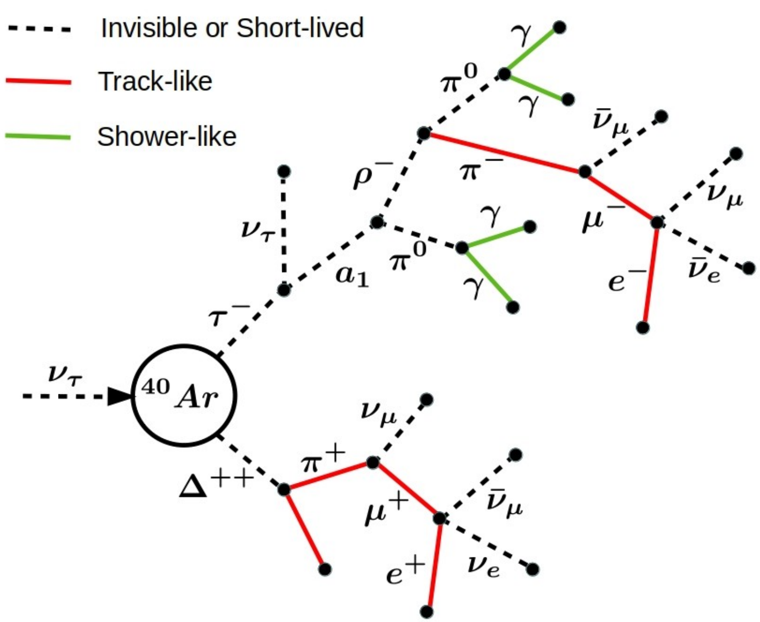
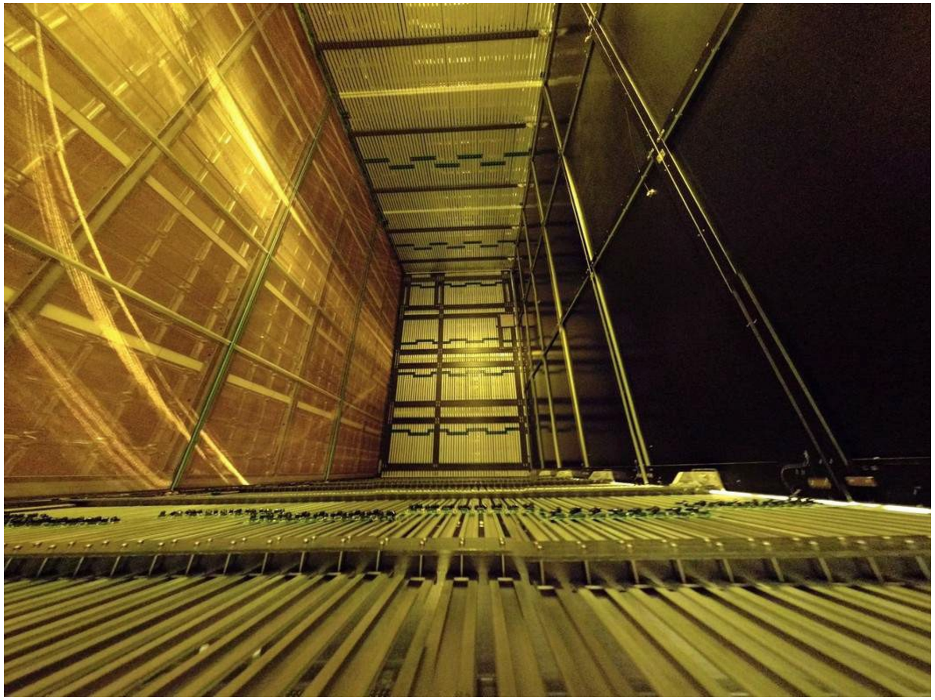
DEEP UNDERGROUND NEUTRINO EXPERIMENT

UNIVERSITY OF Cincinnati

Experimental Detection and Studies of Atmospheric Tau Neutrinos in DUNE



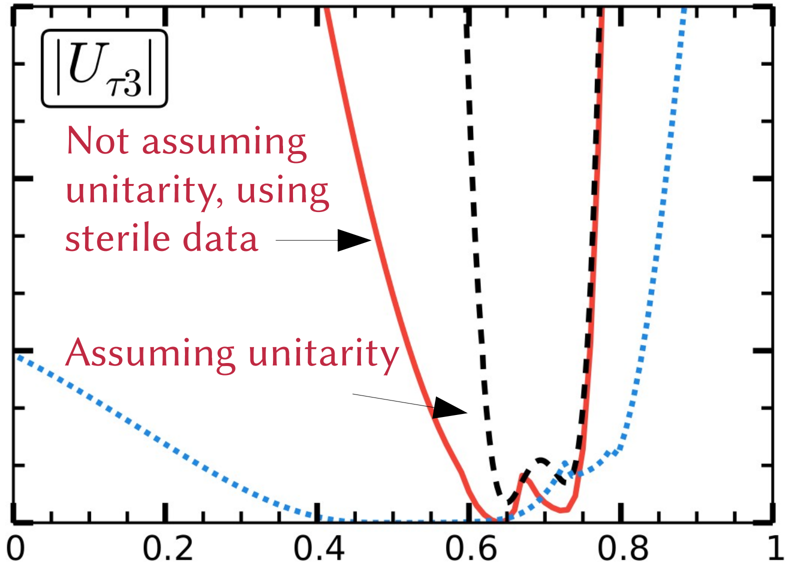


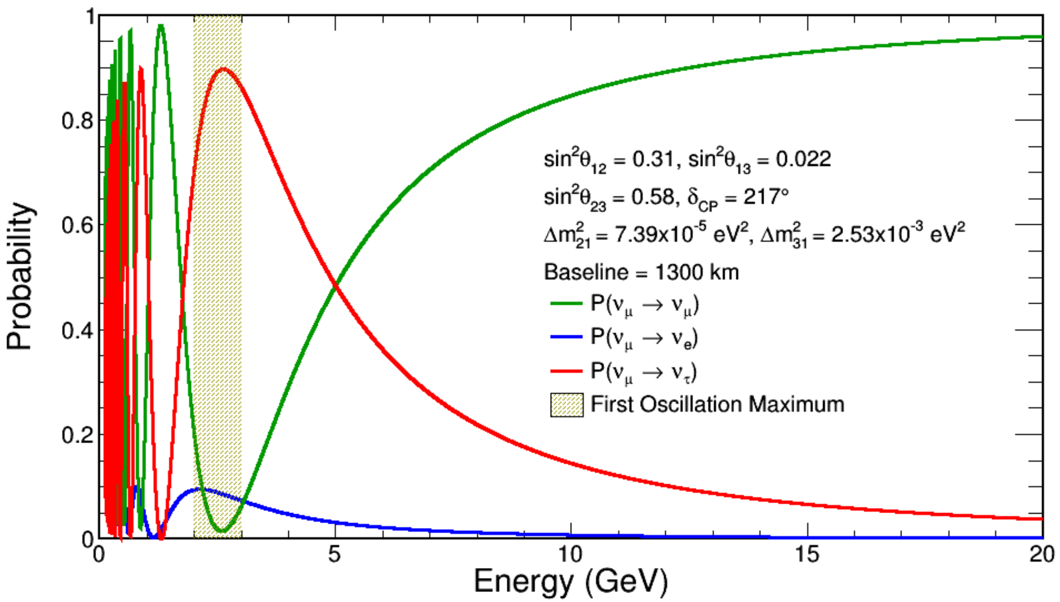
Adam Aurisano for the DUNE Collaboration
University of Cincinnati

Workshop on Tau Neutrinos from GeV to EeV 2021
29 September 2021

Why Tau Neutrinos?

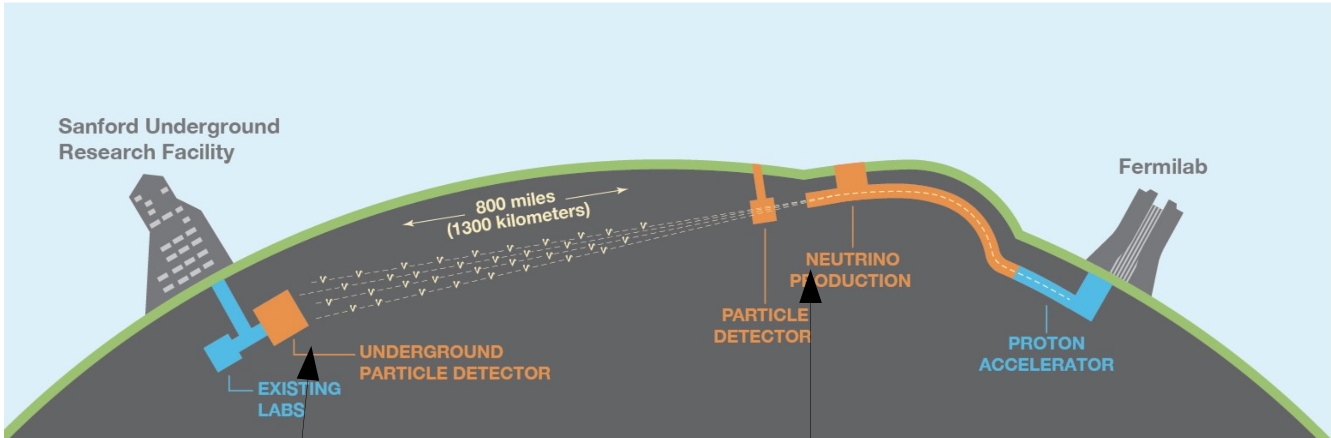
S. Parke and M. Ross-Lonergan, PRD 93, 1103009 (2016)



