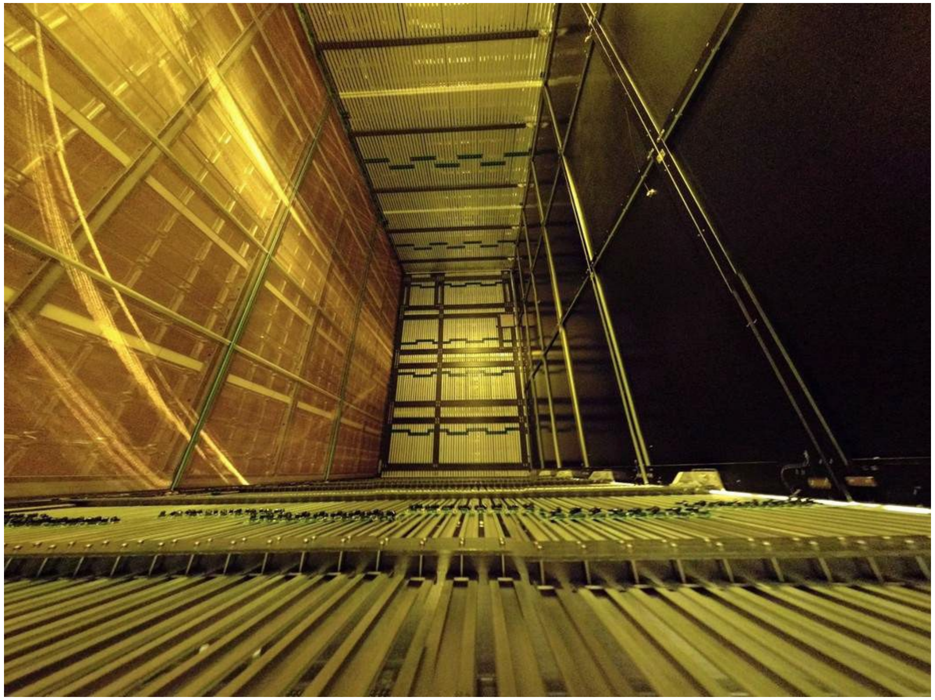
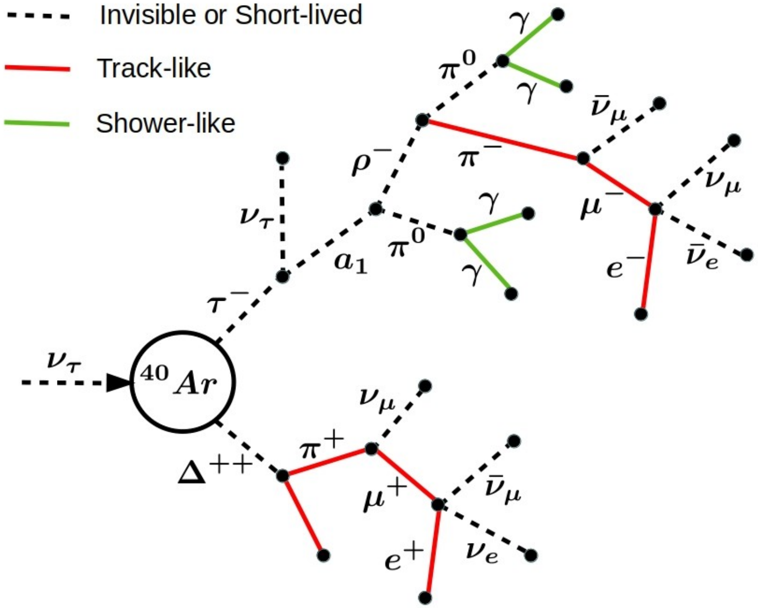
DEEP UNDERGROUND NEUTRINO EXPERIMENT

UNIVERSITY OF Cincinnati

Tau Neutrino Physics at DUNE



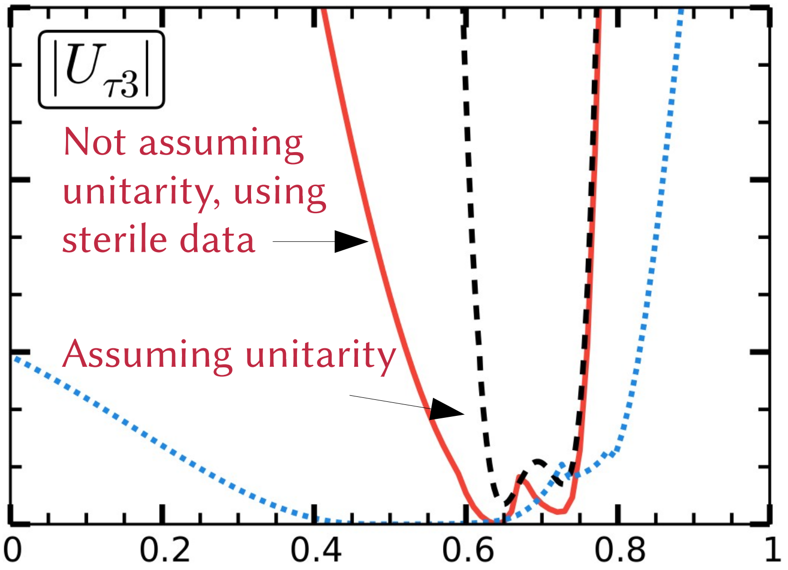


Adam Aurisano for the DUNE Collaboration
University of Cincinnati

The 22nd International Workshop on Neutrinos from Accelerators
8 September 2021

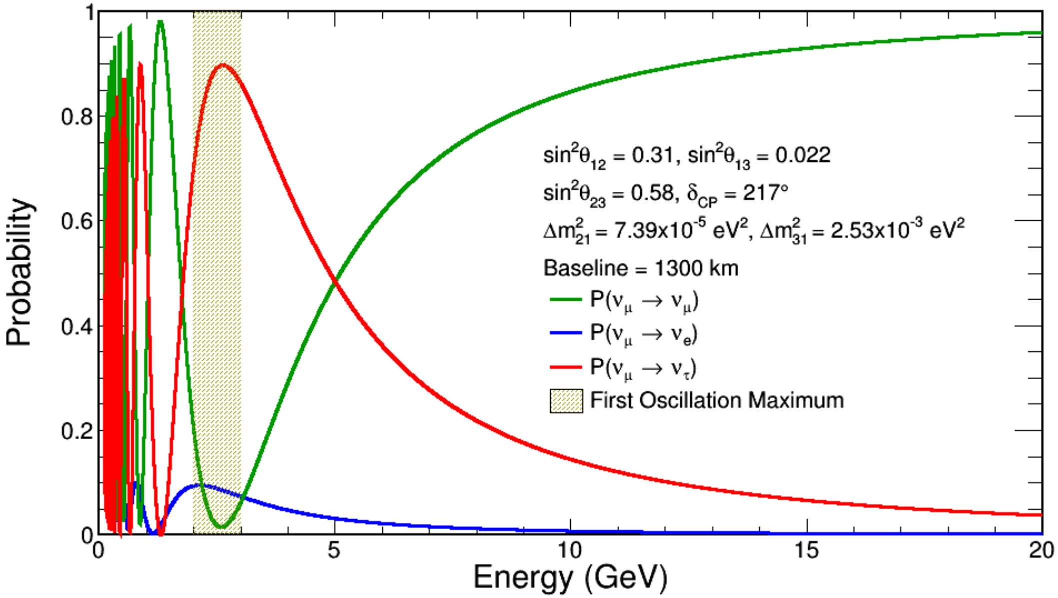
Why Tau Neutrinos?

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



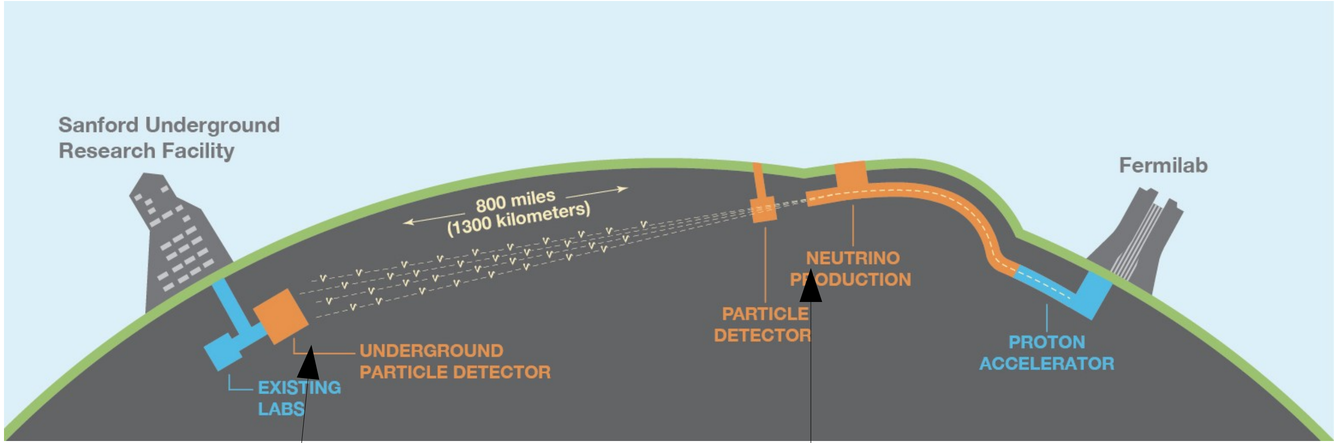
Not assuming unitarity, using sterile data

