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High Luminosity Muon Collider Studies In the U.S.A.

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Abstract

Muon colliders as a future collider project in the U.S.A., have attracted many physicists from many institutions in recent years. Workshops and conferences have been held on the subject in the last few years. The studies show that high luminosity circular muon colliders can be built at high luminosities and at high center-of-mass energies. Some aspects of the muon colliders, physics possibilities, background and detector issues will be discussed. Some comparisons between the muon and hadron colliders, and electron-positron colliders, will be made.

1. Introduction

The possibility of muon colliders was first proposed by G.I.Budker in 1969 [1]. The muon collider idea did not receive much attention until 1994, mainly due to the fact that U.S.physicists were very much involved with the SSC (Super Conducting Supercollider) project in Texas. After the SSC's demise, U.S.physicists started looking into other collider possibilities. Among them have been muon colliders, NLC (Next Linear Collider), and again an inexpensive way of constructing a VLHC (Very Large Hadron Collider).

Due the fact that high energy circular e^+ e^- colliders with energies beyond the LEP collider are not practical due to the synchrotron radiation, linear colliders are considered: NLC (Next Linear Collider in the U.S.), JLC (Japanese Linear Collider), and ELC (European Linear Collider). The linear colliders may be required to be built back to back in separate linacs, full of high Q superconducting clystrons with a total length of linac tunnels extending 50 to 60 km depending on a practical c-m energy. There would be a very large synchrotron radiation loss from e^+ e^- (e.g. 500 GeV beams) if they are accelerated in a single linac tunnel when the beams are brought into collision by bending magnets.

A circular 2 TeV on 2 TeV muon collider ($\mu^+\mu^-$beams) would have negligible synchrotron radiation energy loss due to the fact that the loss is down by a factor of $(m_\mu / m_e)^4$ relative to an e^+ e^- collider. Precision of beam enegies with a muon collider would allow small beam momentum spread, thus production of particles at threshold could be studied. Another important factor with a muon collider is that the muon, being a heavy lepton, would have a factor of $(m_\mu / m_e)^2$ higher Higgs production cross section relative to an electron-positron collider of the same c-m energy. Proton colliders, on the other hand, require a factor of 5 to 10 higher c-m energy relative to a muon collider due to the fact that only a fraction of the proton energy goes to quark-quark, quark-gluon and gluon-gluon interactions.

The muon lifetime is about 0.044 second when the muons are accelerated to 2 TeV, benefiting from the relativistic gamma factor. This time is long enough to cool and accelerate the beams to such an energy. As we will discuss later, collider rings can be filled 10-15 times a second, and the beams can be brought into collision 1000 times per fill, helping to provide high luminosities.

Many advantages of a muon collider were discussed above excepting the fact that no muon collider has been built to date. There have been many good calculations and studies done on machine design, background calculations and detector considerations. Some of these issues will be discussed in the next sections. There is a good group of physicists who are planning to do experiments using protons from the Fermilab main injector which is under construction. There will be production and cooling studies in the coming years.

2. Some Physics Possibilities at Muon Colliders

Depending on the energy of the muon collider some of the physics possibilities can be summarized in the following:

<u>For s ≤ 500 GeV</u>
$t\bar{t}$ threshold physics, W W threshold physics, associated Higgs production
$\mu^+\mu^- \rightarrow Z^* \rightarrow Zh^0$, and s-channel production of Higgs;

<u>for 2TeV ≥ s ≥ 500 GeV</u>
W W scattering, Technicolor and SUSY Spectroscopy;

<u>for s ≥ few TeV</u>
SUSY breaking scale and extended Technicolor scale can be explored.

Figure 1 shows two possible Feynman diagrams, one for s-channel production of $\mathcal{H}, \mathcal{A}$ MSSM Higgs bosons, and the second one for strong W W scattering in $\mu^+\mu^-$ collisions. Estimated cross sections for the associated production of Higgs and background levels are shown[2] in Figure 2.

