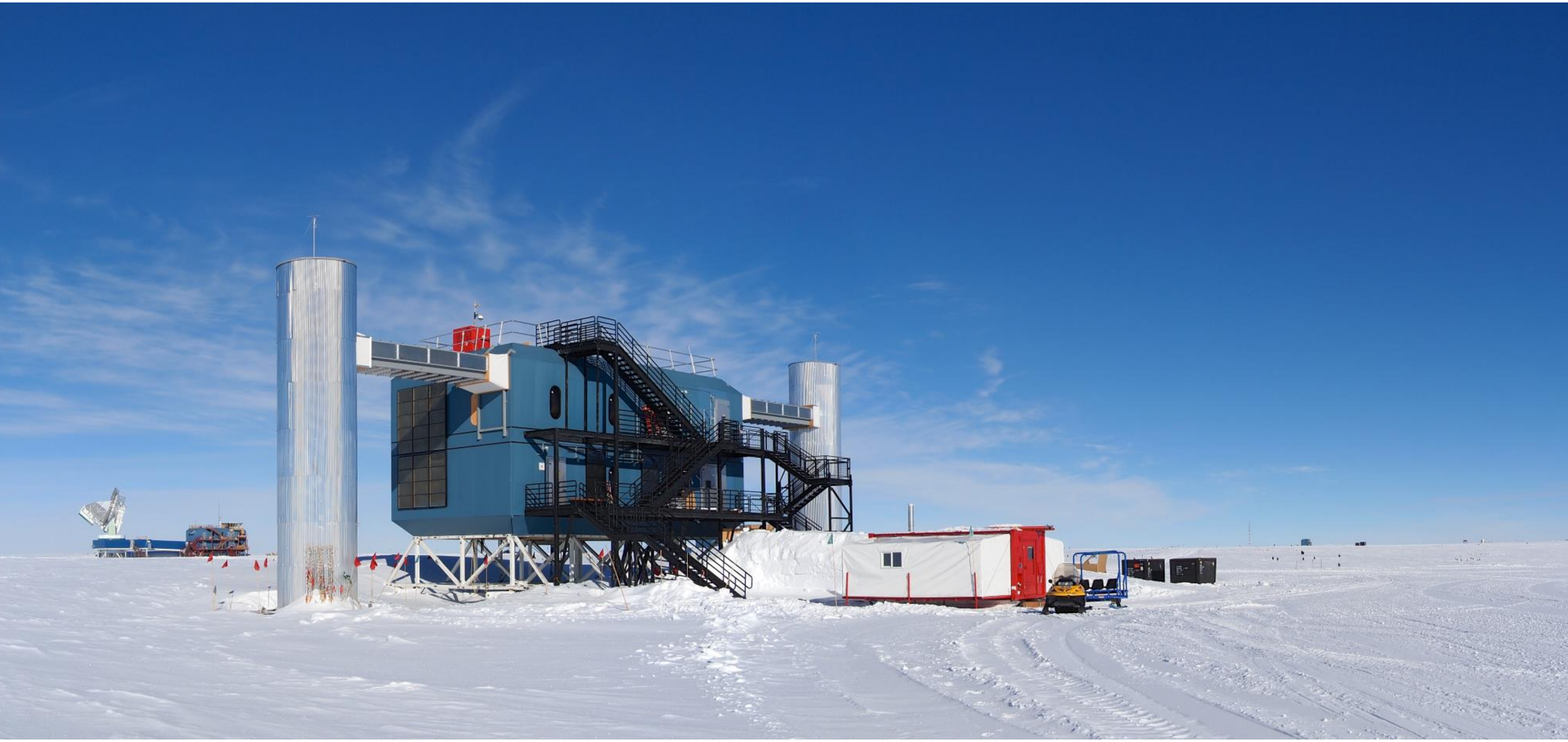

TAU NEUTRINO APPEARANCE IN ICECUBE

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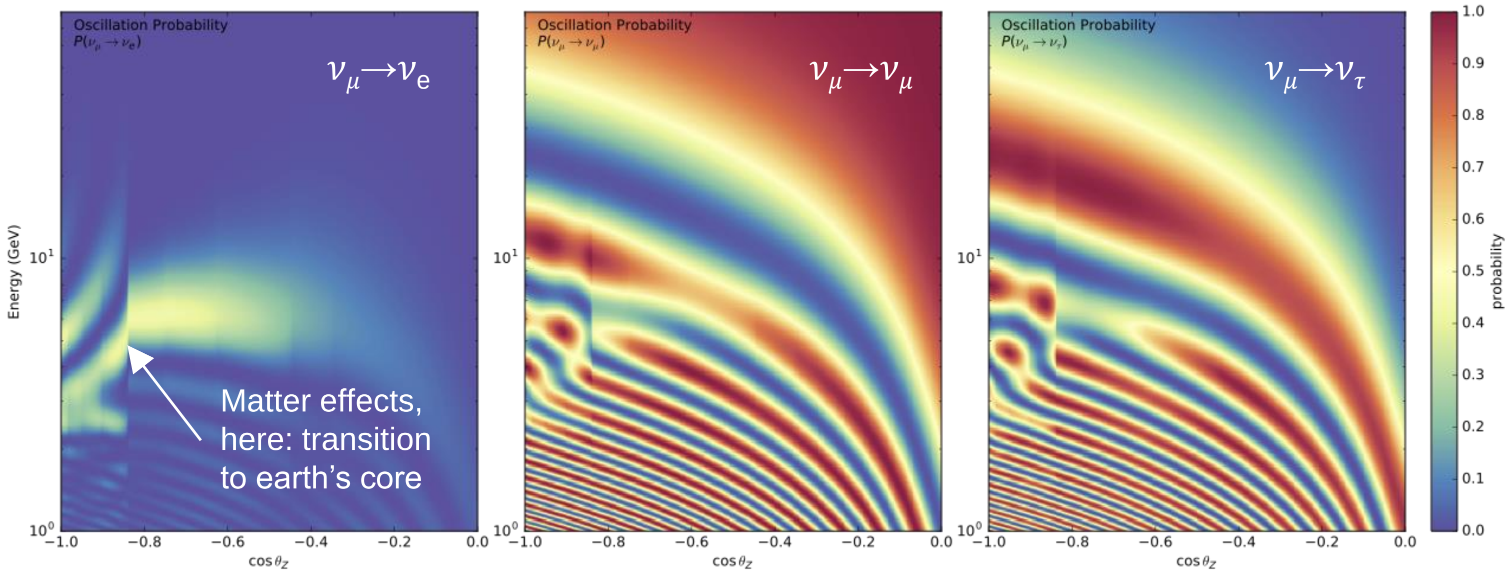
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

ATMOSPHERIC TAU NEUTRINOS

- Intrinsic ν_τ production in atmosphere negligible
- When studying O(10) GeV Neutrinos and below, earth diameter provides perfect L/E to look at ν_μ disappearance
  - We look at events in the Energy-cos(zenith) plane
