Atmospheric ν Oscillation Physics with IceCube/DeepCore

Doug Cowen

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
RWTH Aachen University
Technische Universität Dortmund
Technische Universität München
Universität Mainz
Universität Wuppertal
Westfälische Wilhelms-Universität Münster

JAPAN
Chiba University

NEW ZEALAND
University of Canterbury

REPUBLIC OF KOREA
Sungkyunkwan University

SWEDEN
Stockholms universitet
Uppsala universitet

SWITZERLAND
Université de Genève

UNITED KINGDOM
University of Oxford

UNITED STATES
Clark Atlanta University
Drexel University
Georgia Institute of Technology
Lawrence Berkeley National Lab
Marquette University
Massachusetts Institute of Technology
Michigan State University
Ohio State University
Pennsylvania State University
South Dakota School of Mines and Technology
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California, Berkeley
University of California, Irvine
University of California, Los Angeles
University of Delaware
University of Kansas
University of Maryland
University of Rochester
University of Texas at Arlington
University of Wisconsin–Madison
University of Wisconsin–River Falls
Yale University

FUNDING AGENCIES

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education and Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

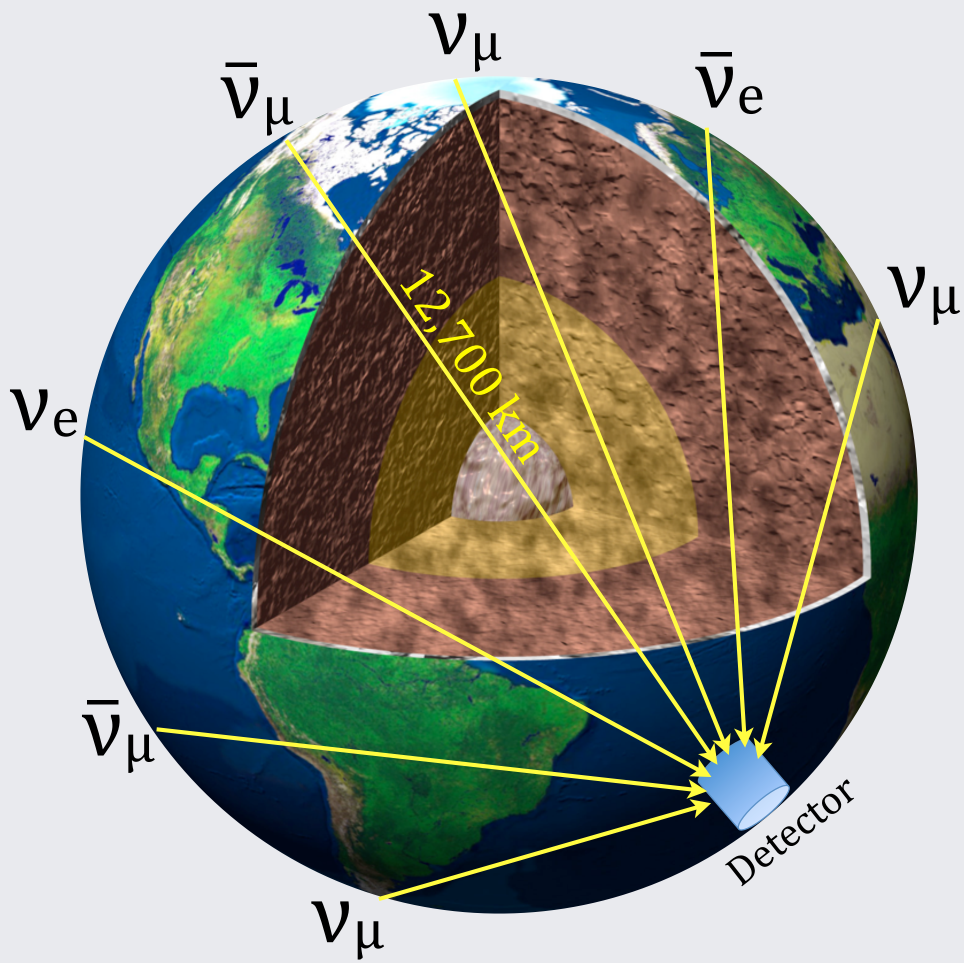
ICECUBE South Pole Neutrino Observatory
icecube.wisc.edu

12 Countries · 49 Institutions · >300 Scientists

- Neutrino Oscillations at the 10 GeV scale
- The IceCube/DeepCore Detector
- Results:
  - Muon neutrino disappearance
  - Tau neutrino appearance
  - Neutrino Mass Ordering
- Future plans

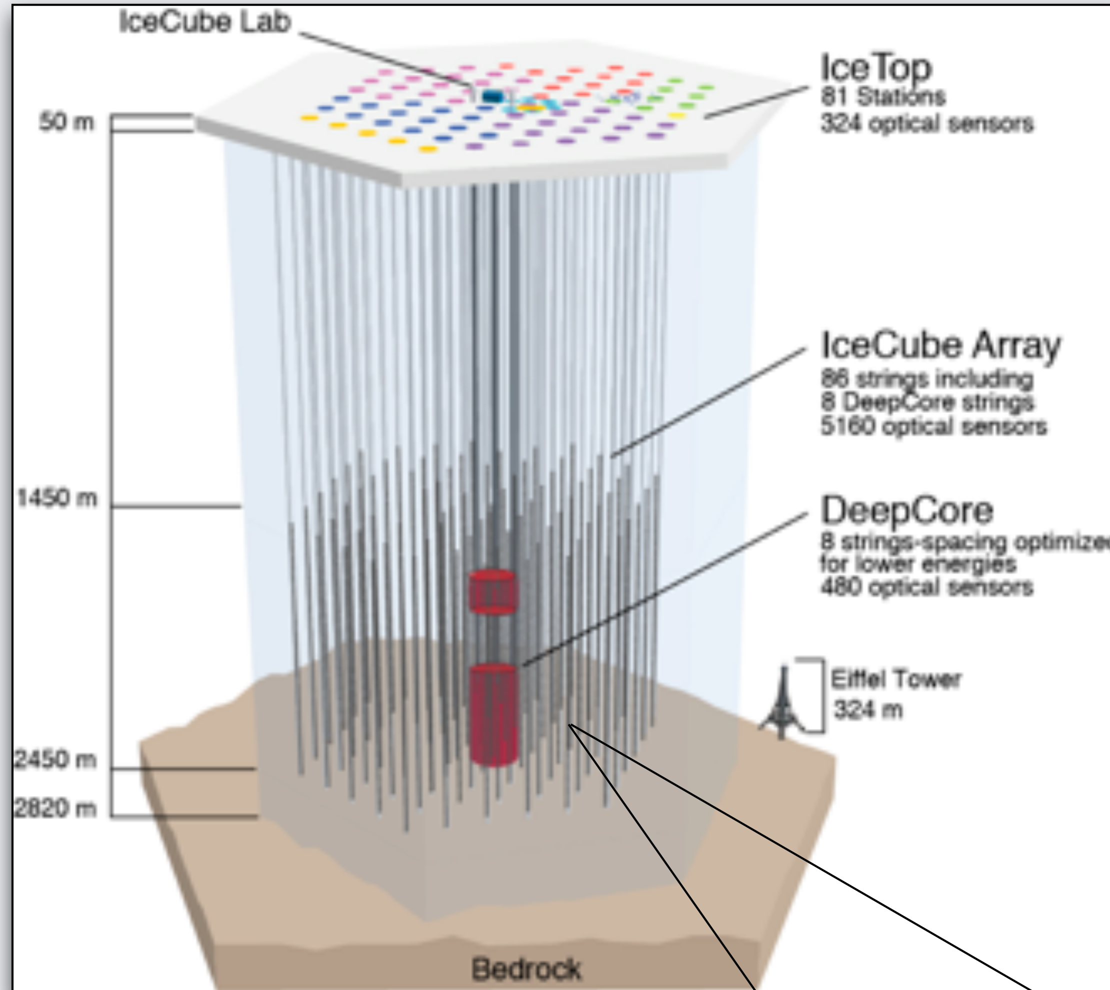
Atmospheric Neutrino Oscillations

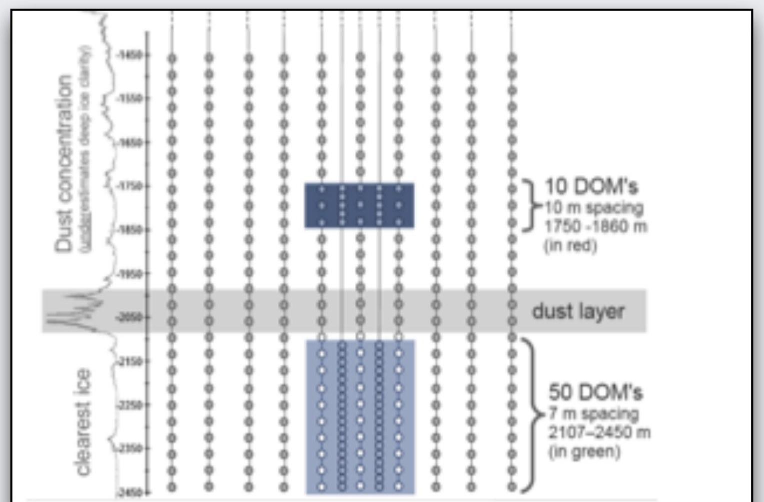
- Atmospheric ν's are observed over wide range of energies & pathlengths (∝ cosθ)
  - oscillations produce distinctive pattern in (E_ν, cosθ, flavor) space
  - constrain systematics using events in "side band" regions where oscillations do not occur
  - large volume ⇒ high statistics
- For reference:
  - at $L = d_E$, $P(\nu_\mu \rightarrow \nu_\mu)$ = min. at $E_\nu \sim 25$ GeV
  - see matter effects below $E_\nu \sim 10$ GeV



The IceCube/DeepCore Detector

- IceCube/DeepCore
  - More densely instrumented region at bottom center
    - DOMs 7m (~40m) apart vertically (horizontally)
  - Below 2100m, high optical clarity
    - ~50m scattering length; ~150m absorption length
  - Surrounding DOMs provide active down-going μ veto

