Status of $\nu_\tau$ appearance search in IceCube and PINGU

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Measuring $\nu_\tau$ appearance

- From theory: “2-3 osc” is $\nu_\mu \rightarrow \nu_\tau$
  - measured by OPERA (5 events)
  - also observed by SK at $\sim 4\sigma$

- Precise measurement of $\nu_\tau$ appearance allows verification of unitarity of mixing matrix

- $\nu_\tau$ CC x-sec turns on at a few GeV
  - need as high $\nu$ energy as possible

- However $\nu_\mu \rightarrow \nu_\tau$ oscillation maximum at much lower energies at typical oscillation baselines
  - maximum at 25 GeV for $\nu$ traveling through Earth’s diameter

![Plot comparing the total charged current $\nu_\mu$ (solid) and $\nu_\tau$ (dashed) per nucleon cross sections divided by neutrino energy and plotted as a function of neutrino energy.](image_url)

![Probability distribution for $\nu_\mu \rightarrow \nu_\nu$ transitions.](image_url)

\begin{align*}
\Delta m^2_{21} &= 7.59 \times 10^{-5} \text{ eV}^2 \\
\Delta m^2_{32} &= 2.42 \times 10^{-3} \text{ eV}^2 \\
\sin^2(2\theta_{12}) &= 0.861 \\
\sin^2(2\theta_{13}) &= 0.098 \\
\sin^2(2\theta_{23}) &= 0.490 \\
\Delta CP &= 0^\circ
\end{align*}
Neutrinos from different baselines and energies

- Baselines vary between $\sim 20$ km to $\sim 12760$ km

Large volume detectors needed for large statistics

$\sim 10^4 \, \nu_\mu$ expected per year at analysis level in DeepCore
• Without DeepCore:
  78 strings,
  125 m string spacing,
  17 m module z-spacing

• Optimized for (very)
  High Energy neutrinos
IceCube-DeepCore

- 78 strings, 125 m string spacing
- 17 m modules z-spacing
- 8 strings, 40-75 m string spacing
- 7 m modules z-spacing
Measurement strategy

- Huge background from atmospheric $\mu$
  - Use IC as veto to reject atm $\mu$ events
  - Same as done for $\nu_{\mu}$ disappearance analysis
    - see J. Hignight’s talk
- Reconstruct $\nu$ energy and direction
  - oscillation distance (L) given by zenith

- Separate $\nu$ events with clear muons from rest
  - only $\sim18\%$ of $\tau$ decay have $\mu$
  - $\nu_{\mu}$ CC is main background to analysis
- Cannot currently separate different types of “cascade”

\[ \begin{array}{ccccccc}
0.0 & 0.1 & 0.2 & 0.3 & 0.4 & 0.5 & 0.6 & 0.7 & 0.8 & 0.9 & 1.0 \\
CC & \mu\nu & CC & e\nu & CC & \tau\nu & NC
\end{array} \]

\[ \begin{array}{ccccccc}
0.1 & 0.2 & 0.3 & 0.4 & 0.5 & 0.6 & 0.7 \\
Fraction of events identified as cascade
\end{array} \]

\[ \begin{array}{ccccccc}
10 & 20 & 30 & 40 & 50 & 60 & 70 & 80 & \text{True } \nu \text{ energy (GeV)}
\end{array} \]
What is the signal in IceCube-DeepCore?

- The oscillation formalism does not relate to how the $\nu$ interacts
  - in that sense, $\nu_\tau$ CC and NC are both signal
- But, uncertainties on the x-sec would affect more $\nu_\tau$ CC rate
  - in that case using signal as only $\nu_\tau$ CC would simplify interpretation

- Currently both $\nu_\tau$ CC and NC considered signal.
  - In future plan to present results in both scenarios
What is the signal in IceCube-DeepCore?

- But fit is not done in L/E, but in $E \times \cos \theta_z$
  - Most signal in cascade channel
  - Pattern in $E \times \cos \theta_z$ helps reduce impact of systematics

Cascade-ID

![Cascade-ID plot]

Expected number of events/year vs. cos(Zen) for different neutrino flavors.

DeepCore

Livetime: 1 year

Preliminary
## Systematic errors and fitting

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Gaussian prior</th>
<th>prior in fit?</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta M^2$</td>
<td>$(2.42 \pm 0.10) \cdot 10^{-3} \text{eV}^2$</td>
<td>Yes</td>
</tr>
<tr>
<td>$\sin^2(\theta_{23})$</td>
<td>$0.490 \pm 0.055$</td>
<td>Yes</td>
</tr>
<tr>
<td>$\nu$ overall normalization</td>
<td>±15%</td>
<td>No</td>
</tr>
<tr>
<td>Atmo. $\mu$ normalization</td>
<td>$1.34 \pm 20%$</td>
<td>No</td>
</tr>
<tr>
<td>$\nu_e/\nu_\mu$ flux normalization</td>
<td>±2%</td>
<td>Yes</td>
</tr>
<tr>
<td>$\bar{\nu}/\nu$ flux normalization</td>
<td>±15%</td>
<td>Yes</td>
</tr>
<tr>
<td>Spectral index of $\nu_\mu$ flux</td>
<td>±0.05</td>
<td>Yes</td>
</tr>
<tr>
<td>DOM efficiency</td>
<td>±10%</td>
<td>Yes</td>
</tr>
<tr>
<td>Hole Ice</td>
<td>$(0.02 \pm 0.01) \text{cm}^{-1}$</td>
<td>Yes</td>
</tr>
</tbody>
</table>

