NAL PROPOSAL NO. 222

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A PROPOSAL TO STUDY HARD HADRON-HADRON COLLISIONS

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Abstract

We propose a novel technique to study hadron-hadron collisions in which a significant fraction of the available energy is carried off in directions transverse to the beam. The technique is independent of the details of the final state so is ideally suited to searching for the jet-like particle clusters predicted by the parton model. The detector consists of a small calorimeter and several planes of 1 meter square proportional chambers.

A STUDY OF HARD HADRON-HADRON COLLISIONS

I. INTRODUCTION

We propose an experiment to measure the cross section and final state characteristics of hard hadron-hadron collisions. The events we are seeking to study are those in which a finite fraction of the available center of mass energy is carried off in directions transverse to the beam direction. One of the proposed triggering schemes is uniquely independent of the nature of the final state, whether there are jet-like clusters of particles, as expected from parton-parton scattering, or an isotropic sea of soft pions. Should jets exist, we have an extremely high efficiency for their detection. The apparatus for this study consists of a modest 1 meter square calorimeter and several planes of proportional chambers of comparable size.

For our "unbiased" trigger the occurrence of a highly inelastic collision is signaled by the absence of a significant amount of energy from the forward direction. The idea follows from the fact that downstream from a 300 GeV hadron-hadron collision most of the energy is concentrated in a narrow cone about the projectile's line of flight. In fact, a calorimeter of 1 meter cross section, 10 meters downstream of the target collects on average 285 GeV. However, a collision containing transverse momenta of 4 GeV/c, back-to-back at 90^{o} in the center of mass, has 100 GeV missing from the calorimeter. Thus the plan is to trigger on highly inelastic collisions and examine the topology of these events with proportional chambers close to the target. One would study the s dependence of the hard cross section and the dependence on the type of bombarding hadron (p,π). The cross section for these hard collisions is completely unexplored and could be appreciable. Present estimates suggest a suppression of conventional hadron collisions by at least 10^5 with no constraint other than low forward cone energy. Should the cross sections of interest be smaller than attainable with this bias free trigger, we will be prepared to add a requirement on multiplicity and/or energy at wide angles.

A lower bound rate estimate based on ISR high P_T measurements and a beam of 10^6 instantaneous over a 100 msec spill gives about 20 events per hour at 4 GeV/c P_T. Because of the exploratory nature of this experiment, we would like to begin running even with very modest beam conditions.

In the sections to follow we discuss in detail the motivation for the experiment, the viability of the trigger and expected data rates, the technical aspects of the detector, together with associated background processes, and finally, the requirements on the Laboratory and the overall cost.

II. MOTIVATION

A well-known characteristic of hadron-hadron interactions is the limited transverse momentum of the secondaries. Early cosmic ray and accelerator studies (1) suggested that

$$< P_T > \approx 0.300 \text{ GeV/c}$$

$$\frac{dn}{dP_T} = AP_T e^{-P_T/B}$$

Because of this peripheral nature of most strong interactions, it has been pointed out that it is difficult to use the strong interaction as a probe of nucleon structure.[(2)] With the advent of a new generation of high energy machines, one asks whether this continues to be the case. Certainly the transverse phase space, which is filled so unevenly, is greatly expanded. Initial studies at the CERN/ISR have mainly concentrated on mapping out the single particle inclusive cross sections over the range of accessible angles, momenta, and incident energies. As at lower energies, the picture which emerges is one with the incident proton energy carried off by a limited number of particles at rather small forward angles, the transverse momenta being again a few hundred MeV/c. In addition to the forward cones,there is a soft flux component at large angles whose cross section rises slowly with energy. We emphasize, however, that these are the prominent features seen in single particle studies. There has been almost no exclusive study of any special class of interaction other than elastic scattering. We believe that new channels could exist with a significant cross section and have gone unnoticed.

One interesting set of ISR observations has been made in the inclusive studies near 90° in the center of mass. Two experiments have measured the pion transverse momentum distribution and both observe that at transverse momenta of ~ 5 GeV/c the cross section is several orders of magnitude larger than expected from a simple exponential fit to the low P_T data. The signifigance of this tail is still to be assessed. One explanation is that in the high P_T collisions, which probe very short distances within the nucleon,one is seeing evidence of some point-like constituent. To date the effect is only seen in collisions with at least one particle of very high P_T. Final states with a cluster of particles at intermediate P_T would have escaped notice. Moreover, other special features of the high P_T final states have never been systematically investigated.

It is on this basis that we wish to measure first the cross section for very hard collisions as a function of s, and secondly, the structure of their final states.

III. EVENT SELECTION

(a) Apparatus

We briefly describe the detector here. A more detailed technical discussion is given later.

A layout of the experimental set-up for P_{INC} = 300 GeV/c is shown in Fig. 1. A pion or proton beam of 10^6 per second enters a 1 meter hydrogen target, where 13% interacts. The forward cone of the hadron-hadron interactions, as well as the non-interacting beam, is directed into a total absorption counter (calorimeter) at a distance of 10 meters from the target. The calorimeter responds to the total energy in the forward cone. Elastic scatters and ordinary diffractive interactions will deposit almost the full 300 GeV in the calorimeter, while the events of interest will have a finite fraction of P_{INC} missing from the forward cone. For these events, we record the trajectories of all charged particles emitted into the 3.4π str c.m. solid angle covered by the proportional chambers shown in Fig. 1. The maximum c.m. production angle to which we are sensitive is 135^0, the minimum is 0^0, the azimuthal acceptance is the full 2π. A chamber system separate from the others is sensitive to all charged particles within the forward cone.

The calorimeter as shown in Fig. 1 covers the angular range from 0 to 50 mr but is on rails so this angle can be changed. We propose to trigger whenever more than 100 GeV is missing from the calorimeter (running with P_{INC} = 300 GeV/c). To see why this is so, we next consider the quantitative characteristics of the forward cone.

(b) Characteristics of the Forward Cone

We would like to answer the questions: how broad is the forward cone? and what are its fluctuations?

To first estimate the magnitudes involved, we calculate how much energy lies outside of a given lab angle, on the average, for the case of massless particles.

For a series of particles with center of mass momenta P_i^* and production angles Θ_i^* (all bigger than some Θ_{MIN}^*), their total lab energy (missing energy) is:

$$E_m = \gamma \sum_i P_i^* \; (1 + \cos \theta_i^*)$$

Writing this in terms of their transverse momenta, P_{T_i} , we have

$$E_m = \gamma \sum_i P_{T_i} \; (1 + \cos \Theta_i^*) \,/\, \sin \Theta_i^*$$

Now we assume (close to reality) that the distribution in P_T is independent of production angle Θ; then we find that the average missing energy, $\overline{E}_m$, is given by

$$\overline{E}_m = \gamma \, \overline{P}_T \int_{\Theta_{min}^*}^{\pi} \frac{1 + \cos \Theta}{\sin \Theta} \, f(\Theta) \, d\Theta$$

Where $f(\Theta)$ is the angular distribution, and $\overline{P}_T$ the average transverse momentum.

Results from the CERN/ISR[3] show that within the central region,

$$\frac{1}{\sigma\ \mathrm{inel}}\ \frac{d\sigma}{d\Omega} = A/\sin^2\Theta \qquad A = \text{number of particles/str}$$

is a good fit to the charged particle angular distribution. Using this form, $f(\Theta) = 2\pi\ A/\sin\Theta$ so that we have

$$\overline{E}_m = 2\pi\gamma\ \overline{P}_T\ A \int_{\Theta^*_{min}}^{\pi} \frac{1}{1-\cos\Theta}\, d\Theta$$

$$= 2\pi\gamma\ \overline{P}_T\ A \cot \frac{\Theta^* \mathrm{min}}{2}$$

Now, using the fact that angles transform as

$$\tan\Theta_{lab} \simeq \frac{\sin\Theta^*}{\gamma(1+\cos\Theta^*)}$$

$$\Theta_{lab} = \left[\ \gamma \cot \frac{\Theta^*_{min}}{2}\ \right]^{-1},$$

we finally have

$$\overline{E}_m = 2\pi\ \overline{P}_T A\ /\ \Theta_{lab},$$

a particularly simple result.

We see that the average energy outside of a given lab angle has only the mild energy dependence of A. (A increases from 0.2 to 0.25 particles/str over the ISR energy range).

If we choose A = 0.3 to include neutrals, then, for $\overline{P}_T$ = .350 GeV/c, we find that outside of 50mr in the laboratory,

$$\overline{E}_m = 13 \text{ GeV}$$

A more complete calculation which also contains the backward cone energy yields

$$\overline{E}_m = 15 \text{ GeV}$$

Fig. 2 shows the results of this calculation which uses scaling and the ISR single particle cross sections to predict the angular energy density in the forward cone.

Next, we consider the fluctuations in the energy deposited in the calorimeter. For this we have generated 20,000 typical p-p events with P_{INC} = 300 GeV/c and looked at the distribution of energy contained within 50mr in the laboratory. The input data to the Monte Carlo calculation are the ISR single particle inclusive cross sections in x and P_T for mesons and baryons. The results of Fig. 3 are for a total multiplicity of 12 and the assumption of no correlations other than energy-momentum conservation. We note, however, that the ISR single particle data are clearly insufficient to predict multiparticle final states and the results can only be considered an estimate based on our present understanding of hadron-hadron collisions. We see in Fig. 3 that there are no events with missing energy greater than 75 GeV out of 20,000 tries.

(c) Sources of Triggers

What type of events satisfy the missing energy requirement? Consider a single pion, produced at 90^o in the center of mass with a transverse momentum of 5 GeV/c. In the laboratory its angle is 83 mr and it carries an energy of 60 GeV. If it is balanced by a similar particle on the other side, then 120 GeV will be missing from the calorimeter and the event will be accepted. Thus we see that for events in which two particles carry off momentum back to back in the c.m. system, we are sensitive to $P_T \geq 4$ GeV/c production with our trigger of $E_m \geq 100$ GeV. This is true for a wide range of production angles since our solid angle in the central region of the c.m. frame is $\sim$ 8 str.

We point out that any single particle production will satisfy this trigger - π^o, π^+, π^- , nucleons, etc.

A second important type of trigger arises from events in which the transverse energy is shared among a number of particles. Consider the expression for the average energy missing from the calorimeter:

$$\overline{E}_m = 2\pi \, \overline{P}_T A/\Theta_{lab}$$

Using $\overline{\Theta}_{lab} = 0.050$ yields

$$\overline{E}_m = 126 \, \overline{P}_T \, A$$

Now our requirement that $E_m \geq 100$ implies

$$\overline{P}_T \, A \geq 0.8$$

Since A is the number of particles per steradian, we can identify $\overline{P}_T A$ with the transverse momentum density. Thus we see that a soft component on the order of 0.8 GeV/str filling the central region will satisfy our trigger. We point out that $\sim$ 30 particles with normal P_T, isotropic in the center-of-mass would satisfy the trigger.

With regard to the search for particle clusters or jets we argue that the trigger described above is, in principle, superior to triggering directly on the jet particles themselves. A magnetic spectrometer would trigger only on single high P_T particles and miss jets containing several particles at intermediate P_T. A single calorimeter triggering directly on the jet would tend to select cluster configuration even if the particles detected were relatively uncorrelated.

(d) Other Triggers

The data with low forward cone energy will certainly contribute a fresh, complimentary piece of information to our understanding of hadron-hadron collisions. The cross sections themselves, independent of the wide angle nature of the events, are of great interest. However, to press for a more complete understanding of these hard hadron-hadron collisions we will take data with two additional selection criteria.

The first is a multiplicity trigger used in conjunction with the calorimeter at zero degrees. The fast outputs from the proportional chambers will be used to set requirements on the charged particle multiplicity in the central region or in the forward cone. For these data the calorimeter energy will only be recorded and not required in the trigger. Exact details of the trigger requirement will depend on findings in the forward energy veto data. This data could provide an important cross-check if new phenomena are observed.

The second triggering mode is an energy requirement at a wide angle and will be employed, depending on findings in the forward energy veto running. The segmented calorimeter described in the next section can be divided into two separate pieces. The individual energy resolution is maintained since the calorimeter as used in anti coincidence must be very deep to avoid energy leakage from the downstream end. These pieces are now used in coincidence on opposite sides of the beam. One calorimeter, positioned at a fixed angle near 90^{0} in the center of mass, would be used to impose a high energy threshold on the triggers. The angle and solid angle of the second calorimeter would be varied and the energy spectrum recorded for each setting.