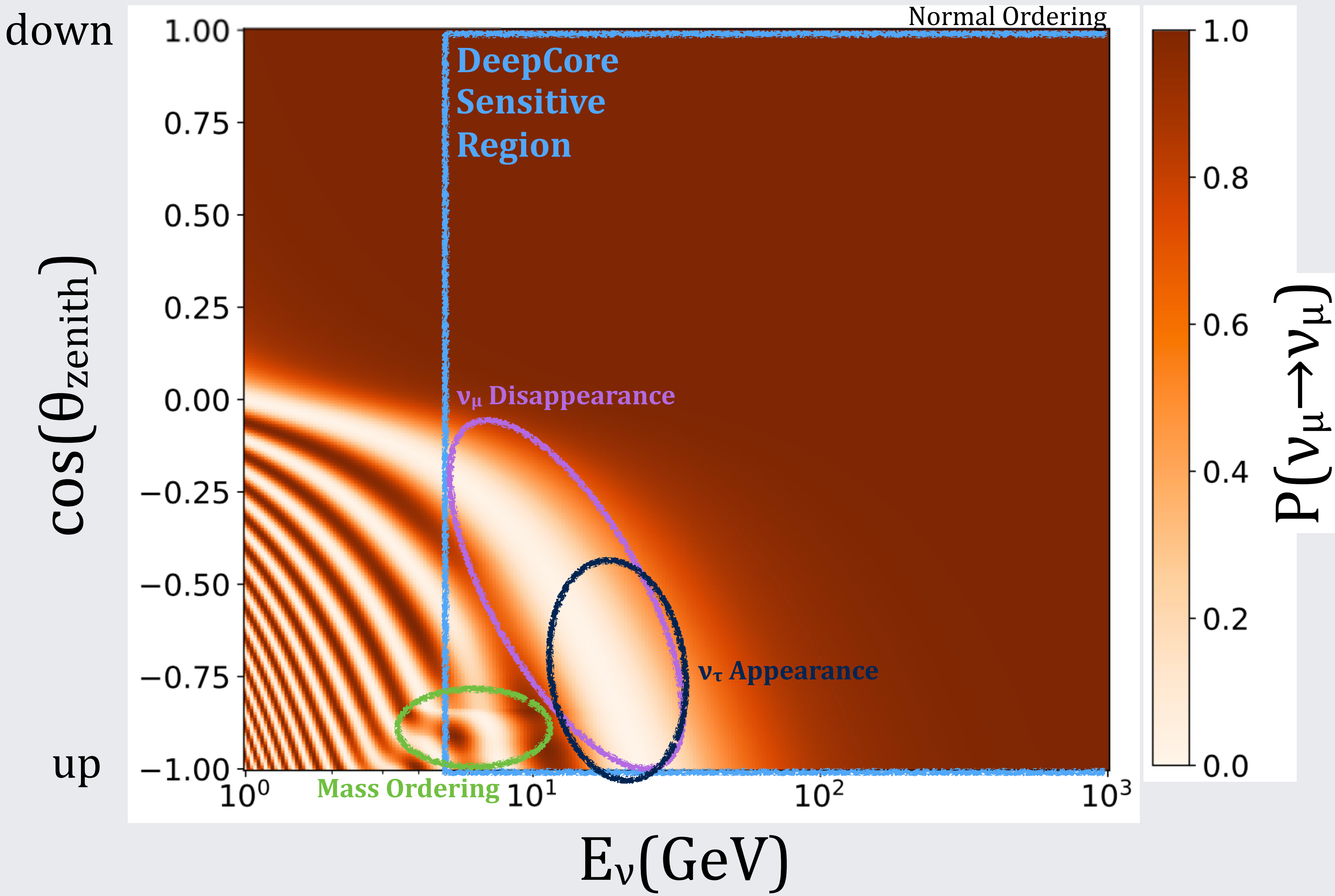




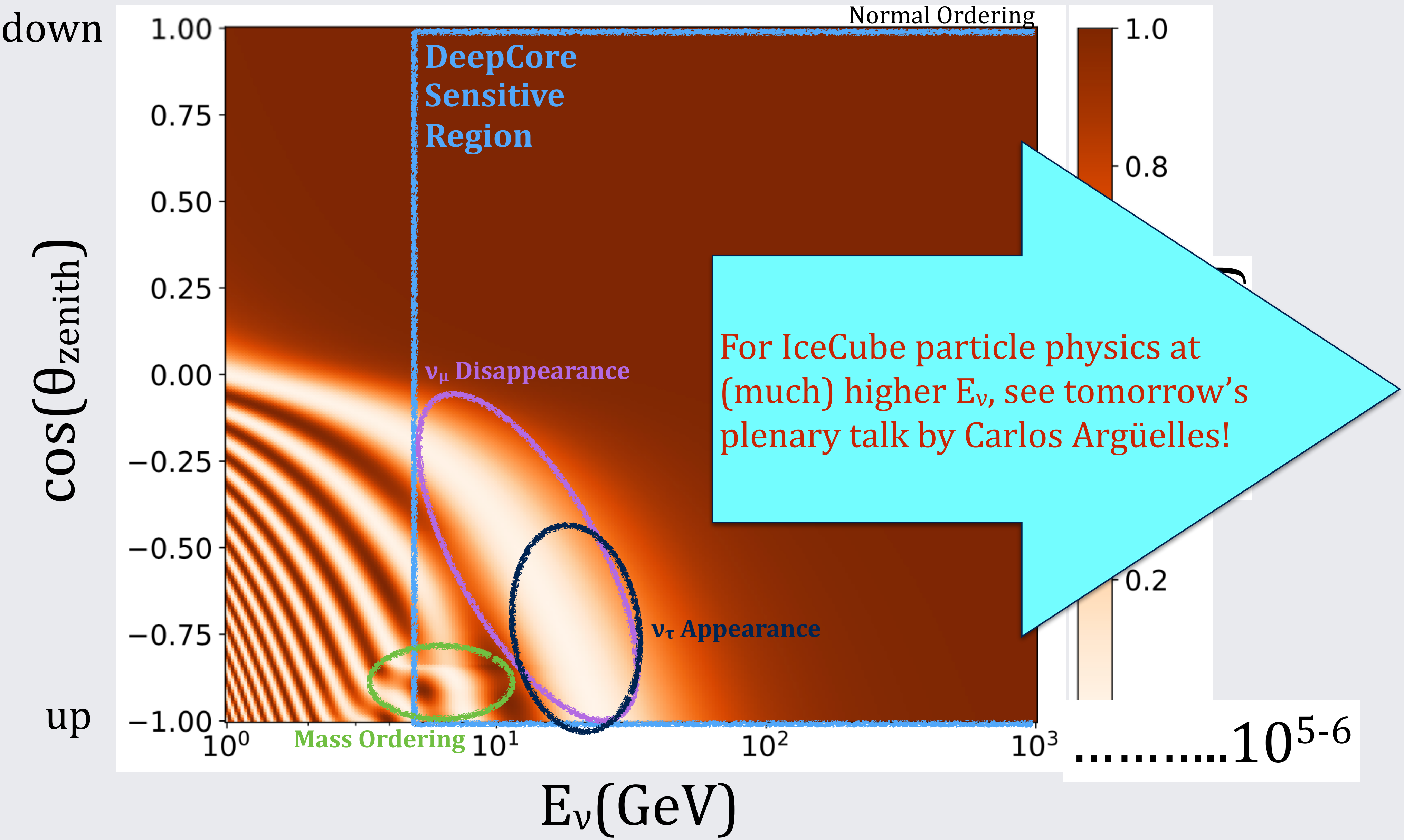
Det. side view

Digital Optical Module (DOM)

Neutrino Oscillogram

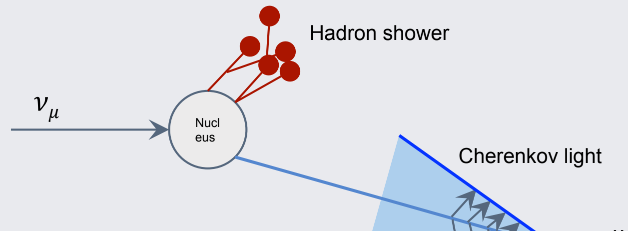


Neutrino Oscillogram

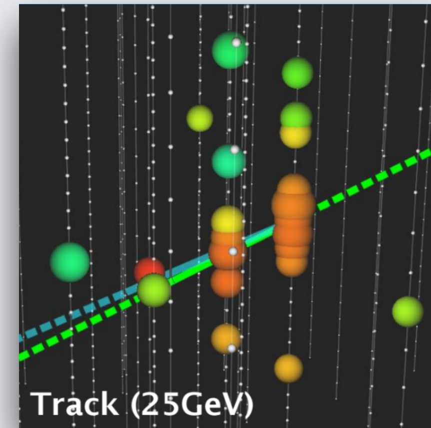


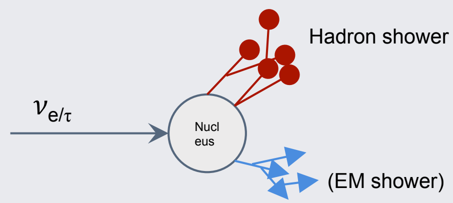
General Features of IceCube Osc. Analyses

- Technique:
  - Use IceCube modules surrounding DeepCore to veto down-going cosmic-ray muon bkgd.
  - Require interaction vertex be contained in DeepCore…
    - …and that muon endpoint be within ~100m of DeepCore edge
  - Constrain systematics by using
    - up- and down-going atm. ν events
    - track-like and cascade-like atm. ν events
  - Use 3 dimensions: (E, cosθ, PID)

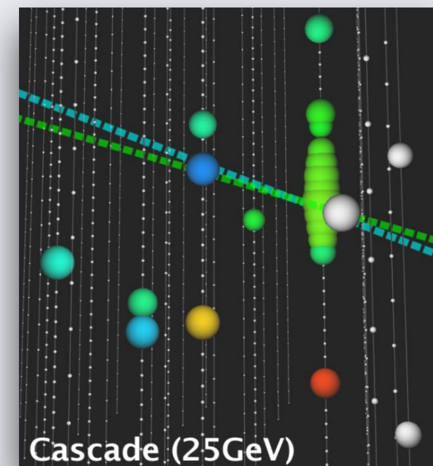


Track-like (ν_μ CC)





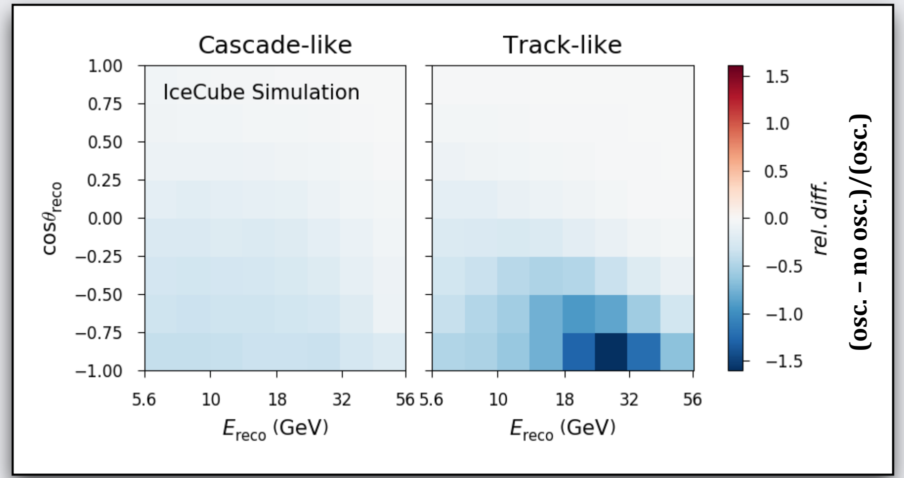
Cascade-like ($\nu_{e,\tau}$ CC, ν_x NC)



General Features of IceCube Osc. Analyses

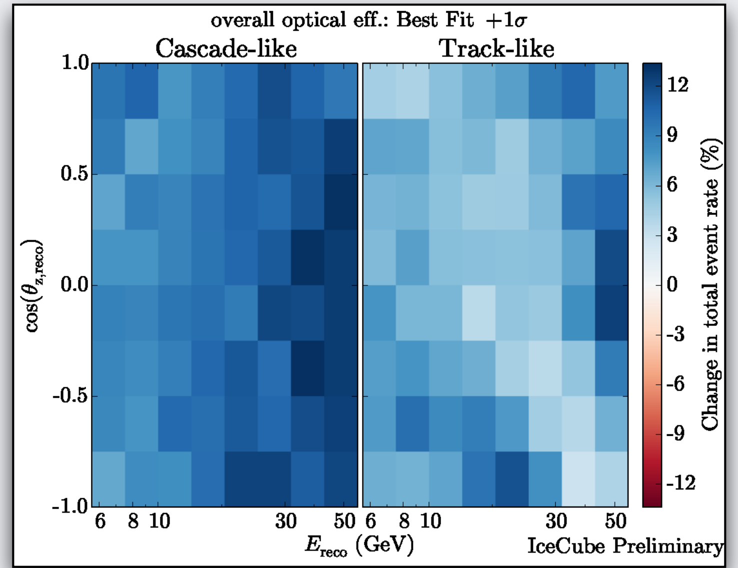
- Analysis highlights:
  - Background rejection: $\sim 10^8$
  - Resolutions
    - ν_μ CC @ 20 GeV (tracks): $\sigma(\theta_{zen}, E)_{trk} = (\sim 20^\circ, \sim 40\%)$
    - ν_x @ 20 GeV (cascades): $\sigma(\theta_{zen}, E)_{cscd} = (\sim 25^\circ, \sim 35\%)$
  - Main nuisance params (of ~dozen total)
    - Detector effects:
      - relative module optical sensitivity
      - ice properties
    - Oscillation parameter uncertainties
    - Flux uncertainties

ν_μ Disappearance: Analysis



Full list of systematics in backup slides.

