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The Physics Potential of Neutrino Beams from Muon Storage Rings

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Abstract. High-intensity neutrino beams could be produced using a very intense muon source, and allowing the muons to decay in a storage ring containing a long straight section. Taking the parameters of muon source designs that are currently under study for future high luminosity muon colliders, the characteristics of the neutrino beams that could be produced are discussed and some examples of their physics potential given. It is shown that the neutrino and antineutrino beam intensities may be sufficient to produce hundreds of neutrino interactions per year in a detector on the far side of the Earth.

INTRODUCTION

The muon source required for a high-luminosity muon collider would enable intense neutrino beams to be produced from muon decays. In the following, calculated beam fluxes and interaction rates are presented for various long- and short-baseline neutrino configurations that exploit a muon collider muon source. To illustrate the physics potential of these beams some examples are discussed. A more detailed description of the calculation is given in Ref. [1].

The muon lifetime is about 100 times longer than the charged pion lifetime. A linear decay channel of the type used to produce conventional neutrino beams would be too short in practice to use efficiently as a muon decay channel. This problem can be overcome by using a muon storage ring with a straight section pointing in the desired direction. We will consider a storage ring that consists of two parallel straight sections connected together by two arcs. If the straight sections are equal in length to the arcs, 25% of the stored muons will decay whilst they are in the straight section pointing at the experiment.

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If the ring lattice is properly designed, a beam divergence $\theta_b \leq O(10^{-4})$ should be achievable [2] in the straight section. Thus, if the circulating muons have momentum $p/m_\mu \ll 10^4$ (corresponding to $p \ll 1000$ GeV/c) the angular divergence of the neutrino beam produced from decays in the straight sections will be dominated by the decay kinematics. In the muon rest-frame the distribution of muon antineutrinos (neutrinos) from the decay $\mu^\pm \to e^\pm + \nu_e\ (\overline{\nu}_e) + \overline{\nu}_\mu\ (\nu_\mu)$ is given by the expression [3]:

$$\frac{d^2N_{\nu_\mu}}{dxd\Omega} \propto \frac{2x^2}{4\pi}\left[(3-2x) \mp (1-2x)P_\mu \cos\theta\right], \tag{1}$$

where $x \equiv 2E_\nu/m_\mu$, θ is the angle between the neutrino momentum vector and the muon spin direction, m_μ is the muon rest mass, and P_μ is the average muon polarization along the chosen quantization axis. The corresponding expression describing the distribution of electron neutrinos (antineutrinos) is:

$$\frac{d^2N_{\nu_e}}{dxd\Omega} \propto \frac{12x^2}{4\pi}\left[(1-x) \mp (1-x)P_\mu \cos\theta\right]. \tag{2}$$

The neutrino beam intensity will depend upon the performance of the muon source. In the following we will assume a source with the parameters given for the workshop, which would produce 7.5×10^{20} muons that can be injected into the storage ring each operational year. If 25% of the muons decay in the straight section pointing at the experimental area the resulting neutrino beam will contain 2×10^{20} neutrinos per year and 2×10^{20} antineutrinos per year, with energy– and angular–distributions described by Eqs. (1) and (2).

FLUXES AND INTERACTION RATES

Consider a geometry in which the plane of the storage ring dips at an angle of 51° to the horizon, and the resulting neutrino beam exits the Earth at the "far site" after traversing 9900 km. This would correspond to a storage ring sited at the Fermi National Accelerator Laboratory in the United States with the far site at the Gran Sasso underground Laboratory in Italy. The calculated neutrino and antineutrino fluxes at the far site are shown in Fig. 1 as a function of the energy and average polarization of the muons in the straight section of the storage ring. The fluxes have been averaged over a 1 km radius "spot" at the far site. The ν_e and $\overline{\nu}_e$ fluxes are very sensitive to the muon spin direction. This can be understood by examining Eq. 2 which shows that for μ^+ (μ^-) decays the ν_e ($\overline{\nu}_e$) flux $\to 0$ for all neutrino energies as $\cos\theta \to +1$ (-1). The charged current neutrino and antineutrino rates in a detector at the far site can be calculated using the approximate expressions [4] for the cross-sections: $\sigma_{\nu N} \sim 0.67 \times 10^{-38}\ cm^2 \times E_\nu(GeV)$ and $\sigma_{\overline{\nu} N} \sim 0.34 \times 10^{-38}\ cm^2 \times E_{\overline{\nu}}(GeV)$. The predicted charged current interaction

