TAU NEUTRINO
APPEARANCE IN ICECUBE

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**ATMOSPHERIC TAU NEUTRINOS**

- Intrinsic $\nu_\tau$ production in atmosphere negligible
- When studying $O(10)$ GeV Neutrinos and below, earth diameter provides perfect L/E to look at $\nu_\mu$ disappearance
  - We look at events in the Energy-$\cos(\text{zenith})$ plane
- A disappeared $\nu_\mu$ should mostly appear in the $\nu_\tau$ flavor

\[
\cos(\text{zenith}) \propto \text{baseline}
\]
PREVIOUS RESULTS

  - CNGS ~17 GeV muon neutrinos / 732 km baseline
  - Observation of $\nu_\tau$ appearance with 5.1 sigma significance
  - Total of 5 individually identified $\nu_\tau$ candidates (over 0.25 total background)
  - Only weak constraints on $\nu_\tau$ normalization: 1.8 -1.1 +1.8 (90% C.L.)

- Super-K 2016 (presented at Neutrino 2016)
  - Evidence with a significance of 4.6 sigma
  - Based on 15 years of data
  - Best constraint on $\nu_\tau$ normalization with 1.42 +/- 0.32 (68% C.L.)
  - Energies around ~5 GeV
- τ-sector of Neutrino oscillations is the least well measured
- Experimental constraints ~order of magnitude worse than for e and μ sectors

- Measurement of tau appearance can be used to test PMNS unitarity
- Deviation from unitarity can be an indicator for new physics

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]
DEEPCORE EXTENSION OF ICECUBE

- Additional 8 strings with densely spaced, high efficiency optical modules (DOMs) in addition to the 78 standard IceCube strings
- In clearest part of Ice (below dust layer)
- Surrounded by IceCube strings (used as atm. muon veto)
- Neutrino energies down to \(~5\) GeV
CC AND NC INTERACTIONS

- **Charged Current (CC)** interaction of neutrinos reveals their flavor from the outgoing lepton
  - This channel needed to unambiguously identify $\nu_\tau$ (e.g. OPERA)
  - Cross-section suppressed by heavy $\tau$, threshold energy of 3.5 GeV, cross section $\sim$order of magnitude lower than that of $\nu_\mu$

- **Neutral Current (NC)** interactions are indistinguishable for the 3 flavors
  - Still, the disappearance and appearance happen in specific locations in L/E
  - can be used to help constrain the $\nu_\tau$ normalization

* for better comparison we provide both result separately, CC+NC and CC-only
**ICECUBE EVENT SIGNATURES**

- Fully contained events inside the DeepCore fiducial Volume
- Reconstructed using a full Cascade + Track hypothesis
  - position, direction, energy and PID (= track or cascade like event)

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**Track like**

```
\nu_{\mu} \rightarrow \text{Nucl eus}
```

Hadron shower

Cherenkov light

\(\mu\)

Typical \(\nu_{\mu}\) event:
Energy deposited in
- Extended muon track (E \(\sim\) length)
- Hadron shower from e.g. DIS

**Cascade like**

```
\nu_{e/\tau} \rightarrow \text{Nucl eus}
```

Hadron shower

\(\nu_{e/\tau}\) event:
All energy deposited in form of showers (hadronic and electro-magnetic)
Spatially more compact (no track)
- Our ability to distinguish track and cascade events mainly depending on neutrino energy
  - Higher energy = longer muon tracks

- Separation based on an additional reconstruction using cascade only (no track)
  - Difference in likelihood to the standard reconstruction used as classifier
- Actual fit of the data is done using two 2d-histograms
  - Reconstructed neutrino energy (between 5.6 and 56 GeV)
  - Reconstructed zenith angle (covering the full sky from \(\cos(\text{zenith}) = -1\) to +1)
  - Using 8x8 bins, for cascade and track like events separately

- \(S/\sqrt{B}\) plot showing region where we get most significance from
  - \(S = \nu_\tau, B = (\nu_e + \nu_\mu + \text{Atm. } \mu)\)
SYSTEMATIC UNCERTAINTIES

- Incorporating a large variety of nuisance parameters in the measurement

- Covering uncertainties of:
  - Initial atmospheric neutrino flux
  - Interaction (cross sections)
  - Oscillation parameters
  - Detector uncertainties (efficiencies of optical modules and ice uncertainties)
  - Atmospheric muon background

