Measurement of Atmospheric ν_μ Disappearance with IceCube/DeepCore

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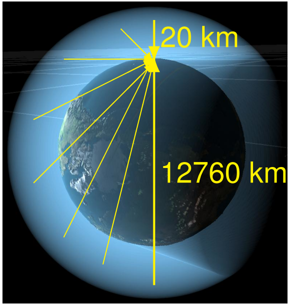
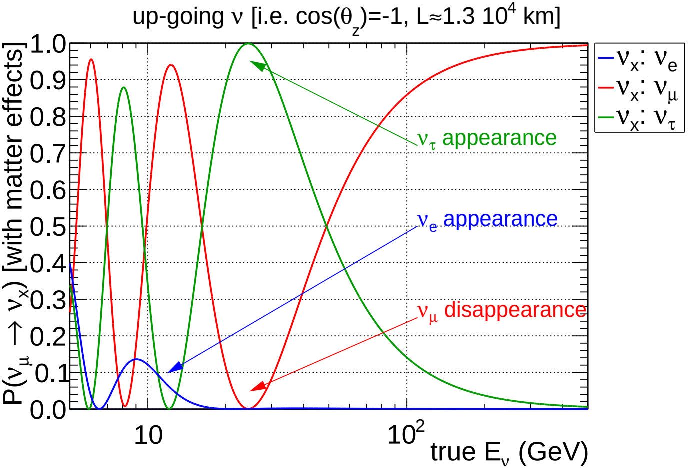
Neutrino oscillations with atmospheric neutrinos

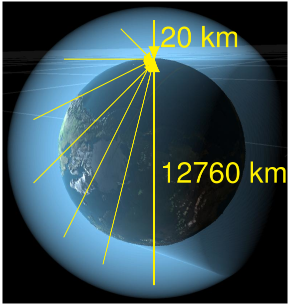


- Several baselines available
  - L/E dependency on oscillation
  - Many orders of magnitude in E
- IceCube/DeepCore:
  - See clear ν_μ disappearance



- IceCube/DeepCore not (very) sensitive to:
  - Neutrino mass ordering, δ_{CP}, ν_e appearance

Neutrino oscillations with atmospheric neutrinos



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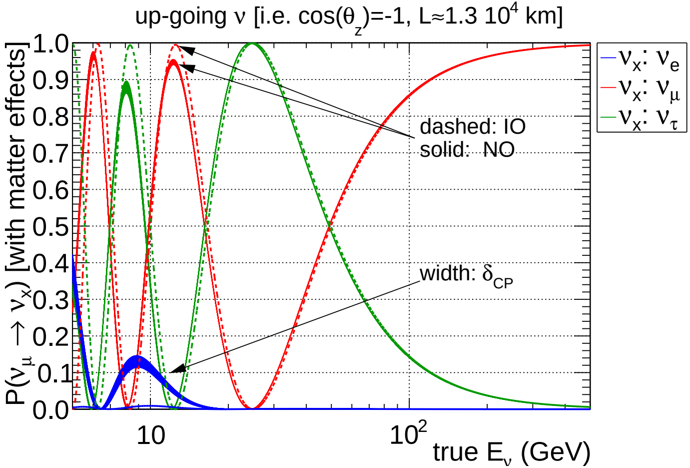

