Measurement of Atmospheric ν_μ Disappearance with IceCube/DeepCore

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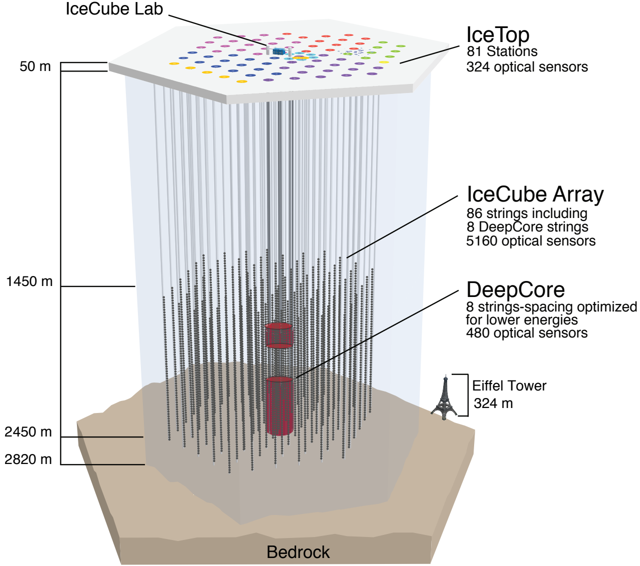
IceCube

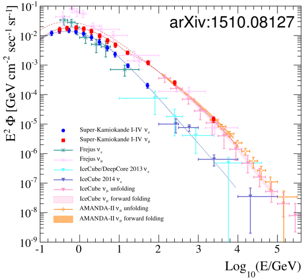


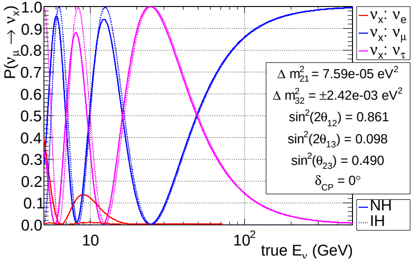
- IceCube: 1 Gton water Cherenkov detector
  - Detector embedded in 3 km thick Antarctic ice sheet
  - Optimized for $E_\nu > 100$ GeV ν's
- DeepCore:
  - $\sim$6 Mton more densely instrumented region in the center of IceCube
  - Located in deepest, clearest ice

  $\Rightarrow$ lower energy detection threshold (down to $E_\nu \sim 5$ GeV)

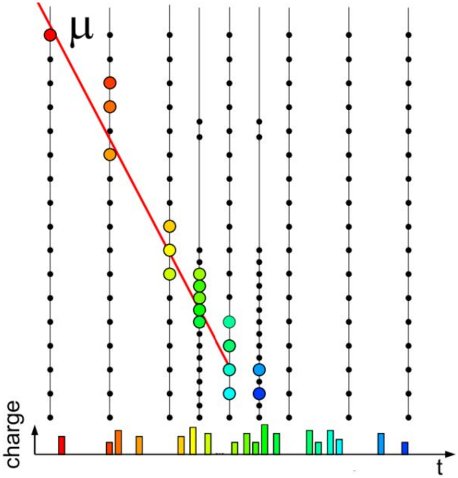
Using atmospheric ν to study ν oscillation

- Large quantity of neutrinos from different baselines and energies
  - $\sim 10^5$/year ν_μ trigger DC
  - $\sim 10^4$/year of those used in oscillation analysis
- Neutrinos oscillating through the Earth's diameter have "first" maximum of ν_μ disappearance at $\sim$ 25 GeV
  - signal accessible with DeepCore
- Hierarchy dependent matter effects below $\sim$12 GeV
  - too low energy for DC $\Rightarrow$ little/no impact on oscillation result





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 $L \times E$ distribution

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

This analysis

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

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.

