DUNE: Long Baseline Sensitivities and Multi-Experiment Complementarities

Luke Pickering for the DUNE Collaboration

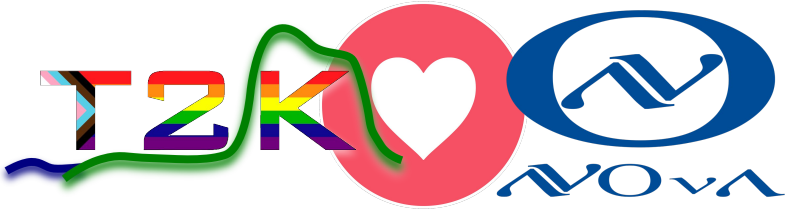
NuFact24, Argonne National Laboratory
2024/09/15

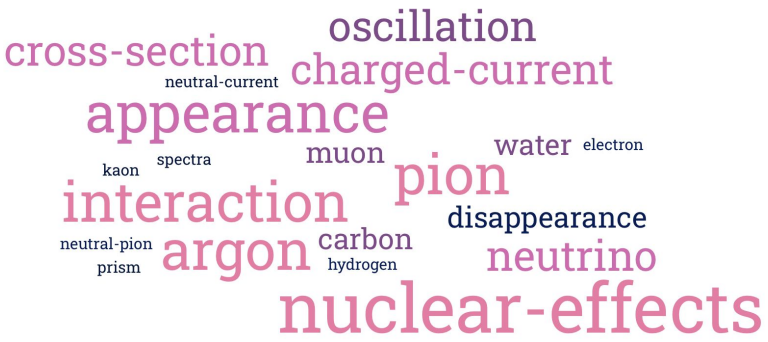
Science and Technology Facilities Council

Supported by URF\R1\211661

THE ROYAL SOCIETY

Wot I Think About





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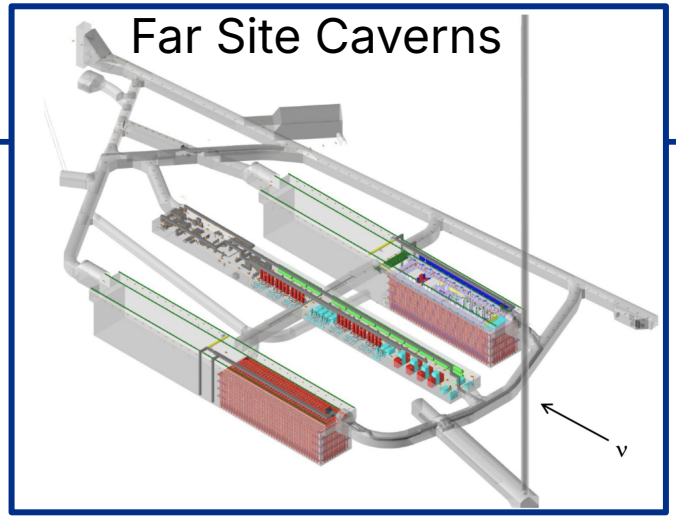
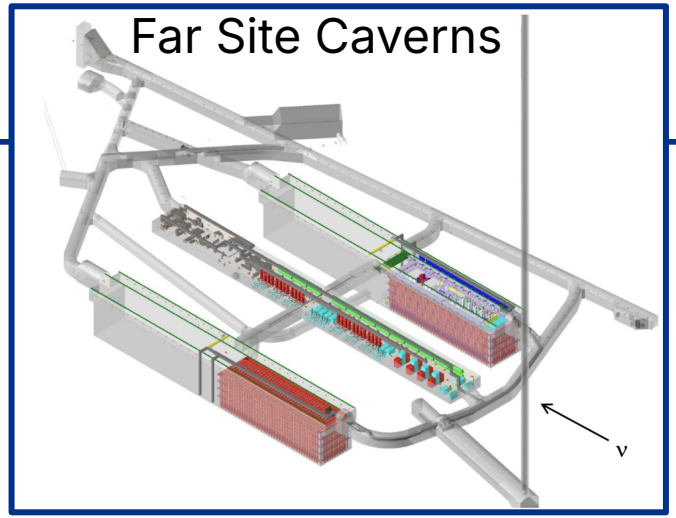
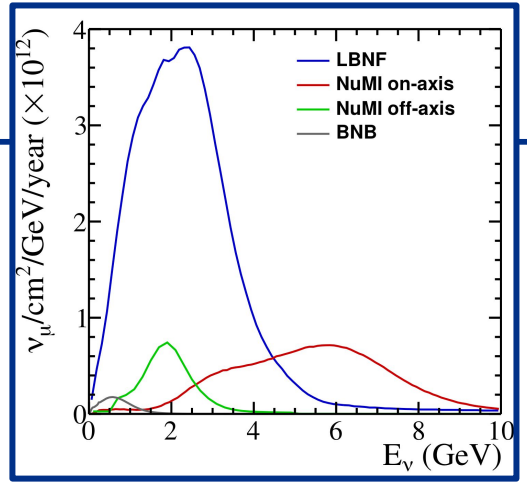


