Latest Measurements of Atmospheric Neutrino Oscillation Parameters With IceCube-DeepCore

Elim Cheung for the IceCube Collaboration

Introduction

PRL2018 [1] and Preliminary are two independent analyses. Both
- measure atmospheric neutrino oscillation parameters Δm^2_{23} and $\sin^2\theta_{23}$;
- use 3 years of IceCube-DeepCore data (2012 to 2014);
- study atmospheric neutrinos between 5 and 56 GeV from all sky.

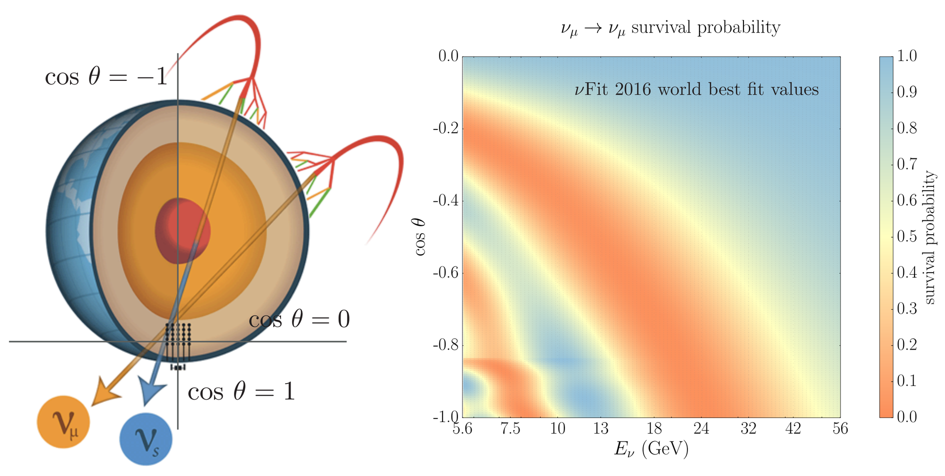

Fig. 1: (left) Atmospheric neutrinos passing through the Earth and arriving at the IceCube-DeepCore detector at different $\cos\theta$. (right) The $\nu_\mu \to \nu_\mu$ survival probability for ranges of $\cos\theta$ and energies, assuming world averaged best fit values of oscillation parameters [2].

The IceCube Neutrino Observatory with DeepCore

- IceCube is a set of optical sensors located at the South Pole station.
- DeepCore, a denser subset of IceCube, pushes the energy threshold down to 5 GeV.
- Cherenkov radiation is detected by optical sensors.

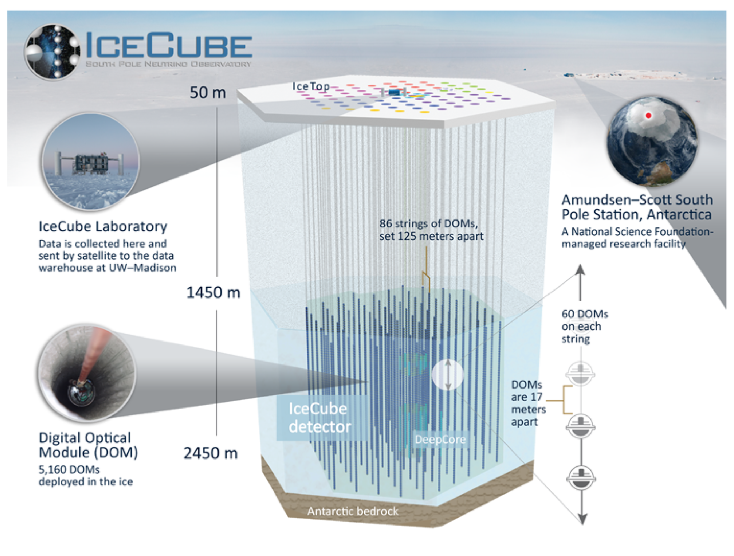

Fig. 2: The structure of the neutrino detector.

