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Proposal for the Development of a Muon Sub-system for a Solenoidal SSC Detector

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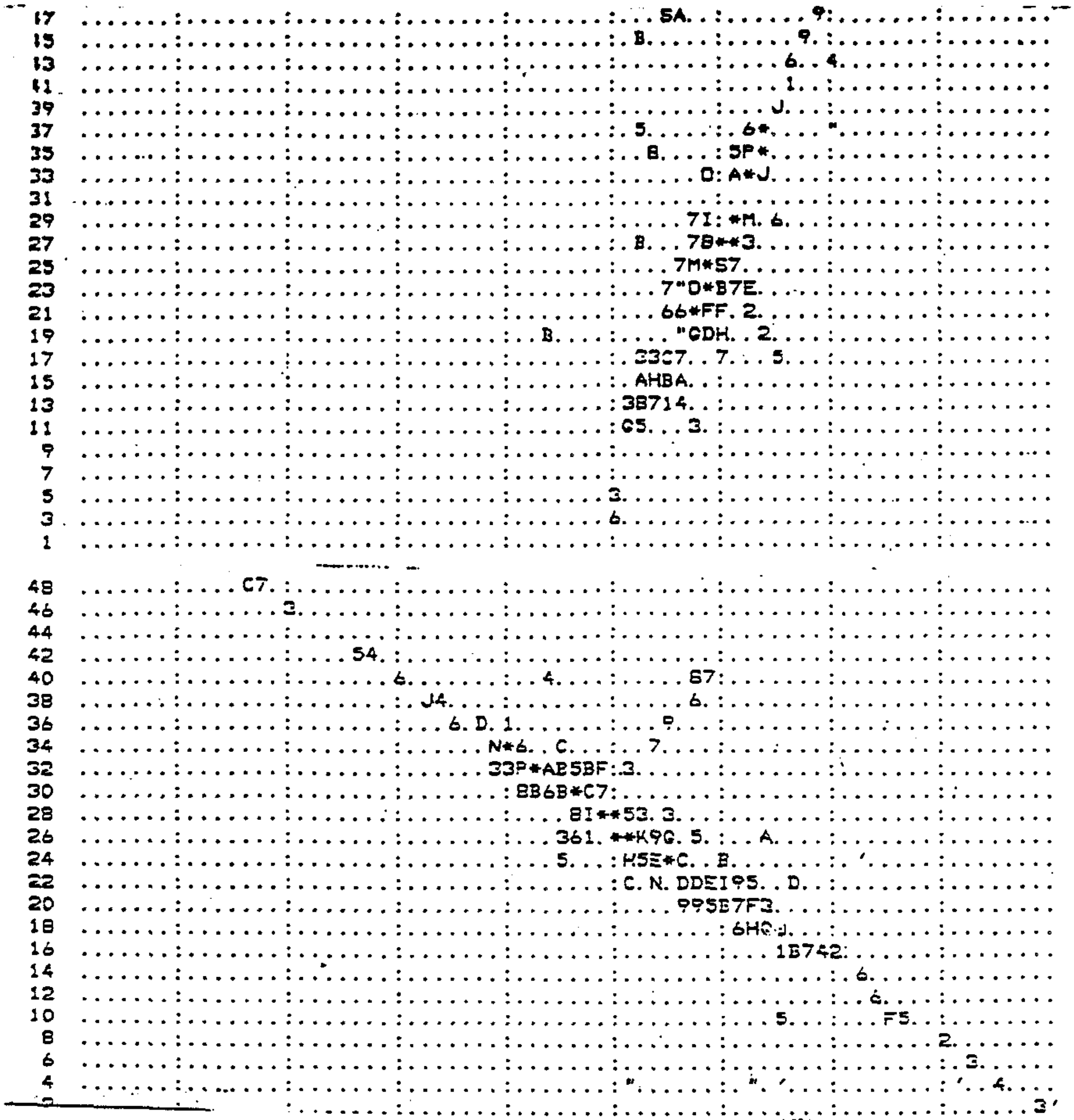
Figure 6. High energy muon bremsstrahlung measured in the Soudan I underground detector. Two views of the same event are shown. The numbers and letters represent pulse heights as measured by proportional tubes in an iron loaded concrete substrate. The height of the detector is 1.9m and the width is 2.9m. The average density of the detector is 1.9 g/cm^3 with a radiation length of 9.5 cm.



1 Introduction

Both experience from present collider and fixed target experiments and general considerations suggest that excellent muon detection and measurement will be fundamentally important for SSC experiments. Searches for new physics and new particles and tests of the validity of the standard model at the SSC will depend on reliable lepton detection and triggering.

A general purpose detector will need the flexibility and counting rate advantages which can be achieved by making 4-momentum measurements over a large angular acceptance and having fast, flexible triggering capabilities for both electrons and muons. We believe these requirements can best be achieved using a detector with charged particle tracking in a large solenoidal magnetic field, combined with electromagnetic and hadronic calorimetry, and surrounded by an external muon detector. In this proposal, we seek to conduct studies to optimally design the muon detection sub-system. The optimization criteria include reliable identification of muons, even those with nearby jets; a fast, programmable trigger with a sharp transverse momentum cut-off; ability to link tracks from the external muon detector to the inner tracker, even in the presence of background; independent measurements of muon 4-momenta; and, for part of the sub-system, effective operation in the high radiation environment associated with large pseudo-rapidities.

In addition to SSC studies at Snowmass and Berkeley, the proponents of this proposal have participated in design work as part of one or more of the large solenoidal detector proto-collaborations in both the U.S. and Japan. Some of us have worked on collider detectors such as Amy, CDF, CLEO, D0, Mark II, SLD and VENUS, thus gaining first-hand experience on issues which will affect an SSC solenoidal detector. For these reasons, we already have some understanding of the design criteria and of the ways of implementing an SSC muon sub-system design. Except as noted, our goal is to develop a muon sub-system which would be compatible with various tracker designs and calorimeter techniques. We also propose to explore the implications for the muon sub-system of various solenoidal coil options.

There exists a coupling between the muon sub-system and the remainder of the solenoidal detector. For small pseudo-rapidities, we expect to rely heavily on the central tracker for muon momentum analysis, both for triggering and for reconstruction, except in the forward direction where additional momentum analysis will be necessary. One outcome of our study will be a set of specifications for the angular coverage, resolution and signal speed necessary from the central detector to yield optimal performance on muons. The muon sub-system can likely compensate for a low resolution central tracker but at some extra cost. On the other hand, superb central tracker performance will likely permit a more modest central muon sub-system because hadron rejection can rely heavily on the quality of matching in angle, position and momentum between internal and external track segments.

Adequate muon systems at existing collider detectors typically account for 15-20% of the total detector cost. A subsystem of this magnitude will provide for independent muon tranverse momentum triggering, with the capability of an adjustable p_t threshold. We propose to explore a wide variety of possible muon detection sub-system design issues for a 4π solenoidal detector at the SSC, focussing principally on the design, performance and cost of a sophisticated and powerful SSC muon detection subsystem. However, we will also investigate the possibility of utilizing a significantly simpler muon sub-system with less capability.

The key elements of our proposal are as follows:

1. Investigation of detailed physics issues concerning muon detection, identification and measurement at energies ≥ 100 GeV. These questions include hadronic punch-through of passive absorber, leakage of neutrons and other soft products from the back of a calorimeter, other soft particle albedo, the effect of muon bremsstrahlung on precision position measurement and muon momentum resolution while tracking through iron. Although several workshop and study group reports already exist on these issues, we believe that a device as important and expensive as the solenoidal SSC detector should be based on a re-examination of all issues using reliable and verified data. We propose to survey existing measurements of rates and detector properties from original published and unpublished data. In cases where existing data do not cover the range of parameters expected at the SSC, we will conduct test beam measurements simulating the SSC environment.

2. Simulation and reconstruction of muons from interesting physics processes and associated background. To the extent necessary, we will validate and extend previous studies of muon rates, required resolutions, necessary background rejection, required pseudo-rapidity coverage, and techniques for resolution of high occupancy confusion. As part of this topic, we will do a cost-benefit study on the desirability of redundant measurements of muon momenta using both the central tracker and the muon sub-system.

3. Assessment of the amount and magnetic properties of iron needed for muon identification and trigger rate suppression. Is a non-magnetized iron muon system for the central region adequate when used in conjunction with data from the central tracking system? We will compare preliminary engineering designs for non-magnetic vs. toroidal and solenoidal ferric and superferric magnetic fields for the external muon sub-system in the central pseudo-rapidity region. For the forward region, we will compare preliminary engineering designs for ferric and superferric toroids. In addition, we will investigate the possible resolution improvements and the system integration questions associated with the use of air-core toroids for both the central and forward regions. We presume that detailed design and costing of air core toroids will be done by another sub-system design group.

4. Preliminary engineering design of muon detectors for the $|\eta| \leq 3$ pseudo-rapidity region. Issues include muon momentum measurement, hadronic punch-through rejection, detector alignment and muon sub-system integration. This item includes a detailed cost-benefit analysis of mature detection techniques such as

plastic scintillator and ionization drift detectors as well as the innovative use of detectors such as Cerenkov counters and resistive plate chambers.

5. In-depth studies of the design, construction and performance of the muon triggering systems for the central, intermediate and forward regions of the detector, including trigger rates and trigger efficiencies and front-end and trigger electronics. We also propose to study the possibility of using fast-track processors for muon momentum analysis in the central and forward tracking systems to implement muon p_t triggering over the entire pseudo-rapidity range of muon coverage. These studies will be carried out through simulation and explicit prototype detector, trigger and readout electronics development.

6. Study of the issues associated with muon detection and triggering for far forward muons ($|\eta| \geq 3$). If we conclude that such detectors are useful and attainable, we will complete a preliminary engineering design of these elements.

2 Physics Rationale

Muon detection at the SSC is extremely important because of the many physics processes in which high-p_t leptons (ν, e, μ or τ) are expected in the final state. Muon detection is complementary to electron detection because of lepton universality associated with the electroweak interactions. If new states of matter are discovered which couple to leptons, it will be important to confirm their discovery and measure their properties in as many different channels as possible.

1. Muon systems are robust. The high interaction rates and resultant high particle flux expected in experiments at the SSC can be reduced to acceptable levels for muons by use of sufficiently thick absorbers. This reduction is particularly important at small angles (large pseudo-rapidities) because of the high flux in this region. Thus, the technology needed for an SSC muon sub-system can be fairly conventional in nature when compared to that of either the central tracker or the calorimeter. We know that we can construct a workable muon sub-system at the SSC. We must choose an optimal design by improving our knowledge of the SSC environment and how detectors will respond in that environment. We thus need to study such issues as hadronic punch-through, calorimeter leakage of neutrons and other low energy secondaries, and muon bremsstrahlung at high energies.

