DEEP UNDERGROUND NEUTRINO EXPERIMENT

UNIVERSITY OF Cincinnati

Snowmass Planning

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Snowmass LOIs

- At our last meeting, we put together a plan for several LOIs. We submitted three LOIs (that I am aware of)
  - Tau neutrino physics
  - Atmospheric tau neutrino appearance at DUNE
  - Tau neutrino reconstruction at DUNE
- I used Gordon Watts's scatter plot tool to find other LOIs on tau neutrinos
  - About 20 in total
    - Tau neutrinos from colliders (FASER)
    - Beam dump neutrinos (SHiP)
    - High energy astrophysical tau neutrinos (IceCube-Gen2)
    - Non-unitarity and BSM long-baseline oscillations (DUNE, IceCube-Upgrade, SK, HK)
- There are related efforts that I didn't find covered in an LOI
  - Measuring relevant production cross-sections (DsTau)
- Overall, I think there is a relatively large potential community that it might be worth reaching out to

Possible White Paper

- Tau neutrinos have a sizable interested community, but they aren't a priority of any existing Snowmass group
  - If we want to impact the process, I think we need to take the initiative to write a white paper
- Should we write a white paper specifically for DUNE, or should we try to pull together a broader effort?
  - If we want to pursue building a broader community, should we have a workshop to flesh out topics and find common ground?

Potential Topics

- Oscillation physics
  - Atmospheric parameters
  - Non-unitarity
  - Sterile neutrinos
- Cross-section physics
  - QE pseudoscalar form factor
  - F_4 and F_5 DIS structure functions
- Simulation needs
  - Improved tau decay models (Pythia or TAUOLA)
  - Heavy flavor modeling for improved intrinsic tau neutrino background
    - Use experience from heavy flavor experiments to model charm production in beams and atmospherics
- Reconstruction needs
  - Machine learning methods
  - Collider-inspired techniques
  - Transverse plane kinematics techniques
- Sources
  - Atmospheric neutrinos
  - LBL beams
  - Forward neutrinos at colliders
  - Beam dumps
  - High energy astrophysical neutrinos
- Reconstruction needs
  - Machine learning methods
    - CNNs
    - GNNs
  - Collider-inspired techniques
  - Transverse plane kinematics techniques
- Experiments
  - DUNE
  - IceCube-Upgrade
    - Also IceCube-Gen2 if we include high energy astrophysical neutrinos
  - SK/HK
  - DsTau
  - FASER
  - SHiP

Possible Tasks Leading to White Paper

- Simulation
  - Pass tau decays to Pythia8 or TAUOLA
  - Modify GENIE to allow for changes to F_P, F_4, and F_5
- Reconstruction
  - Compare selectors in development for beam
  - Develop a selector for the atmospheric sample
- Analysis
  - Develop a more realistic framework for analyzing low energy beam, high energy beam, and atmospherics
    - Some efforts ongoing to build CAFAna analyses
  - Produce semi-realistic sensitivities

Thoughts?

(slides in backup covering some topics in more detail)

Cross-Section Studies

Measuring QE pseudoscalar form factor

arXiv:2008.03527

$$\frac{d\sigma}{dQ^2}(Q^2,E_\nu) = \frac{c_{qq'}^2}{16\pi}\frac{M^2}{E_\nu^2}\left[(\tau + r^2)\,A(Q^2) - \nu B(Q^2) + \frac{\nu^2}{1+\tau}C(Q^2)\right]$$

$$A = \tau\left(G_M^V\right)^2 - \left(G_E^V\right)^2 + (1+\tau)F_A^2 - r^2\left(\left(G_M^V\right)^2 + F_A^2 - 4\tau F_P^2 + 4F_AF_P\right),$$
$$B = 4\eta\tau F_A G_M^V,$$
$$C = \tau\left(G_M^V\right)^2 + \left(G_E^V\right)^2 + (1+\tau)F_A^2,$$

$$r = m_l/2M \qquad \tau = Q^2/(4M^2) \qquad \nu = E_\nu/M - \tau - r^2$$

F_P dependent part of cross section is more significant in tau neutrino interactions

