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Muon Storage Ring Neutrino Source: The Path to a Muon Collider ?

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Abstract

We described a preliminary design study for a muon storage ring neutrino source that could be built as a step towards the first muon collider. In the design we consider, the neutrino beam would be produced by 3×10^{20} muon decays per year occurring within the straight section of a muon storage ring. The resulting neutrino flux is sufficient to produced hundreds of charged current interactions per year in a reasonable sized detector on the other side of the Earth.

1 Introduction

Recent results from atmospheric neutrino, solar neutrino, and short–baseline accelerator neutrino experiments indicate that neutrino oscillations may occur at rates that are within reach of the next generation of accelerator based experiments. If this is the case, we can anticipate a new generation of neutrino experiments designed to precisely measure the oscillation parameters, determine neutrino masses and mixing angles, establish how many neutrino types are involved in the oscillations, and search for CP violation within the neutrino system. This experimental program would benefit from higher intensity and/or higher quality neutrino beams than currently available. It has been pointed out [1] that a new type of intense neutrino source could be constructed by exploiting the very intense muon beams needed for a high–luminosity muon collider [2]. Taking as an example the accelerator scenario and beam parameters being considered in ongoing muon collider feasibility studies [3], and assuming all of the muons from a muon collider muon source are accelerated and injected into a storage ring containing a long straight section [4] pointing in the desired direction, neutrino beams containing $O(10^{20})$ neutrinos and antineutrinos per year seem possible [1].

In this paper we explore the idea that a muon storage ring neutrino source could be constructed as a step towards developing the first muon collider. The components required for a muon storage ring neutrino source are shown in Fig. 1. The muon source that has been considered in muon collider feasibility studies [2] also consists of a proton accelerator, a charged pion production target and collection system, a pion decay channel, and a muon cooling channel. This paper discusses each of these components within the context of a future muon storage ring neutrino source, and also discusses the acceleration scheme and the required muon storage ring. The paper is organized as follows. Section 2 describes the proton driver. Section 3 discusses the pion production target and collection system, and the pion decay channel. The cooling channel requirements are discussed in Section 4. A scheme to capture and accelerate a muon beam occupying a large six-dimensional phase-space is discussed in Section 5. The lattice for a muon storage ring neutrino source is described in Section 6. Calculated neutrino fluxes from the neutrino source are presented in Section 7. Conclusions are summarized in Section 8.

2 Proton source

A 1997 summer study [5] explored the possibility of upgrading the existing proton source at FNAL so that it can deliver the very short intense proton bunches needed at the front end of a muon collider. The overall upgrade would consist of upgrading the 400 MeV Linac energy to 1 GeV, moving the 8 GeV Booster to a new location to overcome radiation limitations and upgrading the Booster energy to 16 GeV, and finally, adding a 3 GeV Pre-Booster to enable the protons to be compressed into short (~ 2 ns) bunches. The upgraded accelerator complex would cycle at 15 Hz, and provide four 16 GeV bunches per cycle, each containing 2.5×10^{13} protons.

The proton source upgrade is stagable. Of the staging scenarios described in [5] we will assume that the Booster is moved and upgraded early since this will (i) enable higher intensity proton bunches to be accelerated in the MI, (ii) postpone until later the linac upgrade which is relatively expensive, and (iii) postpone until later the pre–booster ring which is needed only for the muon collider. The resulting evolution of the proton source parameters is summarized in Table 1. Since we are considering a scenario in which a muon storage ring neutrino source is built as a step towards the first muon collider, we will adopt phase 1 of the proton driver upgrade as a part of the neutrino source project. Hence, we will assume that only the Booster is upgraded, and that the resulting proton

Table 1: Evolution of the proton source parameters in the scenario described in the text. The table is derived from Ref. [5], updated to reflecting current thinking [2]. Phase 1 assumes a new 16 GeV Booster and a modest upgrade of the 400 MeV Linac to double the pulse length. In phase 2 the Linac energy is upgraded and a 3 GeV Pre-Booster added.

	Phase 1	Phase 2
Linac (operating at 15 Hz)		
Kinetic Energy (MeV)	400	1000
Current (mA)	50	65
Pulse Length (μs)	100	300
H^- per pulse	3×10^{13}	1×10^{14}
Pre–Booster (operating at 15 Hz)		
Extraction Kinetic Energy (GeV)		3.0
Circumference (m)		158
Protons per bunch		2.5×10^{13}
Number of bunches		4
Transverse Emittance (mm–mr)		200π
Longitudinal Emittance (eV-sec)		1.5
Booster (operating at 15 Hz)		
Extraction Kinetic Energy (GeV)	16	16
Circumference (m)	474.2	474.2
Protons per bunch	2.5×10^{12}	2.5×10^{13}
Number of bunches	12	4
Extracted bunch length σ_t (ns)	2 – 10	2
Transverse Emittance (π mm–mr)	50π	200π
Longitudinal Emittance (eV-sec)	1.8	2.0

source cycles at 15 Hz, and delivers 12 bunches per cycle, each containing 2.5×10^{12} protons at 16 GeV. In an operational year (10^7 secs) 4.5×10^{21} protons will be available for the pion production target.

3 Pion production, collection, and decay

The muon collider collaboration is currently pursuing an R&D program to develop a pion production target and collection system that can survive the intense short proton pulses required for a muon collider. The baseline target concept that is being pursued [6] consists of a liquid metal jet injected into a 20 T solenoid. The high–field solenoid captures most of the charged pions that are produced in the positive z (downstream) direction. The proton source beam power needed for a muon collider is three times the beam power we are assuming in our neutrino source scenario. Hence,

Table 2: Pion capture and decay channel parameters.

Section	Length (m)	B (T)	Aperture (cm)	RF Frequency (MHz)	Gradient (MV/m)
1	3	$20 \to 2$	$8 \to 24$	–	–
2	3	$2 \to 1.25$	$24 \to 30$	60	5
3	29	1.25	30	30	4
4	5	1.25	30	60	4

a neutrino source project 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 extreme version of the target required for the first muon collider.

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 by allowing the pions to decay. At the end of a 50 m long decay channel [7], consisting of a 1.25 Tesla solenoid with a radius of ~ 1 m and the rf system summarized in Table 2, on average ~ 0.2 muons of each charge would be produced for each proton incident on the pion production target. Hence, there would be about 6×10^{12} muons of the desired charge available at the end of the decay channel per accelerator cycle. In an operational year (10^7 secs) about 9×10^{20} muons would have been produced in the decay channel and collected.

