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Invited talk presented at the International  
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TECHNOLOGY OF HIGH LUMINOSITY DETECTORS

S.C. Loken

November 1983

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TECHNOLOGY OF HIGH LUMINOSITY DETECTORS

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Invited talk presented at  
International Conference on High Energy Accelerators  
Fermilab, 11-16 August 1983

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# TECHNOLOGY OF HIGH LUMINOSITY DETECTORS

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## Summary

The "Workshop on Collider Detectors: Present Capabilities and Future Possibilities" focused on the problems posed by high luminosity and high energy at hadron colliders. Four working groups considered problems in individual detector elements, tracking chambers, calorimeters, triggers and particle identification devices. A fifth group reviewed the general problems of detector systems. The working groups concluded that there are technical solutions for the problems of a luminosity of  $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$ . Everything is difficult and continued R & D is necessary to improve detectors.

## Introduction

This paper summarizes the results of the 1983 DPF Workshop on Collider Detectors: Present Capabilities and Future Possibilities. The workshop was held at the Lawrence Berkeley Laboratory from February 28 to March 4, 1983.

The purpose of the meeting was to define the state-of-the-art in detectors for hadron colliders and to determine the R & D needed to exploit new high-luminosity colliders. The workshop considered luminosities on a continuous range from  $10^{29}$  to  $10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$  and focused on two specific center-of-mass energies, 1 TeV and 20 TeV.

The workshop was attended by 96 physicists. These included 11 from Europe as well as 34 from universities in the United States, 32 from national laboratories, and 17 from Berkeley.

To maintain a workshop atmosphere, there were only three invited talks. These were to describe the experience of groups working at the high luminosity intersection of the ISR (W.J. Willis) or at the SPS Collider (M. Banner and C. Rubbia). Important theoretical input to the workshop included estimates of relevant cross sections (R. Cahn) and of high transverse momentum jets (F. Paige).

After the introductory talks, the participants organized themselves into five groups shown in Table 1. The remainder of this paper is organized along the same lines as the workshop. We will review briefly the workshop input. We then summarize the conclusions of each of the working groups. A complete report of the workshop has been published.<sup>1</sup>

## Workshop Input

The rate in any detector is defined by the total cross section. The value of the total cross section measured at the SPS Collider is about 65 mb. Depending on the method of extrapolation, this is expected to rise to 100 or 200 mb at  $\sqrt{s} = 40 \text{ TeV}$ . It should be noted here that most of the detector studies described in the following sections were carried out for 1 TeV, assuming a cross section of about 50 mb. The rates in detectors at 40 TeV may increase by a factor of 4 or more.

The emphasis of most experiments is the study of processes which are a small part of the total cross section. For example, the cross section for the production of heavy quarks ( $M = 40 \text{ GeV}$ ) is expected to be approximately  $5 \times 10^{-32} \text{ cm}^2$ ; for W or Z production, about  $5 \times 10^{-33} \text{ cm}^2$ . The cross section to produce a lepton pair with mass greater than  $180 \text{ GeV}/c^2$  is about  $10^{-36} \text{ cm}^2$ . High transverse momentum jets become prominent, well-defined features at high energy. The cross section for a  $P_t = 1 \text{ TeV}$  jet at  $\sqrt{s} = 20 - 40 \text{ TeV}$  is expected to be approximately  $10^{-34}$  to  $10^{-33} \text{ cm}^2$ .

The general features of high  $P_t$  jets have been modeled by Monte Carlo methods. Figures 1a, b show events generated at  $\sqrt{s} = 10 \text{ TeV}$  with  $P_t = 1 \text{ TeV}$  and  $|y| < 1.0$ . The particles from these events have been put into a simulation program for a calorimeter segmented into towers with  $\Delta y = 0.1$  and  $\Delta\theta = 5^\circ$ . The energy in each tower is indicated by a solid line, and the energy of each parton is shown by a dotted line.

The above discussion illustrates important lessons for detector designers. The total rates are high, but the interesting events are often a small fraction of the total. A fast, refined trigger is essential to pick out the desired signal. The tight clustering of particles in jets means that detectors must be finely segmented to resolve individual particles. This leads to many wires in chambers or to small towers in calorimeters.

The experience of groups working at the ISR and at the SPS Collider agrees with these generalizations. At the ISR, the luminosity has increased continuously as shown in Figure 2. The arrow indicates the design value. The Axial Field Spectrometer (AFS) began operating in 1979 and has taken data at luminosities up to  $1.4 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$ . Some of the conclusions drawn from the AFS experience are the following.

1. The experiment must evolve. The high rate allows several experiments to coexist, each with its selective trigger. As some are finished, new experiments are added.
2. Trigger considerations dominate the detector design. A multi-level trigger is necessary. Higher levels are more selective and take longer to make decisions.
3. Trigger processing must be overlapped in time with data-acquisition. The signals for data-acquisition are delayed on slow cable while a fast analog trigger does the first level selection.

The experiments at the SPS collider provide a striking confirmation of the Monte Carlo modeling. Figure 3 shows the pattern of energy deposition in the UA2 calorimetric detector. The tight clusters with little background are very similar to the calculated jet behavior illustrated in Figure 1.