Systematic: Optical Efficiency



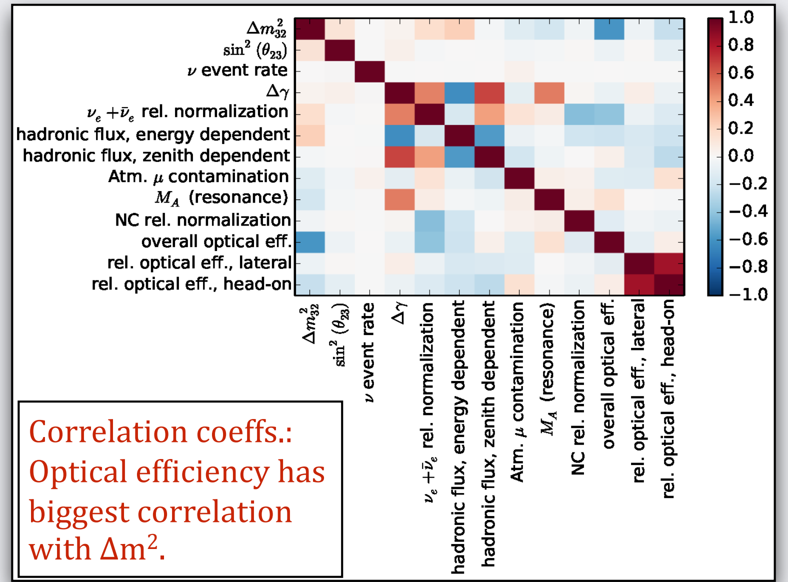
Relative change to event rate when increasing optical efficiency by 10%

$\cos\theta$

E(GeV)

Change has impact across up/down/trk/cscd events; impact in oscillation regime can be disentangled thereby.

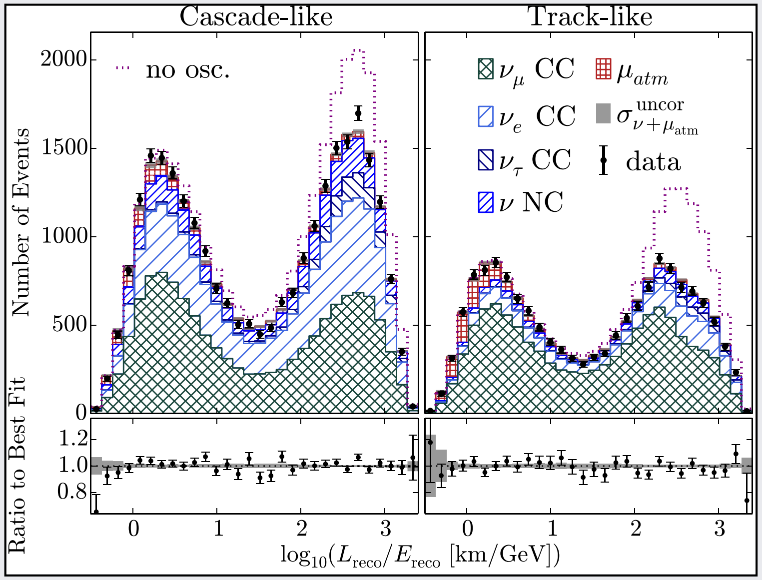
Correlation Coefficients



Correlation coeffs.: Optical efficiency has biggest correlation with Δm^2.

ν_μ Disappearance: Results

PRL 120 071801 (2018)

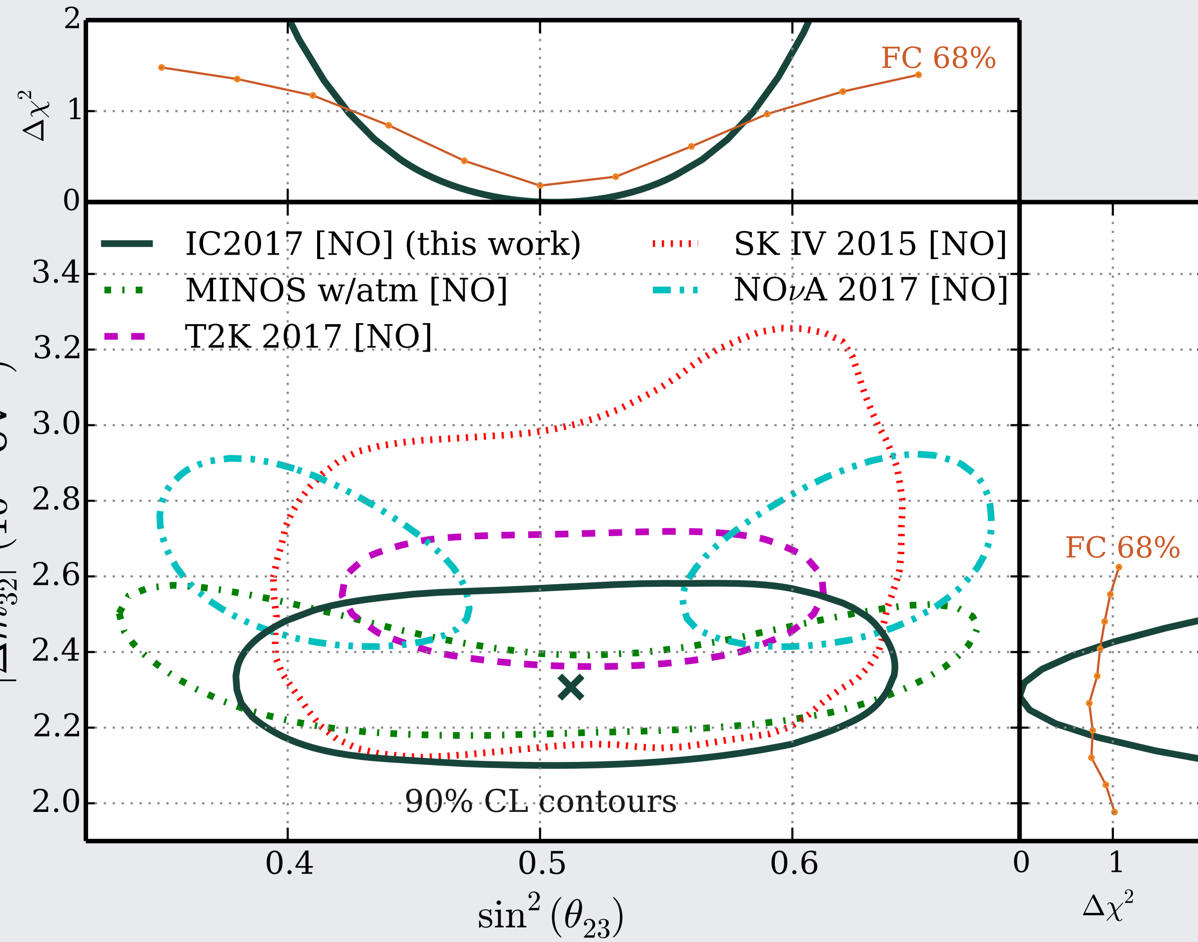


N_{evt}

$\log_{10}$(L/E) (km/GeV)

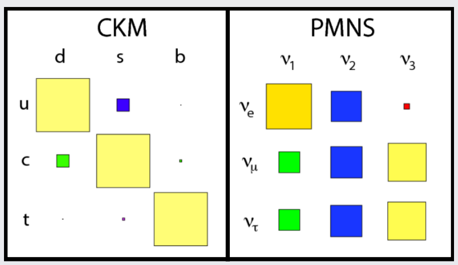
- 1,020 live days (2012-14)
- 41,599 events (full sky)
  - 15,138 track; 26,461 cascade
- Estimate 5.2% atm μ background

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



ν_τ Appearance & PMNS Unitarity

- Testing PMNS unitarity: We have a ways to go before we can reach CKM levels of precision
  - τ sector constraints are ~order of magnitude weaker than for e,μ sectors
  - Significant deviation from unitarity could be indicator of new physics
  - $\nu_\mu \rightarrow \nu_\tau$ probes combination of $|U_{\mu 3}|$^2 and $|U_{\tau 3}|$^2



Precision: 0.1% – 0.01%

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & 0.00351^{+0.00015}_{-0.00014} \\ 0.22520 \pm 0.00065 & 0.97344 \pm 0.00016 & 0.0412^{+0.0011}_{-0.0005} \\ 0.00867^{+0.00029}_{-0.00031} & 0.0404^{+0.0011}_{-0.0005} & 0.999146^{+0.000021}_{-0.000046} \end{bmatrix}$$

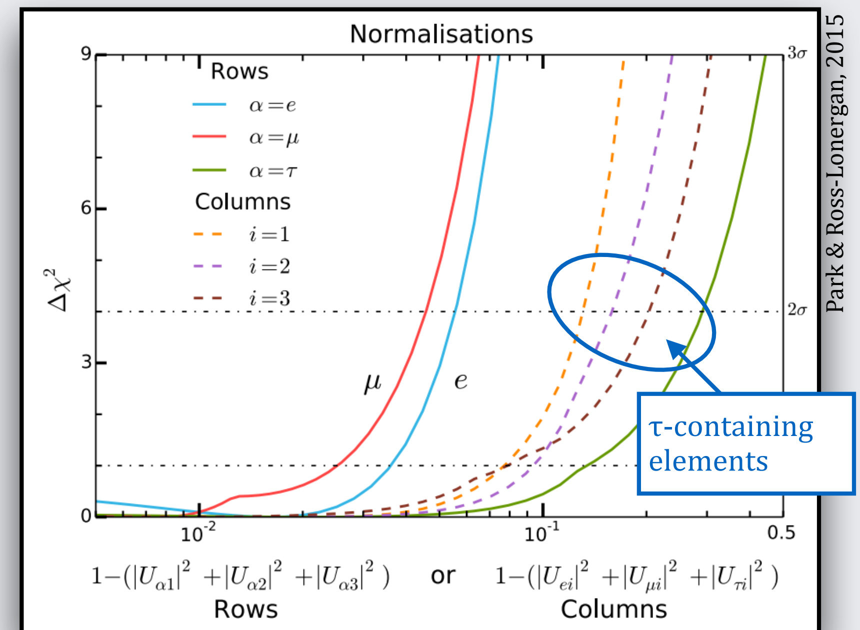
Beringer et al, PRD 86, 010001 (2012)

Precision: ~10%

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} =$$

$$|U|^{\text{w/o Unitarity}}_{3\sigma\,(\text{with Unitarity})} = \begin{pmatrix} 0.76 \to 0.85 & 0.50 \to 0.60 & 0.13 \to 0.16 \\ (0.79 \to 0.85) & (0.50 \to 0.59) & (0.14 \to 0.16) \\ 0.21 \to 0.54 & 0.42 \to 0.70 & 0.61 \to 0.79 \\ (0.22 \to 0.52) & (0.43 \to 0.70) & (0.62 \to 0.79) \\ 0.18 \to 0.58 & 0.38 \to 0.72 & 0.40 \to 0.78 \\ (0.24 \to 0.54) & (0.47 \to 0.72) & (0.60 \to 0.77) \end{pmatrix}$$

Park & Ross-Lonergan, 2015



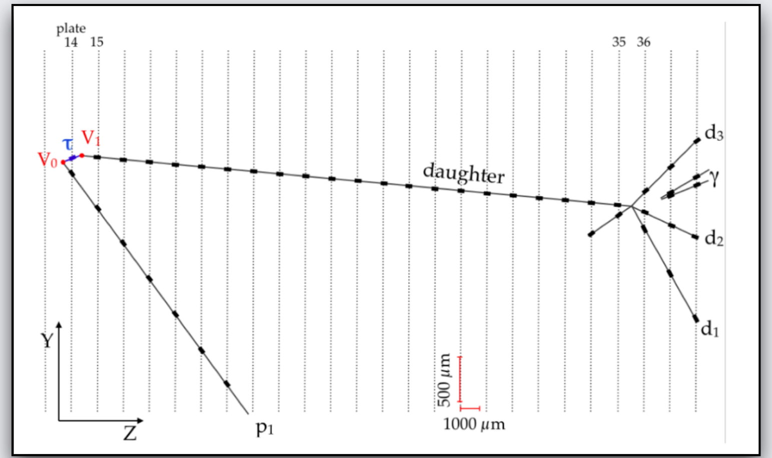
Park & Ross-Lonergan, 2015

ν_τ Appearance: Previous Results

OPERA:

- Best exclusion of no-ν_τ appearance at >5σ
- Constrained ν_τ normalization*: 1.1 –0.4 +0.5 (68% CL)