In summary, hard hadron-hadron collisions can be investigated with three complimentary criteria: (1) low forward cone energy; (2) special multiplicity requirement; (3) energy correlations at wide angles.

IV. THE DETECTOR

(a) Wire Chambers

The configuration shown in Fig. 1 is used to detect final state particles over the center of mass angular range $0 < \Theta^* < \frac{3\pi}{4}$ and $0 \leqslant \phi \leqslant 2\pi$. With a 1 meter target the array is suitable from 50 to 300 GeV. As the incident energy is varied, the chamber spacing is changed to maintain a roughly constant center of mass angular resolution. The relation is not exact because at low bombarding energy the angular acceptance is slightly restricted for reasons of economy. The c.m. solid angle detected as a function of laboratory angle is shown in Fig. 4.

The wire planes themselves are proportional chambers. They allow full multi-track efficiency, short dead time, relative immunity to background tracks, and the possibility of a multiplicity trigger. Each of the 4 modules shown is a double plane of orthogonal wires. The wires of two modules are rotated with respect to the other two to aid in resolving ambiguities. For the same reason, the center of each plane is deadened. The high single wire rates in the center would produce appreciable dead time with the standard electronics envisioned. Thus bands of inefficient wires would exist across the chambers. To handle the forward cone and measure its multiplicity, one would use a set of small, short dead time proportional chambers with current sensitive input amplifiers and cable delay elements.

A 2 mm. wire spacing is planned. This gives a typical laboratory angular resolution of 2 mrad., corresponding to about 25 mrad. at 90^0 in the center of mass for 300 GeV incident. We crudely estimate the characteristic angle within a 5 particle jet of 5 GeV at $\Theta^* = 90^0$ as $< P_T >/< P_L^* > \simeq \frac{0.3}{1.}$ or 300 mrad. Thus the 25 mrad. resolution appears adequate.

Consider next the problem of multi-track ambiguities. If 30 wires are struck randomly in each of the 8 proportional planes then 3 spurious tracks will be generated which appear to come from the target volume. This calculation assumes full chamber efficiency and a uniform distribution of wire hits over the planes. It does not, however, make use of the fact that tracks must come from common vertices within the target. This additional constraint should be effective in eliminating spurious solutions. Before constructing the chambers a more detailed simulation study will be done to verify the adequacy of the proposed configuration.

The wire chamber system shown has about 4000 wires. A system of 10,000 wires has already been built at the Fermi Institute and operated successfully. The electronics cost per wire of the system was $4.

(b) The Calorimeter

Our experiment relies heavily on the calorimeter as an energy measuring device. Since its output is primarily used in anti-coincidence we must exercise special care in its design and optimization. Fortunately there is considerable data available on calorimeter construction and performance.

At NAL two very large calorimeters are presently in operation in the neutrino experiments 1A and 21. A small scale version of the experiment 21 calorimeter has been successfully tested in a 200 GeV proton beam.[4]

At lower energies, detailed studies have been carried out at CERN by the Schopper group.[5] In addition, Monte Carlo calculations are available[6] which fit the available calorimeter data and can be used to predict response as a function of parameters defining the calorimeter.

For reasons of cost and flexibility we choose to build a sampling calorimeter rather than a homogeneous total absorption counter. In a sampling calorimeter the hadronic cascade develops in metal plates and is sampled after each plate by an ionization sensitive device. For the bulk of our calorimeter we use iron plates immersed in liquid scintillator. The design parameters to be fixed are plate thickness, lateral size and longitudinal size.

By way of comparison the Caltech device was 1.4 meters of iron deep with 10 cm. thick plates. Fig. 6 shows their measured resolution of σ=8.5% for 200 GeV protons and Fig. 7 shows their dependence of line width on plate thickness. The response of Fig. 6 is very nearly Gaussian. The few events in the flat background above and below the peak probably arise from off-axis beam particles and accidental effects. The overall result is remarkably good considering the short time available for their test.

In the CERN tests a plate thickness of 2 cm. and a total iron depth of 80 cm. was used. The measured resolution at 23 GeV was σ = 10%. A Monte Carlo evaluation of the response of this device at 300 GeV gives σ = 4.2%. The same calculation predicts for 6 cm. plates at 200 GeV, σ = 8%. This is to be compared with the Caltech measurement of σ = 8.5% with 10 cm. plates at 200 GeV. Thus for our proposed plate thickness of 1.25 cm. a resolution of σ = 4% might be expected. The Monte Carlo prediction is $\sigma \simeq 3\%$.

Consider the question of linearity of response. Since the forward cone particles of each event will have widely differing energies the calorimeter must respond linearly up to 300 GeV. According to the Monte Carlo simulations and the CERN data the linearity is good. In addition, the 8% energy resolution of the Caltech 200 GeV measurement supports this conclusion in the following way. When the primary 200 GeV protons interact in the calorimeter the secondaries have a broad spectrum of energies and multiplicities. Thus the measured response <u>includes</u> the effects of variations in the composition of the initial 200 GeV state.

The data and Monte Carlo studies indicate that the resolution improves with incident energy roughly like $1/\sqrt{E}$. If this were exactly true then our <u>resolution</u> at a given incident energy would also be independent of the composition of the incident state.

The Monte Carlo studies show that a device 6 interaction lengths long and 3 wide contains $\simeq$ 94% of the incident energy. We are proposing to build ours nearly 9 interaction lengths long and 6 wide. The added length is to help suppress low energy tails as discussed below. The width is larger to contain the cascades of off-axis particles of the forward cone.

Fig. 8 shows a possible calorimeter construction. The iron plates are teflon coated for total internal reflection.

The data discussed above clearly demonstrates the feasability of producing the calorimeter required. We do expect, however, to do beam testing of prototype models in order to optimize parameters.

(c) Background Effects

We must carefully guard against backgrounds which simulate energy missing from the foreward cone. One such background is an incident hadron which traverses most of the calorimeter without interacting. The chance of a proton not interacting in 9 interaction lengths is $e^{-9} = 1.2 \times 10^{-4}$ so that these must be effectively vetoed. For pions, the situation is even worse. To guard against this type of event, we have two safeguards. One is that we will measure the energy loss within each of the 9 interaction lengths independently. This data will certainly allow rejection of events in which the hadron shower begins very late. In addition, we will follow our main calorimeter with a section which is much cruder but will give us an indication of the energy leaking out the back of our primary calorimeter. This will consist of many ≃ 20 cm. slabs of iron behind each of which we will measure the number of particles in plastic scintillators. Signals from the rear of this device will identify energetic muons (from π decay) whose energy is unaccounted for.

A second source of less than the full beam energy in the calorimeter is a low energy particle in the beam. For this purpose we will use two 10 ft. bending magnets upstream from the target and will equip the magnets with tiny proportional chambers or hodoscope counters to ensure a particle of proper momentum and trajectory enters the target.

We briefly discuss edge effects. The CERN data explicitly indicates that we can enter the calorimeter within about 10 cm. of the edge without a significant loss in pulse-height or resolution. In our experiment, 10 cm. from the edge corresponds to 40 mrad. in the lab where the typical particle energies are about 10 GeV. Thus edge effects should not be a major source of spurious triggers. Nevertheless, we will have a ring veto counter (with lead to convert γ rays) which will tag (or possibly veto) events having particles entering the calorimeter within the outer 10 cm.

Finally, we mention that if our tests show that we could profit considerably from not having the full beam entering the calorimeter, we would consider having a small hole in it exactly at 0^o through which the non-interacting beam would pass. This will not be a source of spurious triggers since we will employ the cruder section (which will not have a hole) in veto.

(d) Jet Identification from Topology Alone

Since we do not measure the momenta of the wide-angle particles, the question naturally arises as to whether we can indeed identify jet-like events with the trajectories alone in the proportional chambers.

To investigate the question, we have generated a sample of pion jets of various energies and multiplicities with the following model: the particles of a jet are distributed uniformly in their rapidity along the jet axis and are distributed as e^{-6P_T} in P_T^2, where P_T is the particle transverse momentum relative to the axis of the jet.

A simple correlation, relatively independent of the dynamics of jet production, is the azimuth angular separation of the particles. In Fig. 5 we plot the azimuthal separation $\Delta\phi_{ij} = |\phi_i - \phi_j|$ for all pairs of particles in a two-jet final state. The characteristic peaks at 0 and π contrast with a flat distribution from an isotropic final state; in fact, we find that over a wide range of jet energies and multiplicities, we can reject 90% of the isotropic events and still retain ≃ 80% of the jet-like events. Thus, we should be able to verify if the dominant mechanism populating the high P_T region causes a clustering of the particles.

Ultimately, one would like to parameterize each event in terms of a maximum local particle density over the c.m. sphere, together with an effective Θ^* and ϕ^* for the jet (parton) direction.

V. RATE CALCULATIONS

(a) Lower Bound from ISR Data

To establish a pessimistic (lower) limit on our event rate, we have assumed that the majority of the transverse energy in hard collisions is carried off by just two particles on either side of the c.m. system. Then we can use the ISR data (which measures the single particle spectrum) to calculate our event rate.

One further assumption is needed, however, and that relates to how the two particles are correlated in c.m. production angles. If the two particles have production angles Θ_1 and Θ_2, and a common transverse momentum of P_T then the energy missing from the foreward cone is

$$E_m = \gamma P_T \left[\frac{1 + \cos \Theta_1}{\sin \Theta_1} + \frac{1 + \cos \Theta_2}{\sin \Theta_2} \right]$$

The requirement that E_m be greater than 100 GeV then restricts for given P_T, the angular regions in which we are efficient.

We have made two guesses as to how the particles might be correlated. One is that they are emitted exactly back to back, and the other is that they are totally uncorrelated and isotropic.

Finally our acceptance depends upon the fact that we want the laboratory angles to be greater than 50 mrad. (so they miss the calorimeter) and less than 200 mrad. (so we observe them in the chambers).

Table 1 shows our effective solid angles as a function of P_T for the two different models.

Table 1

$P_{INC} = 300$ GeV/c
$E_m \geq 100$ GeV

P_T	Ω (back-to-back)	Ω (uncorrelated)	$d\sigma/d\Omega\, dp$
3 GeV/c	----	0.25 str	3×10^{-31} cm^2/str GeV/c
4 GeV/c	7.5 str	1.5 str	2×10^{-32}
5 GeV/c	7.5 str	2.4 str	2.5×10^{-33}

Table 1 also shows the cross-section used for our rate determinations. These are a factor of 5 larger* than those reported by the CCR** (7) group at CERN for single π^0 production at their lowest $\sqrt{s}$ value (30.6 GeV).

* From the high transverse momentum data of the British Scandinavian group (8) at the ISR, we conclude that the ratio of all single particle production to π^0 production is about 5.

** We note that this is probably a pessimistic estimate as the data reported still has a bias (tending to reduce the cross-section at high P_T) associated with their trigger being not strictly inclusive.

Table 2 shows our expected rates for the two models.

Table 2

P_{INC} = 300 GeV/c
$E_m \geq$ 100 GeV

P_T	Back-to-back	Uncorrelated
	Interacting protons/event	
3 GeV/c	----	6×10^5
4 GeV/c	2.5×10^5	1.3×10^6
5 GeV/c	2×10^6	6×10^6

We see that with 3×10^4 interacting protons/pulse, we can expect one event with $P_T \geq 5$ GeV/c approximately every 100 pulses.

We point out here as well that the rate of such events occurring with $P_T = 2$ GeV/c is one every 500 interactions! These, however, have an average missing energy E_m of 50 GeV so that by lowering our threshold, we can study these as well.

(b) Parton-parton Scattering Rate Estimates

1) Basics

In the parton model of hard proton-proton collisions, a parton of momentum $X_1 P_{cm}$ in the incident proton can collide with one of momentum $-X_2 P_{cm}$ in the target proton and scatter elastically to an angle Θ in the parton-parton center-of-mass frame. The resulting partons, or the hadrons into which they materialize, have the momentum components, in the laboratory, of

$$P_T = \pm \sqrt{X_1 X_2}\, P_{cm} \sin \Theta$$

$$P_Z = X_1 P_{cm}^{\;2} (1 \pm \cos \Theta)$$

(where we have assumed that $\gamma \simeq P_{cm}$).

