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THE RESPONSE OF THE DUMAND OCTAGON ARRAY TO LOW ENERGY NEUTRINOS

With Application to Neutrino Oscillations using Fermilab and Atmospheric Neutrinos

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ABSTRACT

The DUMAND Octagon is better at detecting low energy (< 50 GeV) neutrino events than was originally anticipated. This expands the possibilities for unique studies of neutrino oscillations using either an accelerator beam or atmospheric neutrinos. It is shown that atmospheric neutrinos look particularly promising.

Introduction

The DUMAND II Octagon array design was originally optimized for the detection of through-going muons with energies above 50 GeV. The modules were spaced as far apart as possible to maximize the effective area and angular resolution in the search for point sources of extraterrestrial neutrinos.

In recent months, attention has returned to the fundamental question of neutrino oscillations. The position of DUMAND in the mid-Pacific gives it a large path length L to any accelerator that might aim neutrinos toward the array. It has been proposed that the Fermilab Main Injector (MI) beam be pointed toward DUMAND.[1] The path length from Fermilab is over 6,000 km and matter oscillation effects can greatly enchance the sensitivity to small mixing angles.[2]

The accessible range of neutrino mass square differences δm^2 depends on E/L. Following Parke,[3] $\delta m^2 \geq \sqrt{\epsilon}/1.27\ E/L$ and $\sin^2 2\theta \geq \epsilon$, where E is the neutrino energy in GeV, L is the path length in km, and ϵ is the detectable transition probability from one type of neutrino to another. For the proposed Fermilab MI beam, $\langle E \rangle = 20$ GeV and DUMAND II is capable of exploring down to $\delta m^2 \cong 10^{-3}\ \mathrm{eV}^2$. With matter oscillations, it becomes possible to explore neutrino mixing down to $\sin^2 2\theta \cong 10^{-2} - 10^{-3}$, where θ is the vacuum mixing angle.[2,3]

In addition, the ability of DUMAND to sweep through the horizon in looking for provides for a large variation in path length, from 25 to 12,800 km, for cosmic ray neutrinos produced at the top of the atmosphere (see Fig. 1). This fact, plus the substantial flux of low energy neutrinos, makes it possible to explore smaller mass square differences, perhaps down to $\delta m^2 = 10^{-4}$ eV^2. Further, the greater path length through the earth's diameter makes matter oscillations an even more powerful tool.

Sensitivity of the Octagon

The DUMAND Monte Carlo program DUMC has been used to estimate the effective volume for triggering and reconstructing low energy neutrino events and the ability to distinguish ν_μ from ν_e or ν_τ.

For this study, events were generated randomly within a vertical cylinder that is larger than the enclosed array by 30 m on the top, bottom, and side, a total volume of over $6\text{x}10^6$ m^3. (I have expanded this to 90 m in runs at 1000 GeV, and find no significant difference in results; however future studies will allow for events to occur at any distance where muons could reach the array. The enclosed volume of the array is $2\text{x}10^6$ m^3). Two alternatives on the choice of neutrino direction have been used: (1) from Fermilab (about 30^o below the horizon); (2) randomly distributed in cosZ, where Z = the zenith angle, in the range $-1 \leq \cos Z \leq 0.2$, corresponding to the region where the downward cosmic ray muon background is negligible.

Random noise is also generated in each optical module, at the 60 KHz rate expected from K^{40} background in the ocean.

For ν_e events, the neutrino energy is assumed to convert fully into particles that emit Cherenkov light emanating from the point of interaction. For ν_μ events, the neutrino energy is divided among the muon and the hadronic cascade, according to interaction kinematics. The energy carried away by neutrinos in neutral current events (or, in ν_τ events, where no attempt has yet been made to consider the detection possibilities of the high p_T muon that is often produced) has been neglected.

