ν_μ Disappearance with IceCube/DeepCore

Joshua Hignight
for the IceCube Collaboration

MICHIGAN STATE
UNIVERSITY

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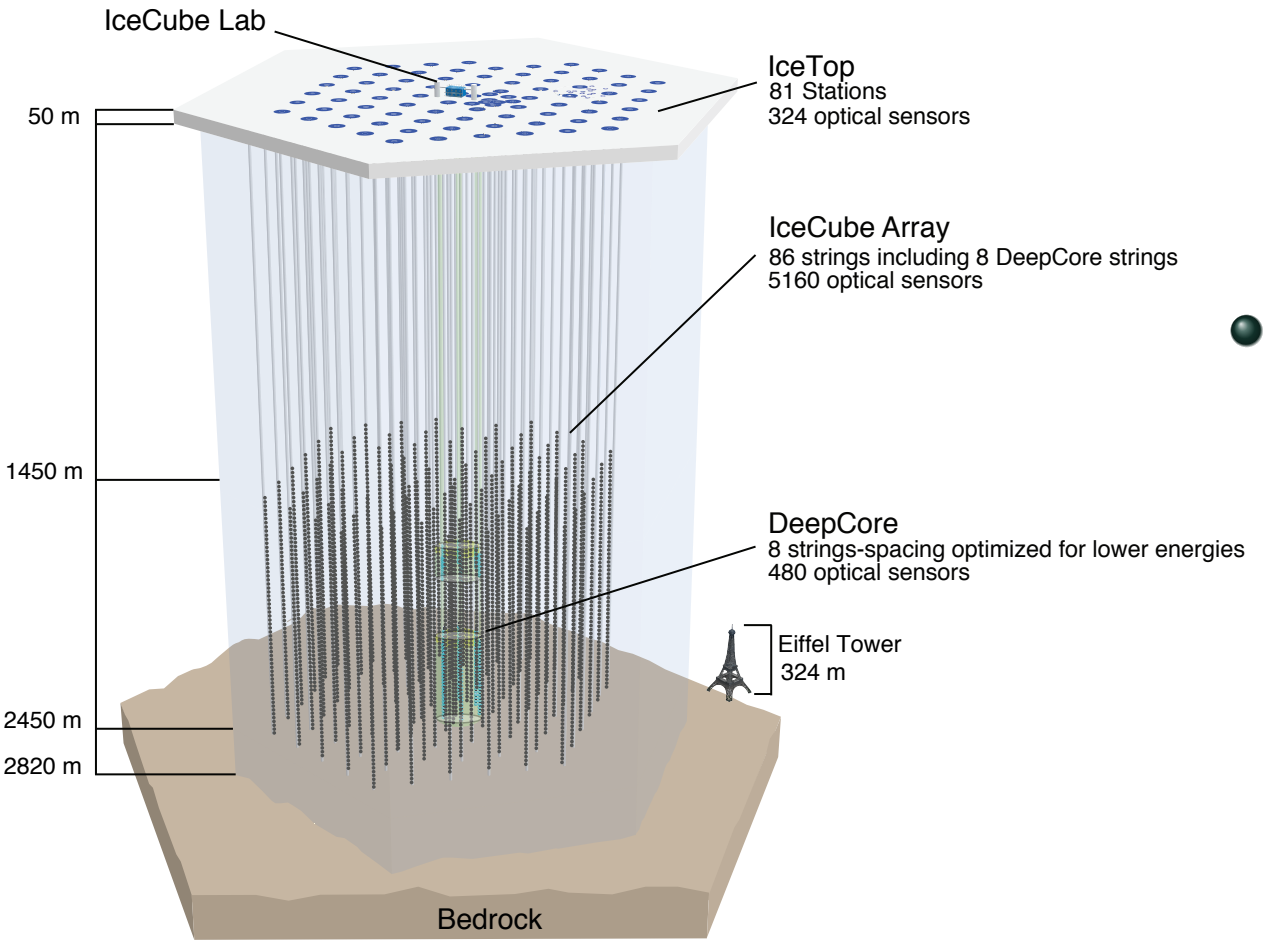
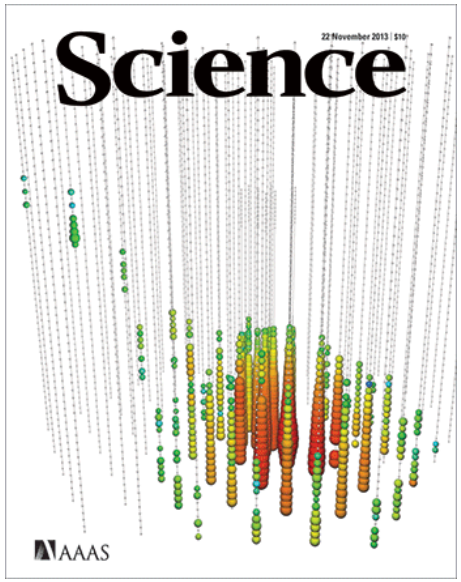
IceCube

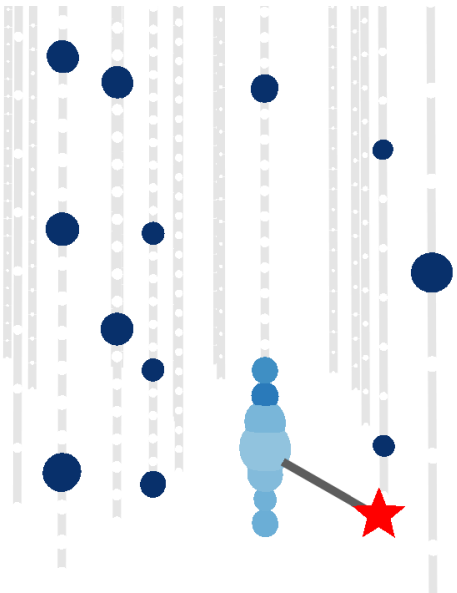


- Without DeepCore:
  78 strings,
  125 m string spacing,
  17 m module
  vertical-spacing
- Optimized for (very)
  High Energy neutrinos



