New atmospheric neutrino oscillation results from IceCube/DeepCore

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Neutrino oscillations

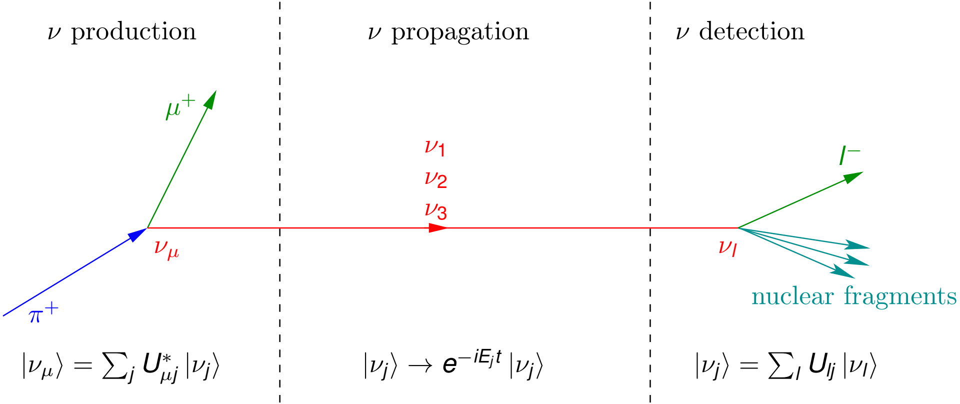
- 3 ν flavors: ν_e, ν_μ and ν_τ
- ν oscillation observed in various experiments since it's discovery
  - Implies that ν are massive particles $\rightarrow$ must also have 3 mass states: ν_1, ν_2, ν_3
- Projection between flavor $\leftrightarrow$ mass states via mixing matrix U:

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

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

  - U is unitary if only 3-flavor mixing
- 6 parameters (Δm^2_{21}, Δm^2_{32}, θ_{12}, θ_{13}, θ_{23} and δ_{CP}) describe ν oscillations
  - possibility of a Majorana term, but does not effect oscillations
- Currently only δ_{CP} and mass ordering (sign of Δm^2_{32}) not measured

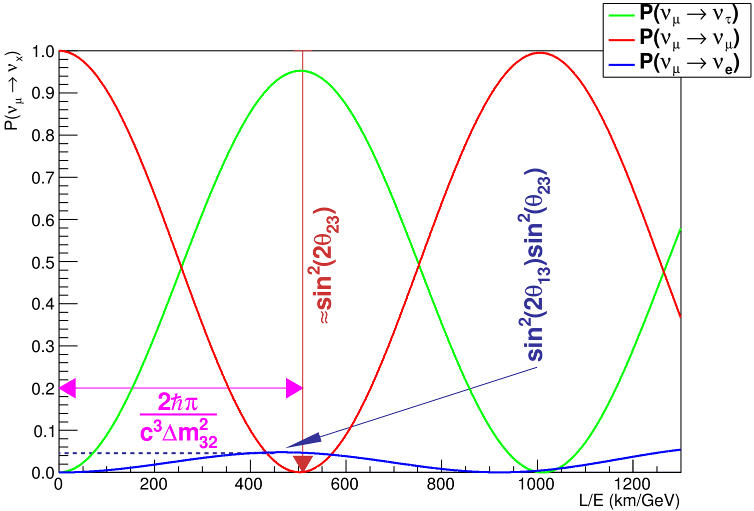
Neutrino oscillation – a schematic view



$$P(\nu_\mu \to \nu_l, t) = ||\langle \nu_l | \nu_\mu, t\rangle||^2 = \sum_{j,k} U_{lj} U^*_{\mu j} U^*_{lk} U_{\mu k} e^{-i(E_j - E_k)t} = \sum_{j,k} U_{lj} U^*_{\mu j} U^*_{lk} U_{\mu k} e^{-i\Delta m^2_{jk} \frac{L}{2E}}$$

$$P(\nu_\mu \to \nu_\mu) \approx 1 - 4|U_{\mu 3}|^2 \left(1 - |U_{\mu 3}|^2\right) \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right) \quad \text{for } \frac{L}{E} \lesssim 1000 \text{ km/GeV}$$

Neutrino oscillations in vacuum

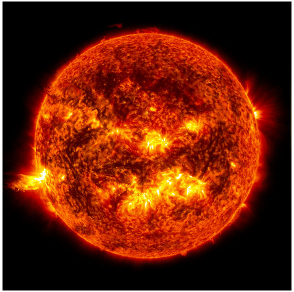
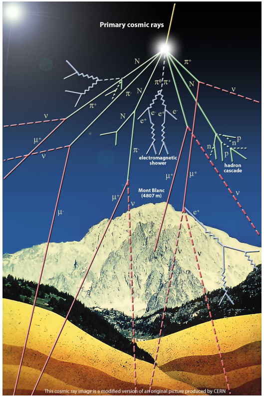


$\theta_{12} = 34^{\circ}$, $\theta_{13} = 8.8^{\circ}$, $\theta_{23} = 45^{\circ}$, $\Delta m^2_{21} = 7.59 \cdot 10^{-5}$ eV^2/c^4, $\Delta m^2_{32} = 2.43 \cdot 10^{-3}$ eV^2/c^4, $\delta_{CP} = 0^{\circ}$.

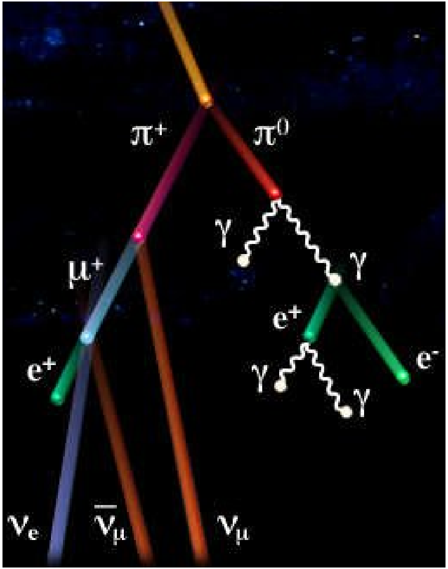
Producing neutrinos

- Nuclear reactors
- Stars
- Accelerators
- Cosmic Rays showers
  - "atmospheric neutrinos"
- ...