The simulated triggers used are those designed primarily for very high energy point sources. The first, called T3, tests if any one of the nine strings has three adjacent optical modules 1–2–3 with hit times obeying the criteria:

$$|t_1 - t_2| \leq 45 \text{ ns}, \ |t_2 - t_3| \leq 45 \text{ ns}$$
$$||t_1 - t_2| - |t_2 - t_3|| \leq 15 \text{ ns}$$

The second trigger, called TE, requires that the sum of the measured PMT integrated charges, $\Sigma q_i \geq 30$ p.e.[4,5]

The effective volume for triggers is defined as the volume in which events are generated, multiplied by the trigger efficiency for these events. This is shown in Fig. 2 as a function of neutrino energy, for ν_μ and ν_e. The results are presented for neutrinos directed from Fermilab, but no significant differences were found when random directions were tried.

When the actual spectral shapes expected from Fermilab and atmospheric neutrinos are folded in, the effective volumes for triggers are as follows:

	Effective Vol. (per 10^6 m^3)	Mean Energy (GeV)
ν_μ from Fermilab:	1.47	19.9
ν_e from Fermilab:	1.23	19.5
ν_μ from atmosphere:	0.33	6.4
ν_e from atmosphere:	0.19	2.7

The mean energy of each type of trigger is also given in the above table; the actual reconstructed events will have higher mean energies (see below).

Event rates from Fermilab will of course depend on beam time. Using the atmospheric neutrino spectra calculated by Mitsui et al,[6] the integral event rate spectra shown in Fig. 3 are obtained. A total of estimate 43,700 $\nu_\mu+\bar{\nu}_\mu$ and 7,060 $\nu_e+\bar{\nu}_e$ triggers per year from the atmosphere ($-1 \leq \cos Z \leq 0.2$) are estimated.

It is interesting to contrast these rates with the estimate of 3,500 atmospheric neutrino events per year for "throughgoing muons" given in Table 1.1 on page 12 of the DUMAND II Proposal (1988). This is consistent with Fig. 3, since the earlier result was based on the assumption that a ν_μ event must have at least 50 GeV for its muon to traverse the array. We previously assumed that sufficiently tight triggers and cuts could be applied to provide a sharp cutoff below 50 GeV. However, as Fig. 2 shows, the T3+TE trigger is very loose, with a 50% efficiency for triggering on all 50 GeV ν_μ events within 30 m of the array, and about 25% at 10 GeV. This, together with the steep atmospheric neutrino spectra, gives us far more atmospheric neutrino triggers than previously anticipated. Whether you view this as good or bad depends on whether you regard atmospheric neutrinos as signal or noise. Further work must be done to see if an adequate filter can be found for these low energy events to keep them from contaminating the search for VHE point sources. In the meantime, let us see what we can do with this welcome new signal.

Secondary Triggers and Cuts

So far I have discussed only the loose first level hardware triggers T3 and TE. These were designed to reduce the raw data rate of $1/\mu s$ to $1/ms$ for further processing. The need for a second level hardware trigger is now under discussion. At a KHz rate, it should be possible for this to act across strings.

In the 1988 Proposal, we assumed a three string trigger that required various combinations of coincident adjacent clusters on any combination of two or three strings: (3–3–2), (4–2–2), (5–2–0), and (4–3–0). That is, two 3–folds and a 2–fold, two 2–folds and a 4–fold, etc. I will r efer to this trigger as "TA". The TA false trigger rate was estimated at the time of the Proposal to be of the order of 1 Hz. In the current study, TA accepts 80% of the ν_μ and ν_e events above 1 TeV and about 30% below 50 GeV. So TA can be used as a high energy filter for point source searches. However, we clearly want to save whatever data we can for further analysis. TA or any other test that throws out low energy events should not be applied in the hardware unless absolutely necessary. We have to be careful about throwing the baby out with the bath water.

Event Reconstruction

In principle, we should cut out any data prior to running them though the fitting process used for event reconstruction. If the fitter is designed properly, it will contain all the information possible and itself act as a filter for unwanted events. In practice, we cannot handle all the raw data so we apply hardware triggers. These should be as non–restrictive as possible, letting through as much as can be processed by the data harvesting system. Once the events are in the computer, any further cuts – such as TA – serve no purpose other than speeding up the processing. With sufficient computer power, everything can be done by the fitter. The ideal fit is a maximum likelihood search for the best parameters that describe the event. In practice, this can be very time–consuming, and furthermore, such searches depend heavily on the quality of the first guess for the parameters.