Event number 5

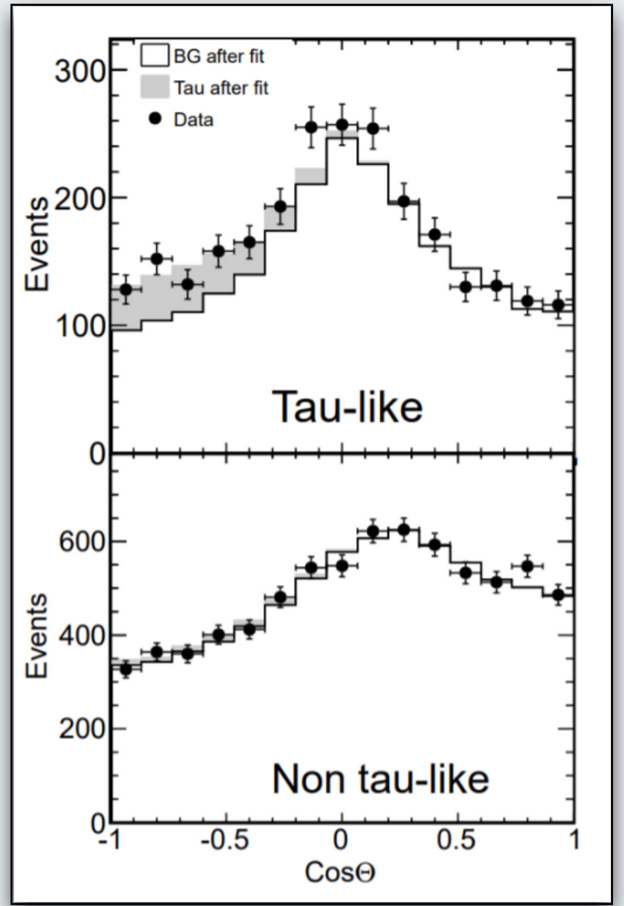


Phys. Rev. Lett. 115, 121802 (2015)

*Defn. of ν_τ normalization:
$\Phi(\nu_\tau)_{\text{measured}}/\Phi(\nu_\tau)_{\text{expected}}$
A ν_τ norm. < 1.0 could indicate new physics (e.g., ν_{sterile})

Super-K:

- Excluded no-ν_τ appearance at >4.6σ
- Best constraint on ν_τ norm: 1.47±0.32 (68% CL, CC-only)



https://arxiv.org/abs/1711.09436

$E_\nu \sim 5$ GeV
Interactions:
- QE
- Resonance

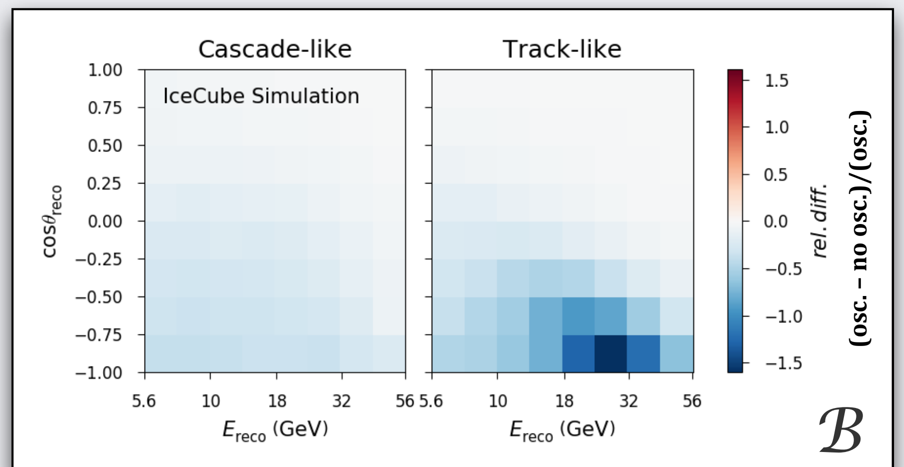
15 yrs of data

ν_τ Appearance with IceCube

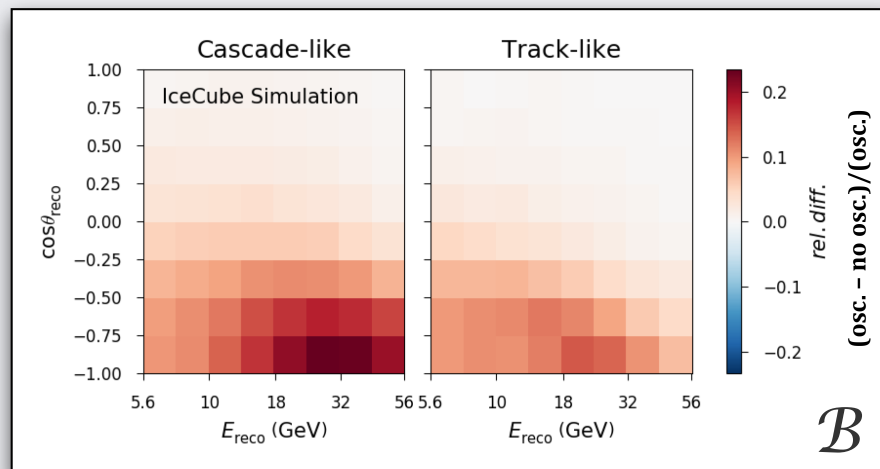
- Osc. max. at E_ν~25 GeV is in DeepCore's sweet spot
- Technique similar to that for ν_μ disappearance:
  - Veto; containment; up/down & track/ cascade events; measure across three dimensions (E, cosθ, PID)

- Two quasi-independent analyses (same underlying dataset, different event selections)
  - Main ("$\mathcal{A}$") analysis:
    - Higher statistics, more background, estimate background from MC
  - Confirmatory ("$\mathcal{B}$") analysis:
    - Lower statistics, higher purity, estimate background from data

ν_μ Disappearance



ν_τ Appearance

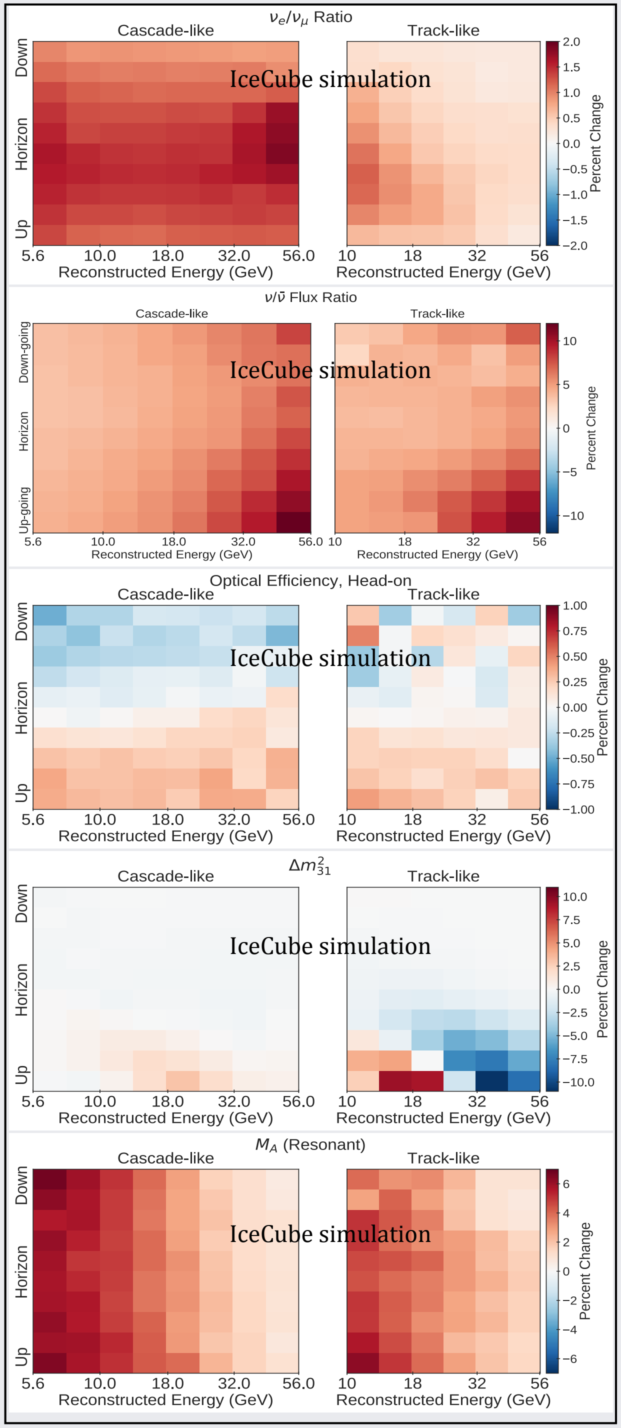


ν_τ App. w/IceCube

Type	Analysis $\mathcal{A}$ Events	$\pm1\sigma$	Analysis $\mathcal{B}$ Events	$\pm1\sigma$
$\nu_e + \bar{\nu}_e$ CC	13462	29	9545	23
$\nu_e + \bar{\nu}_e$ NC	1096	9	923	8
$\nu_\mu + \bar{\nu}_\mu$ CC	35706	48	23852	39
$\nu_\mu + \bar{\nu}_\mu$ NC	4463	19	3368	17
$\nu_\tau + \bar{\nu}_\tau$ CC	1804	9	934	5
$\nu_\tau + \bar{\nu}_\tau$ NC	556	3	445	4
Atmospheric μ	5022	167	1889	45
Noise Triggers	93	27	< 9	2
total (best fit)	**62203**	**180**	**40959**	**68**
observed	**62112**	**249**	**40902**	**202**

$\mathcal{A}$ = main $\mathcal{B}$ = confirmatory

Cascade-like Track-like



$\cos(\theta_{zen})$

ΔN_{evt} (%)

E_{reco} (GeV)

ν_e/ν_μ

$\nu/\nu bar$

optical eff.

