IceCube/DeepCore Results on Neutrino Properties Using Atmospheric Neutrinos

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Outline

● Neutrino mixing (PMNS) matrix & $\nu$ experiments
● Physics motivation:
  ○ Oscillation parameters measurement
  ○ Tau neutrino appearance, PMNS matrix unitarity
● Atmospheric neutrinos
● IceCube/DeepCore
● Analysis:
  ○ Event selections; Systematics
● Results
PMNS matrix & $\nu$ experiments

- KamLAND
  - Reactor LBL
  - $\bar{\nu}_e$ disappearance
- SNO
  - Solar CC/NC Ratio
- Daya Bay, RENO, Double Chooz
  - Reactor SBL
  - $\bar{\nu}_e$ disappearance
- NOvA, T2K
  - $\nu_e$ appearance
- NOvA, T2K
  - $\nu_\mu$ disappearance
- OPERA, Super-K and IceCube-DeepCore
  - $\nu_\tau$ appearance

Based on Parke & Ross-Lonergan
Physics Motivation: What can we learn from atmospheric neutrinos?

- Measure oscillation parameters $|\Delta m_{23}^2|$ and $\sin^2 \theta_{23}$ via $\nu_\mu$ disappearance ($P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 (\Delta m_{31}^2 L/4E)$)
  - To answer whether $\theta_{23}$ is maximal, in the upper or lower octant
  - Important in resolving neutrino mass ordering
- Measure $\nu_\mu \rightarrow \nu_\tau$ appearance, i.e. measure:
  - $\nu_\tau$ normalization = measured $\nu_\tau$ rate / expected $\nu_\tau$ rate (in standard oscillation paradigm)
- Help better constrain PMNS matrix unitarity via $\nu_\tau$ appearance analysis (together with other experiments)
- Other topics (not discussed here):
  - Neutrino mass ordering, Non-standard Interaction, Sterile neutrinos, ...
Unitarity of PMNS matrix means:

\[ U^\dagger U = I \]
\[ UU^\dagger = I \]

i.e. the 12 equations below:

\[ |U_{l1}|^2 + |U_{l2}|^2 + |U_{l3}|^2 = 1 \quad (l = e, \mu, \tau) \]
\[ |U_{ei}|^2 + |U_{\mu i}|^2 + |U_{\tau i}|^2 = 1 \quad (i = 1, 2, 3) \]

\[ |U_{\alpha 1} U_{\beta 1}^* + U_{\alpha 2} U_{\beta 2}^* + U_{\alpha 3} U_{\beta 3}^*|^2 = 0 \quad ((\alpha, \beta) = (e, \mu), (e, \tau), (\mu, \tau)) \]
\[ |U_{ei} U_{ej}^* + U_{\mu i} U_{\mu j}^* + U_{\tau i} U_{\tau j}^*|^2 = 0 \quad ((i, j) = (1, 2), (1, 3), (2, 3)) \]
Current constraints on unitarity:

- $\tau$ sector is the least constrained of PMNS matrix:

Parke & Ross-Lonergan

Deviation from unitarity

All contain $\tau$ elements

Parke & Ross-Lonergan
Why is $\nu_\tau$ appearance important?

- $\tau$ sector is the least constrained part of PMNS matrix
  - $\nu_\tau$ appearance experiments measure $U_{\tau 3}$ and $U_{\mu 3}$
  - So a precision measurement in $\nu_\tau$ appearance can be beneficial. Together with other experiments, it can help constrain the PMNS unitarity much better

- Also for the measurement of $\nu_\tau$ normalization, a deviation from 1 could indicate new physics.
What are atmospheric neutrinos?