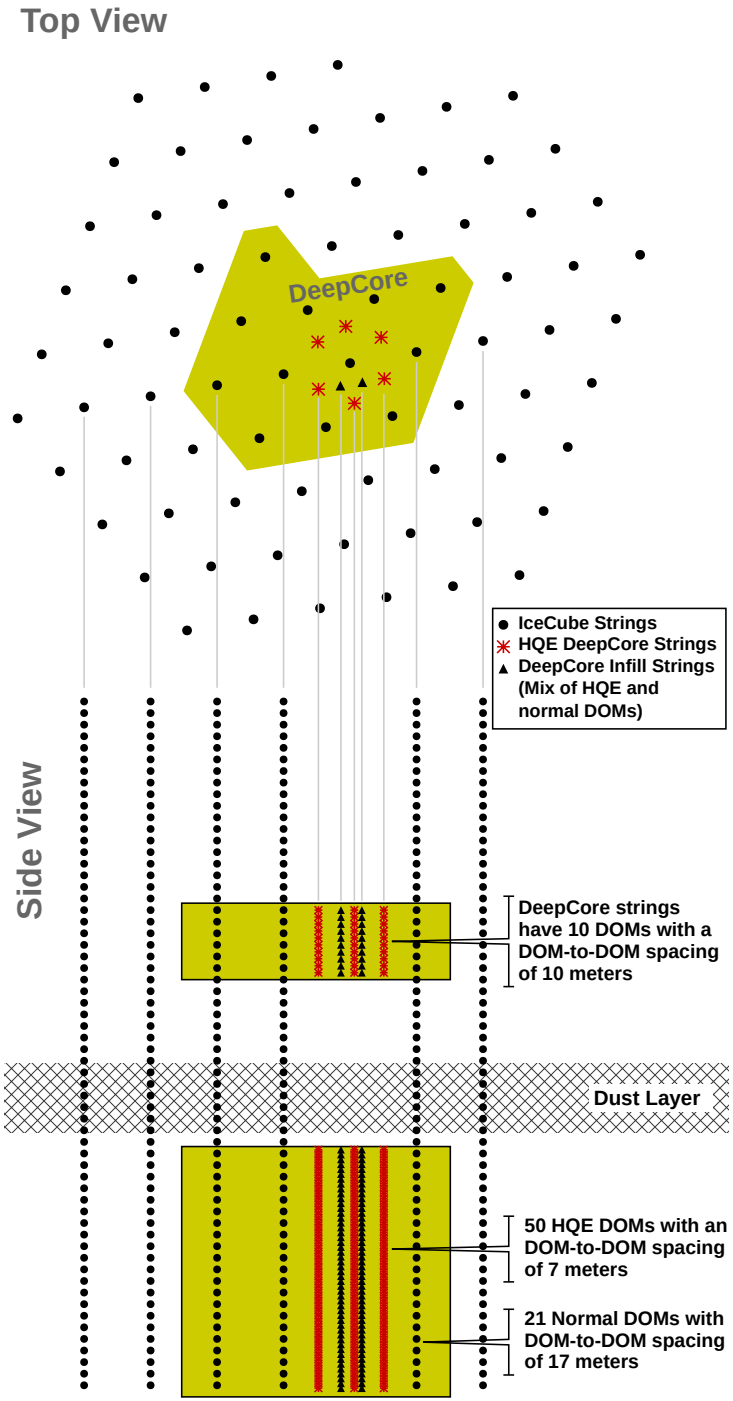
IceCube-DeepCore

- 78 strings, 125 m string spacing
- 17 m modules vertical-spacing
- 8 strings, 40-75 m string spacing
- 7 m modules vertical-spacing