2. Over a large momentum range, external muon tracking through iron and momentum measurement at the SSC will be multiple-scattering dominated. In this regime, measurement accuracies are approximately independent of momentum. This performance of an SSC muon sub-system may be compared with that of the central tracking system which degrades linearly with transverse momentum. For calorimetric measurements of electrons at high energies, the resolution improves with $\sqrt{E}$ together with a constant term of order 1-3 percent, provided that in-

creasing spatial overlap and particle multiplicity do not degrade performance as energy increases.

3. Muon identification and measurement are relatively unaffected by nearby hadrons and photons, so that muons unlike electrons, can be reliably measured within a jet. Although radiative corrections do affect muons, particularly in precision energy scale measurements, these corrections are generally smaller and certainly have different systematics from the radiative corrections for electrons. Furthermore, muons can be momentum analyzed by auxiliary magnetic fields even in those pseudo-rapidity regions where the solenoidal field provides little dispersion.

4. The addition of muon triggering and measurement capabilities doubles the acceptance for particles decaying to single and dileptons and quadruples the acceptance for 4-lepton events, since muon and electron rates for many interesting processes are approximately equal.

3 Schematic Muon Detection Systems

In this section, we describe the design criteria and give three reference designs for a muon sub-system. The purpose of the reference designs is to provide a scale for evaluation of detector performance, complexity and cost. We have chosen a tentative set of design goals for the muon sub-system, considering not only physics but also complexity and cost factors.

3.1 Design Criteria

Because of the geometry defined by the solenoid and its central and forward tracking systems, the muon detection system divides naturally into three parts based on pseudo-rapidity. The exact location of the transitions between regions and the nature of the forward regions depends on the detailed design of the solenoidal coil and the central tracking system.

In any design, the central region ($|\eta| \leq \approx 1.5$) is largest in laboratory solid angle. Here an external muon sub-system makes momentum measurements which are mostly redundant to those made in the central tracker. The expected rates in this region after a calorimeter and a few meters of iron are of order 1 kHz or less. In the intermediate region ($1.5 \leq |\eta| \leq 2.25$), the muon system momentum measurements augment the central tracking momentum measurements. The central tracking system resolution degrades in this region as $L^2 \sin^2 \theta$, where L is the tracker radius and θ is the angle from the beam. The particle flux and area of muon coverage in this region are both moderate. For the forward region ($2.25 \leq |\eta| \leq 3.0$), the muon system provides unique momentum and angle measurements in an environment with an expected flux of order 10^5 Hz after several meters of absorber. We will not discuss here the far forward region ($|\eta| \geq 3.0$), which has received little attention in both the literature and our previous studies.

The discussion of the muon sub-system in terms of pseudo-rapidity regions raises the controversial question of whether the same detector technology should be used in each region or different technologies should be employed to better match each region's characteristics. The argument on one side is that attempting to understand the systematics of several different detector technologies severely compromises the extraction of physics results. The rationale on the other side is that different detector technologies will better match the environments at different pseudo-rapidities than one compromise technology. We expect to study this question in detail, based in part on the experience of actual detectors such as CDF and D0, as part of the proposed sub-system design.

For the purpose of giving concrete examples for this proposal, we will limit our consideration to the use of external ferric or superferric magnets in the central region. As part of the proposed study, we will determine if air core toroids in the central pseudo-rapidity region contribute capabilities which could justify their additional cost. We will consider the use of both air core and iron core toroids, as well as other magnet configurations, for the intermediate and forward regions.

1. Z^0 **Detection:** The Z^0 will be a fundamental part of the signature for many interesting reactions at the SSC. The identification of $Z^0 \rightarrow \mu^+\mu^-$ depends on its unique topology, as demonstrated by both CDF and UA1. Maximal separation from background can be achieved if the dimuon mass resolution allows the reliable identification of the Z^0 and then the Z^0 mass constraint is used for further analysis. The detector must be capable of finding $H \rightarrow Z^0Z^0$ with both Z^0's decaying to muons. Fig. 1 (a) and(c) shows an example of how this signal depends on the momentum resolution of the muon. This study [1] concludes that a $\Delta p_t/p_t = 0.5p_t$ measurement is sufficient to extract the signal for a Higgs' mass up to 400 GeV, even without applying a Z^0 mass constraint. We will, of course, repeat this study including the Z^0 mass constraint. Fig. 2 shows the resolution of several possible detectors as a function of Z^0 momentum [2]. The five resolution curves represent the attained (CDF) and expected (FAST, SDE, Fe toroids, L3+1, and electromagnetic calorimetry) momentum measurement accuracy. The quantitative resolution assumption for each case is indicated on the graph. Both the CDF and FAST trackers use knowledge of the interaction vertex position (i.e. beam constraint) to achieve the resolution shown. (Of course, it is likely that any detector will use the beam constraint to maximal advantage, since it is essentially free.) The horizontal axis indicates the total Z^0 momentum. (The resolution depends little on the Z^0 angle with respect to the beam direction.) The 5 m ferric toroid curve is applicable only if multiple scattering dominates the momentum resolution. If tracking errors make a substantial contribution, the momentum measurement accuracy in this case is worse. (The resolution for 3 m ferric toroids is $\approx$ 40 percent worse; the resolution for superferric toroids might be better depending on the magnetic field.) Angle error contributions to the dimuon mass resolution are not considered in these curves. For reference, the natural width of the Z^0 is also shown.

2. Z'^0 **Search:** The search for the decay $Z'^0 \rightarrow \mu^+\mu^-$ will be optimized if the

dimuon mass resolution is equal to the natural width of the Z'^0. Since Z'^0 masses up to ≈ 6 TeV could possibly be produced at a detectable rate, the momentum precision requirements are stringent if the Z'^0 turns out to be at least as narrow as shown by the curve in Fig. 3 for standard model coupling [3]. Of course, a discovery of the Z'^0 requires only a significant peak over a very small background, so a less stringent momentum resolution is required. Fig. 3 also shows how nearly this resolution goal might be approached for various detectors.

3. **Measurements of States With W Bosons:** The experimental signature of final states containing W bosons is more difficult to recognize than that of the Z. Only the charged lepton (e or μ) will be detected, while a ν carries off missing energy and momentum. However, the cross-section times branching ratio is typically an order of magnitude larger for the W than for the Z. So the SSC will be a copious source of W bosons, some of which will be identifiable. In contrast with LEP or SLC, the SSC will produce large quantities of both W's and Z's. One design criterion for the muon sub-system is to minimize systematic uncertainties for a precision W/Z mass ratio measurement, as well as for width, decay asymmetry and magnetic moment measurements of the W and Z bosons. These data can lead to better measurements of $\sin^2\theta_W$, ρ and structure functions.

4. **Stable/Exotic Particle Search:** At the energy and design luminosity of the SSC, the mass discovery reach is such that searches for heavy stable/exotic particles are feasible up to masses of several TeV (see e.g. [3]). The experimental signatures expected for the production (via gluon fusion) of a broad class of very massive charged stable particles are: they are very penetrating, like muons; they are expected to have a p_t of order 1/2 their mass; they may be fractionally (e.g. 1/3, 2/3, 4/3, etc.) or multiply-integrally charged. Because these particles are so massive, their velocities are also expected to be measurably less than c. In order to distinguish these particles from muons, time-of-flight measurements with ≤ 1 nsec resolution over a several meter flight paths are needed. If these particles are other than singly charged, calorimeter information at the sub-minimum ionizing level or dE/dx information at similar thresholds will be crucial. Flight time, charge and momentum information are all needed to determine the mass of such particles, if they are to be discovered at the SSC.

5. **Angular Coverage:** The Monte Carlo simulations of Carlsmith et al. [4] indicate that overall acceptances averaged over several typical benchmark reactions have the approximate values shown in Table 1. This table shows that a muon detector of 30° minimum angle has poor acceptance for multimuon final states, even though it covers 0.87 of the solid angle. Acceptance down to $\approx 5°$, $|\eta| = 3$ is clearly required. Conventional considerations suggest that muon identification and measurement at $|\eta| \geq 3$ is of marginal value, although we intend to investigate this question further as part of this proposed sub-system design study.

6. **Muon Triggering:** The detection of single muon signals (from, for example, W decays, pair production and decays of heavy quarks as well as muon stud-

Table 1: Fractional acceptance for single and multimuon events as a function of the forward detection cut-off angle.

		Acceptance		
Minimum Angle	η	Single Muons	Dimuons	4-muons
30°	1.32	.5	.3	.2
10°	2.44	.7	.7	.7
5°	3.13	.8	.8	.8

ies of detector performance will require a single muon trigger, set at the lowest possible p_t and possibly combined with other trigger criteria. Similarly, an efficient dimuon trigger is required in order to detect muons from the Z^0, heavy Z's, Higgs particles, W^+W^+ pairs, etc. These triggers can be achieved using information from the muon sub-system in conjunction with fast track information from the central and forward tracking systems. (For example, CDF uses a track processor, which helps sharpen momentum/mass thresholds.) Calorimetric information on minimum ionizing (or less) energy deposition in the calorimeter tower associated with a muon candidate could also be used at the trigger level. (Such a technique would be useful for a stable exotic trigger.) The muon trigger should be designed for maximal sharpness in both effective mass for dimuons and p_t for single muons. If sharp p_t cuts are not possible, the trigger rate will be dominated by low mass and low p_t events with low trigger efficiency but high intrinsic rates. The time required for developing the muon trigger should be of order 1 μsec in order to keep the size of the dynamic storage pipeline required for event data reasonable.

7. **Timing and Occupancy:** The reconstruction complexity for SSC events can be greatly reduced by detectors which can resolve the 16 nsec SSC bunch crossings. We seek to design a muon sub-system which will have this capability. It may even be possible to use high precision drift detectors without such timing accuracy, if the occupancy is sufficiently low that the other fast part of the muon sub-system can uniquely associate the drift information with a particular bunch crossing.

8. **Cost:** Real designs must be based on both technical and economic considerations. We believe that the maximum cost of a muon sub-system is already known to some accuracy. The real challenge is to maximize the physics capabilities of the muon sub-system, given this relatively fixed cost. Our proposed design study thus requires an evaluation of trade-offs. This philosophy will underlie all of our proposed analyses.

3.2 Reference Designs

We describe here three reference designs for the central pseudo-rapidity region. These designs are not intended to be complete, exclusive or to be taken as a practical muon sub-system. Rather, they indicate some markers on a continuum of possible "straightforward" designs. These designs are cumulative. The "Trigger and Tracker" design includes the "Minimal Trigger" system. The third schematic "Trigger and Tracker With Momentum Analysis" includes the first two.