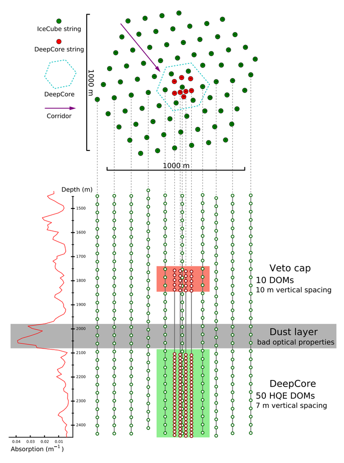

Fig. 3: The top and side views of IceCube-DeepCore.

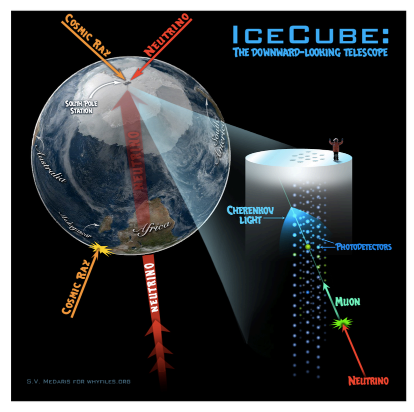

Fig. 4: Neutrinos are detected from Cherenkov radiation induced when relativistic charged leptons, produced from charged-current (CC) neutrino interactions, pass through the Ice.

Selection

Main differences in event selection between two analyses.

	PRL2018[1]	Preliminary
with relative DOM efficiency	✓	✗
selection method	straight cuts + 1 BDT	straight cuts + 2 BDTs
reconstruction	charge-dependent 15m track length segments	charge-independent 5m track length segments
background modeling	data driven	MC

Tab. 1: Differences in the selection methods between two independent analyses.

Reconstruction

- Reconstruction assumes a cascade + track hypothesis.
- Cascade brigtness scales with energy.
- Track is minimum ionizing with an energy loss of 0.2 GeV/m.

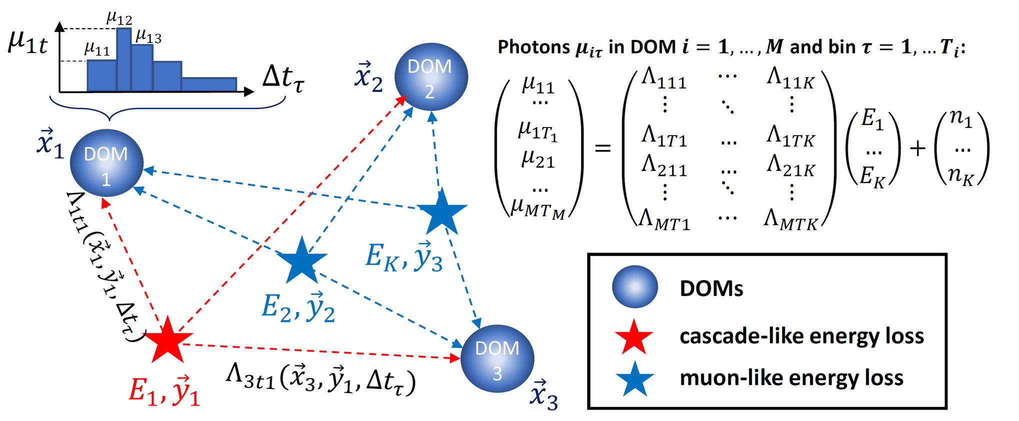

Fig. 5: Reconstruction fits the expected to observed charges. 8 parameters: vertex positions (x, y, z), interaction time, directions (zenith and azimuth angles), cascade energy, and track length segments. Figure adapted from [3].

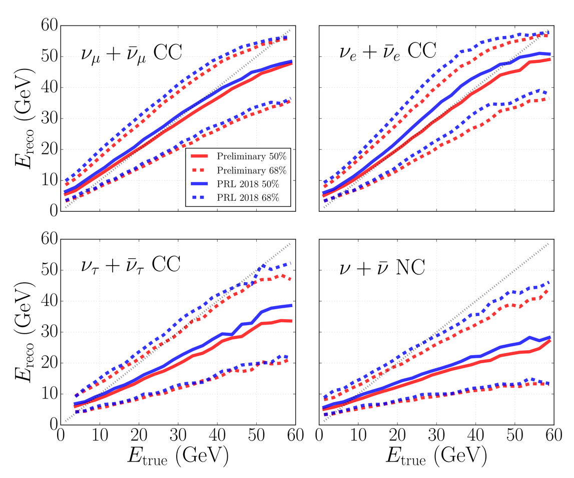

Fig. 6: Energy resolutions.