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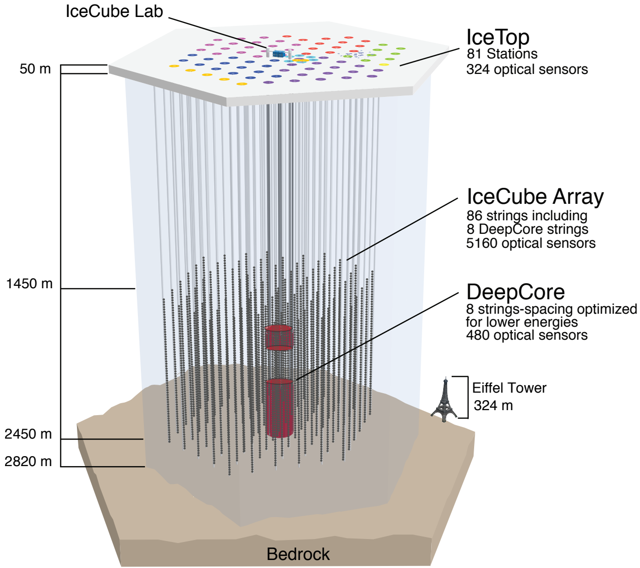
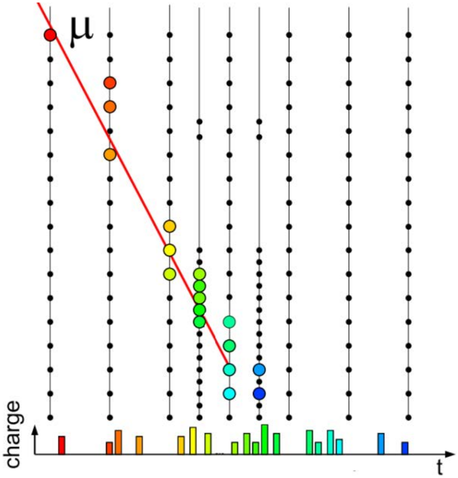
IceCube



- Instrument 1 Gton of ice
- Optimized for TeV-PeV neutrinos
  - Astrophysical ν discovered!
- At its center: DeepCore
  - $\sim$10 Mton region with denser instrumentation
  - Located in clearest ice
  - $\Rightarrow$ lower E threshold
  - $\Rightarrow$ study neutrino oscillations
  - Surrounding detector used as active veto against atmospheric μ

Measurement strategy



- 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 $L \times E \times \text{PID}$

Comparison to last published 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 (not same)

This analysis

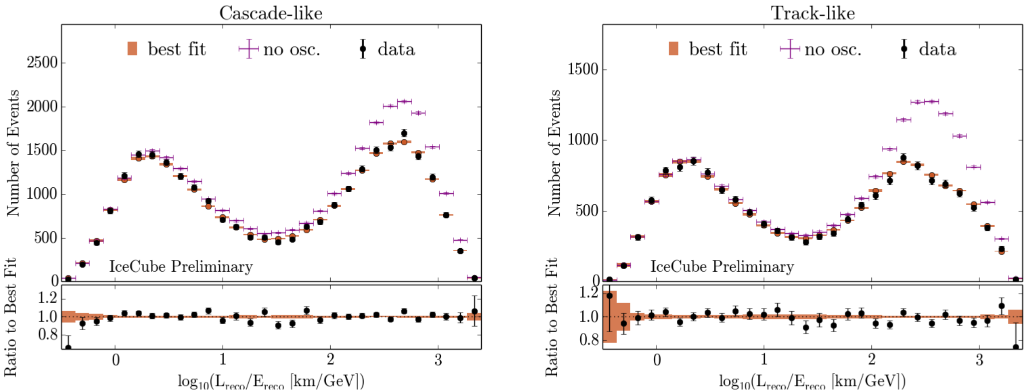
- Order of magnitude increase in statistics
- Reconstruction fits full event topology with likelihood-based method
  - Can fit events with scattered photons
  - Can reconstruct all events
- PID variable separates sample in two:
  - Track: ν_μ CC enriched sample
  - Cascade: mix of all ν flavors
- Full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

Systematics used in analysis and best fit

Parameters	Priors	Best Fit NH	Best Fit IH
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.

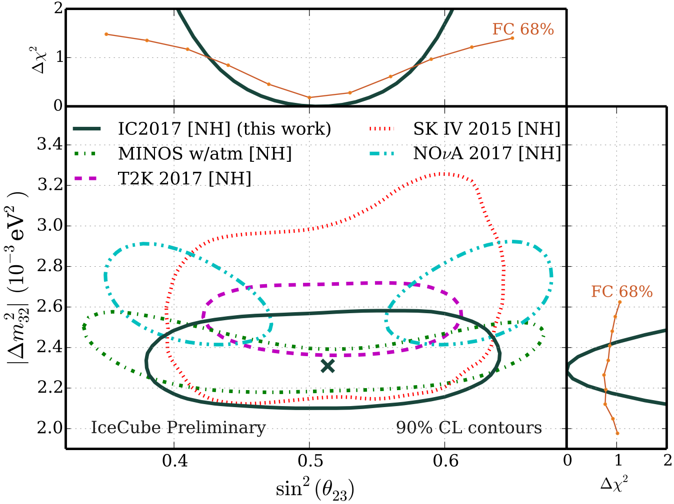
ν_μ disappearance oscillation analysis



best fit uncertainty from statistics and data-driven background shape error

- 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
  - $\chi^2/ndf = 117/119$

ν_μ disappearance oscillation analysis



- Contours calculated using Feldman-Cousins.
- Result consistent with other experiments.
- Using data from 3 years of detector operations.
- This measurement is still statistics limited!