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Prior</th>
<th>Best fit (CC+NC)</th>
<th>Best fit (CC)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flux and cross sections</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\nu_e/\nu_\mu$ ratio</td>
<td>1.0 ± 0.05</td>
<td>1.02</td>
<td>1.02</td>
</tr>
<tr>
<td>$\nu/\bar{\nu}$ ratio, zenith dep. (σ)</td>
<td>0.0 ± 1.0</td>
<td>-1.15</td>
<td>-1.11</td>
</tr>
<tr>
<td>$\nu/\bar{\nu}$ ratio, energy dep. (σ)</td>
<td>0.0 ± 1.0</td>
<td>0.08</td>
<td>0.11</td>
</tr>
<tr>
<td>Δγ (spectral index)</td>
<td>0.0 ± 0.1</td>
<td>-0.072</td>
<td>-0.074</td>
</tr>
<tr>
<td>effective lifetime (y)</td>
<td>-</td>
<td>2.25</td>
<td>2.25</td>
</tr>
<tr>
<td>$M_A$ (quasi-elastic) (GeV)</td>
<td>0.99±0.248</td>
<td>0.884</td>
<td>0.881</td>
</tr>
<tr>
<td>$M_A$ (resonance) (GeV)</td>
<td>1.12±0.22</td>
<td>0.905</td>
<td>0.901</td>
</tr>
<tr>
<td>$\nu$ NC Normalization</td>
<td>1.0 ± 0.2</td>
<td>1.15</td>
<td>1.16</td>
</tr>
<tr>
<td><strong>Oscillation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\theta_{13}$ (°)</td>
<td>8.5 ± 0.21</td>
<td>8.5</td>
<td>8.5</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>-</td>
<td>0.52</td>
<td>0.52</td>
</tr>
<tr>
<td>Δ$m^2_{31}$ (10^{-3}eV²)</td>
<td>-</td>
<td>2.36</td>
<td>2.36</td>
</tr>
<tr>
<td><strong>Detector</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>optical eff., overall (%)</td>
<td>100±10</td>
<td>103</td>
<td>104</td>
</tr>
<tr>
<td>optical eff., lateral (σ)</td>
<td>0.0 ± 1.0</td>
<td>-0.074</td>
<td>0.046</td>
</tr>
<tr>
<td>optical eff., head-on (a.u.)</td>
<td>-</td>
<td>-1.28</td>
<td>-1.16</td>
</tr>
<tr>
<td>local ice model</td>
<td>-</td>
<td>-0.11</td>
<td>-0.07</td>
</tr>
<tr>
<td><strong>Background</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atm. $\mu$ fraction (%)</td>
<td>-</td>
<td>4.9</td>
<td>4.9</td>
</tr>
</tbody>
</table>
DATA SAMPLE

- Result based on 3 years of data
- Total ~41k events
  - 1.5k CC $\nu_\tau$ events
  - 600 NC $\nu_\tau$ events
  - ~2k background events from atmospheric $\mu$
- Excellent Data/MC agreement

<table>
<thead>
<tr>
<th>Type</th>
<th>No. events</th>
<th>Uncert.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e + \bar{\nu}_e$ CC</td>
<td>9391.0</td>
<td>24.4</td>
</tr>
<tr>
<td>$\nu_e + \bar{\nu}_e$ NC</td>
<td>860.7</td>
<td>8.8</td>
</tr>
<tr>
<td>$\nu_\mu + \bar{\nu}_\mu$ CC</td>
<td>23093.5</td>
<td>39.4</td>
</tr>
<tr>
<td>$\nu_\mu + \bar{\nu}_\mu$ NC</td>
<td>3016.5</td>
<td>15.8</td>
</tr>
<tr>
<td>$\nu_\tau + \bar{\nu}_\tau$ CC</td>
<td>1798.6</td>
<td>11.1</td>
</tr>
<tr>
<td>$\nu_\tau + \bar{\nu}_\tau$ NC</td>
<td>778.0</td>
<td>8.1</td>
</tr>
<tr>
<td>atm. $\mu$</td>
<td>2016.0</td>
<td>49.0</td>
</tr>
<tr>
<td>total expected</td>
<td>40954.2</td>
<td>71.2</td>
</tr>
<tr>
<td>observed</td>
<td>40902</td>
<td>202</td>
</tr>
</tbody>
</table>
TAU NEUTRINO DISTRIBUTIONS

- Visible energies distributed around $\sim 15$ GeV (Analysis range $5.6 - 56$ GeV)
- $\nu_\tau$ events appearing in upgoing (-1,0) (earth crossing trajectories)
- Mostly classified in cascade event category

background subtracted data overlayed with best-fit $\nu_\tau$ expectations
RESULT

- $\nu_\tau$ normalization (with 68% C.I.)
  - CC+NC: 1.25 ±0.42 -0.37
  - CC-only: 1.20 ±0.49 -0.45

- $\nu_\tau$ appearance significance (exclusion of no-appearance)
  - CC+NC: 4.1 $\sigma$
  - CC-only: 3.0 $\sigma$

- c.f. talk “IceCube/DeepCore Results and PINGU” from this session, PINGU able to constrain $\nu_\tau$ norm < 10%
CONCLUSIONS

- Measured $\nu_\tau$ normalizations of
  
  $1.25 \pm 0.42 -0.37$ (CC+NC)  
  $1.20 \pm 0.49 -0.45$ (CC only)

- Based on modestly sized 3y dataset
  - Improved event selection underway
  - Additional 2y of data already collected and experiment continues running

- First $\nu_\tau$ appearance measurement by IceCube
  - Consistent with other results
  - Competitive result with worlds best measurements
  - Different (higher) energy regime than Super-K
  - Providing path forward for future measurements of the underexplored $\nu_\tau$ sector

▶ STAY TUNED!