Phase I

- **2×17 kt active LAr far detectors**
  - Atmospheric data from ~2029 with FD1
- 1.2 MW on-axis beam, peaking at 2.3 GeV
  - 1300 km baseline
- Liquid Ar + muon system near detector
  - Moveable through 0–3° off axis
- On-axis beam monitor, SAND

DUNE





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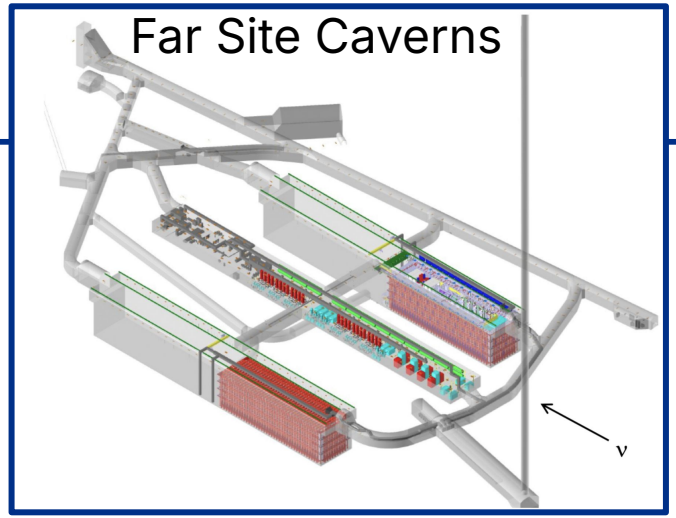

