Atmospheric Tau Neutrino Appearance

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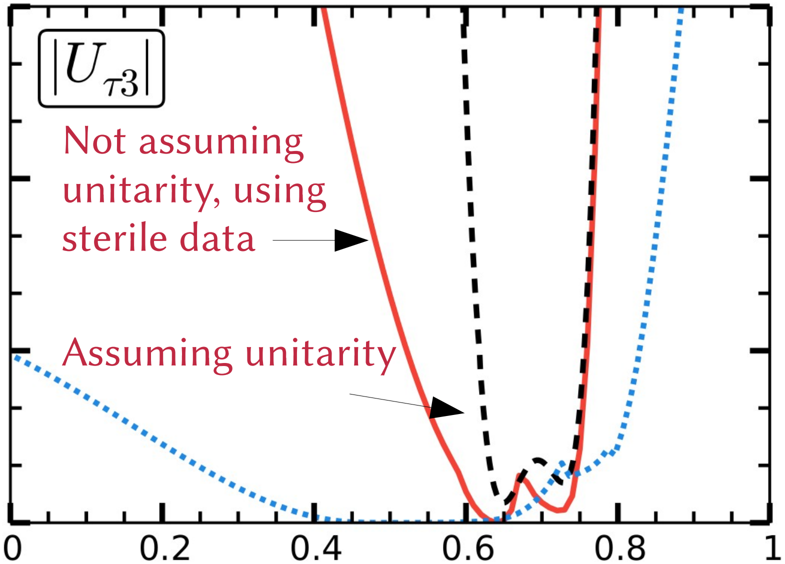
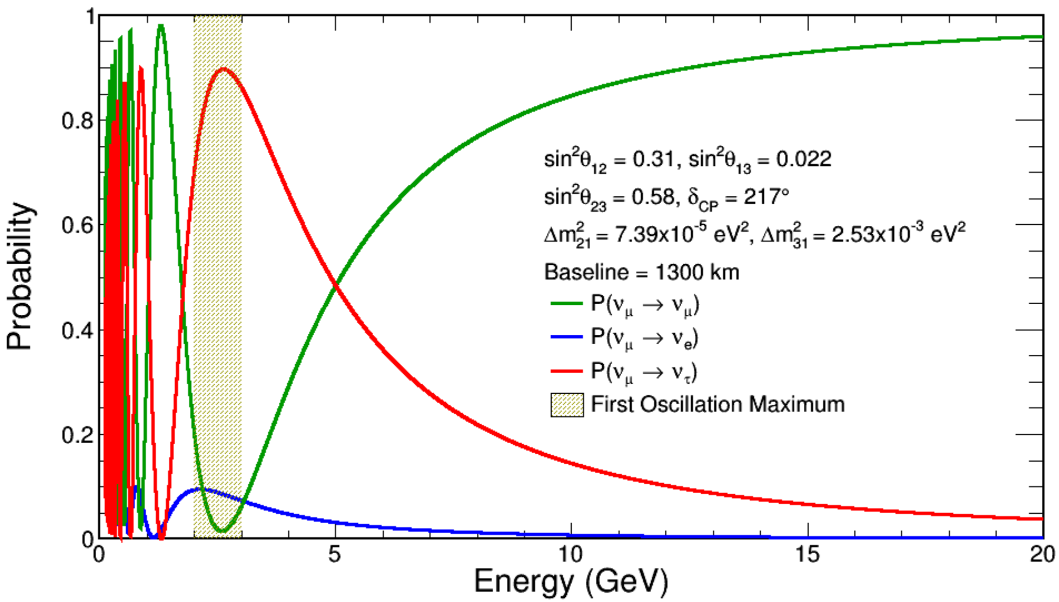
27 August 2021

Why Tau Neutrinos?