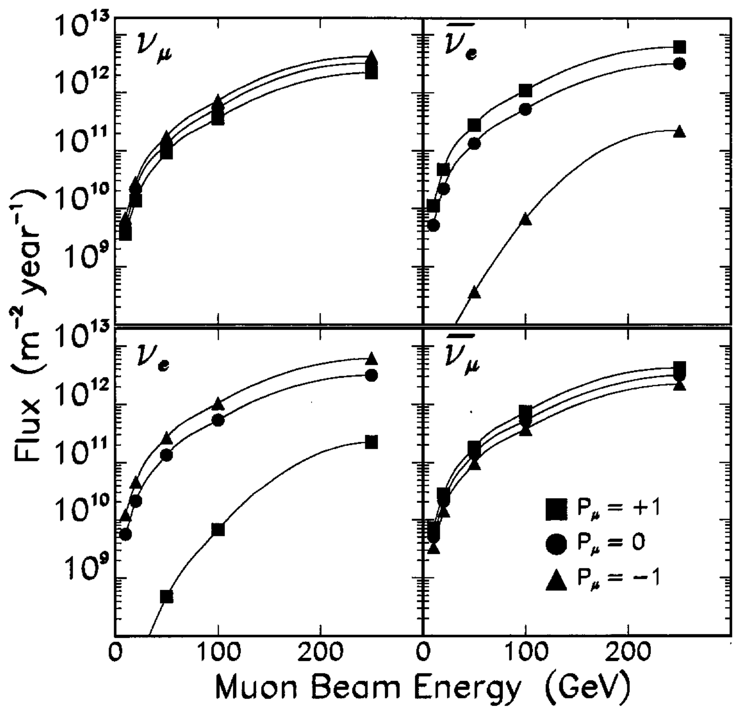

FIGURE 1. Calculated neutrino and antineutrino fluxes at a far site located 9900 km from a muon storage ring neutrino source. The fluxes are shown as a function of the energy of the stored muons for negative muons (top two plots) and positive muons (bottom two plots), and for three muon polarizations as indicated.

rates are shown in Fig. 2 as a function of the energy and average polarization of the decaying muons. We conclude that, for stored muon momenta greater than $\sim$ 20 GeV/c, neutrino and antineutrino interactions should be readily detectable at the far site.

Consider next a long baseline geometry in which the plane of the muon storage rings tilts at just a few degrees to the horizon and the far site is 732 km from the neutrino source. This would correspond [5] to a storage ring sited at the Fermi National Accelerator Laboratory and a far site at the Soudan underground Laboratory in Minnesota. The neutrino fluxes and charged current interaction rates at the far site can be obtained by scaling the results presented in Figs. 1 and 2 by a factor of 183. Predicted fluxes and spectra corresponding to using 10 GeV/c stored muons are shown in Fig. 3. The calculated neutrino and antineutrino fluxes are both $\sim 1 \times 10^{12}$ m^{-2} year^{-1}, and the corresponding charged current interaction yields are 3.1×10^3 μ^- kT^{-1} year^{-1} and 1.4×10^3 e^+ kT^{-1} year^{-1} when negative muons are stored in the ring, and 1.6×10^3 μ^+ kT^{-1} year^{-1} and 2.9×10^3 e^- kT^{-1} year^{-1} when positive muons are stored in the ring. The mean energies of the charged leptons and

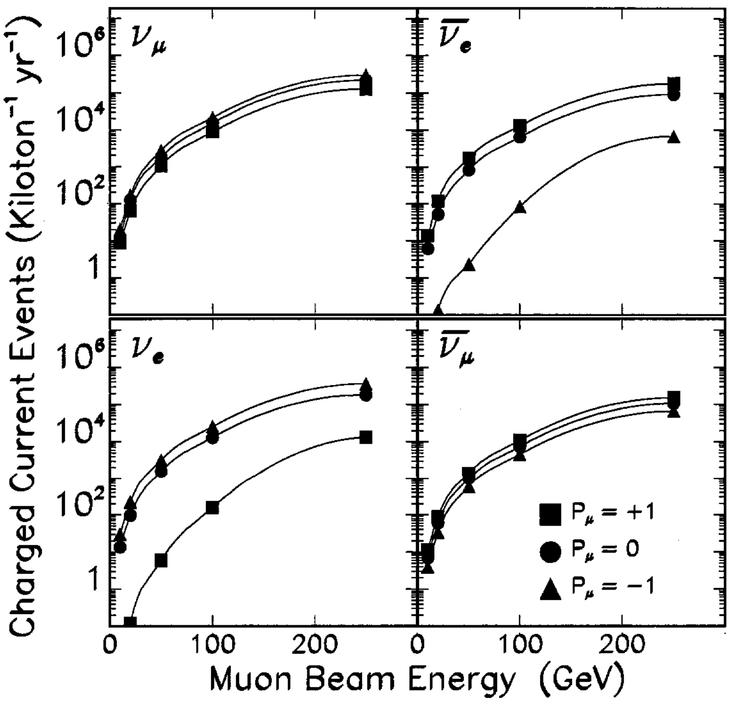

FIGURE 2. Calculated neutrino and antineutrino charged current interaction rates in a detector located 9900 km from a muon storage ring neutrino source. The rates are shown as a function of the energy of the stored muons for negative muons (top two plots) and positive muons (bottom two plots), and for three muon polarizations as indicated.

antileptons produced in these charged current interactions are respectively ~ 3.5 GeV and ~ 2 GeV. Thus, neutrino and antineutrino interactions should be readily detectable at the far site when the decaying muons in the storage ring have momenta as low as 10 GeV/c. The predicted event rates become very large when high energy muons are stored in the ring (for example, 3×10^7 interactions per KT-year when 250 GeV/c muons are stored).

