UNIVERSITY OF COPENHAGEN

Measurements of Tau Neutrino Appearance with IceCube-DeepCore

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Atmospheric Neutrino Oscillations

- Neutrino oscillations are governed by the PMNS matrix
  - Nine separate terms
  - If unitary, can reduce to 3 mixing angles + 1 complex phase

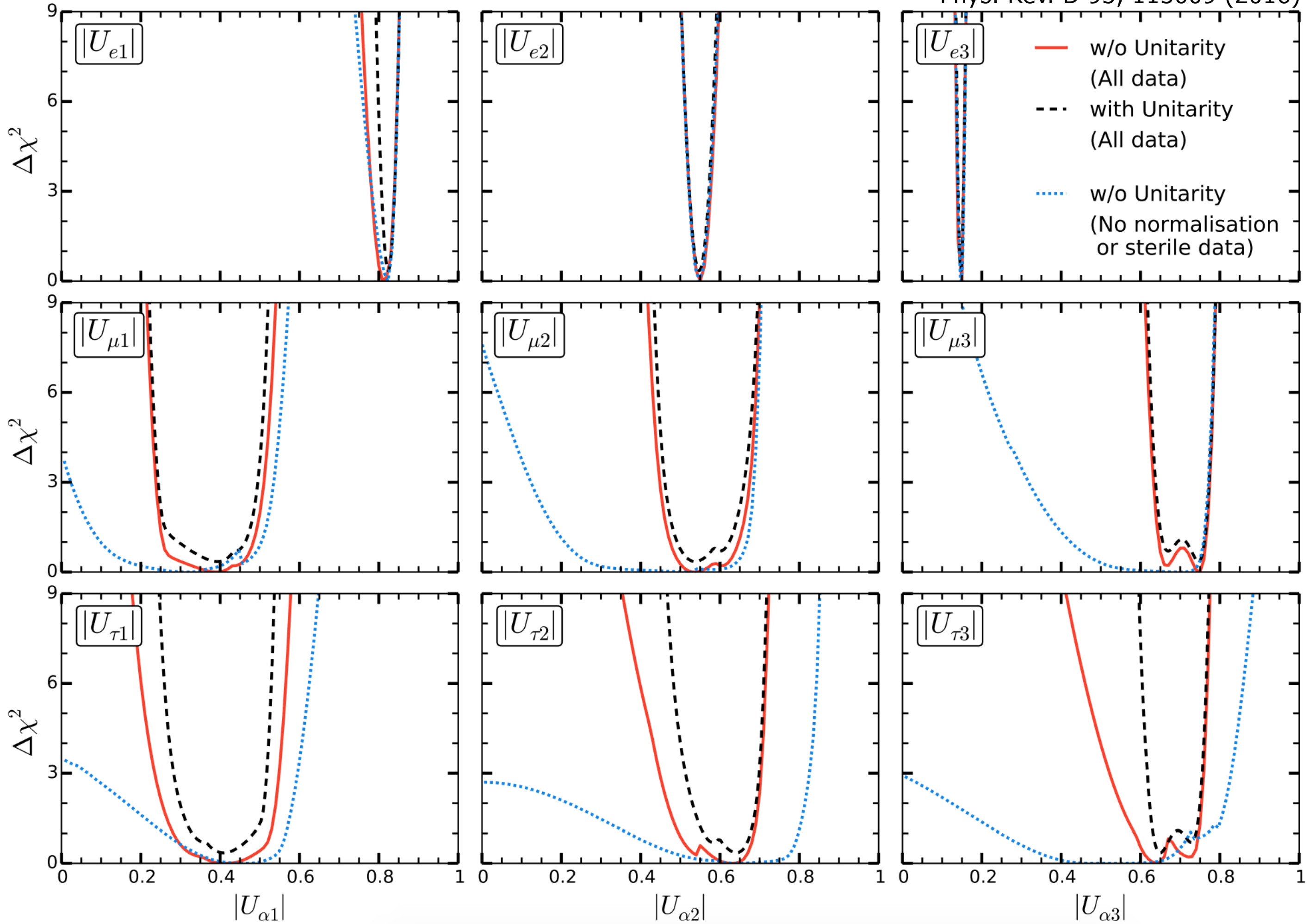
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

- It is possible that the 3x3 matrix is an approximation to a larger NxN mixing matrix
  - 3x3 PMNS matrix approximation would show non-unitarity

- Two approaches are possible to look for non-unitarity:
  - Sterile neutrino searches for 1+N, N+1 mixing terms
  - Improved measurements of standard oscillation parameters
    - Requires information from a variety of energies, baselines

Constraints on 3x3 PMNS Matrix Terms

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

Constraining ν_τ Mixing Elements

- Oscillations occur from atmospheric neutrinos
  - Typically use a baseline of the Earth
  - We are dominated by $\nu_\mu \rightarrow \nu_\tau$ oscillations around 20 GeV

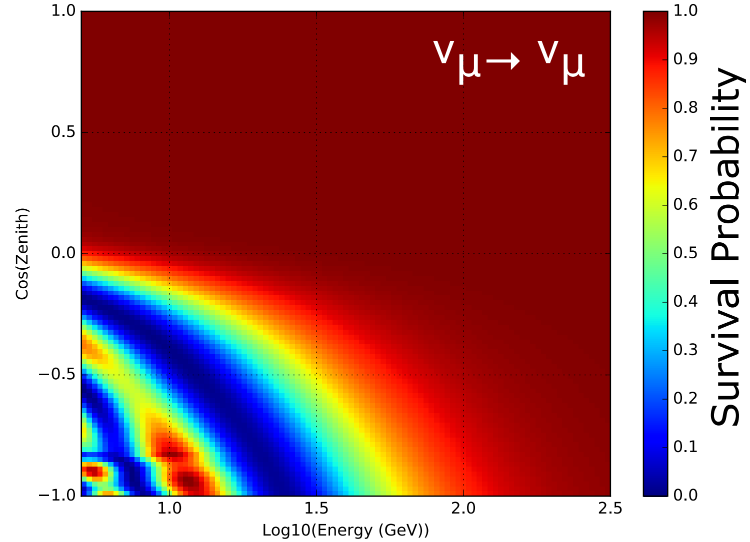
- Two potential measurements here:
  - ν_μ Disappearance:

