Searching for Quantum Gravity with Atmospheric Neutrinos

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Thesis Defense
Outline

- Neutrino detection
- New physics signatures
- Data selection
- Analysis methodology
- Results
- Outlook
Neutrino Detection

1. Need an interaction — small cross-section necessitates a big target!

2. Then detect the interaction products (say, by their radiation)
Earth’s Transparent Medium: H₂O

Mediterranean, Lake Baikal

Antarctic ice sheet
• Array of optical modules on cables ("strings" or "lines")

• High energy muon (~TeV) from charged current $\nu_\mu$ interaction

• Good angular reconstruction from timing ($O(1^\circ)$)

• Rough $\nu$ energy estimate from muon energy loss

• OR, look for cascades ($\nu_e, \nu_\tau, \text{NC } \nu_\mu$)
AMANDA-II

- The AMANDA-II neutrino telescope is buried in deep, clear ice, 1500m under the geographic South Pole

- 677 optical modules: photomultiplier tubes in glass pressure housings

- Muon direction can be reconstructed to within 2-3°
Amundsen-Scott
South Pole Research Station

South Pole Station

Geographic South Pole

skiway

AMANDA-II
Cosmic rays produce muons, neutrinos through charged pion / kaon decay

Even with > km overburden, atm. muon events dominate over ν by ~10^6

Neutrino events: reconstruct direction + use Earth as filter, or look only for UHE events
Current Experimental Status

- No detection (yet) of
  - point sources or other anisotropies
  - diffuse astrophysical flux
  - transients (e.g. GRBs, AGN flares, SN)
  - DM annihilation (Earth or Sun)

- Astrophysically interesting limits set

- Large sample of atmospheric neutrinos
  - AMANDA-II: >5K events, 0.1-10 TeV

Opportunity for particle physics with high-energy atmospheric $\nu$
New Physics with Neutrinos?

- Neutrinos are already post-Standard Model (massive)

- For $E > 100$ GeV and $m_\nu < 1$ eV, $\text{Lorentz } \gamma > 10^{11}$

- Oscillations are a sensitive quantum-mechanical interferometer

Eidelman et al.: “It would be surprising if further surprises were not in store…”
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 ⇒ quantum decoherence of flavor states‡

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* 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)
‡ see e.g. Anchordoqui et al., hep-ph/0506168
“Fried Chicken” VLI

- Modified dispersion relation*:
  \[ E_a^2 = \vec{p}_a c_a^2 + m_a c_a^4. \]

- Different maximum attainable velocities \( c_a \) (MAVs) for different particles: \( \Delta E \sim (\delta c/c)E \)

- For neutrinos: MAV eigenstates not necessarily flavor or mass eigenstates ⇒ mixing ⇒ VLI oscillations

\[
H_\pm \equiv \frac{\Delta m^2}{4E} U_\theta \begin{pmatrix} -1 & 0 & 1 \end{pmatrix} U_\theta^\dagger + \frac{\Delta \delta_n}{2} E^n U_{\xi_n, \pm \eta_n} \begin{pmatrix} -1 & 0 & 1 \end{pmatrix} U_{\xi_n, \pm \eta_n}^\dagger
\]

* see Glashow and Coleman, PRD 59 116008 (1999)
VLI + Atmospheric Oscillations

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

\[ \sin^2 2\Theta = \frac{1}{R^2} \left( \sin^2 2\theta_{23} + R^2 \sin^2 2\xi + 2R \sin 2\theta_{23} \sin 2\xi \cos \eta \right) , \]

\[ \mathcal{R} = \sqrt{1 + R^2 + 2R \left( \cos 2\theta_{23} \cos 2\xi + \sin 2\theta_{23} \sin 2\xi \cos \eta \right)} , \]

\[ R = \frac{\delta c E}{c} \frac{4E}{\Delta m_{23}^2} \]