Finally, consider a short baseline geometry in which the detector is 1 km from a 1.5 GeV/c muon storage ring. Averaging the fluxes at the detector over a "spot" with a radius of 5 m, the predicted neutrino and antineutrino fluxes resulting from unpolarized muon decays are both 1.2×10^{16} m^{-2} per year. The corresponding charged current interaction rates in a 1 kT detector yield 2.9×10^6 μ^+ per year and 5.1×10^6 e^- per year if positive muons are stored in the ring, and 6.0×10^6 μ^- per year and 2.6×10^6 e^+ per year if negative muons are stored in the ring. Hence, a 1 kT detector would record millions of charged current interactions per year with mean charged–lepton energies of ~ 0.6 GeV and mean charged–antilepton energies of ~ 0.3 GeV.

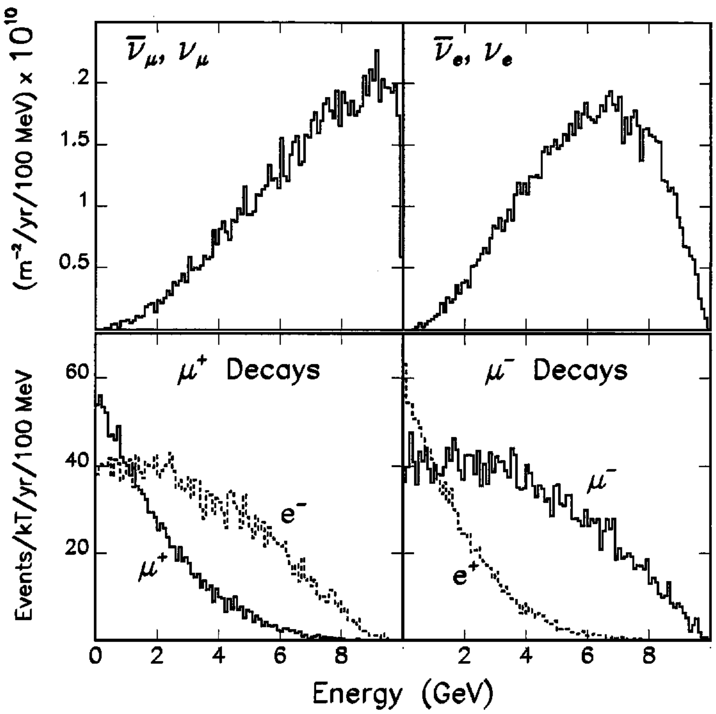

FIGURE 3. Calculated fluxes and spectra in a detector 732 km downstream of a muon storage ring neutrino source in which 10 GeV/c unpolarized muons are circulating. The top two plots show the neutrino and antineutrino spectra, and the bottom two plots show the charged lepton spectra from charged current interactions when positive muons (bottom left) and negative muons (bottom right) are stored in the ring.

PHYSICS POTENTIAL: EXAMPLES

To illustrate the physics potential of the muon storage ring neutrino sources discussed in the previous section, consider the sensitivity of an experiment searching for ν_e–ν_μ or ν_e–ν_τ oscillations performed by searching for charged current interactions producing "wrong-sign" muons. Within the framework of two-flavor vacuum oscillations, the probability that, whilst traversing a distance L, a neutrino of type 1 (mass m_1) oscillates into a neutrino of type 2 (mass m_2) is given by [3]:

$$P(\nu_1 \to \nu_2) = \sin^2(2\theta)\ \sin^2(1.27\Delta m^2\ L/E)\ , \tag{3}$$

where θ is the mixing angle, $\Delta m^2 \equiv m_2^2 - m_1^2$ is measured in eV^2/c^4, L in km, and the neutrino energy E is in GeV. In the absence of backgrounds or systematic uncertainties, a neutrino oscillation experiment can be characterized by the total number of neutrino interactions observed (and hence the minimum observable $P(\nu_1 \to \nu_2)$) and the average L/E for the interacting neutrinos. These parameters are summarized in Table 1 for the experimental configurations discussed in the previous section.

