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PROPOSAL FOR A FORWARD DETECTOR FOR THE D0 AREA

R.C. Ball, C.T. Coffin, H.R. Gustafson, L.W. Jones,

M.J. Longo, T.J. Roberts, B.P. Roe

UNIVERSITY OF MICHIGAN
ANN ARBOR, MICHIGAN 48109

R.J. Abrams, C. Halliwell, D.W. McLeod

UNIVERSITY OF ILLINOIS
CHICAGO, ILLINOIS 60680

SPOKESMAN: Michael J. Longo
Department of Physics
University of Michigan
Ann Arbor, MI 48109

(313) 764-4443

PROPOSAL SUMMARY

We propose to build a detector for the DO area which emphasizes accurate calorimetry and particle tracking down to the smallest practical angles.

One of the most frequently cited signatures of new physics are events which show an apparent violation of momentum-energy conservation due to momentum carried off by missing particles other than neutrinos. For example, supersymmetric scalar quarks, if they exist, are expected to decay into their associated ordinary quark and a photino or gluino. The missing gluinos or photinos (or Goldstinos from their decay) will cause a large apparent imbalance in p_T and p_L as well as an energy deficit. This is probably the best signature for supersymmetric particles. To exploit this signature a detector with good calorimetry over the widest possible solid angle is required. In general, detectors which are sensitive to missing energy-momentum may be essential for probing new physics at Collider energies.

The proposed detector could answer very fundamental questions about the behavior of hadron interactions beyond CERN collider energies. These include the variation of multiplicity and σ_{inel} with energy, energy flow measurements, studies of jets, and searches for new phenomena such as Centauro events which are suggested by cosmic ray data.

This detector could coexist with most of the "central detectors" proposed for the DO area. It will serve as an essential complement to a central detector and will greatly enhance the new physics possibilities by allowing the selection of events most likely to contain new physics. This can be done by requiring events to satisfy criteria such as high multiplicity, little energy going down the beam pipes, or missing p_T.

Introduction

At Fermilab collider energies, most of the secondaries from a $p\bar{p}$ collision go off at angles much less than 10°. For example, about 90% of the energy from a $\sqrt{s}$ = 2000 GeV interaction will on the average appear at angles <2°, the smallest angle which the CDF detector will cover[1]. This appears to be a serious shortcoming of the CDF detector which will prevent it from addressing many basic questions about the general character of hadron-hadron collisions at very high energies and handicap it in searching for new physics. As we shall discuss below, a detector which covers small angles, such as the one proposed here, can also significantly enhance the new physics signal in a "central" detector.

In designing a small-angle detector it is important to be able to model reasonably accurately the general features of high energy hadron-hadron interactions, particularly in regard to the angular distribution of the energy flow. To do this we have adopted a Monte Carlo program used earlier for this purpose by T. Gaisser.[1] This program incorporates a model used by Wdowczyk and Wolfendale[2] and others which takes into account the violation of Feynman scaling observed at Fermilab and ISR energies (and now more dramatically at the CERN collider[3]). This model has one parameter, variously called α or β [where β is variously defined as $\beta \equiv 1-2\alpha$ or $\beta \equiv 1-\alpha$] which is a measure of the violation of Feynman scaling. For α=0 Feynman scaling is recovered, while $\alpha \approx 0.5$ corresponds to a large breakdown of Feynman scaling as might be expected from a statistical model[2]. Data from the ISR and cosmic rays suggest a value of $\alpha \approx 0.2$ (Ref. 2).

In the Monte Carlo program, longitudinal momenta of the secondaries are assumed to grow with s according to

$$\frac{P_L(s)}{P_L(s_0)} = \left(\frac{s}{s_0}\right)^{\frac{1-2\alpha}{2}} \qquad (1)$$

where s_0 is some reference energy for which data are available. Average transverse momenta are assumed to grow slowly with s in a manner suggested by cosmic ray and ISR data. The leading nucleons are assumed to obey Feynman scaling and are given a flat distribution in Feynman x.

The results of this Monte Carlo simulation for $\sqrt{s}$ = 2000 GeV collisions are summarized in Fig. 1. These curves show, for 3 values of α, the fraction of the energy which would be collected in a calorimetric detector which subtends angles down to θ_{min} in both hemispheres. For the case of $\alpha = 0.19$ only, the effect of including leading nucleons is illustrated. Since these are assumed to obey Feynman scaling their contribution is independent of α.

The angular ranges covered by the proposed CDF central and forward detectors are shown for reference. By way of illustration, the curves show that if Feynman scaling were the correct extrapolation from ISR energies (i.e., α=0) the CDF detector would only collect about 2% of the energy from a typical $\sqrt{s}$ = 2000 GeV collision.

The angle marked "Min. Practical Angle" in Fig. 1 is based on a reasonably conservative extrapolation of experience at the ISR, where detectors can be brought within 0.7 cm of the stable circulating beams.[4] We therefore assume a minimum distance of approach of 2.0 cm from beam center for detectors placed ≈20 m from the interaction point. (The straight sections at the collider are approx. 50 m long.) Figure 1 suggests that it should be possible to build a calorimetric detector which, on the average, will efficiently collect most of the energy, with the possible exception of that carried by the leading nucleons.

Figure 2 shows the region of rapidity which would be covered by our detector and by the CDF detector. Note that CDF, even with its forward detector, only covers about half the range. The detector described here with an accompanying central detector would cover essentially the entire range.

Physics Objectives

We believe the proposed detector can do significant physics both on its own and in conjunction with any "Central Detector" which we assume will coexist in the D0 area.

As far as physics the proposed detector can do on its own, some of the more obvious and important things are:

(1) Searches for new particles - Various theoretical ideas such as broken supersymmetry[5] and technicolor suggest the existence of whole new classes of particles with an essentially arbitrary mass scale. Supersymmetry schemes, for example, require a scalar partner to each fermion, as well as spin 1/2 partners to the gluon and photon. Most decay modes involve a gluino or photino. The gluino, if short-lived, will decay to a gluon and Goldstino or a photino and a $q\bar{q}$ pair. The photinos and Goldstinos will not interact in the detector. The net result is an event with a large missing momentum and energy, with no associated muons. This signature seems likely to be important in theories other than supersymmetry. To exploit this signature will require a detector with the best possible calorimetry and the widest possible coverage in solid angle. This can be provided by the detector described here plus an accompanying central detector.

[Other signatures of supersymmetry [5a] would be "one-jet" (plus the beam jets) and "zero-jet" events with large missing energy and momentum.[6] These come about due to the gluon-gluino-Goldstino couplings shown in diagrams such as Fig. 3. The Goldstino(s) will typically carry off 10-20% of the available energy.]

It is clear that a central detector such as CDF which misses ~ 90% of the total energy cannot take advantage of this signature because of statistical fluctuations in the momentum carried off by the missed hadrons.

(2) General features of very high energy interactions -The proposed detector will cover angles down to about 1 mr in either hemisphere. In rapidity this corresponds to $|y| \lesssim 7.5$. (See Fig. 2.) At present, very little is known about even the most basic features of very high energy hadron-hadron interactions. The cosmic ray data are difficult to interpret or controversial. We might expect that at Collider energies the constituent quarks in the nucleons will become apparent and the events will show clear jetlike behavior. A "typical" quark in a nucleon with $\hat{x} \approx 0.3$ which undergoes a hard scatter with $p_T \approx 5$ Gev/c will produce a jet at about 1°. This would be well inside our detector — and well outside any of the contemplated central detectors. — The large range in angle and rapidity covered by the detector will allow studies of correlations between jets. These correlations can give important information on production mechanisms. This physics is much too important to give CERN a monopoly by default.

(3) Energy flow measurements - T. Gaisser[1] has emphasized the importance of these to the understanding of the general behavior of hadronic interactions at very high energies. This will contribute to the resolution of a fundamental astrophysical problem, the composition of primary cosmic rays above 10^{14} eV.

(4) Multiplicity vs. $\sqrt{s}$ - This is a basic measurement which should be continued to the highest available energies. Cosmic ray data from the Brazil-Japan group suggest a new threshold near $\sqrt{s}$ = 500 GeV. (See inset to Fig. 4 which is taken from G. Goggi, CERN-EP/81-08.)

(5) σ_{inel} vs. $\sqrt{s}$ - Again cosmic ray data from the Tien-Shan group suggest a sudden increase in the absorption length above $\sqrt{s} \cong 500$ GeV, as shown in Fig. 5. A central detector with $\theta_{min} \gtrsim 2°$ could miss this effect.

(6) Centauro events - These have been discussed at great length by many authors. As shown in Figure 4, they seem to be restricted to $\sqrt{s} \gtrsim 600$ GeV and may be just out of reach of the CERN collider.

(7) Diffractive production of new flavors - Data from the ISR suggest a large cross section for the diffractive production of Λ_C. This may occur for other heavy flavors as well. The forward region may be the best place to look for heavy baryons beyond the Λ_B. Whether this is practical for any detector without adding particle identification for K's is problematical, however.

The proposed detector would also be generally useful as a luminosity monitor. It could also serve as a veto in support of an elastic scattering experiment. If it becomes possible to move the farthest tracking chambers as close as 0.7 cm to the beam, we will be able to measure elastic scattering for $t \gtrsim 0.2$ (GeV/c)^2. [At 2.0 cm, $t \gtrsim 1.0$ (GeV/c)^2 is covered.]

The CDF detector may not be well suited for much of the above physics. Some of it will, of course, already have been studied at the CERN collider, but it will be important to extend these measurements another order of magnitude in equivalent lab energy at Fermilab. There also seems to be a possibility that the CERN energy is a bit too low to see the rise in multiplicity and σ_{inel} suggested by the cosmic ray data.

In the long run the most important contribution of a detector such as that proposed here might to be in the enrichment of "new physics" from a coexisting central detector. The whole philosophy of the design of the CDF detector and most of the CERN detectors is that "new physics", generally speaking the production of massive new states such as W, Z°, or $t\bar{t}$, or the particles of supersymmetric theories or technicolor, is best studied in the central region and the decay products will go off at relatively large angles. It is expected that the new physics signal will be very difficult to extract from a background of "log s" physics and "old" physics such as $s\bar{s}$, $c\bar{c}$, and $b\bar{b}$ production. Any additional information about an event which will help to reduce these backgrounds in a central detector would be extremely valuable, particularly on the trigger level. This might prove crucial in separating objects like the W from the dominant background.

With the information from a detector such as we propose, the general character of individual events is immediately recognizable. The best way to use this information to reduce backgrounds in a central detector will require some experience to learn. Generally speaking to produce a massive state requires a hard $q\bar{q}$ or gg collision with the maximum possible $\hat{s}$, the center-of-mass energy squared in the $q\bar{q}$ or gg rest system. Events of this type should be characterized by:

(1) higher than average multiplicity

(2) little energy going down the beam pipes.

Our detector would be uniquely capable of answering these questions on an event-by-event basis. Selecting events which satisfy these criteria should significantly reduce the background in searches for the W, t, ... in the central detector.

In addition to the general features suggested above for identifying events richer in new physics, it is possible to define more specific criteria. For example, in searches for particles containing massive quarks such as naked top some of the decay products will go off at angles smaller than those covered by the central detector. Being able to see the decay products in the forward detector will allow selection of only those events which could plausibly contain a t and $\bar{t}$, even if only some of the decay products can be identified. In the sequence

$$p + \bar{p} \rightarrow t\bar{t} + X$$

with $t \rightarrow b + q\bar{q}$, $\bar{t} \rightarrow \bar{b} + q\bar{q}$ where q and $\bar{q}$ represent quarks lighter than b, one would expect 6 jets plus the beam jets in the final state. The chances of collecting enough of the particles to recognize the jet structure of events like these, and even much simpler ones, is exceedingly small in a detector which misses everything within several degrees of the beam.

A very important signature of new physics is the momentum imbalance caused by neutrinos from the semileptonic decays of massive states or, as discussed earlier, by other neutral objects such as Goldstinos or photinos. A central detector which misses ~ 90% of the energy cannot make significant use of this property. If the missing p_T in an event is due only to hadrons which go out the beam "holes", the maximum missing p_T is related to the missing energy as shown in Fig. 6. The missing p_T from this source is quite small for the proposed detector, ~ 1 GeV. With the addition of information from the forward detectors a good measurement of missing p_T is possible and a possibly useful measure of missing p_L. This capability will be extremely useful in searching for semi-leptonic decays of W, t, etc. as well as new massive leptons produced in decays of more massive objects.