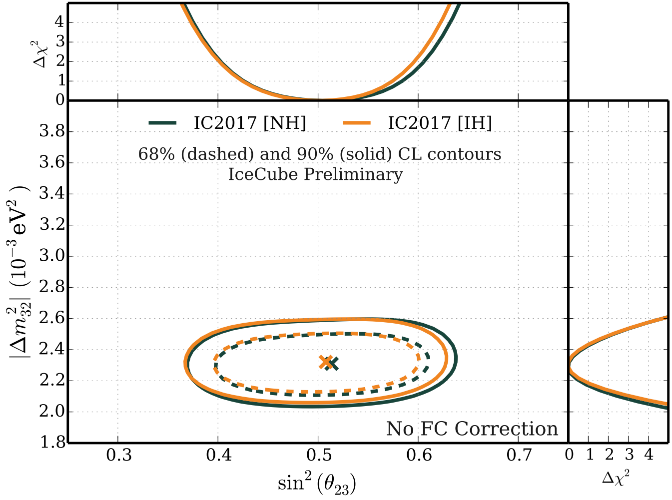
$$\Delta m^2_{32} = 2.31^{+0.11}_{-0.13} \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2\theta_{23} = 0.51^{+0.07}_{-0.09}$$

Conclusion

- Improvements in analysis techniques for IceCube-DeepCore
  - Full sky sample
  - More versatile reconstruction
- Updated measurement of ν_μ disappearance made
  - Significant reduction in θ_{23} and Δm^2_{32} ranges
  - Good data/MC agreement obtained
  - Result consistent with other experiments
    - ⋆ Preference for maximal mixing, same as T2K
  - Publication being prepared currently
- Other measurements with this new sample are under way!
- Stay tuned for more!

Backup

ν_μ disappearance oscillation analysis – inverted hierarchy



- Contours using Wilks' threshold.
- Feldman-Cousins calculated for NH shows contour smaller in Δm^2_{32}

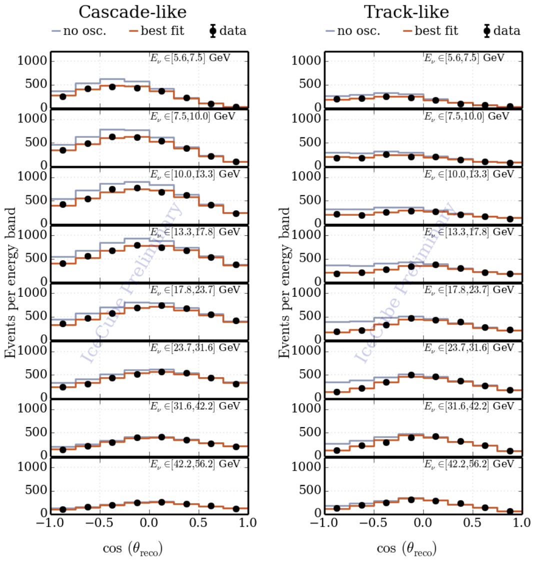
Fitting Function used in this analysis

- 30 years of MC for ν components and several systematic variants
- We use a sideband from data to measure the 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.

