LOW BETA REGION MUON COLLIDER DETECTOR DESIGN*

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Abstract

Detector designs for muon colliders have lacked coverage of the particles emerging from the collision region in the forward and backward angular regions, limiting their physics potential. These regions require massive shielding, mainly due to the intense radiation produced by the decay electrons from the muon beams. Emerging technologies for instrumentation could be used to detect particles in these regions that were filled with inert material in previous designs. New solid state photon sensors that are fine-grained, insensitive to magnetic fields, radiation-resistant, fast, and inexpensive can be used with highly segmented detectors in the regions near the beams. We are developing this new concept by investigating the properties of these new sensors and including them in numerical simulations to study interesting physics processes and backgrounds to improve the designs of the detector, the interaction region, and the collider itself.

INTRODUCTION

Among the primary arguments for lepton colliders in general is complementarity with the physics of a hadron machine such as the Large Hadron Collider (LHC). The relative simplicity of leptons allows greater precision studies of final states compared to hadron colliders. The physics potential of a muon collider in this regard is comparable to that of an electron collider of the same energy and luminosity. Though electron-positron colliders are technologically more mature, there are advantages of muon colliders over electron-positron colliders with the same energy.

1. Because beamstrahlung, a fundamental problem with colliding electron beams, is not present with muon beams, a muon collider can be operated with a smaller energy spread, as little as 0.01 %, making it possible to obtain more precise measurements of masses and widths with a muon collider than with an e^+e^- collider.

2. The direct coupling of a lepton-lepton system to a Higgs boson has a cross section that is proportional to the square of the mass of the lepton. As a result, the cross section for direct Higgs production from the $\mu^+\mu^-$ system is more than 40,000 times that from an e^+e^- system.

The latter point means that the potential of the muon collider for Higgs physics is outstanding. Away from the s-channel Higgs pole, $\mu^+\mu^-$ and e^+e^- colliders have similar capabilities for the same $\sqrt{s}$ and luminosity. Recent advances in muon cooling schemes have increased the competitiveness of potential muon colliders, especially at higher energy[1].

BACKGROUNDS

How well and what kind of physics can be produced with a muon collider depends on how well the backgrounds can be controlled. Most backgrounds are associated with the products of the decaying muons that get into the detector region. A 2 TeV/c muon beam, that was studied for a 4 TeV center of mass muon collider [2], with 2×10^{12} μ per bunch will produce 2×10^5 decays per meter. The size of the beam related backgrounds are proportional to the number of μs in the bunch. Because the number of decays per length scales with $1/\gamma$ from Lorentz contraction and the size of a an interaction region will likely grow with γ, the number of muon decays expected in the region of the detector is approximately independent of energy. The electrons from the muon decays will not have the designed momentum of the collider ring and will either interact with the wall of the beam chamber producing electromagnetic showers or produce synchrotron radiation in regions of large transverse magnetic field. The design of a detector for a muon collider will be constrained by the necessity to reduce the electromagnetic background. The effort to minimize the backgrounds will have a strong influence on both the design of the detector and the design of the collider ring lattice in the vicinity of the intersection region.

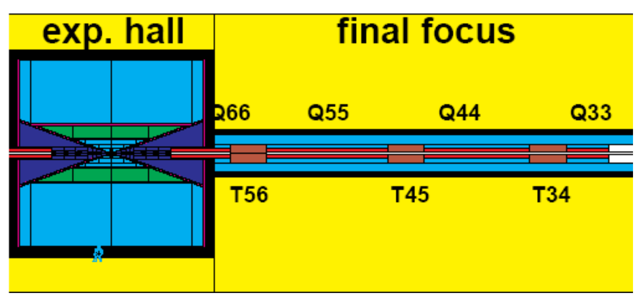

Figure 1: Sketch of the IP region and 130 meters of the final focus magnet system with quadrupoles (Q) and toroids (T). This sketch shows the geometry of the detector used in the 1996 GEANT simulation of a 2 × 2 TeV Muon Collider. The conical tungsten-filled region, shown in dark blue, was required to absorb debris from muon decays in the beams. Because of the limitations of detector technology at the time, this area was not instrumented.

