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Scientific Spokesman:
Thomas H. Fields
Argonne National Laboratory
FTS: 972-6278
Commercial: (312) 972-6278
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JET PRODUCTION IN 1000 GEV HADRON COLLISIONS

M. Arenton, R. Ditzler, T. Fields, R. Stanek
Argonne National Laboratory, Argonne, Illinois

M. Harrison
Fermi National Accelerator Laboratory, Batavia, Illinois

A. Kanofsky
Lehigh University, Bethlehem, Pennsylvania

L. Cormell, W. Kononenko, B. Robinson, W. Selove, G. Theodosiou, B. Yost
University of Pennsylvania, Philadelphia, Pennsylvania

M. Corcoran, H. Miettinen, G. Phillips, J. Roberts
Rice University, Houston, Texas

H. Chen, A. Erwin, A. Hasan, C. Kuehn, M. Thompson
University of Wisconsin, Madison, Wisconsin

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ABSTRACT

We propose to extend our study of the production of jets in hadron collisions into the new energy range available at the Tevatron, using the same apparatus as in E-609, our forthcoming jet experiment. In this document, after brief descriptions of the current status of jet physics and the goals and techniques of our current experiment E-609, we discuss the additional information on jet production expected to be gained by running at higher beam energies. Tevatron energies enable the accessible jet P_T range to be extended from 7 GeV/c to 11 GeV/c, with corresponding improvements in jet identification. Several effects may be studied at Tevatron energies that are not amenable to study at lower energy, such as constituent scattering producing 3 jets in the final state, and the identification and measurement of gluon jets and the study of gluon structure functions by working in the kinematic region of small incident parton momentum x_1. The beam and apparatus requirements for this work are described.

CONTENTS

1. INTRODUCTION

1A - Relationship to E609

This is a proposal to extend our approved (E609) program of studies of jet production in hadron collisions to energies up to 1000 GeV using the Tevatron II. Running at 1000 GeV will provide substantial enhancements to our capabilities for studying the main subjects of E609: the determination of the overall jet structure of high p_T hadronic collisions, and the accurate measurement of cross sections for "two-jet" events. It will also allow us to explore some additional new aspects of hadron jet physics which are not accessible at present Fermilab-SPS energies.

Another similarity of the proposed research to that of E609 is that the same E609 detector system, which will already be located in the M6 beam line, would also be used for 1000 GeV running. In fact, it would be quite feasible for us to intermix Tevatron runs with lower energy E609 running to efficiently utilize the early operation of the Tevatron, and we will need only minimal intensity from the Tevatron.

Because of this close relationship between our proposed research at 1000 GeV and our program in E609, we have included in this document a summary of our present goals and expectations for the E609 experiment as well as a very brief description of the present status of hadron jet physics. The reader who is already conversant with those subjects can now skip to Section 2. (Overall, we have made this a short document because of the close relationship of the proposed studies to E609. Our E609 plans have been described in detail elsewhere.[1])

1B Status of Hadron Jet Physics

The first generation of hadron jet experiments at Fermilab produced several important results, which together constitute evidence that high p_T jet pairs give direct information on parton-parton scattering.[(2-4)] In a number of significant steps along the way to this conclusion, these first generation experiments showed that:

- hadron calorimeters can be effectively used for jet triggering and detection[5,6]
- a calorimeter solid angle $\gtrsim 1$ sterad is required[7,8]
- jet cross sections at large p_T are hundreds of times larger than single particle cross sections[5,6,8,9]
- pairs of large p_T jets are produced with an approximate balance of transverse momentum[5,9]
- πp collisions produce on the average more forward jet pairs than pp collisions[10]
- jet studies can be used to obtain hadron structure functions (parton momentum distributions)[11]
- jet pair studies can be used to make a measurement of parton transverse momentum[12]

At the ISR, several experiments (using mainly spectrometers rather than calorimeters) have accurately studied many single-particle and particle-correlation aspects of large p_T hadron phenomena during the past decade, following the first observations of particle production at large p_T in hadron collisions.[13] Although single-particle spectra can be fitted in many cases by a variety of theoretical models, correlation data are usually more restrictive. The high energy of the ISR is of great value in minimizing "background" from the two spectator ("beam" and "target") jets. Very recent ISR studies have focussed upon measuring the composition (leading charge) in the hadron jet recoiling from the production of a direct single photon.[14] The high energy of the ISR is also advantageous for that type of experiment, since direct photon production is small compared to the π° background for $p_T \lesssim 5$ GeV/c.

Second generation hadron calorimeter experiments (NA5 at the SPS, E557 and E609 at Fermilab, and R807 at the ISR) have a principal goal of determining the overall event structure of inelastic collisions which produce jets at high p_T, so that truly quantitative measurements of jet production can be made. This requires the use of a calorimeter which subtends a large fraction of the entire 4π c.m. solid angle, while at the same time triggering the data acquisition only for that very small fraction ($\sim 10^{-5}$) of inelastic events which produces particles at large values of p_T. This triggering problem is intrinsically difficult, and its difficulty is aggravated by the very steeply falling p_T spectrum and the less-than-ideal spatial and energy resolution functions of a real hadron calorimeter.

