DUNE: Neutrino Symmetry Violation Through a PRISM

Luke Pickering and Linda Cremonesi

RAL PPD PhD Open Day

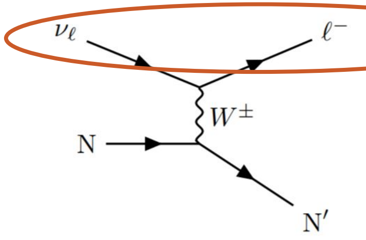
2025/02/19

Science and Technology Facilities Council

Queen Mary University of London

Unknown Properties of Known Neutrinos

Flavor state defined by paired charged lepton at vertex



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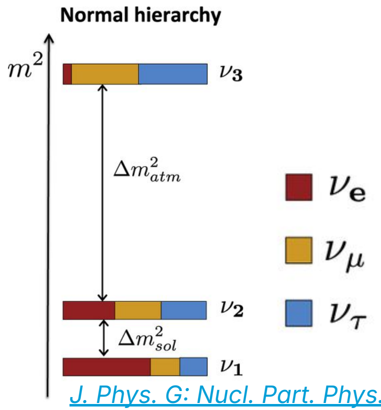

J. Phys. G: Nucl. Part. Phys. **43** 084001

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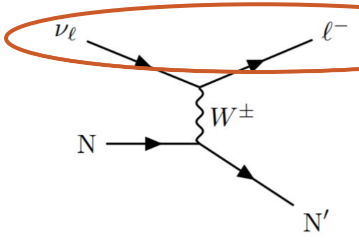

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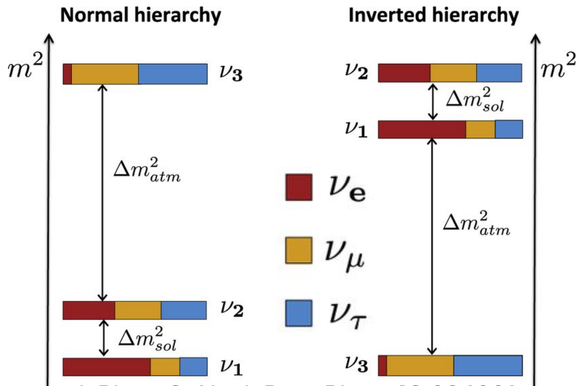

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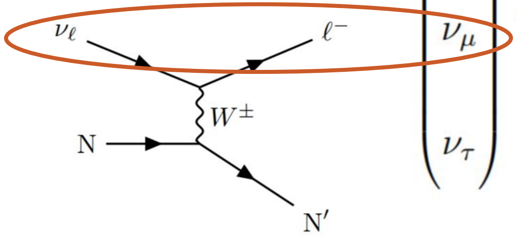

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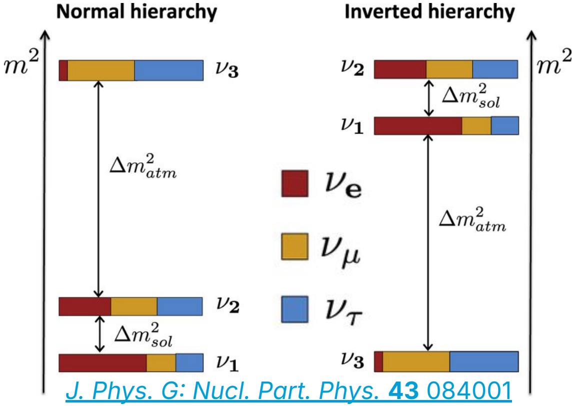

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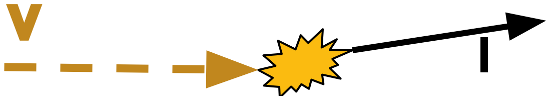

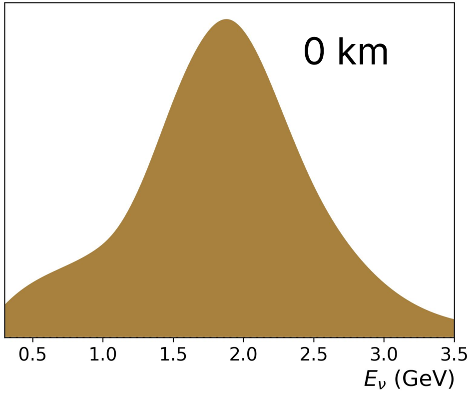

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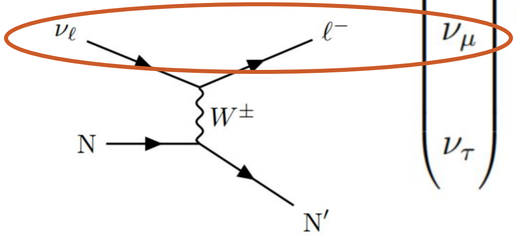

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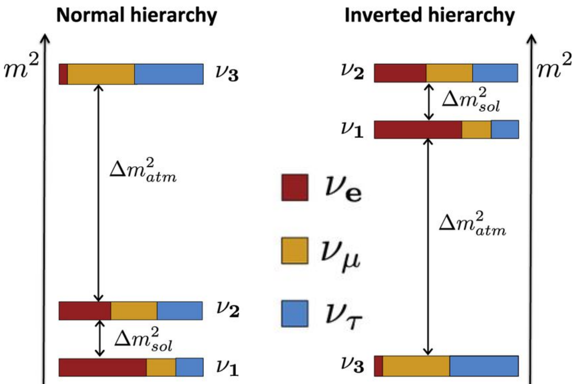

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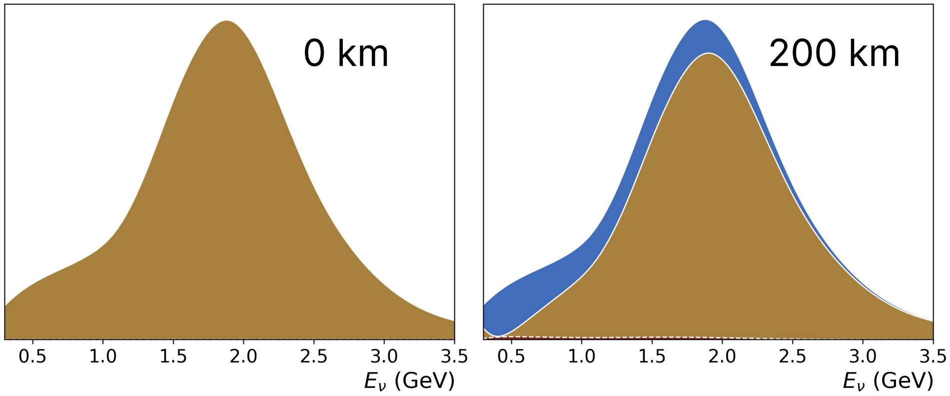

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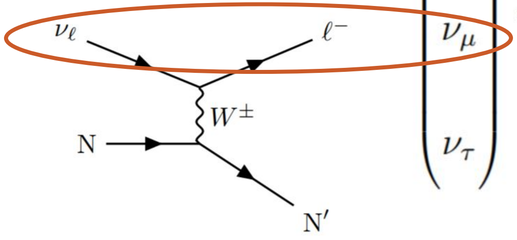

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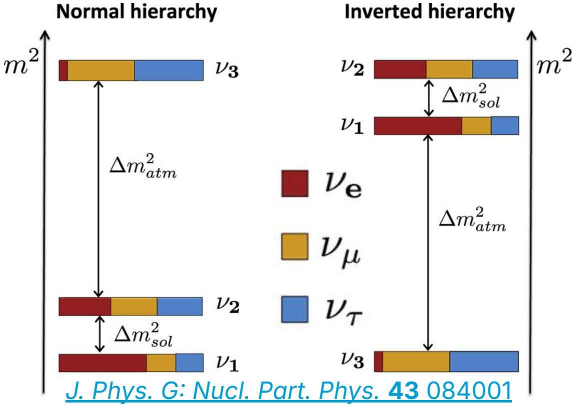

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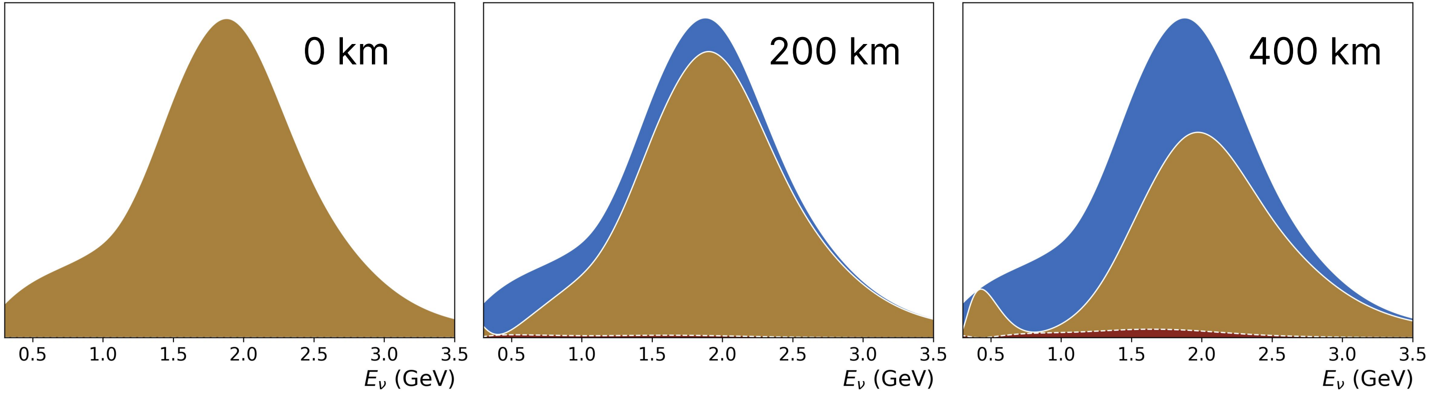

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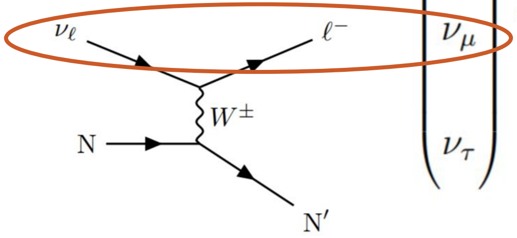

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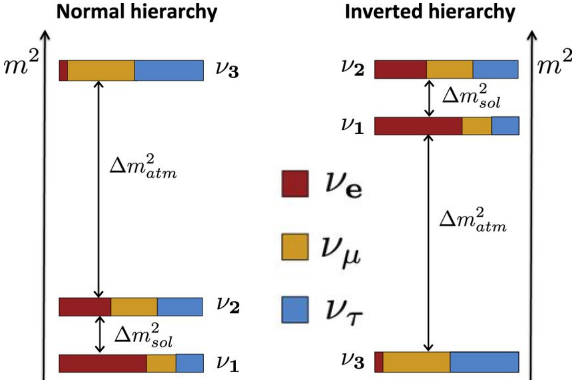

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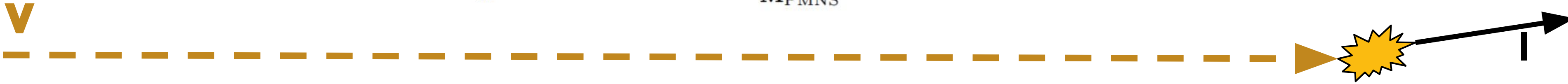

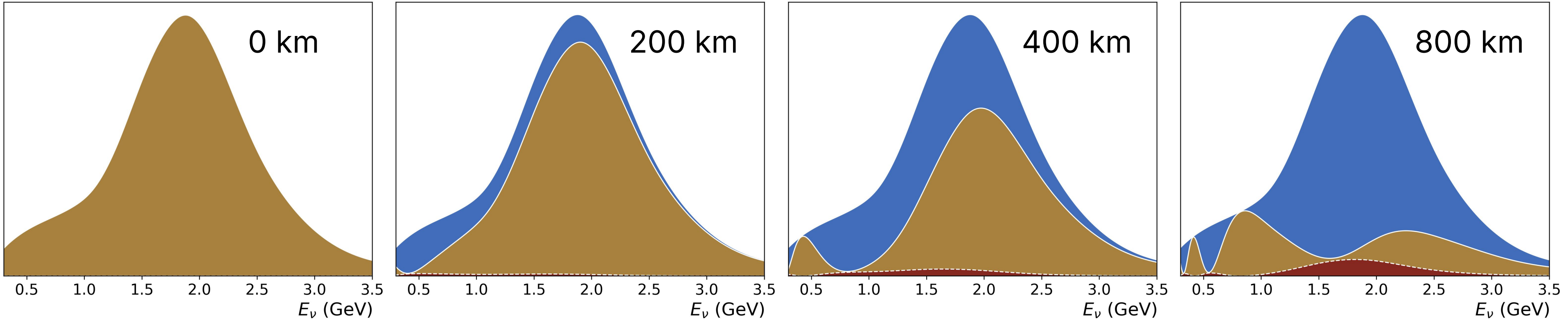

Big Questions

Do neutrinos and antineutrinos oscillate equivalently under Charge-Parity symmetry?

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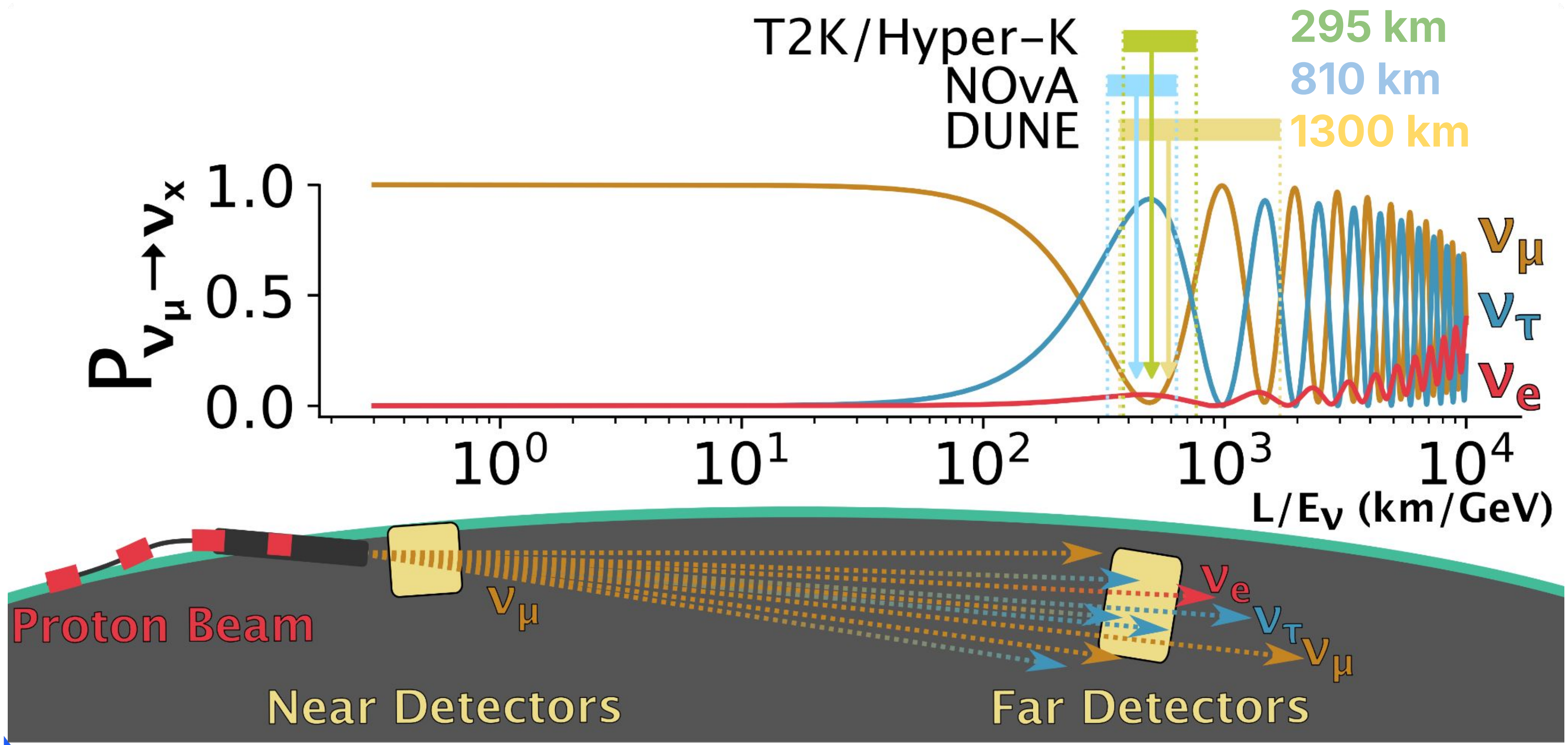
Enough to explain matter/antimatter asymmetry?