Assuming unitarity

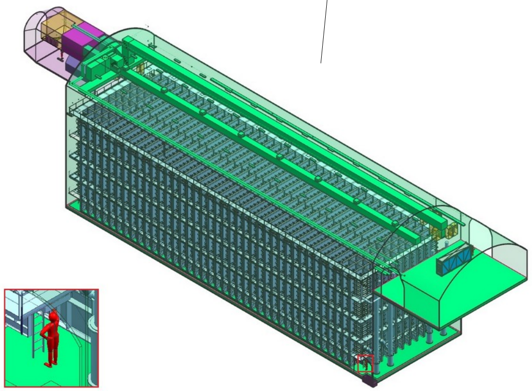


- Contributions of NOvA and T2K provide nearly complete description of three flavor paradigm
  - Flagship analyses of DUNE will continue to increase precision
- Almost all knowledge of ν_τ sector is taken from:
  - Lepton universality for cross sections
  - PMNS unitarity for oscillations
- Almost all ν_μ disappear at oscillation maximum
  - Assumed oscillating into ν_τ
  - Only 10 high-purity, oscillated, ν_τ candidates have ever been observed

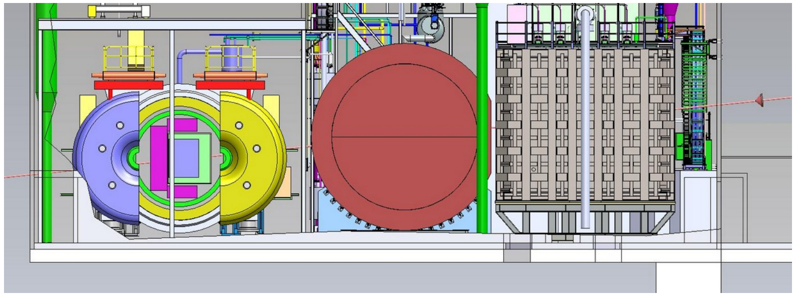
Deep Underground Neutrino Experiment



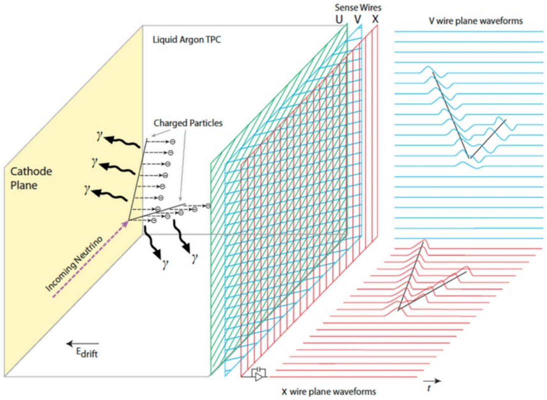
- DUNE is a long-baseline neutrino experiment currently under construction
- DUNE will constrain the three flavor paradigm
  - Will measure δ_{CP} and mass ordering by studying $\nu_\mu \rightarrow \nu_e$ oscillations

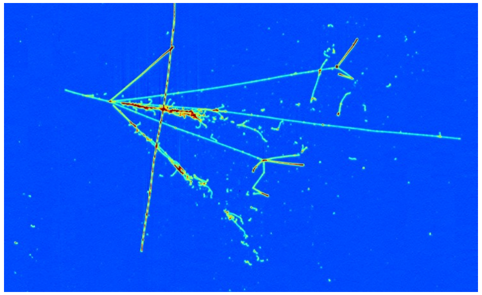


FD:
1300 km baseline
4x17 kton LArTPC



ND:
574 m baseline
Multiple detector system
147 ton LArTPC component

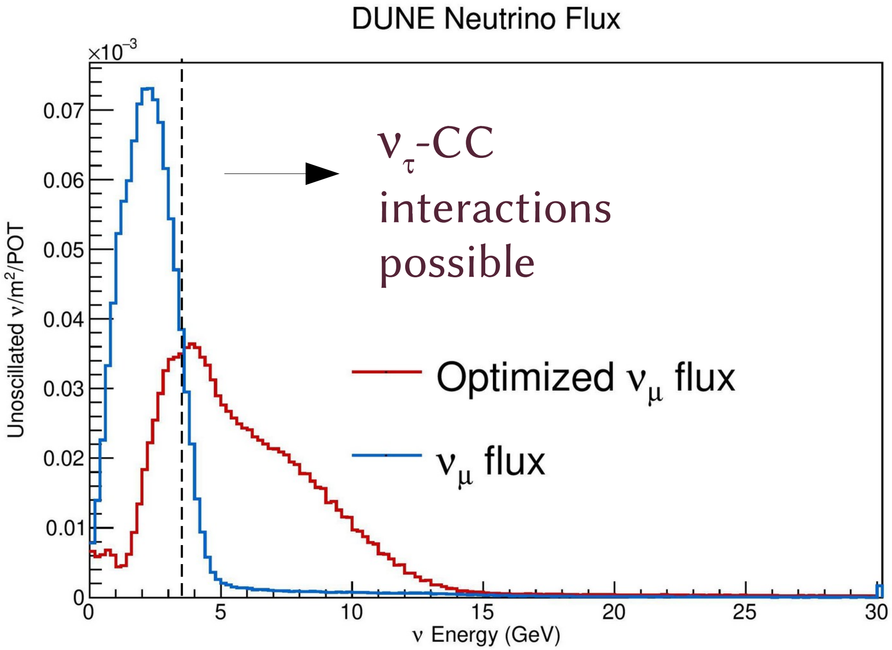




DUNE's large mass, high intensity beam, long baseline, and high resolution LArTPC technology will enable the collection of an unprecedented high-statistics and high-purity ν_τ sample.

Beam Neutrinos

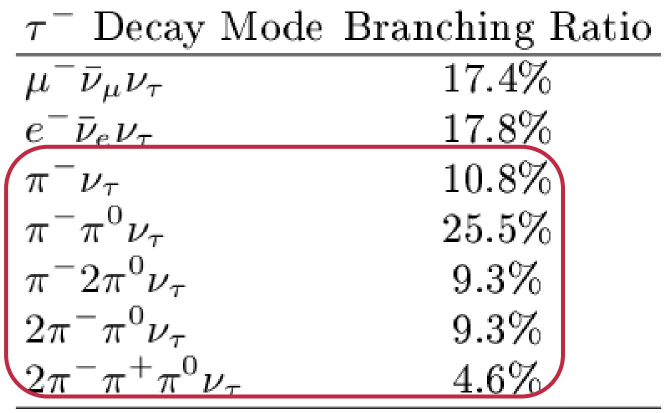
Beam Flux and Selection



- ν_τ are difficult to select
  - Kinematically forbidden at typically beam energy
  - τ-leptons have many decay modes
    - Mimic either ν_e-CC, ν_μ-CC, or NC events
- Consider truth level studies of atmospheric ν_τ
  [J. Conrad, A. de Gouvea, S. Shalgar, J. Spitz, PRD 82, 093012 (2010)]
  - Select ν_τ with hadronically decaying τ-lepton
  - Assume near perfect e/γ and μ/π discrimination
  - Simple kinematic cuts on $\pi^\pm$ yield excellent ν_τ-CC/NC discrimination
- Optimistic assumptions suggest:
  - ~30% flat signal efficiency
  - 0.5% NC background efficiency

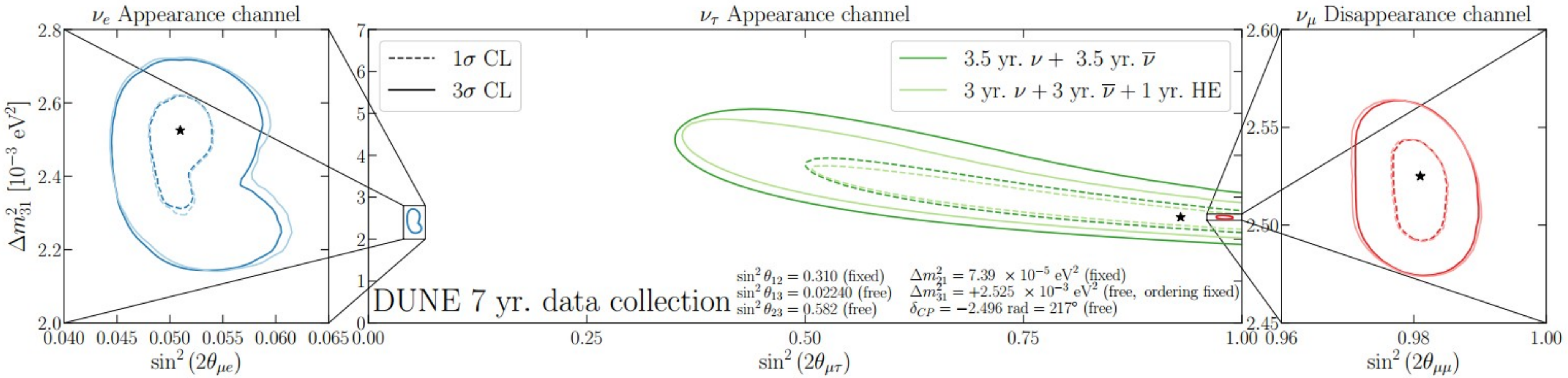
Expected counts/year:

~**130** ν_τ in low-energy neutrino mode
~**30** $\bar{\nu}_\tau$ in low-energy antineutrino mode
~**800** ν_τ in high-energy neutrino mode



