Measurement of Atmospheric ν_μ Disappearance with IceCube/DeepCore

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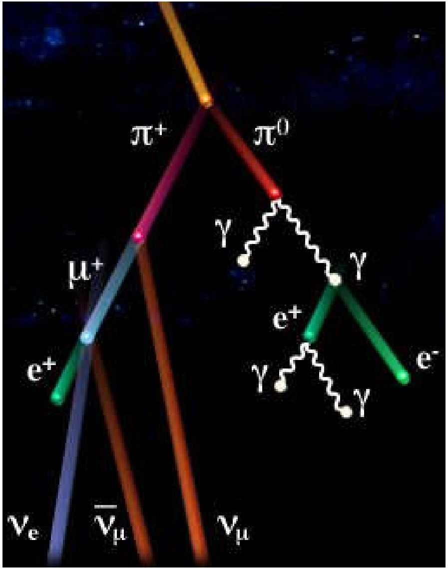
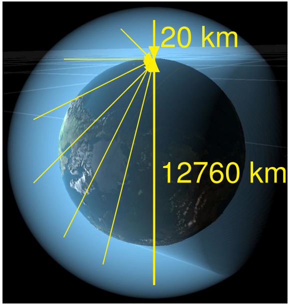
August 2nd, 2017

Atmospheric neutrinos

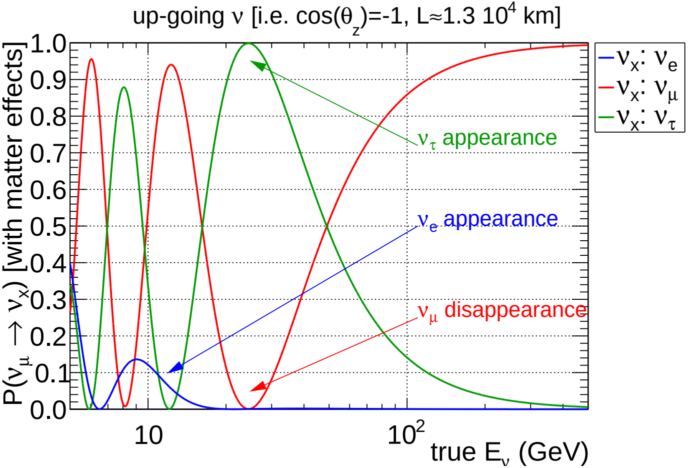


- CR interact with atmosphere producing hadronic shower
  - Decays produce ν
- ν_e:ν_μ:ν_τ produced at $\approx$1:2:0
- similar rate of ν and $\bar{\nu}$
  - however, x-sec for $\bar{\nu}$ smaller than for ν
  - $\Rightarrow$ at detection less $\bar{\nu}$ than ν

Neutrino oscillations with atmospheric neutrinos

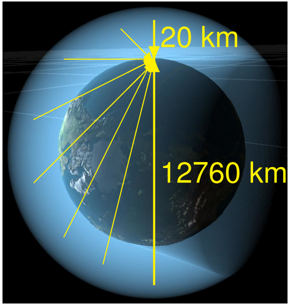


- Several baselines available
  - L/E dependency on oscillation
  - Many orders of magnitude in E
- IceCube/DeepCore:
  - See clear ν_μ disappearance



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

Neutrino oscillations with atmospheric neutrinos



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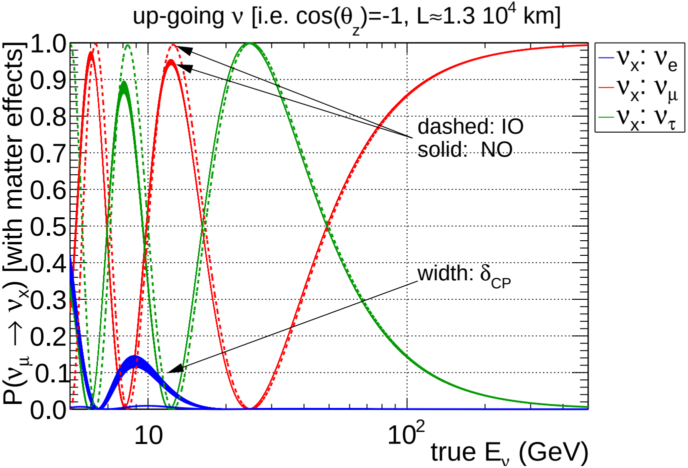