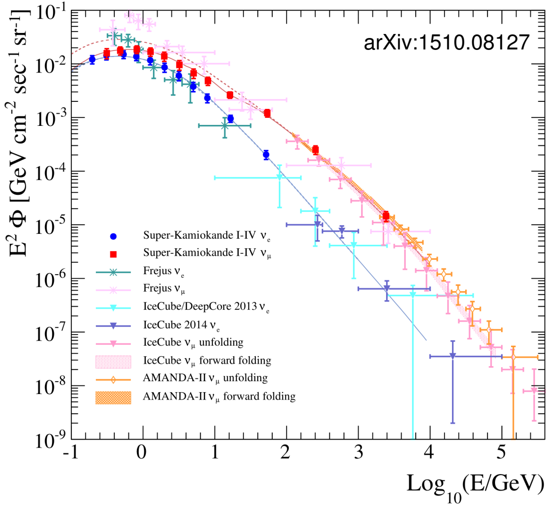
Atmospheric neutrinos



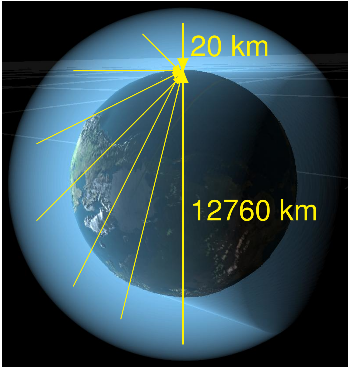
- Cosmic ray (CR) interact with atmosphere, producing hadronic shower
  - Decays produce ν
- ν_e:ν_μ:ν_τ produced at $\approx$1:2:0
- similar rate of ν and $\bar{\nu}$
  - however, cross-sections for $\bar{\nu}$ smaller than for ν

  $\Rightarrow$ at detection less $\bar{\nu}$ than ν

Atmospheric neutrinos



- ν energy over several orders of magnitude
- CR bombard Earth from all directions
  - $\Rightarrow$ neutrinos from all directions!



Matter Effects on Neutrino Oscillations

+ for neutrinos
- for antineutrinos

CC interactions of ν_e with matter

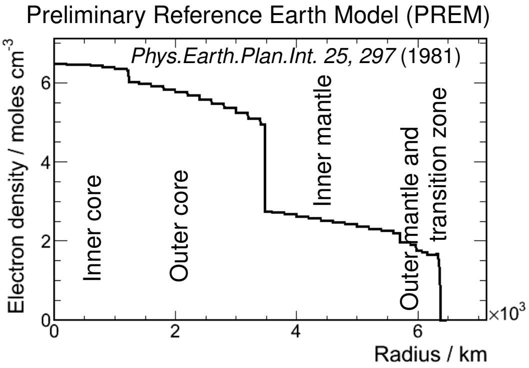
$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}\nu_e\\ \nu_x\end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos(2\theta) \pm \sqrt{2}G_F N_e & \frac{\Delta m^2}{4E}\sin(2\theta) \\ \frac{\Delta m^2}{4E}\sin(2\theta) & \frac{\Delta m^2}{4E}\cos(2\theta)\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_x\end{pmatrix}$$

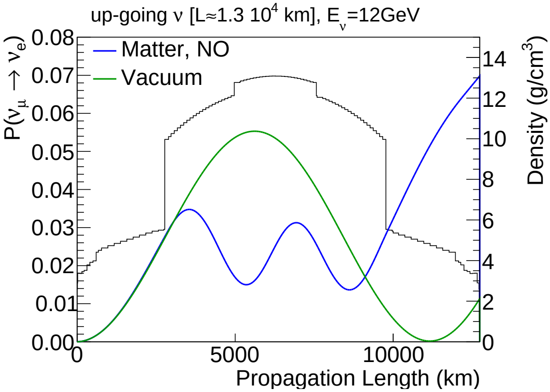
Matter potential modifies neutrino mixing $\rightarrow$ effective mixing angles in matter:

$$\Delta m_M^2 = \sqrt{\left(\Delta m^2 \cos 2\theta - 2E V_{int}\right)^2 + \left(\sin 2\theta \Delta m^2\right)^2}, \qquad \tan 2\theta_m = \frac{\tan 2\theta}{1 - \frac{2E V_{int}}{\Delta m^2 \cos 2\theta}}$$

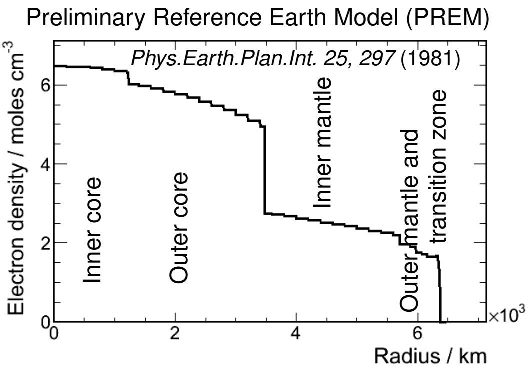
- $V_{int} = \pm\sqrt{2}G_F N_e$; $+$ for ν, and $-$ for $\bar{\nu}$
- Δm^2: $+$ for NO, and $-$ for IO