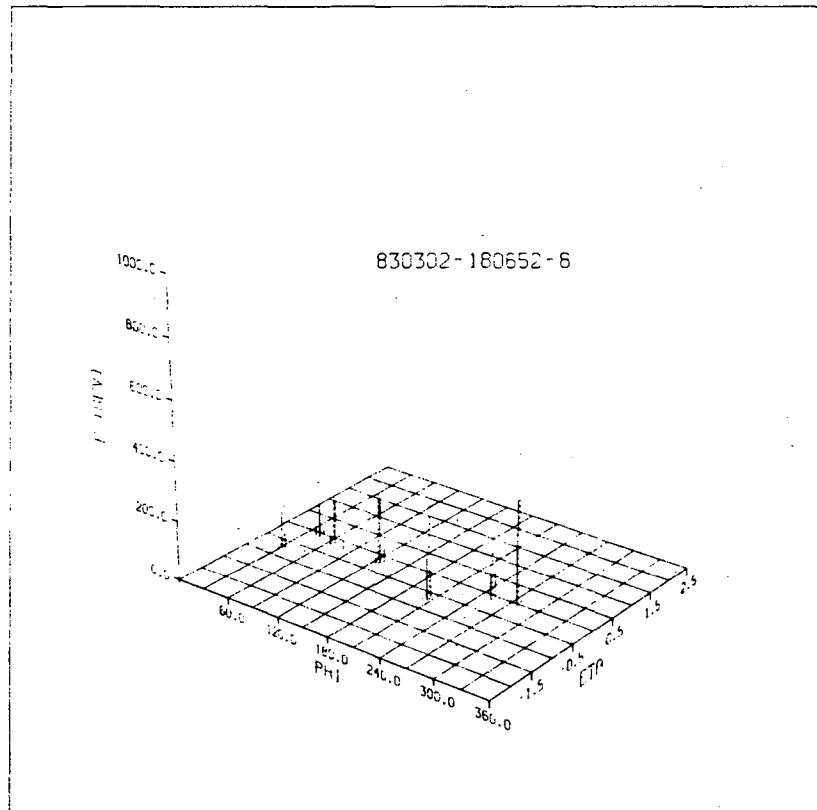
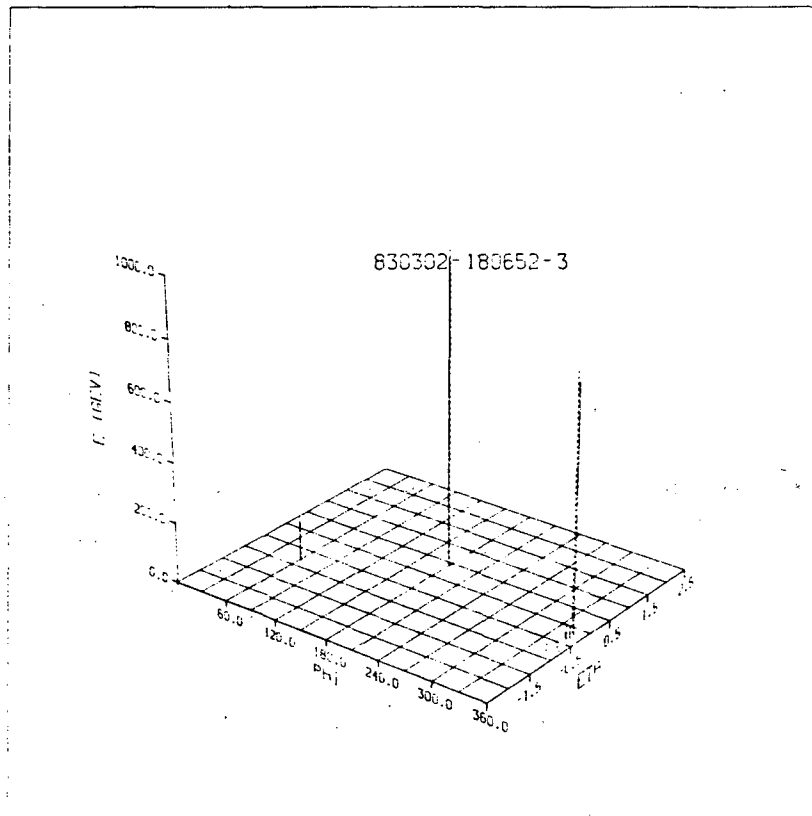
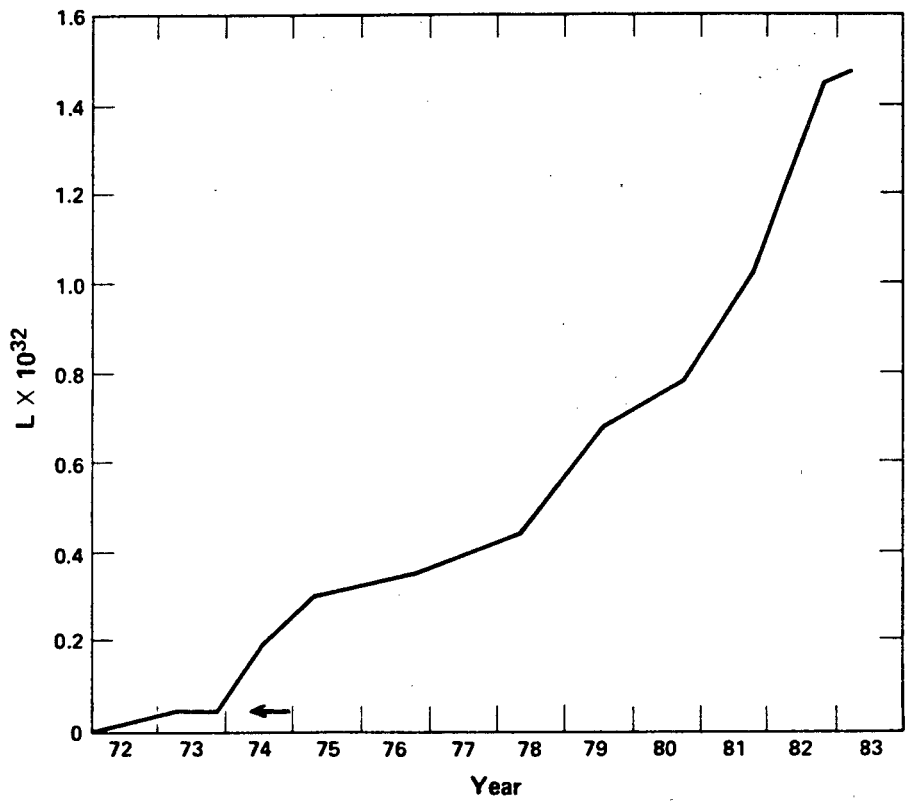


Figure 1. Calorimeter plots of events with  $P_t = 1000$  GeV.

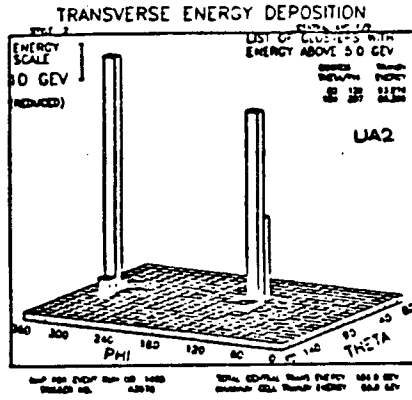
Table 1

WORKING GROUP	GROUP LEADER	SCIENTIFIC SECRETARY
Tracking Detectors	Don Hartill	David Herrup
Calorimetry	Bernie Pope	Melissa Franklin
Triggers	Mel Shochet	Mike Ronan
Particle Identification	Dave Nygren	Rem Van Tyen
Detector Systems	Barry Barish	Mark Nelson

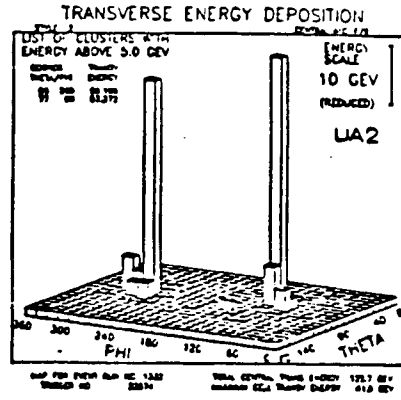


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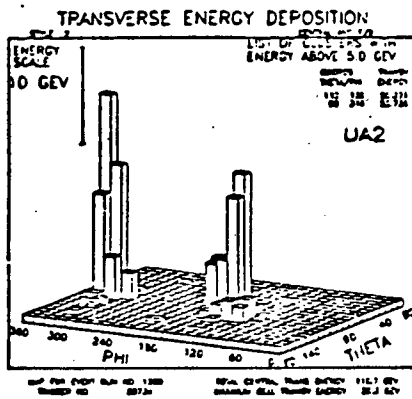
Figure 2. History of the ISR record luminosity. The arrow indicates the design luminosity of the machine.