1. Production
2. Oscillations
3. Detection

IceCube

$\nu_e, \nu_\mu$

Atmospheric $\mu$

$\nu_e, \nu_\mu, \nu_\tau$
Production of atmospheric $\nu$

1. Production

- Cosmic ray: primarily protons
- Protons collide with air particles:

$$p + N \rightarrow \pi^+ (K^+) + \pi^- (K^-) + \ldots$$

- $\pi/K$ decay & $\mu$ decay (only listing main ones):

$$\begin{align*}
\pi^+ (K^+) &\rightarrow \mu^+ + \nu_\mu \\
\pi^- (K^-) &\rightarrow \mu^- + \bar{\nu}_\mu \\
\mu^+ &\rightarrow e^+ + \nu_e + \bar{\nu}_\mu \\
\mu^- &\rightarrow e^- + \bar{\nu}_e + \nu_\mu
\end{align*}$$

IceCube

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flux model: HAKKM, PhysRevD.92.023004

Intrinsic $\nu_\tau$ negligible
Oscillations of atmospheric $\nu$

- Tau neutrino appearance: almost all from $\nu_{\mu}$
- Muon neutrino disappearance: mainly into $\nu_{\tau}$

$$P(\nu_{\mu} \rightarrow \nu_{\mu}) \approx 1 - \sin^2 2\theta_{23} \sin^2 (\Delta m_{31}^2 \frac{L}{4E})$$

$$P(\nu_{\mu} \rightarrow \nu_{\tau}) \approx \sin^2 2\theta_{23} \sin^2 (\Delta m_{31}^2 \frac{L}{4E})$$

$L \sim D \cos(\theta_{\text{zen}})$

(D: Earth diameter)

Energy

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● **IceCube:**
  ○ 1 km$^3$ ice; at the South Pole, 86 strings $\times$ 60 DOMs
  ○ Sparse part: string horizontal spacing: 125m, DOM vertical spacing: 17m
  ○ Goals: neutrino astronomy and multimessenger astrophysics, cosmic ray physics, dark matter, glaciology
  ○ Energy range: up to few PeV

● **DeepCore:** dense part of IceCube
  ○ 8 strings, DOM vertical spacing: 7m & 10 m + 7 standard strings (17m)
  ○ Goals: atmospheric neutrino oscillations, WIMP annihilations, galactic supernova neutrinos, and point sources of neutrinos
  ○ Energy range: 5 - 100 GeV
Detection of atmospheric $\nu$

- Optical sensors in IceCube detect Cherenkov light emitted by secondary particles of $\nu$ interaction.

- Two event topologies:
  - Cascade-like (events without visible $\mu$ track; most of $\nu_\tau$ events end up here)
  - Track-like (mainly $\nu_\mu$ charged-current events that leave a visible $\mu$ track)
Analysis

- Reconstruct the incoming $\nu$ based on the light observed by optical modules
  - Bin events (e.g. a 3-d histogram: energy, direction, topology)
- Compare how different the observed histogram is from simulation:
  Get the best agreement (i.e. maximize binned likelihood) by varying the physics parameter(s) of interest (along with nuisance parameters)
- Fit statistic $\chi^2$ takes into account the MC statistical uncertainty as well as systematic uncertainties.

$$
\chi^2 = \sum_{i \in \text{bins}} \frac{(n_{i}^{\text{exp}} - n_{i}^{\text{data}})^2}{(\sigma_{i}^{\text{exp}})^2 + (\sigma_{i}^{\text{data}})^2} + \sum_{j \in \text{syst}} \frac{(s_{j} - \hat{s}_{j})^2}{\tilde{\sigma}_{s_{j}}^2}
$$
For the $\nu_\tau$ appearance analysis, it is natural for IceCube to measure both CC and NC events. The expected $\nu_\tau$ (CC+NC) events in two analyses are: 1.3k and 2.5k, respectively. Compare with other $\nu_\tau$ experiments: OPERA: 10 CC events in 5 yr, Super-K: 338 CC events in 15 yr.

### Event selections:

**Analysis 1: lower-statistics, lower background, higher-purity**
- Optimized for $\nu_\mu$ disappearance analysis
- Atmospheric muon background: data-driven template estimation
- 41k events*/3 years
- Used in the muon disappearance result: PhysRevLett.120.071801

**Analysis 2: higher-statistics, higher background, lower purity**
- Optimized for $\nu_\tau$ appearance analysis
- Atmospheric muon background: MC simulation
- 62k events*/3 years
1. Production:
   - spectral index, $\nu_e/\nu_\mu$ ratio, $\nu$/anti-$\nu$ flux ratio*, up/horizontal flux ratio*