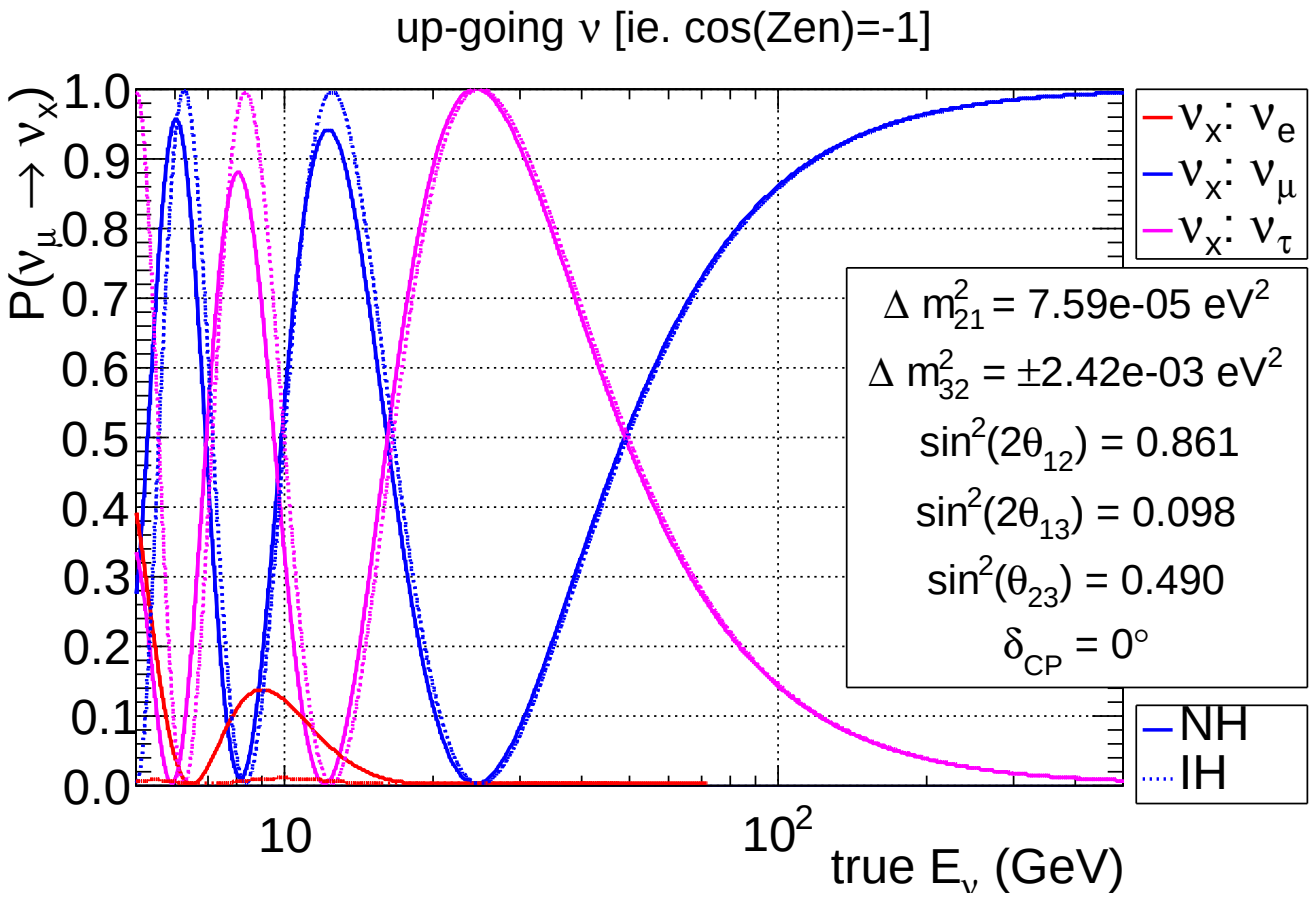
→ Typical LE ν event

→ $E_{\nu_\mu} = 12$ GeV (w/ $E_\mu = 8$ GeV)

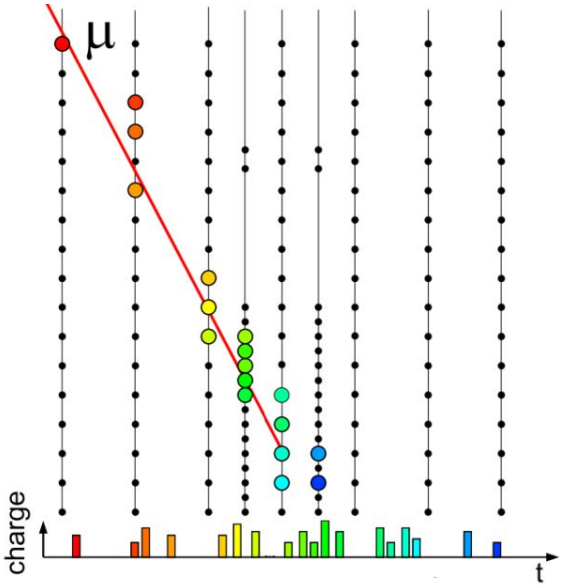


Using atmospheric ν to study ν oscillation

- Neutrinos oscillating through the Earth's diameter have "first" maximum of ν_μ disappearance at $\approx$25 GeV
  - signal accessible with DeepCore
- Hierarchy dependent matter effects below $\sim$12 GeV
  - too low energy for DC, requires higher density of optical modules



Measurement strategy for PRD results

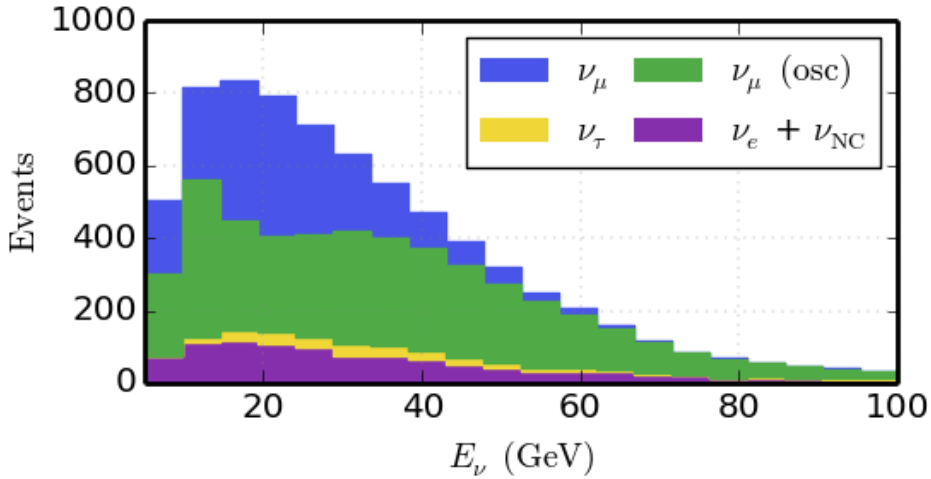


- Main background is atmospheric μ
  - Use IceCube as veto to reject atm μ events
- Reconstruct ν energy and direction
  - oscillation distance (L) given by zenith
- Do oscillation measurement!

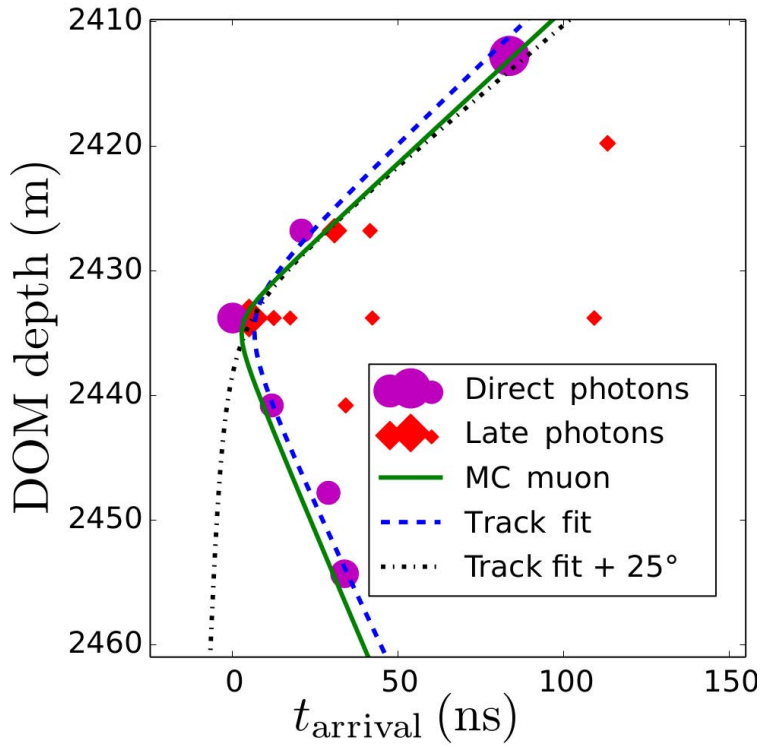
- Focus on ν_μ CC "golden events"
  - Focus on up-going events
  - Clear μ tracks
  - Require several non-scattered γ
- Results in PRD 91, 072004 (2015) [arXiv:1410.7227]