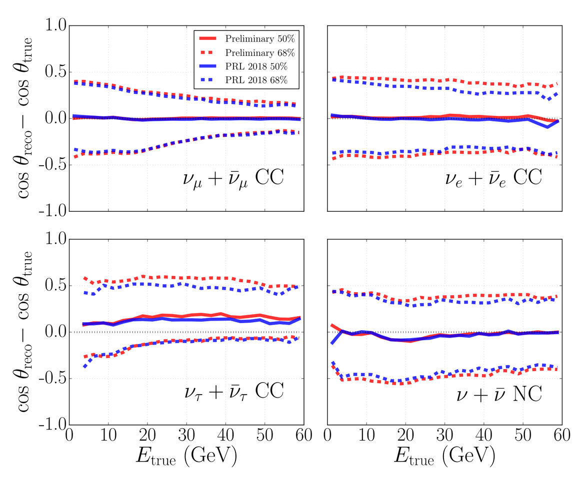

Fig. 7: Zenith angle resolutions.

Analysis Method w/ Systematics

- Main differences in analysis method.

	PRL 2018	Preliminary
particle identification (PID)	$\Delta\mathrm{LLH}_{cascadevstrack}$	track length
$(\sigma_i^{exp})^2$ in χ^2 (Eq. 1)	$\sigma^2_{MC} + \sigma^2_{\mu-shape}$	σ^2_{MC}
use of Hyperplane	✗	✓

Tab. 2: Differences in analysis method between two analyses.

- Both analyses minimize χ^2 per bin.

$$\chi^2 = \sum_{i\in\{bins\}} \frac{(N_i^{exp} - N_i^{obs})^2}{N_i^{exp} + (\sigma_i^{exp})^2} + \sum_{j\in\{syst\}} \frac{(s_j - \hat{s}_j)^2}{\sigma^2_{s_j}}, \quad (1)$$

- Hyperplane is used in Preliminary for a continuous space across all detector systematics.

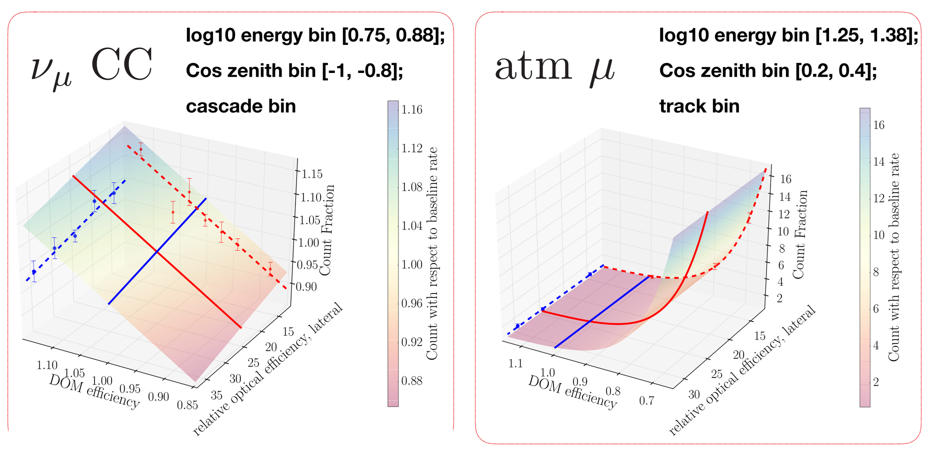

Fig. 8: A hyperplane is applied per bin per event. Two simplified examples are shown from one of ν_μ CC (left) and atm μ (right) bins.

- Preliminary uses track length as PID: cascade-like events between 0 and 50m, and track-like events between 50 and 1000m.
- MC template from Preliminary in 8 energy × 10 cos zenith × 2 track length bins.

