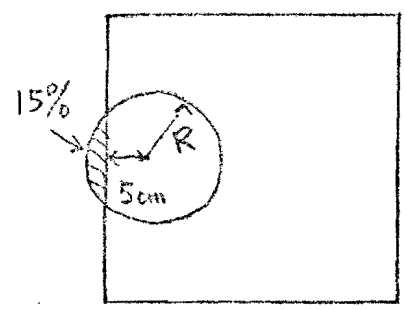


Figure 2.

(4) We examine whether the above crude estimates of R are consistent with each other, by expressing R in units of collision length, as follows.

	Configuration of Matter	Collision Length	R in Collision Length
Our calorimeter	0.5"Fe + 1.5" liq. scintillator	43 cm	0.28 – 0.4
Engler et. al.	2cm Fe + 0.7 cm plastic scint. + 0.8cm gap	28 cm	0.3

The collision length of each detector was obtained using 136 g/cm^2 for one interaction length in Fe. As is shown in the last column, the values of R estimated from two different experiments agree reasonably well.

We thus conclude that, using this model of uniform transverse energy deposition inside a radius R, the value of R is about 0.3 collision length. Some of the slow particles made in a cascade could travel considerably larger distances sideways. Therefore, if one wishes to contain a very large fraction of the total energy, say 90%, one should use a larger "effective radius" than the value of 0.3 collision length obtained in this note.

References: (1) BNL-Penn-Wisconsin Collaboration, Internal Report, October 11, 1973.

(2) J. Engler et. al., Nuclear Instruments and Methods 106, 189 (1973).

T. Kondo and W. Selove
10/18/73

BACKGROUND EFFECTS, FROM PILEUP, IN A HIGH-p_T CALORIMETER EXPERIMENT

(1). In an inclusive high-p_T and high intensity experiment using a calorimeter, more than one interaction might occur within the resolving time of the apparatus. In such a case transverse momenta observed in the calorimeter could be added up to give a false high-p_T signal.

(2). The probability to have n interactions within the resolving time and unresolved in vertex position in the target is given by

$$P_{int}(n) = \frac{m^n e^{-m}}{n!} \qquad m = Nq \tag{1}$$

where N is the number of incident particles in the resolving time and q is the number of interaction lengths in the resolving length in the target. We assume that q is small enough so that only n = 1 and n = 2 are important. The following example is given for N = 1 and q = 0.04 (or for N = 4 and q = 0.01)

$$P_{int}(1) = e^{-0.04}, \quad P_{int}(2) = 0.02\ e^{-0.04}, \quad P_{int}(3) = 0.0003\ e^{-0.04}.$$

and in this case the ratio R_{int} of the double interaction to the single one is

$$R_{int} = \frac{P_{int}(2)}{P_{int}(1)} = 0.02 \tag{2}$$

The quantity R_{int} is plotted in Fig. 1 as a function of the resolving time and of the intensity of the incident beam, for the cases of q = 0.04 and q = 0.01.

(We consider that q = 0.01, which is ~3 inches of liquid hydrogen, is probably reasonably achievable. We also note that when there is an improvement in the microstructure at NAL, one can also profit from the use of sharper time resolution, and can use several times higher beam rate.)

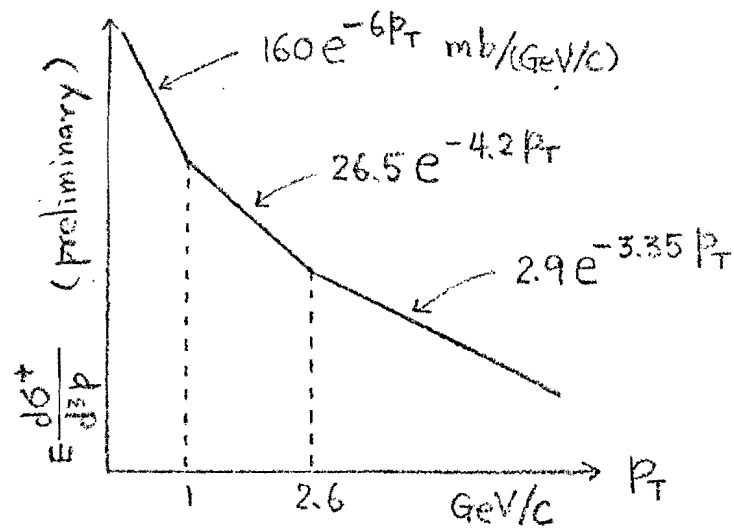
(3). The probability P_1 that one interaction in the target gives a transverse momentum deposit between p_T and $p_T + \Delta p_T$ in the calorimeter of $\Delta\Omega$ sterradian is written as

$$P_1(p_T)\Delta p_T \Delta\Omega = \frac{d\sigma}{dp_T d\Omega} \Delta p_T \Delta\Omega / \sigma_{tot} \tag{3}$$

where $\frac{d\sigma}{dp_T d\Omega}$ is the differential inclusive cross section given by the following approximation at 90°

$$\frac{d\sigma}{dp_T d\Omega} \approx 3 \frac{p_T^2}{E} \frac{d\sigma^+}{d^3p/E} . \tag{4}$$

The invariant inclusive cross section $\frac{d\sigma^+}{d^3p/E}$ for positive particles is taken from the measurement by Cronin et. al. at 300 GeV/c in pp collisions. An approximate representation of these results is shown in the figure. The factor 3 in Eq. (4) is due to the inclusion of negative and neutral particles. The dependence of P_1 on p_T is shown in Fig. 3.



The probability P_2 that two interactions occurring in a resolving time of the apparatus

give a total transverse momentum between p_T and $p_T + \Delta p_T$ into $\Delta\Omega$ steradian is calculated by the formula

$$P_2(p_T)\Delta p_T \Delta\Omega = \Delta p_T (\Delta\Omega)^2 \int_0^{p_T} P_1(p_1) P_1(p_T - p_1)\, dp_1 \tag{5}$$

(4). The overall relative rate to have accidentally coincidenced interations which give a fals high-p_T signal is therefore given by

$$R(p_T) = R_{int} \cdot \frac{P_2(p_T)}{P_1(p_T)} \tag{6}$$

In Fig. 2 we plot $R(p_T)$ against p_T when R_{int} is 0.02 and $\Delta\Omega$ is 1 sr. Note that we have used here the known single-particle p_T distributions in making the calculation. If high-p_T events occur commonly as multi-particle groups, the results shown in Fig. 2 would be modified accordingly.

The relative contributions to the integral in Eq. (5) are plotted against p_1 for several values of p_T in Fig. 4.

U. of Penn. Internal Report
Octo[illegible] 15, 1973

Addendum
NAL #246
APPENDIX 4

PERFORMANCE OF A SAMPLING CALORIMETER AT 3 TO 17 GeV. A PRELIMINARY REPORT.*

BNL-Penn-Wisconsin**

Abstract: A sampling calorimeter has been built aimed at giving improved resolution in the few GeV range compared to previously obtained results. It has been run in a BNL test beam, with π, p, and e, at momenta from 3 to 17 GeV/c. Runs were taken with 2 different arrangements of plate and scintillator thicknesses.

For energies below 8 or 10 GeV, the fractional energy resolution for π and p becomes roughly constant, at about 50% FWHM. The tail of the resolution curve cuts off relatively sharply, at a pulse height about 50% above the peak of the distribution. These results are little different for the 2 geometries used: I) 0.5 inch Fe and 1.5 inch LS (liquid scintillator), and II) 1.0 inch Fe and 1.5 inch LS.

*Work supported in part by U.S. Atomic Energy Commission.

**BNL: F. Turkot; U. of Pennsylvania: E. Harvey, T. Kondo, W. Kononenko, E. M. O'Neill, W. Selove; U. of Wisconsin: R. Diamond, A. R. Erwin, R. Loveless, M. Thompson.

FIGURE 1. Probability Ratio of 2 Interactions to Single Interaction

$$R_{int} = \frac{P_{int}(2)}{P_{int}(1)} = \frac{\text{Probability of 2 interactions in resolving time}}{\text{Probability of 1 interaction in resolving time}}$$

[Target resolving length = 0.01 collision length (solid)
0.04 collision length (dashed)]

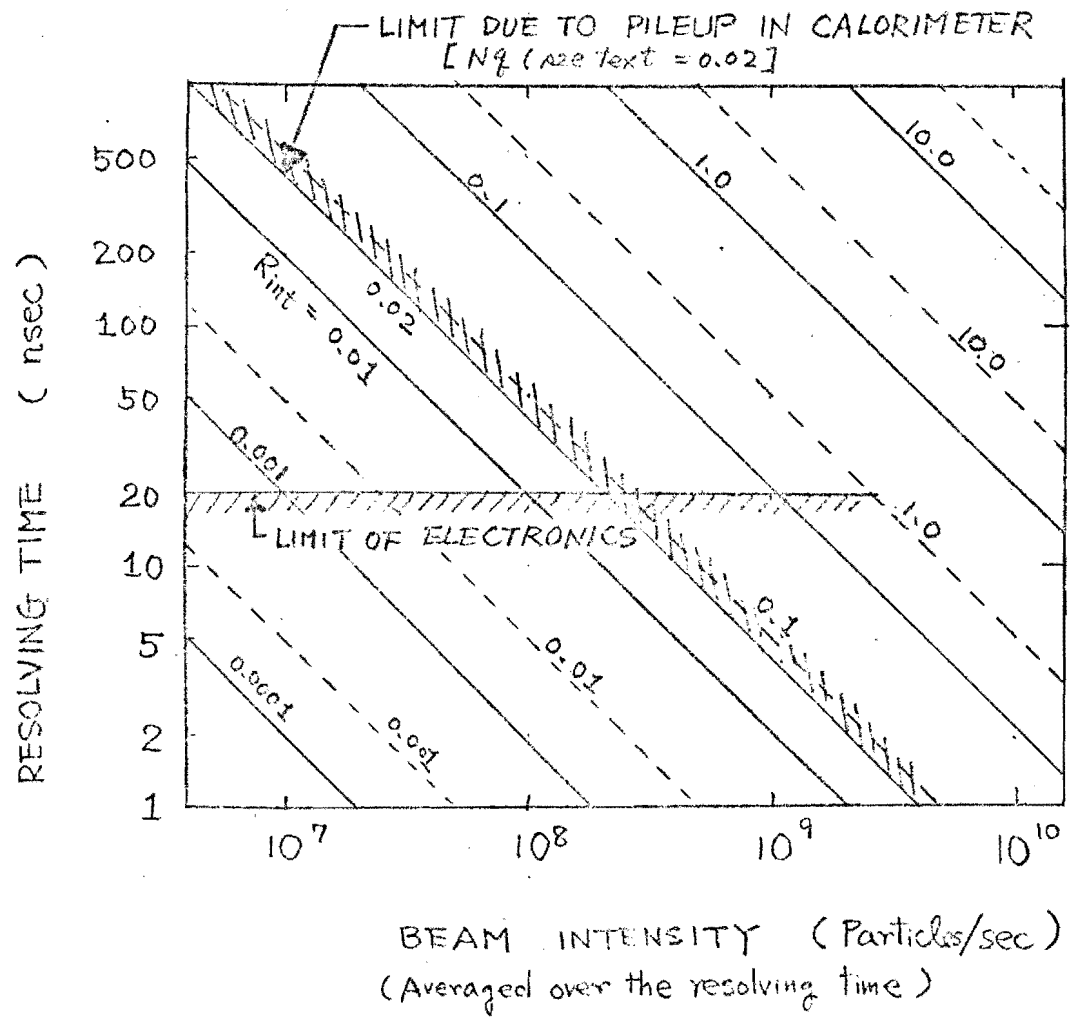


FIG. 2 Probability Ratio, $\frac{P_T \text{ by 2 interaction pileup}}{P_T \text{ in single interaction}}$

