DRAFT
November 10, 1999

Physics Capabilities of a Neutrino Factory

Lots of people

Nice abstract

14.60.Pq, 13.15.+g, 13.35.Bv, 07.77Ka

I. INTRODUCTION

Nice introduction

II. NEUTRINO BEAM PROPERTIES

Positive and negative muons decay via the weak interaction:-

$$\mu^+ \to e^+ \overline{\nu}_\mu \nu_e \ , \tag{1}$$

and

$$\mu^- \to e^- \overline{\nu}_e \nu_\mu \ . \tag{2}$$

Thus, muons decaying within the straight sections of a muon storage ring will produce neutrino beams consisting of 50% ν_μ and 50% $\overline{\nu}_e$ if negative muons are stored, and 50% ν_e and 50% $\overline{\nu}_\mu$ if positive muons are stored. In practice, if the detector only samples part of the beam within a small solid angle, the effective fluxes may differ from the 50% neutrino and 50% antineutrino mixtures suggested by Eqns. 1 and 2. However, the differential lepton and antilepton spectra from muon decay are well known, and the appropriate fluxes can be precisely calculated.

A. Differential spectra

The neutrino fluxes and interaction rates at a given location downstream of a muon storage ring neutrino source depend upon the number of stored muons, the beam divergence within the neutrino–beam forming straight section, and the energies and polarization of the decaying muons.

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 [41]:

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

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 E_ν the antineutrino (neutrino) energy. The corresponding expression describing the distribution of electron neutrinos (antineutrinos) is

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

Thus, the neutrino and antineutrino energy– and angular– distributions depend upon the parent muon energy, the decay angle, and the direction of the muon spin vector. For an ensemble of muons we must average over the polarization of the initial state muons, and the distributions become:

$$\frac{d^2N_{\nu_\mu}}{dxd\Omega} \propto \frac{2x^2}{4\pi}\left[(3-2x) \mp (1-2x)P_\mu\cos\theta\right], \tag{5}$$

and

$$\frac{d^2N_{\nu_e}}{dxd\Omega} \propto \frac{12x^2}{4\pi}\left[(1-x) \mp (1-x)P_\mu\cos\theta\right], \tag{6}$$

where P_μ is the average muon polarization along the chosen quantization axis, which in this case is the beam direction.