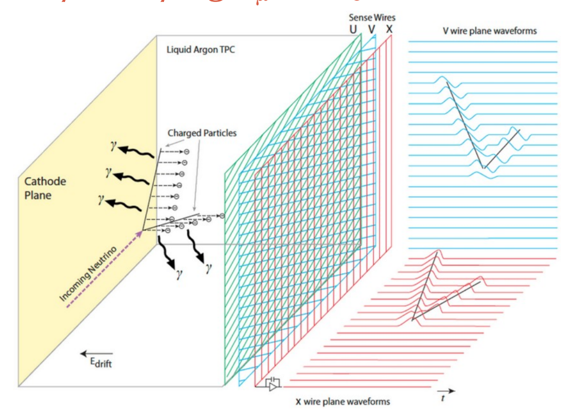


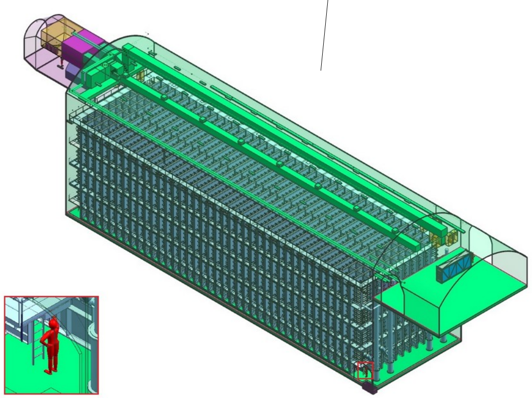
- Current generation of neutrino experiments provides nearly complete description of three flavor paradigm
- Almost all knowledge of ν_τ sector is taken from:
  - Lepton universality for cross sections
  - PMNS unitarity for oscillations
- Almost all ν_μ disappear at oscillation maximum
  - Assumed oscillating into ν_τ
  - Only 10 high-purity, oscillated, ν_τ candidates have ever been observed

Deep Underground Neutrino Experiment

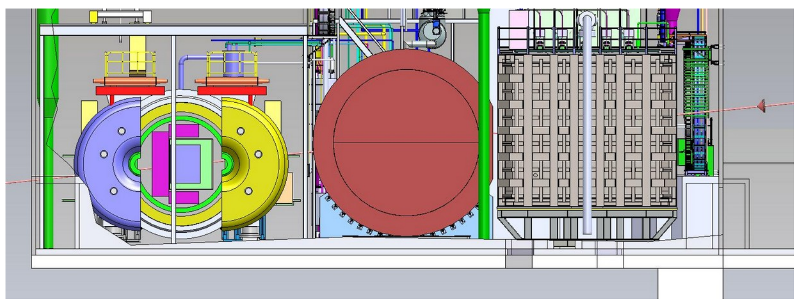


- DUNE is a long-baseline neutrino experiment currently under construction
- DUNE will constrain the three flavor paradigm
  - Will measure δ_{CP} and mass ordering by studying $\nu_\mu \longrightarrow \nu_e$ oscillations

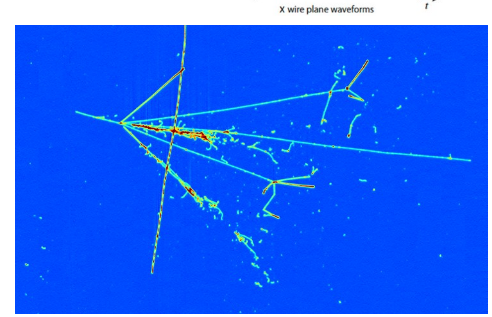




FD:
1300 km baseline
4x17 kton LArTPC

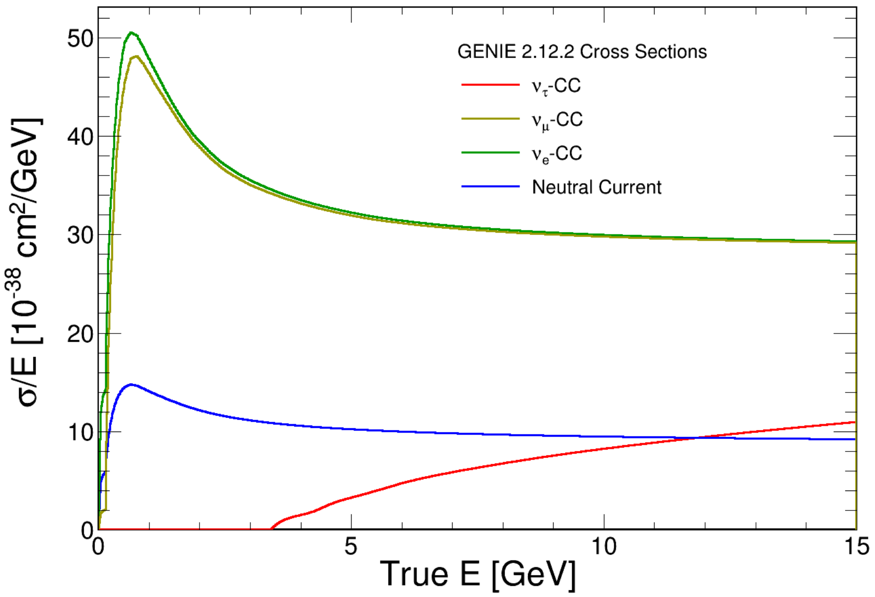


ND:
574 m baseline
Multiple detector system
147 ton LArTPC component



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.

Tau Neutrino Selection



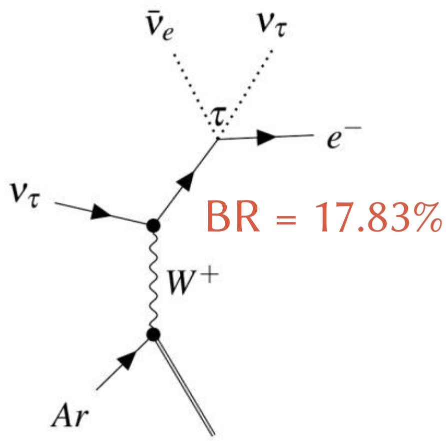
τ^- Decay Mode	Branching Ratio
$\mu^- \bar{\nu}_\mu \nu_\tau$	17.4%
$e^- \bar{\nu}_e \nu_\tau$	17.8%
$\pi^- \nu_\tau$	10.8%
$\pi^- \pi^0 \nu_\tau$	25.5%
$\pi^- 2\pi^0 \nu_\tau$	9.3%
$2\pi^- \pi^0 \nu_\tau$	9.3%
$2\pi^- \pi^+ \pi^0 \nu_\tau$	4.6%

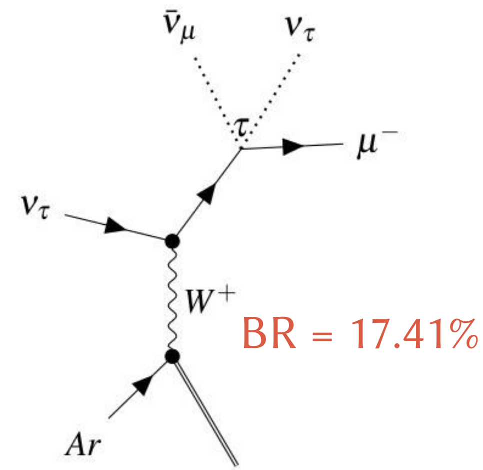
- ν_τ are difficult to select
  - Kinematically forbidden at typical beam energy
    - Even above threshold, cross sections are suppressed
  - τ-leptons have many decay modes
    - Mimic either ν_e-CC, ν_μ-CC, or NC events
- Consider truth level studies of atmospheric ν_τ

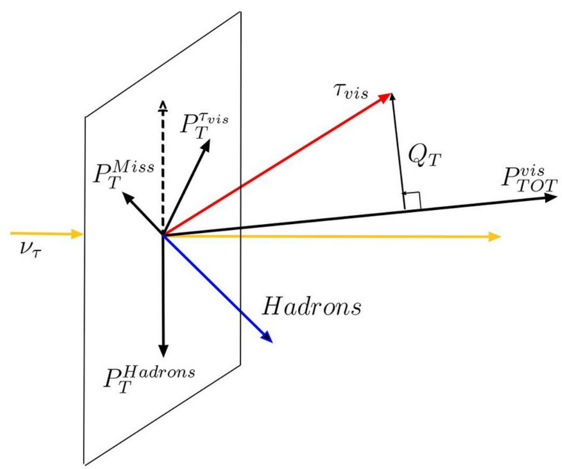
  [J. Conrad, A. de Gouvea, S. Shalgar, J. Spitz, PRD 82, 093012 (2010)]
  - Select ν_τ with hadronically decaying τ-lepton
  - Assume near perfect e/γ and μ/π discrimination
  - Simple kinematic cuts on $\pi^\pm$ yield excellent ν_τ-CC/NC discrimination
- Optimistic assumptions suggest:
  - ~30% flat signal efficiency
  - 0.5% NC background efficiency
- Is something close to this achievable?