- A disappeared ν_μ should mostly appear in the ν_τ flavor



cos(zenith) $\propto$ baseline

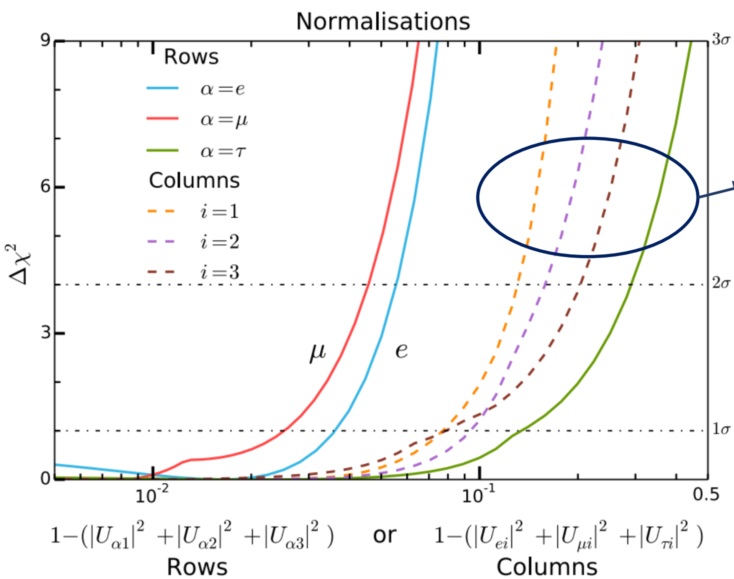
PREVIOUS RESULTS

- OPERA 2015 (https://arxiv.org/abs/1507.01417)
  - CNGS ~17 GeV muon neutrinos / 732 km baseline
  - Observation of ν_τ appearance with 5.1 sigma significance
  - Total of 5 individually identified ν_τ candidates (over 0.25 total background)
  - Only weak constraints on ν_τ normalization: 1.8 -1.1 +1.8 (90% C.L.)