Are standard 3-flavour PMNS oscillations able to explain global observations?

Anatomy of a Neutrino Oscillation Experiment



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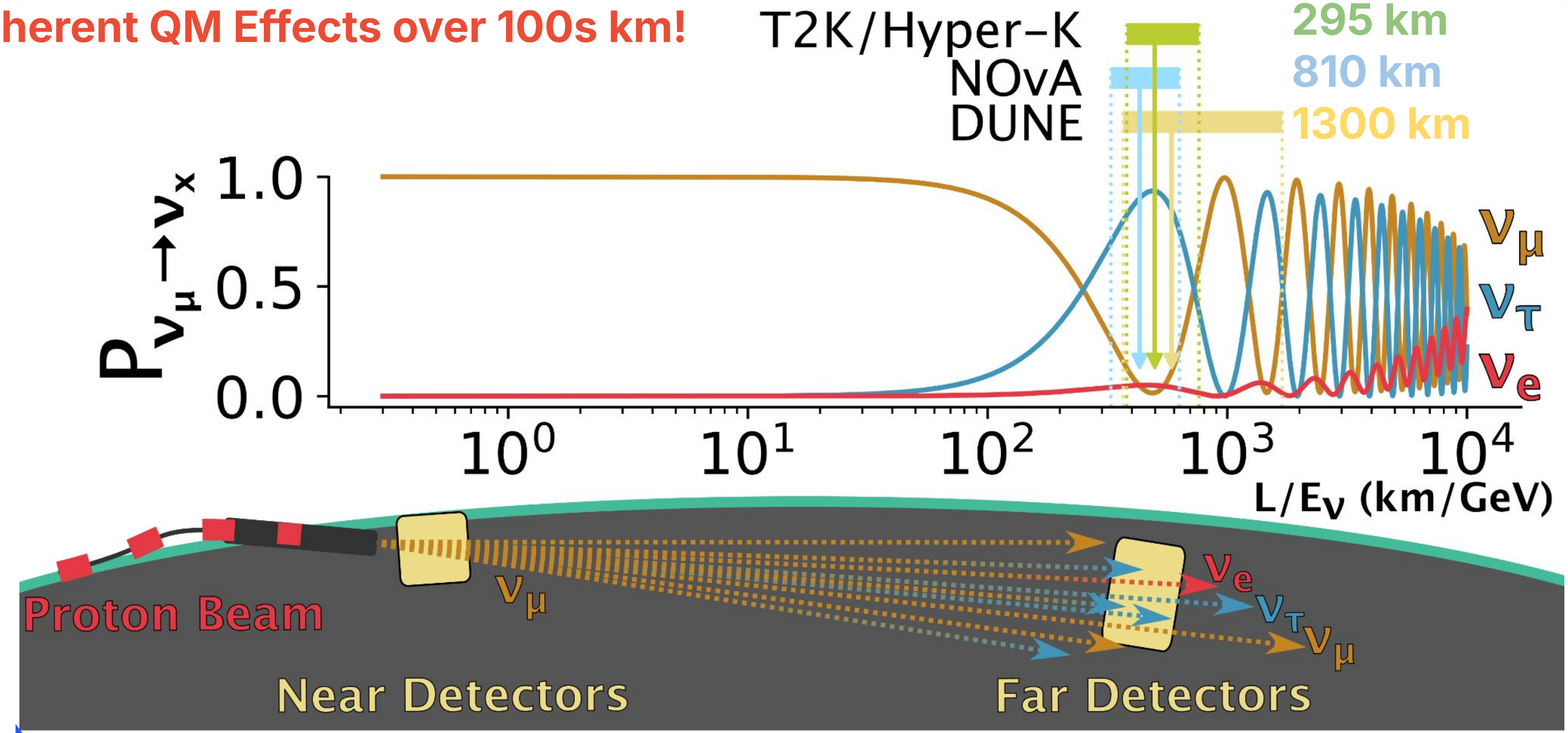
Coherent QM Effects over 100s km!



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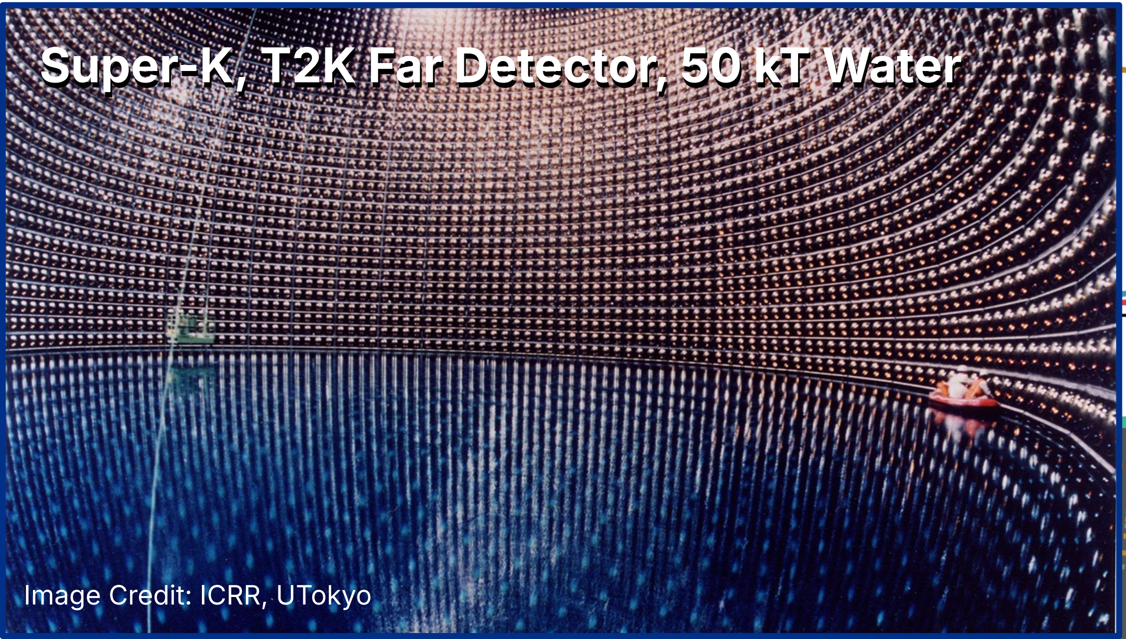

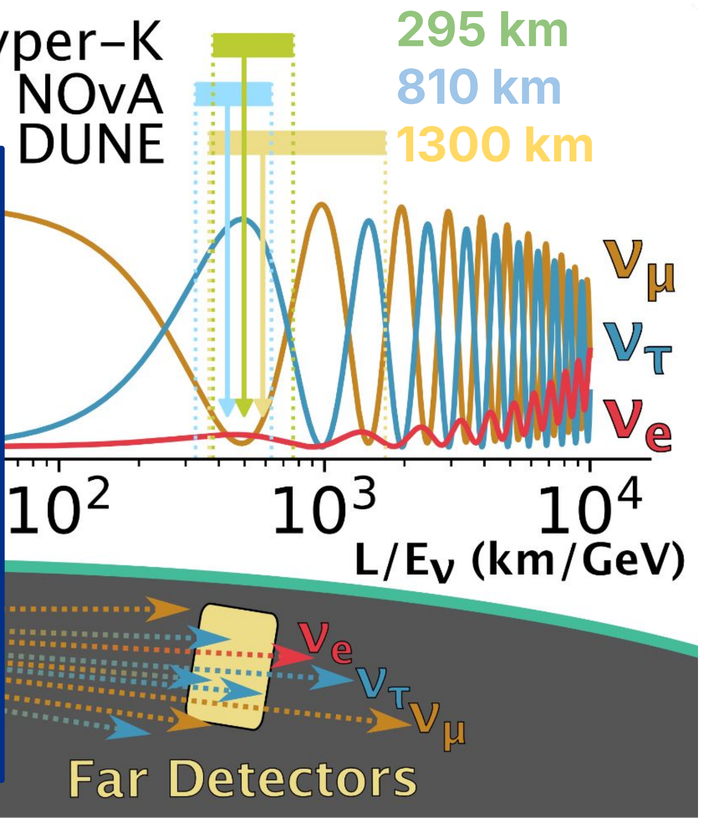

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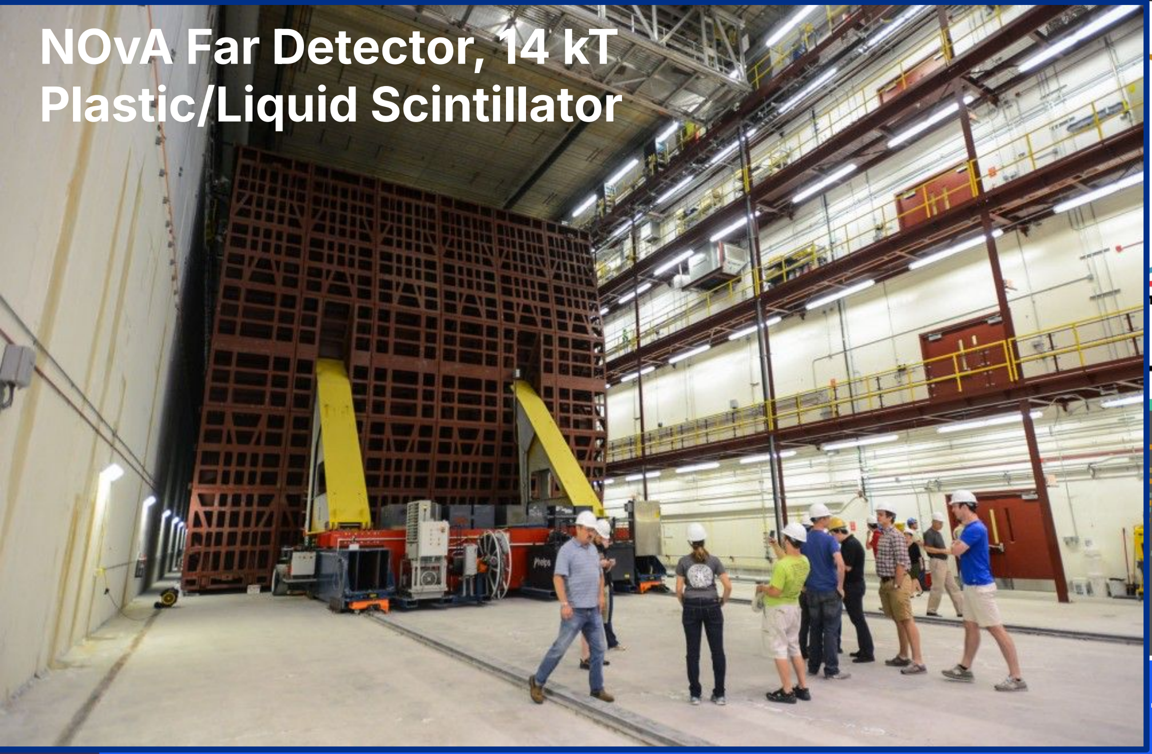