3. 2 + 2 TeV Muon Collider

A muon collider feasibility study was done at a Fermilab Workshop [3]. An overview of a 2 on 2 TeV collider is shown in Fig.3. It was developed after a series of meetings and workshops [3],[5],[6],[7]. The leading institutions have been BNL, FNAL, and LBNL. More details of the figure will not be given here since it is self explanatory. Muon cooling is an essential part of such a collider, therefore it will be briefly considered here. Some of the relevant accelerator parameters to this paper are given in Table 1 below.

Table 1. Some Parameters of a 4 TeV c-m Energy Muon Collider

Maximum c-m Energy (TeV)	4
Repetition rate (Hz)	15
Time between collisions (μs)	12
rms beam size at IP (micron)	2.8
Luminosity life time (No.turns)	900
Pulse length (mm)	3
Luminosity	10^{35} cm^{-2} s^{-1}

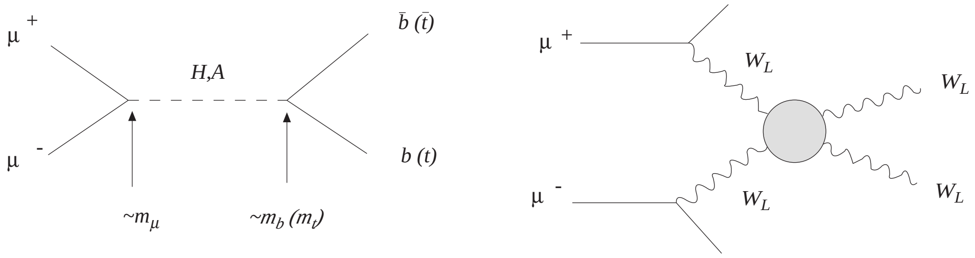


Figure 1. a) s-channel diagrams for production of $\mathcal{H}, \mathcal{A}$ MSSM Higgs, b) strong W W scattering in muon collisions.

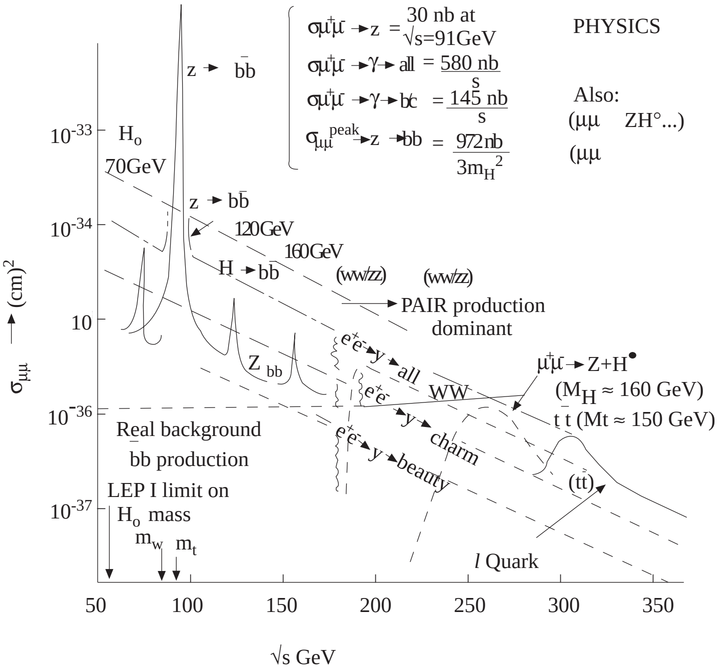


Figure 2. Estimated cross sections and backgrounds for Higgs production for various Higgs mass.