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

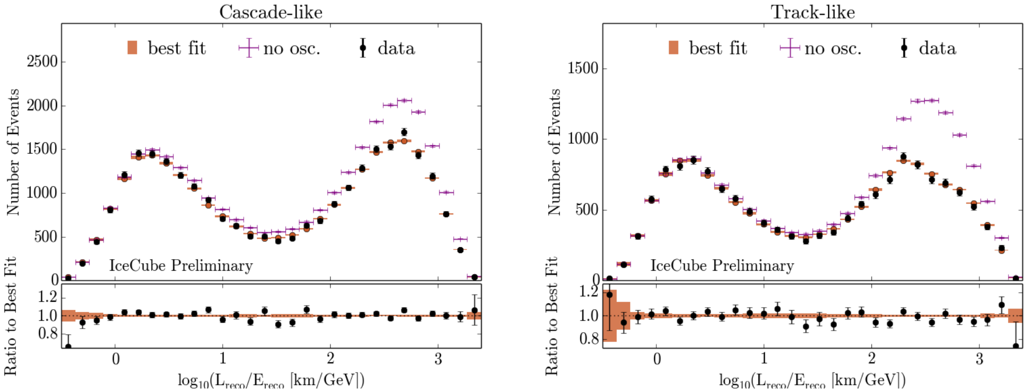
  - n_i^{pred}, n_i^{data}: number of events in bin i for prediction (ν MC + μ sideband) and data
  - σ^{data}: statistical uncertainty in the data for bin i
  - σ_i^{pred}: statistical uncertainty in prediction with additional shape uncertainty in μ sideband
  - $\hat{s}_j$, $\hat{\sigma}_{s_j}$: central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

Systematics used in analysis and best fit

Parameter	Priors	Best fit NH	Best fit IH
Standard neutrino mixing parameters			
Δm^2_{32} [10^{-3} eV^2/c^4]	no prior	$2.31^{+0.12}_{-0.14}$	$-2.32^{+0.12}_{0.13}$
$\sin^2\theta_{23}$	no prior	$0.51^{+0.08}_{-0.08}$	$0.51^{+0.08}_{-0.07}$
Atmospheric neutrino flux parameters			
$\Delta\gamma$ (spectral index)	0.00±0.10	-0.02	-0.02
ν_e normalization	1.00±0.20	1.24	1.24
ν NC normalization	1.00±0.20	1.05	1.05
$\Delta(\nu/\bar{\nu})$, energy dependent	‡	-0.56σ	-0.60σ
$\Delta(\nu/\bar{\nu})$, zenith dependent	‡	-0.53σ	-0.55σ
Cross section parameters (from GENIE)			
M_A (resonance) [GeV]	1.12±0.22	0.91	0.92
Detector parameters			
DOM lateral sensitivity (hole ice)	0.020±0.010	0.022	0.022
DOM forward sensitivity (hole ice)	no prior	-0.76	-0.70
DOM efficiency [% of nominal]	100±10	103	103
Background			
Atm. μ contamination [%]	no prior	5.2	5.2

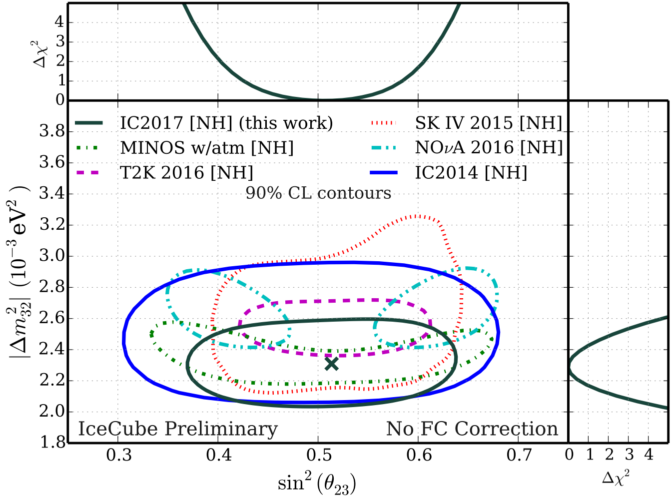
‡: Following Barr, et al., PRD74, 094009.

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
  - $\chi^2/ndf = 123.2/119$

ν_μ disappearance oscillation analysis



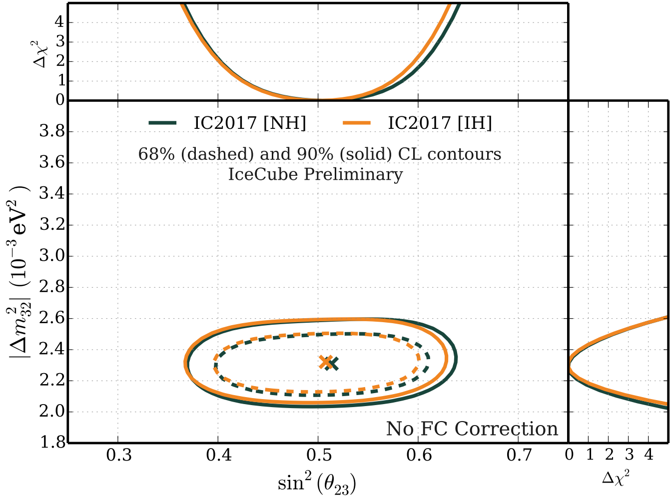
- Preliminary contours using Wilks' threshold, Feldman-Cousins being calculated (contours expected to shrink with FC).
- Result consistent with other experiments.
- Using data from 3 years of detector operations.
- This measurement is still statistics limited!