1. **Minimal Trigger Only.** The minimal muon sub-system in the central region consists of 3 m of iron outside the calorimeter (or perhaps less iron and Cerenkov counters) and several layers of plastic scintillator, each with 1,000 to 2,000 (depending on the detector radius) individual scintillators. These layers would be interspersed through the iron in a projective geometry, with a scintillator size of roughly 1 m^2 in the outermost layer. Approximately 1 m of iron would be used for the solenoidal flux return, while the additional iron would be solely required for hadron absorption by the muon sub-system. Fast pattern recognition electronics would use the scintillator signals to define a crude "roadway" through the iron back to the interaction point. Most cosmic ray events and slow neutron background hits would be rejected at this point. The trigger criteria could be set loose enough to permit triggering by sub-minimum ionizing and slow particles so as to implement a stable exotic search. The trigger "roadway" would then be used to select a region of the outer superlayer of the central tracker for further examination. The inner tracker signals from this region would then be used to compute a transverse momentum for any track stub found in order to make a trigger decision. High-precision, off-line momentum determination for muons would use all of the information available from the inner tracker and the solenoidal magnetic field map.

   From the rates of muons at the SSC calculated at Snowmass 86 [5], shown in Fig. 4, we estimate that the rate outside the calorimeter and beyond 3 m of iron will be less than 10^5 Hz, in the 5° to 10° region, and less than 10^3 Hz at larger angles, comparable to or less than the the cosmic ray rate. This rate is already low enough to allow time for complex electronic logic. The scintillation counter dimensions are chosen to obtain both low counter occupancy and an intrinsic time resolution considerably better than the 16 nsec benchmark time.

   The experience of CDF is that the muon momentum threshold for an external momentum measurement is not sharp, due to multiple scattering in the calorimeter and the iron solenoid yoke smearing the angular resolution. For that reason, the muon trigger will use central tracker information to impose a sharp lower cut-off on the muon transverse momentum. Most interesting SSC physics processes yield muons with $p_t \geq 20$ GeV. The calorimeter plus added steel naturally provide a cut-off at 10 GeV. A possible strategy is to use a 100 GeV/c p_t threshold for a single muon trigger in combination with a lower p_t threshold when a muon appears coincident with other interesting activity in the detector.

   The advantages of this minimal approach are clearly simplicity and low detector element cost. The disadvantage of this minimal system is a lack of redundancy and the resultant ability to function well even in adverse circumstances. Nonfunctioning scintillation counters introduce a "dead" region in the acceptance. The muon sub-system is completely reliant on the central tracker, which may complicate system integration. This design does not permit early, independent operation of the muon sub-system. Most difficult to evaluate is the possibility of accidental coincidences and confusion from other tracks. The muon portion of the trigger is satisfied by a few hits—not a clear track. For some fraction of events, the central tracker will have unrelated hits in the relevant region, possibly a sufficient number of such hits that extracting the transverse momentum of the track stub is unreliable. This problem may be particularly acute if there is an appreciable calorimeter albedo.

The cost of this design is dominated entirely by the acquisition, support and installation cost of the iron. The total iron mass in this design depends crucially on the detector radius but is of order 25 ktons. The likely cost of this sub-system is a few times 10^7 dollars. All costs associated with the scintillation counters (including plastic scintillator, photomultipliers, high voltage, discriminators, mounting, etc.) are small compared to the cost of the iron and its support structures.

2. **Trigger and Tracker.** The second reference design is to augment the system described above with some tracking chambers embedded in the 3 m of iron. The purpose of such chambers would be to establish the existence of a consistent track through the iron. Establishing such a track offers considerable advantages for muon identification and momentum measurement. Defining a track will improve hadronic punch-through rejection by measuring the amount of "wander" in the iron. This parameter, if the particle is a muon, gives a crude momentum determination from multiple scattering, which can be compared to the central tracker momentum determination. It will also help determine which of the track stubs in the central tracker is actually a muon. Finally, tracking through the iron will provide redundant rejection of cosmic rays and insure that no unexpected process defeats the logic of the scintillator trigger system.

   This design entails additional costs associated with segmenting and supporting the iron, as well as costs for drift chamber or drift tube construction and electronics. These costs are likely not to exceed a 25 percent increment to the cost for the minimal muon sub-system described above.

3. **Trigger and Tracker with Momentum Analysis.** A more complete system adds to the "Trigger and Tracker" a magnetic field in the iron and sufficient spatial resolution to independently determine muon momenta. Since the gain in resolution of an iron tracker increases only as $\sqrt{L}$, additional iron may be required. An additional major expense is a support system with sufficient rigidity to insure systematic chamber positional stability of a few tens of microns and a calibration system to determine and monitor chamber positions. There are also smaller additional costs associated with the larger number of drift chambers required for momentum analysis and for the coils required to magnetize the iron. In all, this system costs perhaps 3 to 4 times the cost of the minimal system, likely between 5×10^7 and 10^8 dollars.

   This muon sub-system has several advantages. It would be capable of independent operation. Ideally, reconstruction and perhaps triggering could use two independent determinations of the muon momentum. The identification of muon tracks in the central tracker, even those embedded in jets, would be more certain, because matching from the inner detector to the outer detector could be done in position, angle and momentum space. Hadronic punch-through rejection would also be further enhanced by a high-precision tracking and momentum measurement through the iron. Finally, redundancy always provides hopefully unneeded, but certainly reassuring, insurance against a difficult start-up for the central tracker.

The inner tracker is likely to produce a better momentum determination than the muon sub-system for muons in the central pseudo-rapidity region with momenta less than 500 GeV. These particles comprise the bulk of those muons which are expected to be of interest. For higher energy muons, the momentum resolution of the muon sub-system will depend crucially on its systematic positional accuracy.

All of these muon sub-systems could be constructed. We believe that "Trigger and Tracker with Momentum Analysis" is likely the best solution (Fig. 5). However, we expect an optimal design solution to emerge from the program of investigation described in this proposal. In addition, such "straight-forward" solutions do not even exist for the study of muons at forward pseudo-rapidities.

4 Proposed Work

We propose to develop a muon detection system and trigger which can resolve single bunch crossings, which is nearly 100% efficient for triggering above a cut-off transverse momentum between $\approx$ 20 GeV/c and 100 GeV/c, and which, with high efficiency, rejects lower p_t muons. This system will reject hadrons at the level of 10^5 and will achieve a rate of less than 1 Hz for single muons above 100 GeV transverse momentum. Lower p_t triggers at rates up to 1 kHz will be mixed with other requirements, such as a dimuon or a high p_t jet from the calorimeter, to achieve an overall trigger rate of $\approx$ 1 Hz.This external muon sub-system should also provide a useful measurement of the muon angle and momentum, independent of the central tracker.

We expect to complete the work described below over a period of three years commencing with the funding of this proposal. We intend to integrate our results from these studies into the plans of the large solenoidal detector collaboration. We will also disseminate our results generally throughout the elementary particle physics community.

4.1 Task 1: Simulations, Rates and Backgrounds

4.1.1 Task 1.1: Install and Maintain Simulation Code [Minnesota]

A major task for the initial period of the proposed work is to perform the simulations and calculations required to insure the integrity of the conceptual design efforts. We believe that the most of the required simulation tools already exist. However, a first step is to insure that a consistent set of such programs are distributed and operating properly in all of the collaborating institutions which require them. Argonne National Laboratory has established a simulation group which will provide the tools to us. They will also provide an exchange mechanism for future code development. The work under this task is to establish a liason with ANL and coordinate simulation code installation in the muon sub-system collaboration.

4.1.2 Task 1.2: Simulations [Colorado, FNAL, Illinois, KEK, Michigan, Minnesota, Northern Illinois, Osaka, Wisconsin, SLAC/Harvard]

The design of a muon detection subsystem for use at 40 TeV poses many new challenges. While specific measurements may be necessary, a crucial facet of our design program is the development and full exploitation of sophisticated simulations.

The fundamental techniques of muon identification are well established and familiar. Their extension to SSC energies, however, is not trivial, and extensive studies will be necessary in order to construct an optimal design. The energy-loss mechanism of muons grows increasingly complex as the energy reaches hundreds of GeV. Muon bremsstrahlung becomes an important effect, challenging the conventional assumptions that muon trajectories can be simply extrapolated, and that muons will be detected as clean isolated hits (Fig. 6). Thus, one set of questions about our conceptual design which we will answer with simulations are topics such as the number of stations required for muon identification and measurement, the number of measurements required at each station and the amount of iron between stations required to reduce shower correlation at adjacent stations to an acceptable level.

While the backgrounds to detected muons are the familiar ones–hadronic decays in flight and punch-through–the details are more complex. Extensive hadronic showers produce many secondaries which may penetrate to the muon system. It is also likely that a large flux of neutrons will become a significant component of the background. We will simulate the ability of our conceptual design to identify and measure muons in the presence of this background. Such background can come both from the interaction region and from ambient radiation.

The identification of muons among high-multiplicity jets of particles is another major challenge. An independent momentum-determination capability in the muon detector will specifically address this problem, but simulation studies will be necessary to determine the required performance and whether the proposed sub-system can deliver such performance. Finally, the specific requirements for constructing a clean and efficient inclusive-muon trigger must be determined.

These questions pose general challenges to all techniques for muon detection, and specific ones to particular designs. We must have simulation strategies which are suitable to address all of the problems. Fast calculations, based on physics generators with highly idealized detector models are the first requirement.This software will allow us to determine general design features. Much work of this type has already been performed. These studies have been reported in the proceedings of the SSC workshops at Berkeley in 1987 and at Snowmass in 1988, and elsewhere. The next step is to produce calculations which are based on detailed interaction simulations, but which use simple generalized geometries. The final stage, of fully detailed modeling of real physics in realistic detectors, will be essential for finalizing the details of the detector design.

We plan to rely heavily on existing simulation tools, and to cooperate closely with other SSC simulation efforts. Software systems for generating multi-TeV physics (ISAJET, PYTHIA and PAPAGENO), for constructing specific geometries and managing track propagation (GEANT), and for simulating electromagnetic (EGS, GEANT) and hadronic (GHEISHA and others) processes in detail are all well established. Programs for the complete modeling of detectors for the SSC are currently under development in SSC detector study groups and will be available in the near future.

The computing requirements of these simulations are enormous. A major challenge will be to devise techniques for accelerating the simulation process. Following all particles (and their showers) of a single event through the detector until the complete response has been determined has been estimated to take anywhere from one to seven days of VAX 780 cpu time, an intolerable time except with the largest available computers. These computation times are dominated by the development of showers in absorber. Acceleration and optimization of shower simulation codes are important to facilitating these studies.