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

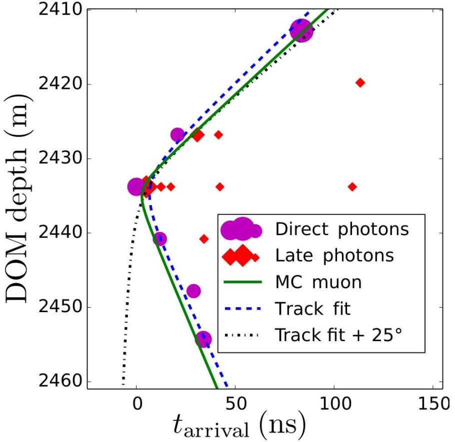
  - n_i^{pred}, n_i^{data}: number of events in bin i for prediction (ν MC + μ sideband) and data
  - σ^{data}: statistical uncertainty in the data for bin i
  - σ_i^{pred}: statistical uncertainty in prediction with additional shape uncertainty in μ sideband
  - $\hat{s}_j$, $\hat{\sigma}_{s_j}$: central value and sigma of a Gaussian prior of systematic s_j
- All bins have large enough number of events a Gaussian distribution approximates well a Poisson distribution

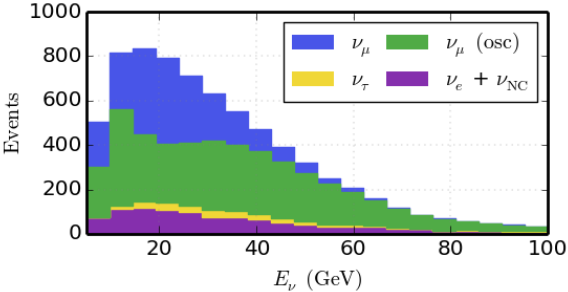
Our data and best fit in analysis binning



"golden events"

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

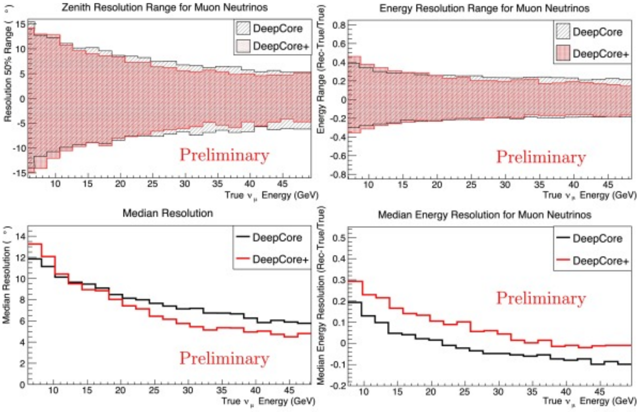




- Require several non-scattered γ
- select events "easy" to reconstruct
  - 10° resolution in neutrino zenith
  - 25% resolution in neutrino energy

HybridReco/MultiNest

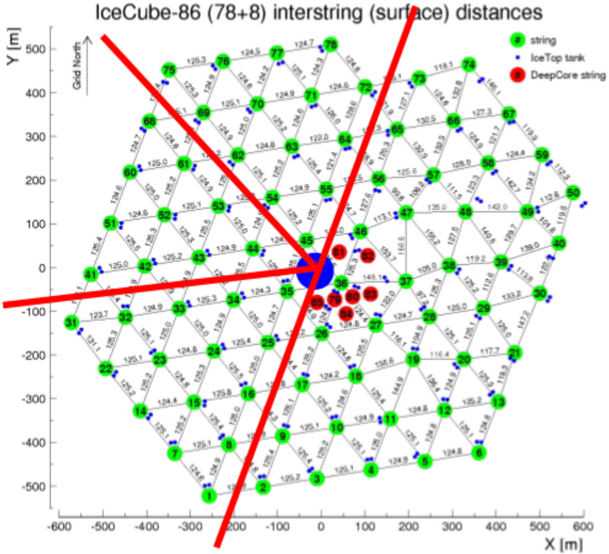
- MultiNest is an implementation of nested-sampling algorithm
  - alternative approach to Markov Chain MC
  - designed to work efficiently in multi-modal likelihood spaces
- We use it in place of a "minimizer"
  - Reconstruct 8 parameters describing low-energy ν_μ CC (HybridReco)
    - ⋆ (x,y,z,t) + (zenith, azimuth) + (track length, cascade energy)
  - If used while fixing track length at 0 m $\Rightarrow$"cascade fit"
  - Use the likelihood function defined in Millipede (Poisson)



(a) Zenith resolution. (b) Energy resolution.

- DeepCore $\rightarrow$ "golden event" analysis
- DeepCore+ $\rightarrow$ this analysis

Inverted Corridor Cut



DOM sensitivity