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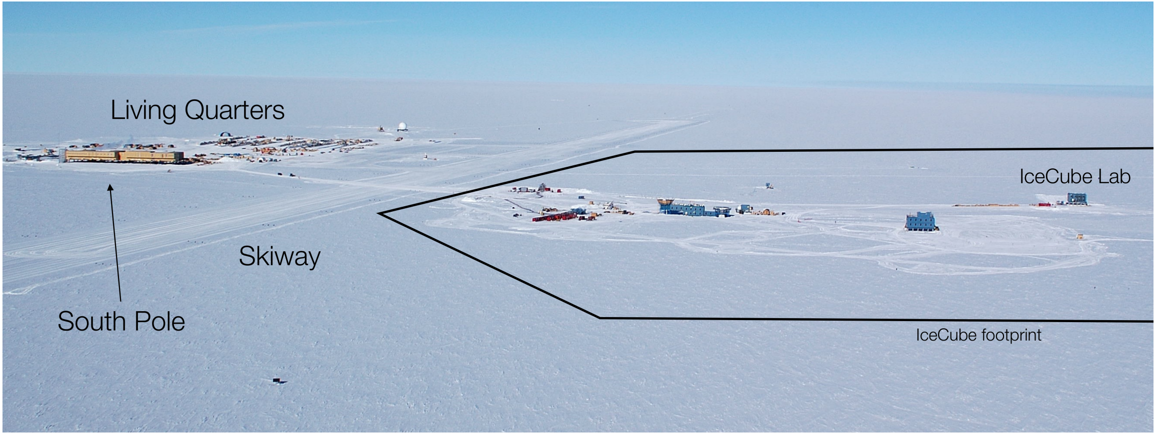
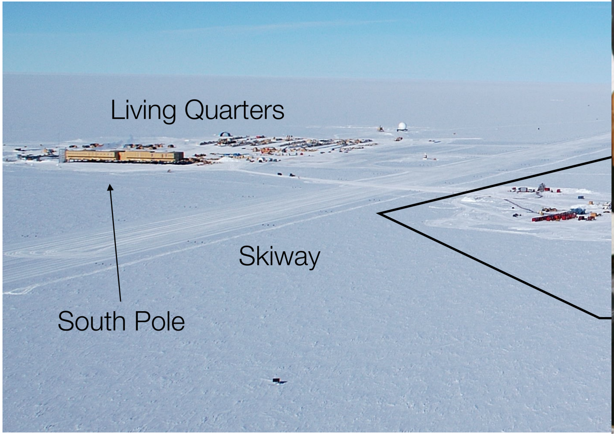
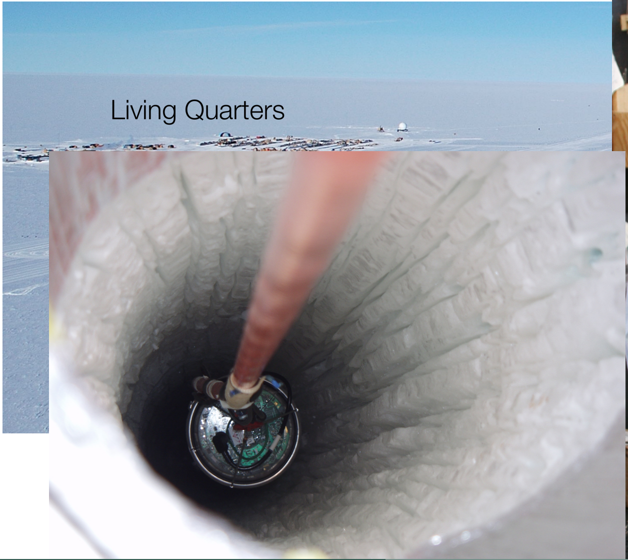
IceCube