Measurement strategy – focus on “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

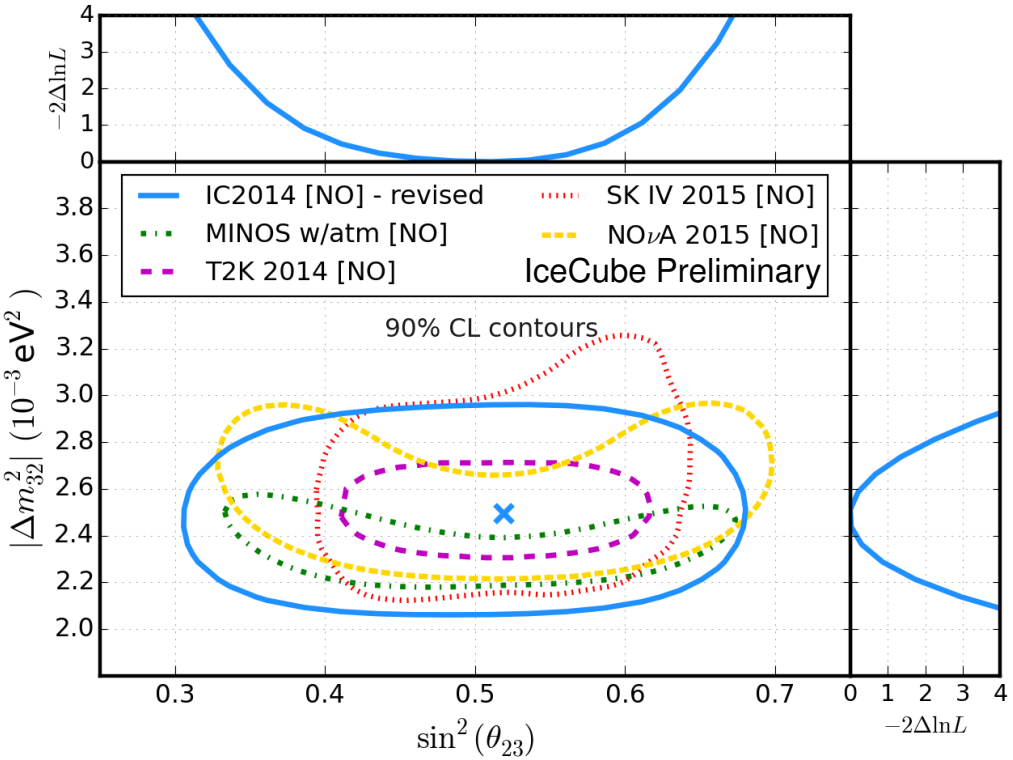


Systematics Included

- Normalization terms
  - Overall neutrino flux
  - ν_e/ν_μ flux ratio
  - Atmospheric muon contamination
- Neutrino Flux
  - Spectral Index
  - π/K ratio
- Detector Effects
  - DOM efficiency
  - Hole ice scattering
  - Bulk ice model
  - noise level

Update to PRD ν_μ disappearance oscillation analysis

PRD 91, 072004 (2015)



- Improved simulation, systematics, and MC/Data agreement results.
- Improved: detector noise model, tighter cut for atm. muon rejection, flux prediction, PE charge calibration, etc.
- Consistent with original results

- Using only events with $E_{reco} < 56$ GeV
- Fitting to data done in 2D space (E, θ)
  - $\chi^2/ndf = 52.4/56$
- Observed ≈5200 events in 953 days

$$|\Delta m^2_{32}| = 2.50^{+0.18}_{-0.24} 10^{-3}\mathrm{eV}^2$$

$$\sin^2(\theta_{23}) = 0.52^{+0.12}_{-0.10}$$

ν Sterile Search with DeepCore

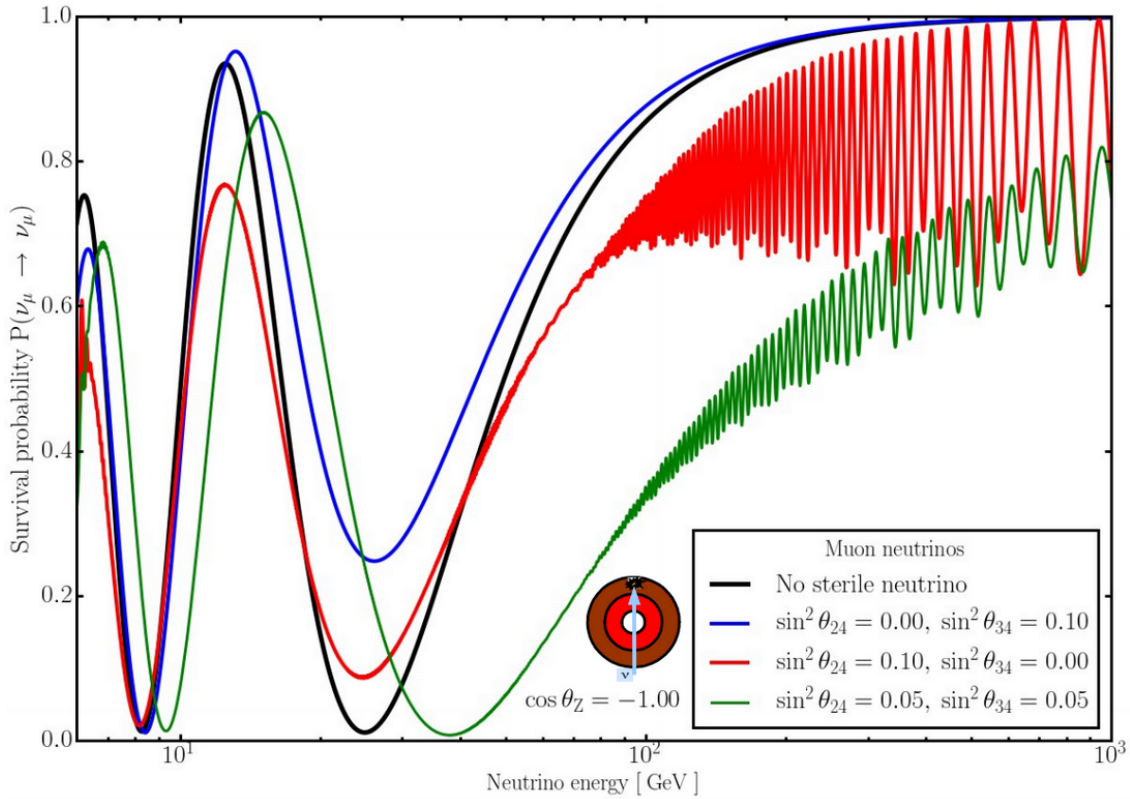
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