4 Cooling channel

The muons exiting the decay channel [7] 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. This transverse emittance is too large to fit within the acceptance of the acceleration scheme that we will describe in the following section, and is also too large to fit within the acceptance of a muon storage ring. Both the transverse acceptance of the accelerating structure and the acceptance of the storage ring would be reasonably well matched if the transverse emittance of the muon bunches could be reduced by a factor of $\geq$ 3–4, so that $\epsilon_N \leq 0.005$ m-rad. Without a reduction in ϵ_N, muons outside of a core having $\epsilon_N \sim 0.005$ m-rad will be lost. Hence we must consider ways to reduce ϵ_N by a factor of a few.

Possible options are to (i) cool the beam using ionization cooling [8], or (ii) decrease the transverse emittance of the beam at the expense of the longitudinal emittance [9] (emittance exchange). In the explicit scenario we are exploring we have chosen to use ionization cooling to reduce the beam emittance. In the spirit of building a neutrino source as a stage towards the first muon collider, this will enable us to exploit cooling prototype devices which are built as part of the muon collider R&D program, and would offer the possibility of constructing, testing, and operating the early part of a muon collider cooling channel. Note that the first muon collider requires a reduction in ϵ_N by a factor of 100. Thus the factor of 3–4 we are seeking for a neutrino source would be a relatively modest part of what we anticipate is one of the most expensive components needed for the first muon collider.

To obtain a reduction of ϵ_N by a factor of 3 we consider the early part of the cooling channel being developed by the MUCOOL collaboration. In the initial design concept proposed by R. Palmer, large aperture solenoids are used in a configuration in which adjacent solenoids have opposite field directions ("Alternating Solenoid cooling channel"). Figure 2 shows a schematic of one 10 m long cooling channel cell, which contains a 60 cm long absorber within a high–field solenoid, an 8 m long 20 MHz rf system, and a 1 m long 40 MHz rf system. The cooling channel would be ~ 150 m long, and would consist of 15 cells in which the high–field solenoids initially provide a field of 1.2 T in the region of the absorbers. The solenoidal field increases down the channel to about 3 T at the end of the channel. The rf cavities within the cooling channel replace the longitudinal momentum lost in the absorbers and provide longitudinal focusing to keep the muons captured within a bunch. The cavity parameters are summarized in Table 2. Simulations with the ICOOL program [10] indicate that the momentum spread will not increase very much as the bunches traverse the cooling channel. The beam loss within the cooling channel is calculated to be about 10%. Hence 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.

5 Capture and Acceleration

A muon storage ring neutrino source does not require the muons to be grouped within a small number of bunches. We can therefore consider injecting the 2 m (rms) long bunches exiting the muon source into a linac that uses rf frequencies high enough to yield reasonable accelerating gradients. The linac will capture a large fraction of the muons into a train of shorter bunches. In the following we consider a linac using cavities operating at 805 MHz ($\lambda = 0.375$ m). This is the frequency of the Fermilab coupled-cavity linac, for which relatively low cost power sources exist. Furthermore, the MUCOOL collaboration is currently developing high-gradient 805 MHz rf cavities [11].

As an example of an explicit acceleration scheme, we consider using 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, used with 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 solenoidal channel. Note that a 5 T solenoidal field is strong enough to confine a 3σ beam envelope ($\epsilon_N =$ 0.005 m–rad) within an 8 cm cavity aperture. The second acceleration stage consists of a 500 m long linac with $V_{rf} = 20$ MV/m and $\phi_s = 60°$. The second stage accelerates the muon bunches to 10 GeV, and uses a quadrupole channel with a FODO lattice to provide transverse focusing.

We have simulated the evolution of the rf bunch structure as the beam traverses the capture and acceleration stages of the 805 MHz linac. The simulations include the longitudinal motion of the muons within the accelerating structure, but do not include the transverse motions. The simulations show that ~60–70% of the muons exiting the cooling channel are captured within the rf buckets of the linac and are accelerated to 10 GeV with final bunch lengths of $\sigma_z \sim 1$ cm and rms energy spreads given by $\sigma_E/E \sim 4\%$. To illustrate the beam dynamics, Fig. 3 shows, for idealized initial conditions, the simulated longitudinal motion of the muons as the bunch propagates down the capture and acceleration stages. The final bunches have $\sigma_E = 0.26$ GeV and $\sigma_\phi = 9.3°$ ($\sigma_z \sim 0.9$ cm). Allowing a 10% beam loss during acceleration to account for muon decay and aperture losses, there would be 4.7×10^{20} muons per operational year accelerated to 10 GeV.

6 Storage ring

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 the design described below we are considering a 10 GeV storage ring with a circumference of 448 m, which includes 150 m long straight sections. Hence, about one third of the muons decay whilst traveling in the desired direction.

The criteria that guide the design of the storage ring lattice are :

(a) The neutrino forming straight section must be a high β region, so that the divergence within the beam is small compared to the typical muon decay angles, which at 10 GeV are O(10 mr). This will ensure that the neutrino beam divergence is not significantly increased due to the divergence within the parent muon beam.

(b) The lattice must accommodate both a large momentum spread and a large transverse beam size.

(c) The ring must have large apertures to accommodate the large transverse beam emittances and large off–momentum orbit excursions.

The challenge in designing the storage ring is to find a lattice that can accommodate the large transverse and longitudinal beam emittance, and transmit the beam from the arcs into and through the high-beta straight sections. Preliminary lattice designs [4] for the arcs and straight sections are shown respectively in Figs. 4 and 5, and the storage ring parameters are summarized in Table 4. The basic features of the lattice are as follows:

(i) The neutrino beam forming section is constructed from five and a half long weak focusing FODO cells which form a 150 m long high-β insert. Note however that the FODO cells are periodic units (Fig. 5) allowing almost complete flexibility in choosing the length of the straight section.

(ii) Strong-focusing FODO cells have been chosen for the arcs to generate a large momentum acceptance ($\Delta p/p = \pm 5\%$), which would be difficult to achieve with more complicated focusing structures. To generate the desired focusing gradients over the large storage ring aperture, large-bore super-conducting quadrupoles are needed.