S. Parke and M. Ross-Longeran, PRD 93, 1103009 (2016)



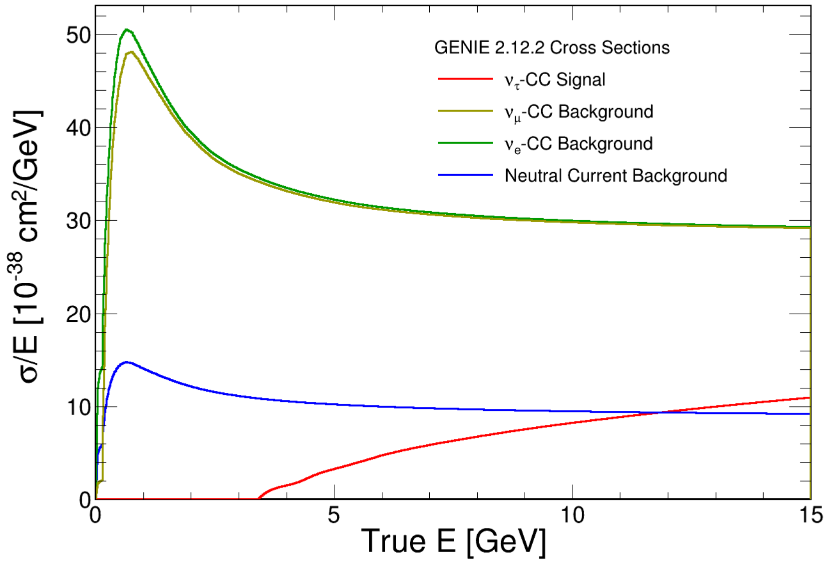


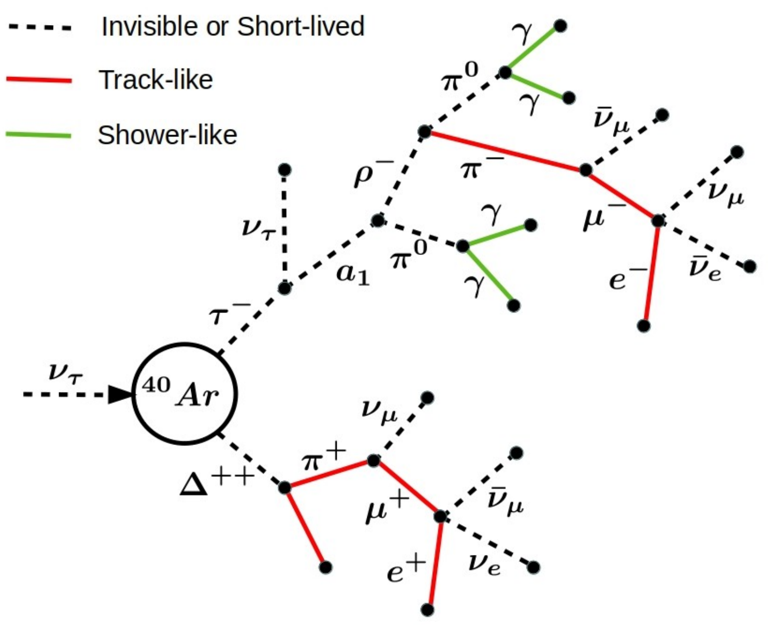
- Despite increasing precision of PMNS mixing angles, all of this knowledge depends on assumption of unitarity
- Almost all disappearing muon neutrinos oscillate into tau neutrinos, but only 10 high-purity, oscillated, tau-neutrino candidates have ever been observed
- DUNE is well positioned to dramatically improve this situation

Selection

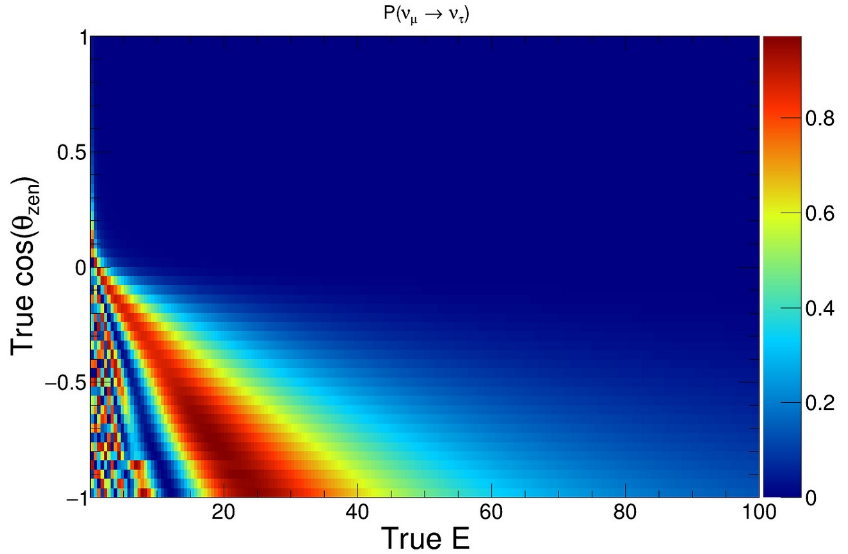
- Tau neutrinos are difficult to select
  - Kinematically forbidden at typically beam energy
  - Cross section is suppressed at higher energies
  - Tau-leptons have many decay modes which mimic either ν_e-CC, ν_μ-CC, or NC events
- Truth level studies of atmospheric tau neutrinos suggest that tau neutrinos with hadronically decaying tau-leptons could be isolated with high purity
  - J. Conrad, A. de Gouvea, S. Shalgar, and J. Spitz, PRD 82, 093012 (2010)
  - Assumes LArTPC can achieve near perfect electron/photon and muon/pion discriminatior
  - Relatively simple kinematic cuts on charged pions achieves good separation between tau neutrinos and NCs
- Assume:
  - 37% flat signal efficiency
  - 0.5% NC background efficiency