- Super-K 2016 (presented at Neutrino 2016)
  - Evidence with a significance of 4.6 sigma
  - Based on 15 years of data
  - Best constraint on ν_τ normalization with 1.42 +/- 0.32 (68% C.L.)
  - Energies around ~5 GeV

RELEVANCE

- τ-sector of Neutrino oscillations is the least well measured
  - Experimental constraints ~order of magnitude worse than for e and μ sectors
- Measurement of tau appearance can be used to test PMNS unitarity
  - Deviation from unitarity can be an indicator for new physics



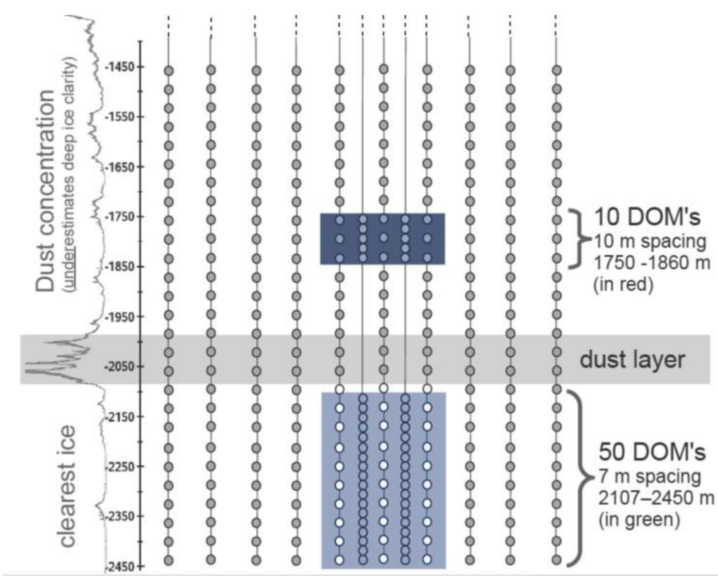
All these contain one or more τ-elements

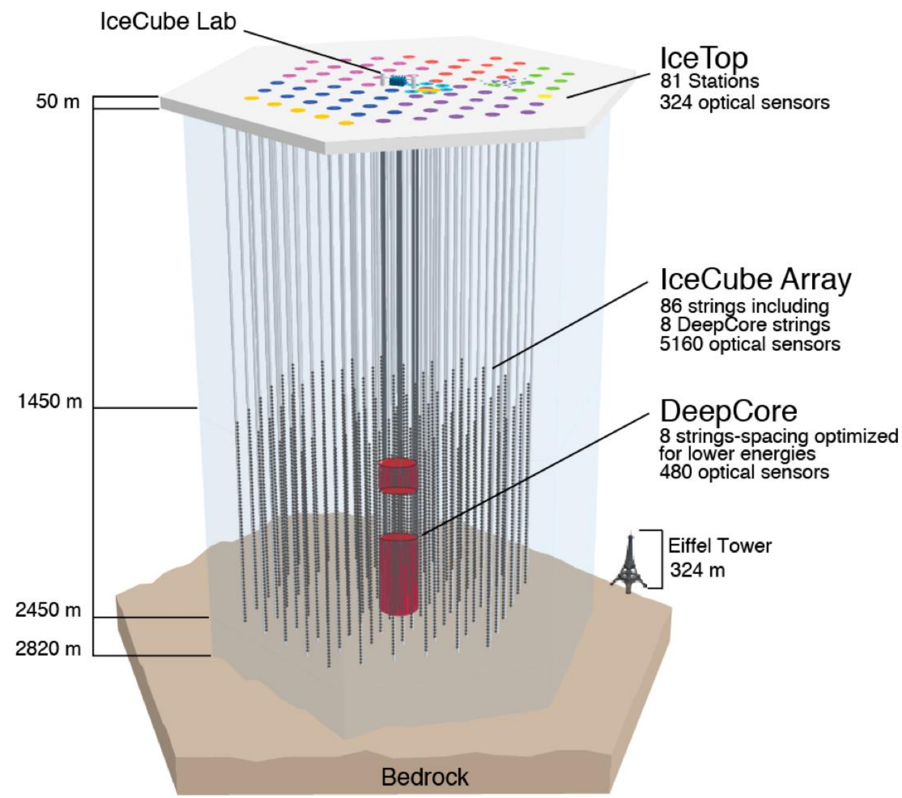
Park & Ross-Lonergan, 2015

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

DEEPCORE EXTENSION OF ICECUBE

- Additional 8 strings with densely spaced, high efficiency optical modules (DOMs) in addition to the 78 standard IceCube strings
- In clearest part of Ice (below *dust* layer)
- Surrounded by IceCube strings (used as atm. muon veto)
- Neutrino energies down to ~5 GeV





