The Detection of Three-Way Neutrino Oscillations at DUMAND

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Pantaleone and others [1,2] have shown that Extra Long Accelerator Neutrino (ELAN) experiments could probe new limits on mixing between neutrino flavors. In particular, muon neutrinos travelling from Fermilab through the mantle of the earth to DUMAND could undergo matter-enhanced mixing with a measurable probability.

In the past, studies have focused primarily on two-flavor mixing effects [2], since ν_μ - ν_τ mixing is not enhanced by matter. These studies indicate that $\nu_\mu \longrightarrow \nu_e$ mixing could be significant, but they claim that systematic errors in current detectors would complicate the interpretation of $\nu_\mu \longrightarrow \nu_e$ mixing effects. Recently, however, Pantaleone has argued that the two-flavor approximation is "inadequate for ELAN experiments." [1] When all three flavors are taken into account, the probability of $\nu_\tau \longrightarrow \nu_e$ transitions is considerably enhanced by matter effects on ν_τ- ν_e mixing. Since the wavelength for ν_μ- ν_τ mixing may be relatively short on this scale, the transition$\nu_\mu \longrightarrow \nu_\tau \longrightarrow \nu_e$ could produce a significant electron neutrino flux that would be detectable by DUMAND.

In his calculations, Pantaleone considers the parameter range in which the ν_e and ν_μ couple to mass states with effectively zero mass, and ν_τ couples predominantly to some non-zero mass, m_3. This reasonable assumption simplifies the transition probability calculations by reducing the variables to two mixing angles, ϕ and Ψ, and one mass-squared difference, m_3^2. Ψ is the muon-taon mixing angle, which is unaffected by matter, and ϕ is the taon-electron mixing angle. For plausible combinations of these parameters, the ν_e flux at DUMAND could be 1-10% of the ν_μ flux.

Since Pantaleone's calculation uses an ideal detector with no cut-off, and since the energy dependence of the indirect muon-electron mixing is not trivial, it is important to check Pantaleone's result with calculations based on more realistic detector efficiencies. To implement this check, we used V. J. Stenger's plot of the effective detector mass for different neutrino energies (Figure 1) [3] to calculate detector efficiencies. Our muon neutrino flux data assumes a decay length of 260m at Fermilab, although changes in the decay lenth do not appreciably affect the flux spectrum (Figure 2). When all the corrections were accounted for, significant numbers of detected ν_e events resulted within ranges of the three parameters similar to those of Pantaleone (Figure 3).

For a mass difference of 10^{-1} to 10^{-2} eV^2, a $\sin^2(2\phi)$ in the same range, and a $\sin^2\Psi$ of 0.3 to 0.03, we predict between 10 and a few hundred detected electron events in an eight-month run. For m_3^2 of 10^{-2} eV^2, $\sin^2(2\phi)$ of 10^{-1}, and $\sin^2\Psi$ of 0.3, our program predicts roughly 300 detected electron events during a run (Figure 4). The number of detected events does not change in order of magnitude as m_3^2 is increased to 1 eV^2. In fact, it even increases around the resonance mass value of $2*10^{-2}$ eV^2, as expected.

Lowering $\sin^2(2\phi)$ results in the expected near-linear decrease in the event rate, but the total number of events is still measurable for values spread over three orders of magnitude

(Figure 5). For m_3^2 of 10^{-2} eV^2, $\sin^2(2\phi)$ of 10^{-2}, and $\sin^2\Psi$ of 0.3, there would still be about 10 detected events in a run. Reducing $\sin^2\Psi$ again linearly decreases the event rate, thus restricting the ranges the other two parameters could have to produce a significant electron neutrino flux. Yet measurable amounts of interactions could still be detected for a mass difference on the order of 10^{-2} eV^2 and a $\sin^2(2\phi)$ of around 10^{-1} for $\sin^2\Psi$ values an order of magnitude lower. For example, about 50 total electron interactions would be detected for m_3^2 of 10^{-2} eV^2, $\sin^2(2\phi)$ of $5*10^{-1}$, and $\sin^2\Psi$ of 0.03.

