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Muon Colliders: A Scenario for the Evolution of the Fermilab Accelerator Complex

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Muon Colliders: A scenario for the evolution of the Fermilab accelerator complex

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We outline the evolutionary steps necessary to build a muon collider at Fermilab early in the 21st Century. We propose a well-defined program to upgrade the Fermilab accelerator complex in which the present facilities are enhanced with the development of an intense proton source and a muon storage ring neutrino source (Step 1), followed by the first muon collider (Step 2), and finally a site–filling 4 TeV muon collider (Step 3). For each step we describe the required facility upgrade, siting issues, the evolution of the physics program, and a strawman schedule. This report was presented to the new Fermilab director for his perusal.

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I. INTRODUCTION

This document describes the conceptual steps necessary for the evolution of the Fermilab accelerator complex in order to make the Muon Collider a reality. The approach described here offers a gradual building of the complex with new physics possible at each step along the way and in some sense is similar to the evolution that has taken place over the years at Cornell. Such a gradual approach has the advantage of spreading the costs associated with building the machine over many years during which a cutting edge physics program can be carried out. In addition, it utilizes and capitalizes on the superb proton accelerator technology base that exists at Fermilab. If successful, it would ensure that the physics program at Fermilab will survive well past the turning on of the Large Hadron Collider at CERN.

The first stage for the program would be to construct a 16 GeV, 15 Hz booster in a manner that would ultimately be used for a muon collider. A derivative benefit of this step would be to increase the protons available for the on-going physics program at Fermilab. One of the by-products of the studies to cool and store muons has been the prospect of generating intense neutrino beams of variable energy and well-determined initial flavor content. Such muon storage rings only require a modest amount of cooling and hence could offer an initial testing ground in learning how to build and operate muon collection and cooling systems. Neutrino oscillation physics and the prospect of observing CP-violation in neutrino mixing would provide sufficient justification by themselves for this initial step.

The second stage proposes the construction of the FMC, the first muon collider. This requires that the R&D program has demonstrated the feasibility of a very intense muon source. The proton source upgrade in this step will require increasing the linac energy to 1 GeV and adding a small compressor ring to the booster. At this point, the muon source would be upgraded to its final configuration, and the energy of the FMC would be dictated by knowing the mass scale to be studied. If the Higgs boson is light, it would have been discovered by then. Several unique features of the muon collider come into play for this first machine which could be built to study the Higgs boson properties. Since muons are 200 times heavier than electrons, the s-channel Higgs production cross section becomes 40,000 times greater than for e^+e^- collisions, and is accessible at a muon collider. Also the large mass of the muons almost eliminates synchrotron radiation in the collider ring and beamstrahlung at the collision point, leading to the possibility of precisely defining the initial state energy. Finally the spin precession of the muon enables the precision measurement of its energy and opens the possibility of a high resolution study of Higgs-like objects. The last two features would also apply to the study of thresholds such as W^+W^- and $t\bar{t}$ production. This first step at muon collisions is to be seen as a learning experience in operating muon colliders and the cost of accelerating the muons and building a low energy collider ring will certainly be much less than the next step, the construction of a high energy collider.

The third stage would be to push the collider ring to the ultimate energy possible at the Fermilab site. Since the source is complete, this means upgrading the muon accelerator and the collider ring. This ultimate energy will probably be set by limits imposed on it by radiation from interactions in the earth of neutrinos from muon decay in the collider ring. This is a unique problem for this type of machine, and much work needs to be done to study ways to ameliorate the problem. Present studies show that machines of center of mass (CoM) energies of 3-4 TeV should be feasible and fit on Fermilab site, if buried at a depth of $\approx$ 200 m. See Figure 1 which shows the plan of a 3 TeV CoM Muon Collider on the Fermilab site.

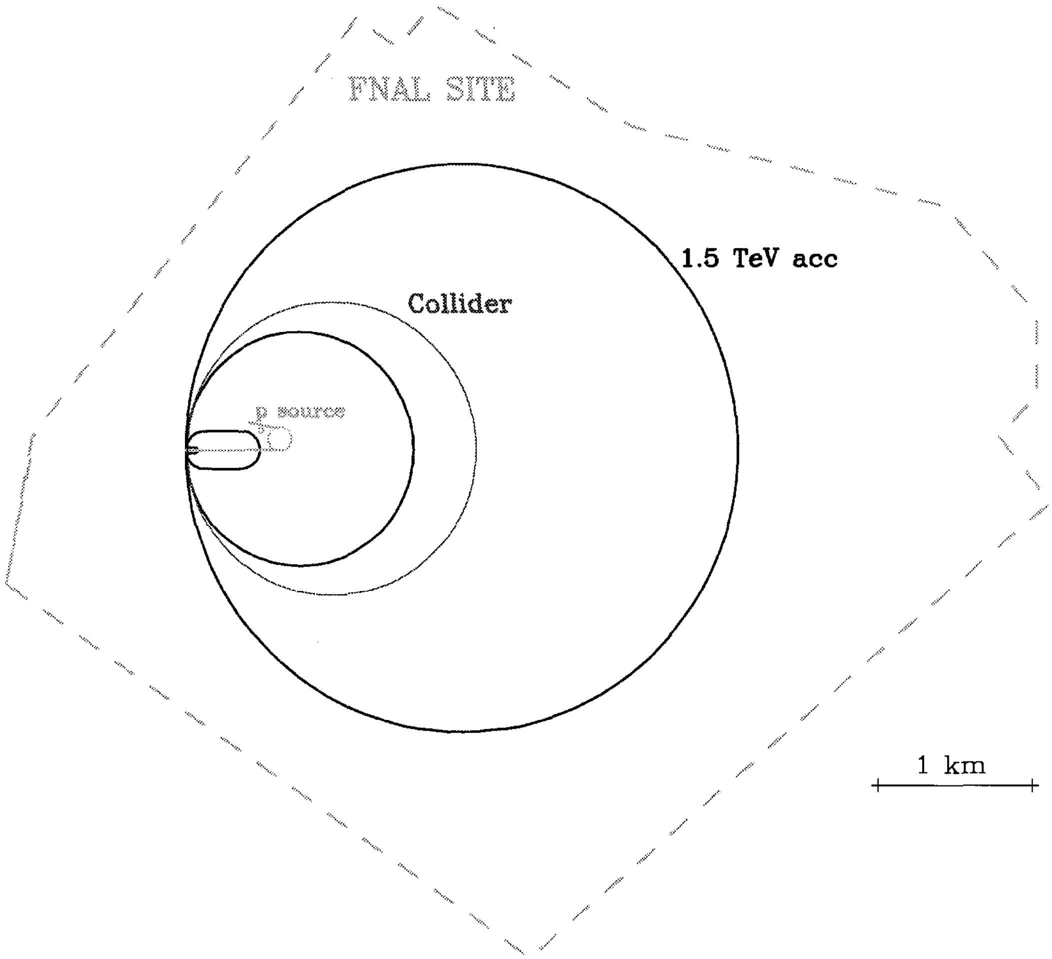

FIG. 1. Plan of a 3-TeV-CoM muon collider shown on the Fermi National Laboratory site as an example.

It should be emphasized that this report is not a proposal to build such a facility. It presupposes at the outset that a high luminosity collider can be built and that the backgrounds in the detector can be controlled to a level that the physics can be carried out. Neither has yet been shown to be true although the studies at this point have not revealed any insurmountable problems. It ignores many problems such as how the international community would become involved in this activity and how its construction would interact with the ongoing physics program. It also is not a document from the Muon Collider Collaboration although we have drawn heavily from this work.

This is a site-specific document that is intended to furnish a reference for the community at large in the hopes that the ideas outlined here can be refined and modified into a form that will lead to a future facility at Fermilab. There are many unanswered problems connected with the cooling process itself, many unanswered questions about the machine configuration and siting, as well as issues involving the physics and detector. These questions need further effort and manpower devoted to them. We hope that this document will stimulate that work.

An overview of the current state of understanding of the muon collider can be found in the status report [1]. In formulating a muon collider staging scenario, we have begun with the conclusions from the workshop [2] on "Physics at the First Muon Collider and Front–end of a Muon Collider" that was held at Fermilab in November 1997. This workshop surveyed the physics that could be done at Fermilab using the accelerator complex at the "front–end" of a muon collider, and considered the physics potential of the first muon collider (FMC).

II. PHYSICS POTENTIAL OF MUON COLLIDERS

We outline briefly here the salient features of muon colliders that give them potential advantages over electron-positron colliders. They are,

- Greater compactness and energy reach– Muon Colliders promise center of mass energies of 3 TeV or higher, while remaining relatively compact in size.
- Ability to form narrow Higgs-like particles in the s-channel.
- Narrow energy spreads that permit the scanning of such narrow resonances and the ability to measure the energy of the beam to precisions of a part in 10^6 using $g-2$ precession [3]. Both the beams are polarizable; polarizations per beam of 30% are easy to achieve.
- Ability to scan thresholds such as the $t\bar{t}$ threshold to extract the top quark mass and other parameters with high CoM energy precision, as a result of lower initial state radiation and beamstrahlung.

Figure 2 shows the Breit-Wigner peak that would be observed in the s-channel for a 110 GeV/c^2 Standard model Higgs boson for various beam-energy spreads. In the narrow energy spread mode (beam spread 0.01%), the central peak is significantly enhanced. The point here is that the muon collider permits beam spreads that are significantly narrower than the corresponding e^+e^- case. Figure 3 shows the ability of the muon collider to scan the nearly degenerate higher mass Higgs of the Minimal Supersymmetric extension of the Standard model (MSSM) and differentiate between the two states. The degenerate states will occur in the decoupling limit of the MSSM. If this is what nature has chosen, neither the LHC nor the e^+e^- collider will be able to separate these states.

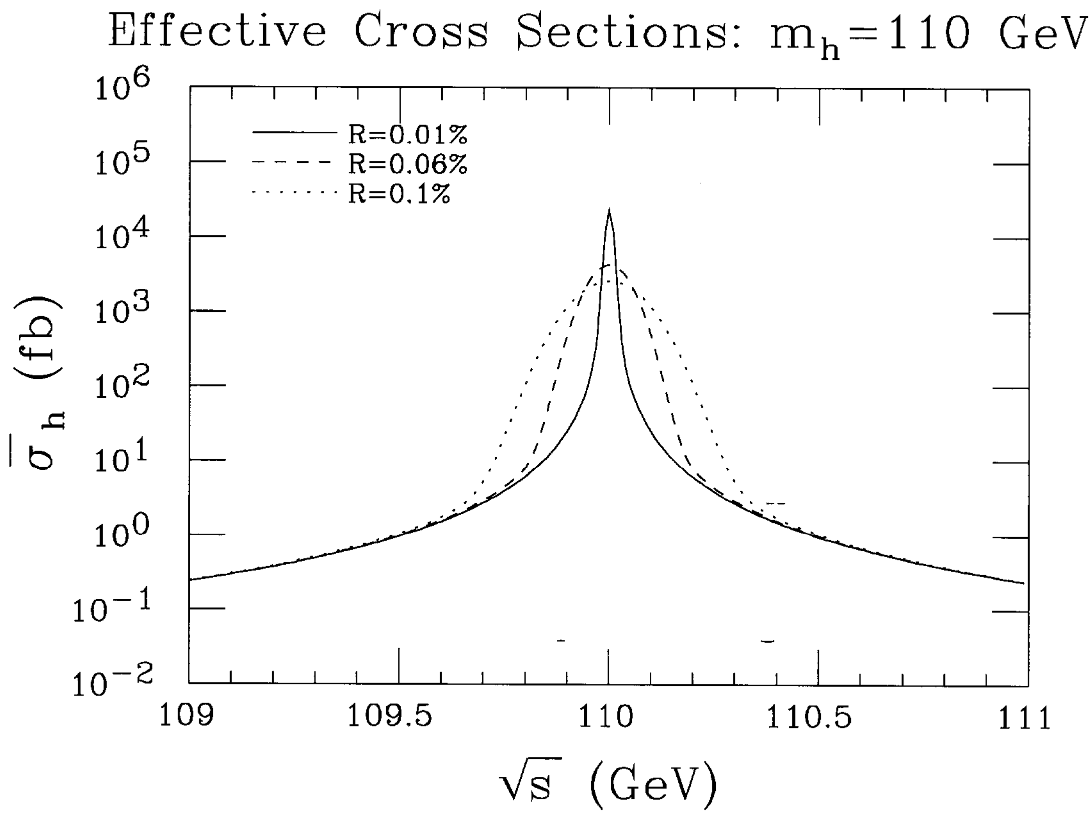

FIG. 2. Effective s-channel Higgs cross section $\bar{\sigma}_h$ obtained by convoluting the Breit-Wigner resonance formula with a Gaussian distribution for resolution R. From Ref. [4].

