[Testing alternative oscillation scenarios with atmospheric neutrinos using AMANDA-II data from 2000 to 2003]

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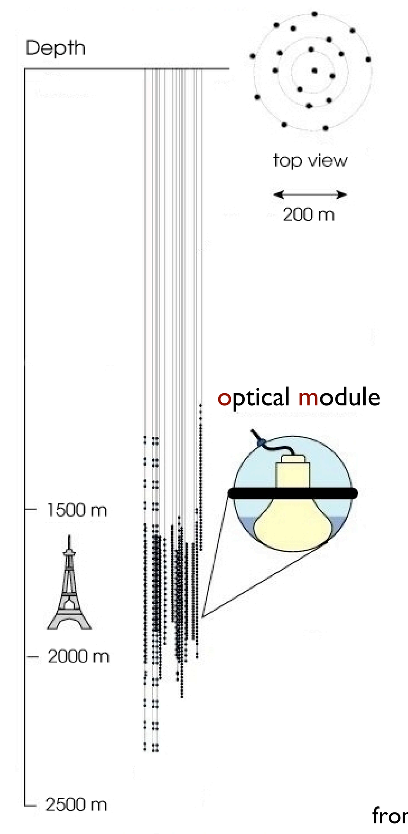
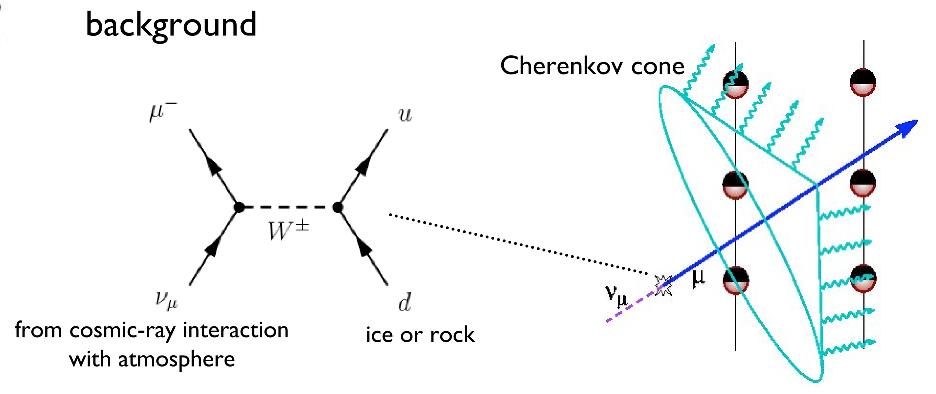
1. Overview

The AMANDA-II neutrino telescope detects **atmospheric muon neutrinos** of energies above 50 GeV. At these energy scales, conventional mass-induced neutrino oscillations are negligible; however, new physics predicted by some models of **quantum gravity**, such as violation of Lorentz invariance or the equivalence principle, could result in **alternative oscillations** visible as deviations from the expected atmospheric neutrino spectrum. Analyzing the AMANDA-II data from the years 2000 to 2003, we find **no evidence** for such oscillations and set **limits** on the Lorentz violation and equivalence principle violation parameters.

2. Detector



- The AMANDA-II neutrino telescope is buried in deep, clear ice, 1500m under the geographic South Pole
- Detector consists of 677 optical modules: photomultiplier tubes in glass pressure housings, deployed along cables ("strings")
- Muon neutrinos generated in the atmosphere can interact near the detector and result in a Cherenkov-radiating muon
- Muon direction can be reconstructed to within 2-3° [1], allowing one to use the Earth to filter out the large cosmic-ray muon background



