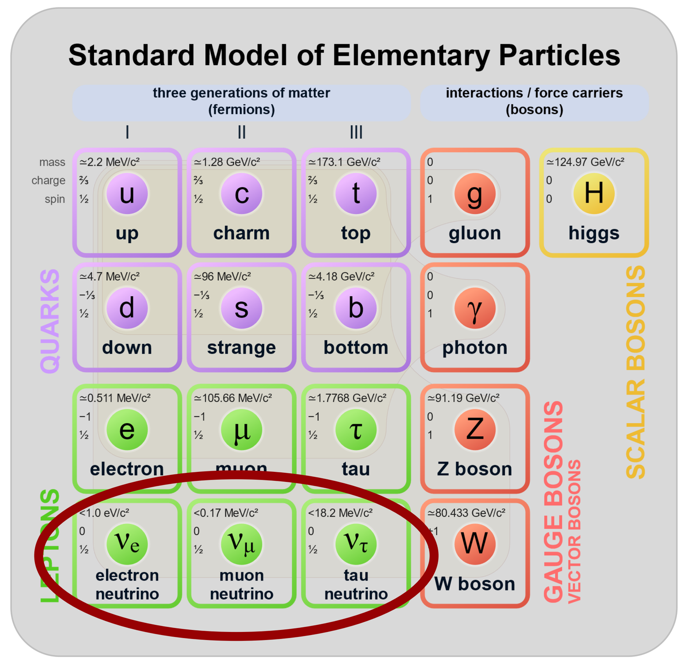
ν_τ Appearance in the DUNE Far Detector

Nicholas Chambers[1], Wei Shi[2], Michael Wilking[2]

[1]University of Arkansas, [2]Stony Brook University

Introduction



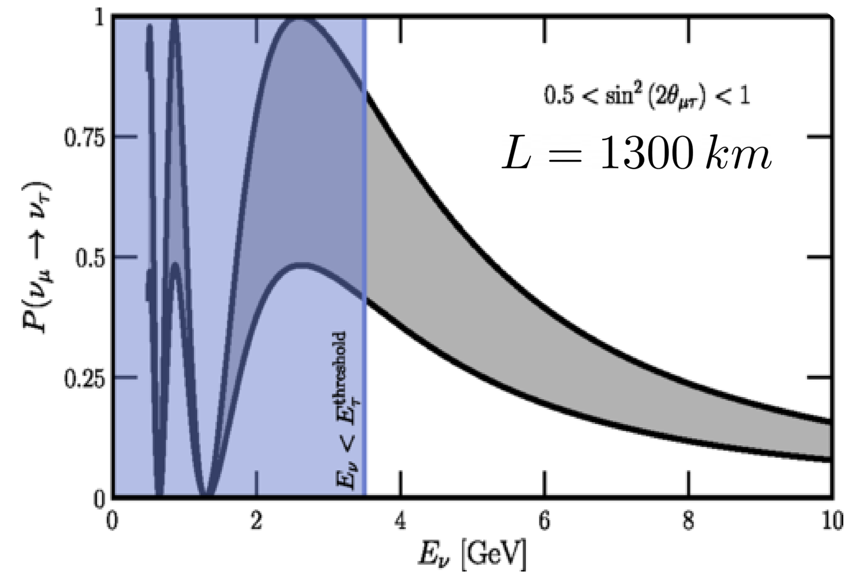
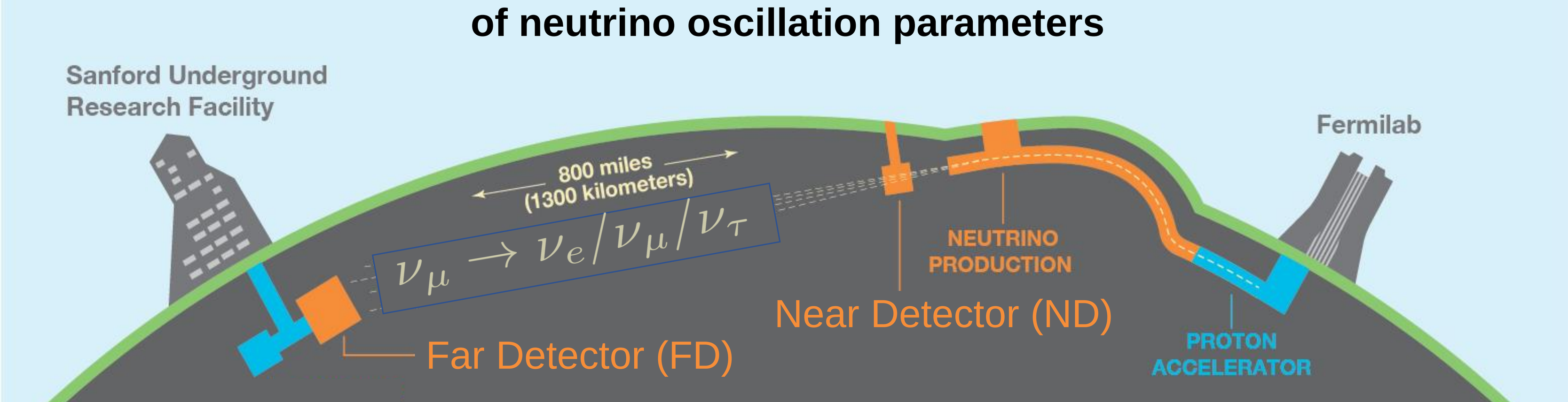