Up to now, the only second-generation calorimeter experiment which has collected a substantial amount of data is NA5 at the SPS. Preliminary reports[15] on their results have focussed upon the apparent lack of jet structure in events triggered by the condition that > 10.5 GeV of transverse energy ($\sum_i E_i^T \approx \sum_i p_i^T$) be detected by their full azimuth calorimeter (45° < θ^* < 135°). In fact, our Monte-Carlo studies of triggering criteria, which are based on the Feynman-Field-Fox QCD-type parton scattering model, indicate that the transverse energy trigger used by NA5 may not be expected to select events with a clear jet structure. The basic reason for this is that the probability of the beam and target jet fragmentations depositing a substantial amount of transverse energy (5 GeV, say) in such a large calorimeter is quite comparable to the probability of occurrence of a pair of large p_T jets.

With single arm triggers, NA5 data yield cross sections similar to those from the previous Fermilab jet experiments mentioned above. Running for NA5 was completed in mid-1980, so that further NA5 results on jet production are to be expected during 1981. This year may also see the observation of jets from $\bar{p}p$ collisions in the ISR (which will provide the first fast "antiquark beam" at ISR energies), and at a later time, $\bar{p}p$ collisions in the SPS are expected to open a new energy regime for hadron jet physics.

1C Goals of E609

The three basic questions which we will be trying to answer in E609 (with runs beginning in fall 1981) are:

1. Is there an experimentally well-defined class of high p_T hadron-hadron collisions consisting of two large p_T jets (from the scattered partons) plus the two residual "diquark" jets (the beam jet and target jet)?

2. Can one utilize calorimetric detectors and triggers in a way which will allow quantitative detection of such "four-jet" events with managable uncertainties due to:

a. trigger biases from calorimeter geometry, parton transverse momentum, and fragmentation functions

b. overlapping of the four jets due to large angle fragmentation products

c. subtleties in calorimeter resolution functions and calibration procedures

3. Given positive answers to the above questions, how can the experimental results best be used to test QCD models of parton-parton scattering and to determine hadron structure functions?

There are also other important goals for the E609 work, but here we wish to emphasize that the above basic questions are not yet quantitatively answered. They can be addressed most effectively by using a hadron calorimeter (with very large solid angle, full azimuth, and a well-behaved pulse height response function) to carry out an extended program of jet studies with various beam particles, beam energies, and triggering arrangements.

1D Jet Physics at the Tevatron

In the context of the present state of hadron jet physics as briefly summarized above, we shall describe in the next section a number of specific goals for our proposed Tevatron experiment. Some of these goals concern the same aspects of large p_T jet physics which can also be studied at present fixed target energies, but for which additional energy will permit the experiment results to be clearer (e.g. observation of the overall structure of a two jet plus beam and target spectator jets event). Other physics goals described in the next section are expected to have an effective energy threshold above Fermilab-SPS energies (e.g. the search for multi jet events). In both types of cases, there will be important experimental advantages to using the same calorimeter, triggering algorithms, and data analysis setups at Tevatron energies as in (almost) concurrent E609 running at present Fermilab energies.

2. Physics Goals

2A. Two-Jet Events, Parton-Parton Scattering

As described above, a primary goal of E609 is to collect a sample of clean large p_T jet events which will allow us to make quantitative comparisons of our data with predictions from QCD-type models. It is expected that jet identification will become more straightforward at the larger values of p_T accessible at the Tevatron since the jet fragmentation products will be more collimated than at lower values of p_T.

The increase in collimation of jets which can be expected by going from 400 GeV to 1000 GeV is illustrated in Fig. 1 by random samples of high p_T events generated with our F-F-F Monte Carlo program for two situations with comparable counting rates, at 400 GeV and 1000 GeV respectively. Because of the decreased overlap with the spectator jets at Tevatron energies, we will be able to study jet production at angles nearer 0° and 180° than is possible at lower $\sqrt{s}$ values. Of course, an important advantage to running at 1000 GeV is the high counting rate for jets in the higher range of p_T values where jet identification is clear and where simpler QCD diagrams are likely to play a more dominant role. We estimate that in 400 hours of running with a 1000 GeV proton beam, we will be able to collect approximately 100,000 dijet events with $p_T > 9$ GeV/c per jet. This estimate is based upon double arm counting rates which were measured(5,9) in E-395.

The above advantages will enable us to evaluate better the triggering biases, both instrumental and intrinsic (e.g. parton transverse momentum effects and fragmentation function effects), which are a key aspect of hadron jet experiments. For these reasons, we believe that 1000 GeV running will allow important additional checks of our data analysis procedures for studying both hadron structure functions and parton-parton scattering.

2B Search for 3-Jet Events

At Tevatron energies, energies in the parton-parton c.m. system of $\hat{W} \approx 25$ GeV become accessible. At these values of $\hat{W}$, one can readily have three jets each of energy > 5 or 6 GeV, whereas at $\hat{W} \sim 10$-15 GeV three-jet events would have at least one jet with $p_\perp$ no larger than 2.5 to 4 GeV.

Experimentally in e^+e^- annihilation, 3-jet type events are visible to the naked eye at $\hat{W} \sim 25$ GeV, and are far less visible (and in fact have not yet been reported, to our knowledge) at $\hat{W} \sim 15$ GeV.

