Event Rates for Off Axis NuMI Experiments

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Event Rates for Off Axis NuMI Experiments

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Abstract

Neutrino interaction rates for experiments placed off axis in the NuMI beam are calculated. Primary proton beam energy is 120 GeV and four locations at 810 km from target and 6, 12, 30 and 40 km off axis are considered.

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1 Introduction

A generic calculation of neutrino event rates for detectors at various locations in the NuMI neutrino beam has been done. Only flux, probability, cross sections and rudimentary energy reconstruction is considered. No particular detector technology is assumed.

2 Baselines

This document gives a calculation of neutrino flux and interaction rates for detectors placed in the various locations in the NuMI beam at 810 km from the target. Four off-axis locations are considered: 6 km (7.4 mrad), 12 km (14.8 mrad), 30 km (37.0 mrad) and 40 km (49.4 mrad).

3 Neutrino Flux

Neutrino flux calculations are performed using the GEANT3 based GNUMI simulation program. The proton beam, target, focussing horns, decay tunnel and other elements are models of what is currently in use by MINOS. The locations of the two focusing horns with respect to the target can focus the neutrino parents to produce different spectra. The so called “Low Energy” (LE)¹ and “pseudo Medium Energy” (pME) tuning are used to confirm the simulation against measured MINOS near detector data while the “Medium Energy” tuning is used for spectra at 810 km to match. Table 1 summarizes the beam tunings used. In all cases a 120 GeV primary proton beam is used.

Name	Target (cm)	Horn 2 (m)	Current (kA)	Version
LE	-10	+10	182	v18
pME	-100	+10	197	v18
ME	-100	+13	182	v15

Table 1: Summary of Neutrino Flux Spectra. Distances are measured w.r.t. face of horn 1.

Figure 1 shows the ν_μ spectra for these three beam configurations. Figure 2 shows the four neutrino components of the flux for the ME configuration.

4 Oscillation Probability

For this study, the neutrino oscillation parameters that were used are given in Table 2. They were calculated using the program “nuosc” part of libnuosc++[1]. This calculation is a full three-neutrino numerical calculation using the Preliminary Reference Earth Model (PREM)[2] for Earth’s density. The calculation mode using constant matter densities averaged over the baseline was used. Figure 3 shows the disappearance and appearance probabilities used.

5 Cross Sections

The interactions considered are:

- Quasi-elastic (QE) charged current (CC)
- Total charged current
- Neutral current (NC) single π^0 productions ($1\pi^0$)

¹More properly, MINOS calls this “LE-10”

Figure 1: Flux spectra of ν_μ neutrinos at 1km for the beams considered. Note, this is not far flux scaled to 1km. It contains effects of the secondary beam being an extended source.

Parameter	Value
Δm_{31}^2	$2.5 \times 10^{-3} eV^2$
Δm_{21}^2	$8.6 \times 10^{-5} eV^2$
$\sin^2 2\theta_{12}$	0.86
$\sin^2 2\theta_{23}$	1.0
$\sin^2 2\theta_{13}$	0.04
δ_{CP}	0

Table 2: Neutrino oscillation parameters used in this study.

ME Flux components on-axis at 1km

Figure 2: Neutrino flux spectra at 1km for the ME beam.

Figure 3: Disappearance (left) and appearance (right) neutrino oscillation probabilities as a function of the neutrino energy. See table 2 for oscillation parameters.

The cross sections used for QE and NC- $1\pi^0$ are shown in Figure 4. The total CC cross sections are parameterized for neutrinos as:

$$\sigma_{\nu\mu,CC} = 0.80 \times 10^{-38} \text{ cm}^2 / \text{GeV} \times E_\nu$$

and anti-neutrinos as:

$$\sigma_{\bar{\nu}\mu,CC} = 0.35 \times 10^{-38} \text{ cm}^2 / \text{GeV} \times E_\nu$$

The neutrino energy in charged current (total and QE) events is assumed to be reconstructed with perfect energy resolution and with no systematic bias. For NC- $1\pi^0$ events the reconstructed neutrino energy is taken to be the true energy of the π^0 and no consideration for shower angle w.r.t. to the incoming neutrino is made. This produces a softer reconstructed energy spectrum than would be found if this angle were considered. In addition, no account of nuclear absorption nor charge exchange by the π^0 is made.

To simulate the energy of the π^0 sets of E_{π^0} spectra were generated using mono-energetic neutrinos with energies chosen in steps of 0.5 GeV. These were generated with the NUANCE[3] simulation. Figure 5 illustrates this.

All cross sections are applied assuming the detector mass is made up of equal numbers of protons and neutrons.

6 Comparison with MINOS Near Detector Data

Figure 6 shows a comparison between GNUMI MC simulation and data collected in the MINOS near detector. There “LE-10” corresponds to the “LE” configuration in this work. The ME simulation used in this work is from a slightly older version (v15) of GNUMI than is used in this comparison (v18). No tuning to the MINOS data has been done and data/MC comparison shows very good agreement.

Figure 4: QE and NC- $1\pi^0$ cross sections.

Q^2 for $E_\nu = 1-10$ GeV

E_{π^0} for $E_\nu = 1-10$ GeV

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Figure 5: (a) q^2 (top) and (b) π^0 energy (bottom) as functions of mono-energetic neutrinos in 1 GeV steps. Calculation uses 0.5 GeV steps in neutrino energy.

Figure 6: MINOS Near Detector data and GNUMI MC simulation comparison of interaction spectra[4]. From left, LE, pME and pHE beams. Top row shows data spectra as black points, MC as gray shaded region with a width representing MC uncertainty. Bottom row shows ratio of data to MC.

7 Off-axis Event Rates

All of the above is combined to estimate interaction spectra and rates for disappearance and appearance modes for detectors placed in the NuMI beam. Figures 7-16 show these spectra for an 810km baseline at 0, 6, 12, 30 and 40 km off axis. The event rates are summaries in Table 3.

km o.a.	ν_μ CC	ν_μ CC osc	ν_e CC beam	ν_e QE beam	NC- $1\pi^0$	$\nu_\mu \rightarrow \nu_e$ CC	$\nu_\mu \rightarrow \nu_e$ QE
0	248.0	225.0	1.80	0.0914	6.96	1.40	0.188
6	71.6	47.0	1.068	0.0770	3.194	0.879	0.171
12	18.1	7.33	0.443	0.0485	1.168	0.305	0.099
30	1.84	1.12	0.0730	0.0152	0.135	0.0216	0.0108
40	0.860	0.479	0.0378	0.0097	0.0605	0.0121	0.0057

Table 3: Summary of event rates per-kTon per- 10^{20} PoT for detectors placed 810 km from the target and various distances off-axis (o.a.).

Figure 7: Disappearance (left) and appearance (right) for 810 km baseline and 0 km off-axis.

Figure 8: Disappearance (left) and appearance (right) for 810 km baseline and 0 km off-axis.

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