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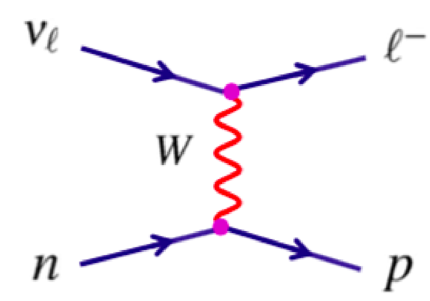
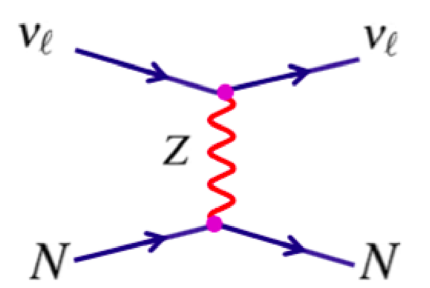
CC AND NC INTERACTIONS

- **Charged Current (CC)** interaction of neutrinos reveals their flavor from the outgoing lepton
  - This channel needed to unambiguously identify ν_τ (e.g. OPERA)
  - Cross-section suppressed by heavy τ, threshold energy of 3.5 GeV, cross section ~order of magnitude lower than that of ν_μ



- **Neutral Current (NC)** interactions are indistinguishable for the 3 flavors
  - Still, the disappearance and appearance happen in specific locations in L/E
  - can be used to help constrain the ν_τ normalization



* for better comparison we provide both result separately, CC+NC and CC-only

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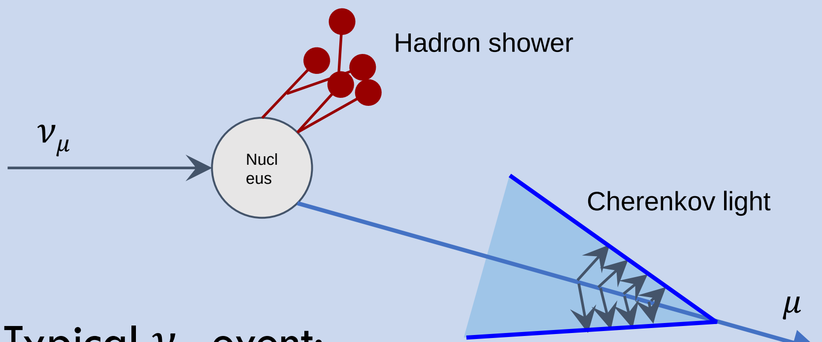
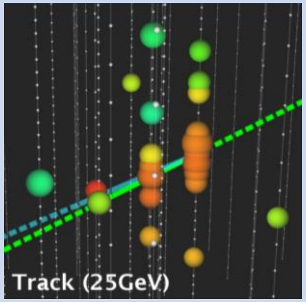
ICECUBE EVENT SIGNATURES

- Fully contained events inside the DeepCore fiducial Volume
- Reconstructed using a full Cascade + Track hypothesis
  - position, direction, energy and PID (= track or cascade like event)

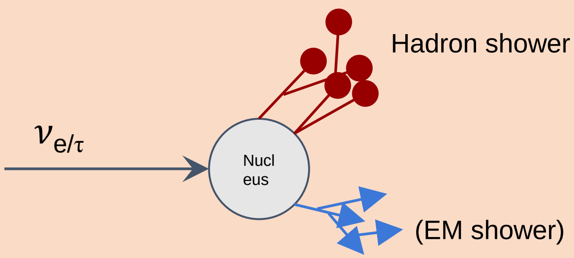
Track like



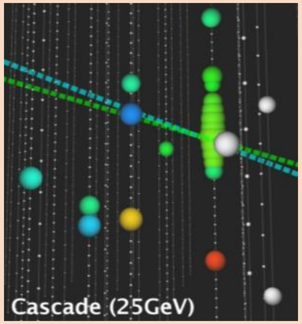
Typical ν_μ event:
Energy deposited in
- Extended muon track (E ~ length)
- Hadron shower from e.g. DIS