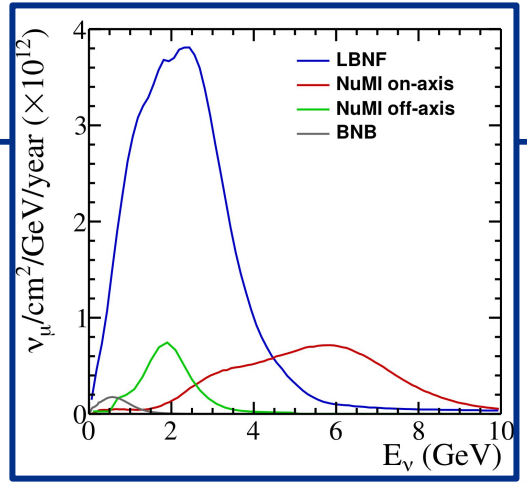

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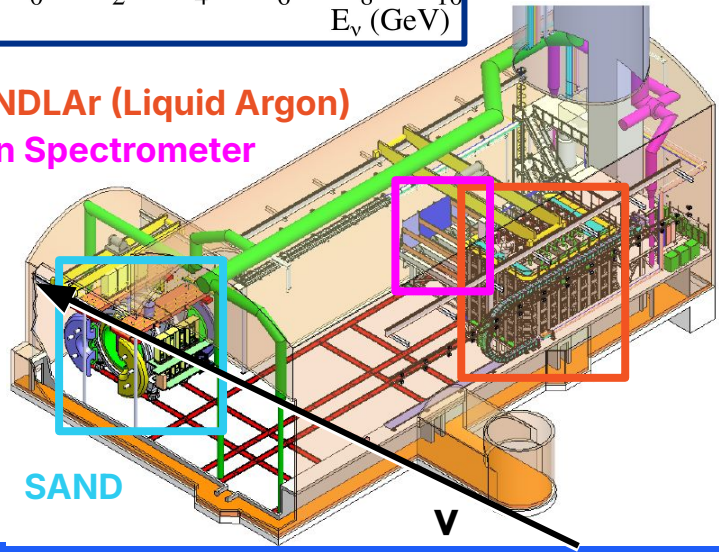

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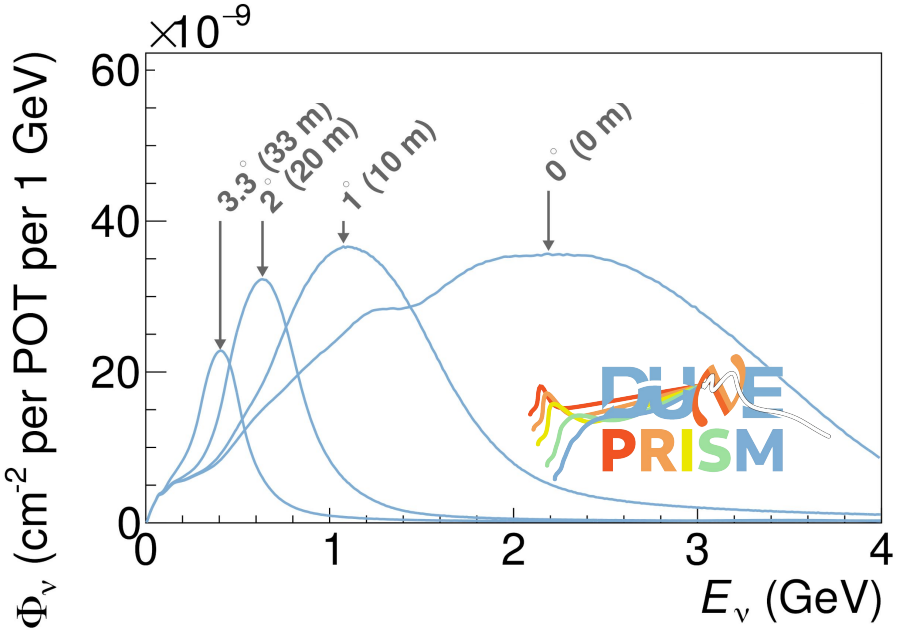

Near Detector Off-Axis Neutrino Spectra

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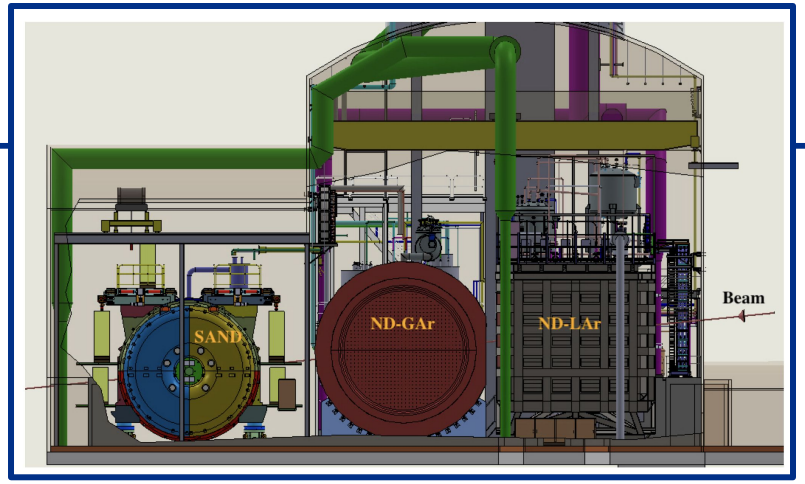