The development of fitting algorithms for DUMAND has been going on for a long time now. They are continually undergoing improvement, so the procedure described next is a snapshot of the current situation.

After some preliminary filtering to reduce background hits, a series of fits is performed, with bad points tossed out and the fit re-done until it is either satisfactory or fails.[7]

Two kinds of fits are now performed:

1) A <u>track fit</u> in which the detected light is assumed to be emitted along a muon track, and

2) A <u>vertex fit</u> in which the detected light is assumed to be emitted from the interaction point.

The two fit types differ in the estimated hit times and PMT charges that go into the χ^2:

$$\chi^2 = \sum_i \frac{(\tilde{t}_i - t_i)^2}{\sigma_t^2} + \sum_i \frac{(\tilde{q}_i - q_i)^2}{\sigma_q^2} \tag{1}$$

where $\tilde{}$ specifies the estimated values of PMT hit time t_i and integrated charge q_i (in p.e.), σ_t = 2.7 ns (2.5 ns for the PMT rms'd with 1 ns least count), and $\sigma_q^2 = \tilde{q} + 1$. The second summation includes non-hit tubes, with $q_i = 0$.

The lowest χ^2 is sought for the following six parameters: the coordinates of the interaction point x_o, y_o, and z_o, the direction angles of the neutrino θ and ϕ, and a factor f that multiplies the nominal expected charge.

Track and vertex fits have been performed on samples of atmospheric and Fermilab events that pass the trigger criterion T3 + TE. The table below lists the number that gave track and vertex fits in each case. Also shown are the numbers that fit both hypotheses, and those for which a decision can be made based on the quality of the fit as to whether an event is a "track" or a "vertex." The criterion used was to choose the smaller mean deviation of the measured OM hit times from those expected for the best fit parameters.

	Atmosphere		Fermilab	
	ν_μ	ν_e	ν_μ	ν_e
T3+TE Hardware Triggers	485	304	239	200
Track fits	95	28	119	104
Vertex fits	69	10	78	58

Fit both	34	4	55	48
Track fit preferred	94	28	117	97
Vertex fit preferred	36	6	25	17

The small fraction of triggers which give a fit is a reflection of the non-restrictiveness of the triggers, as emphasized earlier. T3+TE lets in background and low energy triggers. The main point about this table is that ν_μ events prefer the track fit over the vertex fit, as they should. On the other hand, ν_e events also prefer the track fit. These will constitute a contamination to any ν_μ sample, as well as making it difficult to study ν_e events on their own.

Atmospheric Neutrino Oscillations

The above results indicate that we will have a large and moderately clean sample of fully reconstructed low energy neutrino events from the atmosphere: about 8,600 ν_μ events with an average energy of 10 GeV (from the Monte Carlo) and an 8% "contamination" of 650 ν_e events that give a track fit, with an average energy of 3 GeV.

This suggests that neutrino oscillations can be searched for by ν_μ-disappearance. One way to do that was suggested in 1980.[8] The idea was to plot the atmospheric event rate as a function of a variable ς that flattens out the sec Z^* distribution for atmospheric muons and neutrinos, where Z^* is the zenith angle at the top of the atmosphere, and is related to the zenith angle Z at the array by

$$\sin Z^* = \frac{R - D}{R} \sin Z \qquad (2)$$

where R is the radius of the earth and D is the depth of the detector, measured from the top of the atmosphere. A slightly modified variable η, which accomplishes the same task as ς, is defined such that its magnitude is given by

$$|\eta| = 1 - \frac{\ln \cos Z^*}{\ln \cos Z^*_{max}} \qquad (3)$$

where Z^*_{max} is given by (2) with $Z = 90^o$, and whose sign is taken to be the same as the sign of cosZ. So defined, η varies from -1 to $+1$ as cosZ varies over the same range, and $\eta = 0$ corresponds to $Z = 0$. However, a $\sec Z^*$ distribution will appear flat as plotted against η, and any deviation can then be interpreted as a deviation from $\sec Z^*$. That is, $d\eta = \sec Z^* d\cos Z^*$.