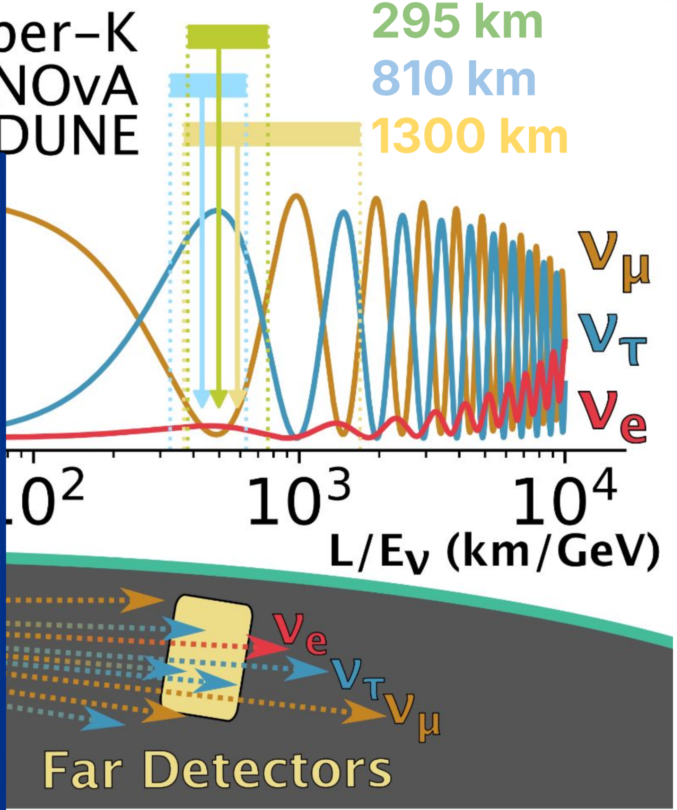

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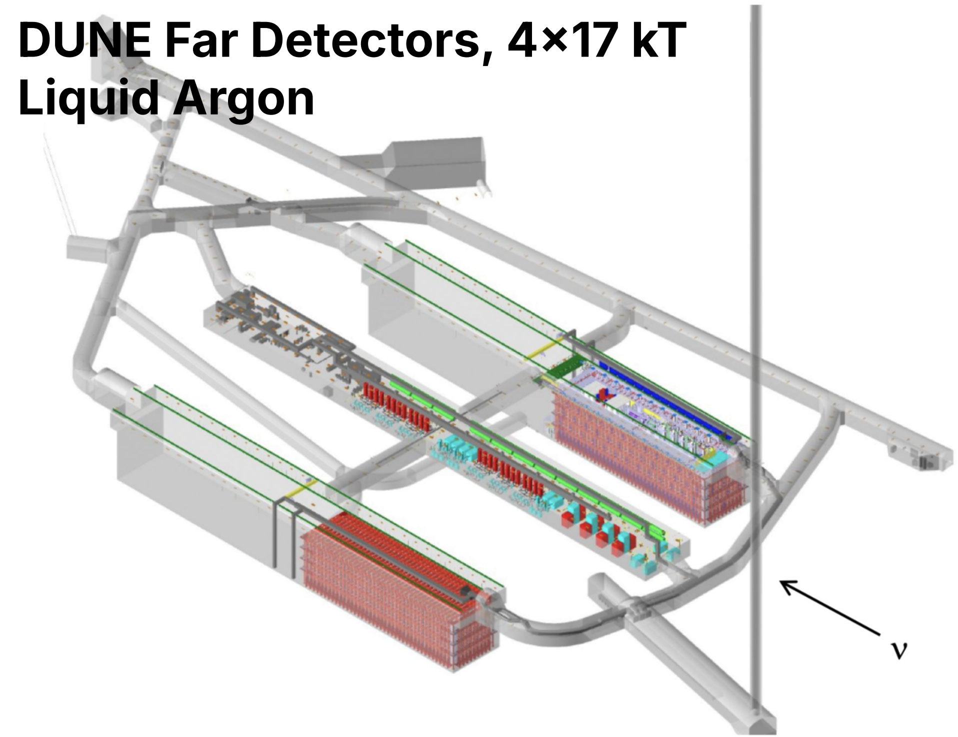
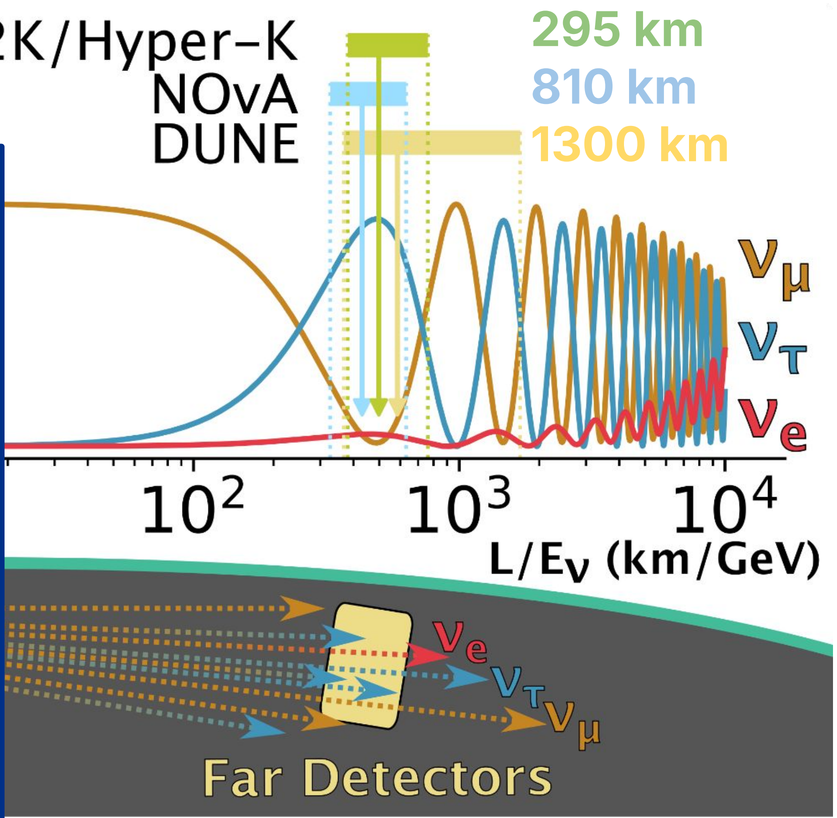
DUNE Far Detectors, 4×17 kT Liquid Argon





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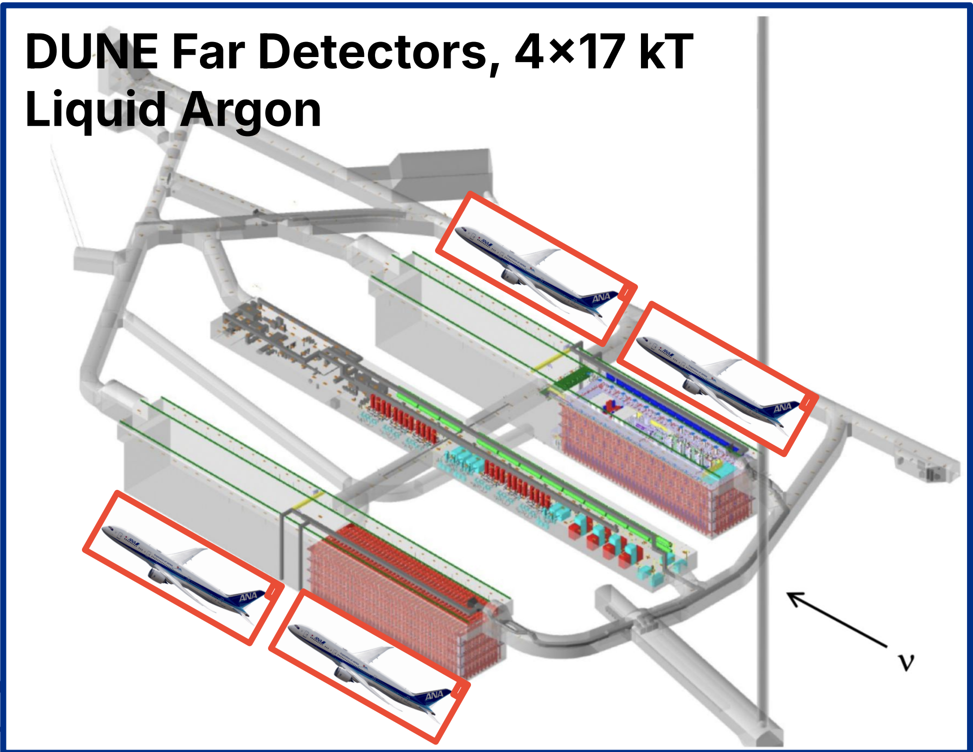

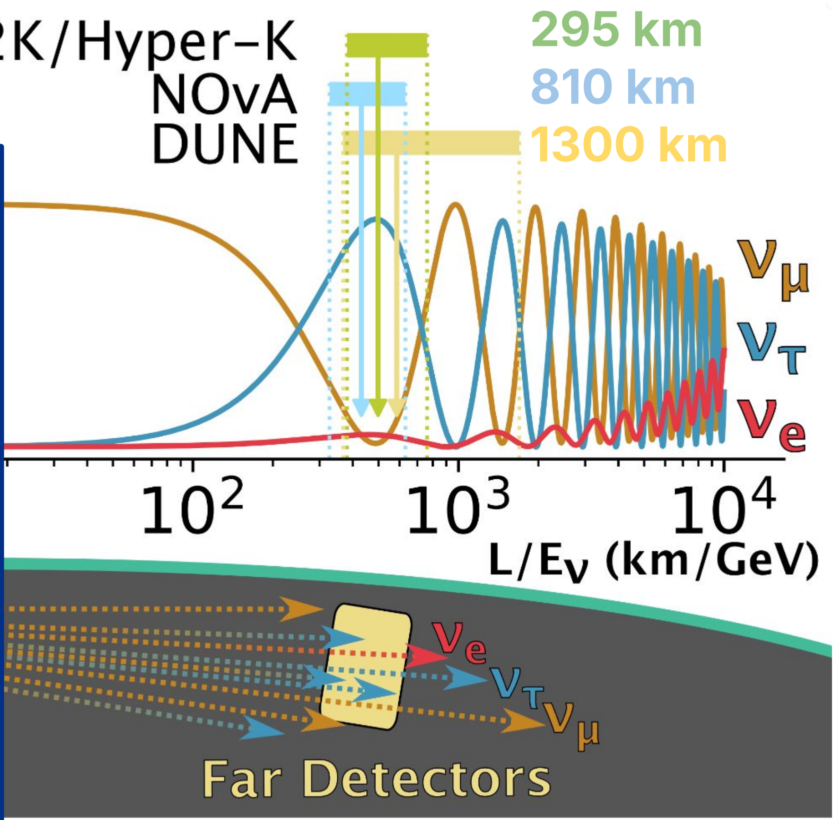

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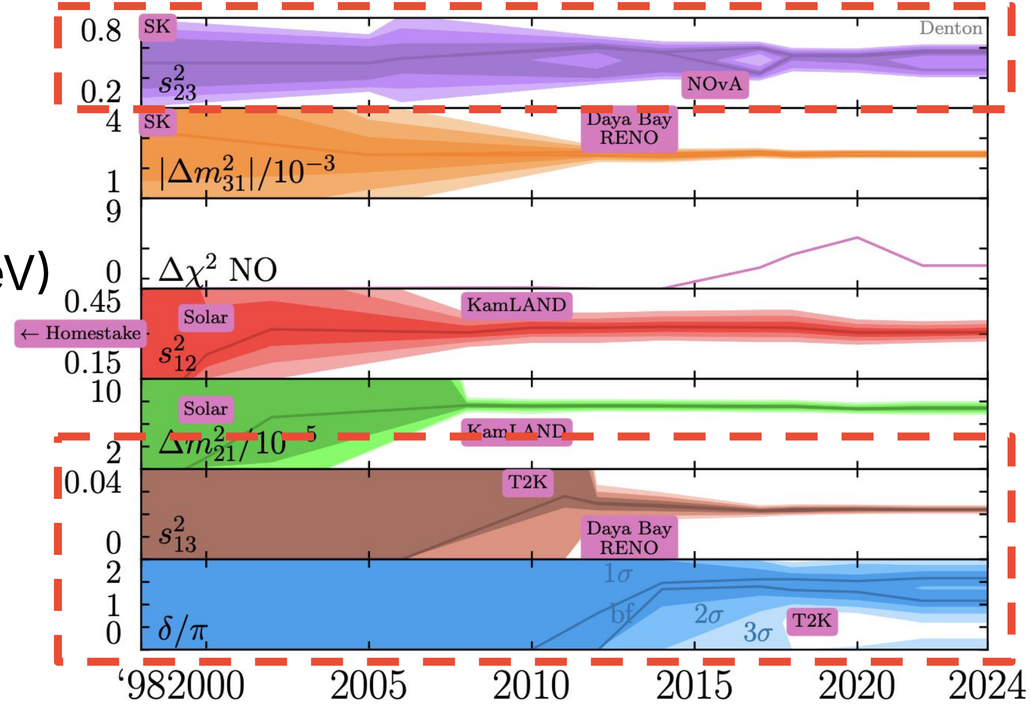
Current Generation Long Baseline:

T2K (Japan, 2009–, 295 km, 0.6 GeV)

NOvA (US, 2013–, 810 km, 1.9 GeV)



P. Denton, NuFact 2024

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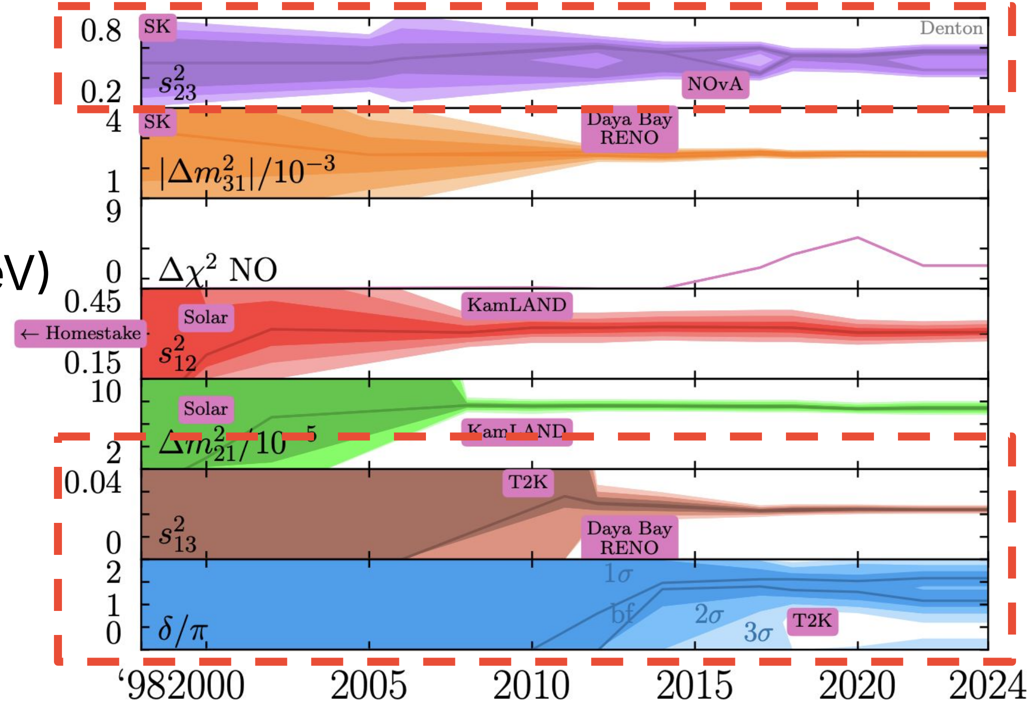

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Next Generation Long Baseline:

Hyper-Kamiokande (Japan, ~2027, 295 km, 0.6 GeV)

DUNE (US, ~2029, 1300 km, 2.3 GeV)

No Time For Details on: Short Baseline, Reactor, Atmospheric, Solar, $0\nu\beta\beta$, ...