2. Oscillation:
   - $\theta_{23}$, $\Delta m_{31}$ (physics parameters for numu analysis, but systematics for nutau analysis)
   - $\theta_{13}$

3. Detection:
   - Neutrino interaction: Axial mass QE and RES (from GENIE)
   - DOM: DOM efficiency
   - Ice: hole ice (3 parameters), bulk ice scattering & absorption

4. Normalization: background $\mu$ norm., NC norm., overall norm.

* Barr et al. PRD74, 094009

Hole ice: refrozen column of ice in which the DOM strings are embedded, it contains residual air bubbles. One of the most important systematics
Results
L/E distributions ($\nu_\mu$ disappearance analysis)

- Good data/MC agreement for both (Top: Analysis 2, Down: Analysis 1)
Atmospheric Oscillation parameters

- **Analysis 1** (primary result, PRL2018): Prefer maximal mixing:
  \[ \Delta m_{23}^2 = 2.31^{+0.11}_{-0.13} \times 10^{-3} \text{eV}^2 \text{ (NO)} \]
  \[ \sin^2 (\theta_{23}) = 0.51^{+0.07}_{-0.09} \]
  (NO: normal mass ordering)

- **Analysis 2**: 90% contour compatible with Analysis 1
  Best fit: non-maximal mixing:
  \[ \Delta m_{23}^2 = 2.55^{+0.12}_{-0.11} \times 10^{-3} \text{eV}^2 \text{ (NO)} \]
  \[ \sin^2 (\theta_{23}) = 0.58^{+0.04}_{-0.13} \]
  Agrees with Analysis 1 within 1σ statistical fluctuation using the same analysis method.
  Shift comes from the considerations of correlations among detector uncertainties and bulk ice systematics.
L/E distributions (ντ appearance analysis)

ντ Analysis 1

Analysis 2

Good data/MC agreement for both

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ντ analysis results:

- ντ CC+NC norm. = 1 in the standard oscillation picture
- Analysis 1
  - CC+NC: 0.59 ± 0.31 - 0.25 (1σ)
- Analysis 2 (Primary result):
  - CC+NC: 0.73 ± 0.31 - 0.24 (1σ)
- Both consistent with standard oscillations
  - Previous experiments: Super-K: 1.47 ± 0.32, OPERA: 1.1 ± 0.5 – 0.4
Summary/Outlook

- IceCube/DeepCore results on neutrino oscillations:
  - $\nu_\mu$ disappearance result:
    - Consistent with maximal mixing
  - $\nu_\tau$ appearance result:
    - $\nu_\tau$ (CC+NC) norm. = $0.73 + 0.31 - 0.24$, precision comparable to world's best result
    - Consistent with the standard 3-flavor oscillation paradigm
- More years of data available
- Expecting improvement on event reconstruction, systematics uncertainties calculation
Thanks!
Backup
Neutrino oscillations

- Flavor eigenstates $|\nu_l\rangle (l = e, \mu, \tau)$ are superpositions of mass eigenstates $|\nu_i\rangle (i = 1, 2, 3)$, PMNS matrix describes the mixing.
  - Mass eigenstates travel with different speeds
  - One flavor may change to another after travelling some distance ($L$)

- Oscillation probability is:

$$P_{\alpha \rightarrow \beta} = \delta_{\alpha \beta} - 4 \sum_{i>j} \mathrm{Re}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2 \left( \frac{\Delta m_{ij}^2 L}{4E} \right)$$

$$+ 2 \sum_{i>j} \mathrm{Im}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin \left( \frac{\Delta m_{ij}^2 L}{2E} \right),$$

where $\Delta m_{ij}^2 = m_i^2 - m_j^2$

- The phase responsible for the oscillation is:

$$\frac{\Delta m^2 c^3 L}{4\hbar E} \approx 1.27 \times \frac{\Delta m^2}{\text{eV}^2} \frac{L}{\text{km}} \frac{E}{\text{GeV}}$$
Neutrino oscillations

