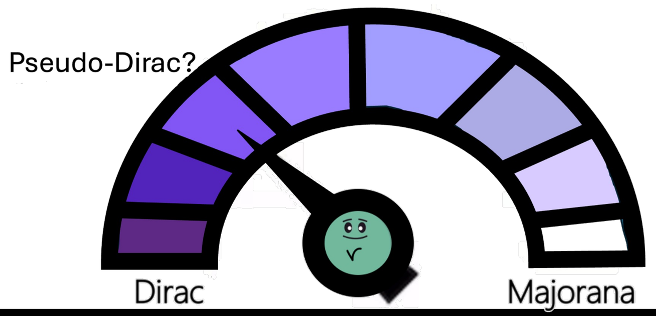

Atmospheric Neutrinos as a Probe for the Pseudo-Dirac Hypothesis

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Introduction

The story of the nature of neutrino masses asks the question: are neutrinos Majorana or Dirac fermions. While our best model independent approach to addressing this lies in Neutrinoless Double Beta Decay ($0\nu\beta\beta$) experiments, no signal for the Majorana option has been seen. With this in mind, we choose to rephrase the question as: to what degree do neutrinos exhibit Dirac-like characteristics (i.e. Pseudo-Dirac). To date, most Pseudo-Dirac neutrino studies have primarily been focused at cosmic scales due to the requirements of an extremely long baseline to observe its effects. However, potential avenues still exist at the terrestrial level. Atmospheric neutrino studies, such as those being planned as the initial studies for the upcoming Deep Underground Neutrino Experiment (DUNE) could potentially probe this parameter space due to their relatively long baseline distances of up to the Earth's diameter. Therefore, motivated by the fact that DUNE will be coming online in the near term (early 2030s), our ongoing work seeks to discuss what sensitivity, if at all, could DUNE have to the Pseudo-Dirac neutrino hypothesis.

Background: Pseudo-Dirac Formalism

Table 1 — Addressing the Nature of Neutrino Masses

Majorana:		Dirac:
➢ Only valid for electrically neutral massive particles	vs	➢ Behaves like all the other Standard Model Fermions
➢ Particle = Antiparticle (2 degrees of freedom)		➢ Particles are different from Antiparticles (4 degrees of freedom)
➢ Lepton Number Violated by 2 units		➢ Lepton Number is Conserved

Table 1: Characteristics for the usual Majorana and Dirac scenarios.

For the Dirac case, two mass degenerate Majorana Fermions form a Dirac Fermion. For the Pseudo-Dirac case, the two mass states are no longer completely degenerate.

Important Limits

Dirac limit: $M = 0$
Majorana limit: $M >> m_D$ (seesaw mechanism)
Pseudo-Dirac limit: $M << m_D$ (anti-seesaw mechanism)

The general neutrino mass matrix after Electroweak Symmetry Breaking in the case of adding 3 Right-Handed Majorana fields:

$$\mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix} \quad (1)$$

where m_D is the usual Dirac mass related to the Higgs VEV and M is Majorana mass. In this general case, $\mathcal{M}$ is a 6 × 6 Majorana mass matrix for $\binom{\nu_L}{N^c}$ basis.

The Pseudo-Dirac limit is where neutrinos behave mostly as Dirac, but with a small non-zero Majorana component. Lepton Number Violation only approximately conserved.

This leads to additional new oscillation frequencies arising from slightly breaking the degeneracy of each mass eigenstate.

We assume maximal mixing of active and sterile (invisible) states.