Figure 4 shows the ability of the muon collider to scan the $t\bar{t}$ threshold to extract information about the top quark mass, α_s and other quantities. The bump in the cross section below the $t\bar{t}$ threshold is due to a set of broad toponium resonances, whose position is con-

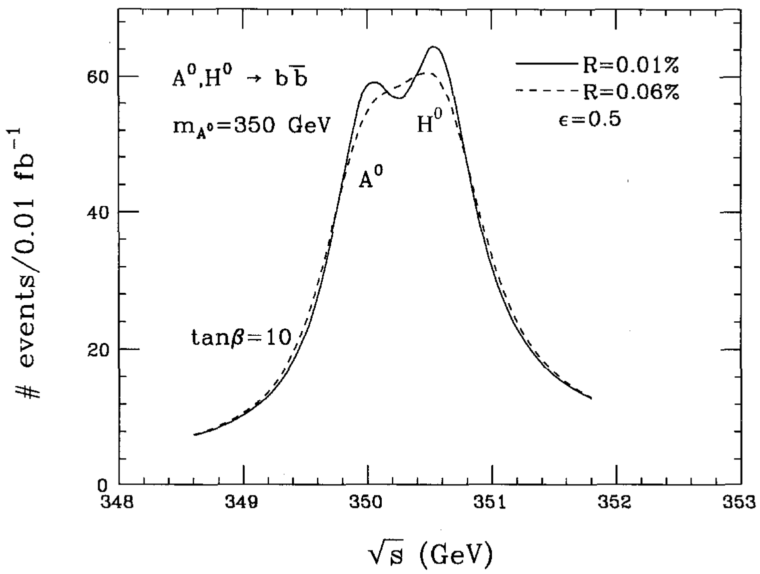

FIG. 3. Separation of A^0 and H^0 signals for $\tan\beta = 10$. From Ref. [4].

trolled by the value of α_s. The muon collider has narrower energy spreads and less initial state radiation than e^+e^- collider, leading to sharper threshold curves and better accuracies in the determination of $t\bar{t}$ threshold parameters. It is worth noting that apart from the WW threshold, the top quark threshold is the only guaranteed piece of physics for a 500 GeV CoM lepton collider. If the threshold for new physics is indeed higher than this, the muon collider becomes increasingly attractive, cost effective and incrementally upgradable.

Figure 5 shows the production cross section of SUSY scalar particles, comparing them to the Higgs pair production cross sections. Since these cross sections are P-wave suppressed, it becomes necessary to go significantly above the threshold to measure them. This again argues for the ability to reach higher center of mass energies with manageable incremental cost.

It may well be that nature has chosen new strong interactions between the electroweak gauge bosons to break electroweak symmetry. The muon collider would explore processes such as shown in figure 6 at high energies to study strong WW scattering.

Along the way to the FMC, it is possible to do neutrino physics using muon storage rings that produce intense neutrino beams of well defined flavor content that can be used

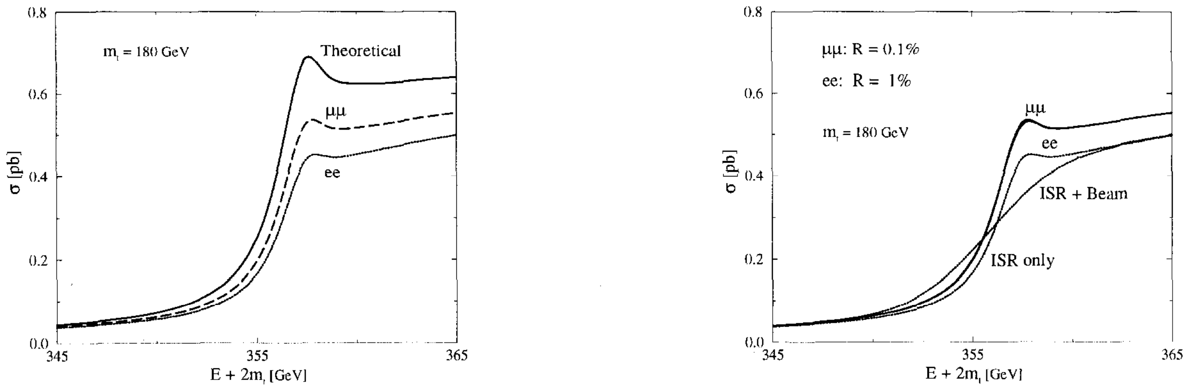

FIG. 4. (a)*left hand figure* Top quark threshold curve for e^+e^- and $\mu^+\mu^-$ with and without initial state radiation effects. (b) *right hand figure* Top quark threshold curve for e^+e^- and $\mu^+\mu^-$ with initial state radiation and beamstrahlung effects.

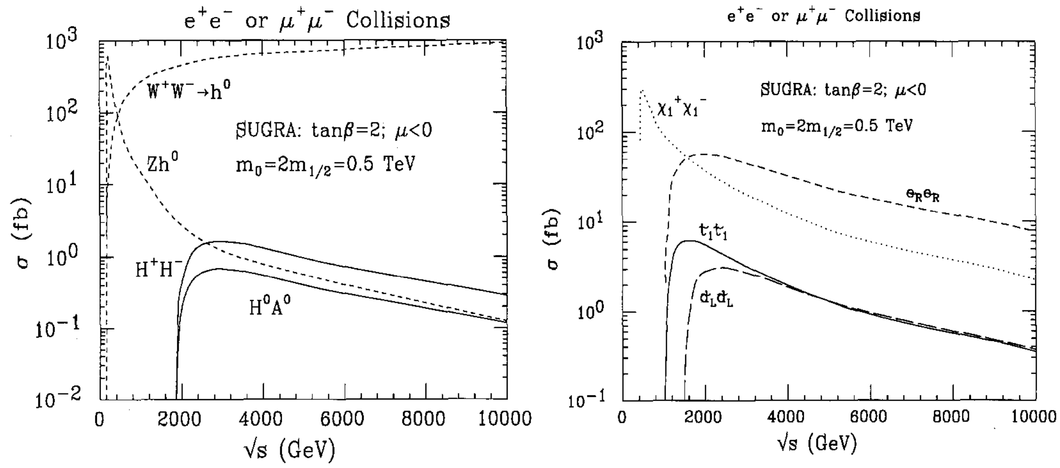

FIG. 5. Cross sections for pair production of Higgs bosons and scalar particles at a high-energy muon collider. From Ref. [5].

to study neutrino oscillations $\nu_\mu \to \nu_e, \nu_\tau$, and $\nu_e \to \nu_\tau$. See figure 7 to get an idea of the reach of muon storage rings in exploring the neutrino oscillation parameter space. Shown are the plots for $\nu_e \to \nu_\tau$ oscillations as a function of energy of the storage ring, and as a function of number of events observed for a given storage ring energy. By changing the sign of the stored muon beam, it becomes feasible to explore CP violation in the lepton sector. CP violation in the lepton sector is likely to become a hot topic in the future.

In what follows, we describe a three step approach to building muon colliders at Fermilab. For each step, we describe the upgrades needed to the facility, and an approximate timescale

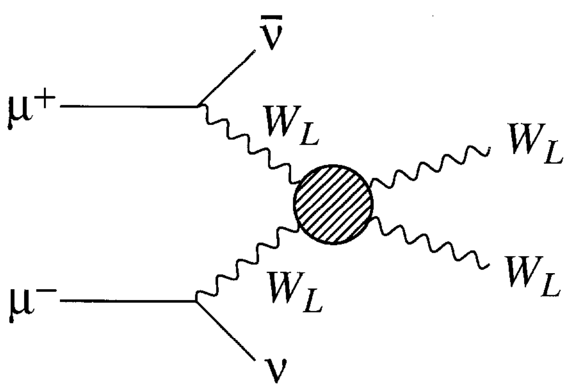

FIG. 6. Symbolic diagram for strong WW scattering.

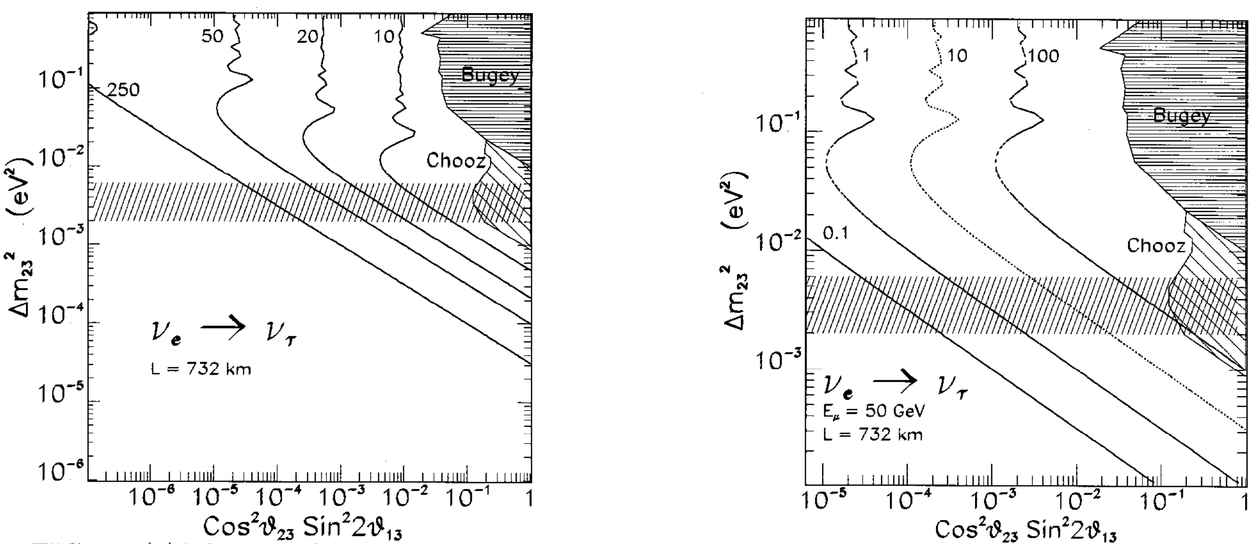

FIG. 7. (a)*left hand figure* Single event contours as a function of the momentum of the muon storage ring in Δm^2, effective mixing angle space for $\nu_e \to \nu_\tau$ oscillations. The baseline is from Fermilab to Soudan. Shown are limits established by reactor based experiments. (b) *right hand figure* Limit contours as a function of the number of events observed in Δm^2, effective mixing angle space for $\nu_e \to \nu_\tau$ oscillations, for a 50 GeV muon storage ring. The horizontal hatched area is the region of interest for current oscillation models.

for its realization. In the final section, we describe the R&D needed to achieve our goals.