Historically, a major advantage of e^+e^- colliders in searching for new physics is that the energy of the intermediate state produced in the e^+e^- annihilation is well known. The equivalent quantity in hadron-hadron collisions is $\sqrt{\hat{s}}$, the total energy of the quarks or gluons which collide to produce a high-mass intermediate state which may then decay into massive particles. At Fermilab collider energies it should be reasonable to identify the spectator quarks or "wounded nucleons" with the leading particles in the lab systems. As shown in Figure 1 the leading nucleons go off at angles less than 1 mr. To the extent that this identification is correct, a calorimetric detector which covers angles down to 1 mr in either direction provides a direct measure of $\sqrt{\hat{s}}$. This information should be particularly useful in looking for very massive states beyond the W and Z. These will be produced mainly from hard $q\bar{q}$ collisions (rather than gg) with the spectators carrying off a small fraction of the energy.

Description of the Proposed Detector

The general philosophy of our design is to cover the largest practical angular range with calorimetry and tracking chambers. As discussed earlier, it should be possible to provide calorimetry down to an angle of about 1 mr from either beam with detectors 20 m from the interaction point which can be moved to within 2 cm of the circulating beams.

We believe the detector described here is practical, effective, and can be built at a very reasonable cost. However we also believe it would be foolish to commit ourselves to a detailed design at this early stage. That outlined here should be considered as a proof of principle.

The design is shown schematically in Figure 7. Note that the transverse dimensions are exaggerated fivefold. The detector has mirror symmetry about the interaction point and the elements cover 2π in azimuth.[7] Tracking chambers precede each of the calorimeters; these are spaced sufficiently from the upstream faces of the calorimeters to minimize problems from albedo. The farthest set of tracking chambers (T_3, T_4) and calorimeters (CAL 3) are moveable so that they can be brought in close to the beams once they are stable. To accomplish this it seems necessary to place the tracking chambers within the vacuum, or place them in rather elaborate "Roman pots", in order to minimize the amount of material the particles must go through. For the farthest calorimeters, this can be accomplished by having each of the sections A, B, C, D of CAL 3 "push" individual sections of the vacuum pipe aside. The total motion necessary is only about 5 cm which can be accommodated by having the sections of pipe connected by standard bellows. A beam's eye view of one section of this calorimeter is shown in the view from A-A.

It is assumed that each of the calorimeters will have an upstream portion made of high Z material which is read out separately. This will allow a distinction between electrons, photons, and hadrons. It should also be possible to distinguish neutrons from charged particles. Muons can be identified by providing chambers downstream of the calorimeters, possibly preceeded by additional shielding.

The calorimeters will be segmented azimuthally and in radius. This will allow an accurate measurement of $E_{transverse}$ and energy flow. The last calorimeter is in sections so that particles produced in one of the upstream sections which leave through the beam pipe side will be captured in one of the downstream sections. Thus the calorimeters will contain the energy of forward-going particles, though crosstalk between sections will sometimes make it difficult to measure the energy of individual particles accurately. The transverse dimensions of the calorimeters are >6" oversize to contain the showers.

One important decision in the design is whether to use scintillators with shifter bars in the calorimeter or to use limited discharge wire chambers of the sort planned for CDF. The use of scintillator would allow a "fast" energy measurement which could be used as part of the trigger for the central detector. It also seems somewhat simpler to build. If it is used, precautions would have to be taken to prevent radiation damage to the scintillator during fixed target running, as occurred in the UA1 detector at CERN[3]. This does not appear to be a serious constraint as the calorimeter units are relatively small and are external to the beam pipe so they can be installed rather quickly. Wire chambers, on the other hand, would allow somewhat finer segmentation and more detailed tracking of energy flow. The decision between these alternatives will depend to some extent on the choice of central detectors.

For the region $\theta \gtrsim 6°$ we show only tracking chambers. We assume that calorimetry for $\theta \gtrsim 6°$ will be provided by the central detector, though we would be happy to go to larger angles. It may be desirable to add shielding between the calorimeters to reduce punchthrough and spray in the tracking chambers downstream.[8]

Luminosity and Other Considerations

Since our detector would see almost the total $\bar{p}p$ cross section, event rates and luminosity are not a factor. However we envision a situation where our detector would coexist with a variety of central detector options. We favor a design for the low β quads which utilize stronger quads in the adjoining sectors of the Doubler magnets. Such a scheme is discussed in the design report for the Doubler[9]. This could provide a $\beta^* \lesssim 10$ m. (See Fig. 8.) CDF Note No. 64 also discusses similar designs which can give $\beta^* \approx 5$ m with a free space of almost 50 m. These designs are relatively inexpensive and in the spirit of the low budget D0 area. Detector designs similar to the one in Fig. 7 which would allow low β quads to be installed downstream of the first or second calorimeters are also possible. This would make particle tracking beyond the quads somewhat more difficult and slightly smear the energy flow measurements. Another option would be to remove our second calorimeter entirely when the highest luminosity is desired and replace it with low β quads. The rest of our detector would still function and provide useful, though less complete information.

Requests of the Laboratory

Our calorimeter modules are fairly small. However, at present the Doubler beam pipe is only 10.5" off the tunnel floor as seen in Figure 9 which also shows the outline of the middle calorimeter from Fig. 7. The nearest calorimeters can be accommodated by extending the central detector pit; this extension need only be perhaps 20" below the present floor and could be as little as 4' wide. It should be possible to build the second and third calorimeters and vacuum pipes within the 10.5" restriction. As seen in Fig. 7 the particle trajectories remain well within 10.5" from the beam. However this limitation on the transverse dimension of the calorimeter below the beam pipe would result in a poorer energy resolution due to shower leakage out the bottom. This constraint would also make the design of the detector considerably more difficult. One solution is to provide additional floor clearance only in the areas near the second and third calorimeters. However in the interest of overall flexibility our suggestion would be to lower the floor for the entire length of the straight section to provide at least 4 ft of clearance below the Doubler beam over a width of about 6 feet.

We would request that the Laboratory build the vacuum pipes for our detector. In the design in Fig. 7, the largest section of pipe is only approx. 2 ft in diameter. A reasonably thin window ahead of tracking chambers T2 would be needed and the beam pipes ahead of T1 and around Cal. 3 should be as thin-walled as possible. We would also request that the Laboratory assist in the design of the tracking chambers T3 and T4 inside the vacuum tank or in the design of an alternative scheme with Roman pots.

Prospects for Future Expansion of the Detector

The longer term physics prospects for a forward detector seem excellent. Any hints of new physics will have to be followed up by further studies with an improved detector. This physics is impossible to predict. We believe it is wise to start with a fairly modest detector and build on it as the circumstances warrant. Possibilities for expansion are numerous. There is plenty of space along the beam pipe to add additional tracking chambers or particle identification (e.g. -transition radiation detectors). As mentioned previously, as beam condition improve we should be able to move the detectors closer to the beams. This will greatly improve our sensitivity to missing energy, particularly if tracking chambers beyond the adjacent Doubler magnets are added. This would allow the energy of a large fraction of the leading nucleons to be measured. Future expansion would be considerably simplified if more clearance under the beam pipe is provided, as discussed earlier.

REFERENCES AND FOOTNOTES

1. T.K. Gaisser, Phys. Lett. 100B, 425 (1981). We have extended Gaisser's calculation to smaller angles using his program.

2. J. Wdowczyk and A.W. Wolfendale, Nuovo Cimento 54A, 433 (1979).

3. A. Kernan, presented at the Second Workshop on Forward Collider Physics, Madison, December 1981.

4. M. Block, Northwestern University, private communication.

5(a). G.L. Kane and J.P. Leveille, "Experimental Constraints on Gluino Masses and Supersymmetric Theories", Univ. of Michigan Preprint UM HE 81-68.

(b). G.L. Kane and J.P. Leveille, "Physics Comparisons of Some Future Accelerators", University of Michigan Preprint UM HE 81-61.

(c). G. Farrar and P. Fayet, Phys. Lett. 76B, 575 (1978).

6. The cross section for producing "zero jet" events through the process in Fig. 3a is, however, quite small. [J.P. Leveille, private communication.]

7. A design with only two calorimeters is, of course, possible. This solution might be preferable if more of the straight section is required to accommodate accelerator paraphernalia.

8. We have had discussions with Y. Muraki of the Institute for Cosmic Ray Research at the University of Tokyo about the possibility of exposing emulsion chambers at small angles to the beam to study γ rays from $\bar{p}$-p collisions. [See Y. Muraki, "Very Forward Photon Detection", CDF Report 112.] The emulsion chambers would each be only 10 cm × 10 cm exposed for about a minute at the design $\bar{p}p$ luminosity at as small an angle as possible. We would be happy to cooperate with Dr. Muraki in this exposure.

9. A Report on the Design of the Fermi National Accelerator Laboratory Superconducting Accelerator, May 1979, p. 17 ff.

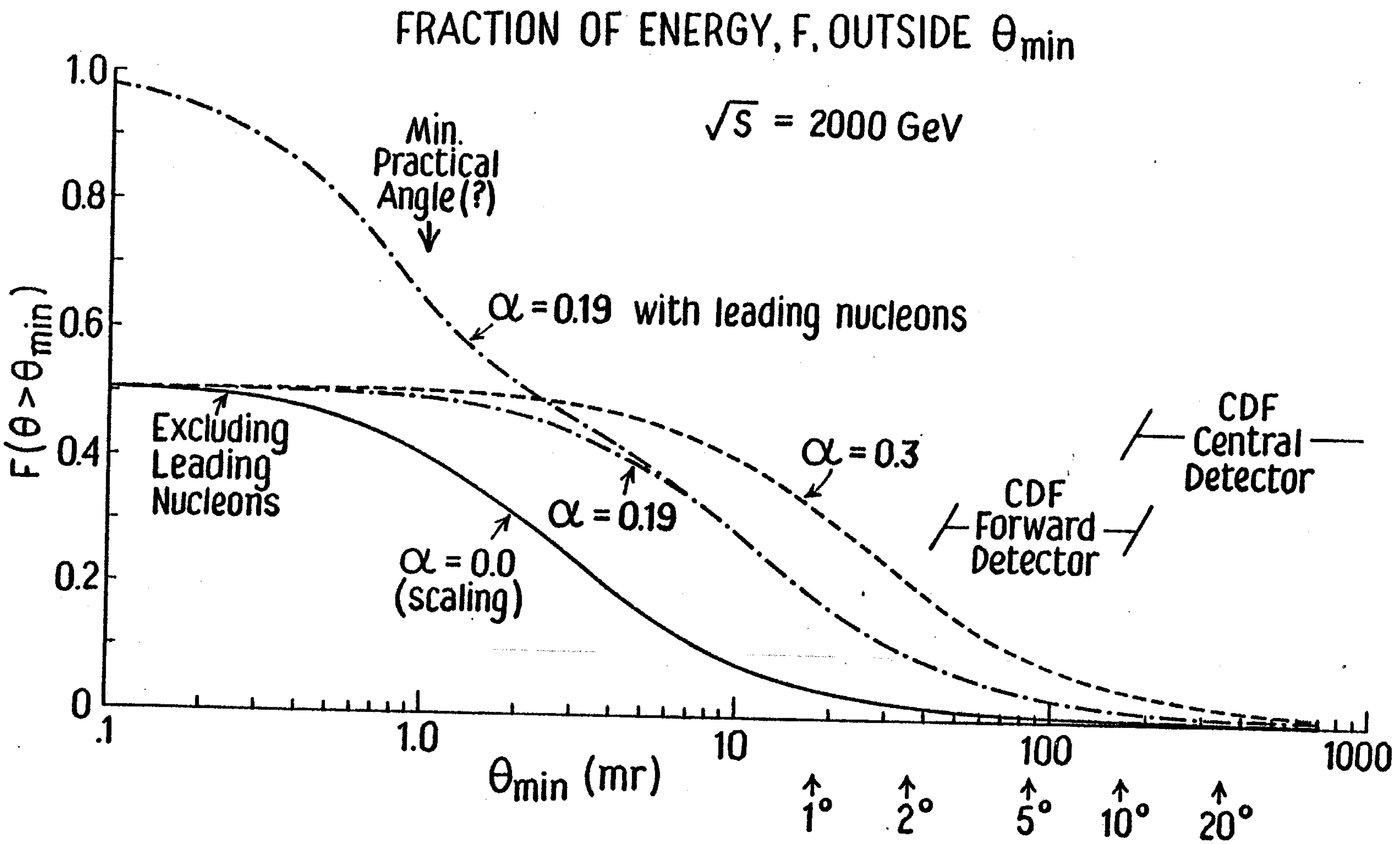


Figure 1 - The fraction of the total energy outside an angle θ_{min} for 3 values of the parameter α. The case α=0 corresponds to Feynman scaling; α=0.3 corresponds to a large deviation from Feynman scaling; α=0.19 is a reasonable estimate from ISR data. For the case of α=0.19 only, the effect of including leading nucleons is illustrated.

