IceCube/DeepCore Results on Neutrino Properties Using Atmospheric Neutrinos

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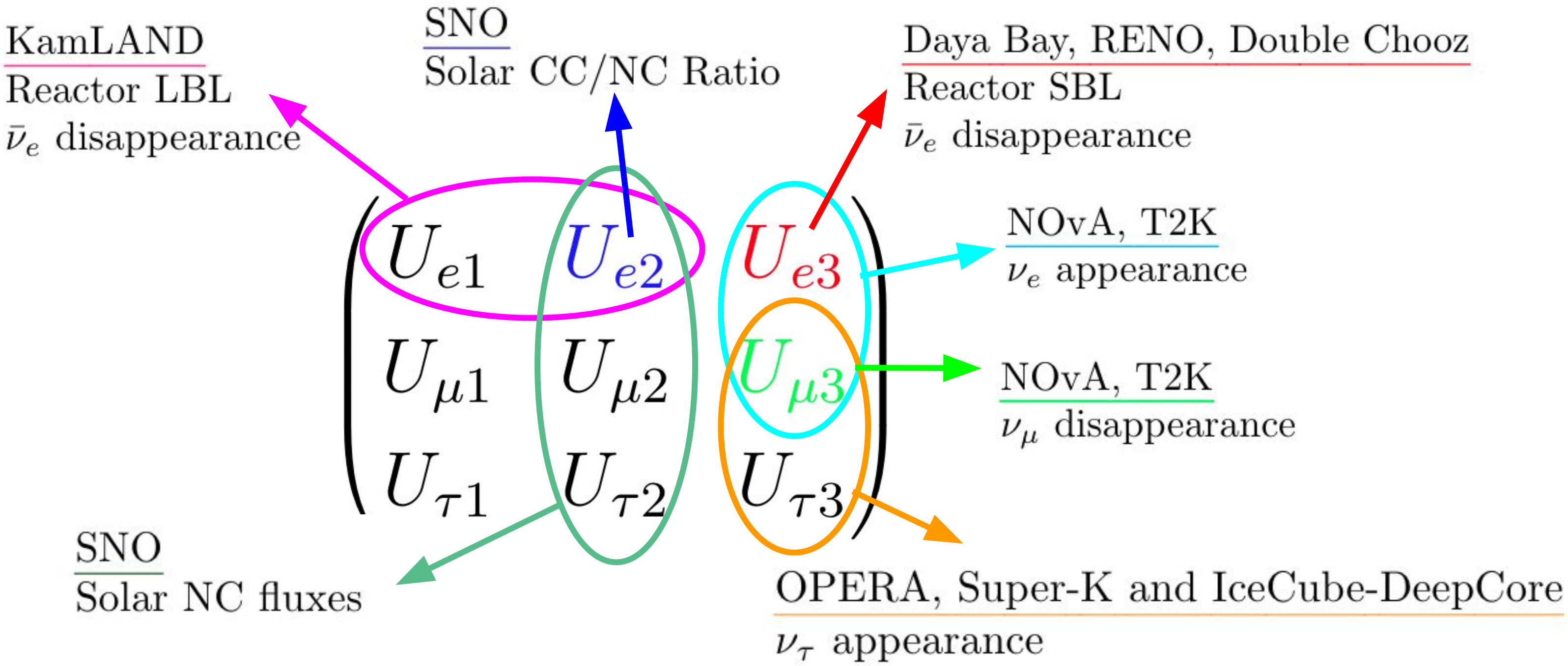
Outline

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

PMNS matrix & ν experiments



KamLAND
Reactor LBL
$\bar{\nu}_e$ disappearance

SNO
Solar CC/NC Ratio

Daya Bay, RENO, Double Chooz
Reactor SBL
$\bar{\nu}_e$ disappearance

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

NOvA, T2K
ν_e appearance

NOvA, T2K
ν_μ disappearance

SNO
Solar NC fluxes

OPERA, Super-K and IceCube-DeepCore
ν_τ appearance

Based on Parke & Ross-Lonergan
Phys. Rev. D 93, 113009 (2016)

Physics Motivation: What can we learn from atmospheric neutrinos?

- Measure oscillation parameters $|\Delta m^2_{23}|$ and $\sin^2\theta_{23}$ via ν_μ disappearance ($P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2(\Delta m^2_{31} \frac{L}{4E})$)
  - To answer whether θ_{23} is maximal, in the upper or lower octant
  - Important in resolving neutrino mass ordering
- Measure $\nu_\mu \to \nu_\tau$ appearance, i.e. measure:

$$\nu_\tau \text{ normalization} = \frac{\text{measured } \nu_\tau \text{ rate}}{\text{expected } \nu_\tau \text{ rate (in standard oscillation paradigm)}}$$

- Help better constrain PMNS matrix unitarity via ν_τ appearance analysis (together with other experiments)
- Other topics (not discussed here):
  - Neutrino mass ordering, Non-standard Interaction, Sterile neutrinos, ...

Unitarity of PMNS matrix:

- Unitarity of PMNS matrix means:

$$U^\dagger U = I \qquad UU^\dagger = I \qquad U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

i.e. the 12 equations below:

$$|U_{l1}|^2 + |U_{l2}|^2 + |U_{l3}|^2 = 1 \; (l = e, \mu, \tau)$$

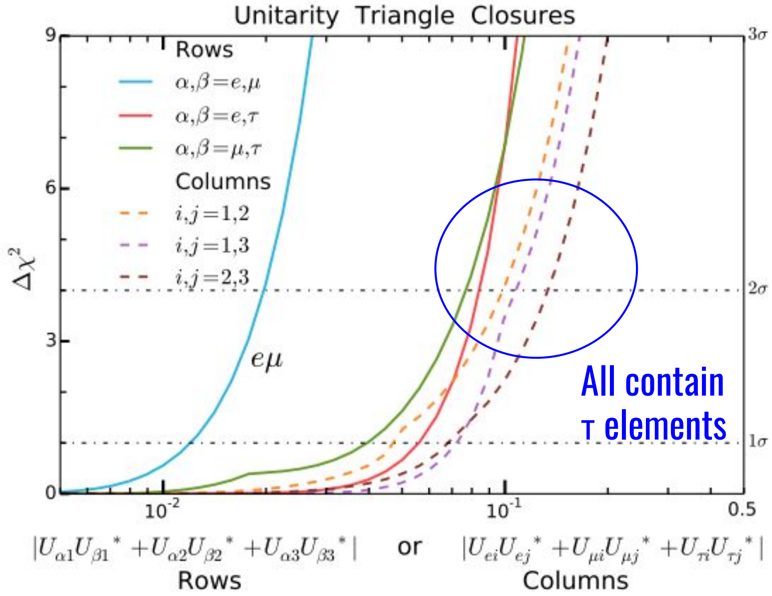
$$|U_{ei}|^2 + |U_{\mu i}|^2 + |U_{\tau i}|^2 = 1 \; (i = 1, 2, 3)$$

$$|U_{\alpha 1}U^*_{\beta 1} + U_{\alpha 2}U^*_{\beta 2} + U_{\alpha 3}U^*_{\beta 3}|^2 = 0 \; ((\alpha, \beta) = (e, \mu), (e, \tau), (\mu, \tau))$$