III. STEP 1: PROTONS, MUONS, AND NEUTRINOS

In the first step towards a high energy muon collider, a muon storage ring neutrino source is constructed. This will facilitate the next generation of neutrino experiments beyond the currently approved program, provide an intense muon R&D facility for muon collider design studies, and offer some optional additional physics facilities (intense stopped muons, stopped pions, intense low energy kaons).

A. Step 1: Facility Upgrade

Figure 8 shows a schematic of the components needed for a muon storage ring neutrino source [6–8]. The Step 1 facility upgrade consists of enhancing the proton source, adding an intense muon source and an intense neutrino source. The muon source will require a pion production target and capture system, a pion decay channel, and a muon cooling channel. The neutrino source will require a muon acceleration system, and a muon storage ring. These upgrades are very similar in character to what would be required by the First Muon Collider (Step 2), although the proton intensities and the amount of cooling needed would be smaller.

1. The Proton Source Upgrade – The Proton Driver

A 1997 summer study [9] explored the possibility of upgrading the existing proton source at Fermilab so that it can deliver the very short intense proton bunches needed at the front end of a muon collider. As a follow-up to that study, a team has been formed in the Beams Division. The charge to this team is to complete a technical design report (TDR) of a new proton source, which is also called the proton driver [10].

The overall upgrade would consist of: (1) a new 16 GeV Booster in a new tunnel, (2) a new 1 GeV linac and, (3) a new 3 GeV Pre-booster. The goal is to increase the proton intensity by a factor of 20 (up to 1×10^{14} protons per pulse) and the beam power by a factor

TABLE I. Evolution of the proton source parameters in the scenario described in the text.

	Present	Phase 1	Phase 2
Linac (operating at 15 Hz)			
Kinetic energy (MeV)	400	400	1000
Peak current (mA)	40	45	80
Pulse length (μs)	25	90	200
H^- per pulse	6.3×10^{12}	2.5×10^{13}	1×10^{14}
Pre-booster (operating at 15 Hz)			
Extraction kinetic energy (GeV)			3
Protons per bunch			2.5×10^{13}
Number of bunches			4
Total number of protons			1×10^{14}
Normalized transverse emittance (mm-mrad)			200π
Longitudinal emittance (eV-s)			2
RF frequency (MHz)			7.5
Booster (operating at 15 Hz)			
Extraction kinetic energy (GeV)	8	16	16
Protons per bunch	6×10^{10}	3×10^{11}	2.5×10^{13}
Number of bunches	84	84	4
Total number of protons	5×10^{12}	2.5×10^{13}	1×10^{14}
Normalized transverse emittance (mm-mrad)	15π	50π	200π
Longitudinal emittance (eV-s)	0.1	0.1	2
RF frequency (MHz)	53	53	7.5
Extracted bunch length σ_t (ns)	0.2	0.2	1
Target beam power (MW)	0.1	1	4

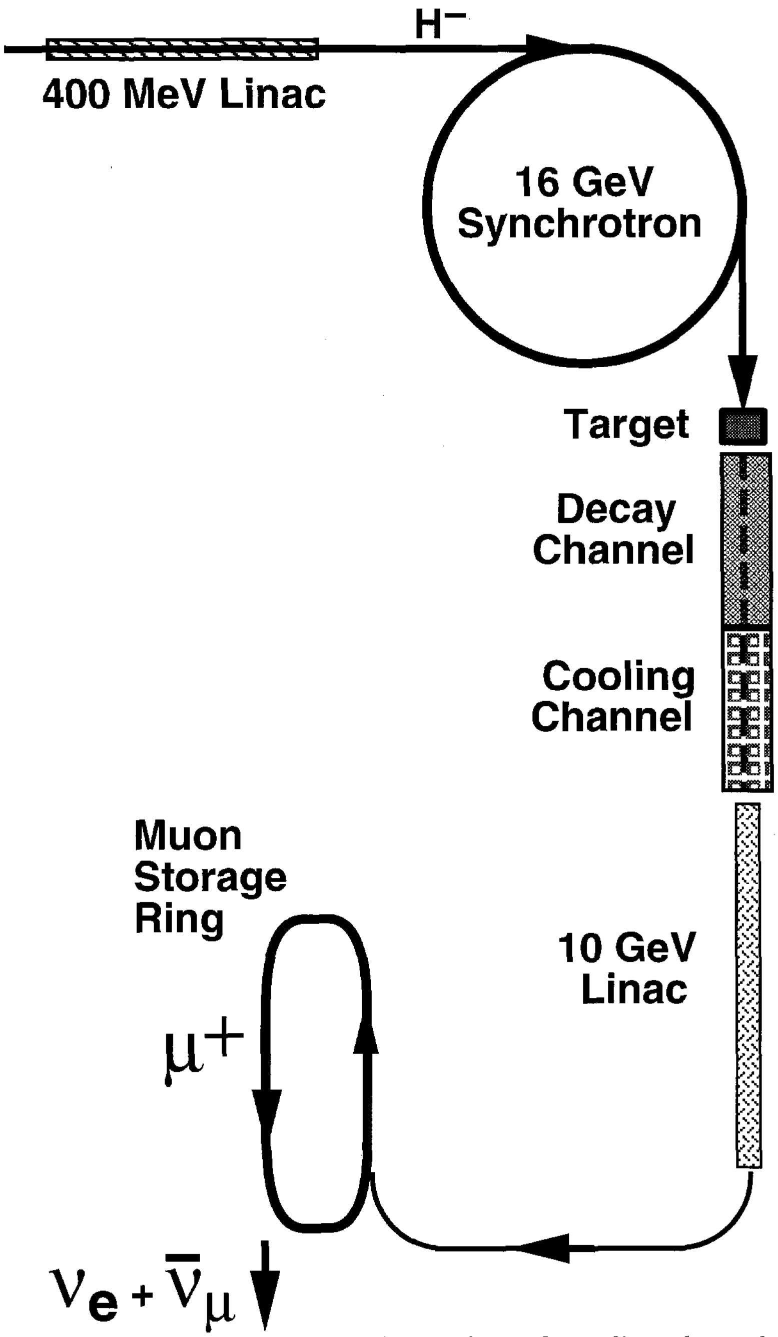

FIG. 8. Schematic of the muon production, decay channel, cooling channel, acceleration linac, and muon storage ring system discussed in the text.

of 40 (up to 4 MW) above the present proton source. The bunch length would be 1-2 ns (rms) at exit.

The implementation of the proton driver would be staged. In Phase 1, a new Booster would be built in a new beam enclosure, while the present 400 MeV linac would still be used as the injector. The repetition rate is 15 Hz as it is now. The present 8 GeV transport line tunnel would house a 400 MeV beamline delivering the linac beam to the new booster. This phase would have a factor of 5 in beam intensity upgrade and a factor of 2 in beam energy upgrade, which gives 10 times the beam power compared to the the present booster. It should be pointed out that Phase 1 would cause minimal disruption to Run II and other HEP programs at Fermilab, because most of the construction and installation work would be carried out in a separate tunnel. In Phase 2, a new linac and a new Pre-booster would be built. It would give another factor of 4 increase in beam intensity. The machine parameters of the present and upgraded proton source are listed in table I.

Phase 1 of the proton driver is part of the Step 1 facility upgrade (a muon storage ring neutrino source), whereas Phase 2, which is part of the Step 2 and 3 facility upgrade (a muon collider), could be delayed until later. In Phase 1, about 4×10^{21} protons would be available for the pion production target in an operation year (10^7 sec).

Note that up to five times more protons per minute could be available to the booster fixed target experiment and for acceleration in the Main Injector than could be provided by any reasonable upgrades to the present 8 GeV booster. The feasibility of accelerating a factor of five more protons in the MI is analyzed in Ref. [11] where it is found to be possible with modest MI upgrades. The Antiproton Source would also probably need upgrades (in the targetry, for instance) to take advantage of the increased intensity.

2. The Muon Source and Acceleration

In our scenario for the evolution of the Step 1 facilities at Fermilab, we will adopt the muon source and acceleration scheme described in Refs. [6,7], summarized in table II, and discussed in the following paragraphs.

We begin by considering the pion production target. The proton beam power for the Step 1 source is ~ 1.2 MW. Although large, this is only 30% of the beam power needed for a high luminosity muon collider [1]. Hence, the Step 1 upgrade would be able to exploit the target technology being developed for a muon collider, and would offer the possibility of constructing, testing, and operating a less demanding version of the target required for the FMC. The current muon collider target concept consists of using a liquid metal jet injected into a 20 T solenoid. The high–field solenoid captures almost all of the charged pions that are produced in the downstream direction. See figure 9 for a schematic of the pion capture and phase-rotation system.

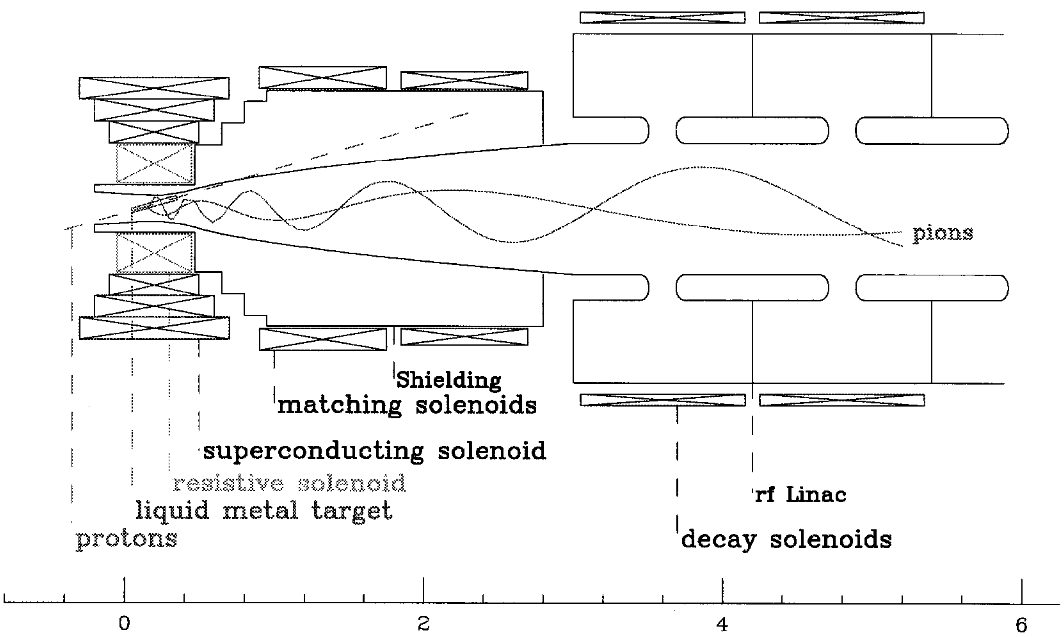

FIG. 9. Schematic view of pion production, capture and initial phase rotation. A pulse of 16 GeV protons is incident on a skewed target inside a high-field solenoid magnet followed by a decay and phase rotation channel.

The 16 GeV protons interact in the target to produce, per incident proton, approximately 0.6 charged pions of each sign captured within the solenoidal channel. To collect as many pions as possible within a useful energy interval, it is proposed to use rf cavities to accelerate the lower energy particles and decelerate the higher energy particles. Muons are produced

TABLE II. Muon source parameters and acceleration parameters for a muon storage ring neutrino source at Fermilab.