A comprehensive program of SSC simulations presents several levels of computing requirements for this collaboration. Small-scale generator computations can be performed on member institutions' present computers. More detailed studies of simple detector geometries can be conducted on low-cost high-speed scalar machines, such as RISC-based workstations. Full simulations of real events in realistic detectors will require the use of powerful vector processors, or perhaps of massively parallel systems presently under development. We estimate that a minimum of 1000 hours of Cray-2 CPU time (budget item 7.2) or the equivalent will be required for detailed simulations necessary to complete this study.

4.2 Task 2: Detector Technical Development

4.2.1 Task 2.1 Drift Modules [Michigan, Tsukuba, Tufts, Wisconsin]

The conventional approach to muon tracking is the use of drift chambers or tubes. Generally, drift detectors deliver excellent spatial resolution over a large area at low cost. We will begin here by surveying the experience with drift modules in previous collider detectors to insure that we have not missed some important aspect prior to our conceptual design.

The more extensive work under this task is to design and prototype vector drift modules. These modules are ones in which the anode wires are arranged in order to minimize the calculations required to determine whether a track points back to the interaction region and whether it has sufficient momentum to trigger. Such an arrangement implies different drift cell sizes at different distances from the interaction region. We then need to evaluate the implications of such differing cell geometries on drift time magnitude and linearity and on charge collection efficiency.

4.2.2 Task 2.2 Fast Time Response Elements [Illinois]

Fast time response detector elements are crucial to muon sub-system triggering. We propose to investigate several such devices. One possibility, in addition to scintillator, is resistive plate chambers. These devices generally have a gap of order 1 mm between two highly resistive plates (materials such as epoxy paper circuitboard). A many kilovolt potential is established across the gap using an external power supply. The inert gas filling the gap may be at high pressure. An ionizing particle crossing the gap initiates a electrical discharge between the two plates. The size of the discharge is limited by the high resistance of the plates. The presence of the discharge may be detected with less than 1 nsec time resolution.

We propose to build several small chambers and to test their performance on both muons and hadrons. Another issue which we will investigate are the system integration implications of using these chambers. Such questions include whether electromagnetic interference generated by the RPC's will adversely affect other detector elements. We will also investigate the possibility of using a variety of plastic scintillator and plastic Cerenkov devices.

4.2.3 Task 2.3: Aerogel Cerenkov Counters [Northern Illinois]

An alternative to gas Cerenkov is Cerenkov counters fabricated with aerogel. Such counters have all the advantages of a gas-filled Cerenkov counter, but they are also much more compact because of the higher index of refraction of the aerogel. On the other hand, aerogel is a much more difficult material to utilize because of clarity, stability and cost problems. We propose in this task to initially procure several aerogel counters and to measure their efficiencies for muons and (possibly) low energy hadrons. We will also measure the background counting rates of these counters near the E-789 beam dump at Fermilab. During the second year, we would install some aerogel counters into the D0 experiment and evaluate their performance. If we find positive results from these studies, we would then do a conceptual and preliminary engineering design for the use of aerogel counters in triggering a solenoidal SSC detector, particularly in the high rate, high momentum forward pseudo-rapidity region.

4.2.4 Task 2.4 Gas Cerenkov Counters [Colorado]

Gas Cerenkov counters may have many advantages for detection and measurement of muons in the forward and perhaps in the central pseudo-rapidity region. Because of the highly directional nature of Cerenkov light, it is possible that such a system will only trigger on muons which come from regions near the collision point. This capability may provide a real time, clean, and accurate trigger for the detection of high mass states. To determine the feasability of this concept, we would need to parameterize the variation in the muon direction as a function of the particular location in the periphery of the detector and develop suitable optics to collect the Cerenkov light.

A schematic concept is the use of nitrogen-filled, atmospheric gas Cerenkov counters about 1.5 m long. Such devices have a threshold energy for muons of ≈ 6 GeV and are fully efficient at 9 GeV. The light angle relative to the particle direction is less than 25 mr. If the total frontal area of these counters is $\approx 2000m^2$, the entire system would require about 2000 5 inch photomultiplier tubes and 8000 aluminized mirrors with reasonably good directional properties.

4.2.5 Task 2.5: Scintillating Fibers, Silicon Detectors and Straw Detectors [Arizona, Rochester]

Several other sub-system proposals focus on the development of tracking detector technology for the central tracker of a solenoidal detector. The proposed technologies include scintillating fiber, large-area silicon detectors and straw tubes. Some or all these technologies may be suitable for external central and forward muon detection. Particularly for forward pseudo-rapidities, the context for muon detection (high rates, small areas, good resolution requirements) are not all that different from that of the central tracker.

The scope in this task is to provide a liason channel with those persons in other sub-system groups who are developing these technologies. In addition, this task includes the consideration of these findings in terms of the particular requirements of the muon sub-system and possibly some prototyping.

4.2.6 Task 2.6 Test Beam [FNAL, Illinois, Minnesota, Rice, Washington, Wisconsin]

A thorough understanding of the interactions of muons with matter is required to optimize the muon momentum measurement strategy. In addition, knowledge of the development of hadronic showers will assist the optimization of muon identification for both isolated muons and those embedded in jets. The particular issues of interest in hadronic shower development are "punch-through" of minimum-ionizing particles and the production slow neutrons and other soft particles ("albedo") out of the calorimeter and hadron absorber.

Our initial approach to these questions is that the required data exist in either published or unpublished form and that currently available simulation programs are generally accurate over the range of interesting parameters. A possible exception is the problem of soft particle flux. Most cascade calculations do not follow particles down to the energies we require because of the large amount of computer resources needed for such calculations. However, we are ready to do test beam measurements, if our review of the existing data indicate that a test beam run might be required to resolve some questions.

If so, we propose to built a small muon detector to study problems associated with tracking high energy muons through various thicknesses of absorbers. We may also investigate background problems associated with hadron absorbers in a test beam set-up. The size of the required system will depend on the questions to be studied and the possibility for prototyping a section of a nearly-final SSC detector.

We will likely use the Fermilab E-665 muon beam for these tests. The E-665 beam is normally tuned to mean momentum of 500 GeV/c, with a FWHM of 120 GeV/c. The expected beam intensity for the 1990 run is 1-2 MHz. The flux above 700 GeV/c is more than 100 Hz. Thus, the FNAL muon beam is well matched to momenta expected for interesting secondary muons at the SSC. We presume that data from the E-665 spectrometer will be available to tag incident muon momenta.

The experimental apparatus required for these beam tests will depend on the questions to be answered. However, the configuration is likely only a few tens of cm in each direction normal to the beam axis. In addition to several measuring stations, the set-up will likely include a block of magnetized iron. Standard off-the-shelf electronics will be used as much as possible to minimize set-up and shakedown time.

With even a minimal system, we can determine the effects of electromagnetic showers on our ability to measure muon track coordinates. These tests will give us a calibration of our simulation and allow us to tune the parameters so that we can do a definitive study for the final design. We can also test the effect of magnetized iron on the efficiency of muon pattern recognition.

The 1992 and later Fermilab fixed target runs will provide opportunity for beam tests of prototype sections of the actual SSC detectors and trigger systems. It is yet too early to specify any particular parameters of such tests, although they are likely to be similar in beam requirements to the early tests described above.

4.3 Task 3: Central Region Detector

Since almost all colliding beam detectors have muon systems which differ substantially, we plan to begin our efforts by examining in detail the performance of each of these systems. We are already very familiar with several such muon systems (CDF, D0, Mark II, AMY, SLD, VENUS and CLEO) but believe a complete and systematic survey of all available data, including fixed target muon and neutrino experiments and underground muon detectors, (published and unpublished) is preferable to redoing what has been done. Of course, no existing detector will have all the characteristics necessary for the SSC. However, there are valuable lessons in re-examining these previous combinations of muon identification, tracking, and magnetic field configuration. Personal interviews with several muon experts from each detector and analysis of existing data with the SSC in mind will probably open many avenues which were not obvious. This exercise will also alert us to possible problems.

After a systematic investigation of existing systems, we will simulate them to assure that our simulation program reproduces the detailed behavior of each system. In particular the reaction of these detectors to the soft tails of electromagnetic and hadronic showers will be important since this behavior will contribute to the efficiency of an SSC muon trigger. Here we are especially concerned with albedo from the inside face of the calorimeter and well as the leakage from the outside of the calorimeter. It is important to understand the details of the very low energy results of showers from the measurement program described elsewhere in this proposal. We will then use this simulation to test the most likely configurations appropriate to the SSC.

We will prototype the detectors that have the desired characteristics to determine ease of large scale construction, mechanical and electrical robustness, ease of alignment, and long term operating characteristics. In addition to configuring scintillation counters and drift modules, we also expect to prototype, on a small scale, more novel devices such as Cerenkov counters and resistive plate chambers. We emphasize that we expect to prototype only a very limited range of detectors, perhaps two scintillation counter configurations, two drift module designs, and one novel application of a detector, which have survived our previous evaluation procedure.

4.3.1 Task 3.1: Conceptual Design [FNAL, Illinois, KEK, Minnesota, Rice, SLAC/Harvard, Tsukuba, Tufts, Washington, Wisconsin]

For the purpose of this proposal, the central region of the detector is defined as that region in which the solenoidal field dispersion as measured by the central tracker yields a transverse momentum resolution of at least 10% at 500 Gev (typically $|\eta| \leq\approx 2.0$). To achieve our goals, we envision that the muon system will include scintillation counters, Cerenkov counters, RPC's or other devices fast enough to define the time bucket of the muon, an external angle and momentum measurement sufficient to reject hadronic punch-through, and a fast tracking device inside the calorimeter to determine the impact parameter of a muon from a track stub. This device could be the outer superlayer of a central tracker or, possibly, a special muon sub-system layer. A fast inner tracking device with a radial extent of 10 cm and a resolution of 600 microns could provide a sharp momentum cut off up to 100 Gev at a radius of 1.8 m from the interaction region with a 2 T central field. The scintillation counters, arranged in either theta, phi projections or pixel towers, give the first indication that a particle penetrated the iron. Additional information from the inner track device, the muon drift modules or the scintillator tower geometry is necessary to reject cosmic rays by pointing potential tracks to the interaction region. A comparison of momenta determined in the inner device and outer muon tracker will be able to reject punch-through and determine the momenta of muons in jets. From various summer studies and working group efforts several detector configurations appear possible. It will be the goal of this proposal to give a cost benefit analysis of those systems which will satisfy the muon sub-system requirements. A schematic of such a system is shown in Fig. 5.