Figure 1

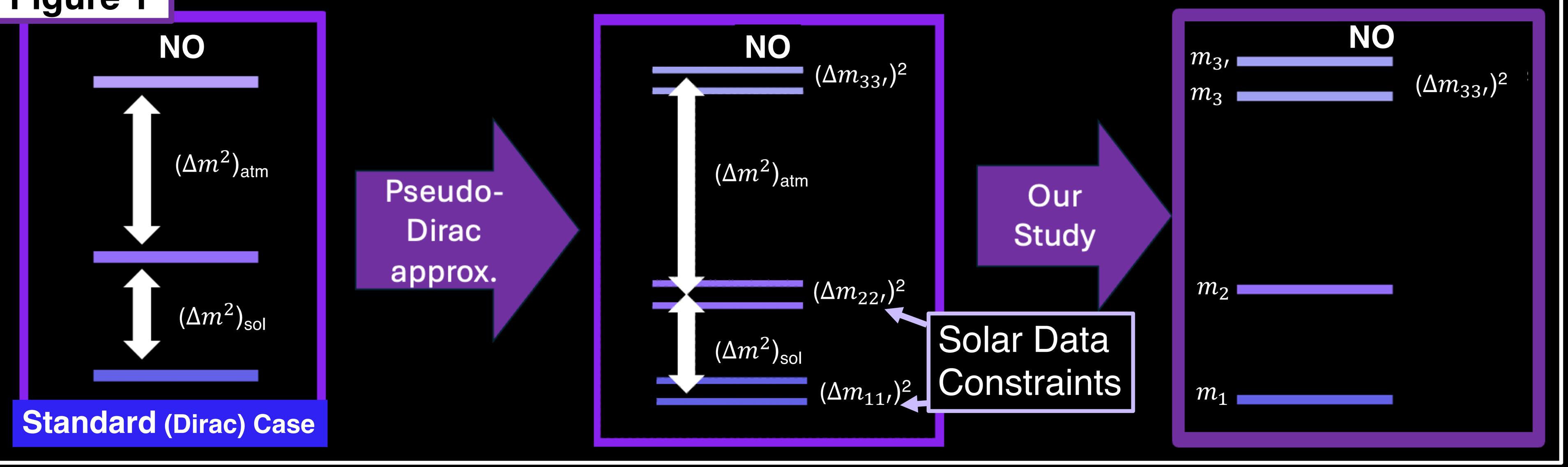

Figure 1: Diagram of the standard normal ordering (NO) picture for 3 neutrino mass states as well as the changes under a Pseudo-Dirac limit.

We quantify: $(\Delta m_{33'})^2 = 2\Delta m_{31}^2\ \varepsilon$ Any new physics is encoded in ε, a dimensionless parameter.

After perturbatively expanding in the Pseudo-Dirac limit, we obtain our usual neutrino evolution as the following Hamiltonian in the flavor basis where U is a modified PNMS matrix, M^2 is the mass matrix, and A is the matter matrix that encodes the modeling of the layers of Earth that atmospheric neutrinos travel through. E_ν is the neutrino energy.

$$H = \frac{1}{2\,E_\nu}\, U\, M^2 U^\dagger + A \quad (2)$$

where:

$$M^2 = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 & 0 \\ 0 & 0 & \Delta m_{31}^2(1+\varepsilon) & 0 \\ 0 & 0 & 0 & \Delta m_{31}^2(1+\varepsilon) \end{pmatrix} \quad A = \begin{pmatrix} A_{CC} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{A_{CC}}{2} \end{pmatrix} \quad U = \begin{pmatrix} U_{e1} & U_{e2} & \frac{U_{e3}}{\sqrt{2}} & -\frac{U_{e3}}{\sqrt{2}} \\ U_{\mu 1} & U_{\mu 2} & \frac{U_{\mu 3}}{\sqrt{2}} & -\frac{U_{\mu 3}}{\sqrt{2}} \\ U_{\tau 1} & U_{\tau 2} & \frac{U_{\tau 3}}{\sqrt{2}} & -\frac{U_{\tau 3}}{\sqrt{2}} \\ 0 & 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