We note that the missing energy, E_m, is given by (we assume $E \simeq P$ for the hadron clusters)

$$E_m = \Sigma P_Z = 2X_1 P_{cm}^2 = X_1 P_{lab}$$

Thus the fractional energy missing from the forward cone has in the parton model this simple interpretation: it is the x value of the parton knocked out of the projectile proton. Distributions in E_m then directly measure the probability of knocking a parton of $x = E_m/P_{lab}$ out to a finite angle.

In addition to the measurement of X_1, if we measure the laboratory angles of the two jets of particles, we can then reconstruct the X_2 and Θ values of the collision without ambiguity. Thus we are observing <u>completely determined parton-parton collisions</u>. The rate of such collisions will than depend upon $s = 4X_1 X_2 P_{cm}^2$ (the s value of the parton-parton collision), Θ, and f(X) (the proton wave function) in the following way:

Collision cross-section

$$= \frac{f(X_1)}{X_1} \frac{f(X_2)}{X_2} \sigma(S,\Theta)$$

In varying P_{lab}, E_m, and Θ, the above expression implies certain consistency relations which we can check, and if valid, we can then <u>measure the parton-parton scattering cross-section over a wide kinematic range</u>.

As one example of the redundancy of the measurements, suppose we wish to study the collision of two 5 GeV/c partons at 90^o. Then

$$S = 100 = 4X_1 X_2 P_{cm}^2 = 2X_1X_2 P_{beam}$$

Thus as long as $\Theta_{cm} = 90^0$ and $(X_1 X_2 P_{beam}) = 50$, we are observing the desired collisions. We can choose $P_{beam} = 50$, $X_1 = X_2 = 1$ in which case $\Theta_{lab} = 200$ mrad., or $P_{beam} = 200$, $X_1 = X_2 = 1/2$, $\Theta_{lab} = 100$ mrad., or $P_{beam} = 200$, $X_1 = 1/4$, $X_2 = 1$, $\Theta_{lab} = 200$ mrad.

In the (likely) event that the different partons within the proton have different wave-functions and interact differently, Bjorken* has pointed out that, at least in a quark-parton model, the sum and difference of rates measured in pp and pn collisions yield more information on the scattering of the different parton types. Also, in πp and Kp scattering, we can observe anti-quark-quark scattering or strange quark-quark scattering.

2) Rate estimates

To calculate expected yields, one must know the f(X) and $\sigma(s, P_T)$ functions in the expression for the collision cross-section. For the cross-section, we have used the model of Bjorken et al.[9] (Vector gluon exchange).

$$E \frac{d\sigma}{d_{P_L} \, d_{P_T}^2} = \frac{4\pi \alpha^2}{|P_T|^4} \left[\frac{u^2}{s^2} \left(1 + \frac{t^2}{s^2} \right) \Big/ 2 \right] \delta \left(1 + \frac{u}{s} + \frac{t}{s} \right)$$

We have used the value $\alpha = 1/2$ for the coupling constant; this value results in a good fit to the ISR single π^0 production cross-section.[10]

For the parton probability distributions, we have used $f_p = 4(1 - X)^3$ and $f_\pi = 2(1 - X)$ to represent the proton and pion.

* Private communication

The event rates as a function of P_T, the transverse momentum of the final partons, are shown in Table 3 for P_{INC} = 300 GeV/c. We have integrated over the $X_1 - X_2$ plane, imposed the criteria that $E_m \geq 100$ GeV (i.e., $X_1 \geq 1/3$), required that $\Theta_{lab} \geq 50$ mrad. (outside the calorimeter) and required that $\Theta_{lab} \leq 200$ mrad. (within the chambers).

Also shown are the resulting cross-sections and the effect of our biases (mainly $E_m \geq 100$) on the rate. We see that the cross-sections are large: with 10^5 incident protons ($\sim 1.5 \times 10^4$ interactions/pulse in 1m H_2) there occurs one event per 10 pulses with one half of the available energy carried off in the transverse directions ! The corresponding rate in πP collisions is approximately 5 times higher still.

Table 3

P_{lab} = 300 GeV/c
$E_m \geq 100$ GeV
proton-proton collisions

P_T	σ $(cm^2/GeV/c)$	Interacting protons/event	Interacting protons/ observed event
3.6	2.1×10^{-29}	1.9×10^3	4.8×10^3
4.8	2.8×10^{-30}	1.4×10^4	1.8×10^4
6.0	2.1×10^{-31}	1.9×10^5	1.9×10^5
7.2	1.8×10^{-32}	2.2×10^6	2.2×10^6
8.4	1.2×10^{-33}	3.3×10^7	3.3×10^7
9.6	1.3×10^{-34}	3.1×10^8	3.1×10^8

VI. BEAM REQUIREMENTS, RUNNING TIME, AND MANPOWER

(a) Beam Requirements

We are interested in the highest energy proton and meson beams that the laboratory can provide. We would like the best duty cycle attainable; however, we have made our rate estimates on the basis of a beam of 10^5 particles/pulse with a spill length of 100 msec.

In regard to the other parameters of the beam, we would like to take data at an energy as low as 50 GeV. Our calorimeter may provide an energy resolution, at 300 GeV, of $\sigma = 3\%$; therefore, we would require the momentum bite of the beam to be the order of $\pm$ 1%. A spot size of approximately 1 cm. is adequate.

At present, the straight leg of the M1 beam in the meson lab is most suited to our requirements. It contains Çerenkov counters for identifying the incoming particle and, in addition, the beam is well matched to our flux requirements. At present the maximum energy available is 250 GeV.

Concerning floor space, we would require about 50 m. downstream of our target, and, at a distance of 10 m. from the target, we need a full width of 5 m. Upstream of the target, we need space for two 10 ft. bending magnets.

(b) Running Time

Because total absorption counters have been very little studied at NAL energies, and because we are especially interested in understanding their low energy tails, it is difficult to estimate how much testing time will be needed. Much of our testing could be performed in a parasitic fashion in any of the high energy charged beams. However, we foresee that for final tuning, we will require a beam with the requirements outlined. Also, some testing time with electrons is needed.

Before invoking the requirement on high missing energy, we would like to map out ordinary P P or πP collisions to the level of 10^5 events at each of 4 radial positions, 4 angular positions, and at 3 different energies (say 50, 150, and 250 GeV). This will involve moving the calorimeter downstream radially by up to 50 m., and out in angle (10 m. away from the target) to 200 mrad. The information obtained will aid us greatly in understanding our backgrounds and as well will yield valuable information on the ordinary collisions.

The above program requires

$$3 \times (4 + 4) \times 10^5 = 2.5 \times 10^6 \text{ recorded events}$$

At a data acquisition rate of 100 events/pulse, we then need 2.5×10^4 pulses or 42 hours of running.

The bulk of our running will be with the requirement of large missing energy. From the ISR data, we see that we can expect 10^2 events where 1/2 of the available energy is carried off (at least on one side) by single particles in 3×10^9 interactions, or 10^5 pulses, (100 msec. spill assumed). (The parton model would predict 10^4 such events in P-P collisions). To obtain the same statistics at 3 energies would require

$$3 \times 10^5 \text{ pulses} = 500 \text{ hours of running.}$$

Thus we request 600 hours of running.

(c) Manpower

Besides the investigators listed, at least one post doc and two students will also be involved with the proposed experiment. We estimate that construction and testing of a prototype calorimeter will take approximately 9 months. This activity will begin upon approval.

(d) Additional Laboratory Support

While we would undertake construction of the proportional chambers and calorimeter, we would need additional support for the data acquisition electronics. This would include PREP electronics for the fast logic and pulse height encoding, and a small on-line computer. Some elements of an on-line computer are available at the Fermi Institute, but these include only a PDP 11/20 CPU, EAE and teletype. We note that even for calorimeter testing some of this electronics would be required.

References

1. J. Nishimura, Soryushiron Kenkyu, 12, 24 (1956) and G. Cocconi et al. UCRL - 10022 (1961).

2. G. Cocconi, Int. Conf. on Theoretical Aspects of Very High Energy Phenomena, CERN (1961), p. 128.

3. G. Barbiellini et al., Physics Letters 39B, 294 (1972).

4. B. Barish et al., Experiment 21, Internal Memorandum 5-9-73, and B. Barish, private communication.

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

6. These Monte Carlo predictions were kindly supplied by K. McDonald and H. Schopper. They are based on the program of Ranft.

7. J. C. Sens, Ph.D., Review of Recent Results from the CERN ISR; presented at the New York Academy of Sciences Conference on Recent Advances in Particle Physics, April, 1973.

8. B. Alper et al., Production of High Transverse Momentum Particles in P-P Collisions in the Central Region at the CERN ISR, March, 1973.

9. S, M. Berman, J. D. Bjorken, J. B. Kogut, PR - D4 - 1388 1 Dec., 1971.

10. S. Ellis, M. Kislingler, Implications of Parton Model Concepts for Large Transverse Momentum Production of Hadrons, NAL Preprint.

Figures

1. The experimental layout at 300 GeV. The drawing does not show the last beam dipole which is equipped with small defining counters to ensure the momentum and trajectory of the incident particles.

2. The mean angular energy density in the forward cone from 300 GeV P P collisions. The individual densities are shown for nucleons, and $\pi^{\pm}$. The curve marked TOTAL includes these as well as π^{0}'s,K's,$\overline{P}$.

3. A possible energy spectrum from a calorimeter subtending 50 mrad. around zero degrees. The prediction is based on uncorrelated ISR single particle production data.

4. Center of mass angle vs. lab angle at 100 and 300 GeV. The detector covers from 0 to 135^{0}.

5. Azimuthal angular separations of all particle pairs for two 8 GeV jets with 4 particles in each jet.

6. The observed response of an iron plate calorimeter to 200 GeV protons. The smooth curve is a Gaussian fit to the data.

7. The measured calorimeter resolution vs. plate thickness at 200 GeV.

8. A possible structure for the calorimeter. The principal energy measurement is done in the fine grained section. The course section at the rear vetos events with substantial energy leakage.