Fig. 4 shows the distribution in relative muon intensity expected in η for 10 GeV neutrinos, the average energy for reconstructed atmospheric events, and four values of δm^2. Maximal mixing is assumed. For a given mixing angle θ, the new relative intensity can be obtained by multiplying $\sin^2 2\theta$ by 1 – the ordinate of this plot. Here δm^2 and θ are the vacuum mixing parameters for $\nu_\mu \rightarrow \nu_\tau$ or the matter mixing parameters, which can be easily computed from the vacuum parameters, in the case of $\nu_\mu \rightarrow \nu_e$. See Parke equation 2.4.[3]

We can see from Fig. 4 that quite detectable vacuum (or $\nu_\mu \rightarrow \nu_\tau$) oscillations occur for δm^2_o greater than or about 5×10^{-4} eV^2 and $\sin^2 2\theta_o$ greater than or about 0.2. For $\nu_\mu \rightarrow \nu_e$, matter oscillations convert these parameters to vacuum parameters δm^2_o of greater than or about 3×10^{-3} eV^2 and $\sin^2 2\theta_o$ greater than or about 5×10^{-3}. Both of these regions are not ruled out by current experiments.

Conclusions

By loosening up on our hardware trigger, we have been able to push the DUMAND Octagon neutrino detections capability down to a few GeV. This makes it quite feasible to study neutrino oscillation in a beam aimed from Fermilab, with average energy 20 GeV, or with atmospheric neutrinos, with an average energy for fully reconstructed ν_μ events of about 10 GeV. In one year's running, we will have about 9,000 atmospheric events. Both $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_\tau$ oscillations can be studied in parameter regions not yet ruled out by current experiments.

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References

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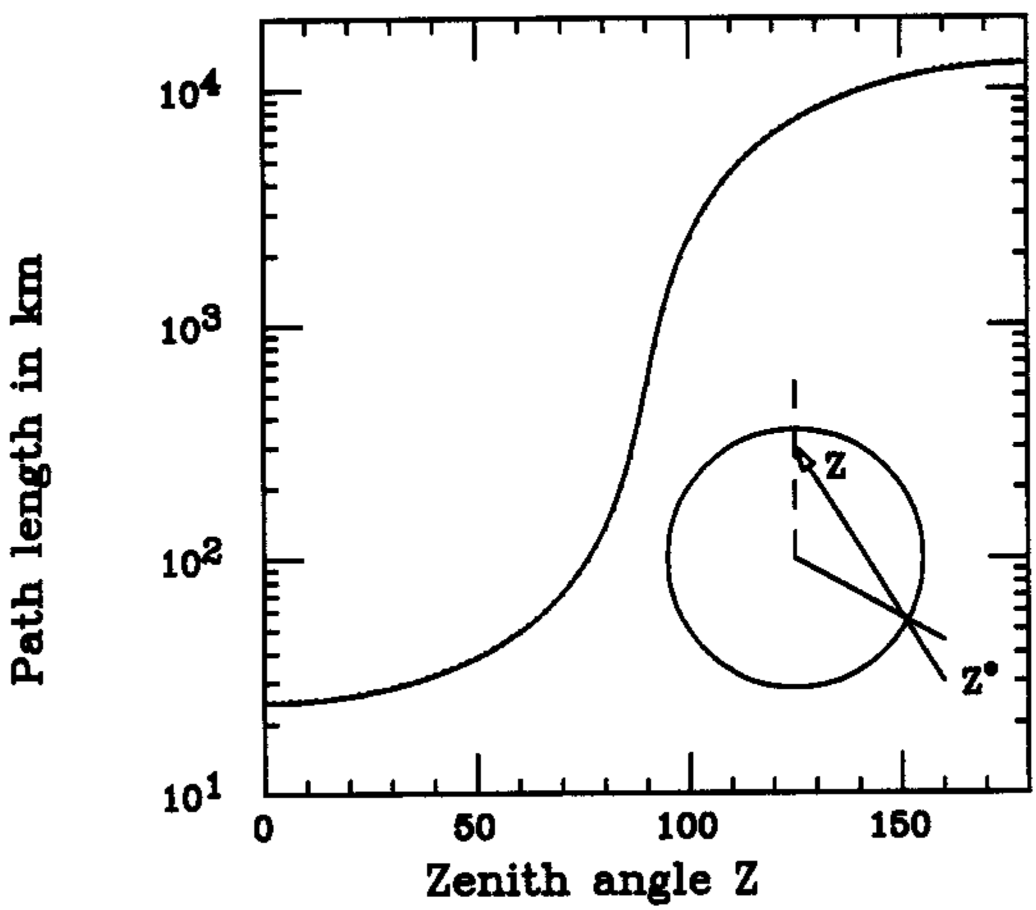