Cascade like



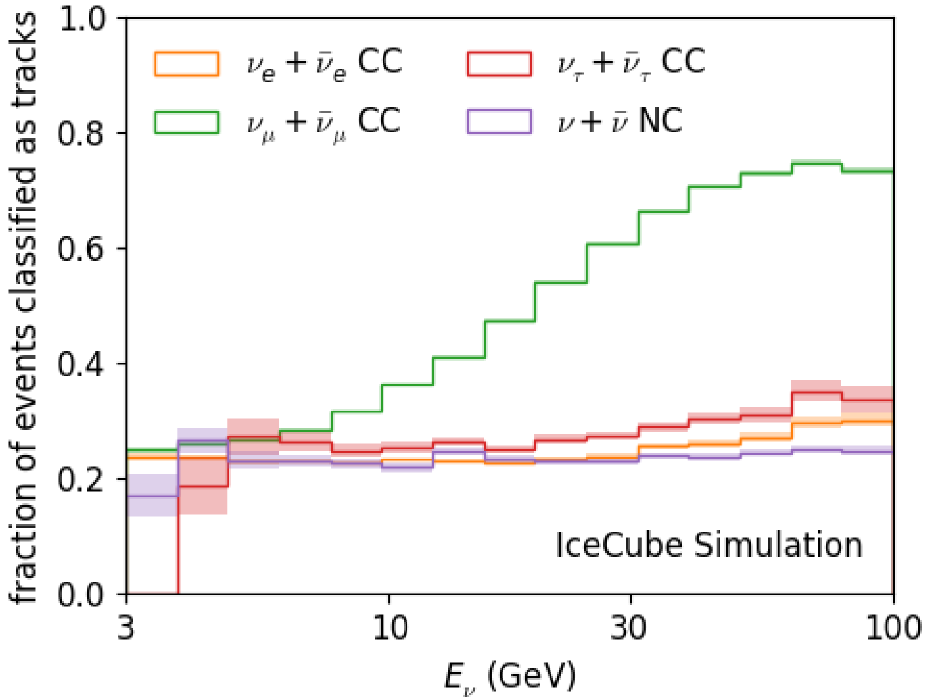
Typical $\nu_{e/\tau}$ event:
All energy deposited in form of showers (hadronic and electro-magnetic)
Spatially more compact (no track)



EVENT CLASSIFICATION

- Our ability to distinguish track and cascade events mainly depending on neutrino energy
  - Higher energy = longer muon tracks

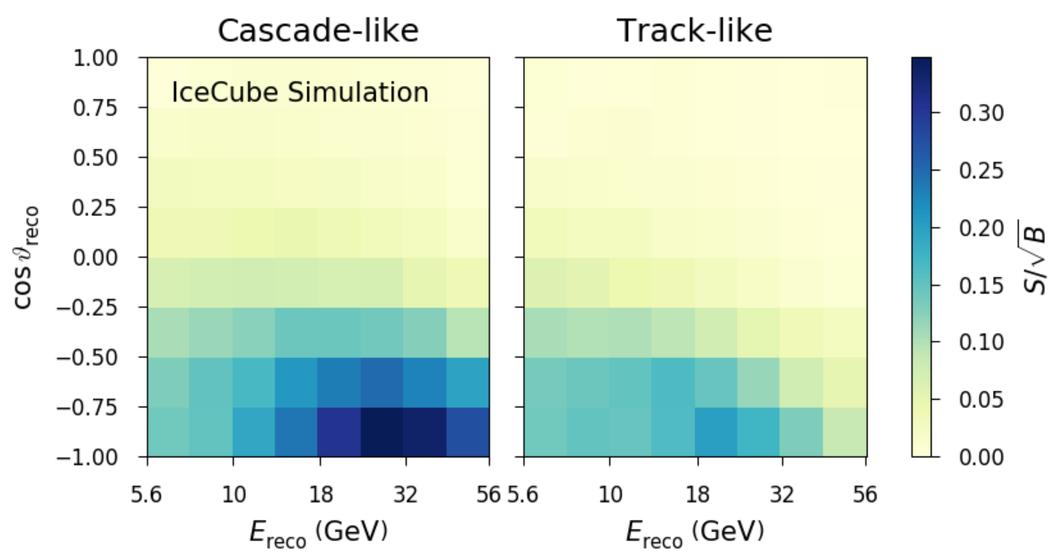
- Separation based on an additional reconstruction using cascade only (no track)
  - Difference in likelihood to the standard reconstruction used as classifier



ANALYSIS

- Actual fit of the data is done using two 2d-histograms
  - Reconstructed neutrino energy (between 5.6 and 56 GeV)
  - Reconstructed zenith angle (covering the full sky from cos(zenith) -1 to +1)
  - Using 8x8 bins, for cascade and track like events separately

  - S/sqrt(B) plot showing region where we get most significance from
    - S = ν_τ, B = ($\nu_e + \nu_\mu$ + Atm. μ)