EXPERIMENTAL LAYOUT AT 300 GeV

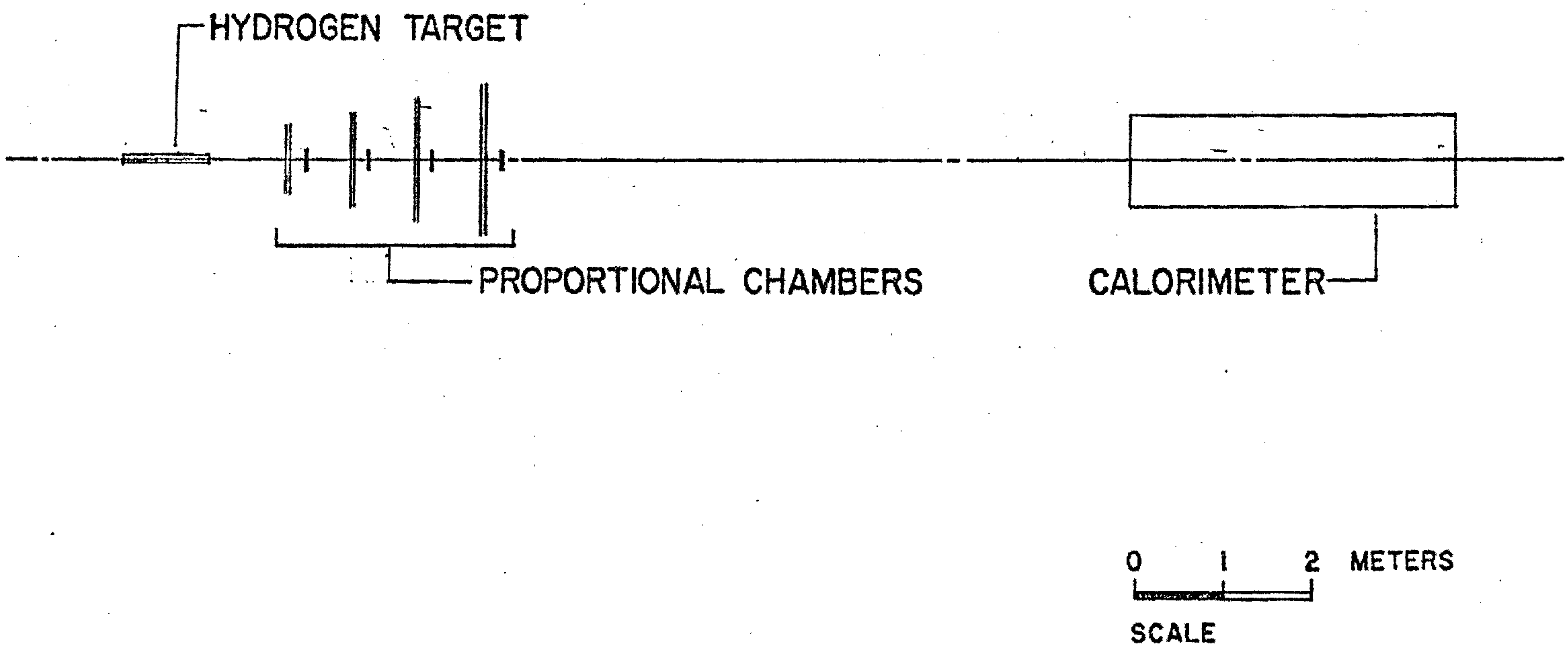


Fig. 1

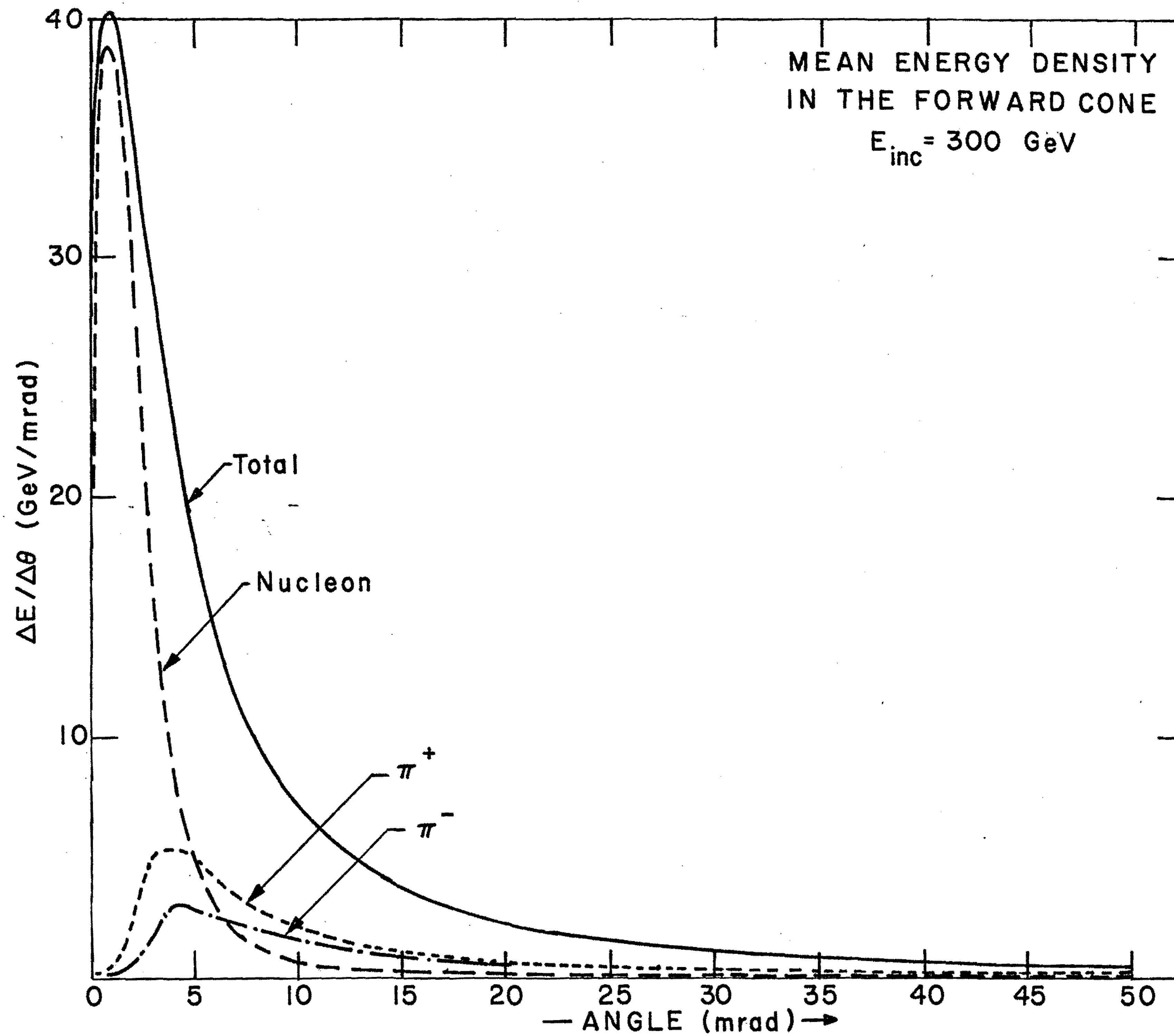

MEAN ENERGY DENSITY
IN THE FORWARD CONE
E_{inc} = 300 GeV
Total
Nucleon
π^+
π^-
$\Delta E/\Delta\theta$ (GeV/mrad)
— ANGLE (mrad) →
0
5
10
15
20
25
30
35
40
45
50
10
20
30
40

Fig. 2

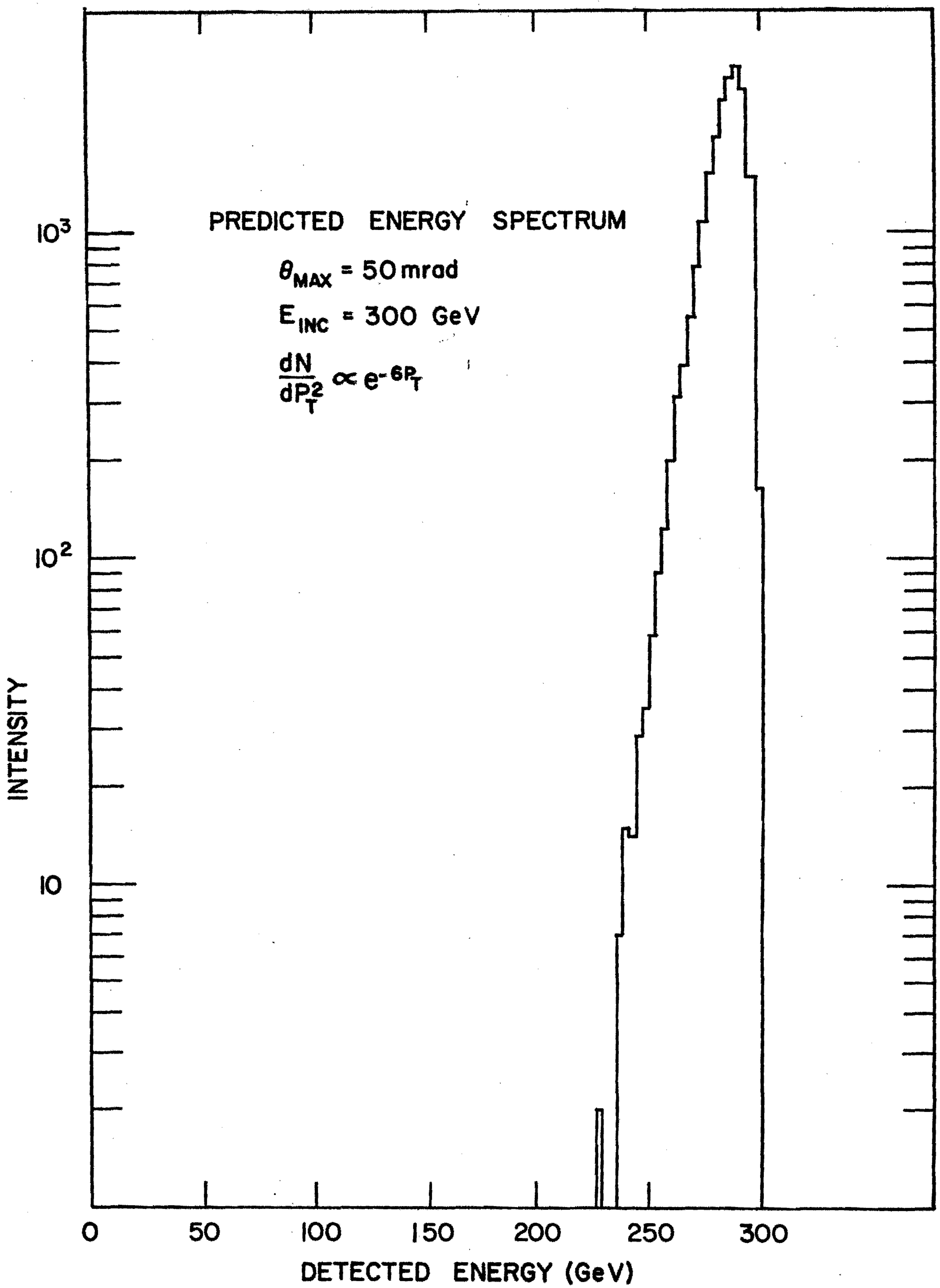

PREDICTED ENERGY SPECTRUM
θ_{MAX} = 50 mrad
E_{INC} = 300 GeV
$\frac{dN}{dP_T^2} \propto e^{-6P_T}$
INTENSITY
10^3
10^2
10
0
50
100
150
200
250
300
DETECTED ENERGY (GeV)

Fig. 3

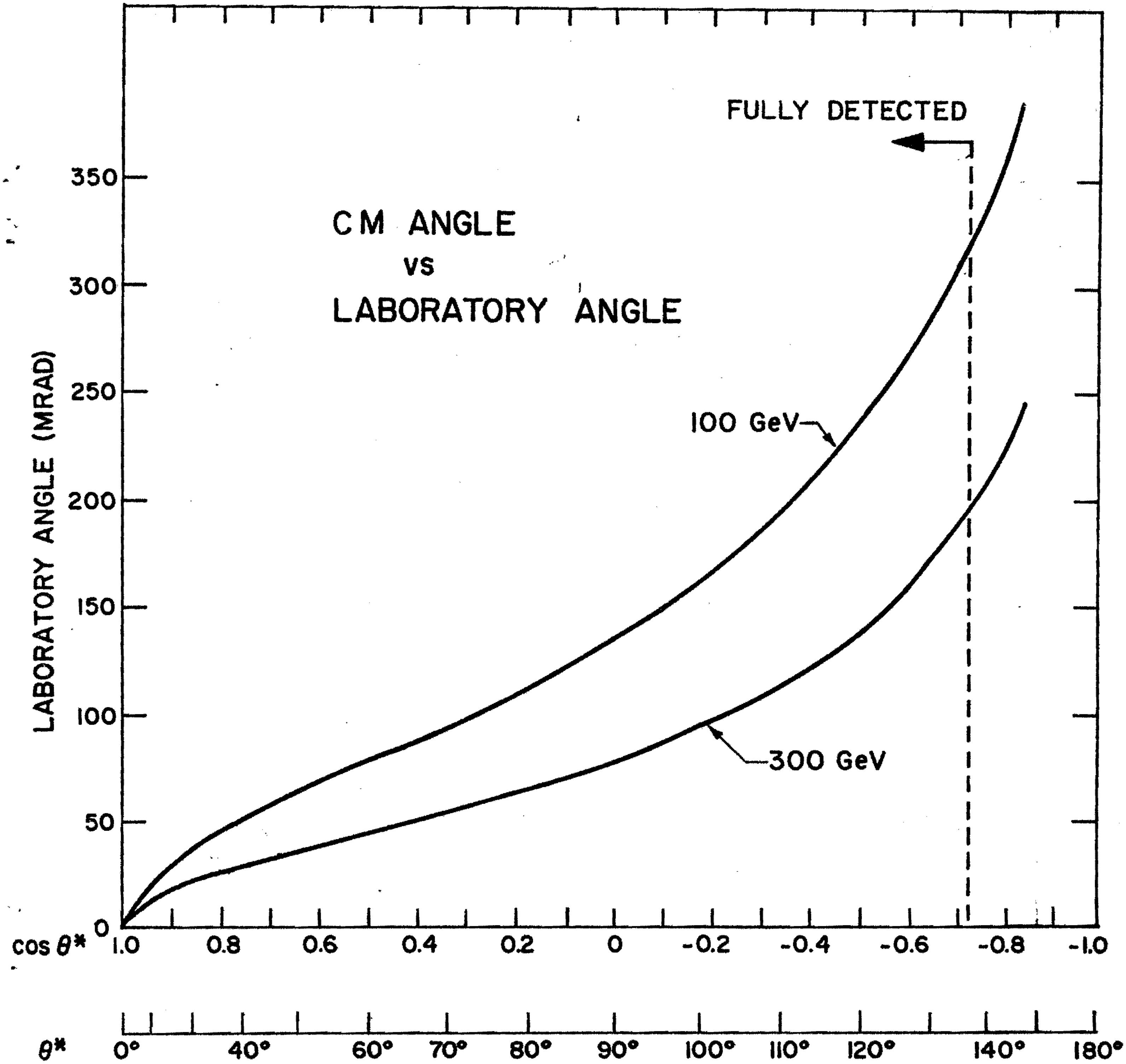

FULLY DETECTED
CM ANGLE
vs
LABORATORY ANGLE
100 GeV
300 GeV
LABORATORY ANGLE (MRAD)
350
300
250
200
150
100
50
0
cos θ*
1.0
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1.0
θ*
0°
40°
60°
70°
80°
90°
100°
110°
120°
140°
180°