Background: Atmospheric Neutrinos

Figure 2

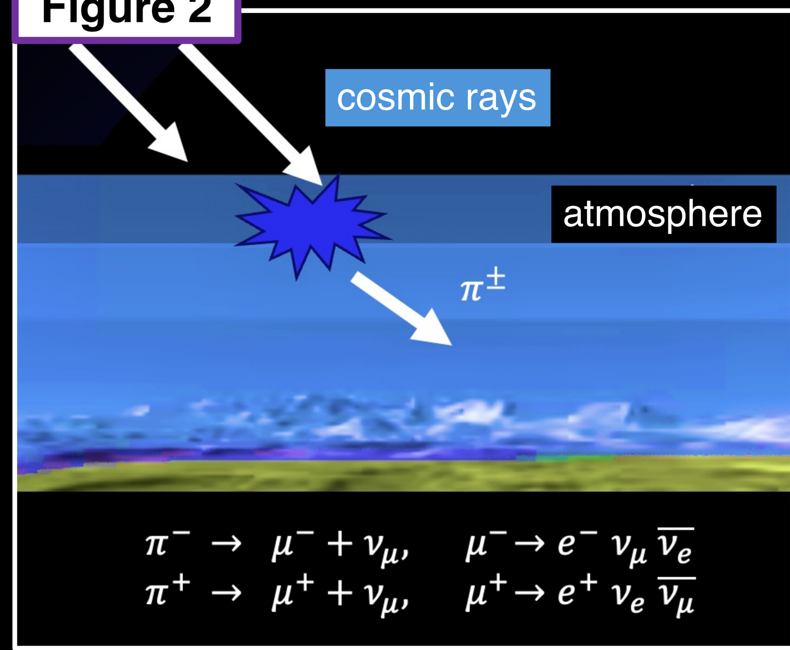

Figure 2: How atmospheric neutrinos are produced from cosmic rays interacting with nucleons in Earth's atmosphere. The relevant decays that produce neutrinos are also shown.

Figure 3

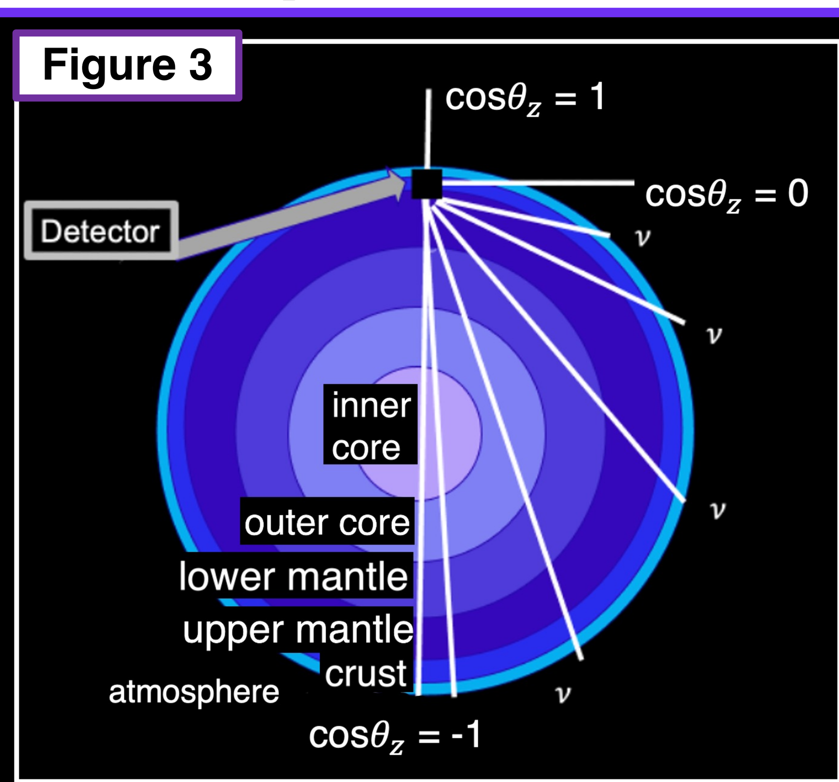

Figure 3: Neutrino trajectories from atmosphere locations to an example detector point on Earth. We describe neutrino distances by zenith angle θ_z. Up-going neutrinos: $\cos\theta_z = [-1, 0]$ and down-going neutrinos: $\cos\theta_z = [0, 1]$.

Advantage of Atmospheric Studies: long neutrino propagation distances (up to Earth's diameter of 12,742 km).