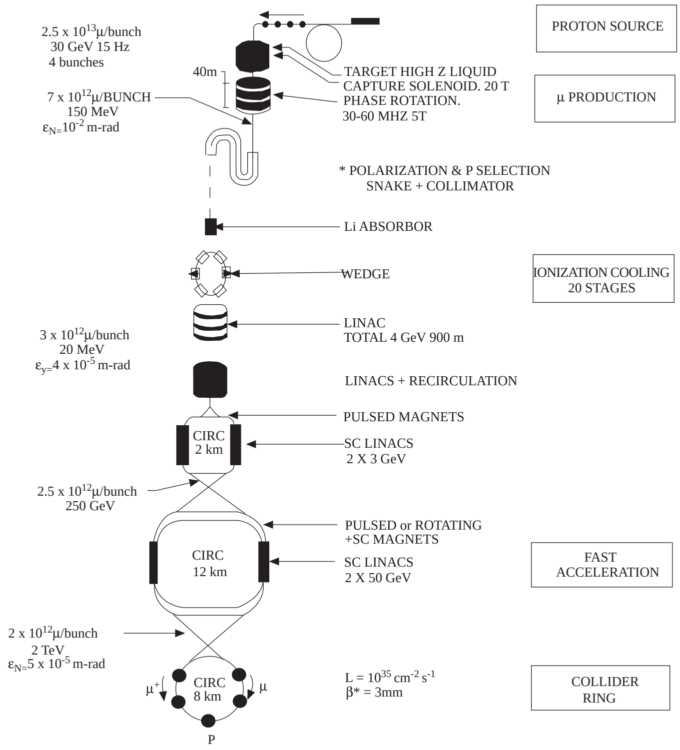


Figure 3. An overview of a 2+2 TeV muon collider.

4. Ionization Cooling

Due to the slowness of electron beam or Stochiastic cooling, ionization cooling is proposed to be used for cooling of muons. Principles of the ionization cooling are given by V.V.Parkhomchuk and A.N.Skrinsky [8] and D.Neuffer [9]. For this to succeed, low energy pion beam emittance should be as small as possible, the pions should be produced by hundreds of GeV protons through perhaps a Lithium target under a very high magenetic field (about 20 T), and the pions should decay in a strongly focused channel. Then the muons can be accelerated and spread in momenta before passing through wedges in succession as shown in Fig.4. Higher momenta muons would go through longer path of material and lower momenta muons would go through shorter paths. This way they would have longitudinal cooling at each stage. Weakly interacting muons allow such a special cooling. Accelerating and focusing the beams, together with the wedge cooling, may produce a very small beam size with a very short bunch length as estimated in the Table 1.

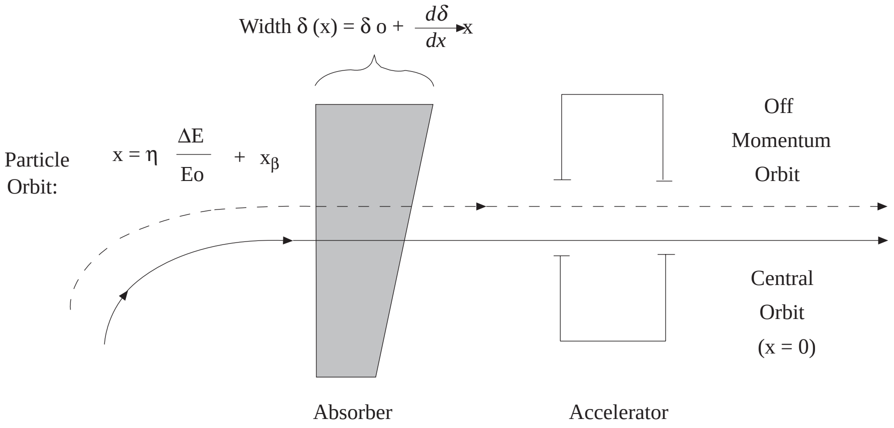


Figure 4. A schematic view of the ionization cooling.

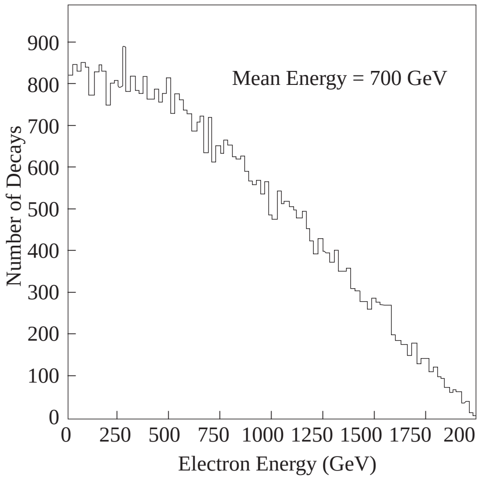
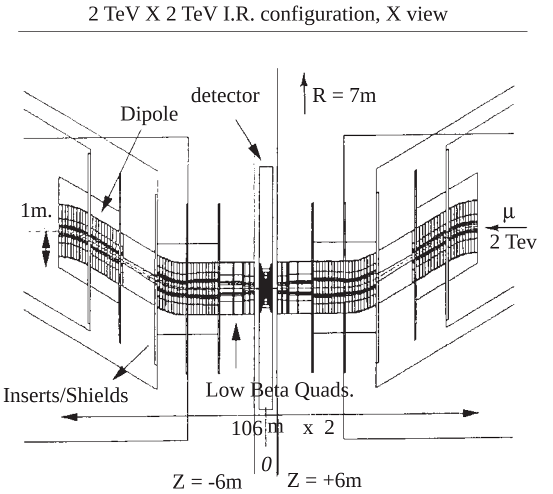