Fig. 1: $\nu_\mu \to \nu_\tau$ oscillation probability. Peak energy shifts right with increasing L. Amplitude given by mixing angles (θ_{13}, θ_{23}). [1]

- Neutrino oscillations were the first recorded instance of physics beyond the Standard Model, and investigations into neutrino phenomena could answer questions in physics related to **Dark Matter** and the **Baryon Asymmetry** problem.

Comparing neutrino flux at the near/far detector allows for a measurement of neutrino oscillation parameters



Dune Features:

- Large FD and robust particle tracking
- Longer baseline and High ν_μ flux

- ν_μ will oscillate mostly into ν_τ, as depicted by *Fig. 1*. Despite **the high population of ν_τ**, this oscillation channel remains **completely unexplored**. Reliable ν_τ detection would be another groundbreaking feature of the DUNE experiment.

ν_τ-Appearance Physics

Why is ν_τ detection important?

- PMNS Matrix Unitarity Check
- Measurement of ν_τ charged-current (CC) cross-section
- Oscillation parameter measurement (θ_{23}, Δm^2_{31})

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$$P(\nu_\mu \to \nu_\tau) = 4|U_{\mu3}|^2|U_{\tau3}|^2 \sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right)$$

$$4|U_{\mu3}|^2|U_{\tau3}|^2 = \cos^4\theta_{13}\sin^2 2\theta_{23}$$

Why is ν_τ detection difficult?

- ν_τ CC interaction requires E > 3.5 GeV
- τ must be inferred from decay products
- Tough to separate τ signal from background (See *Fig. 2*)