- 3+N sterile models alter normal 3-flavor oscillations
- For 3+1, IceCube/DeepCore is sensitive to $|U_{\mu 4}|^2$ and $|U_{\tau 4}|^2$ via ν_μ disappearance.
- Assuming θ_{14}=0$\rightarrow$ $|U_{e4}|^2$= 0 and all CP violating phases are 0:

$$|U_{\mu 4}|^2 = \sin^2\theta_{24}$$
$$|U_{\tau 4}|^2 = \sin^2\theta_{34}\cos^2\theta_{24}$$

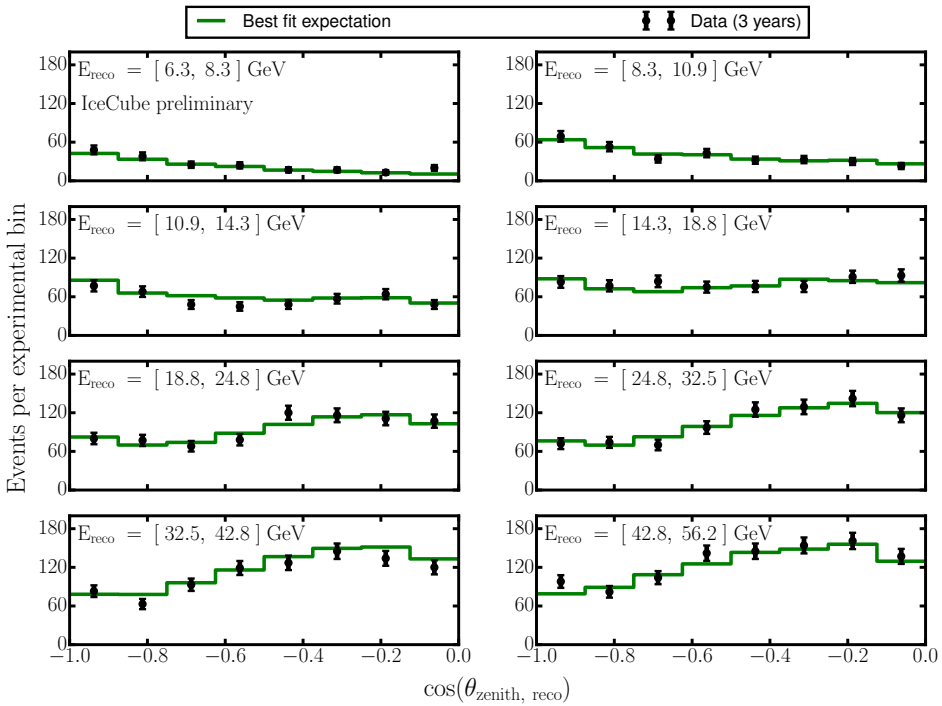
Sterile ν Search with DeepCore

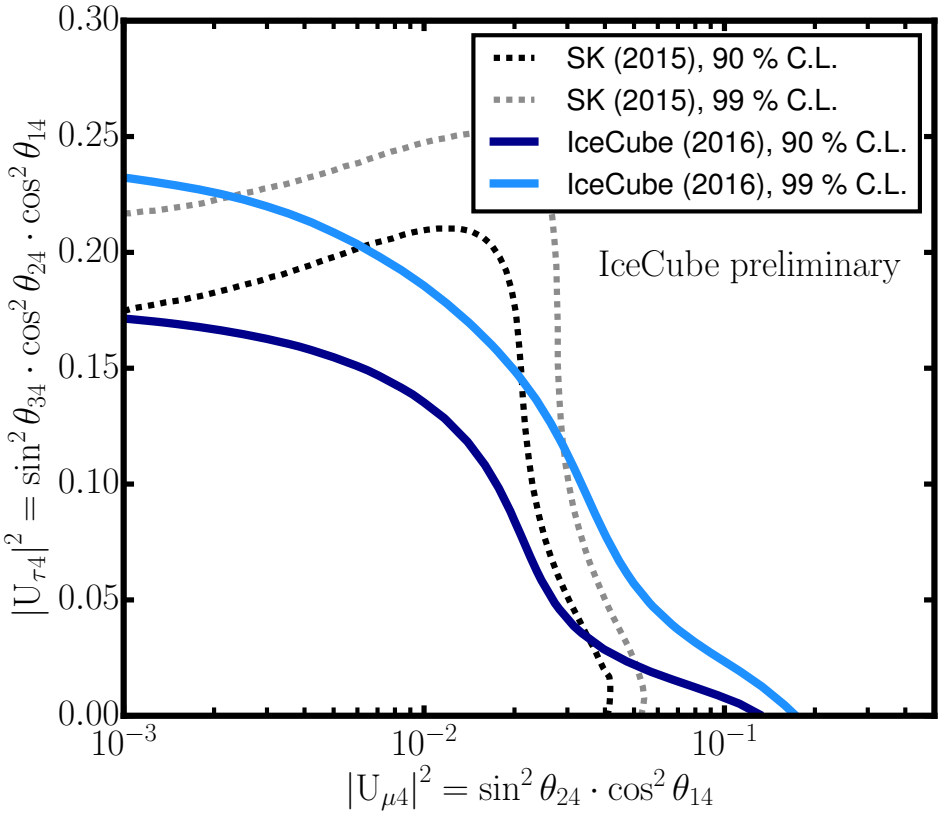
- Effects of sterile neutrinos below 100 GeV[1]:
  - Modifies standard neutrino oscillations
  - Effect is proportional to amount of matter along neutrino path
- ν_μ disappearance minimum:
  - Change of depth
  - Shifts in energy
  - Independent of sterile neutrino mass (for $\Delta m^2_{14} > 0.3 eV^2$)