Probe high Q^2 QE interaction near threshold

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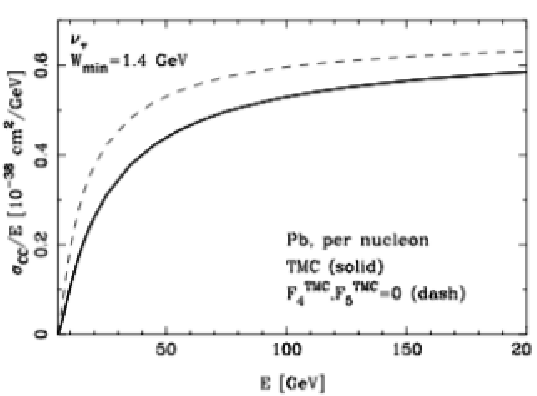
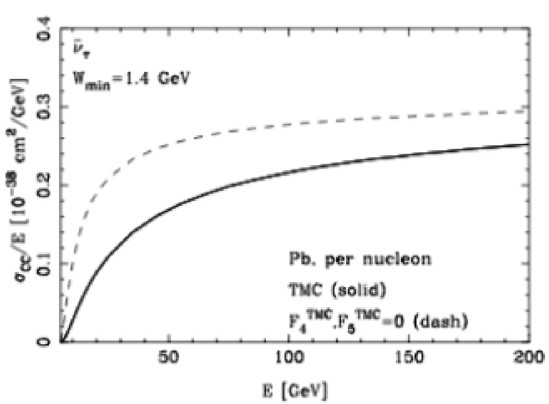
arXiv:1504.04956

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



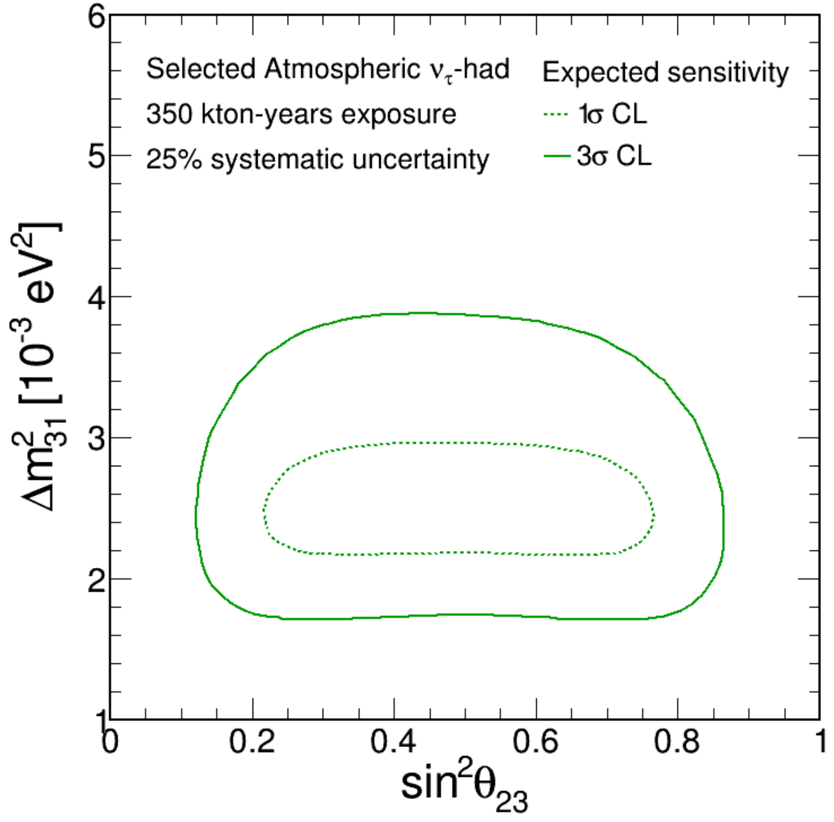


Structure function F_4 and F_5 are suppressed for electron and muon neutrinos, but they are accessible for tau neutrinos

