New Measurement of Atmospheric Neutrino Oscillations with IceCube

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Data is collected here and sent by satellite to the data warehouse at UW–Madison

50 m

IceTop

86 strings of DOMs, set 125 meters apart

1450 m

Digital Optical Module (DOM)
5,160 DOMs deployed in the ice

2450 m

DeepCore

Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility

60 DOMs on each string

DOMs are 17 meters apart

Antarctic bedrock
IceCube DeepCore

- A more densely instrumented region at the bottom center of IceCube
  - Eight special strings plus 12 nearest standard strings
  - Hamamatsu high Q.E. PMTs
  - String spacing \(\sim 70\) m, DOM spacing 7 m: \(\sim 5\)x higher effective photocathode density than IceCube
- In the clearest ice, below 2100 m
  - \(\lambda_{\text{atten}} \approx 45-50\) m, very low levels of radioactive impurities
- IceCube provides an active veto against cosmic ray muon background
DeepCore Physics: 5-100 GeV

• Searches for dark matter-induced neutrino flux from…

• Direct searches for exotic particles, e.g. slow monopoles: *Eur. Phys. J.* C74, 2938 (2014)

• Neutrino astronomy: neutrino bursts from, e.g. choked GRBs: *Astrophys. J.* 816, 75 (2016)

• Atmospheric neutrino spectrum: first measurements of $\nu_e$ above 50 GeV:

• … and atmospheric neutrino oscillations

*see talk by Morten Medici*
Oscillations with Atmospheric Neutrinos

- Neutrinos available over a wide range of baselines, with energies from a few GeV to 100 TeV
- Oscillations produce distinctive pattern in 2D energy-angle space
  - Rather than near and far detectors, we have a range of beams and a single detector
  - Multi-MTon volume/high statistics allows deconvolution of oscillations (unique dependence on angle and energy) from systematics
Probing oscillation physics at a range of baselines and energies not accessible to long-baseline or reactor neutrino experiments
Oscillograms

- Measure atmospheric parameters ($\Delta m^2_{atm}$, $\theta_{23}$) at high energies
  - Tau neutrino appearance also accessible – test of 3x3 mixing paradigm
  
- Below 10-15 GeV, matter resonances depending on mass ordering

see talk by Michael Larson

see talk by Martin Leuermann
Atmospheric Oscillations with DeepCore

- 41,599 events from 2012-14 data sets, $\chi^2$/n.d.f. = 117 / 119
- Full analysis is $L \times E_\nu \times$ particle type, projected onto $(L/E_\nu)$ for illustration
- Shaded range shows uncertainty in prediction at best fit (mostly atm. $\mu$)
Nuisance Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Priors</th>
<th>Best Fit NO</th>
<th>Best Fit IO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrino event rate [% of nominal]</td>
<td>no prior</td>
<td>85</td>
<td>85</td>
</tr>
<tr>
<td>$\Delta \gamma$ (spectral index)</td>
<td>$0.00\pm0.10$</td>
<td>-0.02</td>
<td>-0.02</td>
</tr>
<tr>
<td>$\nu_e + \bar{\nu}_e$ relative normalization [%]</td>
<td>$100\pm20$</td>
<td>125</td>
<td>125</td>
</tr>
<tr>
<td>NC relative normalization [%]</td>
<td>$100\pm20$</td>
<td>106</td>
<td>106</td>
</tr>
<tr>
<td>$\Delta (\nu/\bar{\nu}) \ [\sigma]$, energy dependent [42]</td>
<td>$0.00\pm1.00$</td>
<td>-0.56</td>
<td>-0.59</td>
</tr>
<tr>
<td>$\Delta (\nu/\bar{\nu}) \ [\sigma]$, zenith dependent [42]</td>
<td>$0.00\pm1.00$</td>
<td>-0.55</td>
<td>-0.57</td>
</tr>
<tr>
<td>$M_A$ (resonance) [GeV]</td>
<td>$1.12\pm0.22$</td>
<td>0.92</td>
<td>0.93</td>
</tr>
</tbody>
</table>

Detector parameters

<table>
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<th>Priors</th>
<th>Best Fit NO</th>
<th>Best Fit IO</th>
</tr>
</thead>
<tbody>
<tr>
<td>overall DOM efficiency [%]</td>
<td>$100\pm10$</td>
<td>102</td>
<td>102</td>
</tr>
<tr>
<td>relative DOM efficiency, lateral [\sigma]</td>
<td>$0.0\pm1.0$</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>relative DOM efficiency, head-on [a.u.]</td>
<td>no prior</td>
<td>-0.72</td>
<td>-0.66</td>
</tr>
</tbody>
</table>

Background

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Priors</th>
<th>Atm. $\mu$ contamination [% of sample]</th>
<th>Atm. $\mu$ contamination [% of sample]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>no prior</td>
<td>5.5</td>
<td>5.6</td>
</tr>
</tbody>
</table>

- Held fixed due to lack of impact on fit: $\Delta m^2_{21} = 7.53 \times 10^{-5} \text{ eV}^2$, $\sin^2 \theta_{12} = 0.304$, $\sin^2 \theta_{13} = 2.17 \times 10^{-2}$, and $\delta_{CP} = 0^\circ$
Best fit: $\Delta m_{32}^2 = 2.31^{+0.11}_{-0.13} \times 10^{-3} \text{ eV}^2$, $\sin^2 \theta_{23} = 0.51^{+0.07}_{-0.09}$
Outlook

• In addition to multimessenger astrophysics, IceCube’s copious background of atmospheric neutrinos enables investigation of a range of neutrino physics

• Observations in a unique energy range
  • Different systematics than long-baseline experiments
  • Sensitivity to possible new physics in the neutrino sector

• New measurement of atmospheric oscillations has precision similar to NOvA, T2K, MINOS; prefers maximal mixing
  • Follow-on analyses using this data set, and a variant with even higher statistics, are underway
Digital Optical Module

- Onboard capture of PMT waveforms
  - 300 MS/s for 400 ns with custom ATWD chip
  - 40 MS/s for 6.4 µsec with commercial ADC
- Absolute timing < 2 ns (RMS)
- Dynamic range ~1000 p.e./10 ns
- Noise rate ~600 Hz (underlying Poisson rate 260 Hz)
- DOM electronics dead time < 1%
- Survival rate: 98.5%