In jet events produced in hadron collisions one can similarly expect to be able to see clear 3-jet type events at $\hat{W} \sim 25$ GeV, whereas at $\hat{W} \sim 15$ GeV this will be much more difficult if not impossible. Such 3-jet events will be very interesting to study. The 3-jet events observed in e^+e^- annihilation seem to have properties which are in general agreement with QCD predictions, with a "3rd" jet having been produced by a hard gluon radiated by a quark.

In hadron-produced jet events this gluon-radiation process will also occur, where now the gluon may be radiated from a gluon parent also, but it is not the only mechanism which can produce multiple jet events. Such events can also be produced by radiation from the initial-state partons, and also by scattering of outgoing high-p_T quarks or gluons by other quarks or gluons present in the original hadrons. The observation and detailed study of multiple-jet events, at Tevatron energies, may yield significant information on these various processes.

2C Gluon Structure Functions

With the higher incident energies which the Tevatron will provide, significant jet studies can be carried out with incident partons of relatively low fractional momentum x_1. For example, at 400 GeV a pair of jets with total laboratory energy say 150 GeV come from an incident parton with x_1 = 150 GeV/400 GeV = 0.375. Hadron structure functions vary with x in such a way that for x = 0.375 the parton is most likely to be a (valence) quark. For 1000 GeV beam energy, however, the same 150 GeV energy incident parton corresponds to a considerably smaller x of 0.15, and for this value of x the parton is most likely to be a gluon.

In both cases the outgoing jet pair will consist of two jets of average energy 75 GeV each. The detection characteristics of the jets will be virtually unchanged. And yet at 1000 GeV one can expect the incident parton, for these jet energies, to be dominantly a gluon.

As one example of the kind of studies made possible by this availability of dominant-gluon incident partons, we consider here a possible method of obtaining approximate gluon structure function information.

More specifically, we consider a method for obtaining the ratio of gluon structure functions for pions and protons. This method is similar to that used in E-395 to obtain structure function information for quarks in the pion,[11] and involves measuring a ratio of structure functions by measuring a ratio of cross sections, for different incident hadrons. In the present case we consider a study over a range of relatively small x_1, say 0.08 to 0.15, and relatively large x_2, say about 0.5 (x_2 is the momentum fraction of the target parton).

These collisions can be expected to be predominantly gluon-quark collisions. We consider a beam energy of 600 GeV, where we could readily obtain a high flux of mesons. For 600 GeV incident hadrons, the outgoing jet pairs can readily be detected with the large angle coverage of our calorimeter. The transverse energy values per jet for this example will range from about 3-1/2 to 4-1/2 GeV, and the lab energies of the jets will range between about 25 GeV and 45 GeV each, for parton scattering angles $\hat{\theta}$ near 90°.

Following reference 11, the ratio of cross sections

$$R = \frac{\sigma(\pi p \rightarrow 2 \text{ jets} + x)}{\sigma(pp \rightarrow 2 \text{ jets} + x)}$$

will give in this case an approximate value for the ratio of structure functions:

$$\frac{f_{g/\pi}(x_1)}{f_{g/p}(x_1)} \approx R \ .$$

2D Identification of Gluon Jets

In section 2C above, we have described how at Tevatron energies one can expect to obtain jet pair events in which the event will mainly contain one gluon jet and one quark jet. For 1000 GeV incident, and $x_1 = 0.15$, $x_2 = 0.45$, for example, the $\hat{\theta} = 90°$ events would have two jets of laboratory energy 75 GeV each and transverse energy 5.6 GeV ($p_T \approx 4.5$ GeV).

For such events, dominantly of one-quark-jet plus one-gluon-jet nature, one could try identification techniques involving particle identity, or multiplicity, or other jet characteristics, to attempt to distinguish gluon jets and quark jets. For example, since the leading particle in a quark jet is expected to have a substantial flavor correlation with the originating quark, K^- mesons are unlikely leading particles for quark jets from valence quarks in protons and pions; on the other hand gluon jets are expected to be relatively uninhibited in producing leading K^- mesons.

The attempt to distinguish gluon jets and quark jets can be further assisted, using the wide-angle coverage of the E-609 detector, by studying events with gluon scattering angle $\hat{\theta}$ appreciably smaller than 90°. For example, for $\hat{\theta} = 75°$, an angle which is detectable in our detector, the number of gluon jets will be almost 3 times as large as the number of quark jets. This estimate is based on lowest order QCD formulas[16] for $qG \rightarrow qG$. Thus a gluon/quark identification technique could be checked using this enriched sample.

2E Other Phenomena

There are several other aspects of high p_T jet phenomena at Tevatron energies which we plan to explore with our detector. The following paragraphs give a few examples.

At Tevatron energies it may become possible to search for new particles with complex decay modes using calorimeters. The many possible decay modes, frequently involving several neutral hadrons, might preclude other methods of detection. Because of the increased laboratory energy of the decay fragments at the Tevatron one might expect the mass resolution of the calorimeter to improve with the energy resolution, yielding a mass resolution of $\sim$ 5% at the higher end of our range near 25 GeV/c^2. This is beginning to be small enough so that fortuitous circumstances such as low background, judicious data cuts, or copious production could allow the observation of a mass bump.