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

- VLI oscillations turn on at high energy ($L E$ dependence), depending on size of $\delta c/c$, and distort the zenith angle / energy spectrum (other parameters: mixing angle $\xi$, phase $\eta$)

González-García, Halzen, and Maltoni, hep-ph/0502223
VLI Atmospheric $\nu_\mu$ Survival Probability

maximal mixing, $\delta c/c = 10^{-27}$
Quantum Decoherence (QD)

- Another possible low-energy signature of quantum gravity: quantum decoherence

- Heuristic picture: foamy structure of space-time (interactions with virtual black holes) may not preserve certain quantum numbers (like ν flavor)

- Pure states interact with environment and decohere to mixed states
Decoherence + Atmospheric Oscillations

Energy dependence depends on phenomenology: \( \gamma_i = \gamma^*_i E^n \), \( n \in \{-1, 0, 2, 3\} \)

- \( n = -1 \) preserves Lorentz invariance
- \( n = 0 \) simplest
- \( n = 2 \) recoiling D-branes*
- \( n = 3 \) Planck-suppressed operators‡

\[
P[\nu_\mu \rightarrow \nu_\mu] = \frac{1}{3} + \frac{1}{2} e^{-\gamma^3 L \cos^4 \theta_{23}} + \frac{1}{12} e^{-\gamma^8 L (1 - 3 \cos 2\theta_{23})^2} + 4e^{-\frac{\gamma^6 + \gamma^7}{2} L} \cos^2 \theta_{23} \sin^2 \theta_{23} \left( \cos \left[ \frac{L}{2} \sqrt{(\gamma_6 - \gamma_7)^2 - \left( \frac{\Delta m^2_{23}}{E} \right)^2} \right] + \sin \left[ \frac{L}{2} \sqrt{(\gamma_6 - \gamma_7)^2 - \left( \frac{\Delta m^2_{23}}{E} \right)^2} \right] \right)
\]

derived from Barenboim, Mavromatos et al. (hep-ph/0603028)

\*Ellis et al., hep-th/9704169

‡ Anchordoqui et al., hep-ph/0506168
QD Atmospheric $\nu_\mu$ Survival Probability

Survival probability (decoherence, $E^2$ model, $\log_{10} \gamma^* = -31$)

$p = 1/3$
Event Selection (2000-2006 data)

• Initial data filtering
  – noise + crosstalk cleaning
  – bad optical module filtering
  – fast directional reconstruction, loose “up-going” cut
  – 80 Hz $\rightarrow$ 0.1 Hz

• Final quality cuts
  – iterative full likelihood reconstruction (timing of photon hits)
  – cuts on track quality variables
    • smoothness of hits, angular error estimate, likelihood ratio to downgoing muon fit, space angle between reconstructions, etc.
  – 0.1 Hz $\rightarrow$ 4 / day (for atm. $\nu$: 24% eff., 99% purity)

• Final sample: 5544 events below horizon (1387 days livetime)
Purity Level

- Simulating final bit of background not feasible

- Estimate contamination by tightening cuts until data/MC ratio stabilizes

- Procedure shows essentially no contamination at final cut level (strength = 1)
Event 5119326 (May 30, 2005)

199 OMs hit

zenith angle 158°

angular error 0.7°

ν energy > ∼20 TeV
Simulated Observables

reconstructed zenith angle

$N_{\text{channel}}$ (energy proxy)

QG signature: deficit at high energy, near vertical
Testing the Parameter Space

Given observables $x$, want to determine values of parameters $\{\theta_r\}$ that are allowed / excluded at some confidence level.

