Searches for Tau Neutrinos from Oscillations with IceCube/DeepCore

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The IceCube-DeepCore Detector

- Neutrino detector built at the South Pole
- Sensitive to a wide range of physics goals
  - Atmospheric neutrinos at low energies
  - Astrophysical neutrinos at higher energies

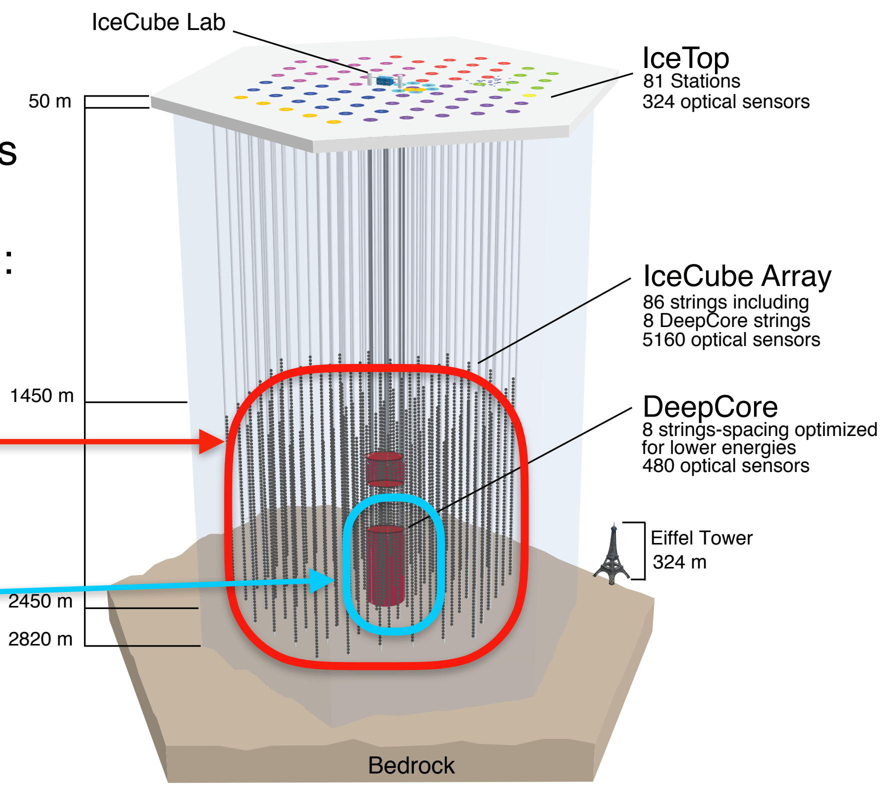
- Two major parts of the detector buried in the ice:

IceCube:

- Primarily optimized for TeV energies
- Provides active veto for DeepCore

DeepCore:

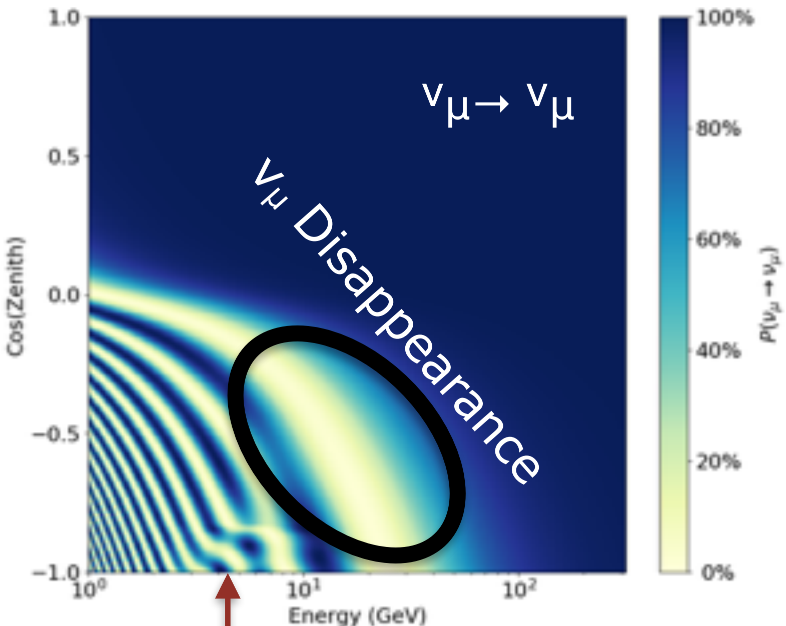
- Denser string, PMT spacing
- Clearest ice available
- Sensitive to ~5 GeV neutrinos



Atmospheric Neutrino Oscillations

- Cosmic ray interactions in the Earth's atmosphere lead to significant neutrino flux
- Oscillations result in changes to flavor composition of flux
    - Approximately parametrized in terms of mixing angles and mass splittings

$$P\left(\nu_\mu \to \nu_\mu\right) \approx 1 - \sin^2 2\theta_{23}\, sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

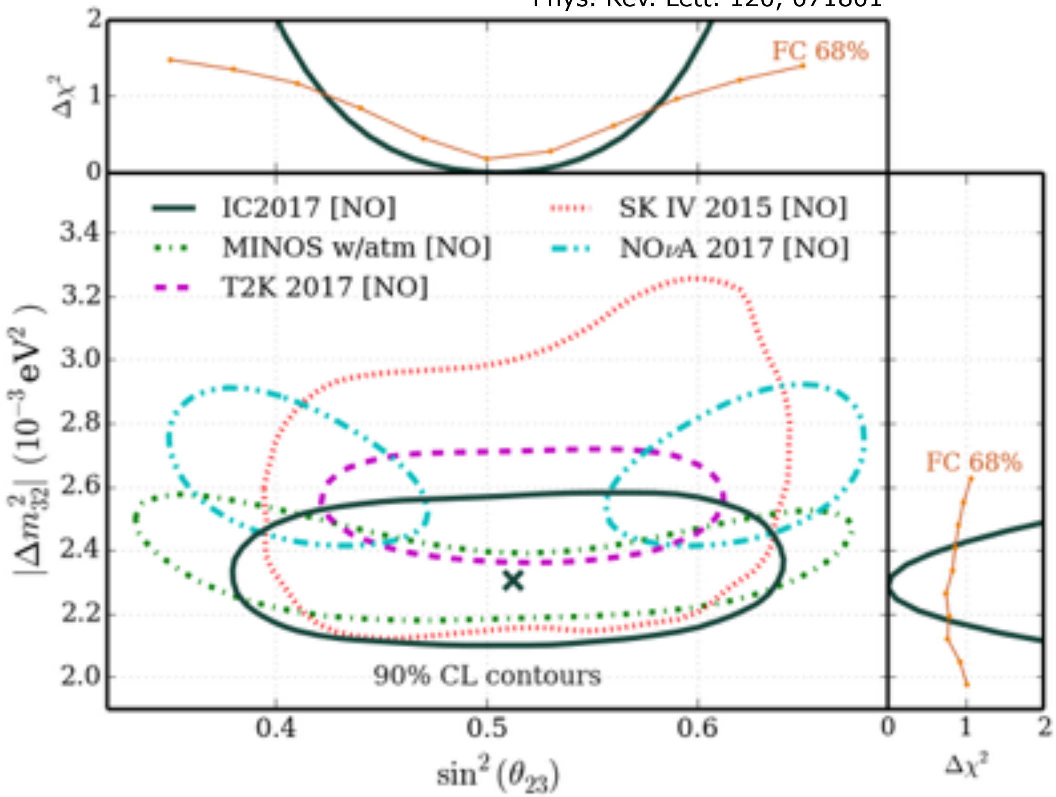


Matter effects in Earth's core

IceCube (and Others) Measures $\nu_\mu \rightarrow \nu_\tau$ Oscillations

- New result using 3 years of DeepCore data recently published
- Search for ν_μ disappearance with full-sky sample, 5.6-56 GeV
- Separation into cascade-like, track-like events provides control region for systematics
- Observed 40962 events
- Good data/MC agreement
- Competitive constraints consistent with other experiments