(iii) Each arc is composed of six FODO cells, an extra half FODO cell, and four cells (two at each end of the arcs) having reduced deflections to suppress dispersion in the matching sections and high-β insert. The cell properties are given in Table 3, and lattice functions are displayed in Fig. 4. The arc cells are designed to keep the off-momentum excursions under ± 8 cm so that arc quadrupole apertures are reasonable.

Table 3: Parameters of the large-momentum acceptance arc cells for a 10-GeV muon storage ring.

intermagnet spacing	m	0.2
dipole length	m	0.645
dipole full aperture	cm^2	6×15
dipole bend	rad	0.174
dipole field	T	9
quadrupole length	m	0.387
quadrupole bore	cm	15
quadrupole strength	m^{-2}	1.8
cell phase advance	deg	≈ 90
horiz. sextupole strength	T	2.3
vert. sextupole strength	T	3.5

Table 4: Storage Ring Parameters.

Circumference	448.4 m
Production straight (includes matching)	190.5 m
High-β, low divergence FODO straight	147.9 m
High-β quadrupole radius	20 cm
$\beta_{xmax}/\beta_{ymax}$	73 m/73 m
ν_x/ν_y	8.252/8.741
χ_x/χ_y, sextupoles on	-1.8/-2.4
χ_x/χ_y, sextupoles off	-9.7/-10.7

(iv) The arc quadrupole strengths are tuned to give a nearly $\pi/2$ phase advance [12] per cell, which is done to accommodate sextupole correctors that are inserted at the center of each quadrupole. The sextupoles reduce the momentum dependence of the tune, preventing the large tune spread from spanning an integer or half-integer resonance.

(v) The weak focusing high-β structure is matched to the strong–focusing arc lattice with two 20 m long matching sections that consist of antisymmetric doublet quadrupole doublets. The matching section is carefully designed to transmit a large range in momenta and a large transverse emittance.

The momentum dependence of the lattice was studied and tracked using the MAD code [13]. The tune of the ring is given by $\nu_x = 8.252$ and $\nu_y = 8.741$. The momentum range of the uncorrected lattice design is shown in Fig. 6 to be -6.0% to +4.5%. With the sextupoles canceling most of the linear chromaticity, the total tune swing is reduced from $\delta\nu_{x,y} \approx 1$ to

$\delta\nu_x = 0.28$ and $\delta\nu_y = 0.21$, which allows the tune to be optimized between half-integer and integer resonances. Further reduction of this tune swing is possible, but does not appear necessary. The normalized 3σ emittance accepted by the high-beta quadrupoles (assuming a 20 cm quadrupole radius with a β_{max} of 100 m) is about 0.0042 m-rad. Increasing this bore to 25 cm increases this acceptance to 0.0066 m-rad.

7 Neutrino fluxes and physics potential

The neutrino fluxes at a distant site located downstream of the straight section of a 10 GeV muon storage ring depend upon the number of muons circulating in the ring, the position dependent beam divergences within the straight section, and the average polarization of the decaying muons.

In the scenario we are considering, at the end of the last acceleration stage there are 4.7×10^{20} muons per year, and 33% of the muons injected into the storage ring decay within the neutrino beam forming straight section. Hence there are 1.6×10^{20} muon decays per operational year within the straight section of the storage ring. In one muon lifetime (0.2 ms at 10 GeV) the muons make 134 revolutions in the storage ring. We will assume that the time averaged polarization of the decaying muons is zero, although this requires further study.

With the muon storage ring located at Fermilab, the 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 [1, 14]. The annual neutrino and antineutrino fluxes at the distant sites are calculated to be $8 \times 10^{11}\ m^{-2}$ and $8 \times 10^{9}\ m^{-2}$ 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 year, and $\sim 9 \times 10^3$ (~ 90) charged current $\overline{\nu}_e$ interactions per year in a 10 KT detector at L = 732 km (L = 7332 km). To ensure the uncertainty on the neutrino flux at the far site is smaller than the statistical error on the observed number of events, the flux uncertainty should be less than or comparable to O(0.1%) for the L = 732 km scenario. To achieve this the beam current within the storage ring must be monitored with a precision of O(0.1%), and the beam divergence within the relevant parts of the straight section must be monitored with a precision O(0.1 mr).

To illustrate the physics potential of a 10 GeV muon storage ring neutrino source with a baseline length of 7332 km (FNAL $\rightarrow$ Gran Sasso), consider a search for $\nu_\mu \rightarrow \nu_\tau$ oscillations, and assume that the associated neutrino–mass–difference squared is at the lower end of the range suggested by the Super–Kamoikande results ($\Delta m^2 \sim 0.001$ eV^2 with $\sin^2 2\theta = 1$). In this case the MINOS experiment may have difficulty establishing a convincing signal. With the muon storage ring neutrino beam described above, the predicted ν_μ disappearance signal at Gran Sasso is shown in Fig. 7. The oscillation signal is striking. With no oscillations, 220 ν_μ CC interactions per 10 kt–yr would be expected. With oscillations this number is reduced to 43 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 (FNAL $\rightarrow$ Soudan), consider a search for $\nu_\mu \rightarrow \nu_\tau$ oscillations, and assume that the associated neutrino–mass–difference squared is towards the upper end of the range suggested by the Super–Kamoikande results ($\Delta m^2 \sim 0.01$ eV^2 with $\sin^2 2\theta = 1$). In this case the MINOS experiment should establish a convincing disappearance signal. If a hybrid emulsion detector is added to the MINOS detector, then ν_τ interactions should also be observed. With the muon storage ring neutrino beam described above, the predicted ν_μ disappearance signal at Soudan is shown in Fig. 8. The oscillation signal is striking. With no oscillations, 22100 ν_μ CC interactions per 10 kt–yr would be expected. With oscillations this number is reduced to 4500 ν_μ CC interactions per 10 kt–yr, with a very different energy spectrum. In addition, in a 1 kt hybrid emulsion detector, xxx ν_τ CC interactions would be expected per operational year. Note that if the sign of the τ lepton charge was 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.

8 Further work

Much further work will be needed before a muon storage ring neutrino source can be proposed. In particular, the following topics need serious study :

(i) Realistic rf parameters. The decay channel, cooling channel, and acceleration scheme all require high–gradient rf cavities providing peak accelerating gradients beyond those currently readily available. Further work must be done to assess the rf parameters that might be achievable with a few years of R&D, and then restrict the design to use only these "realistic" parameters. This is particularly true for the low–frequency rf systems in the decay channel and cooling channel.