Pion Target	
π^- bunches per cycle	12
π^- captured per proton	0.6
π^- captured per year (10^7 secs)	2.8×10^{21}
Decay Channel	
μ^- bunches per cycle	12
μ^- captured per proton	0.2
μ^- captured per year (10^7 secs)	9×10^{20}
Mean muon energy (E)	250 MeV
Energy spread (σ_E/E)	0.15
Bunch length (σ_z)	1.5 m
Transverse Emittance (ϵ_N)	0.017 m-rad
Cooling Channel	
Cooled μ^- bunches per cycle	12
μ^- cooled per year (10^7 secs)	8.1×10^{20}
Mean muon energy (E)	230 MeV
Energy spread (σ_E/E)	0.20
Bunch length (σ_z)	2 m
Transverse Emittance (ϵ_N)	0.005 m-rad
Acceleration	
μ^- bunches per cycle	$16 \times 12 = 192$
μ^- accelerated per year (10^7 secs)	4.7×10^{20}
Mean muon energy (E)	10 GeV
Energy spread (σ_E/E)	0.004
Bunch length (σ_z)	1 cm

when the pions decay. At the end of a 50 m long decay channel [1], consisting of a 1.25 T solenoid, on average 0.2 muons of each charge would be produced for each proton incident on the pion production target. Hence, in each accelerator cycle the Step 1 muon source would produce 6×10^{12} muons of the desired charge at the end of the decay channel. In an operational year (10^7 secs) about 9×10^{20} muons would be produced in the decay channel and collected.

Simulations of the muon source described above have been made as a part of the muon collider feasibility studies being pursued by the muon collider collaboration [1]. The simulations predict that the muons exiting the decay channel would be captured within bunches with rms lengths $\sigma_Z = 1.5$ m, would have a mean energy of 250 MeV ($p_\mu = 227$ MeV/c), an energy spread $\sigma_E/E \sim 15\%$, and would populate a very diffuse transverse phase space corresponding to a normalized transverse emittance $\epsilon_N \sim 0.017$ m-rad. The transverse emittance is too large to fit within the acceptance of an acceleration and storage ring system. In order to reduce ϵ_N by a factor of ≈ 3, there are a few cooling sections similar to the type being developed by the MUCOOL collaboration [12] downstream of the decay channel in figure 8. The solenoids initially provide a field of 1.2 T, increasing down the channel to about 3 T as the emittance decreases towards the end of the channel. The beam loss within the cooling channel is calculated to be about 10%. At the end of the cooling channel there would be about 5.4×10^{12} muons of the desired charge available per accelerator cycle, contained within 12 bunches, each with rms lengths $\sigma_Z \sim 2$ m, a mean energy of 230 MeV, an energy spread $\sigma_E/E \sim 20\%$, and a normalized transverse emittance $\epsilon_N \sim 0.005$ m-rad. Hence, there would be 8.1×10^{20} cooled muons per operational year.

Downstream of the cooling channel, the scheme described in Refs. [6,7] uses a two–stage 805 MHz rf system to capture and accelerate muons from a long bunch with a broad energy distribution into 16 stable bunches with an interbunch spacing of ~ 0.375 m. The first stage consists of a 140 m long linac with $V_{rf} = 15$ MV/m and a central accelerating phase $\phi_s = 30°$. This stage captures the muons exiting the cooling channel, and provides the initial acceleration up to an energy $E_\mu = 1$ GeV. To keep the beam confined transversely, this first accelerating stage would consist of a string of rf cavities within a 5 T solenoid channel. The second acceleration stage described in Refs. [6,7] consists of a 500 m long linac with $V_{rf} = 20$ MV/m and $\phi_s = 60°$. In principle this second stage could use a recirculating linear accelerator (RLA) rather than a straight linac. In Refs. [6,7] the second stage accelerates the muon bunches to 10 GeV, and uses a quadrupole channel with a FODO lattice to provide transverse focusing. Approximately 60% of the muons exiting the cooling channel are expected to be captured within the rf buckets of the linac, and accelerated to 10 GeV. The final bunch lengths are given by $\sigma_z \sim 1$ cm, and the rms energy spreads are given by $\sigma_E/E \sim 4\%$. At the end of the last acceleration stage there are 4.7×10^{20} muons per operational year.

3. The Muon Storage Ring Neutrino Source

The muon storage ring needed to create an intense neutrino beam consists of two long straight sections connected together by two arcs. One of the straight sections is used for injection and extraction to a beam dump. The other straight section provides the neutrino beam, and must therefore point in the appropriate direction. It is desirable that the straight sections are long and the arcs are compact, so that a large fraction of the muons circulating in the storage ring decay within the neutrino beam–forming straight section. In our scenario for the evolution of the Step 1 facilities, we will adopt the design described in Refs. [6,7] for a 10 GeV storage ring with a circumference of 448 m, and 150 m long straight sections. Hence, about one third of the muons decay whilst traveling in the desired direction, and there are 1.6×10^{20} muon decays per operational year within the neutrino beam–forming straight section of the storage ring.

B. Step 1: Siting Issues

Figure 10 shows the accelerator enclosures needed for Step 1. The sizes of the proton source enclosures are taken from Fig. III.1 of Ref. [9]. The 16 GeV Booster is located as

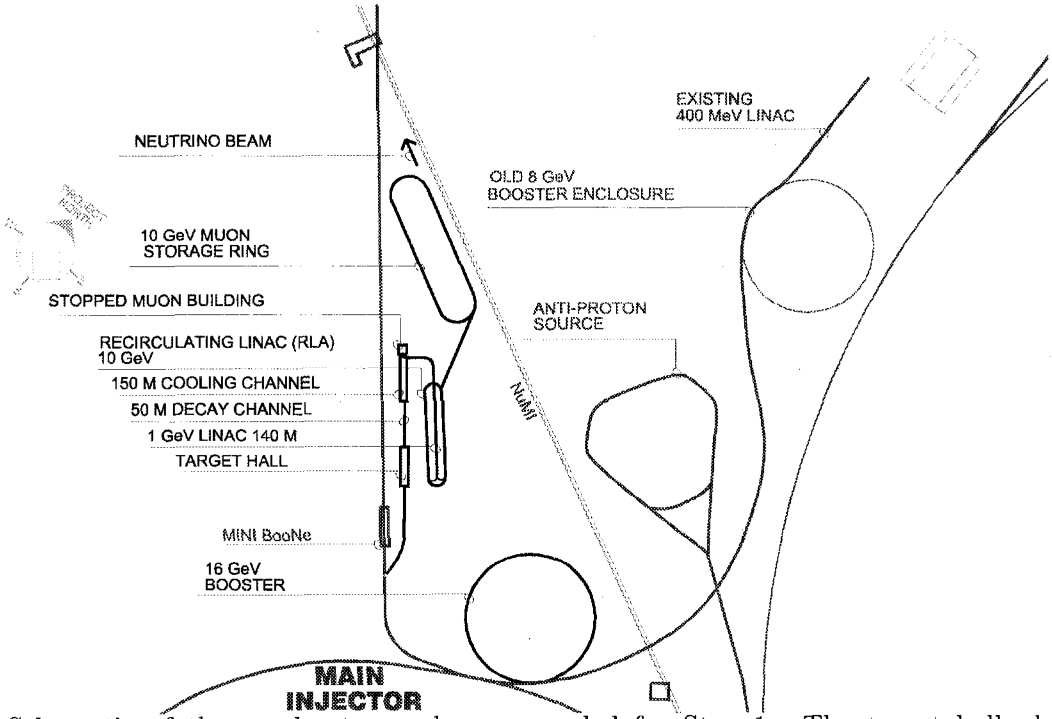

FIG. 10. Schematic of the accelerator enclosures needed for Step 1. The target hall, decay channel, muon cooling channel, and acceleration systems are sited in a field near MiniBooNE. The stopped muon building is optional, depending on whether stopped muon physics is of sufficient interest to drive this addition to the program.

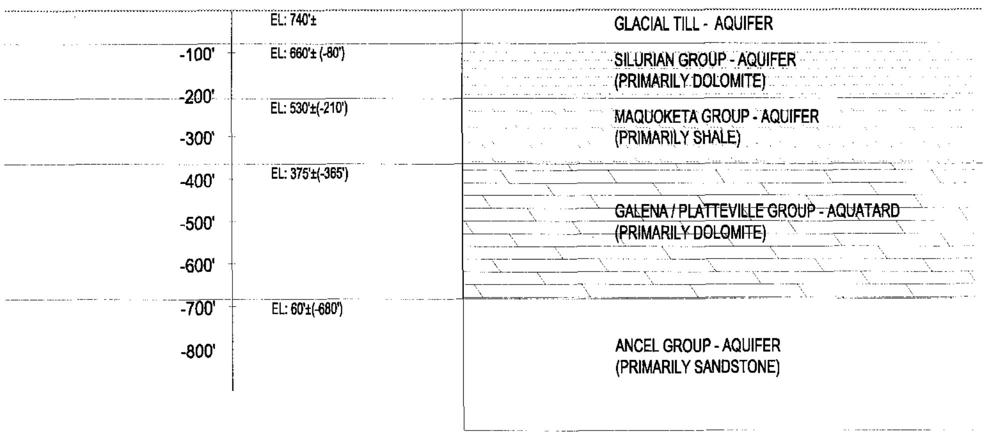

FIG. 11. Schematic of the geological layers below the Fermilab site.

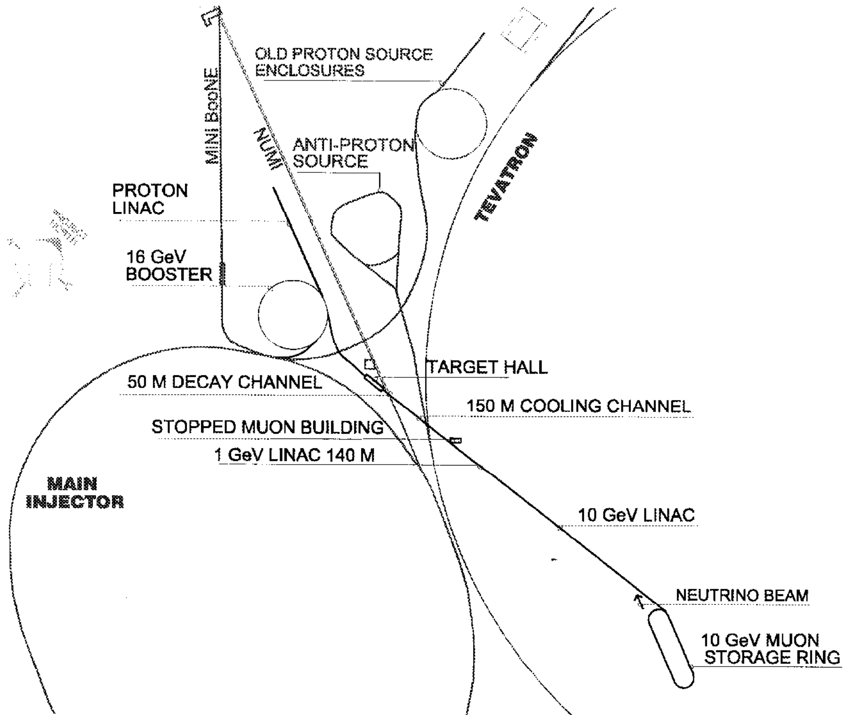

FIG. 12. Schematic of an alternative location for the accelerator enclosures needed for Step 1, with the target hall, decay channel, cooling channel, and acceleration systems installed in a long straight tunnel.