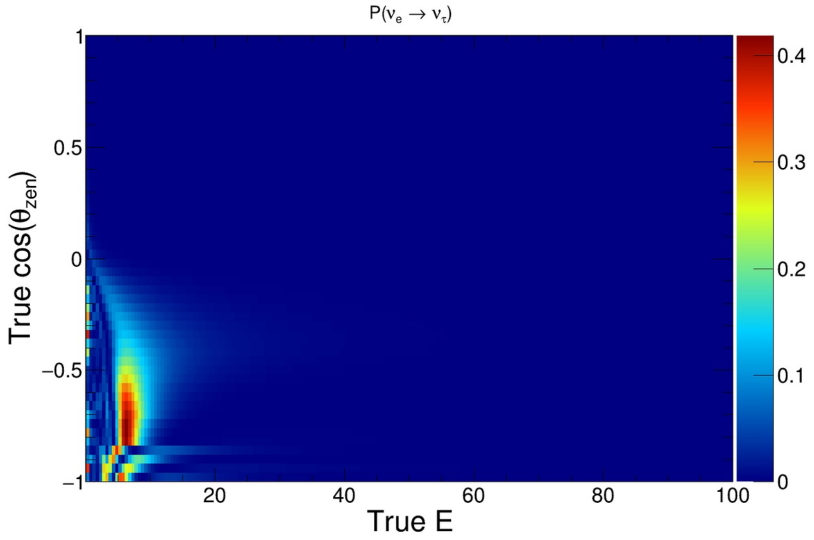
τ^- Decay Mode	Branching Ratio
$\mu^- \bar{\nu}_\mu \nu_\tau$	17.4%
$e^- \bar{\nu}_e \nu_\tau$	17.8%
$\pi^- \nu_\tau$	10.8%
$\pi^- \pi^0 \nu_\tau$	25.5%
$\pi^- 2\pi^0 \nu_\tau$	9.3%
$2\pi^- \pi^0 \nu_\tau$	9.3%
$2\pi^- \pi^+ \pi^0 \nu_\tau$	4.6%





Atmospheric Oscillations



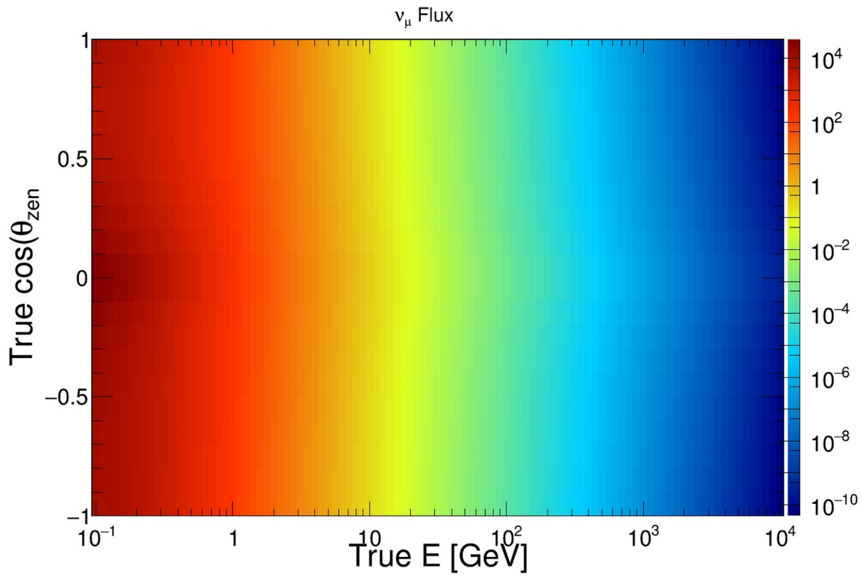


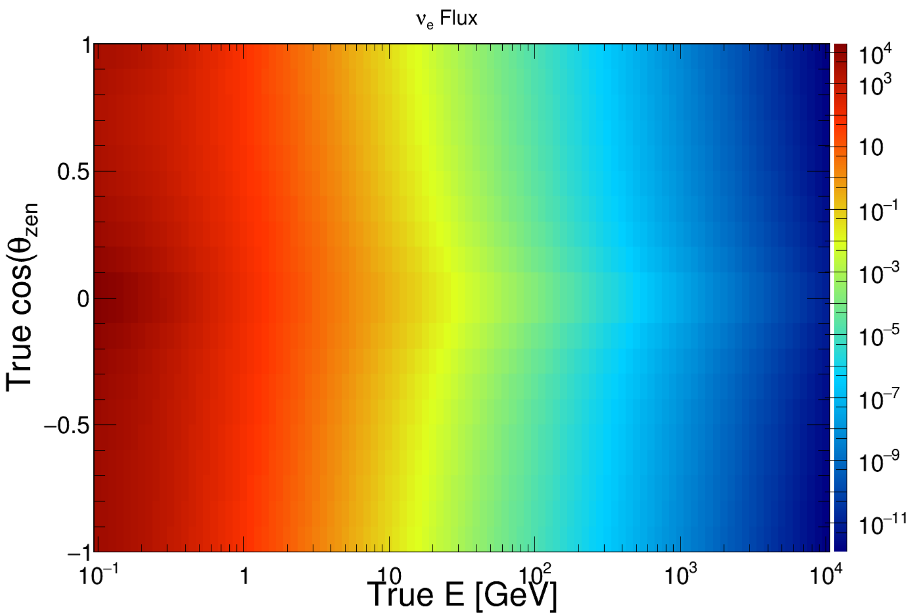
- Generate mu ⟶ tau and e ⟶ tau oscillograms using oscillation calculator: https://github.com/joaoabcoelho/OscProb
- Uses a 15 layer PREM model

$$\sin^2\theta_{12} = 0.310, \quad \sin^2\theta_{13} = 0.02240, \quad \sin^2\theta_{23} = 0.582, \quad \delta_{CP} = 217° = -2.50 \text{ rad},$$

$$\Delta m^2_{21} = 7.39 \times 10^{-5} \text{ eV}^2, \quad \Delta m^2_{31} = +2.525 \times 10^{-3} \text{ eV}^2$$