Another interesting facet of the mixing is its complex dependence on the neutrino energy. Both the matter-enhanced mixing angle, ϕ_m, and the matter-enhanced mass difference, M_{32}^2, depend on the energy through the matter effect A within a sum (see equations (6) and (7) in [1]). Further complicating the energy-dependence is the oscillatory term depending on M_{32}^2 over energy (equations (8) and (11) in [1]). This oscillation in energy dependence is quite obvious around a vacuum mass difference of about 10^{-1} (Figure 5), and moves to lower energies as the mass difference is decreased, as expected from the M_{32}^2/E term in Pantaleone's eqn 11 [1] (Figures 6, 7).

DUMAND's chances of detecting matter-enhanced mixing effects in neutrinos sent from Fermilab are very encouraging. The long baseline through the earth's mantle would enhance the $\nu_\tau - \nu_e$ mixing enough to be measurable for parameter ranges of a couple of orders of magnitude. While our parameter limits match those of Pantaleone, the mixing angles recently suggested by Wolfenstein [4] are as yet an order of magnitude out of reach. Still, the ranges most likely to explain the atmospheric neutrino results are easily accessible by DUMAND [1], making the proposed ELAN experiment relevant and potentially earth-shattering.

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References

[1] J. Pantaleone, "ν_e Appearance for $\nu_\mu - \nu_\tau$ Oscillations in matter," submitted to Phys. Lett., May, 1992.

[2] R. H. Bernstein and S. J. Parke, Phys. Rev. D 44, 2069 (1991).

[3] V. J. Stenger, Proceedings of the Workshop on Long-Baseline Neutrino Oscillation, ed. Maury Goodman, November, 1991, p. 317.

[4] L. Wolfenstein, Phys. Rev. D 45, R4365 (1992).

Figure Captions

1. V. J. Stenger's plot of the effective detector mass vs. neutrino energy

2. Total muon neutrino flux from Fermilab reaching DUMAND in 8 mo., mixing ignored

3. Pantaleone's contour plot for ranges of parameters making electron neutrinos detectable at DUMAND

4. Total number of detected electron events predicted for $\sin^2\Psi=0.3$ as a function of m_3^2.

5. Total number of detected electron events predicted for $\sin^2\Psi=0.3$ as a function of $\sin^2 2\phi$.

6,7,8. Detected electron neutrino events as a function of energy for $\sin^2\Psi=0.3$, $\sin^2 2\phi=10^{-1}$, and $m_3^2=10^{-1}$, $2*10^{-2}$, 10^{-2} eV^2. Notice how the oscillations that extend out to 30 GeV in Figure 6 move over to 10 GeV in Figure 7, and how they are completely off of the scale in Figure 8.