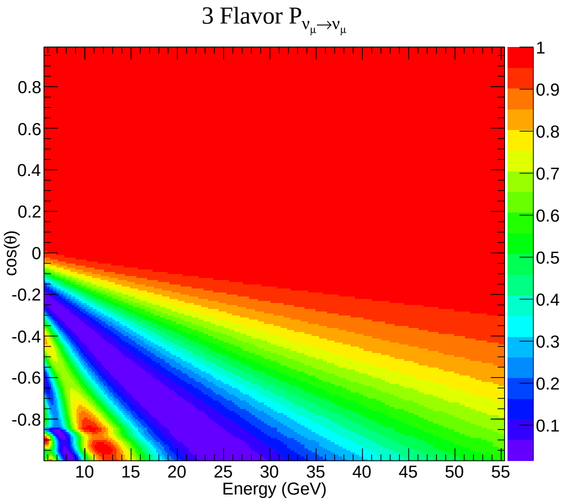
Matter Effects on Neutrino Oscillations



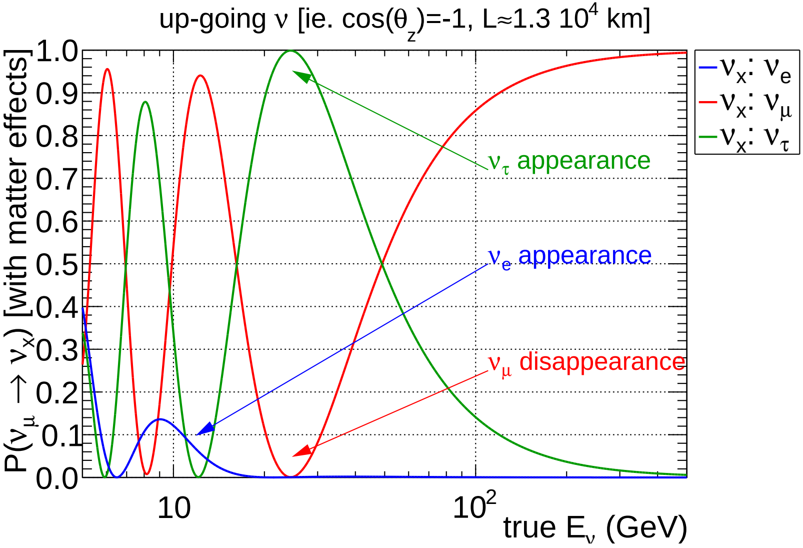


Matter Effects on Neutrino Oscillations



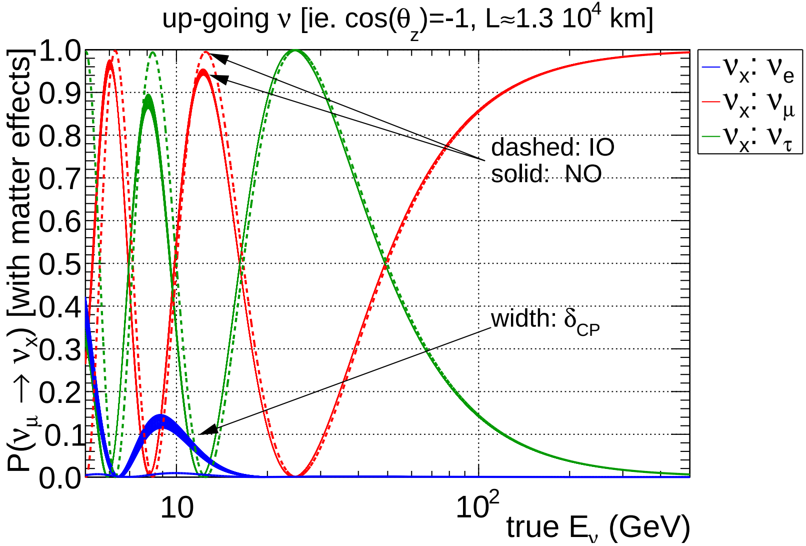


Atmospheric neutrinos oscillations across the Earth



- Largest baseline L shown
- First oscillation maxima at $\sim$ 25 GeV
- ν_e appearance at lower-E due to matter effects
- Sign of Δm^2_{32} and δ_{CP} effects below $\sim$ 12 GeV

Atmospheric neutrinos oscillations across the Earth



- Largest baseline L shown
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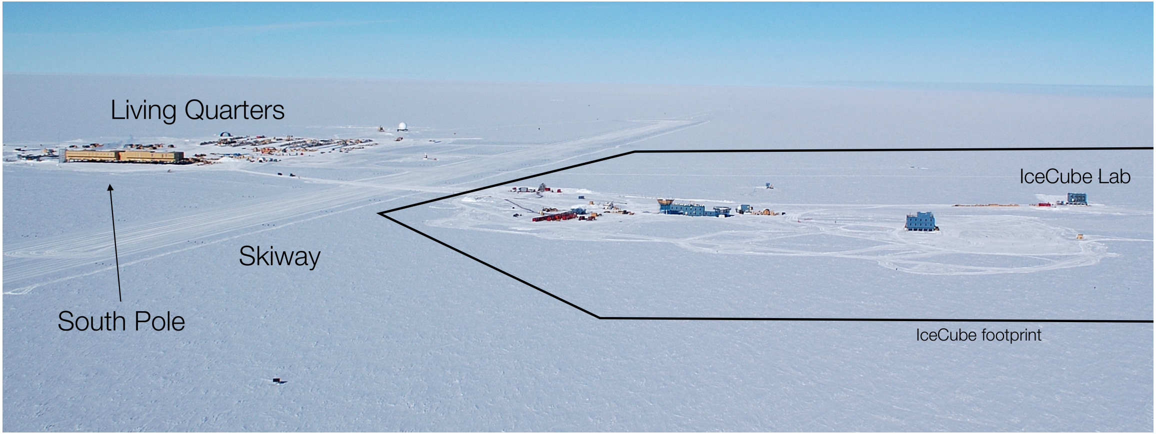
IceCube


Living Quarters
IceCube Lab
Skiway
South Pole
IceCube footprint


THE ICECUBE COLLABORATION
AUSTRALIA
University of Adelaide
BELGIUM
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel
CANADA
SNOLAB
University of Alberta–Edmonton
DENMARK
University of Copenhagen
GERMANY
Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Ruhr-Universität Bochum
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Technische Universität Dortmund
Technische Universität München
Universität Mainz
Universität Wuppertal
Westfälische Wilhelms-Universität Münster
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REPUBLIC OF KOREA
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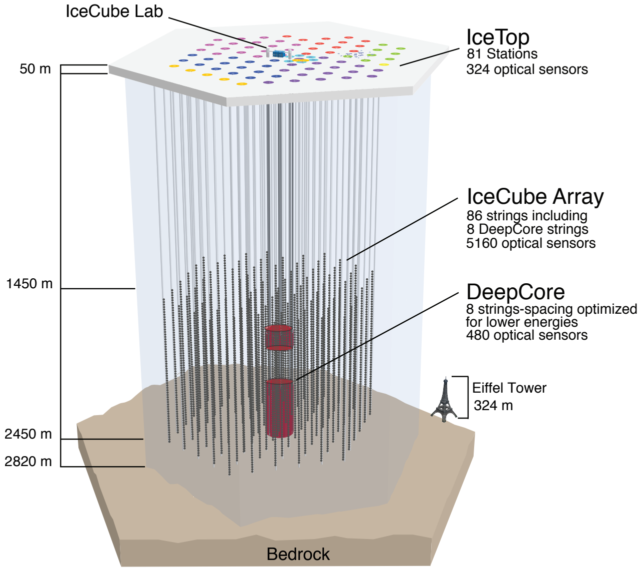
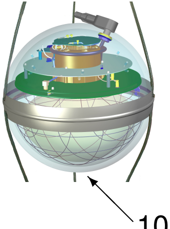
IceCube



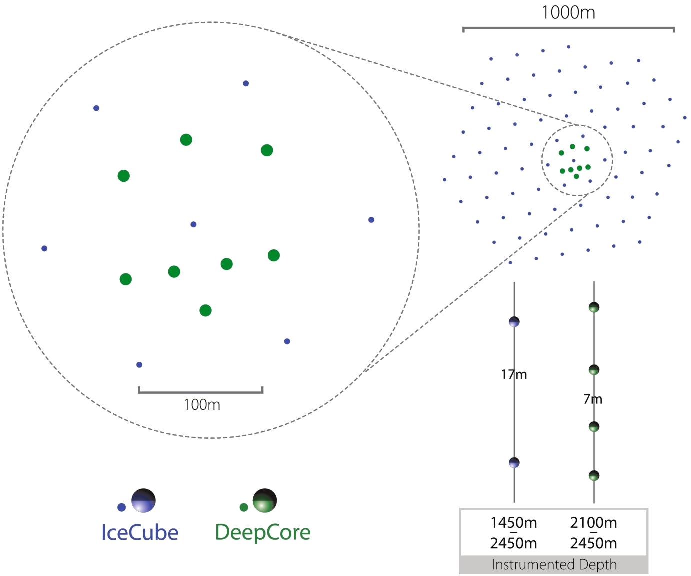
- Instrument 1 Gton of ice
- Optimized for TeV-PeV neutrinos
  - Astrophysical ν discovered!
- DeepCore
  - $\sim$10 Mton region with denser instrumentation
  - Pushes thresholds down to ≈ 5 GeV