Phys. Rev. Lett. 120, 071801

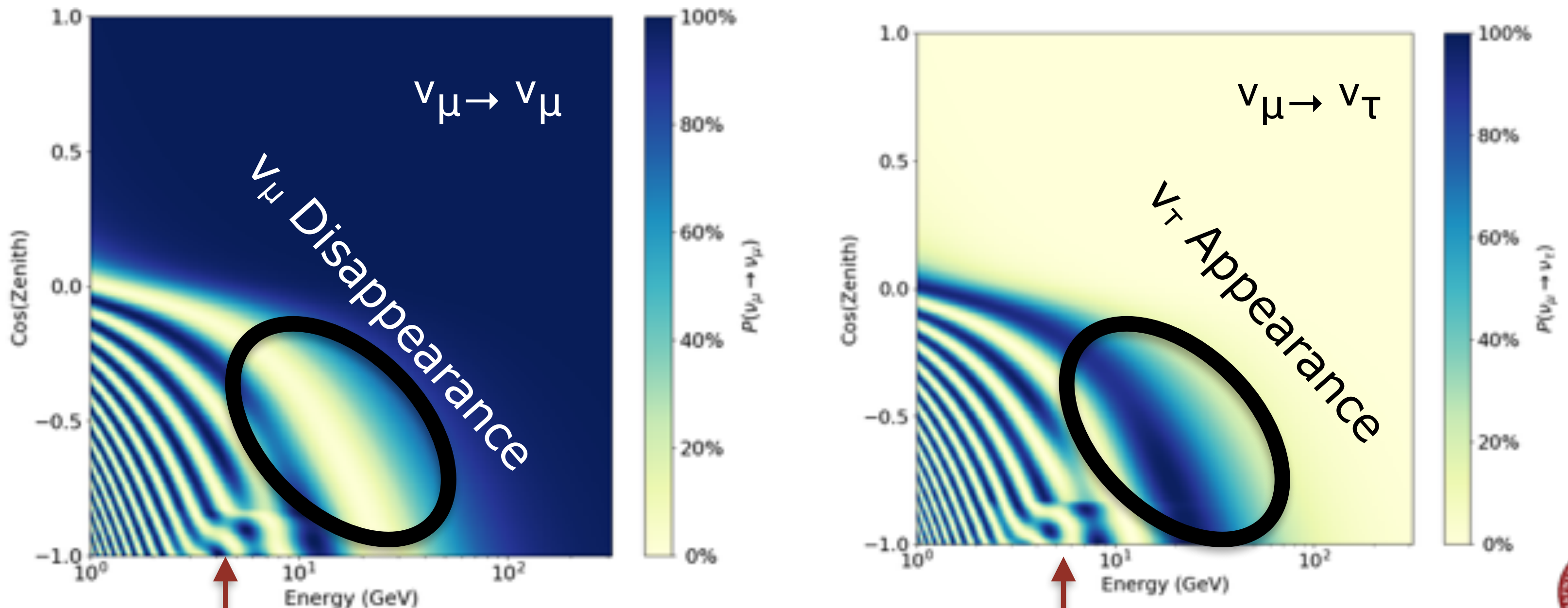


Atmospheric Neutrino Oscillations

- Approximately parametrized in terms of mixing angles and mass splittings

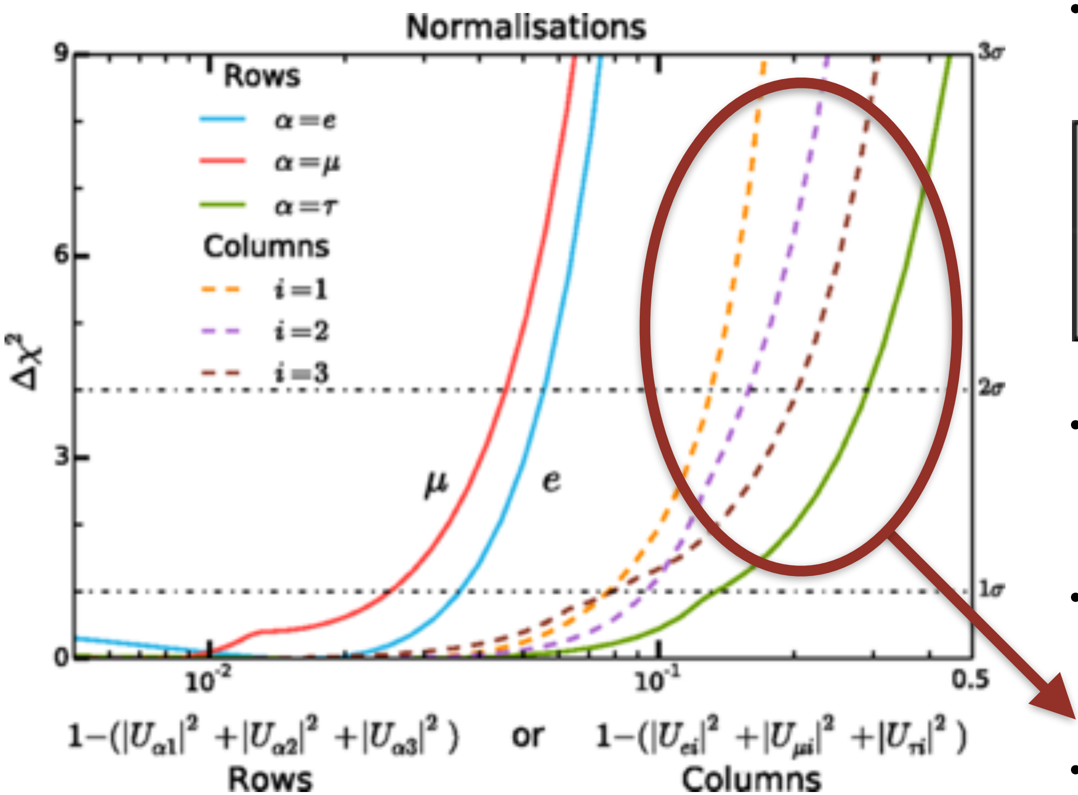
$$P\left(\nu_\mu \rightarrow \nu_\mu\right) \approx 1 - \sin^2 2\theta_{23}\, sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$$

$$P\left(\nu_\mu \rightarrow \nu_\tau\right) \approx \sin^2 2\theta_{23}\, sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$$



Matter effects in Earth's core

Why Measure Tau Neutrinos?



Parke and Ross-Lonergan,
Phys. Rev. D 93, 113009 (2016)

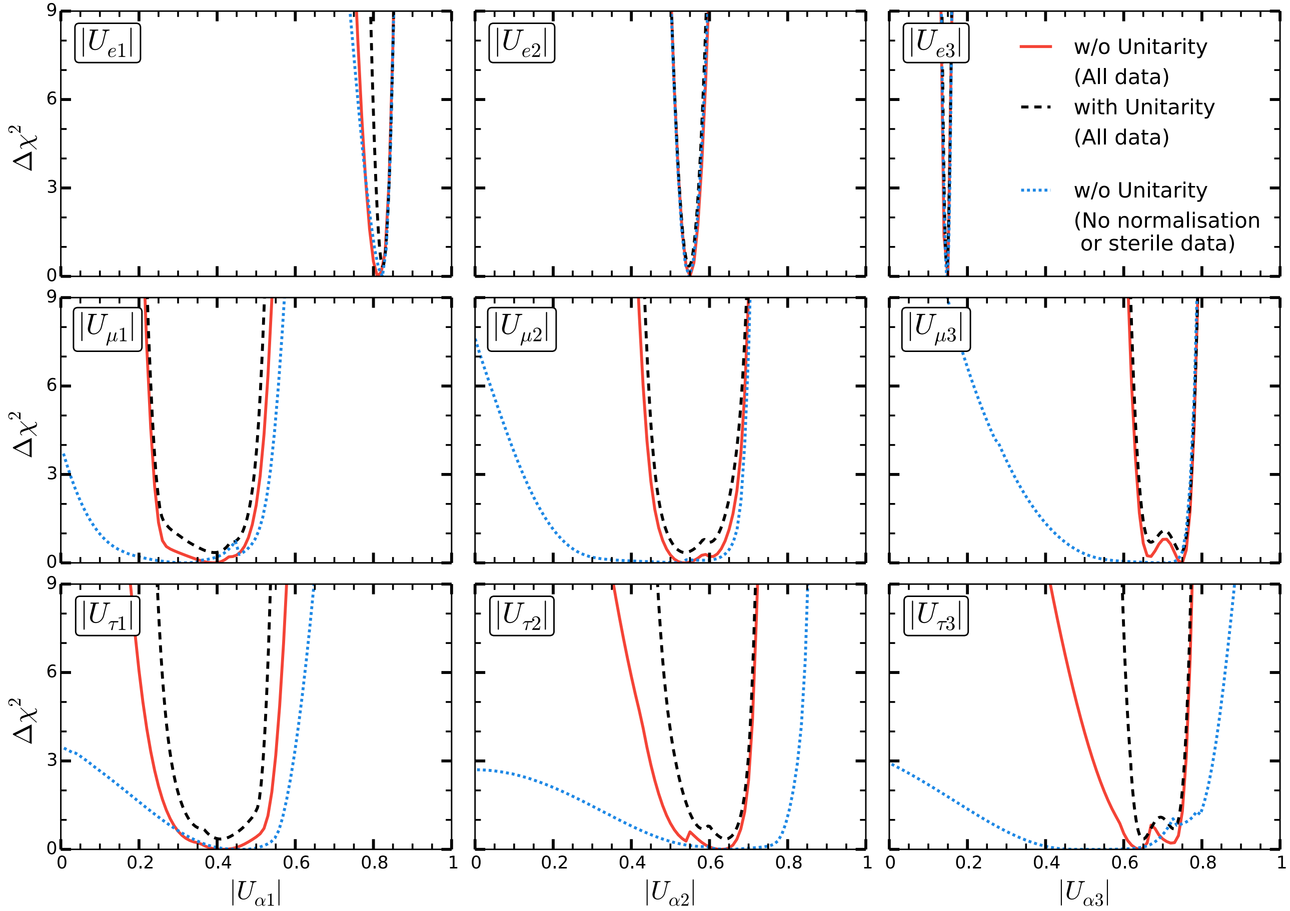
- Mixing between flavors described by PMNS mixing matrix

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{bmatrix}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

- Matrix is **assumed** to be unitary for oscillation experiments
- Unitarity can be **tested** with existing experimental data
- Largest uncertainties in unitarity measurements in τ-related elements

Why Measure Tau Neutrinos?

Parke and Ross-Lonergan, Phys. Rev. D 93, 113009 (2016)



- Strong experimental constraints on ν_e and ν_μ terms even without unitarity
- Large uncertainties on ν_τ related terms without unitarity constraints

Why Measure Tau Neutrinos?

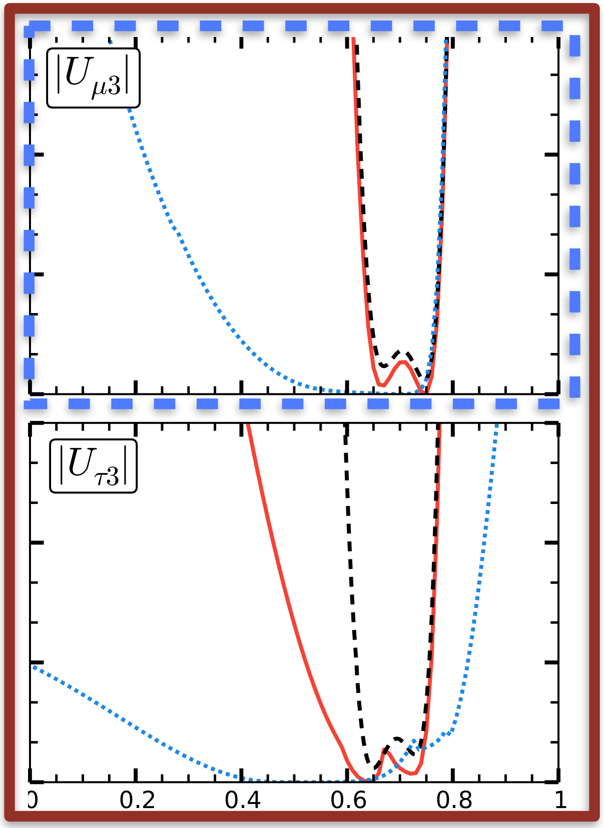
Parke and Ross-Lonergan,
Phys. Rev. D 93, 113009 (2016)

Atmospheric ν_μ Disappearance

$$P\left(\nu_\mu \rightarrow \nu_\mu\right) = 1 - \left| \sum_i U_{\mu i}^* U_{\mu i} e^{-i m_i^2 L/2E} \right|^2$$