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
  - Feldman Cousins contour being calculated, expected to shrink shown contour
- Other measurements with this new sample are under way!
- Stay tuned for more!

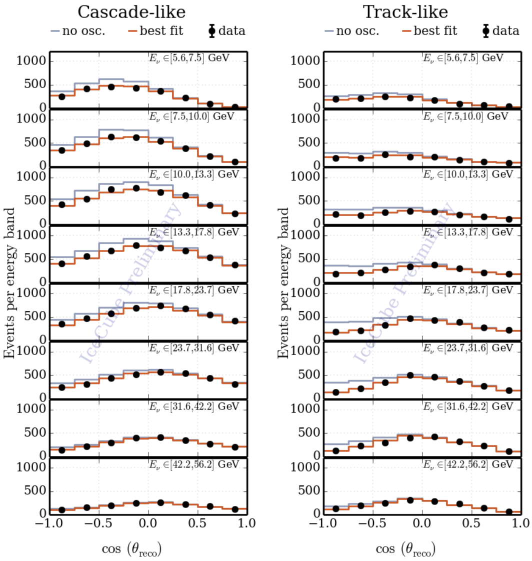
Backup

ν_μ disappearance oscillation analysis – inverted hierarchy



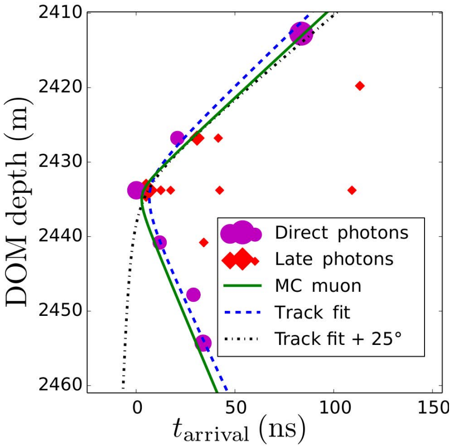
- Preliminary contours using Wilks' threshold, Feldman-Cousins being calculated (expect contours to shrink with FC).

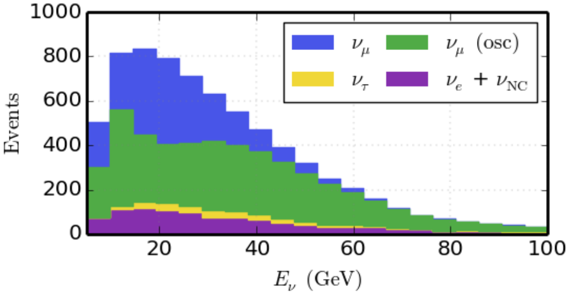
Our data and best fit in analysis binning



"golden events"

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

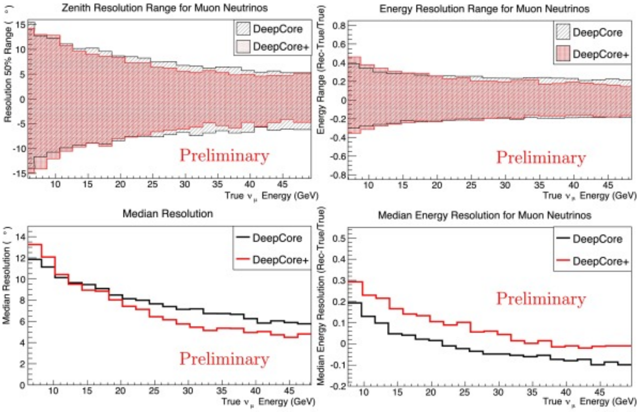




- Require several non-scattered γ
- select events "easy" to reconstruct
  - 10° resolution in neutrino zenith
  - 25% resolution in neutrino energy