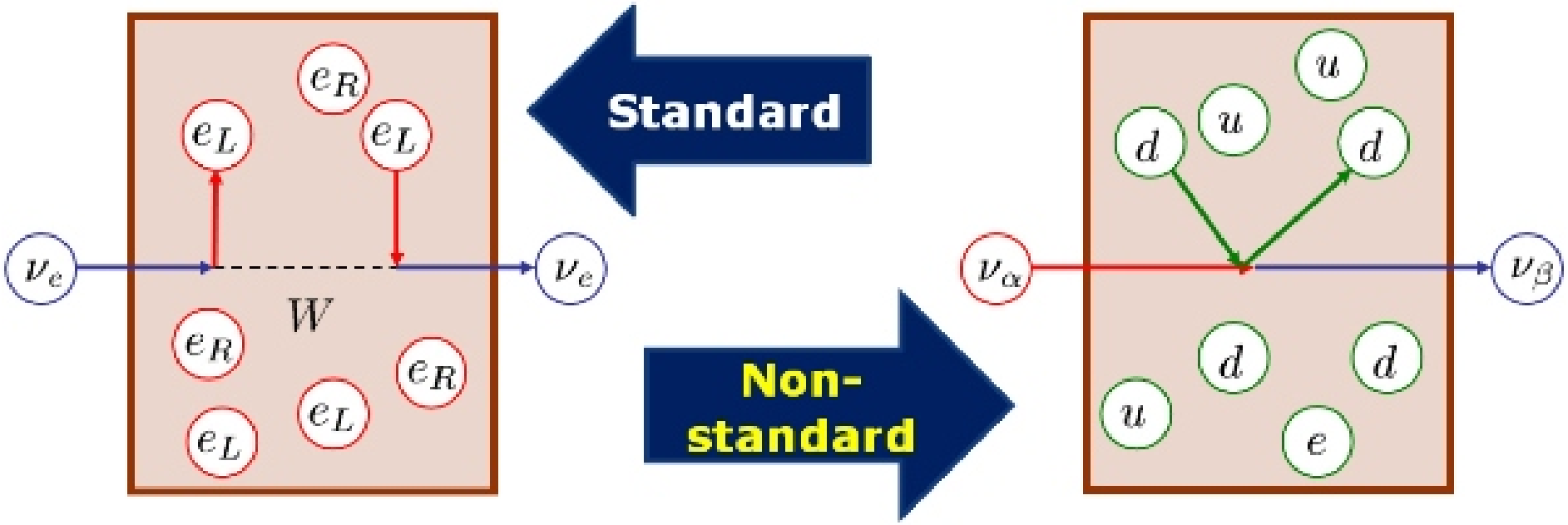
[1] For E>100 GeV see talk by Carlos Argüelles @ 17:00

Results of Sterile ν Search with DeepCore





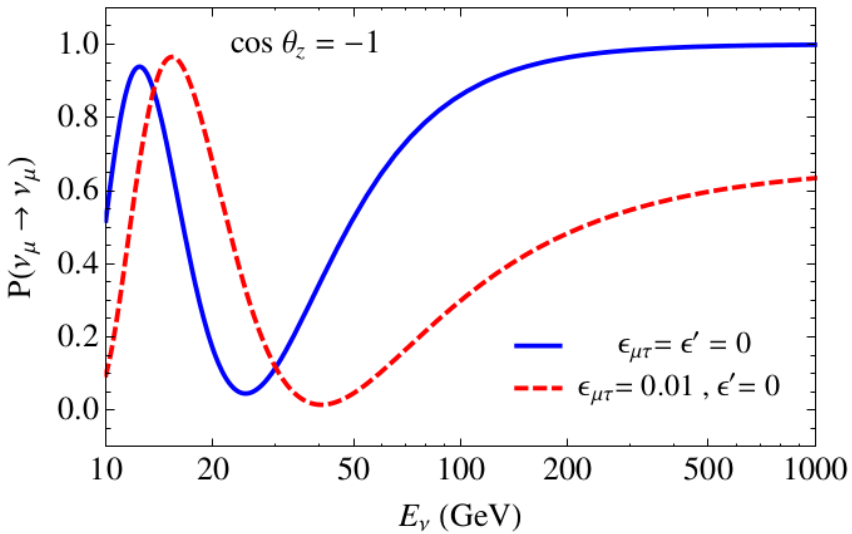
Non-Standard Interactions (NSI) in Matter

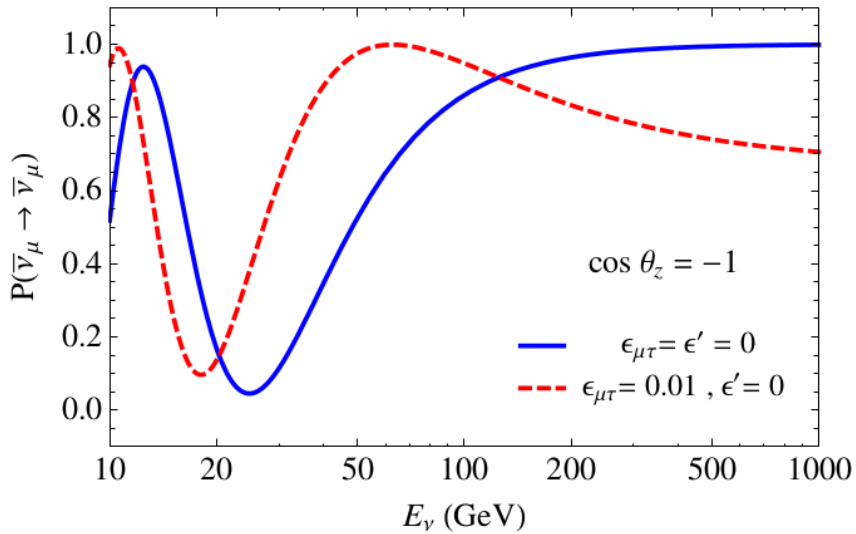


$$H_{\alpha\beta} = \frac{1}{2E_\nu} U_{\alpha j} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger_{k\beta} + V_{MSW} + \sqrt{2} G_F N_f \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau} & \epsilon_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