Figure 1 shows a sketch of the geometry of a muon collider detector along with the final focus magnets of the collider ring, that was used in the 1996 Muon Collider Feasibility Study [3]. A number of features that were

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imposed on the design of the final focus region of the intersection point included:

- A conical tungsten shield surrounding the beam enclosure extending to 20º in both the forward and backward directions
- The inner surface of the shielding cone designed such that the detector does not see any surface that a decay electron can.
- The open space between the interaction point (IP) and the tungsten shielding constrained to several cm).
- The inner surface of the conical shield shaped in a sawtooth manner. to collimate the electrons in the beam and maximize the absorption of the electromagnetic showers from the electrons that graze the cone surface..

A high field dipole magnet with a collimator inside is placed upstream of the first quadrupole magnet to sweep decay electrons away before the final collimation. In particular, the first three constraints were to limit the interactions with the detector. However, the presence of the conical shields in the forward and backward directions limits a muon collider physics reach; t^+t^- production will occur predominantly in the forward region of energy frontier machines, and is a very important handle on possible new physics. There are many asymmetries that are most easily seen in that region [4]. With advances in particle detection and read-out technology in the years since the 1996 Muon Collider Feasibility Study, the detector coverage can be pushed into the forward region previously considered unsuitable for particle detection.

PHOTON DETECTORS

New technology is emerging that has several advantages for the application proposed here. In particular, developments in Geiger-mode avalanche photo diodes have enabled great advances in calorimeter performance in challenging environments [5]. They are very compact and have high gain (~10^5) and good particle detection efficiency. Furthermore they have been shown to be insensitive to magnetic fields as high as 4.4T [6] and have good (sub-nanosecond) time resolution [7], and good radiation tolerance, with no deterioration seen at 1 Mrad gamma radiation exposure[8]. The primary challenges are: thermal noise rate, non-linear response due to limited number of pixels (saturation effect), sensitivity to temperature change and cross-talk and after-pulsing.

CALORIMETRY

Recently, detector R & D for the ILC and other future colliders has included designs of calorimeters for luminosity measurements, beam monitoring, and diagnostics[9]. Silicon-tungsten calorimeters are being measurements using Bhabha scattering. Detectors for beam diagnostics using beamstrahlung photons and pairs are being considered with instrumented tungsten. Figure 2 shows examples of calorimeters currently under study for use in very far forward regions in advanced lepton colliders with large backgrounds and radiation environments. These technologies can be adapted to the similarly severe conditions of a muon collider detector extended down to lower forward angles than have been previously considered.

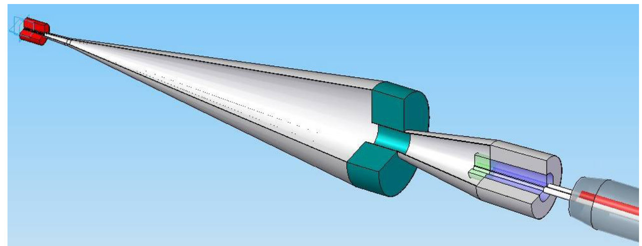
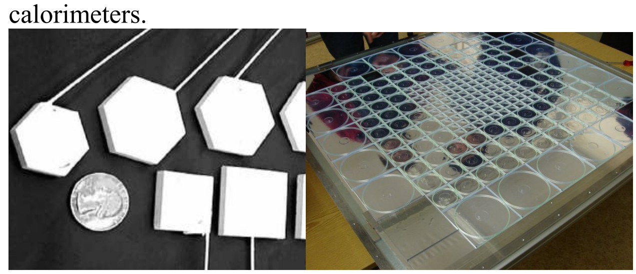


Figure 2: Illustration of conceptual forward calorimeters for luminosity (40-140 mr, shown in teal) and beam diagnostic (<40 mr, shown in blue) measurements. Advances in electronics that allow these designs can be used in a muon collider detector.