Atmospheric ν_τ Appearance

$$P\left(\nu_\mu \rightarrow \nu_\tau\right) = \left| \sum_i U_{\mu i}^* U_{\tau i} e^{-i m_i^2 L/2E} \right|^2$$



- Appearance and disappearance are sensitive to different elements
  - Appearance depends on multiple elements
  - Measure both simultaneously in full 3-flavor framework

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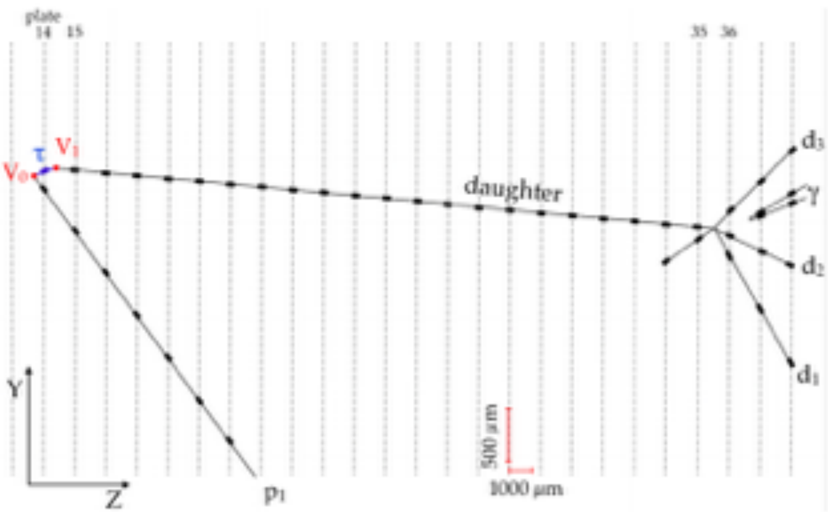
Previous Limits on Appearance

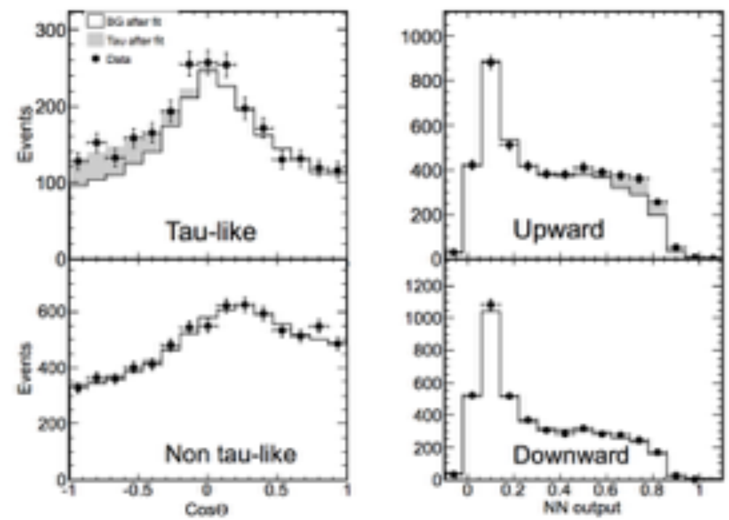
OPERA



Phys. Rev. Lett. 115, 121802 (2015)

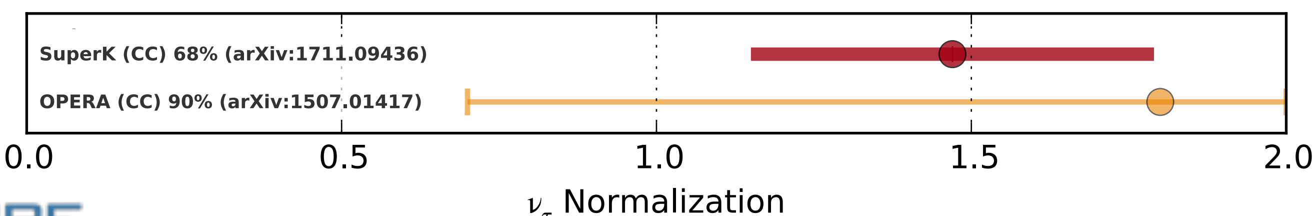
- Measurement of individual ν_τ events
- Identified 5 events
- 5.1σ rejection of no-appearance

Super-Kamiokande



arXiv:1711.09436

- Statistical fit to identify ν_τ events
- Found (1.47±0.32) x expectation



Parametrizing ν_τ Appearance

- Define "tau normalization", N_τ, as modification of expected tau neutrino event rate from standard muon neutrino flux, cross section, oscillations, etc.

$$R'_{\nu_\tau} = N_{\nu_\tau} \; R_{\nu_\tau}(\theta_{23}, \theta_{13}, \Delta m^2_{31}, \ldots)$$

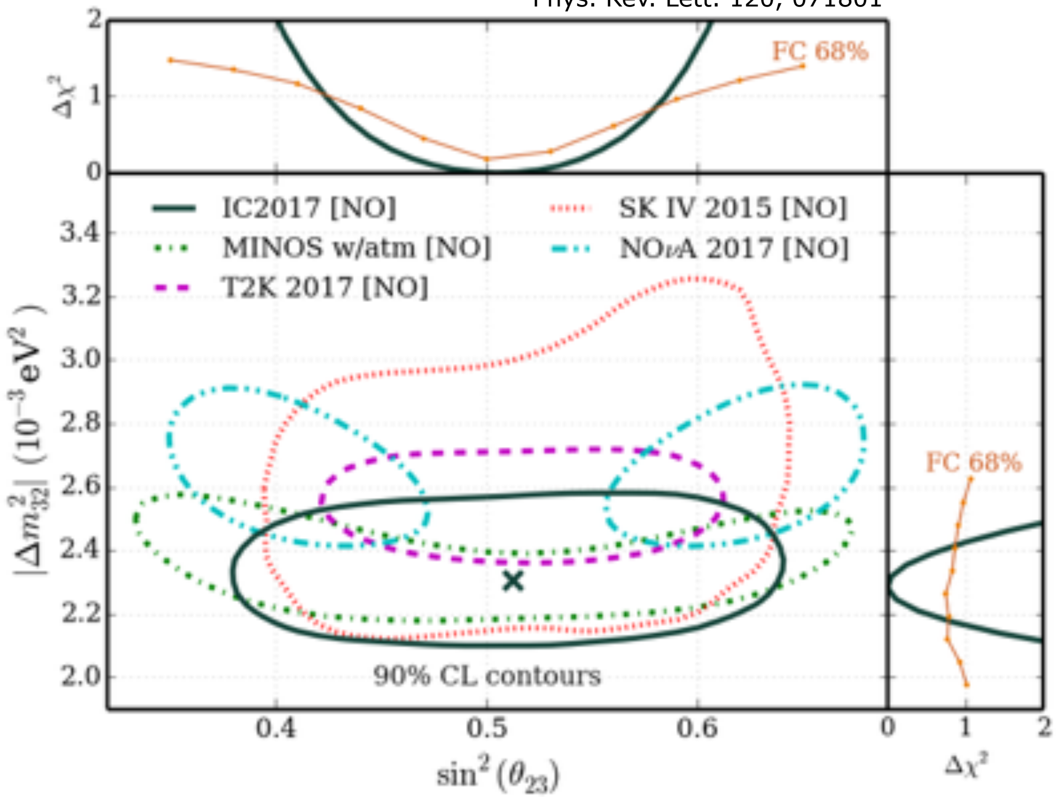
- Fitting systematics (including disappearance) simultaneously
  - N_τ always with respect to current expectation

- Can apply this to just CC ν_τ or both (NC+CC) ν_τ interactions
  - Super-K, OPERA performed CC-only measurement
  - Showing the NC+CC measurement today. CC-only in backup

Using an Existing Selection

- New result using 3 years of DeepCore data recently published
- Search for ν_μ disappearance with full-sky sample, 5.6-56 GeV
- Separation into cascade-like, track-like events provides control region for systematics
- Observed 40962 events
- Good data/MC agreement
- **Can be used for ν_τ appearance search as well!**

Phys. Rev. Lett. 120, 071801



Increasing Sensitivity to Appearance

- The existing event sample was designed for a very clean muon neutrino disappearance measurement
  - ν_τ were not actively rejected
  - … but also not actively selected for.
- Can we build a more sensitive dataset for appearance? Yes!

Analysis 1

- Developed for ν_μ disappearance measurement
- Uses data to model background muons
- Strong containment on starting, stopping vertex
- Observed 41k events/3 years

Analysis 2

- Developed for ν_τ appearance measurement
- Uses simulation to model background muons
- Strong containment on starting vertex only
- Recently unblinded
- Found 62k events/3 years

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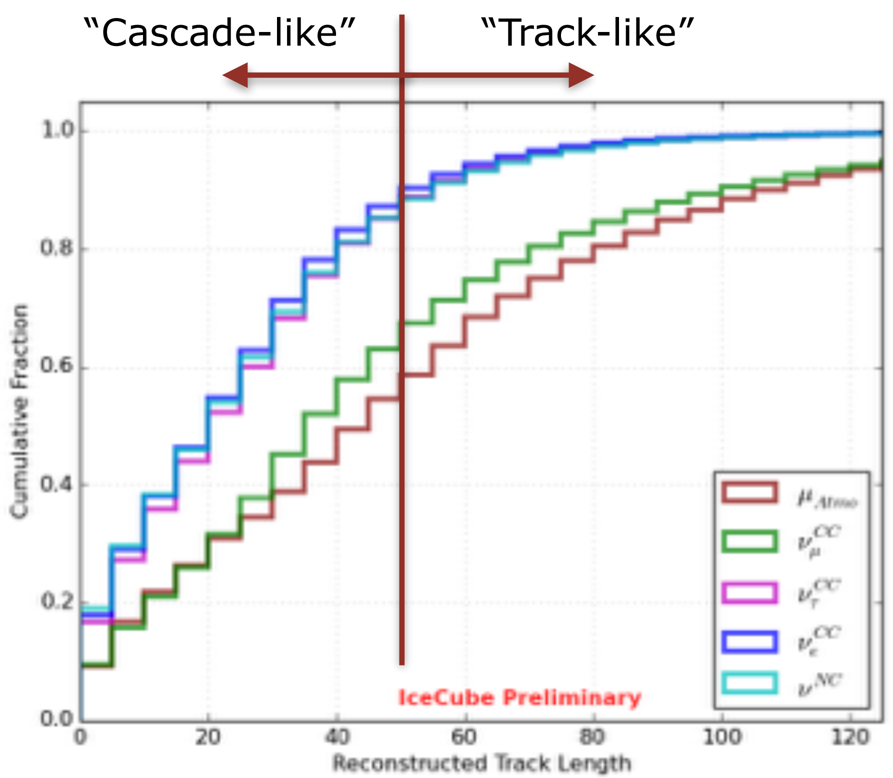
Analysis 2: Higher Statistics