Figure 5. Energy distribution of the decayed electrons from 2 TeV muons as a function of frequency.

5. Background and Detectors

It is expected to have substantial background at the intersection region where the detector components are going to be exposed, depending on how cleaverly the region within 50 meters from the intersection point is designed. We would have 2x 10^5 decays/ m from 2x 10^{12} muons per bunch. Fig.5 shows the number of decays as a function of energy of electrons. At 2 TeV, the mean energy of electrons from the decay is about 700 GeV. Such high energy electrons can produce large backgrounds by interacting with the magnets and detector components. In the last two years a large number of physicists from Fermilab and BNL [9] have been working on the background and the detector issues. C.Johnstone, Fermilab, has been designing the magnet components near the intersection region and N.Mokhov, Fermilab, using MARS Code and I.Stumer, BNL, using GEANT Code, in calculating the background for a given lattice design. The Fermilab and BNL goup's team effort has reduced the background in the detector region by almost two orders of magnitute in two years. High field dipole magnets together with low-beta quadrupoles have produced the lowest background so far. Very much out of proportion of the lattice design around the intersection region is shown in Fig.6. All the magnets shown in the figure are lined with tungsten absorbers to minimize the heat loss in the magnets and to reduce the background around the intersection region. Fig.7 shows how well the electrons from the decayed muons are swept away from the detector region.



* Dipoles are 15 m. long, segmented in 10 straight sections.

* 1.5 m. radius Iron inserts are sed as shields
Also implemented are 15 cm. thick Tungsten absorbers.
All magnets have 2 cm. Tungsten liners.

Figure 6. Estimated cross sections and backgrounds for Higgs production for various Higgs mass.

Major backgrounds are produced by electron showers, synchrotron radiation, photonuclear interactions and Bethe-Heitler muons. Background fluence as a function of radii per bunch crossing is shown in Fig.8. The background rate in the detector appears to be better than the rate in the LHC (Large Hadron Collider) detectors (ATLAS and CMS) at CERN. A sketch of a general purpose detector[10] is shown in Fig.9. The figure shows specially designed tungsten nose cones very close to the intersection region to minimize the background in the detector. We start with semiconductor pixel tracker, and semiconductor strip detectors and segmented TPCs (Time Projection Chambers) for high resolution tracking within a solenoidal magnet. The author has started doing R&D on SI-SiC semiconductors with the hope that they could become future radiation hard semiconductor detectors for high luminosity and high multiplicity tracking. Poly-Boron and concrete have been added wherever practical to moderate the neutrons. The type of EM and Hadron calorimeters are under consideration at this time.