(ii) More realistic capture, decay channel, and cooling simulations. More complete simulations are needed to optimize the optics, and study the behavior of the 6–dimensional phase space occupied by the muon bunches as they traverse the muon source and acceleration systems.

(iii) More detailed acceleration scheme studies. In particular a 10 GeV linac is probably not the most cost–effective solution. Other schemes (recirculating linear accelerators ?) need to be considered.

(iv) Large bore super-conducting magnet design. The large storage ring apertures require large bore high–field dipoles and quadrupoles. Some design work is required to ensure the assumed parameters are achievable.

(v) An error analysis of the storage ring lattice design.

We believe that muon storage ring neutrino sources are sufficiently interesting to warrant these further design studies.

9 Summary

In this paper we have described a preliminary design study for a muon storage ring neutrino source that could be built as a step towards the first muon collider. Further work must be done to arrive at a more detailed and realistic design that could lead to a conceptual design report. However, a muon storage neutrino source seems to be a natural step towards a high luminosity muon collider, and the physics potential of this new type of neutrino source seems well matched to the needs of a new generation of neutrino oscillation experiments beyond the currently approved next–generation experiments.

Acknowledgments

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References

[1] S. Geer, Phys. Rev. **D57**,6989 (1998).

[2] "Status of Muon Collider Research and Development and Future Plans", C. Ankenbrandt et al. (The Muon Collider Collab.), Fermilab-PUB-98/179.

[3] C. Ankenbrandt and S. Geer, "Accelerator Scenario and Parameters for the First Muon Collider and Front–End of a Muon Collider", Proc. Workshop on Physics at the First Muon Collider and Front-End of a Muon Collider, Fermilab 6-9th November, 1997, Fermilab-Conf-98/086.

[4] C. Johnstone, "High Intensity Muon Storage Rings for Neutrino Production: Lattice Design", Proc. Workshop on Physics at the First Muon Collider and Front-End of a Muon Collider, Fermilab 6-9th November, 1997.

[5] S. Holmes et al., "A Development Plan for the Fermilab Proton Source", FERMILAB-TM-2021, September 1997, unpublished.

[6] "An R&D Program for Targetry and Capture at a Muon Collider Source", J. Alessi et al; Submitted to the BNL AGS Division, Sept. 1998.

[7] A. Van Ginneken and D. Neuffer, "Muon Collection Channel", FN 98-296, to be published in NIM A (1999).

[8] A.N. Skrinsky and V.V. Parkhomchuk, Sov. J. Part. Nucl. **12**, 223 (1981).

[9] R. B. Palmer, presented at the Sept. 1998 MUCOOL collaboration meeting.

[10] R. Fernow, http://www-pat.fnal.gov/muSim/icool.html

[11] "Ionization Cooling Research and Development Program for a High Luminosity Muon Collider", MUCOOL Collaboration, Fermilab Proposal P904, April 15th, 1998.

[12] S. Ohnuma, private communication

[13] H. Grote and F. Iselin, "The MAD program (Methodical Accelerator Design)," CERN publication CERN/SL-90-13(AP), version 8.17.

[14] S. Geer, "Long Baseline Neutrino Physics with a Muon Storage Ring Neutrino Source", Fermilab FN-677, in preparation.

