Sensitivity to New Physics using Atmospheric Neutrinos and AMANDA-II

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Penn State Collaboration Meeting
State College, PA
June 2006
New Physics Effects

- Violation of Lorentz invariance (VLI) in string theory or loop quantum gravity*

- Violations of the equivalence principle (different gravitational coupling)†

- Interaction of particles with space-time foam \(\Rightarrow\) quantum decoherence of pure states‡

* see e.g. Carroll et al., PRL 87 14 (2001), Colladay and Kostelecký, PRD 58 116002 (1998)
† see e.g. Gasperini, PRD 39 3606 (1989)
VLI Oscillations

\[ P_{\nu_\mu \rightarrow \nu_\mu} = 1 - P_{\nu_\mu \rightarrow \nu_\tau} = 1 - \sin^2 2\Theta \sin^2 \left( \frac{\Delta m^2 L}{4E} R \right) \]

\[ \sin^2 2\Theta = \frac{1}{\mathcal{R}^2} \left( \sin^2 2\theta + R_n^2 \sin^2 2\xi_n + 2R_n \sin 2\theta \sin 2\xi_n \cos \eta_n \right), \]

\[ \mathcal{R} = \sqrt{1 + R_n^2 + 2R_n \left( \cos 2\theta \cos 2\xi_n + \sin 2\theta \sin 2\xi_n \cos \eta_n \right)}, \]

\[ R_n = \sigma_n^+ \frac{\Delta \delta_n E^n}{2} \frac{4E}{\Delta m^2}, \]

Gonzalez-Garcia, Halzen, and Maltoni, hep-ph/0502223

- For atmospheric \( \nu \), conventional oscillations turn off above \( \sim 50 \text{ GeV} \) \((L/E \text{ dependence})\)

- VLI oscillations turn on at high energy \((L/E \text{ dependence})\), depending on size of \( \delta c/c \), and distort the zenith angle / energy spectrum
$\nu_\mu$ Survival Probability
(Violation of Lorentz Invariance)

$\delta c/c = 10^{-27}$
$\nu_\mu$ Survival Probability
(Quantum Decoherence)

\[ P[\nu_\mu \rightarrow \nu_\mu] = \frac{1}{2} + e^{-(\alpha + \alpha_0)L} \cos \left( 2 \frac{\Delta m^2 L}{4E} \right) \quad (\sin^2(2\theta) = 1, \ b = \beta = d = \delta = 0) \]

\[ \kappa \text{ model, } a = \alpha = 4 \times 10^{-32} (E^2 / 2) \]
Data Analysis

Look for distortions in $N_{ch}$ vs. zenith angle

No New Physics

VLI, $\delta c/c = 10^{-25}$
Binned Likelihood Test

Poisson probability

\[ P(n) = e^{-\mu} \frac{\mu^n}{n!} \]

Product over bins

\[ P_p(\{n_i\}) = \prod_{i=1}^{N} e^{-\mu_i} \frac{\mu_i^{n_i}}{n_i!} \]

Test Statistic: LLH

\[ \chi_{\text{Poisson}}^2 = -2 \ln P_p(\{n_i\}) \]

\[ = 2 \sum_{i=1}^{N} (\mu_i - n_i \ln \mu_i + \ln n_i!) \]
Feldman-Cousins Recipe

- For each point in parameter space \( \{\theta_i\} \), sample many times from parent Monte Carlo distribution (MC “experiments”)

- For each MC experiment, calculate likelihood ratio:
  \[ \Delta L = \text{LLH at parent } \{\theta_i\} - \text{minimum LLH at some } \{\theta_{i,best}\} \]

- For each point \( \{\theta_i\} \), find \( \Delta L_{\text{crit}} \) at which, say, 90% of the MC experiments have a lower \( \Delta L \) (FC ordering principle)

- Once you have the data, compare \( \Delta L_{\text{data}} \) to \( \Delta L_{\text{crit}} \) at each point to determine exclusion region

- Primary advantage over \( \chi^2 \) global scan technique: proper coverage

Feldman & Cousins, PRD 57 7 (1998)
VLI: Sensitivity using only $N_{ch}$

Median Sensitivity $\delta c/c$ ($\sin(2\xi) = 1$)
- 90%: $3.2 \times 10^{-27}$
- 95%: $3.6 \times 10^{-27}$
- 99%: $5.1 \times 10^{-27}$

2000-05 livetime simulated

MACRO limit*: $2.5 \times 10^{-26}$ (90%)

*hep-ex/0503015
Decoherence Sensitivity  
(Using $N_{ch}$, $\kappa$ model)

Normalization free

Norm. constrained $\pm 30\%$
Decoherence Sensitivity

<table>
<thead>
<tr>
<th>Median Sensitivity $\kappa_{a,\alpha}$ (GeV$^{-1}$)</th>
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</thead>
<tbody>
<tr>
<td>90%: $3.7 \times 10^{-31}$</td>
</tr>
<tr>
<td>95%: $5.8 \times 10^{-31}$</td>
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<tr>
<td>99%: $1.6 \times 10^{-30}$</td>
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SuperK limit (90%)‡: $0.9 \times 10^{-27}$ GeV$^{-1}$

Almost 4 orders of magnitude improvement!

‡ Lisi, Marrone, and Montanino, PRL 85 6 (2000)
To Do List

- 2005 data and Monte Carlo (with Photonics) processing underway

- Improve quality cuts for atmospheric sample — leverage work done at Mainz

- Extend analysis capabilities
  - better energy estimator?
  - full systematic error treatment
  - multiple dimensions (observable and parameter space)
  - optimize binning
Extra Slides
Systematic Errors

- Atmospheric production uncertainties
- Detector effects (OM sensitivity)
- Ice Properties

Can be treated as nuisance parameters: minimize LLH with respect to them

Or, can simulate as fluctuations in MC experiments

Normalization is already included!
(free parameter — could possibly constrain)