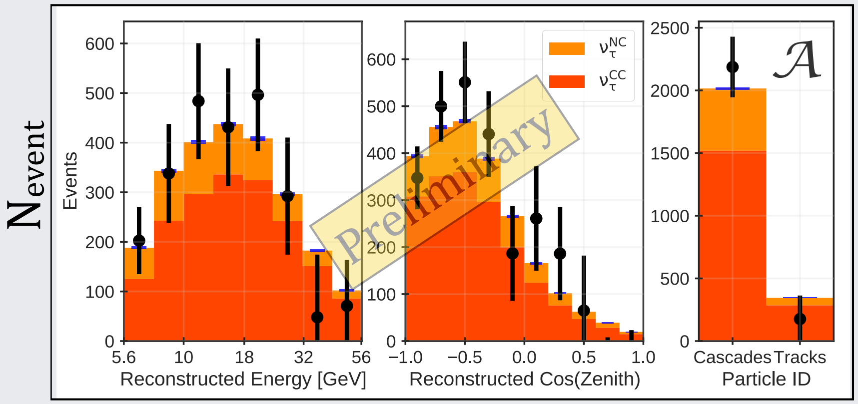
$\Delta m^2(31)$

M_A

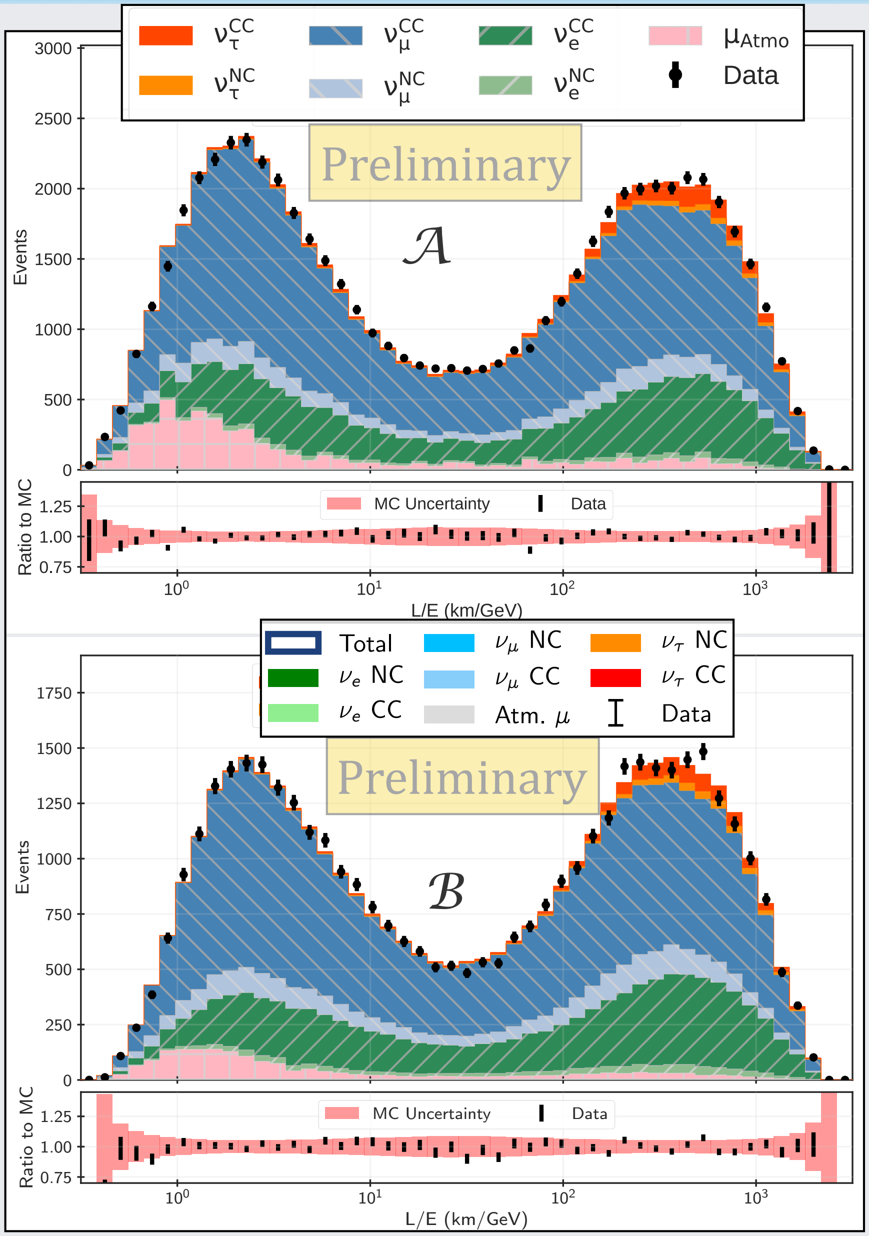
Effect of several systematics, increased by 1σ, on event distribution.

ν_τ Appearance with IceCube

Data distributions with best-fit ν_e+ν_μ and μ backgrounds subtracted (points with stat. error bars), overlaid with best fit ν_τ hypotheses.



E_{reco} (GeV) $\cos(\theta_{zen})_{reco}$ PID_{reco}



$(L/E)_{reco}$ (km/GeV)

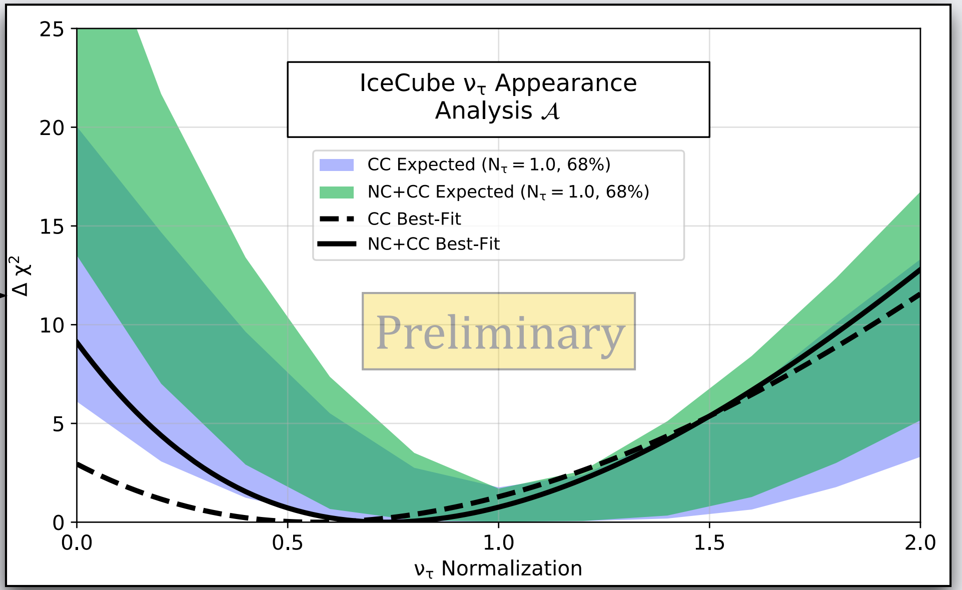
Data distributions vs. L/E (points with stat. error bars), with best-fit ν and μ bkgds. shown (hists.).

Bottom of each plot shows data/MC at best fit point, with shaded region showing stat. unc. of best fit.

ν_τ Appearance with IceCube: Result

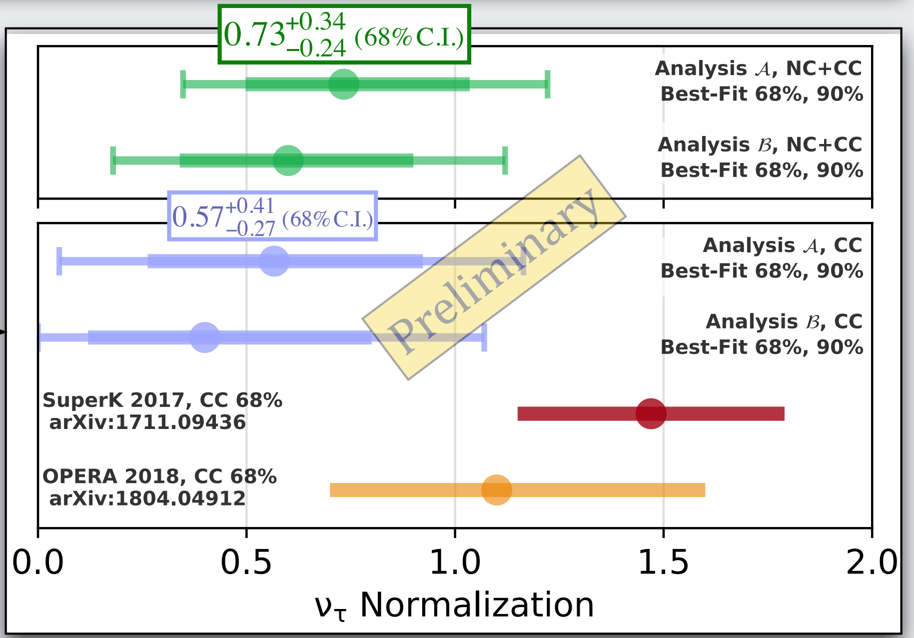
Observed $\Delta\chi^2$ from the best fit (CC+NC) and CC-only.
Shaded bands show 68% ranges of expected $\Delta\chi^2$ distribution from pseudo-experiments.

Used nominal values for osc. params with ν_τ norm. = 1 to show sensitivity of analysis.



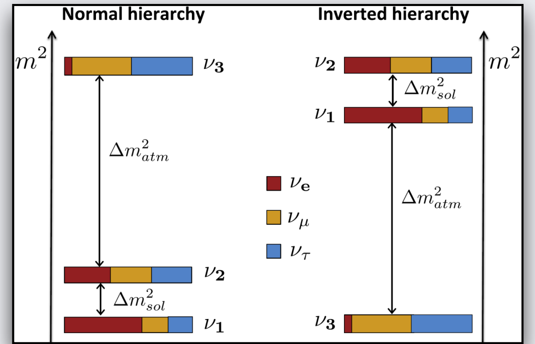
Comparison of all results.

- IceCube $\mathcal{A}$ & $\mathcal{B}$ results internally consistent.
- Super-K, OPERA and IceCube results mutually consistent.
- All results consistent with PMNS unitarity.



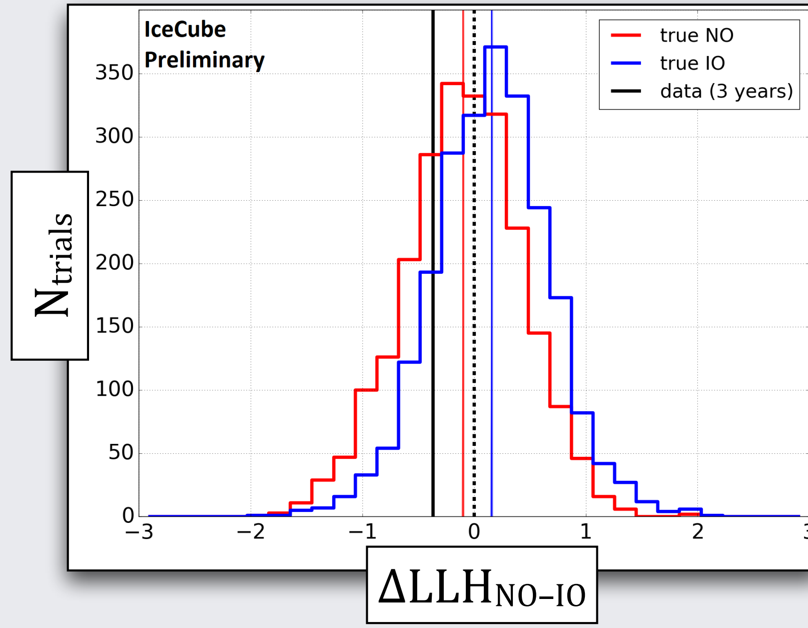
Neutrino Mass Ordering (NMO)

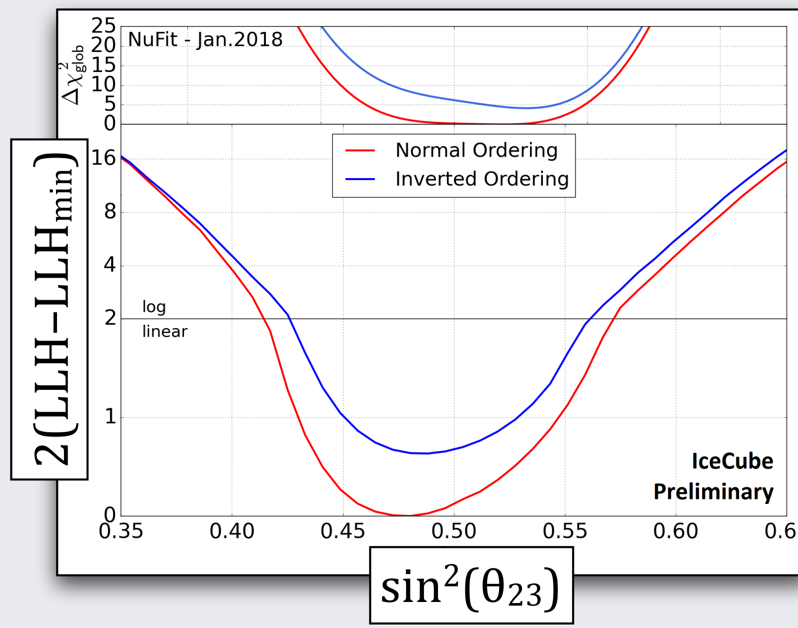
- Use 3 yrs of IceCube data (~43k events) in *proof-of-principle* measurement of NMO



arXiv:1401.2046v2

- Msmt. relies on matter effects on earth-crossing ν at E_ν~5GeV
  - Near energy threshold of DeepCore
- Analysis using "$\mathcal{A}$" dataset prefers NO over IO at p = 15% and in first octant (close to maximal mixing)
  - Consistent with expected sensitivity

