Neutrino Flavor Physics with IceCube & PINGU

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for the IceCube Collaboration
The Rencontres du Vietnam Flavour Conference
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The IceCube–PINGU Collaboration

47 institutions, ~300 members
http://icecube.wisc.edu/
Two Covers

Observation of PeV-Energy Neutrinos


Evidence for High-Energy Extraterrestrial Neutrinos

Science 342, 1242856 (2013) [arxiv:1311.5238]

Color : Time order, Size : Amplitude
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IceCube : 1 km³ Neutrino Telescope

- Detects Cherenkov photons in ice from charged particles created by high-E neutrino interactions
- 5160 Digital Optical Modules (DOMs) with a 10 inch PMT on 86 vertical strings
- IceTop air shower array
  - 162 Tanks each with 2 DOMs
- Low-E ($E_{\text{threshold}} \sim 10$ GeV) DeepCore array
  - 8 strings include high quantum efficiency DOMs

Waveforms from charged particles in ice

- Charged particles produce radiation from ionizations and stochastics in ice
- DOMs digitize the PMT waveforms of photoelectrons
- Arrival time and recorded charge information used to reconstruct events
# Detection Methods: Cherenkov Radiation

- **Upward-going Muon**
  - **track**
  - limited energy resolution
  - $\sim 1^\circ$ angular resolution

- **$\sim 1$ PeV Cascade**
  - cascade
  - $\sim 15\%$ energy resolution
  - $\sim 10^\circ$ angular resolution

<table>
<thead>
<tr>
<th>symbols</th>
<th>process</th>
<th>signature</th>
<th>note</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_{\mu}^{CC}$</td>
<td>$\nu_{\mu} + N \rightarrow \mu + X$</td>
<td>track</td>
<td>cascade+track if contained</td>
</tr>
<tr>
<td>$\nu_{e}^{CC}$</td>
<td>$\nu_{e} + N \rightarrow e + X$</td>
<td>cascade</td>
<td></td>
</tr>
<tr>
<td>$\nu_{\tau}^{CC}$</td>
<td>$\nu_{\tau} + N \rightarrow \tau + X$</td>
<td>cascade</td>
<td></td>
</tr>
<tr>
<td>$\nu_{\alpha}^{NC}$</td>
<td>$\nu_{\alpha} + N \rightarrow \nu_{\alpha} + X$</td>
<td>cascade</td>
<td>$\alpha = \mu, e, \tau$</td>
</tr>
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</table>

N= Target Nucleon and X = Hadronic Shower
IceCube Detector Performance

- The full detector (86 strings) has been running for 3 years (Currently taking the fourth year data)
- IceCube built on time, on budget, and exceeds design requirements
  - 5160 Sensors are deployed, only 1.5% not taking data
  - 99% up-time
- Cosmic ray Moon shadow verifies better than 1° angular resolution and correct pointing.
- Understanding optical properties in ice is an ongoing calibration effort (NIM. A711 (2013) 73)
- High-E sample $\sim 7 \times 10^4 \nu_\mu$ per year (1.3 event per 10 min) at final analysis level ($<E> \sim 1$ TeV).
- Low-E sample (DeepCore) $\sim 10^4 \nu_\mu$ per year at final ($<E> \sim 30$ GeV)
Sources of Neutrinos (Atmospheric/Astrophysical)

\[ \nu_\mu + \bar{\nu}_\mu \rightarrow \mu^\pm, \pi^\pm, K^\pm, K_L^0 \]

\[ \nu_\mu/\nu_e \sim 2 \]

\[ \nu_\mu/\nu_e \sim 20 \]

\[ \nu_e + \bar{\nu}_e \rightarrow \mu^\pm, K^\pm, K_L^0 \]

\[ \nu_\tau + \bar{\nu}_\tau \rightarrow \nu_\mu \rightarrow \nu_\tau \]

Energy:
- 1 GeV
- 100 GeV
- 10 TeV
- 1 PeV

Detector Locations:
- PINGU
- DeepCore
- IceCube
- Spectrum/Charmed Particles/Astrophysical sources

Oscillations:
- NMH
Neutrino Oscillations: $\nu_\mu$ Disappearance

Zenith Angle and Energy with 3 year DeepCore (953 days)

- Veto bkg. events that originate outside of the fiducial volume
- Analysis optimized for the lowest energy upward neutrino events
- No osc. prediction: 7000 events total (~30% disappeared)
- Energy Resolution: 30% at 10 GeV
- Zenith Resolution: 12 deg. at 10 GeV
Neutrino Oscillations: $\nu_\mu$ Disappearance
Zenith Angle and Energy with 3 year DeepCore (953 days)