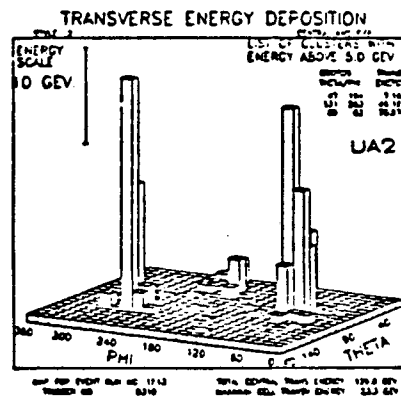
a)



b)



c)



d)

Figure 3. Typical  $\theta - \phi$  distributions of the transverse energy in large  $\Sigma E_t$  events from the UA2 detector at the CERN SPS Collider.

### Tracking Detectors

The tracking group concerned itself with two topics. These were the central and forward regions for a  $1 \text{ TeV}$  proton-proton collider with a luminosity of  $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$  and the general vertex detector. The question of tracking devices for a 20 TeV hadron-hadron collider was studied by a subgroup of the systems working group.

To discuss a tracking detector, the group first defined a detector geometry. A central solenoid was selected to facilitate fast tracking at the trigger level. Open frame dipoles covering the forward and backward directions aid in the detection of particles at small angles by sweeping them out of the beam. We consider first the central detector.

The requirements for the central tracking detector are:

- o rapidly coverage  $y = \pm 1.5$  ( $26^\circ < \theta < 154^\circ$ )
- o  $\Delta p/p = 10\%$  at  $p = 100 \text{ GeV}$ , sufficient to measure the charge

o Operation at  $L = 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$

o Efficient detection of individual particles in the core of a  $100 \text{ GeV}/c$  jet.

The luminosity requirement implies an interaction rate of  $5 \times 10^7/\text{sec}$  at 1 TeV so that the central detector has a charged particle rate of  $5 \times 10^8/\text{sec}$ . To limit particle fluxes to  $2 \text{ MHz}$  per sense wire, each layer of the central detector must have at least 250 wires.

The requirement of efficient particle detection in jets also dictates fine granularity. Figure 4 shows the fraction of missed tracks because of overlap in a cell. For a  $p_t = 40 \text{ GeV}/c$  jet a detection efficiency of 70 to 80% can be achieved with 300 to 500 cells. At higher  $p_t$  the number of cells required will increase as shown in Figure 5.

To limit the number of overlapping events, a system of small cells is also desired. For a drift distance of 2 mm the drift time is 40 ns giving an average of two events per trigger for the  $50 \text{ MHz}$  interaction rate.



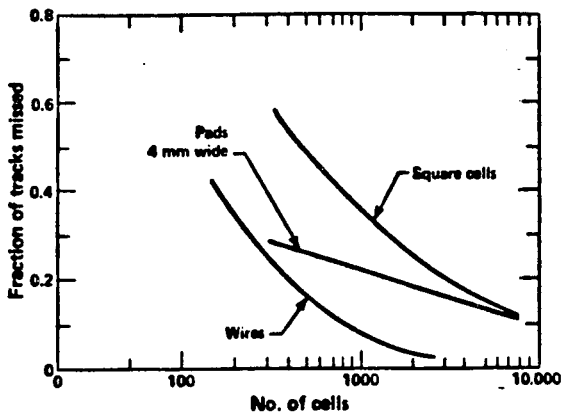


Figure 4. Inefficiency in resolving tracks in jets as a function of cell density.  $P_T(\text{Jet}) = 40 \text{ GeV}/c$

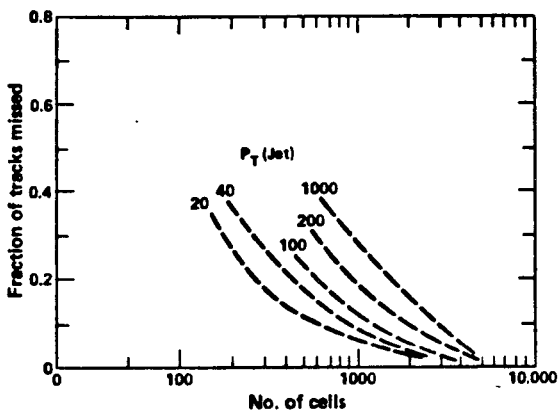


Figure 5. Track resolving inefficiency for different values of  $P_T$ .

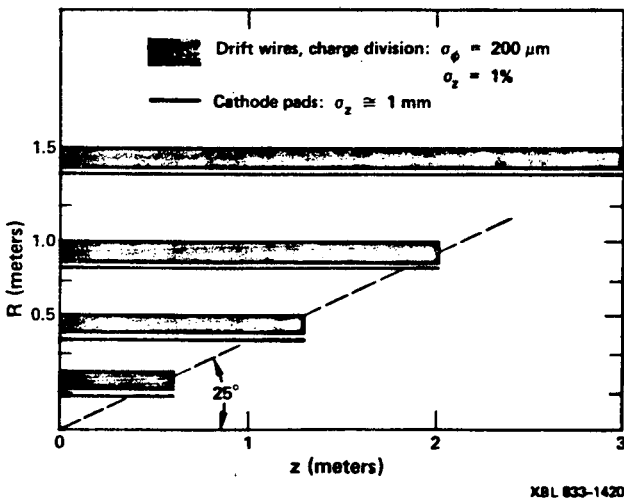
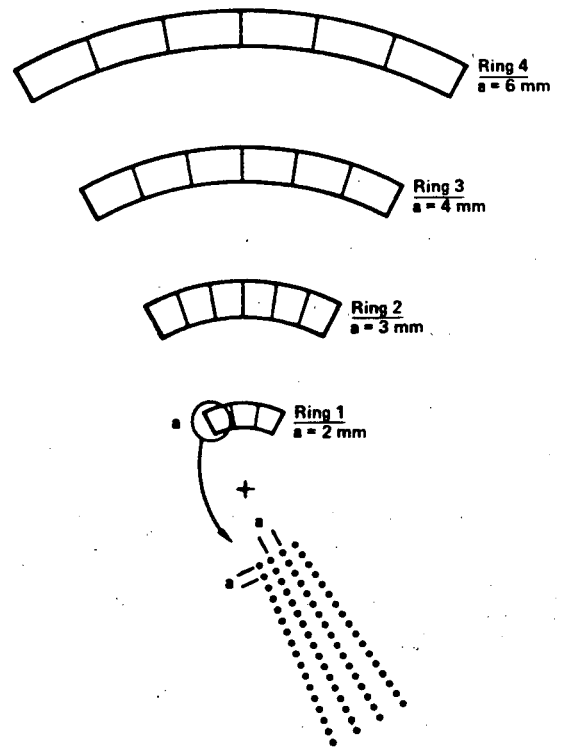


Figure 6. Quarter section of cylindrical drift chamber.