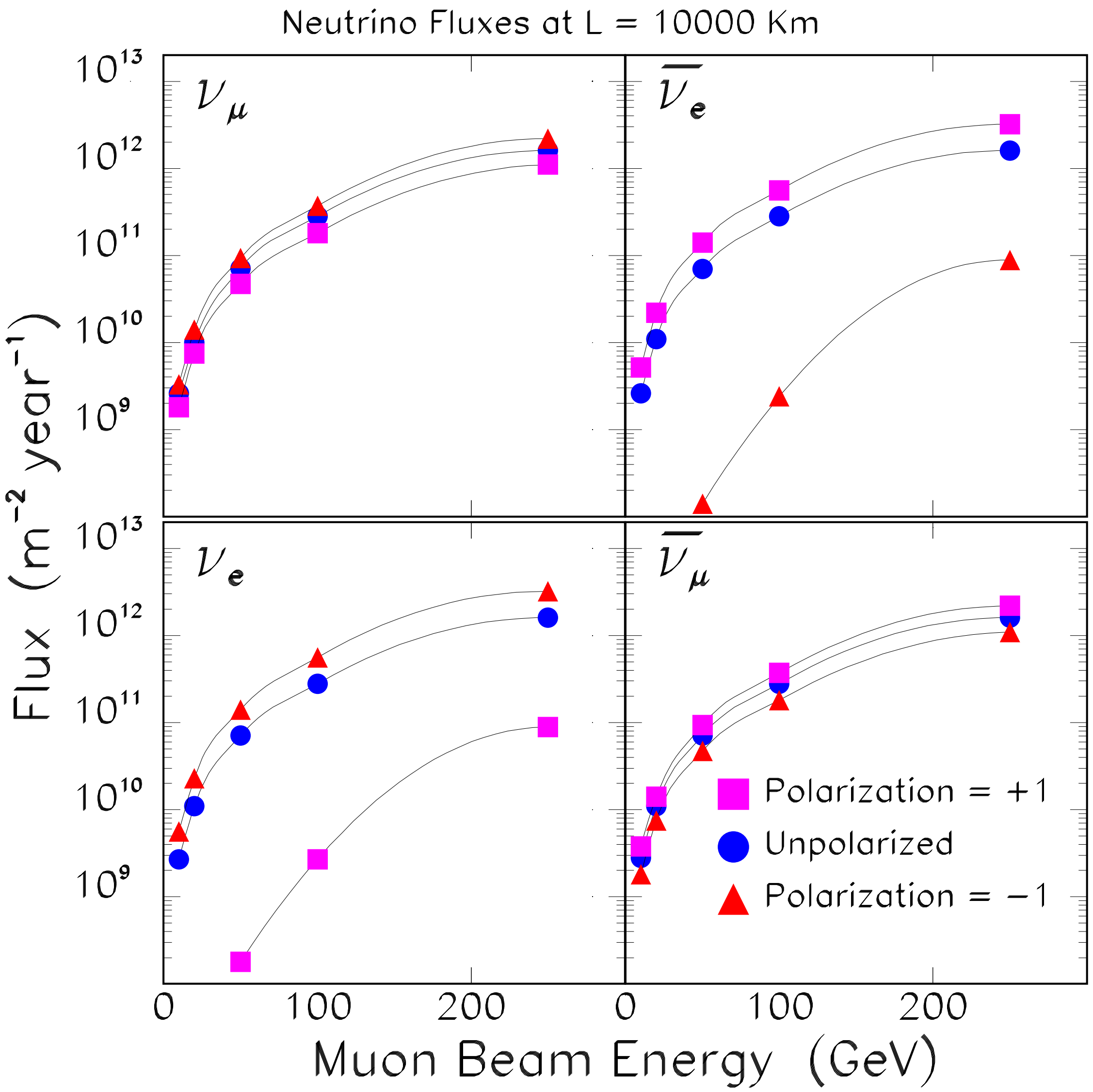

FIG. 1. Calculated neutrino and antineutrino fluxes at a far site located 10000 km from a neutrino factory in which 1×10^{20} muons have decayed in the beam–forming straight section. The fluxes are shown as a function of the energy of the stored muons for negative muons (top two plots) and positive muons (bottom two plots), and for three muon polarizations as indicated. FIGURES NEEDS UPDATING

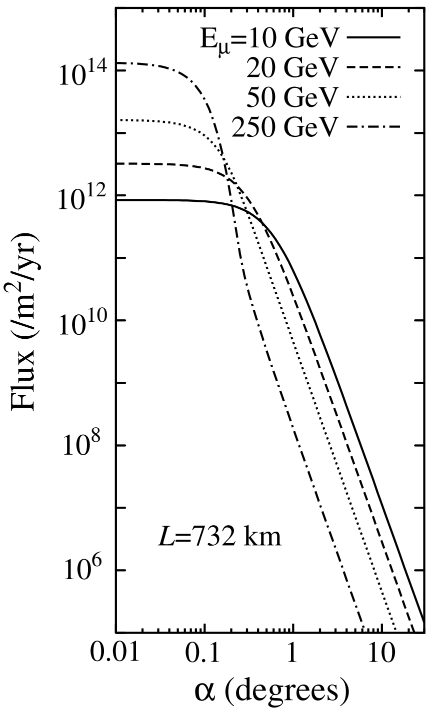

FIG. 2. Total neutrino flux of a given flavor versus angle at the source from the beamline at $L = 732$ km for $E_\mu = 10$ GeV (solid line), 20 GeV (dashed), 50 GeV (dotted), and 250 GeV (dot–dashed), assuming 1.6×10^{20} neutrinos in the beam per operational year. A Gaussian muon beam divergence of 1 mr has been folded in. The total antineutrino flux is the same. FIGURE NEEDS UPDATING