Atmospheric Fluxes



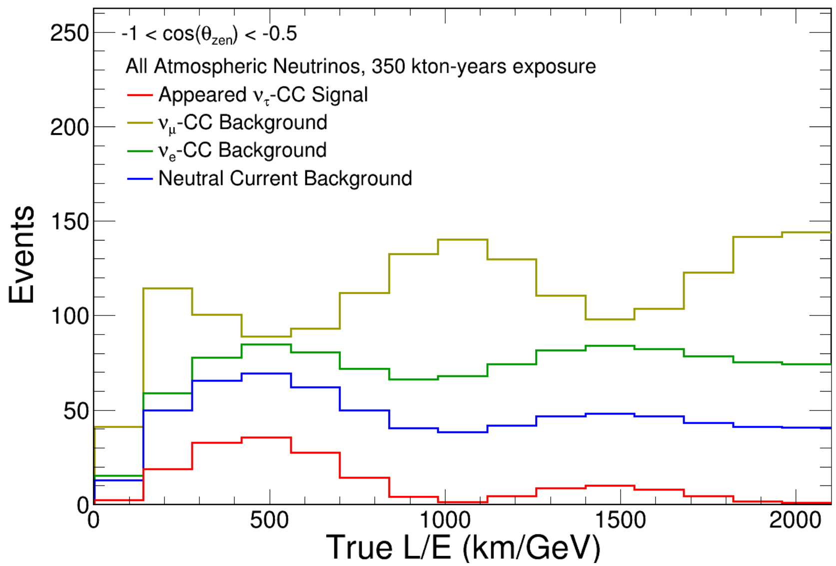


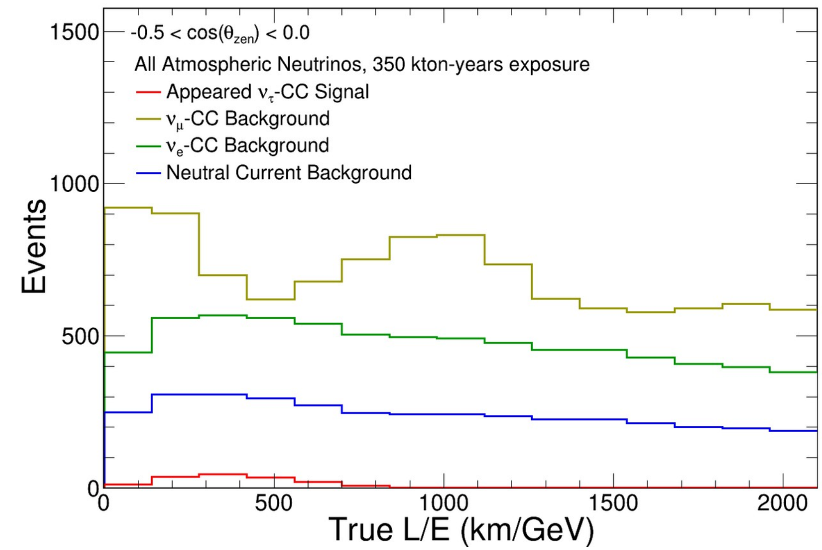
- Use Honda fluxes from http://www.icrr.u-tokyo.ac.jp/~mhonda/nflx2014/index.html
- Predicted number of tau neutrino events from flux*xsec*oscWeights

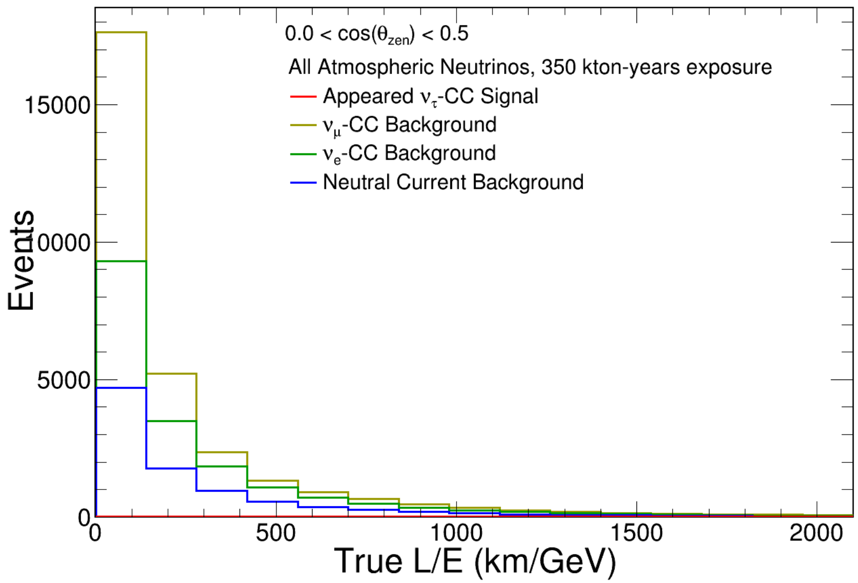
In 350 kton-years, before selection we expect:

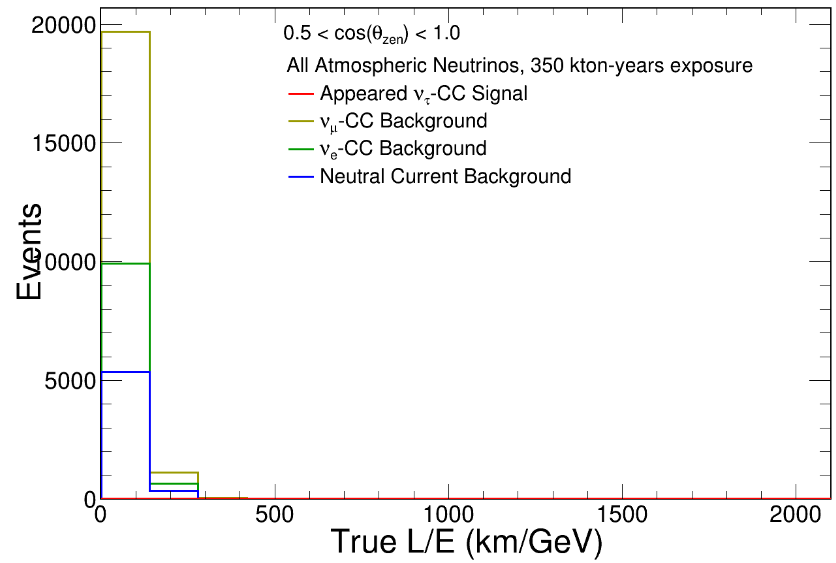
350 ν_τ-CC
31020 ν_e-CC
37500 ν_μ-CC
33040 NC