The p_T range that becomes accessible with 1000 GeV beams makes the study of events with high p_T single photons much more practical than at lower energy. ISR experiments that have observed high p_T single photon production begin to see significant cross sections at $p_T \sim 5$ GeV/c, with increasing cross sections as p_T increases. Depending on the success of the photon detectors that we are currently developing (see Section 3E), we may be able to resolve events containing high p_T single photons.

The ring imaging Cerenkov detector (ORCID, described in Section 3D) which is being developed for E-609 is designed to allow the identification of charged kaons in large p_T jets. Assuming that this objective can be achieved in the presence of charged particles in the same jet, two kinds of experimental goals are clear: 1) determination of the x distribution of the strange quark in the kaon, by measuring the production of strange quark jets at large p_T by incident kaon beams; 2) acquiring information regarding the identity of the fragmenting parton, with gluon jets expected to be relatively rich in kaon pairs and in leading K^- mesons, as mentioned in Sect.2D.

3. Apparatus

3A General

We plan to use the same detector system for Tevatron running as we will be using in the meantime in E-609. Figure 2 shows the layout of the E-609 detector system. In fact, all of the elements of the E-609 detector system have been designed from the start to function well at 1000 GeV. However, it will apparently be necessary to move the E-609 detector from M6 east beam line to the M6 west line since Fermilab does not expect to be able to steer the highest energy beams from the Tevatron down M6 east.

The following sections describe our apparatus and beamline plans in more detail.

3B Beam

As mentioned above, we are assuming that M6W will be the most convenient and appropriate beam line to use. We would need the proton beam to deliver 1000 GeV/c at a rate of up to 10^7 pps in a spot size no larger than 2 cm in diameter. If the focussing of a 1000 GeV/c beam within the meson building is not sufficient for this, this spot size can be achieved by collimation.

A pion beam of 600 GeV/c is also required. The M6 beam line is expected to have enough Cerenkov counters and transition radiation detectors to distinguish pions and protons to a sufficient degree for our purposes at this momentum, and kaons up to perhaps a slightly lower momentum. The pion spot size may also have to be controlled by collimation. This in turn would require more protons on target than the acceptance of the M6 beam line would normally suggest.

3C Calorimeter

The calorimeter is the same one we will be using in E-609. A view of the segmentation of the front face is shown in Fig. 3. The 5 x 10 cm^2 and the 10 cm square segments near the beam line are ~ 8.5 absorption lengths in depth. Larger segments have correspondingly less depth, the smallest being ~ 6.5 absorption lengths deep.

This absorption power should be sufficient for Tevatron running as long as the front face of the calorimeter is at its normal operating distance from the target of ~ 6 meters. For the larger operating distances which may be used to examine more jet detail and smaller center of mass angles, a small amount of energy may leak out the back of the calorimeter as more energetic particles strike the thinner segments. This systematic effect will be corrected by using the calibration studies.

3D Wire Chambers and Cerenkov Detector

Fig.2 shows the location of the wire chambers and Cerenkov detector. These devices, together with the SCM105 wide aperture analysis magnet which will be operated at $\Delta p_T = 0.1$ GeV/c, comprise a magnetic spectrometer which will yield additional information on jets detected by the calorimeter.

The spectrometer is not meant to provide high resolution in momentum. Instead, it will be used to provide the following types of information:

-- primary vertex location

-- determination of charge sign for jet hadrons

-- improvement over calorimeter energy resolution for low momentum tracks

-- charged multiplicity

-- search for presence and sources of background tracks

-- track direction information for analysis of Cerenkov detector data.

Table 1 lists the parameters of the various wire chambers.

The imaging Cerenkov detector known as ORCID (optical readout Cerenkov imaging device) is shown schematically in Fig. 4. Cerenkov light is focussed by a primary spherical mirror and collected by a secondary mirror, which in turn focusses the Cerenkov light upon the face of a two stage image intensifier. The image size is reduced by fibre optic couplings and the Cerenkov photons are finally detected by a charge coupled device (CCD). The angular coverage of this detector is from about 25 mr to 200 mr in the lab on either side of the beam. The radiator in ORCID is Freon 12 ($n-1 = 1.1 \times 10^{-3}$) which will produce large angle Cerenkov rings and therefore a larger number of photoelectrons in a short length than threshold counters using smaller indices of refraction.

At present the ORCID is being tested and debugged at the U. of Pennsylvania. Only one image intensifier exists but a second will be purchased when the operation of the present one is fully evaluated. This is estimated to occur by mid-1981. During the next few months we hope to test the ORCID device in M5 after cosmic ray testing is carried out at Penn.

3E Photon Detection

We are building a test module electromagnetic shower detector which will yield greatly improved spatial resolution over that achieved in E-395. The design of this detector is based closely upon the shower detector development work being done for the Fermilab Colliding Detector Facility. This type of detector may be well suited to the demanding task of single photon detection at Fermilab energies.

We plan to run tests of this module during 1981. In addition, we are looking at the possibility of using its two-dimensional readout MWPC to increase the spatial resolution of the e.m. shower layer of the existing E-609 calorimeter. The results of these tests will be used to decide upon the best e.m. shower detection arrangement for our Tevatron runs.