CALORIMETER TILES

Northern Illinois University (NIU) has been involved with the design, optimization, construction, commissioning and operation of a silicon-tungsten electromagnetic calorimeter and a steel-scintillator hadron shower imager as part of the CALICE test beam program at the H6B area at CERN for a month each in 2006 and 2007. The hadron shower imager physically consists of two devices: a hadron calorimeter (HCAL) and a tail-catcher/muon tracker (TCMT). NIU had the primary responsibility for the latter device. The NIU group has pioneered use of arrays of plastic scintillator tiles in calorimeters.



(a) (b)

Figure 3 (a): Examples of plastic scintillator tiles for use in calorimeters made by the NIU group; (b): Array of scintillating tiles arranged on 1m x 1m plate of a prototype CALICE hadron calorimeter. The tiles are arranged as a mosaic with smaller tiles in the high rate regions and larger tiles farther away.

Samples of small tiles and an array of tiles mounted to a 1m x 1m plate in the CALICE hadron calorimeter. Earlier versions, as in Figure 3(a), were read out by means of fibers, but with solid state detectors such as MPPCs and integrated electronics, more compact highly efficient calorimeters are now being used. Using simulations to provide expected particle flux rates at different depths in the shielding cones, the sizes and arrangements of tiles that can function will be computed. Prototypes of "instrumented shielding" that will comprise a forward region muon collider detector will be designed.

MACHINE-DETECTOR INTEGRATION

The development of muon collider experimental detectors must be in concert with the machine designers. This has been obvious in the past where, for examples, the length of the low beta lattice insertion of colliders has limited detector size, the distance from the IP to the nearest quad of the focusing triplet has been a compromise between the low beta value and detector coverage, or the beam halo has affected the placement of silicon vertex detectors because of background rates and sensitivity to radiation damage.

In a muon collider, this concept of machine-detector integration may be more important than in the past. An example of this concept may be understood from the excerpt below, which was taken from Fermilab's Muon Collider Task Force 5-year Plan Proposal that was submitted to the MUTAC, the technical advisory committee that advises the managements of BNL, FNAL, and LBNL on muon related research. Table 1 presents of this excerpt, three different scenarios for muon colliders described in the plan which have very different implications for detectors. (The table also has many caveats since none of the three scenarios is entirely credible, requiring devices and techniques that are not yet available.)

Table 1. Parameters for a 1.5 TeV (c.m.) muon collider.

	LEMC	MEMC	HEMC
Avg luminosity (10^{34} cm^{-2} s^{-1})	2.7	1.33	1
Avg. bending field (T)	10	6	6
Proton driver rep. rate (Hz)	6.5	40	13
β^* (cm)	0.5	1	1
Muons per bunch (10^{11})	1	11.3	20
Norm. Trans. Emittance (μm)	2.1	12.3	25
Norm. Long. Emittance (m)	0.35	0.14	0.07
Energy spread (%)	1	0.2	0.1
Estimated muon survival (%)	31	20	7

CONCLUSIONS AND FUTURE PLANS

New detector designs for a muon collider will enable higher luminosity muon collider designs with more aggressive beam focusing systems for the interaction regions. The improvements to the acceptance in the forward direction expected from this project will make a muon collider more attractive in that it will be able to address a broader range of physics questions.

Simulations that approximate conditions in the forward regions for contemporary muon collider design parameters are being used to specify requirements for large-scale, high-granularity instrumentation for these regions. Bench tests of state of the art sensors and electronics will be made to determine their suitability to extend the physics reach of energy frontier muon colliders. Technological advances in particle detection make it possible to instrument a portion of the forward region of muon collider detectors, previously considered only for shielding in detector designs for muon colliders. The innovation of "instrumented shielding" in the forward region with calorimetry or timing detectors for active read-out would take maximal advantage of the higher luminosity of recent muon collider designs. Calorimetry in the forward region would also enhance beam diagnostics and luminosity measurements. With better muon beam cooling and more aggressive beam focusing systems, the physics reach of these machines will be extended.

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