4.3.2 Task 3.2: Preliminary Engineering Design [FNAL, Michigan, SSC]

Depending upon the final thickness chosen for the iron absorber in the muon subsystem (2 to 5 meters most likely) and upon the actual size of the inner detector/magnet configuration, the required mass of iron will lie in the range 20 to 50 thousand tons. This large mass has implications for the full detector system. Mechanical support, floor loading, and surveying are all aspects which should be given full consideration at a very early stage of design.

A simplistic estimate of floor subsidence due to this mass can be obtained from the modulus of subgrade reaction (spring constant), which has typical values in the range 50 to 500 ton/cubic ft. for various types of sands and clays. From this, we can estimate a likely overall subsidence of 0.1 to 1 inch, depending upon the flexibility of the concrete footing, moisture content of the earth, etc. Deflections of this magnitude are of serious significance for the central detector components, some of which may require surveying to accuracies of a few microns (in the case of a silicon strip system, for example). Such deflections will also be of significance to the SSC itself.

Consultation with professional civil and mechanical engineers is required for a preliminary consideration of these problems at the earliest stages of design. The concrete footing for the detector will require specialized design, and should be incorporated into the overall design of the experimental area. It is likely that equipment surveying will be a continual process, as the earth is likely to consolidate gradually with time. Some experience has already been gained with existing large detector systems. The various surveying techniques already developed should be reviewed.

The support system for the muon system itself will be massive, leading to possible difficulties in installation and later access to detector components, although by appropriate design the iron could presumably be made self-supporting.

4.3.3 Task 3.3: Prototyping

The eventual goal of this sub-system design is the protytping of a large section of our eventual detector to provide a test of both fabrication procedures and performance. This prototyping task will likely commence during the second year. Most of our efforts during the third year will be directed towards this prototyping task. We will develop more definite proposals concerning prototyping as part of the conceptual design phase, which will be the focus of our first year's efforts.

One possible way to test the behavior of the central muon tracking and triggering subsystem is use of a cosmic ray test stand similar to that which has proved so useful in testing the D0 muon system. (The existing D0 test system may be modified for this purpose.) This test stand would contain all of the devices of the candidate muon system including magnetized iron covering an area of approximately 6m x 6m to insure adequate cosmic ray rate and enough complexity to test system integration effects of electronic signals.

4.4 Task 4: Forward Region Detector

4.4.1 Task 4.1: Conceptual Design [Arizona, Colorado, Illinois, Minnesota, Northern Illinois, Tsukuba]

Considerations of momentum resolution and triggering for forward pseudo-rapidities are similar to those in the central region. Previous studies have indicated that for Higgs→ZZ channels, one needs a momentum resolution better than 20% for muons with a transverse momentum of 500 GeV/c. Of course, if the Higgs were discovered, one would want to measure its mass to better than its natural width. For an intermediate mass Higgs (about 300 GeV), this criterion gives a desired muon momentum resolution of 4% for $p_t \leq 100$ GeV. We see no other compelling reason for momentum resolutions below 5% but would like to maintain reasonable resolution, including sign selection, up to the kinematic reach of the SSC. With the forward angular coverage extending to $\eta = 3$, this criterion means achieving the desired momentum resolution for muons with momenta in the 2-4 TeV/c region. As part of the work proposed, we will repeat and extend quantitative calculations of the expected signal/noise as a function of muon momentum resolutions for all predicted interesting processes. For example, Rosner [6] has pointed out that one signature of new Z's is a lepton asymmetry which is largest in the region $2 \leq |\eta| \leq 3$. This asymmetry can be a function of mass due to interference with the standard Z. Precision studies of this asymmetry would follow the discovery of a new Z requiring optimization of the forward region muon detector as part of a detector upgrade. Provisions for upgrades of the forward muon detector system will be considered as part of the proposed work.

For purposes of this proposal, the muon detection in the forward region is broken up into two regions, $1.25 \leq |\eta| \leq 2.25$ ($12° \leq \theta \leq 32°$) and $2.25 \leq |\eta| \leq 3.0$ ($5.5° \leq \theta \leq 12°$). We denote these regions as the intermediate and small angle regions, respectively. These regions blend smoothly into the central region but it is obvious that the problems of momentum resolution, occupancy, and rates are qualitatively different in the small angle region as compared to the central region. In addition, there will be no redundant momentum measurement available from the solenoidal field for the small angle region. This division of the forward region allows us to consider the possibility that different and more expensive technologies such as air core toroids and silicon strip arrays might be exploited in the small angle (highest rate) region because of the limited area per layer of detector (approximately 10% the area of the central region coverage). In the intermediate region, one could also afford modest increases in the cost of detectors and magnet to match the environment. For example, one might use superferric toroids and decrease the drift distance by a factor of 2 compared to the central region (should drift modules be employed). The triggering technique employed in the two regions could also be quite different. The muon flux in the forward angle region will be roughly (1-10) MHz while that in the intermediate region should be about 100 kHz depending on the absorber thickness. In fact, the thickness and arrangement of the absorber is an important issue in this study. There will also be a large rate in the forward region produced by particles hitting the beam pipe, edges of the calorimeter, or other material. Extrapolating from CDF measurements and D0 studies leads us to expect a 500 Megahertz rate from this source. Due to these large rates, it will probably be necessary to include multiple technologies even in early stages of the trigger. An example is to use a combination of aerogel and gas Cerenkov counters to reduce the counting rate from low-energy particles while still providing good spatial resolution. This "Cerenkov" trigger could then be combined with a transverse momentum trigger based, perhaps, on proportional drift modules with graded wire spacing. Alternatively one might think of using drift technology combined with scintillating fibers or silicon strip arrays to provide low occupancy as well as a fast trigger.

Both regions of the forward muon detector will probably consist of passive absorber, i.e. calorimetry and/or nonmagnetized iron, for muon identification followed by a magnetic spectrometer. We propose to investigate the exact boundaries of the two regions which must be tuned to match the central region muon detector performance.

Our study of the forward section of the muon detector will follow closely our procedure in the central region. In fact, most of the necessary tools for the study (such as detailed simulations and comparisons with data) are common to both regions. Of course, the average muon energy will be higher leading to more severe problems with bremsstrahlung and punch-through, as discussed previously. We plan to enlarge the detector simulation to include the reactions of interest, those reactions giving a muon background and the more difficult processes which give rise to detector noise, such as particle scatter from the beam pipe. We can then evaluate various magnet and detector dispositions for: trigger speed, trigger efficiency, momentum determination in trigger and off-line, coverage and efficiency, sensitivity to background, measurement ambiguity and cost.

Finally, we will address the issues of alignment and spatial accuracy in the forward region. As compared to the central region, the smaller solid angle subtended will allow some flexibility. Position resolution, lever arms, and magnetic field length can be varied such that a number of different configurations would give identical resolutions. Air-gap magnets, combined with the large flux of muons from the interaction point, could allow for short "magnet off" alignment runs.

4.4.2 Task 4.2: Preliminary Engineering Design [FNAL, Michigan, SSC]

The comments in Section 3.2 also apply to this task, although the engineering problems in the forward direction are less severe with regard to the mass of iron required.

4.4.3 Task 4.3: Prototyping

The comments in Section 3.3 also apply to this task.

4.5 Task 5: Trigger

4.5.1 Task 5.1: Simulation Tools [Illinois]

Physicists are accustomed to the use of simulation software to understand the high energy physics aspects of detector design. Simulation tools also exist and can be developed further to guide and test the electronics aspects of detector design. The use of computer-aided design (CAD) and computer-aided engineering (CAE) software offers considerable potential cost-saving and improved reliability over standard "breadboarding" techniques. We expect to use such tools in all aspects of our electronics development.

We propose to use CAE tools to model the data acquisition and trigger electronics for SSC experiments. The first phase of such an effort is to write a functional model for the system. This model does not necessarily have the physical attributes of a real system, however it can contain as much of the functional attributes as required. Several different architectures could be tried and evaluated. The stimulus for the simulation would come from Monte Carlo generated events.

The second phase would be to take the best functional model and convert it to a structural model. At this time the description of the electronics is partitioned more nearly into the physical units that will be constructed. The structural model is tested against the funtional model to insure consistency. This model, after refinement, becomes the design document for the electronics. All groups designing at the gate level will have the behavioral models of their subsystem and the interfaces to the rest of the data acquisition system to test the design against. This will insure that all parts are consistent with the agreed-to system. The gate level designs can be mixed with the higher-level behavioral designs and the entire system simulated.

The models will be parametrized so that different scenarios can be tested. These could include buffer sizes, processing rates, signal or event acceptance/rejection statistics, data transmission rates, trigger efficiencies, trigger biases, etc.

This type of modelling will be an ongoing part of the system design. As new ideas are developed, models can be written to test them out. Also, when the gate-level design is started, it is probable that some unexpected design problems will arise. The solution may require that adjustments be made in the structural model. Before the change is made, the model can be modified and the overall effect tested.

4.5.2 Task 5.2: Custom IC Development [Michigan]

This work is already supported under an SSC generic R&D proposal.

4.5.3 Task 5.3: Acoustic Charge Transport [Washington]

This work is already supported under an SSC generic R&D proposal.

4.5.4 Task 5.4: Prototype [Arizona, Minnesota, Wisconsin]

Work under this task will design and prototype elements which may be useful in constructing a muon trigger. One such element is the fast table look-up of momentum based on particular hit patterns in the muon tracking detectors. Another element is the comparison of track segments from the muon system and the central tracker. The result of these small-scale investigations will be incorporated in the conceptual design described in Task 5.5.

4.5.5 Task 5.5: Conceptual Design [Arizona, Illinois, KEK, Michigan, Minnesota, Northern Illinois, Okayama, Wisconsin]

We propose to design and prototype a fast electronic trigger. This trigger must have a time jitter of less than 10 nsec (to resolve bunch crossings), with a decision time of $\approx 1\mu$sec, to minimize the length of the overall detector pipeline. We expect that such a trigger may be based on fast detector coincidences together with the ability to examine tracking vectors from stubs in small tracking detector regions determined by the trigger detector. Impact parameters would be matched to those desired by fast parallel multistage table lookup. Current technology offers large scale memory with better than 50 nsec access time so that even 10 stage matching falls within the design parameters of the trigger. We propose to first design a computer simulation of this trigger and then build a prototype. We will also design and build a programmable electronic device to simulate the electronic signals from the detectors which make up the muon trigger. This signal simulator will be used to test models of the trigger electronics.