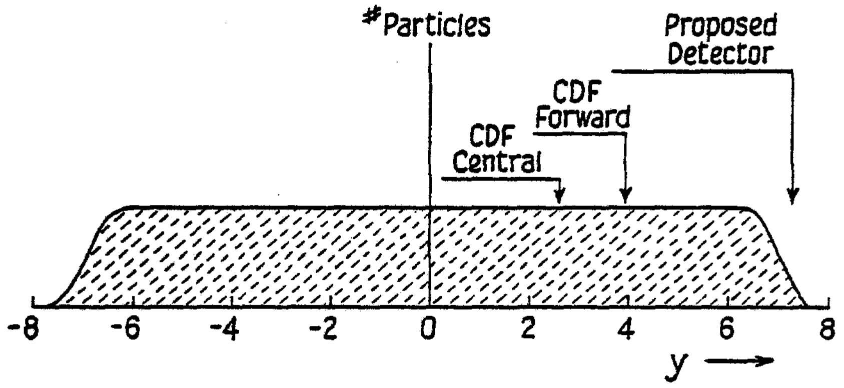


Figure 2 - The total rapidity range at $\sqrt{s}$ = 2000 GeV and the range covered by the proposed detector.

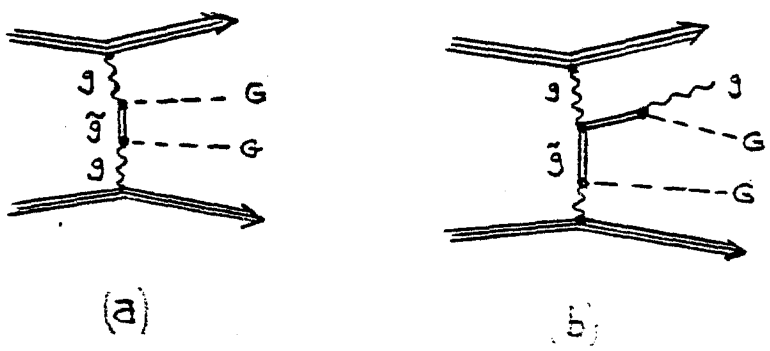


Figure 3 - Diagrams which lead to a large missing momentum and energy and no muons, [g = gluon, $\tilde{g}$ = gluino, G = Goldstino]. In (a) only the beam jets would be observed; while (b) would result in a gluon jet plus the beam jets.

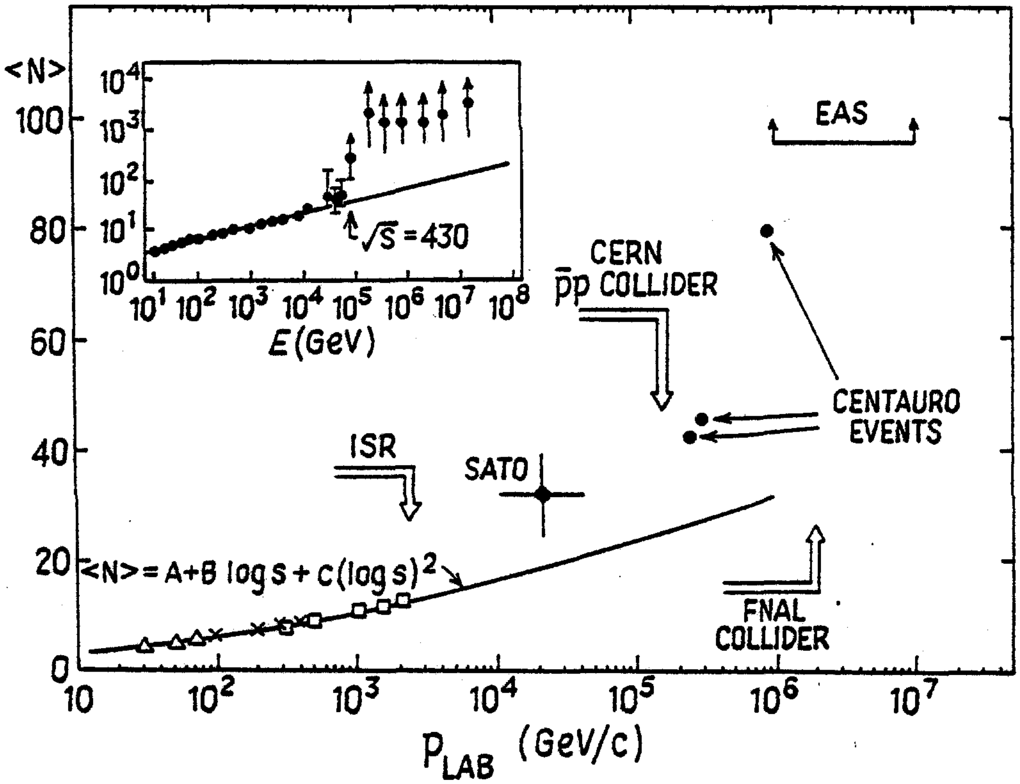


Figure 4 - Average charge multiplicity vs. lab momentum (from CERN-EP/81-08). The inset shows data from the Brazil-Japan cosmic ray emulsion experiments.

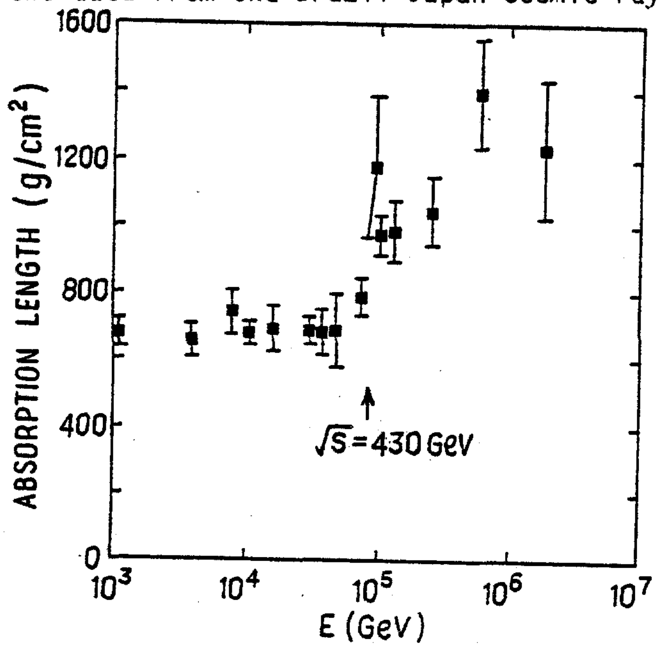


Figure 5 - Measured absorption length vs. lab energy from the Tien-Shan cosmic ray experiment.

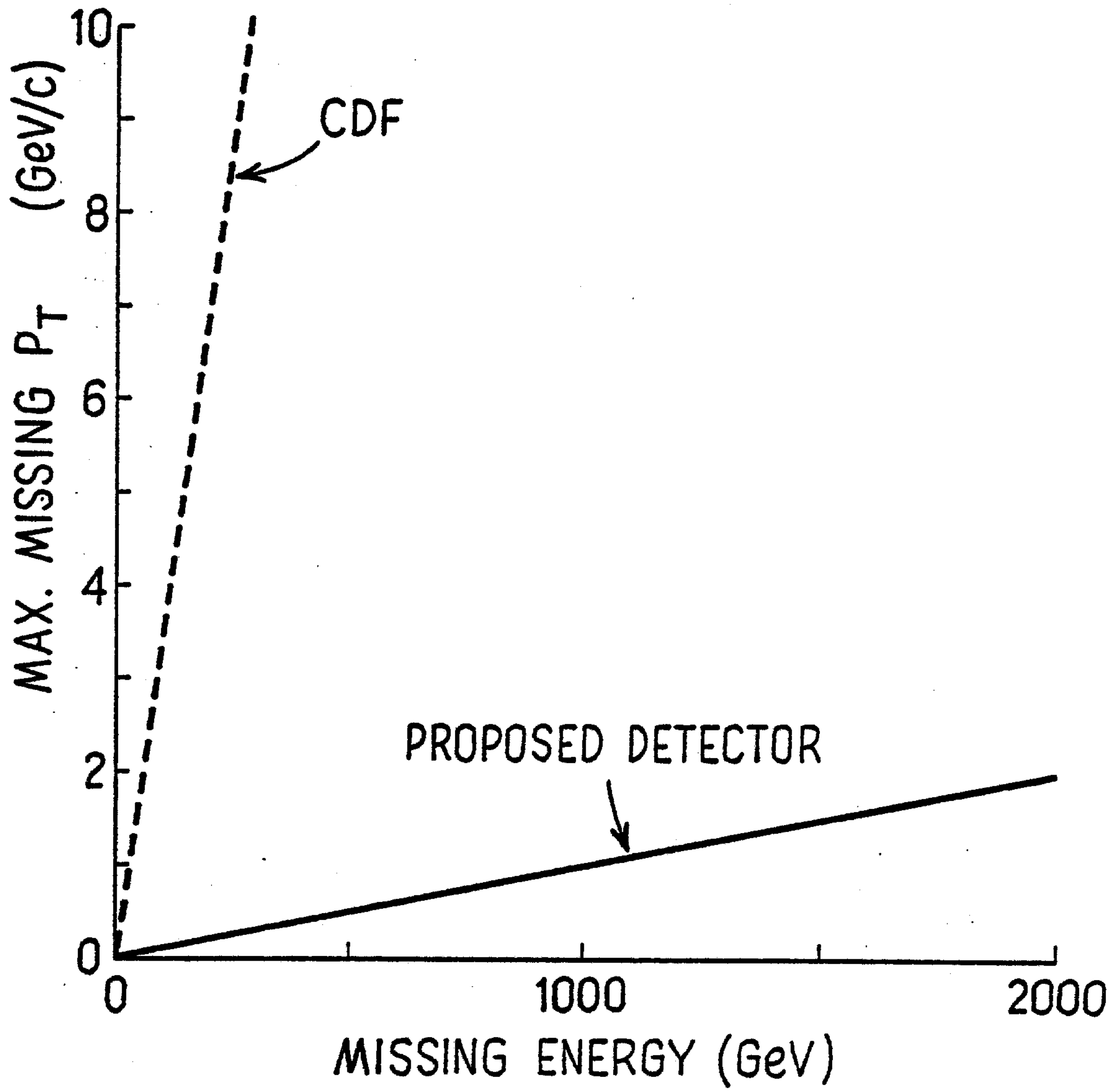


Figure 6 - Maximum missing p_T vs. missing energy for the proposed detector if $|\theta| \geq 1$ mr is covered with calorimetry. This assumes that only hadrons are missed and they all go off at θ=1 mr on the same side of the beam. Energy and angular resolution of the calorimeters are not included. Neutrinos, photinos, Goldstinos, and other noninteracting particles will generally give a missing p_T of the same order of magnitude as the missing energy.