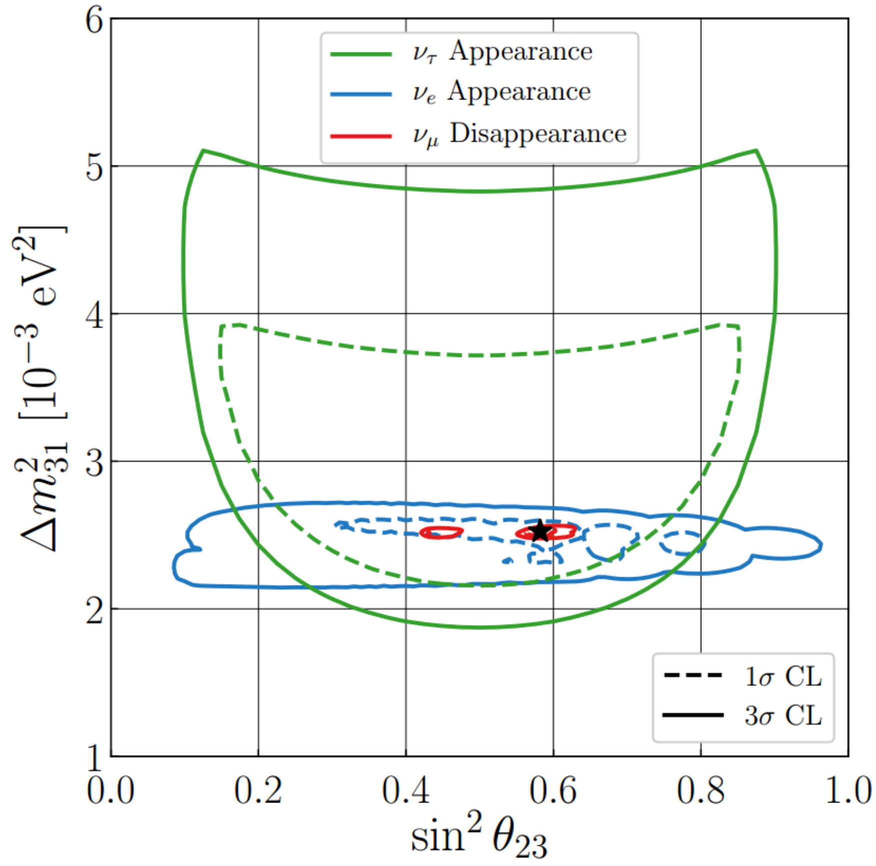
The SHiP technical proposal showed large modifications to the tau neutrino DIS cross section if those structure functions are zero