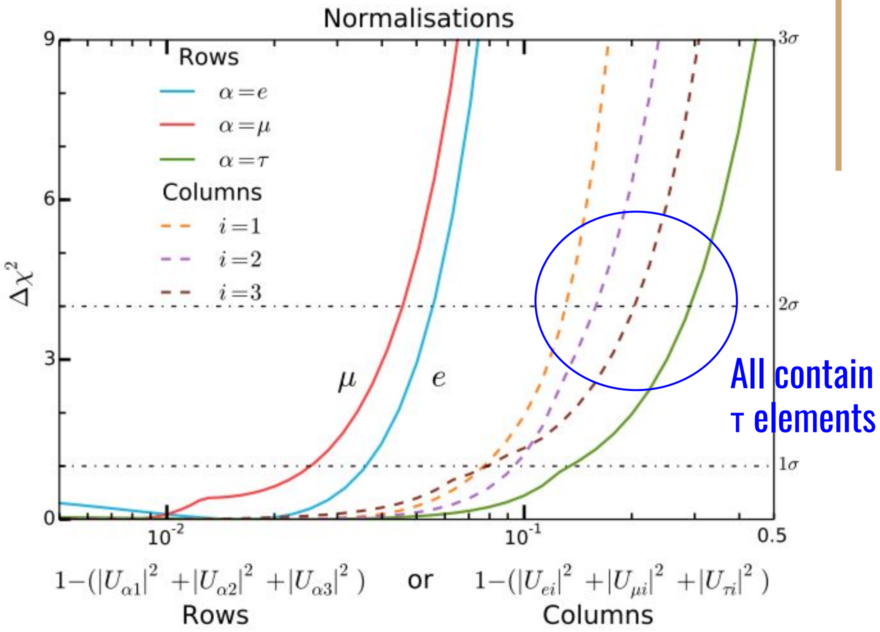
$$|U_{ei}U^*_{ej} + U_{\mu i}U^*_{\mu j} + U_{\tau i}U^*_{\tau j}|^2 = 0 \; ((i, j) = (1, 2), (1, 3), (2, 3))$$

Current constraints on unitarity:

- τ sector is the least constrained of PMNS matrix:



All contain τ elements



All contain τ elements

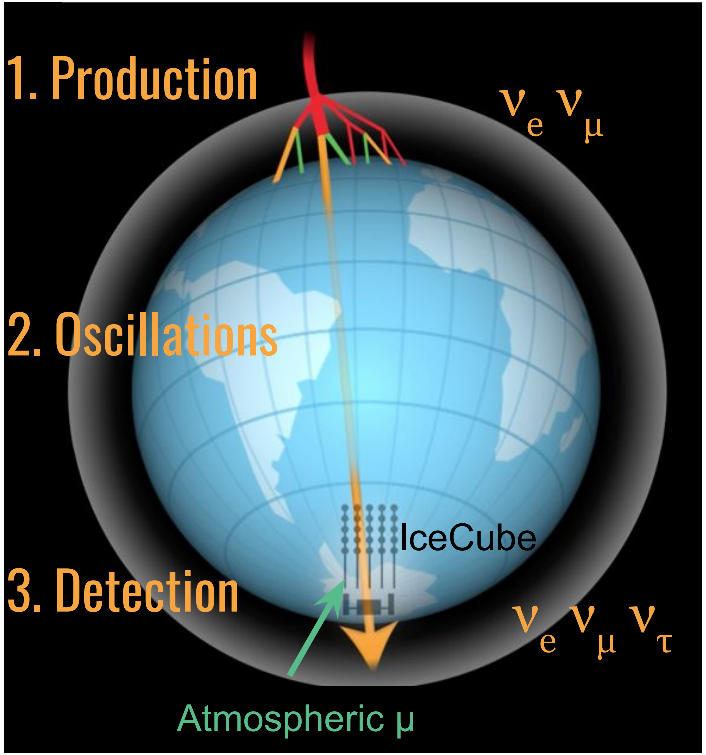
Deviation from unitarity

Parke & Ross-Lonergan
Phys. Rev. D 93, 113009 (2016)

Why is ν_τ appearance important?

- τ sector is the least constrained part of PMNS matrix
  ν_τ appearance experiments measure $U_{\tau 3}$ and $U_{\mu 3}$
    - So a precision measurement in ν_τ appearance can be beneficial. Together with other experiments, it can help constrain the PMNS unitarity much better
- Also for the measurement of ν_τ normalization, a deviation from 1 could indicate new physics.

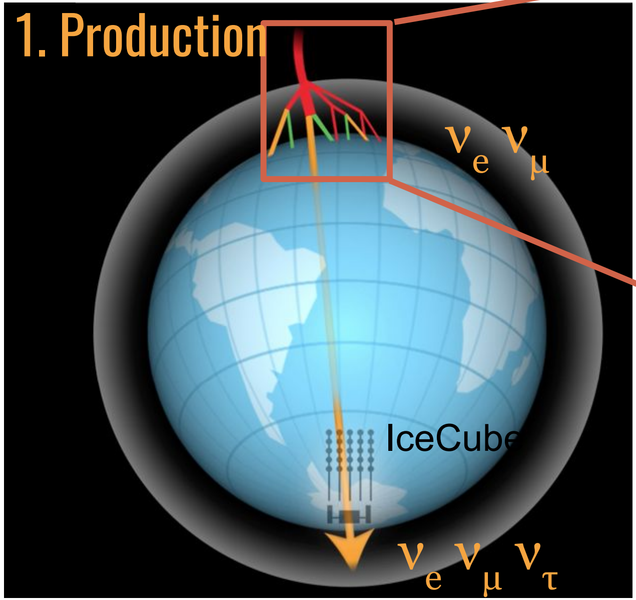
What are atmospheric neutrinos?