Fig. 4

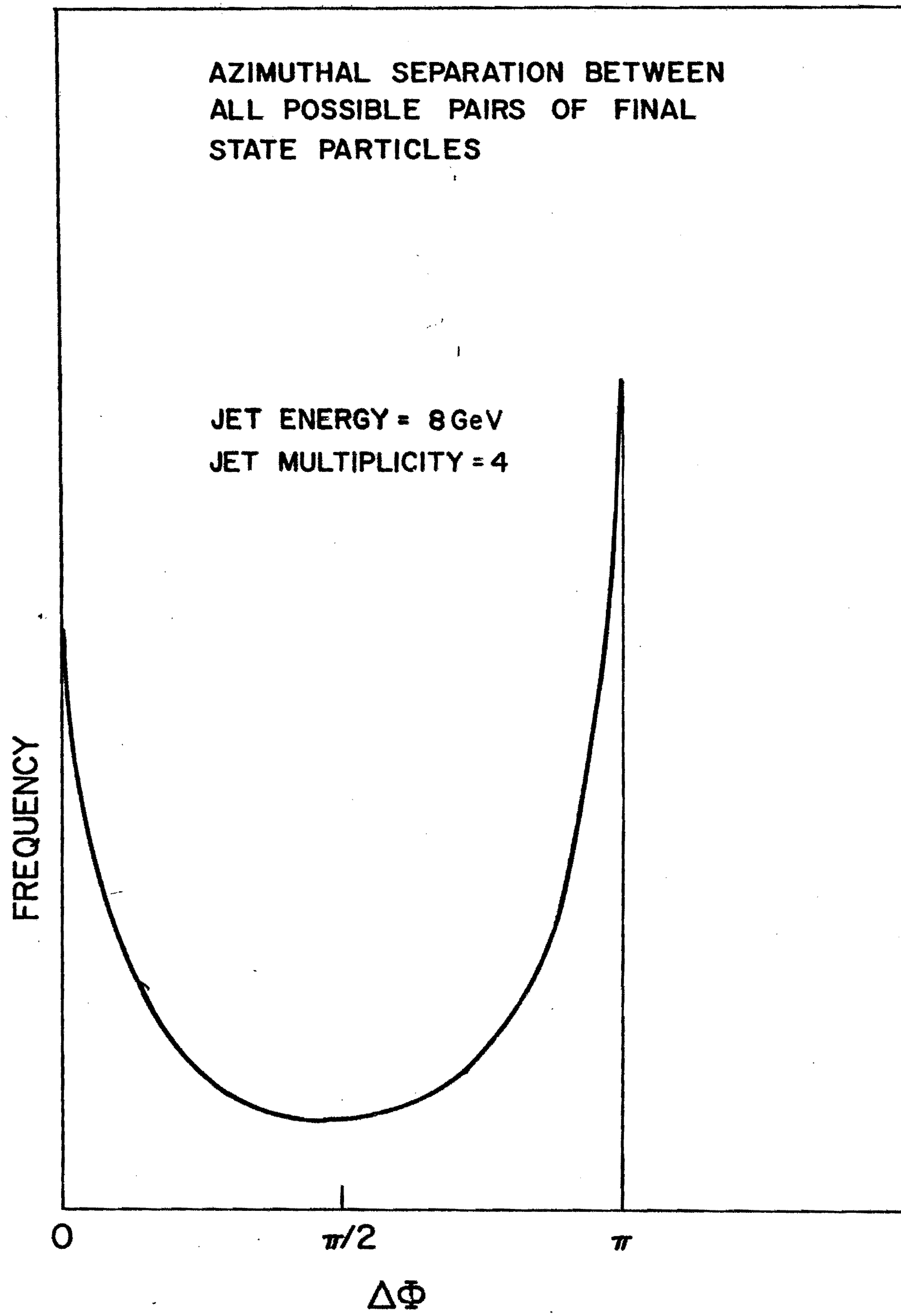

AZIMUTHAL SEPARATION BETWEEN
ALL POSSIBLE PAIRS OF FINAL
STATE PARTICLES
JET ENERGY = 8 GeV
JET MULTIPLICITY = 4
FREQUENCY
0
π/2
π
ΔΦ

Fig. 5

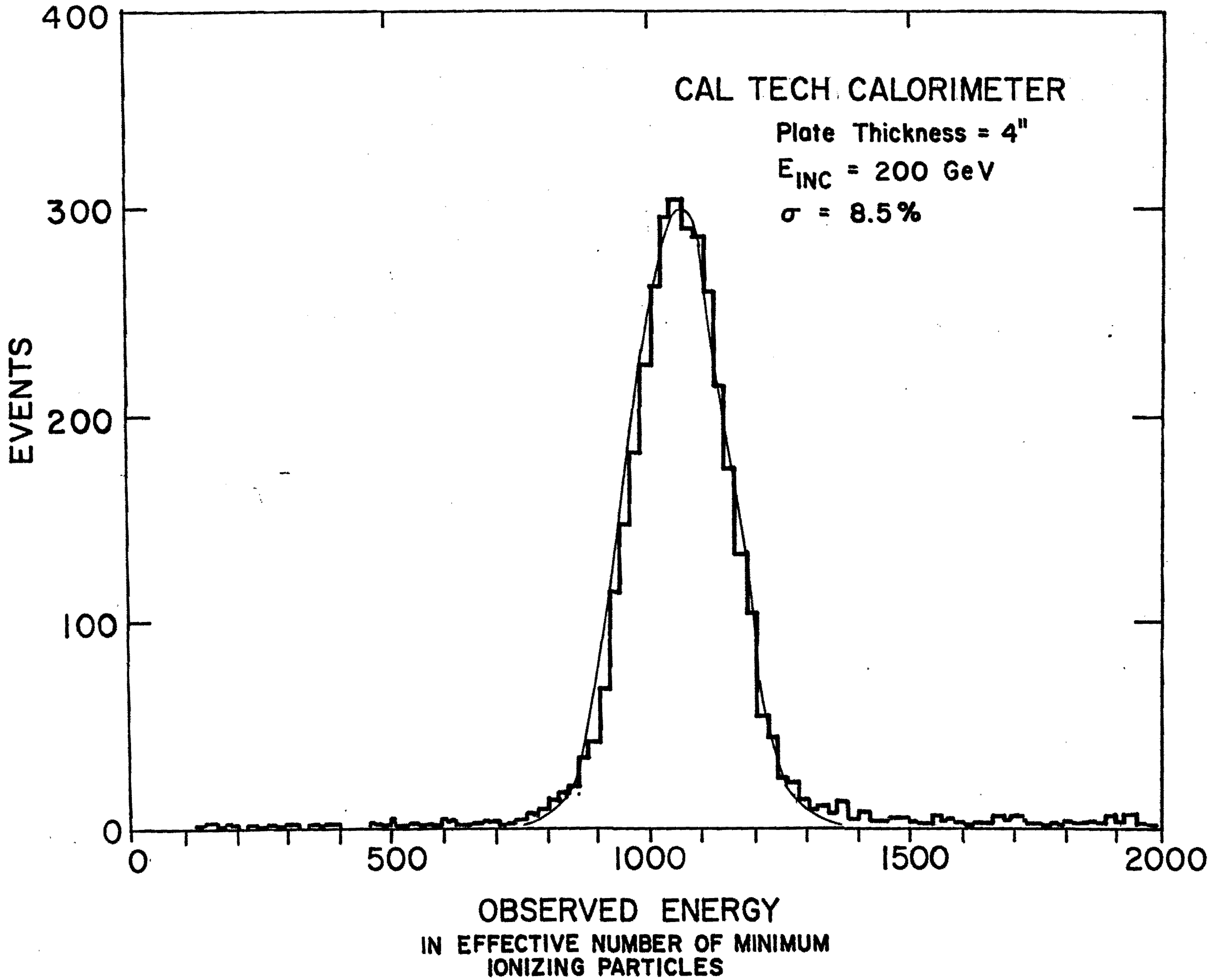

CAL TECH CALORIMETER
Plate Thickness = 4"
E INC = 200 GeV
σ = 8.5%
EVENTS
400
300
200
100
0
0
500
1000
1500
2000
OBSERVED ENERGY
IN EFFECTIVE NUMBER OF MINIMUM
IONIZING PARTICLES

Fig. 6

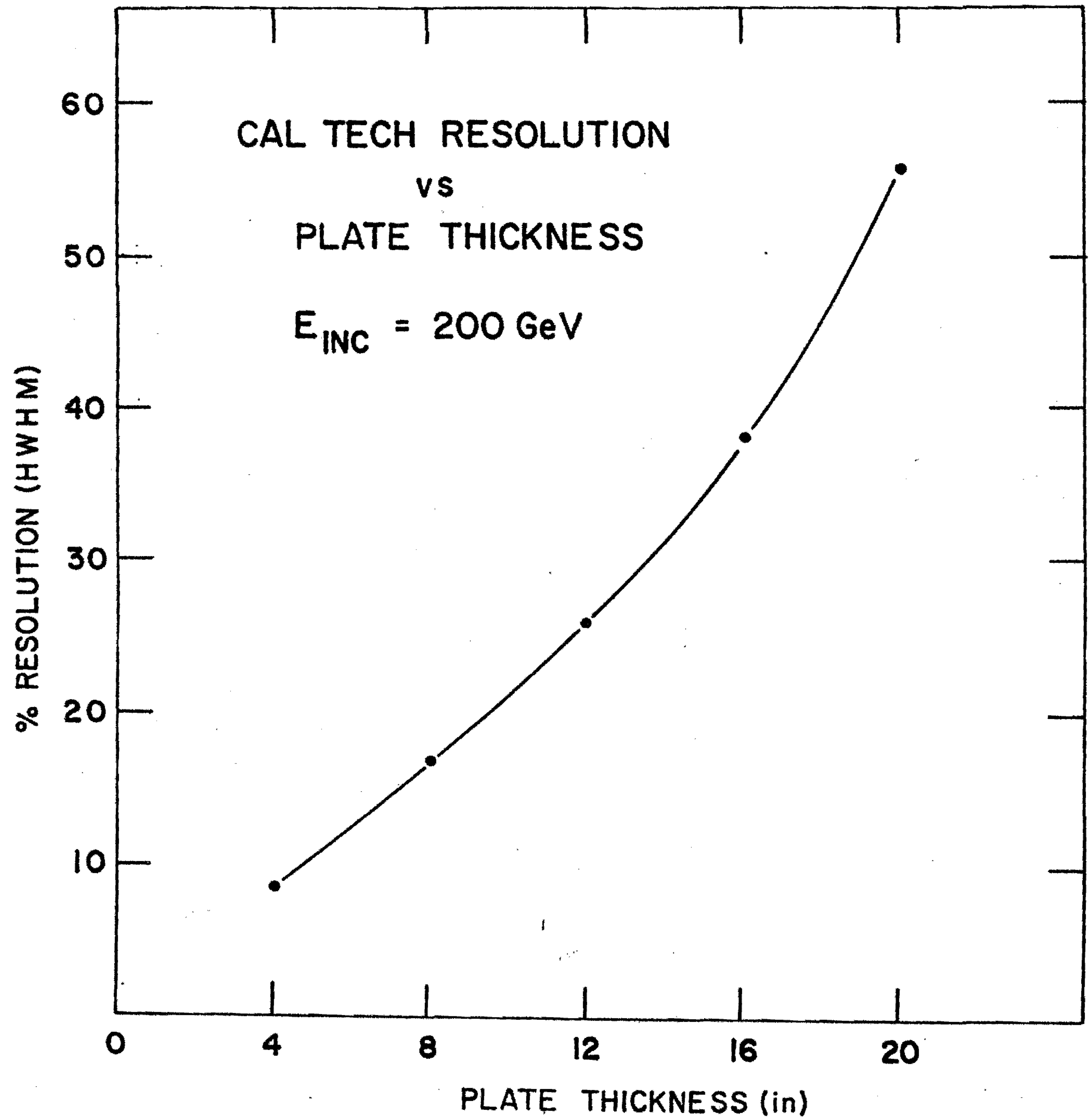

CAL TECH RESOLUTION
vs
PLATE THICKNESS
E_{INC} = 200 GeV
% RESOLUTION (HWHM)
PLATE THICKNESS (in)
0
4
8
12
16
20
10
20
30
40
50
60