Figure 4

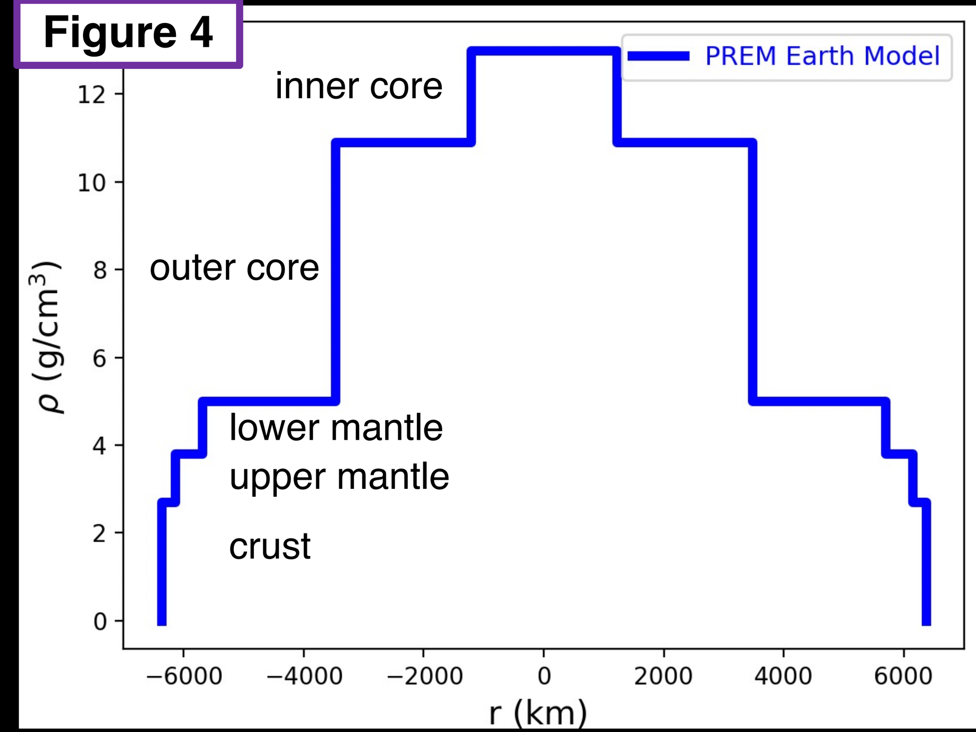

Figure 4: PREM: Preliminary Reference Earth Model for densities of Earth layers as function of Earth radius.