XBL 833-1427

Figure 7. Partial end view of drift chamber with blow-up of sector.

Figure 6 shows the drift chamber configuration. The detector achieves 10% momentum resolution at 100 GeV/c using 45 measurements with 200  $\mu\text{m}$  resolution over a 130 cm path in a 1.5 Tesla field. Figure 7 illustrates the basic cell configuration in more detail. The sense wires are all parallel to the beam axis and the z coordinate is measured by charge division on every sense wire. The layers are grouped in four rings. Table 2 summarizes the construction of the rings and the number of channels.

Table 2 Central Tracking Chamber

Ring 1	$r_1 = 20 \text{ cm}$ $a = 2 \text{ mm}$ 314 sense wires/layer 15 layers	4700 sense wires 3000 pads
Ring 2	$r_1 = 50 \text{ cm}$ $a = 3 \text{ mm}$ 523 sense wires/layer 15 layers	7850 sense wires 3000 pads
Ring 3	$r_1 = 90 \text{ cm}$ $a = 4 \text{ mm}$ 722 sense wires/layer 10 layers	7220 sense wires 6000 pads
Ring 4	$r_1 = 140 \text{ cm}$ $a = 6 \text{ mm}$ 1460 sense wires/layer 5 layers	7330 sense wires 6000 pads

Total sense wires = 27,000  
 Total pads = 18,000  
 Total electronic channels =  $2 \times 45,000 = 90,000$

The sense wire charge division provides resolution of 1% of the wire length, approximately 1 cm in the inner ring and 4 cm at large radius. To improve this resolution, each ring has a cathode strip system as illustrated in Figure 8. The strips are a few mm wide and 16 mm to 48 mm long (covering four sense wires). They are connected to form a pad. A charge-sensitive amplifier at each end gives resolution of about 1 mm.

The forward direction covers the rapidity range from 1.5 to 7, or polar angles from 0 to 26°. To reduce the rate per sense wire, the small angle chambers must be far from the interaction region. A dipole field aids in sweeping particles from the beam direction as well as providing a momentum measurement.

Figure 9 illustrates a forward detector covering the rapidity range from 1.5 to 5.5. Two window frame dipoles are used with a central solenoid. If a dipole is used for the central detector the smaller dipole can be omitted. The drift chamber uses 2 mm cells oriented vertically, horizontally, and at ± 45°. Table 3 summarizes the chamber sizes and the number of electronic channels for the forward or backward detectors. The total number of channels for two detectors is 73.6 K.

Table 3

Module	Position	Area	No. of Sense Wires
1	4 m	1.6 x 1.6 m <sup>2</sup>	3200
2	8 m	3.2 x 3.2 m <sup>2</sup>	6400
3	12 m	4.8 x 4.8 m <sup>2</sup>	9600
4	16 m	4 x 2 m <sup>2</sup>	3600
5	20 m	5.6 x 2.8 m <sup>2</sup>	6300
6	25 m	7.2 x 3.6 m <sup>2</sup>	7700
Total			<u>36.8K</u>

Figure 8. Schematic layout of cathode strip system.

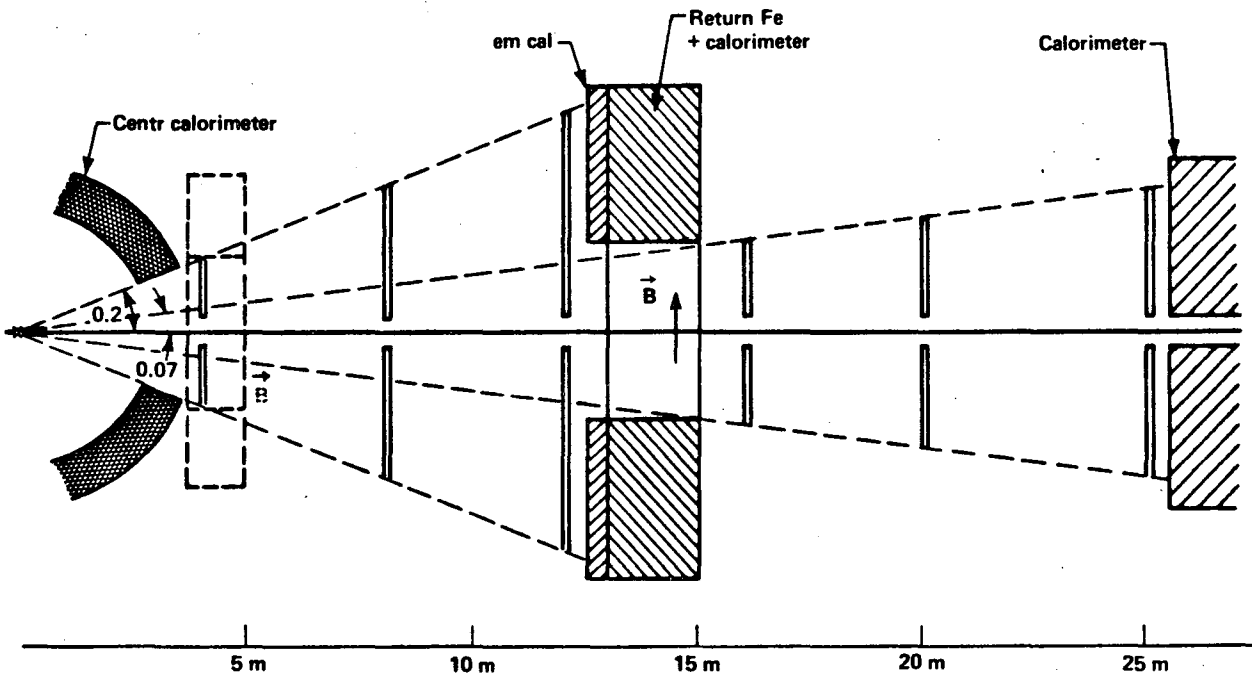
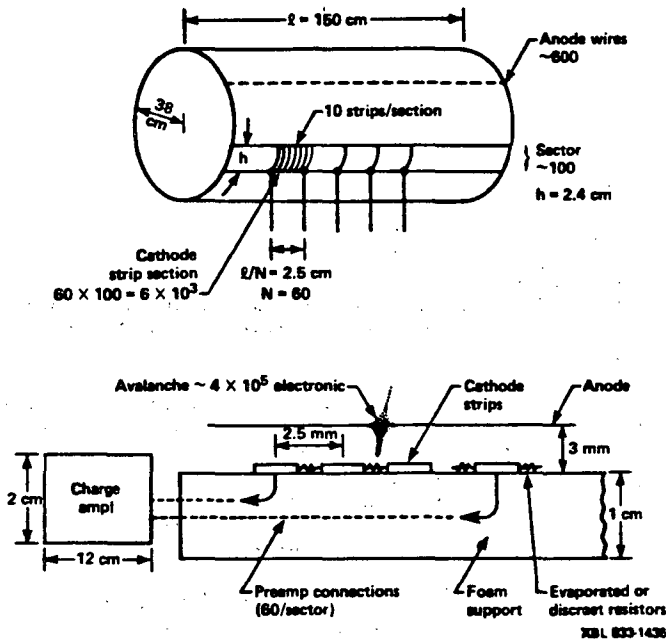


Figure 9. Layout of forward detector. The window frame magnet is 4 x 2 x 2 m<sup>3</sup>; second magnet (dashed line) is 2 x 2 x 2 m<sup>3</sup>.