- Independently developed sample with wide energy reach
- Similar reconstruction algorithms
- Use of direct MC simulation to model backgrounds

- 62212 events observed in data
    - ~50% more total neutrinos than previously used selection
- Including 3 years of detector data

- For this work, match energy range of previous analysis
- Events separated into "cascade-like", "track-like" based on reconstructed muon length

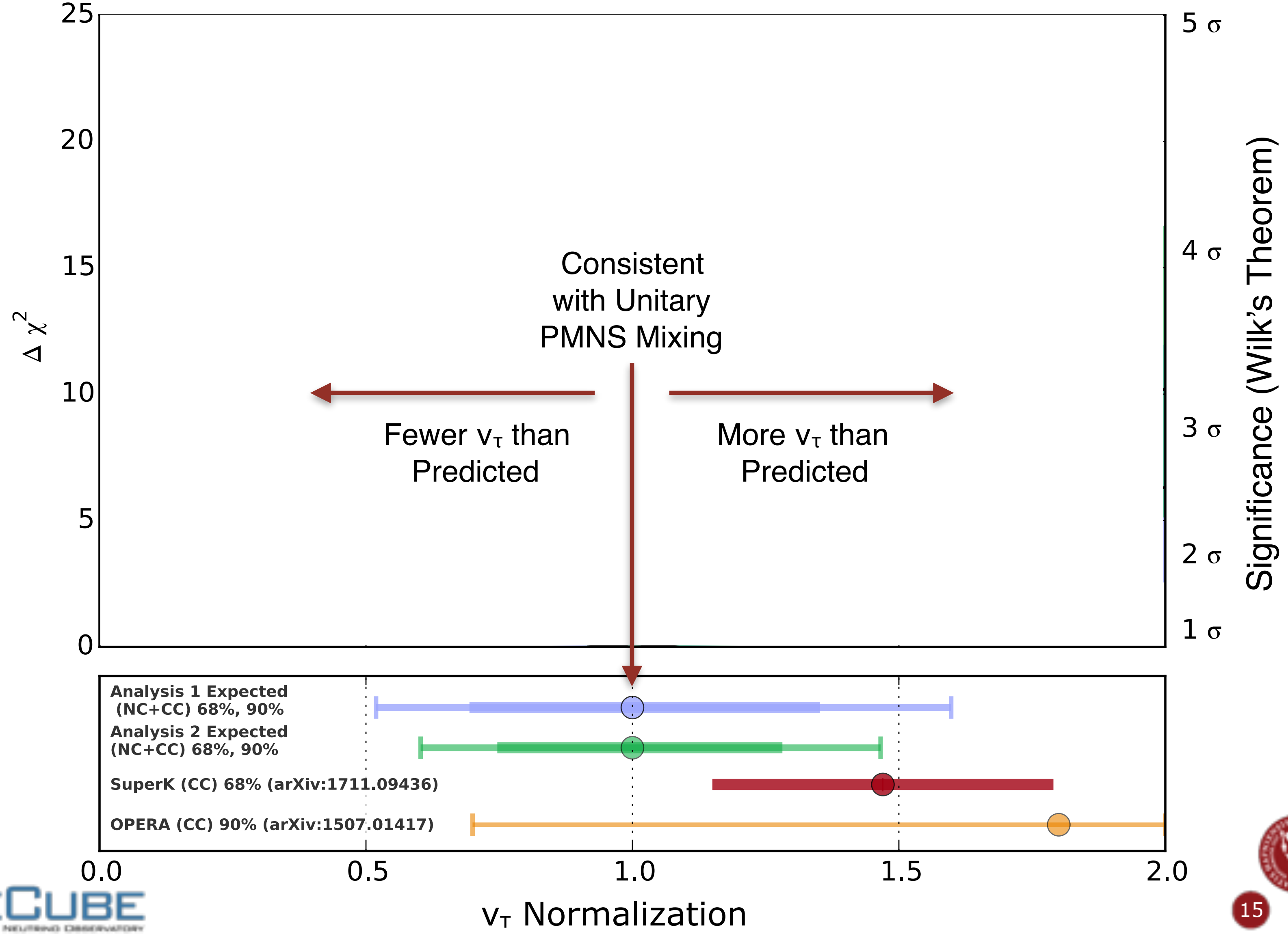


Systematics Included for Appearance Fits

Parameter Type	Fit Parameter	Analysis 1	Analysis 2
Oscillations	Δm^2_{32}	✓	✓
	$\sin^2(\theta_{23})$	✓	✓
	$\sin^2(\theta_{13})$	✓	
	N_τ	✓	✓
Cross-section	Axial Mass (QE)	✓	✓
	Axial Mass (RES)	✓	✓
	N_{NC}/N_{CC}	✓	✓
Neutrino Flux	ν_μ Normalization	✓	✓
	ν_e/ν_μ Ratio	✓	✓
	γ_ν	✓	✓
	$\nu/\bar{\nu}$ Ratio	✓	✓
	Up/Horizontal Ratio	✓	✓
	$f_{Coincident}$		✓
Muon Flux	μ Norm	✓	✓
	γ_{CR}	-	✓
Detector	DOM Efficiency	✓	✓
	Hole Ice Model	✓	
	Lateral Sensitivity	✓	✓
	Forward Sensitivity	✓	✓
	Absorption	✓	✓
	Scattering	✓	✓

- Wide range of systematics included
- Similar systematics used between analyses
- Differences only in parameters with very weak sensitivity
- Note: Analysis 1 uses data-driven background estimate

Expected Precision of the Two Analyses



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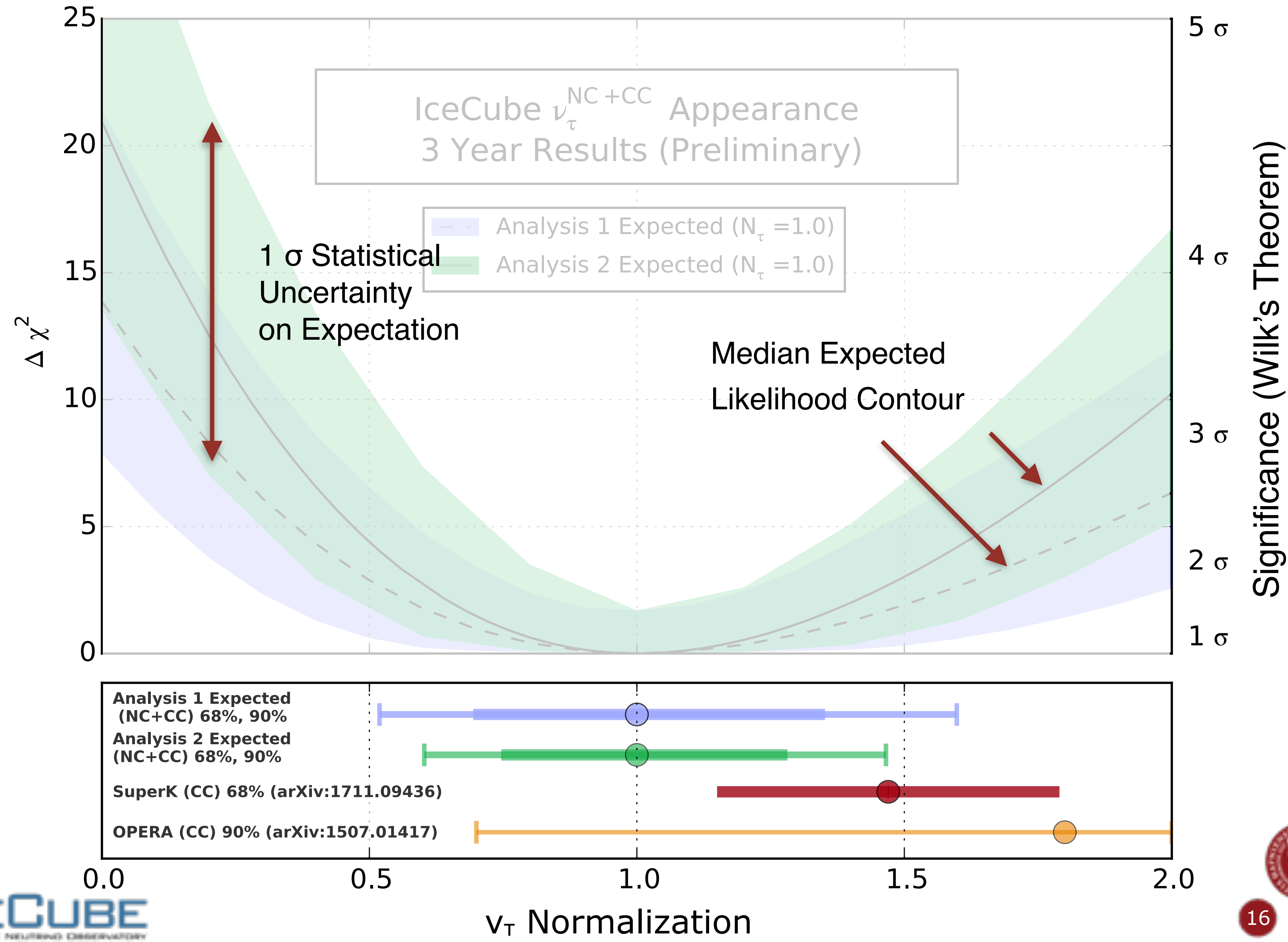