assuming single-particle inclusive cross-section applies directly

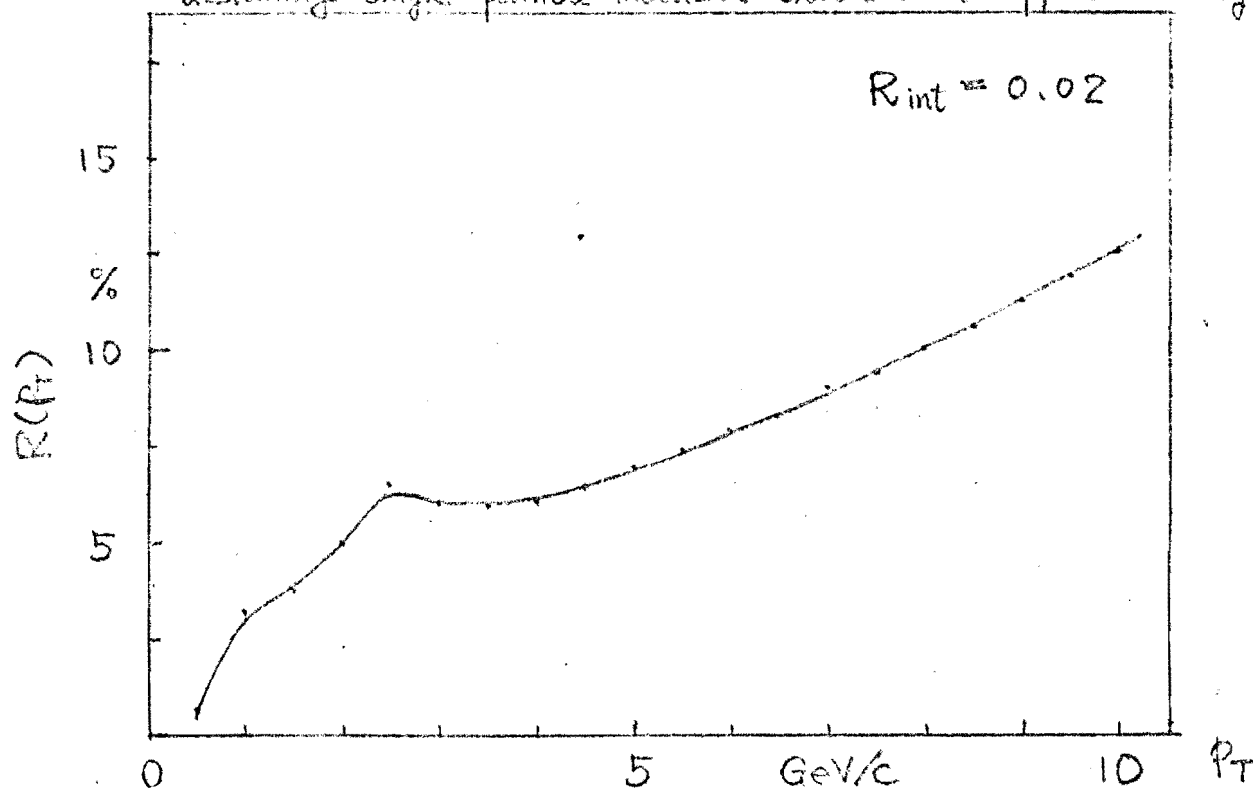
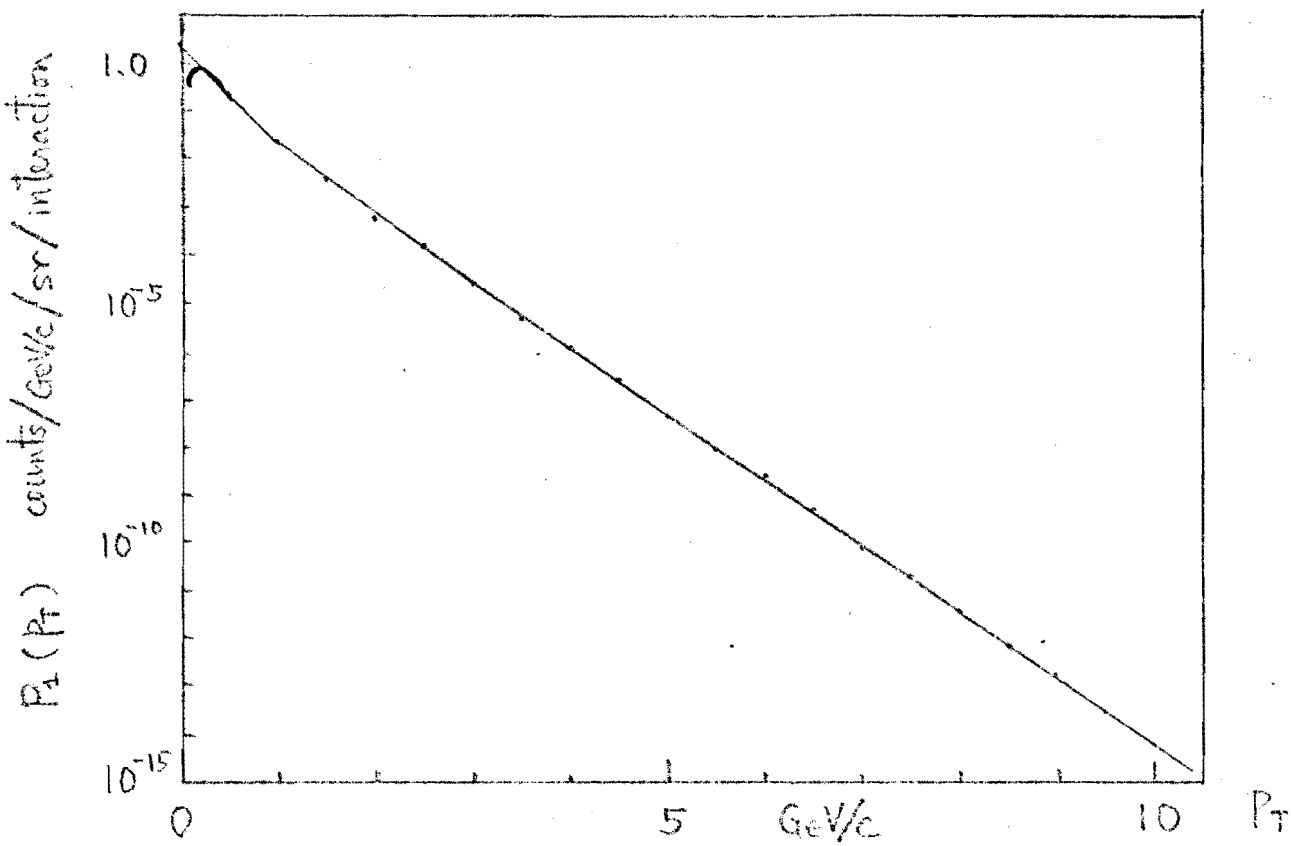


FIG. 3



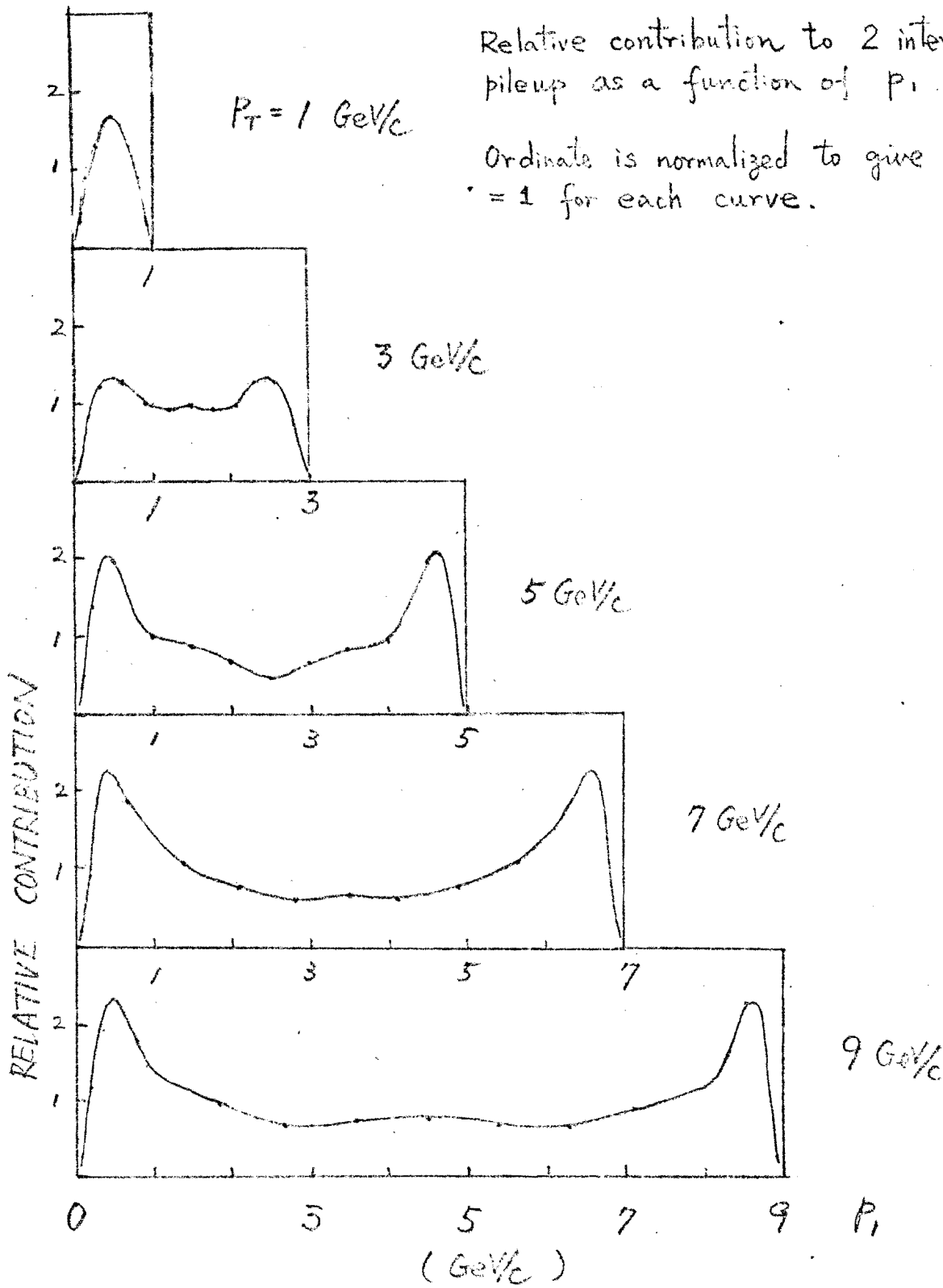

Relative contribution to 2 interaction pileup as a function of P_1.
Ordinate is normalized to give average = 1 for each curve.
P_T = 1 GeV/c
3 GeV/c
5 GeV/c
7 GeV/c
9 GeV/c
RELATIVE CONTRIBUTION
0
3
5
7
9
P_1
(GeV/c)

FIGURE 4

1. For some experiments aimed at studying high-p_T phenomena, one needs a calorimeter detector for hadrons having individual energies of 2 to 10 GeV. The most complete recently reported work in this energy range was that of Engler et al.[1] They found, with a sampling calorimeter, a FWHM resolution approximately constant at ΔE for protons of about 5 to 20 GeV; the ΔE(FWHM) in their detector was about 5 GeV. For work in the steeply falling momentum spectrum found for single π's near 90° at the ISR, such a resolution is useless below 10 GeV or so, since signals corresponding to a nominal 5 GeV, say, would in fact be totally dominated by signals from particles with a true energy as low as 1 or 2 GeV, which are thousands of times more numerous.

In a study of what resolution might be theoretically obtainable, it was concluded that it might be possible to obtain a resolution of about 50% FWHM, and an end point about 50% beyond the peak, independent of energy.[2] This resolution could in principle be obtained by using a much higher proportion of scintillator than that of Engler et al. A resolution of 50%, and a corresponding end point, would be just about satisfactory for use with a spectrum as steep as that at ISR at 90°. (At angles more forward than 90° less resolution is needed; and for multi-particle groups less resolution is needed.)

2. We have built and tested a calorimeter designed to answer several questions. 1) What resolution can be obtained for this energy range? 2) What does the tail at large pulse heights look like? 3) What effect does plate thickness have in a range of convenient thicknesses?

The calorimeter uses steel plates in liquid scintillator (LS). It has overall dimensions approximately 120 cm square (active area) by 250 cm thick. It is built in the form of 15 cases, each one 15 cm thick with 2 cm of wood between cases. Each case has 1/8 inch thick faces, and was operated with steel plates inserted so as to divide the 15 cm thickness into 3 or 2 compartments. Light is taken from the edges, collected 3 cases at a time into one 5 inch PM (54 AVP) on each side; the 15 cases are thus grouped into 5 triads, looked at by a total of 10 PM's. 1 to 2 per cent of the light reaching the edges was collected by the light pipes going to the PM's.

In "Geometry I", we used steel packages in each case which gave 1/2 inch Fe layers separated by $1\frac{1}{2}$ inch LS. The end faces of two adjacent cases, plus reflecting liners in the cases, plus the wood spacer, constituted approximately 1/2 inch Fe equivalent of nuclear interaction, roughly equivalent in thickness to the inserted 1/2 inch plates. Each case was thus divided into 3 gaps, and each gap was sampled at 3 points by light pipes.

In "Geometry II", the insert consisted of a 1 inch Fe plate in the center, bordered by two $1\frac{1}{2}$ inch LS gaps with 1/4 inch Fe plates outboard. In effect, the light from each of the two $1\frac{1}{2}$ inch gaps was then collected by a set of 3 light pipes, in the light pipe bundles going to the PM's.

The calorimeter could be moved vertically (operating at the reference height or at higher locations), and horizontally. Most of the data were taken with beam defining counters giving a beam 2 inches square entering the calorimeter, acurately aligned parallel to the calorimeter axis.

Figures 1-7 show some details of the physical arrangements.

The case faces, and the plates which were inserted, were lined with FEP teflon, following a technique developed by Cline, Mann, and Rubbia.[3] Extremely good reflection was obtained, as indicated in Figure 8.

3. Data were recorded on magnetic tape, and generally also on a PHA (this is mostly photographically). The PM gains were balanced, to within about ± 10%, by using muons. Each tube's output was amplified 40 times and connected to an individual ADC. The tube outputs, amplified by 10, were also combined into a video sum signal, which was also connected to an ADC. All ADC outputs were recorded on the magnetic tape.

To trigger separately on electrons, or to trigger separately on protons or non-protons, we used a gas Cherenkov counter located about 20 meters upstream. At momenta of 3 GeV/c and lower we used time-of-flight for the beam particles, to separate protons from other particles. For a muon trigger we used a scintillation counter positioned behind 15 feet of concrete following the calorimeter.

Beam rates were in the range of 50 K to 300 K per 800 millisec spill depending on beam momentum and polarity, and on whether we had lead blocks inserted far upstream in the beam. The beam intensity was not always under our control; but for careful measurements of tail effects we were able to take data with relatively low intensity in the beam. We could also, by software processing of the final data, use the first triad of the calorimeter as a veto on signals showing more than one minimum ionizing particle in the first triad, within the ADC time gate of about 200 nsec. (One triad is equivalent to about one collision length,

and about 7 radiation lengths.) With this veto cut we could obtain a purified sample of data for pions and for protons, although not for electrons, which typically deposited about 75% of the total energy into the first triad.

During a major part of the running, the test beam had many occupants simultaneously, and the beam region ahead of the calorimeter had some 20 gm/cm^2 of material distributed in the 20 meters ahead of the calorimeter.

4. A bird's eye view of some major features of the results can be seen in Figures 9 and 10. These were taken in 2 days or preliminary running which we had at the end of May. (Data taking resumed, after an AGS shutdown, in mid August.) These Figures show the following features. (All plots shown below were taken with the entering beam centered in the calorimeter and with no trigger requirements other than beam defining telescope and Cherenkov counter.)

1) For electrons the response is quite linear with energy.
2) The typical FWHM for electrons is about 20% for 5 to 7 GeV/c, and the spectrum shape cuts off sharply at about ± 10% from the peak.
3) For π's, the peak of the pulse height distribution occurs at close to 2/3 of the peak position for e's of the same momentum.
4) The end point of the π spectrum occurs close to where the electron (pure e-m shower) peaks; this is what is to be expected for charged-π events in which almost all of the energy of the π gets converted to π^0's in the first nuclear interaction. Thus the end point of the π spectrum is at about 1.5 times the pulse height of the peak.
5) The shape of the π spectrum, between peak and end point, is approximately linear. Thus the FWHM of the spectrum is also

approximately 50%.

6) The 50% FWHM value, and the 1.5 ratio of end point to peak, hold almost constant for incident energies between 3 and 7 GeV.

5. A few further features of the results are shown in Figures 11 to 14. There the following can be seen:

1) In Figure 11, π^- and e^- are shown for Geometry II. One sees that the resolution is very similar to that for Geometry I (Figures 9 and 10).

2) In Figure 12, the $\pi^\pm$ spectra are shown for 5 to 15 GeV, Geometry II. One sees the end point, say at the level with 1% to 2% of the area remaining, occurring about 50% beyond the peak position, for 5 to 10 GeV, and slightly closer for 15 GeV.

3) In Figure 13, π^+ and proton spectra are shown for 7 GeV/c, for both geometries. These two geometries have respectively Fe thicknesses of 1/2 inch and 1 inch. The resolution curves are almost indistinguishable for these two cases.

4) Finally, in Figure 14, π^+ and proton spectra are shown, this time for 15 GeV/c. At this higher momentum the FWHM is a smaller percentage than for the lower energy range, about 40% or a bit less compared to about 50%. Our preliminary examination of further results at the higher momenta in our data also suggests that the FWHM for protons may decrease a bit faster than for π's, with increasing energy.

6. We have benefited from much assistance given by the University of Pennsylvania machine shop, and by many individuals. We particularly thank M. Hearn and his Staff, and W. Mueller. Discussions with H. Schopper, and calculations he provided for us, were invaluable. A. Mann and C. Rubbia were generous in providing information and assistance. We profited much from discussions with W. Willis, T. A. Gabriel, and R. G. Alsmiller. We thank D. Berley, R. Stafford, and the AGS staff, for much help.

REFERENCES

(1) J. Engler et al., Nuclear Instruments and Methods 106, 189 (1973).