4 Running Time Request

We propose to run protons at full Tevatron energy and mesons at at least one lower energy. The total beam time requested is 1000 hours, of which about 200 hours would be used for testing and tuneup.

We estimate that 400 hours of data taking with 1000 GeV protons will yield approximately 100,000 jet-pair events with $p_T \gg 9$ GeV/c. Our estimate of testing and tuneup time is based on the assumption that our Tevatron runs will be occurring at times close to those of E-609, so that our apparatus and software will be in a state of readiness for Tevatron running.

We will require a beam intensity of no more than 10^7 particles/sec incident upon our hydrogen target. This means that we can run with 1000 GeV protons at full efficiency even if the Tevatron beam is not running at high intensity. Furthermore, since our apparatus will be already well tuned up in E-609 running, we could efficiently use very early runs of the Tevatron.

TABLE 1

Wire Chamber Parameters

P1 - P3

x, u and v-coordinates

2 mm spacing

Active area 0.6 x 0.3 m^2

P4 - P5

2 planes of x-coordinates

2 x 16 cells 1.2 cm wide

2 x 2 transition cells 2.2 cm wide

2 x 30 cells 3.2 cm wide

Active area 1.2 x 0.6 m^2

P6 - P7

2 planes of x-coordinates and 1 y-coordinate delay line

2 x 12 cells 2.4 cm wide

2 x 2 transition cells 2.8cm wide

2 x 35 cells 3.2 cm wide

Active Area 1.5 x 0.75 m^2

P8 - P13

6 planes of x-coordinate and 1 y-coordinate delay line

6 x 34 cells 2.4 cm wide

6 x 2 transition cells 2.8 cm wide

6 x 50 cells 3.2 cm wide

Active area = 2.4 x 1.5 m^2

P14

x-coordinate

2 mm spacing

Active area 2.6 x 1.75 m^2

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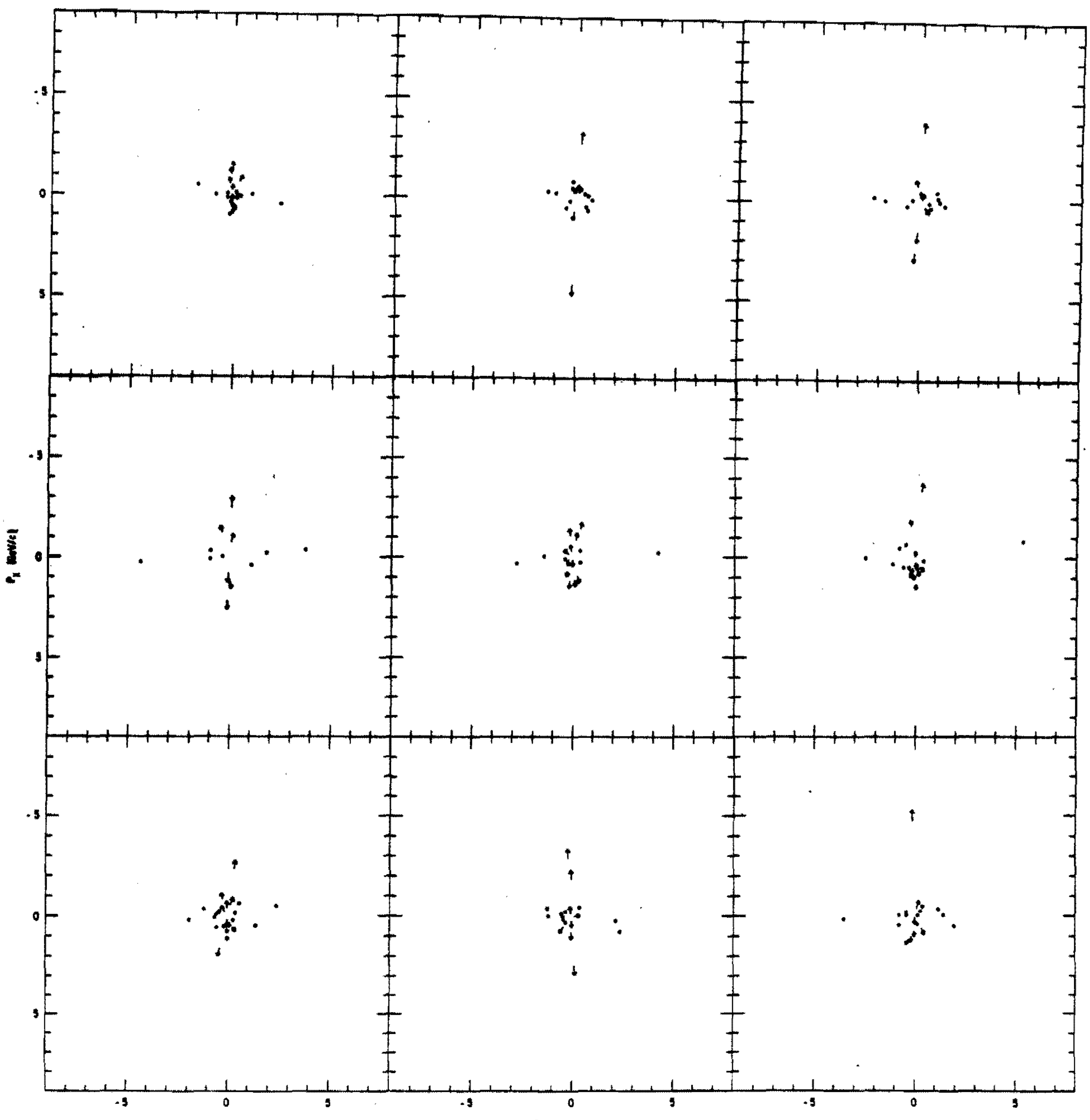

Figure 1a) Plan view in the c.m. system of typical Monte Carlo events with 90° jets, each of $p_\perp = 6$ GeV/c, at 400 GeV beam momentum. Arrows are the jet fragments and the dots are the beam and target fragments.