TABLE III. Directions (dip and heading), baseline lengths (L), and the elevation change from the center of one arc to the center of the opposite arc (Δx), listed for some interesting far sites for long baseline neutrino oscillation experiments. Numbers from Ref. [13]

	L (km)	Dip (Degrees)	Heading (Degrees)	Δx (feet)
Fermilab $\to$ Soudan	732	3	336	34
Fermilab $\to$ Gran Sasso	7332	35	50	370
Fermilab $\to$ Kamioka	9263	47	325	470

close as is reasonable upstream of the Main Injector injection point. Note that the present design of the proton beam transport to MiniBooNE allows for an upgrade to enable the transport of a 16 GeV beam, and also allows for a switch to send beam to an area other than MiniBooNE, which we take to be the target station for the Step 1 muon source. We presently propose to use this area to conduct the MUCOOL [12] experiment. The new Booster is fed by the currently existing 400 MeV Linac using the MI8 beam enclosure with a new beam transport. Downstream of the target hall and decay channel, the muon cooling channel is shown within a single 50 m long building. Following the cooling channel, a linac is shown which accelerates the muons to 1 GeV, followed by a recirculating linac (RLA) to accelerate the muons to 10 GeV. The extraction line from the RLA goes to a 10 GeV muon storage ring neutrino source, with a neutrino beam–forming straight section pointing at the Soudan Mine in Minnesota. Other interesting directions are summarized in table III.

The siting of the 10 GeV muon storage ring has not been carefully considered because it is not sufficiently constrained at this time. A ring producing a neutrino beam pointing at Soudan could be located near the surface based on cut and fill, or it could be located at a depth similar to NuMI. The elevation change from one arc to the opposite arc is significant for rings tilted at large angles, and this must be considered in deciding where to place a neutrino source pointing towards Europe or Japan, for example (see table III). The geology below Fermilab is well known (see Fig. 11). Our present understanding is that the vertical region below the surface that is "good" for blast and drill tunneling begins at a depth of about 150 ft, in the middle of the Silurian Group, and extends down to about 650 ft, close to the bottom of the $\sim$ 330 ft thick Galena/Platteville dolomite layer. Hence, the elevation change from the top to the bottom of a steeply tilted ring should not exceed about 500 ft. This "vertical acceptance" seems sufficient to accommodate a 10 GeV muon storage ring neutrino source pointing to Gran Sasso, or even the Kamioka mine.

One possible disadvantage of the configuration shown in Fig. 10 is that the Fermilab physics program would be interrupted whilst the new 16 GeV beam transport is installed in the MI8 enclosure. Figure 12 shows an alternative Step 1 configuration which uses a completely new set of enclosures for the new Proton Source, and also houses the muon cooling channel in a tunnel aligned with the decay channel and the 10 GeV acceleration systems. The muons are transported to a muon storage ring on the inside of the Tevatron ring. Note that the Linac and 16 GeV Booster are both in new beam enclosures. If the existing 400 MeV Linac was replaced with a new Linac one could consider continuing the ongoing physics program until the new Proton Source is functional. At that time, the 16 GeV beamline from the new Booster would be connected to the very downstream end of the MI8 enclosure and the physics program could then be continued with up to five times the hourly beam intensity. The particular location of the Proton Source shown in the figure is somewhat arbitrary, but this location minimizes the length of the extraction line to the downstream end of the MI8 enclosure. In principle, one could locate the new Proton Source further away from the Main Injector injection point and construct a longer extraction beamline without compromising performance.

C. Step 1: Physics Program

In our Step 1 scenario, a greatly extended neutrino oscillation physics capability is the primary enhancement to the Fermilab physics program. It seems likely that in the next decade neutrino oscillations will remain a "hot physics topic". It is hoped that the next generation of approved neutrino experiments at Fermilab (MINOS and MiniBooNE) will establish the oscillation phenomenon, and perhaps begin to sort out the neutrino flavor mixing scheme, and measure the associated parameters. If this is the case, we can anticipate that a further generation of experiments at improved neutrino facilities will be required to better constrain the underlying neutrino masses, and to measure the mixing matrix that relates the neutrino flavor eigenstates to the mass eigenstates. Knowledge of these fundamental parameters may yield insights into physics at high energy scales (sea–saw mechanism ?) and into the origin of CP Violation (Is there CP violation in the neutrino system ?). Hence, in the following we focus on the impact of Step 1 on the neutrino physics program at Fermilab,

TABLE IV. Summary of neutrino charged current event rates per kt-year at Soudan for three tunes of the NUMI beamline with 3.7×10^{20} POT per year, compared with various muon storage ring neutrino source options. The ν_τ rates assume $\nu_\mu \to \nu_\tau$ oscillations with $\sin^2 2\theta = 1$. Note that the fiducial mass of the MINOS detector is 5.4 kT, so in one year of data taking the MINOS experiment would see 5.4 times the number of events shown in the table.

Option	ν_μ	ν_e	$\overline{\nu_\mu}$	$\overline{\nu_e}$	ν_τ ($\Delta m^2 =$ 0.01 eV^2/c^4)	ν_τ ($\Delta m^2 =$ 0.001 eV^2/c^4)
Minos: Low Energy	458	5.4	64	1.3	27	0.5
Minos: Medium Energy	1439	13	45	0.9	135	2.6
Minos: High Energy	3207	18	34	0.9	312	4.1
μ–ring: 10 GeV μ^-	2217	–	–	958	259	4.6
μ–ring: 10 GeV μ^+	–	2035	1214	–	143	2.5
μ–ring: 15 GeV μ^-	7827	–	–	3377	893	12.1
μ–ring: 15 GeV μ^+	–	6631	3952	–	451	6.2
μ–ring: 20 GeV μ^-	18685	–	–	8016	1775	21.5
μ–ring: 20 GeV μ^+	–	15915	9526	–	906	11.0

and only briefly discuss the other physics possibilities.

1. Muon Storage Ring Neutrino Source

Muon storage ring neutrino sources offer the possibility of providing intense neutrino beams that (a) have precisely known fluxes, (b) are flavor pure (there is initially only one flavor of neutrino and one flavor of antineutrino in the beam), (c) have equal amounts of ν_μ and $\overline{\nu_e}$ (or ν_e and $\overline{\nu_\mu}$), and (d) if needed could be pointed downwards at large angles to send

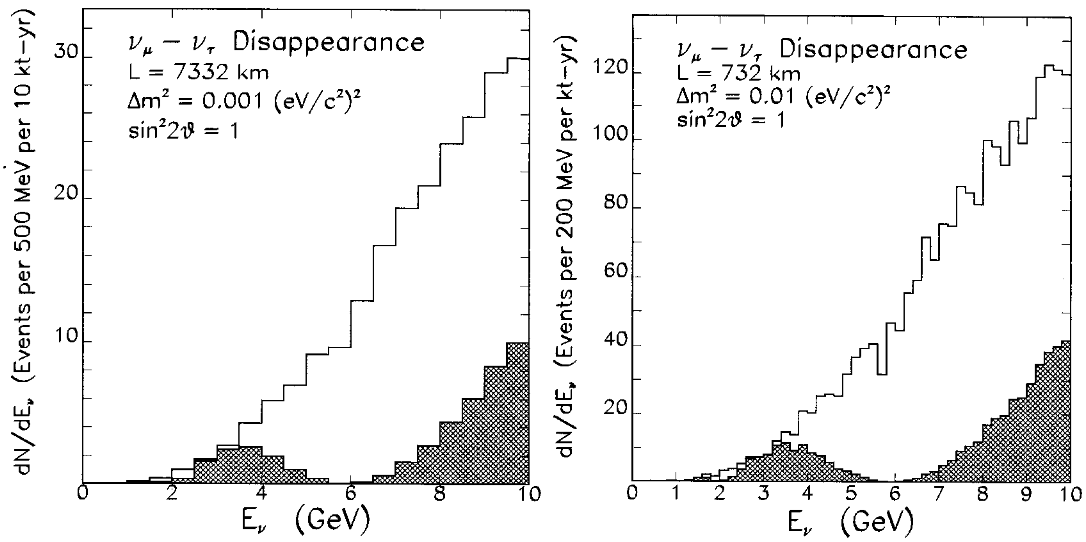

FIG. 13. Predicted signal for $\nu_\mu \to \nu_\tau$ disappearance using a 10 GeV muon storage ring neutrino source at Fermilab pointed towards the Gran Sasso underground laboratory (*left hand figure*) and the Soudan Minnesota mine (*right hand figure*), assuming a 10 kt–year exposure. The open histogram is the prediction for the energy dependent CC interaction rate with no oscillations, and the shaded histogram is the prediction with oscillation parameters $\Delta m^2 = 0.001$ eV^2/c^4 (*lhs*), $\Delta m^2 = 0.01$ eV^2/c^4 (*rhs*) and $\sin^2 2\theta = 1$.

a neutrino beam through the Earth (table III). The optimum beam energy and baseline length for a future generation of neutrino oscillation experiments using a muon storage ring neutrino source will depend on, for example, the results from the MINOS experiment.

With the muon storage ring located at Fermilab, neutrino fluxes at the Soudan mine in Minnesota (L = 732 km), and at the Gran Sasso underground laboratory in Italy (L = 7332 km), have been computed [14,15]. Downstream of the 10 GeV Step 1 muon storage ring, the annual neutrino and antineutrino fluxes at the distant sites are calculated to be 8×10^{11} m^{-2} and 8×10^{9} m^{-2} for respectively L = 732 km and 7332 km. If the finite muon beam divergence within the straight section of the storage ring is included in the calculation, the fluxes at the far sites are decreased by ~10%. With these fluxes, in the absence of neutrino oscillations, there will be $\sim 2.2 \times 10^4$ ($\sim 2.2 \times 10^2$) charged current ν_μ interactions per operational year in a 10 kt detector at L = 732 km (L = 7332 km).

To illustrate the physics potential of a 10 GeV muon storage ring neutrino source with a baseline length of 7332 km (Fermilab $\rightarrow$ Gran Sasso), consider a search for $\nu_\mu \rightarrow \nu_\tau$ oscillations, and assume that Δm^2 is at the lower end of the range suggested by the Super–Kamoikande results ($\Delta m^2 \sim 0.001$ eV^2/c^4 with $\sin^2 2\theta = 1$). With the muon storage ring neutrino beam described above, the predicted ν_μ disappearance signal at Gran Sasso is shown in Fig. 13 (*left hand figure*). The oscillation signal is striking. With no oscillations, 221 ν_μ CC interactions per 10 kt–yr would be expected. With oscillations this number is reduced to 45 ν_μ CC interactions per 10 kt–yr, with a very different energy spectrum.

To illustrate the physics potential of a 10 GeV muon storage ring neutrino source with a baseline length of 732 km (Fermilab $\rightarrow$ Soudan), consider a search for $\nu_\mu \rightarrow \nu_\tau$ oscillations, and assume that Δm^2 is towards the upper end of the range suggested by the Super–Kamoikande results ($\Delta m^2 \sim 0.01$ eV^2/c^4 with $\sin^2 2\theta = 1$). In this case the MINOS experiment should establish a convincing disappearance signal. With the muon storage ring neutrino beam described above, the predicted ν_μ disappearance signal at Soudan is shown in Fig. 13(*right hand figure*). The oscillation signal is striking. With no oscillations, 22170 ν_μ C-C interactions per 10 kt–yr would be expected. With oscillations this number is reduced to 4470 ν_μ CC interactions per 10 kt–yr, with a very different energy spectrum. In addition, in a 1 kt hybrid emulsion detector, 259 ν_τ CC interactions would be expected per operational year. Note that if the charge of the τ lepton is also measured, then $\nu_\mu \rightarrow \nu_\tau$ oscillations can be distinguished from $\nu_e \rightarrow \nu_\tau$ oscillations, and the sensitivity for $\nu_e \rightarrow \nu_\tau$ oscillations would be comparable to the sensitivity for $\nu_\mu \rightarrow \nu_\tau$ oscillations ... a unique physics capability of the muon storage ring neutrino source. Finally, other Fermilab $\rightarrow$ Soudan muon storage ring scenarios are summarized in table IV.