IceCube-DeepCore

IceCube DOM

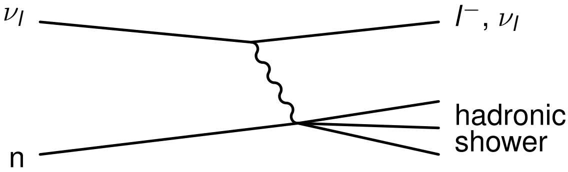


10” PMT

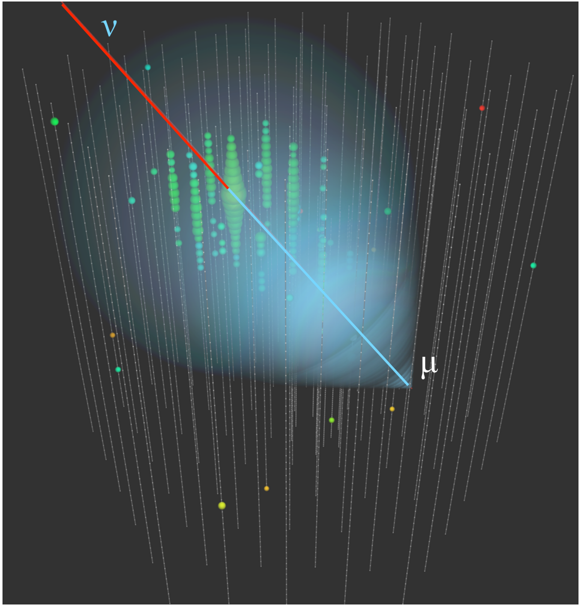


Detecting neutrinos in IceCube

- Neutrinos interact in the ice



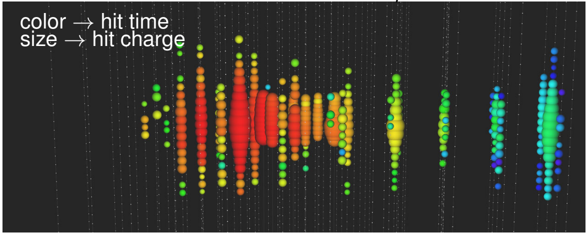
- Charged particles moving faster than the speed of light in ice produce Cherenkov light cone
- 3D array of PMTs detect produced light



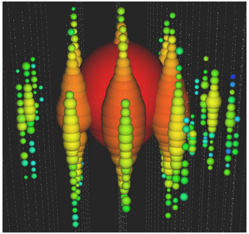
Event topology in IceCube

- Look for 2 distinct event topologies

Track-like events: typically ν_μ CC events

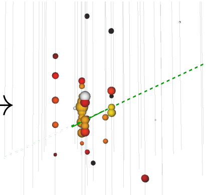


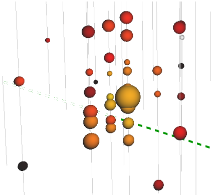
Cascade-like events



- Topologies much harder to distinguish at energies needed for oscillation analysis...

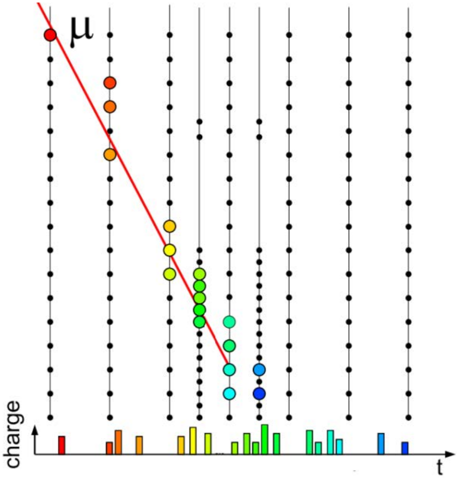
30 GeV ν_μ CC →





← 31 GeV ν_e CC

Measurement strategy for neutrino oscillations



- Main background is atmospheric μ
  - Use IceCube as veto to reject atm μ events
- Reconstruct ν energy and direction
  - oscillation distance (L) given by zenith
- Measure oscillation by fitting $L \times E \times PID$

Comparison to last published ν_μ disappearance results

IC2014 analysis

- Results in PRD 91, 072004 (2015)
- Focus on ν_μ CC "golden events"
  - Clear μ tracks
  - Several non-scattered photons
- Use only up-going events

Similarities in both analyses

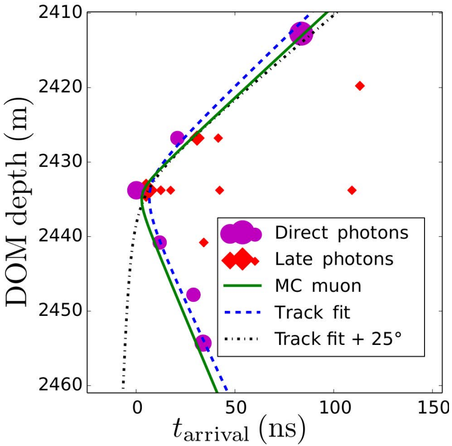
- Atmospheric μ background shape estimated from data
- ν reconstruction resolution similar
- Both are 3 year data sets

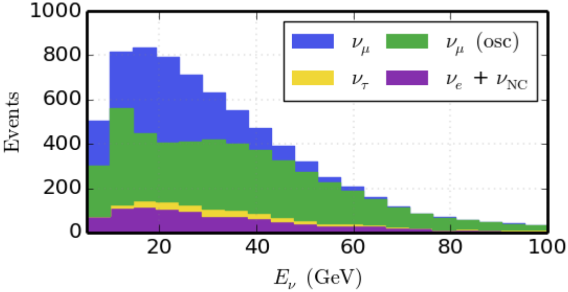
This analysis

- Order of magnitude increase in statistics
- Reconstruction fits full event topology with $\mathcal{L}$-based method
  - Can fit events with scattered photons
  - Can reconstruct all ν types
- PID variable separates sample in two:
  - Track: ν_μ CC enriched sample
  - Cascade: mix of all ν flavors
- Full sky analysis
  - Better control of systematics
- Fitting includes term accounting for statistical uncertainty from prediction