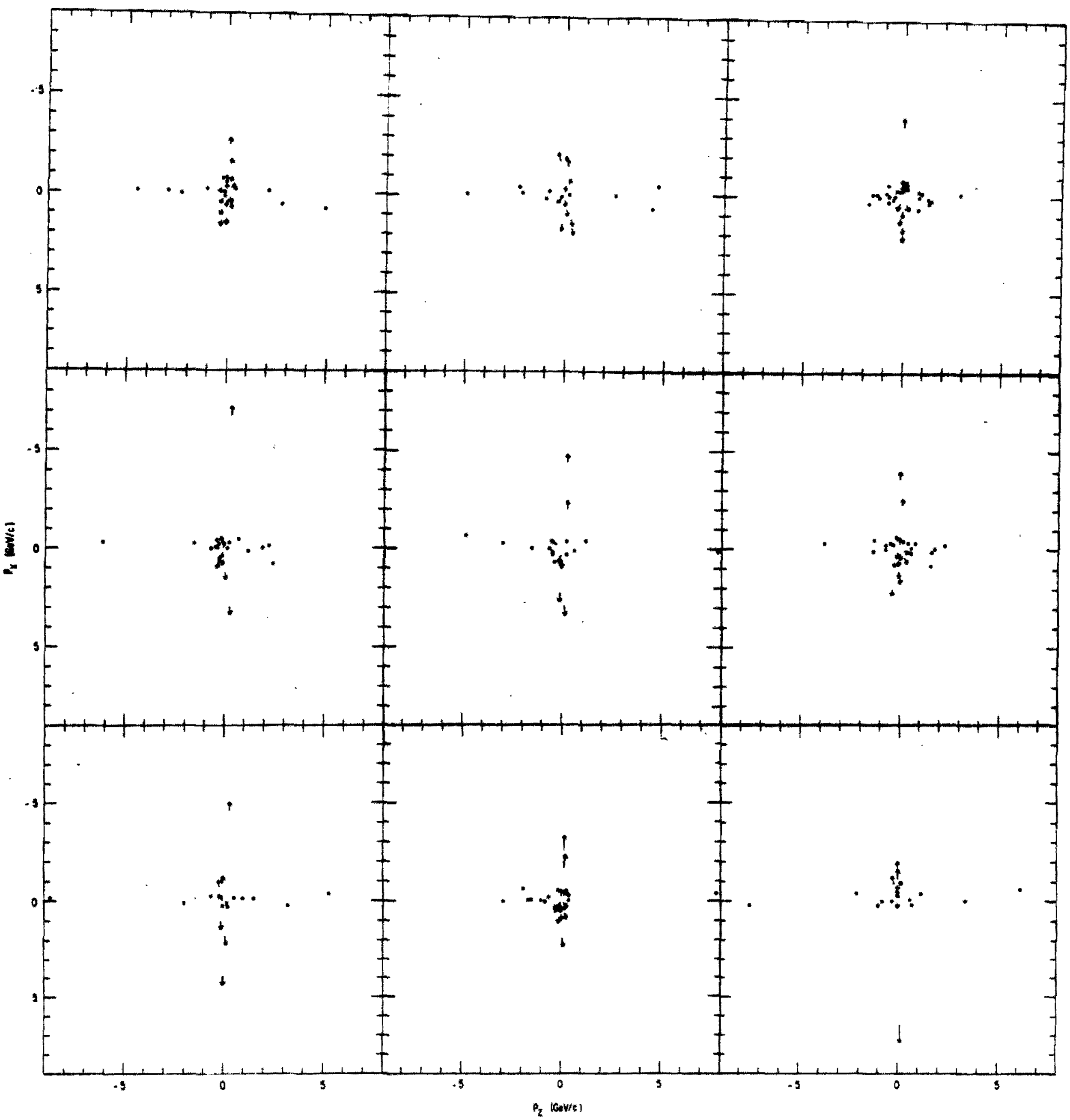

Figure 1b) Same as Fig. 1a except for $p_\perp$ = 8 GeV/c at 1 TeV/c beam momentum.