Figure 1 - Stenger's Effective Detector Mass Plot

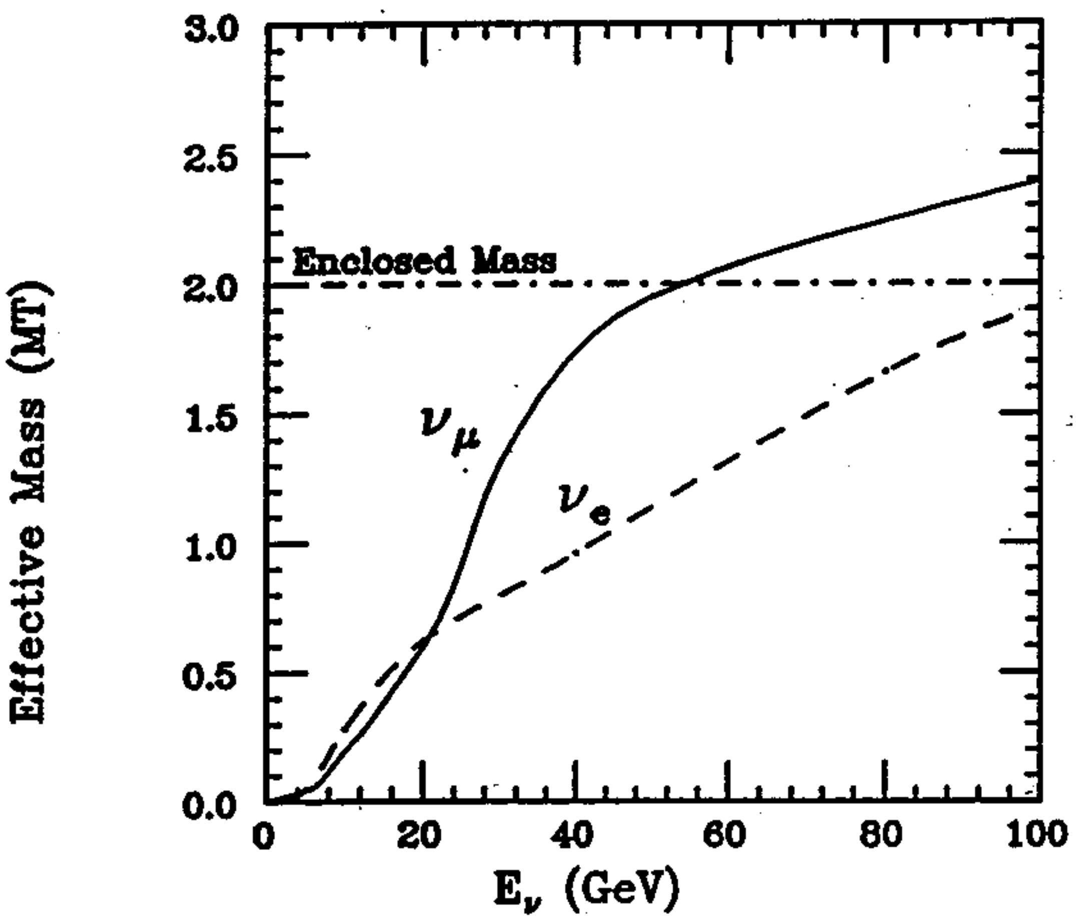

Figure 2 - Total Muon Neutrino Flux in 8 mo.