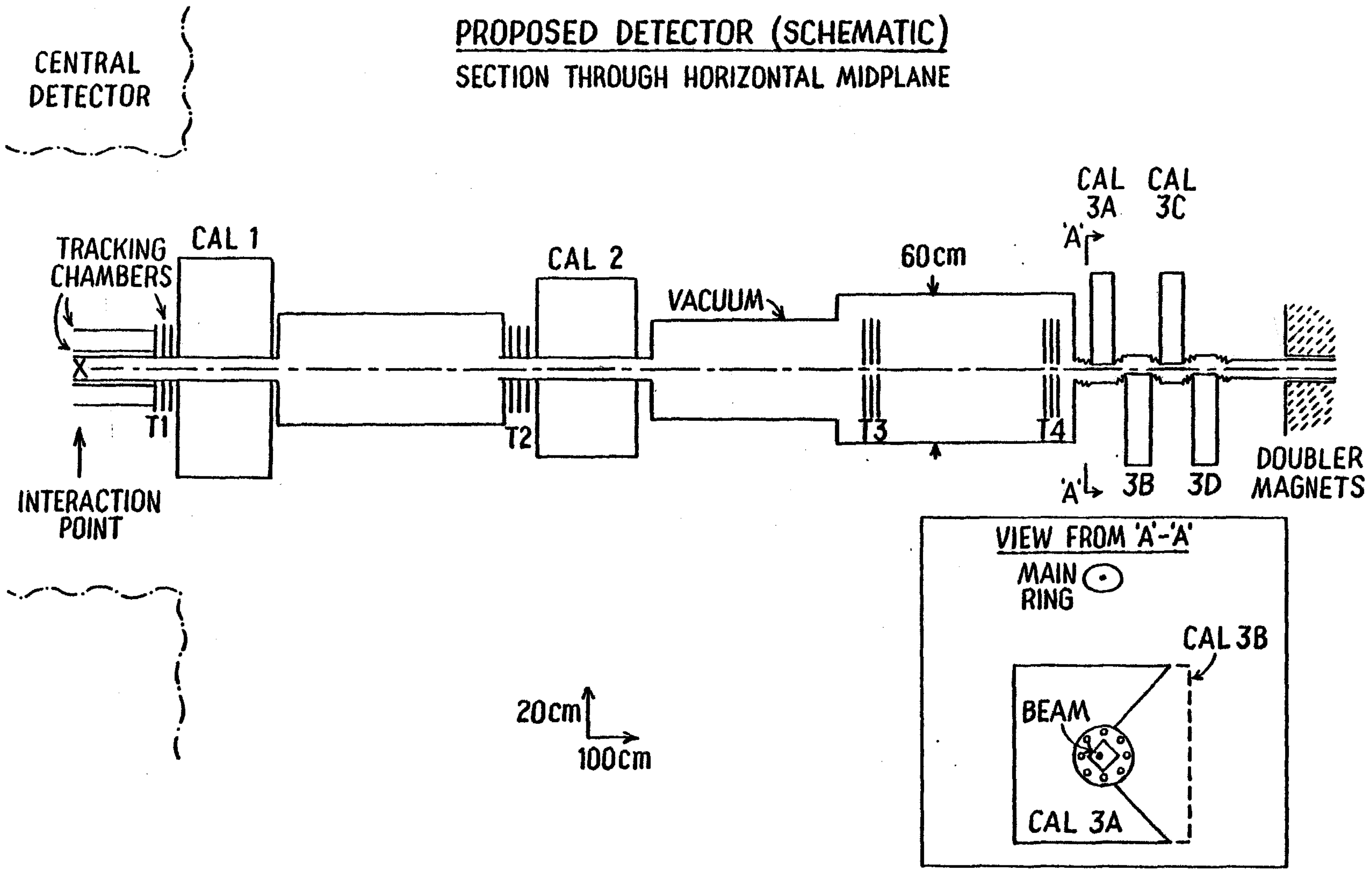
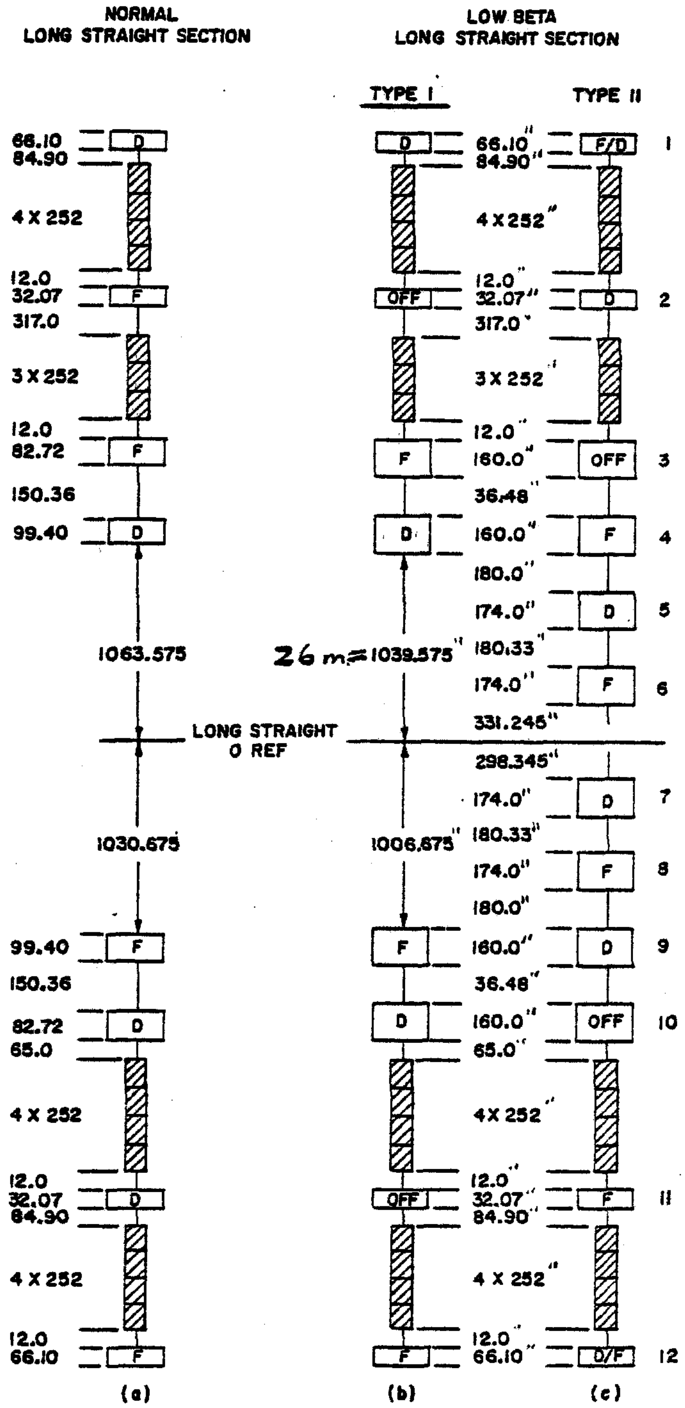
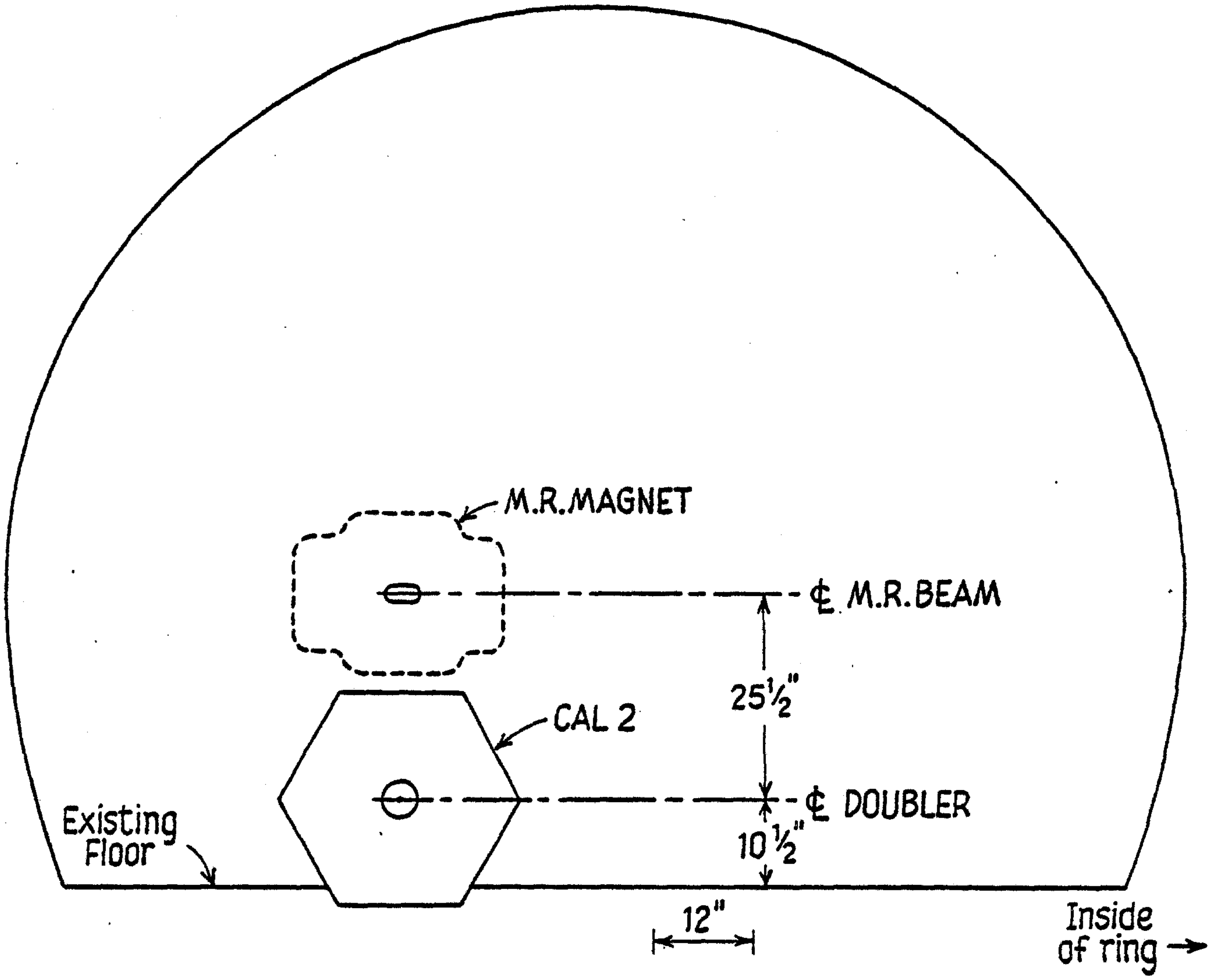


Figure 7 - Schematic of the proposed detector. Note the exaggerated transverse scale. Additional shielding and muon detectors are not shown. The inset shows a beam's eye view of one of the sections of CAL 3 which can be moved closer to the circulating beams once they are stable.



Layout of normal and two types of low-beta long straight section.

Figure 8 - A low beta option (Type I) which provides approx. 50 m of clear space along the straight section [from Fig. 2-4 of FNAL Superconducting Accelerator Design Report]. Similar designs can give $\beta^* \lesssim 5$ m.



Cross Section through DO at CAL 2

Figure 9 - Cross section through DO at the middle calorimeter, showing approximate clearances in the existing tunnel. There is ample space on either side of the Doubler, but clearance over the existing floor is a problem.

May 14, 1982

TO: Fermilab Program Advisory Committee

FROM: M. Longo, Spokesman P-709

Enclosed is an addendum to our proposal which addresses the questions raised by the P.A.C. I would also like to take this opportunity to give my own views on questions of a more general nature regarding the D_0 area.

First I would like to stress the overall importance of the D_0 area to the U.S. high-energy program. The B_0 area is dedicated to CDF which is already pretty much cast in concrete. It is a detector generally similar to the CERN detectors and is already so far along that it cannot realistically respond to any surprises or unanticipated features seen at CERN energies. I am convinced that much of the strength of the future U.S. program in very high energy hadron collisions will depend on the D_0 area. This is particularly true now that ISABELLE seems unlikely to be built. Rather than downgrading the D_0 area, the Laboratory should be thinking in terms of a third area at the Collider.

The boundary conditions imposed on D_0 in the Laboratory's plans seem totally unrealistic and inappropriate in view of the importance of D_0. These plans include the allotment of only $1.5 million to the construction of the area, a much later start for D_0 construction than for B_0, and the possibility of approving the first D_0 experiments only a year and a half before they are to start. I generally subscribe to the view that D_0 users should compete by being more clever (even though this implies that the CDF and CERN groups are somehow not very clever). There is, however, a limit to how much you can do by cleverness, particularly at a collider where one is intrinsically limited to total interaction rates << 10^5 sec^{-1}. CDF has a head start of many years, an advantage of more than an order of magnitude in money, manpower and perhaps luminosity.

I believe our proposal does represent clever new ideas. We have figured out a novel, but practical, way to get calorimeters very close to the beam. We can address physics questions that CDF and the CERN detectors cannot. For example, in the early running we can study hadron interactions in the forward region. In later running we can look for new, noninteracting particles such as goldstinos, and, as discussed in the Addendum, measure the decay $Z^\circ \rightarrow 2\nu$ which will give a count of the number of neutrino species. These are difficult experiments which will require the development of new techniques. They are of such importance that Fermilab must mount an effort soon or risk losing this physics to CERN by default.

I would like to make two specific requests of the P.A.C. in regard to D_O. One is to give at least "Phase 1 approval" to some of the D_O proposals this summer. It is completely unrealistic to expect that the smallish university groups using D_O can plan and mount a new experiment in 1 1/2 years as suggested by the Director. This is especially true for proposals such as ours which pioneer new techniques. Getting the various D_O detectors to mesh with each other and the area is a very difficult job. Some mechanism such as a full time Fermilab coordinator has yet to be set up for this to even begin. Future proposals for D_O can build on those already approved, so that together the users can have a really powerful detector. This requires coordination on a scale that university and other "outside" groups have never attempted. Conventions for data acquisition and sharing will have to be agreed upon. These things can't even begin until we have some idea who the users will be. For example, a central detector to supplement our forward detectors (as alluded to in the P.A.C.'s Question 4) is necessary to study missing p_T. Hopefully the existence of some approved experiments would also help pressure the laboratory to upgrade their plans regarding D_O.

My second request of the P.A.C. is to press the laboratory to plan a bypass for the D_O straight section. Present laboratory plans call for a bypass for the B_O area only. This means the D_O experimenters would have to compete with the fixed target program for setup time, without any "support" from the CDF group (who can work on their detector while fixed target physics goes on if the B_O bypass is built). This seems particularly incongruous because, once the CDF is debugged, it will need relatively little access, while D_O is viewed as handling relatively shortlived experiments and will always need frequent access.