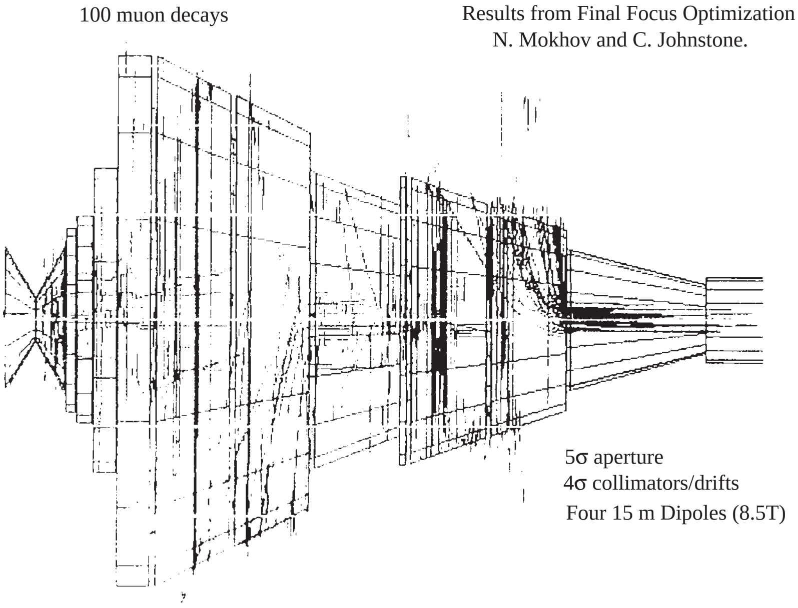


Figure 7. Estimated cross sections and backgrounds for Higgs production for various Higgs mass.

Due to the large background, to select vertex originated tracks, a muon collider detector must have directional triggering capability with the tracking systems. This can be done using a vertex-semiconductor pixel tracker. S.Geer, [11] Fermilab, has proposed doublets of pixel trackers which are 2mm apart (Fig.10). This way very large gamma ray background (average energy of gamma ray background is around 1 MeV) can be eliminated using coincidence between the two layers of pixels. It is a very small probability for a 1 MeV gamma to interact with the vertex tracker, and when it converts to an electron, the electron curls between the two layers under a 2 T solenoidal field, thus it could not make a coincidence.

A directional muon trigger could be provided by a directional muon jet-chamber proposed by the author during the 1996 Snowmass Summer Study [12]. The concept is shown in Fig.11. We can have 25 cm drift spacing with such a directional jet chamber due to 12 microsecond bunch crossing time.

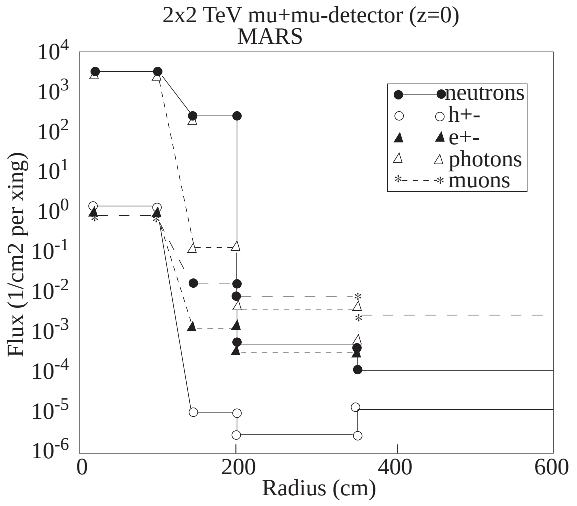


Figure 8. Background fluence as a function of the radii.