It is impossible with present-day techniques to construct a high resolution vertex detector to operate at a luminosity of  $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$  at 1 TeV. The collider optics must be adjusted to give a 2 cm long interaction region with a maximum luminosity of  $10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$ .

Silicon strip detectors can provide spatial resolution of 5  $\mu\text{m}$  or better but are costly, radiation-sensitive, and are thick in terms of radiation lengths. Resolution of 20-30  $\mu\text{m}$  can be achieved with high pressure drift chambers of the microjet or mini drift types. The pressure vessel required for up to 5 atmospheres contributes significantly to the radiation length thickness. Silicon drift chambers promise 5 to 10  $\mu\text{m}$  resolution but are still under development.

The detectors described here meet the design goals of the workshop but are a minimal solution. Much work remains to be done to design an optimal detector. These efforts include improving the longevity of drift chambers, reducing the cost of front-end electronics, and developing better vertex detectors.

### Calorimetry

The calorimetry working groups reviewed the properties of various types of calorimeters to determine their suitability as detectors at high luminosity or at high energy. The devices considered were divided into four categories:

- o continuous calorimeters
- o scintillation sampling calorimeters
- o gas sampling calorimeters
- o liquid ionization calorimeters.

Two issues determine the use of various calorimeters at high luminosity. These are radiation damage and integration time.

The effects of radiation damage were calculated using a model of particle production as a function of angle, energy and luminosity. The model is based on data from the SPS Collider. The results are shown in Figure 10. Also shown are estimates of the amount of radiation required to reduce transmission by 10% for various detectors.

The integration time of a calorimeter also determines its suitability as a detector for high luminosity. Gates as short as 10 ns are essential to reduce the number of overlapping events. Short gates, however, may degrade energy resolution because slow neutrons are not collected. Short gates also increase the problems of timing for large detector arrays.

Table 4 summarizes the suitability of detectors considered by the calorimeter group. They conclude that a suitable calorimeter can be found for each of three angular regions. A calorimeter with 4 $\pi$  coverage can be constructed to operate at luminosities of  $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$ .

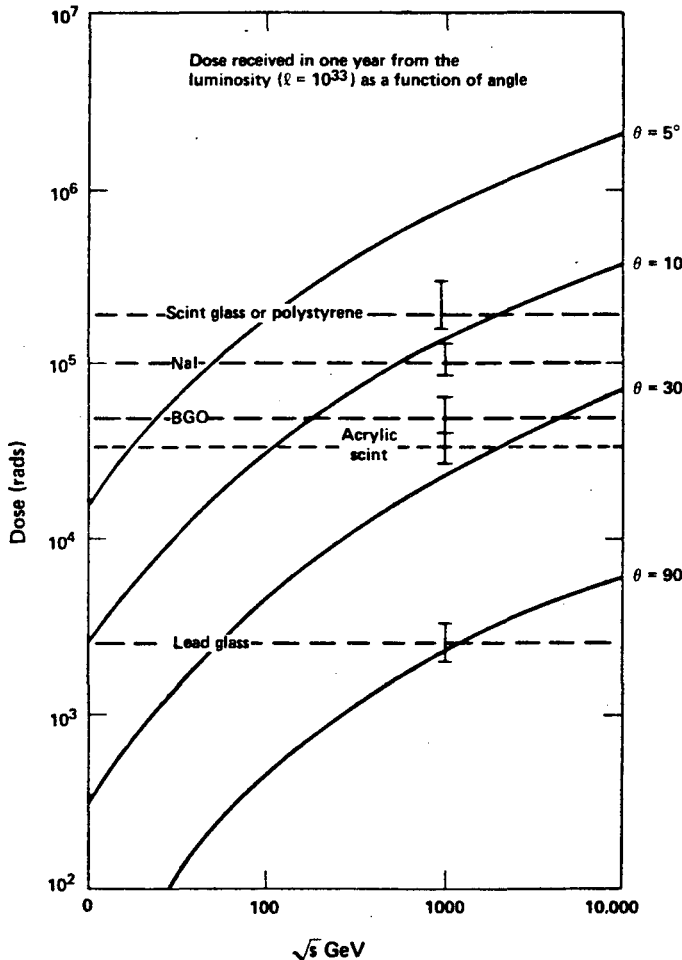


Figure 10. Dose limits in detector materials.

TABLE 4  
SUITABLE CALORIMETERS FOR HIGH LUMINOSITY  
(At  $\sqrt{s} = 1 \text{ TeV}$ )

Detector	Effect of Rad. Damage	Effect of Integ. Time
Lead Glass	X	N/A
Scint. Glass	$\theta > 10^\circ$	$\theta > 30^\circ$
BGO	$\theta > 30^\circ$	X
NaI	$\theta > 20^\circ$	X
BaF <sub>2</sub>	$\theta > 10^\circ?$	$\theta > 10^\circ$
Acrylic Scint.	$\theta > 40^\circ$	$\theta > 40^\circ$
Polystyrene Scint.	$\theta > 10^\circ$	$\theta > 10^\circ$
Polystyrene + P.D.	$\theta > 5^\circ?$	$\theta > 5^\circ$
Prop. Tubes (Fast Gas)	✓	$\theta > 30^\circ$
Sat. Avalanche	✓	X
Streamer Tubes	✓	X
High Dens. Proj. Chamber	✓	X
Liquid	✓	$\theta > 10^\circ$
Liquid Argon + CH <sub>4</sub>	✓	✓?
<b>Conclusions</b>	<b>Region</b>	<b>Candidate</b>
	$\theta > 5^\circ$	LA + CH <sub>4</sub>
	$\theta > 5^\circ - 10^\circ$	Polystyrene, BAF <sub>2</sub> ?, LA
	Central	Scint. Glass, Prop. Tubes

## Triggers

The trigger group concentrated on two problems associated with the design of front-end triggers for a high luminosity detector. The two problems are pile up from multiple interactions and the trigger speed required for the high interaction rate. The first level trigger considered here uses calorimeter modules and analog logic. The choice of higher level triggers depends greatly on the physical process to be studied and is not discussed in this report.