Michael J. Longo

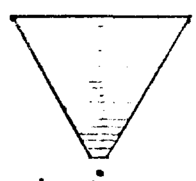
May 14, 1982

Addendum to Proposal 709 - A Forward Detector for the D_O Area

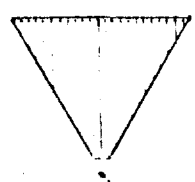
As requested by the Program Advisory Committee we present here a more detailed design of the proposed detector and discuss their specific questions regarding tracking, scattering from upstream calorimeters, resolution in missing p_T, sensitivity to gluino production, and requirements for a central detector.

I. More Detailed Design of the Detector

A more detailed design of the detector is discussed in Appendix A and will be summarized here. The design is shown schematically in Fig. 1 which shows half the detector. The other half is a mirror image. Each of the "upstream" sets of tracking chambers T_0, T_1, T_2 and the calorimeters CAL 1 and CAL 2 are organized into 6 sectors, each of which encompasses 60° in ϕ. The split tracking chambers T_3 A-D and calorimeters CAL3 A-D are organized into overlapping sectors as shown in the inset to Fig. 1. Except for the T_O tracking chambers which surround the beam pipe close to the interaction point, we assume the following minimum configuration for each set of tracking chambers: 4 planes of wires along the direction of increasing ϕ ("ϕ wires" in sketch) to measure the distance of the track from the beam, 1 plane of wires perpendicular to the ϕ wires ("r wires"), and one set of wires at +60° and one at -60° to the ϕ wires. This

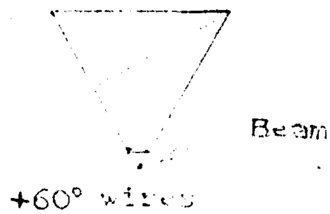


ϕ wires



r wires

gives a total of at least 7 coordinates measured for each track. In this provisional design we have stressed measurements of radial position to allow accurate determination of the space angle θ of the track. This is because most of the quantities of physics interest such as p_T, p_L, and pseudorapidity depend on θ, not ϕ. Therefore even if in a particular event one sector of a tracking chamber contains several particles and there is an unresolvable stereo ambiguity, it will have little effect on the physics.



The calorimeters are also organized into sectors, which correspond to the tracking chambers. The calorimeters CAL 1 and CAL 2 each contain scintillators with wavebar readout and 19 planes of proportional wire chambers. The scintillators in each sector are organized into 3 sections in depth: the first section looks at light from the first part of the calorimeter which is made of lead plates; the second and third sections comprise the bulk of the calorimeter which is made of iron plates. The longitudinal sections are further subdivided into 3 radial segments. The light from each is brought to wavebars along the periphery of the calorimeter so there is no dead space near the beam. The split calorimeters CAL 3 A-D have a similar segmentation. This gives a total of 504 photomultiplier tubes in the calorimeters, each of which will be digitized. This does not include a possible calorimetric central detector which will be discussed below. More details on the calorimeters are given in Appendix A.

II. Using projections from the SPS data, how severe are the tracking problems at small angles? Does leakage and scattering from upstream calorimeters ruin the downstream tracking?

The SPS collider data[1] and cosmic ray data suggest a charge multiplicity $\langle n_{ch} \rangle$ of approx. 38 at $\sqrt{s}$ = 2000 GeV. [See also Fig. 4 in our proposal.] Since we have 4 sets of tracking chambers in each hemisphere, each divided into 6 sectors, the charge multiplicity per sector averaged over all sectors will be ≈1. Thus even with events with multiplicities several times the average there should be no difficulty in tracking. The tracking chambers at the smallest angles (T_3) in fact see the lowest multiplicity, as discussed below. To investigate the angular distribution of particles, we have used a Monte Carlo simulation of events with $\sqrt{s}$ = 2000 GeV. This starts with reasonable distributions[2] in x_F and p_T. The average charge multiplicity has been adjusted to be approx. 40. Figure 2 shows the multiplicity distribution from the Monte Carlo. Figure 3 shows the distribution in pseudorapidity and the range covered by each set of tracking chambers. Table I gives the approx. angular range covered by each set of tracking chambers and the average number of charged particles per sector from the Monte Carlo. As a check we have used the pseudorapidity distributions found at CERN and scaled them to Fermilab energies. This procedure gives charge multiplicities comparable to those in Table I.

TABLE I

Average charge multiplicity per sector in the tracking chambers

Chambers	Ang. Range (mr)	Pseudorapidity Range	$\langle n_{ch} \rangle$ per sector
T_3	1.0-4.8	7.6-6.0	0.20
T_2	4.8-25	6.0-4.4	0.50
T_1	25-130	4.4-2.7	0.85
T_0	100-1570	3.0-0	1.30
Total (2 hemispheres)			39

The multiplicities seen by the corresponding calorimeters will be approx. double these when photons from π° decay are included. Since the calorimeters are subdivided into 3 segments radially, the average multiplicity per radial segment will range from ≈ 0.13 for CAL 3 to ≈ 0.6 for CAL 1. Fig. 4 shows how a "typical event" might look in an online display.

It should be emphasized that in the absence of magnetic fields and with an interaction region which is effectively a point source, tracking algorithms are fairly trivial. One considers a line from the interaction point to each hit in the closest ϕ tracking chamber and looks for hits in the other ϕ chambers which lie along the line within the expected resolution. Extraneous hits from sources other than the interaction point, such as spray from upstream calorimeters, will be largely ignored by this algorithm. These will only be a problem if they are so numerous that chance alignments occur in say 3 of the 4 ϕ chambers with an appreciable probability. Large numbers of extraneous hits may make it difficult to find the correct ϕ angle of a given track but this should not significantly dilute the physics if the θ angle can be determined reasonably accurately.

As discussed in our proposal, the calorimeters would be backed up by passive shielding. For simplicity this is not shown in Fig. 1. From past experience with similar calorimeters at Fermilab energies, we do not expect this to be a significant problem. Leakage out of the sides is harder to estimate. For a variety of reasons we do not expect it will be a serious problem in the majority of events:

(1) As discussed above, tracks originating from points other than the interaction point are easy to discriminate against. They only pose a problem if they are so numerous that they cause accidental alignments of hits in the tracking chambers which appear to radiate from the interaction point or if they swamp the readout electronics. We intend to initiate studies in the M5 test beam so that our final design incorporates sufficient tracking accuracy and readout capability so this will not be a problem.

(2) As illustrated in Table I, most of the particles go out at rather large angles so relatively few hit near the inner edges of the forward calorimeters. The average energy for a hadron going off at 5 mr is ≈ 100 GeV and the average photon energy is ≈ 50 GeV. For high multiplicity events, which in many respects are the most interesting, the average energies are correspondingly less.

(3) Soft particles leaking at largish angles from upstream calorimeters will not carry enough energy to cause a significant error in the energy flow measurements in the downstream calorimeters.

(4) Even if tracking becomes hopelessly confused in a small fraction of the events (which seems unlikely) the physics would not suffer appreciably. In physics questions which require accurate measurements of missing p_T such events can be ignored.

We hope to make measurements shortly in the M5 test beam to study this potential problem. If results are available before the June P.A.C. meeting they will be reported separately.[3] It is perhaps worth pointing out that if one wishes to have a detector with unique capabilities it is necessary to take some unique risks. We believe spray from the upstream calorimeters will <u>occasionally</u> be a problem but with experience we can cope with it. Other detectors have had to learn to handle similar problems. The E605 detector, for example, will have to cope with spray from particles hitting the inner faces of the iron return yokes of their spectrometer magnets. We feel we are in a somewhat better position since we only have to cope with $\sim 10^3$ interactions per second while they will have $\sim 10^{13}$. The CDF plans to have low beta quadrupoles well upstream of their forward detector. These appear to have a bore of approx. 1.5" in radius and outer dimensions <6". Thus they are effectively all "edge" as far as showers are concerned.

III. What is the resolution in missing p_T? How does scattering from one side of a calorimeter to the other affect the resolution?

For simplicity in estimating the resolution in p_T^{miss} we consider a "typical" interaction which produces ≈40 charged particles and ≈20 π°'s. The transverse momentum of the i^{th} particle is

$$p_{Ti} \cong p_i \; \theta_i$$

and the uncertainty in p_{Ti} is

$$\Delta p_T = [(p\ \Delta\theta)^2 + (\theta\ \Delta p)^2]^{1/2}$$

where we drop the subscript to simplify the notation. We take

$$p \sim \langle p \rangle = \frac{2000}{\langle n \rangle} \sim 33 \text{ GeV/c}$$

$$p_T \sim \langle p_T \rangle \sim 0.5 \text{ GeV/c}$$

$$\theta \sim p_T/p \sim .015$$

For the energy resolution of the calorimeters we use a typical value for current calorimetric detectors[4],

$$\Delta p/p \sim 0.65/\sqrt{p} \sim 0.11$$

The resolution for photons will be significantly better. This gives an average uncertainty in momentum

$$\langle \Delta p \rangle \sim 0.11 \times 33 \cong 3.5 \text{ GeV/c}$$

For the error in measuring the radial position r of a track relative to the beam we take 1 mm for charged particles, 10 mm for neutrals or an average of approx. 4 mm. Thus

$$\frac{\langle \Delta\theta \rangle}{\langle \theta \rangle} = \frac{\langle \Delta r \rangle}{\langle r \rangle} \sim \frac{0.4 \text{ cm}}{12 \text{ cm}} \approx .035.$$

where for $\langle r \rangle$ we take an average radius for the tracking chambers (Fig. 1). This gives $\Delta\theta \approx .035 \times \theta \sim 5 \times 10^{-4}$. Combining all these numbers, we get for a typical particle,

$$\begin{aligned}\Delta p_T &\cong [(p\ \Delta\theta)^2 + (\theta\ \Delta p)^2]^{1/2} \\ &= [(33 \times 5 \times 10^{-4})^2 + (.015 \times 3.5)^2]^{1/2} \\ &= [2.7 \times 10^{-4} + 2.8 \times 10^{-3}]^{1/2} = .055 \text{ GeV/c}\end{aligned}$$

The overall uncertainty in missing p_T will be the incoherent sum of some 60 such measurements so

$$\Delta p_T^{miss} \approx \sqrt{\langle n \rangle}\ \Delta p_T \approx \sqrt{60} \times .055 \cong 0.43 \text{ GeV/c}$$

This is slightly pessimistic because we have taken the energy resolution for γ's to be the same as that for hadrons.

Scattering from one side of the calorimeter to another is not a significant problem as is clear by considering an example. Consider a 200 GeV particle which goes off at 3 mr and strikes the inside edge of CAL 3A. Suppose half of its energy crosses the beam pipe and appears near the inside edge of CAL 3B. This will cause an apparent $p_T^{miss} \sim 0.6$ GeV/c. As discussed below, even if no correction is made, this is not large enough to jeopardize a search for new massive particles which decay into noninteracting particles such as goldstinos. In practice, first-order corrections based on the tracks seen in the tracking chambers can be applied, or events which appear likely to have this problem can be disregarded in such searches.

As we discuss in our proposal, missing p_T due to particles going down the beam pipe is relatively small and can be made negligible by cuts on the maximum missing energy. As we emphasize in the proposal, "new physics" is unlikely to be found in events in which a large fraction of the energy goes down the beam pipe.

IV. At what level of cross section would the experiment be sensitive to gluino production? It would be useful to prepare a Monte Carlo simulation which would show what gluino production at some cross section level would look like.

We have prepared a Monte Carlo simulation of gluino production and decay into a gluon plus goldstino. Briefly, the model we used is that of Kane and Leveille[5] which is based on a perturbative QCD calculation and should give a lower limit on gluino production. Kane and Leveille find that the invariant cross section for production of a gluino of mass m can be described by

$$E \frac{d^3\sigma}{dp^3} \propto (1-|x_F|)^5 \, e^{-0.34 \, m_T}$$

where $m_T^2 = \tilde{m}^2 + p_T^2$. They also give estimates of the total production cross section as a function of gluino mass. The production follows a power law

$$\sigma(\tilde{m}) \cong 10^{-28} \, (\tilde{m}/10)^{-3.56} \quad cm^2$$

for $\tilde{m}$ in GeV/c^2. If we take an inelastic cross section ≈25 mb, the fraction of all inelastic interactions which contain a gluino will be

$$\frac{\tilde{g}}{all} \sim \frac{1}{250} \left(\frac{\tilde{m}}{10}\right)^{-3.56}$$

Table II gives some values of $\tilde{g}$/all for various values of gluino mass. Also shown are the total number of gluinos produced for an integrated luminosity of 10^{36} cm^{-2} which corresponds to a run of 120 days at an average luminosity of 10^{29} cm^{-2} sec^{-1}.

TABLE II

Gluino production vs. gluino mass $\tilde{m}$

$\tilde{m}$ (GeV)	$\sigma(\tilde{g})$ (cm^2)	$\tilde{g}$/all	Events/10^{36} cm^{-2}
10	10^{-28}	.004	10^8
20	8.5×10^{-30}	3.4×10^{-4}	8×10^6
30	2.0×10^{-30}	8.0×10^{-5}	2×10^6
40	7.2×10^{-31}	2.9×10^{-5}	7×10^5
50	3.2×10^{-31}	1.3×10^{-5}	3×10^5
100	2.7×10^{-32}	1.1×10^{-6}	3×10^4

From the table we see that even for a gluino mass of 100 GeV, about 30,000 gluinos would be produced and about $1/10^6$ of the interactions contain gluinos.