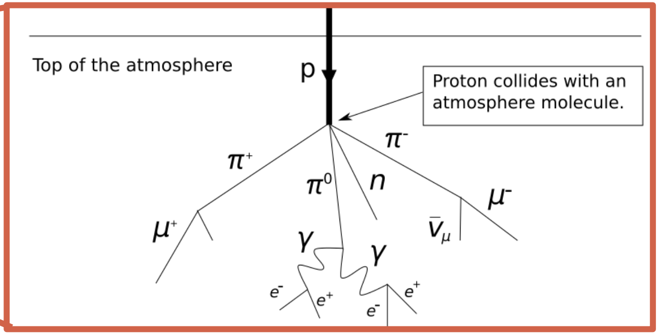


PennState

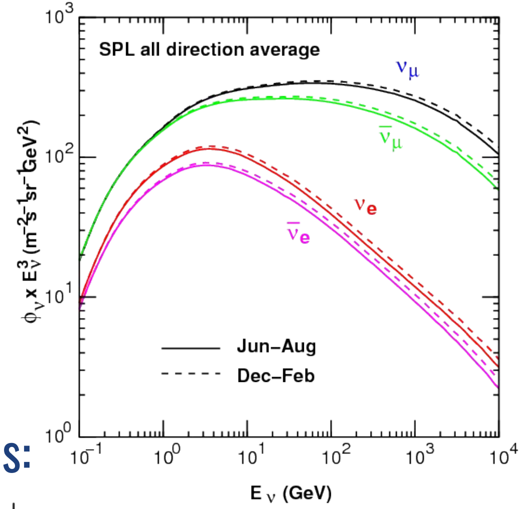
Feifei Huang, May 31 2018, CIPANP

Production of atmospheric ν





flux model: HAKKM, PhysRevD.92.023004



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

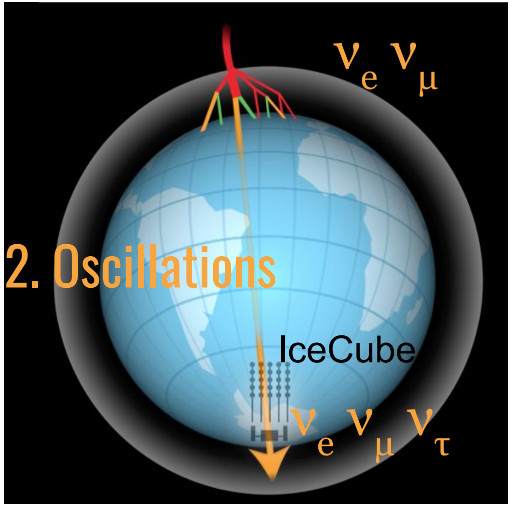
$$p + N \rightarrow \pi^+(K^+) + \pi^-(K^-) + \ \ldots$$

- π/K decay & μ decay (only listing main ones):

$$\left\{\begin{array}{l} \pi^+(K^+) \rightarrow \mu^+ + \nu_\mu \\ \pi^-(K^-) \rightarrow \mu^- + \bar{\nu}_\mu \\ \mu^+ \ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \\ \mu^- \ \rightarrow e^- + \bar{\nu}_e + \nu_\mu \end{array}\right.$$

Intrinsic ν_τ negligible

Oscillations of atmospheric ν



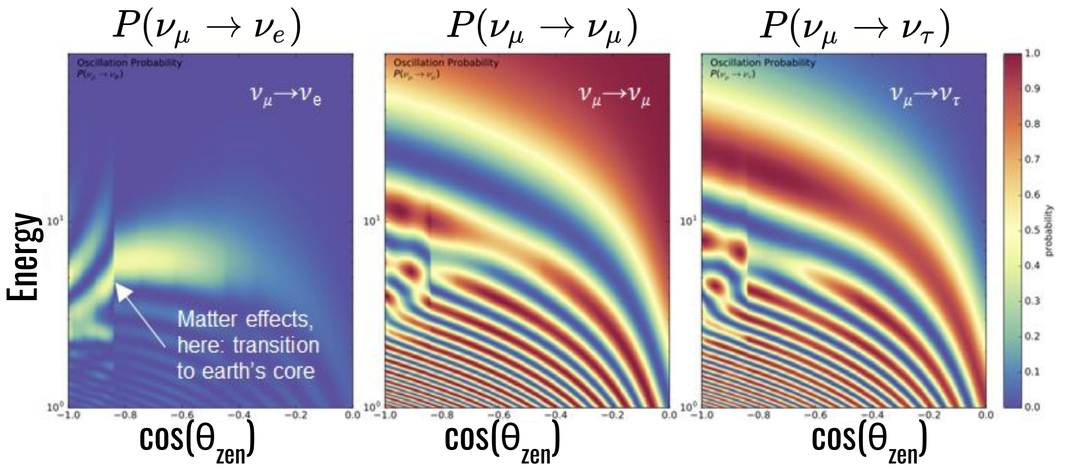
- Tau neutrino appearance: almost all from ν_μ
- Muon neutrino disappearance: mainly into ν_τ

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\Delta m^2_{31} \frac{L}{4E}\right)$$

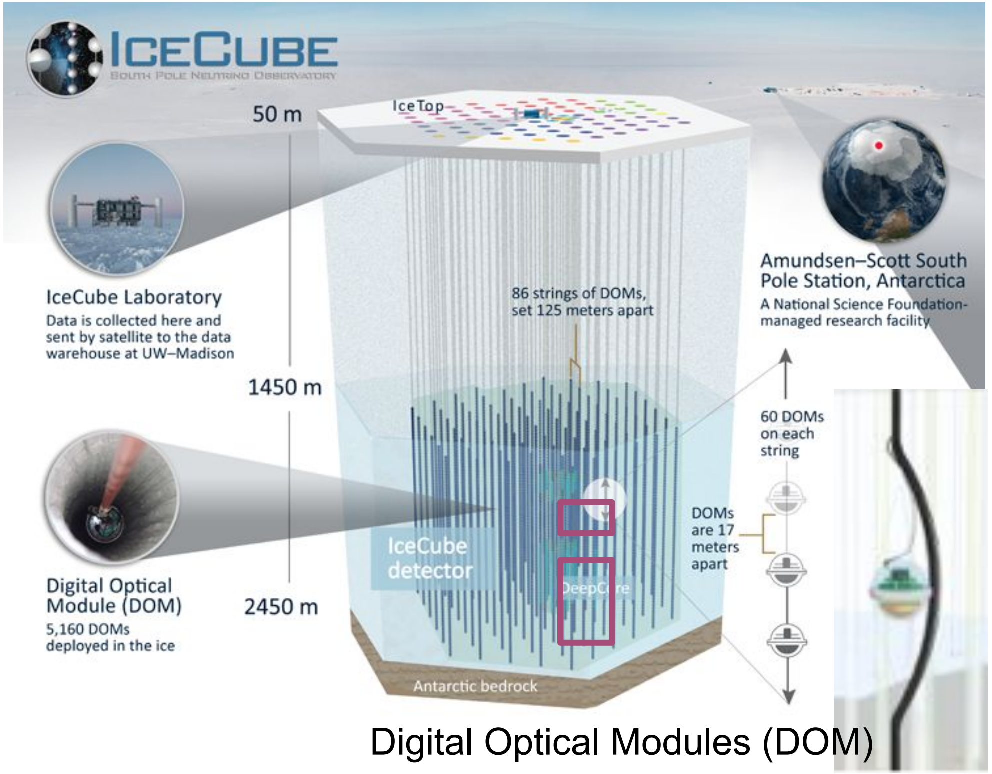
$$P(\nu_\mu \to \nu_\tau) \approx \sin^2 2\theta_{23} \sin^2\left(\Delta m^2_{31} \frac{L}{4E}\right)$$