Living Quarters
IceCube Lab
Skiway
South Pole
IceCube footprint

IceCube



IceCube

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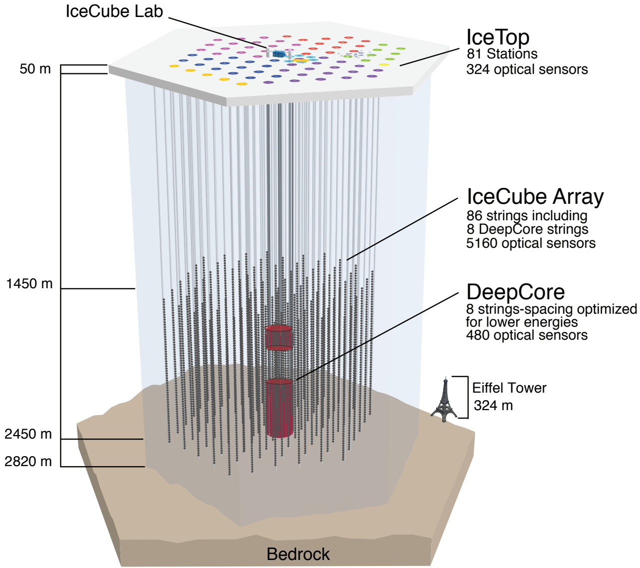
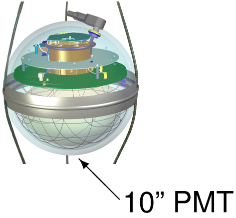
The IceCube Detector



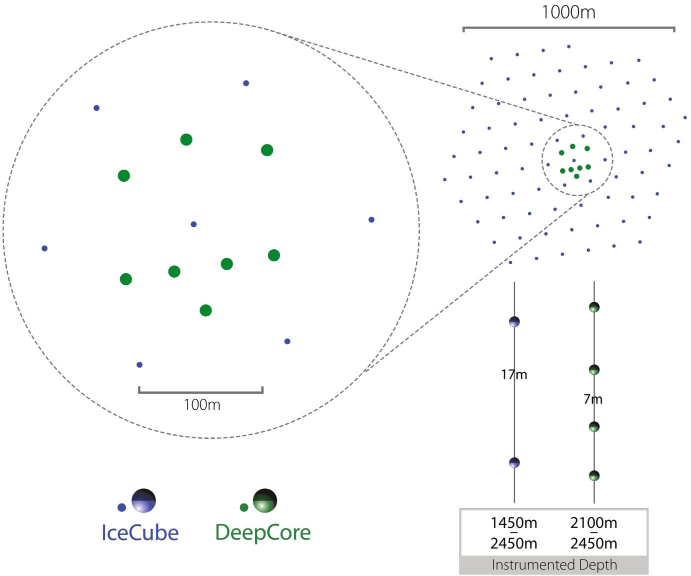
- Instrument 1 Gton of ice
- Optimized for TeV-PeV neutrinos
  - Astrophysical ν discovered!
- At its center: DeepCore