Figure 5 shows some results of the Monte Carlo calculation of the missing p_T due to gluino production and subsequent decay to an invisible goldstino for $\tilde{m}$ = 10 GeV/c^2. Superimposed is the approx. distribution in p_T^{miss} from ordinary events if the resolution in p_T^{miss} is twice that calculated above, i.e., 0.86 GeV/c. The gluino events which have a mean p_T^{miss} of 5.8 GeV/c for $\tilde{m}$ = 10 GeV/c^2 are well resolved from the ordinary events. For higher values of $\tilde{m}$ the situation is even better. Although the production drops fairly rapidly with increasing $\tilde{m}$ (Table II), $\langle p_T^{miss} \rangle$ increases approx. linearly with the gluino mass so the gluino events will be clearly resolved with a distribution in p_T^{miss} which peaks near $\tilde{m}/2$.

As we discussed above, in a search for gluinos we can discard any event which we believe might have an apparent missing p_T due to particles crossing the beam pipe or for any other reason. Even in the unlikely circumstance that we had to throw out 90% of the events we would still have >1000 gluino events if $\tilde{m}$ < 100 GeV. Other supersymmetric particles such as the $\tilde{Z}$ are expected to have decay modes involving goldstinos and their production will also be signalled by missing p_T.

For large gluino masses we will encounter a background from Z° decays to 2 neutrinos. Dunbar[6] estimates the cross section for $\bar{p}+p \rightarrow Z^\circ + X$ with $Z^\circ \rightarrow 2\nu$ to be $\approx 2\times 10^{-33}$ cm^2 at $\sqrt{s}$ = 2000 GeV. The signature[6] for this process is similar to that for the production of gluinos of mass ~ 60 GeV, a peak in the p_T^{miss} spectrum at about 35 GeV. The gluino signal is expected to be about an order of magnitude larger[5] for $m(\tilde{g}) \sim m(Z^\circ)$. For an integrated luminosity $\sim 10^{36}$ cm^{-2}, we would expect ~2000 $Z^\circ \rightarrow 2\nu$ events. In view of the very large p_T^{miss} these events will exhibit, they should be fairly easy to identify[7]. The branching ratio for $Z^\circ \rightarrow \bar{\nu}_e \nu_e$ is $2.0(Z^\circ \rightarrow e^+e^-)$. If there are three species of neutrinos then $Z^\circ \rightarrow 2\nu$ is about 18% of the total. As Dunbar points out, a measurement of the cross section for $Z^\circ \rightarrow 2\nu$ relative to $Z^\circ \rightarrow 2\mu$ can lead to a direct measure of the number of neutrino species. This would provide crucial information on the number of fermion generations. We emphasize again that this type of experiment can only be done with a detector of the sort described here.

V. Describe your detailed requirements for a central detector.

Our requirements for a central detector depend strongly on the physics under discussion. In early running with low luminosity we expect to mainly address questions on the overall features of hadron interactions at very high energies. For this physics, the detector in Fig. 1 is quite adequate. For later running at higher luminosity when missing p_T becomes an important consideration we will, of course, need complete coverage of the central region with calorimetry. To make the situation clear, we briefly review our physics objectives.

A. General Features of $\sqrt{s} \cong 2000$ GeV hadronic interactions.

1. Multiplicity, charged and neutral

   - General behavior (variation with energy, KNO scaling?)
   - Anomalies (Centauro events, Geminions,...)

The proposed detector can do all these measurements except for neutrals in the central region. The latter is not a significant shortcoming because it is covered by numerous other detectors [LAPDOG(?), CDF, UA1,...].

2. Interaction cross sections.

   - Variation with energy
   - Tien-shan anomaly?

The proposed detector can do this without any central detector.

3. Rapidity distributions and correlations.

Again, except for neutrals in the central region, which is well covered by other detectors, the proposed detector is sufficient.

4. Jets

   (Same as # 3)

5. Elastic scattering, $|t| \gtrsim 1$ (GeV/c)^2

   (No central detector required.)

B. "New" Physics

1. Search for new, noninteracting particles.

This obviously requires a central detector with good calorimetry and muon detection over the entire central region.

2. Massive stable hadron search.

This requires only time of flight and energy measurements and could be done with our detector alone.

3. Central collision "trigger" to enhance new physics in central detector.

This obviously needs a central detector.

4. Measurement of $Z^\circ \to 2\nu$

(Central detector requirements same as B-1.)

The most stringent requirement for a central detector would be for the search for noninteracting particles which requires calorimetry over the entire central region. It seems very unlikely to us that by 1986-87 when this search might begin, there will not be an adequate central detector approved for D_O. In that eventuality we are prepared to build the central detector ourselves.

We have begun to consider designs of a suitable central detector and believe it can be done at a reasonable cost. However in the short time available to answer these questions with most of us involved in a major Fermilab experiment now taking data, it has not been possible to come up with even a conceptual design.

It is worth noting that elements of our detector could be used as the forward hadron detector for the e-p collider proposed for D_O. We would be happy to cooperate in such a joint venture with the e-p or other groups. The strength of the overall program in D_O will depend on cooperation and sharing of facilities by all users. We hope the P.A.C. will take the initiative in encouraging this.

References and Footnotes

1. A. Kernan, talk presented at the Topical Conference on Collider Physics, Madison, Wisconsin, Dec. 1981.
2. T.K. Gaisser, Phys. Lett. 100B, 425 (1981); Fermilab, Pub. 80/104, December 1980.

3. Other options we are considering for our detector are:
   (i) an arrangement with 2 instead of 3 sets of calorimeters which might reduce any edge scattering problem.
   (ii) the use of uranium plates in the calorimeters rather than lead plus iron. Although expensive, this alternative would allow better shower containment and better resolution in energy and p_T.

4. P. Rapp et al., Nucl. Inst. and Meth. 188, 285 (1981).
5. G.L. Kane and J.P. Leveille, Experimental Constraints on Gluino Masses and Supersymmetric Theories, UM HE 81-68 (to be published in Phys. Lett. B).
6. I.H. Dunbar, Counting Neutrinos in $p\bar{p}$ Collider Experiments, Nucl. Phys. B197, 189 (1982).

7. Dunbar assumes that the average p_T of the $Z°$ grows as $a+b\sqrt{s}$ as suggested by lepton pair production data at lower energies. If the growth is in fact slower, the missing p_T from this process would be somewhat smaller. This should not be a problem in looking for $Z° \to 2\nu$ decays unless there is a large background from other sources of missing p_T (such as gluino decay).

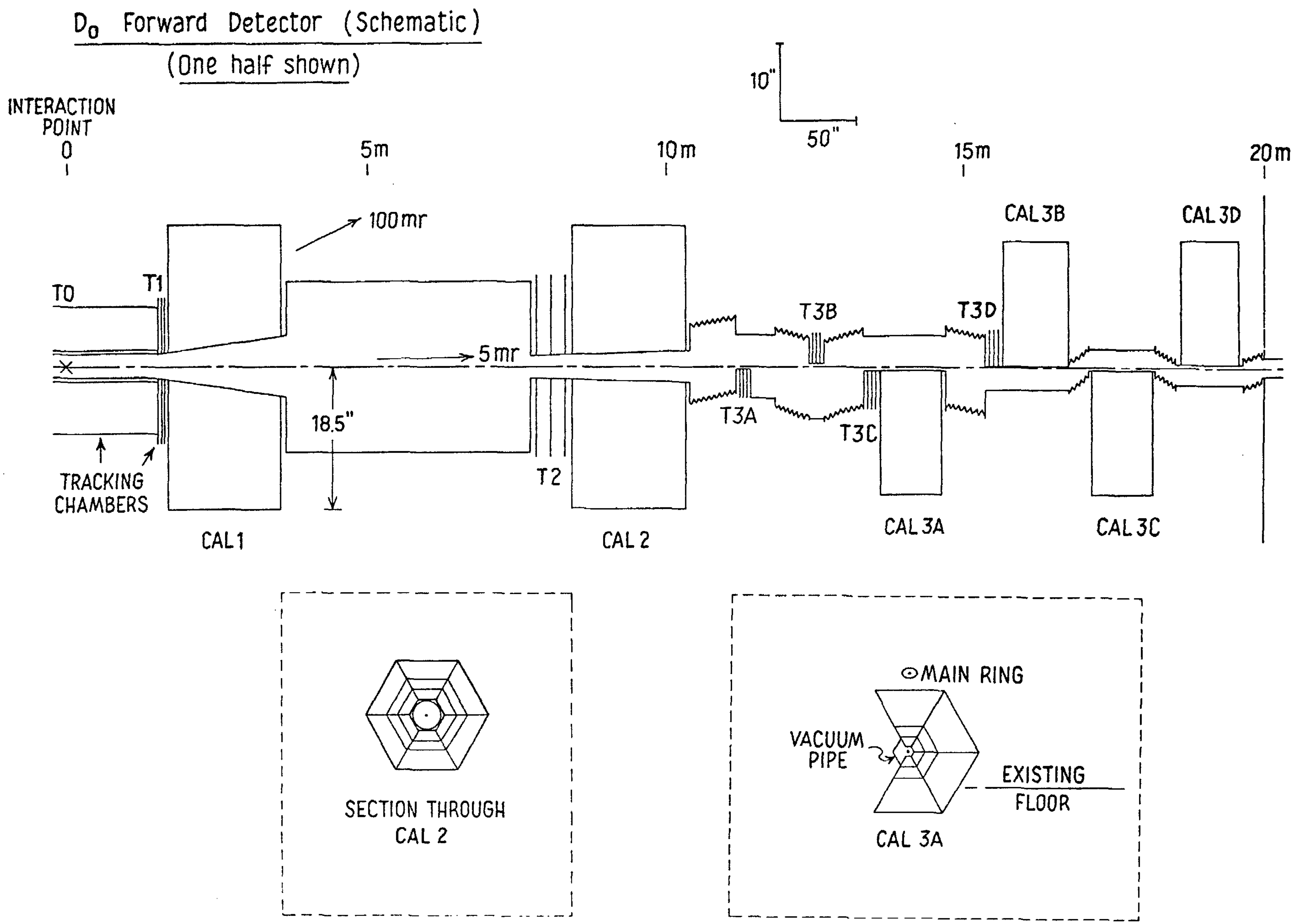
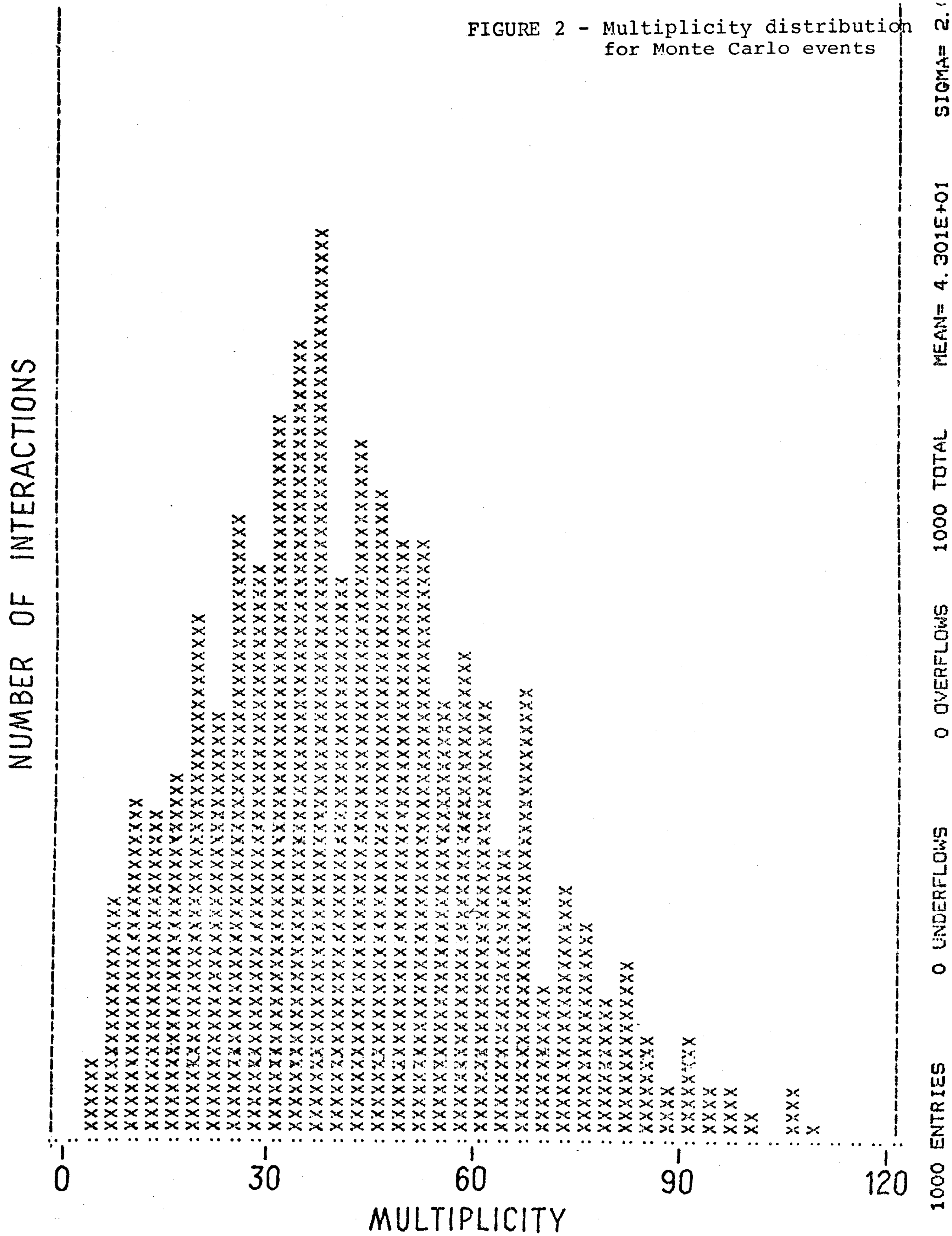