Fig. 7

A POSSIBLE CALORIMETER STRUCTURE

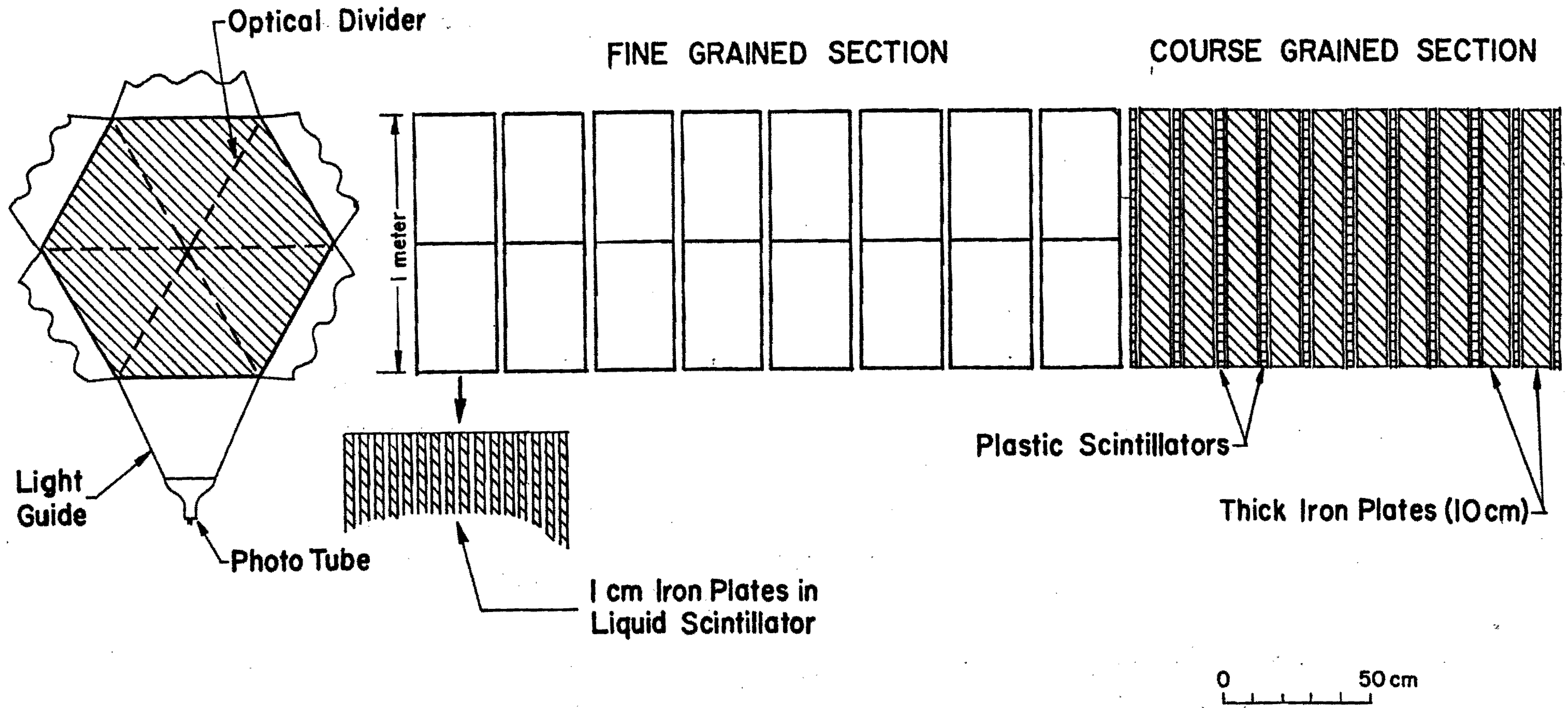


Fig. 8

ADDENDUM TO PROPOSAL 222 A

I. INTRODUCTION

Our Proposal 222 presents ideas for studying hard hadron-hadron collisions where a substantial amount of the total energy appears at large angles with respect to the incident beam. Since the submission of our proposal we have further investigated our capability for studying one type of these hard collisions - those where particle clusters or jets appear at wide angles. We wish to update Proposal 222 with ideas developed from these studies.

First we are still committed to the original philosophy of a global triggering criterion as set out in the proposal. Thus we have the following requirements on the detector:

1) The trigger is unbiased in the ϕ dependence, i.e., it accepts a full 2π in the azimuth, and does not <u>require</u> momentum clustered in a small ϕ range.
2) The trigger detects neutrals as well as charged particles (specifically it is still a calorimeter of steel plates and liquid scintillator and measures energy).
3) The apparatus has a very large acceptance in Θ as well as ϕ.
4) Charged particle configurations are detected in proportional chambers between the target and the calorimeter.

To enhance our ability to analyze the details of the final states of the hard collisions, we propose now a calorimeter configuration which is the complement of the calorimeter described in Proposal 222. Instead of measuring the energy missing from the forward direction via a calorimeter in the beam, we propose to measure the wide angle energy directly by using a ring calorimeter subtending a full 2π in the azimuth, and an angle Θ between 35 mr and 200 mr in the lab(45^{o} to 135^{o} in the CM system at 300 GeV). One of the 4 calorimeter modules is shown in Figure 1. This technique offers the advantage that the triggering device now also serves as an analyzer of the final state particle energies. Moreover, it allows us to use an order of magnitude more beam intensity since the triggering calorimeter is outside the beam.

Each module of the calorimeter would be segmented in 12 optically independent sections (see Fig.2) to give ϕ information on the deposition of energy. The hole in the center would allow the forward cone to miss the calorimeter. The trigger is obviously very flexible, and would consist initially of just requiring a certain amount of energy (say 100GeV) deposited in the ring calorimeter.

This modified detector is especially well suited to searching for jet-like particle clusters at wide angles since it is sensitive to the energy of neutrals as well as charged particles and can examine ϕ correlations of particle momenta without imposing them in the trigger. Our Monte Carlo studies show that in reasonable models of jets the momentum in the lab is well collimated, although the trajectories of the particles emanating from the jet are not. This is because the "soft" particles of the jet can be at large angles in the lab, and are easily confused with target fragmentation. Consequently, we feel that the detection of clustering of momentum is the ideal way to search for jets. It seems to us that the segmented calorimeter at large angles provides advantages that cannot be supplied by smaller aperture (in ϕ) magnetic spectrometers or wide angle individual calorimeters.

Another interesting feature is that we can, in the framework of the parton model, investigate differences in the internal structure of the incoming hadron - π, p, k, etc. This is by virtue of the fact, already mentioned in our original proposal, that we measure the X_1 of the parton in the incoming hadron which participated in the parton-parton collision. Namely,

$$X_1 = E_m/P_{lab}$$

where E_m is the energy missing from the forward cone, or the detected energy in the wide angle calorimeters, and P_{lab} is the laboratory momentum of the incoming hadron.

We note that in the parton model, the cross section for a given amount of energy outside of the forward cone, $\sigma(E_m)$, is then expressible in the following form:

$$\sigma(E_m) = \frac{f(X_1)}{X_1} . F(E_m, \Theta_c)$$

where the function F represents an integral over X_2 and the parton-parton cross section. The fact that this function depends only upon E_m and Θ_c, the minimum laboratory angle of the calorimeter, means that by holding E_m and Θ_c fixed and varying P_{lab}, the ratios of $\sigma(E_m)$ at different lab energies directly yields the shape of $f(X_1)$. Thus comparison with νW_2

from SLAC will be an interesting test of the parton model as will the comparison between π and p.

II. MONTE CARLO RESULTS OF CALORIMETER STUDIES

To study the general problem of designing an apparatus to detect jets we wrote a simple Monte Carlo. The initial assumptions were:

1) 6 GeV jets were produced at some angle Θ in the pp c.m.
2) The jet multiplicity was variable, but was guided by 5 GeV photoproduction data.
3) The jet fragmentation was assumed to be described by $G(X) = 2(1-X)$.
4) The P_T distribution to the jet direction was given by $e^{-5.3P_T}$.
5) All particles were assumed to be pions.
6) Momentum was conserved.

Figure 3 shows the pulse height distribution in each of the 12 channels of the segmented calorimeter for 6 GeV jets of multiplicity 5. Jets were produced at 90° in the p-p center of mass, and were centered on segment 7 of the calorimeter in the azimuth. One sees that the momentum of the jet is contained almost completely in one azimuthal segment of the calorimeter. Figure 4 shows a typical jet geometry - one sees that the particles are not well collimated in ϕ, even though the momentum is. Finally, Figure 5 shows the response of the calorimeter as a function of the c.m. angle of the jet (holding P_{Jet} fixed at 6 GeV, and varying Θ). One sees that the calorimeter contains most of the energy of the jet over a very wide range of c.m. angles.

III. APPARATUS LAYOUT AND DESIGN

The apparatus, with the exception of the calorimeter, remains as shown in our original proposal (see Figure 6). The ring calorimeter would be 4m downstream of a 30 cm H_2 target. Behind the target would be proportional chambers as described in the proposal. We should note that, since low energy particles in the beam are no longer a problem with this detector, we no longer require beam defining chambers and bend magnets upstream of the target.

The calorimeter design is an extension of a detailed design made for the original forward energy trigger calorimeter. Each of the 4 modules would consist of 25 teflon coated 3/8" thick steel plates. The modules would be filled with liquid scintillator. 12 phototubes (RCA 8055) per module would look into optically baffled segments of the calorimeter giving the azimuthal information. We feel we have worked out an inexpensive and efficient method of producing the modules and the light pipes for the phototubes.

One possible problem with the ring calorimeter could be jet events at angles far from 90^{0} in the c.m., such that a large amount of energy is deposited close to the edge of the calorimeter. We propose two methods to monitor this. One would be to have a ring scintillator in the center (see Figure 1) to measure the number of charged particles leaking out (or going into) the calorimeter. Tests by Schopper at CERN show that only 15% of the energy leaks out if a particle enters 5 cm from the edge. The second technique would be to place between the modules area integrating proportional chambers to give us radial information as to where the energy in the jet is. Chambers similar in principle have been built by one of us. Each azimuthal segment of the calorimeter would be covered by 4 radial sections of the chamber, each integrating the charge from many wires over the area. One would thus have 48 segments from each plane between the calorimeter modules sampling the energy distribution in the radial direction. One would use this information to measure the effective lab angle of the jet in cases where several particles enter one azimuthal section of the calorimeter.

IV. BEAM REQUIREMENTS AND NAL SUPPORT

We would need approximately the same beam conditions as listed in our proposal. The amount of floor space along the beam, however, has been drastically reduced - a total now of about 20m is required. We would require testing time as mentioned in the proposal. The M1 beam in the meson lab still seems adequate for initial data taking, but ultimately the highest energy pion and proton beam attainable at NAL would be most desirable.

Early results of Cronin, et al., in experiment 100 show that there is very strong s dependence in the particle yields at high P_T. The cross section at P_T = 6 GeV/c increases by a factor of 7 going from 200 to 300 GeV. Thus the requirement of the highest energy beam is very important. Because of the large size of the detector the beam conditions must be relatively clean.

The construction of the detector is well within the capabilities of the Fermi Institute. We will require, however, some support from NAL for readout electronics, on-line computer, and possibly some raw materials for the calorimeter. A detailed cost estimate is appended.