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

(D: Earth diameter)



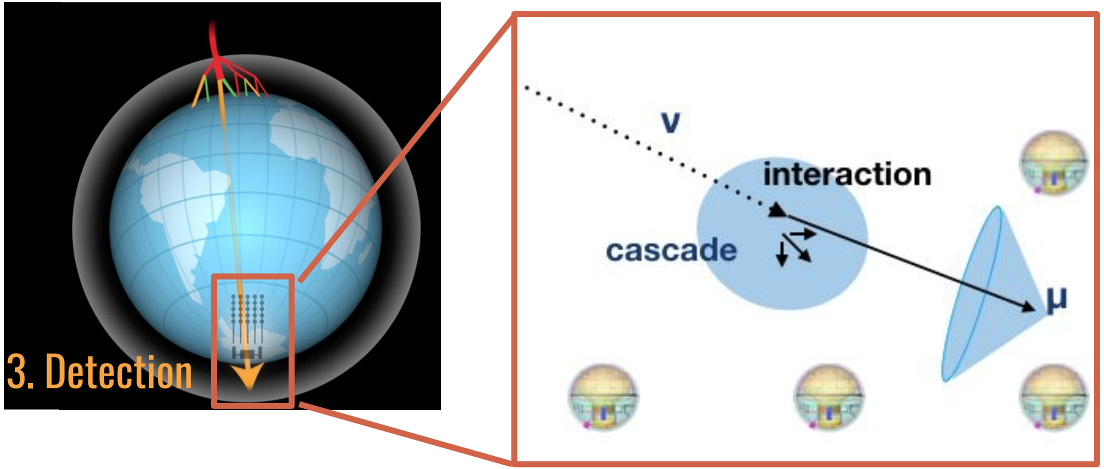
IceCube/DeepCore



Digital Optical Modules (DOM)

- IceCube:
  - 1 km^3 ice; at the South Pole, 86 strings × 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 ν



- Optical sensors in IceCube detect Cherenkov light emitted by secondary particles of ν interaction

- Two event topologies:
  - Cascade-like (events without visible μ track; most of ν_τ events end up here)
  - Track-like (mainly ν_μ charged-current events that leave a visible μ track)

Analysis

- Reconstruct the incoming ν 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 χ^2 takes into account the MC statistical uncertainty as well as systematic uncertainties.

$$\chi^2 = \sum_{i \in bins} \frac{(n_i^{exp} - n_i^{data})^2}{(\sigma_i^{exp})^2 + (\sigma_i^{data})^2} + \sum_{j \in syst} \frac{(s_j - \hat{s}_j)^2}{\hat{\sigma}_{s_j}^2}$$

Event selections:

- Analysis 1: lower-statistics, lower background, higher-purity
    - Optimized for ν_μ 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 ν_τ appearance analysis
    - Atmospheric muon background: MC simulation
    - 62k events*/ 3 years

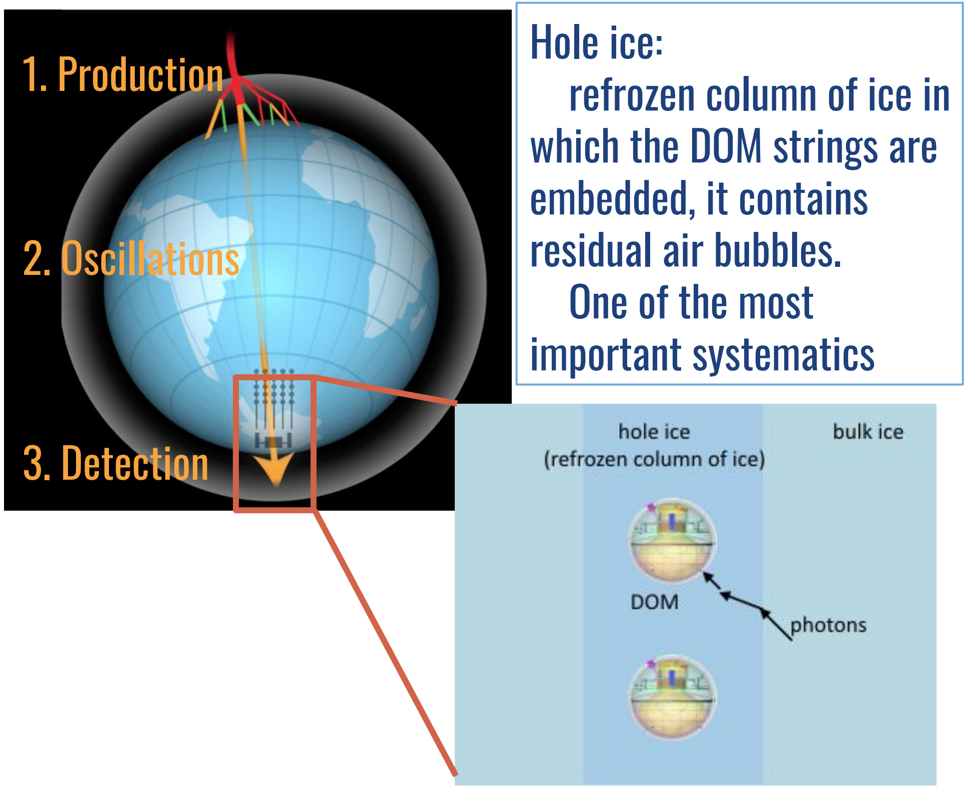
* For the ν_τ appearance analysis, it is natural for IceCube to measure both CC and NC events
The expected ν_τ (CC+NC) events in two analyses are: 1.3k and 2.5k, respectively

Compare with other ν_τ experiments:

OPERA: 10 CC events in 5 yr Super-K: 338 CC events in 15 yr

Systematics

Hole ice:
refrozen column of ice in which the DOM strings are embedded, it contains residual air bubbles.
One of the most important systematics