IceCube DOM



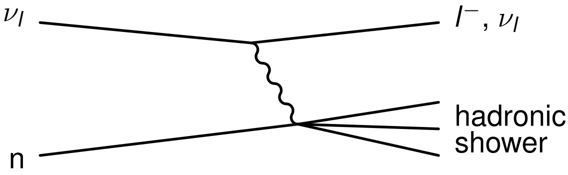
IceCube-DeepCore

- 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

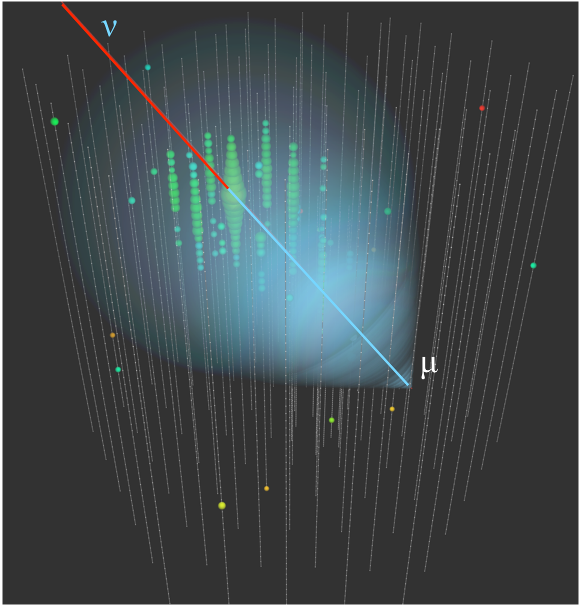


Detecting neutrinos in IceCube

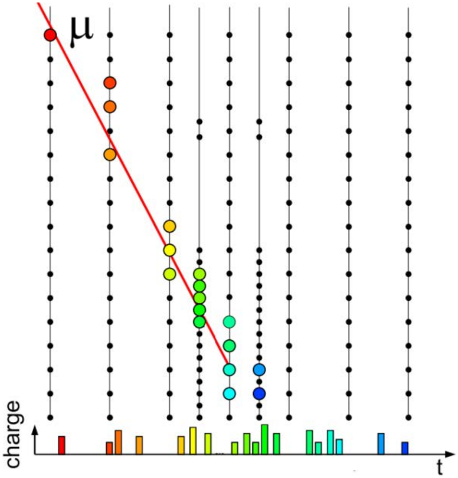
- ν interact in ice surrounding strings



- Charged particles moving at greater than speed of light in ice $\Rightarrow$ Cherenkov light cone
- 3D array of PMTs detect produced light



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 $L \times E \times$ 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

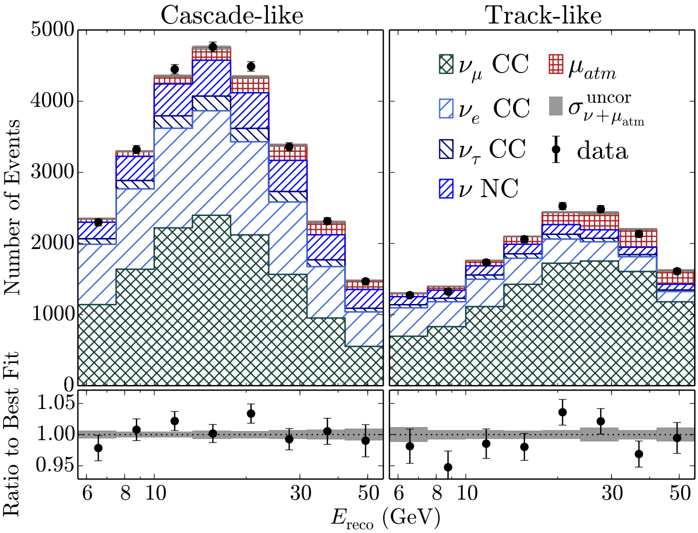
- Atmospheric μ background shape estimated from data
- ν reconstruction resolution similar
- Both are 3 year data sets (not same)

This analysis

(arXiv:1707.07081)

- 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
- Full sky analysis
  - Better control of systematic uncertainties
- Fitting includes term accounting for statistical uncertainty from prediction

Sample used in this analysis



- Analysis done with events with $E_{reco} \in [5.6, 56]$ GeV
- PID variable separates sample in two:
  - Track: ν_μ CC enriched sample
  - Cascade: mix of all ν flavors
- 41599 events from Apr. 2012-May 2015 used

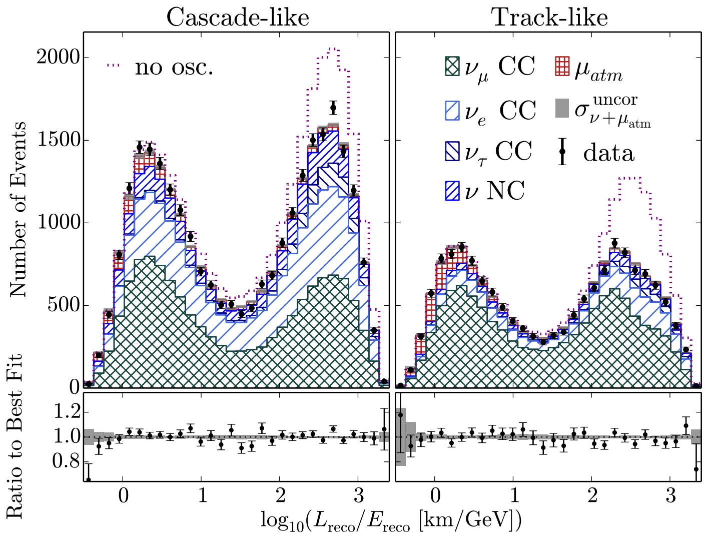
best fit uncertainty from statistics and data-driven background shape error

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.