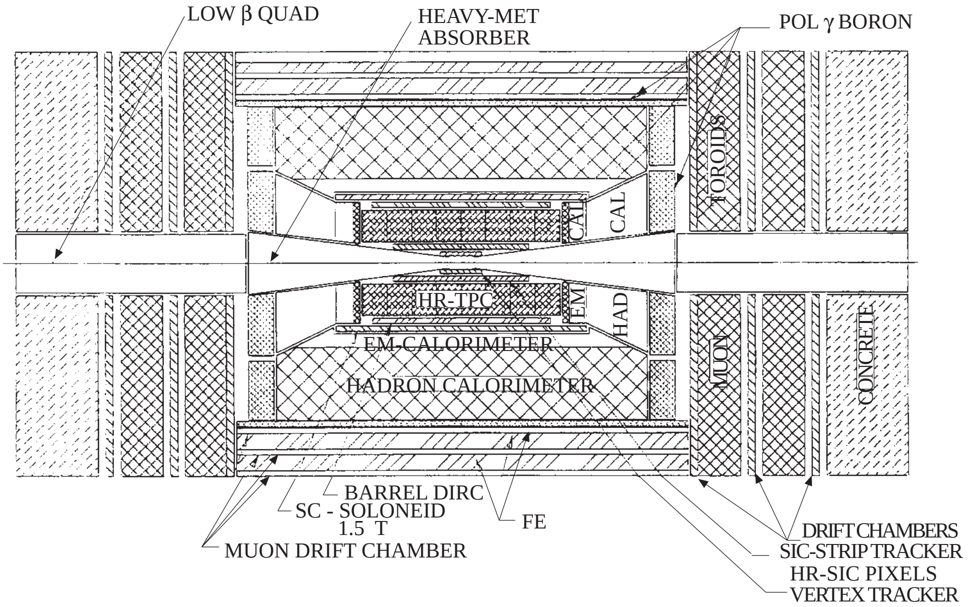
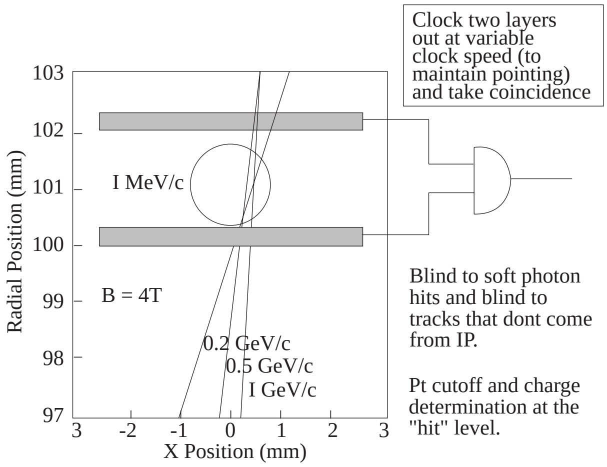


Figure 9. Cross section view of a general purpose muon collider detector.

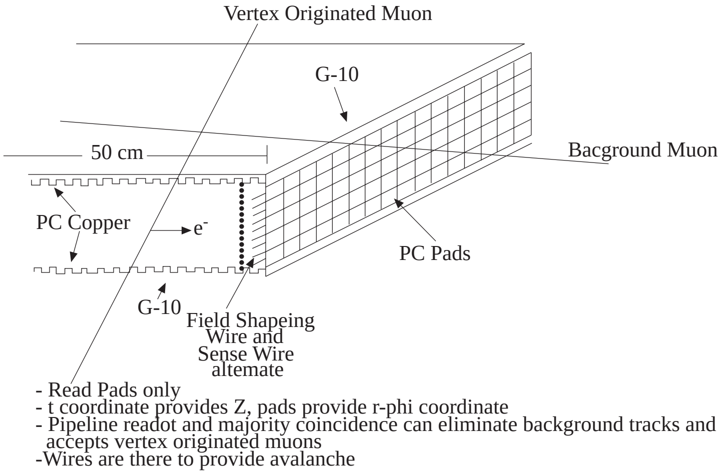


Clock two layers out at variable clock speed (to maintain pointing) and take coincidence

Blind to soft photon hits and blind to tracks that dont come from IP.

Pt cutoff and charge determination at the "hit" level.

Figure 10. Schematic view of a pixel detector doublet for selecting vertex originated tracks. It removes unwanted low energy gamma-ray background by coincidence between the layers.



- Read Pads only
- t coordinate provides Z, pads provide r-phi coordinate
- Pipeline readot and majority coincidence can eliminate background tracks and accepts vertex originated muons
-Wires are there to provide avalanche

Figure 11. A sketch of the directional muon jet chamber that can remove almost parallel coming Bethe-Heitler muons and select vertex originated muons.

Due to the large number of hits per anode wire, we do not read the wires at all; pad readout only. Depending on the background fluence, the gap between anode and pad planes and the pad size can be chosen. We can select vertex originated muons and neglect the background tracks using simple majority coincidence between the signals obtained from the pads. Vertex originated tracks can be chosen by the timing measurements. 25 cm drift spacing would require relatively high voltage. For this reason, we need fairly deep grooves between the field shaping strips. The deep grooves can prevent the surface discharge probability between the strips. The author called this design a "Groovy Chamber." For a muon chamber we could use thick G-10 plates with deep grooves between the Cu-strips.

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