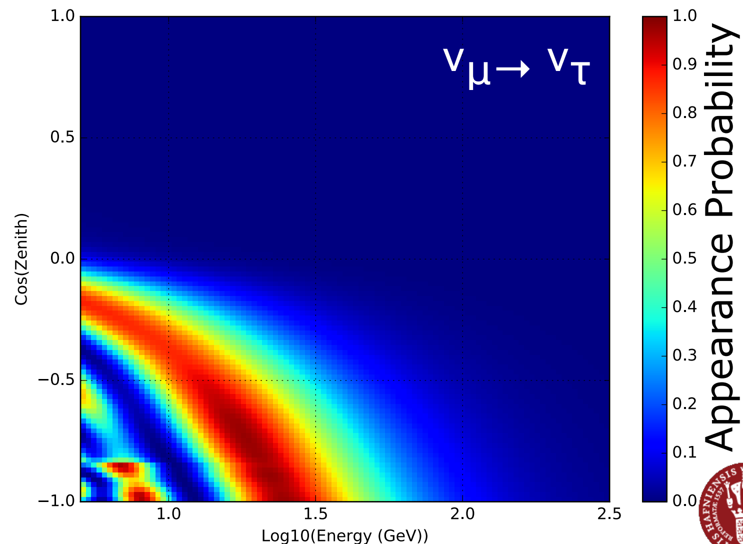
$$P_{\nu_\mu \rightarrow \nu_\mu} = \left| \sum_j U^*_{\mu j} U_{\mu j} e^{-i m_j^2 L/2E} \right|$$

  - ν_τ Appearance:

$$P_{\nu_\mu \rightarrow \nu_\tau} = \left| \sum_j U^*_{\mu j} U_{\tau j} e^{-i m_j^2 L/2E} \right|$$

- The two channels are sensitive to different elements
  - Measure both to improve limits on some of the ν_τ elements





Measurements of ν_τ Appearance in OPERA

- Measurement of CERN ν_μ at Gran Sasso from 2008-2012
  - Looking for CC interactions
- Emulsion cloud chambers
  - High precision position resolution
  - Allows direct observation of τ lepton
- Observed 5 ν_τ candidate events
  - Expected signal: 2.64 ± 0.53 events
  - Expected background: 0.25 ± 0.05 events
- Rejection of no-appearance at 5.1σ

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

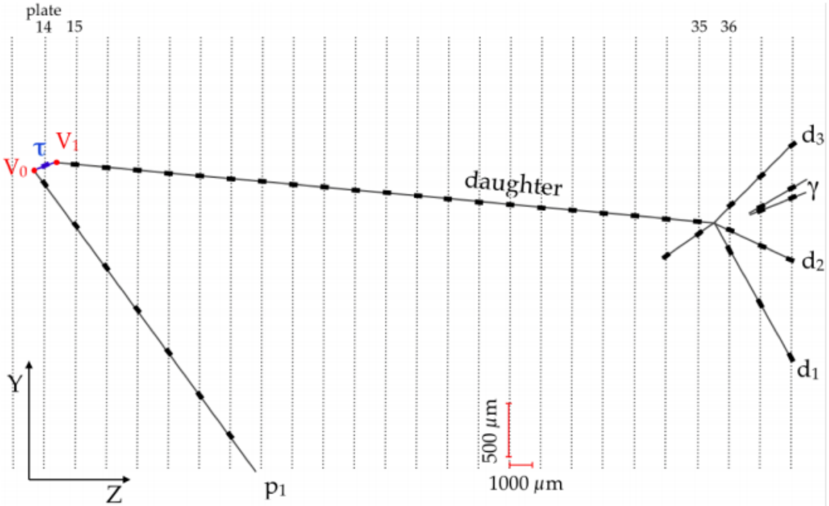


FIG. 2: Event display of the fifth ν_τ candidate event in the horizontal projection longitudinal to the neutrino direction. The primary and secondary vertices are indicated as V_0 and V_1, respectively. The black stubs represent the track segments as measured in the films.

Measurements of ν_τ Appearance in SuperK

Phys. Rev. Lett. 110, 181802 (2013)