COST ESTIMATES

1. Ionization Calorimeter

   (i) Materials

steel plates	$ 7K
liquid scintillator	7K
teflon film, with adhesive	4K
lead sheets for front module	2K
photomultiplier tubes 60 x$120	7.2K
photomultiplier bases and magnetic shields 60 x$50	3K
light guides 60 x$50	3K
mechanical supports	5K
	$38.2K

   (ii) Assembly — $20K

Subtotal $58.2K

2. Segmented Proportional Counters (5 planes)

   (i) Materials

aluminum backing plates	$0.9K
G-10 frames	0.9K
support frames	2.0K

   (ii) Labor

machining of backing plates and preparation of G-10 frames	5K
Winding and gluing wires	5K

   (iii) Electronics

amplifiers 250 channels x$10 ea.	2.5K
power supplies	1.K

Subtotal 17.3K

3. Trajectory Determining Proportional Chambers

   (i) Mechanical Frames including material and labor — 10K

   (ii) Amplifiers and readout electronics 4000 wire @ $5.00 / wire — 20K

Subtotal $30K

4. Scintillation Counters for Triggering

20 fast photomultiplier tubes 20 x $250		5K
bases & magnetic shields 20 x$50		1K
scintillator and light guides		2K
	Subtotal	$8K

5. Cables 5K

TOTAL $118.5K

The PREP electronics requirement remains unchanged except for one item. Our request for 9 octal ADC's (LRS-$14K) is changed to 39 octal ADC's (new model LRS - $31K).

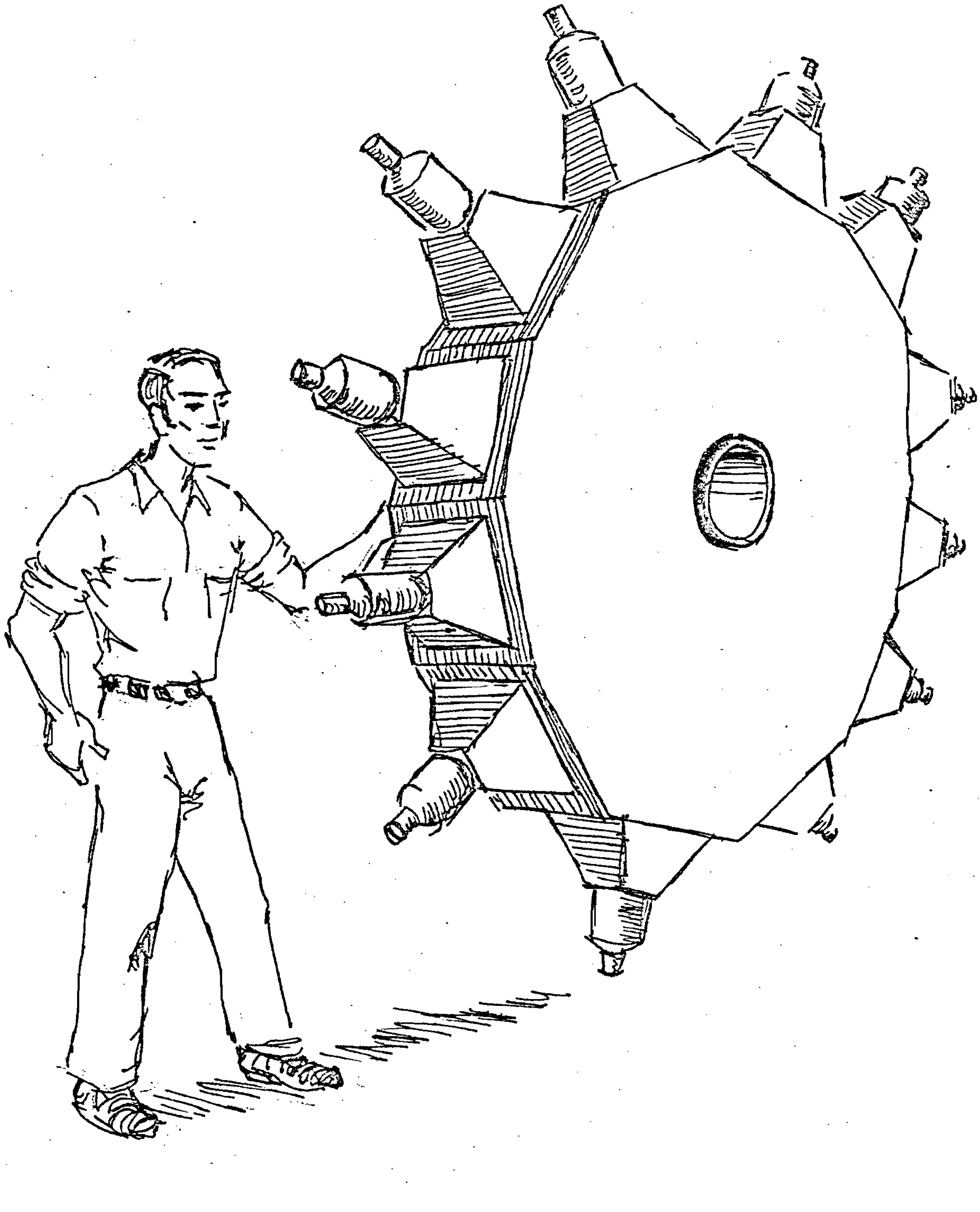


Fig I.

CALORIMETER - FRONT VIEW

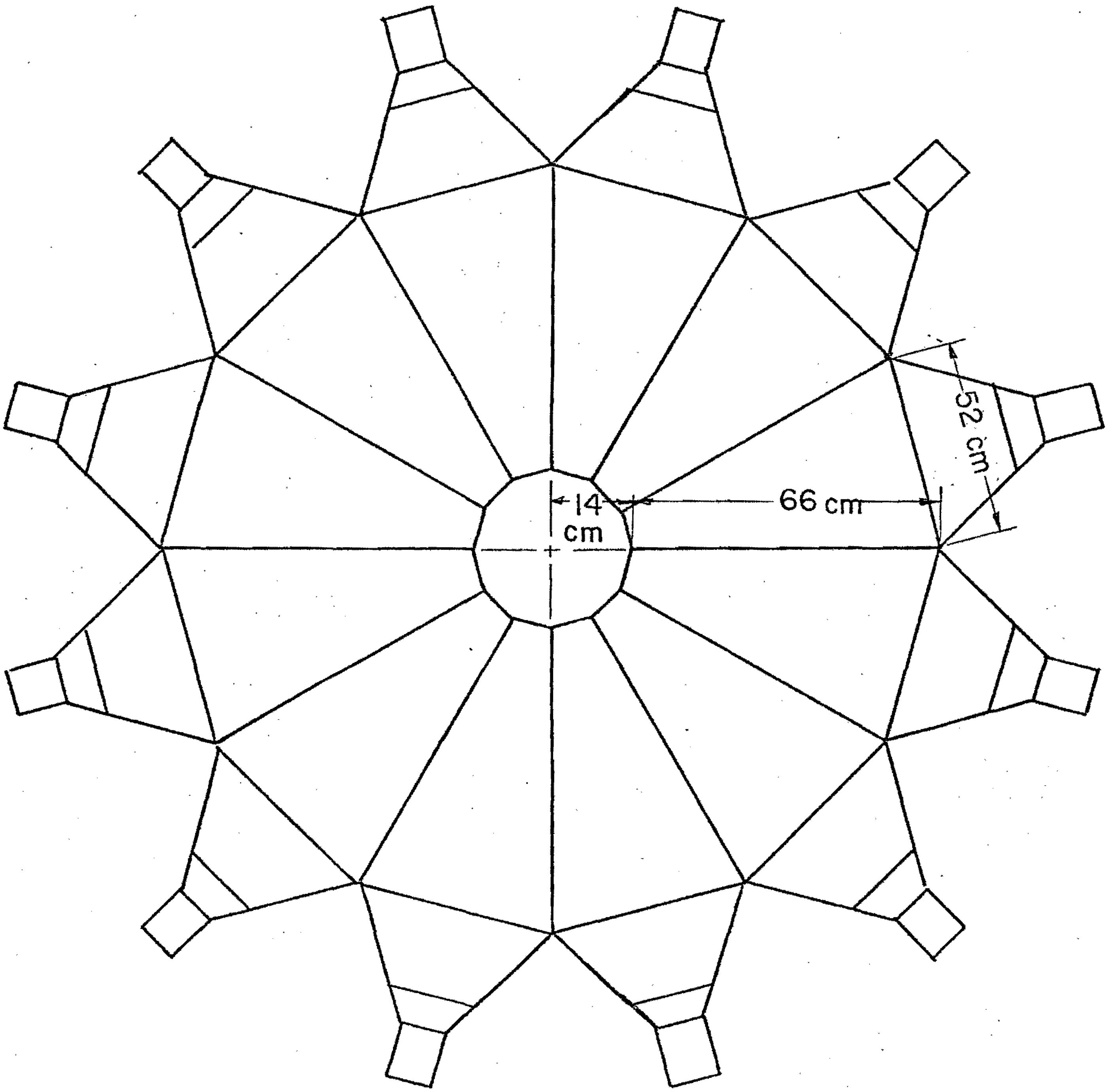


Fig 2.

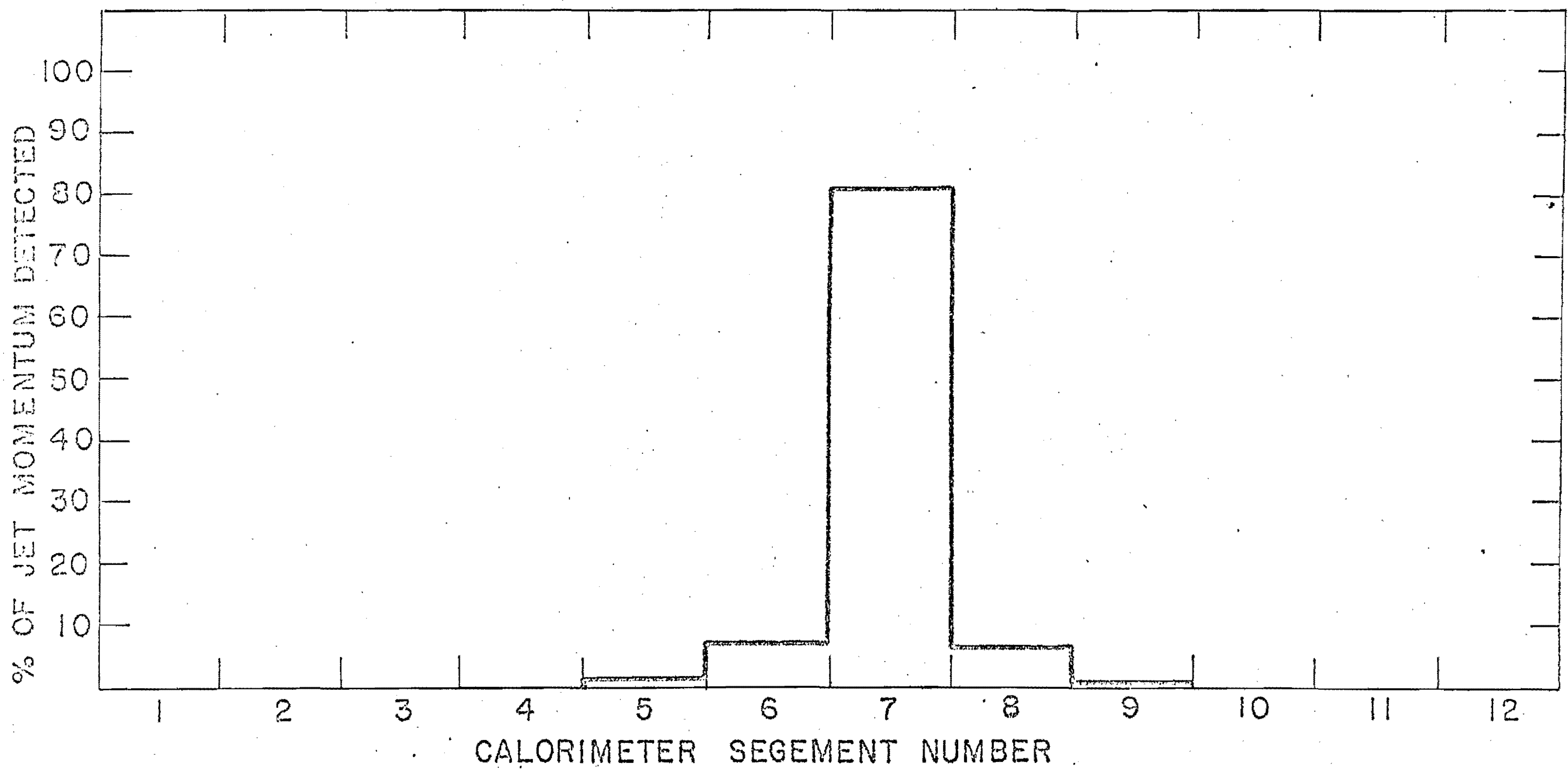

% OF JET MOMENTUM DETECTED
100
90
80
70
60
50
40
30
20
10
1
2
3
4
5
6
7
8
9
10
11
12
CALORIMETER SEGEMENT NUMBER

Fig 3.