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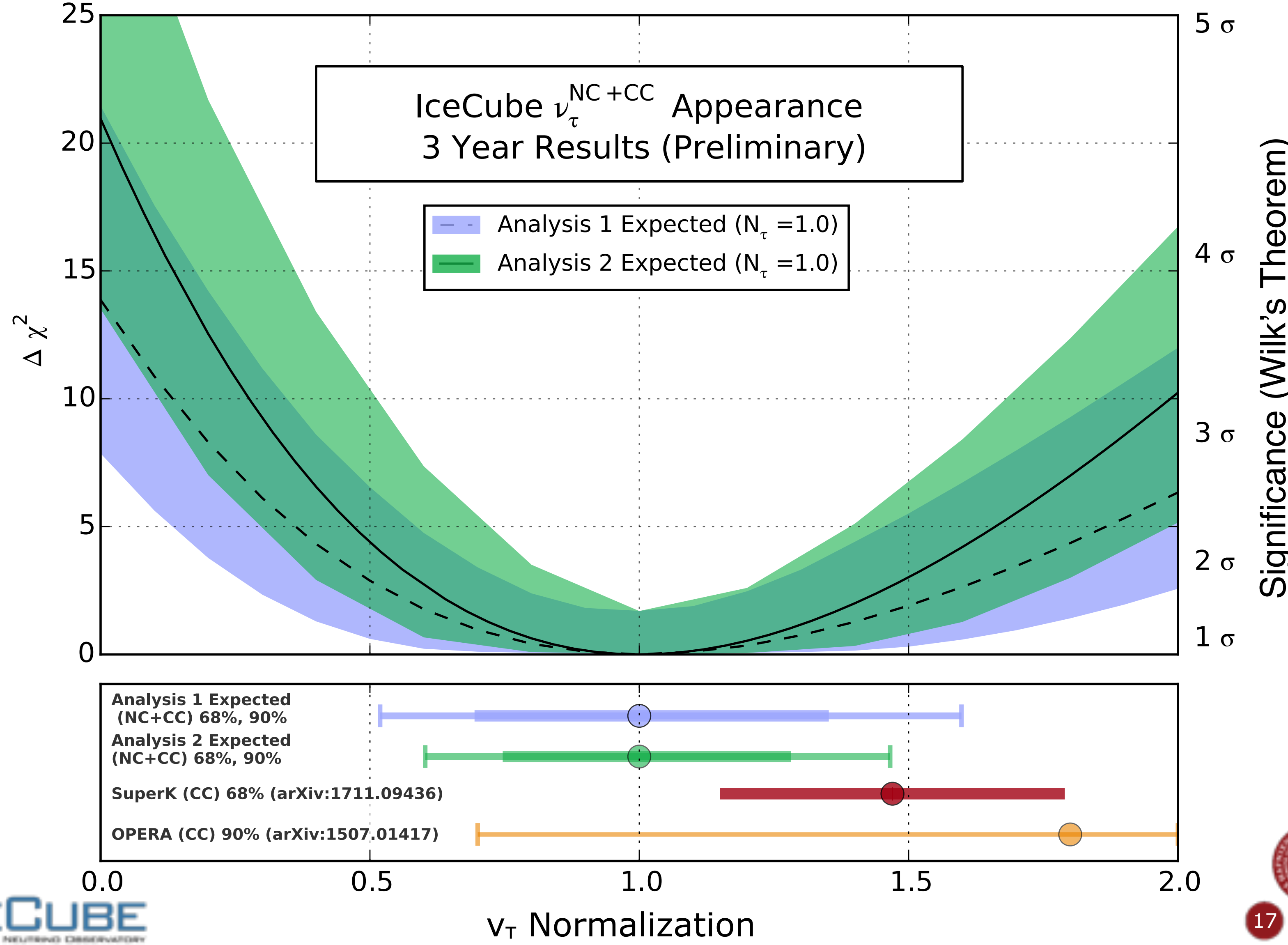
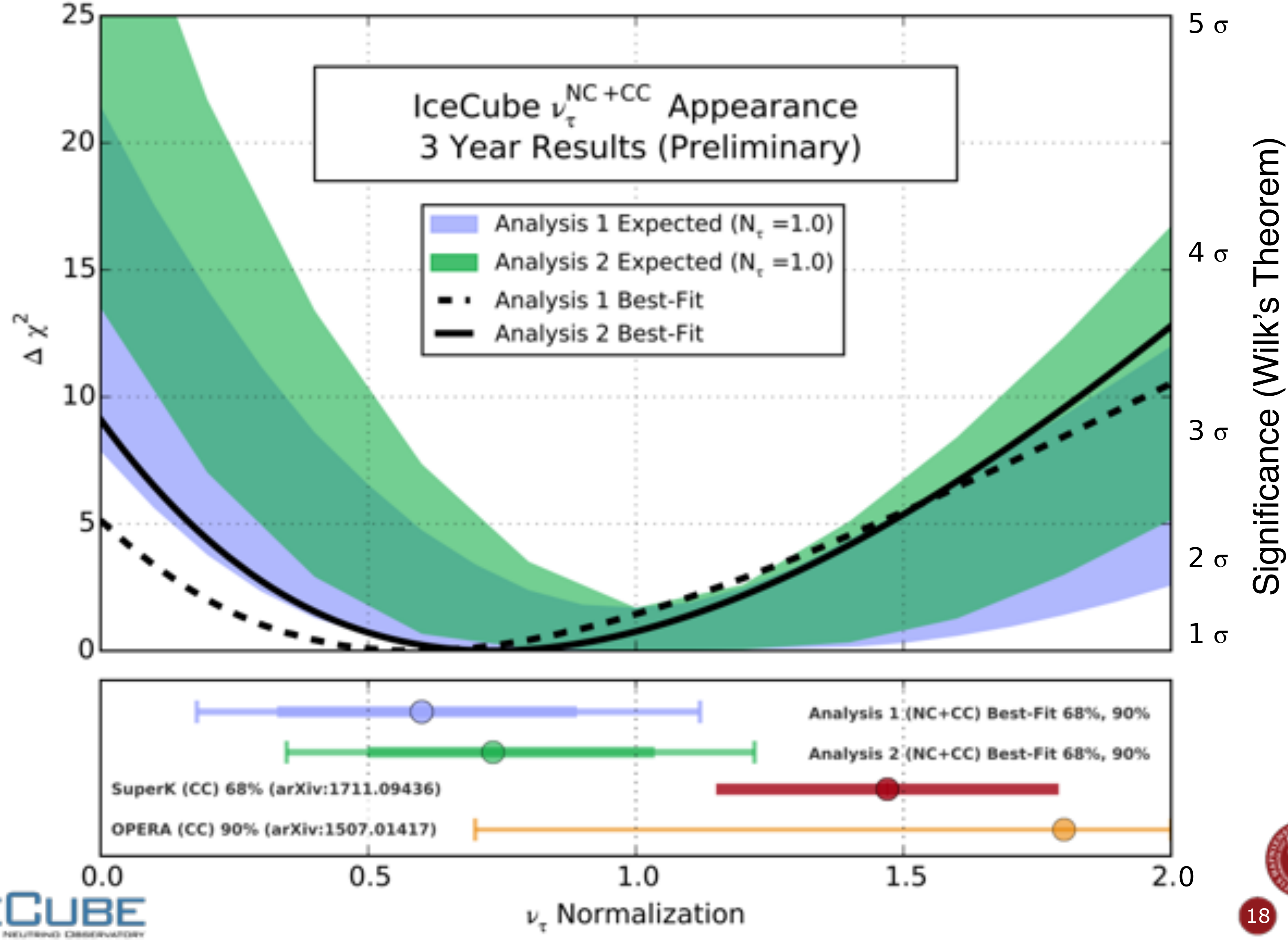


Appearance Best-Fit Values from DeepCore



Tau Appearance Results from DeepCore

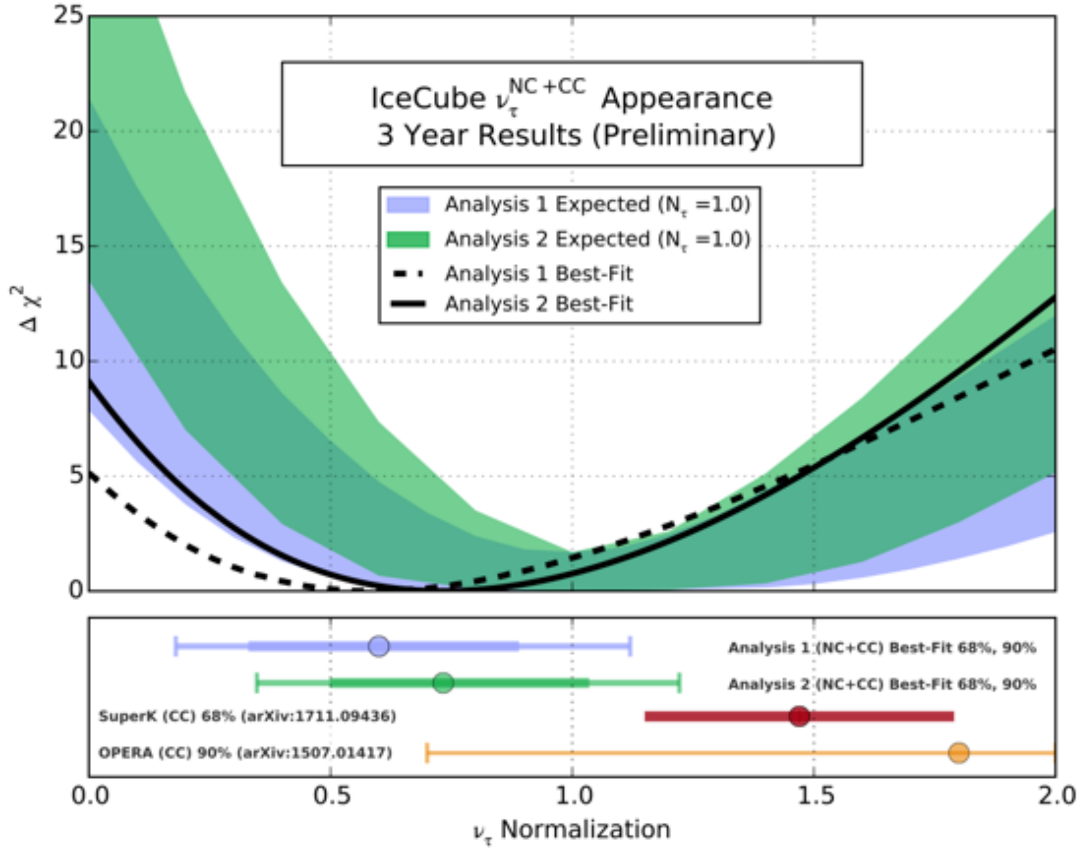
- Analysis 1:

$$N_{\tau}^{NC+CC} = 0.58^{+0.31}_{-0.25}$$

- Analysis 2:

$$N_{\tau}^{NC+CC} = 0.73^{+0.31}_{-0.24}$$

- Consistent results from both analyses
- First results with $N_{\tau} < 1$
- Results consistent with unitary oscillations, cross section, ect