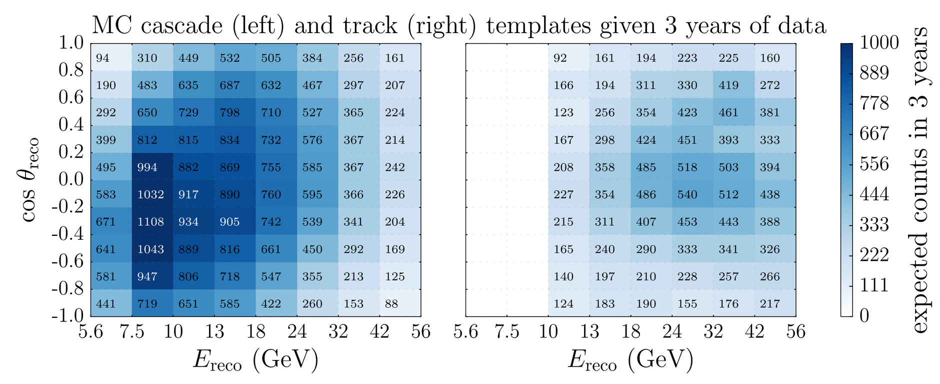

Fig. 9: MC template from Preliminary. All track-like events have reconstructed energy above 10 GeV. World averaged best fit values of oscillation parameters [2] are assumed.

- 16 systematic uncertainties are considered in Preliminary, including bulk ice properties (absorption and scattering).
- Two examples of systematic effects from absorption and ν_e/ν_μ flux ratio.

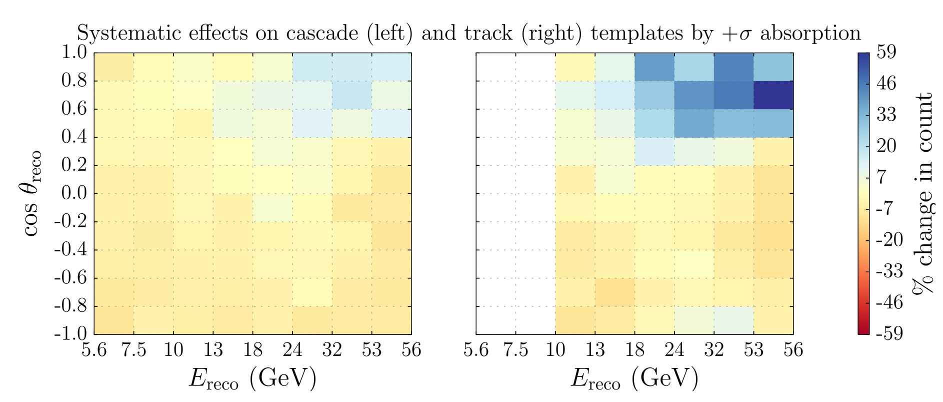

Fig. 10: Percentage change in event count per rate when the nuisance parameter related to absorption is pulled up by 1σ.

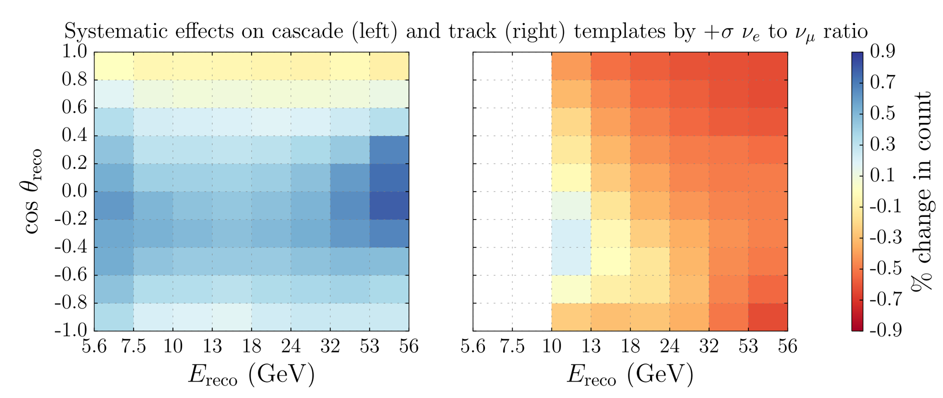

Fig. 11: Percentage change in event count per rate when the nuisance parameter related to ν_e/ν_μ flux ratio is pulled up by 1σ.

