Neutrino Oscillations with IceCube DeepCore and PINGU

Tyce DeYoung
Department of Physics
Pennsylvania State University

VLVVvT
Stockholm, Sweden
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Oscillations of Atmospheric Neutrinos

• Neutrinos oscillating over one Earth diameter have a $\nu_\mu$ survival minimum at ~25 GeV
  • Hierarchy-dependent matter effects below ~10-20 GeV

• Neutrinos are available over a wide range of energies and baselines
  • Comparison of observations from different baselines and energies is crucial for controlling systematics
  • Essentially, a generalization of the up-down ratio approach
The IceCube Neutrino Observatory

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- $\mathcal{O}(10^5)$ atmospheric neutrino triggers per year, $\mathcal{O}(10^4)$ in final data sets
IceCube DeepCore

- A more densely instrumented region at the bottom center of IceCube
  - Eight special strings plus 12 nearest standard strings
  - High Q.E. PMTs
  - ~5x higher effective photocathode density
- In the clearest ice, below 2100 m
  - $\lambda_{\text{atten}} \approx 45-50$ m
- IceCube provides an active veto against cosmic ray muon background (around $10^6$ times atmospheric neutrino rate)
Muon Disappearance – First Analysis

- Compare zenith-dependent response of standard IceCube muon analysis (high energy) to a modified version for DeepCore
  - Look for oscillation signature in event rate suppression at low energies
  - Detector systematics reduced by comparing HE and LE rates
  - Based on traditional muon analysis, no new techniques designed for DeepCore – lower efficiency accepted

![Plot of expected distribution of neutrino energy]

arXiv:1305.3909 (accepted PRL)

Tyce DeYoung

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Muon Neutrino Disappearance

Statistically significant angle-dependent suppression at low energy, high energy sample provides constraint on uncertainties in simultaneous fit

- Shaded bands show range of uncorrelated systematic uncertainties; hatched regions show overall normalization uncertainty
Muon Neutrino Disappearance

- Oscillation parameter allowed regions extracted from zenith distributions
  - Systematics included
- Excellent agreement with world average measurements (with large uncertainties)
  - Potential for significant improvement with inclusion of energy estimators, more advanced reconstructions and event selections

![Diagram showing confidence regions for atmospheric neutrino oscillations](image)
Measuring Flux Modulation due to Oscillations

- Wide range of baselines and energies observed permits marginalization over nuisance parameters
  - Theoretical uncertainties
  - Detector systematics
- Actual analysis is done in 2D, but difficult to visualize
  - Projected here onto reconstructed L/E for illustration

![Graph](image)
Coming Improvements

• First two-dimensional analyses (energy and angle) coming soon
  • Still based on single year data sets – focus now on technique development

• Multiyear results also in the works
  • Estimated sensitivity for several years is encouraging, even without further improvements on systematics
• Targeting 40 additional strings of 60-100 Digital Optical Modules each, deployed in the DeepCore volume
  • 20-25 m string spacing (cf. 125 m for IceCube, 73 m for DeepCore)
  • Precise geometry under study
  • Systematics will be better understood with additional in situ calibration devices

• Cost and technical issues well understood from IceCube experience
  • Start-up costs of $8M – $12M
  • ~$1.25M per string
DeepCore Only

- 9.28 GeV $\nu_\mu$ event:
  - 4.9 GeV muon
  - 4.5 GeV cascade
- $\sim$20 vs. $\sim$50 hit DOMs
PINGU Energy Range

- A preliminary event selection based on DeepCore analysis
  - 23,000 muon neutrinos per year after oscillations
  - Oscillation signature is the disappearance of 12,000 events per year
- Sufficient to measure neutrino mass hierarchy via matter effects in the 5-20 GeV range without direct $\nu_\mu - \bar{\nu}_\mu$ discrimination
  - Exploit asymmetries in cross sections and kinematics

Expected number of events:

- ~10,000 events per year
- ~23,000 per year
- ~390,000 per year

Use an improved version of this event selection for PINGU:
- Define an additional veto layer
- Implement tighter and further containment cuts

Expect twice as much statistics for PINGU.
Neutrino Oscillations in Vacuum

\[ P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta) \sin^2 \left( \frac{\Delta m^2 L}{4E} \right) \]

\[ \Delta m^2_{32} = 2.32 \times 10^{-3} \text{ eV}^2 \]

\[ \sin^2(2\theta_{23}) = \frac{\pi}{4} \]
Neutrino Oscillations in Matter

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Neutrinos

Antineutrinos

Normal hierarchy

Inverted hierarchy
Preliminary Hierarchy Sensitivity Studies

• Measuring a somewhat complicated modulation of a complicated two-dimensional distribution
  • Rather difficult to visualize the data in a simple way

• A useful metric for visualizing the signature is the significance estimate of Akhmedov, Razzaque & Smirnov (arXiv:1205.7071)
  • Binned counting experiment in energy and zenith angle, comparing difference in expected number of events for normal vs. inverted hierarchy due to mass effects

\[ S_{tot} = \sqrt{\sum_{ij} \frac{(N_{ij}^{IH} - N_{ij}^{NH})^2}{N_{ij}^{NH}}} \]

\[ i = \cos(\text{zenith}) \]
\[ j = \text{energy} \]
Experimental Signature of the Mass Hierarchy