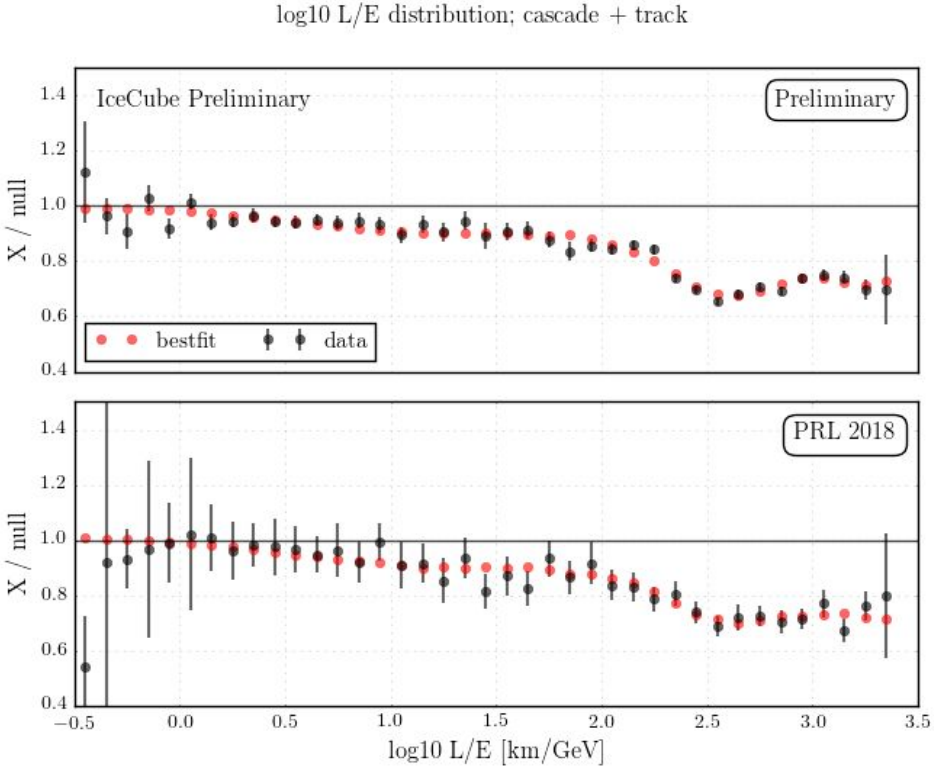


1. **Production:**
   - spectral index, ν_e/ν_μ ratio, ν/anti-ν flux ratio*, up/horizontal flux ratio*
2. **Oscillation:**
   - θ_{23} ,Δm_{31} (physics parameters for numu analysis, but systematics for nutau analysis)
   - θ_{13}
3. **Detection:**
   - Neutrino interaction: : Axial mass QE and RES (from GENIE)
   - DOM: DOM efficiency
   - Ice: hole ice (3 parameters), bulk ice scattering & absorption
4. **Normalization**: background μ norm., NC norm., overall norm.

* Barr et al. PRD74, 094009

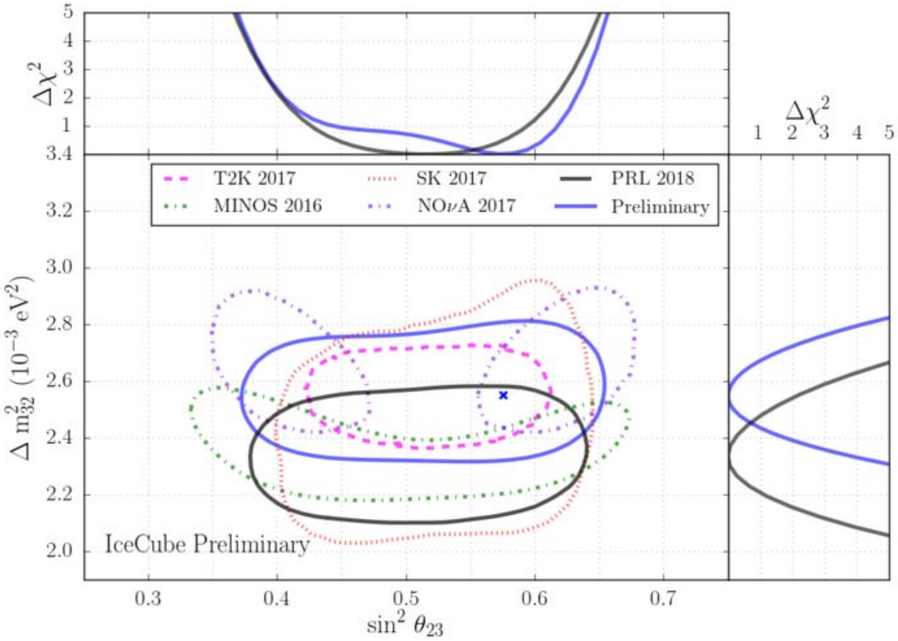
Results

L/E distributions(ν_μ disappearance analysis)



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

Atmospheric Oscillation parameters



- Analysis 1 (primary result, PRL2018):
  Prefers maximal mixing:

$$\Delta m^2_{23} = 2.31^{+0.11}_{-0.13} \times 10^{-3}\mathrm{eV}^2(\mathrm{NO})$$

$$\sin^2(\theta_{23}) = 0.51^{+0.07}_{-0.09}$$

  (NO: normal mass ordering)

- Analysis 2:
  90% contour compatible with Analysis 1
  Best fit: non-maximal mixing:

$$\Delta m^2_{23} = 2.55^{+0.12}_{-0.11} \times 10^{-3}\mathrm{eV}^2(\mathrm{NO})$$

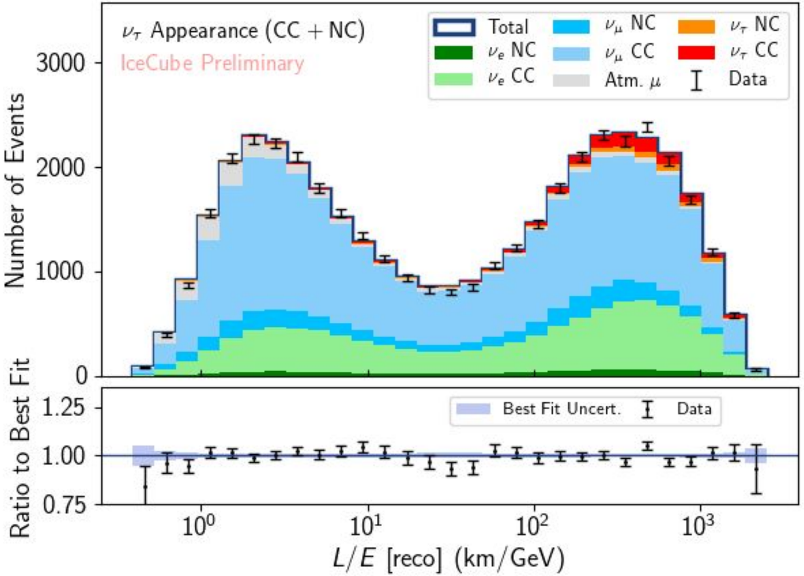
$$\sin^2(\theta_{23}) = 0.58^{+0.04}_{-0.13}$$

Agrees with Analysis 1 within 1σ statistical fluctuation using the same analysis method.