4.6 Task 6: Magnets

4.6.1 Task 6.1: Conceptual Design [Argonne, Wisconsin]

The solenoidal magnet in the central pseudo-rapidity region is not part of the muon sub-system. However, the central region magnetized iron and the forward pseudo-rapidity region magnets are included in this sub-system. The possibilities for the forward region include toroidal and dipole magnetic fields, implemented with ferric, superferric or air-core magnets. This task will develop a conceptual design for such magnets considering physics requirements, system integration requirements and rough cost estimates.

4.6.2 Task 6.2: Preliminary Engineering Design [Michigan, SSC, Wisconsin]

In the second and third years, we will do a preliminary engineering design of our chosen magnet configurations for both the central and forward pseudo-rapidity regions.

4.7 Task 7: Support and Coordination

4.7.1 Task 7.1: Computer Time

The collaboration intends to purchase supercomputer time at the best possible price and/or matching funds arrangement either at one of the collaborating institutions or at a national facility.

4.7.2 Task 7.2: Travel

Although we intend to use electronic communications as much as possible, travel is essential to coordinating the activities of a broad collaboration. Travel costs include collaboration meetings, visits to vendors, work at other institutions and test beam work at accelerator laboratories.

5 Effort, Coordination and Budget

5.1 Effort

Doing research and development on an SSC subsystem requires the effort of people already engaged in active high energy physics research programs. It is just such programs which must lead smoothly to the SSC era. This proposal involves faculty members and laboratory personnel with full research agendas but who see the need to begin the work which will lead to an SSC detector immediately. We propose to obtain the effort necessary for the proposed work by obtaining release time from their other duties not related to high energy physics research, i.e. teaching for faculty members, for approximately one third of a year. We know however that outside responsibilities whether in a laboratory or a university will always exist as long as a person is physically present. To achieve efficient use of time for this project, we envision that collaborators will either travel to another site or host others at their site during the time when working exclusively on this project. Thus each project member is either away from his/her home institution or is interacting with other members of the collaboration visiting his/her institution. We expect the time for each working visit to be on the order of a week for with the host site rotating among the members of each working subgroup.

In addition, we propose to hire post docs who can work part time on this project while participating with members of this collaboration in ongoing experiments which result in physics output. This will allow post docs to contribute to the SSC development effort without sacrificing their prospects for advancement and their taste for finding new physics. The strong university component in this collaboration can supply additional effort by graduate students who can be involved at least part time while still being permitted to participate in data taking and analysis of ongoing experiments. We expect that this R&D work will result in some M.S. and Ph.D. theses. Finally, part-time effort by electrical and mechanical engineers and technicians experienced in high energy physics detector work will be supplied by the participating institutions on a cost-reimbursement basis.

5.2 Coordination

Although we have separated this proposal into various subtasks, these tasks are all directed to establishing the costs and benefits of realistic muon triggering and detection options. All efforts will be coordinated to that end. Indeed several subtasks such as measurements in testbeams will involve most members of this collaboration. We will establish the same simulation code at each institution with a central code maintenance facility. Long simulations such as shower studies will be executed on large mainframe computers (such as Cray 2's) and examined using user's Vax systems. Simulations involving only particle tracking will run on each institution's Vax.

Subgroups will keep in constant contact with each other through electronic mail with a central information distribution being established at Minnesota for distributing group notes and frequent progress reports. We expect meetings of the entire group will occur at a period of about two months. This is enough to keep the group focussed without withdrawing significant effort from the work at hand. Because of the nature of the problem, the group as a whole will periodically decide whether to pursue any particular technology to the next stage of development (e.g., simulation to small scale prototype, etc.) Maintaining constant contact between all of the subgroups and facilitating these decisions will be one of the responsibilities of the spokespeople of this proposal.

5.3 Budget

The attached tables outline the budget for this proposal by task and sub-task, as described in Section 4 of this proposal. The description in that section together with the budget tables also indicate the timing of the proposed work. For the first year, we provide a breakdown for each sub-task by category of expenditure and by responsible institution. For Years 2 and 3, such a detailed breakdown is not possible for this type of R&D project. For that reason, we provide only overall requests by sub-task for these later years.

The categories of expenditure are Effort, Materials, Engineering, Technical Support and Other. "Effort" includes the costs of salaries, fringe benefits and overheads associated with the work of physicists—senior, post-doctoral and pre-doctoral. "Materials" are supplies which are small and short-lived and thus do not meet the normal tests for capital equipment. The category of "Engineering" includes funds mostly to reimburse national or university laboratories for time of professional engineers and their assistants. "Technical Support" includes all costs associated with technicians, computer programmers, machinists and similar persons. The "Other" category mostly includes the cost of purchased supercomputer time and travel.

The amounts listed under "Effort" generally refer to fractional time of various physicist personnel. In the short-term, such time can be made available only by diverting existing personnel from other tasks. Several requirements make such diversion difficult. These problems include the necessity to continue to operate the current national high energy physics program to keep the field of elementary particle physics in the United States vital during the pre-SSC years. A second difficulty is the professional career development of junior faculty, post-doctoral research associates and graduate students. It is generally not advisable for such people to devote their entire efforts to an SSC experiment because of the long time delay prior to expected physics results. It may be possible, however, for some graduate students to complete a Ph.D. dissertation on SSC instrumentation. A third problem is that university physics departments will only tolerate limited diversion of professorial faculty from teaching, which is another mode for obtaining some of the required effort. For these reasons, the mix of effort from senior and junior Ph.D. physicists and graduate students will vary by time and institution.

The budget lists many lines with no explicit funding included. These entries denote acceptance of responsibility with funding supplied by other means than this proposal. For example, our Japanese collaborators are already supported with their national funds. Several of us have received generic R&D funding for topics which are relevant to this proposal. We expect, in addition, to request capital funding as necessary from the State of Texas.

6 References

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2. K. Heller et al., FASTnote 2, September, 1989.
3. S. Errede, H. Tye, Snowmass Summer Study, 1984, p. 175.
4. D. Carlsmith, D. Hedin, B. Millikan, Snowmass Summer Study, 1986, p. 431.
5. D. Carlsmith, et al., Snowmass Summer Study, 1986, p. 405.
6. J. Rosner, Snowmass Summer Study 1986, p. 213.

	Effort	Materials	Engineering	Year 1 Technical	Other	Total Year 1	Year 2	Year 3
Task 1: Simulations, rates and backgrounds								
1.1 Install and maintain simulation code							$25,000	$25,000
Minnesota	$15,000			$20,000		$35,000		
1.2 Simulations							$105,000	$50,000
Colorado	$20,000					$20,000		
FNAL								
Illinois	$10,000			$10,000		$20,000		
KEK								
Michigan	$10,000					$10,000		
Northern Illinois	$10,000					$10,000		
Osaka								
Wisconsin	$10,000					$10,000		
Minnesota	$10,000					$10,000		
SLAC/Harvard				$15,000		$15,000		
Total Task 1	$85,000			$45,000		$130,000	$130,000	$75,000
Task 2: Detector Technical Development							$600,000	$100,000
2.1 Drift Modules								
Tsukuba								
Michigan								
Tufts	$10,000	$20,000		$35,000		$65,000		
Wisconsin	$20,000	$10,000		$15,000		$45,000		
2.2 Fast time response elements								
Illinois	$15,000	$10,000		$20,000		$45,000		
2.3 Aerogel								
Northern Illinois	$15,000	$30,000				$45,000		
2.4 Gas Cerenkov								
Colorado	$20,000	$20,000		$25,000		$65,000		
2.5 SciFi, Si and Straws								
Arizona	$15,000	$10,000				$25,000		
Rochester								
2.6 Test Beam							$20,000	$200,000
FNAL		$30,000		$20,000		$50,000		
Illinois	$10,000					$10,000		
Minnesota	$10,000					$10,000		
Rice	$20,000					$20,000		
Washington	$30,000	$20,000		$25,000		$75,000		
Wisconsin	$10,000					$10,000		
Total Task 2	$175,000	$150,000		$140,000		$465,000	$620,000	$300,000

	Effort	Materials	Engineering	Year 1 Technical	Other	Total Year 1	Year 2	Year 3
Task 3: Central Detector								
3.1 Conceptual Design							$150,000	$100,000
FNAL								
Illinois	$10,000					$10,000		
KEK								
Minnesota	$10,000					$10,000		
Rice				$20,000		$20,000		
SLAC/Harvard				$15,000		$15,000		
Tsukuba								
Tufts	$10,000					$10,000		
Washington	$10,000					$10,000		
Wisconsin	$10,000					$10,000		
3.2 Preliminary Engineering Design							$160,000	$300,000
FNAL			$40,000			$40,000		
Michigan								
SSC								
3.3 Prototyping							$300,000	$500,000
Total Task 3	$50,000		$40,000			$125,000	$610,000	$900,000
Task 4: Forward Detector								
4.1 Conceptual Design							$100,000	$100,000
Arizona	$15,000					$15,000		
Colorado	$10,000					$10,000		
Minnesota	$10,000					$10,000		
Northern Illinois	$10,000					$10,000		
Tsukuba								
4.2 Preliminary Engineering Design							$120,000	$200,000
FNAL			$20,000			$20,000		
Michigan								
SSC								
4.3 Prototyping							$300,000	$500,000
Total Task 4:	$45,000		$20,000			$65,000	$520,000	$800,000

	Effort	Materials	Year 1 Engineering	Year 1 Technical	Other	Total Year 1	Year 2	Year 3
Task 5: Trigger								
5.1 Simulation tools (CAD/CAE)							$200,000	$100,000
Illinois			$60,000	$15,000		$75,000		
5.2 Custom IC Development								
Michigan (generic R&D)								
5.3 Acoustic Charge Transport								
Washington (generic R&D)								
5.4 Prototype							$250,000	$400,000
Arizona (forward)	$20,000	$10,000		$10,000		$40,000		
Minnesota (sig sim, table lookup)	$20,000	$10,000	$40,000	$20,000		$90,000		
Wisconsin (track segment match)	$10,000	$10,000	$30,000	$10,000		$60,000		
5.5 Conceptual design							$150,000	$150,000
Arizona	$10,000					$10,000		
Illinois	$10,000		$40,000			$50,000		
KEK								
Michigan								
Minnesota	$10,000					$10,000		
Northern Illinois								
Okayama								
Wisconsin	$10,000					$10,000		
Total Task 5	$90,000	$30,000	$170,000	$55,000		$345,000	$600,000	$650,000
Task 6: Magnet								
6.1 Conceptual design							$40,000	$40,000
Argonne (air core)								
Wisconsin (iron)								
6.2 Preliminary Engineering Design							$80,000	$150,000
Wisconsin (iron)			$40,000			$40,000		
Michigan								
SSC								
Total Task 6			$40,000			$40,000	$120,000	$190,000