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%

Model-Independent Non-Unitarity



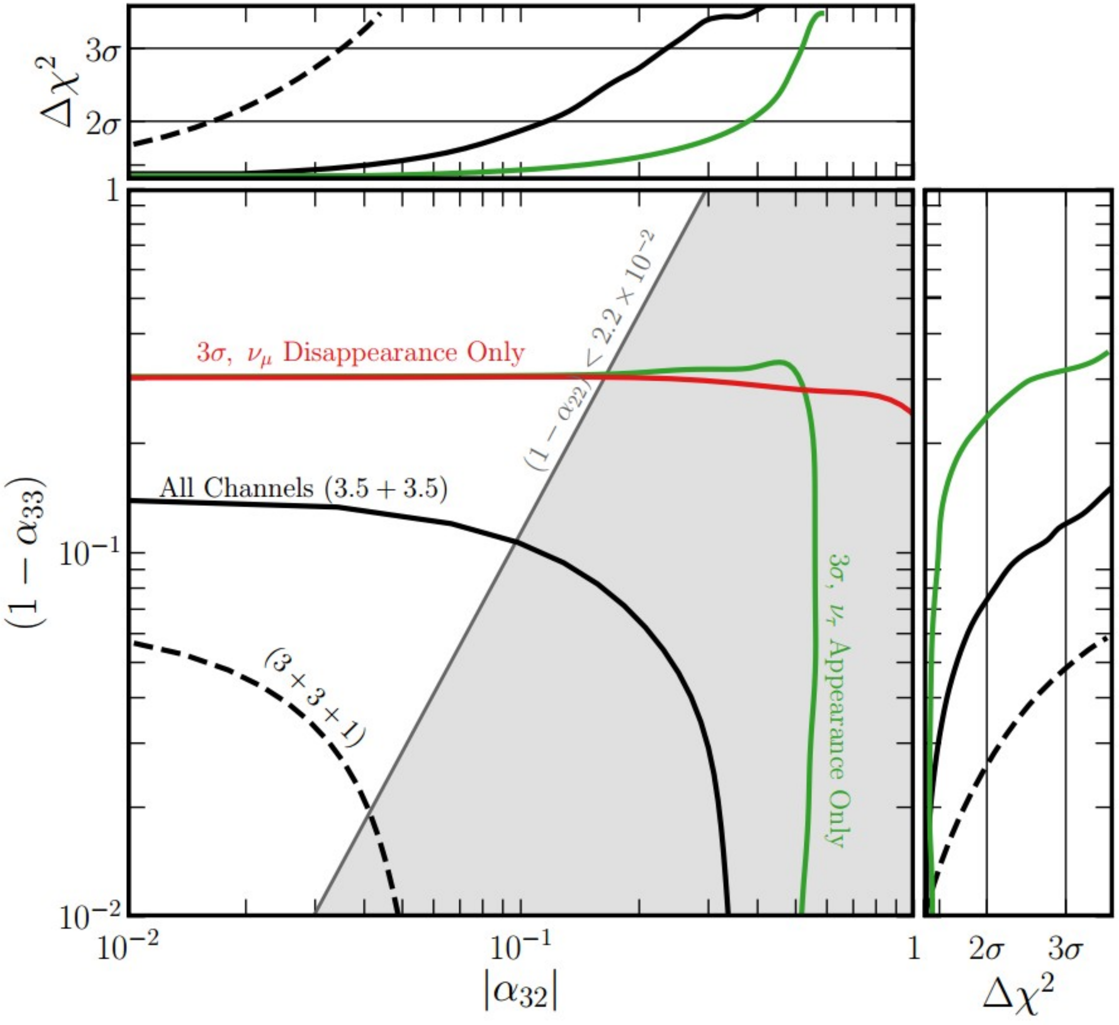
de Gouvea, Kelly, Stenico, Pasquini, PRD 100, 016004 (2019)

- Independent constraints on effective mixing angles from each channel provide model independent test of unitarity:

$$\sin^2(2\theta_{\mu e}) + \sin^2(2\theta_{\mu\tau}) = \sin^2(2\theta_{\mu\mu})$$

- DUNE data alone expected to constrain normalization of 3rd PMNS column to ~5%
- All other neutrino data constrains normalization to ~7.5% [S. Parke, M. Ross-Lonergan, PRD 93, 1103009 (2016)]

Parameterized Non-Unitarity



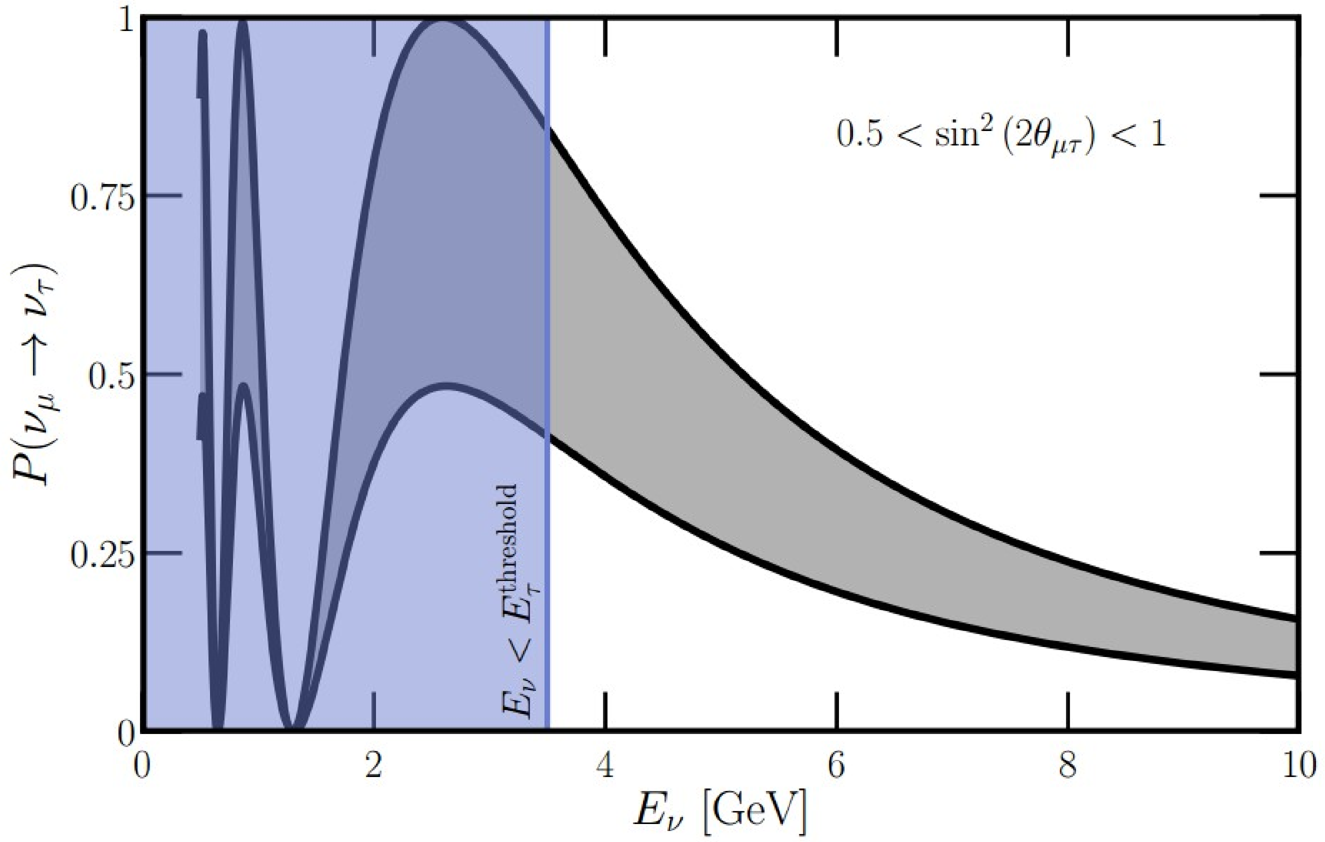
de Gouvea, Kelly, Stenico, Pasquini, PRD 100, 016004 (2019)

$$U \to NU = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U$$

- Can also constrain non-unitarity using α parameters
- Tau neutrino data, in addition to other channels, improves bounds on α_{33}
- A year of high energy data is particularly useful for this measurement

Limitations of the Beam Sample

de Gouvea, Kelly, Stenico, Pasquini, PRD 100, 016004 (2019)

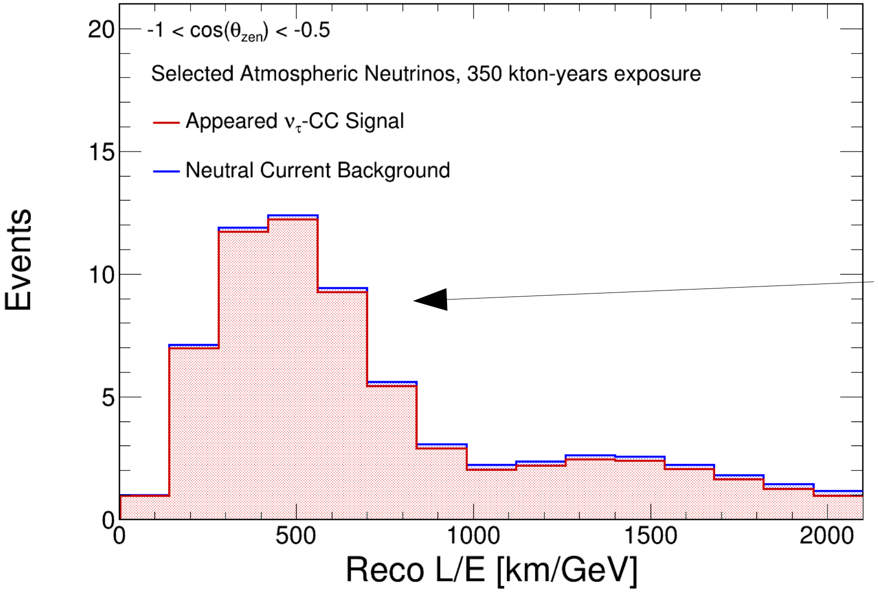


- Since the beam is at a fixed baseline, the first oscillation maximum is below the ν_τ-CC kinematic thresholds
- This creates some ambiguities between Δm^2_{31} and $\sin^2\theta_{23}$
- Atmospheric neutrinos may help