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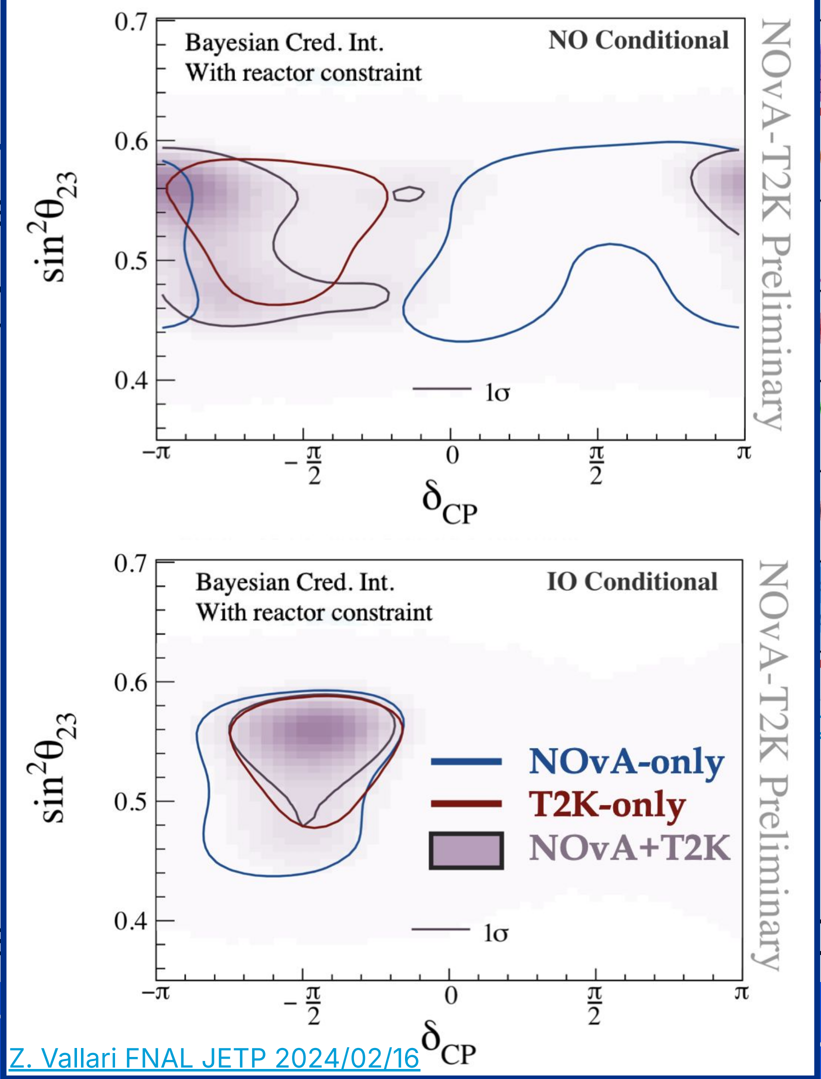
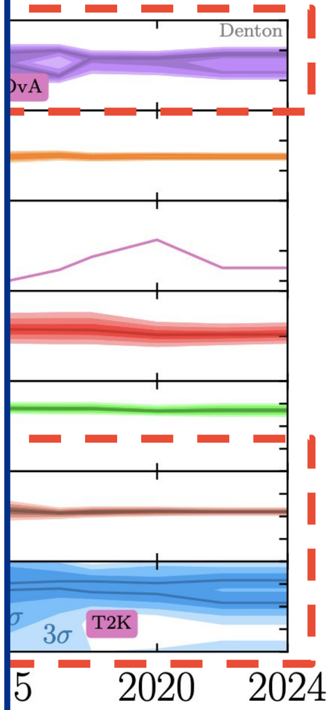


[Z. Vallari FNAL JETP 2024/02/16]



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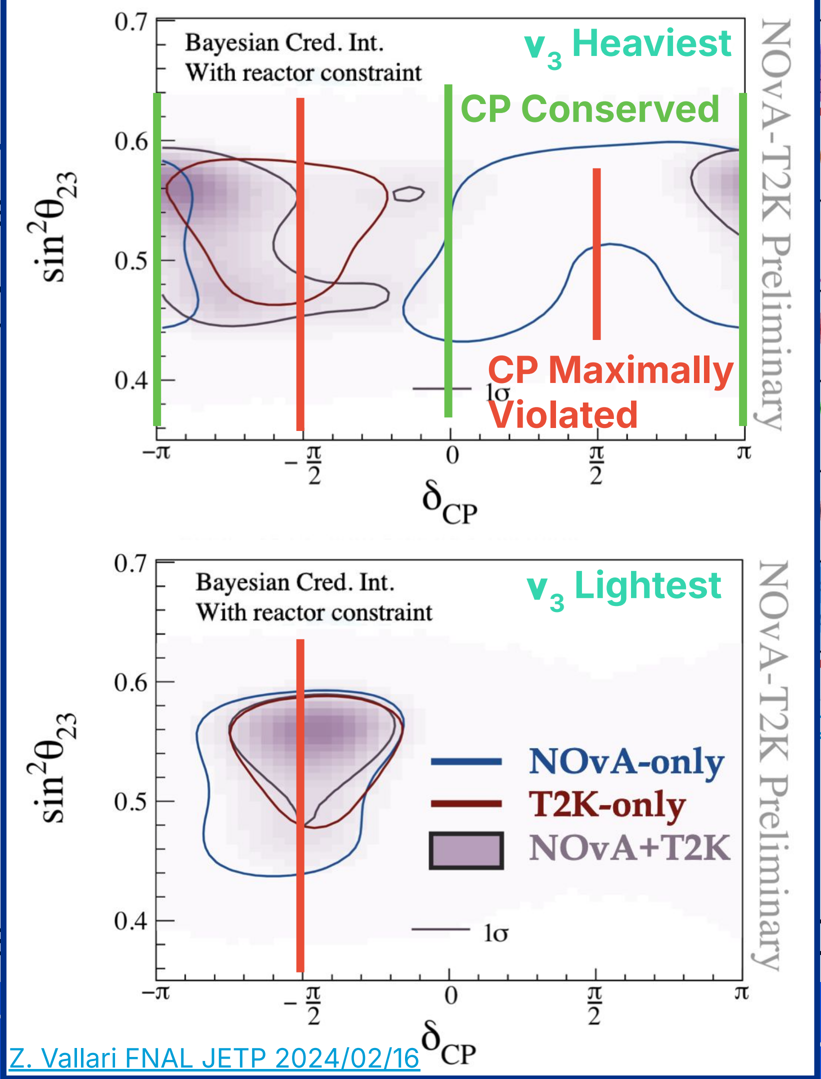

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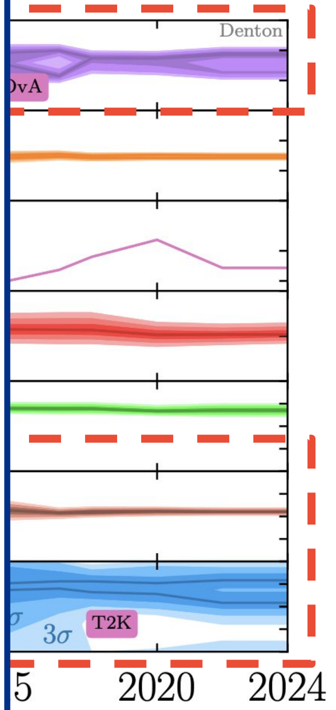

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0νββ, ...

The Deep Underground Neutrino Experiment

- >1400 collaborators from >200 global institutions

- Liquid Argon Time Projection Chamber Detectors
  - Unprecedented event reconstruction for a Far Detector

- Unique sensitivity to answer those Big Questions with a single experiment:
  - Unambiguous mass hierarchy measurement in a few years
  - Ultimate sensitivity to measure CPV-generating parameter

- Rich physics program beyond long baseline oscillations:
  - Solar, SuperNova Core Collapse, Geo-, Sterile Neutrinos

Appeared ν_e

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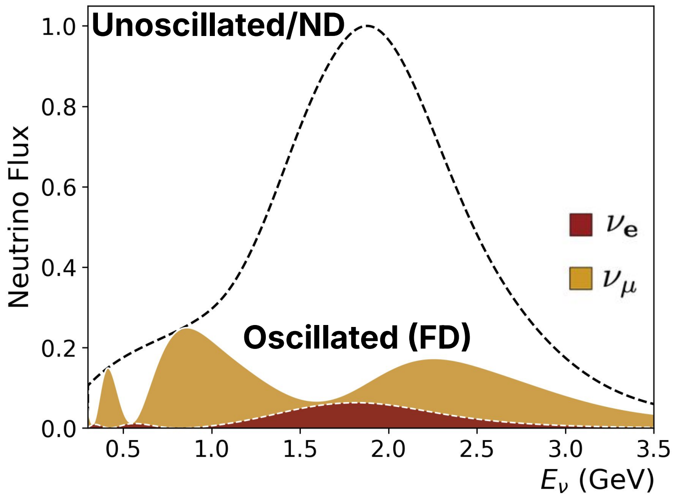
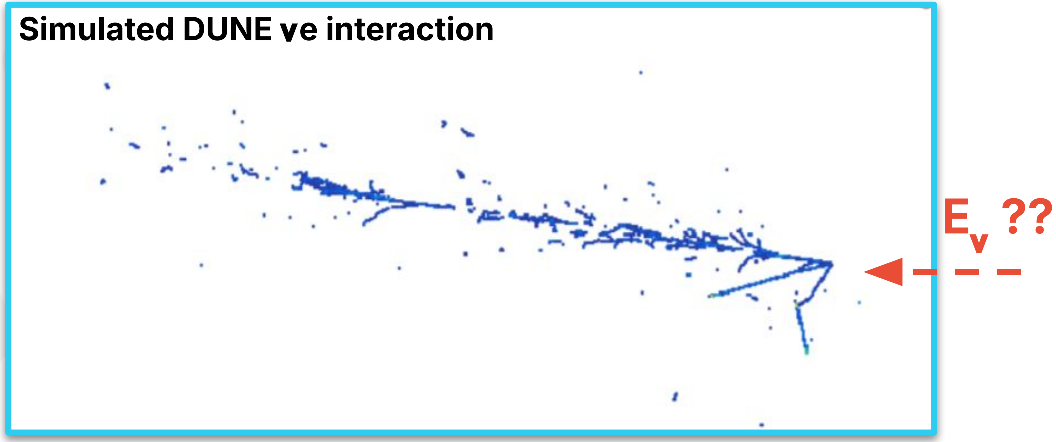
Appeared ν_e

DUNE in the UK

- Hardware:
  - Far Detector Module 1 Readout Hardware
  - Proton Accelerator Components
  - Neutrino Beam Targetry
  - DUNE Phase-II Near and Far Detector R&D
- Software:
  - Data Acquisition Software
  - Neutrino Interaction Simulations
  - Near and Far Detector Simulation and Reconstruction
- Analysis:
  - Beam + Atmospheric Long Baseline Oscillations

Why Precision Measurements Are Difficult





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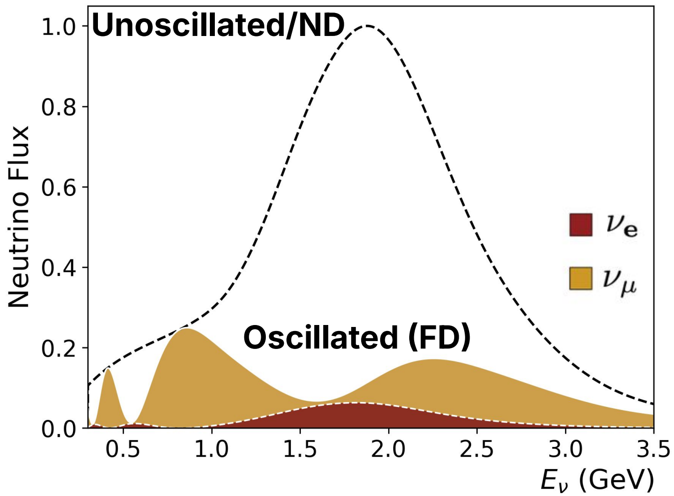

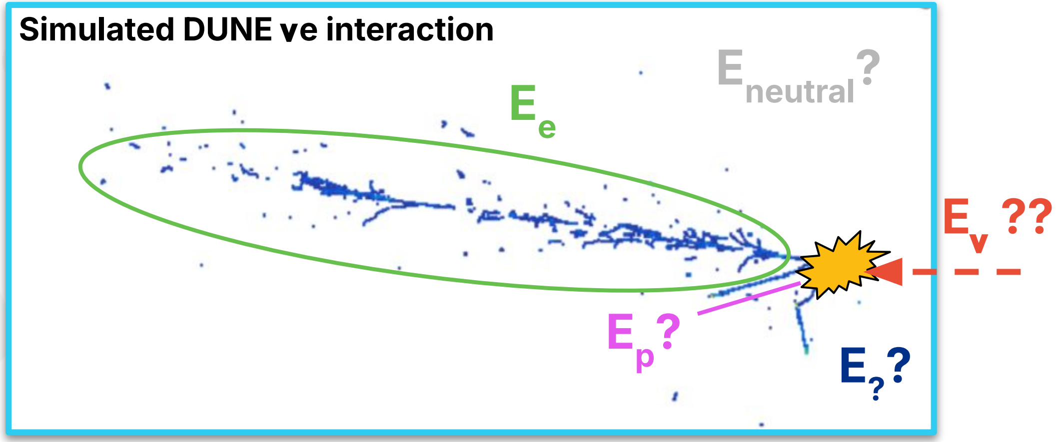

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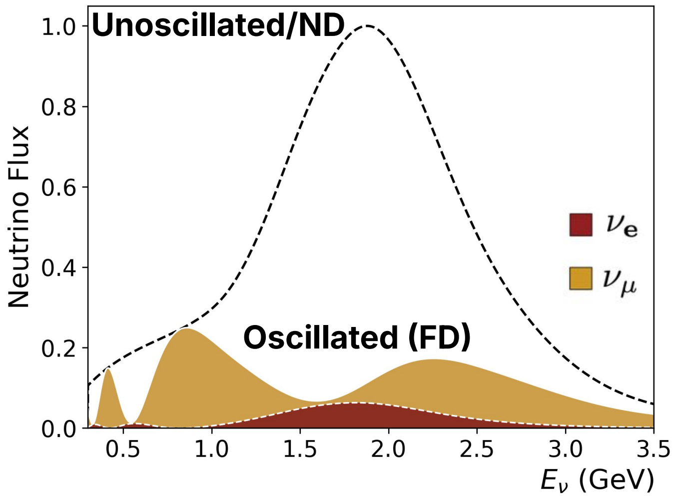

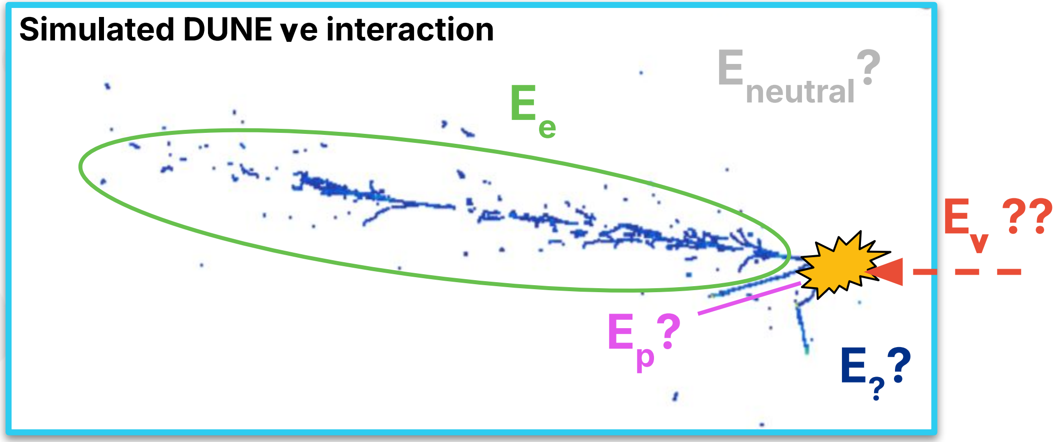

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  - Must use models to infer true energy distributions from observed energy deposits
  - Few-GeV neutrino–nucleus interactions particularly hard to model
  - Have to use Near Detector (ND) to learn as much as we can about neutrino interactions.
  - **Fundamental Problem:** ND is wide-band, but oscillated spectrum has crucial fine structure so we cannot blindly apply constraints from ND to FD

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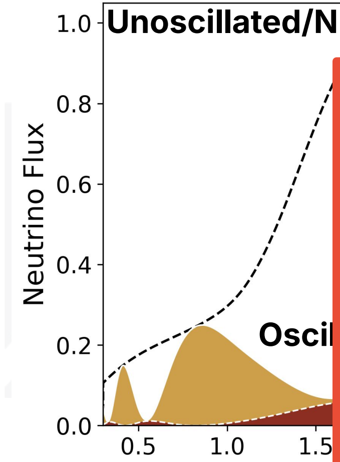

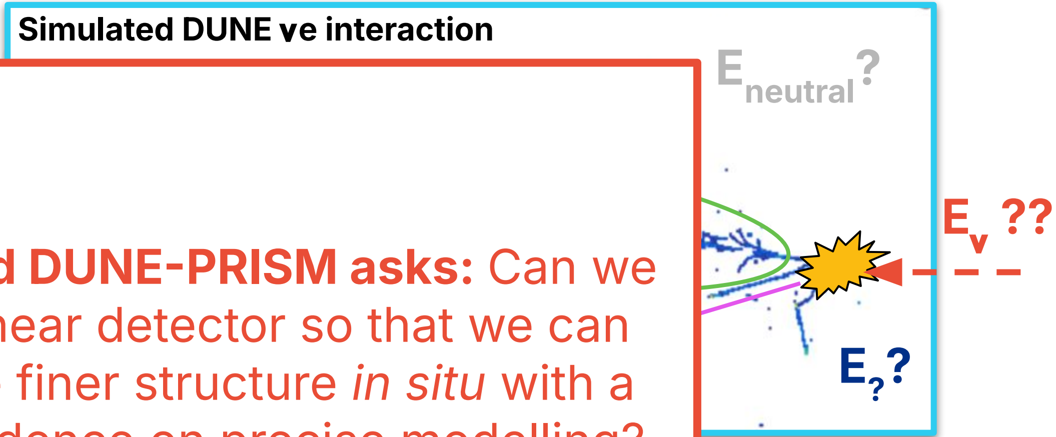

This Project and DUNE-PRISM asks: Can we configure the near detector so that we can learn about the finer structure *in situ* with a reduced dependence on precise modelling?