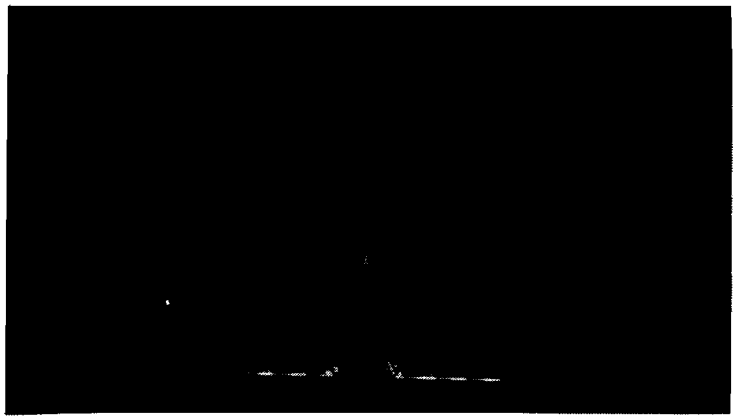
(2) W. Selove, NP Internal Report 72-25, 1972 (CERN).

(3) Private communication.

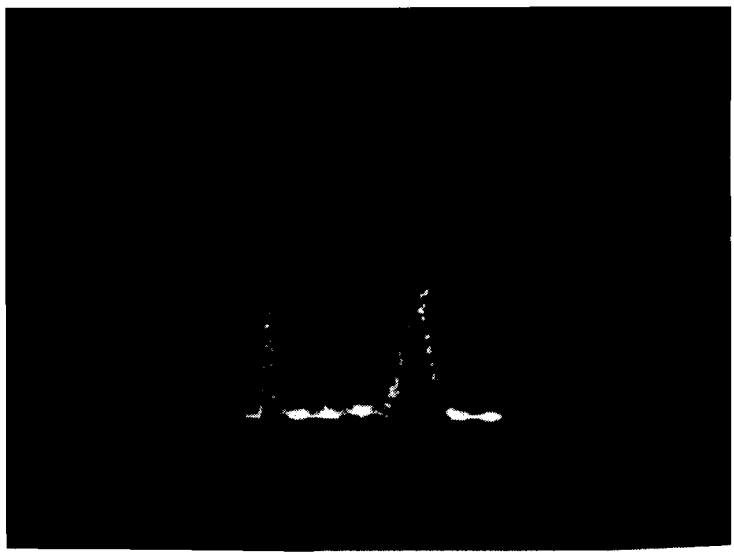
e^-

2.5 GeV

5 GeV

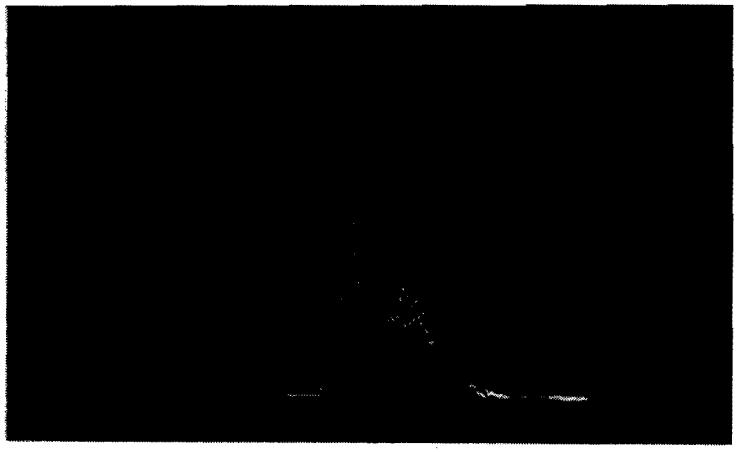


7 GeV

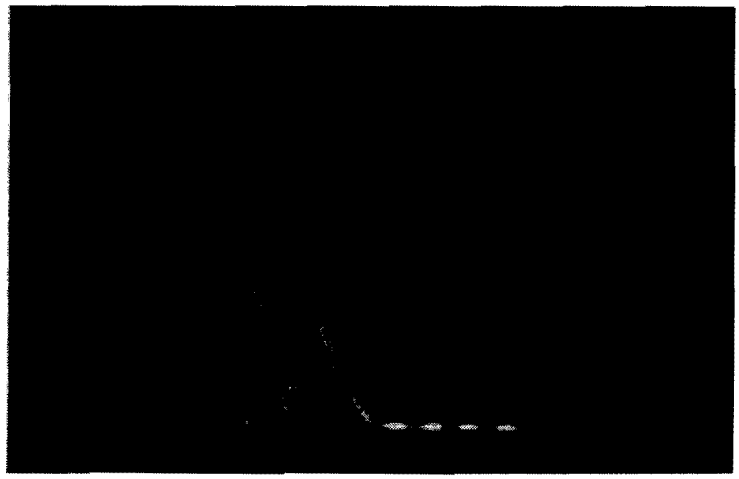


π^+

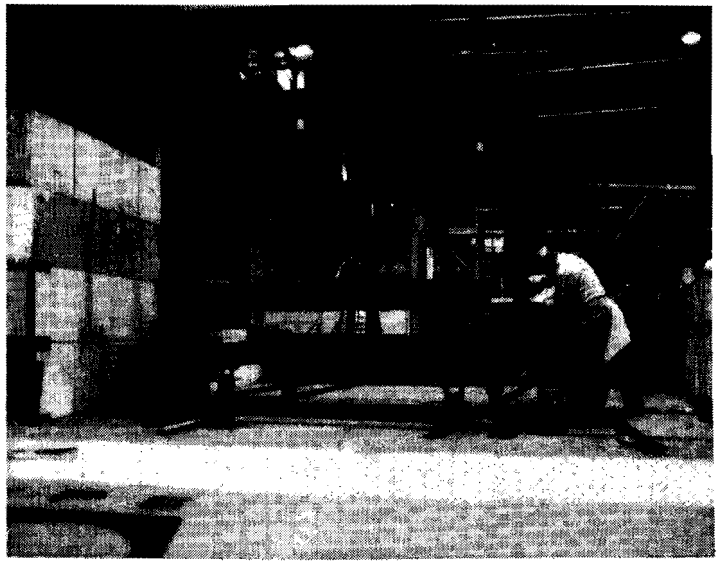
3 GeV

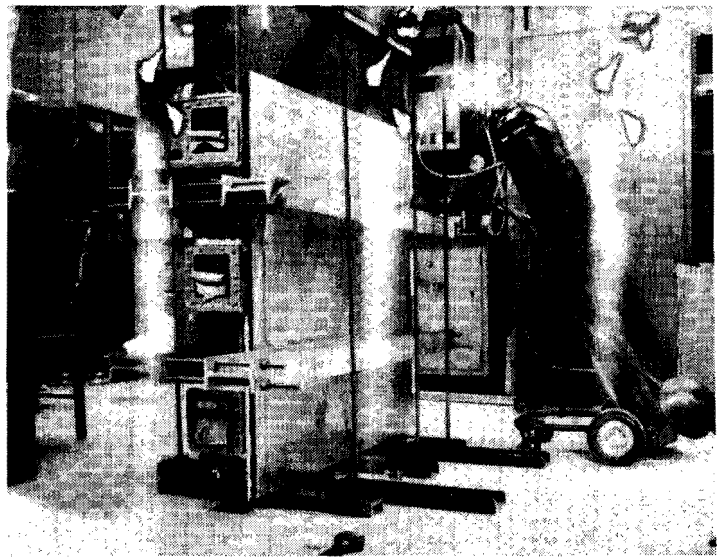


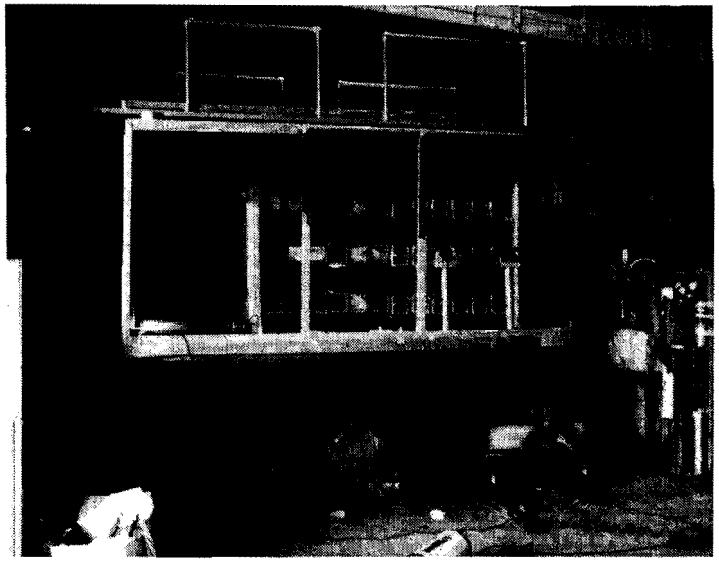
5 GeV

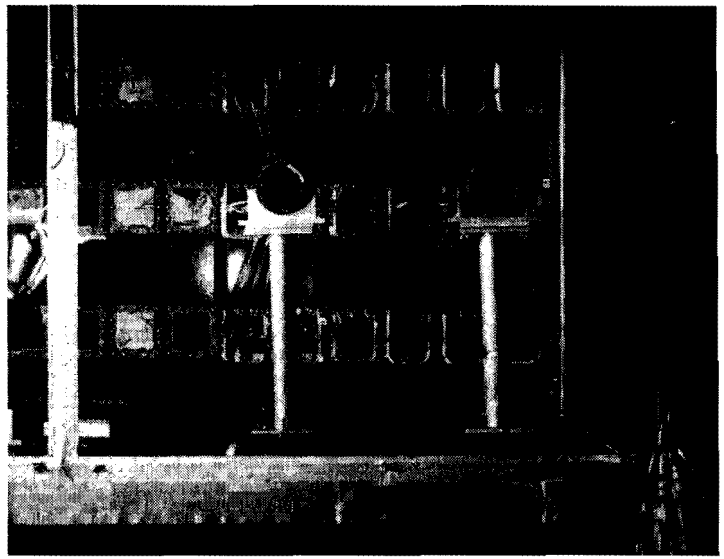


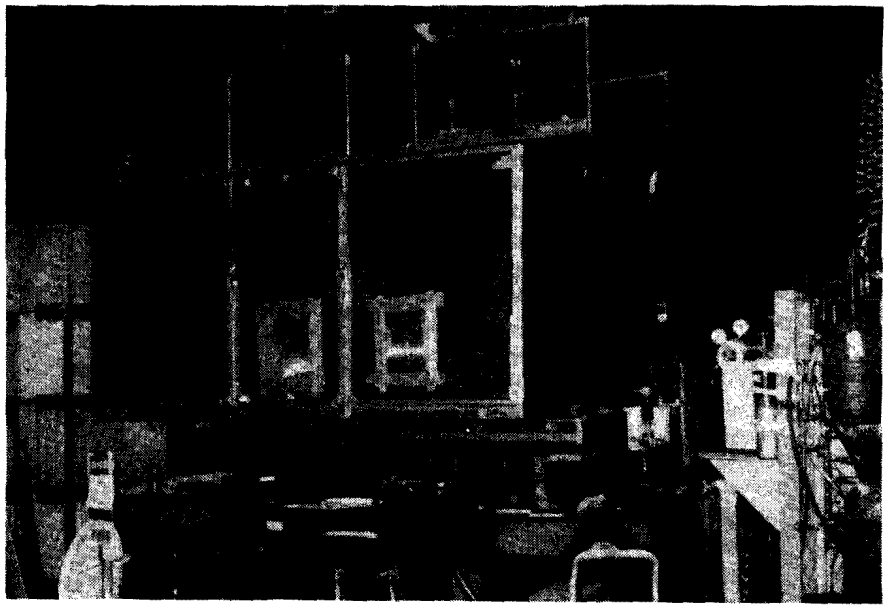
7 GeV

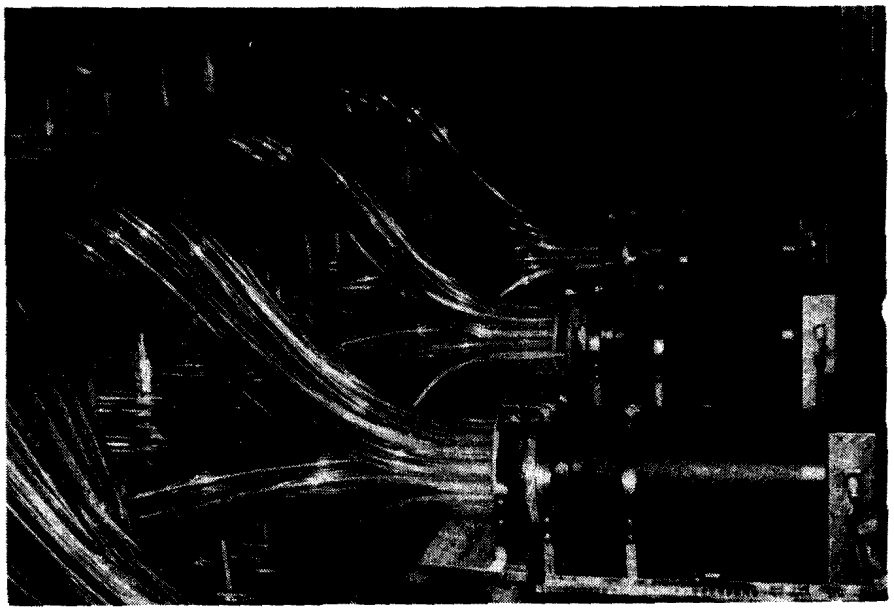












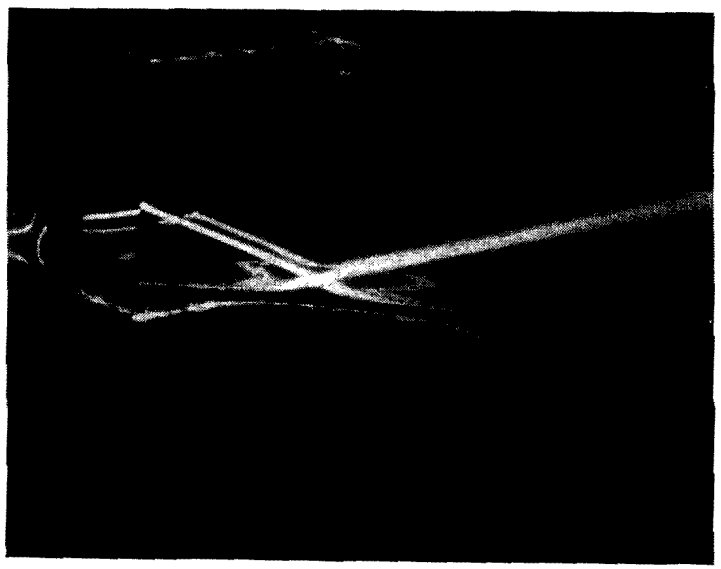