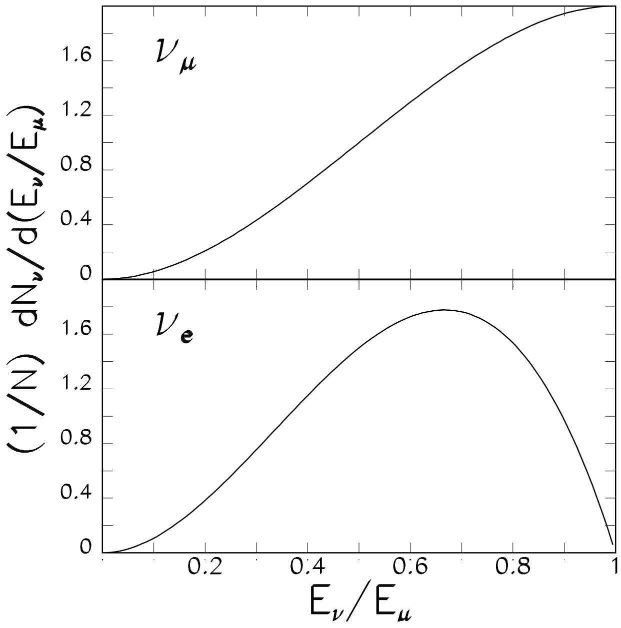

FIG. 3. Neutrino and antineutrino spectra for muon–type neutrinos (top) and electron–type neutrinos (bottom) in the beam downstream of a muon storage ring neutrino source containing unpolarized muons.

B. Fluxes

Using Eqs. 5 and 6 the ν_μ, ν_e, $\overline{\nu}_\mu$, and $\overline{\nu}_e$ fluxes downstream of a muon storage ring neutrino source have been calculated [19] as a function of P_μ, the baseline length (L), and the energy of the stored muons (E_μ). The resulting fluxes are shown for $L = 10000$ km in Fig. 1. As an example, if 1×10^{20} unpolarized 20 GeV muons decay in the beam forming straight section, the resulting neutrino and antineutrino fluxes on the other side of the Earth are O(10^{10}) per m^2. Note that at fixed E_μ, a change of the muon polarization from $+1$ to -1 results in a change of the ν_μ ($\overline{\nu}_\mu$) flux at the distant site by a factor of approximately two. In contrast, the ν_e ($\overline{\nu}_e$) flux is suppressed by roughly two orders of magnitude if $P_\mu = +1$ (-1). Therefore, if the muons in the storage ring are polarized, changing P_μ can be used to statistically separate processes arising from an initial electron–type neutrino from processes originating from an initial muon–type neutrino.

For unpolarized muons, to a good approximation the calculated fluxes are reproduced by the formula:

$$\Phi \equiv \frac{d^2N_\nu}{dAdt} = \frac{n_0}{4\pi L^2\gamma^2(1-\beta\cos\alpha)^2} \ , \tag{7}$$

where n_0 is the number of muon decays per unit time in the beam–forming straight–section, $\gamma = E_\mu/m_\mu$, $\beta = p_\mu/E_\mu$, α is the angle between the beam axis and the direction of interest, and dA is the differential area at the detector. In the extremely forward direction $\cos\alpha \simeq 1$, and using the approximation $\beta \simeq 1 - 1/(2\gamma^2)$, the neutrino flux is given by:

$$\Phi \simeq \frac{n_0\gamma^2}{\pi L^2} \ . \tag{8}$$

Note that the neutrino and antineutrino fluxes are proportional to $(E_\mu/L)^2$.

The neutrino flux decreases if the far site is away from the beam axis ($\alpha > 0$). The flux is shown as a function of α in Fig. 2 for several values of E_μ and L. Note that for $E_\mu < 50$ GeV the flux is insensitive to beam mis-alignments ($\Delta\alpha$) provided $\Delta\alpha < 1$ milliradian.