- Assume standard 3-flavor oscillation:
  - PMNS matrix can be parametrized by three mixing angles and CP violation term $\theta_{23}, \theta_{13}, \theta_{12}, \delta$:

\[
U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

where $c_{ij} = \cos \theta_{ij}$, $s_{ij} = \sin \theta_{ij}$

- PMNS matrix is unitary under the standard 3-flavor oscillation theory, i.e.:

\[
\begin{aligned}
|U_{ll}|^2 + |U_{l\mu}|^2 + |U_{l\tau}|^2 &= 1 (l = e, \mu, \tau) \\
|U_{ei}|^2 + |U_{e\mu}|^2 + |U_{e\tau}|^2 &= 1 (i = 1, 2, 3) \\
|U_{\alpha\beta_1} U_{\alpha\beta_2}^* + U_{\alpha\beta_3} U_{\beta_3}^*|^2 &= 0 ((\alpha, \beta) = (e, \mu), (e, \tau), (\mu, \tau)) \\
|U_{ei} U_{e\mu}^* + U_{\mu\mu} U_{\mu\mu}^* + U_{\tau\tau} U_{\tau\tau}^*|^2 &= 0 ((i, j) = (1, 2), (1, 3), (2, 3))
\end{aligned}
\]
IceCube/DeepCore $\nu_\tau$ results:

- CC-only result (1$\sigma$):
  - Analysis 1: $0.43 + 0.35 - 0.31$
  - Analysis 2 (Primary result): $0.566 + 0.356 - 0.303$
Previous $\nu_{\tau}$ appearance experiments

- **Super-K 2017 result:**
  - significance $4.6 \sigma$
  - $\nu_{\tau}$ CC norm: $1.47 \pm 0.32$ (68%)
  - $338.1 \pm 72.7$ CC events in 14.5 yr

- **OPERA 2018 result:**
  - significance $6.1 \sigma$
  - $\nu_{\tau}$ CC norm: $1.1 + 0.5 - 0.4$ (68%)
  - 10 CC events in 5 yr (background $2.0 \pm 0.4$)
# PMNS matrix & ν expriments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Measured quantity with unitarity</th>
<th>Without unitarity</th>
<th>Normalisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor SBL ($\bar{\nu}_e \rightarrow \bar{\nu}_e$)</td>
<td>$4</td>
<td>U_{e3}</td>
<td>^2 (1-</td>
</tr>
<tr>
<td>Reactor LBL ($\bar{\nu}_e \rightarrow \bar{\nu}_e$)</td>
<td>$4</td>
<td>U_{e1}</td>
<td>^2</td>
</tr>
<tr>
<td>SNO ($\phi_{CC}/\phi_{NC}$ Ratio)</td>
<td>$</td>
<td>U_{e2}</td>
<td>^2 = \cos^2 \theta_{13} \sin^2 \theta_{12}$</td>
</tr>
<tr>
<td>SK/T2K/MINOS ($\nu_\mu \rightarrow \nu_\mu$)</td>
<td>$4</td>
<td>U_{\mu_3}</td>
<td>^2 (1-</td>
</tr>
<tr>
<td>T2K/MINOS ($\nu_\mu \rightarrow \nu_e$)</td>
<td>$4</td>
<td>U_{e3}</td>
<td>^2</td>
</tr>
<tr>
<td>SK/OPERA ($\nu_\mu \rightarrow \nu_\tau$)</td>
<td>$4</td>
<td>U_{\mu_3}</td>
<td>^2</td>
</tr>
</tbody>
</table>

**TABLE I:** Example experiments and the leading order functions of $U_{PMNS}$ matrix elements they measure, in both the unitary and non-unitary case. The third column shows the normalisation that can be bound if the experimental measurements of the fluxes and backgrounds are known to a high enough degree.
L/E distributions (PRL 2018)

- Good data/MC agreement

PhysRevLett.120.071801
Oscillation parameters (PRL 2018)

- Best fit values:
  \[ \Delta m_{23}^2 = 2.31^{+0.11}_{-0.13} \times 10^{-3} \text{eV}^2 (\text{NO}) \]
  \[ \sin^2 \theta_{23} = 0.51^{+0.07}_{-0.09} (\text{NO}) \]

- Result prefers maximal mixing

PhysRevLett.120.071801