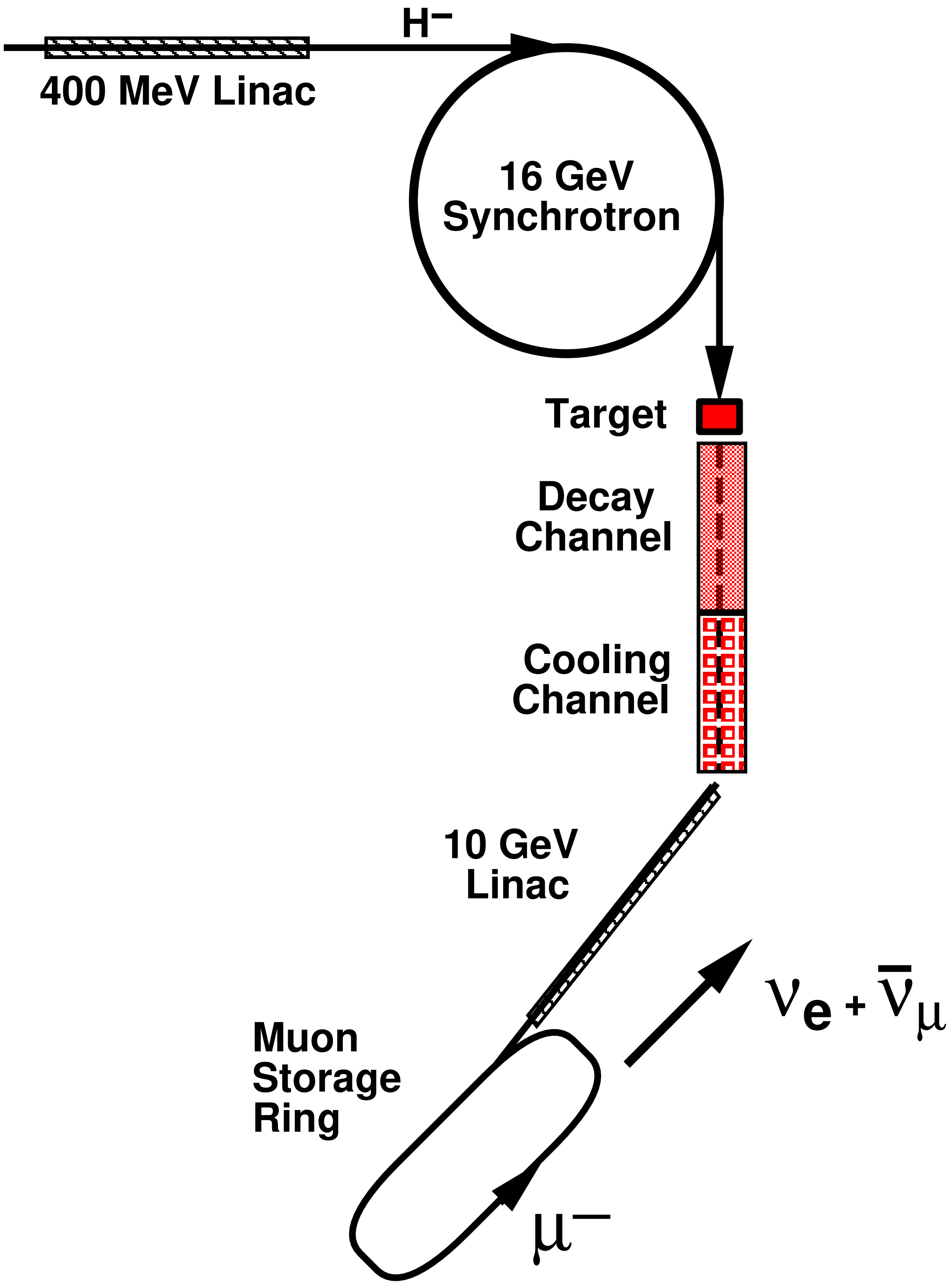

Figure 1: Schematic of the muon production, decay channel, cooling channel, acceleration linac, and muon storage ring system discussed in the text.

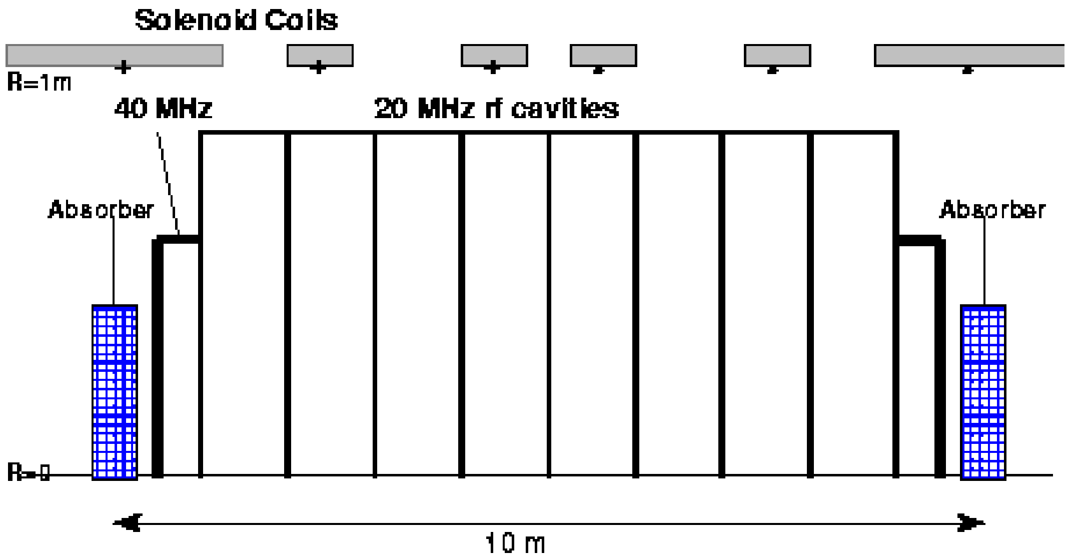

Figure 2: Schematic of a 10 m long cooling cell. Fifteen cells are required for the cooling scheme discussed in the text.

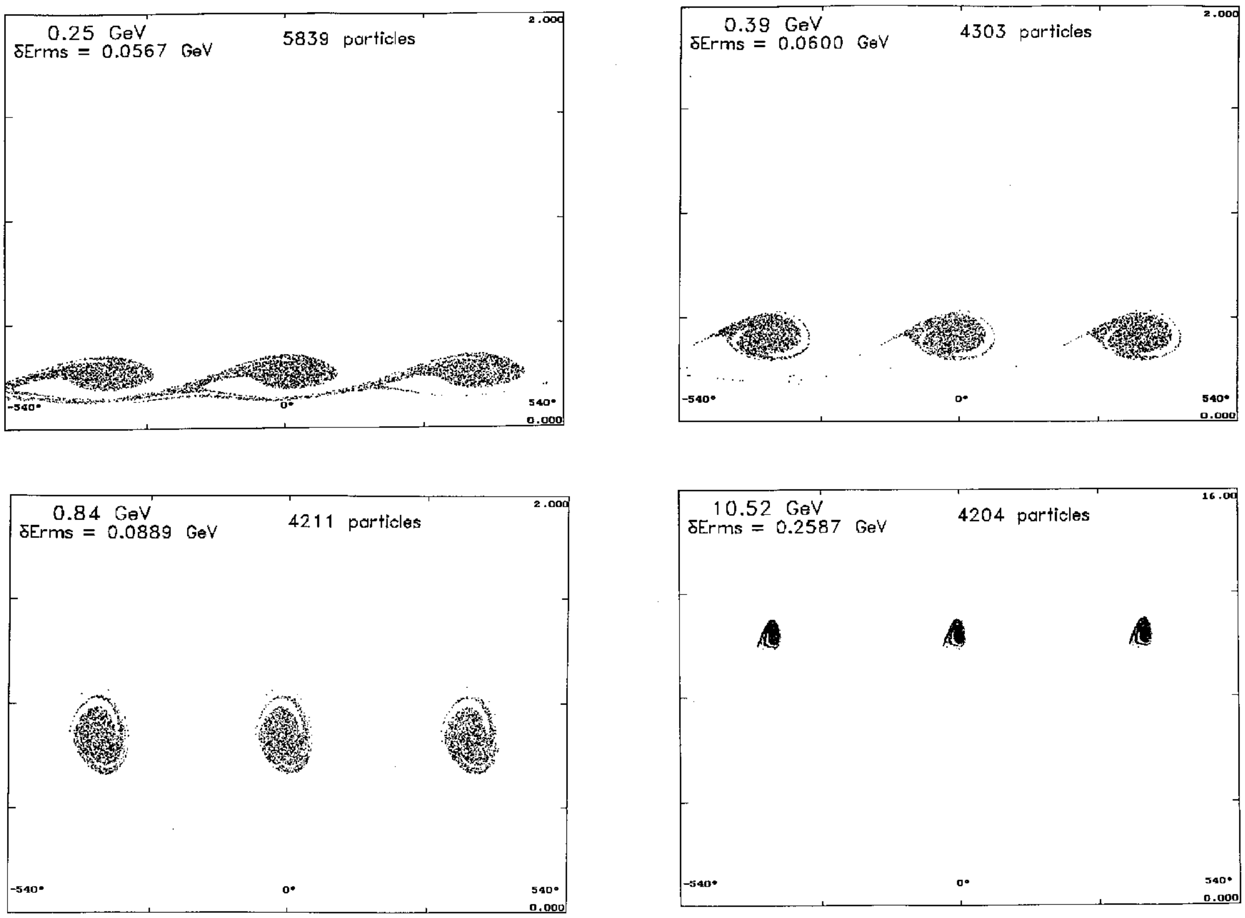

Figure 3: Simulations of longitudinal motion showing capture of a long 200 ± 50 MeV muon beam into a string of 800 MHz bunches (3 are shown), with acceleration to 0.25, 0.39, 0.84, and 10.5 GeV. From an initial set of 6000 macroparticles, 4200 are trapped and accelerated. The horizontal scale is phase and the vertical scale is particle energy. Note change of scale in last picture.