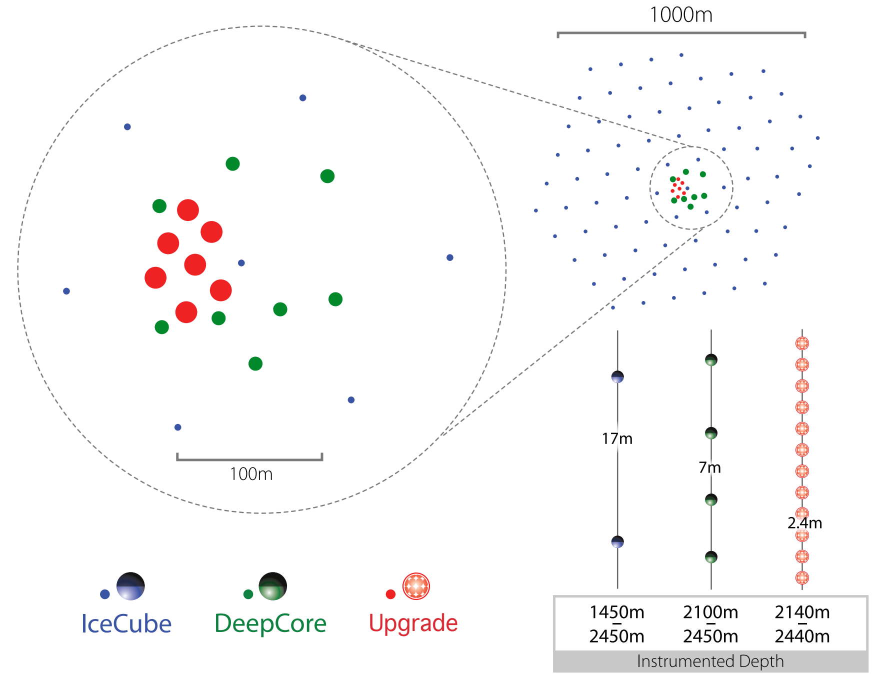




Future Plans

- In process of analyzing ~6 years of data, roughly doubling dataset
- Exploring several ways to improve our low-energy reconstruction
  - E.g., with larger dataset & ~10% improvement in (E, θ_{zen}) resolutions: Improve error on ν_τ norm. by factor of ~1.5
- IceCube Upgrade likely to be approved soon
  - Add 7 new strings in DeepCore fiducial volume to
    - improve ν_τ normalization to better than 10%
    - improve understanding of ice properties for better reconstruction and reduced systematics at low *and* high E_ν

The IceCube Upgrade



7 strings with 875 advanced DOMs and improved calibration devices

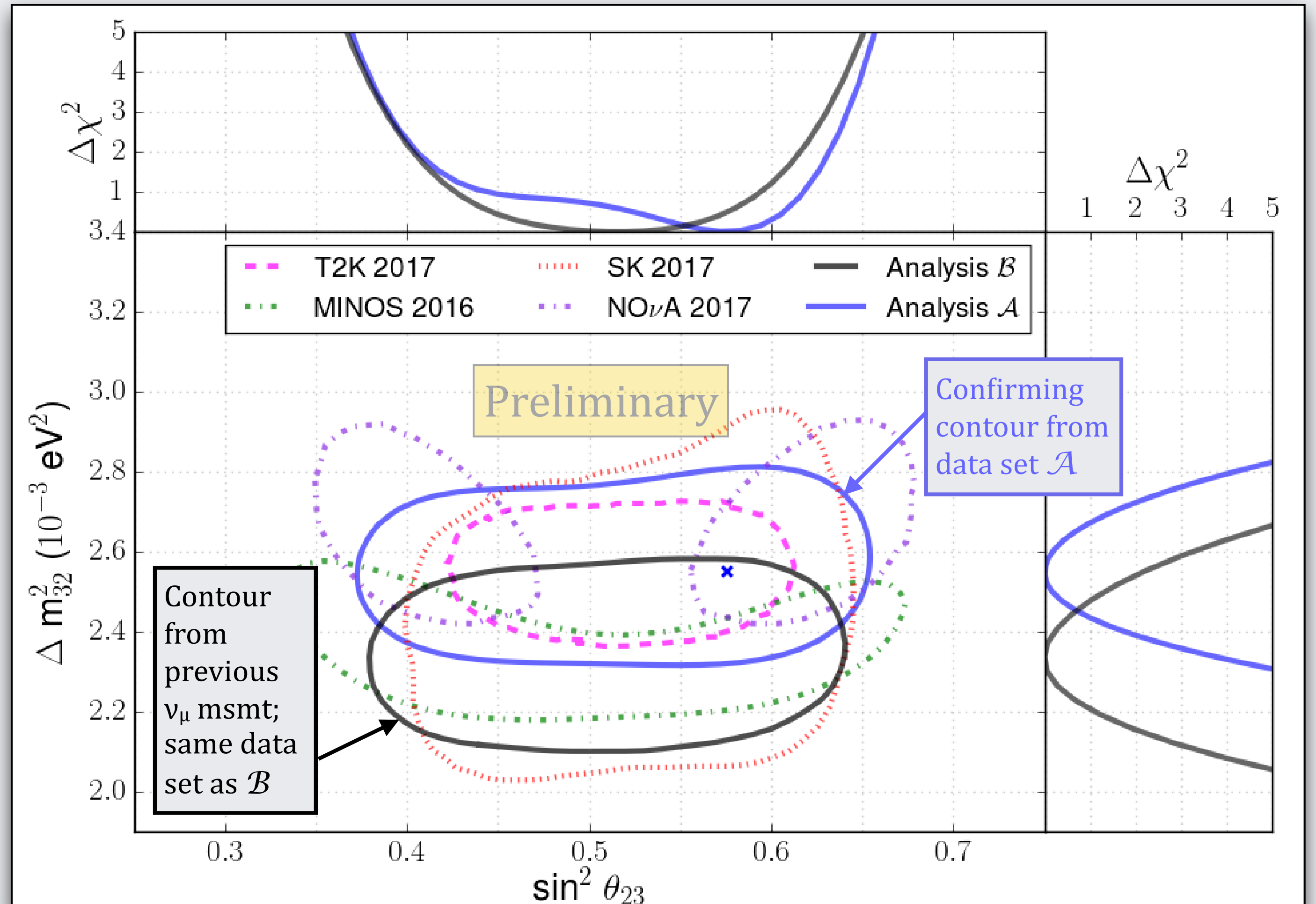
Conclusions

- IceCube/DeepCore have produced very competitive, fundamental neutrino oscillation measurements, and will continue to do so
- Large-volume ν detectors are the best known way to improve the measurement of ν_τ appearance
  - Will eventually produce world-leading measurement, especially with IceCube Upgrade
- The future is bright!

Backup

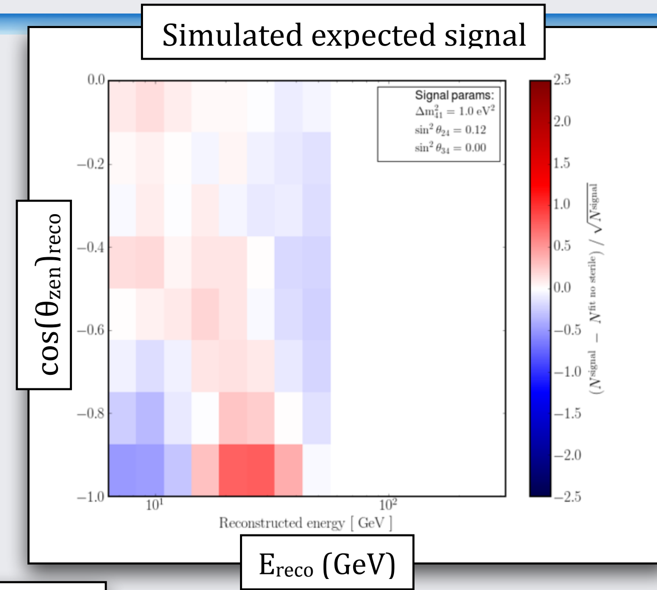
ν_τ Appearance with IceCube

- Check for consistency via measurement of ν_μ disappearance using dataset $\mathcal{A}$

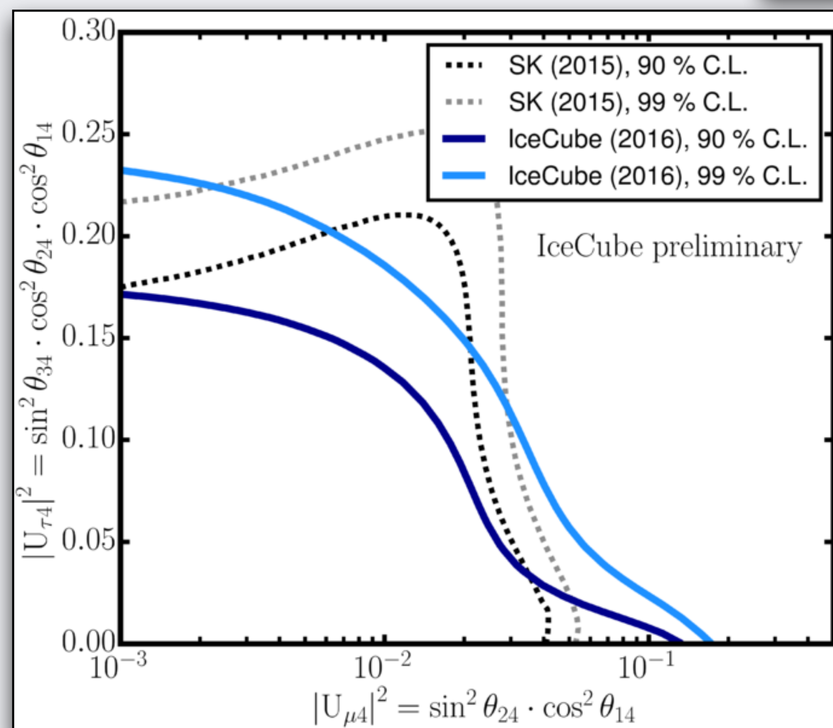


Low-E_ν Sterile ν Search

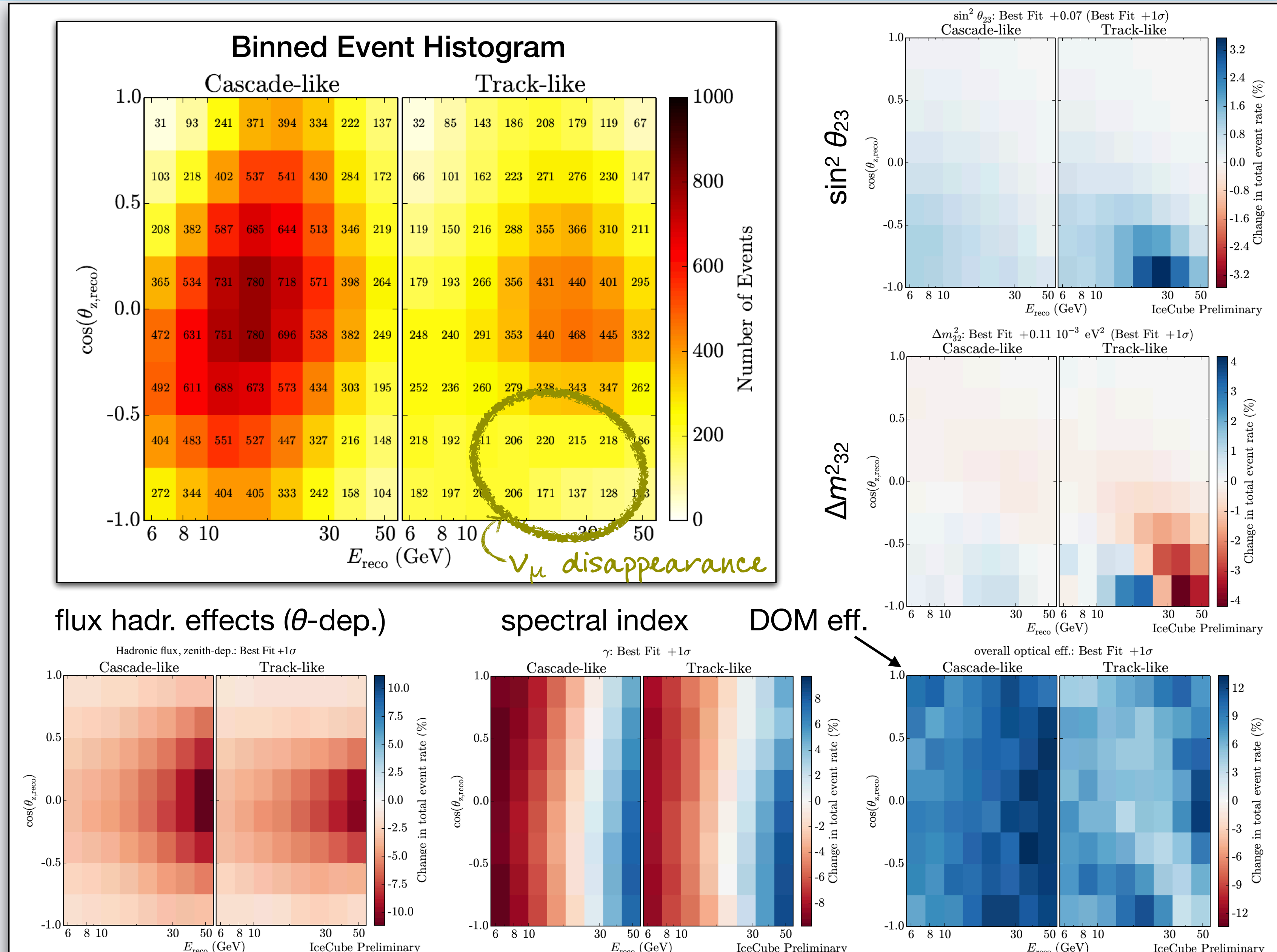
- Sterile ν could distort $\cos(\theta_{zen})$ vs E_ν space between 10-100 GeV