	Year 1						Year 2	Year 3
	Effort	Materials	Engineering	Technical	Other	Total Year 1		
Task 7: Support and Coordination								
7.1 Computer time					$100,000	$100,000	$150,000	$100,000
7.2 Travel							$150,000	$175,000
Argonne					$4,000	$4,000		
Arizona					$12,000	$12,000		
Colorado					$10,000	$10,000		
FNAL					$6,000	$6,000		
Illinois					$12,000	$12,000		
Michigan					$8,000	$8,000		
Minnesota					$17,000	$17,000		
Northern Illinois					$10,000	$10,000		
Rice					$5,000	$5,000		
SLAC/Harvard					$6,000	$6,000		
Tufts					$10,000	$10,000		
Washington					$12,000	$12,000		
Wisconsin					$12,000	$12,000		
Total Task 7					$224,000	$224,000	$300,000	$275,000
Grand Total	$445,000	$180,000	$270,000	$240,000	$224,000	$1,359,000	$2,900,000	$3,190,000
Budget by Institution								
Argonne					$4,000	$4,000		
Arizona	$60,000	$20,000		$10,000	$12,000	$102,000		
Colorado	$40,000	$20,000		$25,000	$10,000	$95,000		
FNAL		$30,000	$60,000	$20,000	$6,000	$116,000		
Illinois	$55,000	$10,000	$100,000	$45,000	$12,000	$222,000		
Michigan	$10,000		$0		$8,000	$18,000		
Minnesota	$75,000	$10,000	$40,000	$40,000	$17,000	$182,000		
Northern Illinois	$35,000	$30,000			$10,000	$75,000		
Rice	$20,000			$20,000	$5,000	$45,000		
SLAC/Harvard				$30,000	$6,000	$36,000		
Tufts	$20,000	$20,000		$35,000	$10,000	$85,000		
Washington	$40,000	$20,000		$25,000	$12,000	$97,000		
Wisconsin	$70,000	$20,000	$30,000	$25,000	$12,000	$157,000		