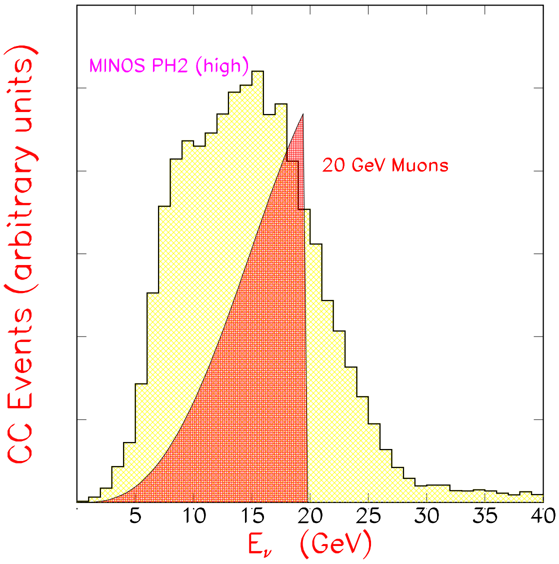

FIG. 4. Distribution of energies for interaction muon–type neutrinos 730 km downstream of the neutrino source for the MINOS PH2 WBB (open histogram) compared with the corresponding distribution downstream of a neutrino factory (shaded histogram).

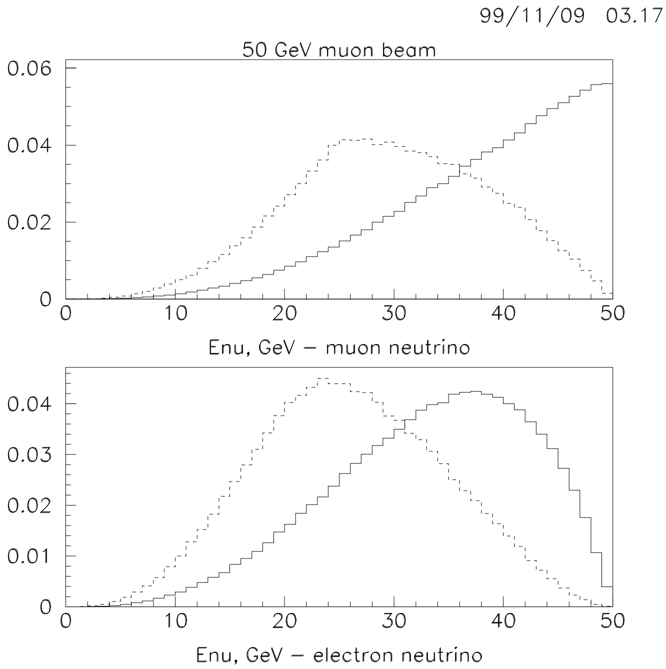

FIG. 5. Energy spectra far cf near from Heidi

Equations 5 and 6 can also be used to calculate the distribution of ν_μ and ν_e energies within the beam (dN_ν/dE_ν) using the approximation that, in the laboratory frame, $x \to E_\nu/E_\mu$ for forward neutrinos from high energy muon decays ($E_\mu >> m_\mu$). The calculated spectra are shown in Fig. 3. Note that the ν_μ spectrum peaks at the stored muon beam energy, whereas the ν_e spectrum peaks at two–thirds of the stored muon beam energy. The spectrum of interacting ν_μ (given by the energy weighted dN_ν/dE_ν distribution) is compared in Fig. 4 with the coressponding distribution for the MINOS WWB generated by the PH2 horn configuration. It can be seen that the neutrino factory beam can be considered to be a narrow band beam.

C. Interaction rates

Consider a neutrino with energy E_ν interacting with a proton of mass M_p. It is useful to define the energy transfer to the nucleon in the laboratory frame (ν). The fractional energy transfer $y = \nu/E_\nu$ is related to the the center–of-mass scattering angle: $(1-y) = (1+\cos\theta_{CM})/2$. Within the framework of the naive quark parton model the differential cross sections for charged current (CC) neutrino and anti-neutrino scattering from a proton are given by:

$$\frac{d\sigma^{\nu p}_{CC}}{dxdy} = \frac{4M_W^4 G_F^2 M_p E_\nu x}{\pi(Q^2+M_W^2)^2}\left[[\mathrm{d}_L(x)+\mathrm{s}_L(x)] + [\overline{\mathrm{u}}_R(x)+\overline{\mathrm{c}}_R(x)](1-y)^2\right] \tag{9}$$

and

$$\frac{d\sigma^{\overline{\nu} p}_{CC}}{dxdy} = \frac{4M_W^4 G_F^2 M_p E_\nu x}{\pi(Q^2+M_W^2)^2}\left[[\overline{\mathrm{d}}_R(x)+\overline{\mathrm{s}}_R(x)] + [\mathrm{u}_L(x)+\mathrm{c}_L(x)](1-y)^2\right] \tag{10}$$

where u_L, d_L, s_L, ($\overline{\mathrm{u}}_R$, $\overline{\mathrm{d}}_R$, $\overline{\mathrm{s}}_R$) are the probabilities for finding a quark (antiquark) with the correct helicity carrying momentum fraction x inside the nucleon, $x = Q^2/2M\nu$, and Q^2 is the four–momentum–transfer squared.

Most heavy targets have approximately equal numbers of protons and neutrons. Isospin invariance implies that:

$$\mathrm{u}(x)_p = \mathrm{d}(x)_n, \overline{\mathrm{u}}(x)_p = \overline{\mathrm{d}}(x)_n \tag{11}$$

$$\mathrm{d}(x)_p = \mathrm{u}(x)_n, \overline{\mathrm{d}}(x)_p = \overline{\mathrm{u}}(x)_n \tag{12}$$

$$\mathrm{s}(x)_p = \mathrm{s}(x)_n, \overline{\mathrm{s}}(x)_p = \overline{\mathrm{s}}(x)_n \tag{13}$$

$$\mathrm{c}(x)_p = \mathrm{c}(x)_n, \overline{\mathrm{c}}(x)_p = \overline{\mathrm{c}}(x)_n \tag{14}$$

and provided $M_W >> Q^2$, the differential CC cross sections are given by:

$$\frac{d\sigma^{\nu N}_{CC}}{dxdy} = \frac{G_F^2 M_p E_\nu x}{\pi}\left[[\mathrm{u}(x)+\mathrm{d}(x)+2\mathrm{s}(x)] + [\overline{\mathrm{u}}(x)+\overline{\mathrm{d}}(x)+2\overline{\mathrm{c}}(x)](1-y)^2\right] \tag{15}$$

and

$$\frac{d\sigma^{\overline{\nu} N}_{CC}}{dxdy} = \frac{G_F^2 M_p E_\nu x}{\pi}\left[[\mathrm{u}+\mathrm{d}(x)+2\mathrm{c}(x)](1-y)^2 + [\overline{\mathrm{u}}(x)+\overline{\mathrm{d}}(x)+2\overline{\mathrm{s}}(x)]\right] . \tag{16}$$

Data taken on iron [?,?,?] indicate that the momentum–weighted integrals of the parton distributions $x\mathrm{q}(x)$ are approximately (0.26, 0.15, 0.015, $<$ 0.01) for $(x\mathrm{u}, x\mathrm{d}, x\mathrm{s}, x\mathrm{c})$, and the corresponding integrals for $(x\overline{\mathrm{u}}, x\overline{\mathrm{d}}, x\overline{\mathrm{s}}, x\overline{\mathrm{c}})$ are (0.030, 0.035,0.015,$<$ 0.01). This yields the approximate expressions:

$$\frac{d\sigma^{\nu N}_{CC}}{dy} = \frac{G_F^2 M_p E_\nu}{\pi}\left[0.44 + 0.065(1-y)^2\right] \tag{17}$$

$$\frac{d\sigma^{\overline{\nu} N}_{CC}}{dy} = \frac{G_F^2 M_p E_\nu}{\pi}\left[0.41(1-y)^2 + 0.095\right] \tag{18}$$