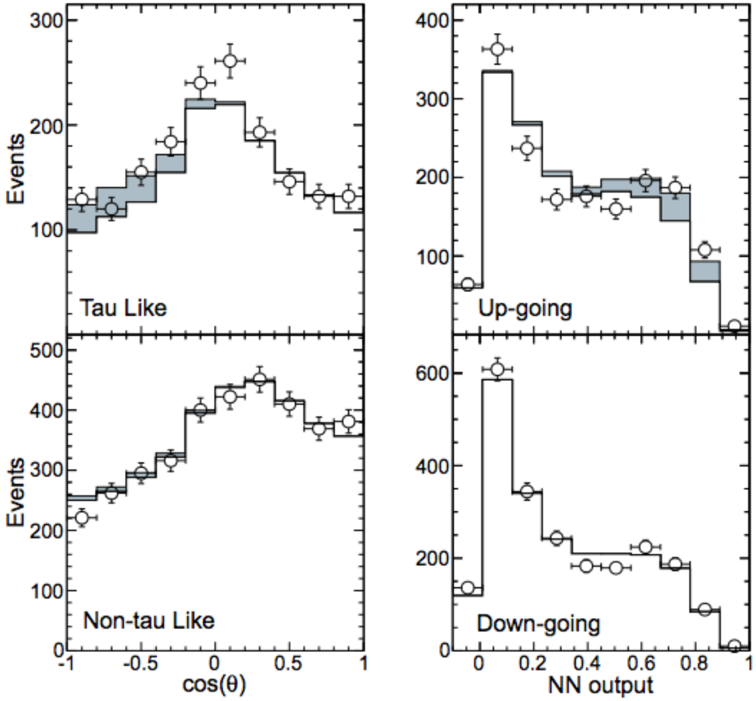


FIG. 3. Fit results showing projections in the NN output and zenith angle distribution for taulike (NN>0.5), upward-going [$\cos(\theta) < -0.2$], nontaulike (NN<0.5), and downward-going [$\cos(\theta) > 0.2$] events for both the two-dimensional PDFs and data. The PDFs and data sets have been combined from SK-I through SK-III in this figure. The fitted tau signal is shown in gray.

- Atmospheric neutrino search using Super-Kamiokande
  - SKI-III (1996-2008)
  - Looking for CC interactions
- Can't identify individual ν_τ events like OPERA
  - Relies on neural net to separate τ-like from other interactions
- Observed signal:
  - $180.1 \pm 44.3(\text{stat})^{+17.8}_{-15.2}(\text{syst})$
- Expected signal:
  - $120.2^{+34.2}_{-34.8}(\text{syst})$
- Rejection of no-appearance at 3.8σ
  - More recently, at 4.6σ with SKI-IV

Tau Neutrino Appearance in IceCube-DeepCore

- Constraints not yet precise enough for strong statements on PMNS unitarity
  - Largest uncertainties on τ-related mixing elements
  - ν_τ appearance measurements can begin to give an additional handle for unitarity tests

- Current IceCube analyses constrain $\nu_\mu \rightarrow \nu_\tau$ from disappearance channel
  - Observation of ν_μ disappearance implies $\nu_\mu \rightarrow \nu_\tau$ appearance

- Challenge:
  - Identify 20-30 GeV τ leptons
    - Expected decay length: O(mm)
    - DeepCore sensor granularity: 7 m
  - DeepCore cannot identify τ interactions individually

- Instead, focus on a inclusive appearance measurement like SuperK

Defining an "Appearance Strength" Parameter

- Use what OPERA, Super-Kamiokande have done previously
  - Define "tau normalization", N_τ, as modification of expected tau neutrino event rate from standard muon neutrino flux, oscillations

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

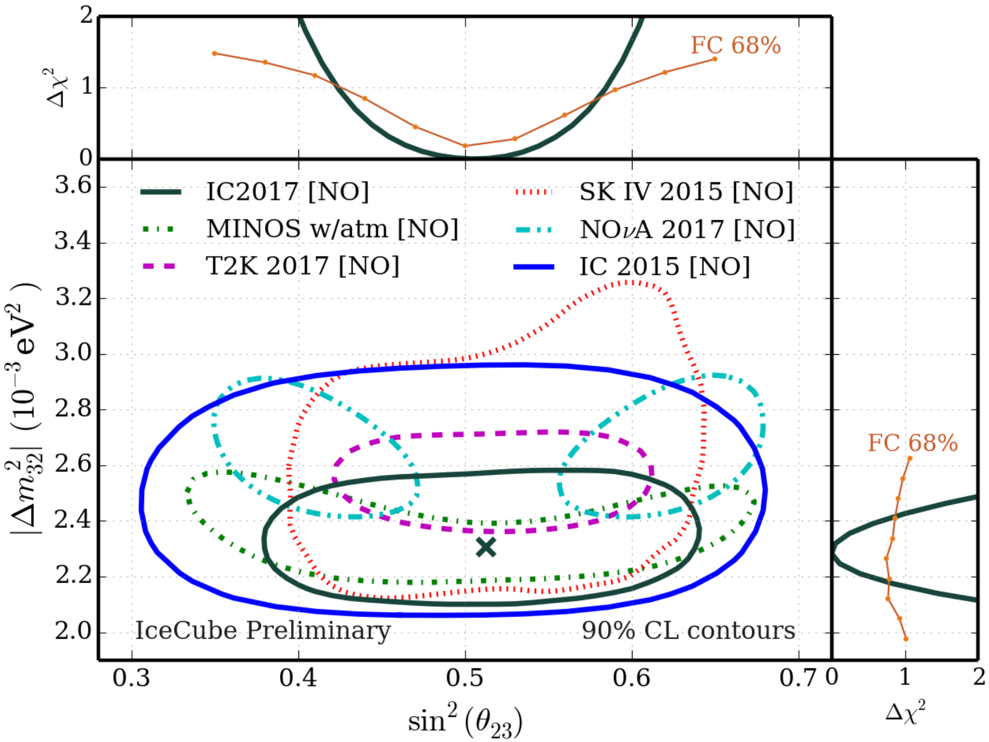
- Fit both disappearance and appearance simultaneously
  - Disappearance primarily in track-like events
  - Appearance primarily in cascade-like events

- Can apply this to just CC ν_τ or both (NC+CC) ν_τ interactions
  - DeepCore does not have strong differentiation between NC events and ν_τ interactions
  - Showing the latter today. CC-only in backup