True Atmospheric Spectra, No Selection

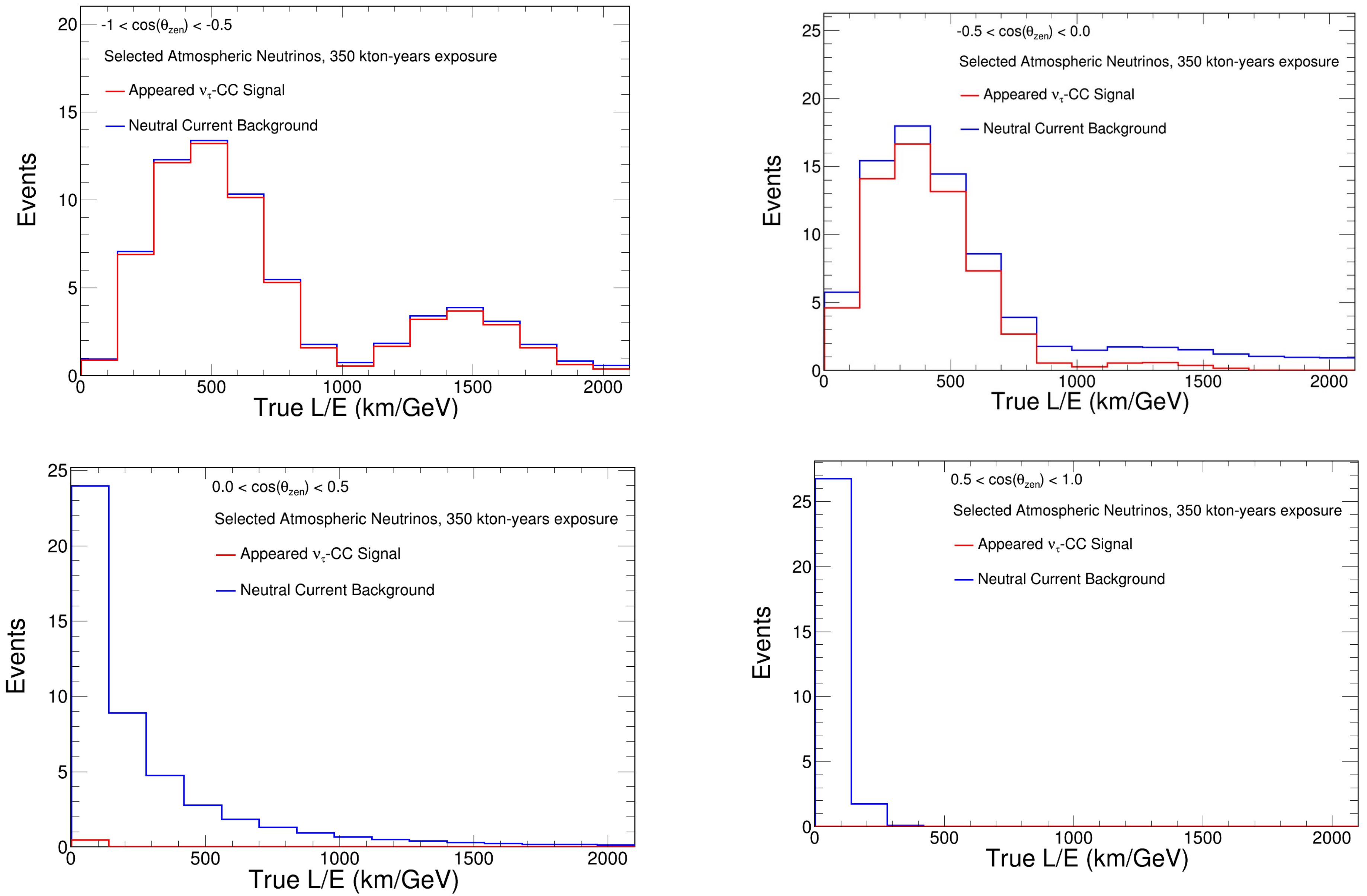








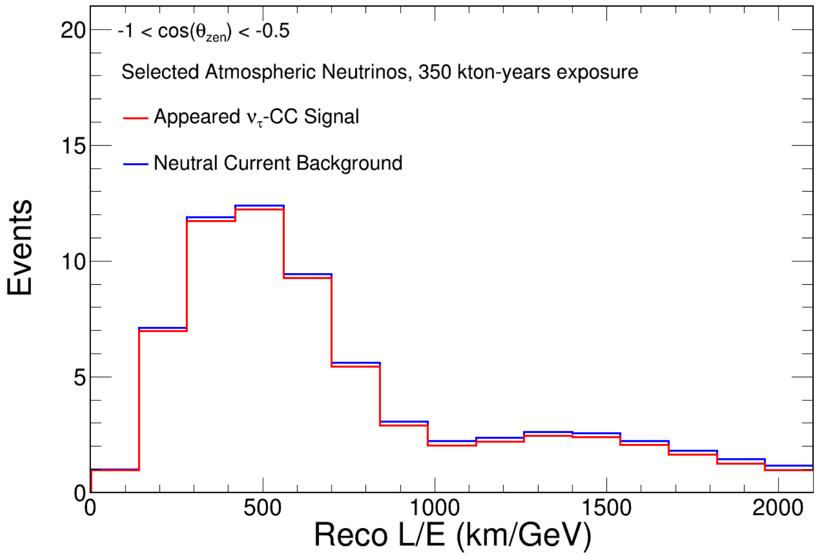
True Atmospheric Spectra, Optimistic Selection