Figure 1. M_{ZZ} vs. Muon Momentum Resolution for H^{-} ZZ

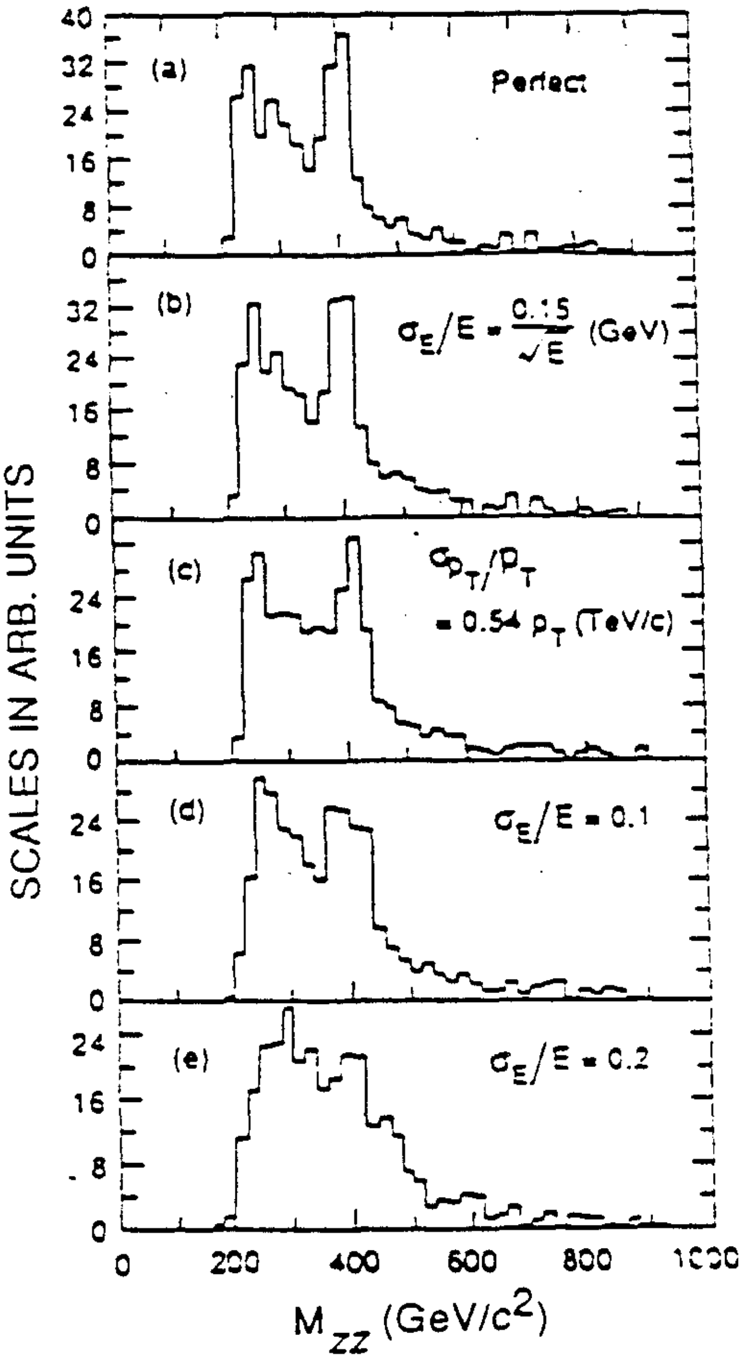


Figure 2. Mass Resolution for $Z^0 \to \mu^+\mu^-$

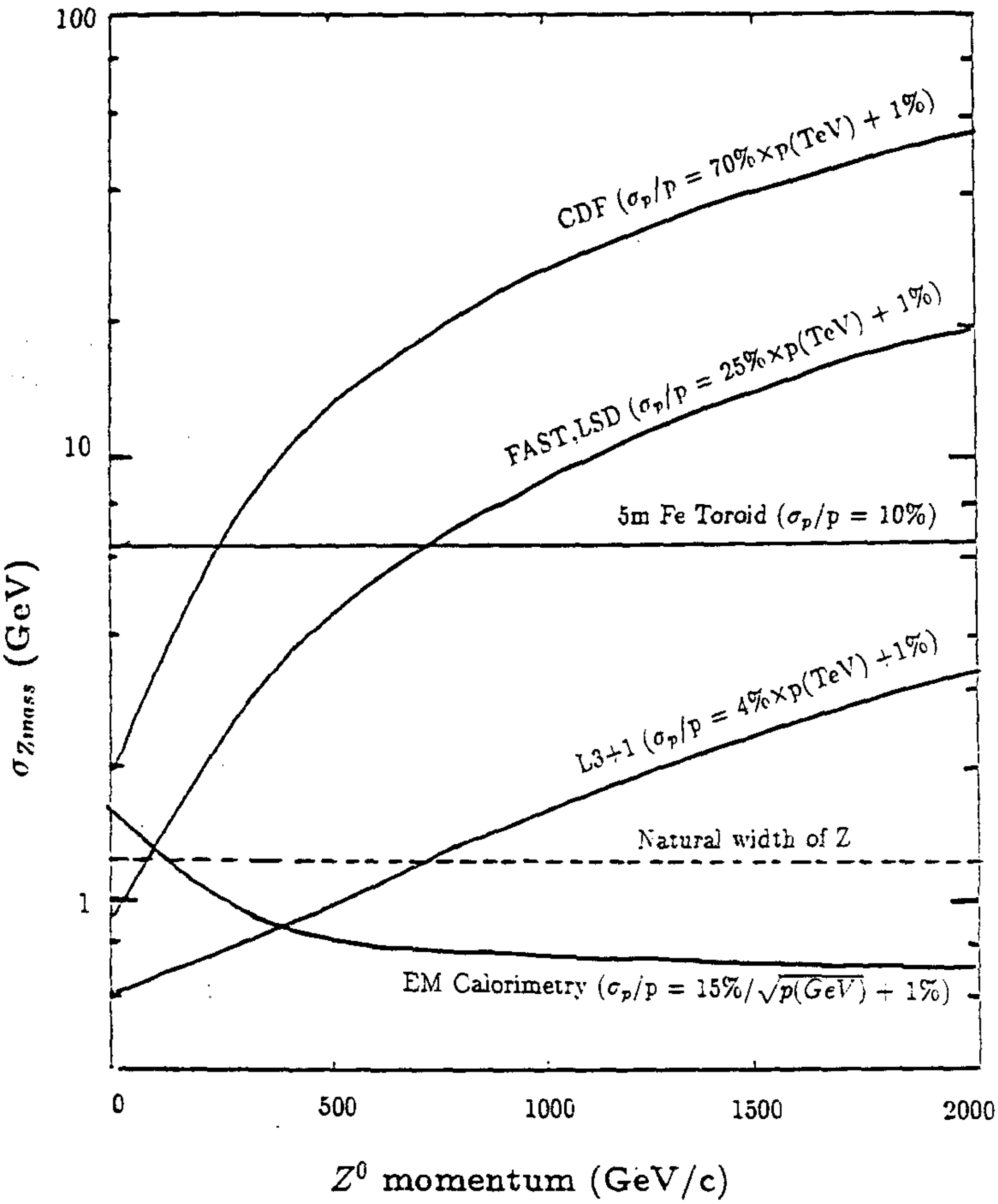


Figure 3. Mass Resolution for $Z' \to \mu^+\mu^-$

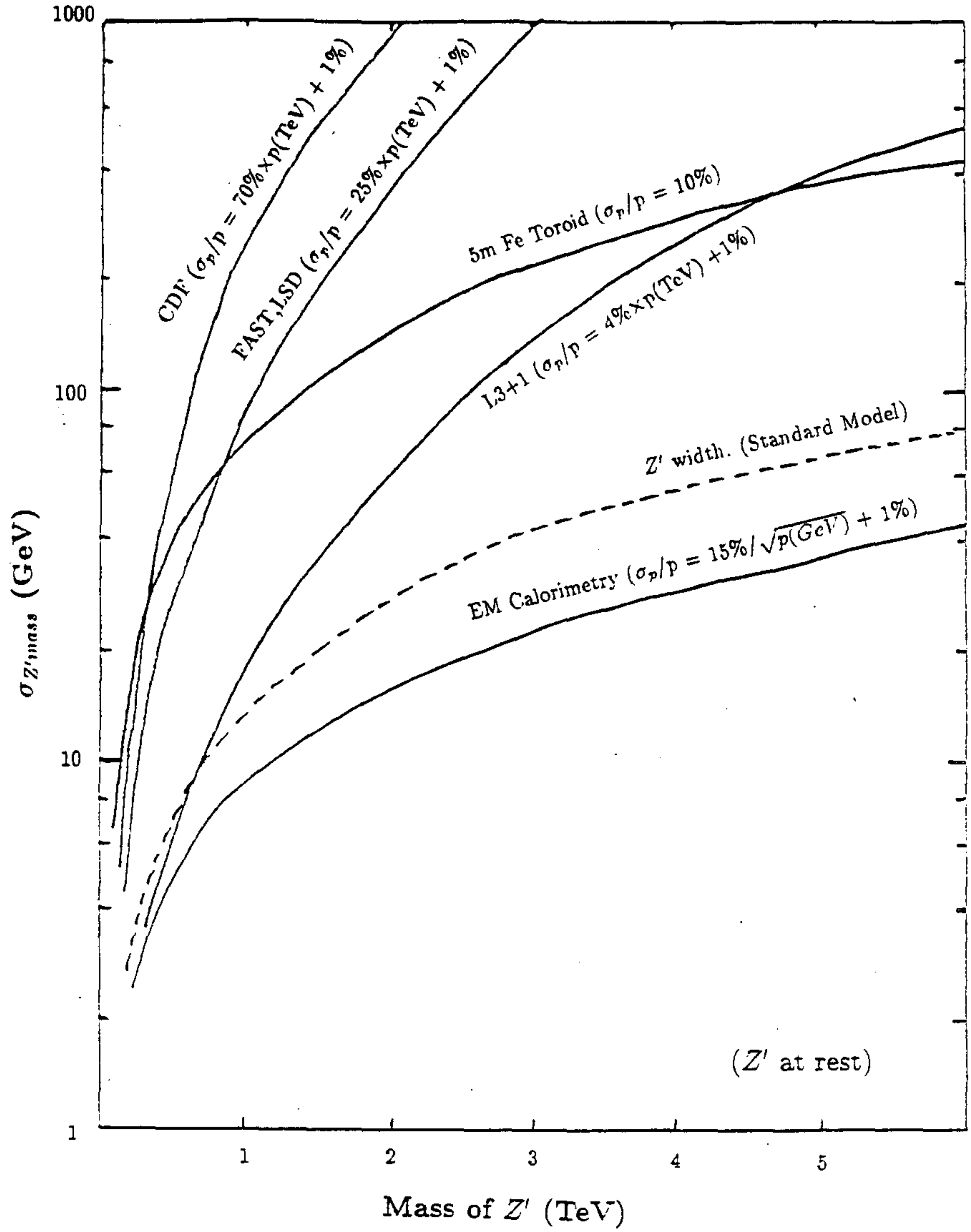
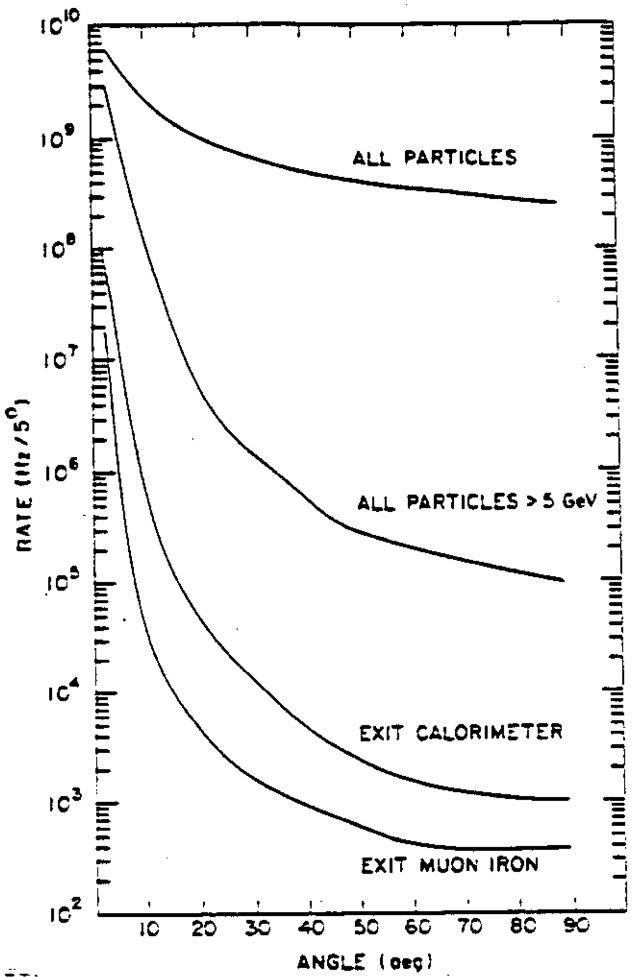
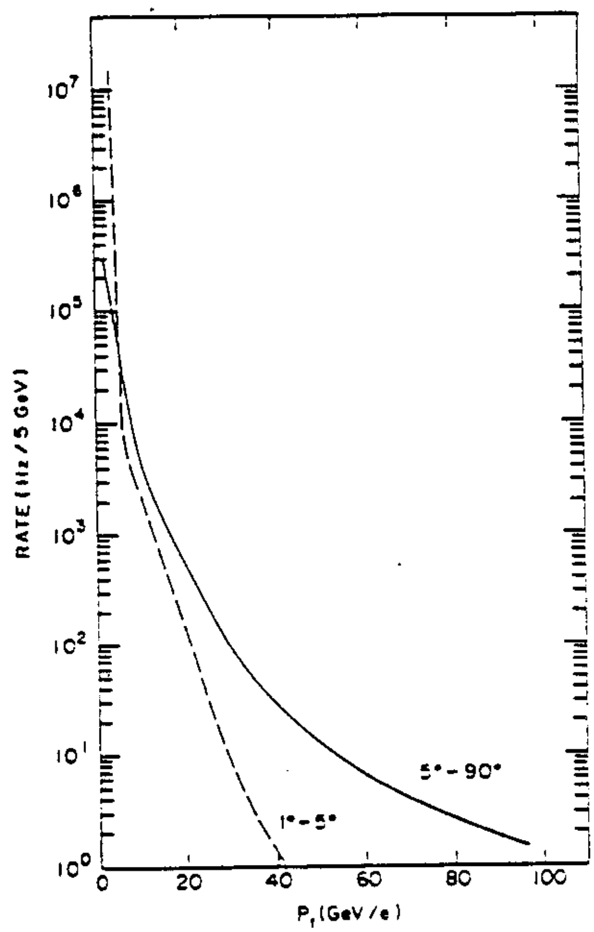


Figure 4. a)



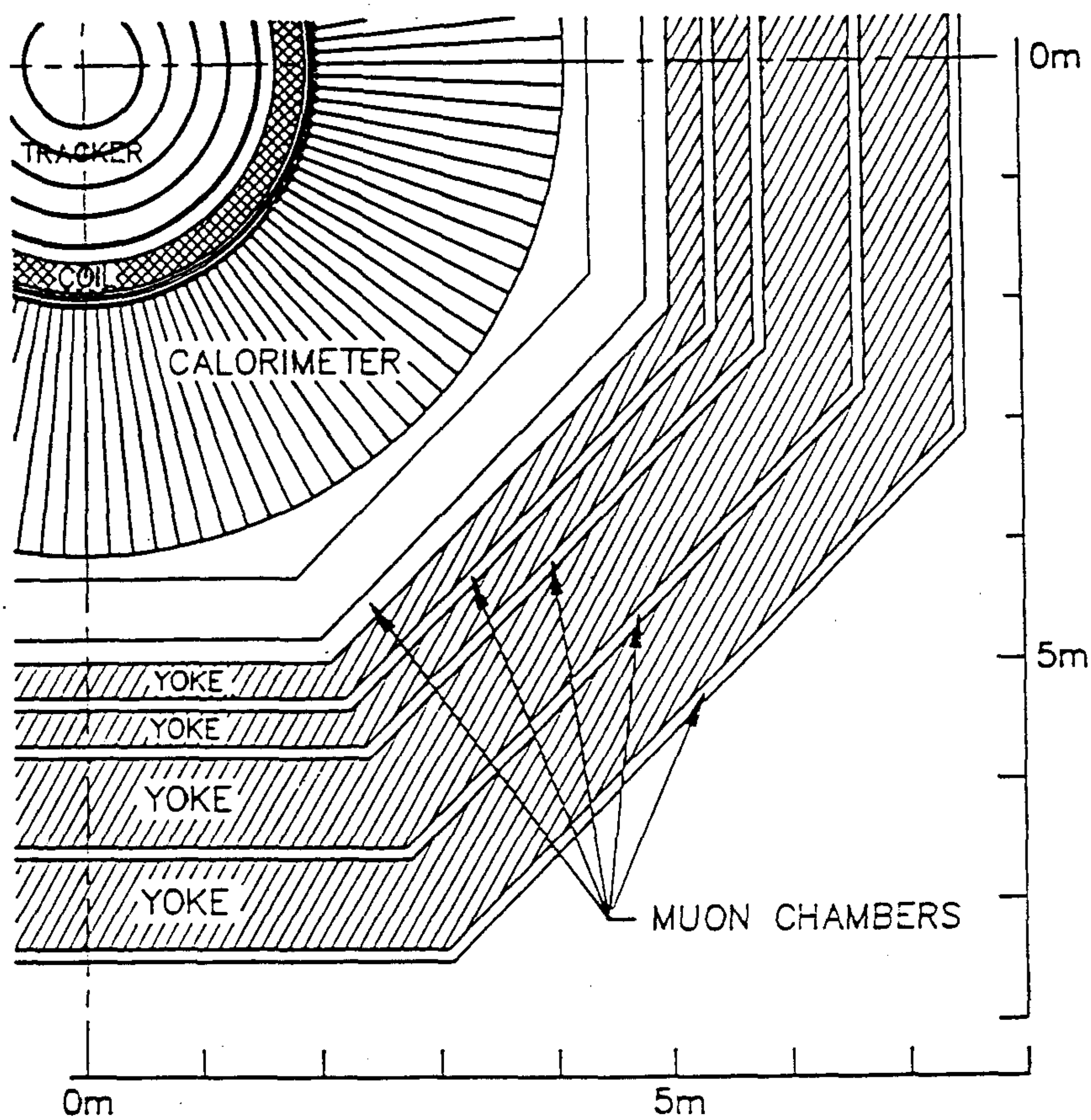
Raw angular rates for all particles, all particles greater than 5 GeV, all particles exiting the coarse calorimeter, and all particles exiting the muon iron.

b)



Rates versus p_t for particles exiting the muon iron in the end (1° – 5°) and central (5° – 90°) regions.

Figure 5.



TRACKER
COIL
CALORIMETER
YOKE
YOKE
YOKE
YOKE
MUON CHAMBERS
0m
5m
0m
5m