- Idealized case with no background, perfect flavor ID, 100% signal efficiency
Experimental Signature of the Mass Hierarchy

• Idealized case with no background, perfect flavor ID, 100% signal efficiency
  • Different assumed resolutions smear the signature but do not eliminate it

• Hierarchy signature is a distinctive structure in energy-angle plane
  • Key to our approach to controlling systematics

\[
\left( \frac{N^{\text{IH}} - N^{\text{NH}}}{N^{\text{NH}}} \right)^{1/2} \text{ [PINGU 1 Year]}
\]

smeared: 3 GeV in $\nu_\mu$ energy and 11.25° in $\mu$ zenith resolution
**PINGU Performance and Sensitivity Studies**

- Currently using DeepCore algorithms
  - More computationally intensive algorithms can improve resolution
- Systematics studied so far:
  - $\theta_{23}$, $\theta_{13}$, $\Delta m^2_{atm}$, $\delta_{CP}$ within world average ±2σ ranges
  - Efficiency errors (30%)
  - Atmos. $\nu$ spectral index (±0.05)
  - Energy calibration (10% bias)
  - Pointing accuracy (10% bias)
  - Energy resolution (10% error)
  - Angular resolution (10% error)
- Further studies underway now
PINGU Hierarchy Sensitivity

- Sensitivity depends on final detector scope, assumed analysis efficiency, detector resolution, etc.
  - Caveat: not all systematics included in each study
- Even with pessimistic assumptions, $3\sigma$ determination expected (median) with 2 years’ data
  - $5\sigma$ in 2-4 more years
- Working now to refine details and extend systematic studies

arXiv:1306.5846
First Steps Toward Flavor Identification

- Current sensitivity studies assume no flavor ID – statistical subtraction of backgrounds from $\nu_x$ NC, $\nu_e$, $\nu_\tau$

- First step: tag $\nu_\mu$ CC based on presence of track with $v > c/n$
  - Good efficiency for $\nu_\mu$ with $E_\mu > 3$ GeV with 40 string geometry

PRELIMINARY

20 strings

PRELIMINARY

40 strings
Other Neutrino Measurements

• $\delta_{CP}$ has no effect on our hierarchy measurement
  • Hierarchy determination via $\nu_\mu$ disappearance, not appearance – resolve degeneracy for other experiments

• High-statistics measurement of $\nu_\tau$ appearance
  • In the standard oscillation scenario, the disappearing $\nu_\mu$ are converted to $\nu_\tau$ – confirmation of tau appearance at expected rate is an interesting test
  • Oscillation effects scale as $L/E_\nu$, so longer baselines move effect to higher energy with reduced kinematic suppression of tau neutrino cross section

• Improved measurement of atmospheric oscillation parameters

• Over-constraint of parameters in the standard oscillation paradigm is essential for testing non-standard scenarios (e.g. A. Friedland)
Advantages of PINGU

- Relatively cheap
  - Start up costs of $8-12M, plus ~$1.25M per string, split between the US and foreign partners
  - Well understood technology and techniques – low risk

- Relatively quick
  - Could begin deployment in the 2016/17 austral summer season, completion in 2-3 years (depending on scope)
  - $\sigma$ determination of the hierarchy by 2020, 5$\sigma$ in 2-4 more years

- Targeted measurement would resolve degeneracies
  - Allow LBNE to focus on CP violation

- Working now on a detailed Letter of Intent and full proposal
Backup Slides
Best-fit Oscillations

- Statistical significance of observation established with respect to world average oscillation parameters

- As a second step, we fit $\Delta m^2_{23}$ and $\sin^2(2\theta_{23})$ by $\chi^2$ minimization, with nuisance parameters fit simultaneously

  - $\Delta m^2_{23} = 2.3 \times 10^{-3}$ eV$^2$, $\sin^2(2\theta_{23}) = 1.0$

  - $\chi^2 = 15.7$ for 18 degrees of freedom
Theoretical Uncertainties

- E.g., uncertainty in $\Delta m_{31}^2$ is partially degenerate with the hierarchy

\[
\frac{(N_{\text{H}} + N_{\text{NH}})}{(N_{\text{NH}})^{1/2}} \text{ [2 GeV, 10° Smearing]}
\]

\[
\frac{(I_{\text{H}} - N_{\text{H}})}{(N_{\text{H}})^{1/2}} \text{ [2 GeV, 10° Smearing]}
\]
PINGU

- One of several candidate geometries under investigation
  - Exploring requirements for mass hierarchy measurement – additional strings may be added if better angular and energy resolution is needed
  - Systematics can be addressed with additional in situ calibration devices

![Graph showing PINGU geometry with IceCube, DeepCore, and PINGU markers.](image)

![Graph showing PINGU (26m String Spacing) Effective Volume.](image)