Binned likelihood + Feldman-Cousins
Feldman-Cousins Recipe
(frequentist construction)

• Test statistic is likelihood ratio:
\[ \Delta L = LLH \text{ at parent } \{ \theta_r \} - \text{ minimum } LLH \text{ at some } \{ \theta_{r,best} \} \]
(compare hypothesis at this point to best-fit hypothesis)

• For each point in parameter space \( \{ \theta_r \} \), perform many simulated MC “experiments” to see how test statistic varies (close to \( \chi^2 \))

• For each point \( \{ \theta_r \} \), find \( \Delta L_{\text{crit}} \) at which, say, 90% of the MC experiments have a lower \( \Delta L \)

• Compare \( \Delta L_{\text{data}} \) to \( \Delta L_{\text{crit}} \) at each point to determine exclusion region

Feldman & Cousins, PRD 57 7 (1998)
How to include nuisance parameters \( \{ \theta_s \} \):

– test statistic becomes \textit{profile likelihood}

\[
l = \frac{L(x|\theta_0, \hat{\theta}_s)}{L(x|\hat{\theta}_r, \hat{\theta}_s)}
\]

<table>
<thead>
<tr>
<th>Variable</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \theta_r )</td>
<td>physics parameters</td>
</tr>
<tr>
<td>( \theta_s )</td>
<td>nuisance parameters</td>
</tr>
<tr>
<td>( \hat{\theta}_r, \hat{\theta}_s )</td>
<td>unconditionally maximize ( L(x</td>
</tr>
<tr>
<td>( \hat{\theta}_s )</td>
<td>conditionally maximize ( L(x</td>
</tr>
</tbody>
</table>

– MC experiments use “worst-case” value of nuisance parameters (Feldman’s \textit{profile construction} method)

  • specifically, for each \( \theta_r \), generate experiments fixing n.p. to data’s \( \hat{\theta}_s \), then re-calculate profile likelihood as above
Atmospheric Systematics

• Separate systematic errors into four classes, depending on effect on observables:
  – normalization
    • e.g. atm. flux normalization
  – slope: change in primary spectrum
    • e.g. primary CR slope
  – tilt: tilts zenith angle distribution
    • e.g. π/K ratio
  – OM sensitivity (large, complicated shape effects)
    • includes uncertainties in ice properties
### Systematics Summary

<table>
<thead>
<tr>
<th>error</th>
<th>type</th>
<th>size</th>
<th>method</th>
</tr>
</thead>
<tbody>
<tr>
<td>atm. $\nu$ flux model</td>
<td>norm.</td>
<td>$\pm 18%$</td>
<td>MC study</td>
</tr>
<tr>
<td>$\sigma_{\nu}$, $\nu$-$\mu$ scattering angle</td>
<td>norm.</td>
<td>$\pm 8%$</td>
<td>MC study</td>
</tr>
<tr>
<td>reconstruction bias</td>
<td>norm.</td>
<td>$-4%$</td>
<td>MC study</td>
</tr>
<tr>
<td>$\nu_{\tau}$-induced muons</td>
<td>norm.</td>
<td>$+2%$</td>
<td>MC study</td>
</tr>
<tr>
<td>charm contribution</td>
<td>norm.</td>
<td>$+1%$</td>
<td>MC study</td>
</tr>
<tr>
<td>timing residuals</td>
<td>norm.</td>
<td>$\pm 2%$</td>
<td>5-year paper</td>
</tr>
<tr>
<td>$\mu$ energy loss</td>
<td>norm.</td>
<td>$\pm 1%$</td>
<td>5-year paper</td>
</tr>
<tr>
<td>rock density</td>
<td>norm.</td>
<td>$&lt;1%$</td>
<td>MC study</td>
</tr>
<tr>
<td>primary CR slope (incl. He)</td>
<td>slope</td>
<td>$\Delta\gamma = \pm 0.03$</td>
<td>Gaisser et al.</td>
</tr>
<tr>
<td>charm (slope)</td>
<td>slope</td>
<td>$\Delta\gamma = +0.05$</td>
<td>MC study</td>
</tr>
<tr>
<td>$\pi$/$K$ ratio</td>
<td>tilt</td>
<td>tilt $+1/-3%$</td>
<td>MC study</td>
</tr>
<tr>
<td>charm (tilt)</td>
<td>tilt</td>
<td>tilt $-3%$</td>
<td>MC study</td>
</tr>
<tr>
<td>OM sensitivity, ice</td>
<td>OM sens.</td>
<td>sens. $\pm 10%$</td>
<td>MC, downgoing $\mu$</td>
</tr>
</tbody>
</table>
Results: Observables