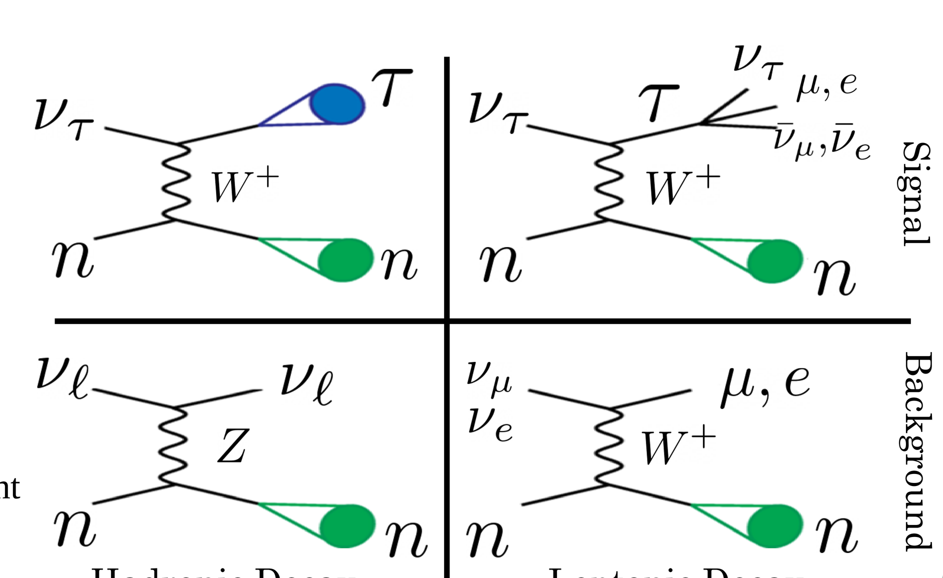


Fig. 2: Feynman diagrams for nutau weak interactions and subsequent tau decays. (Top/bottom) rows represent (signal/background) processes in the cases of hadronic/leptonic) tau decays (left/right) [2]

Previous ν_τ Studies

- Current experiments like T2K and Nova cannot probe the $\nu_\mu \to \nu_\tau$ channel. DUNE will be the first long-baseline experiment to have a substantial flux of detectable ν_τ in its FD. (See *Fig. 3.*)
- Phenomenology reports suggest that a reliable ν_τ selection algorithm could result in **ν_τ discovery** in ~2.5 years of measurements

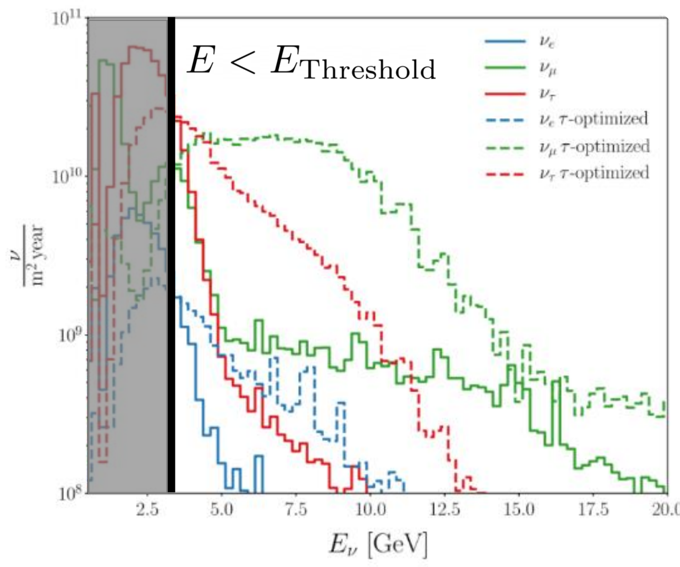


Fig. 3: Neutrino flux in the FD by flavor. A large tail of ν_τ (solid red) extends beyond the 3.5 GeV threshold. [2]

Previous ν_τ/ν_μ Selection

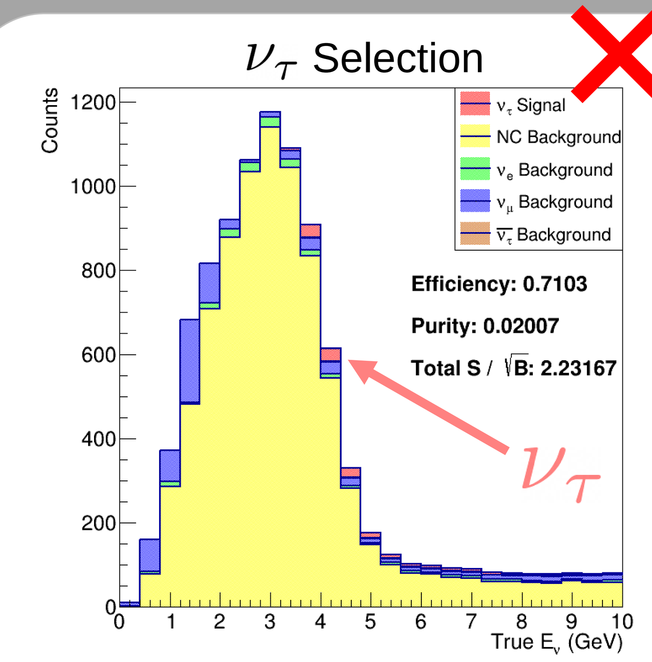


Fig. 4: Stacked histogram of events that pass a naive cut for ν_τ selection. **Red events are actual ν_τ.**