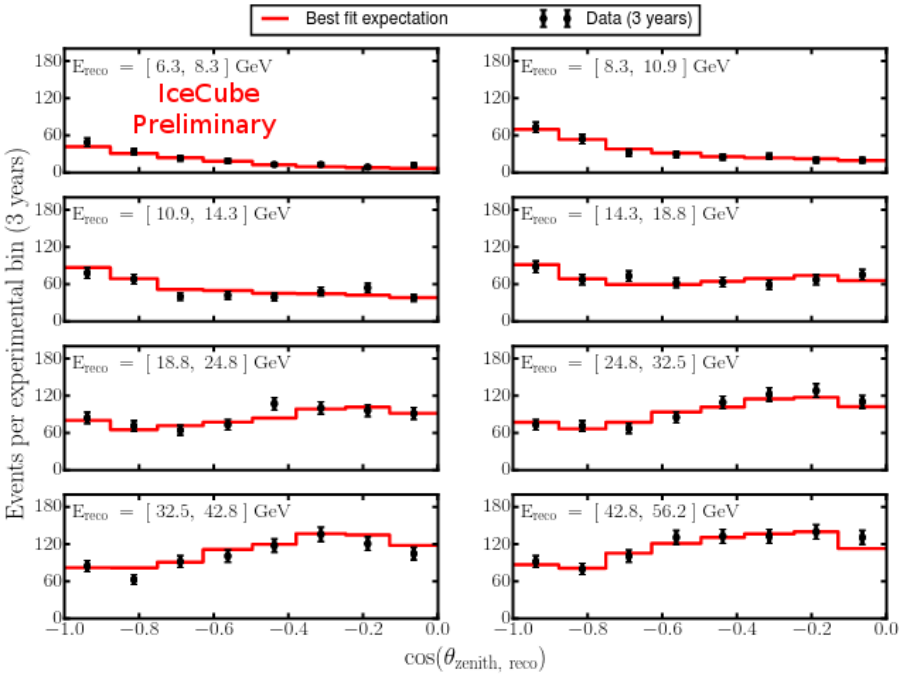
Non-Standard Interactions (NSI) in Matter

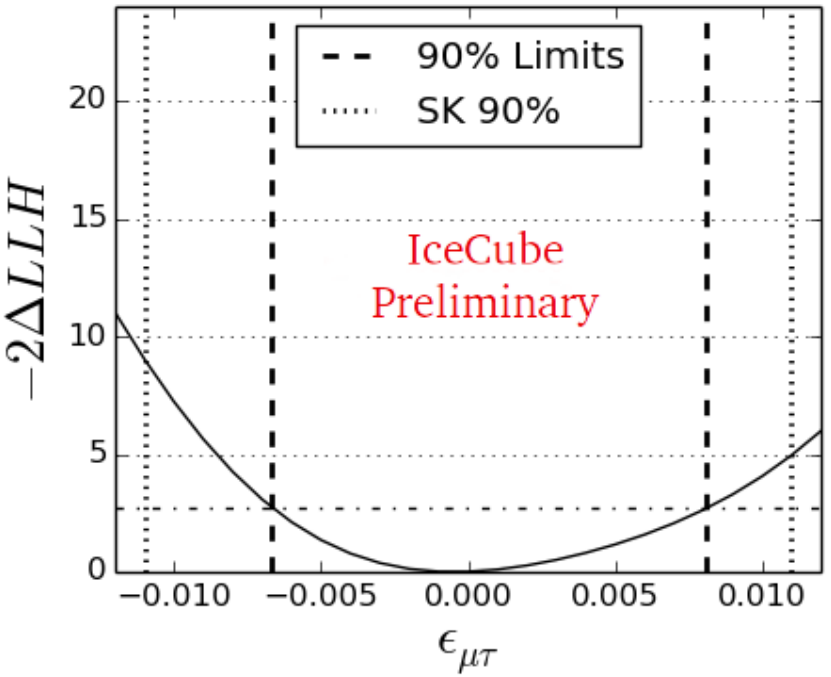
- NSI in matter modulates the normal 3-flavor oscillation pattern
  - Effect is different for ν and $\bar{\nu}$
  - Impact of $\epsilon_{\mu\tau} \neq 0$ would be seen in ν_μ disappearance





DeepCore NSI Results [2]