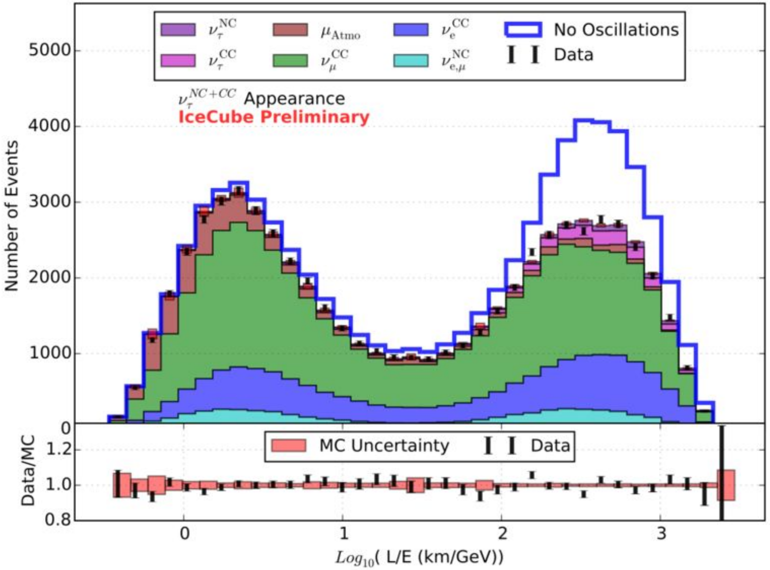
Shift comes from the considerations of correlations among detector uncertainties and bulk ice systematics.

L/E distributions(ν_τ appearance analysis)

ν_τ Analysis 1



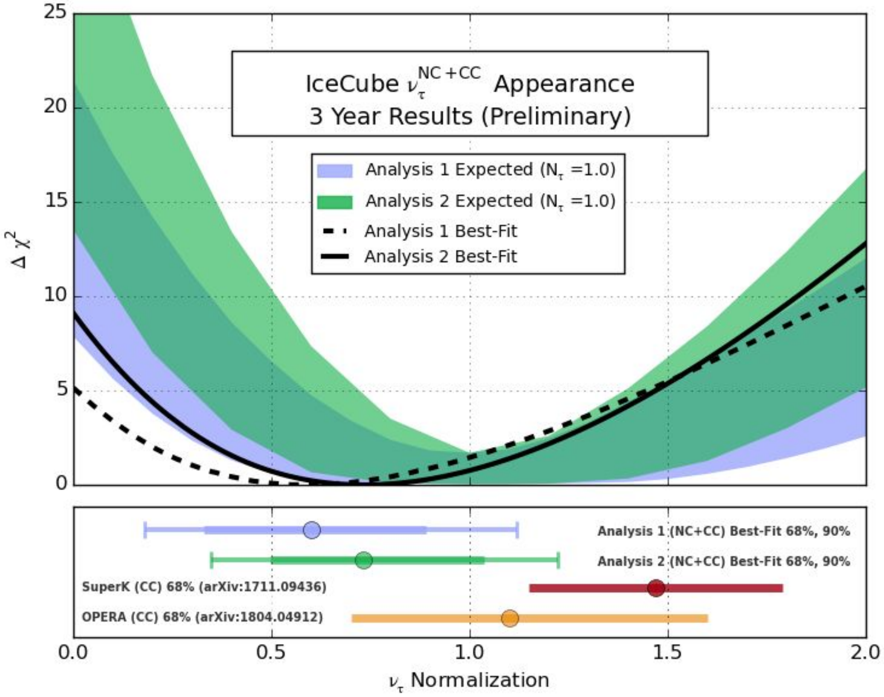
ν_τ Analysis 2



Good data/MC agreement for both

ν_τ analysis results:

- ν_τ 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:
  - ν_μ disappearance result:
    - Consistent with maximal mixing
  - ν_τ appearance result:
    - ν_τ (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)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Oscillation probability is:

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$
$$+ 2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin\left(\frac{\Delta m^2_{ij} L}{2E}\right),$$

where $\Delta m^2_{ij} = m^2_i - m^2_j$

- The phase responsible for the oscillation is:

$$\boxed{\frac{\Delta m^2\, c^3\, L}{4\hbar E} \approx 1.27 \times \frac{\Delta m^2}{\mathrm{eV}^2} \frac{L}{\mathrm{km}} \frac{\mathrm{GeV}}{E}}$$

Neutrino oscillations

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

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

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

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

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$|U_{l1}|^2 + |U_{l2}|^2 + |U_{l3}|^2 = 1 \; (l = e, \mu, \tau)$$

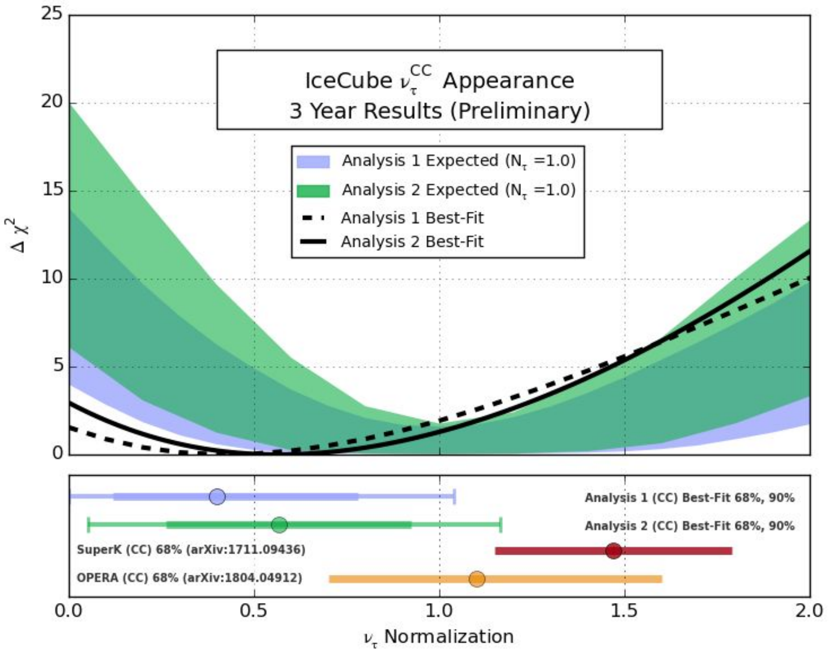
$$|U_{ei}|^2 + |U_{\mu i}|^2 + |U_{\tau i}|^2 = 1 \; (i = 1, 2, 3)$$

$$|U_{\alpha 1}U_{\beta 1}^* + U_{\alpha 2}U_{\beta 2}^* + U_{\alpha 3}U_{\beta 3}^*|^2 = 0 \; ((\alpha, \beta) = (e, \mu), (e, \tau), (\mu, \tau))$$

$$|U_{ei}U_{ej}^* + U_{\mu i}U_{\mu j}^* + U_{\tau i}U_{\tau j}^*|^2 = 0 \; ((i, j) = (1, 2), (1, 3), (2, 3))$$