Data consistent with atmospheric neutrinos + O(1%) background
Results: VLI upper limit

- SuperK+K2K limit*: \( \delta c/c < 1.9 \times 10^{-27} \) (90%CL)
- This analysis: \( \delta c/c < 2.8 \times 10^{-27} \) (90%CL)
- Limits also set on \( E^2 \), \( E^3 \) effects

\[\text{maximal mixing}\]

Results: QD upper limit

\[ \log_{10} \gamma_i^{6,7} / \text{GeV}^{-1} \]

\[ \log_{10} \gamma_i^{3,8} / \text{GeV}^{-1} \]

**E^2 model (E, E^3 limits also set)**

- **SuperK limit**\(^\ddagger\) (2-flavor):
  \[ \gamma_i < 0.9 \times 10^{-27} \text{ GeV}^{-1} \] (90% CL)

- **ANTARES sensitivity**\(^*\) (2-flavor):
  \[ \gamma_i \sim 10^{-30} \text{ GeV}^{-1} \] (3 years, 90% CL)

- **This analysis:**
  \[ \gamma_i < 1.3 \times 10^{-31} \text{ GeV}^{-1} \] (90% CL)

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\* Morgan et al., astro-ph/0412618
\^ Lisi, Marrone, and Montanino, PRL 85 6 (2000)
Conventional Analysis

- Parameters of interest: normalization, spectral slope change Δγ relative to Barr et al.
- Result: determine atmospheric muon neutrino flux (“forward-folding” approach)

90%, 95%, 99% allowed
Translation to Flux

Range of allowed flux determined by envelope of curves
Result Spectrum

Installation Status & Plans

- **AMANDA**
- **IceCube**

**IceCube string deployed** 01/05

**IceCube string deployed** 12/05 – 01/06

**IceCube string deployed** 12/06 – 01/07

**IceCube string and IceTop station deployed** 12/06 – 01/07

**IceCube string deployed** 12/07 – 01/08

**IceCube Lab commissioned**

2500m deep hole!

40 strings taking physics data

Update: 3 of ~16 strings this season
$E_{\text{primary}} \sim 1 \ \text{EeV}$
DOM Calibration

- With J. Braun, developed primary DOM calibration software (“DOM-Cal”)

- Bootstrap approach calibrates:
  - front-end amplifier gain
  - waveform charge vs. time
  - PMT gain vs. high voltage
  - PMT transit time vs. high voltage

- Entire detector (2500+ DOMs) calibrates itself in parallel in ~1 hour
### Gain Calibration

<table>
<thead>
<tr>
<th>Name</th>
<th>DOM Id</th>
<th>1200V</th>
<th>1300V</th>
<th>1400V</th>
<th>1500V</th>
<th>1600V</th>
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<tr>
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<td>b804f6f38a45</td>
<td><img src="image1" alt="Graph" /></td>
<td><img src="image2" alt="Graph" /></td>
<td><img src="image3" alt="Graph" /></td>
<td><img src="image4" alt="Graph" /></td>
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<td>Erik_the_Red</td>
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<td><img src="image7" alt="Graph" /></td>
<td><img src="image8" alt="Graph" /></td>
<td><img src="image9" alt="Graph" /></td>
<td><img src="image10" alt="Graph" /></td>
</tr>
<tr>
<td>Cholesterol</td>
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<td><img src="image12" alt="Graph" /></td>
<td><img src="image13" alt="Graph" /></td>
<td><img src="image14" alt="Graph" /></td>
<td><img src="image15" alt="Graph" /></td>
</tr>
</tbody>
</table>

