PINGU and the Neutrino Mass Hierarchy

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Neutrino Oscillations

- Neutrino oscillations parametrized by
  - mass squared differences $\Delta m^2_{ij}$
  - mixing angles $\theta_{ij}$
  - CP phase $\delta_{CP}$
- Several questions remain
  - What is the mass hierarchy ($m_3 > m_1$?)
Neutrino Mass Hierarchy

- Focus on the mass hierarchy in this talk
- We know $\Delta m^2_{13}$ but not the sign
Experiments

- Several experiments targeting the mass hierarchy
- NOvA to start data collection soon
- R&D ongoing on Daya Bay II, LBNE, GLACIER, LENA, ORCA, PINGU
Theory - Atmospheric Neutrinos

• Why use atmospheric neutrinos?
  • Not usually considered for use in precision parameter determination
• Broad range of baselines (~50 - 12500 km)
• Broad range of energies (~GeV - PeV)
Theory

• Case for atmospheric neutrinos has been studied previously (Phys. Rev. D 78, 093003 (2008) in particular although there are others)

• In essence this requires distinction between normal and inverted hierarchy in counts

• Hierarchy effects seen as neutrinos pass through matter
  • \( \nu \) oscillation probability is enhanced if hierarchy is normal
  • \( \bar{\nu} \) oscillation probability is enhanced if hierarchy is inverted
  • and: \( \nu, \bar{\nu} \) have different cross sections

• Matter effects depend on size of \( \theta_{13} \) which is now better defined
• Interested primarily the $\nu_\mu$ survival probability

• Note in particular the dependence on $\Delta m^2_{31}$

\[
P_{\nu_\mu \rightarrow \nu_\mu} = 1 - \left[ \cos^2 \theta^m_{13} \sin^2 \theta_{23} \times \sin^2 2\theta \right]^{1.27} \left( \frac{\Delta m^2_{31} + A + (\Delta m^2_{31})^m}{2} \right) \frac{L}{E} 
- \sin^2 \theta^m_{13} \sin^2 \theta_{23} \times \sin^2 2\theta \left[ 1.27 \left( \frac{\Delta m^2_{31} + A - (\Delta m^2_{31})^m}{2} \right) \frac{L}{E} \right] 
- \sin^4 \theta_{23} \sin^2 2\theta^m_{13} \sin^2 2\theta \left[ 1.27 (\Delta m^2_{31})^m \frac{L}{E} \right] \]
Starting Point Plots

- Clear differences emerge between the hierarchies
- This is at a fixed zenith angle, ~150 degrees
Preliminary Reference Earth Model (PREM)

- Current “best guess” as to the variation of density in the Earth
- Been around a long time, still retains the preliminary name
Matter effects

- Previous probabilities were just for one path length
- Upgoing neutrinos experience effect of traveling through the Earth (or a fraction of it)
Matter Effects - I

- At angles $>146^\circ$
- $\nu$ pass through mantle and core
- Parametric enhancement of oscillations take place
Matter Effects

- These are almost directly upgoing
- Two different energies show magnitude of final effect
- This zenith dominated by parameteric resonance
Matter Effects - II

- At angles $< 146^\circ$
- $\nu$ pass through mantle only
- MSW enhances $\nu_\mu$ to $\nu_e$
Matter Effects

- Much less upgoing angles show MSW effects
- Note change in Earth density plot

\[ P(\nu_\mu \rightarrow \nu_\mu) \text{ with Travel Through the Earth - 6 GeV, 126}^\circ \]
Detection Method

- IceCube and DeepCore successfully detecting neutrinos for years
- IceCube: ~5160 PMTs in 1 km³
- DeepCore: denser string and DOM spacing
- High efficiency PMTs
Detection Method

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- DeepCore: denser string and DOM spacing
- High efficiency PMTs
DeepCore Energy Range

- Detection threshold lowered to ~10 GeV in DeepCore
- Effective volume at trigger level increased below 100 GeV
Step up to PINGU

- Add another 20 strings
- Denser string and DOM spacing
- Energy threshold lowers again
Step up to PINGU

- Add another 20 strings
- Denser string and DOM spacing
- Energy threshold lowers again
Now we need to extend this to two dimensions to show the probability vs energy and zenith angle.
Distinguishability