"Golden Events"

- Clear μ tracks
  - Reduce contamination of cascades (primarily ν NC and ν_e CC)

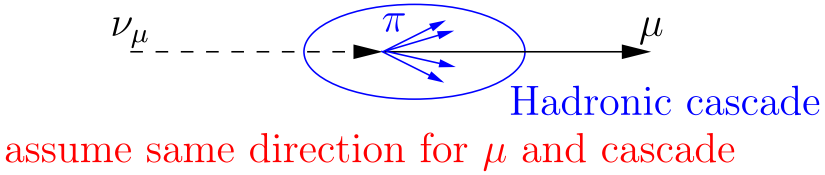




- Require several non-scattered γ
- select events "easy" to reconstruct
  - 10° resolution in neutrino zenith
  - 25% resolution in neutrino energy

Reconstructing low-energy events: $\mathcal{L}$-based techniques

- Goal: reconstruct ν_μ CC (DIS) interactions

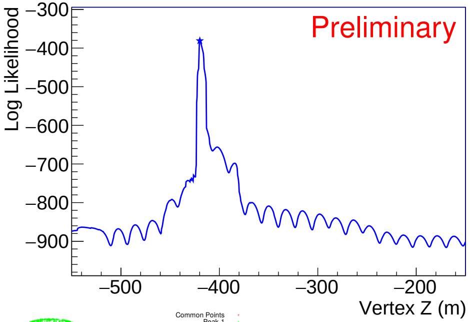


- Maximize likelihood ($\mathcal{L}$) of hypothesis to correspond to the data
  - $\mathcal{L}$ calculation based on tables with expected charge-time from EM cascade and μ track
    - ⋆ Fairly complex tables to account for natural medium properties
    - ⋆ EM cascade energy converted to hadronic cascade energy a posteriori
- Same event hypothesis in reconstruction also works for cascade events
  - In that case μ track length $\rightarrow 0$
  - Currently cannot distinguish EM and hadronic cascades
- Distinguish between track/cascade based on presence or absence of μ
  - Compare $\mathcal{L}$ between fit with and without track

Low-energy reconstructions: a minimization problem

- 8D $\mathcal{L}$ space is very rough
- Regular minimizers don't work
  $\Rightarrow$ use MultiNest algorithm

  by *F. Feroz et al. (arXiv:0809.3437)*
  - designed to explore the highly dimensional $\mathcal{L}$ space with multiple minima



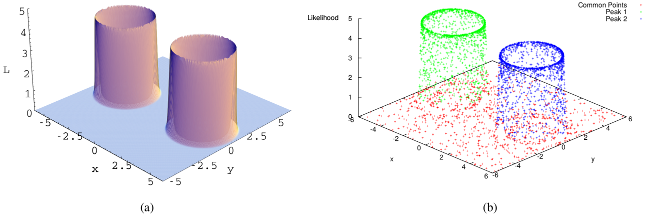
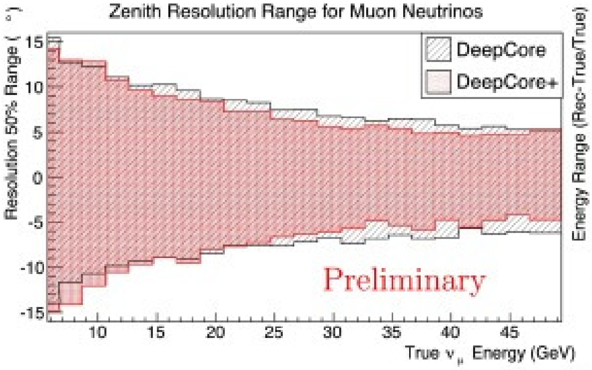
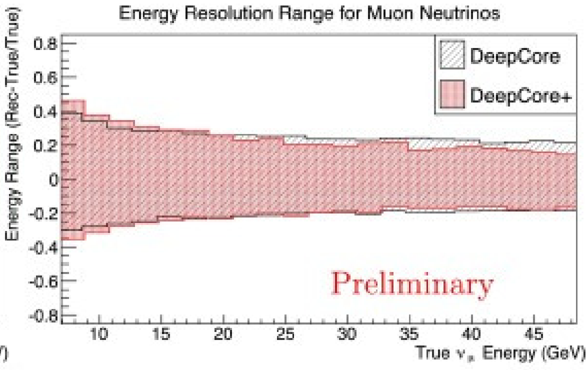


Figure 6. Toy model 2: (a) two-dimensional plot of the likelihood function defined in Eqs. (32) and (33); (b) dots denoting the points with the lowest likelihood

Low-energy reconstructions: resolutions





- DeepCore $\rightarrow$ From previous published analysis
- DeepCore+ $\rightarrow$ From this ($\mathcal{L}$-based) analysis, events classified as track-like
- Resolutions are similar, but
  - DeepCore+ has significantly larger statistics!
  - DeepCore+ can reconstruct cascade-like events also

Fitting Function used in new ν_μ disappearance analysis

- 30 years of MC for ν components and several systematic variants
- Data-driven estimate of atmospheric μ background shape
  - Similar method used in PRD sample
- Need to account for uncertainty in prediction, especially for background muons
- Our solution is to fit a χ^2 function instead of a $\mathcal{L}$ function.

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

  - $n_i^{\nu_\mu}$, n_i^{data}: number of events in bin i for prediction (ν MC + μ sideband) and data
  - σ^{data}: statistical uncertainty in the data for bin i
  - $\sigma_{\nu+\mu}^{uncor}$: statistical uncertainty in prediction with additional shape uncertainty in μ sideband
  - $\hat{s}_j$, $\hat{\sigma}_{s_j}$: central value and sigma of a Gaussian prior of systematic s_j
- Have a total of 128 bins: 8 cos(θ)$\times$ 8 Energy $\times$ 2 PID
- All bins have a large enough number of events that a Gaussian distribution approximates well a Poisson distribution.