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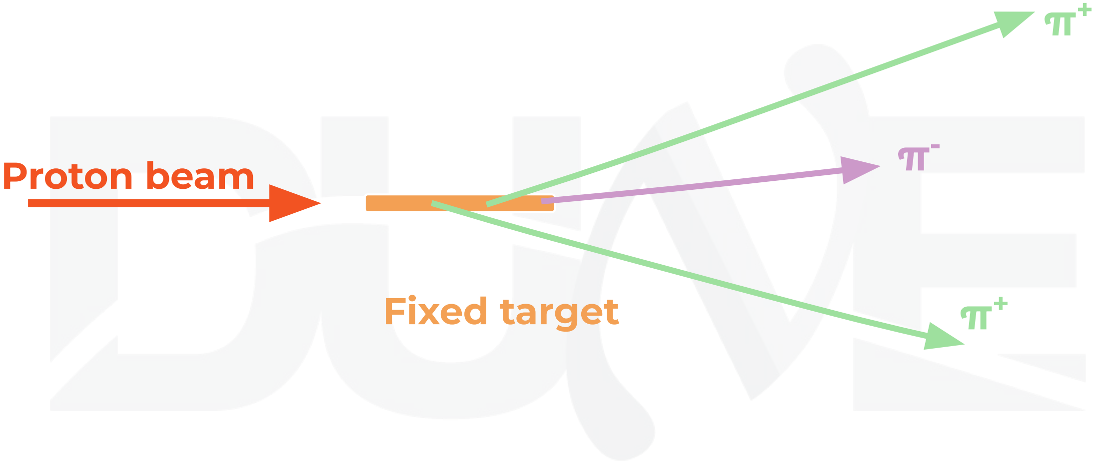
Neutrino Beams



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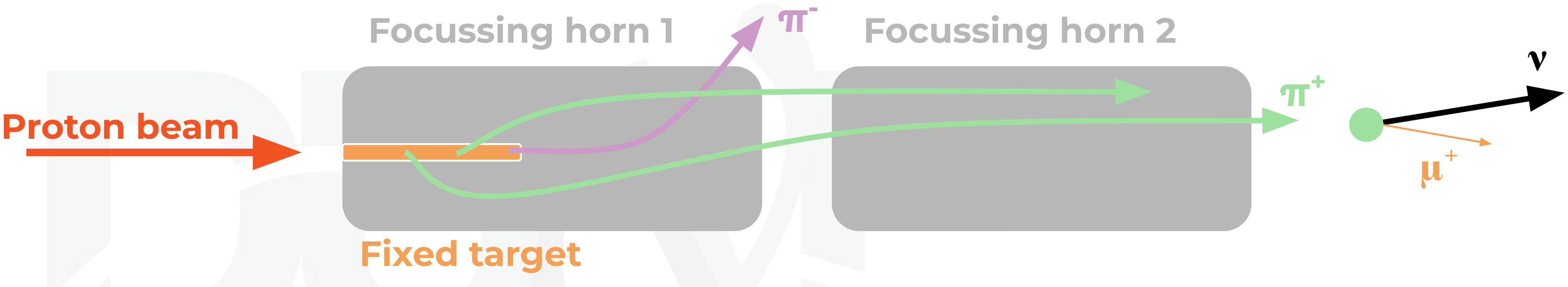

Neutrino mode, focussing positive particles

- Proton beam strikes a fixed target producing secondary hadrons: mostly pions and kaons
- These are sign-selected and focussed by one or more magnetic horns.
- This secondary beam of particles decays to produce neutrinos.

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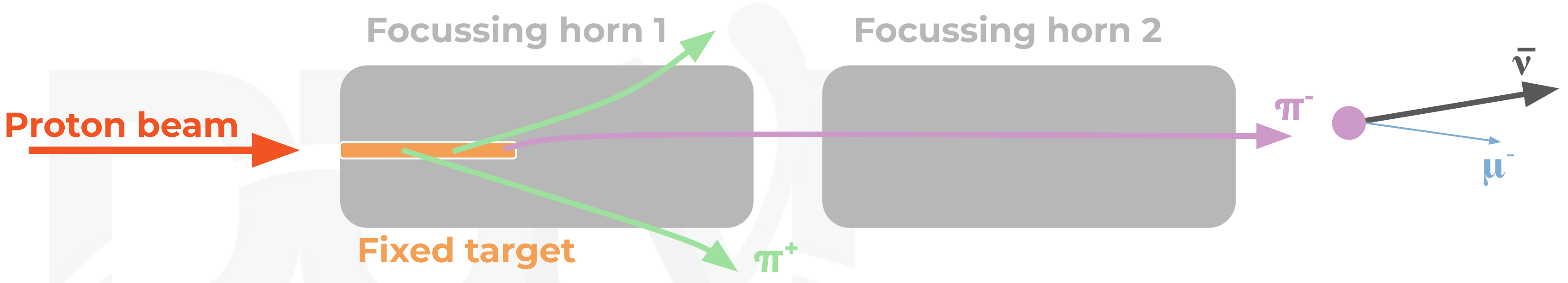

Anti-neutrino mode, focussing negative particles

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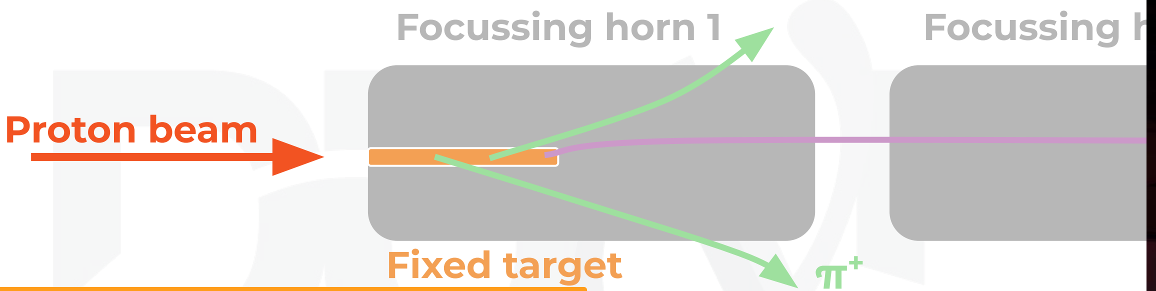
Neutrino Beams



The intensity frontier

- > 1 MW beam power
- ~10^{14} Protons per spill

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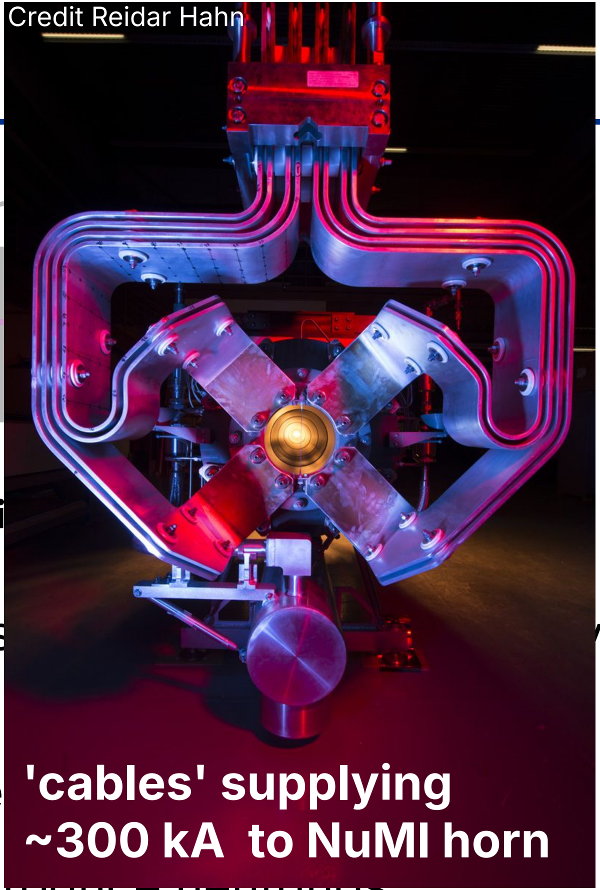
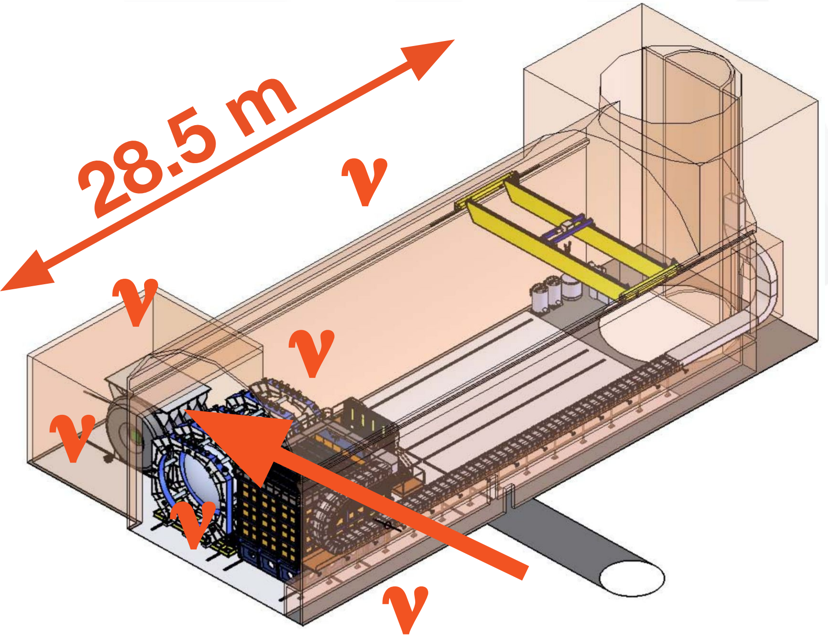


100 Ton Liquid Argon ND on rails!



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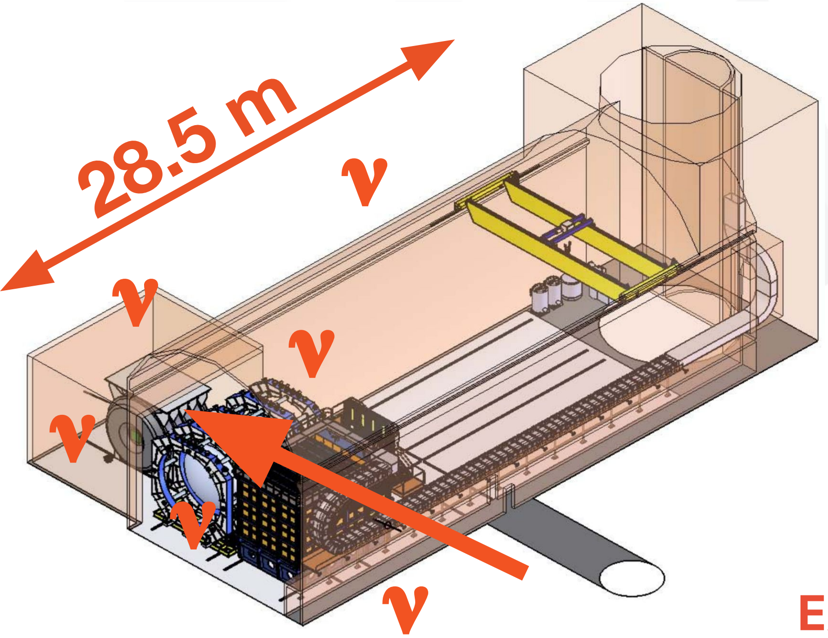
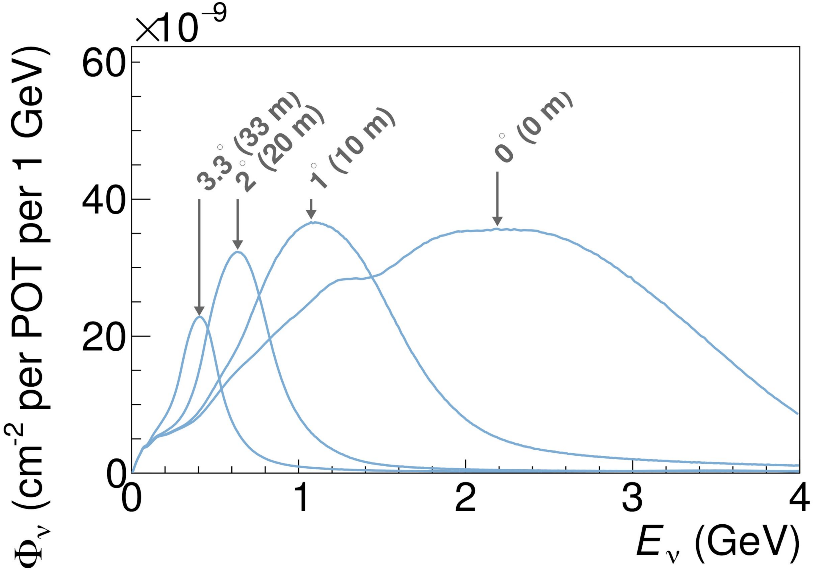
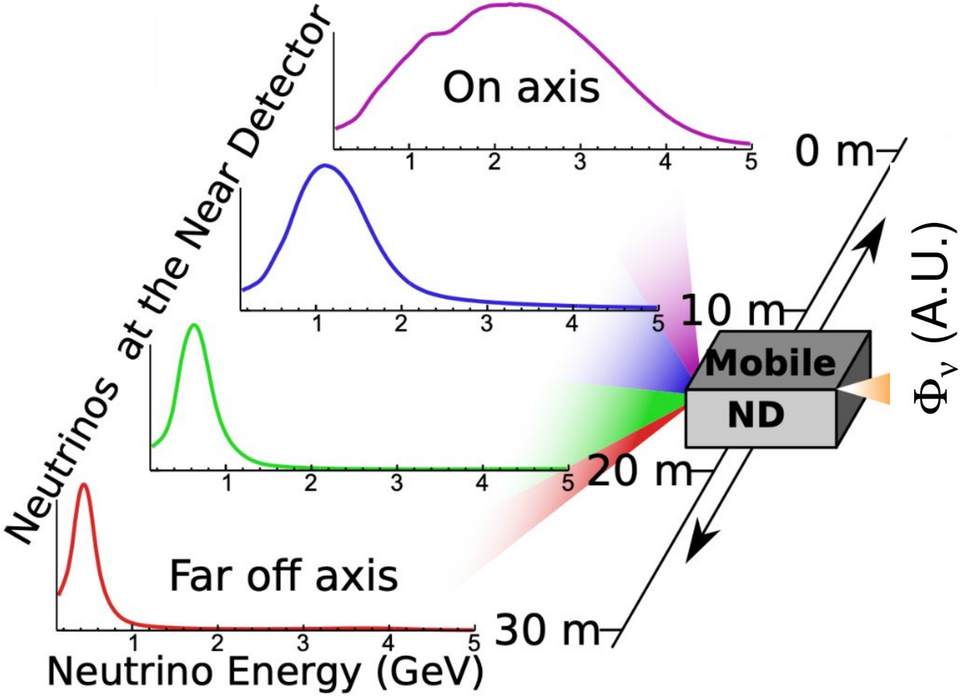
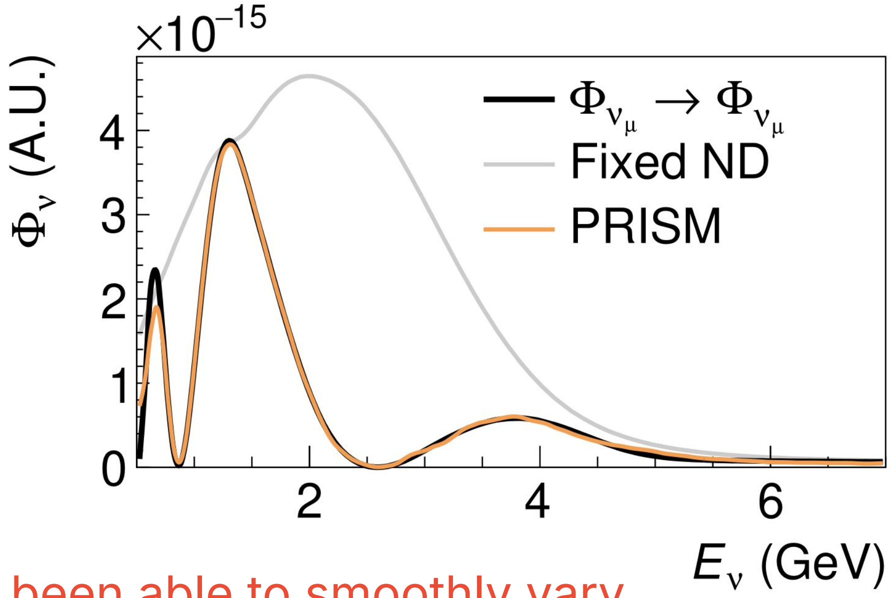