Atmospheric Parameters

Atmospheric sample



Beam sample



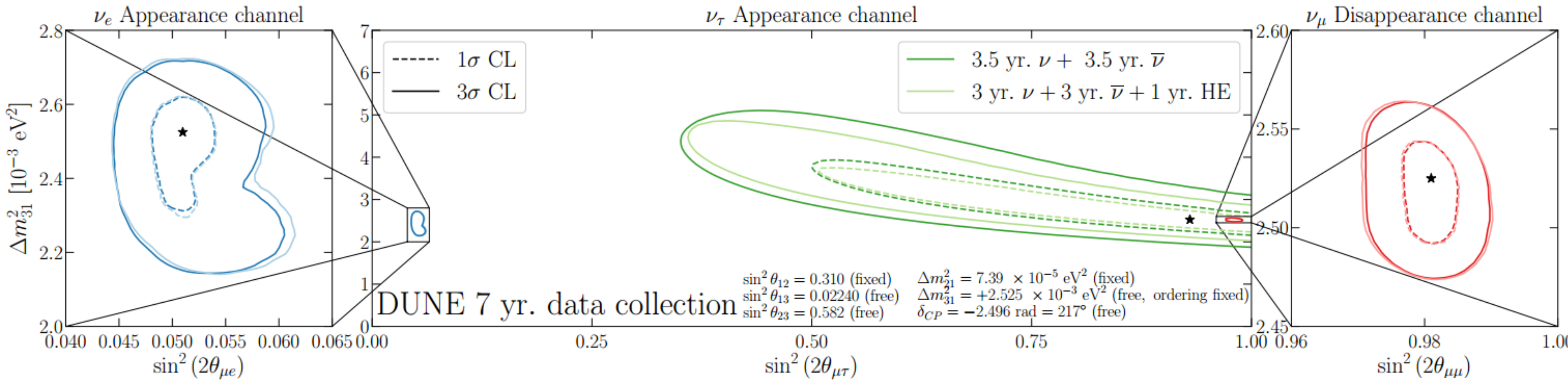
Assume a 25% normalization uncertainty

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

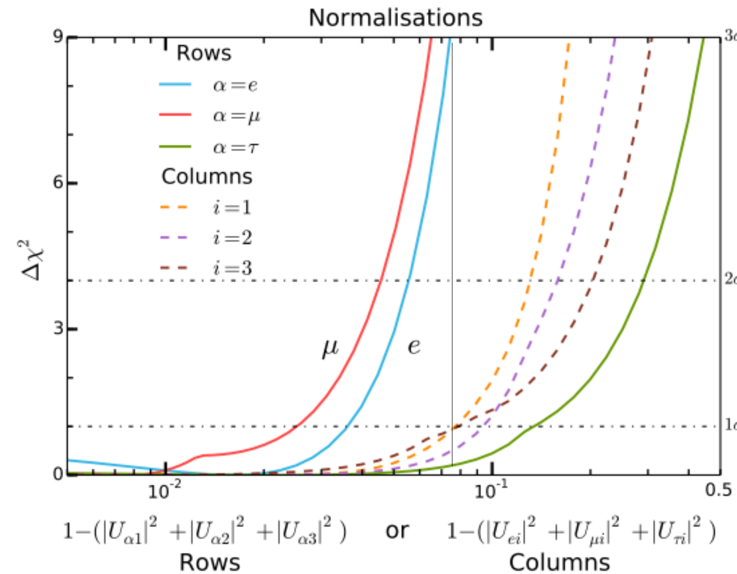
Combined Beam and Atmospheric Sample

- Assume 25% normalization systematics for atmospherics, FHC beam, and RHC beam
  - Treat as three uncorrelated errors
- Would like to understand better what limits reach in $\sin^2\theta_{23}$