2. Other Physics Possibilities: Low energy Kaon and Muon physics

The proton source required for the FMC would allow a continuation of low and intermediate energy kaon physics with intensities a factor of 20 more than presently available at the AGS, and a factor of a few greater than foreseen at the Fermilab MI, an upgraded

AGS, or the proposed KEK JHF. Rare kaon decays and precision kaon CP and CPT studies can provide windows on physics beyond the Standard Model and are likely to remain of interest well into the future. As an example consider the rare decays $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$. Precise measurements of these decay modes would enable a precise determination of V_{td} and the CP violation parameter η. The first $K^+ \to \pi^+\nu\bar{\nu}$ event has been reported by the BNL E787 collaboration. The decay $K_L \to \pi^0\nu\bar{\nu}$ has not yet been observed. Future experiments at the AGS and at the Fermilab MI may yield a few of these rare K^+ and K_L decays per year. It has been estimated [16] that at the muon collider proton source of order 100 events per year could be observed in each mode. However, this kaon physics program would require the addition of a stretcher ring to the FMC proton source. Other interesting kaon experiments that might be pursued include muon transverse polarization in $K^+ \to \pi^0\mu^+\nu_\mu$ or $K^+ \to \mu^+\nu_\mu\gamma$, spin–spin correlations in $K^+ \to \pi^+\mu^+\mu^-$, and polarization effects in $K_L \to \mu^+\mu^-$.

The Step 1 muon source would provide low energy muon beams with intensities of 10^{14} μ per second. This is an enormous increase over the fluxes available at current low energy muon beam facilities, which produce typically 10^7–10^8 μ per second. Hence, a small fraction of the muons at the Step 1 facility could be used to support a broad range of low energy muon experiments. Examples are searches for muon–number violation in rare muon decays ($\mu \to e\gamma$, $\mu \to eee$), muonium–antimuonium oscillation, or $\mu \to e$ conversion. However, it should be noted that in general the bunch structure at the muon source is not ideal for low energy muon experiments, which tend to require either a DC muon beam to minimize instantaneous rates or a CW beam with $\sim 2\mu$s between bunches. Further study is needed to assess the real potential for exploiting the extremely high muon intensities at a low energy Step 1 muon facility.

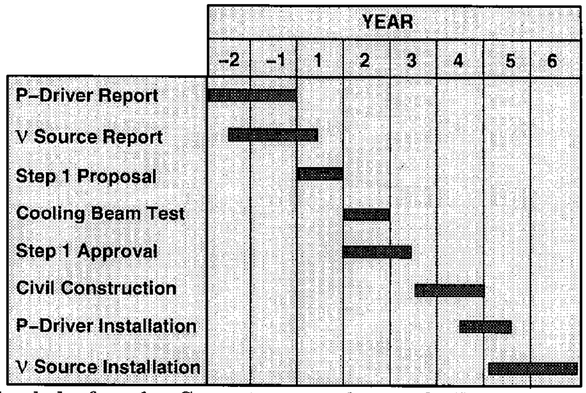

FIG. 14. Speculative schedule for the Step 1 upgrade, with "Year 1" defined as the year in which the Step 1 proposal is finalized and submitted.

D. Step 1: Schedule Considerations

We can only speculate on what might be a plausible schedule for the Step 1 facility upgrade. Nevertheless, attempting to imagine what a reasonable, but aggressive, schedule might be helps to focus on the critical path. A vigorous R&D program will be needed before the Step 1 muon source, acceleration system, and storage ring could be built. We will assume this is undertaken and goes well.

Our speculative schedule is summarized in Fig. 14. A proton driver upgrade design study is currently in progress, with the goal of delivering a design report by the end of 2000. If a similar activity was initiated for a muon storage ring neutrino source, it is plausible that a Step 1 design report could also be available by mid–2001. We can only guess at the time required for approval and construction ... we will guess that 5 years is aggressive but not impossible, with the proton driver upgrade part of the project completed in 3–4 years. Defining "Year 1" as the year in which the Step 1 proposal is finalized and submitted, the ability to accelerate a factor of 5 more protons in the MI would come in "Year 5", and the muon storage ring neutrino source would begin operation in "Year 7".

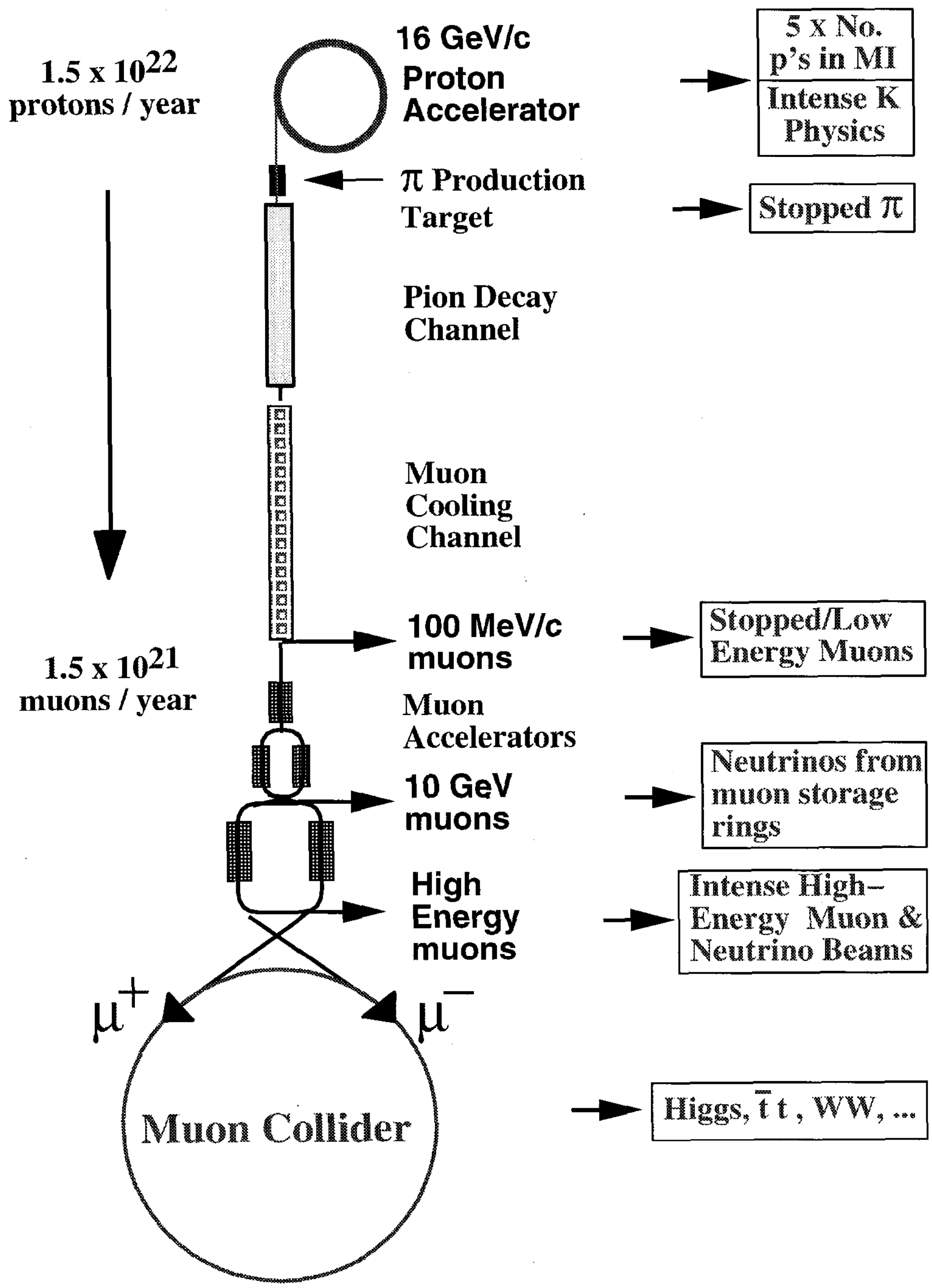

FIG. 15. Schematic showing the components of a muon collider accelerator complex.

IV. STEP 2: THE FIRST MUON COLLIDER

In the following we will assume that the FMC will have a center–of–mass energy between 100 GeV and 500 GeV. To be explicit, we will consider two possible FMC choices, namely:

(a) An s–channel Higgs factory with $m_H = 110$ GeV/c^2, and hence the muon collider beam energies are $E_\mu = 55$ GeV. This scenario makes sense if a Higgs–like boson is discovered before or during early LHC running, and no other new particles have been discovered.

(b) A 500 GeV muon collider ($E_\mu = 250$ GeV). This would be a sensible choice if new particles had been observed within this energy range at, for example, the LHC.

A. Step 2: Facility Upgrade

A muon collider accelerator complex is shown schematically in Fig. 15. The decay channel and parts of the required proton driver, pion production target system, and muon cooling system would be in place from the Step 1 upgrade. Further upgrades to the proton and muon sources would be needed in Step 2, along with the addition of a muon acceleration system, collider ring, and experiment. The Step 2 facility upgrade is summarized in the following.

1. The Proton Driver Upgrade

The Step 2 proton driver upgrade corresponds to Phase 2 upgrade shown in table I, and consists of constructing a new 1 GeV linac and adding a 3 GeV Pre–booster. The upgraded proton driver accelerates protons to 16 GeV, is cycling at 15 Hz, and produces 4 proton bunches per cycle, each containing 2.5×10^{13} particles. The beam power delivered to the target is about 4 MW. The rms bunch length at extraction is 1-2 ns. The latter is a unique feature of the proton driver, which is not required by any other high intensity proton facilities (*e.g.*, the ISIS, PSR, SNS, ESS and JHF).

TABLE V. Parameters of muon bunches downstream of the FMC ionization cooling channel.

	Narrow σ_p	Broad σ_p
muons per bunch	8.5×10^{12}	8.5×10^{12}
μ^+ bunches per cycle	1	1
μ^- bunches per cycle	1	1
Momentum (MeV/c)	200	200
σ_p/p	5%	10%
Bunch length (cm)	1.8	10
Normalized $\epsilon_\perp$ (mm–mr)	200π	60π
Repetition rate (Hz)	15	15
μ^- per year (10^7 secs)	1.3×10^{21}	1.3×10^{21}

2. The Muon Source Upgrade

The Step 2 muon source upgrade consists of upgrading the pion production target to survive the 4 MW proton beam power of the phase 2 proton source, and upgrading the cooling channel with an additional long section to further reduce the 6–dimensional beam emittance for a high luminosity muon collider. The length of this additional cooling section is estimated to be in the range of 400–800 m.

The upgraded muon source will produce muon bunches using two proton bunches extracted from the proton source, and combined to form a super–bunch containing 5×10^{13} protons incident on the pion production target. The first super–bunch would be used to make and collect positive muons, and the second used for negative muons. Each super–bunch interacts to produce $\sim 3 \times 10^{13}$ charged pions of each sign captured within the high field solenoid decay channel. At the end of the decay channel described in section III A 2 there would be 1.7×10^{13} muons per bunch. In an operational year $\sim 5 \times 10^{21}$ muons would

TABLE VI. Muon accelerator parameters for a 2×2 TeV Collider. The acceleration scheme is based on Ref. [1], but modified to produce 2 TeV beams.