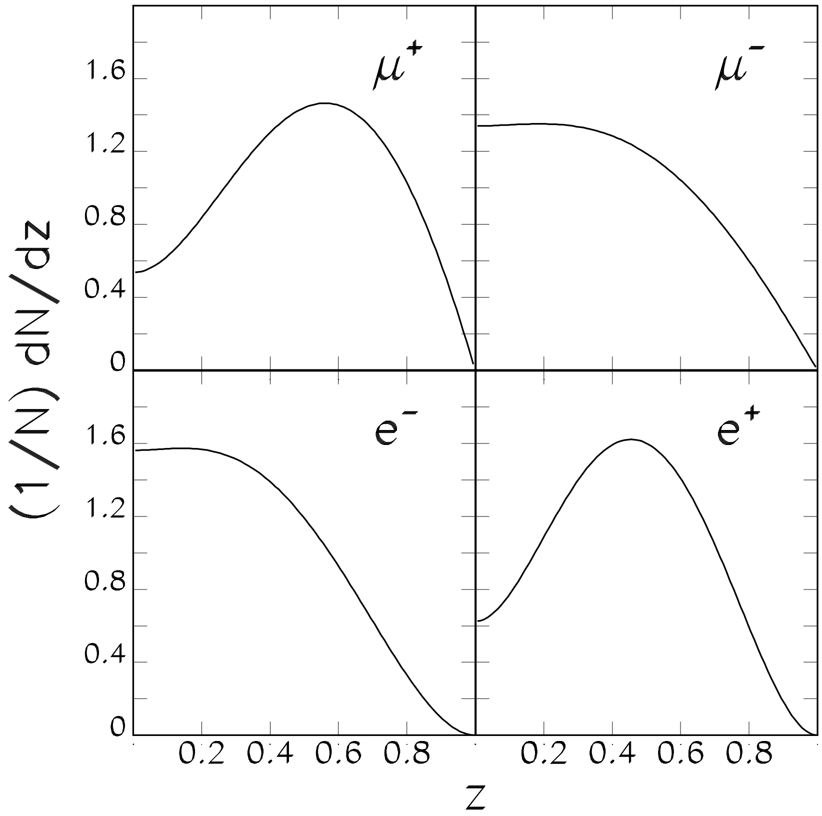

FIG. 6. Lepton energy spectra at a neutrino factory for CC $\overline{\nu}_\mu$ (top left), ν_μ (top right), ν_e (bottom left), and $\overline{\nu}_e$ (bottom right) interactions.

The neutrino cross section is thus approximately flat in the inelasticity variable y while the antineutrino cross section favors low values of y and hence high values for the scattered lepton energy. It is convenient to define the normalized charged lepton energy

$$z \equiv E_l/E_\mu \, . \tag{19}$$

At high energies $(1-y) \simeq z/x$, and it can be shown that if the stored muons are unpolarized the lepton spectra are described by:

$$\frac{dN_{\mu^+}}{dz} \propto 1 + 20z^2 - 32z^3 + 11z^4 \, , \tag{20}$$

$$\frac{dN_{e^-}}{dz} \propto 5 + 6z^2 - 32z^3 + 21z^4 \, , \tag{21}$$

$$\frac{dN_{\mu^-}}{dz} \propto 5 + 4z^2 - 16z^3 + 7z^4 \, , \tag{22}$$

$$\frac{dN_{e^+}}{dz} \propto 1 + 30z^2 - 64z^3 + 33z^4 \, . \tag{23}$$

The charged lepton spectra computed from Eqs. 20–23 are shown in Fig. 6.

Eqns 17–?? are modified by higher-twist processes (quasi-elastic scattering, non-conserved axial vector currents, resonances), final state mass effects (if a charm particle or τ lepton appears in the final state), and perturbative Quantum Chromodynamic corrections (which introduce a $\log Q^2$ dependence). However, if E_ν is greater than $\sim$ 20 GeV, the corrections to Eqns 17–?? are small, and the total cross section is given approximately by:

$$\sigma(\nu + N \to \mu^- + X) \approx 0.68 \times 10^{-38}\mathrm{cm}^2 \times (E_\nu, \mathrm{GeV})\ , \tag{24}$$

$$\sigma(\overline{\nu} + N \to \mu^+ + X) \approx 0.34 \times 10^{-38}\mathrm{cm}^2 \times (E_{\overline{\nu}}, \mathrm{GeV})\ . \tag{25}$$