Exposed to different neutrino energy spectra as it is moved out of the centre of the beam





New Capability: First time we will have been able to smoothly vary the neutrino energy spectrum of an experiment

This Project

Study how best to use PRISM information to maximise DUNE Long Baseline Physics Reach

You will develop oscillation analysis software infrastructure that will form the basis for early DUNE flagship measurements

Opportunities to:

- Bring state-of-the-art parameter inference techniques to bare on fundamental physics problems
- Work with realistic detector simulation/reconstruction to study impact of detector performance on DUNE physics
- Use existing neutrino scattering data to demonstrate PRISM insensitivity to plausible variations of the neutrino interaction model

Supervisors

- Convenes DUNE Long Baseline Physics Group
- Convenes T2K Neutrino Interactions Group
- Develops neutrino interaction simulations and neutrino scattering data comparison tools

- NOvA Analysis Coordinator
- Convenes DUNE Near Detector Simulation/Reconstruction Group
- Interest in neutrino interactions and neutrino oscillation measurements

PhD Example Timeline

QMUL (1yr)

Oct 25 - Jan 26: University of London Particle Physics Course
Feb - Sept 26: Near Detector Simulation/Reconstruction Work

RAL (1yr)

October 26 - Sept 27: Oscillation Analysis Development

LTA (~6m)

Oct 27 - Mar 28: @FNAL/UMN Experience Midwestern winter & Work on PRISM movement prototype

RAL (1yr)

Apr 28 - Dec 28: PRISM Analysis Studies
Jan - Mar 29: Write-up and Defend

→ Gainful Onward Employment!

Why I Love Working With Neutrinos

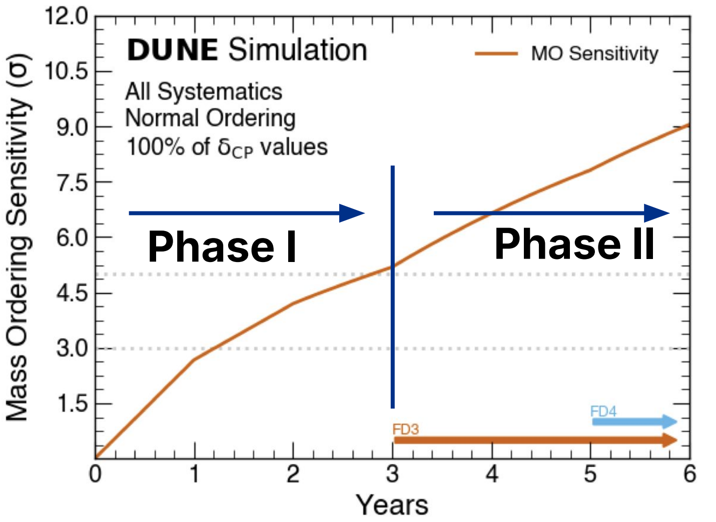
- **Tiny weak force cross sections** combined with **colossal detectors** and ludicrously intense (anti)**neutrino beams** result in large, clean event samples to do physics with!
- Neutrino oscillations are the only confirmed probe of BSM phenomenon
  - We pretty much know from T2K/NOvA data that we **will** learn new things about fundamental symmetries from DUNE/Hyper-K:
    - Strong CPV in neutrino oscillations?
    - Normal or inverted neutrino mass ordering?
    - $\boldsymbol{v}_{23}$ mixing still consistent with maximal?
  - Now we get to measure them!
- Collaborations are small enough that individual students and RAs have a chance to have an outsized impact on some of the biggest known unknowns in particle physics

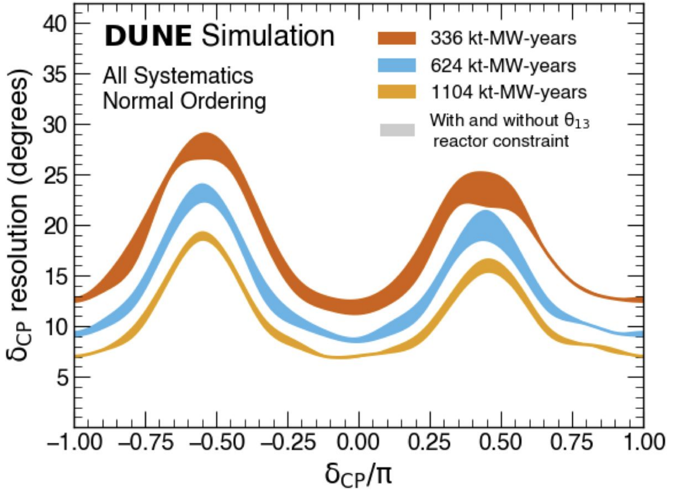
Backups

DUNE LBL Physics Goals

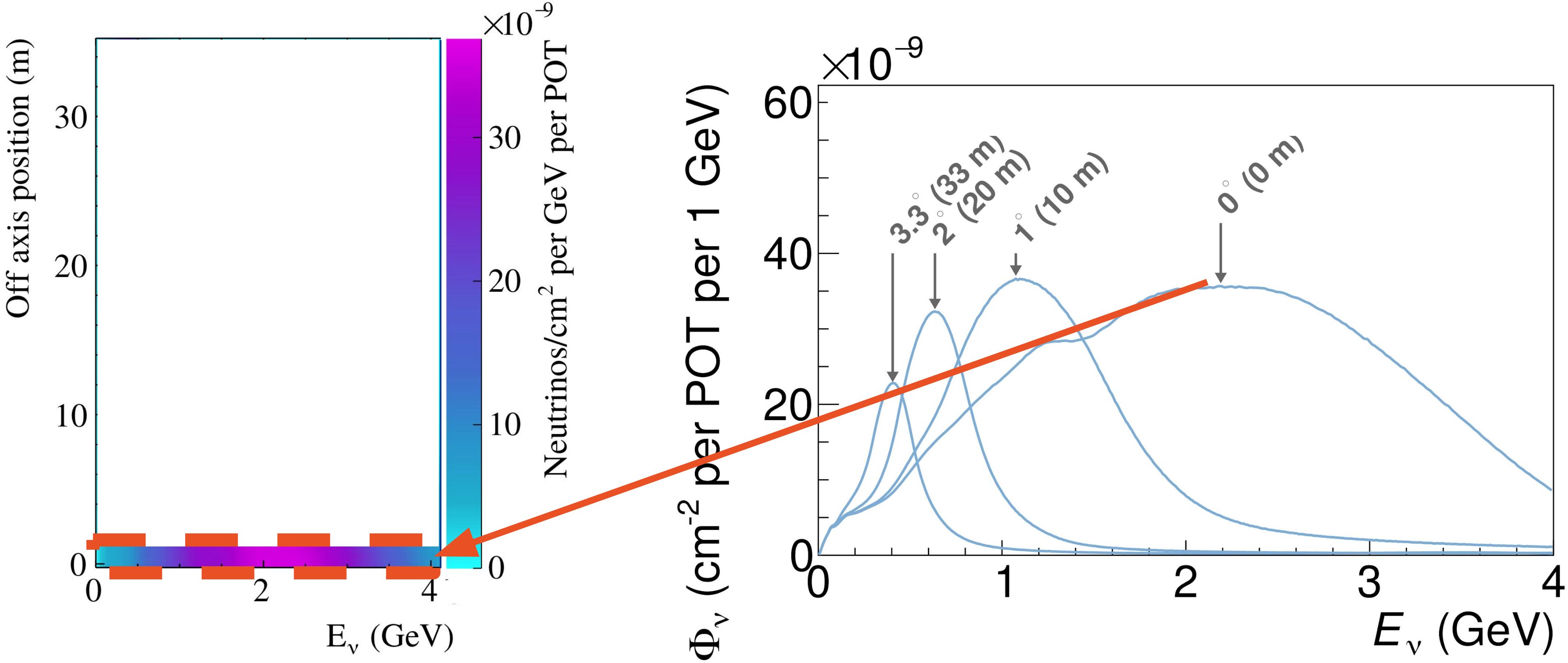
Split into two phases

- **Phase I:**
  - 5σ Mass ordering measurement independent of other mixing parameters
  - Exclude CP conservation at 3σ for true $\boldsymbol{\delta}_{CP} = \pm\pi$
- **Phase II:**
  - Measure $\boldsymbol{\delta}_{CP}$
  - Exclude CP conservation at:
    - > 3σ for 75% of $\boldsymbol{\delta}_{CP}$ values
    - > 5σ for 50% of $\boldsymbol{\delta}_{CP}$ values
  - Precision constraint of PMNS mixing
  - Non-unitarity searches including tau appearance channel





Off Axis at the Near Detector



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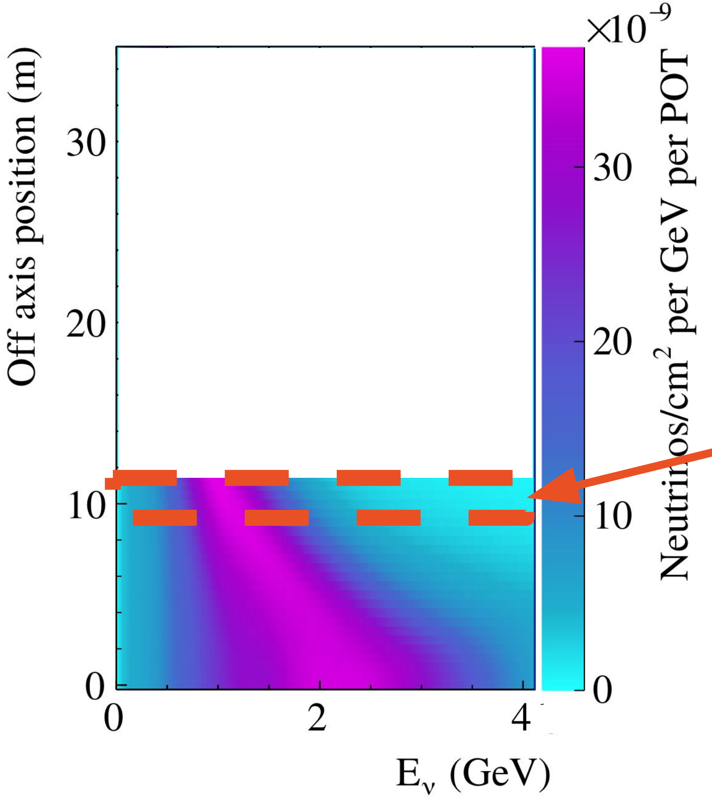