The pile up problem is indicated in Figure 11 as a probability distribution for exceeding a transverse energy threshold,  $E_T$  (min). The distribution is exponential at low  $E_T$ . At large  $E_T$  the distribution has a power law behavior so that the effect of multiple events does not grow with increasing  $E_T$  but rather is a uniform shift in the  $E_T$  scale. The shift is equal to mean number of interactions multiplied by the average  $E_T$  per interaction.

This shift can be minimized if the incremental  $E_T$  is low. This is accomplished by the use of a cluster algorithm. Figure 12 shows the probability of exceeding a trigger threshold as calculated using the ISAJET Monte Carlo simulation. The trigger rate is significantly increased if multiple interactions are included

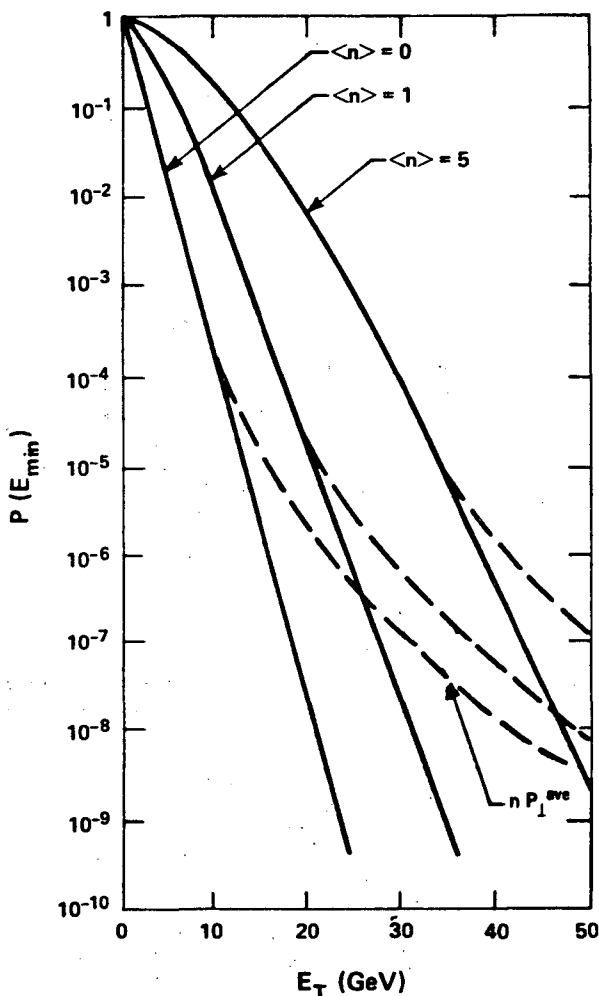


Figure 11. Probability of exceeding  $E_T$  for different numbers of overlapping events.

over the whole solid angle. The effect is reduced if only the solid angle near the jet is included. If, in addition, only calorimeter modules containing  $E_T > 1$  GeV are included, the trigger rate is increased very little over that for no multiple interactions.

This cluster algorithm is used in the trigger system shown schematically in Figure 13. The calorimeter signal passes through an integrating amplifier. The output enters a 500 ns delay line to allow time for a first level trigger. The calorimeter signals are stored using a BEFORE-AFTER circuit. The BEFORE switch is opened just before the event signals associated with the trigger leave the delay line. The AFTER opens 100 ns later. The output of the difference amplifier is proportional to the charge collected by the detector element in that 100 ns.

The level 1 trigger logic uses a difference amplifier to provide a signal proportional to the charge collected in the last 50 ns. Resistor chains proportional to the sine and cosine of the detector element's azimuthal angle are used to give signals proportional to the total  $P_x$  and  $P_y$ . These are used to define a transverse momentum imbalance trigger. A third circuit provides the total  $E_T$  for all cells above  $P_t$  threshold.

Lepton identification can also be included in the first level trigger. Information from a subset of the inner tracking chamber is used to set a minimum transverse momentum and to associate a track with a single calorimeter tower. Muons are identified outside the central detector and are correlated with a single high transverse momentum track and with a single calorimeter module. Electrons are identified by calorimetric separation or using transition radiation detectors.

Calculations indicate that the first level trigger can reduce the event rate to 50 kHz. A second level trigger can reduce the rate to 5 kHz. A powerful and versatile trigger can be constructed to operate at a luminosity of  $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$ .

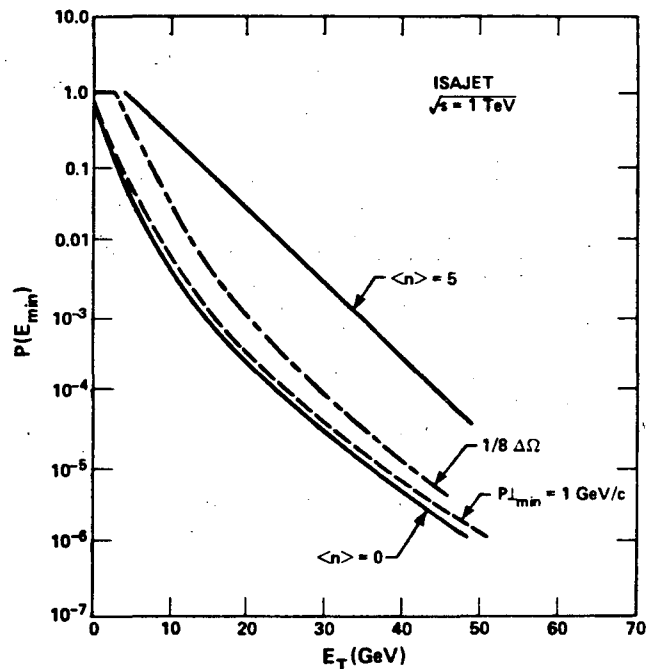


Figure 12. Isajet simulation of jet  $E_T$  probability distribution.