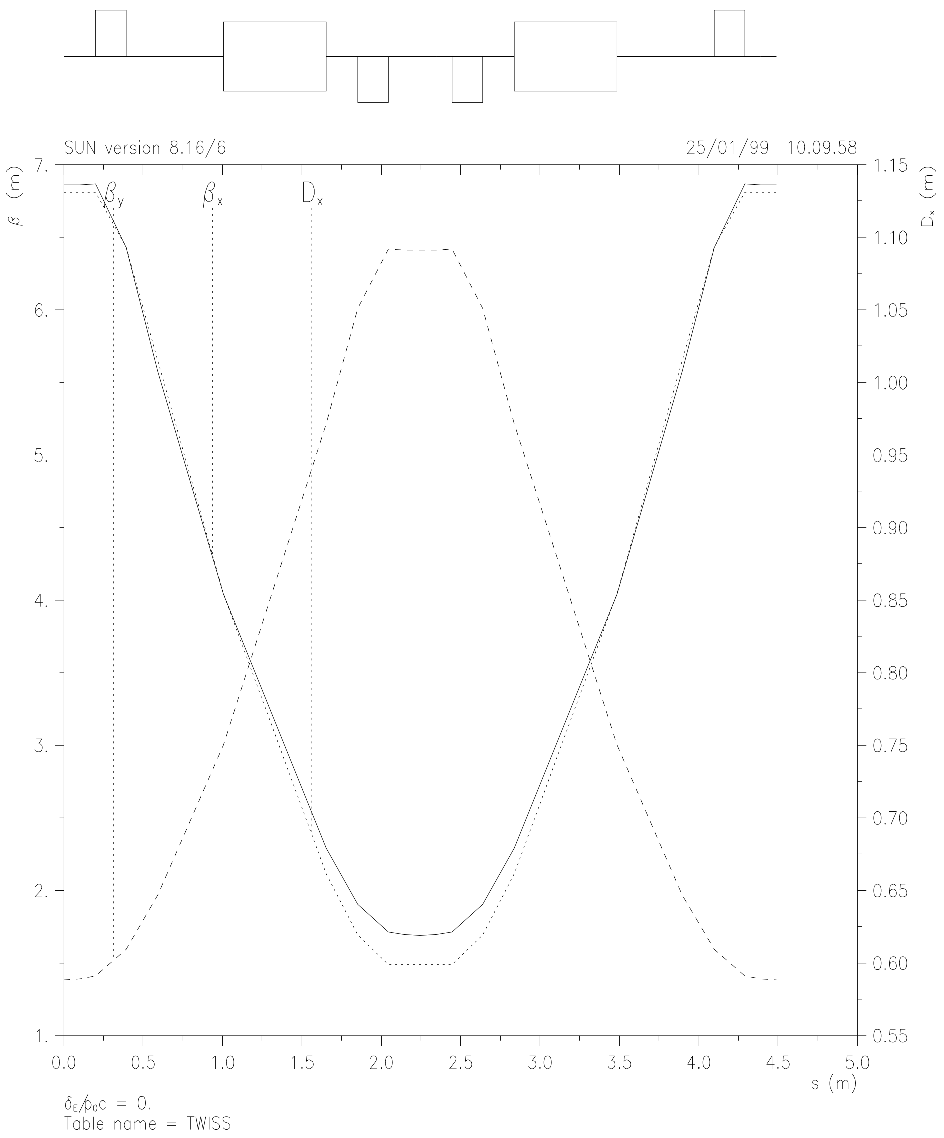

Figure 4: Storage ring arc lattice.