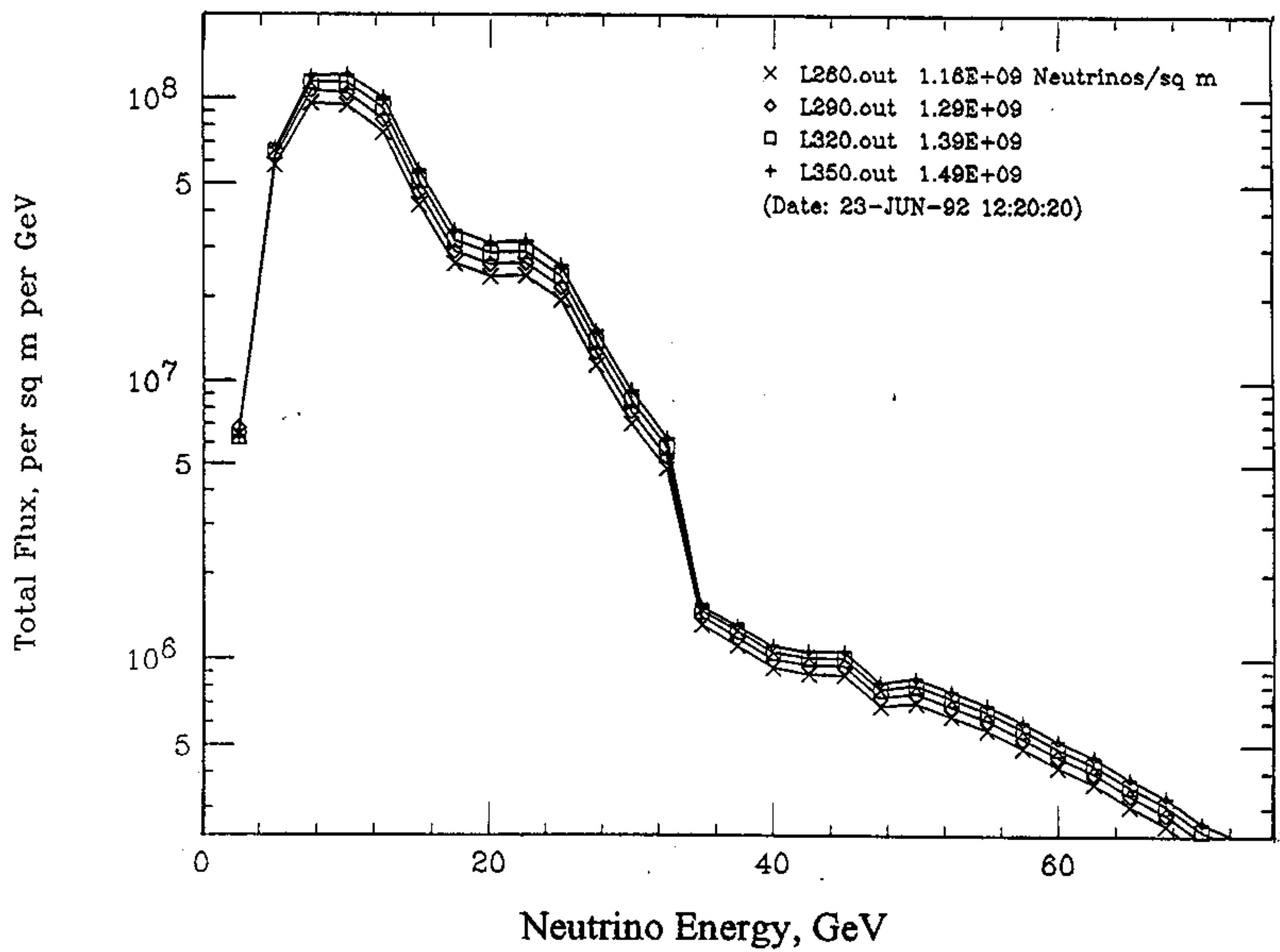

Figure 3 - Pantaleone's Contour Plot

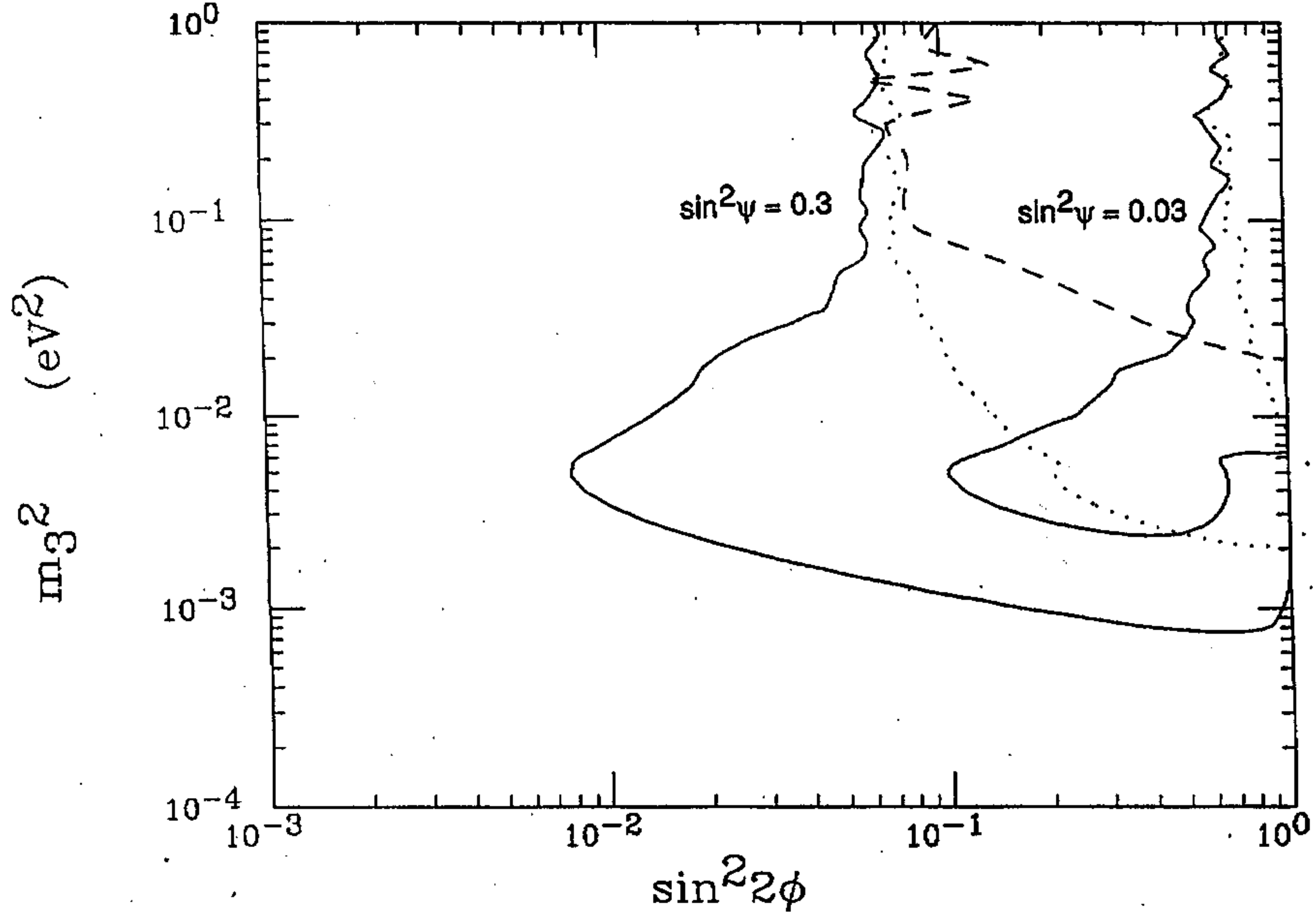

Figure 4 - Detected Electron