The number of ν_e and ν_μ CC events observed per incident neutrino on an isoscalar target of mass density ρ and length l is:

$$N(\nu + N \to \mu^- + X) = 0.67 \times 10^{-38}\mathrm{cm}^2 \times (E_\nu, \mathrm{GeV})\rho l N_A \tag{26}$$
$$= 1.13 \times 10^{-14}(E_\nu, \mathrm{GeV})\text{events per gr/cm}^2\ , \tag{27}$$

and

$$N(\overline{\nu} + N \to \mu^+ + X) = 0.34 \times 10^{-38}\mathrm{cm}^2 \times (E_\nu\ , \mathrm{GeV})\rho l N_A = \tag{28}$$
$$= 0.56 \times 10^{-14}(E_{\overline{\nu}}, \mathrm{GeV})\text{ events per gr/cm}^2\ . \tag{29}$$

Using Eqs. 27 and 29, the calculated ν_e and ν_μ CC interaction rates resulting from 2×10^{20} muon decays in the beam–forming straight–section of a neutrino factory are compared in Table I with expectations for the corresponding rates at the next generation of accelerator–based neutrino experiments. Note that event rates at a neutrino factory increase as E_μ^3, and are significantly larger than expected for the next generation of approved experiments if $E_\mu > 20$ GeV.

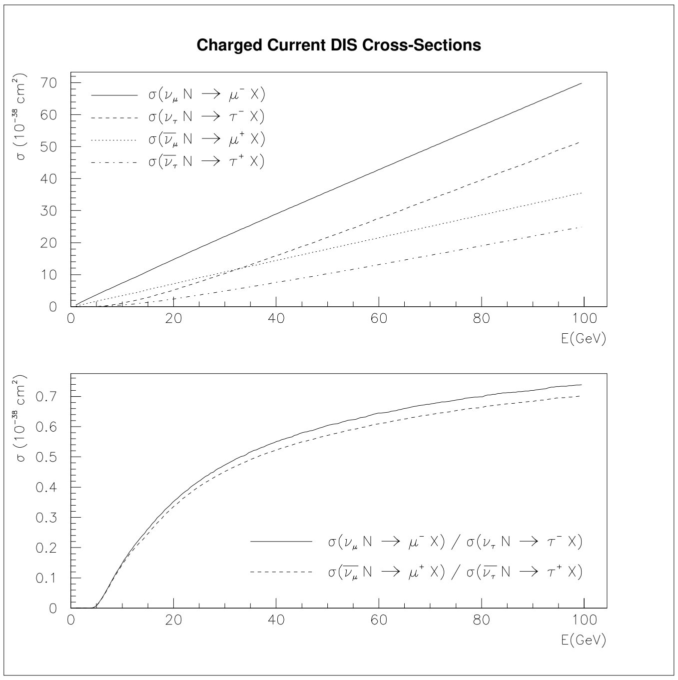

Figure 5: Charged Current Deep Inelastic Scattering Cross Sections

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FIG. 7. Tau–neutrino CC cross-section compared with the corresponding muon–neutrino cross-section.

Tau neutrino interaction rates are substantially different than those for lighter quarks, especially near the production threshold at xxx.gev. The presence of the tau mass in the final state shifts the definitions of the kinematic variables. Furthermore, the mass terms in the leptonic current can no longer be ignored and allow the axial vector structure functions W4 and W5 to play a more important role. Figure 7 shows a calculation [43] of the interaction rate ratios for tau and muon charged current events. At near threshold, contributions from quasi-elastic and single pion production dominate. If the ν_τ cross sections from Ref. [44] are used, the predicted event rates are 20–30% higher.