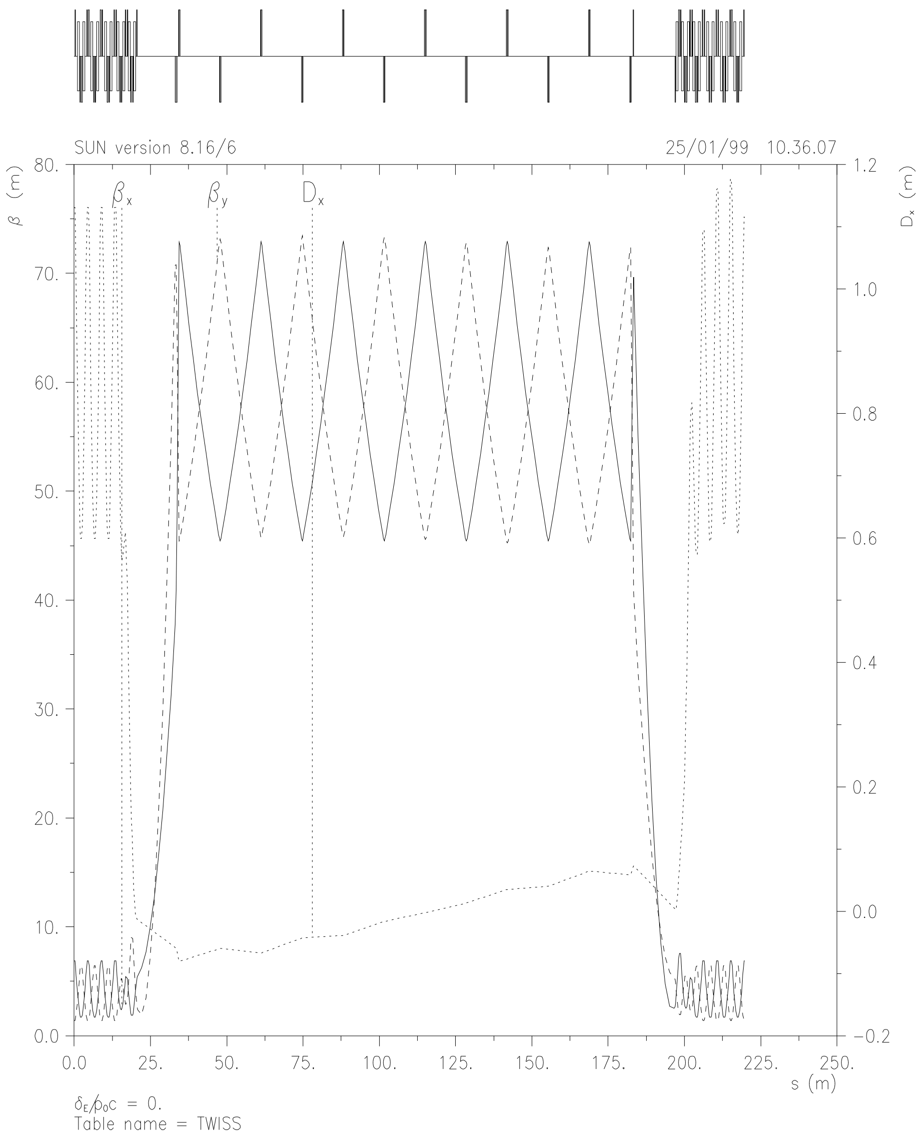

Figure 5: Storage ring straight section lattice.

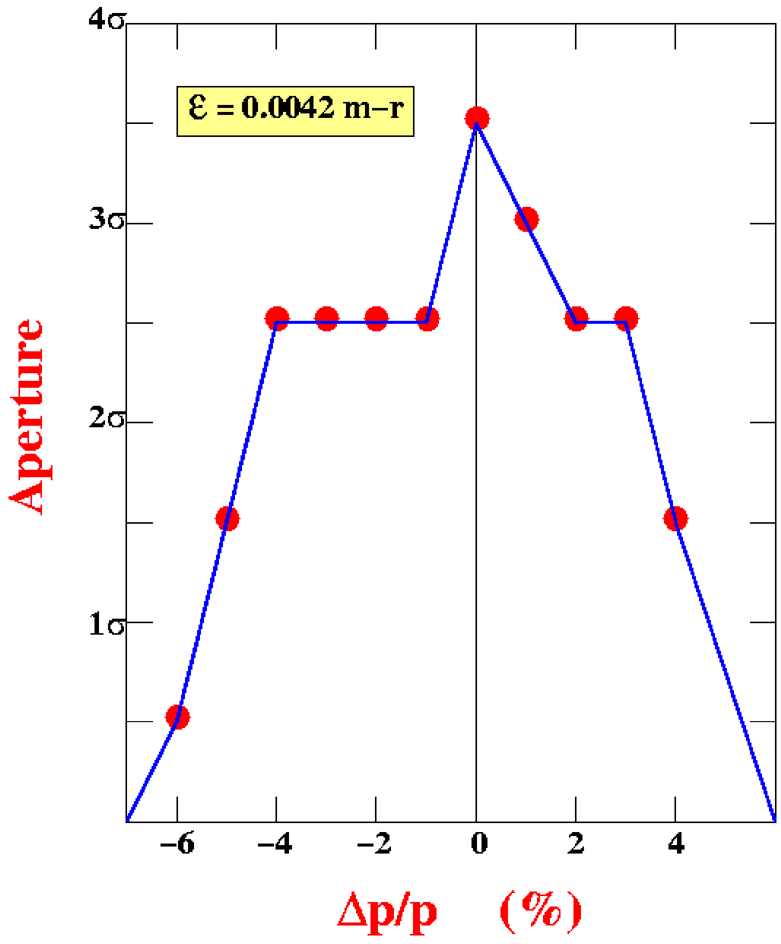

Figure 6: Momentum acceptance in the muon storage ring.