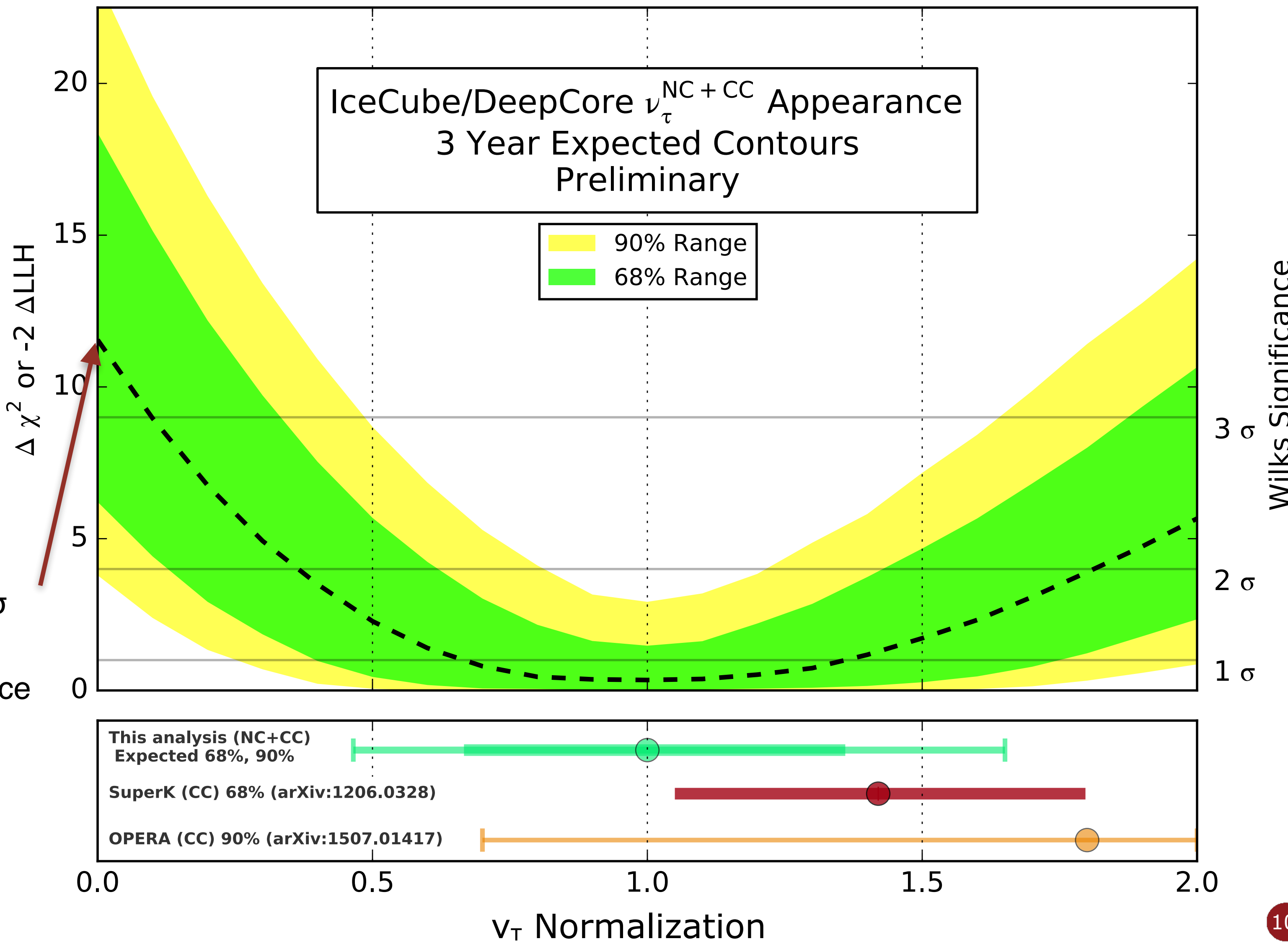
Start by Using the Existing Event Selection

- ν_μ disappearance gives a significant background uncertainty
- We can use the existing event selection from previous talk
  - Already constrains disappearance signal
  - Provides both track-like events and cascade-like events
- Using a similar set of systematics, we produce an expected sensitivity

arXiv:1707.07081



Using the Disappearance Event Selection (Analysis 1)



More than 3σ rejection of no-appearance expected

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 better dataset for appearance? Yes!