In addition to CC interactions, neutrinos also interact via neutral current (NC) scattering. For an isoscalar target the differential cross sections are described by:

$$\frac{d\sigma^{\nu N}_{NC}}{dxdy} = \frac{M_W^4 G_F^2 M_p E_\nu}{\pi(Q^2+M_W^2)^2} x \left[[L_{\mathrm{d}}^2 + R_{\mathrm{d}}^2(1-y)^2](\mathrm{d}(x)+\mathrm{u}(x)+2\mathrm{s}(x)) + [L_{\mathrm{u}}^2(1-y)^2 + R_{\mathrm{u}}^2][\overline{\mathrm{u}}(x)+\overline{\mathrm{d}}(x)+2\overline{\mathrm{c}}(x)] \right], \quad (30)$$

$$\frac{d\sigma^{\overline{\nu} p}_{NC}}{dxdy} = \frac{2M_W^4 G_F^2 M_p E_\nu}{\pi(Q^2+M_W^2)^2} x \left[[L_{\mathrm{u}}^2(1-y)^2 + R_{\mathrm{u}}^2](\mathrm{u}(x)+\mathrm{d}(x)+2\mathrm{c}(x)) + [L_{\mathrm{d}}^2 + R_{\mathrm{d}}^2(1-y)^2][\overline{\mathrm{u}}+\overline{\mathrm{d}}(x)+2\overline{\mathrm{s}}(x)] \right] \quad (31)$$

where the L_q and R_q are the left and right handed weak couplings for u-type and d-type quarks, with $L_{u,c} = 0.5 - 0.67\sin^2\theta_W$, $L_{d,s} = -0.5 + 0.33\sin^2\theta_W$, $R_{u,c} = -0.67\sin^2\theta_W$, and $R_{d,s} = 0.33\sin^2\theta_W$. To a first approximation the total NC cross sections for high energy neutrinos:

$$\sigma(\nu + N \to \nu + X) \sim 0.5 \times \sigma(\nu + N \to l^- + X)\ , \tag{32}$$

$$\sigma(\overline{\nu} + N \to \nu + X) \sim 0.5 \times \sigma(\overline{\nu} + N \to l^+ + X)\ . \tag{33}$$

D. Beam divergence, momentum spread, and straight-section length

In practice the detailed properties of the muon beam within the straight section of the storage ring will affect the neutrino fluxes at near and far detector sites. In particular the beam divergence (σ_θ) and the beam momementum spread σ_p must be considered, and in addition, for near experiments, the finite length of the straight section.

A finite σ_θ will result in a decrease of the neutrino flux at a distant site. Current design studies have taken as a reasonable design criteria $\sigma_\theta \leq 0.1/\gamma$. If the beam divergence $\sigma_\theta = 0.1/\gamma$ in both transverse directions the flux at the far site will be decreased by $\sim 8\%$. A finite σ_p tends to increase event rates at a distant site. For example, with $\sigma_p/p = 0.02$ and $p = 50$ GeV/c, the event rates are increased by $\sim 1\%$.

This is where Heidi adds a few lines plus a plot showing effect of finite straight section length on short baseline rates.

TABLE I. Muon neutrino and electron antineutrino CC interaction rates in the absence of oscillations, calculated for baseline length $L = 732$ km (FNAL $\to$ Soudan), for MINOS using the wide band beam and a muon storage ring with $E_\mu = 10, 20, 50$ and 250 GeV.

Experiment		$\langle E_{\nu_\mu}\rangle$ (GeV)	$\langle E_{\bar{\nu}_e}\rangle$ (GeV)	N(ν_μ CC) (per kt–yr)	N($\bar{\nu}_e$ CC) (per kt–yr)
MINOS	Beam				
	Low energy	3	–	458	1.3
	Medium energy	6	–	1439	0.9
	High energy	12	–	3207	0.9
Muon ring	E_μ (GeV)				
	10	7	6	2200	1300
	20	14	12	18000	11000
	50	35	30	2.9×10^5	1.8×10^5
	250	175	150	3.6×10^7	2.3×10^7

[1] See for example B. Kayser, "Neutrino mass: Where do we stand, and where are we going ?", hep-ph/9810513, 28 Oct. 1998; J. Conrad, "Recent results on neutrino oscillations", hep-ex/9811009, 5 Nov. 1998.

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