Events in 8 mo. for $\sin^2\Psi=0.3$

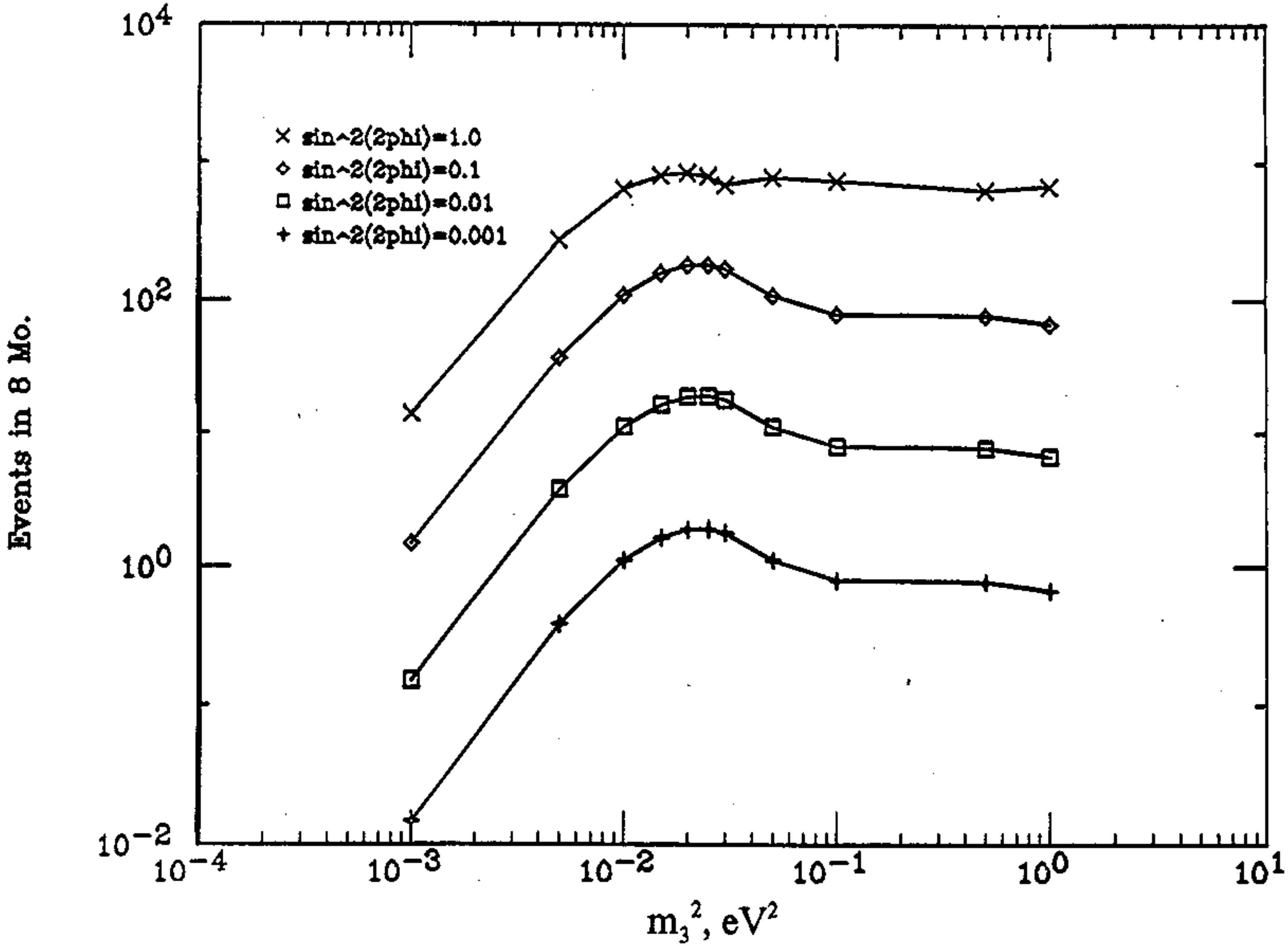

Figure 5 - Detected Electron Events in 8 mo. for $\sin^2\Psi=0.3$