Best-Fit Event Rates (NC+CC Fit)

- Large number of tau neutrinos detected in each analysis
- Analysis 1: Data-driven atmospheric muon background, larger statistics
- Analysis 2: Simulated atmospheric muon background

Type	Analysis 1 Events	Analysis 1 $+1\sigma$	Analysis 2 Events	Analysis 2 $+1\sigma$
$\nu_e + \bar{\nu_e}$ CC	9548	23	13462	29
$\nu_\mu + \bar{\nu_\mu}$ CC	23854	39	35706	48
$\nu_e + \bar{\nu_e} + \nu_\mu + \bar{\nu_\mu}$ NC	4295	19	5559	21
$\nu_\tau + \bar{\nu_\tau}$ CC	927	5	1804	9
$\nu_\tau + \bar{\nu_\tau}$ NC	442	4	759	5
Atmospheric μ	1890	45	5023	167
Accidental Triggers	-	-	93	27
Total Expected (NC+CC Best Fit)	40958	68	62406	180
Observed	40902	202	62112	249

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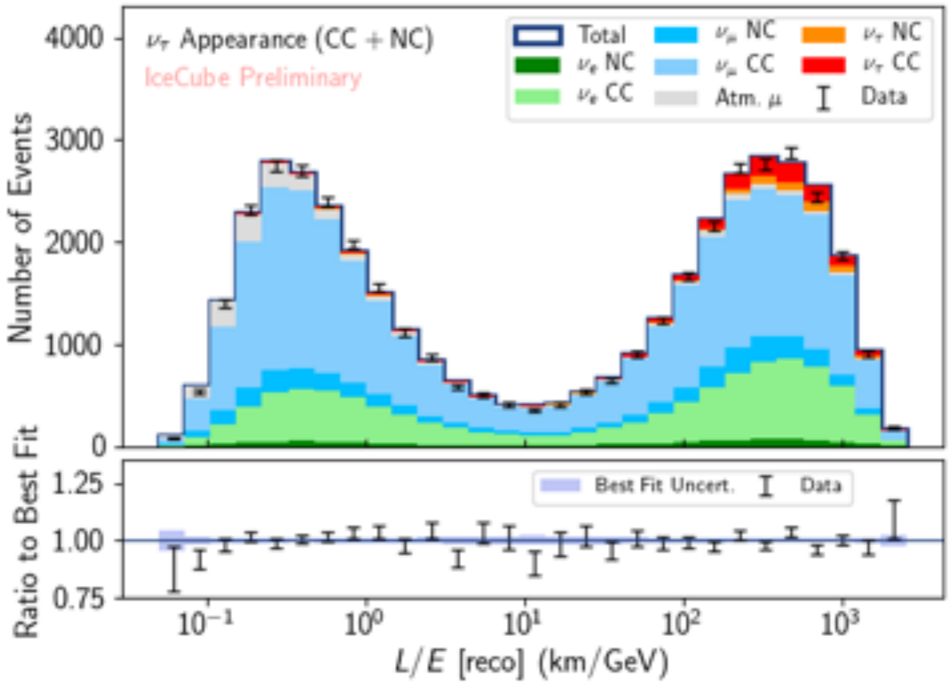
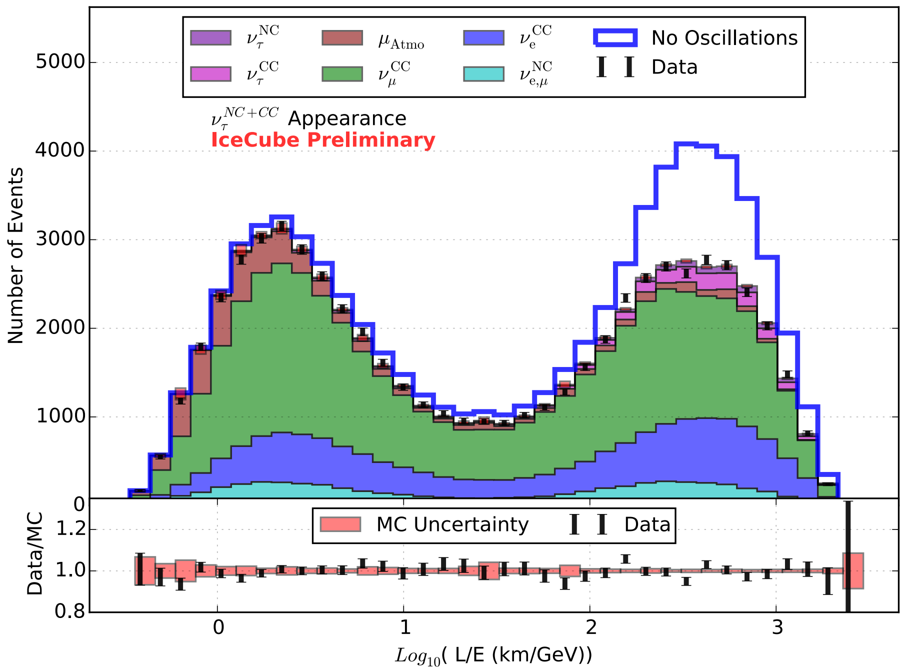
Good Data/MC Agreement with Both Analyses

Analysis 1



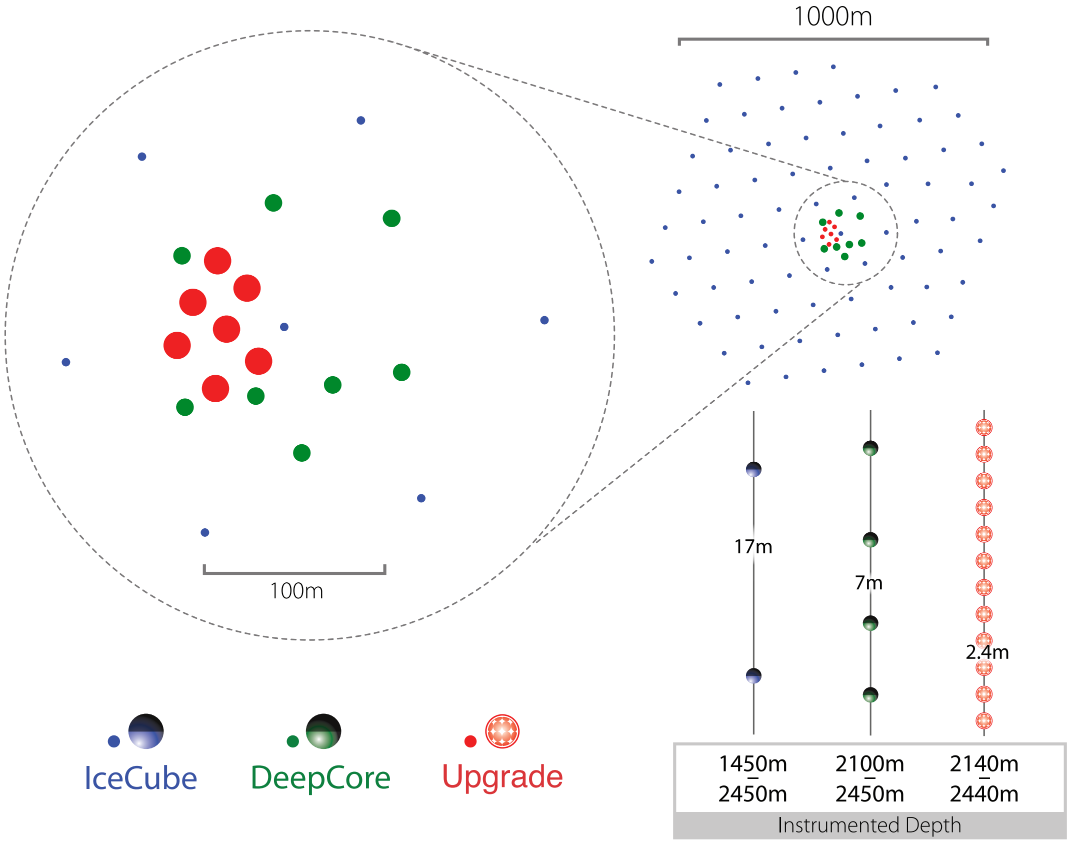
Analysis 2



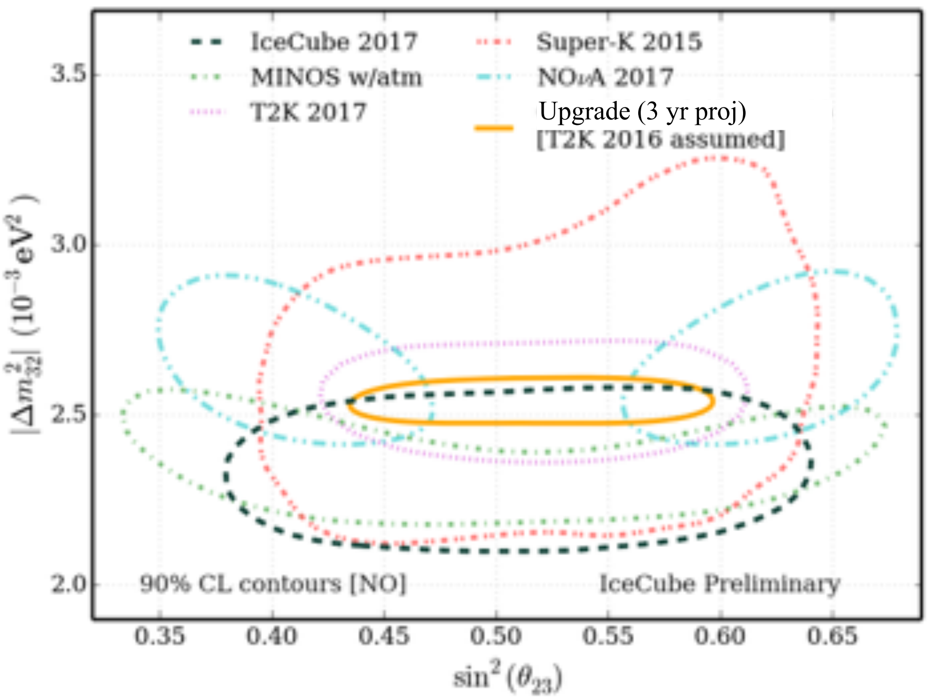
- Both analyses show good data/MC agreement
- Best fit values are consistent with unitary oscillations