3. New Physics

- Standard mass-induced atmospheric neutrino oscillations are negligible in the AMANDA-II energy range (above 50 GeV) [2]
- Violation of Lorentz invariance (VLI) can introduce another set of neutrino eigenstates characterized by different maximal attainable velocities c_n and differing by $\delta c/c$ [3]
- Violation of the weak equivalence principle (VEP) can behave similarly, with gravitational neutrino eigenstates characterized by different couplings γ_n to the local potential ϕ [4]
- Both VLI and VEP can result in neutrino oscillations at high energies, with VLI parametrized by $\delta c/c$ and VEP by $2|\phi|\delta\gamma$, plus a new mixing angle θ_c and complex phase η

Survival probability: $P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\Theta\ \sin^2(\Omega L)$

$$2\Theta = \arctan(s/t) \qquad \Omega = \sqrt{s^2+t^2}$$

$$s = 2.92\times 10^{-3}\,|1/E_\nu + 8.70\times 10^{20}\,\delta c/c\,\sin 2\Theta_c\,E_\nu\,e^{i\eta}|$$

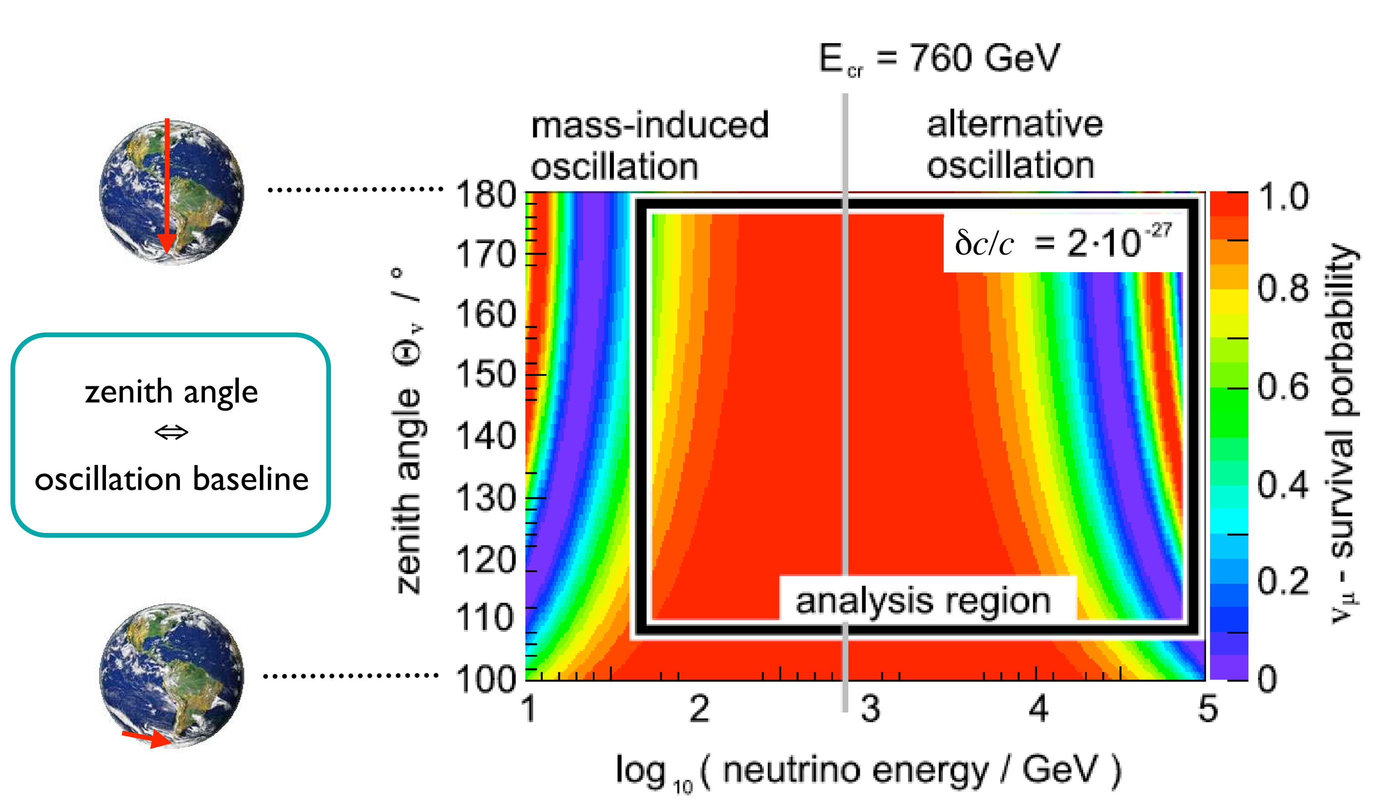
$$t = 2.54\times 10^{18}\,\delta c/c\,\cos 2\Theta_c\,E_\nu$$