DOMs fit their own single PE charge spectra!
IceCube VLI Sensitivity

- IceCube: sensitivity of $\delta c/c \sim 10^{-28}$
  Up to 700K atmospheric $\nu_\mu$ in 10 years

(González-García, Halzen, and Maltoni, hep-ph/0502223)
Other Possibilities

- Extraterrestrial neutrino sources would provide even more powerful probes of QG
  - GRB neutrino time delay
    (see, e.g. Amelino-Camelia, gr-qc/0305057)
  - Electron antineutrino decoherence from, say, Cygnus OB2 (see Anchordoqui et al., hep-ph/0506168)

- Hybrid techniques (radio, acoustic) + Deep Core will extend energy reach in both directions
Thank you!
Violation of Lorentz Invariance (VLI)

- Lorentz and/or CPT violation is appealing as a (relatively) low-energy probe of QG


\[ (i \Gamma_{AB}^\nu \partial_\nu - M_{AB}) \nu_B = 0 \]
\[
\Gamma_{AB}^\nu \equiv \gamma^\nu \delta_{AB} + e_{AB}^\mu \gamma_\mu + d_{AB}^{\mu \nu} \gamma_5 \gamma_\mu + e_{AB}^\nu + i f_{AB}^\nu \gamma_5 + \frac{1}{2} g_{AB}^{\lambda \mu \nu} \sigma_{\lambda \mu},
\]
\[
M_{AB} \equiv m_{AB} + i m_{5AB} \gamma_5 + a_{AB}^\mu \gamma_\mu + b_{AB}^\mu \gamma_5 \gamma_\mu + \frac{1}{2} H_{AB}^{\mu \nu} \sigma_{\mu \nu}.
\]

Addition of renormalizable VLI and CPTV+VLI terms; encompasses a number of interesting specific scenarios
VLI Phenomenology

- Effective Hamiltonian
  (seesaw + leading order VLI+CPTV):

\[
(h_{\text{eff}})_{ab} = |\vec{p}| \delta_{ab} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \frac{1}{2|\vec{p}|} \begin{pmatrix} (\tilde{m}^2)_{ab} & 0 \\ 0 & (\tilde{m}^2)_{ab}^* \end{pmatrix} 
\]

\[
+ \frac{1}{|\vec{p}|} \left( \begin{pmatrix} \frac{1}{2} \sigma_{\mu\nu}^{ab} \frac{(a_L)^{\mu\nu} p_{\mu} p_{\nu}}{\epsilon_+} \right)_{ab} - \frac{1}{\sqrt{2}} p_{\mu} (\epsilon_+)_\nu [(g_{\mu\nu}^\sigma p_\sigma - H_{\mu\nu}) C]_{ab} 
\]

- To narrow possibilities we consider:
  - rotationally invariant terms (only time component)
  - only $c_{AB}^{00} \neq 0$ (leads to interesting energy dependence…)

## Galactic Plane Limits

<table>
<thead>
<tr>
<th>On-source region</th>
<th>On-source events</th>
<th>Expected background</th>
<th>90% event upper limit</th>
<th>Line source limit</th>
<th>Diffuse limit</th>
<th>Gaussian limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>±2.0°</td>
<td>128</td>
<td>129.4</td>
<td>19.8</td>
<td>$6.3 \times 10^{-5}$</td>
<td>$6.6 \times 10^{-4}$</td>
<td>—</td>
</tr>
<tr>
<td>±4.4°</td>
<td>272</td>
<td>283.3</td>
<td>20.0</td>
<td>—</td>
<td>—</td>
<td>$4.8 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

**Data used:** AMANDA 2000-03

Limits include systematic uncertainty of 30% on atm. \( \nu \) flux

Energy range: 0.2 to 40 TeV

### Graphical Elements

- **GeV\(^{-1}\) cm\(^{-2}\) s\(^{-1}\) rad\(^{-1}\)**
- **GeV\(^{-1}\) cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\)**