Effective Angles

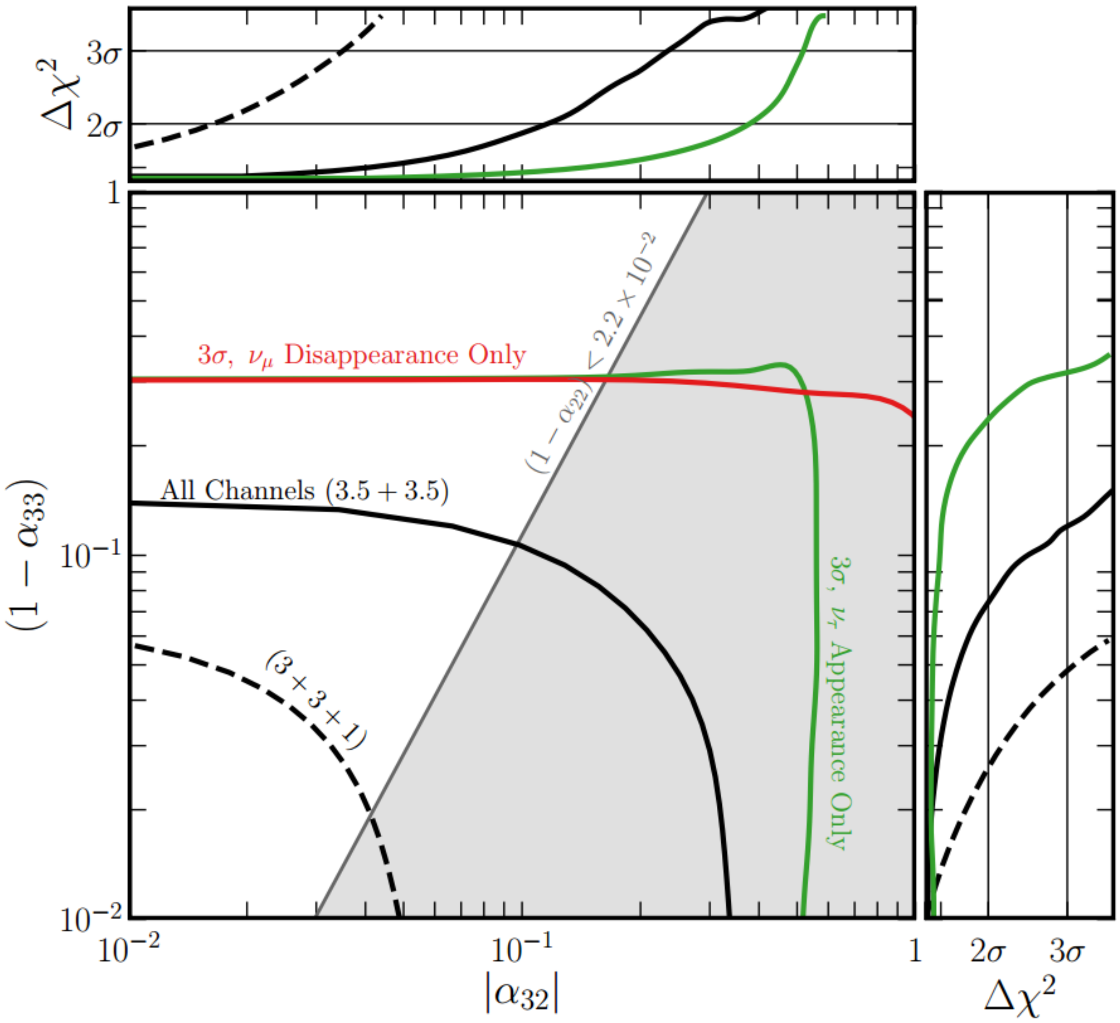


- Consider independent constraints on effective mixing angles from each channel
- Tau neutrino constraint is much weaker than the other two, but these aren't independent
  - The sum of two must equal the others, assuming unitarity
- Model independent unitarity constraint using only DUNE data should be better than the Parke constraint derived from all other neutrino data
- The 3+3+1 configuration is not significantly better than the 3.5 + 3.5 configuration



$$|U_{e3}|^2 + |U_{\mu 3}|^2 + |U_{\tau 3}|^2 = 1^{+0.05}_{-0.06}\ (1\ \sigma)\ [\text{or}\ |U_{e3}|^2 + |U_{\mu 3}|^2 + |U_{\tau 3}|^2 = 1^{+0.13}_{-0.17}\ (3\ \sigma)]$$