Results

Parameters	Priors	PRL2018[1] (NO)	Preliminary (NO)
Physics Parameters			
$\Delta m^2_{23} (\times 10^{-3}\ \mathrm{eV}^2)$	-	$2.31^{+0.11}_{-0.13}$	$2.55^{+0.12}_{-0.11}$
$\sin^2\theta_{23}$	-	$0.51^{+0.07}_{-0.09}$	$0.58^{+0.04}_{-0.13}$
Atmospheric Neutrino Flux Parameters			
ν_e/ν_μ ratio	1.0 ± (0.2, 0.05)	1.25	1.03
Hadronic flux, zenith dependent [σ]	0.0 ± 1.0	-0.55	-0.21
Hadronic flux, energy dependent [σ]	0.0 ± 1.0	-0.56	-0.70
ν spectral index $\Delta\gamma_\nu$	0.0 ± 0.1	-0.02	-0.05
Neutrino event rate [% of nominal]	-	85	91.8
Atmospheric Flux Parameters			
Coincident $\nu + \mu$ fraction [%]	0.0 ± 10	-	3
μ spectral index γ_μ [σ]	0.0 ± 1.0	-	0.11
μ fraction [%]	-	5.5	8.1
Cross Section Parameters			
Quasi elastic M_A^{CCQE} [GeV]	$0.99^{+0.248}_{-0.149}$	-	0.89
Resonance M_A^{CCRES} [GeV]	1.12 ± 0.22	0.92	0.96
ν NC relative normalization	1.00 ± 0.2	1.06	1.02
Detector Parameters			
Overall optical efficiency [%]	100 ± 10	102	98
Relative optical efficiency, lateral [σ]	0.0 ± 1.0	0.2	0.22
Relative optical efficiency, head-on	-	-0.72	-0.84
Bulk ice, absorption [%]	100 ± 10	-	101
Bulk ice, scattering [%]	100 ± 10	-	103

Tab. 3: Best fit values of all parameters; both analyses prefer normal ordering. For ν_e/ν_μ, PRL2018 applies a prior of 20%, while Preliminary has a tighter prior of 5%.