Fig. 1. Path length from the top of the atmosphere to DUMAND, as a function of the zenith angle at the array.

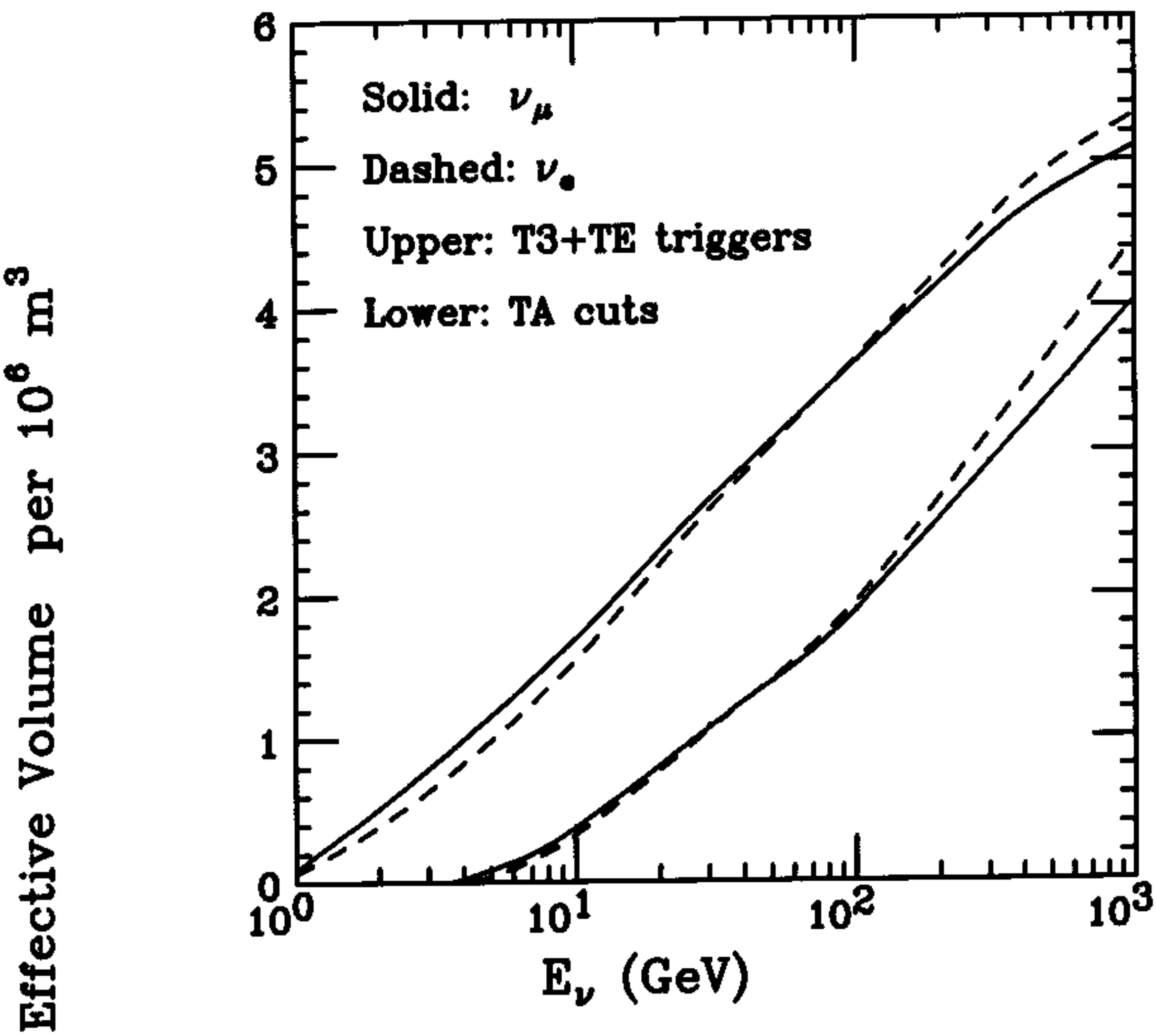
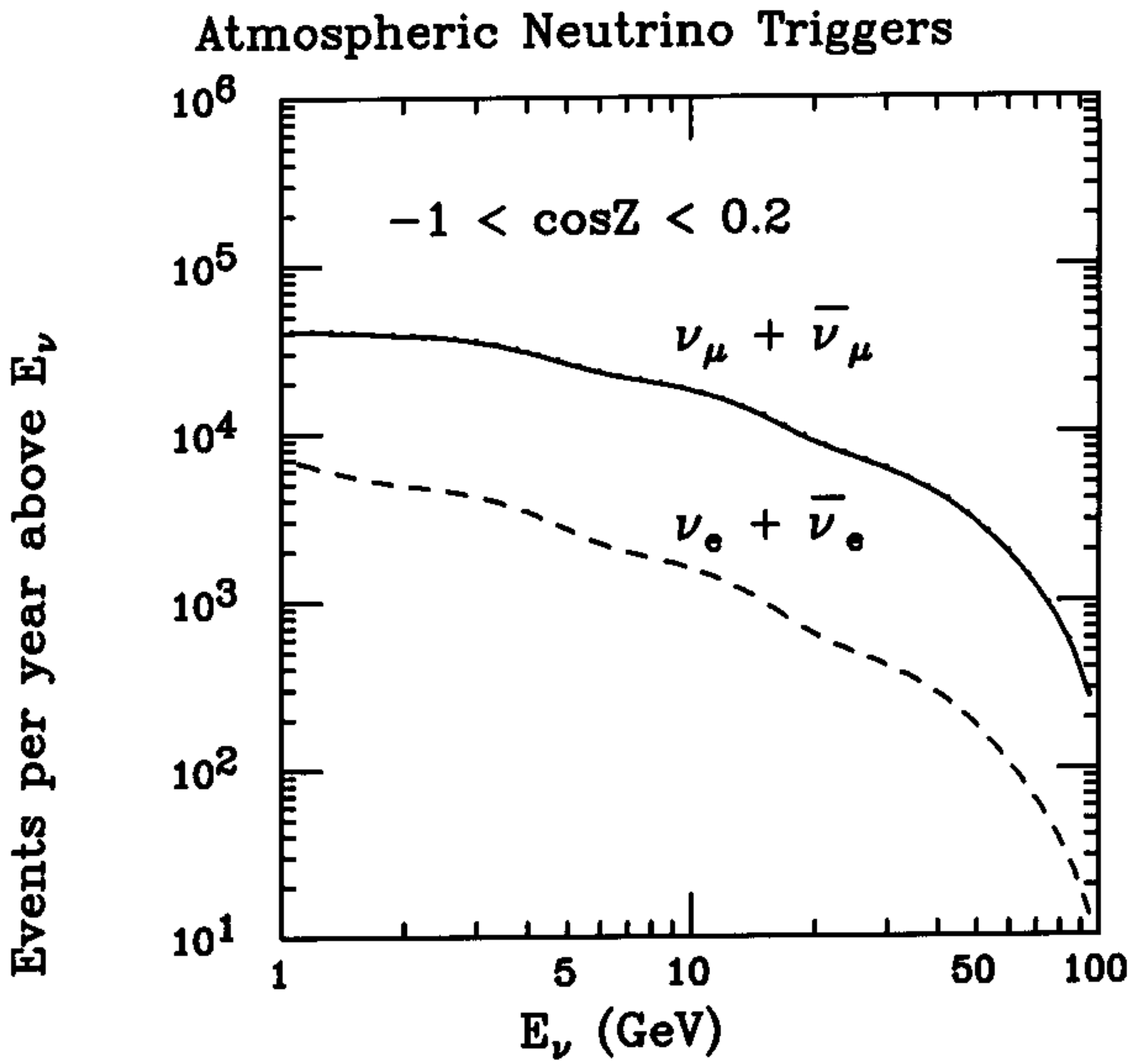