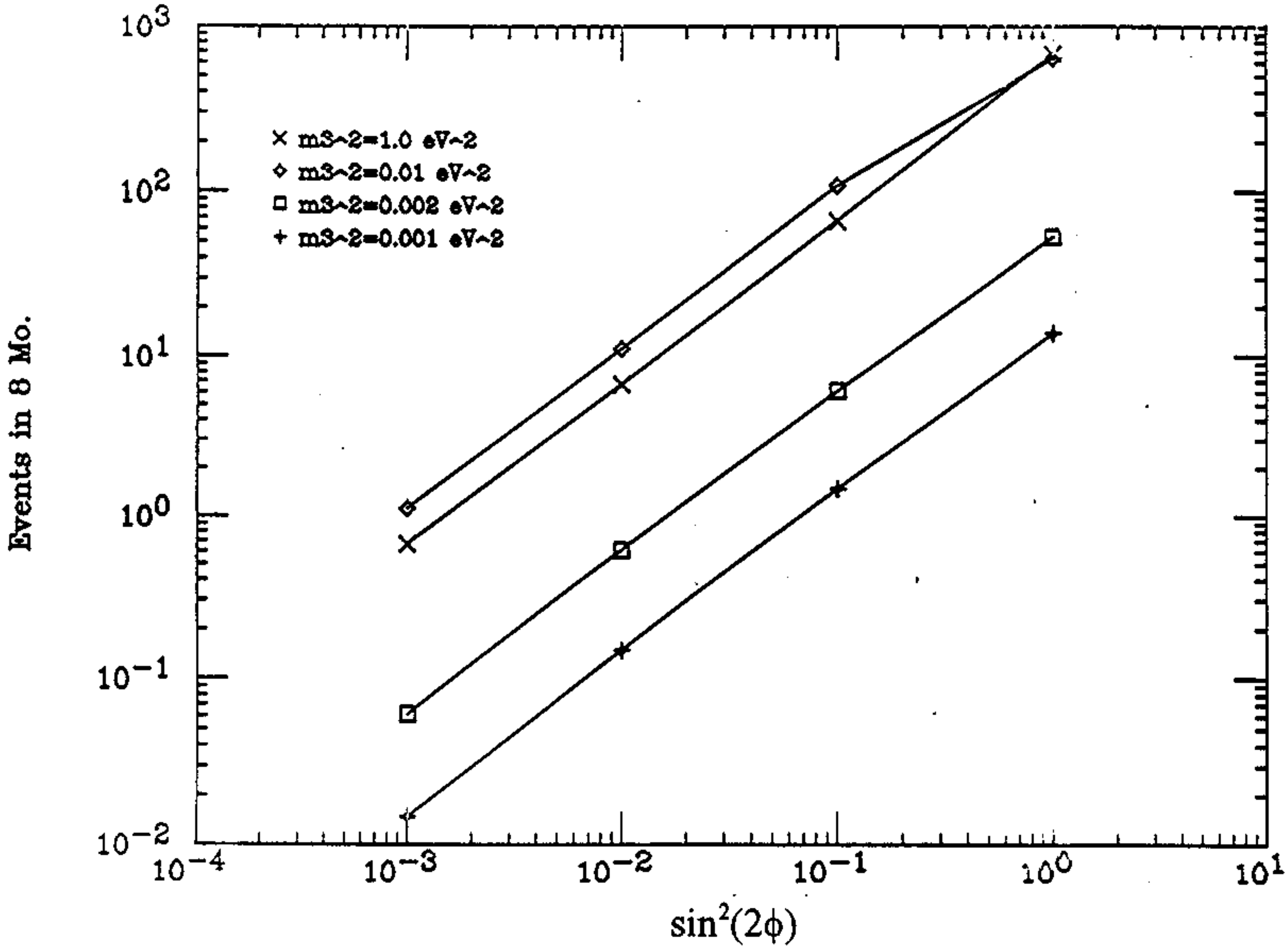

Figure 6 - Detected Electron Events in 8 mo. for $\sin^2\Psi=0.3$, $\sin^2 2\phi=10^{-1}$, and $m_3^2=10^{-1}\ eV^2$