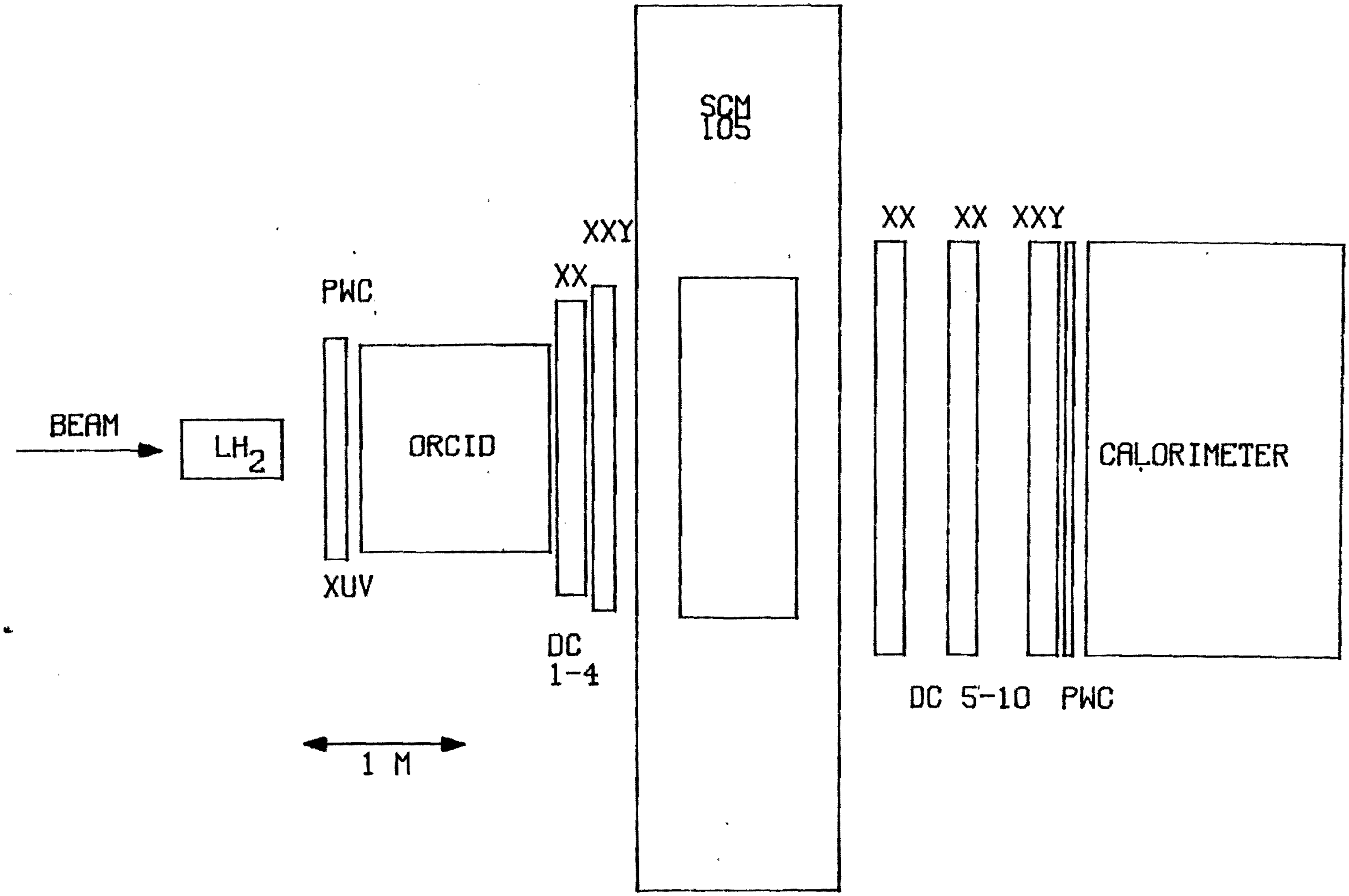

Figure 2 Plan view of the detector system.