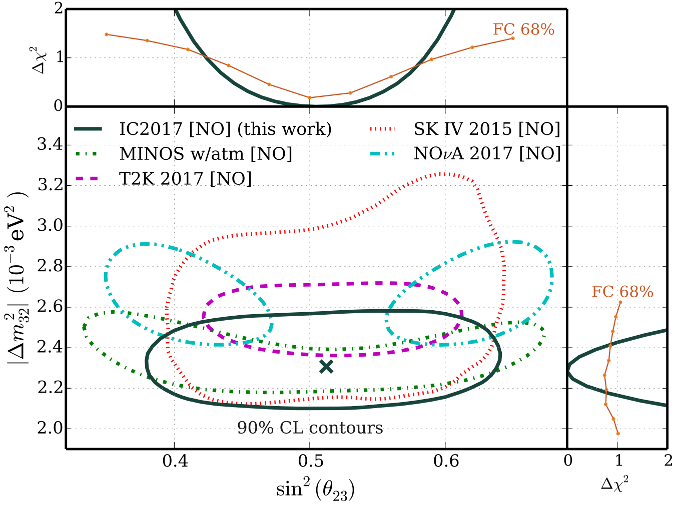
ν_μ disappearance oscillation analysis



- Fitting to data done in 3D space $(E, \cos\theta, PID) \rightarrow$ projected onto L/E for illustration
  - $\chi^2/ndf = 117/119$
- Deficit of neutrinos on Cascade-like sample coming from ν_μ id-ed as cascades

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

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!

$$\Delta m^2_{32} = 2.31^{+0.11}_{-0.13} \times 10^{-3}\ \text{eV}^2$$

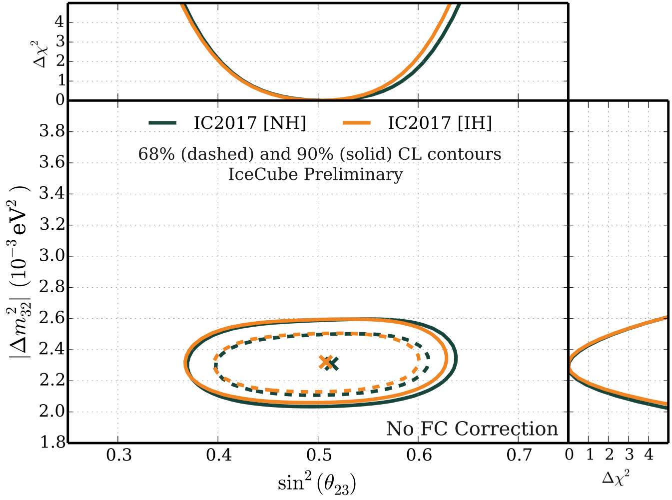
$$\sin^2\theta_{23} = 0.51^{+0.07}_{-0.09}$$

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
    - Higher energy of our sample $\rightarrow$ small/no impact from QE and RES uncertainties
  - Just posted in arXiv (1707.07081) and submitted to PRL
- 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}

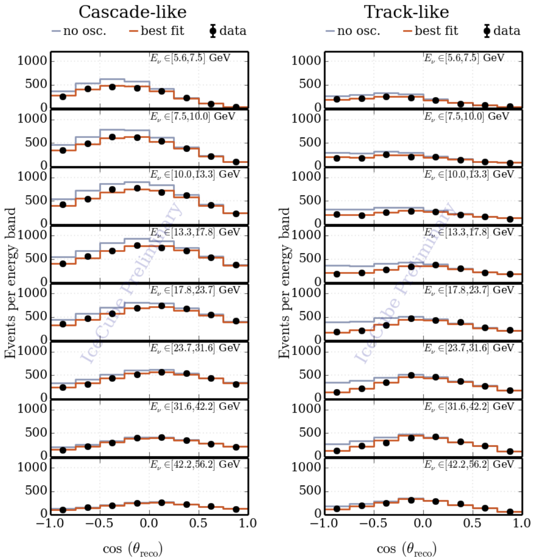
Fitting Function used in this analysis

- 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.