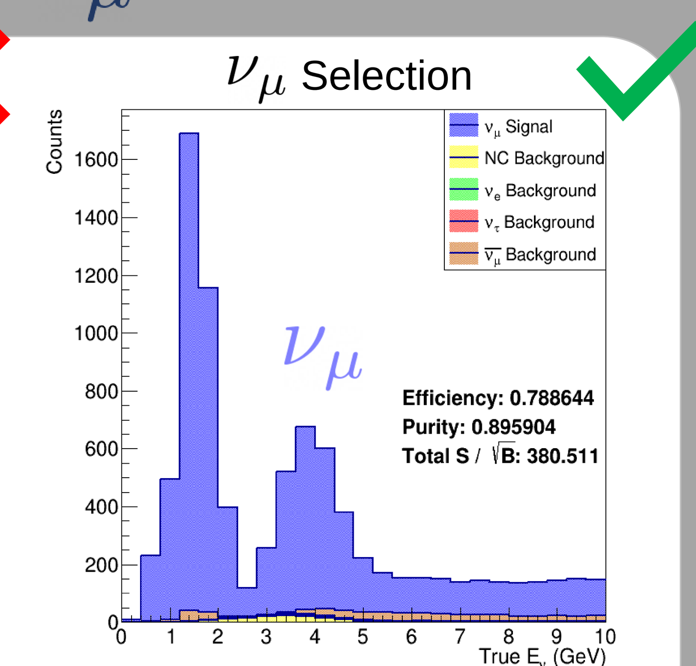


Fig. 5: Stacked histogram of events that pass the current ν_μ selection criteria. **Blue events are actual ν_μ.**

- Current DUNE software utilizes a **visual neural network** to identify ν_e, ν_μ. This neural network is **not well-trained** for ν_τ.
- *Fig 5.* shows that current ν_μ identification performs well
- There is hope for ν_τ: **many weak classifiers** exist based on τ lepton decay kinematics

Boosted Decision Tree

- Each node of events is split according to the variable with the **best separation**
- Single decision tree is useful for a large data set with many weak classifiers but is **susceptible to overtraining**
- Circumvent overtraining by adaptive boosting – use 800 decision trees
- Previously **misclassified events** are **prioritized** in subsequent trees