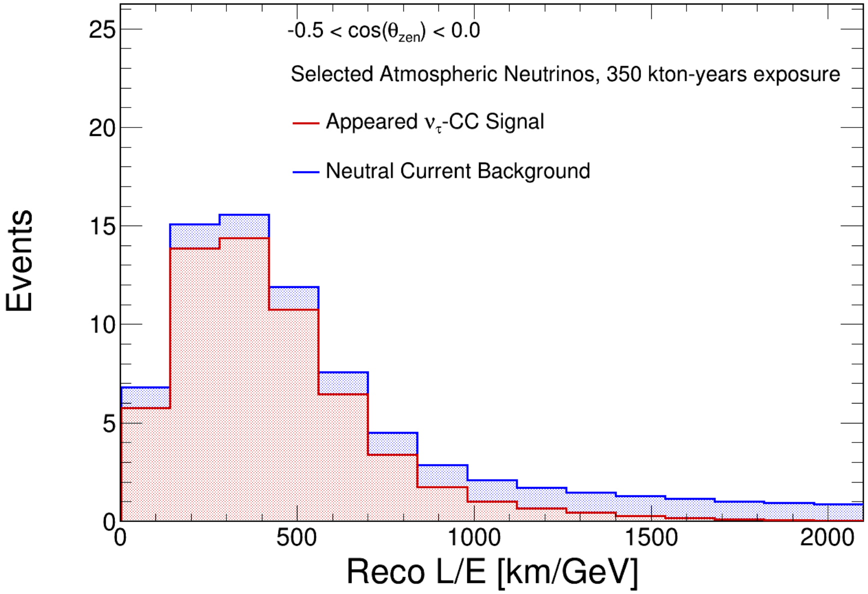
Atmospheric Neutrinos

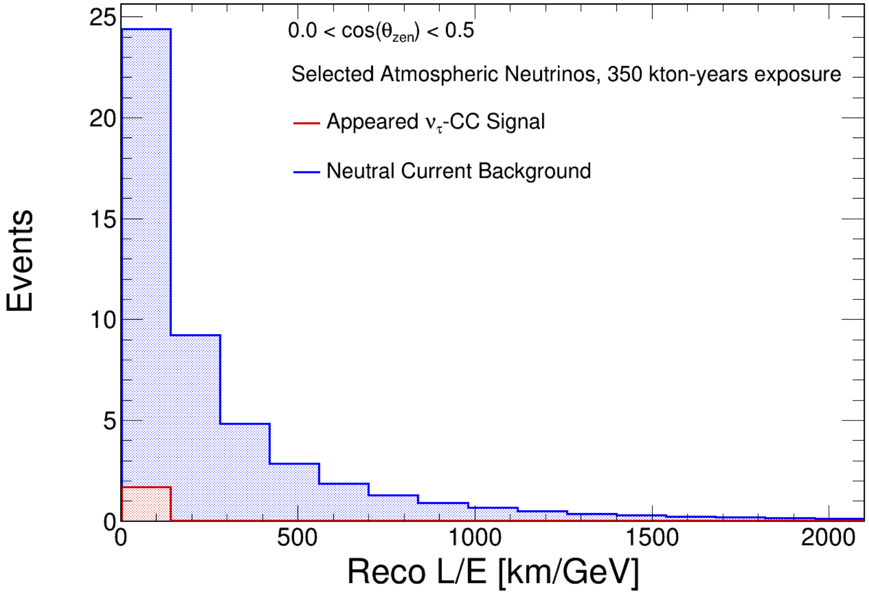
Reconstructed Atmospheric Spectra

Expect ~1 ν_τ-CC/kton-year

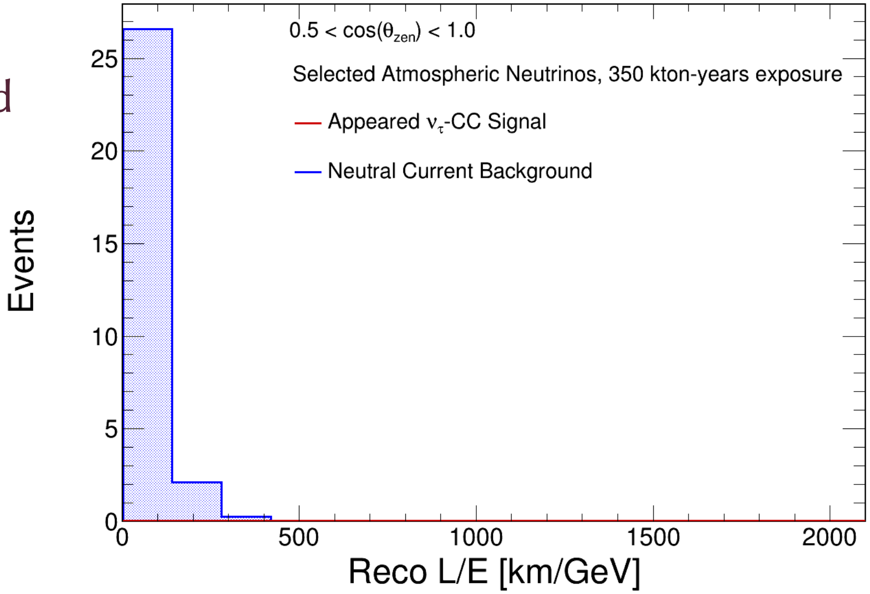


Clear 1st oscillation maximum after smearing



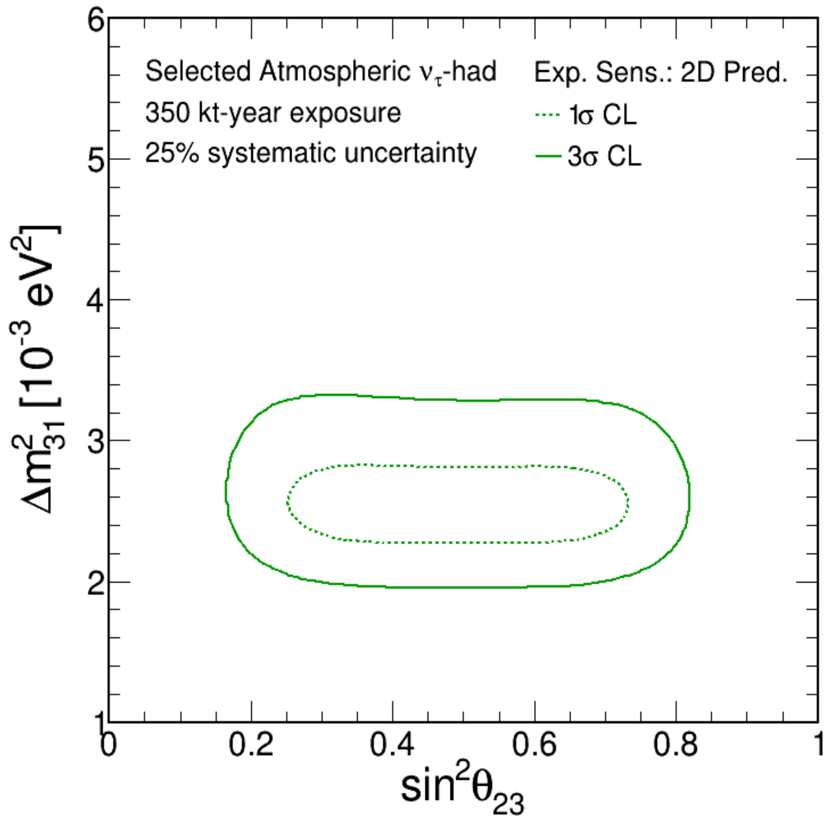


Use optimistic selection and smearing from studies of visible particles above threshold