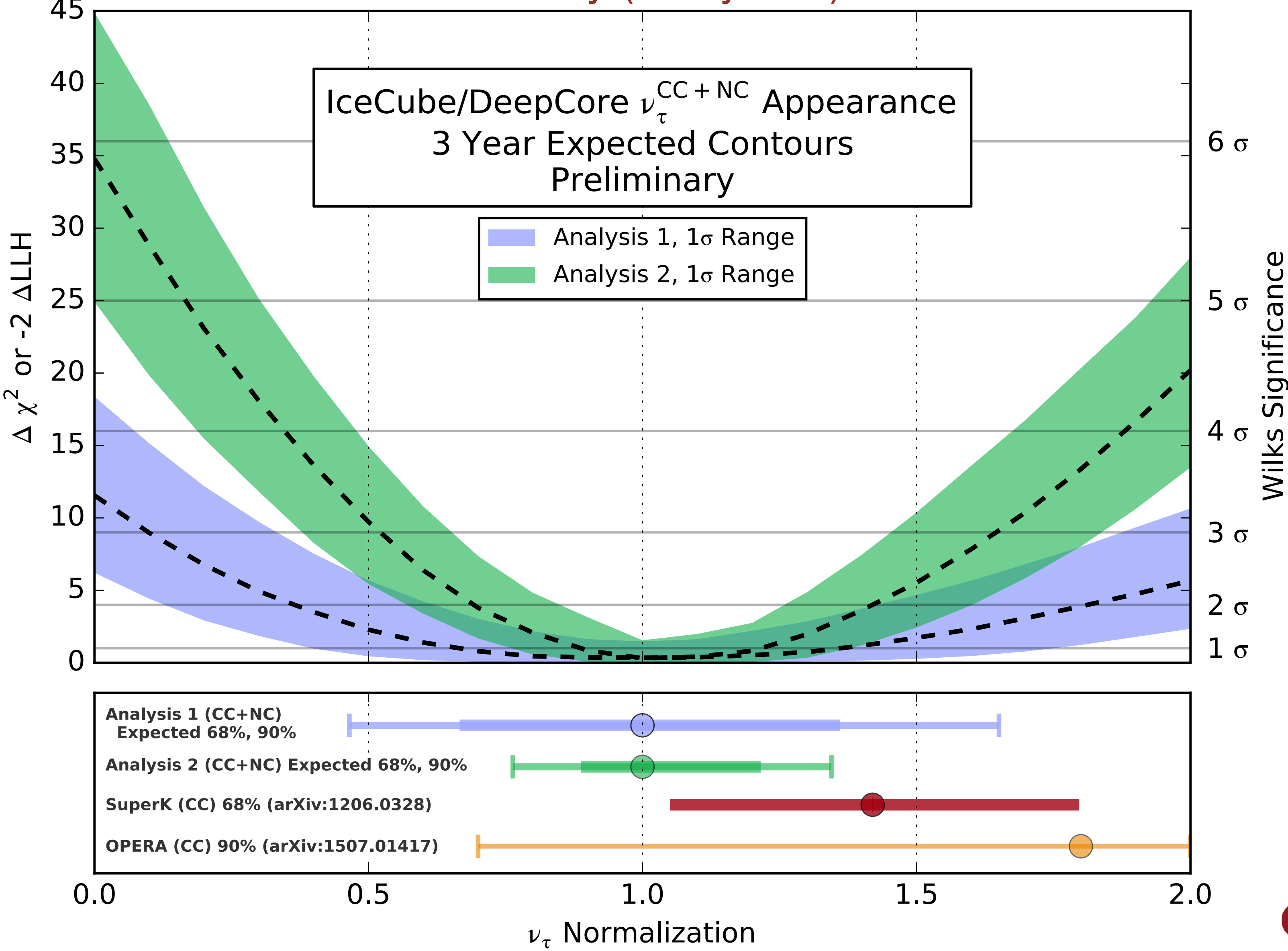
Analysis 1

- Developed for ν_μ disappearance measurement
- Uses data to model background muons
- Strong containment on starting, stopping vertex
- Weaker reliance on BDTs
- Shown to give good data/MC agreement
- Expects 40k events/3 years

Analysis 2

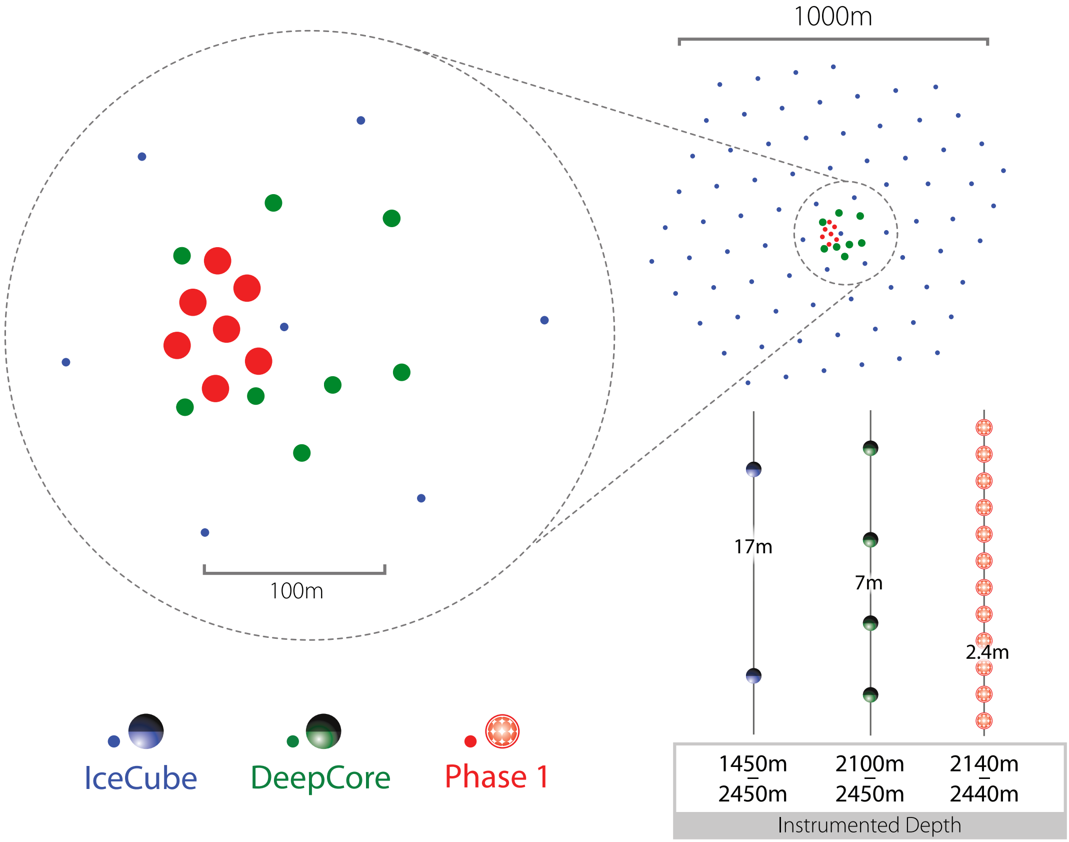
- Developed for ν_τ appearance measurement
- Uses simulation to model background muons
- Strong containment on starting vertex only
- Stronger reliance on BDTs
- Currently in development
- Expects 85k events/3 years

Tau Normalization Sensitivity (Analysis 2)