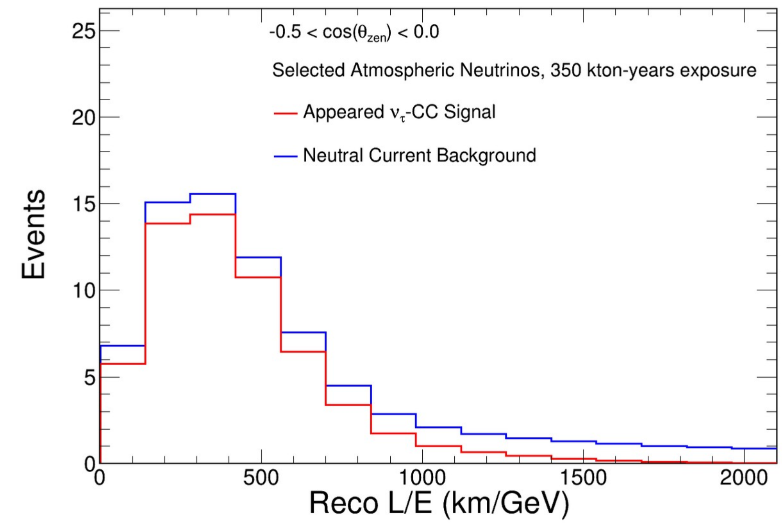


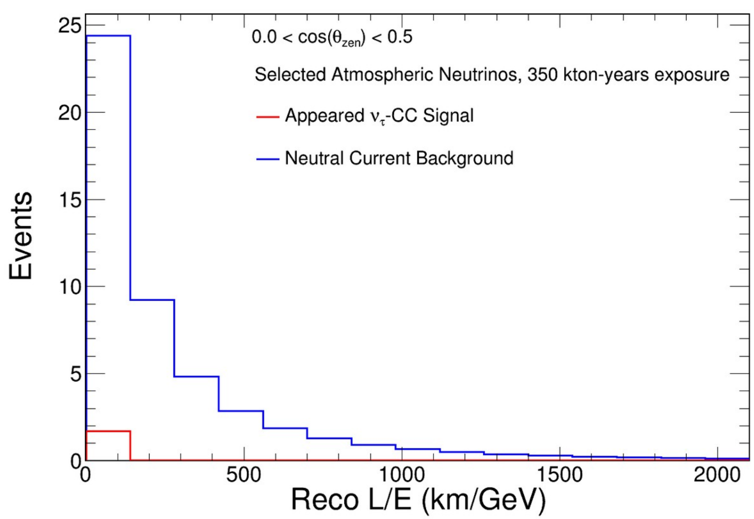
Energy and Angular Resolution

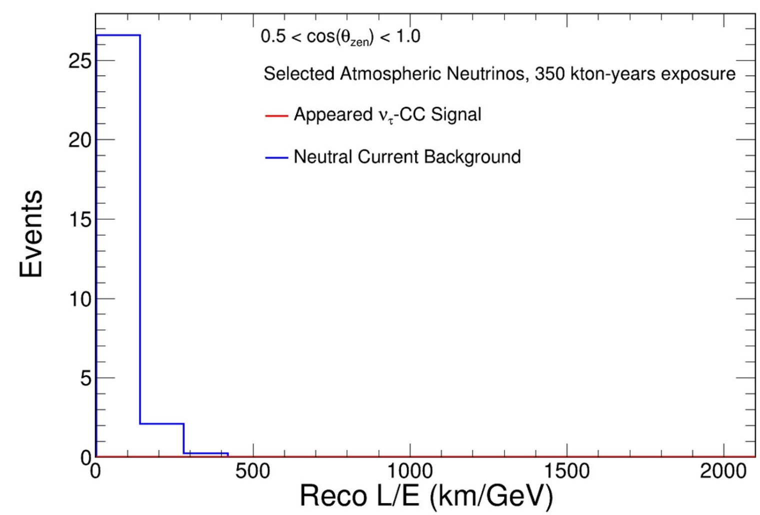
- Performed MC study of energy and angular resolution using Honda fluxes + GENIE + calorimetric energy reconstruction
- Calorimetric energy resolution
  - ~17% resolution for both ν_t-CC and NC
  - On average, 47% of ν_τ-CC energy is visible, while 54% of NC energy is visible
- θ_{zen} resolution
  - ~5° for ν_τ-CC and ~7° for NC
- Generate migration matrices for signal and background, also accounting for bias in reconstructed energy, which are different for signal and background
  - Use truncated Gaussian for energy throws and von Mises-Fisher for $\cos\theta_{zen}$