Systematics

- Overall, the systematics can be split up into three broad categories:

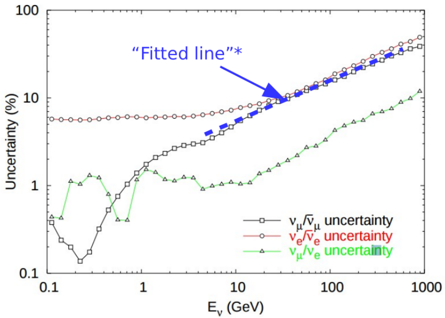
  1. Flux and cross-section
     - ⋆ Neutrino normalization
     - ⋆ Spectral index (γ)
     - ⋆ $\nu_e + \bar{\nu}_e$ normalization
     - ⋆ NC normalization
     - ⋆ $\Delta(\nu/\bar{\nu})$ as both energy and zenith dependence
     - ⋆ M_A^{RES}
  2. Detector related parameters
     - ⋆ Overall DOM efficiency
     - ⋆ Relative DOM efficiency in both lateral and head-on directions
  3. Atmospheric background

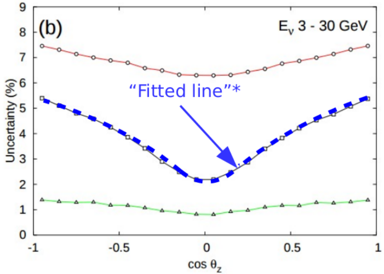
Systematics: Flux and Cross-section

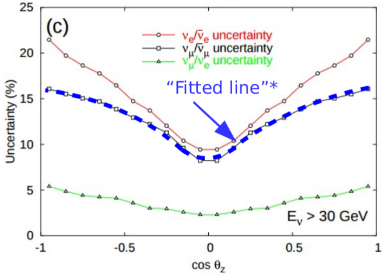
- Flux and cross-section systematics reweight our default models.
  - We use Honda's 2015 flux model for our default MC production (arXiv:1502.03916)
  - GENIE is used for our default cross-section models.
- $\Delta\gamma \rightarrow$ energy-dependent shift in event rate:
  - This can arise from uncertainty on γ (nominally $\gamma = -2.66$) or from uncertainties in the DIS cross section.
    - ★ Studies on DIS cross-section included uncertainties on the Bodek-Yang model used in GENIE, uncertainties in the differential cross-section of DIS neutrino scattering, and studies of hadronization uncertainties for high-W DIS events.
    - ★ It was found these were highly degenerate with the spectral-index and overall normalization or negligible so were not included in the fit.
- The value of M_A^{RES} was found to have a small impact on the results so is included in the fit.
  - M_A^{CCQE} was also investigated but found to be negligible

Systematics: Flux and Cross-section

- The normalizations of $\nu_e + \bar{\nu}_e$ events and of NC events, defined relative to $\nu_\mu + \bar{\nu}_\mu$ CC events.
- The $\nu/\bar{\nu}$ ratio have a directional/energy dependence, so a more sophisticated approach was used.
  - From the K/π ratio of the atmospheric shower
- Parameterizations uses predictions from Barr et al. (arXiv:0611266v1)

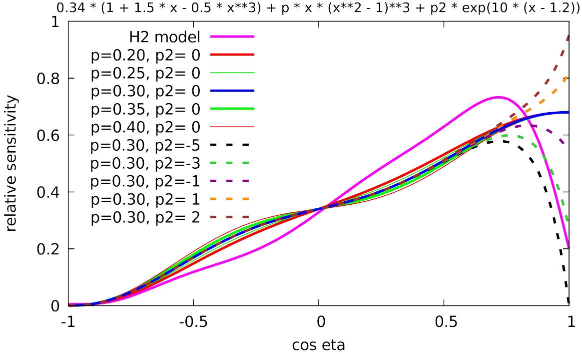






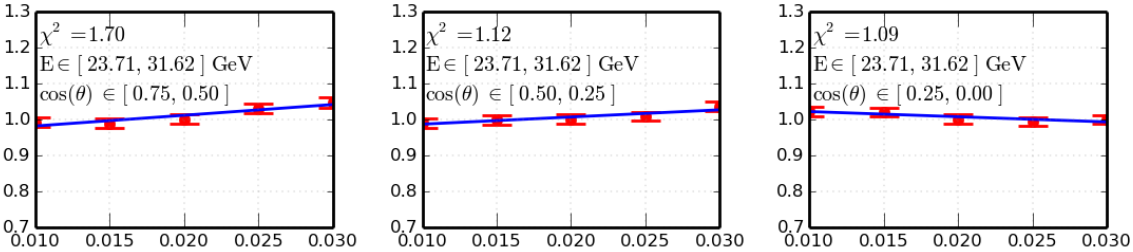
Systematics: Detector

- By far, the largest uncertainty in our measurement comes from the detector systematics.
- We have one that has to do with our overall DOM efficiency.
  - This just scales up and down the amount of light seen in each PMT
- There are also two systematics related to how the local ice properties effects our DOM acceptance.



Systematics: Detector

- These effects are estimated by Monte Carlo at discrete values
- A continuous distribution is determined by linear interpolation between the discrete simulated values for each bin in the (energy, direction, track/cascade) analysis histogram

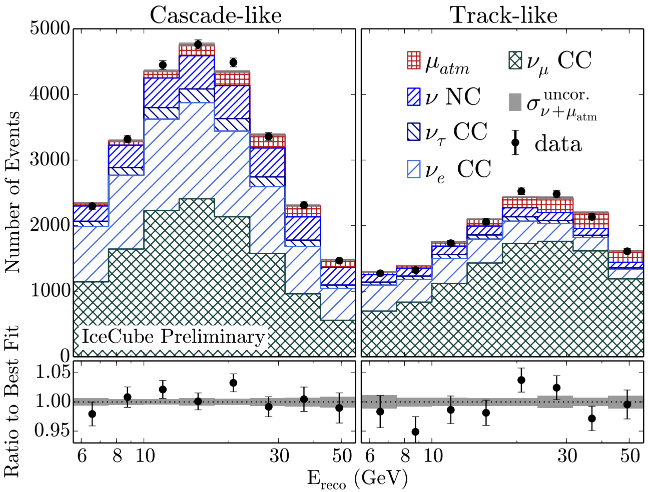


Systematics used in analysis and best fit

Parameters	Priors	Best Fit NO	Best Fit IO
Flux and cross section parameters			
Neutrino event rate [% of nominal]	no prior	85	85
$\Delta\gamma$ (spectral index)	0.00 ± 0.10	-0.02	-0.02
$\nu_e + \bar{\nu}_e$ relative normalization [%]	100 ± 20	125	125
NC relative normalization [%]	100 ± 20	106	106
$\Delta(\nu/\bar{\nu})$ [σ], energy dependent‡	0.00 ± 1.00	-0.56	-0.59
$\Delta(\nu/\bar{\nu})$ [σ], zenith dependent‡	0.00 ± 1.00	-0.55	-0.57
M_A (resonance) [GeV]	1.12 ± 0.22	0.92	0.93
Detector parameters			
overall DOM efficiency [%]	100 ± 10	102	102
relative DOM efficiency, lateral [σ]	0.0 ± 1.0	0.2	0.2
relative DOM efficiency, head-on [a.u.]	no prior	-0.72	-0.66
Background			
Atm. μ contamination [% of sample]	no prior	5.5	5.6

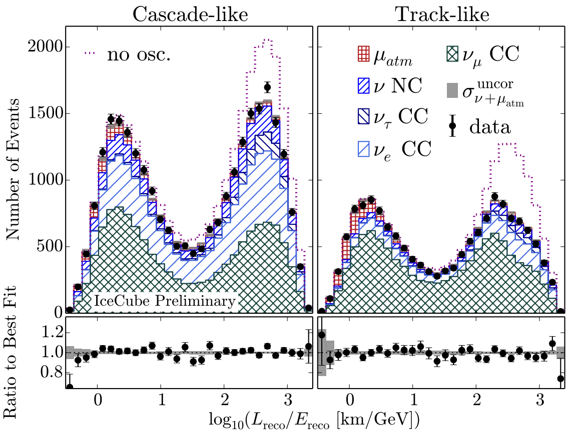
‡: Following Barr, et al., PRD74, 094009.