Bands: variations allowed by the systematic uncertainties assumed

3-flavor oscillations measured with the high energy atmospheric neutrinos
Measurements are consistent with other results
We continue to improve the systematic uncertainties.
Atmospheric Spectrum Analysis (Cascades)
Observables: Energy, Zenith angle, and PID

3-D Likelihood Fit with systematics as nuisance parameters to disentangle atmospheric components from astrophysical components
Atmospheric Neutrino Flux

- Conventional Neutrino flux (π/K) follows a steep spectrum $\sim E^{-3.7}$
- NuE components are obtained from unfolding
- Measurements agree with models
- Prompt neutrino flux follows a spectrum $\sim E^{-2.7}$ (not measured yet)

ERS : Baseline Prompt Model
PHYSICAL REVIEW D 78, 043005 (2008)

Atmospheric Neutrino Veto
PHYSICAL REVIEW D 90, 023009 (2014)
High Energy Starting Event Search

- Search for starting events at high energy
- Total charge > 6000 photoelectrons
- Require early charge to be relatively high
- ~400 Megaton effective volume
- Sensitive to all flavors above 60 TeV
- Backgrounds
  - Atmospheric muons: estimation from data (tagged muons)
  - Atmospheric neutrinos: very low but large uncertainty
Astrophysical Neutrinos

37 events in three years of data
- 8.4 +/- 4.2 atmospheric muons (background)
- 6.6+5.9-1.6 atmospheric neutrinos (background)
High confidence of non-atmospheric source of neutrinos (5.7 sigma rejection of atmospheric-only hypothesis)
Future Direction: PINGU
(Precision IceCube Next Generation Upgrade)

- Instrument additional 40 strings
- 60-100 DOMs in each string
- Detect neutrinos below 10 GeV
- Low risk, Quick deployment

Neutrino Mass Hierarchy measurement with PINGU
- Neutrinos with Earth matter and density effect in varying baseline
- Understanding the systematics is the key to the measurement
- Additional calibration devices can be added
Oscillation Probability x Cross-section x Flux = Event Rate(N)

\[ \nu_\mu \times \text{anti-} \nu_\mu \times N_{\text{IH}} = N_{\text{NH}} \]

\[ \sigma(\nu) \sim 2\sigma(\text{anti-} \nu), \]
\[ \phi(\nu_{\text{atm}}) > \phi(\text{anti-} \nu_{\text{atm}}) \]
\[ \therefore N_{\text{NH}} \neq N_{\text{IH}}! \]

(True for \( \nu_e \), too)

**Distinguishability Plot**

**Illustration only**

**NH**: Normal Hierarchy

**IH**: Inverted Hierarchy
Event Reconstruction Status

Zenith Angle Resolutions

Fractional Energy Resolutions

IceCube Preliminary

νμ CC

νe CC

IceCube Preliminary

νμ CC

νe CC

IceCube Preliminary
NMH Sensitivity

- 3 sigma result of neutrino mass hierarchy in 3.5 years of data
- Energy Scale & Neutrino Cross section are key systematics

### Parameter

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<th>Description</th>
</tr>
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<tbody>
<tr>
<td>$\Delta m^2_{31}$, $\theta_{23}$, $\theta_{13}$</td>
<td>Oscillation parameters</td>
</tr>
<tr>
<td>$\nu / \bar{\nu}$ cross-section</td>
<td>Cross-section/flux normalization (fully degenerate)</td>
</tr>
<tr>
<td>$A_{\text{eff}}$ energy dependence</td>
<td>Degenerate with spectral index of atmospheric flux</td>
</tr>
<tr>
<td>Energy scale</td>
<td>$E_{\text{reco}} / E_{\text{true}}$</td>
</tr>
</tbody>
</table>
Summary

• The IceCube detector is running at full strength
  • Three years of 86-string data are being analyzed while taking the fourth year of 86-string data
  • The detector runs very smoothly (~99% uptime)

• IceCube is a multi-purpose detector
  • Measurement of Atmospheric neutrino flux
  • Observation of astrophysical neutrinos and active prompt neutrino search program
  • Particle physics with DeepCore low energy extension, or possibly with PINGU
  • Other projects: Indirect Dark Matter searches, Exotic particle searches, Follow-up programs, Air shower physics, and so on.

• Highlights from Recent Results
  • The High Energy Starting Event search found 37 events (3 events above PeV) inconsistent with atmospheric backgrounds at ~5.7 $\sigma$.
  • Atmospheric neutrino oscillations & neutrino flux measurements ($\nu_\mu$ and $\nu_e$) agree well with models of atmospheric neutrinos and world average.
  • More data with improved analyses coming soon and PINGU can help determine NMH.