IceCube/DeepCore ν_τ results:

- CC-only result (1σ):
    - Analysis 1: 0.43 + 0.35 - 0.31
    - Analysis 2 (Primary result): 0.566 + 0.356 - 0.303

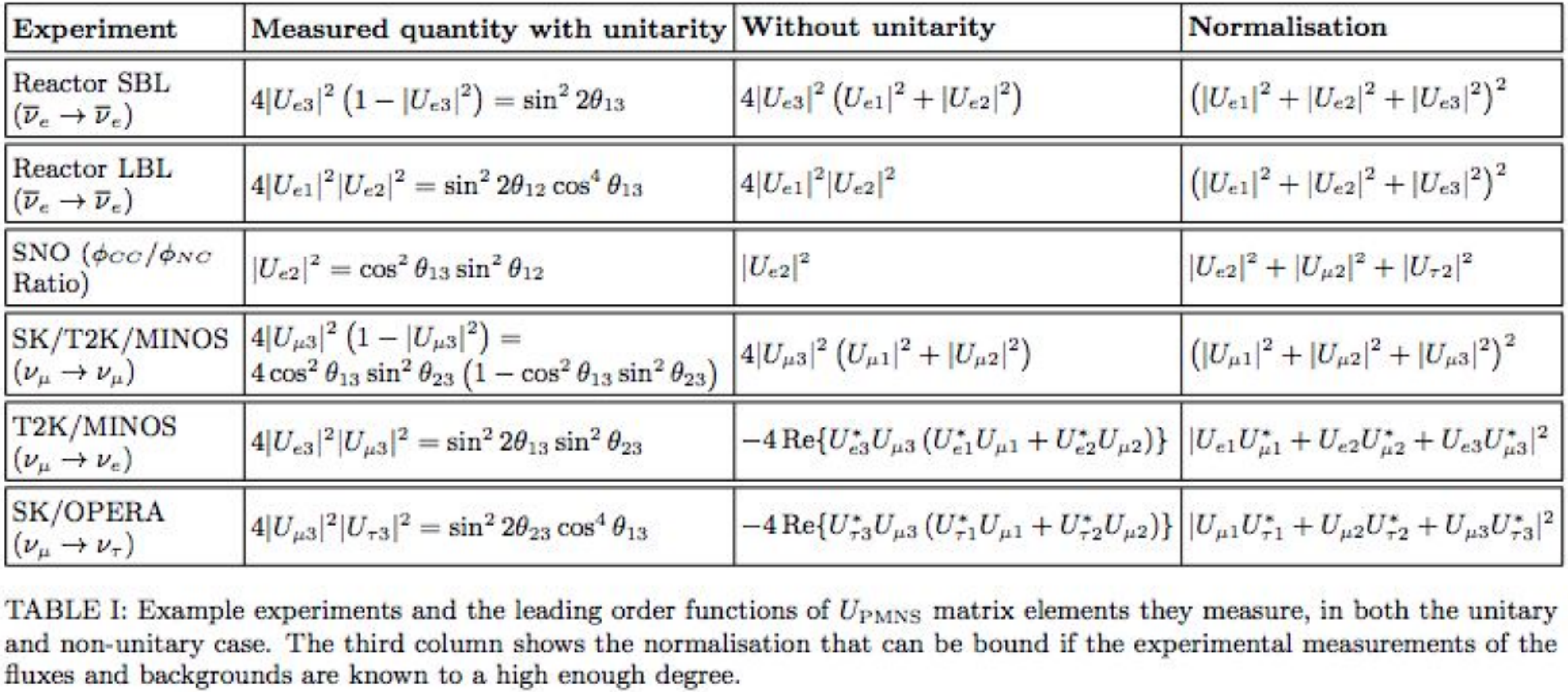


Previous ν_τ appearance experiments

- Super-K 2017 result:
    - significance 4.6 σ
    - ν_τ CC norm: 1.47 ± 0.32 (68%)
    - 338.1 ± 72.7 CC events in 14.5 yr

- OPERA 2018 result:
    - significance 6.1 σ
    - ν_τ CC norm: 1.1 + 0.5 – 0.4 (68%)
    - 10 CC events in 5 yr (background 2.0 +/- 0.4)