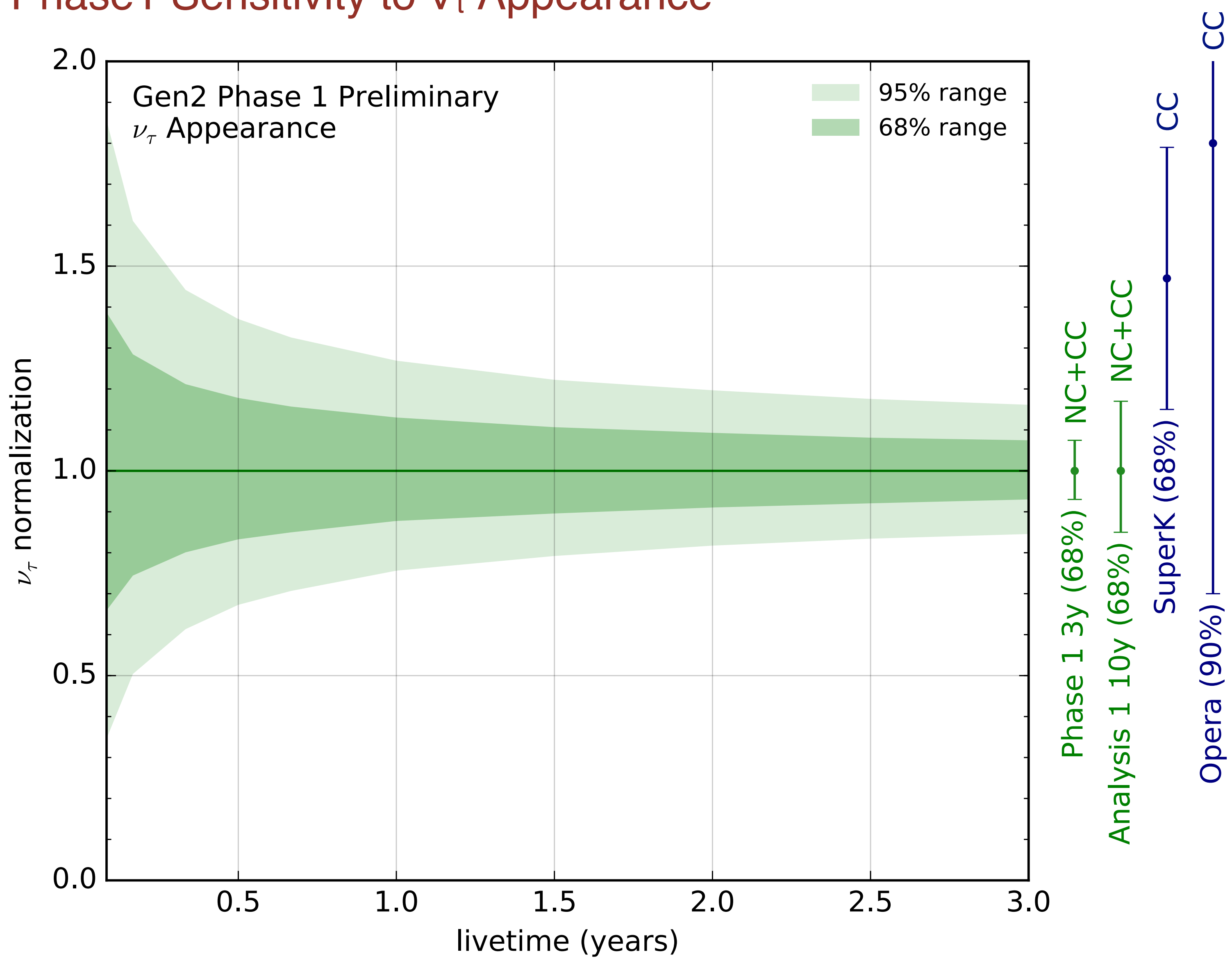


The Future of ν_τ Appearance Measurements with Phase1

- How can we further improve sensitivity to ντ appearance?
  - Perform an upgrade to IceCube-DeepCore
- Initial studies are very promising
  - 7 additional strings
  - More precise calibrations
  - Significantly more GeV-scale events
- For more detail, see talk by Ken Clark later this session
- Using existing tools, perform a simple event selection to search for appearance



Phase1 Sensitivity to ν_τ Appearance



Conclusions

- IceCube-DeepCore can observe inclusive ν_τ appearance

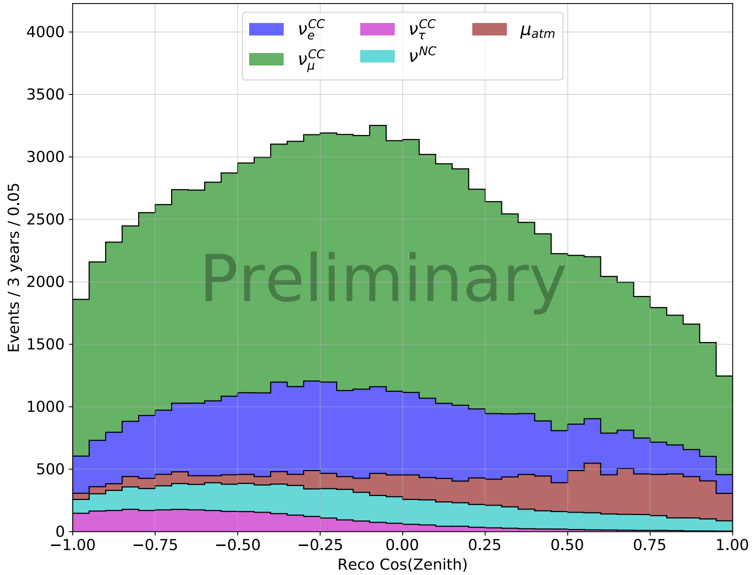
- Current disappearance event selection is being used
  - Well-understood, reasonable results