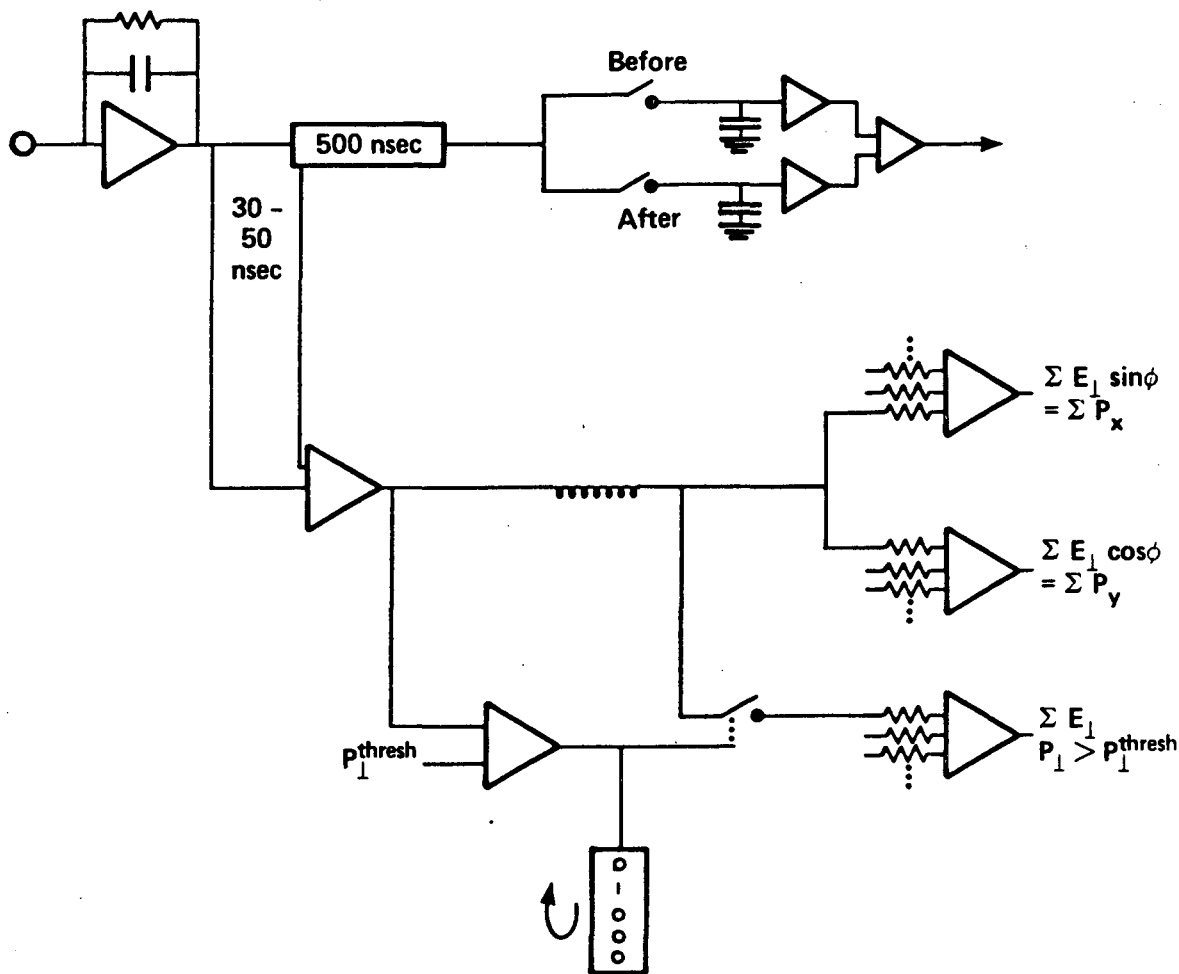


Figure 13. Schematic of a level 1 trigger for a calorimeter.

### Particle Identification

The particle identification group addressed a variety of subjects to establish the practical limits of detectors at high luminosity. The main focus of their work was on the problems of particle identification at 1 TeV.

Cerenkov ring imaging remains an attractive technique, realized currently in beam line geometries but not yet in collider configurations. Because the  $\gamma$  range can be adjusted through choice of radiator to span a large dynamic range by cascaded detectors, the technique is, in principle, very promising and deserves a large R & D effort.

Other topics considered by the particle ID group included transition radiation, synchrotron radiation, time-of-flight, a high  $P_T$  spectrometer, heavy quark tagging with leptons, a general purpose  $\mu$  and  $e$  detector, and  $dE/dx$ . The general conclusion is that there are no fundamental limitations on the use of particle identification at luminosities up to  $10^{33}$   $\text{cm}^{-2} \text{sec}^{-1}$ .

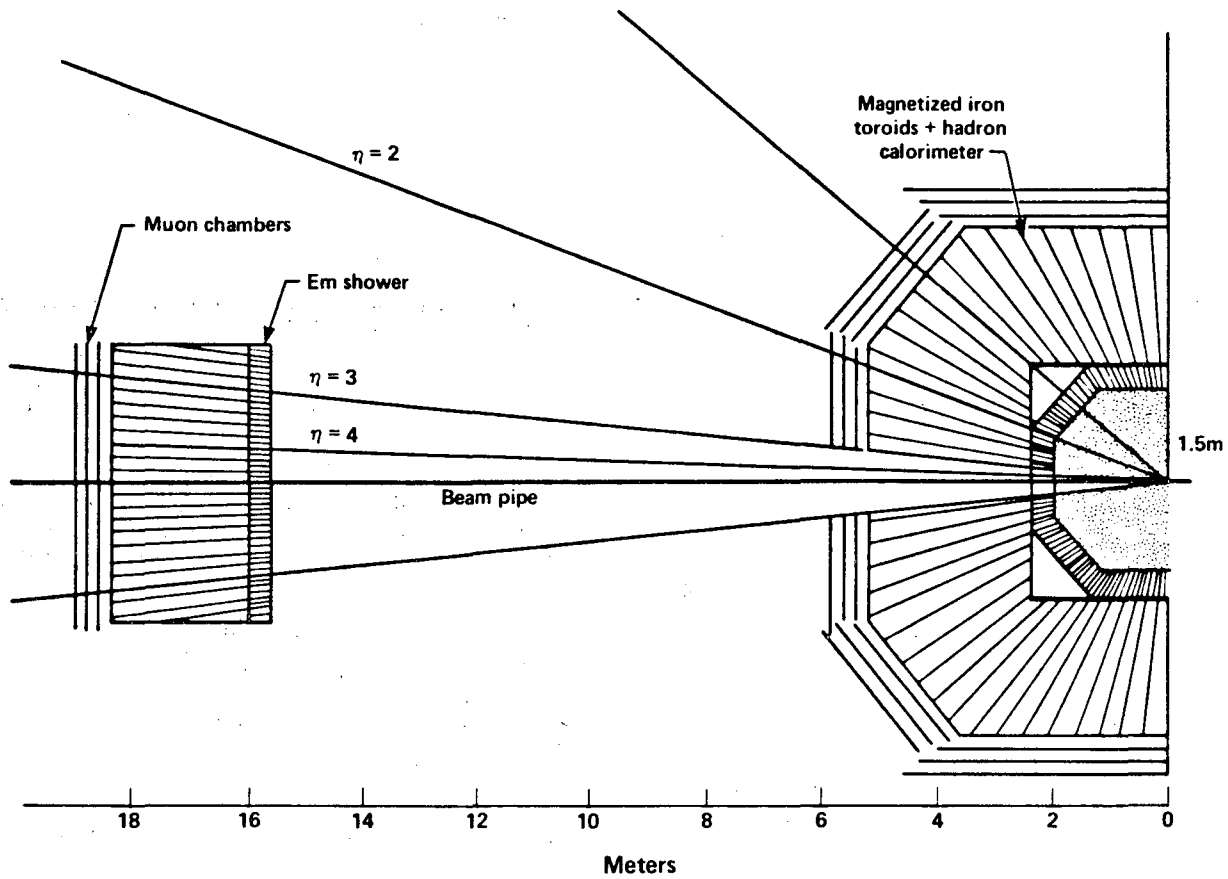
### Detector Systems

The systems group was charged with picking up all the details that were not considered by the other four working groups. They considered a wide variety of issues related to both high luminosity and high energy. The group considered the character of 20 TeV events and the general features of detectors for 20 TeV colliding beams. The nature of high energy jets has been discussed in a previous section. We turn here to consideration of the 20 TeV detectors.