SYSTEMATIC UNCERTAINTIES

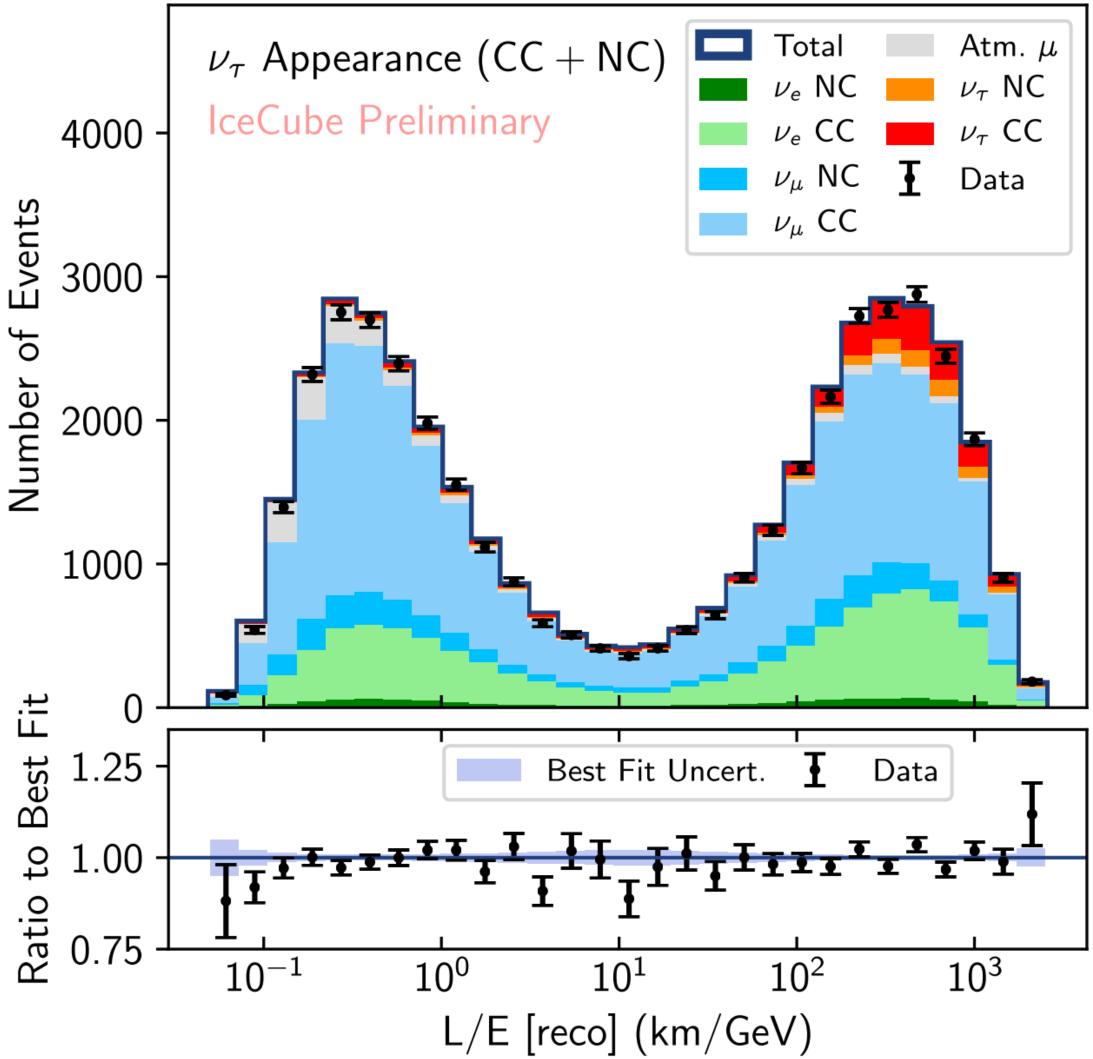
- Incorporating a large variety of nuisance parameters in the measurement
- Covering uncertainties of:
  - Initial atmospheric neutrino flux
  - Interaction (cross sections)
  - Oscillation parameters
  - Detector uncertainties (efficiencies of optical modules and ice uncertainties)
  - Atmospheric muon background