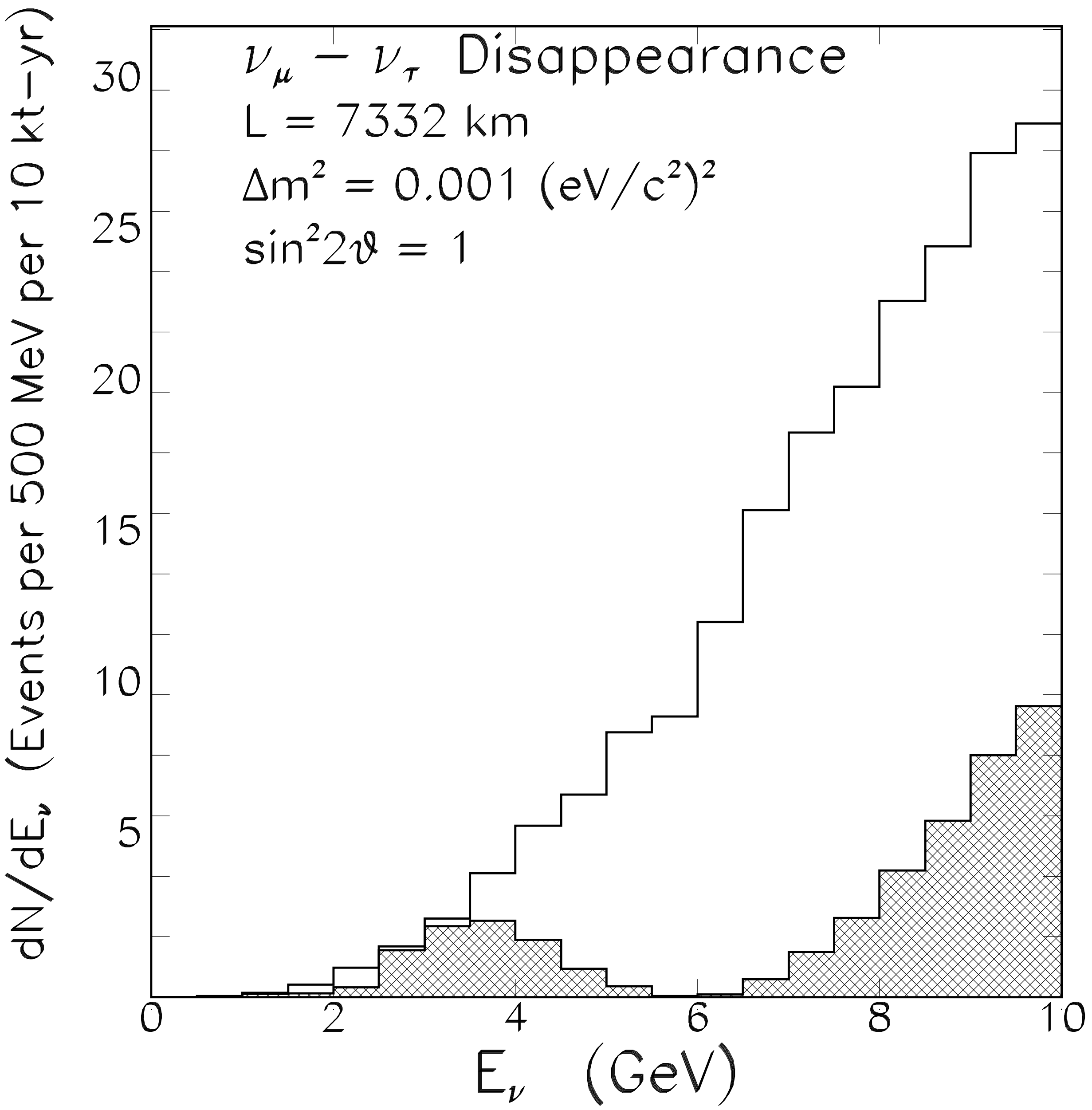

Figure 7: Predicted signal for $\nu_\mu \to \nu_\tau$ disappearance using a 10 GeV muon storage ring neutrino source at FNAL, pointed towards the Gran Sasso underground laboratory, assuming a 10 kt–year exposure. The open histogram is the prediction for the energy dependent CC interaction rate with no oscillations, and the shaded histogram is the prediction with oscillation parameters $\Delta m^2 = 0.001$ eV^2 and $\sin^2 2\theta = 1$.

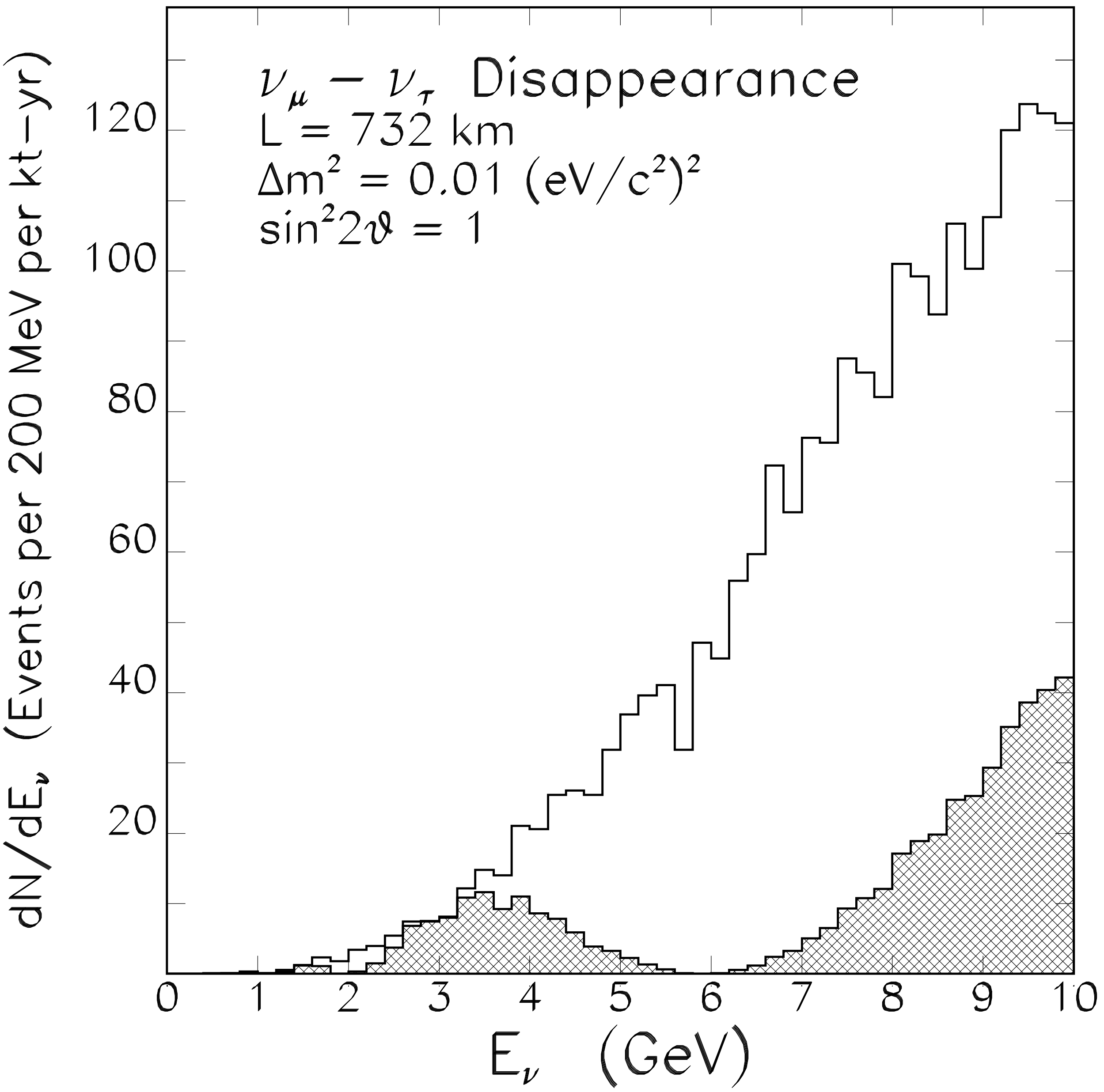

Figure 8: Predicted signal for $\nu_\mu \to \nu_\tau$ disappearance using a 10 GeV muon storage ring neutrino source at FNAL, pointed towards the Soudan mine in Minnesota. The open histogram is the prediction for the energy dependent CC interaction rate with no oscillations, and the shaded histogram is the prediction with oscillation parameters $\Delta m^2 = 0.01$ eV^2 and $\sin^2 2\theta = 1$.