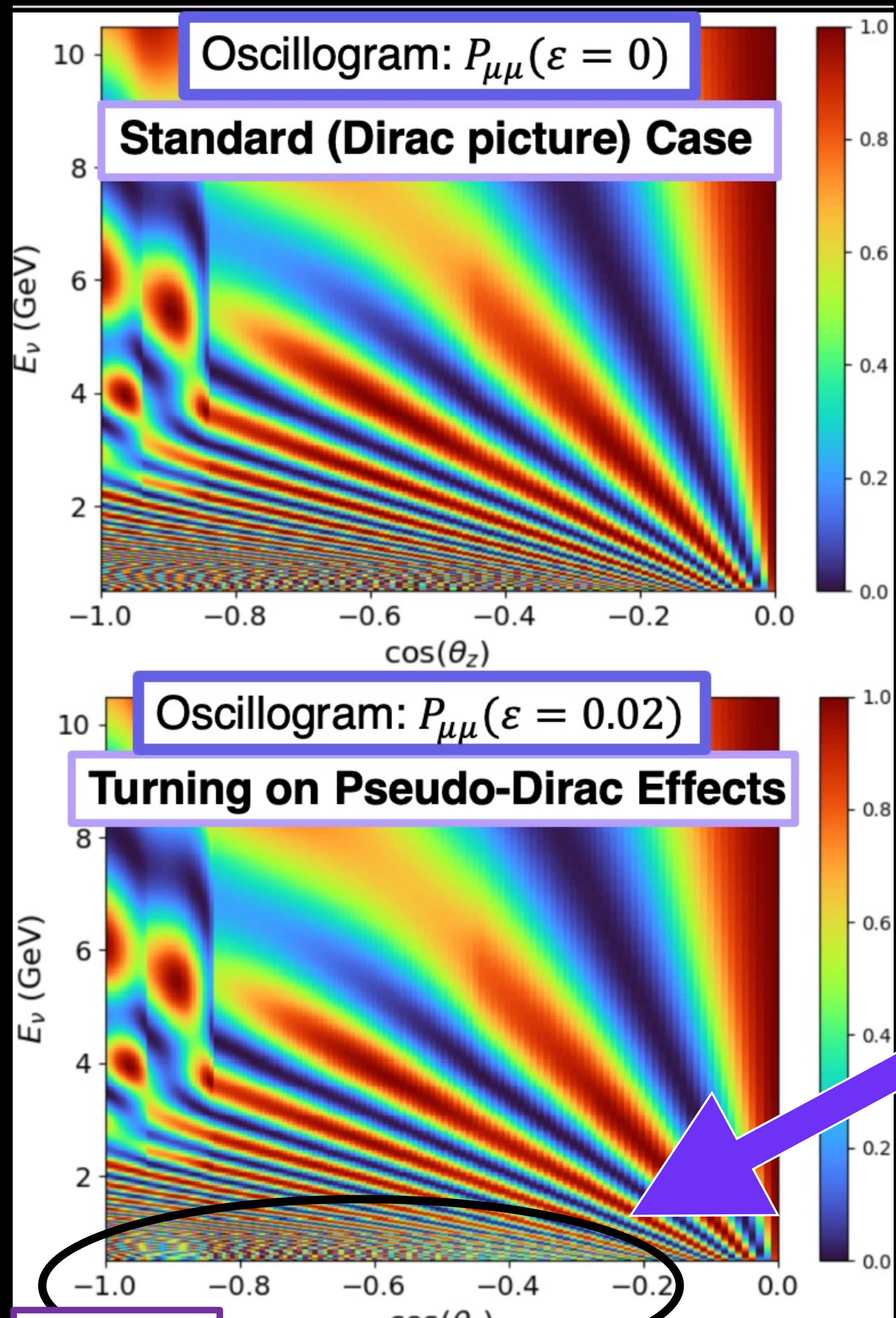

Figure 5

Differences/distorted spectral features at low energy due to the effects of turning on a non-zero ε.

Figure 5: Shown are 2D oscillograms of the ν_μ disappearance probability for upward-going neutrinos. The top plot is the typical three flavor standard model case whereas the bottom plot shows the effects of turning on a non-negligible value for ε.

Preliminary Results

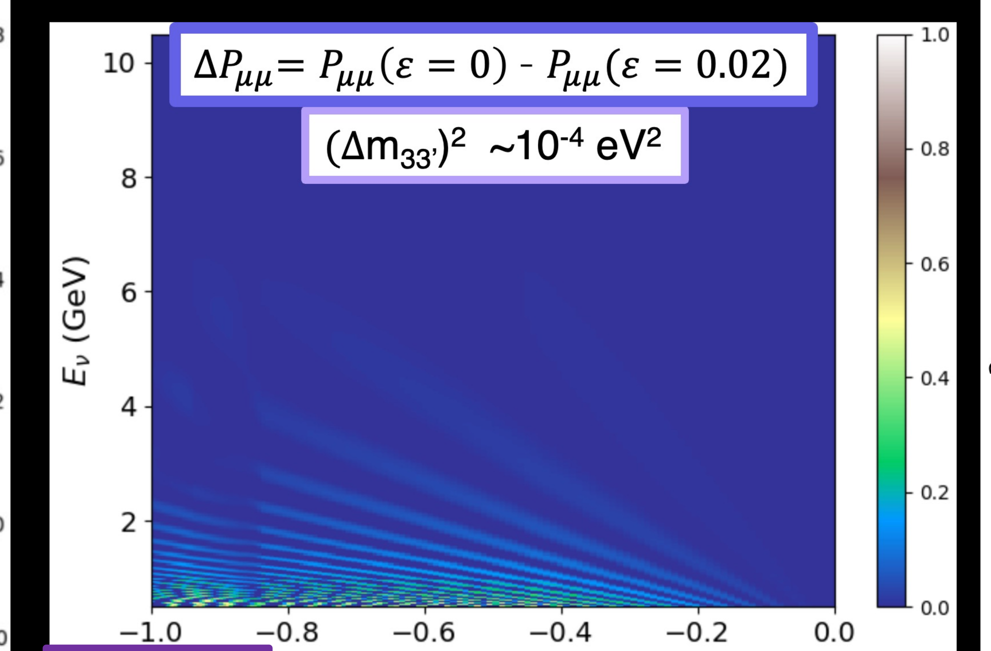

Figure 6

Figure 6: Difference in probabilities shown in figure 5.