Parameter	Prior	Best fit (CC+NC)	Best fit (CC)
Flux and cross sections			
ν_e/ν_μ ratio	1.0 ± 0.05	1.02	1.02
$\nu/\bar{\nu}$ ratio, zenith dep. (σ)	0.0 ± 1.0	-1.15	-1.11
$\nu/\bar{\nu}$ ratio, energy dep. (σ)	0.0 ± 1.0	0.08	0.11
$\Delta\gamma$ (spectral index)	0.0 ± 0.1	-0.072	-0.074
effective lifetime (y)	-	2.25	2.25
M_A (quasi-elastic) (GeV)	$0.99^{+0.248}_{-0.149}$	0.884	0.881
M_A (resonance) (GeV)	1.12 ± 0.22	0.905	0.901
ν NC Normalization	1.0 ± 0.2	1.15	1.16
Oscillation			
θ_{13} ($^\circ$)	8.5 ± 0.21	8.5	8.5
$\sin^2\theta_{23}$	-	0.52	0.52
Δm^2_{31} (10^{-3}eV^2)	-	2.36	2.36
Detector			
optical eff., overall (%)	100 ± 10	103	104
optical eff., lateral (σ)	0.0 ± 1.0	-0.074	0.046
optical eff., head-on (a.u.)	-	-1.28	-1.16
local ice model	-	-0.11	-0.07
Background			
Atm. μ fraction (%)	-	4.9	4.9

DATA SAMPLE

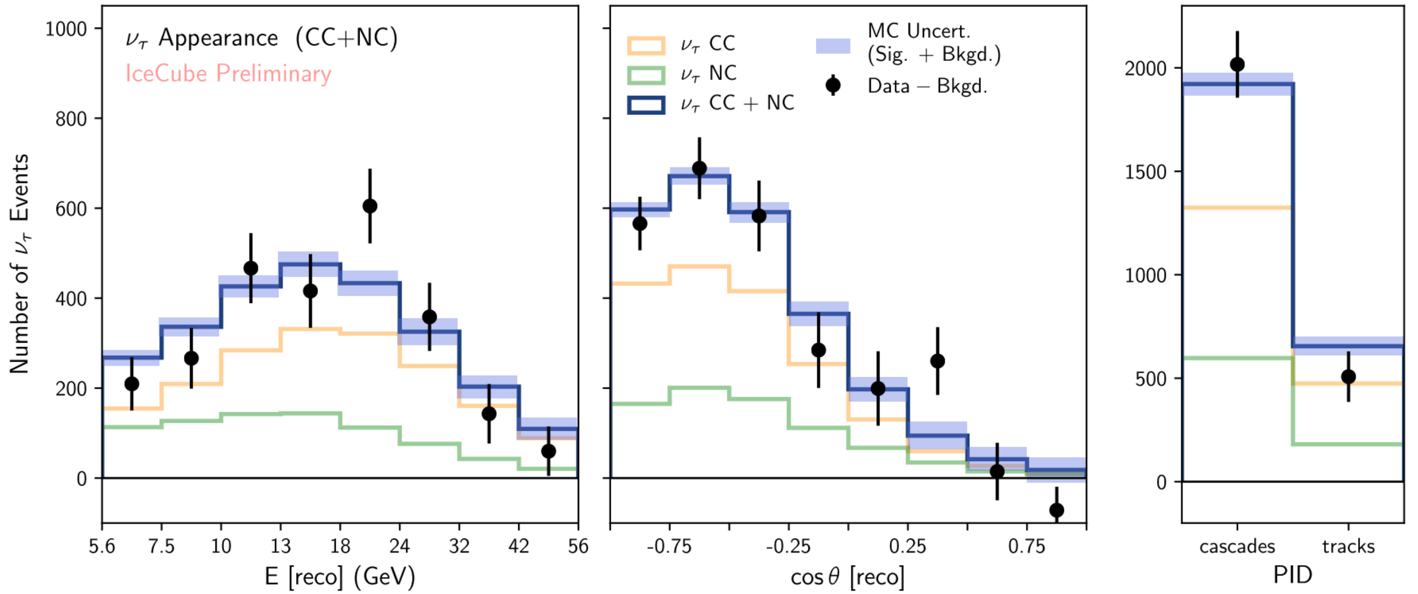
- Result based on 3 years of data
  - Total ~41k events
    - 1.5k CC ν_τ events
    - 600 NC ν_τ events
    - ~2k background events from atmospheric μ
  - Excellent Data/MC agreement

Type	No. events	Uncert.
$\nu_e + \bar{\nu}_e$ CC	9391.0	24.4
$\nu_e + \bar{\nu}_e$ NC	860.7	8.8
$\nu_\mu + \bar{\nu}_\mu$ CC	23093.5	39.4
$\nu_\mu + \bar{\nu}_\mu$ NC	3016.5	15.8
$\nu_\tau + \bar{\nu}_\tau$ CC	1798.6	11.1
$\nu_\tau + \bar{\nu}_\tau$ NC	778.0	8.1
atm. μ	2016.0	49.0
total expected	**40954.2**	**71.2**
observed	**40902**	**202**