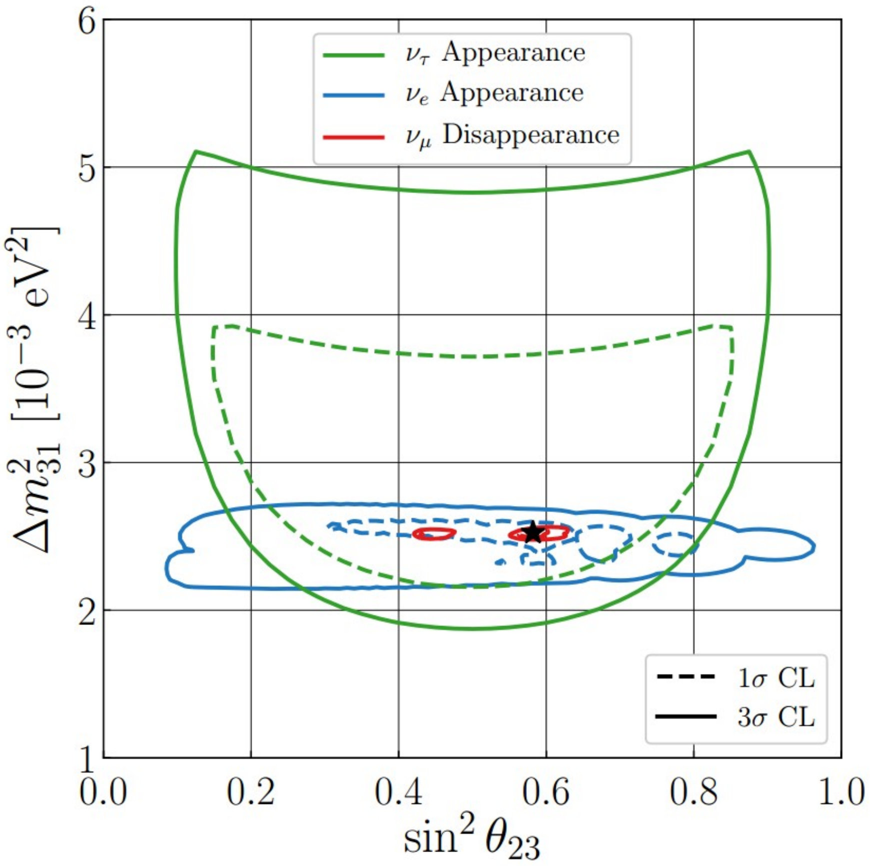
Atmospheric Parameters

Atmospheric sample



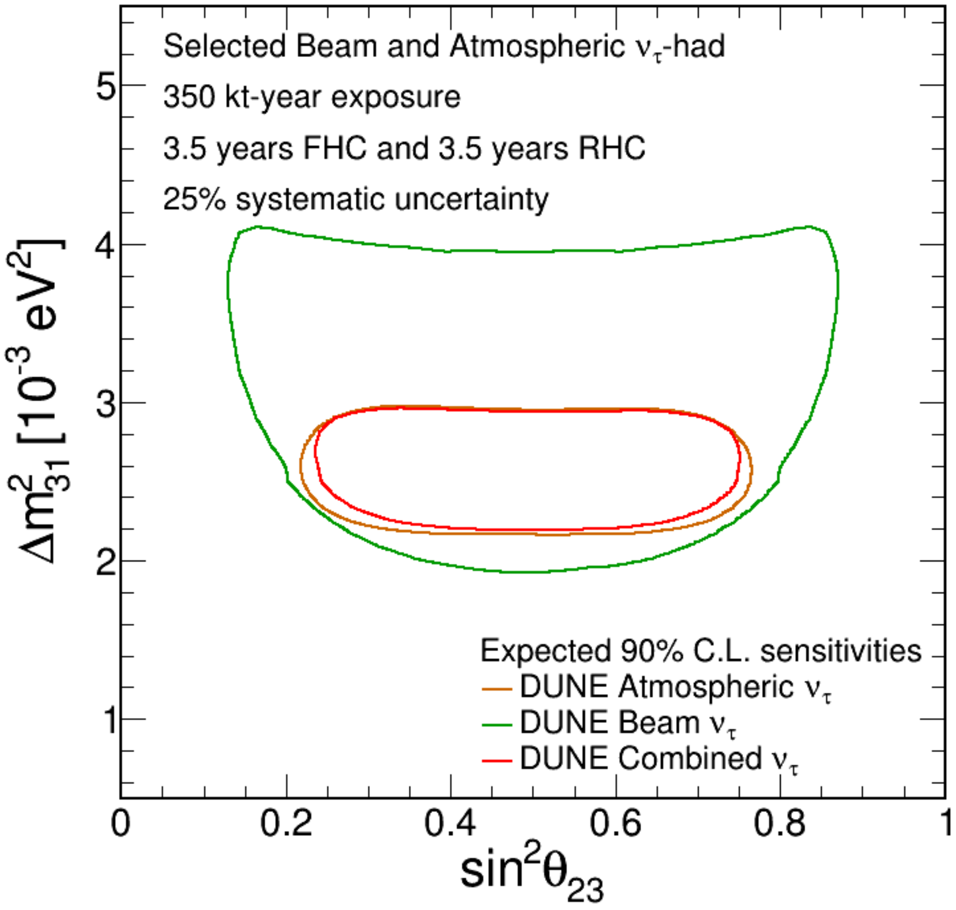
Assume a 25% normalization uncertainty

Beam sample



de Gouvea, Kelly, Stenico, Pasquini, PRD 100, 016004 (2019)

Combined Beam and Atmospheric Sensitivity



Beam likelihood calculator courtesy of de Gouvea, Kelly, Stenico, Pasquini

- Assume 25% normalization systematics for atmospherics, FHC beam, and RHC beam
  - Treat as three uncorrelated errors
- Sensitivity driven by atmospherics, but interplay between atmospherics and beam may help constrain systematic uncertainties

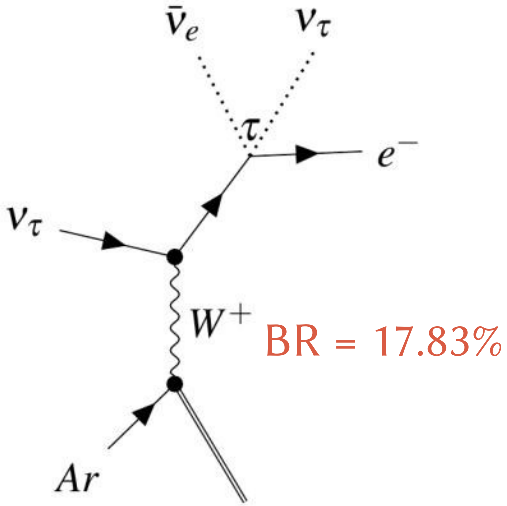
Short-Baseline Sterile-Driven ν_τ Appearance

Short-Baseline Sterile-Driven ν_τ Appearance

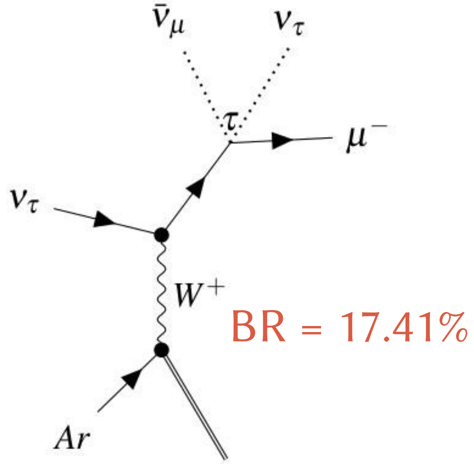
- In three flavor scenario, we expect ~no ν_τ-CC events in ND
- In 3+1 scenario with new mass state ~1 eV, ν_τ-CC events can appear in ND

$$P(\nu_\mu \to \nu_\tau) = \sin^2(2\theta_{\mu\tau}) \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

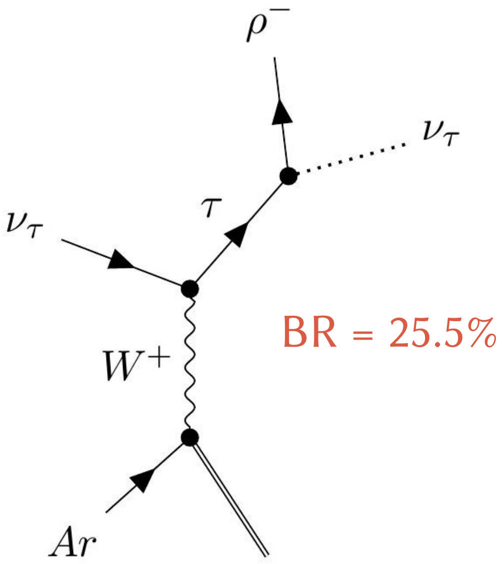
- Look for ν_τ-CC events with τ-leptons decaying into e, μ, and ρ-mesons in the high-energy beam



BR = 17.83%

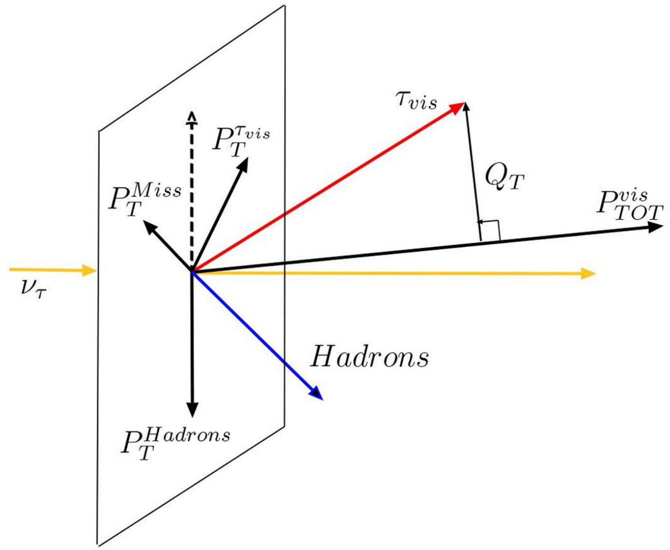


BR = 17.41%

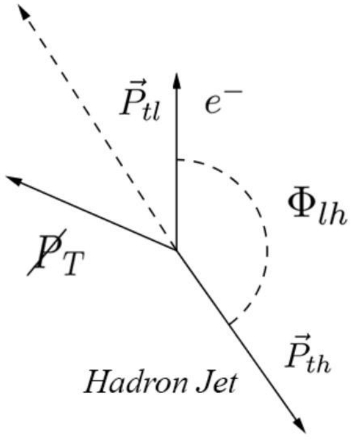


BR = 25.5%

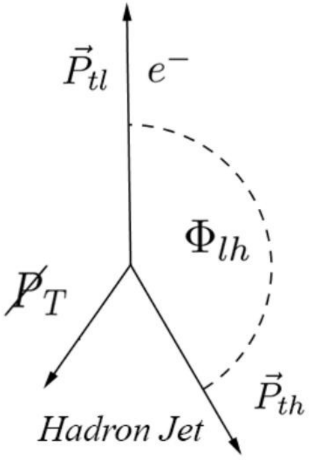
Selection: Transverse Kinematic Variables