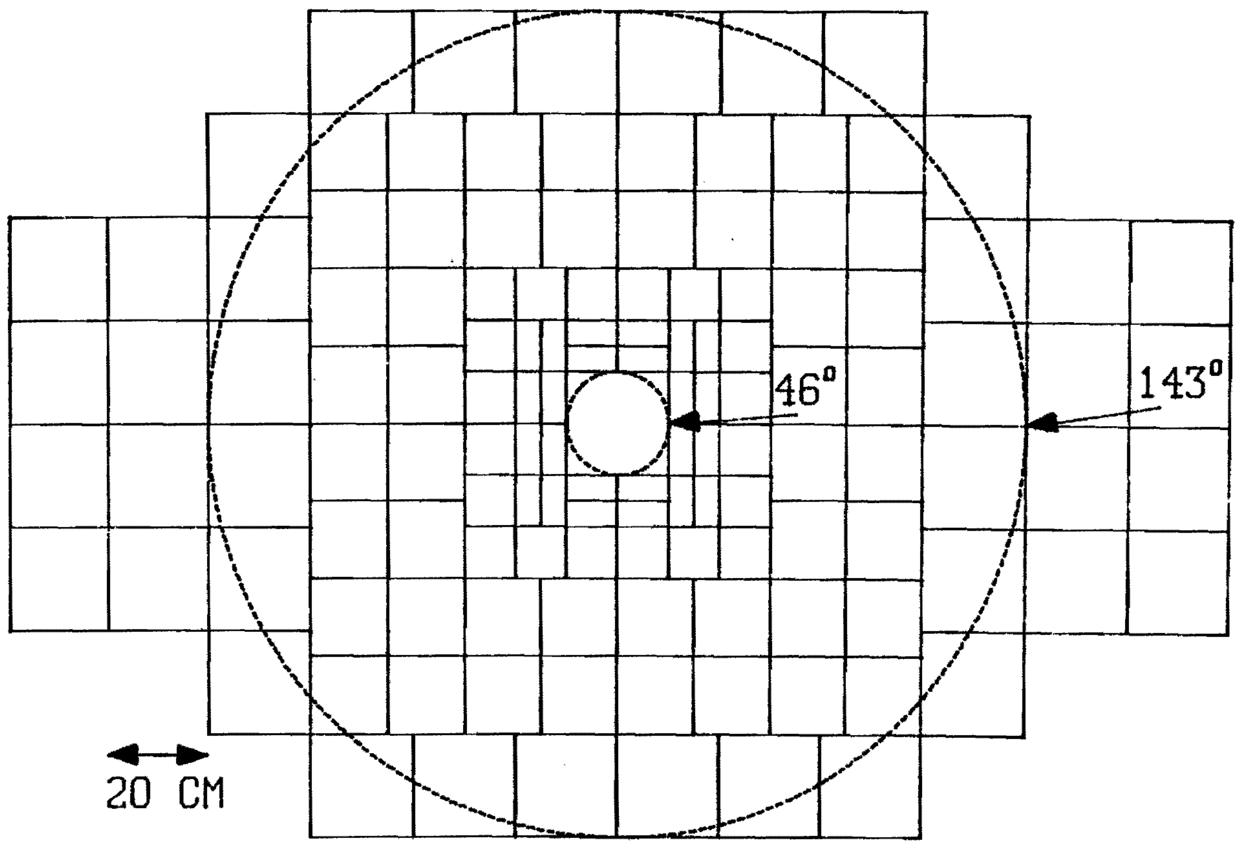

Figure 3 Front view of the calorimeter. The c.m. angles are for p_{inc} = 1000 GeV with the calorimeter at the 6 meter position as shown in Figure 2.

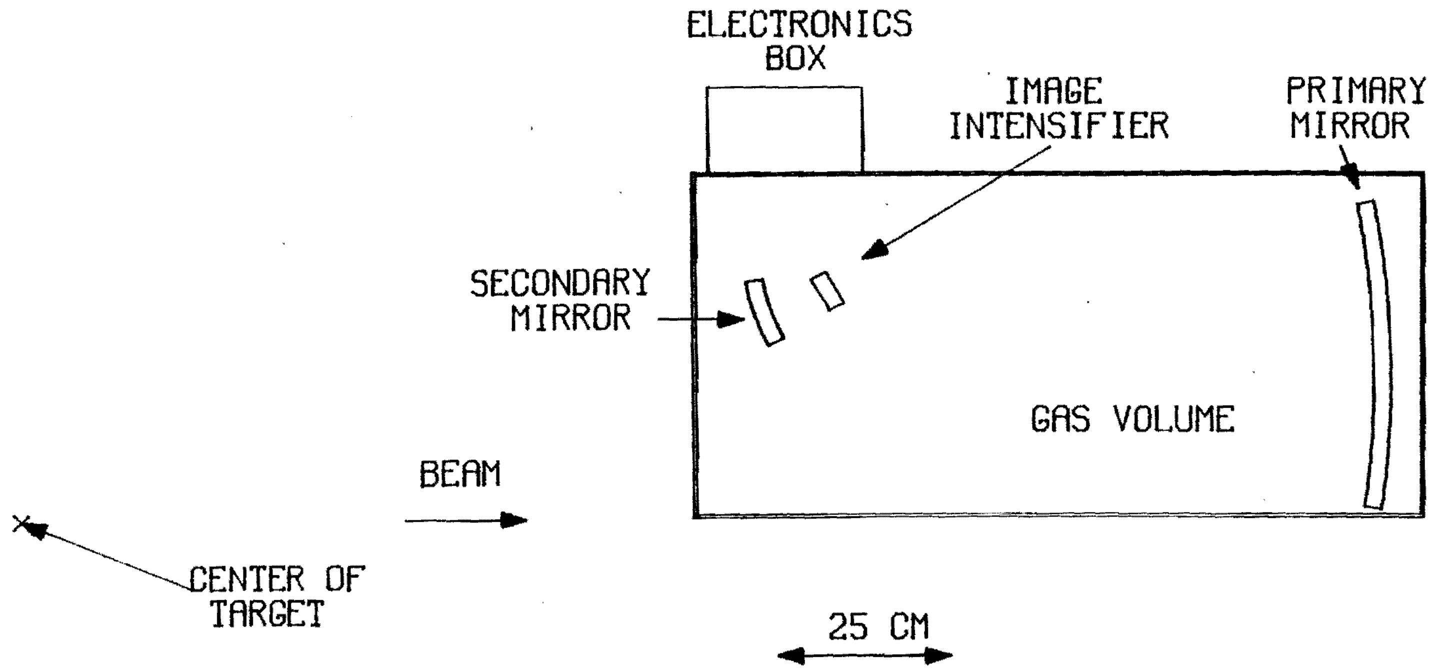

Figure 4 Diagram of the imaging Cerenkov detector.