	Linac	RLA1	RLA2	RLA3	S1	S2	S3
Input Energy (GeV)	0.1	0.7	2	7	70	250	1250
Output Energy (GeV)	0.7	2	7	70	250	1250	2000
Circumference (km)	0.07	0.12	0.26	2.27	5.81	15	15
No. of Turns	2	8	10	12	18	27	20
Loss (%)	6.1	12.3	10.8	14.6	11.2	9.9	3.0
rf Freq (MHz)	200	100	200	200	800	1300	1300
Acc. Gradient (MV/m)	8	8	10	10	15	25	25
Acc./turn (GeV)	0.40	0.17	0.50	5.25	10	37.5	37.5
Acc. time (μs)		3	8	91	349	1351	1001

exit the decay channel, 2.5×10^{21} in positive muon bunches and 2.5×10^{21} in negative muon bunches. A high luminosity muon collider will require the 6–dimensional phase–space occupied by the muons within the muon bunches exiting the decay channel to be reduced by a factor of 10^5–10^6. This will require a cooling channel that in the current muon collider feasibility study design is about 600 m long. At the end of the cooling channel each muon bunch is expected to contain about 8.5×10^{12} muons with a momentum of order 200 MeV/c, a momentum spread given by $\sigma_p/\mathrm{p} \sim 0.05$, a bunch length $\sigma_Z \sim 1.8$ cm, and a transverse emittance $\epsilon_N \sim 200\pi$ mm-mrad. In an operational year (10^7 secs) there are 1.3×10^{21} muons of each sign exiting the decay channel.

Table V summarizes the properties of the muons at the end of the cooling channel. Note that the phase–space occupied by the muons can be optimized either to maximize the luminosity of the collider, or alternatively to minimize the beam energy spread at the expense of luminosity.

3. Acceleration and the First Muon Collider Ring

The muons exiting the cooling channel must be rapidly accelerated to high energy before they decay. A number of different acceleration schemes have been considered. The one summarized in table VI is based on Ref. [1]. In this scheme the FMC acceleration system would consist of a linac to accelerate the muons to 700 MeV, followed by 3 recirculating linear accelerators (RLAs), to produce muons with energies of up to 70 GeV. For our Higgs factory example the FMC would take beams from RLA3 at 55 GeV. Note that in this case 63% of the muons survive the acceleration system. Hence, there are 5.4×10^{12} muons per bunch available for the Higgs factory. For our 500 GeV muon collider example, 70 GeV beams from RLA3 would be injected into a synchrotron (S1) and accelerated to 250 GeV. In this case 49% of the muons survive, and there are 4.2×10^{12} muons per bunch available for the FMC.

For both the Higgs factory and 500 GeV examples, the high energy muons are injected into the muon collider, which is a storage ring using high–field dipoles to minimize the orbit length and hence maximize the number of revolutions before muon decay has reduced the luminosity to an uninteresting level. The ring is therefore relatively compact. For example, a 110 GeV collider ring would be comparable in size to the existing Antiproton Accumulator ring. A 500 GeV collider ring would be about one–sixth of the size of the existing Tevatron. The FMC average luminosity for a 110 GeV collider would be $L \sim 4 \times 10^{31}$ cm^{-2} s^{-1} with a beam energy spread of 0.01%, or alternatively $L \sim 2 \times 10^{31}$ cm^{-2} s^{-1} with a beam energy spread of 0.003%. The average luminosity for a 500 GeV collider would be $L \sim 1 \times 10^{33}$ cm^{-2} s^{-1} with a beam energy spread of 0.14%.

4. TESLA cavities as a driver for a high energy Muon Collider

The superconducting rf cavities being proposed for the TESLA linear collider [17] permit the acceleration of the comparatively large emittances encountered in muon beams. The

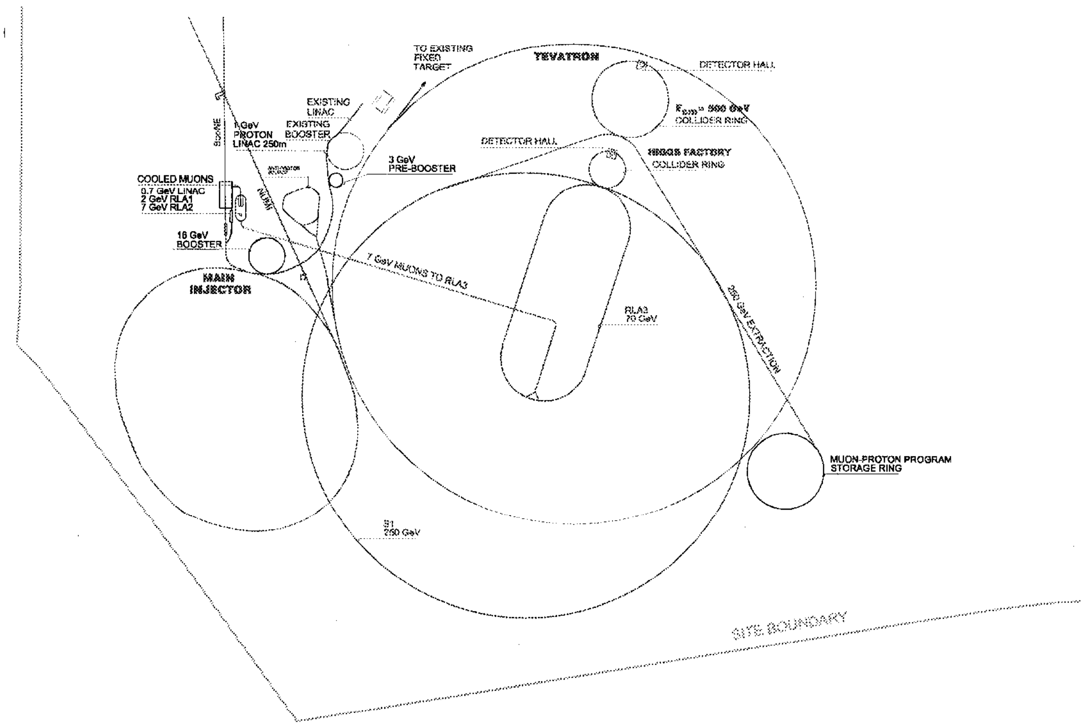

FIG. 16. Schematic of the accelerator enclosures needed for Step 2. RLA3 and the collider rings are located in the Dolomite layer below Fermilab. The μp collider is optional.

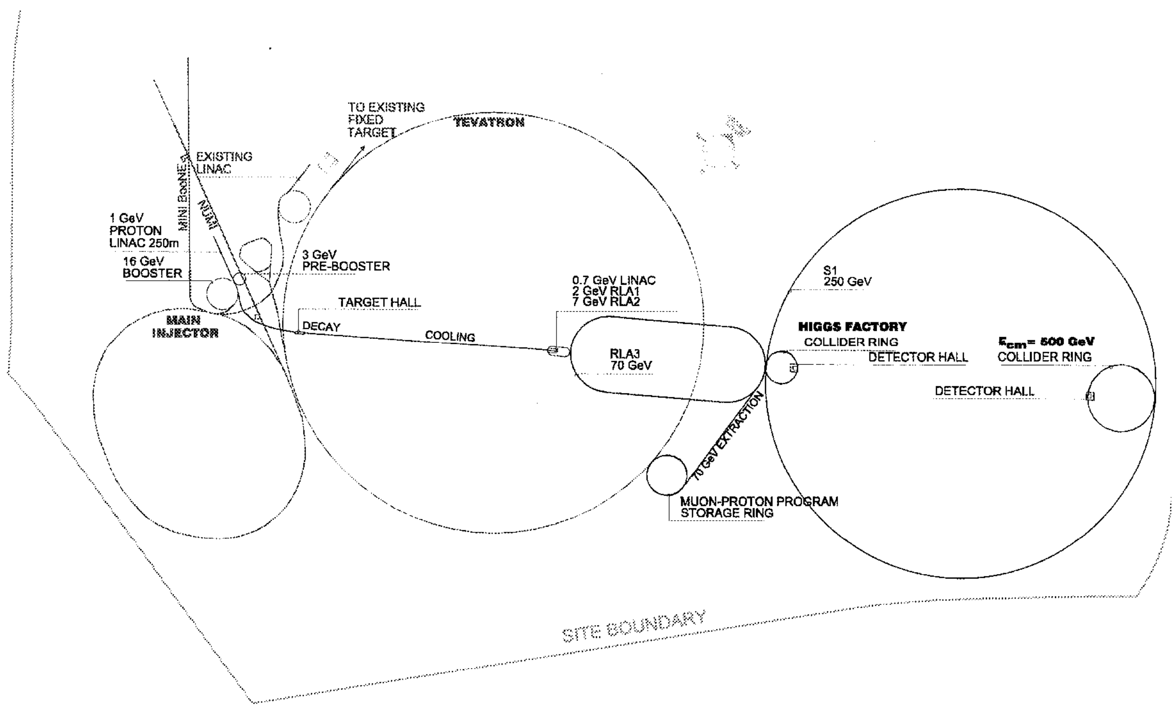

FIG. 17. Schematic of an alternative scheme for the accelerator enclosures needed for Step 2. All beam enclosures are near the surface. The μp collider is optional.

relatively low rf frequency (1.3 GHZ) encountered in the TESLA cavities provide a large aperture in the cavity and reasonable longitudinal acceptance. The injection into the TESLA linac would start after the third recirculating linac (RLA 3) from table VI. Another advantage of the TESLA accelerating system stems from the fact that it has a high transfer efficiency from ac to beam power which becomes more and more an issue as the center of mass energy increases.

A number of acceleration scenarios are presented in [18] which generate muon beams between 0.5-5 TeV center of mass, converting the superconducting e^+e^- linear collider into a muon accelerator by adding recirculating arcs to the linac.

B. Step 2: Siting Issues

Figure 16 shows the muon source, RLA1, and RLA2 sited close to the 16 GeV Booster. The upgrade of the proton linac energy to 1 GeV requires an extension of the linac which is assumed to be possible within the present beam enclosures. The 3 GeV Pre-booster is located close to the 1 GeV linac and is in a new enclosure. The 7 GeV muon beam from RLA2 is transported to the inside of the Tevatron ring where it is injected into RLA3, and either (i) accelerated to 55 GeV and injected into a Higgs factory, or (ii) accelerated to 70 GeV, injected into S1, further accelerated to 250 GeV, and finally injected into a 500 GeV collider ring.

We have considered the possible locations for the FMC detector. The only constraint for the Higgs factory detector that we are aware of at this time is that it should be at the same depth as RLA3, which produces the injection energy of 70 GeV. A convenient position in the FMC ring may be opposite to the RLA3 extraction point. There are, however, several criteria for the location of the 500 GeV FMC detector. It is thought that it might be useful to locate it near the existing infrastructure for one of the large detectors at Fermilab. We chose CDF because of the location of the energy frontier detector described in section V. In addition, the FMC will need cryogenics and the Central Helium Liquefier is located near

CDF. Note that we have also included a beam line to a muon storage ring tangent to the Tevatron at DØ for a possible μp collider experiment.