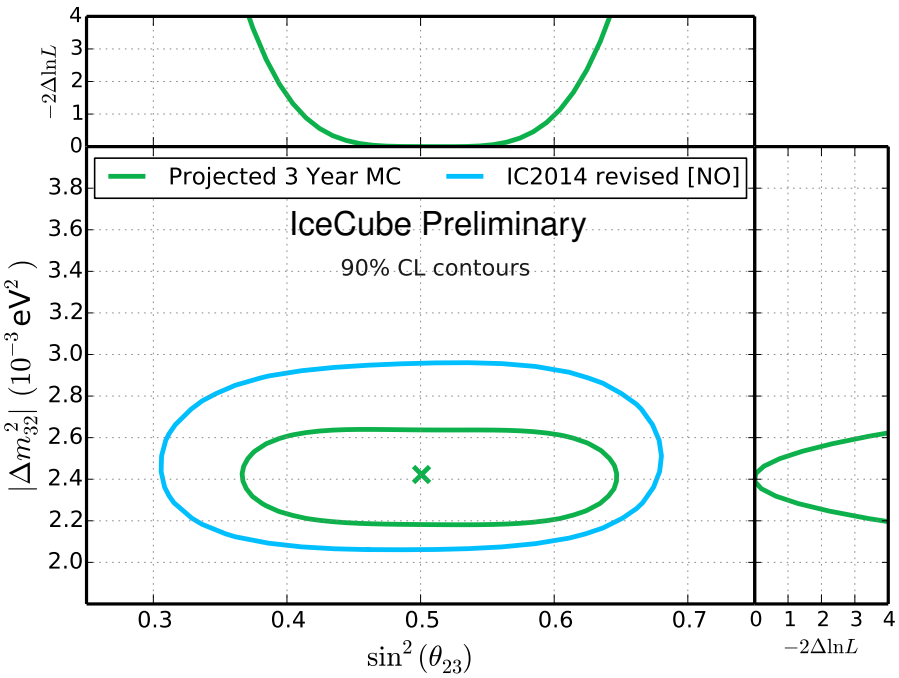


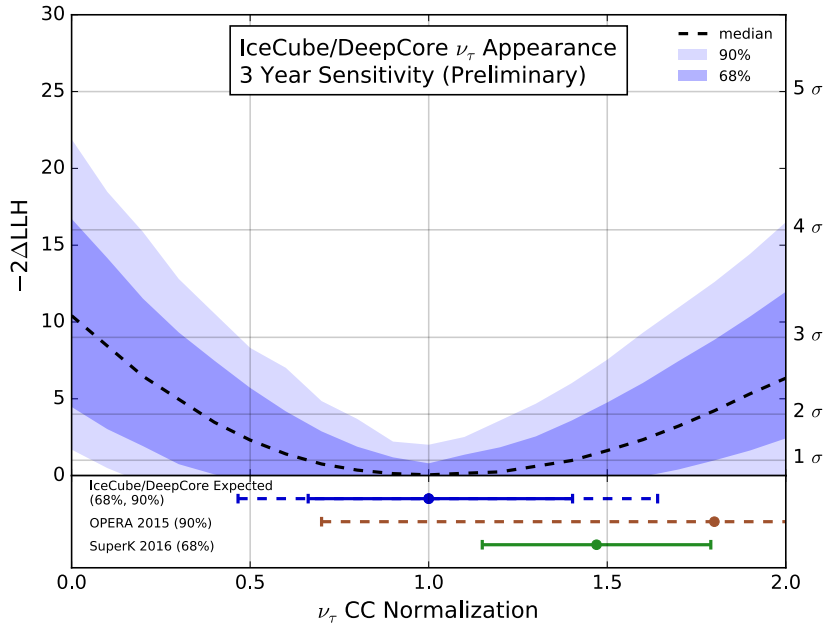
[2] For more information please see poster by Melanie Day on the 8th August 2016, 18:30

DeepCore Analyses Future

- Expand data set beyond using high-purity track samples of up-going “golden” events.
- Use more high quality events
  - New reconstruction techniques allow for 10x statistics without degradation of resolution.
- Maximize the control sample
  - keep cascade-like events (CC ν_e, CC ν_τ, NC)
  - keep down-going region
  - improves constraint on systematics such as flux
- Know what is already working and keep it.
  - use background sample from inverted veto of real data
  - use similar analysis code

Future Analyses Sensitivity





- Significant step forward from PRD results
  - Significant advancement in ν_μ disappearance, especially in mass splitting.
  - ν_τ appearance measurements can now be done.

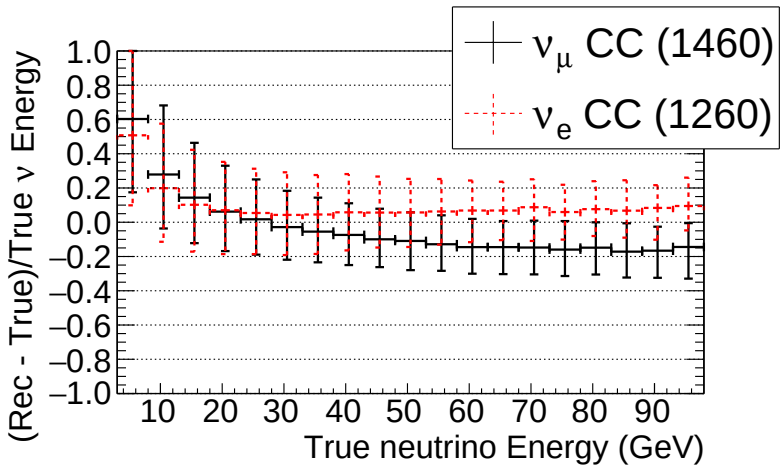
Conclusion

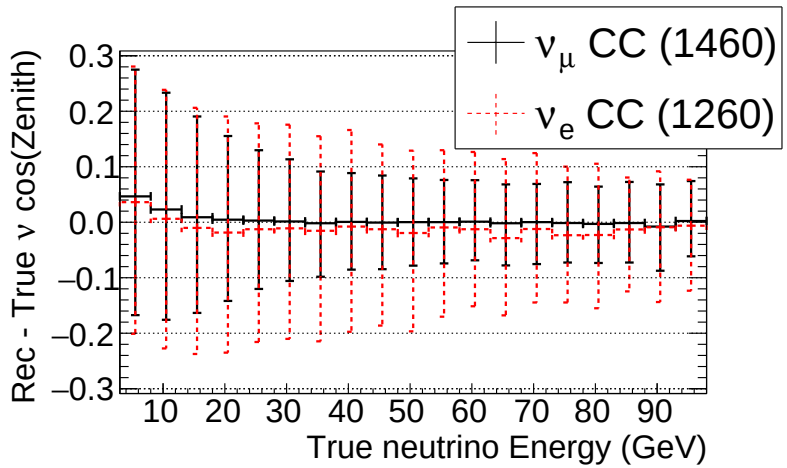
- IceCube/DeepCore is producing results using high-purity track-like events
  - Improved simulation, systematics, detector noise, etc. has provided updated ν_μ disappearance results.
  - The 3+1 sterile model has been constrained using neutrinos with E<100 GeV
  - New limits on NSI parameter $\epsilon_{\mu\tau}$ have also been set.
- New high statistics data samples are currently being prepared.
  - These samples will allow for better measurement of all low energy ν_μ disappearance results.
  - Will also allow for high precision ν_τ measurements.

Backup

HybridReco/MultiNest

- MultiNest[3] 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 $\Rightarrow$“cascade fit”
  - Use the likelihood function defined in Millipede (Poisson)





[3] Feroz et al. MNRAS 398, (2009)