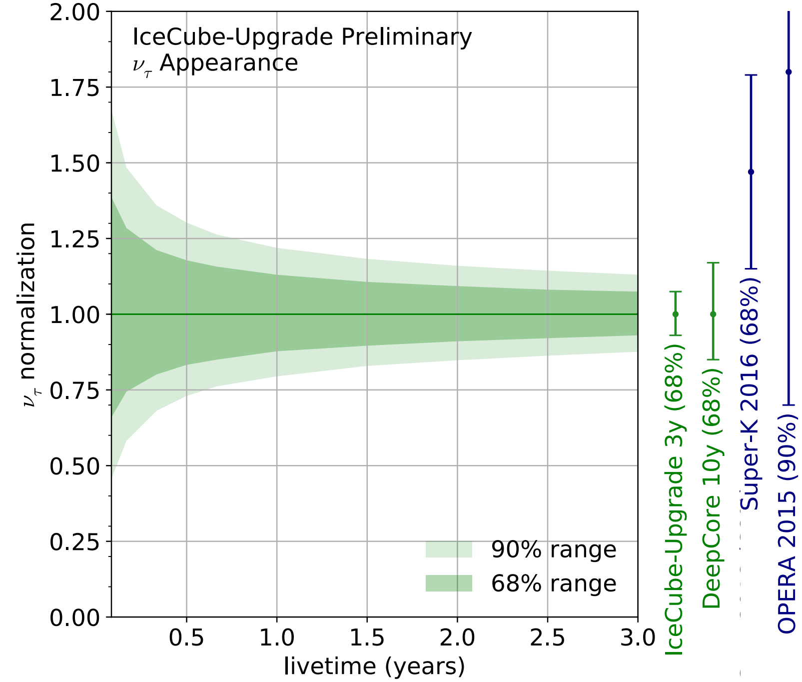
Future Measurements with Upgrades to IceCube

- How can we further improve sensitivity to ν_τ appearance?
  - Perform an upgrade to IceCube-DeepCore
- Initial studies are very promising
  - 7 additional strings
  - More precise calibrations
  - Significantly more GeV-scale events
- Using existing tools, perform a simple event selection to search for oscillations



Future Measurements with Upgrades to IceCube

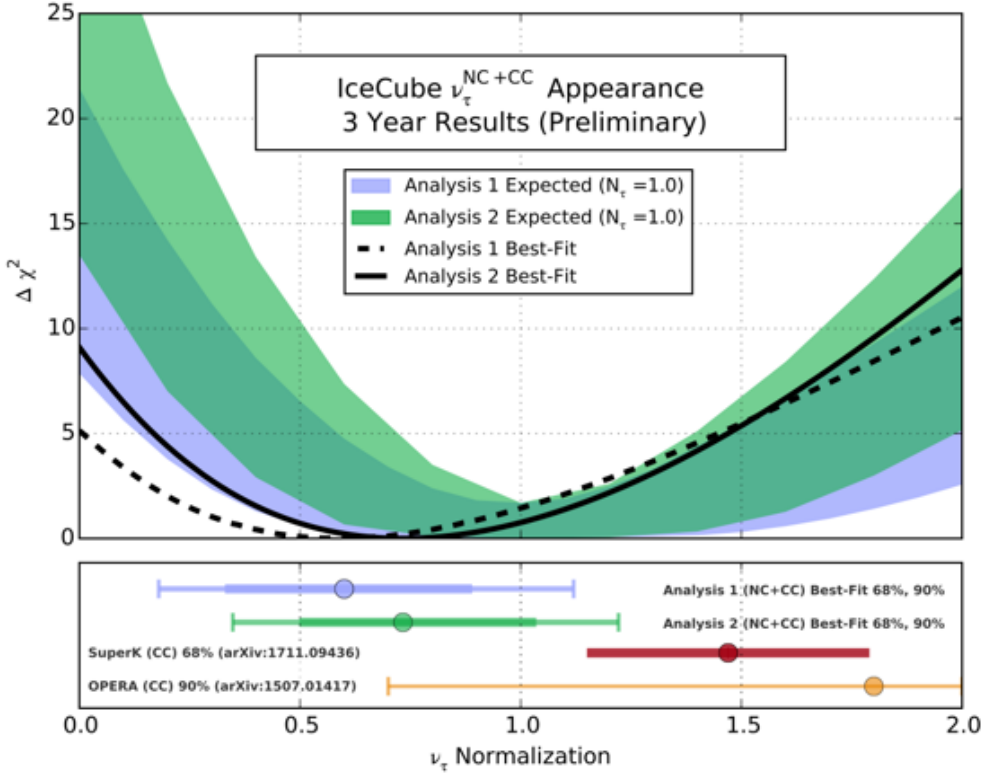




- Upgrading the low-energy portion of IceCube will significantly improve measurements of both disappearance and appearance
- Awaiting response from NSF in the US

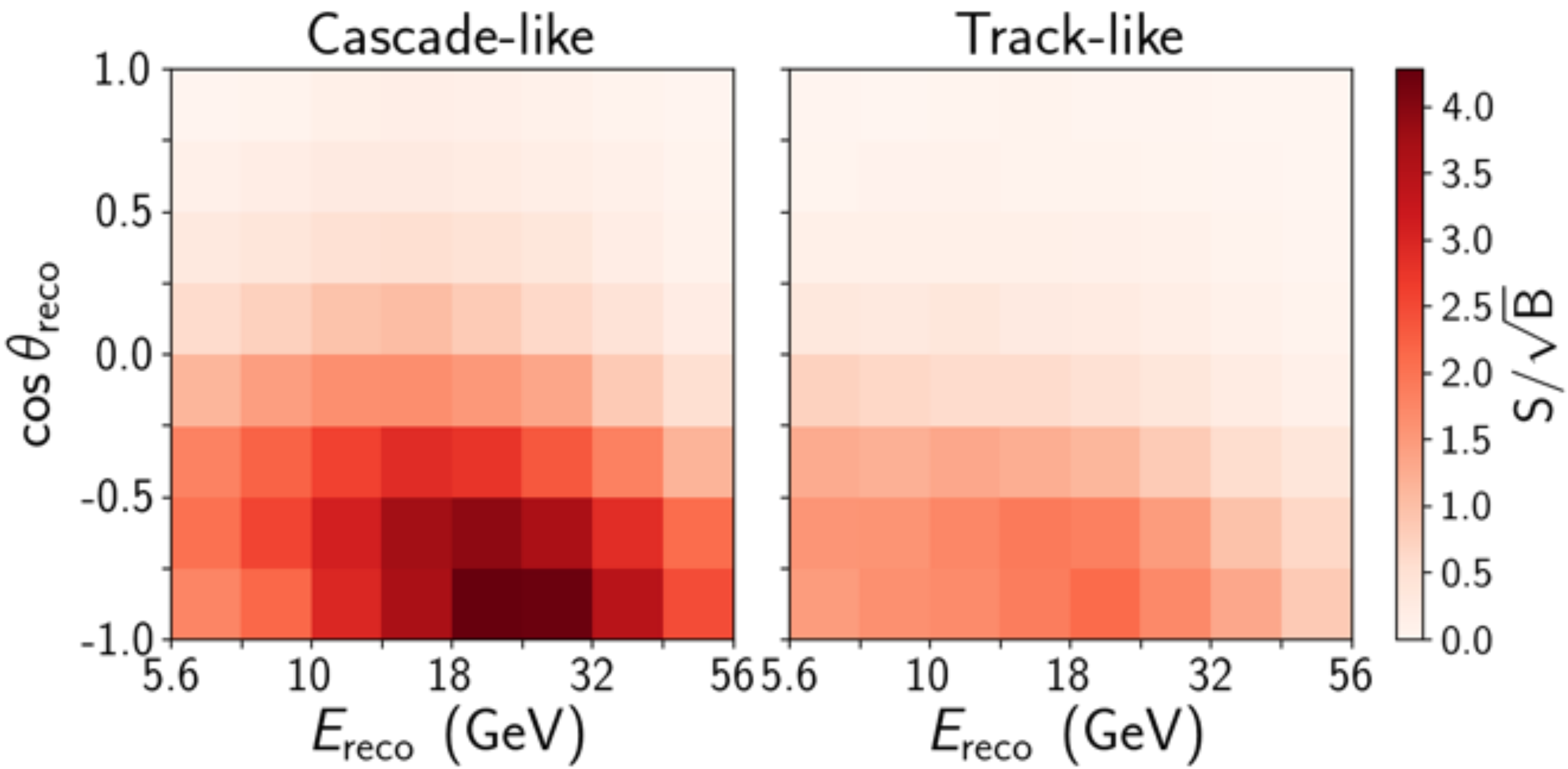
Summary

- New atmospheric oscillation results out of IceCube
  - Disappearance result published gives competitive constraints on oscillation parameters
- Published event selection shows reasonable sensitivity
- New oscillation event selection is available within IceCube
  - 50% more events
  - Better sensitivity to oscillations
- Both selections fit to data
  - Good data/MC agreement in both analyses
  - First results with $N_\tau < 1$



Backup Slides

ν_τ Signal (Analysis 1)