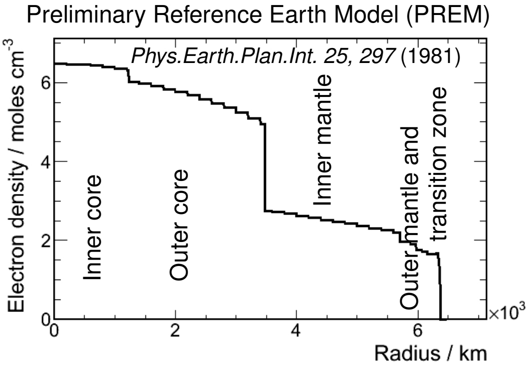
$$\chi^2 = \sum_{i \in \{\text{bins}\}} \frac{(n_i^{pred} - n_i^{data})^2}{(\sigma_i^{pred})^2 + (\sigma_i^{data})^2} + \sum_{j \in \{\text{syst}\}} \frac{(s_j - \hat{s}_j)^2}{\hat{\sigma}_{s_j}^2}$$

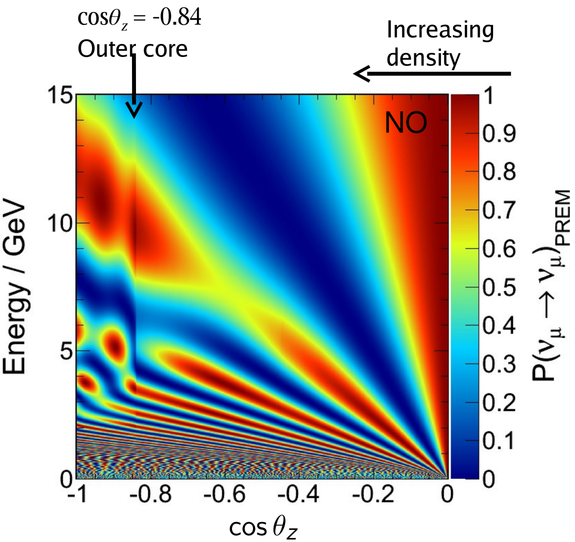
  - n_i^{pred}, n_i^{data}: number of events in bin i for prediction (ν MC + μ sideband) and data
  - σ^{data}: statistical uncertainty in the data for bin i
  - σ_i^{pred}: statistical uncertainty in prediction with additional shape uncertainty in μ sideband
  - $\hat{s}_j$, $\hat{\sigma}_{s_j}$: central 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



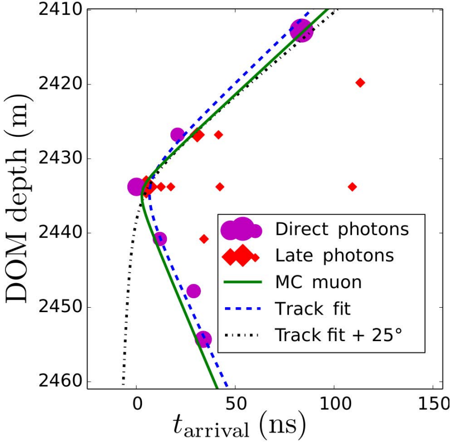
Matter Effects on Neutrino Oscillations

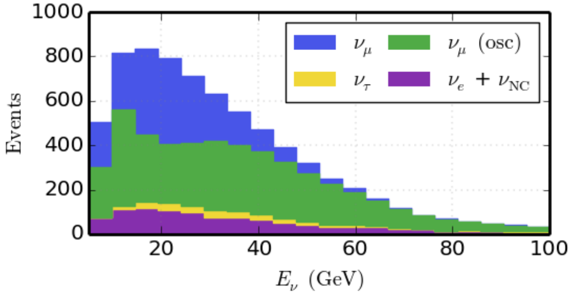




“golden events”

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

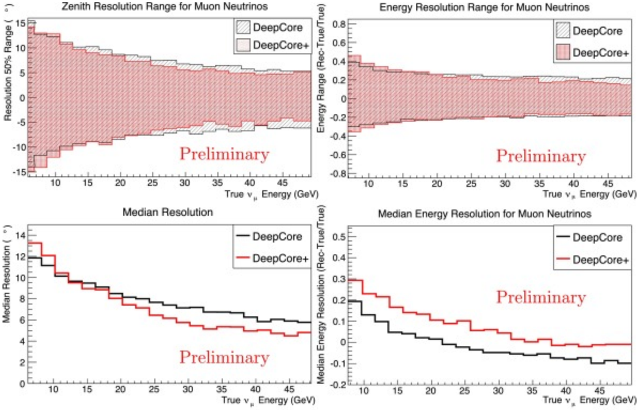




- Require several non-scattered γ
- select events “easy” to reconstruct
  - 10° resolution in neutrino zenith
  - 25% resolution in neutrino energy