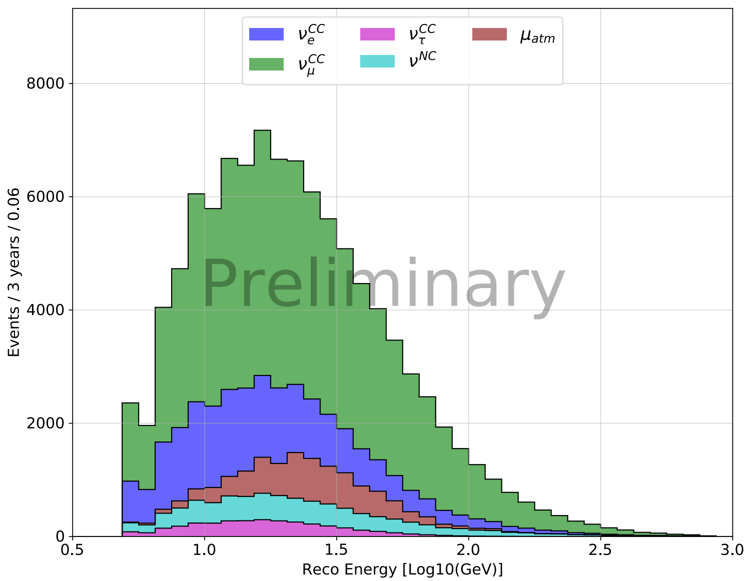
- A new event selection is being developed
  - Significantly higher statistics
  - Improved sensitivity to oscillation effects

- The Phase1 upgrade to DeepCore can help
  - Can be used for better calibration, especially at low energies needed for appearance studies
  - Improved sensitivity to GeV-scale neutrinos
  - Even with relatively simple event selection, improving on sensitivity relative to DeepCore

Backup Slides

Analysis 2: Improving the Sensitivity



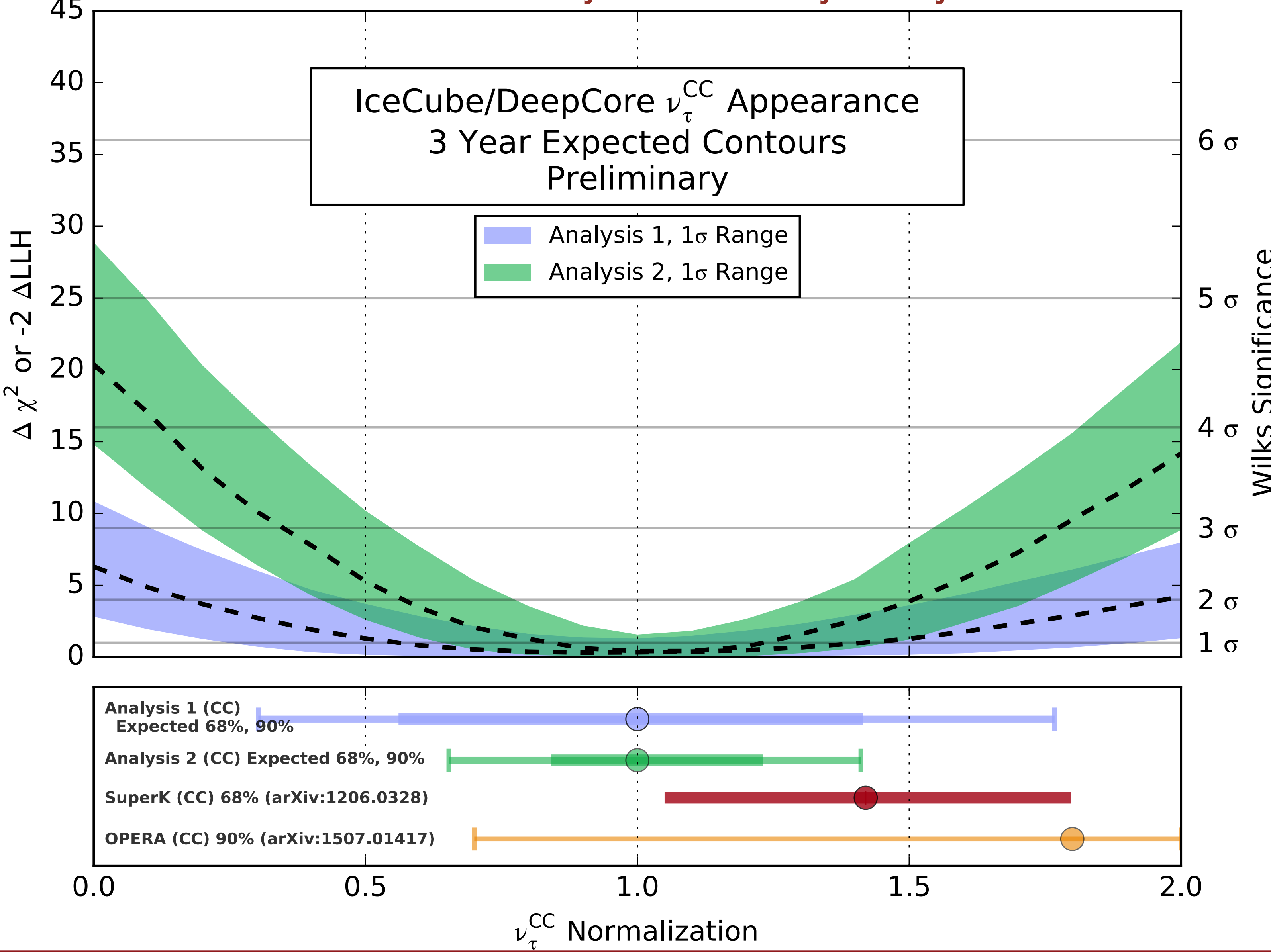


- Wide energy reach
  - High energy events used as control region
- High statistics:
  - Expect approximately 85k events/3 years