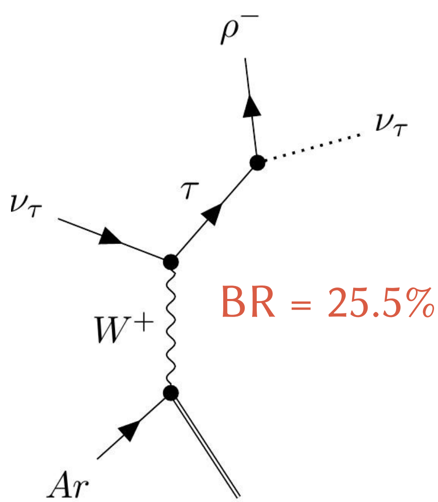
Transverse Kinematic Variable Approach

- In ν_τ-CC interactions, have same particle content as ν_e-CC, ν_μ-CC, or NC events
  - Angular correlations due to missing neutrino(s) from τ-lepton decay is the key signature
- Transverse kinematic variable approach studied by Miriama Rajaoalisoa and Thomas Kosc
  - See their talks for more details
- Look for ν_τ-CC events with τ-leptons decaying into e, μ, and ρ-mesons
- Use a BDT trained on transverse kinematic variables to distinguish signal from background
  - Input variables from GENIE simulation smeared by expected reconstruction performance



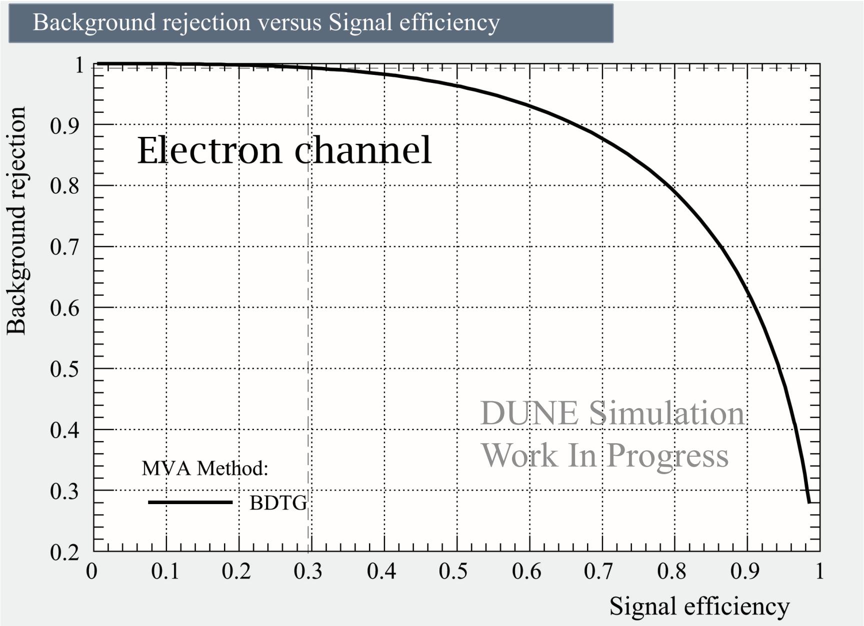


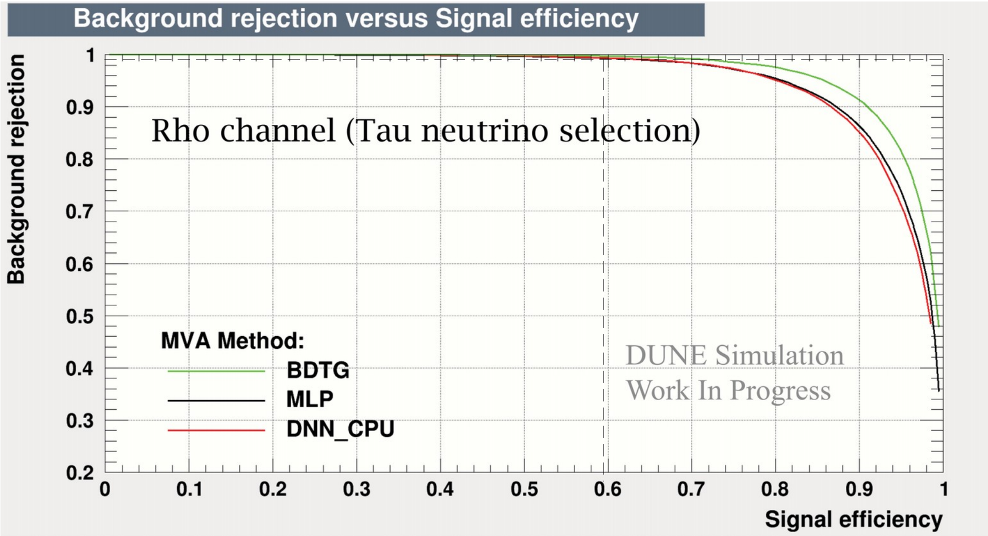


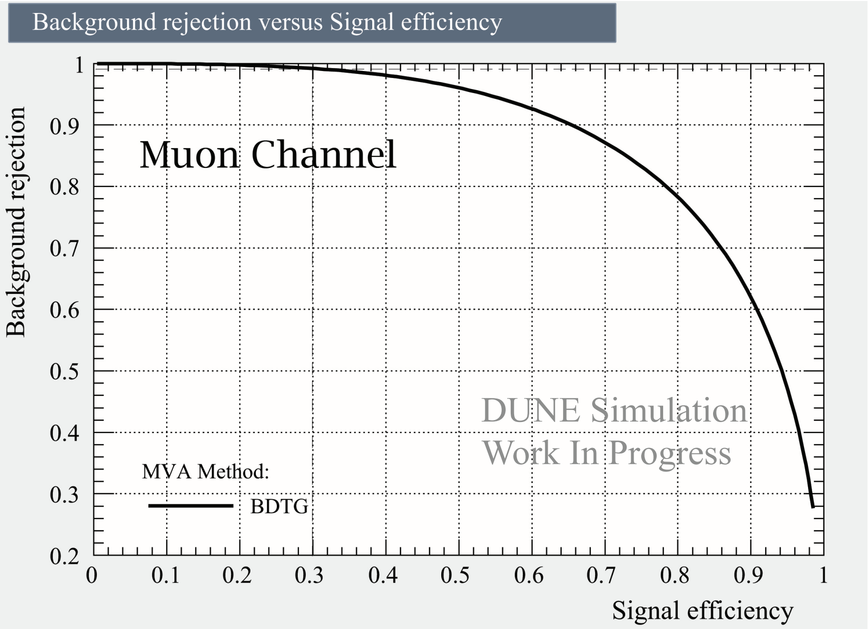


Transverse Kinematic Variable Approach

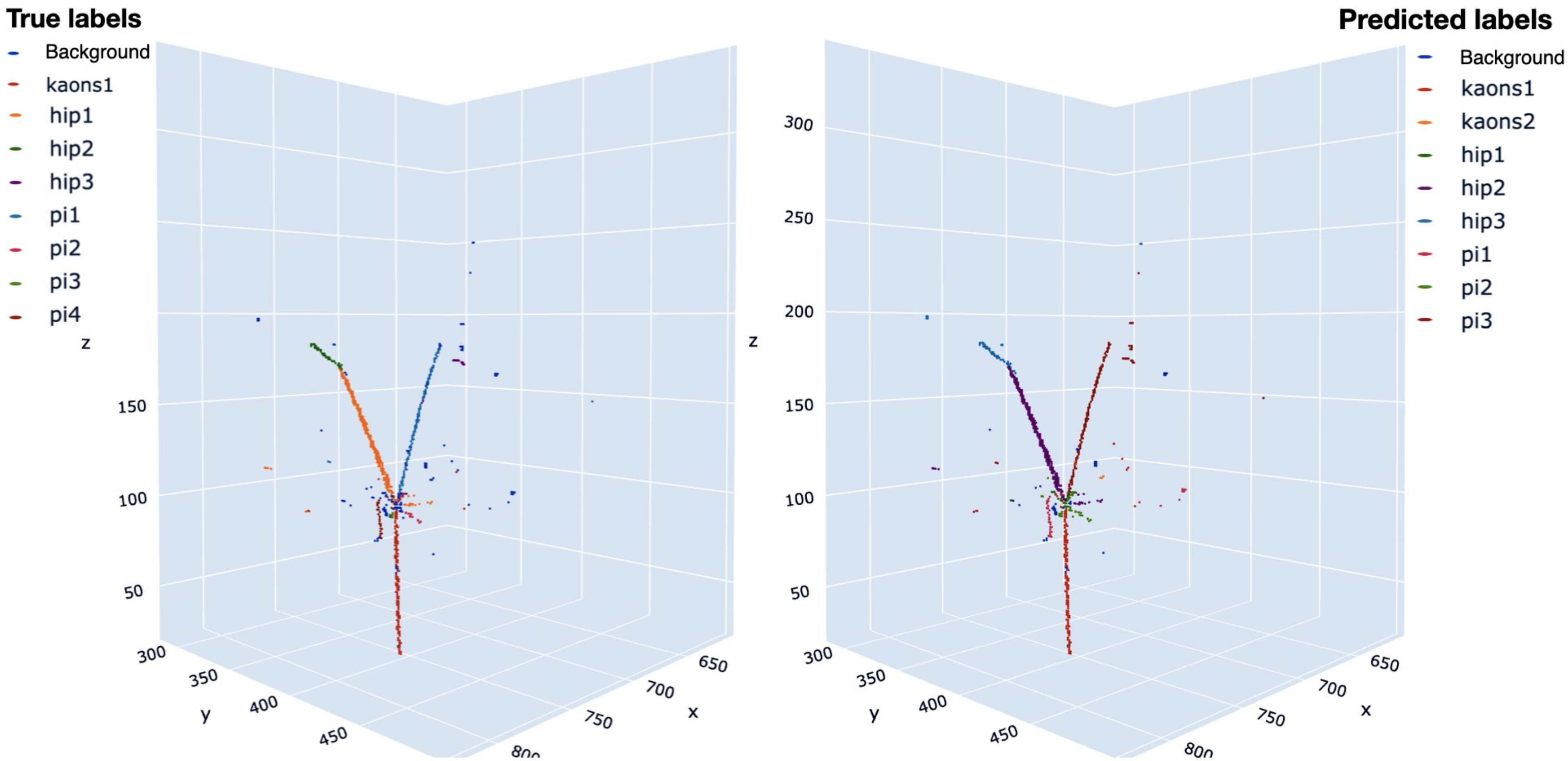
- Performance in three channels comparable to optimistic assumptions
  - For assumed background rejection, signal efficiency ≥ 30%
- Caveats:
  - These are for beam neutrinos
    - Incoming direction is necessary to define transverse plane
  - Assumes excellent particle identification capabilities
  - Does not yet account for π and a_1 hadronic decay modes