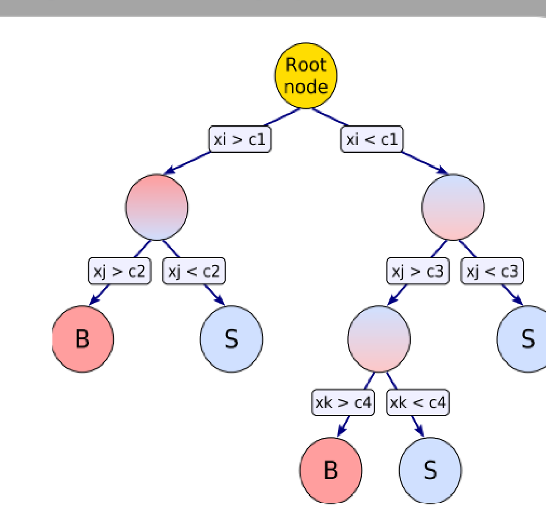


Fig. 6: Graphical representation of a decision tree. *Source:* TMVA User Guide

Results

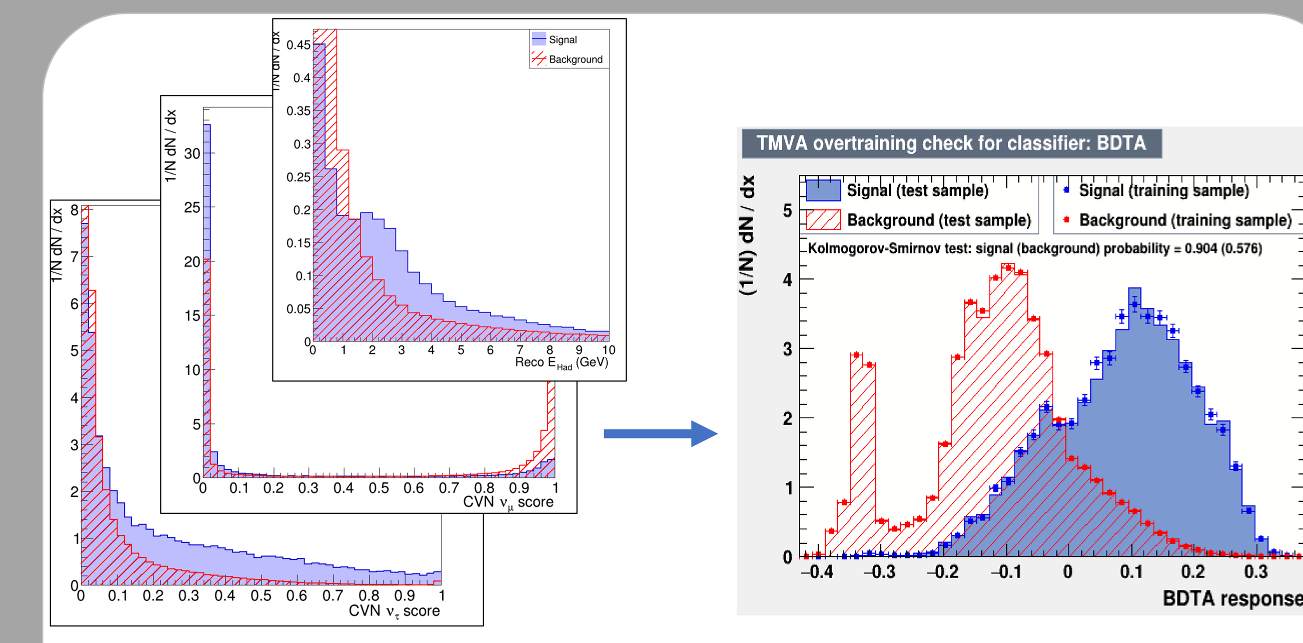


Fig. 7: (Left/Right) (ν_τ weak classifiers / BDT response) values for FD events

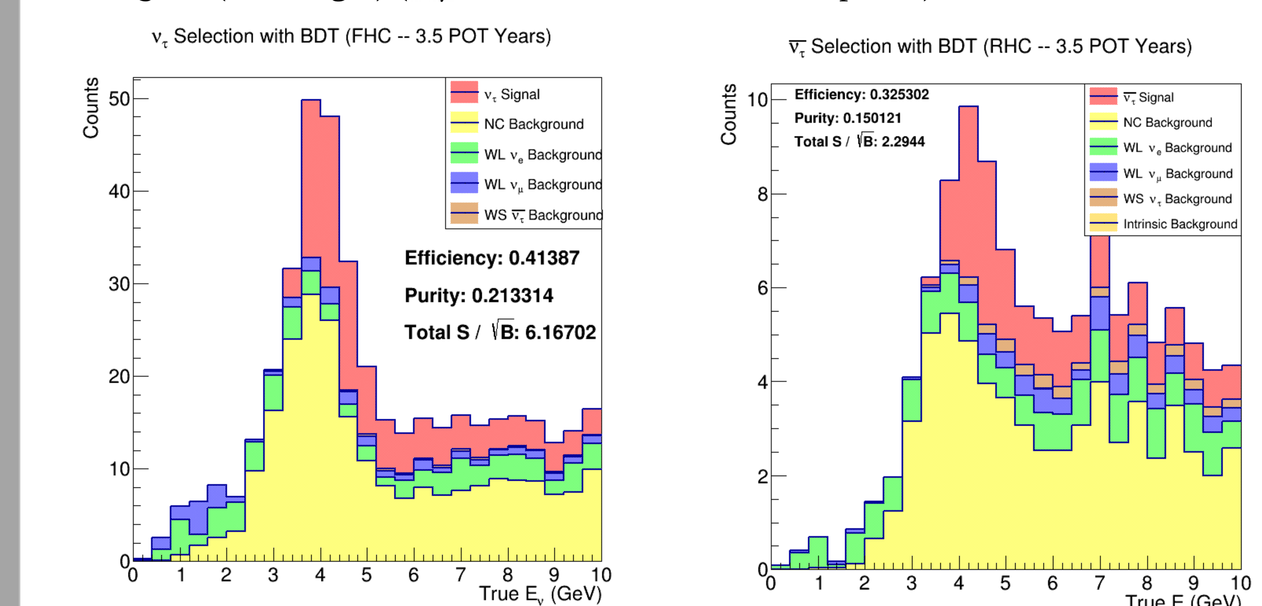


Fig. 8: (Left/Right) Stacked histograms of FD events that pass the optimal BDT cut for (Neutrino / Anti-neutrino) beam configurations. **Red events are actual ν_τ.**