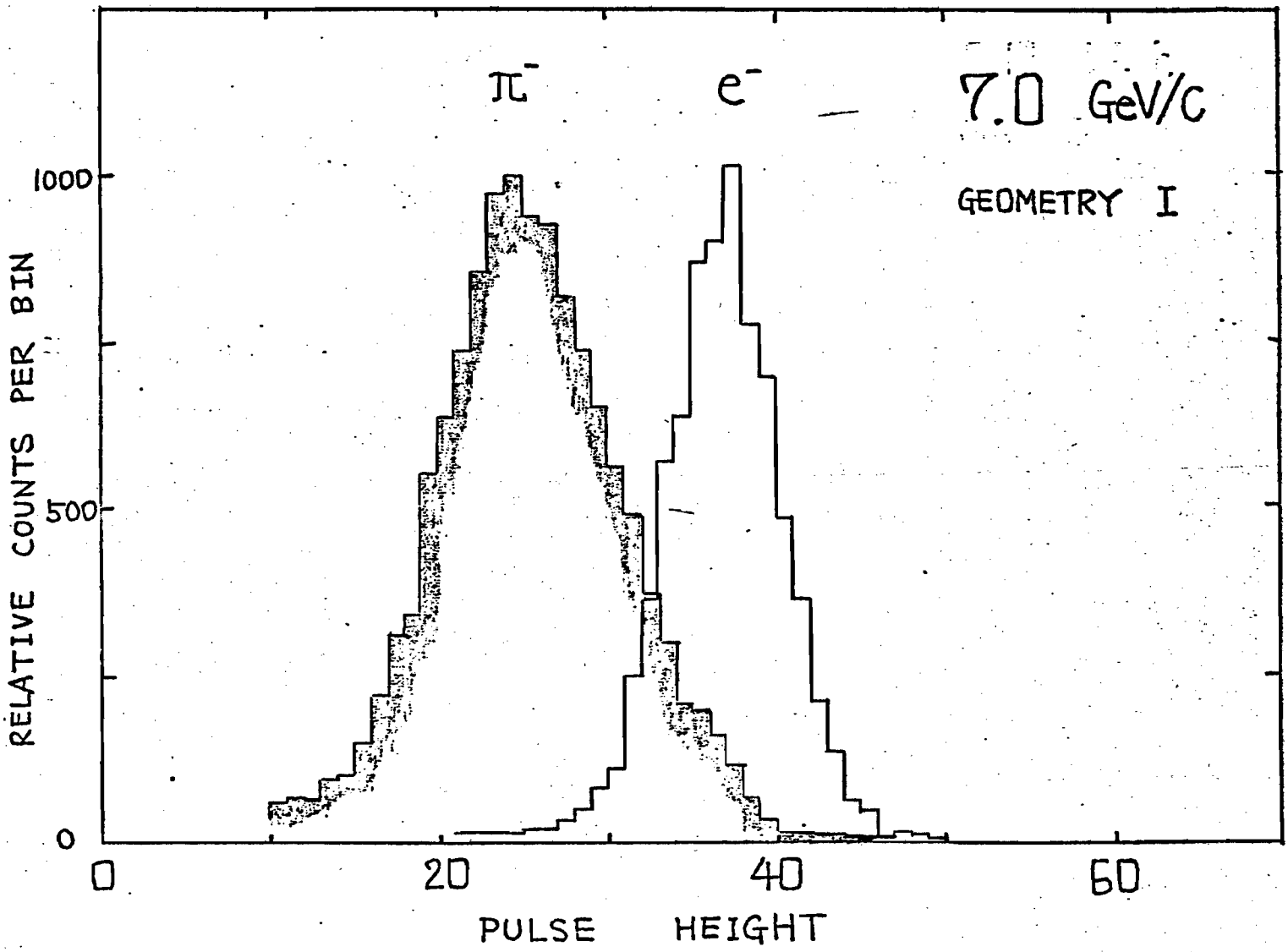


FIGURE 11


π⁻
e⁻
7.0 GeV/C
GEOMETRY I
1000
500
0
RELATIVE COUNTS PER BIN
0
20
40
60
PULSE HEIGHT

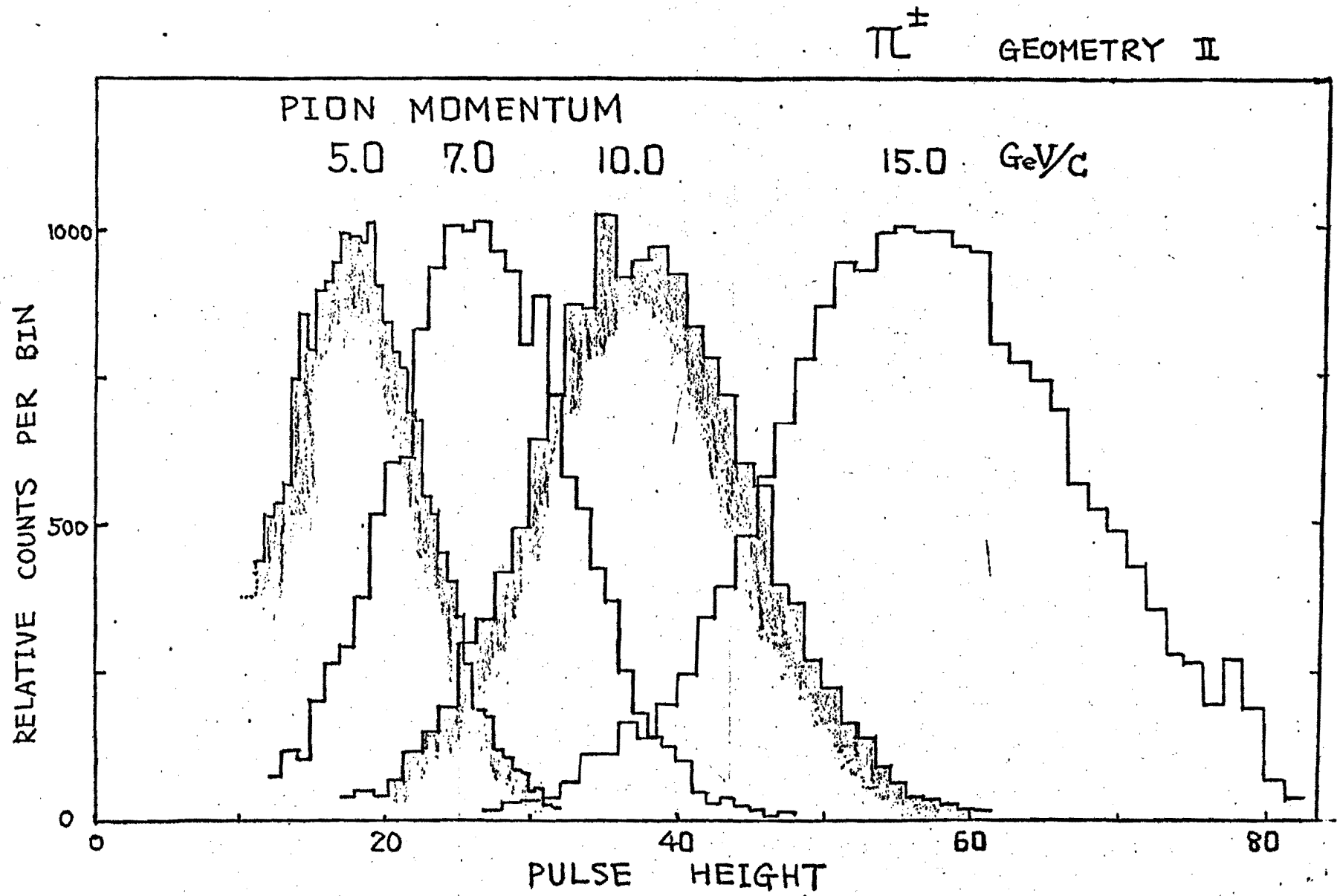
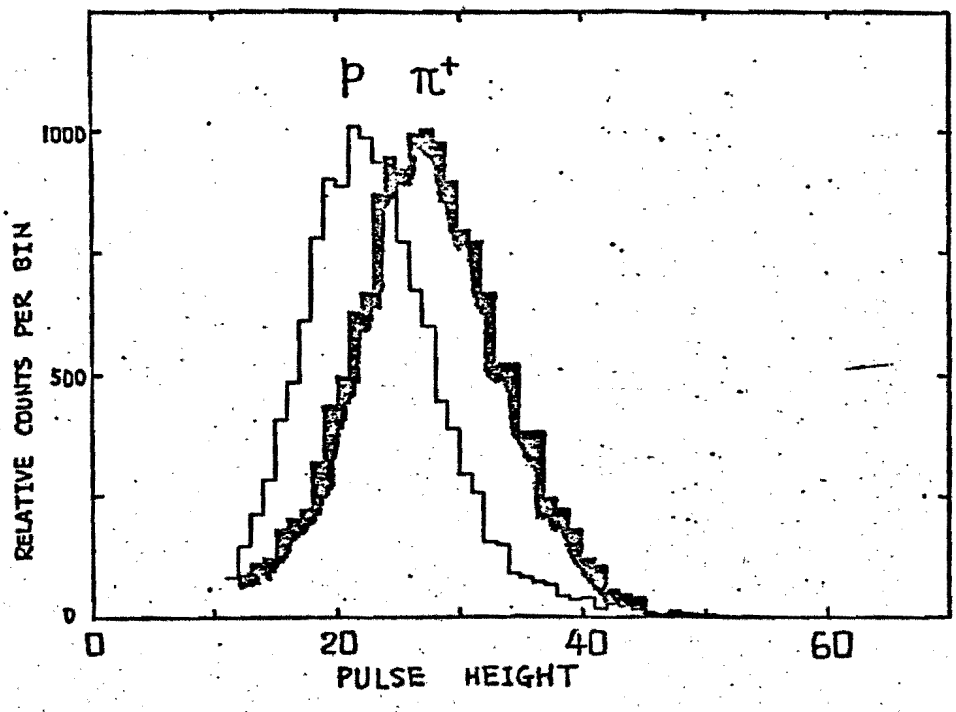

$\pi^{\pm}$ GEOMETRY II
PION MOMENTUM
5.0 7.0 10.0 15.0 GeV/c
RELATIVE COUNTS PER BIN
1000
500
0
0
20
40
60
80
PULSE HEIGHT

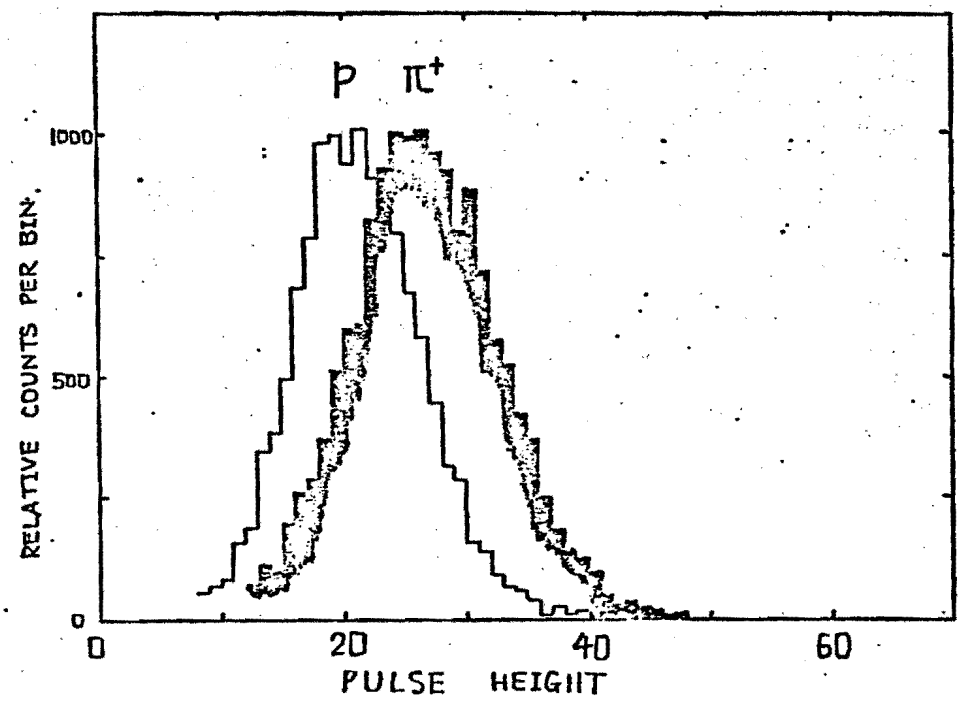
FIGURE 12

FIGURE 13

7.0 GeV/c



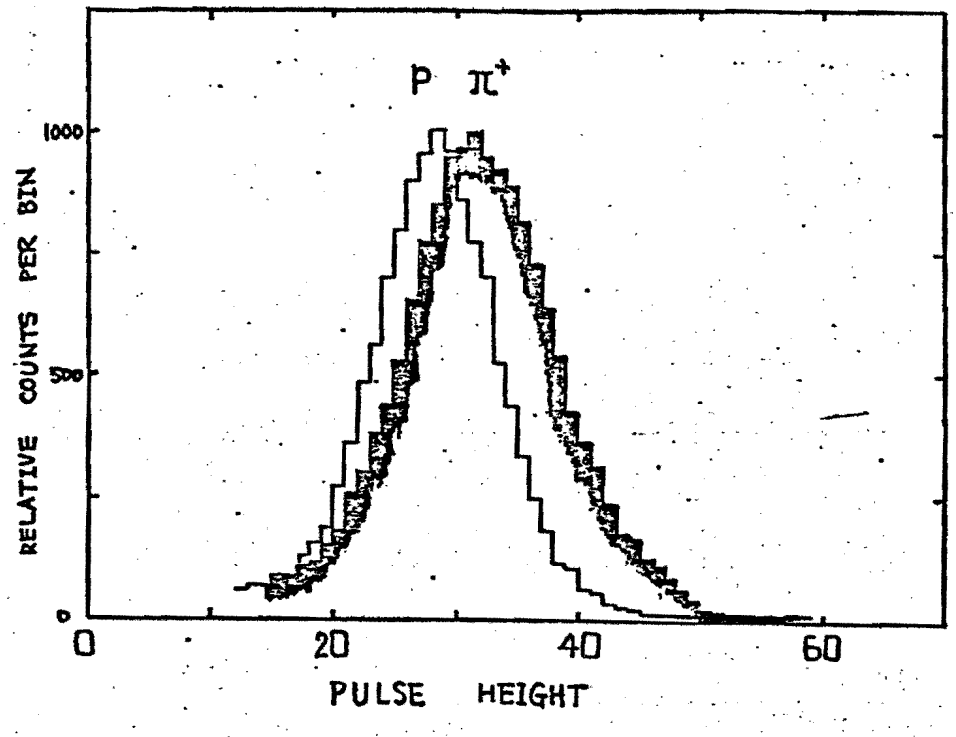
GEOMETRY I



GEOMETRY II

FIGURE 14

15.0 GeV/c



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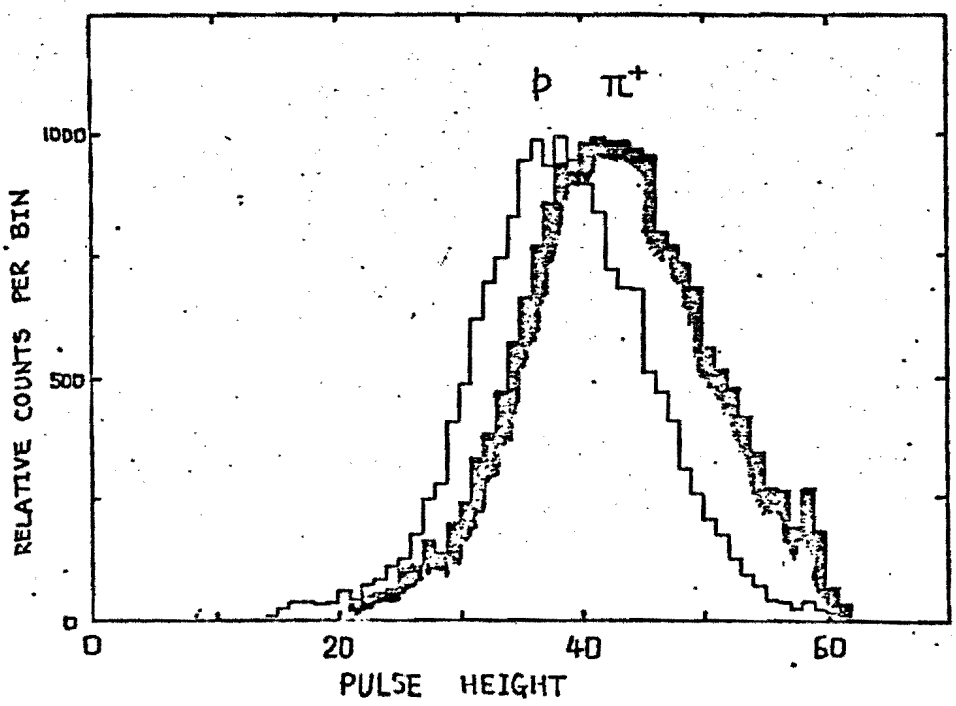