E_ν in GeV, L in km

$\Delta m^2 = 2.3\times 10^{-3}\,\mathrm{eV}^2$

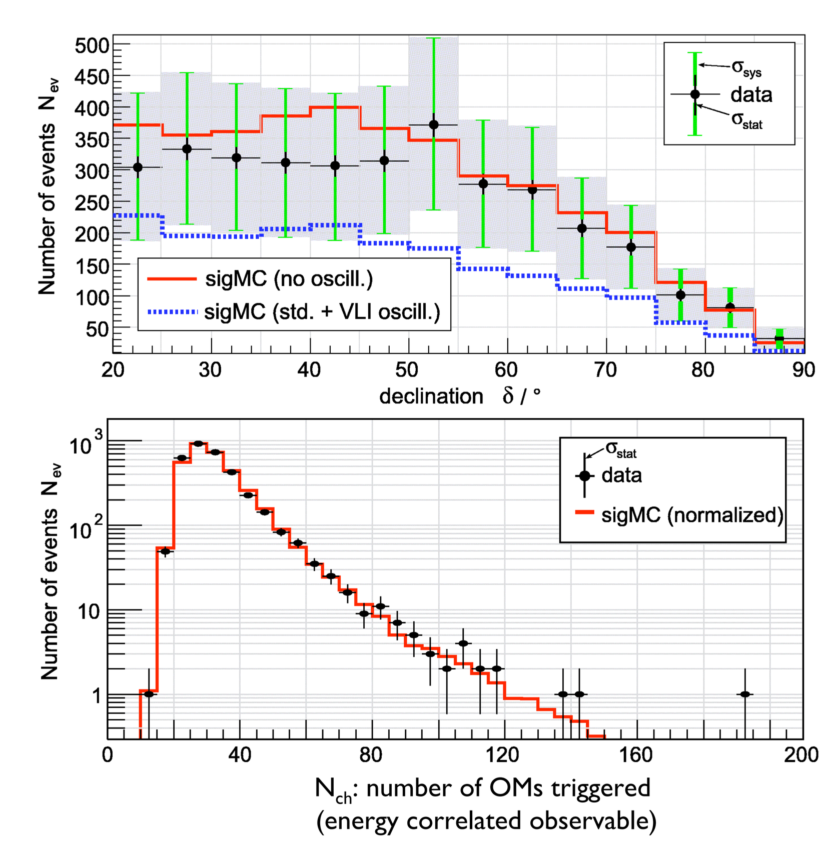
$\Theta_m = 45°$

4. Alternative Oscillations



5. Data Selection

- Quality selection criteria used to separate neutrinos from background atmospheric muons
- Bad OMs, electrical crosstalk, and mis-reconstructed muons eliminated
- Total livetime is 807.2 days
- 3401 neutrino candidate events survive the selection criteria



6. Analysis Method

- Analysis uses a χ^2-test incorporating systematic errors to compare zenith angle and N_{ch} distributions of data with Monte Carlo simulations incorporating VLI effects

$$\chi^2(\delta c/c, \Theta_c, \cos\eta) = \sum_{i=1}^{N_{\rm Bins}} \frac{\left(N_i^{\rm D} - N_i^{\rm BG} - F\cdot N_i^{\rm MC}(\delta c/c, \Theta_c, \cos\eta)\right)^2}{N_i^{\rm D} + N_i^{\rm BG} + (\sigma_i^{\rm MC})^2} + \left(\frac{\alpha}{\sigma_\alpha}\right)^2 + \left(\frac{\kappa}{\sigma_\kappa}\right)^2 + \left(\frac{\epsilon}{\sigma_\epsilon}\right)^2$$