Sample of events used for this analysis



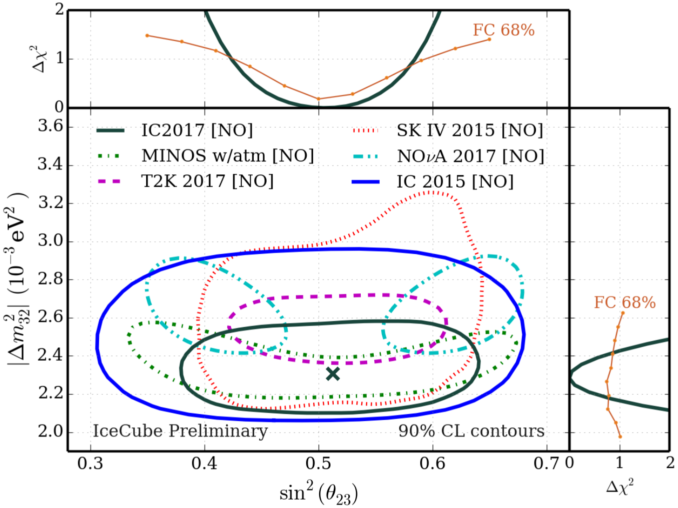
- Track-like sample composed mainly of ν_μ CC
- Cascade-like sample more mixed
- Uncertainties shown are uncorrelated uncertainties
- $\mu_{atm.}$ mainly reconstructed down-going

ν_μ disappearance oscillation analysis



- Analysis done with events with $E_{reco} \in [5.6, 56]$ GeV
- Fitting to data done in 3D space $(E, \cos\theta, PID) \rightarrow$ projected onto L/E for illustration
  - $\chi^2/ndf = 117.4/119$

ν_μ disappearance oscillation analysis



- Result consistent with other experiments.
- Using data from 3 years of detector operations.
- This measurement is still statistics limited!
  - Will need at least 6 years of data to become statistically limited.

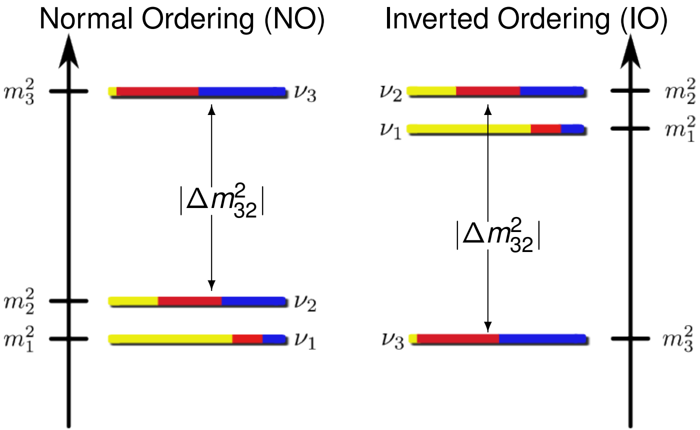
$$\Delta m^2_{32} = 2.31^{+0.11}_{-0.13} \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2\theta_{23} = 0.51^{+0.07}_{-0.09}$$

Summary

- IceCube-DeepCore detector: good instrument to measure neutrino oscillations
- Many updates to the ν_μ disappearance analysis since 2014:
  - New reconstruction being used
  - All types of ν's and whole sky
- Latest θ_{23} and Δm^2_{32} measurement of similar precision to those from accelerators
  - Preference to maximal mixing like T2K
- Many more topics using this same event selection are currently underway
  - ν_τ appearance
  - Sterile ν searches
  - NSI
  - WIMP searches
  - ...

Backup slides

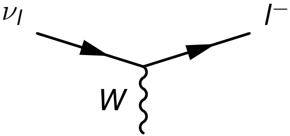
Neutrino Mass Ordering

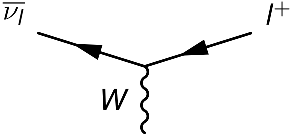


- Neutrino mass ordering: sign of Δm^2_{32}
- No effects visible in vacuum oscillations
- Matter effects induce different changes for NO and IO

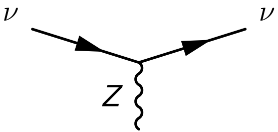
Measuring Neutrinos: Neutrino interaction with matter

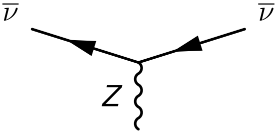
Charged Current (CC) interaction :





Neutral Current (NC) interaction :

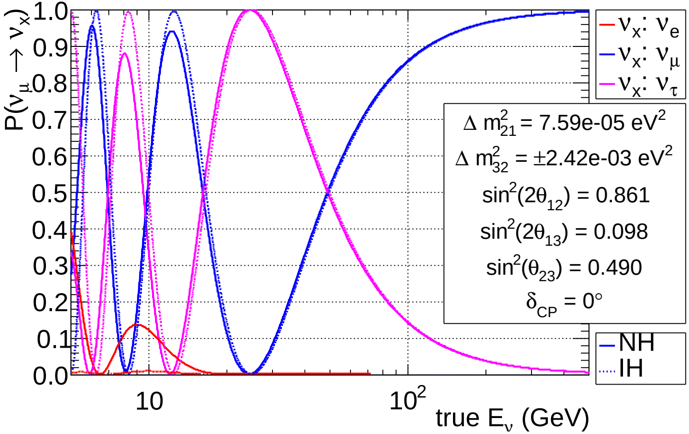




- Measure of produced lepton (l) $\rightarrow$ define ν flavor
- Measure recoil of nucleus or hadronization in some detectors
- Further classification of interaction depends on what happens in nucleus