GEOMETRY II

FNAL Proposal 246A

May, 1977

Spokesman: W. Selove
(FTS 480-8159)

A STUDY OF THE STRUCTURE OF HIGH P_T HADRONIC INTERACTIONS

Lehigh-Michigan State-Pennsylvania-Wisconsin

ABSTRACT

An upgraded form of the segmented calorimeter detector described in E-246 and E-395 is described, along with the broad set of physics objectives which can be pursued with this detector in the detailed study of high p_t events produced in hadron-hadron collisions.

I. Introduction

This is an updated version of the proposal for E-246. E-246 was approved in 1974, for running in the high-intensity P-West beam. When E-395, a slightly reduced version of E-246, was approved in 1975, E-246 was changed to a deferred status.

E-395 is about to run, in M-2. Normally, we would have waited for results from E-395 before submitting an updated version of E-246. Since the PAC, however, may wish to consider jet proposals to some extent at its forthcoming summer meeting, we thought it useful to submit this brief update at this time. We will provide a more detailed supplement as soon as results from E-395 make it appropriate.

E-395 uses a highly segmented modular calorimeter of relatively good energy resolution. This calorimeter is of novel and advanced design, and uses individual modules of a design developed by us, and tested, in a quite substantial array, in M-5. E-395 has a two arm detector. One arm has full hadron detection capability, in a 25-segment array; the second arm has a 24-segment π° detector, and in addition some hadron capability of smaller solid angle. The entire calorimeter array can be moved along the beam line, so as to subtend solid angles in each arm up to 2sr at energies of 200 and 400 GeV.

This relatively large solid angle, together with the highly segmented form of the detector, gives a capability for studying high p_t events, jet-like or otherwise, which should show some of their features much more clearly than have existing experiments.
In 246, and subsequently, we have developed in detail a set of ideas for a detector of still much more capability. We describe briefly in this document some of those ideas, and some of the physics objectives which can be addressed with the expanded detector. We plan to submit a more detailed description after we have obtained some results in E-395. We remark here, as an introduction, that the apparatus, indicated in Fig. 1, has the following features:

1) It uses an expanded set of the calorimeter modules we have developed, to provide much increased solid angle coverage with full hadron detection ability.

2) The angular coverage includes the entire forward hemisphere, and substantial coverage at θ (cm) beyond 90°--out to approximately 135° at 200 GeV and higher (i.e., out to tan θ_{LAB} ~ 0.2 rad, or even more in a later phase).

3) The energy resolution for charged particles, and for most jets, is sharply improved by the use of an optimized degree of magnetic deflection, using a magnet of large aperture and small deflecting power (~ 3 kg-m).

4) Very comprehensive particle identification capability is included, permitting π/k/p separation of every charged particle detected, for particles with γ's between about 20 and 80. is done with a particle identifying device of new design.

II. Objectives

A large amount of experimental information exists on high-p_t events in hadronic collisions. From ISR experiments one has evidence of jet-like structure and an indication of roughly coplanar jet-jet type structure and recently from Fermilab E-260 much clearer evidence that jets are produced and in much greater abundance than singles at high p_t.

These results all agree in a general way with the picture of high-p_t hadronic events as occurring through quark-quark collisions (or collisions of other partons) as originally suggested by Berman, Bjorken and Kogut, and others. The possibility that this is indeed the dominant mechanism, and the corresponding possibility of obtaining experimental information on quark-quark forces, is what makes the study of these high p_t events so very important.

It is clear from existing experiments that a much more detailed experimental study must be done, to more fully understand the nature of high p_t events. Some major aspects of these events may be observed for the first time in E-395. E-246A would continue this study in much more detail. The objectives of a comprehensive study are of large scope, and include the following:

1) The fundamental objective is to study the hard-scattering mechanism which appears to dominate hadronically produced high p_t events. This requires a segmented calorimeter system of very large solid angle coverage, including also very large azimuthal coverage. Only with such a system can many of the following objectives be studied.

2) Two fundamental experimental quantities to be obtained are dN/dp_t (total) for jets, and the corresponding two-jet distribution. These quantities, and that of item (3), bear on the fundamental question whether high-p_t jet-jet events, and/or single-jet events, follow a p_t^8 law or instead more nearly the p_t^4 behavior expected in a simple model.

3) The possible extraction, from the data, of $d\sigma/dt'$ for quark-quark (etc.) scattering. (t', and s', are used to designate the variables in the quark-quark system.)

4) The experimental study of scaling or its absence. This question has many fundamental aspects, including the question of the detailed mechanism by which a quark turns into a jet, and the question of how closely the "fragmentation function" for quarks going into hadrons is similar to that for lepton-induced processes.

5) The study of coplanarity, or more generally of opposite-side momentum balance. This question involves fundamental questions of possible multi-jet structure, of internal transverse momentum for the initial quarks, of the p_t exhibited by the presumed beam jet, etc.

6) Measurement of particle species in jets to elucidate the quantum number flow.

7) Study of "asymmetries" in πp, Kp, pp collisions. (See E-246 for a detailed example of the result one might expect from the 2-quark/3-quark difference of π and p structure.)

8) Study of target dependence of high p_t phenomena. (This relates particularly to item 4 above.)

9) Study of the beam jet, or more generally jet structure in the near-beam region. This has to do with item 5 above, but also with the study of low-x phenomena, involving questions of internal x-distributions in the incident hadrons, possible study of quark-sea contributions, etc.

These objectives are ambitious. But nothing short of an experiment of the scope discussed here can provide an answer to the questions we have listed. Such an experiment must have large solid angle multi-segmented calorimeters, good resolution, and extensive particle identification capability.

The next section describes such a detector.

III. Apparatus

Fig. 1 shows a plan view of the apparatus, and Fig. 2 shows a front view of the calorimeter.

The basic features are the following:

1) In a very compact arrangement, the detector includes a large solid angle segmented calorimeter, magnetic deflection, drift chambers for tracking, and a new particle identifying system, the Čerenkov Imaging Detector (CID).

2) The calorimeter uses predominantly the same type of modules used in E-395. Approximately a doubled number is needed. We remark that 80% of these modules were built and tested in under 6 months.

3) Three of the four drift chamber modules shown (two planes per module) are the chambers from E-395; only one additional module is to be built for the new experiment.

4) The magnet shown is the BNL type 72D18. In the arrangement shown it gives a momentum resolution of about ±0.4%p (GeV/c). For energies below 30 GeV or so this gives better energy resolution than the calorimeter.

5) The magnetic "kick" of the magnet is small, about 0.1 GeV/c. This permits jet detection with negligible magnetic dispersal of the individual tracks and with negligible smearing of the p_t threshold.

The C.I.D. is a gas Čerenkov counter of a new type. It uses two spherical mirrors, one on each side of the beam, to image the Čerenkov light for individual tracks onto an image intensifier, with subsequent CCD registration and output. The performance which can be expected has been studied in detail, and with the region very close to the beam excluded, we expect to be able to identify π/k/p species for particle energies between about 10 GeV and 40 GeV, and to distinguish π from k/p down to 3 or 4 GeV. The system will readily handle tracks whose imaged Čerenkov light circles are interleaved or partially overlapped -- it uses the information on the diameter of each circle, in conjunction with the drift chamber

information on the location of each circle's center, to give identification even in the interleaved case. We remark that in a certain energy range the C.I.D. together with the magnet and calorimeter information also gives substantially improved energy resolution for k's and p's.

Initial development of the C.I.D. is under way. Work on various parts of it will be done by members of the collaboration at Michigan State, Pennsylvania and Wisconsin.

The calorimeter array is shown in Figure 2. Because of the modular nature of our calorimeter, it is readily possible to expand the solid angle coverage or the number of segments. It is also possible, as in E-395, to vary the distance of a part or all of the calorimeter array from the target, and thus to increase the angular fineness of the calorimeter coverage over some fraction of the solid angle covered.

The array shown in Fig. 2 covers the entire forward hemisphere, including the beam region, with elements which give sufficient p_t resolution to address the physics objectives given above. This complete azimuthal coverage to θ (cm) = 90° is provided at energies of 200 GeV or higher. In addition, substantial coverage exists at larger value of θ (cm), out to about 135° at 200 GeV or 250 GeV. At higher energies, of course, more solid angle is covered, by the entire system.

We are interested in adding still more modules, to give more angular coverage, in a later phase. The only limitation is money -- the modules are produced almost 100% industrially.

IV. Beam, Rates, Running Time

We propose to use the new P-West secondary beam. The prospective wide range of energies and intensities is of great value for the study proposed here.

Our present expectation is that most of our running would be done at a beam flux of a few x 10^7 particles/sec (averaged over the burst), or an interaction rate of a few x 10^6/sec. At this interaction rate we could obtain complete coverage of all particles except those in the beam line itself. For special purposes such as the study of the highest possible p_T region we would use a higher flux, probably up to several times 10^8. We expect to typically use a target of 5 to 10 percent interaction length. The flux levels usable are in general limited only by the time resolution of the calorimeter.

We request an initial time allocation of 1500 hours. 500 hours of this time is for testing and tune-up, and 1000 hours is for data taking. Some of the test/tuneup time could probably be done with simultaneous use of the beam by other experiments, particularly downstream of our setup.

We will also require substantial time in M-5 for testing of components of the detection system. Much of this time however is totally compatible with simultaneous use of the M-5 beam by many other experimental groups--we did much of our testing for E-395 in that mode.

V. Collaborators

The present collaborators for E-246A are listed below:

Lehigh: A. Kanofsky

Michigan State: C. Chang, K. W. Chen, I. Kostoulas, L. Litt

Pennsylvania: L. Cormell, M. Dris, W. Kononenko, B. Robinson, W. Selove, B. Yost

Wisconsin: M. Corcoran, A. R. Erwin, E. Harvey, R. Loveless, M. Thompson

In addition, we expect two to five graduate students to become engaged in this experiment.

We would welcome additional collaborators, although construction and running of the experiment described here are within our present capabilities.

VI. Costs

The equipment for this experiment will consist of:

(1) The present E-395 apparatus, virtually in its entirety.

(2) The C.I.D.--estimated cost $40K to $50K for the prototype and $30K for the second unit.

(3) Additional calorimeter modules--$150K.

(4) One additional pair of drift chamber planes--$20K.

(5) Miscellaneous--$50K.

In addition, a magnet, like the BNL 72D18, is needed. We would look to Fermilab for aid in providing such a magnet.

VII. Time Schedule

The equipment can be ready in less than one year from date of approval and of availability of funds.