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 ⇒"cascade fit"
  - Use the likelihood function defined in Millipede (Poisson)

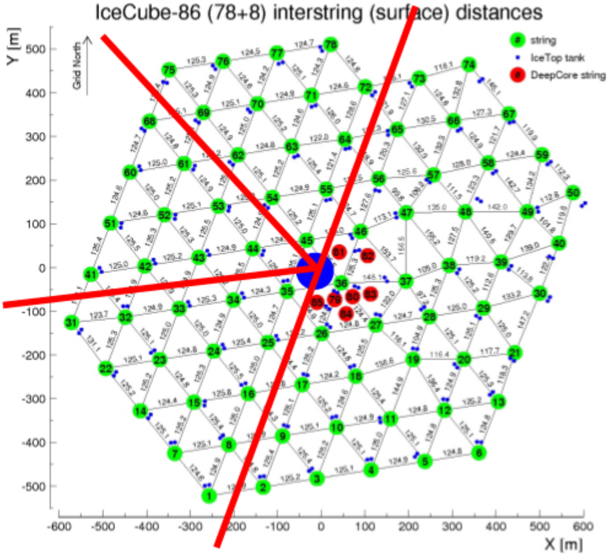


(a) Zenith resolution.

(b) Energy resolution.

- DeepCore → "golden event" analysis
- DeepCore+ → this analysis

Inverted Corridor Cut



Systematics

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

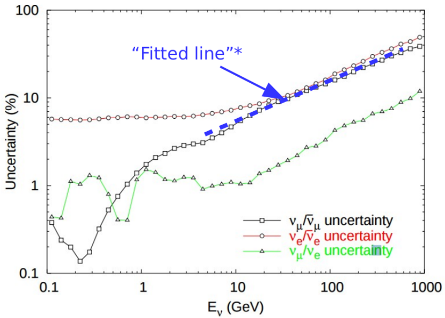
  1. Flux and cross-section
     - ⋆ Neutrino normalization
     - ⋆ Spectral index (γ)
     - ⋆ $\nu_e + \bar{\nu}_e$ normalization
     - ⋆ NC normalization
     - ⋆ $\Delta(\nu/\bar{\nu})$ as both energy and zenith dependence
     - ⋆ M_A^{RES}
  2. Detector related parameters
     - ⋆ Overall DOM efficiency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

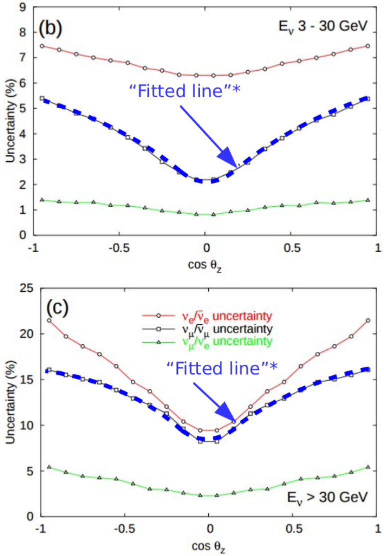
Systematics: Flux and Cross-section

- 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

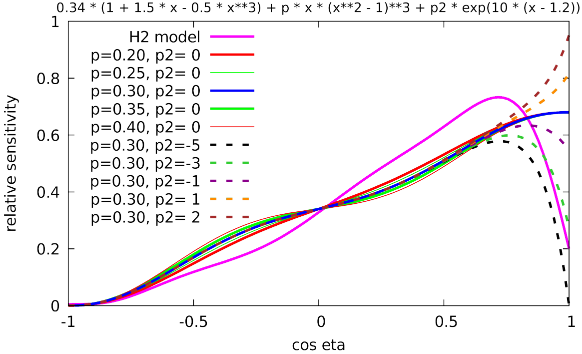
- The normalizations of $\nu_e + \bar{\nu}_e$ events and of NC events, defined relative to $\nu_\mu + \bar{\nu}_\mu$ CC events.
- The $\nu/\bar{\nu}$ ratio have a directional/energy dependence, so a more sophisticated approach was used.
  - From the K/π ratio of the atmospheric shower
- Parameterizations 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