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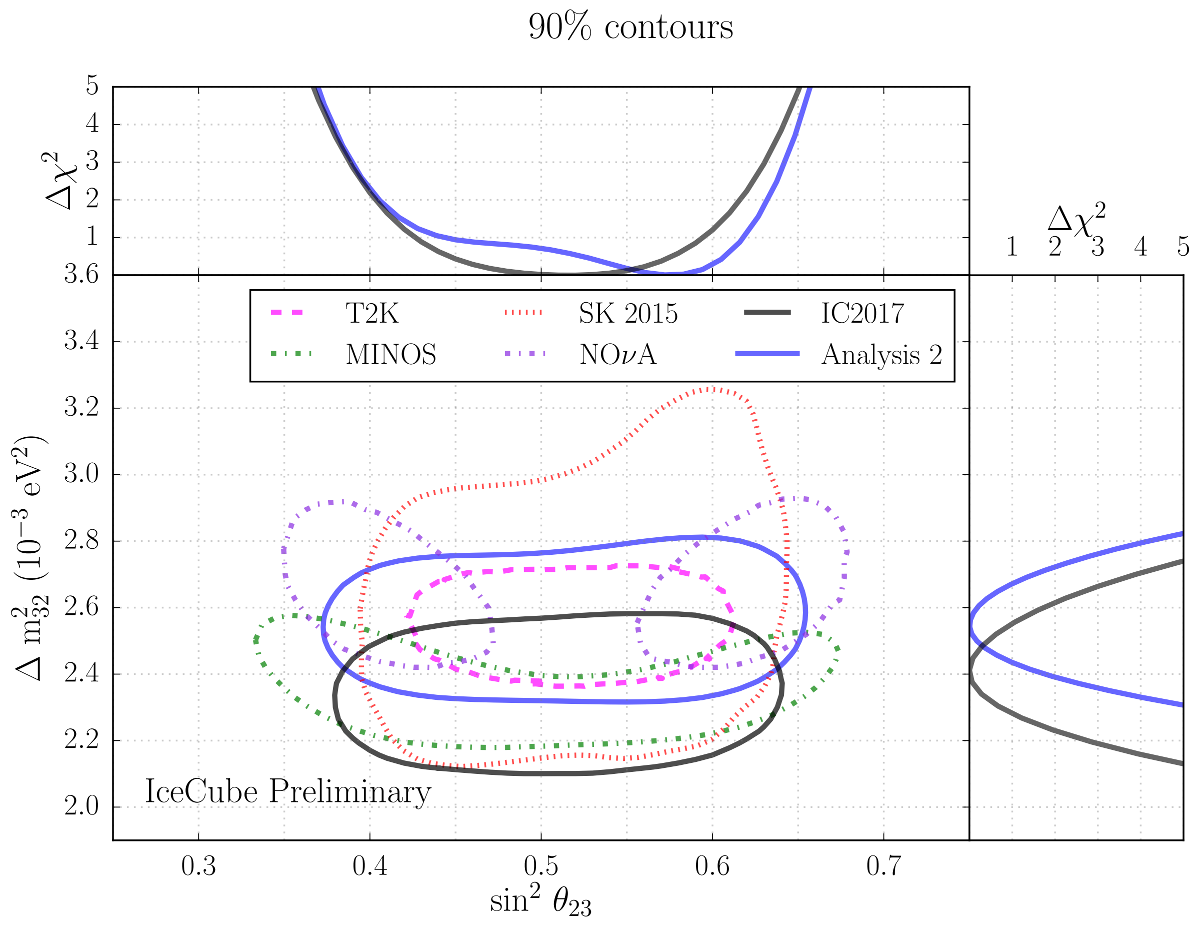
Disappearance with the New Sample

- Disappearance also fit with new selection
- Improved sensitivity over published result
- Feldman-Cousins tests currently running
- Details at Neutrino 2018
- Results in good agreement with other experiments
- First DeepCore results off maximal mixing



Preliminary

CC-Only Results

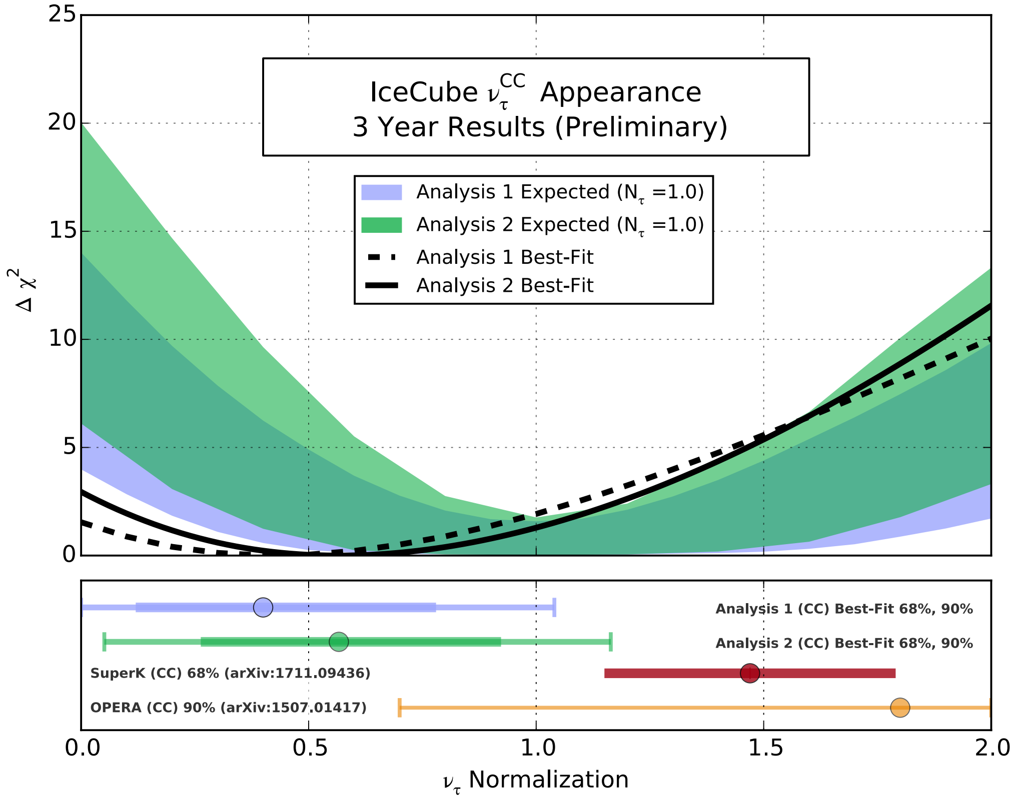
- Weaker sensitivity than NC+CC
- Analysis 1:

$$N_\tau^{CC} = 0.43^{+0.35}_{-0.31}$$

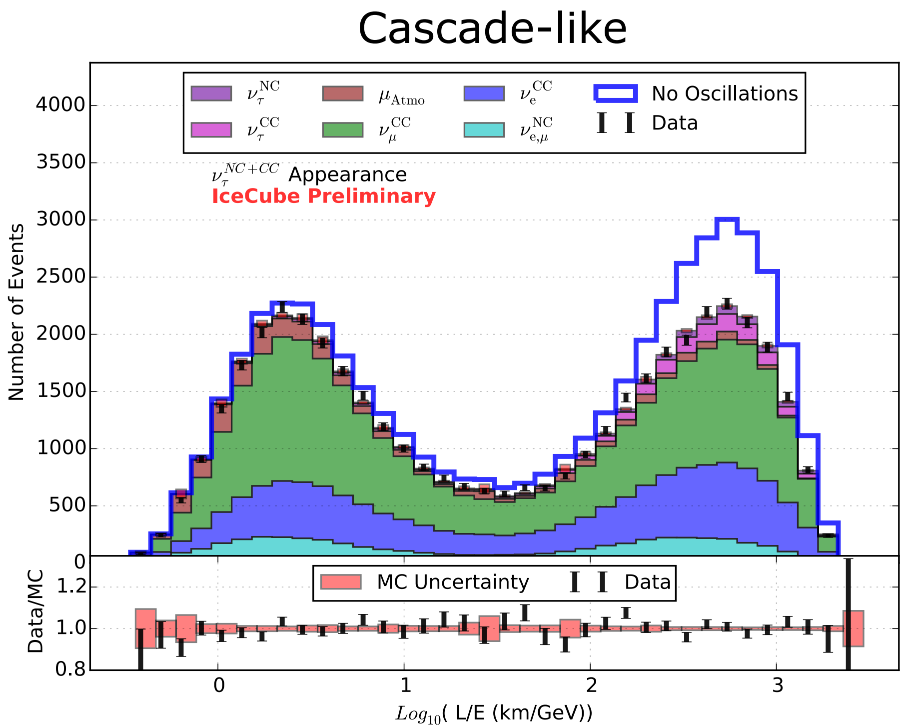
- Analysis 2:

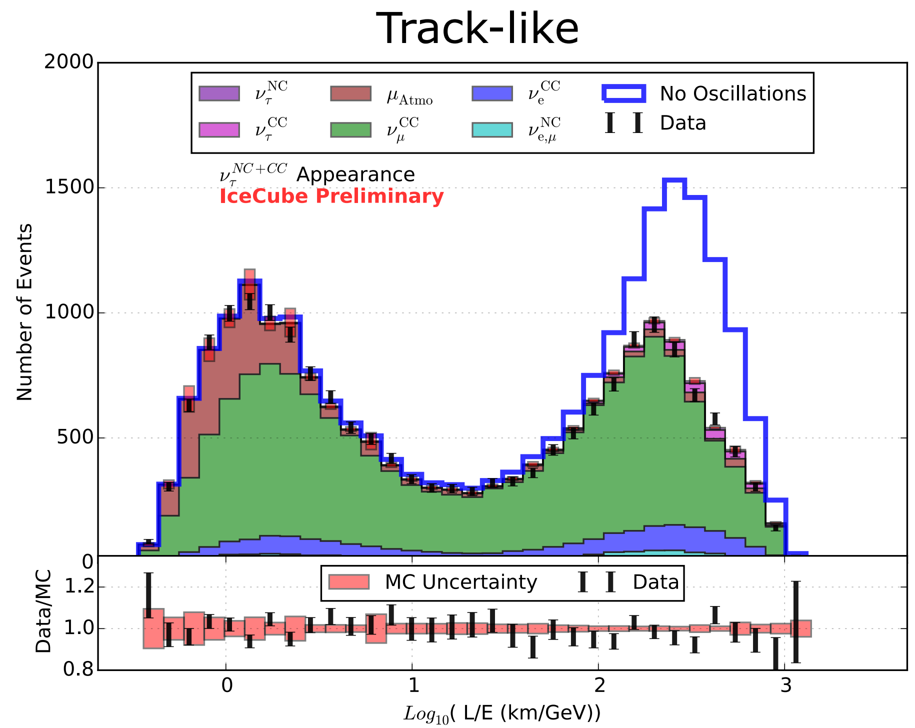
$$N_\tau^{CC} = 0.57^{+0.36}_{-0.30}$$

- Consistent results from both analyses
- Results consistent with unitary oscillations



Good Data/MC Agreement in Analysis 2





- Good agreement in both cascade-like and track-like events
- Clear appearance effect in cascade-like histogram

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