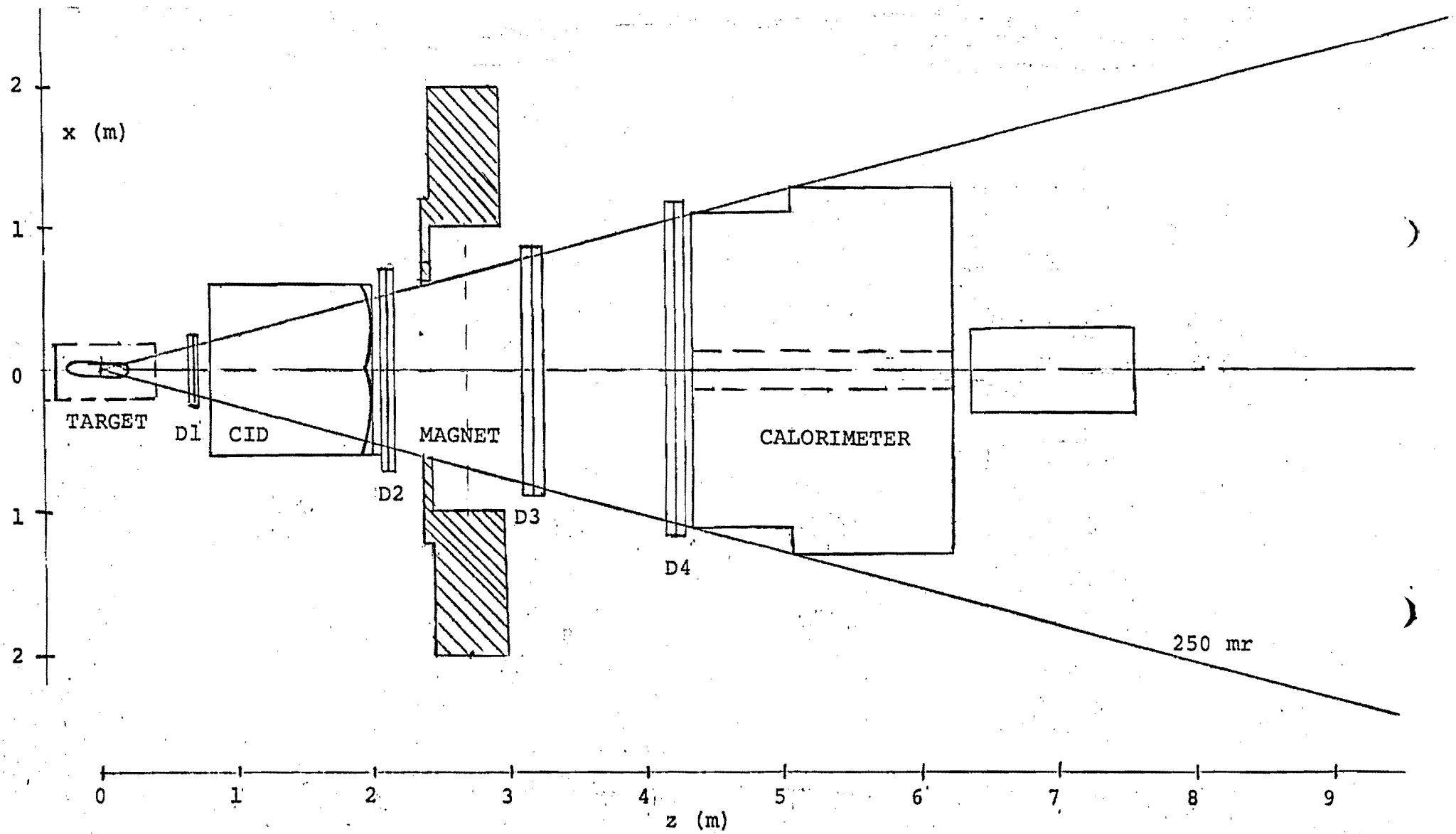

Fig. 1 Experimental layout

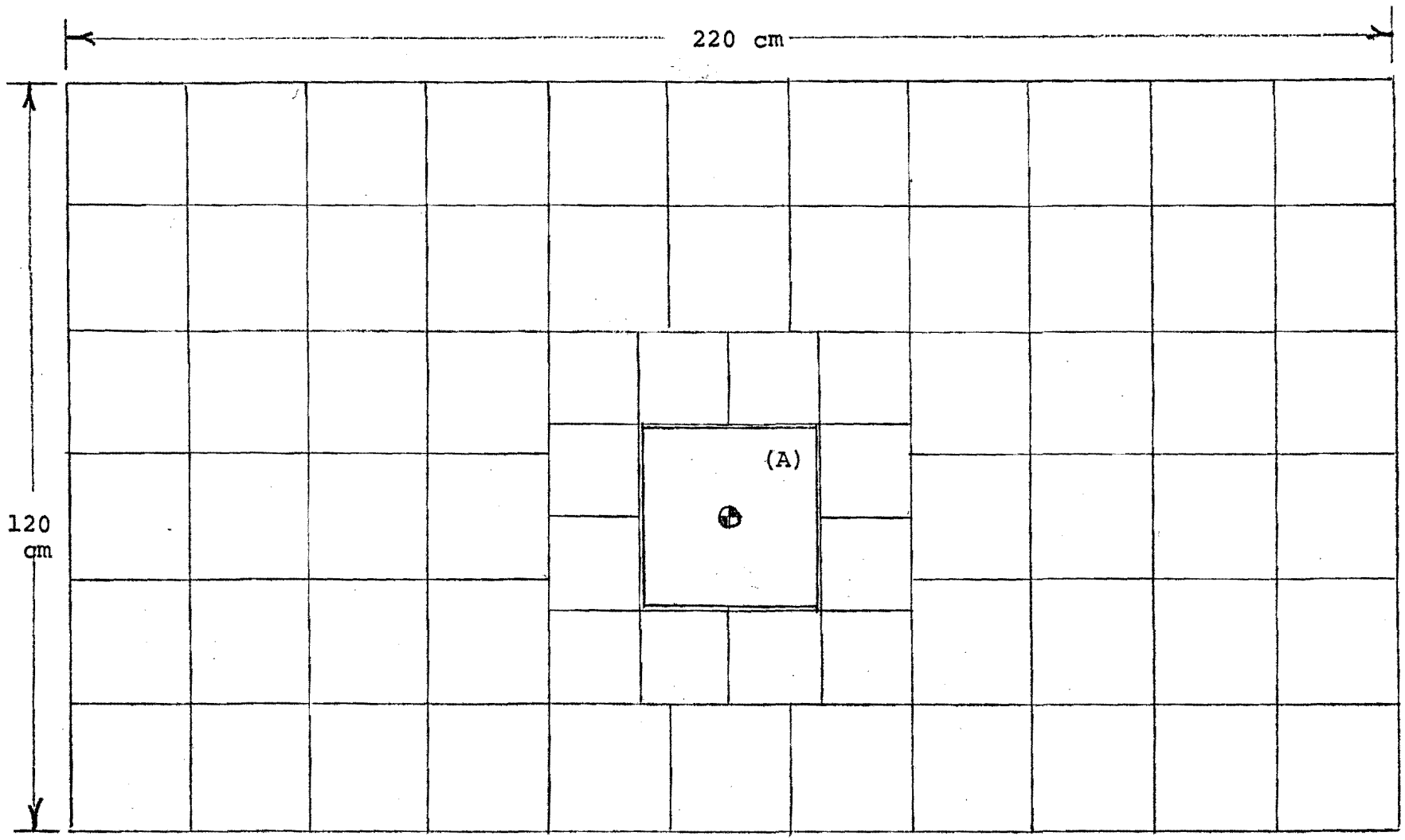

Fig. 2 Front face of calorimeter array

(A) The angular region close to the beam is covered by a more finely segmented section behind the main section

NAL PROPOSAL NO. 246

SCIENTIFIC SPOKESMAN:
W. Selove
Physics Department
University of Pennsylvania
Philadelphia, Pa. 19174

FTS/COMMERCIAL:
215-594-8159

SEARCH FOR DIFFERENCE IN PION/PROTON INTERNAL STRUCTURE

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

September 26, 1973

SEARCH FOR DIFFERENCE IN PION/PROTON INTERNAL STRUCTURE

September 26, 1973

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1. Introduction

2. Partons and Jet Pairs

3. Magnitude of the Asymmetry

4. Multiplicities in Jets

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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 three, 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.

In the parton model, the pion has a higher probability of having high momentum internal components (i.e., with a large value of the fractional momentum, x) than does the proton. This effect, somewhat analogous to the effect that would result from a 2-quark versus 3-quark structure, would cause the products of a parton-parton collision, from a πp initial state, to carry forward along the π's direction. There would thus exist a forward-backward asymmetry, in the overall πp CM system, for the products of a parton-parton collision. We estimate this asymmetry to be quite large in high-p_T events, which may be dominated by parton-parton collisions; no such strong asymmetry is necessarily to be expected in low-p_T events.

We propose to look for such an asymmetry. It seems likely that its presence, or absence, will constitute important evidence on the validity of the parton model, and could accordingly give important information on the structure of hadrons. Aside from any detailed model of parton distributions and interactions, moreover, the observation of such an asymmetry would constitute direct evidence of a difference in internal structure of the pion and proton.

The form of detector best suited to this study is a calorimeter hodoscope. To study the asymmetry, a pair of calorimeter detectors, on the two sides of the beam, is necessary. To obtain important additional information on the structure and multiplicity of high-p_T clusters, the calorimeters should be hodoscoped more finely than would be required for study of the asymmetry alone. The angular resolution and energy resolution required, the sensitivity required, the beam intensity and target length needed, and other details are described below. For sufficiently sensitive conditions, we estimate that a large asymmetry is expected.

In addition to information on an asymmetry, the detector we propose would be able to give information on many other features of high-p_T events, including the important ratio of event rates with jets of a given p_T compared to single particles of the same p_T, the distribution of multiplicities in jets and correlations in these multiplicities for jet pairs, much additional information on internal jet structure and on jet angular distributions, and some information on particle species in jets. We emphasize, in all this, that the basic asymmetry expected is not in any way dependent on whether multi-particle jets occur or not. Moreover, the asymmetry would occur regardless of the behavior of the parton-parton scattering cross section as a function of s' and t', the parton-pair energy and momentum-transfer variables.

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^o 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 <u>multi-</u>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 different kinds of particles. (We remark, as an aside, that evidence already exists indicating that some clustering <u>does</u> occur in high-p_T events; moreover, some clustering <u>must</u> occur, if only from production of resonances of high p_T.)

(2) In the experiment which we 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 $(\vec{P}_1+\vec{P}_2)_z$

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

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

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

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

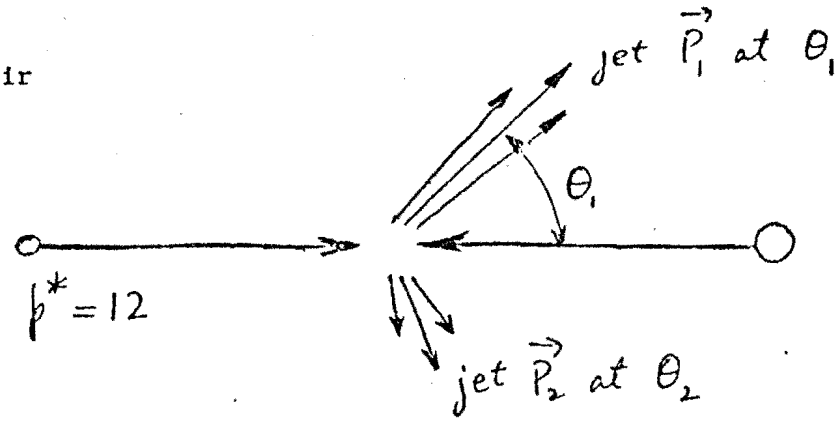
$$= \frac{g_\pi(.78)g_p(.55)}{g_\pi(.55)g_p(.78)} \approx 4 \ .$$

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

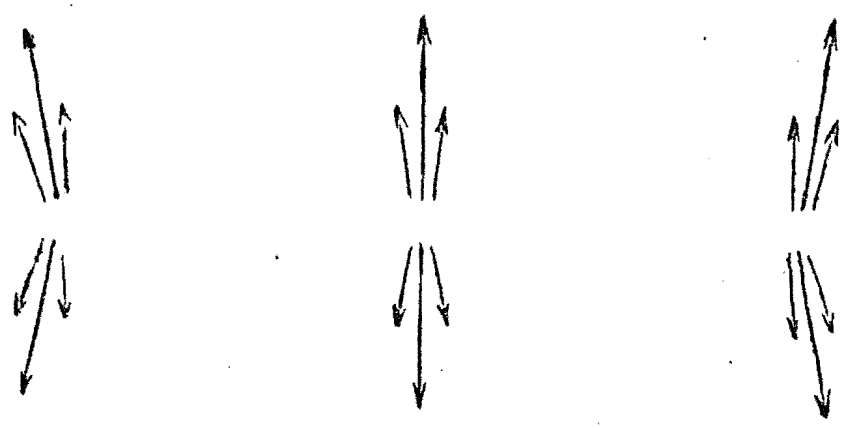
a) General jet pair



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

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

$\theta = 100°$ $\theta = 90°$ $\theta = 80°$



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 single π^o's of that p_T by a factor $\approx \frac{3}{2}(n-1)(n-2)$, 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) ~ 200 times as large as $\frac{dN}{dp_T}(\pi^o)$, at ~ 4 GeV/c.

If multi-particle jets were found this much more frequently than single π^o'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 ~ 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 ~ 1.5 GeV, a second of ~ 1.0 GeV, at an angle of ~ $\frac{1}{2}$ radian from the first, and ~ 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^0'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 resoltuion, 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 appears to be somewhat broader for charged π's than for protons. (For π^0's the resolution is considerably narrower than for other particles.) The physical mechanism which produces the broader resolution appears to be fluctuations in the fraction of the energy going into π^0'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.

(g) Detector layout. A schematic representation of a detector layout incorporating the above principles is shown in Figure 1.

COUNTING RATES

Our principal objectives require the highest possible sensitivity. (1) We wish to measure coincidences, and correlated multiplicities, between a pair of high-p_T clusters or particles. (2) We wish to measure the intensity of jets compared to singles. Both of these objectives 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 cycle 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.

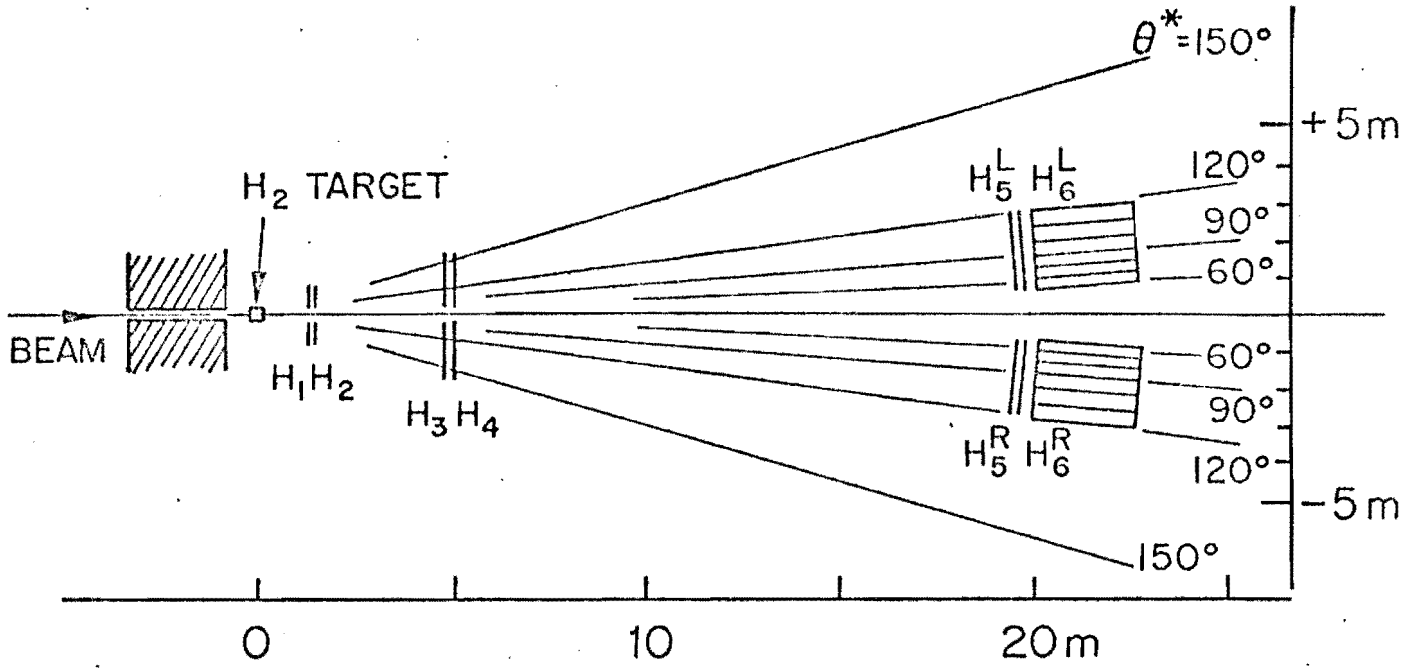
To what p_T will this permit us to go? We first discuss the answer in the case of pp collisions, and single π^o's. On the parton model, the rate for jets of a given p_T will be much higher; and on the parton model, the rate for πp collisions with very large p_T will be higher than for pp.