Figure 14 shows one of the detectors considered by the group. The apparatus is designed to detect high  $P_T$  jets, taus and electrons,  $W^\pm$  and  $Z^0$  jets, and missing  $P_T$ . The design gives up muon momentum measurement above about 300 GeV and electron charge determination above approximately 50 GeV.

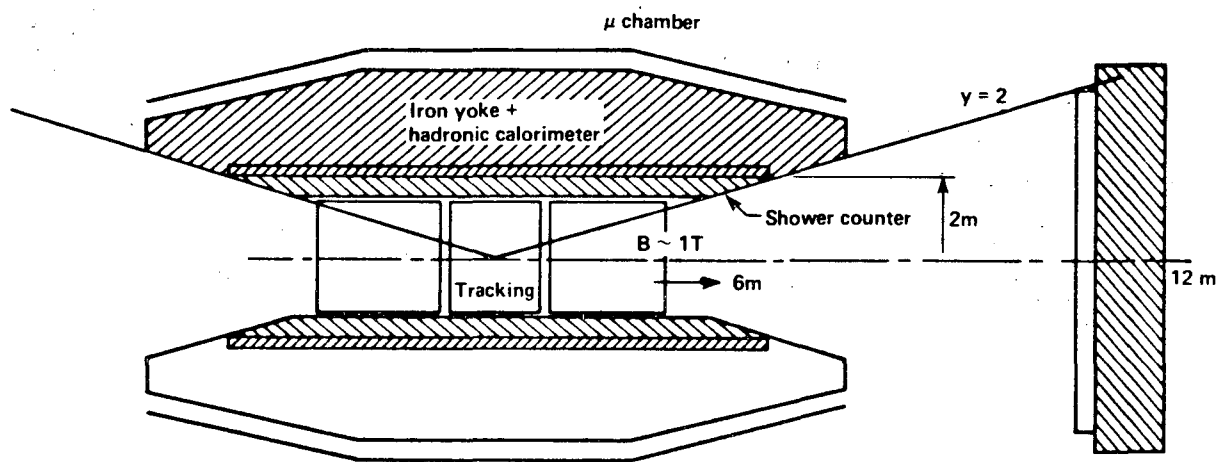
The  $4\pi$  hadronic calorimetry is done with small towers:  $\Delta y \sim 0.1$  and  $\Delta\theta = 40$ . The electromagnetic shower counters have finer segmentation a factor of 4 smaller in both dimensions. The central tracking is used to identify stiff particles, find the vertex, measure multiplicity, and identify T and W jets. The iron toroids are used to measure muon momentum. Because the hadronic and electromagnetic shower depths do not change rapidly with energy, this type of detector is very similar to a 1 TeV device.

20 TeV detector = (1.5 - 2) \* CDF



XBL 833-1440

Figure 14. Calorimetric 20 TeV detector.



XBL 833-1442

Figure 15. Solenoidal 20 TeV detector.

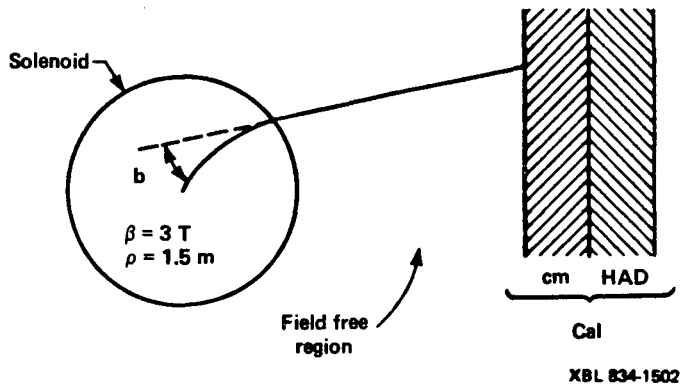


Figure 16. Momentum measurement by impact parameter.

A more conventional detector system is shown in Figure 15. The apparatus consists of 2500 towers in the central hadronic calorimeter, 10,000 towers at two depths for the electromagnetic calorimeter. The end caps contain 1250 channels of hadronic calorimeter and 5000 electromagnetic calorimeter channels at each of two depths. The tracking device contains approximately 10,000 wires.

A third alternative is illustrated in Figure 16. Particle tracking is done in the field free region outside the superconducting solenoid. Multiple scattering in the coil and uncertainties in the vertex position give rise to a  $\delta p/p$  of 5 to 10% at 1 TeV.

In general, the detectors for 20 TeV are not very different from those for 1 TeV. The principle difficulty is the large number of channels required to subdivide the detector into small segments.

The systems group considered the performance of completed experiments at high luminosity. This study defines the state of the art in dealing with high luminosity. There are four issues that need to be considered in this review.

- 1) Solid angle or acceptance must be translated to a "standard  $4\pi$ " collider detector.
- 2) Environments may be quite different.
- 3) Multiplicity varies with  $\sqrt{s}$ .
- 4) Open and closed geometries must be compared.

The conclusion from this review is that experiments have been limited to effective luminosities of the order  $5 \times 10^{30}$  to  $10^{31}$ .

The group also studied the effect of multiple interactions. No fundamental difficulties were uncovered. Although effects exist, the trigger for hard scattering will function satisfactorily. The measurement of leading partons can be made. In the case of tracking, determining the jet core should not be a problem, but the overall tracking will be difficult.

A subgroup considered the processing requirements for high luminosity experiments. It appears technically feasible to handle rates from a luminosity of  $10^{33}$  in terms of preprocessing and processing. A great deal of R & D effort is needed to provide the hardware necessary for flexible and powerful event selectors and data analysis systems.

A final topic was a cost estimate for a large general purpose detector for high luminosity. The group concluded that such a device would cost approximately 3.7 times the cost of the CDF detector. The total cost would then be approximately \$150M. The major cost component was the front end electronics needed to instrument the large number of detector channels. It can be expected that these costs will drop significantly in the near future.

### Conclusions

The workshop investigated many facets of detectors for hadron colliders at high luminosity and at high energy. The participants concluded that there are no fundamental limitations on the use of colliding beam facilities either at high luminosity or at high energy. Continued R & D effort will make significant contributions to the development of devices with better performance and for lower cost.

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### Reference

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