FIGURE 1 - Schematic of detector

FIGURE 2 - Multiplicity distribution for Monte Carlo events



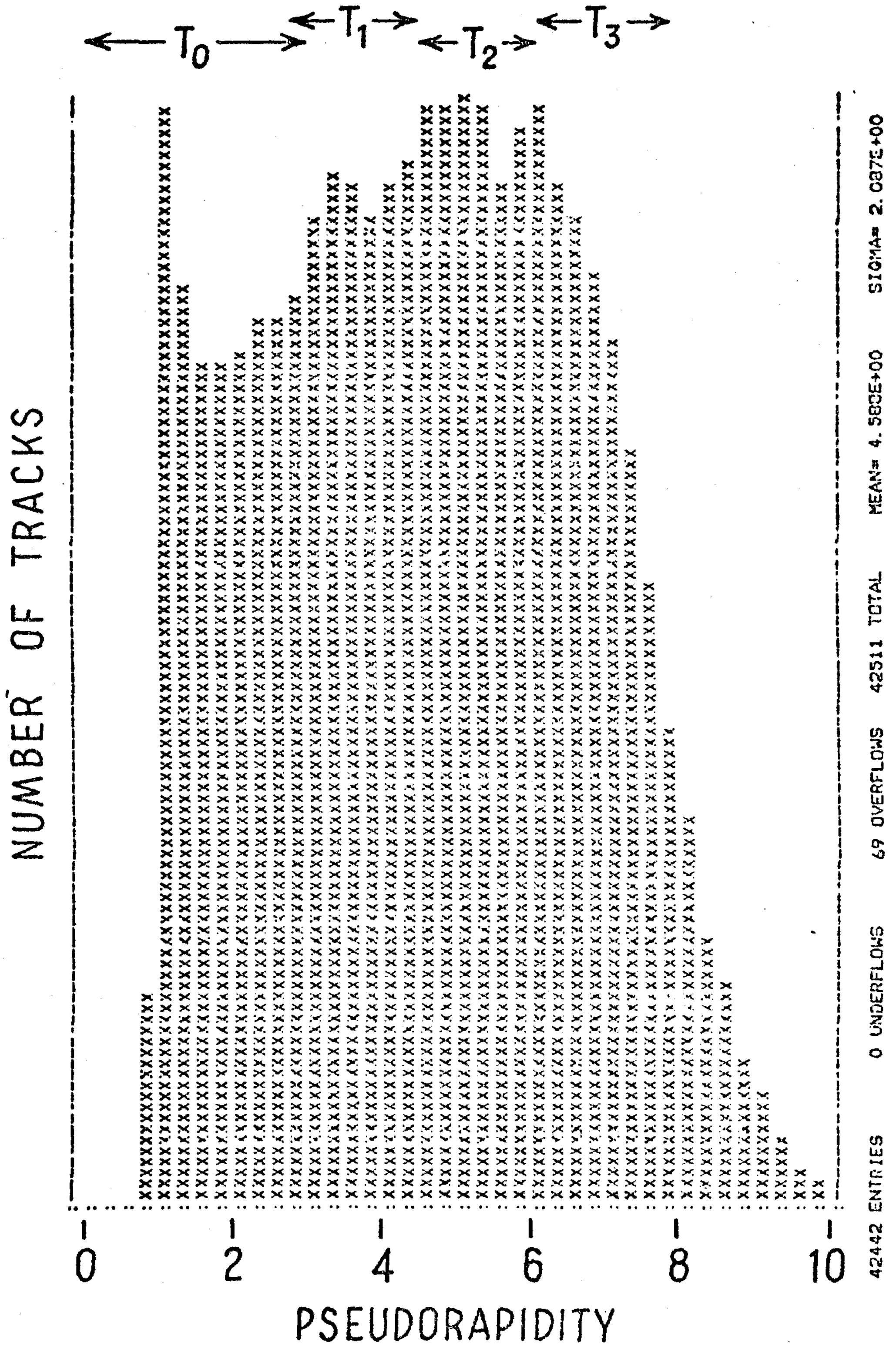


FIGURE 3 - Pseudorapidity distribution of tracks from Monte Carlo. The approximate range covered by each set of tracking chambers is shown.

DΦ FORWARD DETECTOR
TYPICAL EVENT WITH TWO OF 6 SECTORS
OF TRACKING CHAMBERS SHOWN

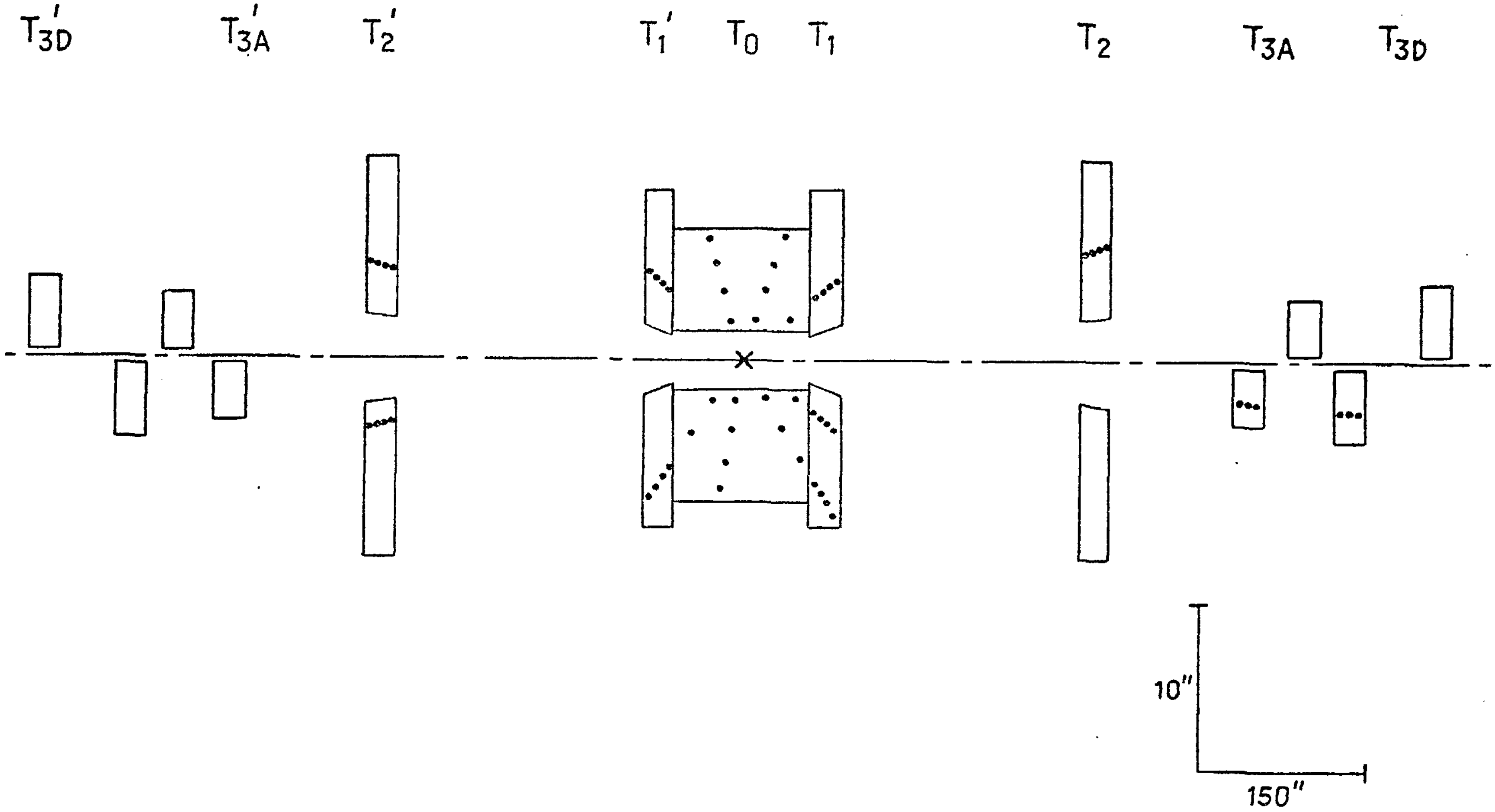


FIGURE 4

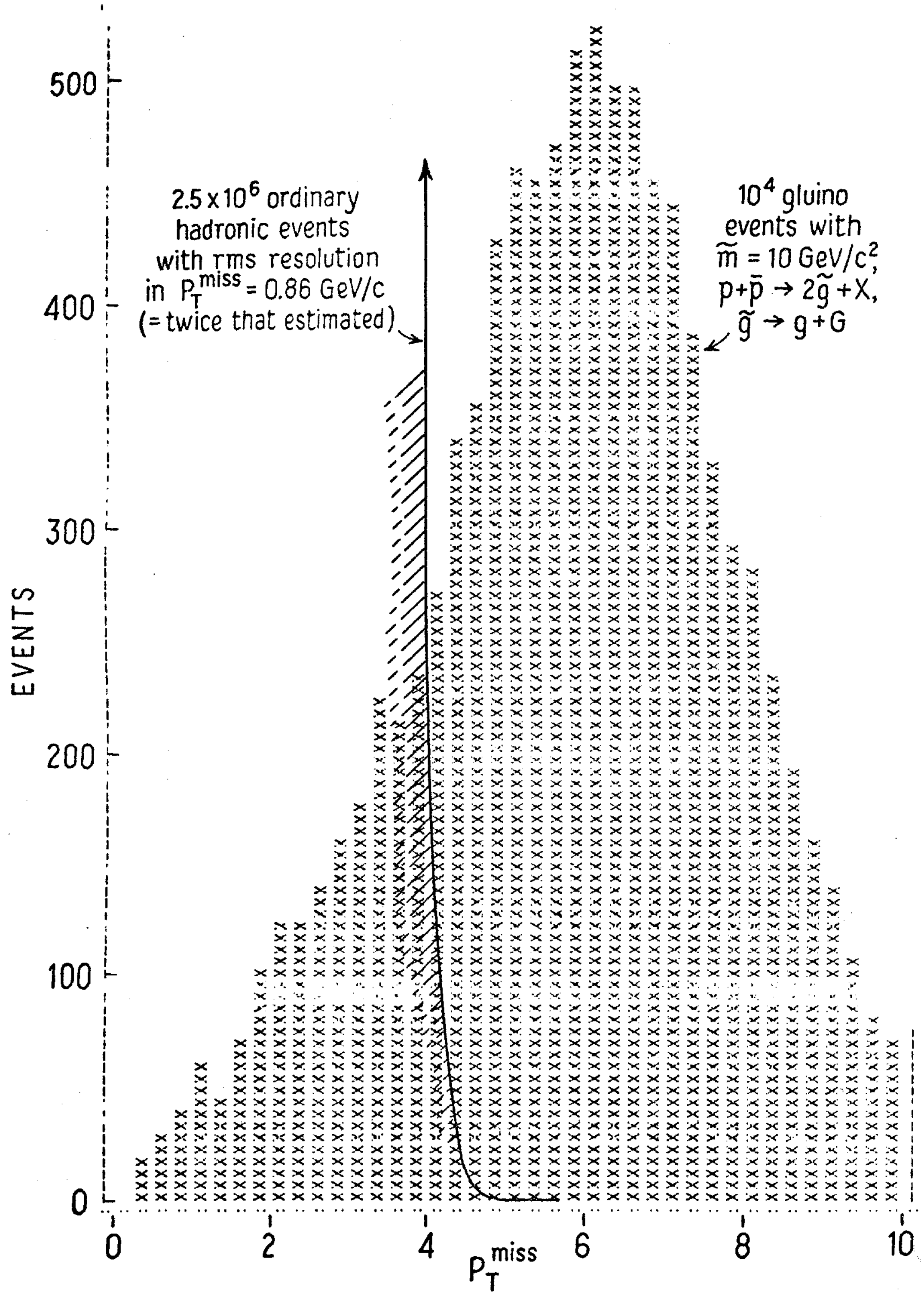


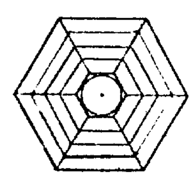
FIGURE 5 - Missing p_T distribution for gluino events, $\tilde{m}$=10 GeV/c^2

Appendix A - Detector Design

The overall detector layout is shown in Figure 1. Note the exaggerated transverse scale. Some details, such as passive shielding downstream of the calorimeters, have been omitted for clarity. A notable feature is that the downstream tracking chambers T_3 A-D and calorimeters CAL 3 A-D are split in half so that they can be moved to within 2 cm of the circulating beams once they are stable. This movement is made possible by connecting successive sections of the vacuum pipe with a flexible bellows. This design requires no tracking chambers or other detectors inside the vacuum. The diameters of the bellows are large enough that particles from the interaction point do not go through the walls of the bellows which are shadowed by calorimeters upstream of them. Particles that go off at small angles exit through vacuum windows approximately along a normal.