(a) Singles rates, pp collisions. For π^o's near 90°, made in pp collisions, the CCR data give a cross section:

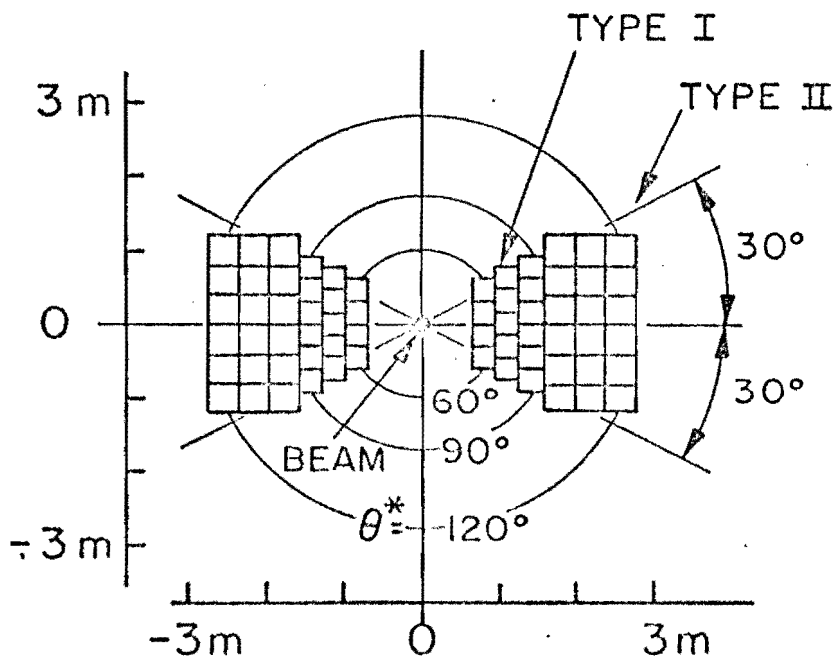
$$\frac{d\sigma}{d^3p/E}(\pi^o) \approx \frac{1.5 \times 10^{-26}}{p_T^{8.24}} \; e^{-26p_T/\sqrt{s}} \quad \frac{cm^2}{GeV^2\ sr}$$

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

FIG. 1 SCHEMATIC LAYOUT OF THE EXPERIMENT



BEAM VIEW AT 20m DOWNSTREAM



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 (roughly the fiducial area of our proposed detector on each side of the beam), we have finally $3.5 \times 10^{-34}\ cm^2$ [$\sigma(\pi^o)$, at 90°, above 4.6 GeV, into $\frac{1}{2}$ sr]. 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. Thus one would still get very usable singles rates at $p_T(\pi^o)$ well above 4.6 GeV. It is indeed important to go to higher p_T. 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. These asymmetry values would be reduced slightly by angular smearing due to the unseen members of a jet.

An estimate indicates it is unlikely that we can get to 8 GeV for single π^o's in this proposed experiment. 6 GeV however does seem possible. For 6 GeV an extrapolation of the above cross section gives a rate, into $\frac{1}{2}$ sr, about 30 times less than for 4.6 GeV, or about 10 events per hour. It can be expected that π^+ and π^- will add about twice the π^o intensity, so we conclude that a reasonable estimate for single π's above 6 GeV p_T in our proposed detector (one side of the beam) with the proposed interaction rate is ~ 30 π's per hour, in pp collisions. What <u>coincidence</u> rate can then be expected, for events showing high p_T simultaneously in our detectors on both sides of the beam?

The answer to this question is of course severely model dependent. What we wish to see is whether on a reasonable parton model, with as few assumptions as possible, we can expect a respectable counting rate, and a measurable asymmetry. If so then the presence or absence of such an asymmetry will probably give useful evidence on the validity of a parton model.

(b) Coincidence rates, single-π "trigger", pp collisions. We have estimated above that 6 GeV single π's will occur, as one-sided high-p_T events, at a rate of the order of 30 per hour. (4.6 GeV π's, similarly, would come at about 1000 per hour.) We now ask for the probability, on a parton-parton scattering model, that if one such π is seen on one side that the other "jet" (which could be a single particle, or a multi-particle cluster) go into our detector. For purposes of measuring the asymmetry we have discussed, we are interested in the probability that the second jet be directed at some angle within an interval of about 10° (and also in the probability that if the first jet is at say 80° then the second is between about 60° and 120°).

This angular correlation question has been discussed by Bjorken,[11] and by Ellis and Kislinger.[17] We show below in Figure 2 the results of a calculation using their formulation. In this calculation we have neglected the t'-dependence (and s'-dependence) of the fundamental parton-parton scattering cross section $\frac{d\sigma}{dt'}(s',t')$. As explained above, the asymmetry on which we are seeking evidence does not depend on the s',t' dependence of $\frac{d\sigma}{dt'}$; the detailed curves below would be modified by such a dependence but the ratio of cross sections $\frac{d\sigma}{d\Omega_1 d\Omega_2}(\theta_1=80°, \theta_2=80°)$ to $\frac{d\sigma}{d\Omega_1 d\Omega_2}(\theta_1=100°, \theta_2=100°)$ would not be modified.

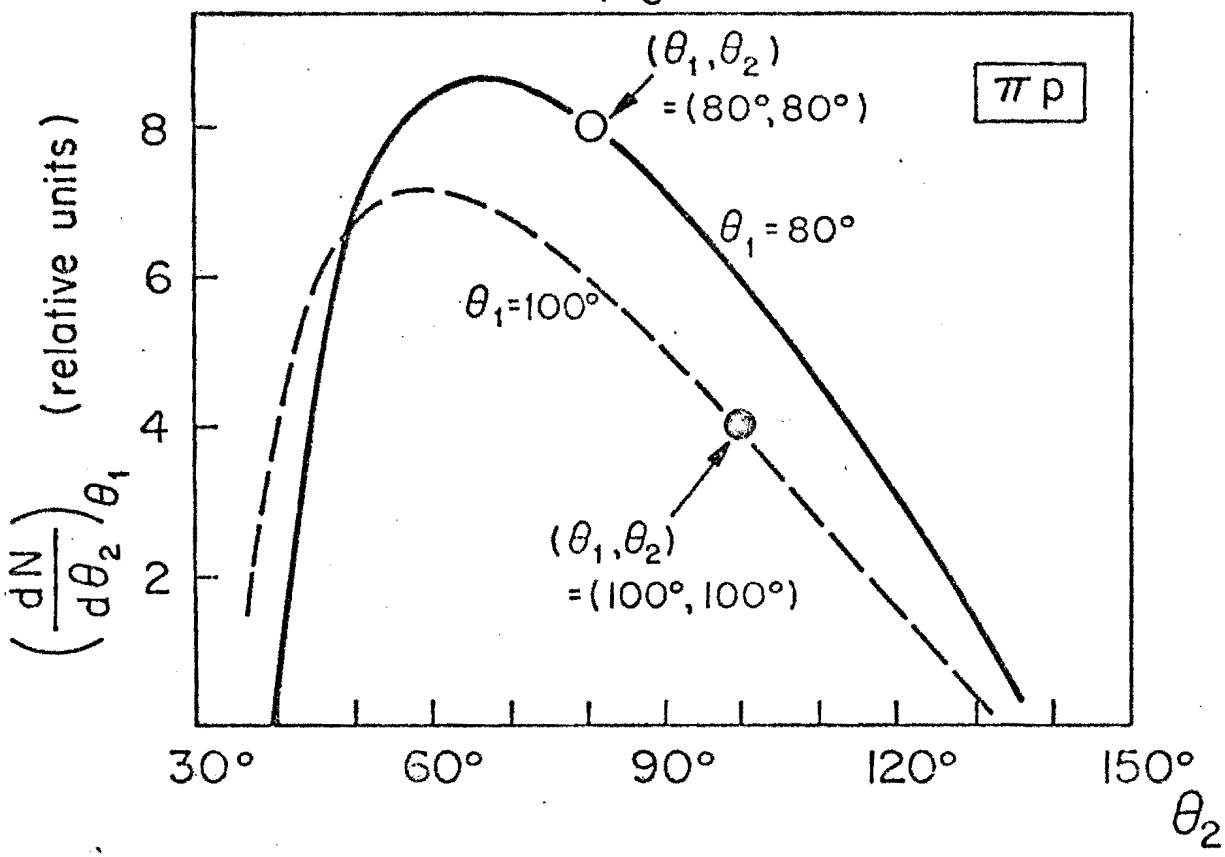
The angular correlation calculation has been made assuming partons, rather than single π's, of 6 GeV p_T. For that case, we find that for pp and πp both, a 10° slice of angle on the "other" side of the beam will show typically a 10% to 15% coincidence rate. (We take the two opposite-side jets to be coplanar.) One also finds that the πp single jet rate is about 50% higher than the pp rate, in this range of p_T and angle.

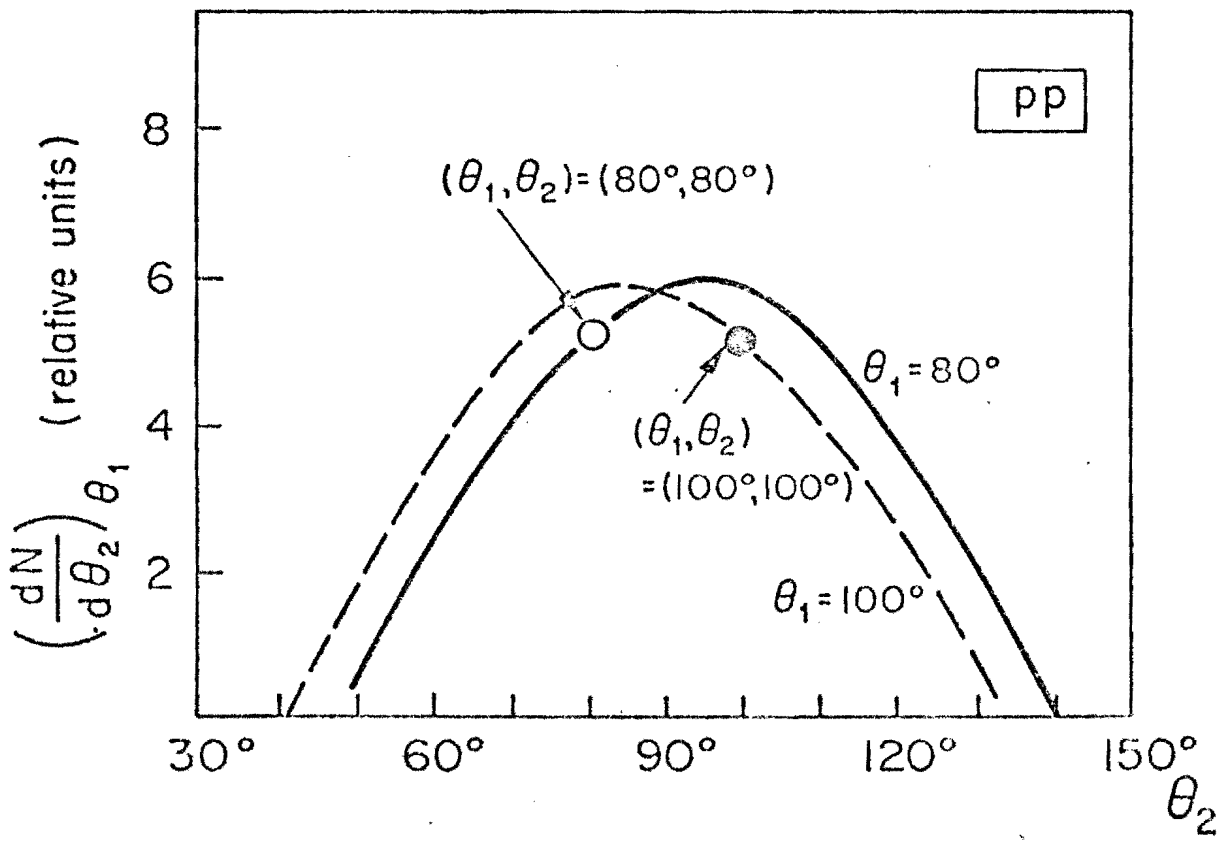
Effects from (a) the probable t'-dependence of $\frac{d\sigma}{dt'}$, and from (b) the unseen members of the jet, work in opposite directions on the coincidence rate. We therefore take 10% as a reasonable estimate for the coincidence rate per 10°.

FIG. 2

ANGULAR CORRELATIONS IN PARTON-PARTON SCATTERING

AT $\frac{2p_T}{\sqrt{S}} = 0.5$





We thus arrive at the following estimate. For an interaction rate in the target of $\sim 10^7$/sec time average, we expect to see about 30 single π's per hour, and about 15 coincidences per hour, in pp collisions, for the $\frac{1}{2}$ sr fiducial area on each side, triggered by single π's above 6 GeV. (15 out of 30 represents the roughly 50% of the time that the coincidence "recoil" high p_T object is detected.) For πp collisions, we expect a slightly higher coincidence rate. But now if we sort these coincidences into the various combinations of angular intervals, taken about 10° wide each, we find for πp collisions, and 6 GeV single π's, about 1 coincidence per hour in each pair of 10° intervals. Thus in several hundred hours, at this rate, we would see for the πp case an intensity ratio, for $(\theta_1,\theta_2) = (80°,80°)$ compared to $(100°,100°)$, of about 2 to 1, with a statistical accuracy of about 7%-10%, so a 5 to 7 standard deviation effect.

This would be a marginal effect. However, one can expect a considerably larger effect, on the parton model, for several reasons. First, the probability for a 6 GeV (detected) multi-particle jet is much greater than for a 6 GeV single π. Secondly, we can expect a larger asymmetry from such <u>jets</u>, because a multi-particle jet with 6 GeV <u>detected</u> corresponds to a "true" jet energy of 7 to 8 GeV, and such jets have a substantially higher asymmetry than for 6 GeV. Finally, we can expect to see a larger asymmetry, by using angles farther apart than 80° and 100°. We also note that the event rate rises rapidly with decreasing p_T--though the asymmetry may also rapidly decrease with decreasing p_T.

We thus conclude that an interaction rate in the target of 20 to 40 MHz is likely to give sufficient sensitivity to observe the asymmetry we wish to look for--and that such a high interaction rate is also necessary.

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 cannot 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 negative π 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 $\pm 5\%$ would be quite satisfactory, as would be 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 $\sim$ 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 momentum distribution (longitudinal and transverse) in jets, some information on ratios of numbers of π^0's, other neutrals, and charged particles, in jets, and information 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).