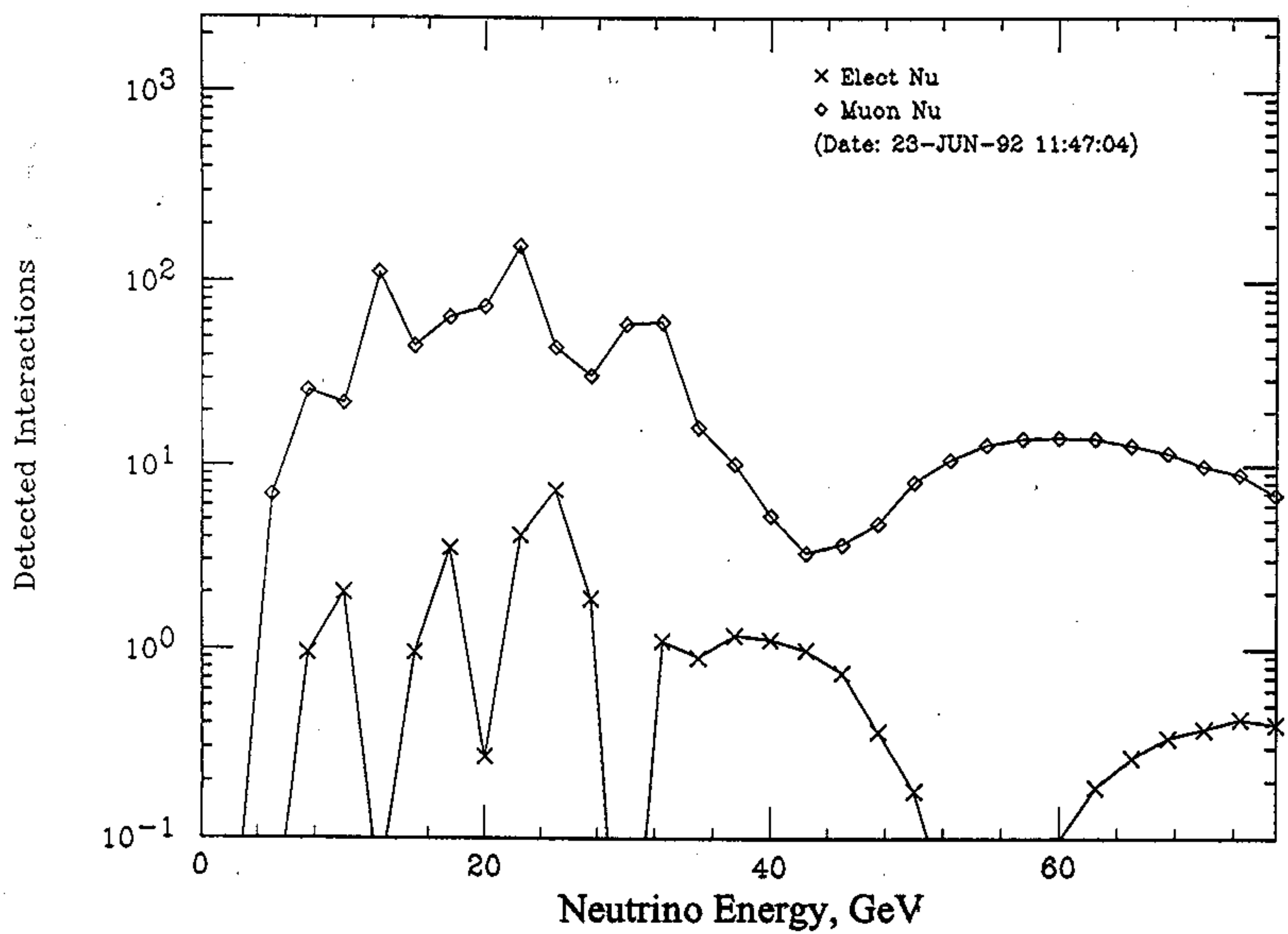

Figure 7 - Detected Electron Events in 8 mo. for $\sin^2\Psi=0.3$, $\sin^2 2\phi=10^{-1}$, and $m_3^2=2*10^{-2}$ eV^2