- No distortion seen. Set limits:



ν_μ Disappearance: Systematics



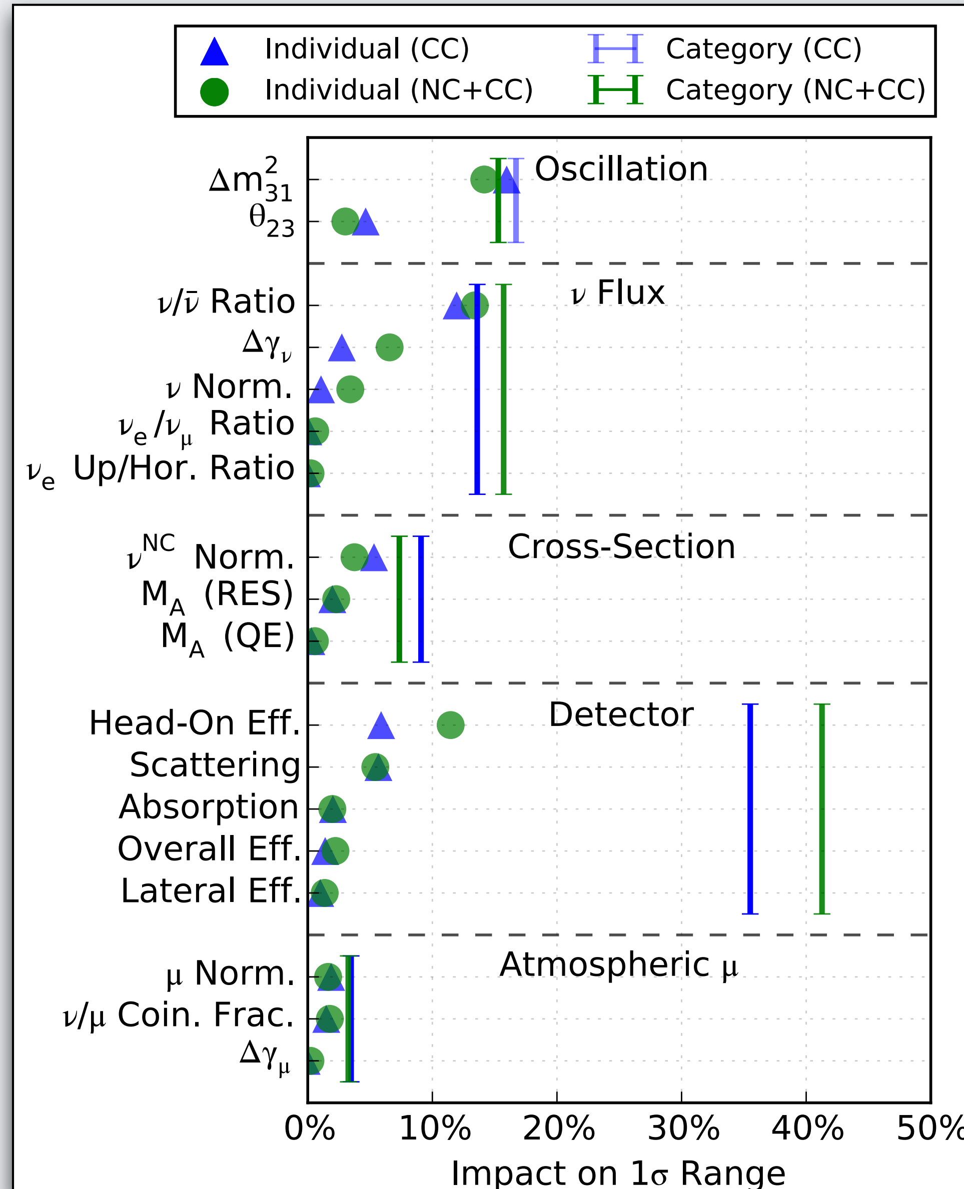
T. DeYoung, Neutrino 2018

ν_μ Disappearance: Systematics

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
M_A (resonance) [GeV]	1.12 ± 0.22	0.92	0.93
$\nu_e + \bar{\nu}_e$ relative normalization [%]	100 ± 20	125	125
NC relative normalization [%]	100 ± 20	106	106
Hadronic flux, energy dependent [σ]	0.00 ± 1.00	−0.56	−0.59
Hadronic flux, zenith dependent [σ]	0.00 ± 1.00	−0.55	−0.57
Detector parameters			
Overall optical efficiency [%]	100 ± 10	102	102
Relative optical efficiency, lateral [σ]	0.0 ± 1.0	0.2	0.2
Relative optical efficiency, head-on [a.u.]	No prior	−0.72	−0.66
Background			
Atm. μ contamination [% of sample]	No prior	5.5	5.6

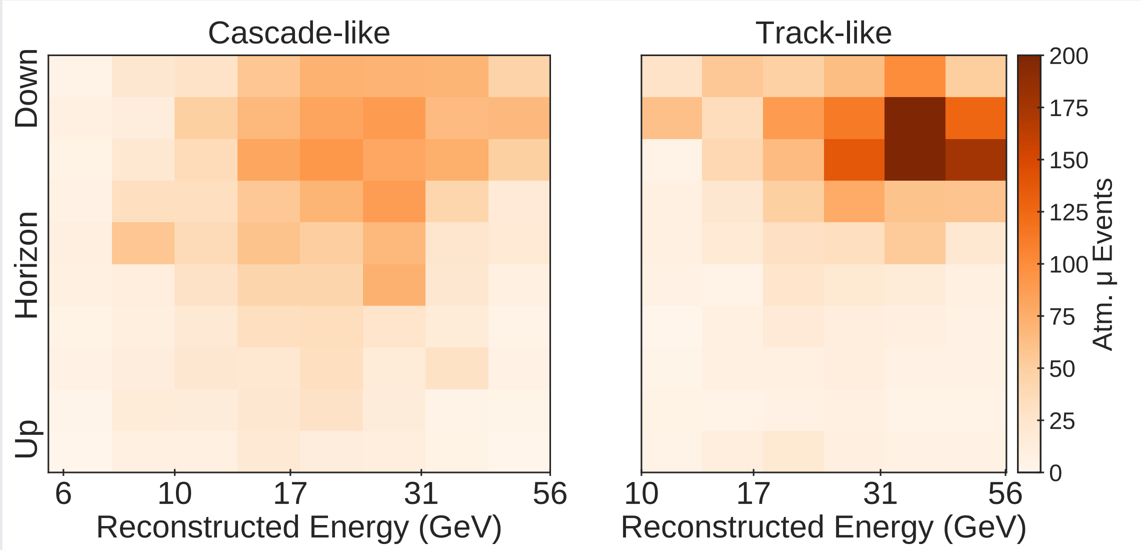
ν_τ Appearance: Systematics

Parameter	Prior	Analysis $\mathcal{A}$ Best fit (CC+NC)	Analysis $\mathcal{A}$ Best fit (CC)	Analysis $\mathcal{B}$ Best fit (CC+NC)	Analysis $\mathcal{B}$ Best fit (CC)
Neutrino Flux:					
ν_e/ν_μ Ratio	1.0 ± 0.05	1.03	1.03	1.03	1.03
ν_e Up/Hor. Flux Ratio (σ)	0.0 ± 1.0	-0.19	-0.18	-0.25	-0.24
$\nu/\bar{\nu}$ Ratio (σ)	0.0 ± 1.0	-0.42	-0.33	0.01	0.04
ν $\Delta\gamma$ (Spectral Index)	0.0 ± 0.1	0.03	0.03	-0.05	-0.04
Effective Livetime (years)	-	2.21	2.24	2.45	2.46
Cross-section:					
M_A (Quasi-Elastic) (GeV)	$0.99^{+0.248}_{-0.149}$	1.05	1.05	0.88	0.88
M_A (Resonance) (GeV)	1.12 ± 0.22	1.00	0.99	0.85	0.85
NC Normalization	1.0 ± 0.2	1.05	1.06	1.25	1.26
Oscillation:					
θ_{13} ($^\circ$)	8.5 ± 0.21	-	-	8.5	8.5
θ_{23} ($^\circ$)	-	49.8	50.2	46.1	45.9
Δm^2_{32} (10^{-3}eV^2)	-	2.60	2.63	2.38	2.34
Detector:					
Optical Eff., Overall (%)	100 ± 10	98.4	98.4	105	104
Optical Eff., Lateral (σ)	0.0 ± 1.0	0.49	0.48	-0.25	-0.27
Optical Eff., Head-on (a.u.)	-	-0.63	-0.64	-1.15	-1.22
Local Ice Model	-	-	-	0.02	0.07
Bulk Ice, Scattering (%)	100.0 ± 10	103.0	102.8	97.4	97.3
Bulk Ice, Absorption (%)	100.0 ± 10	101.5	101.7	102.1	101.9
Atmospheric Muons:					
Atm. μ Fraction (%)	-	8.1	8.0	4.6	4.6
$\Delta\gamma_\mu$ (μ Spectral Index, σ)	0 ± 1	0.15	0.15	-	-
Coincident $\nu + \mu$ Fraction	0 ± 0.1	0.01	0.01	-	-
Measurement:					
ν_τ Appearance Rate	-	0.73	0.57	0.59	0.43

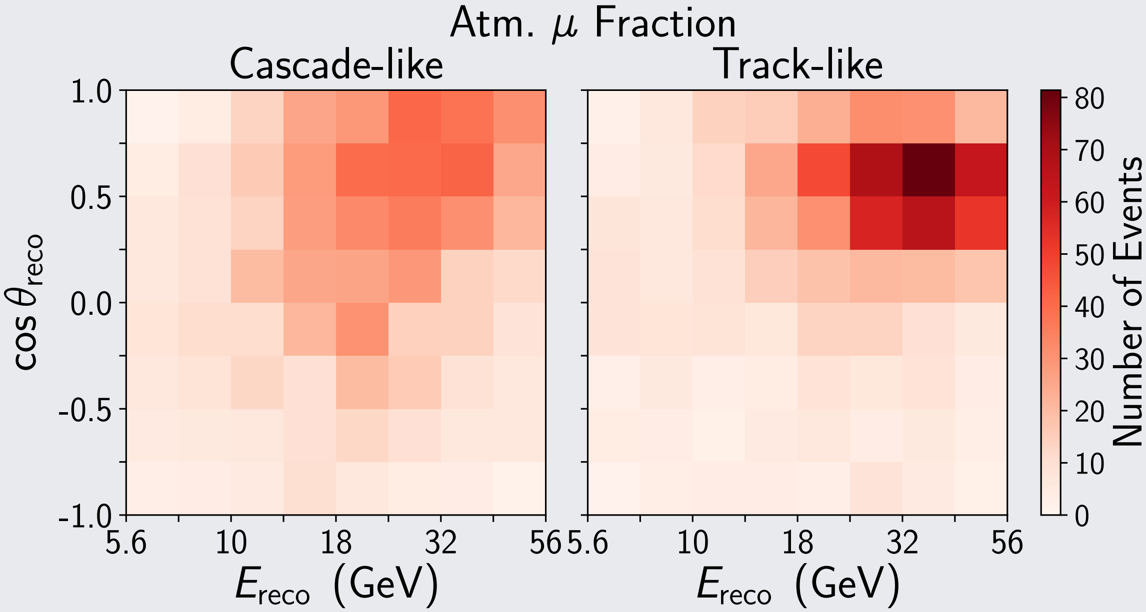


ν_τ Appearance: μ Background

Event distributions of atm. μ bkgd. for analysis $\mathcal{A}$ from best-fit simulation.