4 bins: 2 zenith × 2 N_{ch}; function parametrizing sys. errors; VLI parameter space

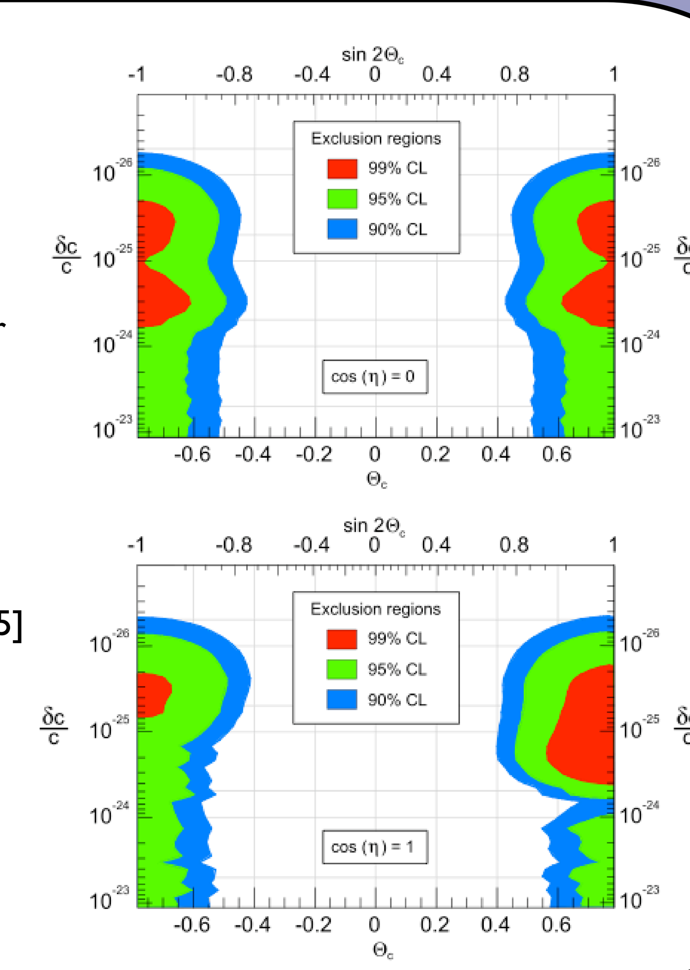
systematic errors: σ_α = flux normalization (30%); σ_κ = OM sensitivity (11.5%); σ_ϵ = $K^\pm / \pi^\pm$ ratio (6%)

7. Results

- No evidence for alternative oscillations found (exclusion regions to right)
- 90% CL limit set on VLI and VEP parameter for maximal mixing angle:

$\delta c/c,\ 2|\phi|\delta\gamma \le 5.3 \times 10^{-27}$

- Result comparable to other experiments [5]
- Further improvements expected using more AMANDA-II data [6] and with the next-generation IceCube experiment [7]



8. Notes and References

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[3] S. Coleman and S.L. Glashow, *Phys. Lett.* B405, 249 (1997).
[4] M. Gasperini, *Phys. Rev.* D38, 2635 (1988).
[5] M.C. González-García and M. Maltoni, *Phys. Rev.* D70, 033010 (2004); G. Battistoni *et al.*, *Phys. Lett.* B615, 14 (2005).
[6] J.L. Kelley *et al.*, astro-ph/0701333 (2007)
[7] M.C. González-García, F. Halzen, and M. Maltoni, *Phys. Rev.* D71, 093010 (2005).