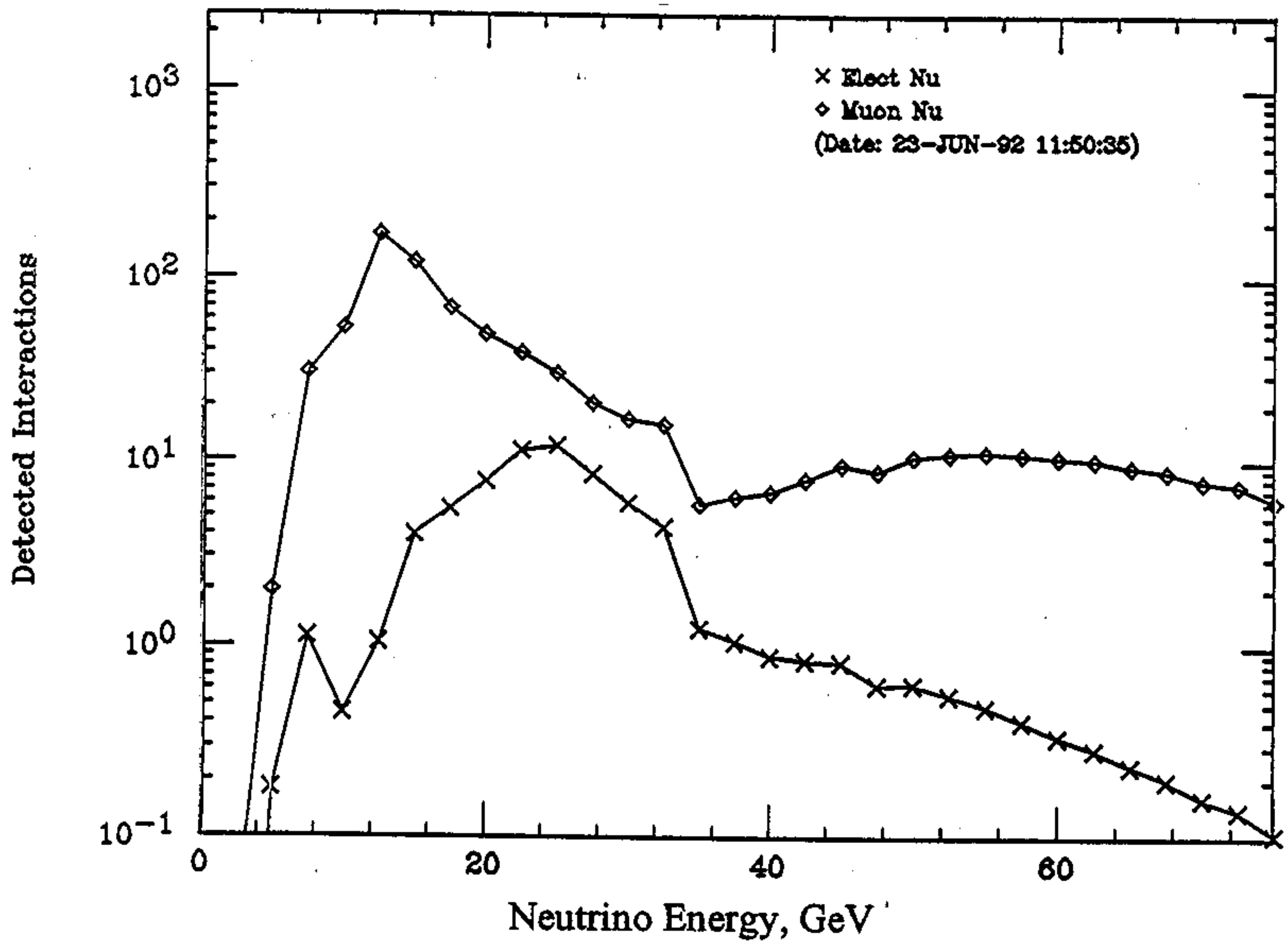

Figure 8 - Detected Electron Events in 8 mo. for $\sin^2\Psi=0.3$, $\sin^2 2\phi=10^{-1}$, and $m_3^2=10^{-2}$ eV^2