• Use method outlined in arXiv:1205.7071 (Akhmedov, Razzaque and Smirnov)

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

• Essentially bin everything up and subtract the two hierarchies, scaled by the number of events in the Normal hierarchy bin
Simulations

- Simulations now carried out using IceCube MC structure
- Currently studying different PINGU geometries with different spacings
Simulations

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Distinguishability Plots

- Use our simulations
- First use neutrino zenith angle and energy
- Shown without square root to illustrate pattern

Distinguishability Metric $[(IH-NH)/NH^{1/2}]$
Distinguishability Plots

- Matter effects due to MSW
Distinguishability Plots

- Primarily parametric oscillation effects in this region
Distinguishability Plots

- Then use muon zenith angle and neutrino energy
- Shown without square root to illustrate pattern
Reconstruction

• Previous plots showed perfect detector resolution
• This (probably) won’t be the case
• Need to account for the reconstruction effects
• Add a gaussian “smearing” to the angles and energies
Detector Resolution

Distinguishability Metric \(\frac{(IH-NH)}{NH^\frac{1}{2}}\)

- **0 GeV, 0°**
- **2 GeV, 11.25°**
- **3 GeV, 15°**
- **4 GeV, 22.5°**

Energy (GeV)

Cos(zenith angle)
Detector Resolution

Distinguishability Metric \[\frac{(IH-NH)}{NH^{1/2}}\]

0 GeV, 0°

2 GeV, 11.25°

3 GeV, 15°

4 GeV, 22.5°
Comparisons

- Following model in publication, used three different resolution pairs
- \((2\text{GeV}, 11.25^\circ), (3\text{GeV}, 15^\circ), (4\text{GeV}, 22.5^\circ)\)

![Graph showing calculated total sigma - PINGU](image-url)
Systematics

• Studied several effects
  1. Systematic energy shift +/-5%, +/-10%
  2. Systematic angle broadening +/-5%, +/-10%
  3. PREM quantities incorrect
    • Core radii +/-5%, +/-10%
    • Core densities +/-5%, +/-10%
Systematics - Illustrated

\[ \chi^2(IH_{(T)} : NH_{(T)}) \]
\[ \Delta \chi^2 = \chi^2(IH_{(T)} : NH_{(S)}) - \chi^2(NH_{(T)} : NH_{(S)}) \]

\[ \Delta \chi^2 > 0 \rightarrow ProperID \]

\[ \Delta \chi^2 < 0 \rightarrow WrongID \]
Energy Shift

- Systematic shift in energy has little effect
Angle Broadening

- Not a systematic shift in zenith
- Misunderstanding of the detector resolution
Next Steps

• Next objective is to include detector resolution effects properly using reconstructions
• Need to perform detailed analysis of systematics
• Start with quantification of best geometry
**Timescale**

- **Early 2012**: Begin simulation studies for 18-20 string detector with threshold ~1 GeV. Targeted Physics: neutrino hierarchy, WIMPs, SN.

- **Spring 2012**: Complete 1st DeepCore analyses.

- **Fall 2012**: Submit Letter of Interest to NSF.

- **Summer 2013**: Finish Detailed PINGU studies.

- **Fall 2013**: Submit PINGU Proposal.

- **Winter 2016/17**: Begin deploying PINGU including R&D strings.


- **March 2011**: 1st PINGU workshop - NIKHEF
- **Jan 2012**: 2nd PINGU workshop - Penn State
- **May 2012**: 3rd PINGU workshop - Erlangen
Conclusion

• Determination of the neutrino mass hierarchy with atmospheric neutrinos appears feasible

• PINGU allows for this determination quickly in a cost effective implementation
Things seem to compare reasonably well
Detector Resolution Plots

- Shown with detector resolution 2 GeV, 11.25°
Reality(-ish)

- For $\nu_\mu$-like events we really get a mixture of $\nu_\mu$ and $\bar{\nu}_\mu$
Systematics

• Can also add systematics on the simulated data:

1. Apply detector resolution to both hierarchies (IH and NH)

2. Copy both hierarchies

3. Apply systematic shift to one copy for each

4. For each copy, calculate the significance of the opposite unshifted hierarchy and the same unshifted hierarchy

5. Subtract the same from the opposite value