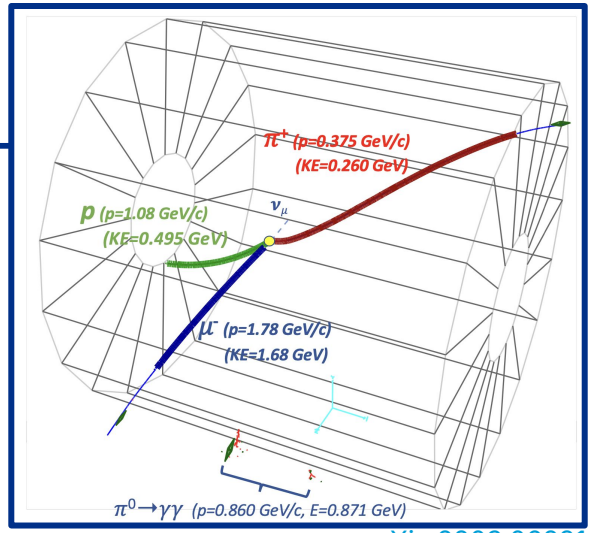

arXiv:2203.06281

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- Beam upgrade to 2.2 MW
- **ND muon system upgrade to dual-purpose, high-pressure gaseous Argon detector (MCND)**
  - Significantly improved capabilities for interaction uncertainty reduction

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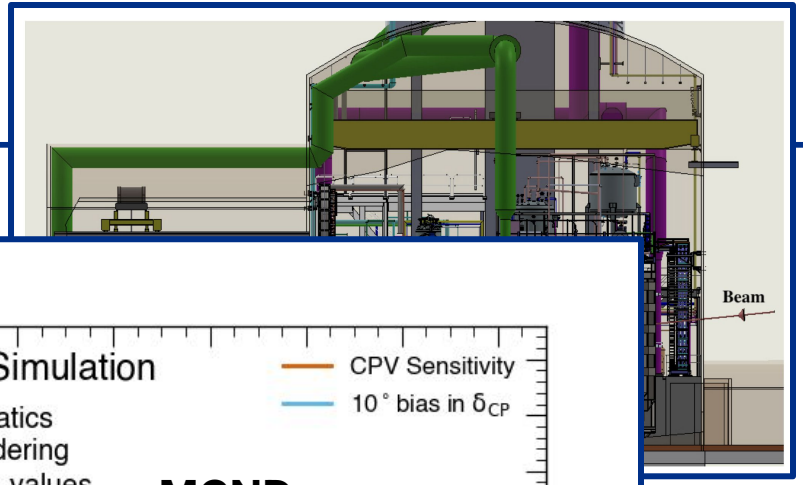