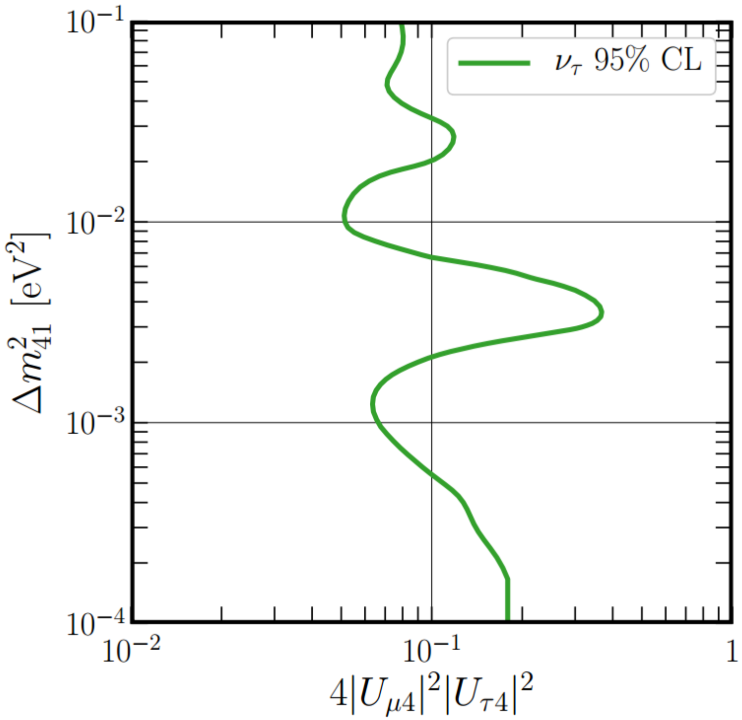
Non-Unitarity

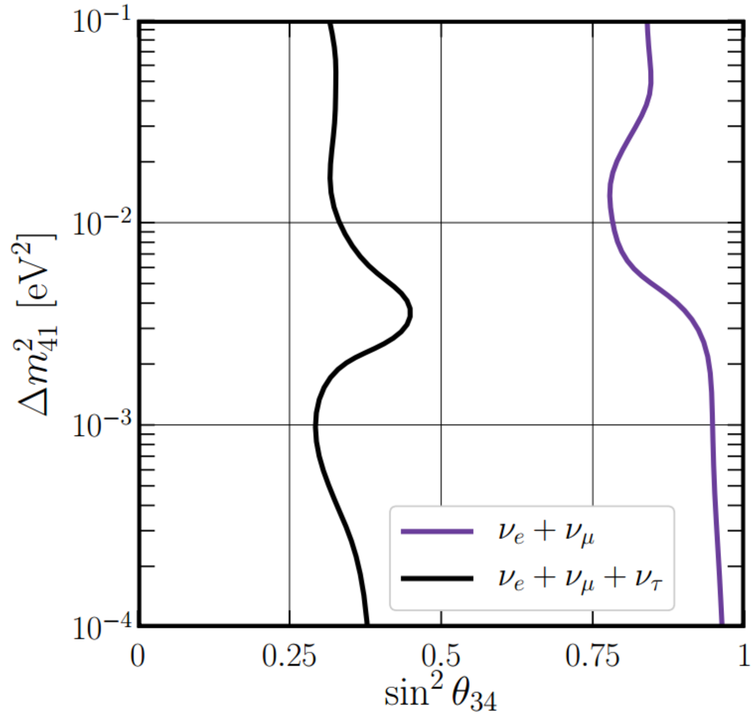


$$U \to NU = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U$$

- Can also constrain non-unitarity using the above 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