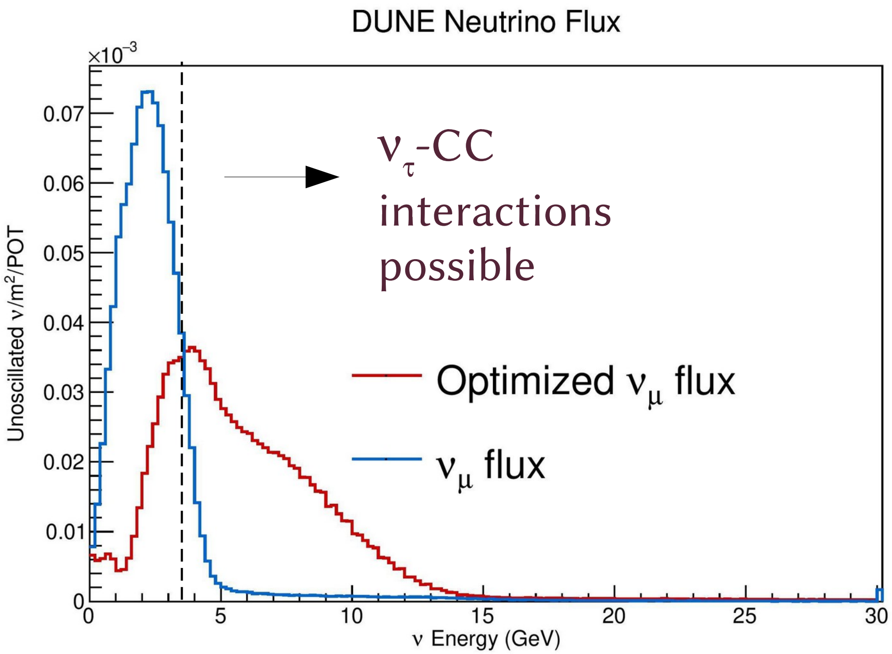


Particle Identification



- Many machine learning techniques are being developed to utilize full power of LArTPC technology
- Panoptic segmentation approach convolutional neural networks to label individual space-points and cluster them into particles
- Still under development, but currently achieving > 80% accuracy in classifying space-points

Beam Flux

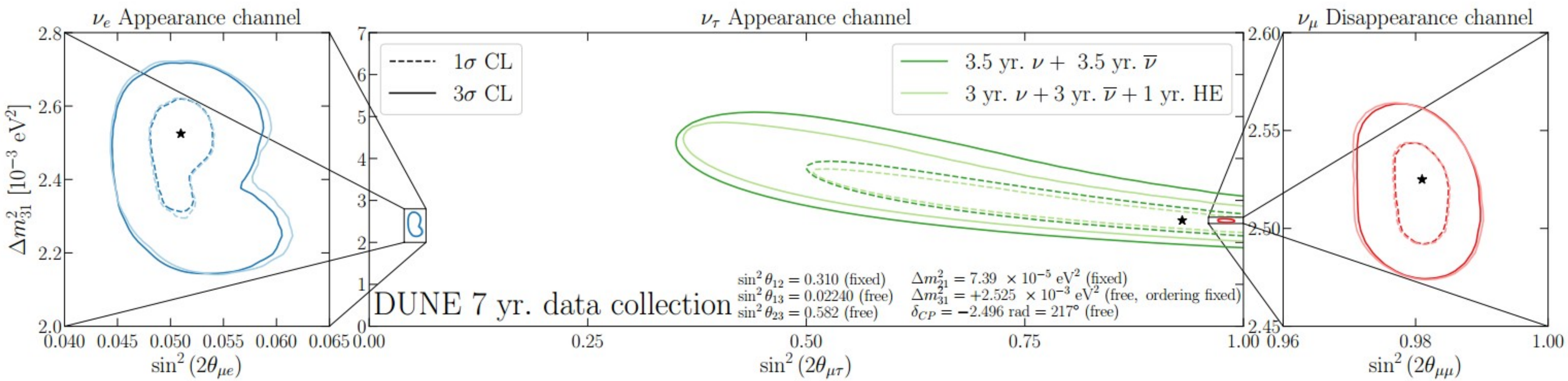


Expected counts/year (1.2 MW beam):

~**130** ν_τ in CP-optimized neutrino mode
~**30** $\bar{\nu}_\tau$ in CP-optimized antineutrino mode
~**800** ν_τ in Tau-optimized neutrino mode

- Given these results, optimistic assumptions are a good starting point
- Before considering atmospherics, let's consider the beam sample
  - CP-optimized beam
    - Low energy
    - Default starting configuration
  - Tau-optimized beam
    - Higher energy
    - Possible configuration after CP program has completed

Model-Independent Non-Unitarity



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

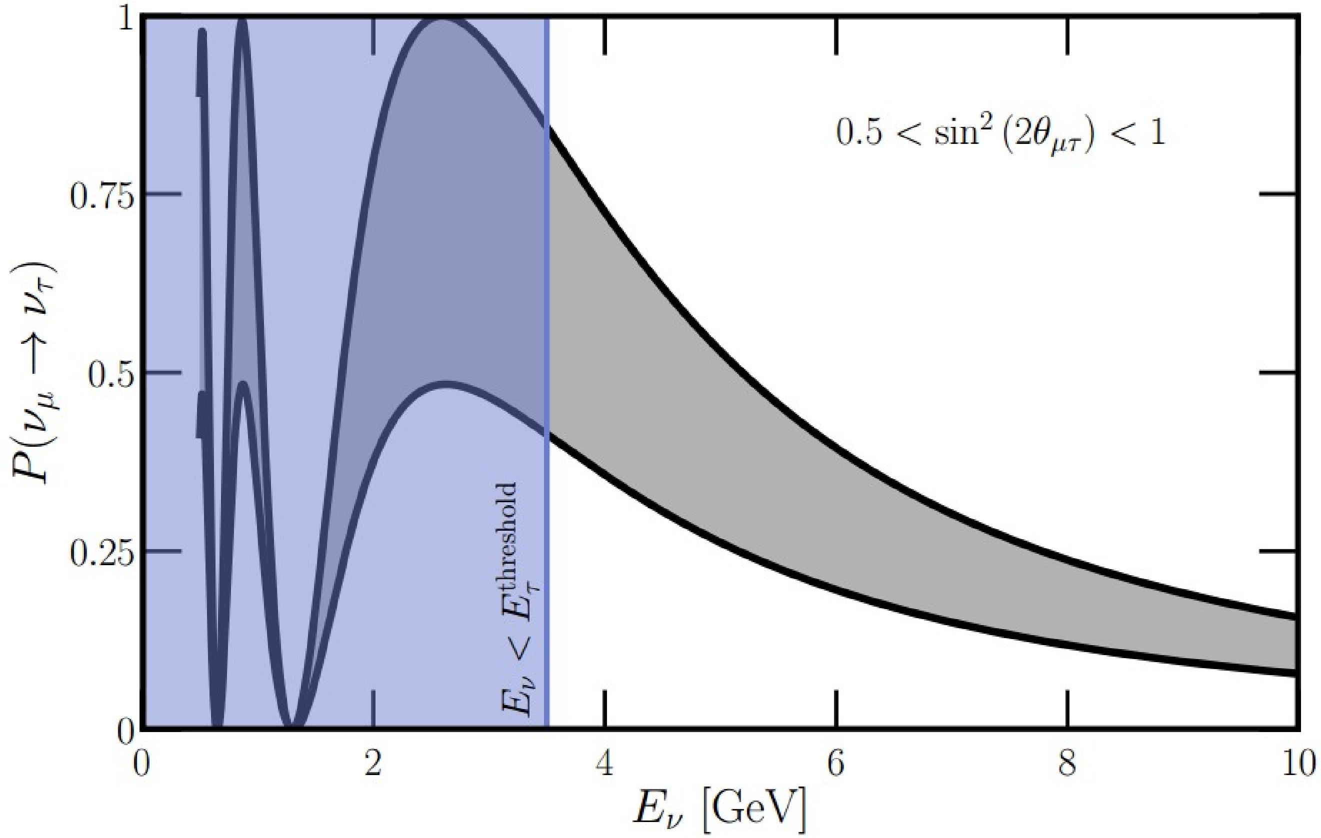
- Independent constraints on effective mixing angles from each channel provide model independent test of unitarity:

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

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

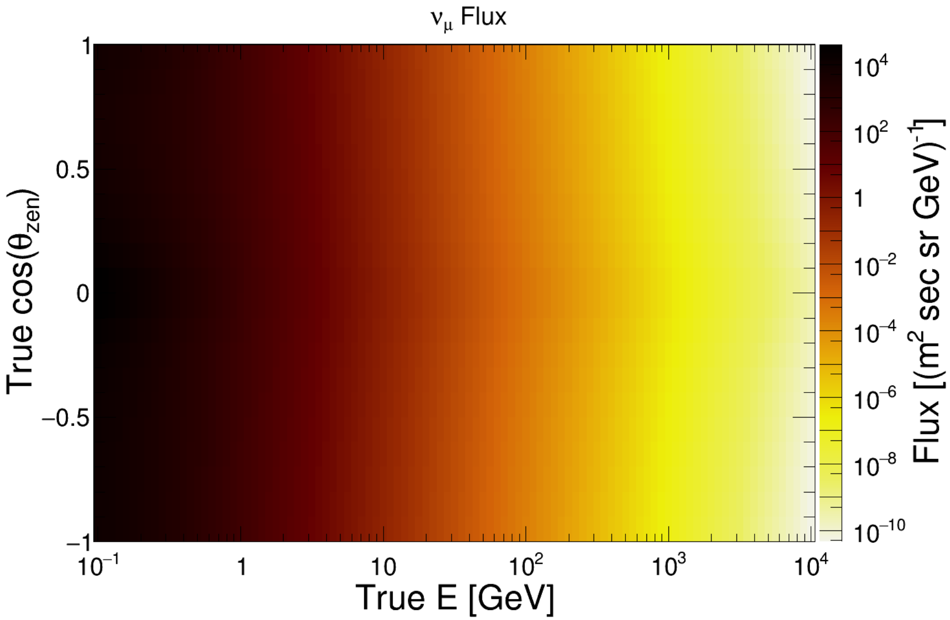
Limitations of the Beam Sample

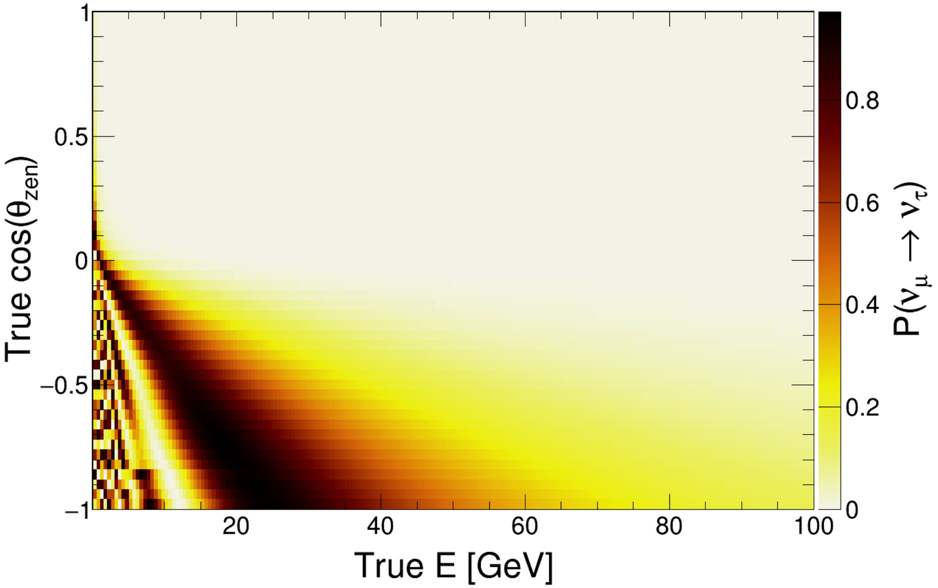
de Gouvea, Kelly, Stenico, Pasquini, PRD 100, 016004 (2019)



- Since the far detector is at a fixed distance from the neutrino production point, 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 Predictions

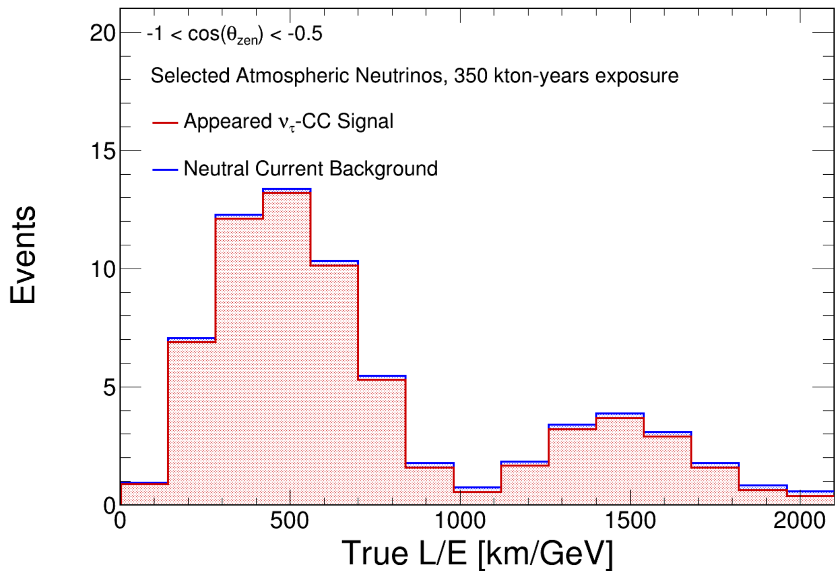




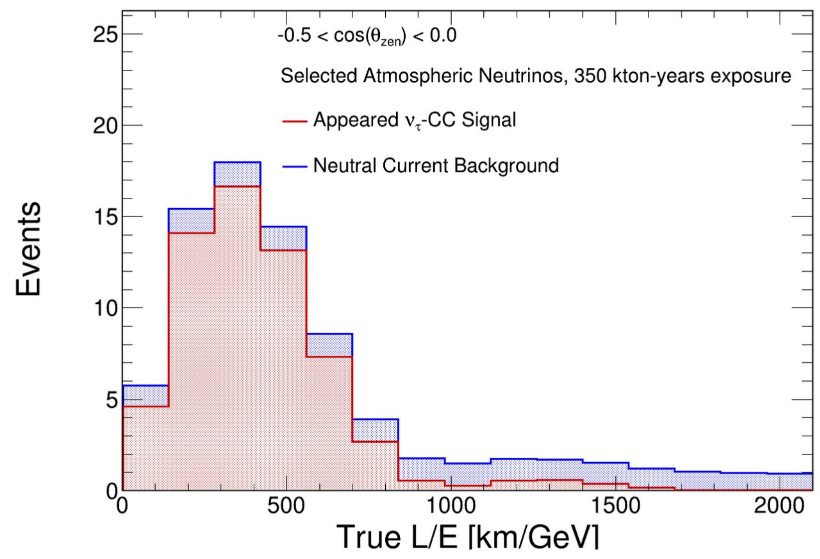
- Build atmospheric predictions in true cosθ vs true E
- Use Honda flux prediction for Homestake
- Compute oscillograms using OscProb calculator with 15 layer PREM model
- Use GENIE 2.12.2 cross section predictions
- Fit in bins of $\cos\theta_{zen}$ and L/E