The Galena-Platteville layer of rock under the Fermilab site is composed of material which is very good for tunneling. It extends from approximately 360 feet to 690 feet under the site (Fig. 11). It is an aquatard, but is located above an aquifer that we wish to avoid. In our scenario, we have located the FMC in the top of the Galena-Platteville dolomite rock layer 480 feet under the surface. This choice requires the 7 GeV beam transport line to have a slope of about 8% in order to arrive deep enough in the top of the Galena-Platteville layer to construct beam and detector enclosures. The FMC ring and detector would be built and operated at depths comparable to the depths of the big detectors at the CERN LEP collider.

An alternative is to locate the FMC near the surface. However, a shallow FMC would probably disturb the environment more than a deep FMC. A near–surface layout for the FMC accelerator complex is shown in Fig. 17. In this layout the primary protons are transported to a target hall on the inside of the Tevatron ring, and the pion decay channel and muon cooling channel are located in a long straight tunnel. The 500 GeV FMC ring and its injector occupy the south–eastern corner of the Fermilab site.

C. Step 2: Physics Program

If a light Higgs boson is discovered in the next few years, then a good choice for the FMC might be a Higgs factory. If no Higgs–like boson is discovered before construction of the FMC begins, or if other more exciting new particles are discovered within reach of a 500 GeV FMC, then a 500 GeV collider might be the right choice. The physics potential for these two options is summarized in Ref. [1].

The Step 2 physics facilities would include :

(i) The FMC, either a Higgs factory or a 500 GeV collider.

(ii) Neutrino beams from one or more muon storage ring neutrino sources, and/or neutrino beams that necessarily are formed downstream of the straight sections in the RLAs.

The Step 2 physics facilities might also include :

(iii) An intense low energy kaon physics facility using the 16 GeV Booster.

(iv) Conventional low energy neutrino beams using the 16 GeV Booster.

(v) An intense stopped pion physics facility.

(vi) An intense low energy muon physics facility.

(vii) A 70 GeV (or 250 GeV) $\times$ 1000 GeV μ p collider (this needs further study).

1. Physics at a Higgs Factory

The production of Higgs–like bosons in the s–channel with interesting rates is a unique capability of a muon collider. The goals of an FMC Higgs factory would be to measure the Higgs mass, width, and branching fractions with sufficient precision to differentiate between a standard model Higgs boson, and the light Higgs–like boson of the minimal supersymmetric extension to the Standard Model (MSSM). In addition, within the MSSM there are heavier neutral Higgs bosons (H^0 and A^0) which the FMC measurements might be able to locate in preparation for higher energy muon collider upgrade options.

It has been shown [1] that the length of time needed for scanning the Higgs resonance and making the required measurements is of order 1 year to complete the first scan of a 110 GeV/c^2 Higgs boson and measure its mass with a precision of $\Delta m_h \sim 1$ MeV/c^2. With a further 2 years of running at 0.2 fb^{-1} per year, the following precisions could be achieved: 16% for Γ_{Tot}, 1% for σ·B($b\bar{b}$), and 5% for σ·B($WW^\star$). The ratio B($b\bar{b}$)/B($WW^\star$) would be sensitive to the presence of a heavier A^0 boson up to masses of about 500 GeV/c^2. Thus, the FMC would be a world class machine offering a cutting–edge physics program at Fermilab.

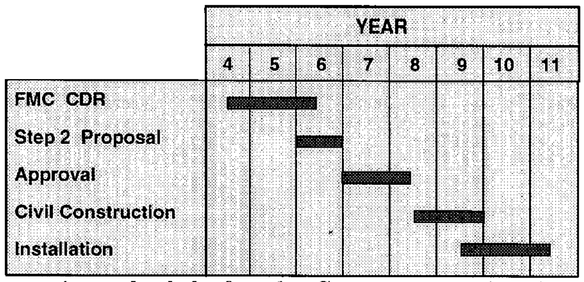

FIG. 18. Speculative aggressive schedule for the Step 2 upgrade. "Year 1" is defined as the year in which the Step 1 proposal is finalized and submitted.

2. Physics at a 500 GeV FMC

If there are new particles (MSSM particles, techni–particles , ...) with masses within reach of a 500 GeV lepton–antilepton collider then they will probably be discovered at the LHC. We take the particles of the MSSM as a popular example. Although the LHC may be a great discovery machine, it will be very difficult, perhaps impossible, at the LHC to (i) make a precise measurement of the mass of the lightest supersymmetric particle (LHC measurements give sparticle mass differences), (ii) study sleptons with masses greater than about 200 GeV/c^2, (iii) study heavy gauginos which are mainly Higgsino, and (iv) study heavy Higgs bosons if $\tan\beta$ is not large. We can anticipate that a 500 GeV FMC would have an extensive physics program to pursue.

3. Physics at the Front-End

We note in passing that with the further Step 2 upgrades of the proton source and muon source, and with the addition of high energy intense muon beams, the potential non–muon–collider physics program at Fermilab would be enhanced, with several options for extending, for example, the neutrino physics program.

D. Step 2: Schedule Considerations

Once again, we can only speculate about what might be an aggressive, but plausible, schedule. Our guess is shown in Fig. 18. We assume that the current muon collider feasibility studies go well, and that by "Year 6" (with "Year 1" defined as the Step 1 proposal year) a Step 2 conceptual design report could be completed, with the Step 2 proposal submitted at the end of "Year 6". This would coincide with the completion of the Step 1 upgrade. Allowing 18 months for the approval process, there will be significant experience with the Step 1 muon source before the Step 2 construction begins. In our speculative schedule the FMC would be completed in "Year 11", after 4-5 years of dedicated Step 1 muon storage ring neutrino source running.

V. STEP 3: RECAPTURING THE ENERGY FRONTIER

Our ultimate muon collider goal is to build a high energy muon collider with a center–of–mass energy of 4 TeV, and recapture the energy frontier at Fermilab.

A. Step 3: Facility Upgrade

The Step 3 facility upgrade would consist of building further site–filling muon acceleration systems to raise the muon beam energy to 2 TeV (see table VI), constructing a 4 TeV collider ring which would be about the size of the present Tevatron ring, and building a high energy muon collider detector facility.

B. Step 3: Siting Issues

Figure 19 shows the elements needed for the Step 3 upgrade. The sizes of the accelerator enclosures are based on table 7.6 of Ref. [19], modified to accommodate a 4 TeV collider (rather than 3 TeV). We would locate the energy frontier collider ring and its accelerators

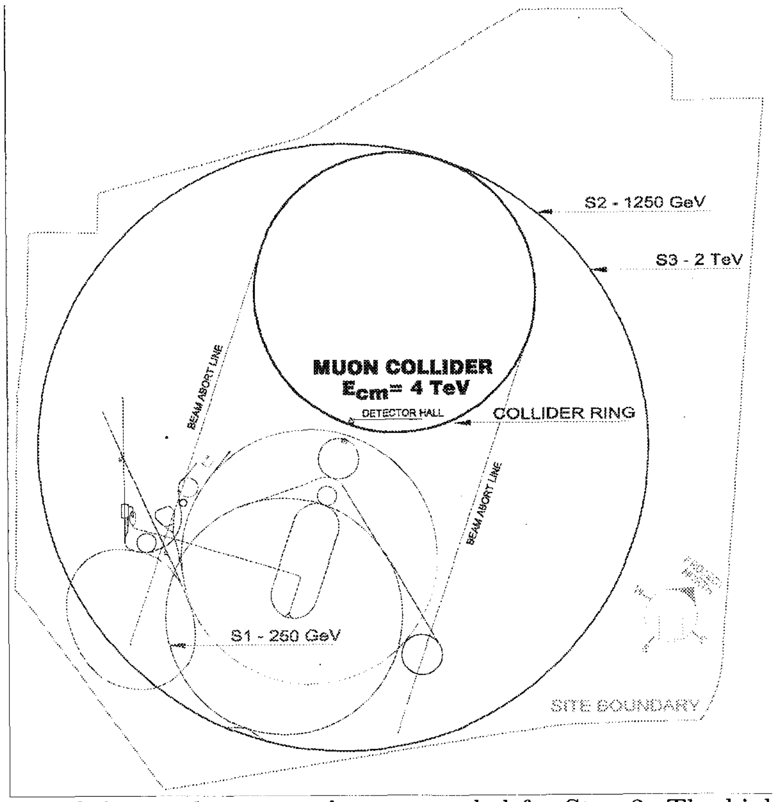

FIG. 19. Schematic of the accelerator enclosures needed for Step 3. The high energy accelerator complex and collider are constructed in tunnels within the Dolomite layer below Fermilab.

as close as possible to the bottom of the Galena-Platteville dolomite rock layer. This puts them at about 600 feet below the surface of the Fermilab site. Instead of sending beam to the FMC collider ring, beam transfer lines send it to S2 (synchrotron 2) and S3, which are located in a common beam enclosure. The circumference of this tunnel is sized to fit under the Fermilab site. After joining S3 to the injection lines of the high energy muon collider ring, and locating the detector opposite to this injection point, the detector is located under the neighborhood of CDF. Also note that the abort lines from the collider fit under the Fermilab site and are in solid rock. The residual radiation is therefore contained under the Fermilab site.

The energy frontier collider ring has a unique radiation issue. It is placed as deep as possible under the Fermilab site because of the radiation resulting from the interaction of neutrinos with the earth. The neutrinos are produced from the decay of the muons around the circumference of the collider ring. If the muon beams are held steady in the collider, the neutrinos are tightly collimated in a disc which starts in the rock at the level of the collider ring, extends underground in all directions off-site, until it finally exits the surface of the Earth at some radius from the collider. The center of mass energy and the depth of the collider can be chosen so that the radiation level at the exit of the surface of the Earth is equal to the Fermilab limit for the annual dose to the public [20]. For example, a collider located at a depth of 600 ft has a neutrino exit radius of 30 miles.

C. Step 3: Physics Program

In the final step a 4 TeV collider is constructed to recapture the energy frontier at Fermilab. The Step 3 muon collider might be designed to scan any massive resonant phenomenon discovered previously at the LHC, for example, or indicated by precision measurements at the FMC. If no high–energy resonances have been discovered before the high energy muon collider proposal, then it is likely that measurements of the scattering of longitudinally polarized W bosons at the highest possible energies will be very important. The high energy muon collider would provide a frontier tool for probing the strong scattering of weak bosons. In addition, the front–end physics potential would be further enhanced with, for example, the possibility of very high–energy neutrino experiments using compact highly instrumented detectors.

Step 3: Schedule Considerations

We can only offer some general considerations when speculating about the timescale for completing the Step 3 part of the evolution. The general considerations are that (i) we assume that it takes about 5 years to construct any significant machine once a proposal has been submitted, and (ii) a proposal is probably inappropriate before the FMC has been operating for 1 year.

VI. PROPOSED RESEARCH & DEVELOPMENT PROGRAM

There are three main fronts of research that are currently being conducted. They are

- Targetry and pion capture. Details of the research program may be found in Ref. [21]
- Ionization Cooling. Details of the research program may be found in Ref. [12]
- Physics and backgrounds simulation. Details of the resarch program may be found in Ref. [22]

VII. CONCLUSIONS

We have described a scenario for the future evolution of the accelerator complex at Fermilab towards a site–filling high–energy high–luminosity 4 TeV muon collider. It provides a plausible approach to regaining the energy frontier that makes full use of the existing Fermilab accelerator complex. In this look ahead the present facilities are enhanced with the addition of a muon storage ring neutrino source (Step 1), followed by the first muon collider (Step 2), and finally the 4 TeV muon collider (Step 3). The overall timescale to reach the 4 TeV goal is clearly long. Nevertheless, the muon collider scenario has some very attractive features. It would enable Fermilab to retain a cutting–edge world class physics program over the next two decades, whilst maintaining a diverse capability, and significant flexibility to respond to new discoveries.

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