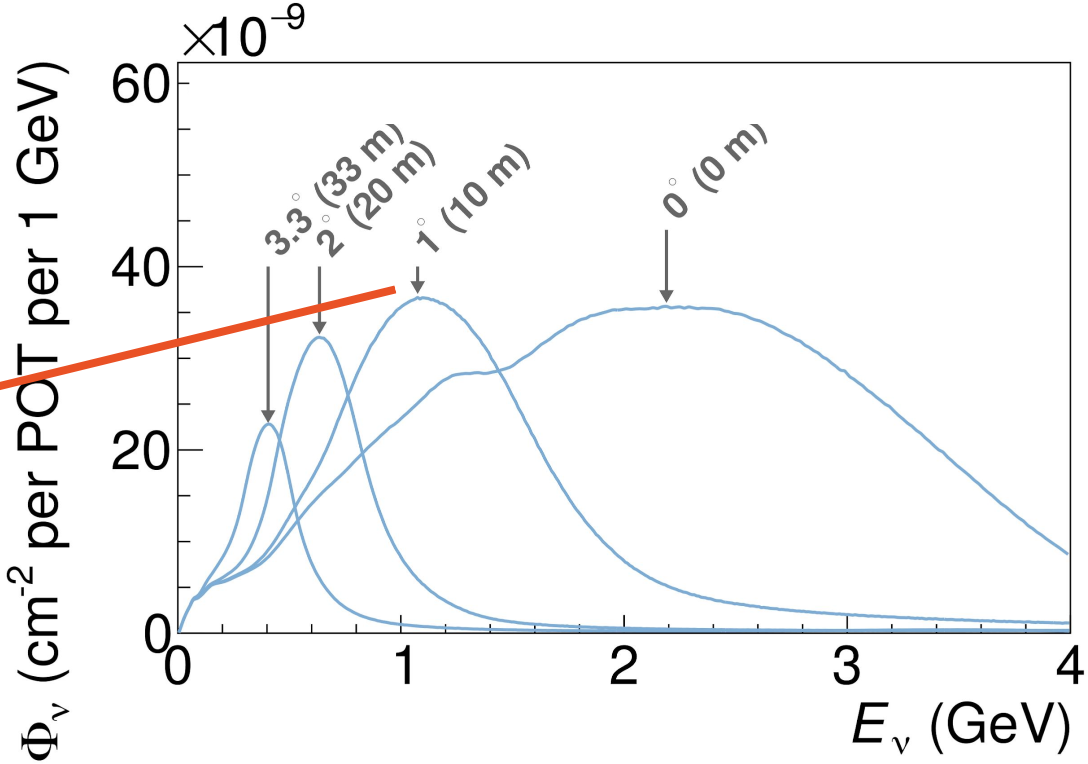

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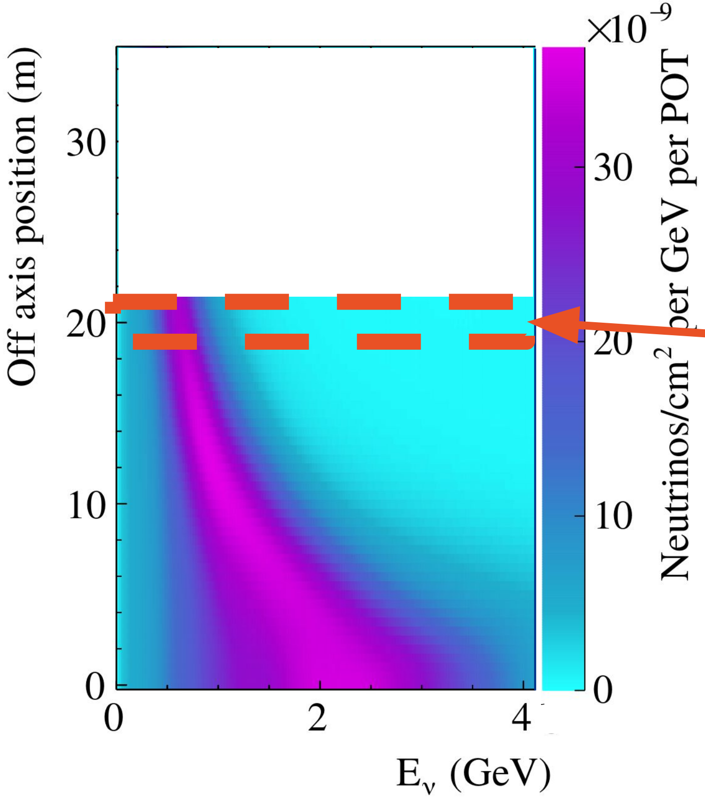

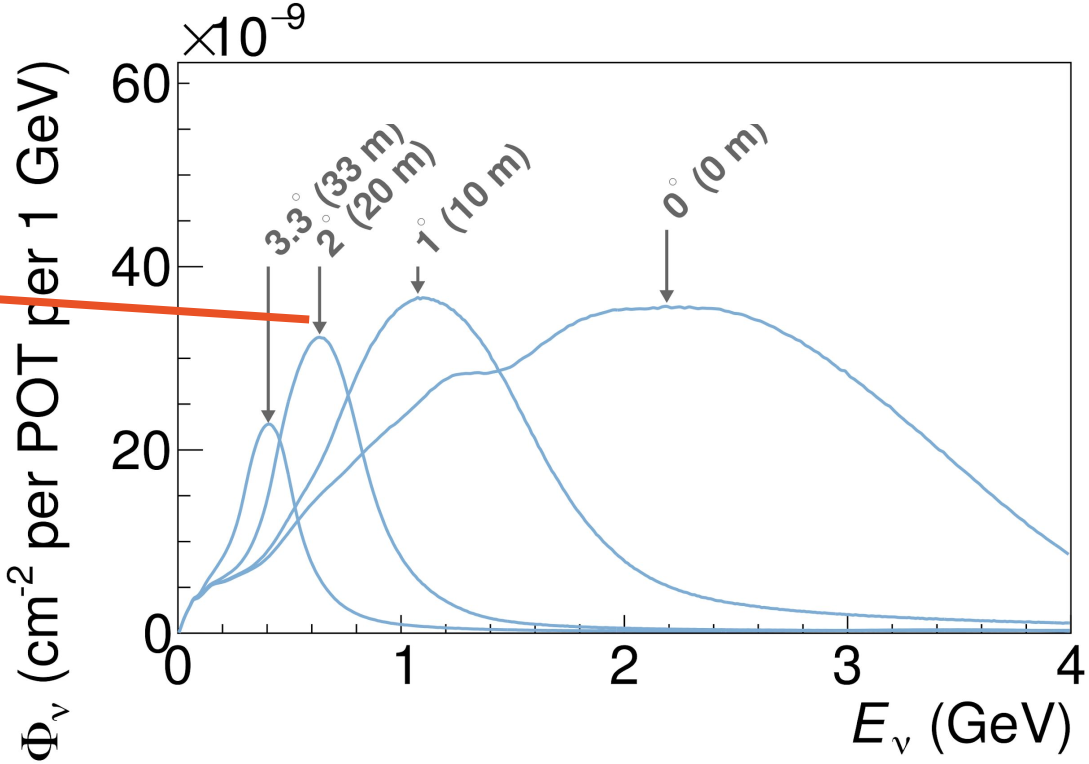

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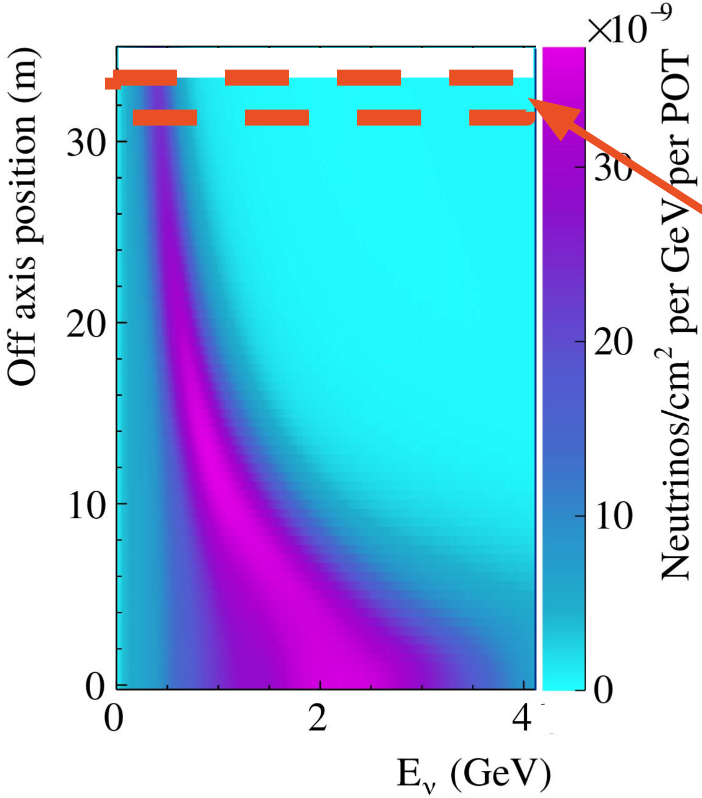
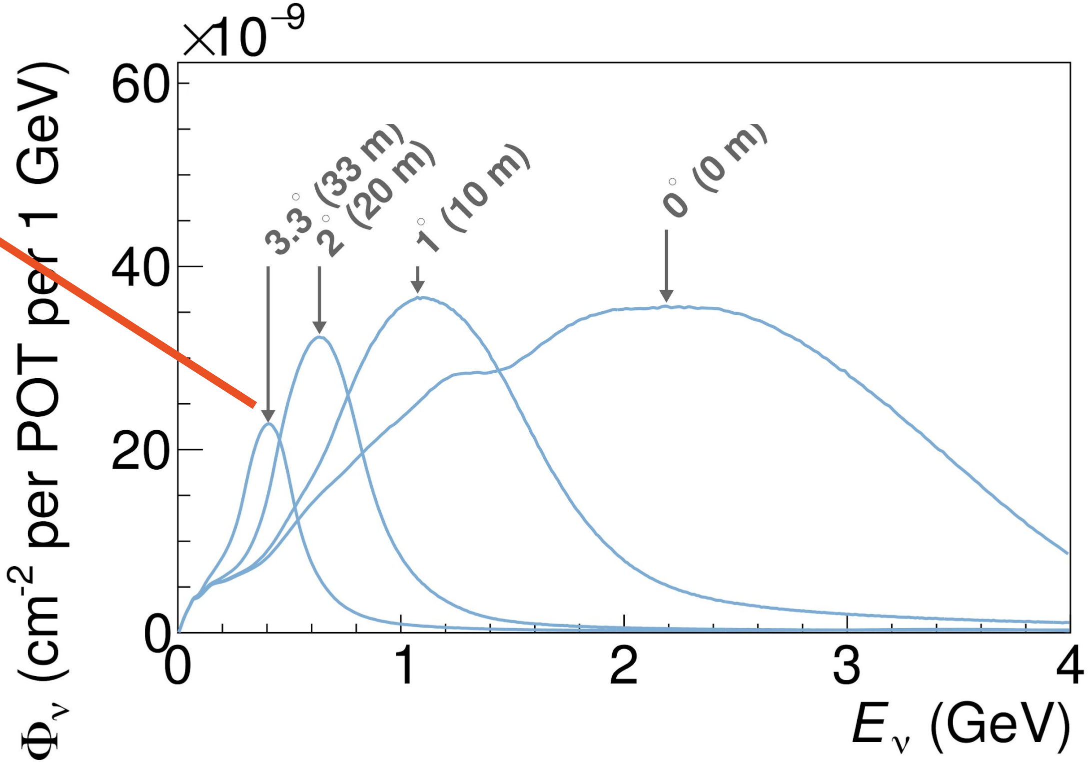
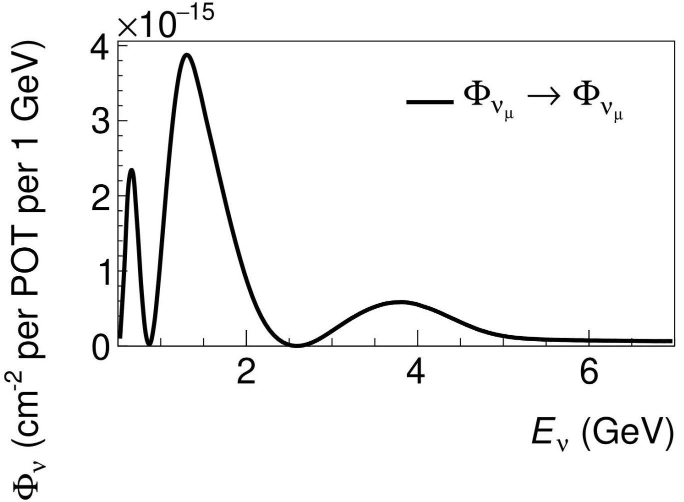




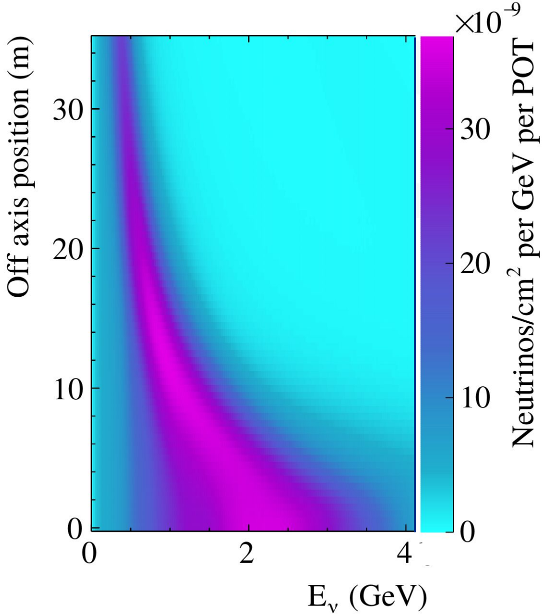
Predicting Oscillations with the Near Detector

$$\Phi^{\nu}_{\text{Far}} \cdot P^{\mathcal{H}}_{\text{Osc}}$$

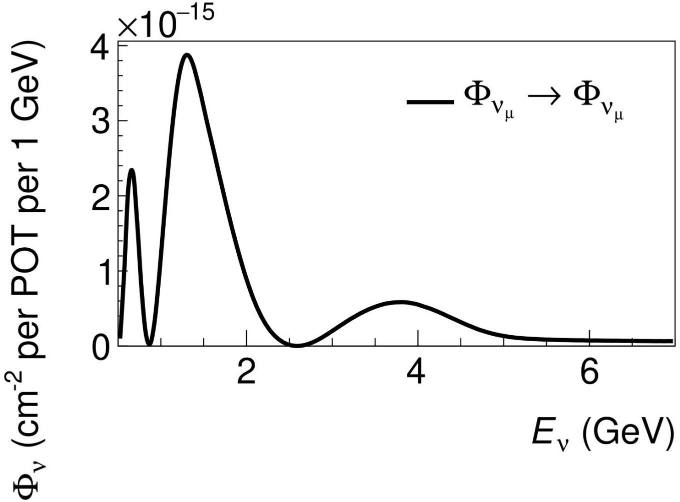


Predicting Oscillations with the Near Detector

$$\Phi^{\nu}_{\mathrm{Near}}$$

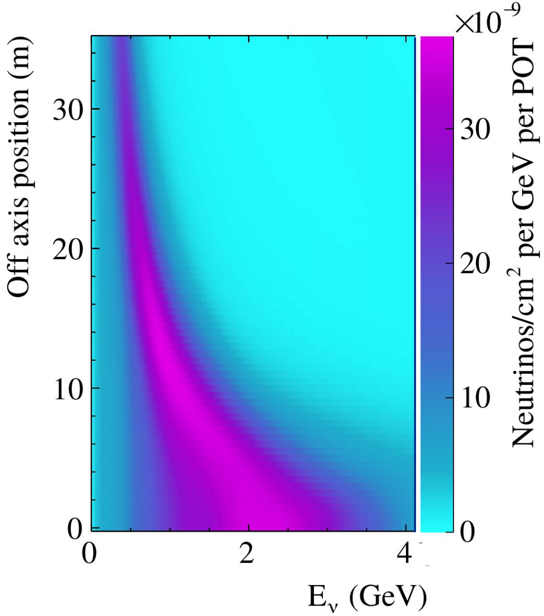


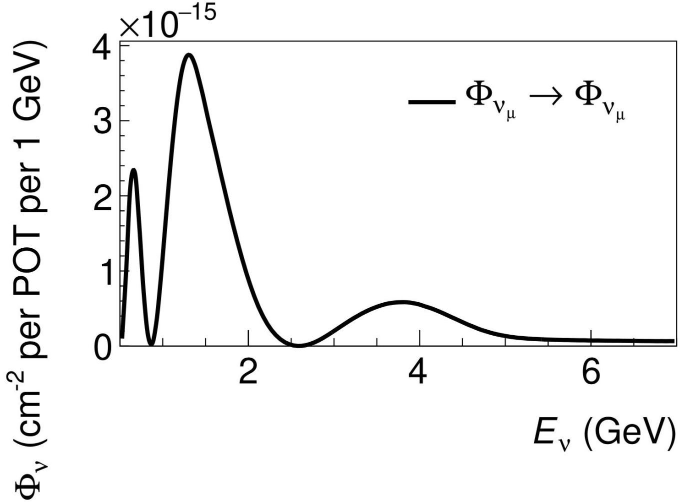
$$\Phi^{\nu}_{\mathrm{Far}} \cdot P^{\mathcal{H}}_{\mathrm{Osc}}$$