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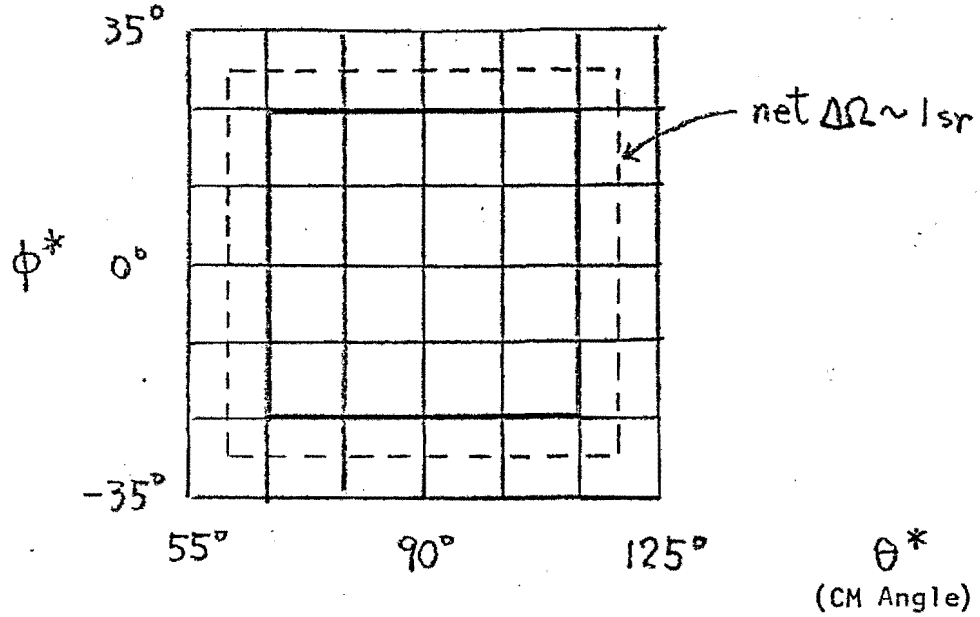
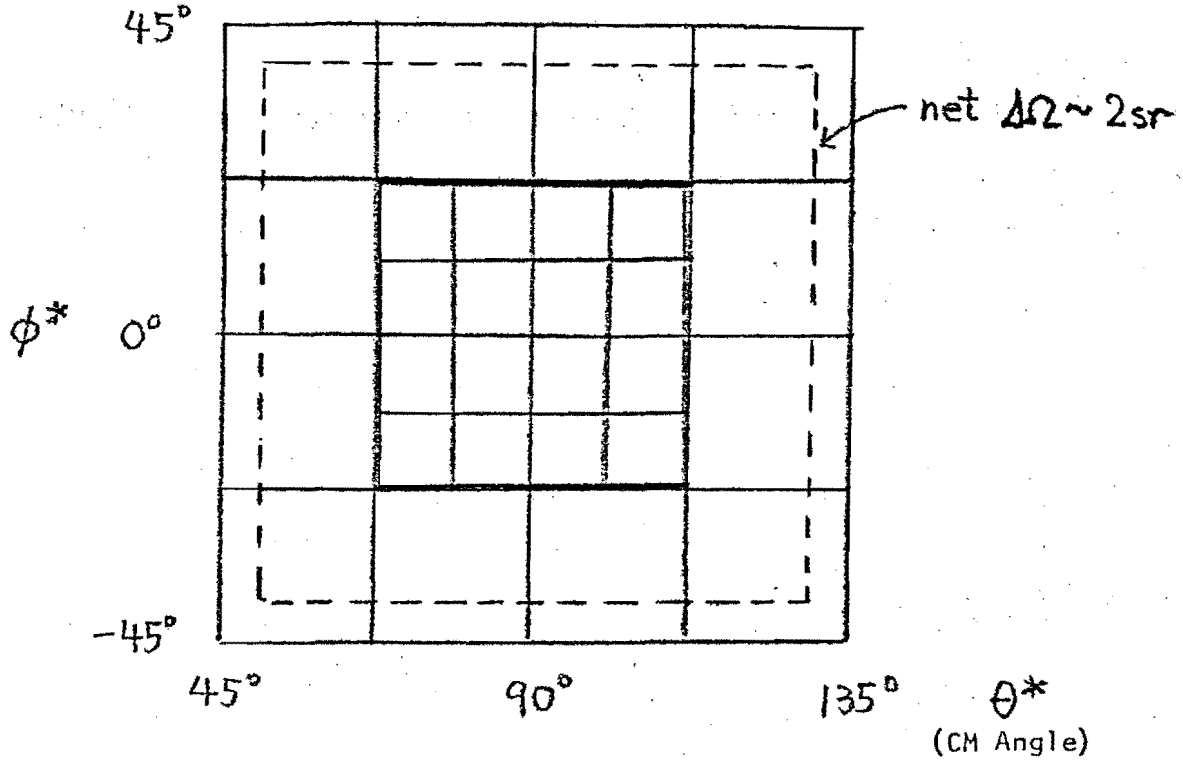
FIGURE 1. APPROXIMATE REPRESENTATION OF CALORIMETER GEOMETRY

(A) Original Design



(B) Improved Design



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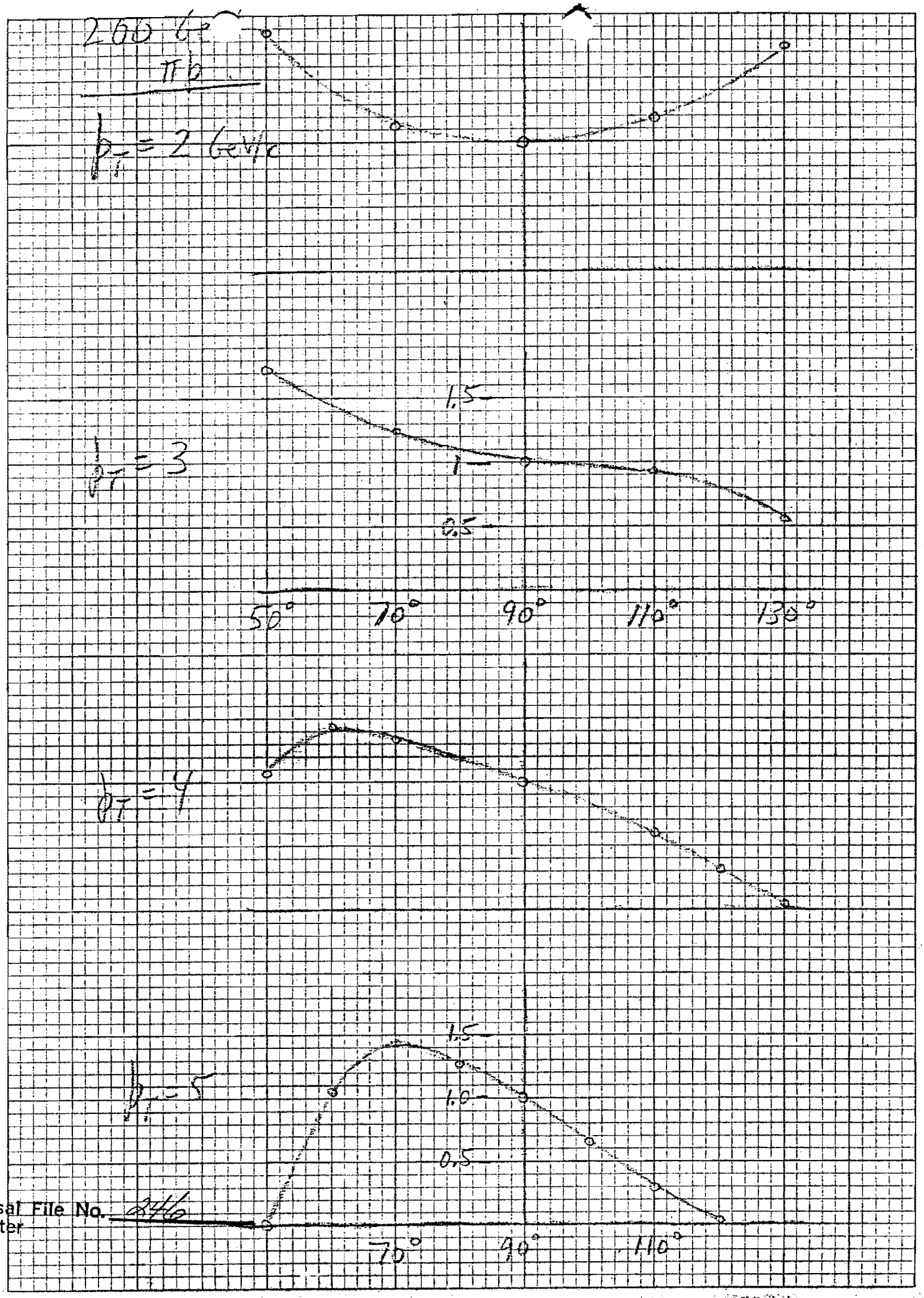

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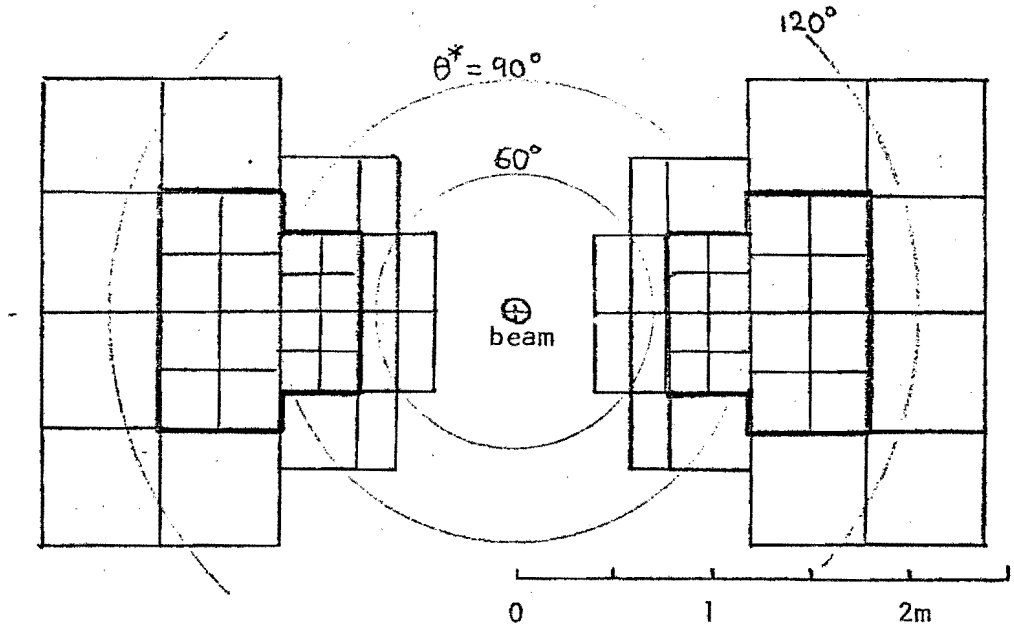
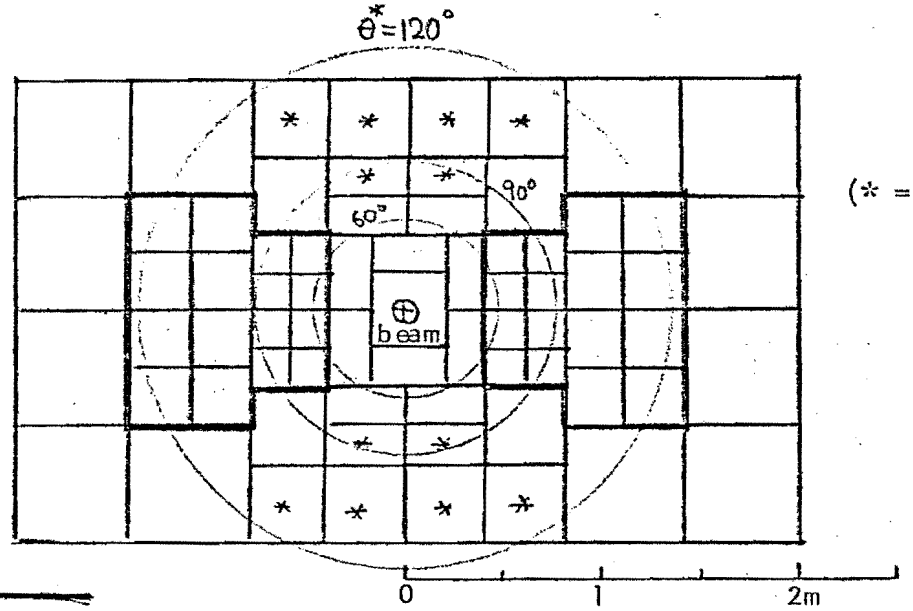
FIGURE 2. BEAM VIEW OF DETECTOR

(A) BETTER RESOLUTION (0.2 rad); detector distance 12 m.
2 sr each side
80 tons



(B) GREATER COVERAGE; detector distance 8 m
4 sr each side
100 tons



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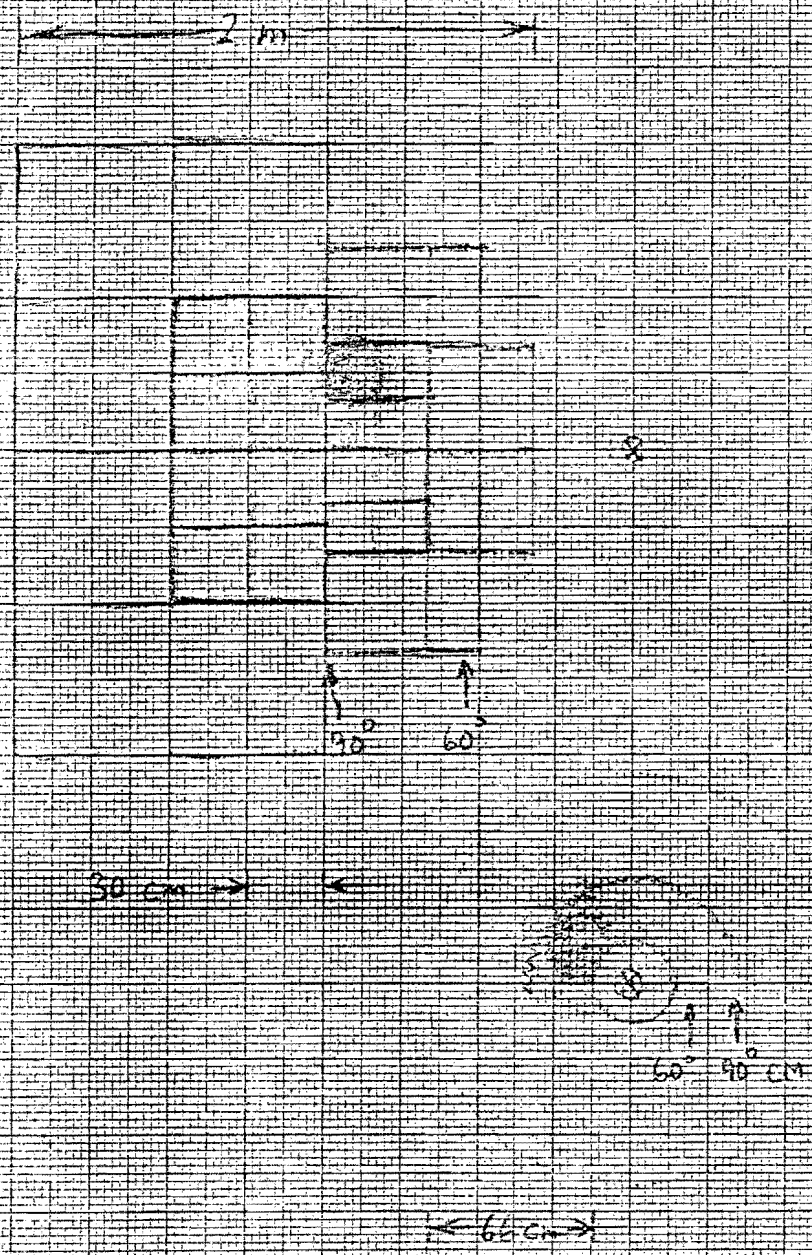

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