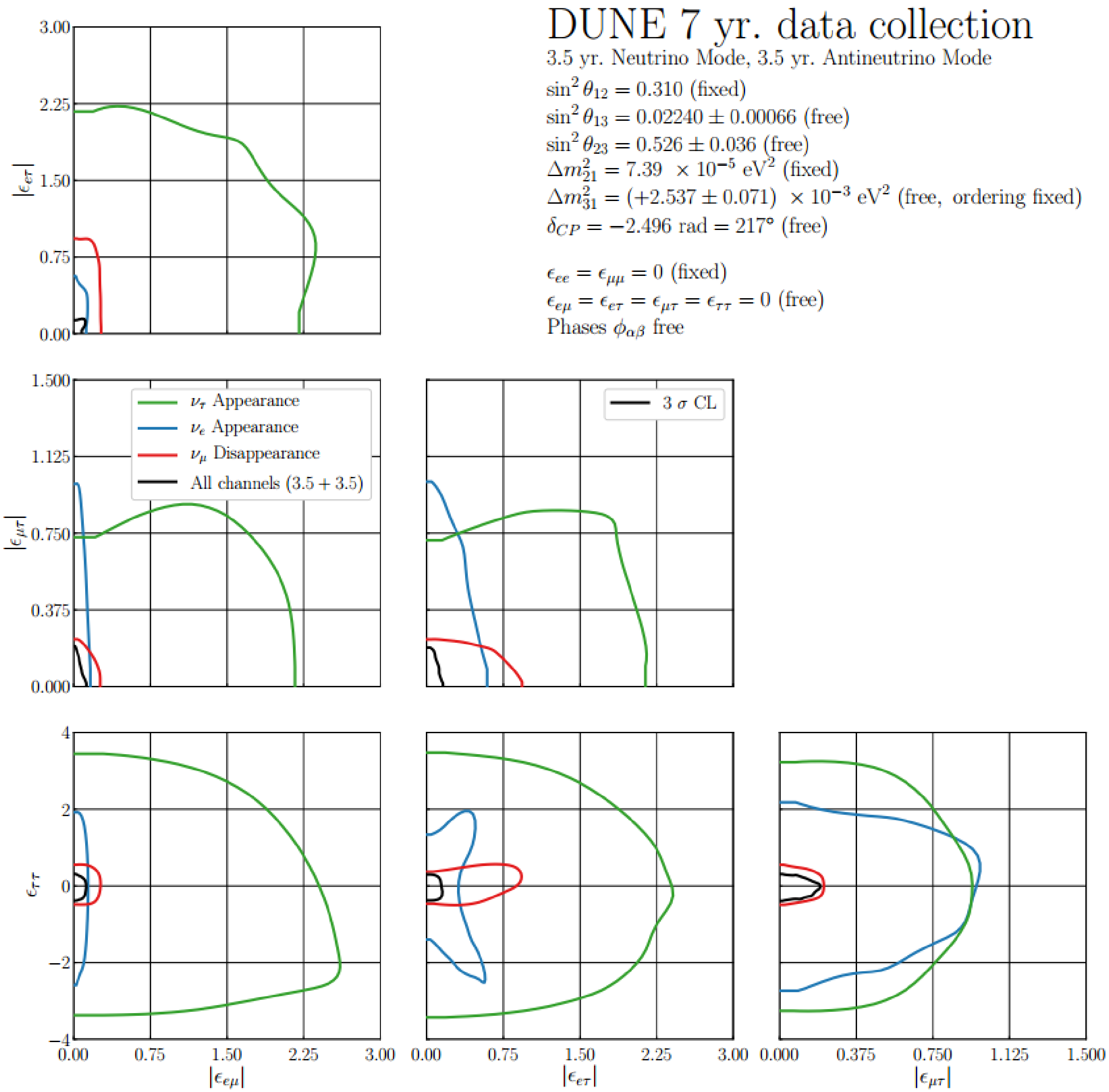
3+1 Model





- Tau neutrino data provides constraints on $|U_{\tau 4}|^2$ even in the case where $|U_{\mu 4}|^2 \longrightarrow 0$
- May be worth studying how this combines with the NC analysis

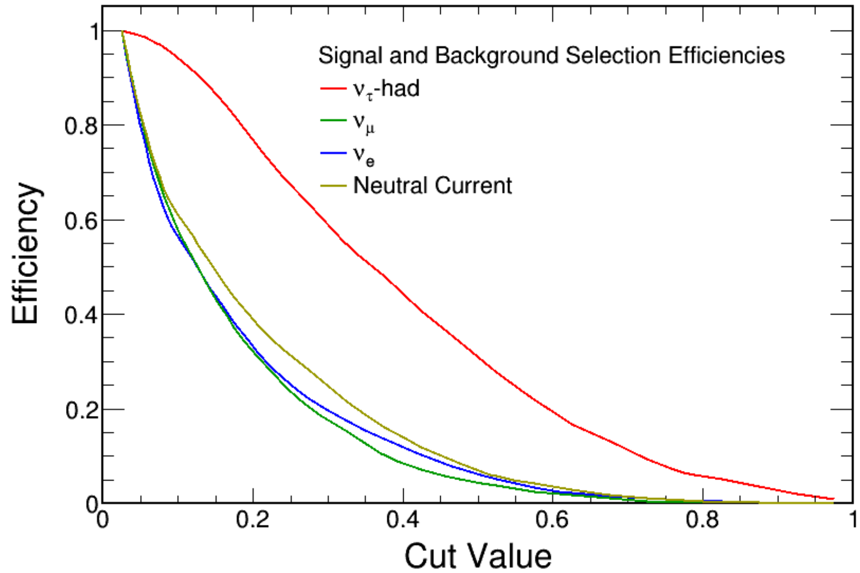
NSI Constraints



Tau neutrinos, in combination with other channels, provides a modest improvement in NSI reach

Realistic Reconstruction

- Next major step: make a realistic reconstruction
- Pandora reconstruction does not provide necessary pion PID and energy estimation necessary to implement simple cuts from optimistic selection
- CNNs have been very successful for electron and muon neutrinos → try those first



- Pure CNNs currently do not give good enough results
- Out-of-the-box CVN does not work → tau neutrino fraction in training sample much too low
- Modified version of DUNE CVN with enhanced tau neutrino training fraction and splitting tau decay categories achieved 30% signal efficiency and 5% background efficiency for beam events
- Still an order of magnitude too much background
- No corresponding numbers for atmospherics yet

Realistic Reconstruction

- Some ideas why CNNs aren't working as well as expected
  - Tau neutrino events are big
    - High energy atmospheric example crosses 500 wires and ~2000 ticks
  - Tau neutrino events are sparse
    - Typically ~1% of channels in minimal box containing all activity are occupied
- Exploring deep-learning-based reconstruction ideas to attain the necessary performance
  - Need to scale to larger images without being hurt by high sparseness
    - Sparse networks
    - Graph networks
  - Need to be able to handle directionality of atmospherics
    - Graph networks
    - Capsule networks