- Sample is divided using reconstructed muon length
  - “Track-like”: L ≧ 50 m
  - “Cascade-like”: L < 50 m

- Using common systematics with previous analyses

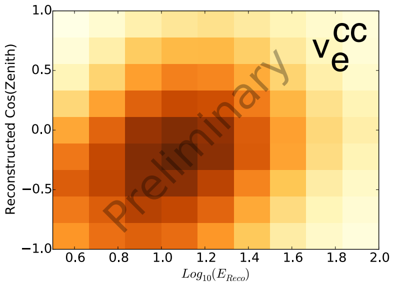
Tau Normalization Sensitivity for CC-Only Analyses



Included Systematics

Normalizations	
$N_{atm.\mu}$	Normalization of Atm. Muons
N_e	Flux normalization of ν_e
N_{NC}	Normalization of neutral current interactions
f_{Coin}	Fraction of neutrino events with a coincident muon
Oscillations	
θ_{23}	Atmospheric mixing angle
θ_{13}	Reactor mixing angle
Δm^2_{23}	Mass difference between ν_2, ν_3
Detector Uncertainties	
$L^{Sca.}_{holeice}$	Scattering length in refrozen ice
$L^{Sca.+Abs.}_{bulkice}$	Scattering, absorption in glacial ice
ε_{PMTs}	Efficiency of the PMTs
Flux Uncertainties	
γ_ν	Neutrino spectral index
γ_μ	Cosmic ray spectral index
σ^{Flux}_ν	Zenith angle uncertainty in the neutrino flux
ν-$\bar{\nu}$ Ratio	Neutrino-antineutrino ratio
Cross-section Uncertainties	
M^{QE}_A	Quasi-elastic axial mass
M^{RES}_A	Resonant axial mass
σ_{DIS}	Shape uncertainty associated with DIS interactions

Method for Statistical Appearance Measurement



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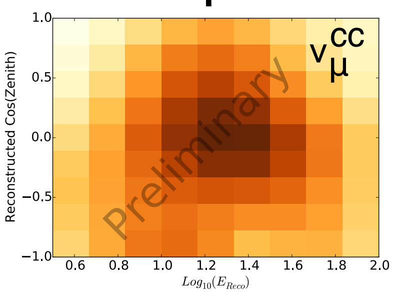

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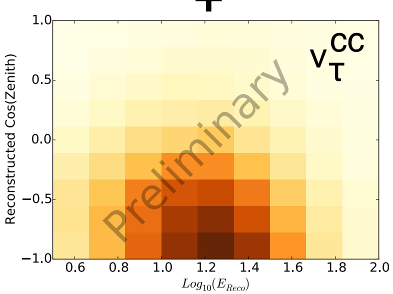

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Reconstructed Energy, Zenith angles

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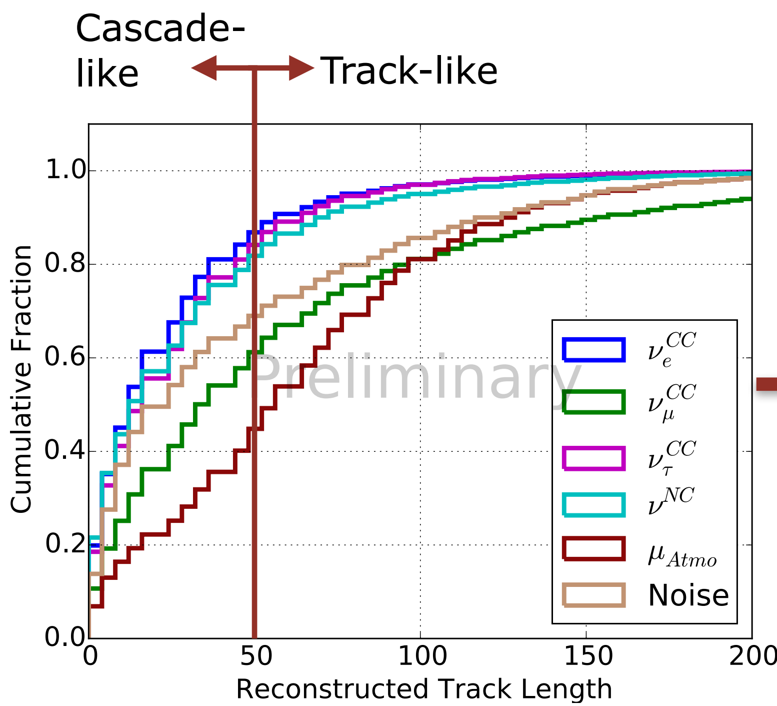
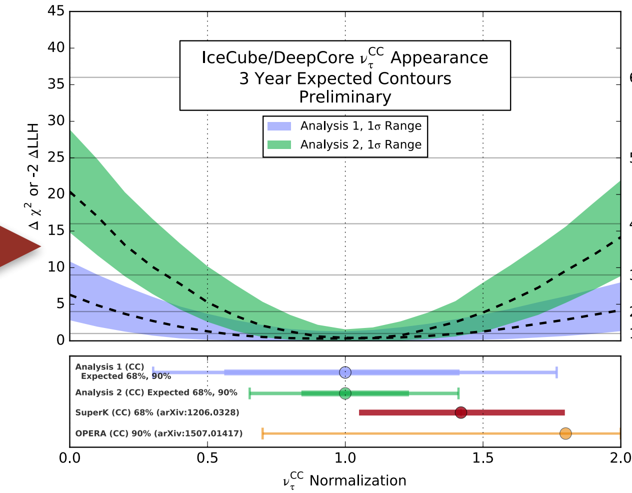


Track length as particle identification



Final Expected Contour