A-1. Tracking Chambers

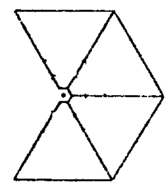
The tracking chambers are arranged in four groups. Successive chambers in each group are spaced sufficiently to allow particles to be traced back to the interaction point with good accuracy. The T_o chambers surround the beam pipe near the interaction point and see particles going off at angles $\gtrsim 6°$ to either beam. These contain 5 concentric layers of wire chambers as shown in the sketch. The wires run along the Z direction (parallel to the beam). End to end current division is used to get the Z-coordinate of each hit.



T_0 chambers - end view

The T_1 and T_2 chambers are each divided into 6 sectors which each encompass 60° in ϕ. Each sector covers the same ϕ range as the corresponding sector in the T_0 chambers. The sectors will be offset along the Z-direction so that the wires from each sector can be brought to the edge of the active volume. Thus there will be no dead regions; the useful area will be defined by deadening the area adjacent to the sector. Each set of tracking chambers, T_1 or T_2, contains at least 7 planes of wires as described on pages 1 and 2 of the main text.

The T_3 chambers can have a similar arrangement, except that two of the 6 sectors are missing in each. (See sketch.) The top and bottom sectors of T_{3A} and T_{3B} overlap completely when the tracking chambers are at the "in" position.



T_{3A} end view

The electronics for the tracking chambers has not yet been decided. We first wish to do studies in a test beam of possible problems due to scattering off the edges of upstream calorimeters to get a better estimate of accuracy requirements and multihit capability. We also plan to do an extensive survey of readout systems so we can choose the most appropriate.

A-2. Calorimeters

The upstream section of each calorimeter will contain lead plates alternating with scintillator and proportional chambers. These will be used for the identification of photons and measurement of their energies. The remainder of the calorimeter consists of thicker iron plates, scintillators, and proportional chambers. These will contain the hadron-initiated showers and measure their energy. The scintillators will provide the more accurate energy measurement and can be used for fast triggering and event selection. The proportional chambers will be more finely segmented with cathode pads and proportional readout. These will be used to obtain more accurate localization of the energy flow. The overall configuration of a representative calorimeter is summarized in Table A-1.

Table A-1 - Calorimeter Parameters (CAL 1 and CAL 2)

Electromagnetic Section:

Total lead plates = 15
Total scintillators = 15
Total prop. chambers = 7
Total length of lead = 11 cm
= 20 rad. lengths
= 0.6 abs. length

Hadronic Section:

Total iron plates = 30
Total scintillators = 30
Total prop. chambers = 12
Total length of iron = 137 cm
= 8 abs. length

Segmentation:

Scintillator - 6 sectors azimuthally, 3 segments radially, 3 segments in depth.
Proportional chambers - 6 sectors azimuthally, 30 cathode pads per sector which are ganged in groups of 2 or 3 deep. (1260 "towers" per calorimeter, each with proportional readout).

Total length: 213 cm.
Total weight: approx 10 tons each

The CAL 1 and CAL 2 scintillators are each divided into 6 sectors azimuthally which parallel those in the tracking chambers. Each sector is divided into 3 segments radially as shown in Figure A-1. Light from the inner radial segments is piped to the periphery so that there is no dead region near the beam. The scintillators are organized into three groups in depth. The light from each group is brought to a separate photomultiplier. The wavebars and phototubes are completely shielded by the bulk of the calorimeter so that "hotspots" will be avoided. The most upstream section is the electromagnetic shower detector. The proportional chamber complement of each calorimeter is summarized in the table. Cathode pads from 2 or 3 successive chambers are ganged to form towers.

The split calorimeters CAL 3 A-D are arranged like the T_3 tracking chambers. Only CAL 3A and CAL 3B contain electromagnetic sections. The iron is split roughly equally between the halves on either side of the beam. The total length of iron will be somewhat larger than in the more upstream calorimeters.

Figure A-2 shows a schematic perspective view of one of the calorimeters.

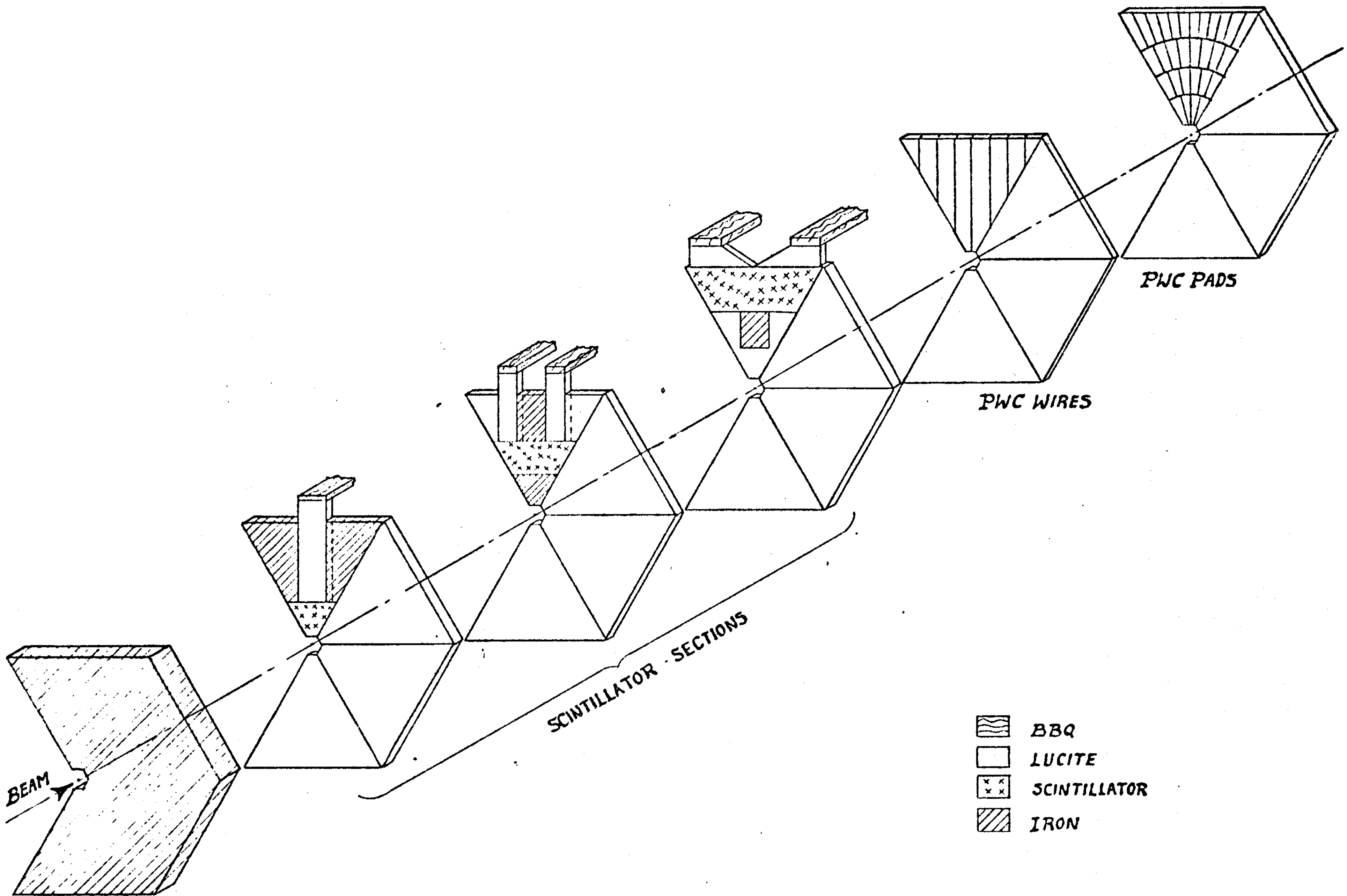

PWC PADS
PWC WIRES
SCINTILLATOR · SECTIONS
BEAM
BBQ
LUCITE
SCINTILLATOR
IRON

FIGURE A-1

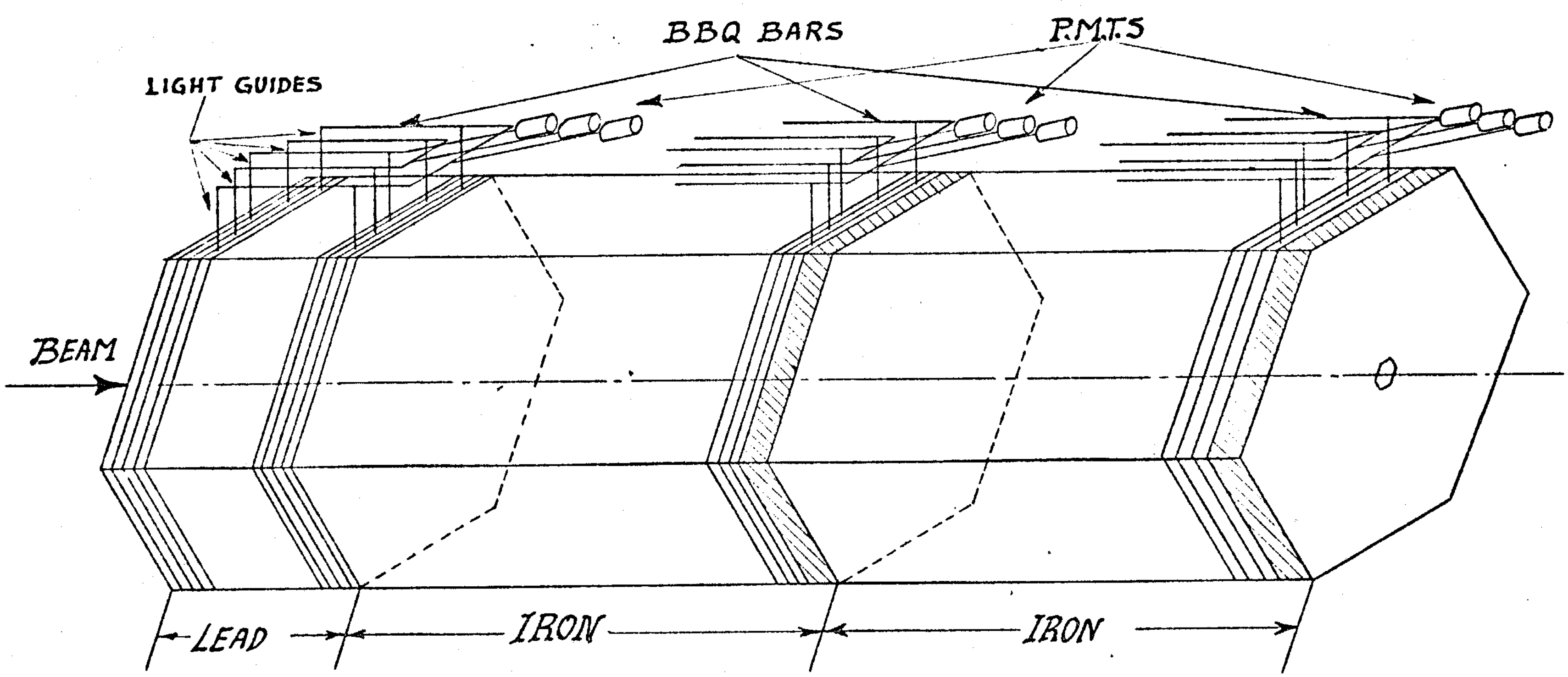


FIGURE A-2