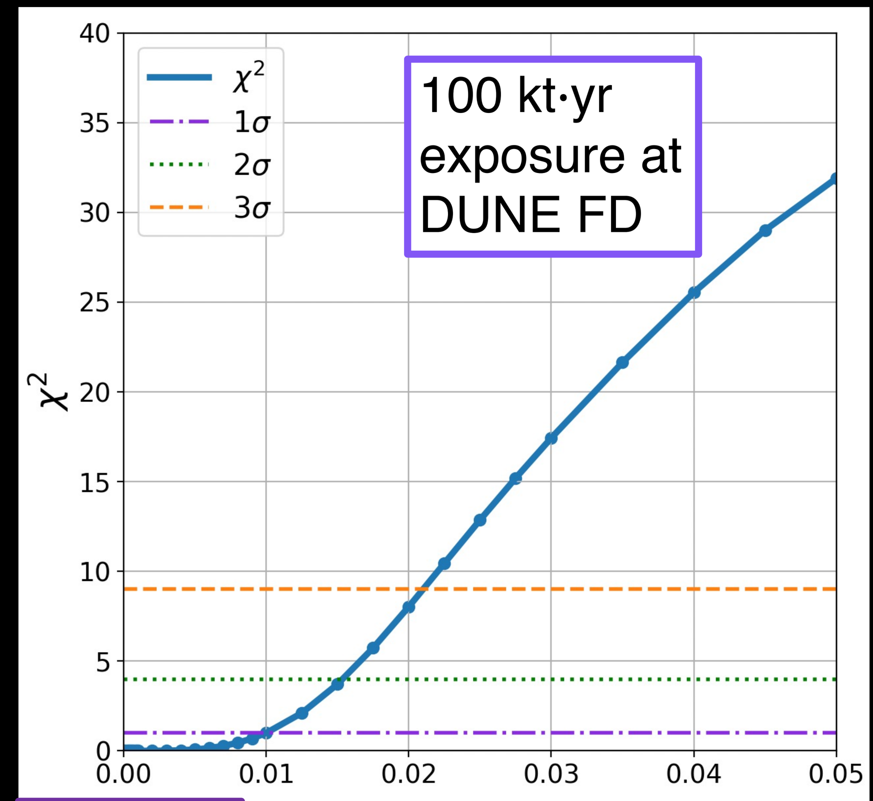

Figure 7

Figure 7: Preliminary result at 3σ for our new mass squared splitting $(\Delta m_{33'})^2$. We assume 100 kt·yr exposure at the DUNE Far Detector (FD).

Preliminary Result at 3σ:
$\varepsilon \lesssim 2\text{x}10^{-2} \Leftrightarrow \Delta m^2_{3,3'} \lesssim 1\text{x}10^{-4}\ eV^2$

Matches expectation of sensitivity:
$(\Delta m_{33})^2$ ~$\mathcal{O}(\Delta m_{21}^2)$~ 10^{-4} eV²

Competitive with DUNE beam*:
$(\Delta m_{33})^2 \lesssim 5.5\text{x}10^{-5}\ eV^2$ at 3σ

*PHYSICAL REVIEW D 100, 035032 (2019) (G. Anamiati, V. De Romeri, M. Hirsch, C. A. Ternes,& M. Tórtola)

Main Takeaway/Next Steps

This study looks at DUNE's possible sensitivity to the Pseudo-Dirac hypothesis.

While the conclusions presented here are *preliminary*, early indications point towards our work providing a *non-trivial answer* that is competitive with other future long-baseline results, providing a possible complimentary window into Pseudo-Dirac neutrino studies.

Additional work will focus on understanding the effects of marginalization over the oscillation parameters as well as looking to account for a more realistic simulation of the future DUNE experiment.

Acknowledgements

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