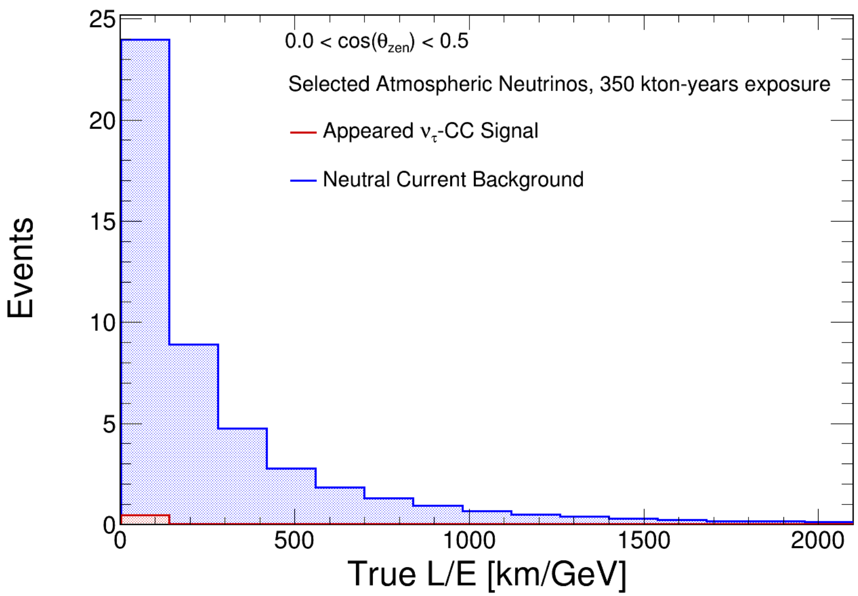
Expect ~**1** ν_τ/kton-year

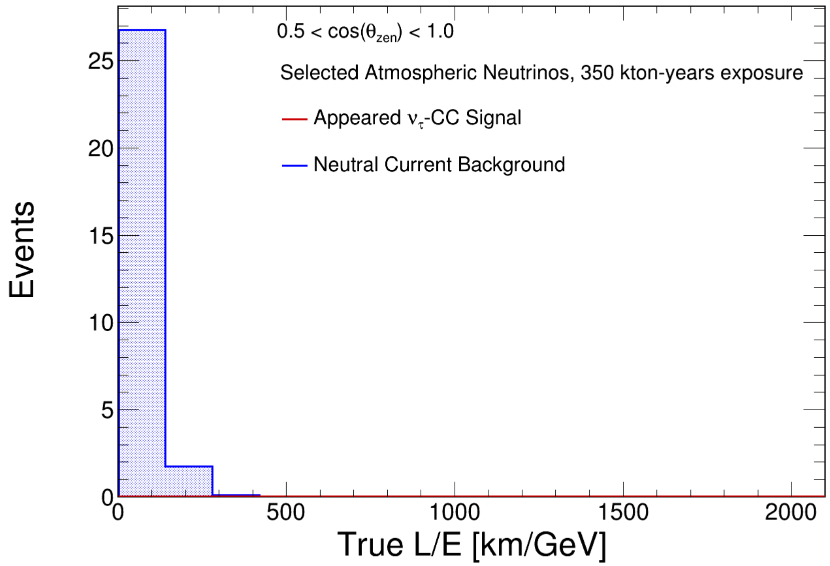
True Atmospheric Spectra



Clear 1st and 2nd oscillation maxima in true L/E

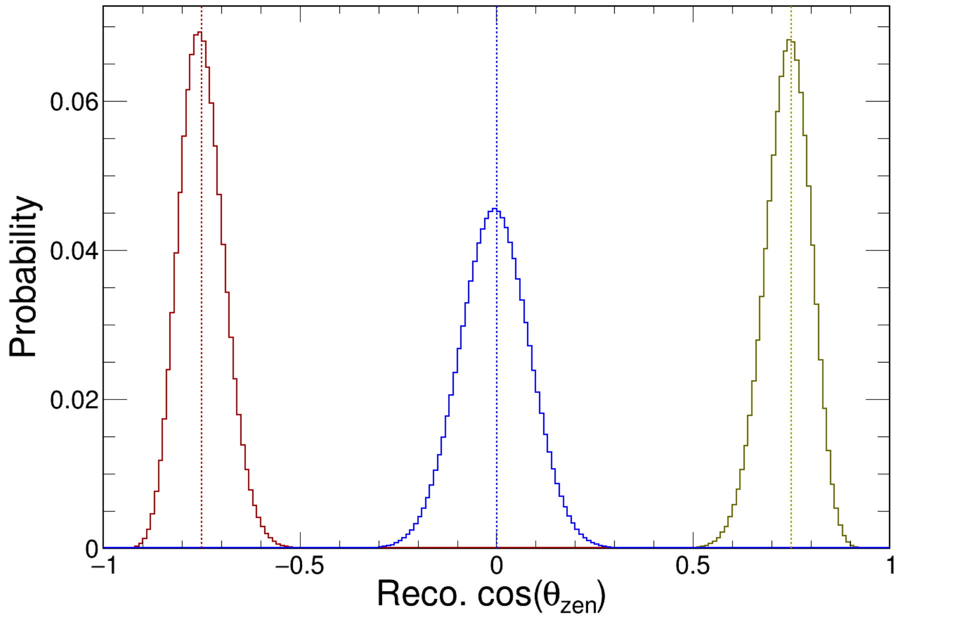


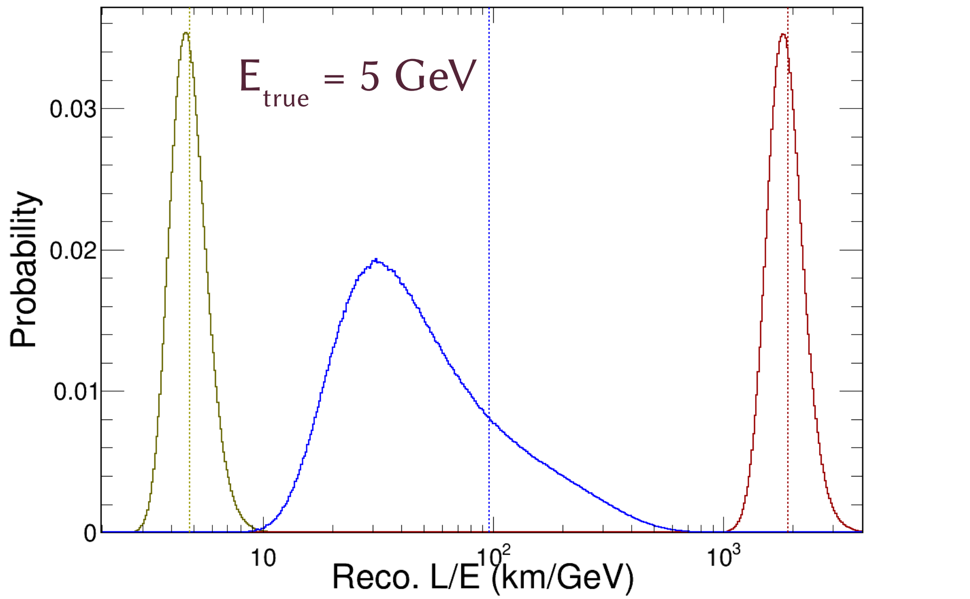




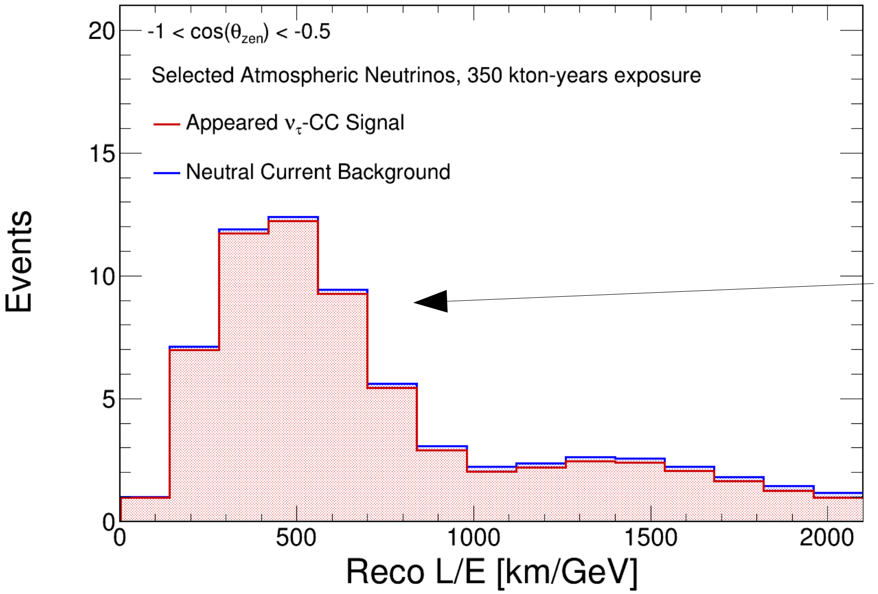
Energy and Angular Resolution

- Performed MC study of energy and angular resolution using visible particles in simulated ν_τ-CC and NC events
- Calorimetric energy resolution
  - ~17% resolution for both ν_τ-CC and NC
  - On average, 53% of ν_τ-CC energy is visible, while 46% 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 and von Mises-Fisher for $\cos\theta_{zen}$