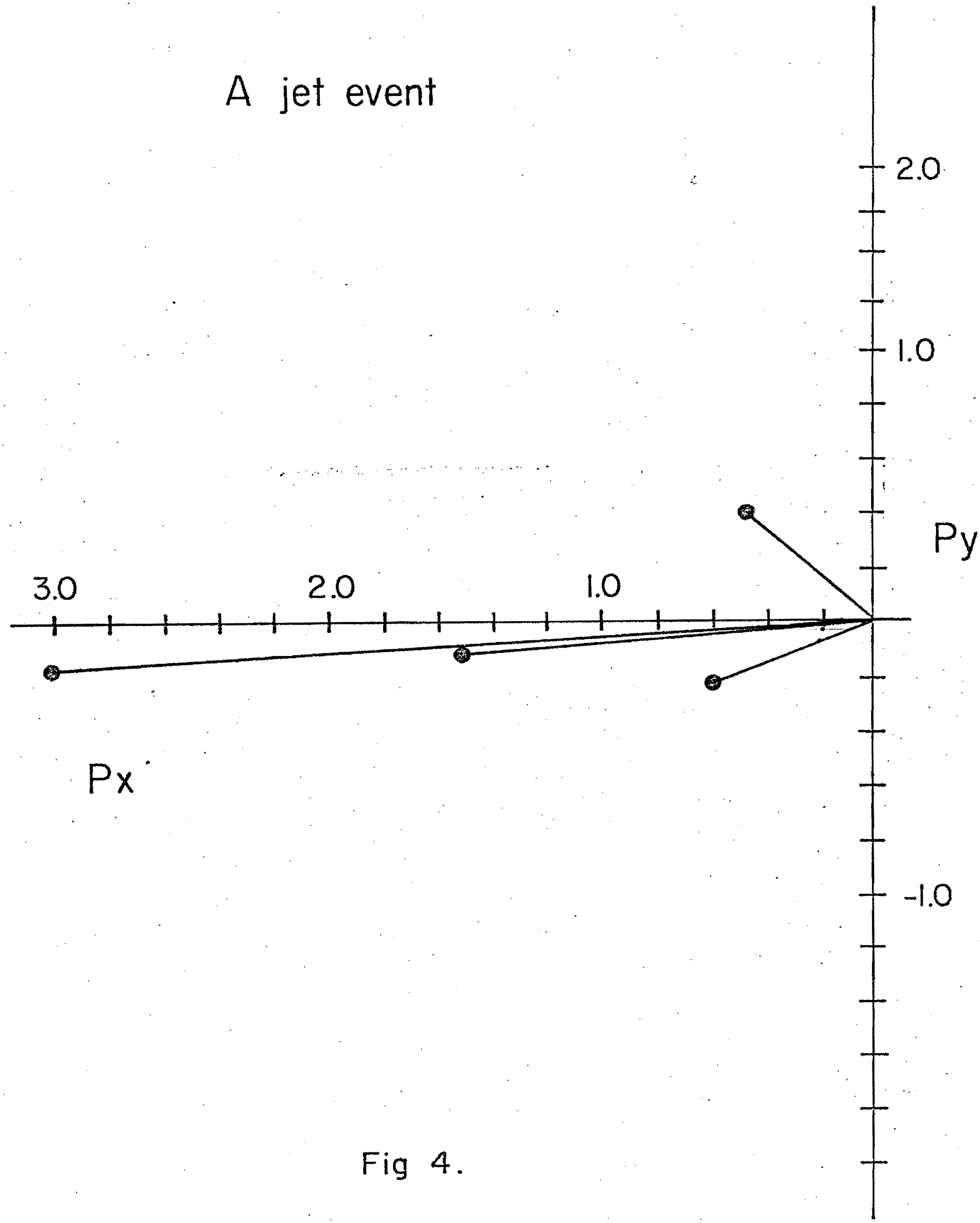
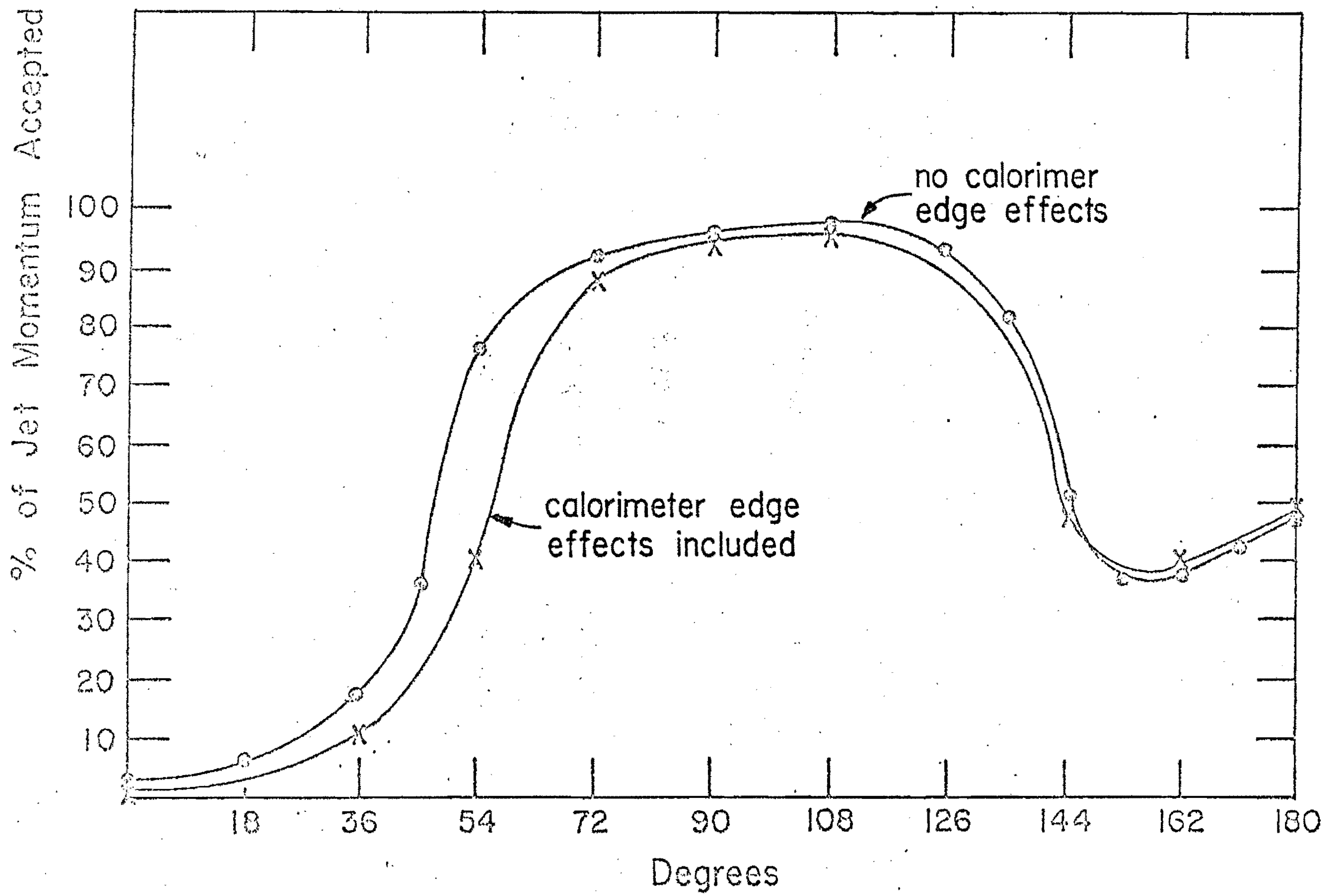


Fig 4.



% of Jet Momentum Accepted
100
90
80
70
60
50
40
30
20
10
18
36
54
72
90
108
126
144
162
180
Degrees
no calorimer edge effects
calorimeter edge effects included

Fig 5.

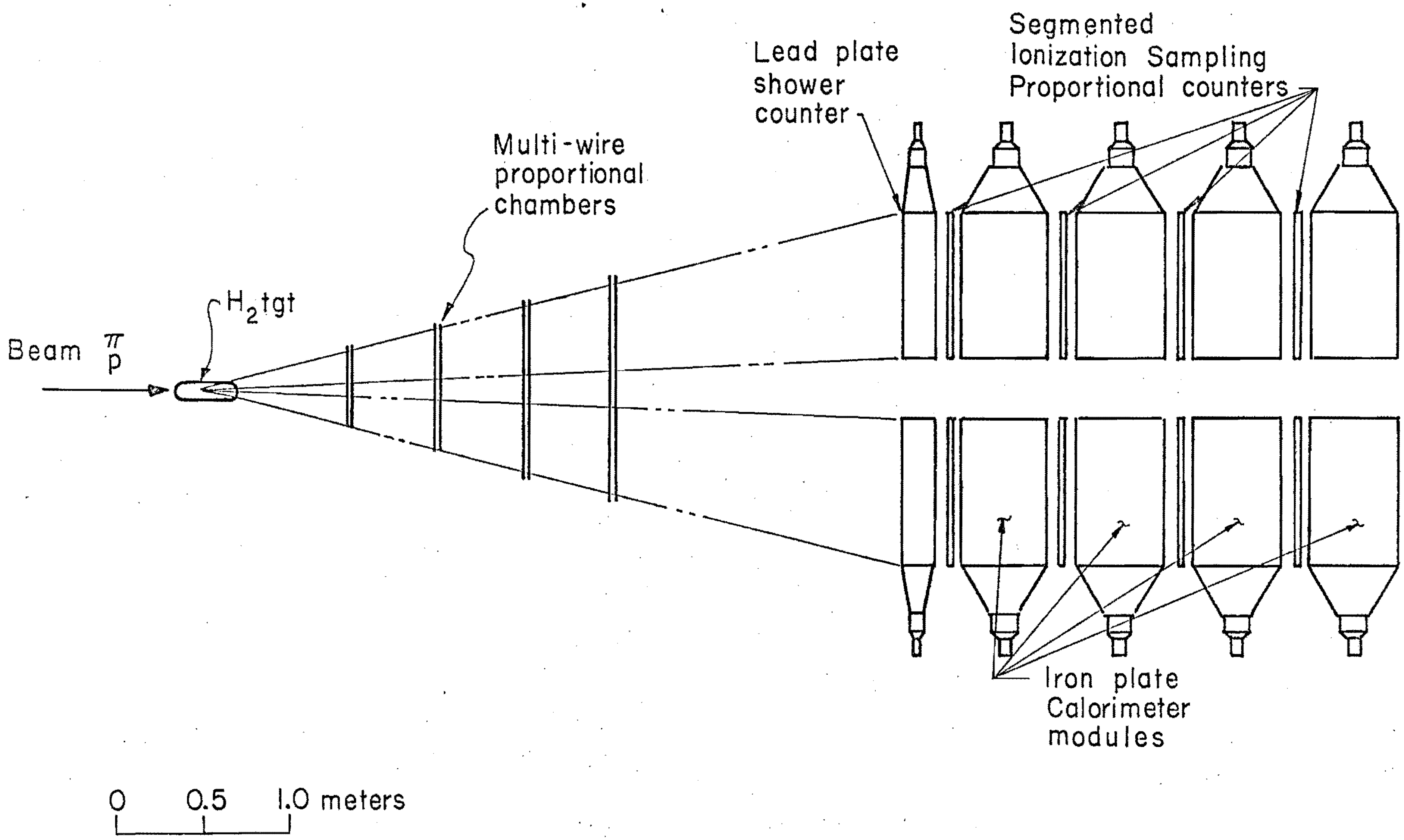

Segmented
Ionization Sampling
Proportional counters
Lead plate
shower
counter
Multi-wire
proportional
chambers
H_2 tgt
Beam π p
Iron plate
Calorimeter
modules
0 0.5 1.0 meters

Fig 6.