TAU NEUTRINO DISTRIBUTIONS

- Visible energies distributed around ~15 GeV (Analysis range 5.6 – 56 GeV)
- ν_τ events appearing in upgoing (-1,0) (earth crossing trajectories)
- Mostly classified in cascade event category

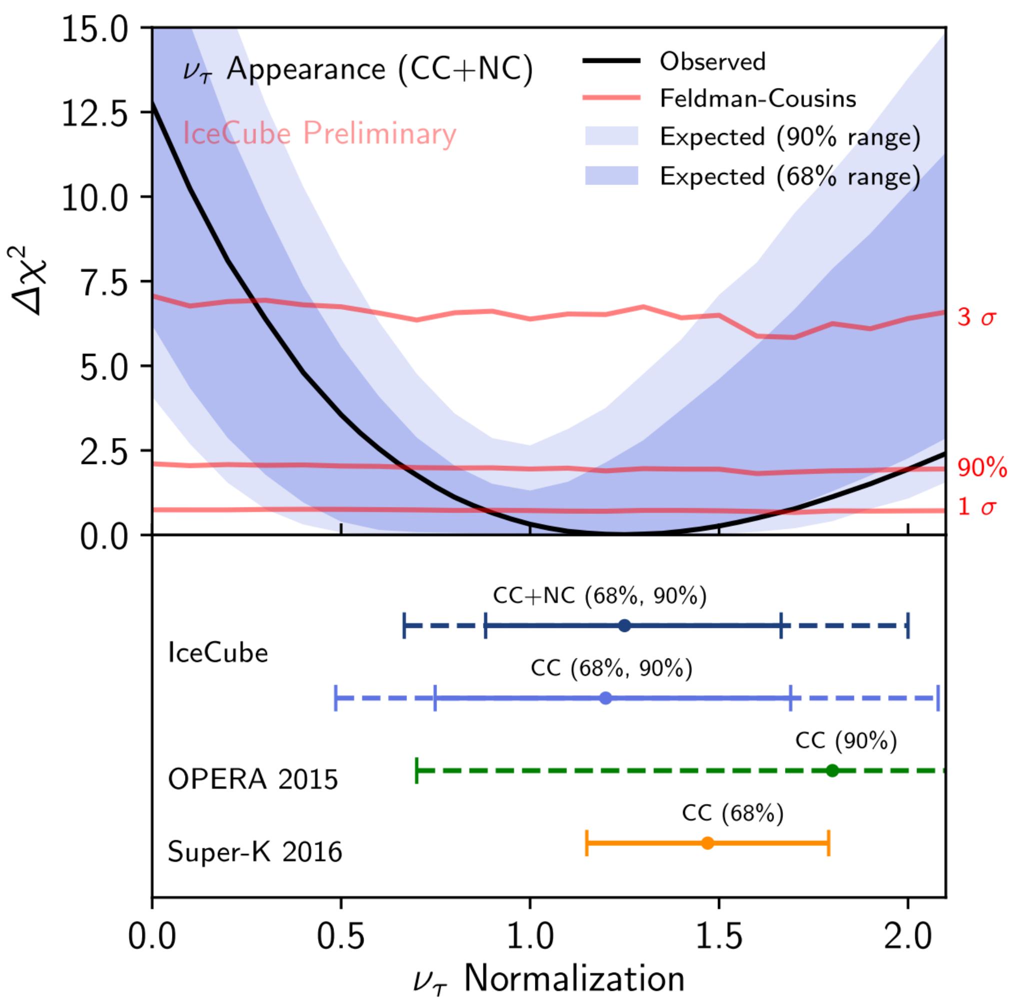


background subtracted data overlayed with best-fit ν_τ expectations

RESULT

NEW!

- ν_τ normalization (with 68% C.I.)
  - CC+NC: **1.25 +0.42 -0.37**
  - CC-only: **1.20 +0.49 -0.45**
- ν_τ appearance significance (exclusion of no-appearance)
  - CC+NC: **4.1 σ**
  - CC-only: **3.0 σ**
- c.f. talk "IceCube/DeepCore Results and PINGU" from this session, PINGU able to constrain ν_τ norm < 10%



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CONCLUSIONS

- Measured ν_τ normalizations of

  1.25 +0.42 -0.37 (CC+NC)
  1.20 +0.49 -0.45 (CC only)

- Based on modestly sized 3y dataset
  - Improved event selection underway
  - Additional 2y of data already collected and experiment continues running

- First ν_τ appearance measurement by IceCube
  - Consistent with other results
  - Competitive result with worlds best measurements
  - Different (higher) energy regime than Super-K
  - Providing path forward for future measurements of the underexplored ν_τ sector

► **STAY TUNED!**