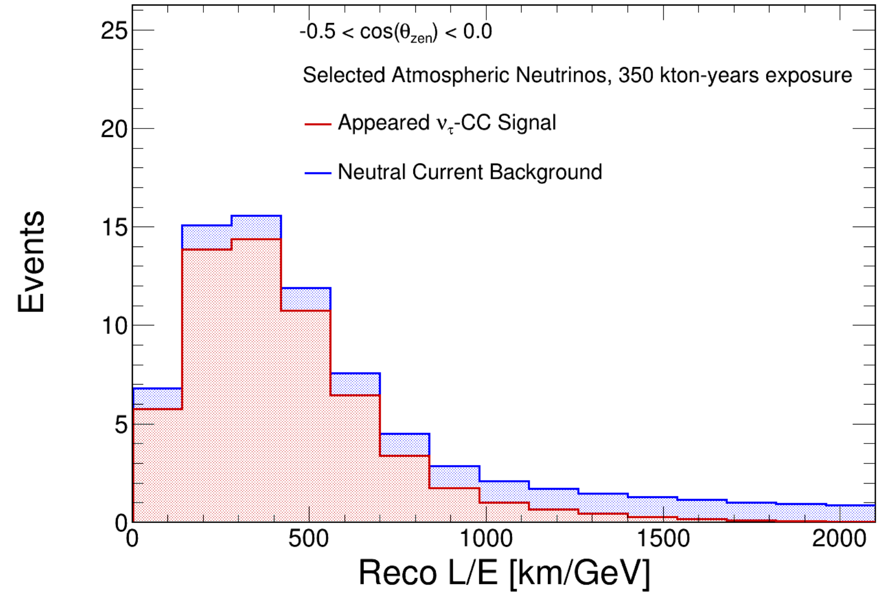


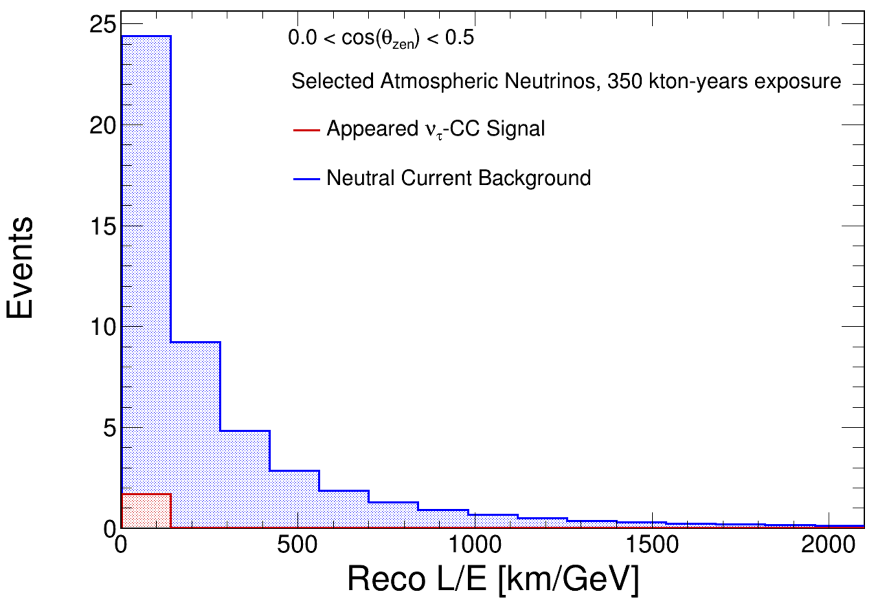


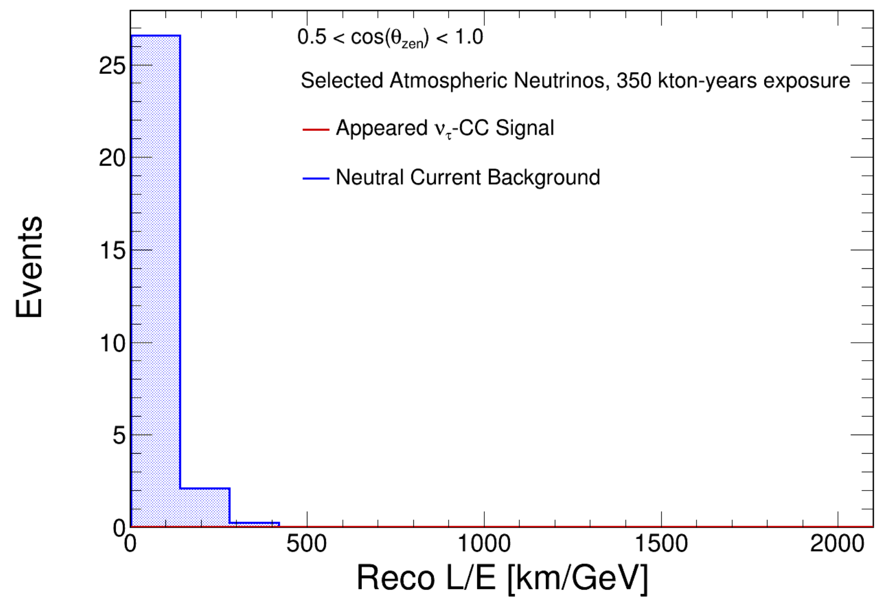
Reconstructed Atmospheric Spectra



Clear 1st oscillation maximum after smearing

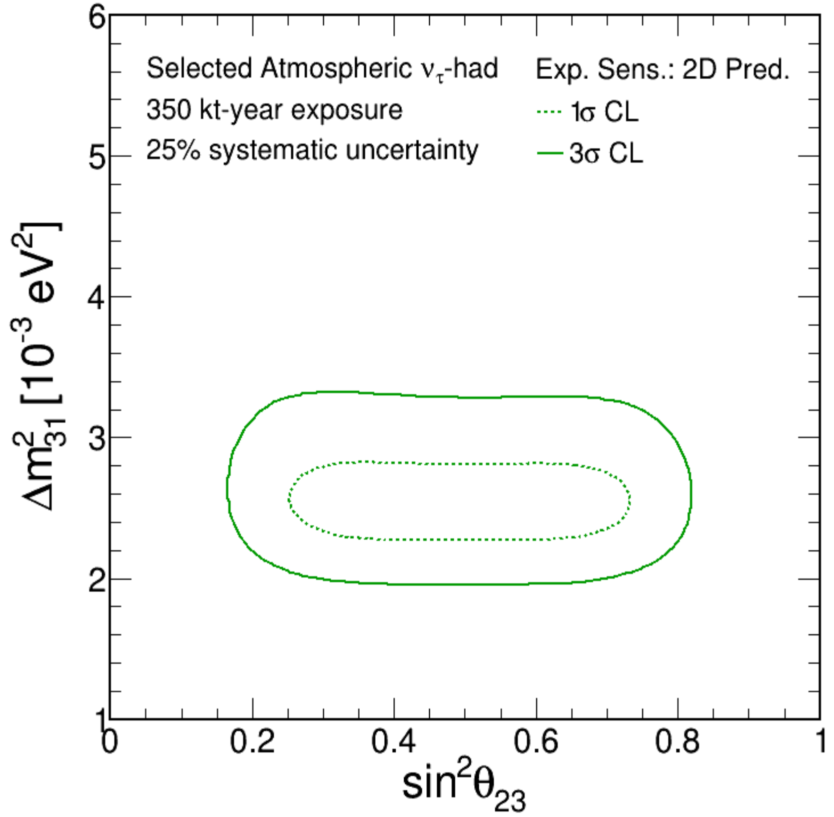






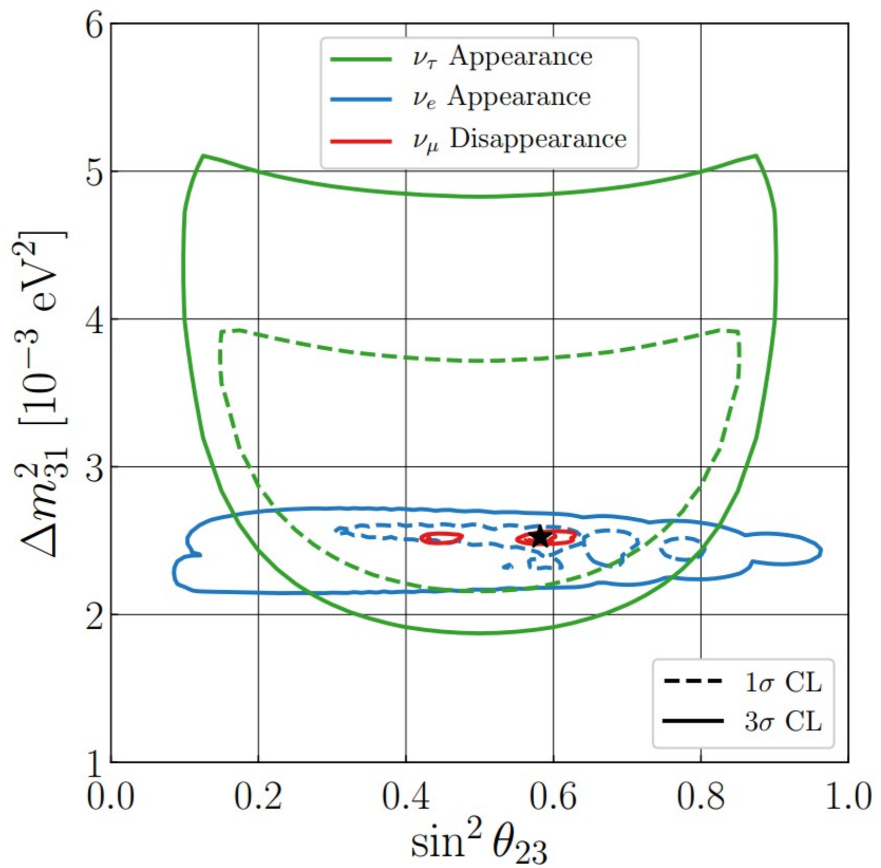
Atmospheric Parameters

Atmospheric sample



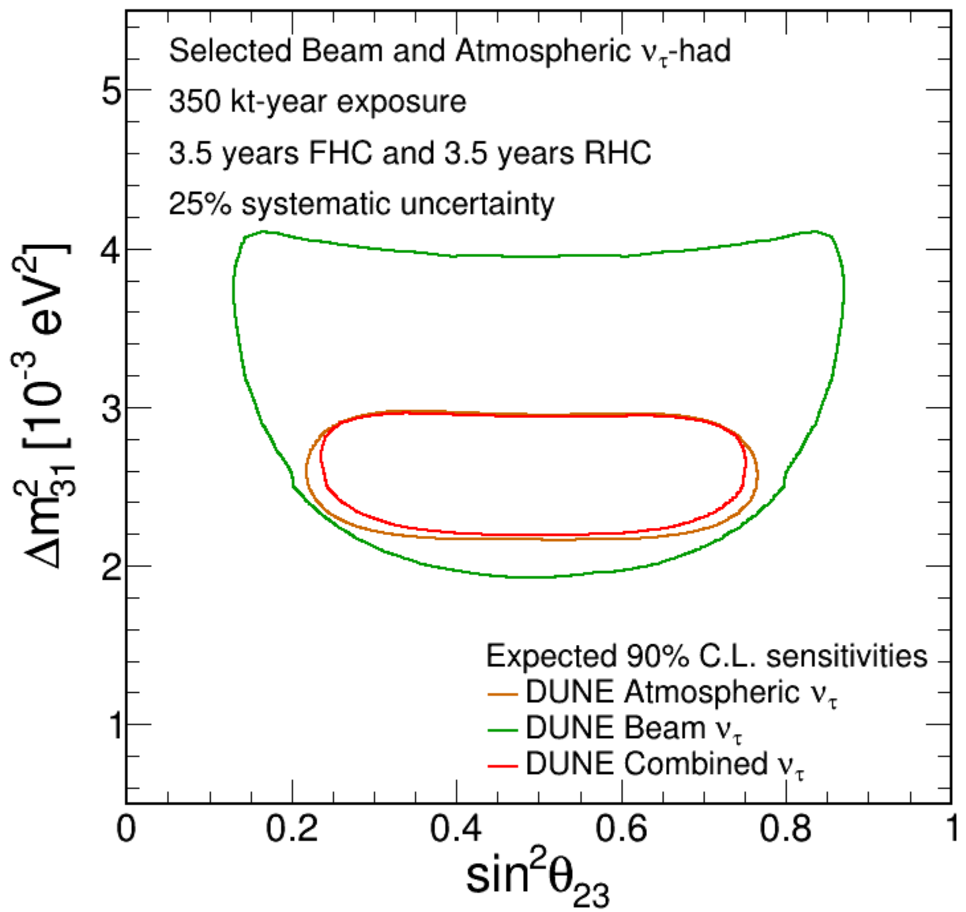
Assume a 25% normalization uncertainty

Beam sample



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

Combined Beam and Atmospheric Sensitivity

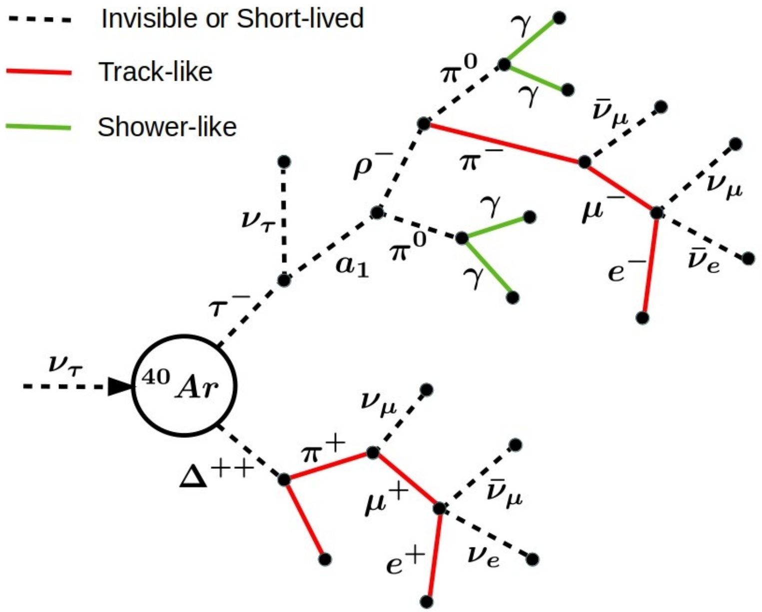


Beam likelihood calculator courtesy of de Gouvea, Kelly, Stenico, Pasquini

- 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 and shed light on possible BSM scenarios
  - Atmospherics have a favorable L/E, but beam has defined direction and a near detector for systematic uncertainty reduction