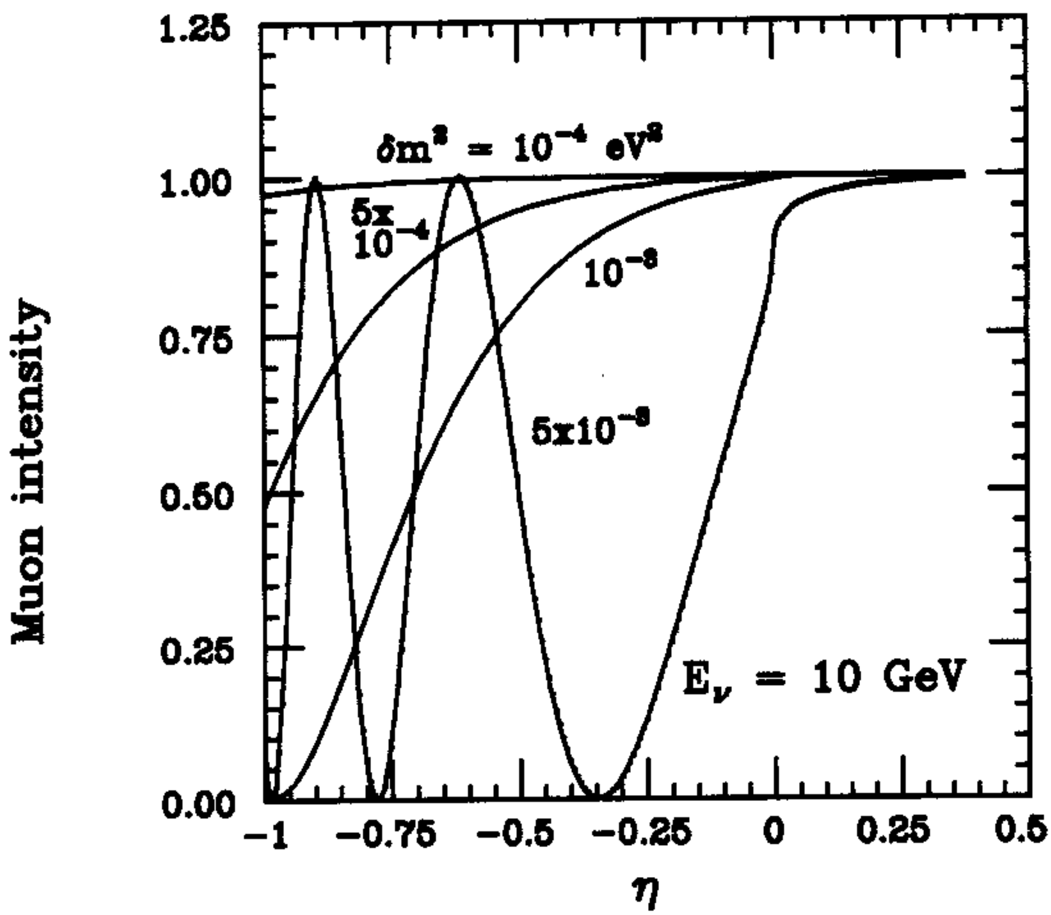


Fig. 2. Effective volume as a function of neutrino energy.



3. Expected number of events per year above a given neutrino energy.



4. The effect of neutrino oscillations on muon intensity as a function of the variable η which flattens out the $\sec Z^*$ distribution normally expected with no oscillations. Maximal mixing is assumed. Curves are drawn for $E_\nu = 10$ GeV and four values of δm^2.