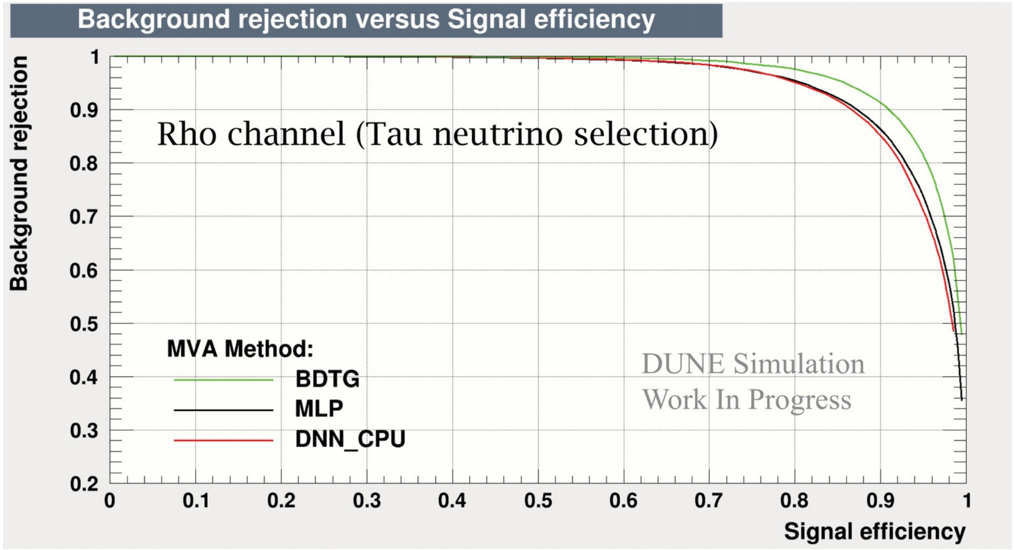
- ν_τ-CC interactions have same particle content as ν_e-CC, ν_μ-CC, or NC events
- Angular correlations are distinguishing feature
- Use a BDT trained on transverse kinematic variables to distinguish signal from background
  - Input variables from GENIE simulation smeared by expected reconstruction performance
- In ρ-mode, a BDT identifying ρ decay products acts as a preselection



Signal interaction products

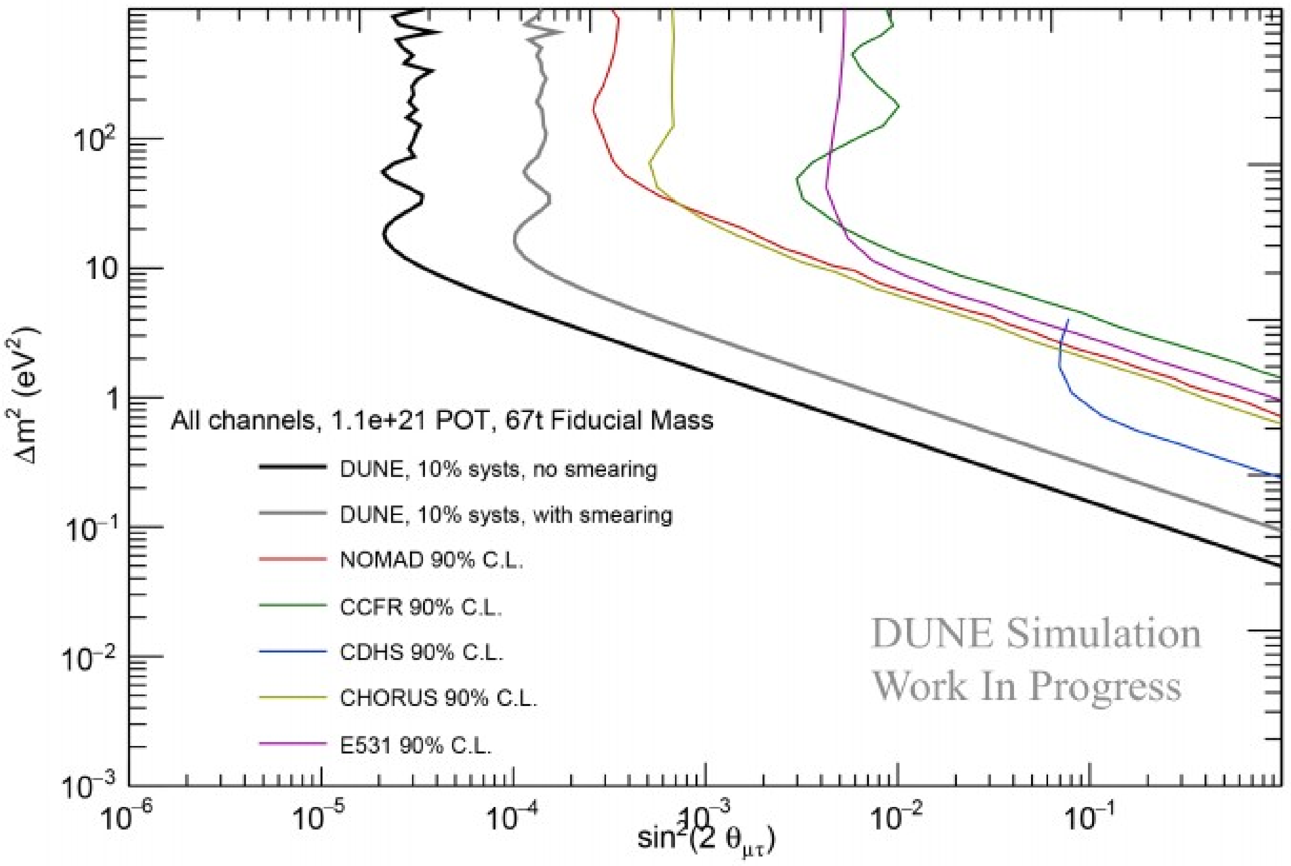


Background interaction products



DUNE Simulation
Work In Progress

Sensitivity

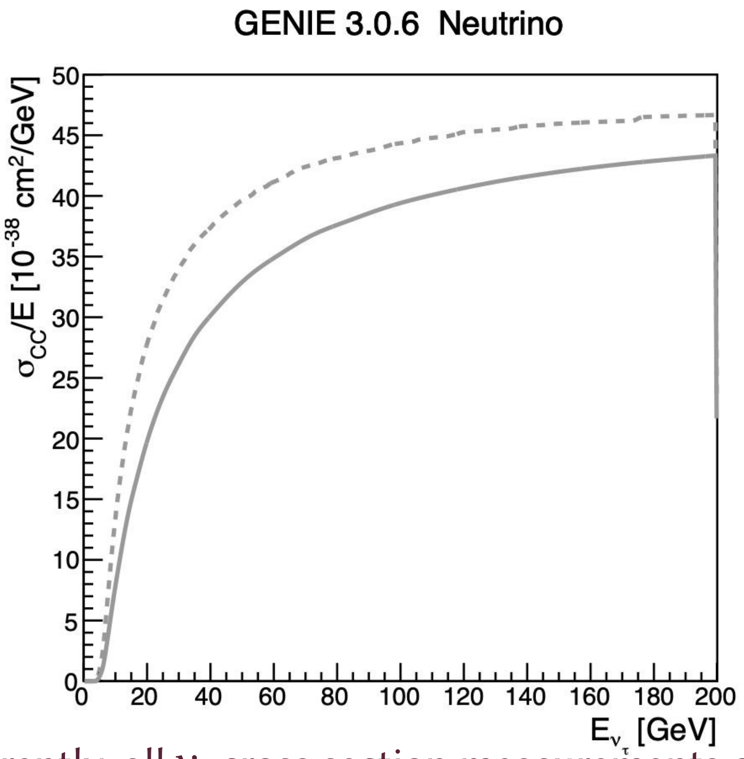


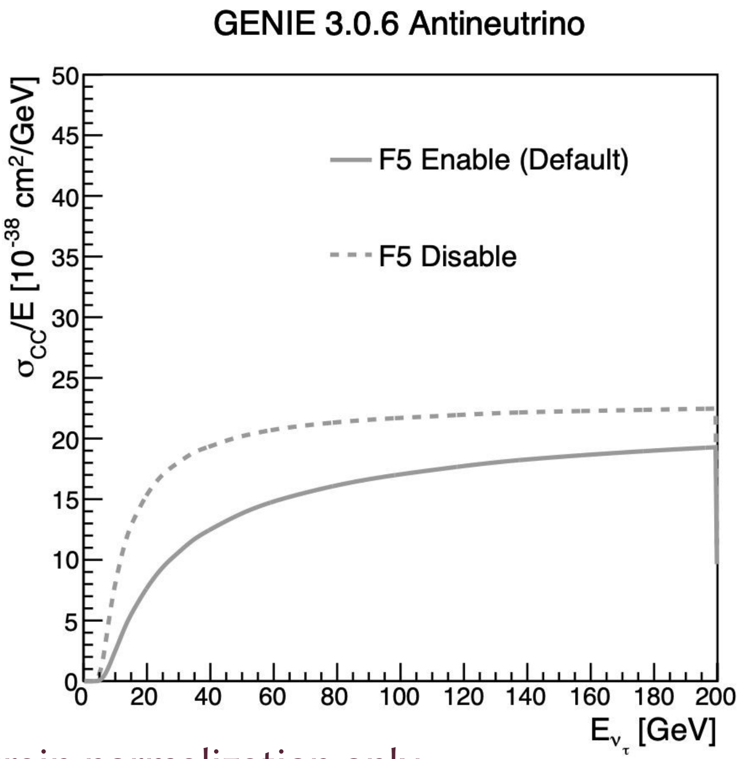
Require high BDT scores to reach ~background free region

Assume a 10% systematic uncertainty on both signal and background

ν_τ Cross Sections

ν_τ Cross Sections





- Currently, all ν_τ cross section measurements constrain normalization only
- ν_τ-CC interactions give access to cross section physics not accessible otherwise:

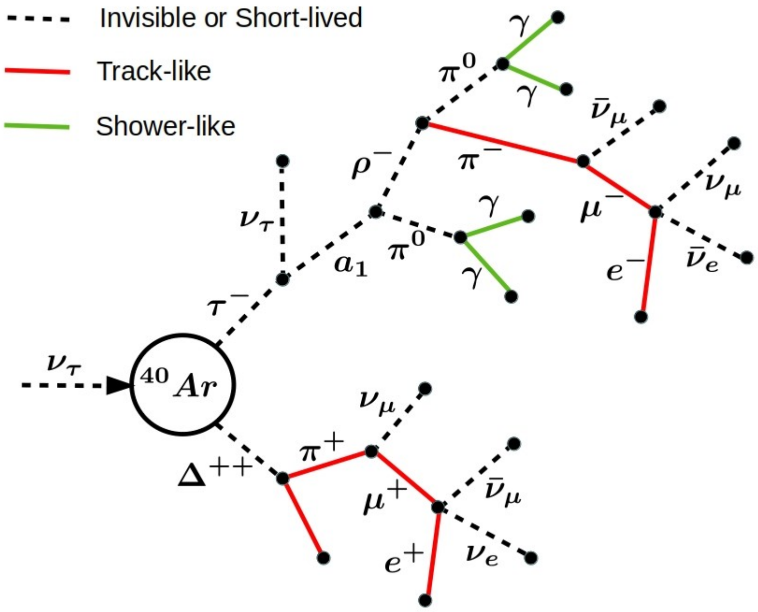
$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dx\,dy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\left((y^2x+\frac{m_\tau^2 y}{2E_\nu M})F_1 + \left[(1-\frac{m_\tau^2}{4E_\nu^2})-(1+\frac{Mx}{2E_\nu})\right]F_2 \pm \left[xy(1-\frac{y}{2})-\frac{m_\tau^2 y}{4E_\nu M}\right]F_3 + \frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2 M^2 x}F_4 - \boxed{\frac{m_\tau^2}{E_\nu M}F_5}\right),$$

F_5 structure function suppressed for ν_μ and ν_e at usual energies

- With tau-optimized beam, we expect ~800 ν_τ-CC interactions/year
  - Currently studying if differential cross sections are possible
- High-energy beam complements CP-optimized beam and atmospheric neutrino

Conclusions

- DUNE is uniquely capable of providing a high-purity, high-statistics sample of beam and atmospheric tau neutrinos
- Tau neutrinos are challenging to select and reconstruct, but they provide a needed independent check of the three flavor model
- Performance of selection using transverse plane kinematics is comparable to optimistic assumptions
- A high-energy beam mode will provide opportunities to study anomalous ν_τ-CC appearance in the ND and ν_τ-CC cross sections in the FD
- With excellent results from truth-level analyses, work is now moving to reproduce the results with the full DUNE simulation and reconstruction chain



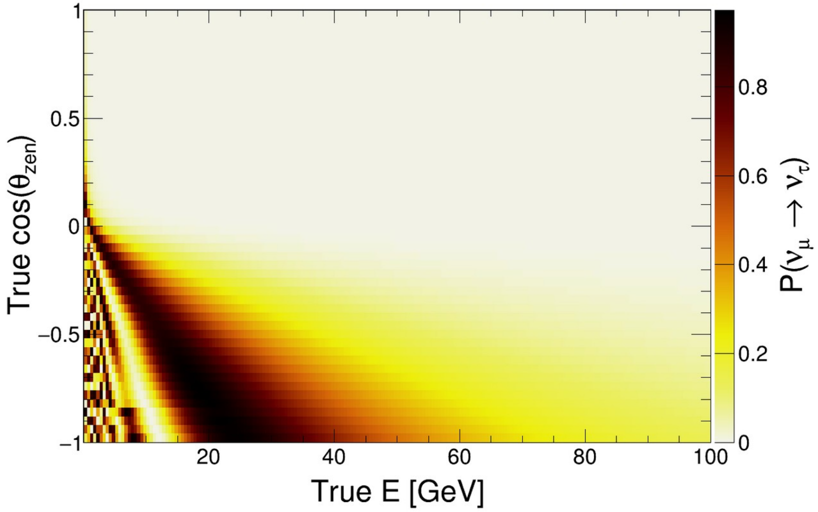
Thank you!

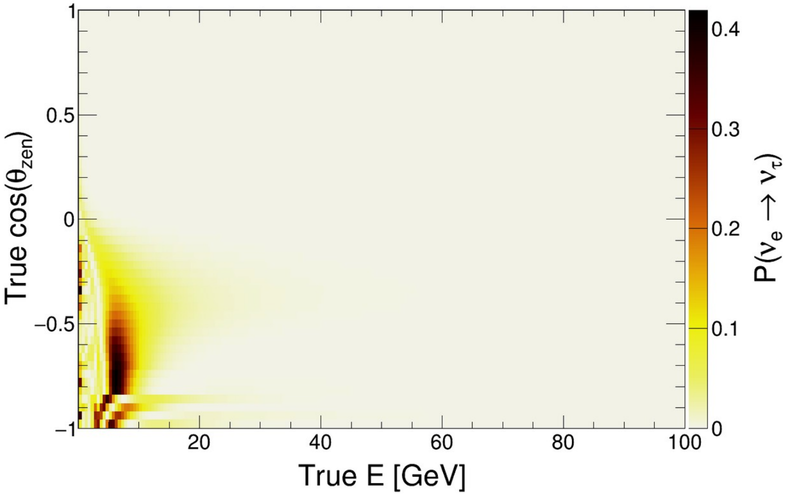
Backup Slides

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 $\cos\theta_{zen}$

Atmospheric Oscillations



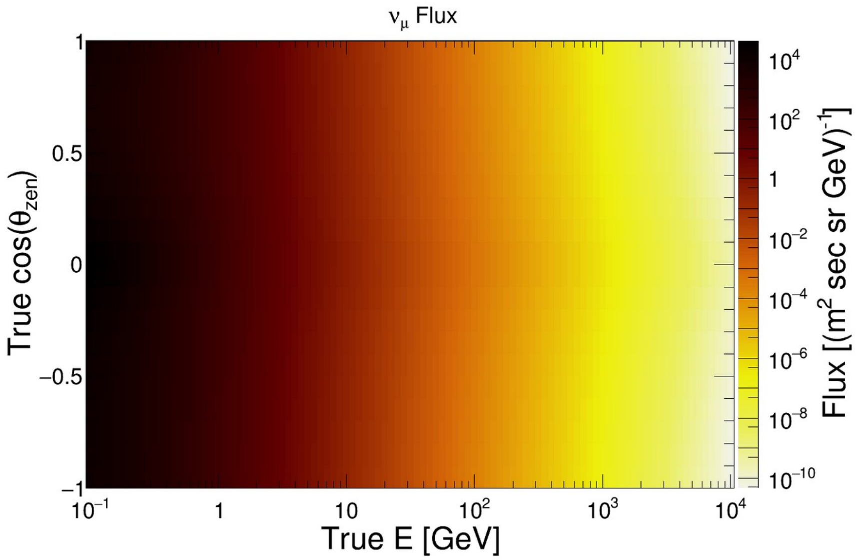


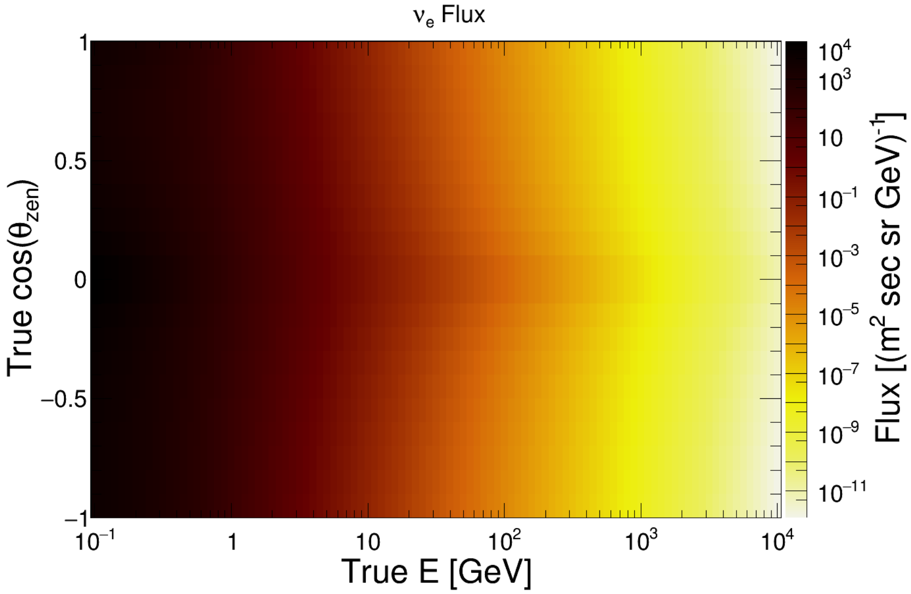
- Generate mu ⟶ tau and e ⟶ tau oscillograms using oscillation calculator: https://github.com/joaoabcoelho/OscProb
- Uses a 15 layer PREM model