Conclusions

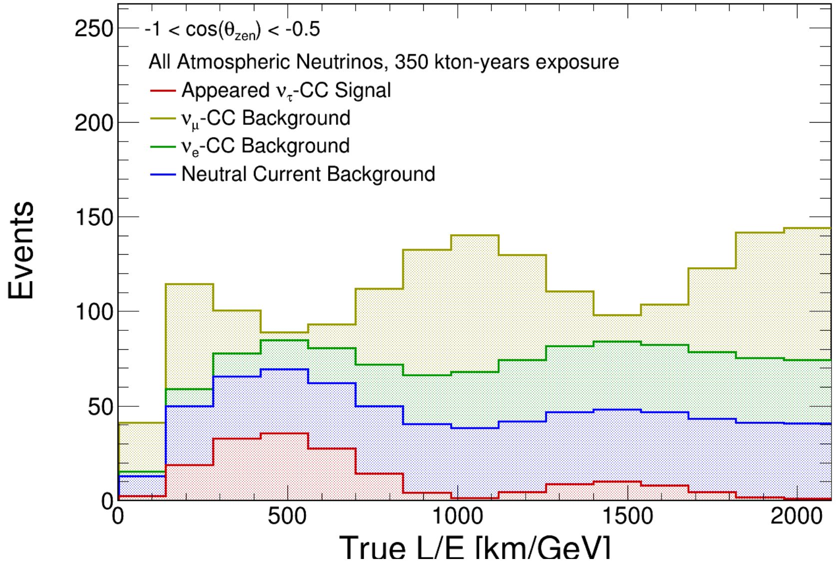
- DUNE is uniquely capable of providing a high-purity, high-statistics sample of beam and atmospheric tau neutrinos
- Tau neutrinos are challenging to select and reconstruct, but they provide a needed independent check of the three-flavor model
- Performance of selection using transverse plane kinematics is comparable to optimistic assumptions
- Atmospheric tau neutrinos provide a high-purity window into 1st atmospheric oscillation maximum
- With excellent results from truth-level analyses, work is now moving to reproduce the results with the full DUNE simulation and reconstruction chain

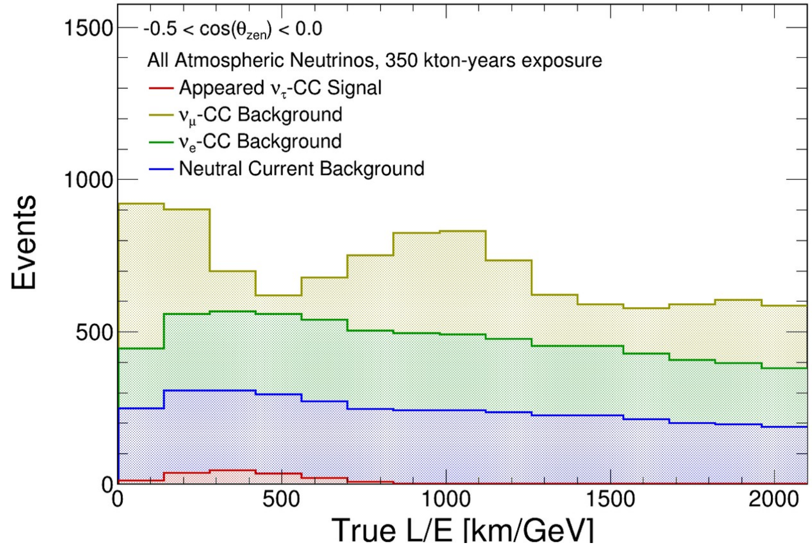


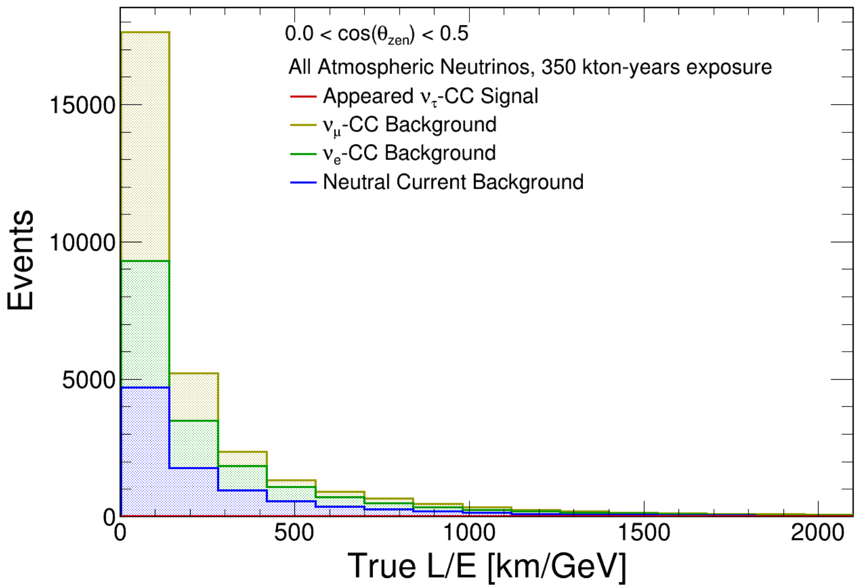
Thank you!

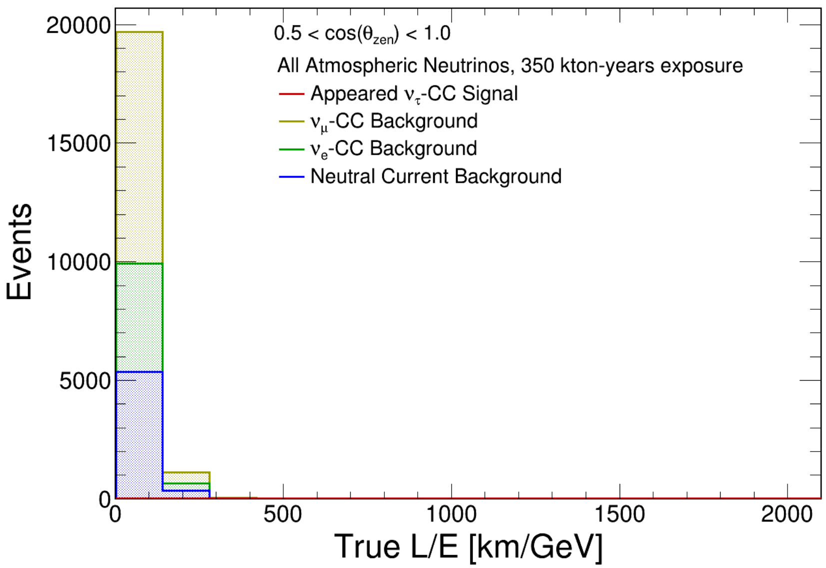
Backup Slides

True Atmospheric Spectra, No Selection

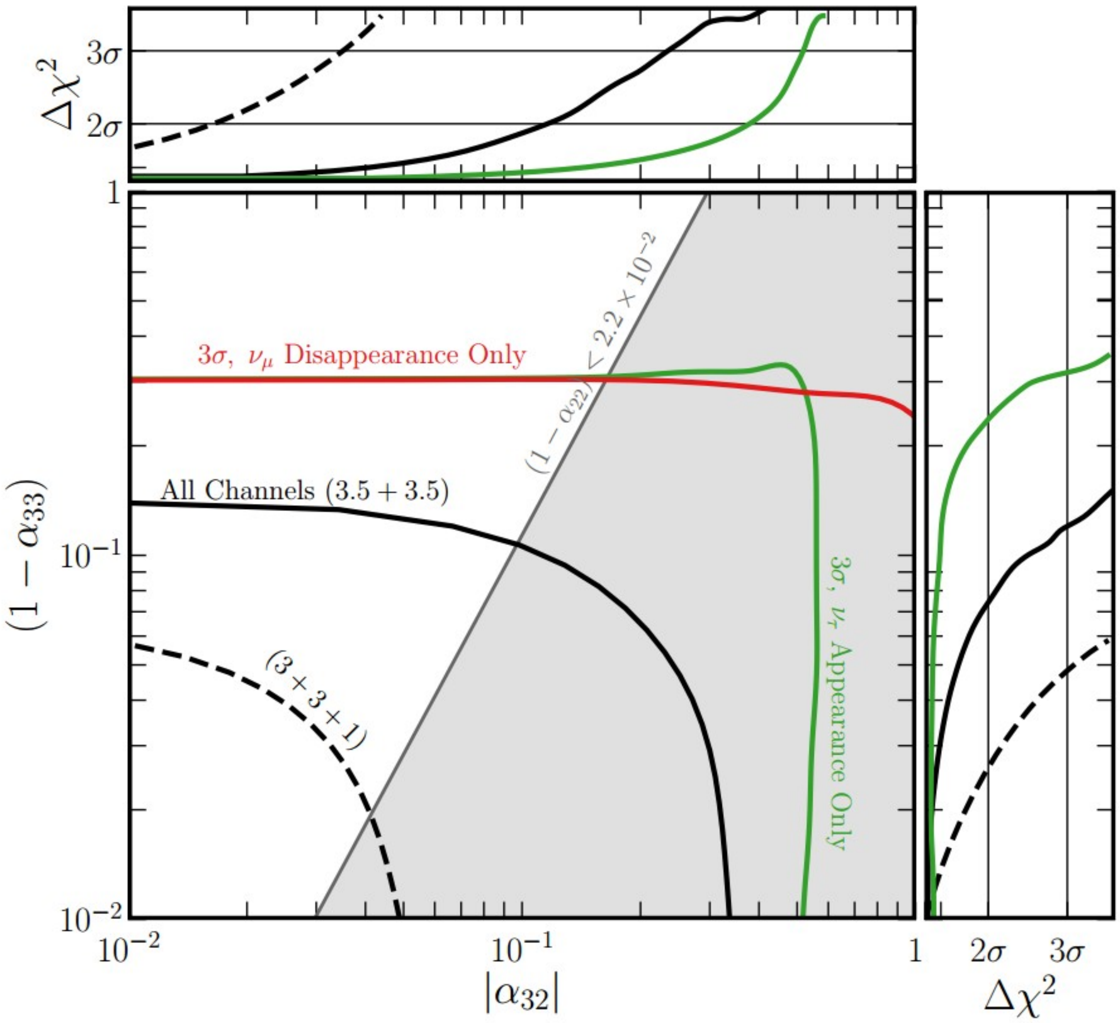








Parameterized Non-Unitarity



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