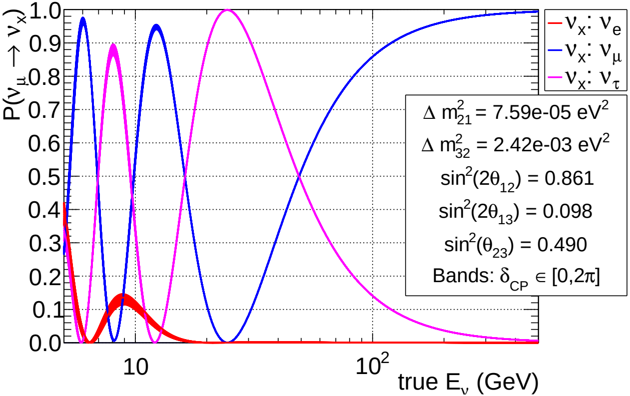
  nuclear recoil [QE] $\longleftrightarrow$ [DIS] large hadronization

Atmospheric neutrinos oscillations

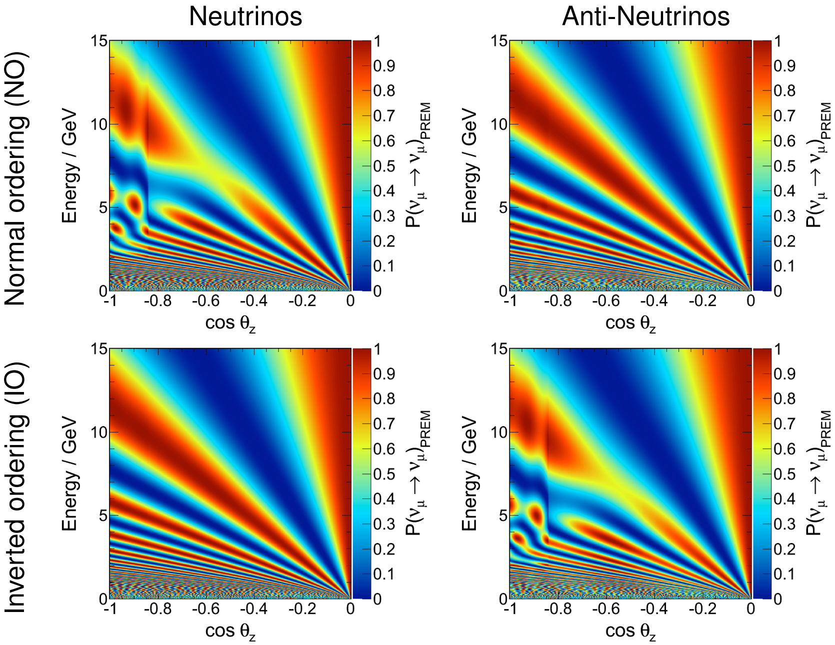


- Largest baseline (L=12760 km, cos $\theta_z = -1$) has:
  - First oscillation maxima at $\sim$ 25 GeV
  - Matter effects below $\sim$ 12 GeV
  - Potential for ν_e appearance at 8 GeV

Atmospheric neutrinos oscillations

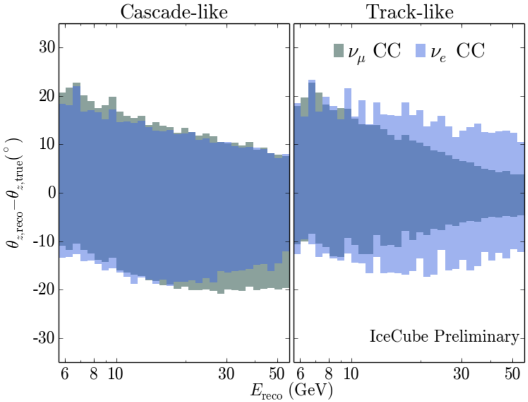


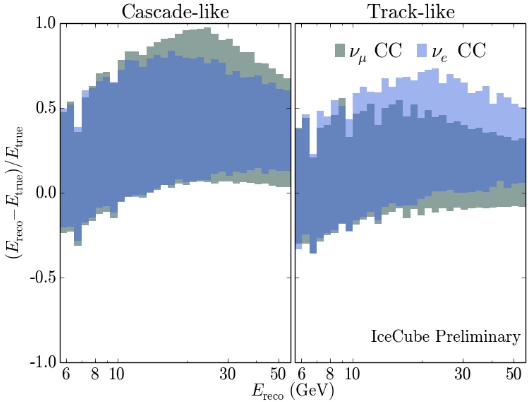
- Largest baseline (L=12760 km, $\cos\theta_z = -1$) has:
  - First oscillation maxima at $\sim$ 25 GeV
  - δ_{CP} below $\sim$ 12 GeV
    - ★ but matter effects dominate that region
  - Potential for ν_e appearance at 8 GeV



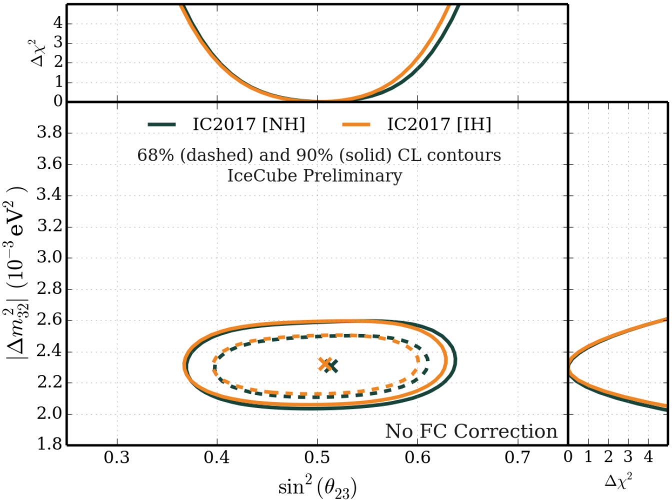
Neutrinos
Anti-Neutrinos
Normal ordering (NO)
Inverted ordering (IO)
Energy / GeV
cos θz
P(νμ → νμ)PREM

Low-energy reconstructions: resolutions

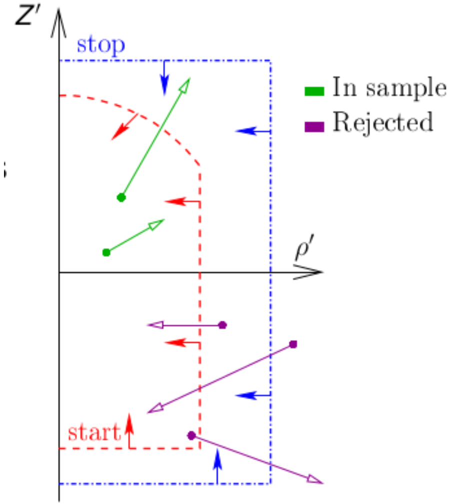




Comparison to IO (NO FC!)



Containment Cut



Background Cut