Figure 4a compares the ν_e–ν_μ oscillation single–event sensitivity contours in the (Δm^2, $\sin^2(2\theta)$)–plane. The long– and very–long–baseline configurations have similar Δm^2 reaches as $\sin^2(2\theta) \to 1$, approaching single event sensitivities of $\sim 10^{-5}$ eV^2/c^4, more than an order of magnitude better than the expected reaches of the next generation of proposed neutrino experiments. The large charged current event rates expected for the short baseline configuration would enable sensitivities approaching $\sin^2(2\theta) \sim 10^{-7}$ for large Δm^2 ($\Delta m^2 \sim 1$ eV^2/c^4). This $\sin^2(2\theta)$ reach is almost a factor of 1000 better than the expected reaches of presently proposed experiments, but would only be attained in the absence of backgrounds from, for example, secondary production of neutrinos from interactions in the vicinity of the experiment, or a component of neutrinos produced from the decays of "wrong–sign" muons produced upstream of the storage ring. Figure 4b shows the single–event contour in the (Δm^2, $\sin^2(2\theta)$)–plane for a ν_e–ν_τ oscillation search corresponding to the highest energy (250 GeV/c stored muons) configuration in Table 1, where once again the search is based on looking for wrong-sign muons. The pure ν_e component in the neutrino beam from a muon storage ring would enable the sensitivity of ν_e–ν_τ searches to improve beyond the sensitivities of past searches [6,7] by many orders of magnitude.

We conclude that a muon source of the type being developed for future high-luminosity muon colliders could produce very intense neutrino beams. If O(10^{20}) muons per year decayed within a 20 GeV/c storage ring with a straight section pointing in the desired direction, the resulting beam would produce hundreds of neutrino interactions per 10 kT-year on the other side of the Earth. High beam intensities, together with the purity of the initial neutrino beam flavor content, would provide unique opportunities for neutrino experiments. The neutrino physics program using muon storage ring neutrino sources could begin with short baseline experiments using low energy muons (O(1 GeV)) as soon as an intense muon source became operational, and be extended to include higher energy storage rings and longer baseline experiments as higher

TABLE 1. Summary of the neutrino oscillation experimental configurations considered in the text.

p (GeV/c)	m_{DET} (kT)	L (km)	$< E_\nu >$ (GeV)	L/$< E_\nu >$ (km/GeV)	ν_e CC interactions/yr
20	10	9900	13	744	1×10^3
20	10	732	13	57	2×10^5
10	10	732	6.6	111	3×10^4
1.5	1	1	1	1	5×10^6
250	10	732	161	4.5	3×10^8

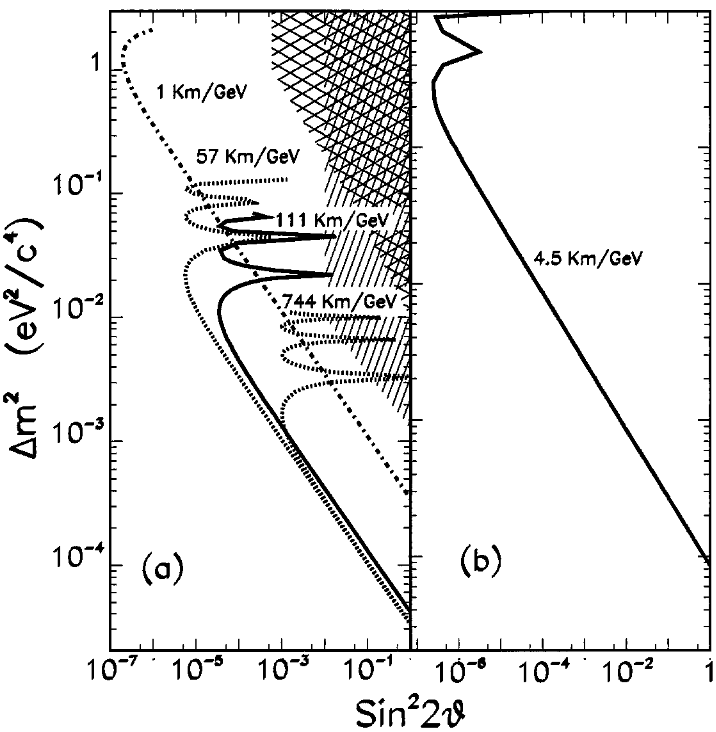

FIGURE 4. Contours of single–event sensitivity for (a) ν_e–ν_μ oscillations and (b) ν_e–ν_τ oscillations. The ν_e–ν_μ contours correspond to 1 year of running with the first four detector configurations summarized in Table 1. The hatched and cross-hatched areas show the expected regions that will be explored by respectively the MINOS experiment [4] after 2 years of running and the MiniBooNe experiment [7] after 1 year of running. The ν_e–ν_τ contour corresponds to the fifth detector configuration in Table 1.

energy muon beams became available.

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