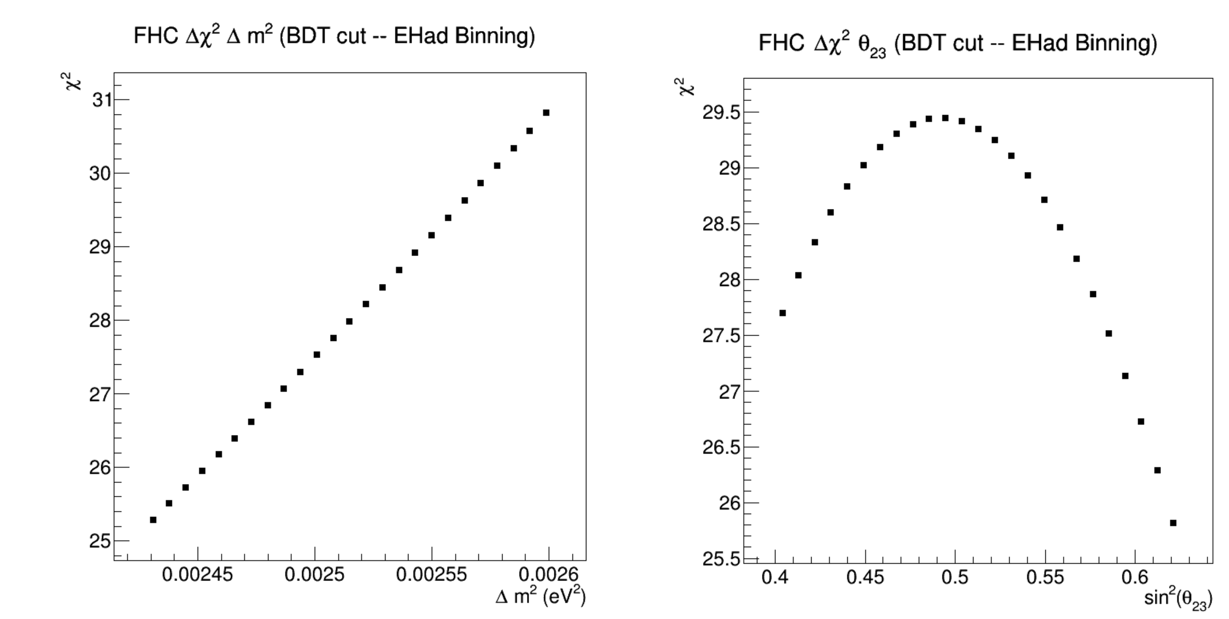


Fig. 9: (Left/Right) $\Delta\chi^2$ signal significance given by BDT cut as a function of ($\Delta m^2_{31}/\theta_{23}$). $\Delta\chi^2$ was calculated for neutrino beam configuration and flux histograms were binned according to total hadronic energy deposits in the FD

- Comparing *Fig 4.* and the left histogram in *Fig 8.*, we see a **3x increase** in **ν_τ discovery significance** as well as a drastic increase in **signal purity**
- *Fig 9.* shows that our results attain the necessary $\sqrt{\chi^2} > 5\sigma$ significance to claim ν_τ discovery across 99% of oscillation parameter values – an unprecedented result using the DUNE FD full simulation sample

References & Acknowledgements

[1] Andre de Gouvea, Kevin J. Kelly, G. V. Stenico, and Pedro Pasquini. Physics with beam tau-neutrino appearance at dune. Phys. Rev. D, 100:016004, Jul 2019.

[2] Pedro Machado, Holger Schulz, and Jessica Turner. Tau neutrinos at dune: New strategies, new opportunities. Phys. Rev. D, 102:053010, Sep 2020.

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