HybridReco/MultiNest

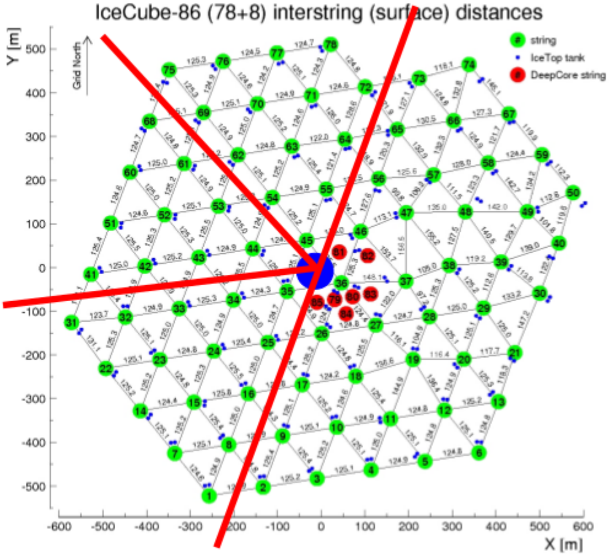
- MultiNest is an implementation of nested-sampling algorithm
  - alternative approach to Markov Chain MC
  - designed to work efficiently in multi-modal likelihood spaces
- We use it in place of a “minimizer”
  - Reconstruct 8 parameters describing low-energy ν_μ CC (HybridReco)
    - ⋆ (x,y,z,t) +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



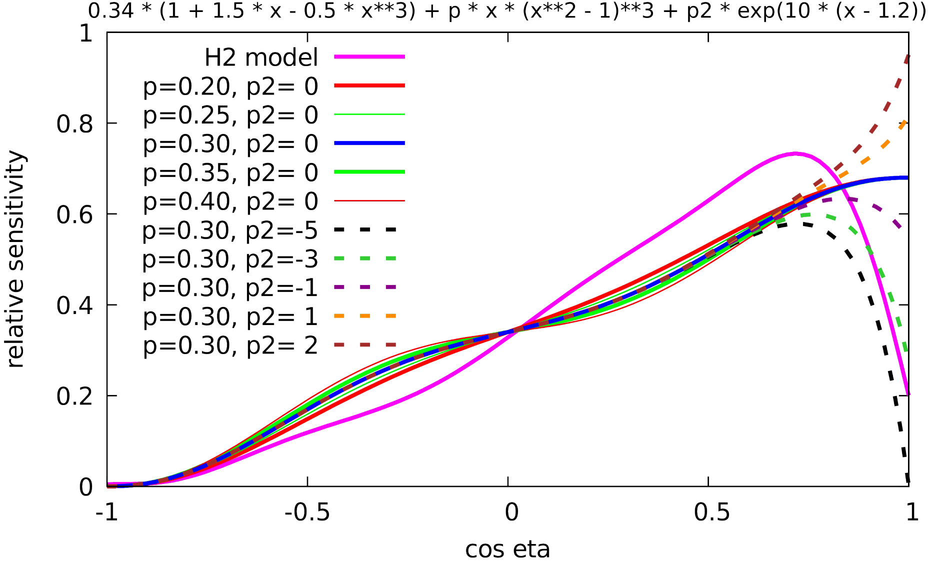
(a) Zenith resolution.

(b) Energy resolution.

Inverted Corridor Cut



DOM sensitivity



L4: straight cuts

- Noise triggers rejection:
  - RT Fiducial charge > 7 PE in [-250,+500] ns from trigger
  - -(400m)$^2 \leq \Delta s^2 = (\Delta x)^2 - (c\Delta t)^2 \leq 0$ m^2
  - Number of DOMs in SRTTWOfflinePulsesDC ≥ 8
  - 7 m $\leq \sigma_{COGz} \leq$ 100 m
  - $\sigma_{COGt} \leq$ 1000 ns
- Atmospheric μ rejection:
  - DeepCore Classic veto charge < 5 PE
  - *Causal track veto*: veto charge < 7 PE
- Preliminary containment (Quality cut):

  Z' and ρ' are centered at string 36 with Z at -350 m in IC coordinates, that is the "center" of DeepCore
  - -125 m $\leq Z'_{1stHLC} \leq$ 150 m
  - $\rho'_{1stHLC} \leq$ 150 m
  - -125 m $\leq Z'_{COGQ1} \leq$ 200 m
  - $\rho'_{COGQ1} \leq$ 150 m

L5: BDT cut

- BDT score ≥ 0.2
- 11 variables used in BDT:
  - NumHitDOMs
  - Total charge
  - σ_{COGz}
  - COG_{Q1} ρ and COG_{Q1} z
  - Separation: spacial distance between COG_{Q1} and COG_{Q4}
  - QR3 and C2QR3
  - SPE11 zenith
  - Linefit zenith and speed

L6: final cuts

- Corridor Cut: maximum of 1 DOM hit
  - Inverted Corridor Cut: 2 or more DOM hits
- Containment on HybridReco/MultiNest fit:
  - -125 m $\leq Z'_{start}$ and $r'_{start} \leq$ 125 m if $Z'_{start} \geq$0 m
  - $\rho'_{start} \leq$ 100 m
  - -150 m $\leq Z'_{stop} \leq$ 150 m
  - $\rho'_{stop} \leq$ 150 m