Reconstructed Atmospheric Spectra



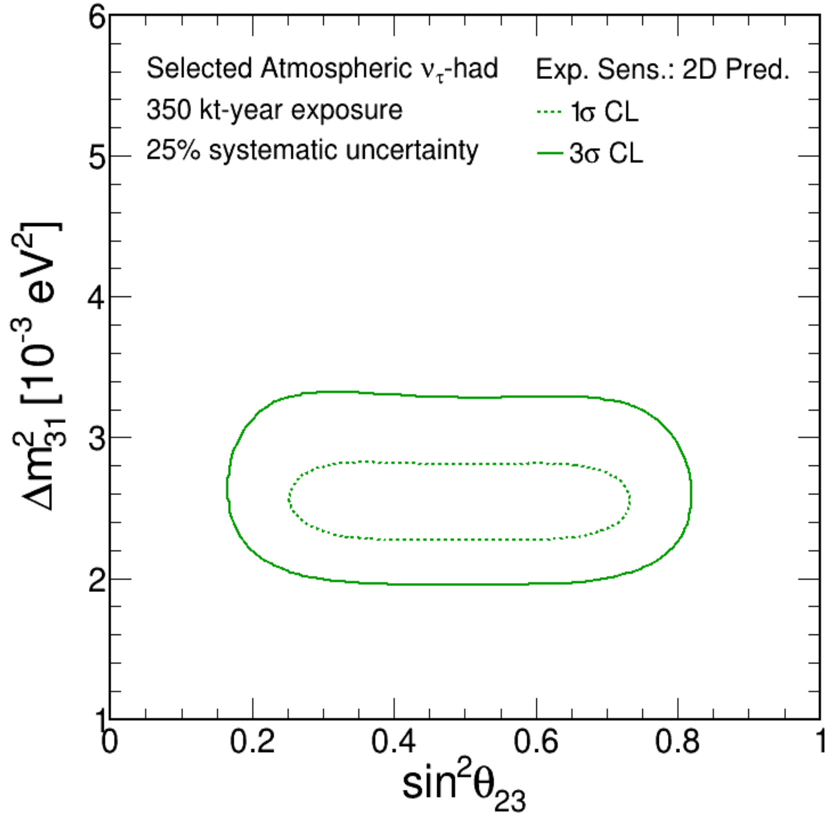




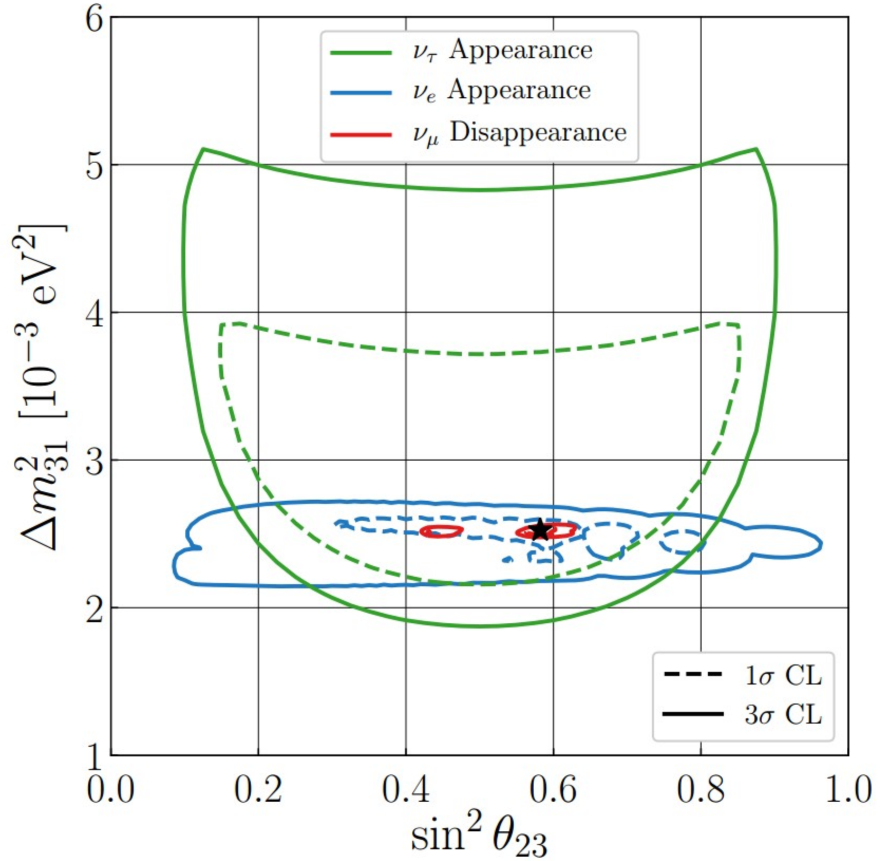


Atmospheric Parameters

Atmospheric sample



Beam sample

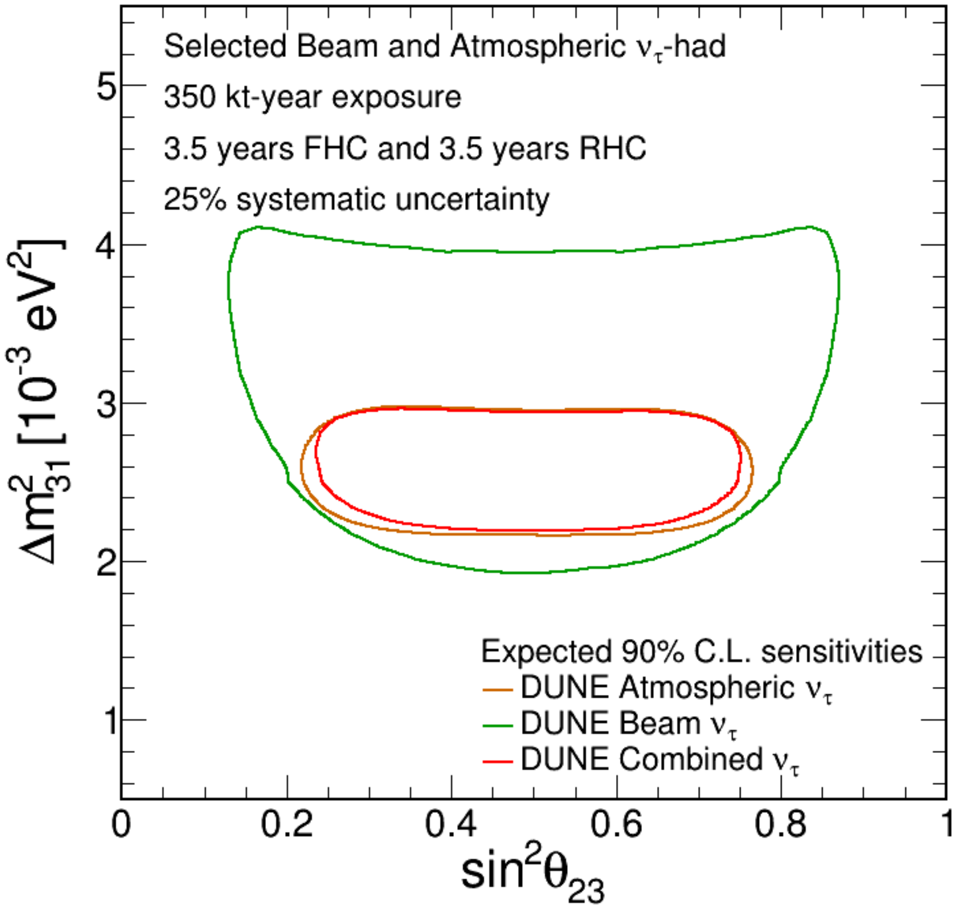


Assume a 25% normalization uncertainty

N.B. The atmospheric fit does not profile over θ_{13}

Beam contours from de Gouvea, Kelly, Stenico, and Pasquini, Phys. Rev. D 100, 016004 (2019)

Combined Beam and Atmospheric Sample



- Used likelihood calculator from authors of beam contour paper to create a joint surface
- Assume 25% normalization systematics for atmospherics, FHC beam, and RHC beam
  - Treat as three uncorrelated errors

Conclusions

- DUNE is uniquely capable of providing a high-purity, high-statistics sample of atmospheric tau neutrinos
- Tau neutrinos are challenging to select and reconstruct, but they provide an independent check of the three flavor model
- A 2-dimensional fit to the atmospheric prediction improves constraints on the atmospheric parameters
- Combinations with a sample of beam tau neutrinos , especially a potential high energy sample, may provide additional constraints on tau neutrino cross sections