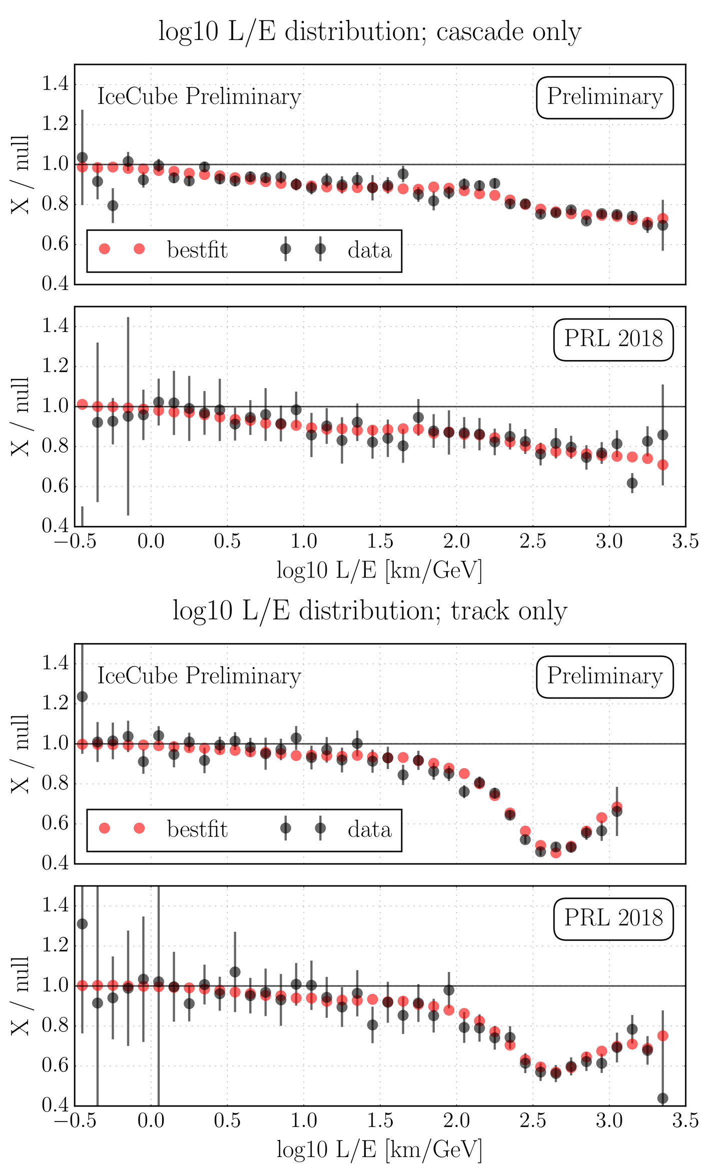

Fig. 12: The ratio of L/E in the cascade (top) and track (bottom) channel from data and best fit to that from null hypothesis.

Conclusion

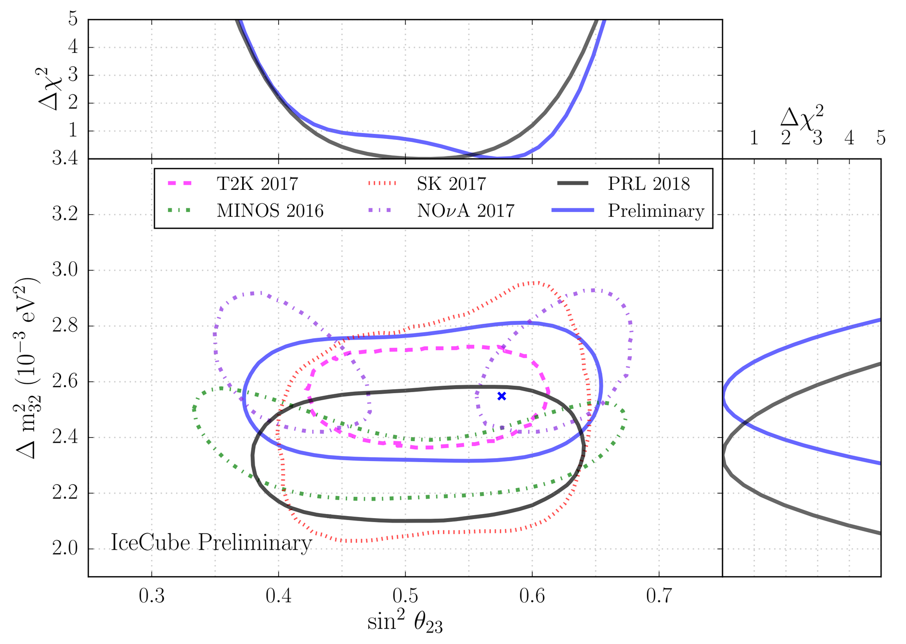

Fig. 13: (top) 1D $\Delta\chi^2$ in $\sin^2\theta_{23}$ from Preliminary and PRL2018. (right) 1D $\Delta\chi^2$ in Δm^2_{23}. (bottom left) Contours from Preliminary (in blue) and PRL2018[1] (in gray) compared to results from T2K[4], SK[5], MINOS[6], and NOνA[7].

- Preliminary result supports PRL2018 within statistical fluctuation.
- Both analyses agree with other long baseline neutrino experiments.

[1] The IceCube Collaboration. In: Phys. Rev. Lett. 120.7 (2018), p. 071801. arXiv: 1707.07081 [hep-ex].
[2] I. Esteban et al. In: JHEP 01 (2017), p. 087. arXiv: 1611.01514 [hep-ph].
[3] M. Leuermann. Pending. Ph.D. Rheinisch-Westfalische Technische Hochschule (RWTH) Aachen, 2018.
[4] The T2K Collaboration. In: PoS EPS-HEP (2017), p. 112. arXiv: 1709.04180 [hep-ex].
[5] The SK Collaboration. In: Phys. Rev. D97.7 (2018), p. 072001. arXiv: 1710.09126 [hep-ex].
[6] The MINOS Collaboration. In: Nucl. Phys. B908 (2016), pp. 130–150. arXiv: 1601.05233 [hep-ex].
[7] The NOνA Collaboration. In: Meeting of the APS Division of Particles and Fields. 2017. arXiv: 1710.03829 [hep-ex].

Elim Cheung: elims@icecube.wisc.edu
Joshua Hignight: hignight@ualberta.ca