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

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

Atmospheric Fluxes



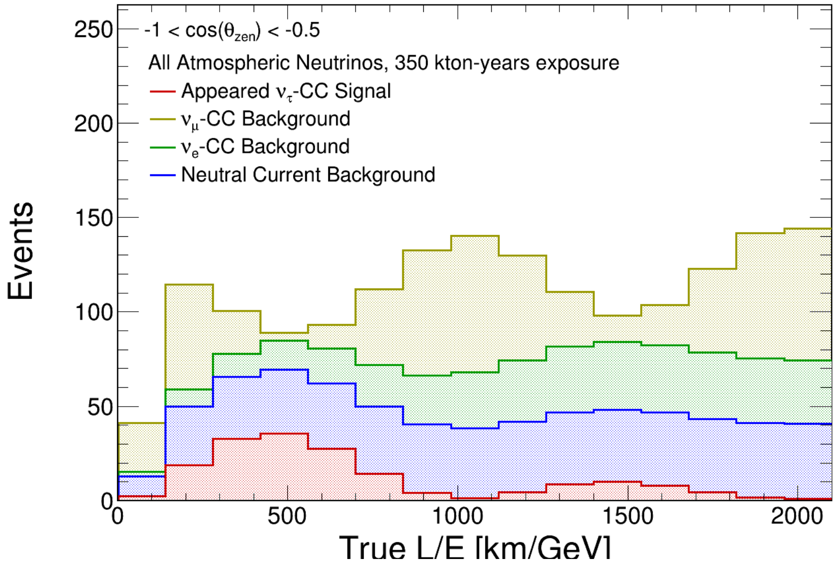


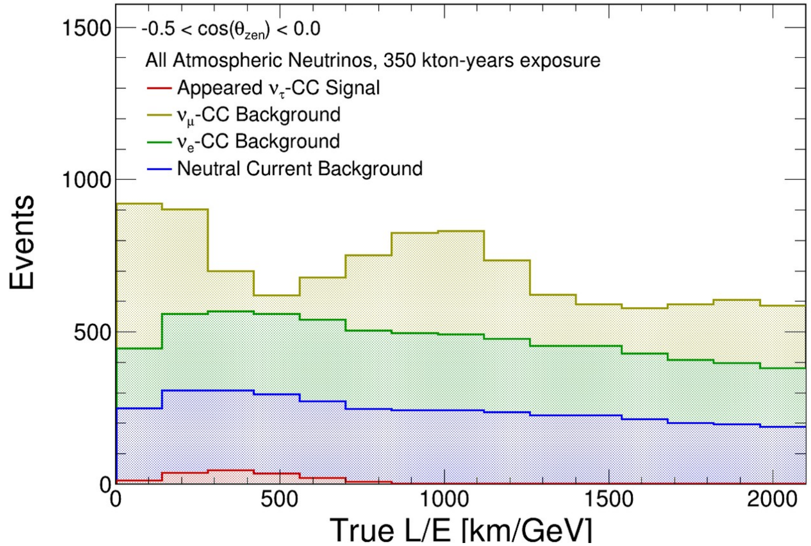
- Use Honda fluxes from http://www.icrr.u-tokyo.ac.jp/~mhonda/nflx2014/index.html
- Predicted number of tau neutrino events from flux*xsec*oscWeights

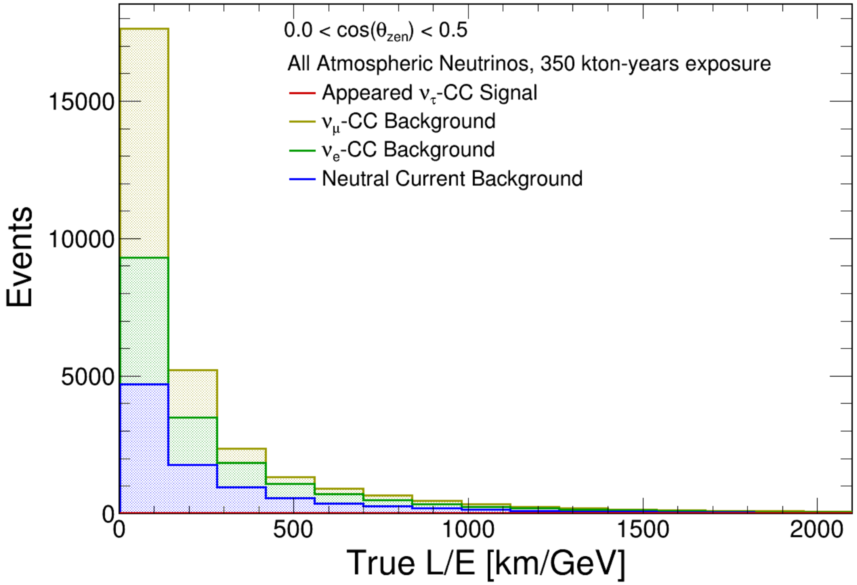
In 350 kton-years, before selection we expect:

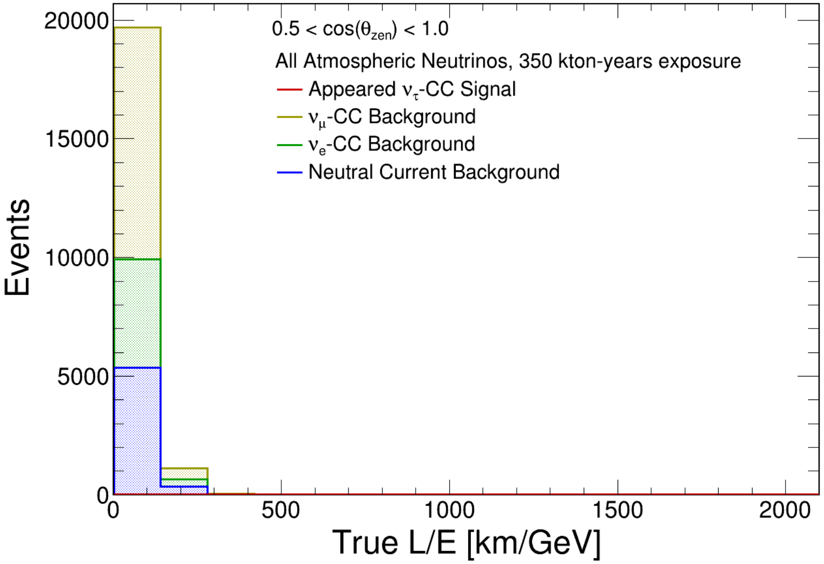
350 ν_τ-CC
31020 ν_e-CC
37500 ν_μ-CC
33040 NC

True Atmospheric Spectra, No Selection

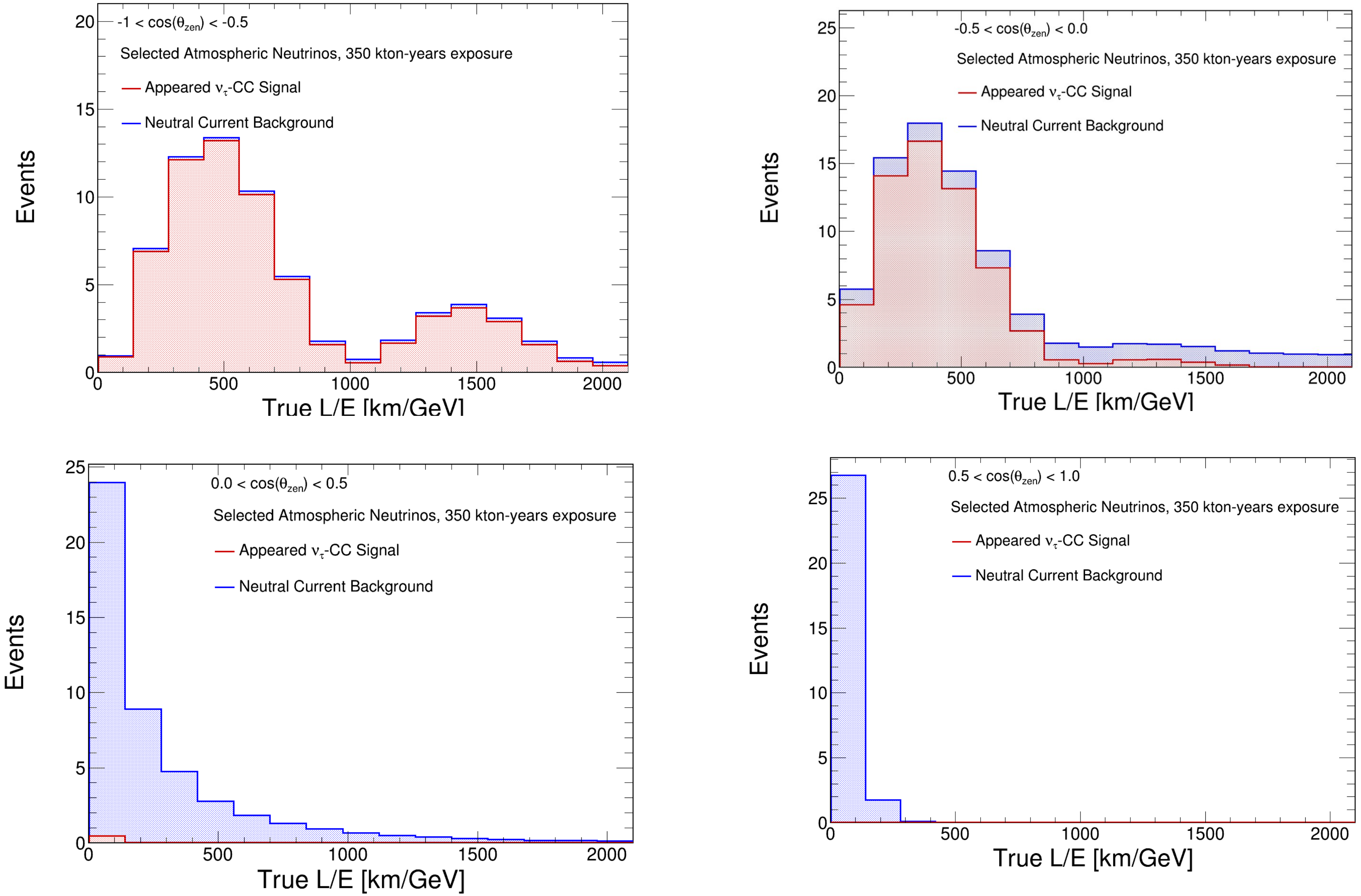








True Atmospheric Spectra, Optimistic Selection



Cross Sections