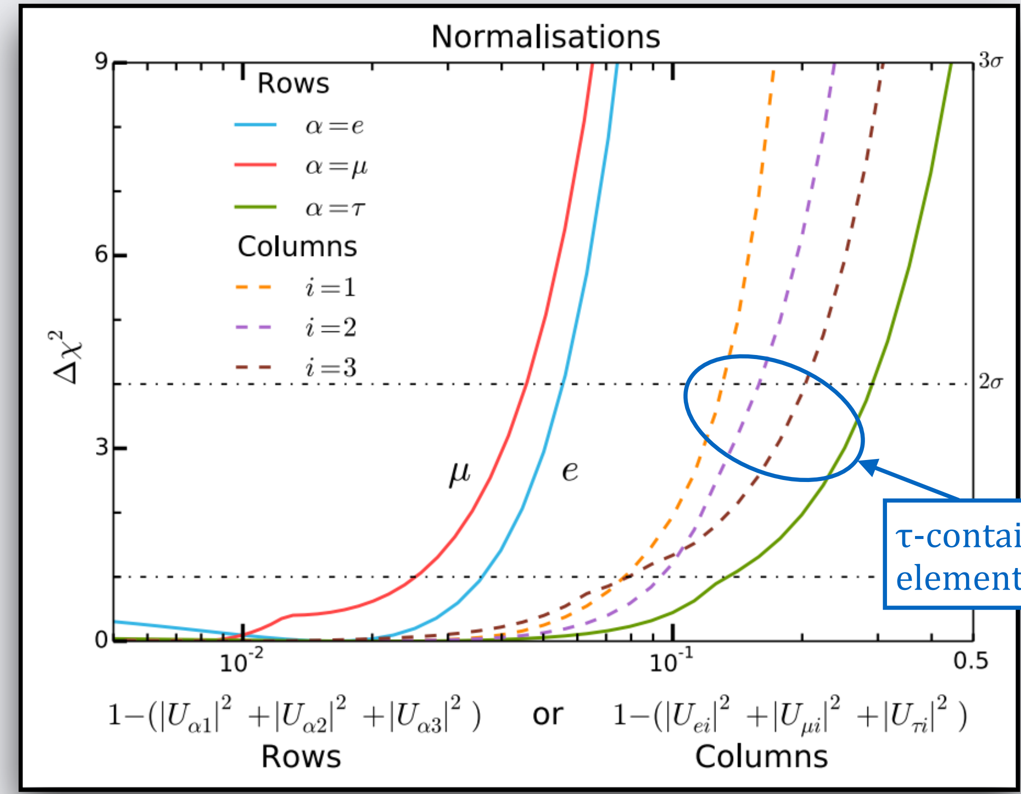


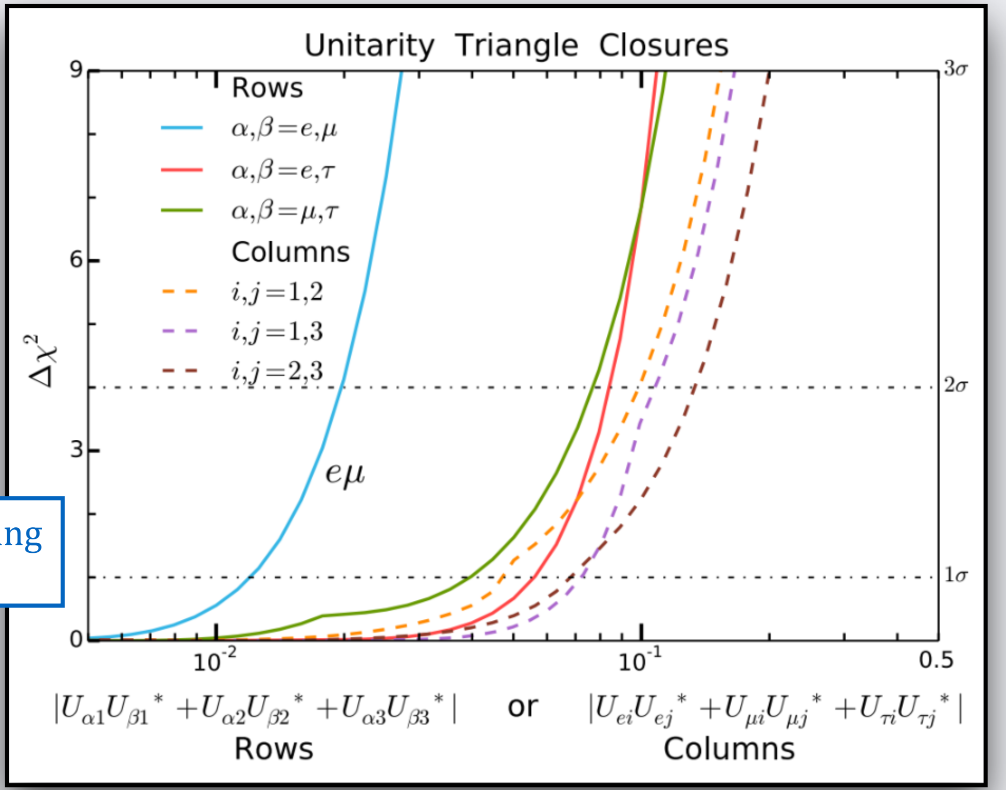
Event distributions of atm. μ bkgd. for analysis $\mathcal{B}$ from data sideband.



ν_τ Appearance & PMNS Unitarity

- Testing PMNS unitarity: We have a ways to go before we can reach CKM levels of precision
  - τ sector constraints are ~order of magnitude weaker than for e,μ sectors
  - Significant deviation from unitarity could be indicator of new physics
  - $\nu_\mu \rightarrow \nu_\tau$ probes combination of $|U_{\mu 3}|$^2 and $|U_{\tau 3}|$^2

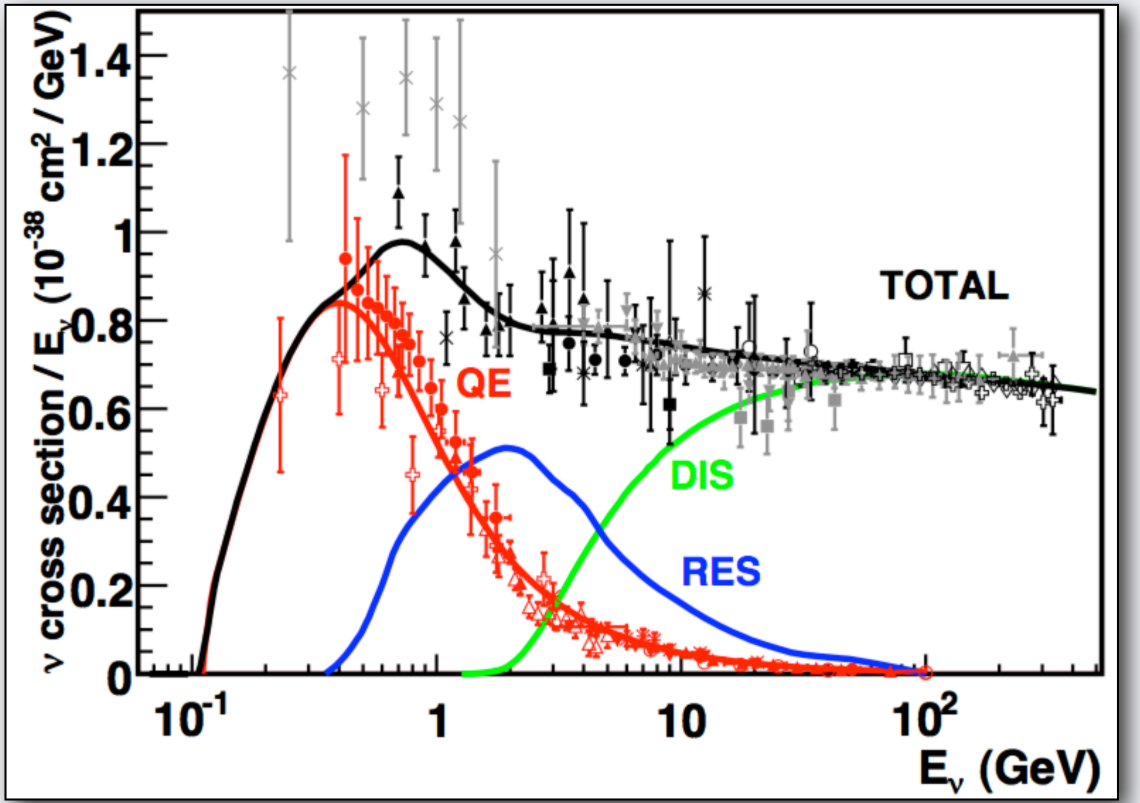




Park & Ross-Lonergan, 2015

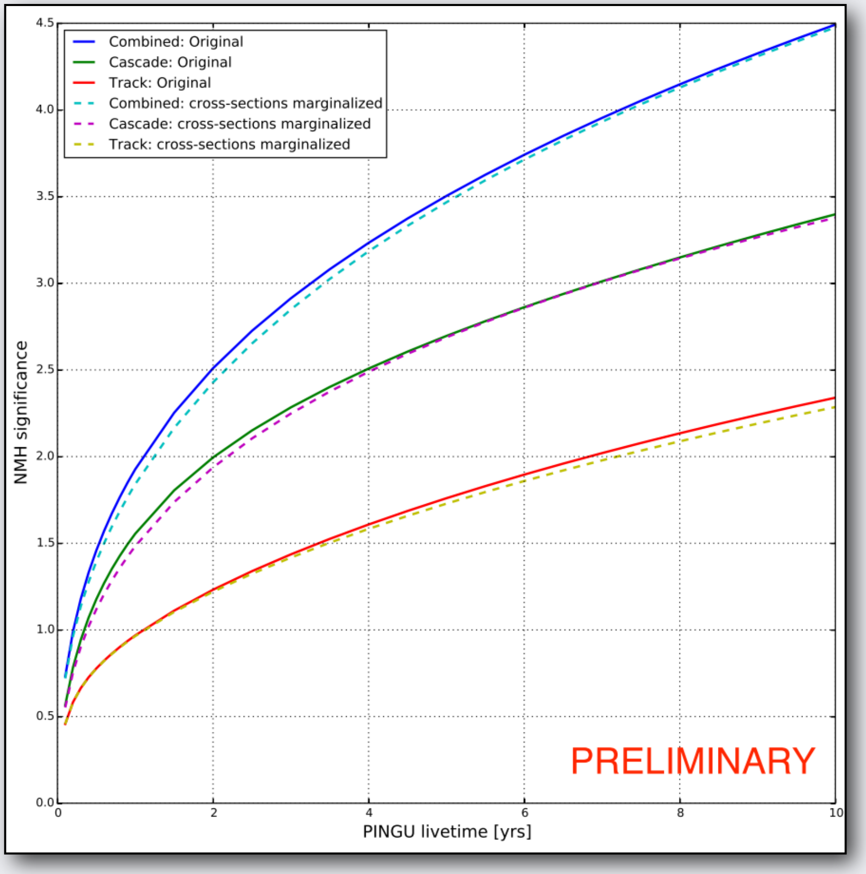
Neutrino Cross Sections

- At the E_ν relevant for DeepCore and PINGU, cross section dominated by DIS



Neutrino Cross Section Systematics

- Performed full treatment of systematics through GENIE, varying over 10 separate parameters
  - Impact on final significance much smaller than that of oscillation parameter uncertainties
  - Largest impacts seen from m_A in CCQE and resonance interactions, and higher twist parameters in Bodek-Yang DIS model



Atmospheric Neutrinos

- Production mechanism
- Wide variety of energies and baselines
- Lots of possible oscillation signatures