- Fit is done using Gaussian priors for most systematic errors and flat prior for $\nu_\tau$ normalization (between 0.0 and 2.0)
  - in future will use more complicated prior for oscillation parameters
- For estimation of sensitivity, fit performed on several pseudo data generated from MC
  - When fit without prior, Gaussian prior is used for sampling of parameter used for pseudo-data creation.
- While main systematics already accounted for, still evaluating impact of other systematics
Reconstructed $\nu_\tau$ normalization – 1 year

- Reasonable separation between default 3-flavour oscillation and no $\nu_\tau$ appearance with 1 year DeepCore data
- Significance to exclude no $\nu_\tau$ appearance: $\sim 6.5\sigma$ (Gaus approx)
Sensitivity for $\nu_\tau$ normalization – “3 years”

- Significance to exclude no $\nu_\tau$ appearance: $\sim 9.4\sigma$ (Gaus approx)
- 25% precision on $\nu_\tau$ normalization
IceCube-DeepCore-PINGU

- 78 strings, 125 m string spacing
- 17 m modules z-spacing
- 8 strings, 75 m string spacing
- 7 m modules z-spacing
- 40 strings, 22 m string spacing
- 3 m modules z-spacing
  - all optical modules in clearest ice

For more on PINGU analysis see T. DeYoung’s talk
\( \nu_\tau \) appearance in PINGU

- Follow same procedure as for DeepCore
  - Denser array \( \Rightarrow \) improved reconstruction and PID
- \( \nu_\tau \) composes larger part of final sample than in DeepCore

Cascade-ID

PINGU

- True \( E_\nu \in [1, 80] \) GeV

\( \nu_e \)
\( \nu_\mu \)
\( \nu_\tau \)

E_\nu (GeV)

PINGU
(livetime: 1 year)

N/\( N_{\nu_e+\nu_\mu} \) (all flavours)
$\nu_\tau$ appearance in PINGU – expected sensitivity

- $5\sigma$ exclusion of no $\nu_\tau$ appearance after 1 month of data
- 10% precision in the $\nu_\tau$ normalization after 6 months
Summary and outlook

- Atmospheric $\nu$ various baselines and energies permit measurement of $\nu_\tau$ appearance

- IceCube-DeepCore should currently be able to statistically measure it with high significance
  - Progress being made towards this measurement
  - Expected 25% precision on normalization with already taken data

- PINGU should further increase sensitivity to $\nu_\tau$ appearance
  - < 10% precision on normalization after 1 year of data
Backup slides
Event display at PINGU

Interaction Type: no interaction

Primaries:
- Type: NuMuBar
  Energy: $1.78 \times 10^1 \text{GeV}$
- Muon
- Type: MuPlus
  Energy: $1.48 \times 10^1 \text{GeV}$
- Cascade
  Type: P0
  Energy: $1.18 \times 10^0 \text{GeV}$

Interaction Type: no interaction

Primaries:
- Type: NuEBar
  Energy: $4.09 \times 10^1 \text{GeV}$
- Cascade
  Type: EPlus
  Energy: $3.03 \times 10^1 \text{GeV}$
Reconstruction resolutions

**coszen Resolutions**

**energy Resolutions**

![Graphs showing coszen and energy resolutions for PINGU, DeepCore, PINGU νμ, and PINGU νe.](image)

- For PINGU, σE/E ~ 20% and σθ ~ 10 - 20 deg.
- Effective Area
- Event Reconstruction
- Physics goals for PINGU
  - Hypothesis: all events are
    - Interaction (CC vs. NC)
  - Calculating PINGU's Sensitivity to the Neutrino Mass Hierarchy
- Trained distribution agrees well with data in DeepCore
- New calibration methods for IceCube, DeepCore and PINGU
- Reduced time for 10% Q (ns)
  - Early hit charge (pe)
  - Reduced time for 10% Q (ns)

**References:**
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**Note:** Preliminary results.
PINGU Particle identification

![Graph showing rate vs. MVA score for different types of events: Cascade-like and Track-like. The graph also shows the distribution of neutrino types: $\nu_e$, $\nu_\mu$, and $\nu_\tau$.](image)