PMNS matrix & ν expriments

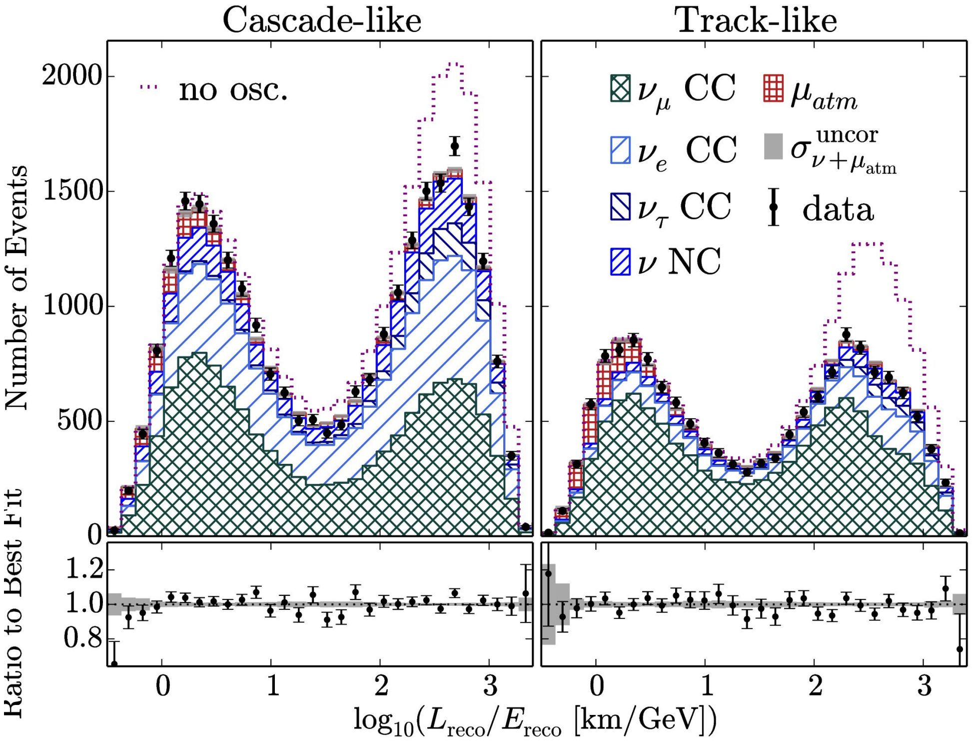


Experiment	Measured quantity with unitarity	Without unitarity	Normalisation
Reactor SBL $(\overline{\nu}_e \to \overline{\nu}_e)$	$4\lvert U_{e3}\rvert^2\left(1-\lvert U_{e3}\rvert^2\right)=\sin^2 2\theta_{13}$	$4\lvert U_{e3}\rvert^2\left(\lvert U_{e1}\rvert^2+\lvert U_{e2}\rvert^2\right)$	$\left(\lvert U_{e1}\rvert^2+\lvert U_{e2}\rvert^2+\lvert U_{e3}\rvert^2\right)^2$
Reactor LBL $(\overline{\nu}_e \to \overline{\nu}_e)$	$4\lvert U_{e1}\rvert^2\lvert U_{e2}\rvert^2=\sin^2 2\theta_{12}\cos^4\theta_{13}$	$4\lvert U_{e1}\rvert^2\lvert U_{e2}\rvert^2$	$\left(\lvert U_{e1}\rvert^2+\lvert U_{e2}\rvert^2+\lvert U_{e3}\rvert^2\right)^2$
SNO $(\phi_{CC}/\phi_{NC}$ Ratio)	$\lvert U_{e2}\rvert^2=\cos^2\theta_{13}\sin^2\theta_{12}$	$\lvert U_{e2}\rvert^2$	$\lvert U_{e2}\rvert^2+\lvert U_{\mu 2}\rvert^2+\lvert U_{\tau 2}\rvert^2$
SK/T2K/MINOS $(\nu_\mu \to \nu_\mu)$	$4\lvert U_{\mu 3}\rvert^2\left(1-\lvert U_{\mu 3}\rvert^2\right)=$ $4\cos^2\theta_{13}\sin^2\theta_{23}\left(1-\cos^2\theta_{13}\sin^2\theta_{23}\right)$	$4\lvert U_{\mu 3}\rvert^2\left(\lvert U_{\mu 1}\rvert^2+\lvert U_{\mu 2}\rvert^2\right)$	$\left(\lvert U_{\mu 1}\rvert^2+\lvert U_{\mu 2}\rvert^2+\lvert U_{\mu 3}\rvert^2\right)^2$
T2K/MINOS $(\nu_\mu \to \nu_e)$	$4\lvert U_{e3}\rvert^2\lvert U_{\mu 3}\rvert^2=\sin^2 2\theta_{13}\sin^2\theta_{23}$	$-4\,\mathrm{Re}\{U_{e3}^* U_{\mu 3}\left(U_{e1}^* U_{\mu 1}+U_{e2}^* U_{\mu 2}\right)\}$	$\lvert U_{e1}U_{\mu 1}^*+U_{e2}U_{\mu 2}^*+U_{e3}U_{\mu 3}^*\rvert^2$
SK/OPERA $(\nu_\mu \to \nu_\tau)$	$4\lvert U_{\mu 3}\rvert^2\lvert U_{\tau 3}\rvert^2=\sin^2 2\theta_{23}\cos^4\theta_{13}$	$-4\,\mathrm{Re}\{U_{\tau 3}^* U_{\mu 3}\left(U_{\tau 1}^* U_{\mu 1}+U_{\tau 2}^* U_{\mu 2}\right)\}$	$\lvert U_{\mu 1}U_{\tau 1}^*+U_{\mu 2}U_{\tau 2}^*+U_{\mu 3}U_{\tau 3}^*\rvert^2$

TABLE I: Example experiments and the leading order functions of $U_{\rm PMNS}$ 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.

Parke & Ross-Lonergan
Phys. Rev. D 93, 113009 (2016)

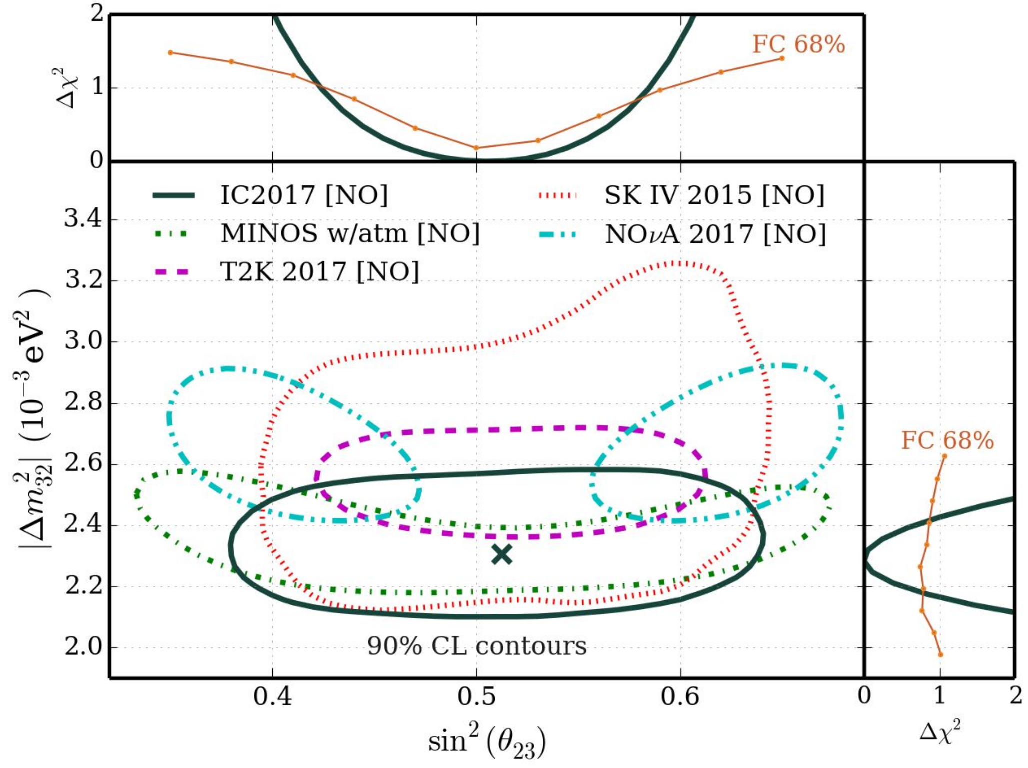
L/E distributions (PRL 2018)



- Good data/MC agreement

PhysRevLett.120.071801

Oscillation parameters (PRL 2018)



- Best fit values:

$$\Delta m^2_{23} = 2.31^{+0.11}_{-0.13}$$
$$\times\, 10^{-3}\mathrm{eV}^2\,(\mathrm{NO})$$
$$\sin^2\theta_{23} = 0.51^{+0.07}_{-0.09}\,(\mathrm{NO})$$

- Result prefers maximal mixing

PhysRevLett.120.071801