Predicting Oscillations with the Near Detector

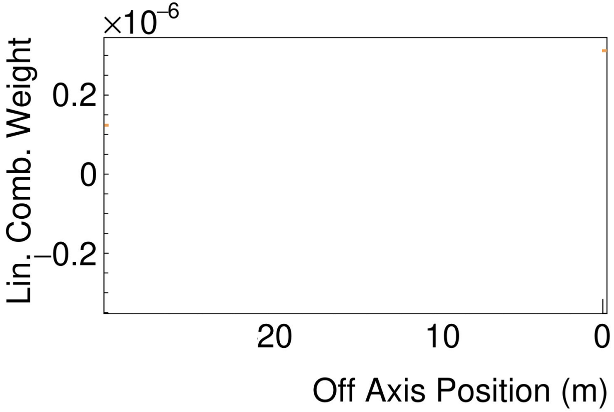
$$\Phi^{\nu}_{\text{Near}} \qquad \vec{\Phi}^{\nu}_{\text{Far}} \cdot P^{\mathcal{H}}_{\text{Osc}}$$

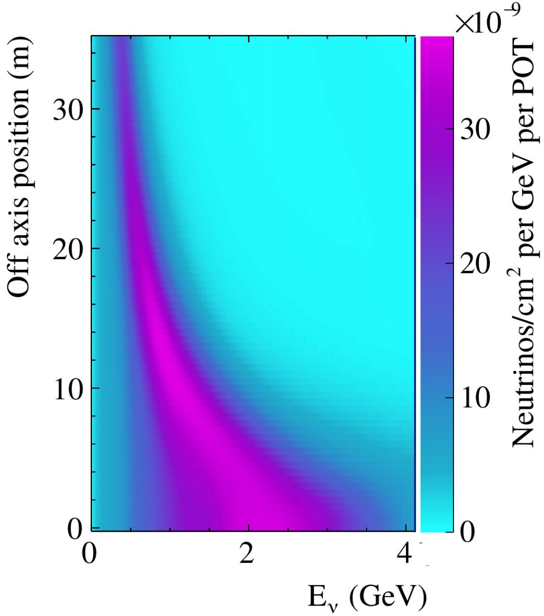


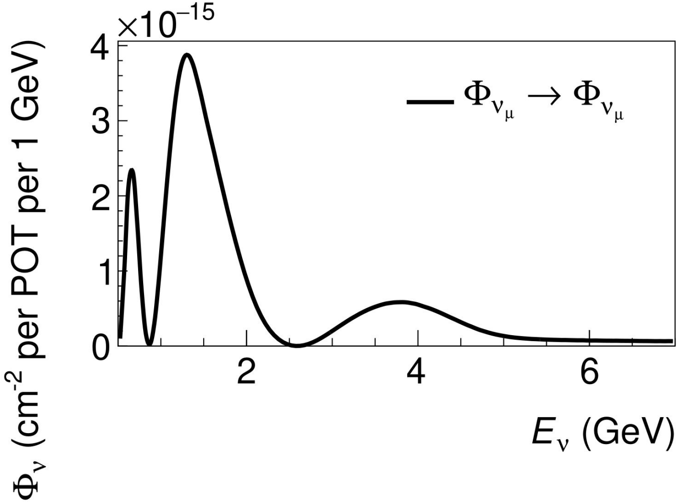


Predicting Oscillations with the Near Detector

$$\vec{\mathcal{C}} \cdot \Phi^{\nu}_{\text{Near}} = \vec{\Phi}^{\nu}_{\text{Far}} \cdot P^{\mathcal{H}}_{\text{Osc}}$$

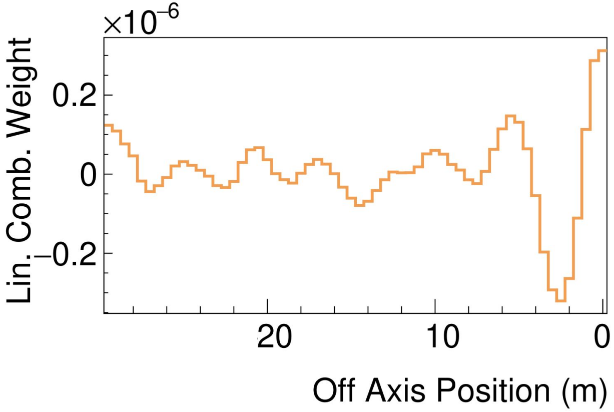


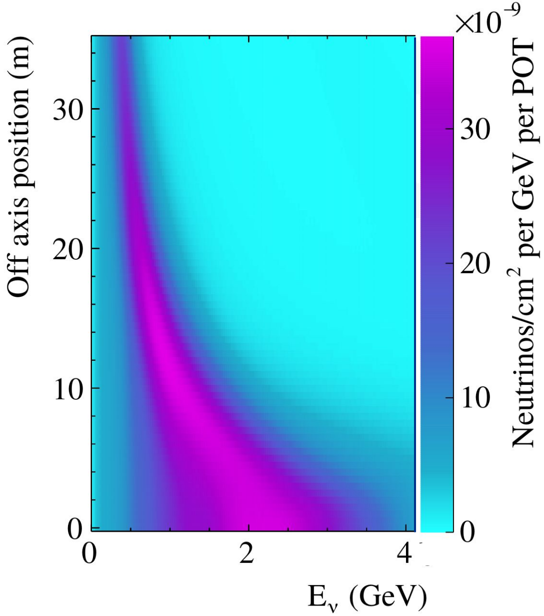


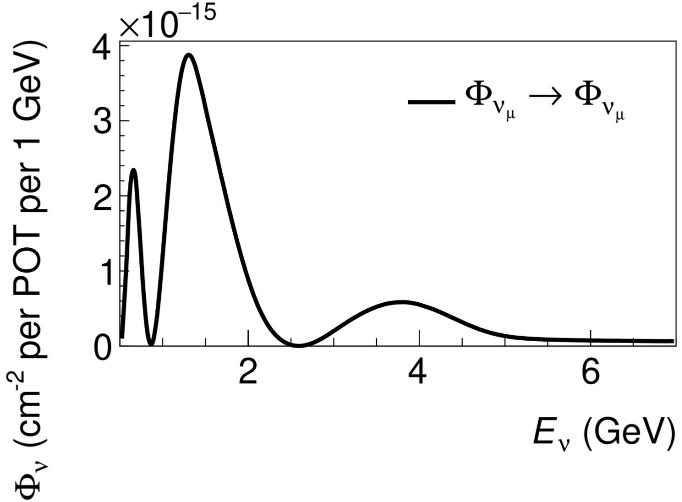


Predicting Oscillations with the Near Detector

$$\vec{\mathcal{C}} \cdot \Phi^{\nu}_{\mathrm{Near}} = \vec{\Phi}^{\nu}_{\mathrm{Far}} \cdot P^{\mathcal{H}}_{\mathrm{Osc}}$$

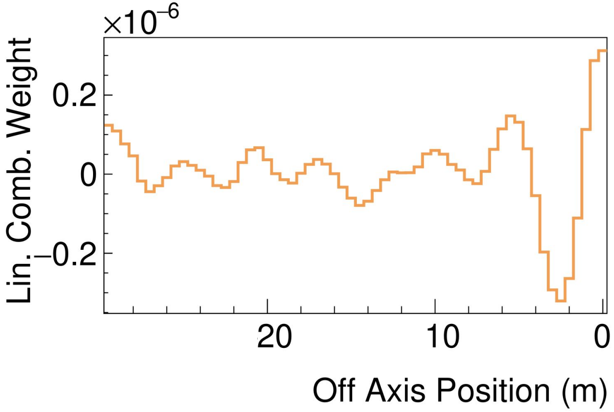


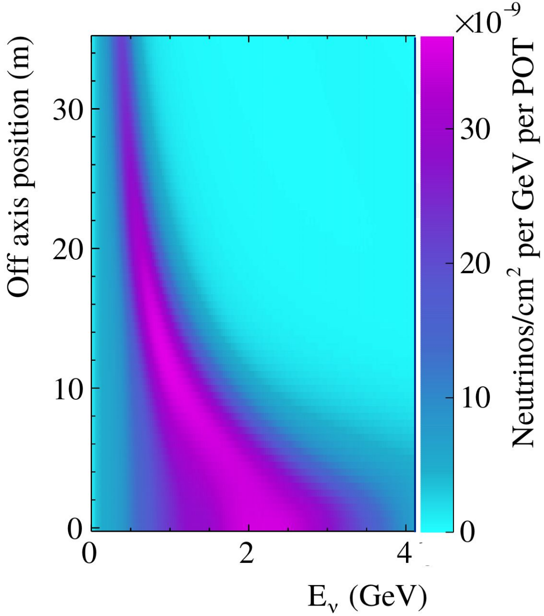


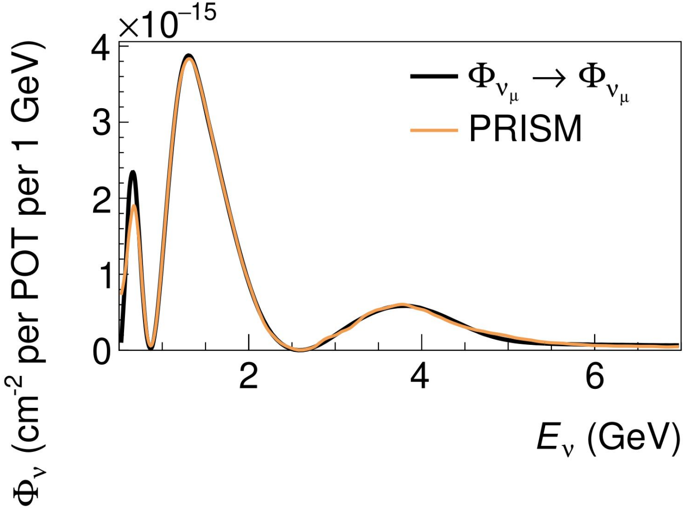


Predicting Oscillations with the Near Detector

$$\vec{\mathcal{C}} \cdot \Phi^{\nu}_{\mathrm{Near}} = \vec{\Phi}^{\nu}_{\mathrm{Far}} \cdot P^{\mathcal{H}}_{\mathrm{Osc}}$$

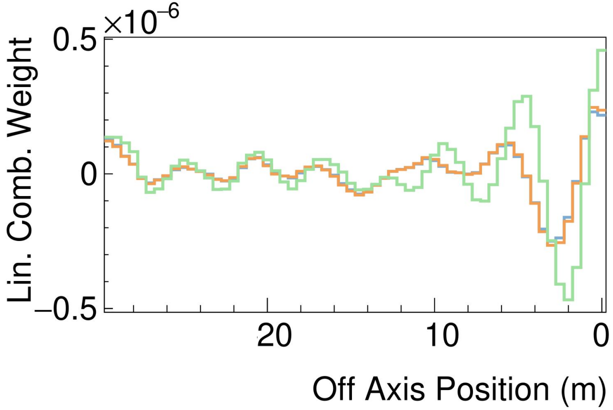


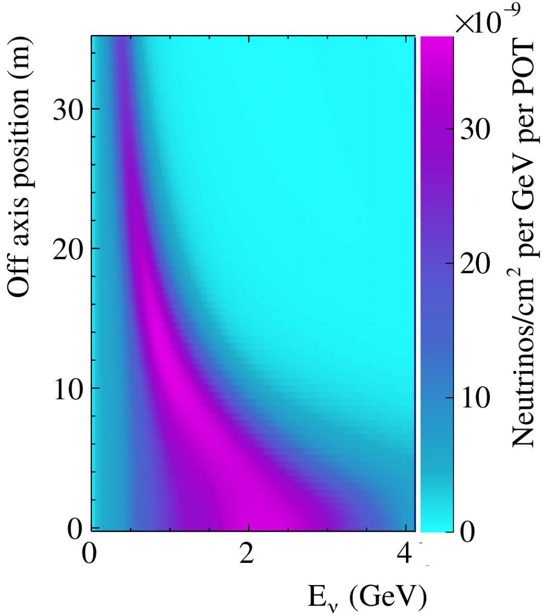


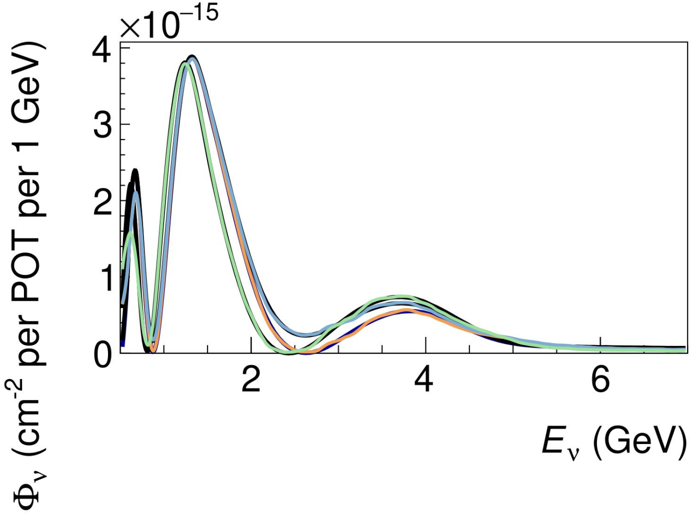


Predicting Oscillations with the Near Detector

$$\vec{\mathcal{C}}\left(P^{\mathcal{H}}_{\mathrm{Osc}}\right) \cdot \boldsymbol{\Phi}^{\nu}_{\mathrm{Near}} = \vec{\boldsymbol{\Phi}}^{\nu}_{\mathrm{Far}} \cdot P^{\mathcal{H}}_{\mathrm{Osc}}$$







Predicting Oscillations with the Near Detector

$$\vec{\mathcal{C}}\left(P^{\mathcal{H}}_{\mathrm{Osc}}\right) \cdot \underset{\left(=\,\Phi^{\nu}_{\mathrm{Near}}\cdot\sigma^{\nu}\right)}{\mathbf{R}^{\nu}_{\mathrm{Near}}} = \underset{\left(=\,\vec{\Phi}^{\nu}_{\mathrm{Far}}\cdot P^{\mathcal{H}}_{\mathrm{Osc}}\cdot\sigma^{\nu}\right)}{\vec{\mathrm{R}}^{\nu}_{\mathrm{Far}}}$$