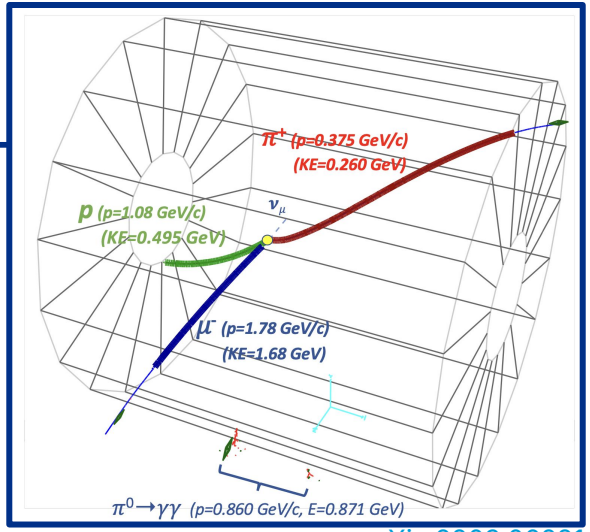

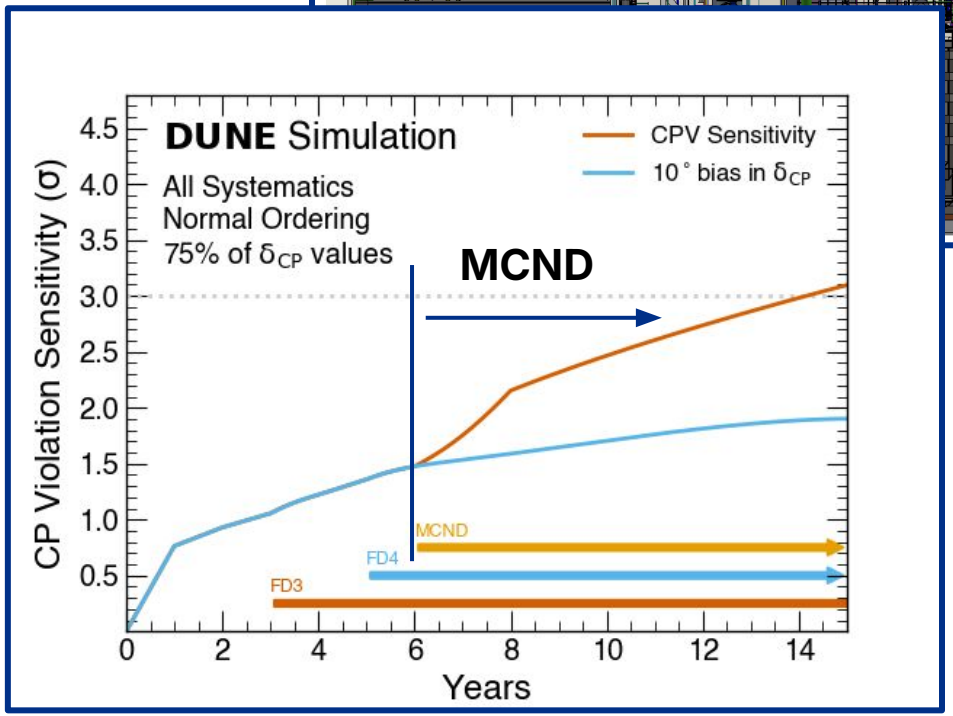

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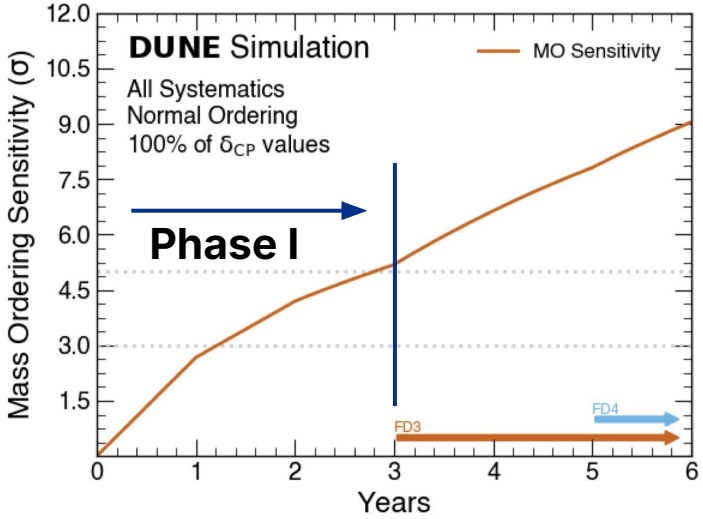
DUNE LBL Physics Goals

Split into two phases

- **Phase I**:
  - 5σ Mass ordering measurement independent of other mixing parameters
  - Exclude CP conservation at 3σ for true $\boldsymbol{\delta}_{CP} = \pm\pi$



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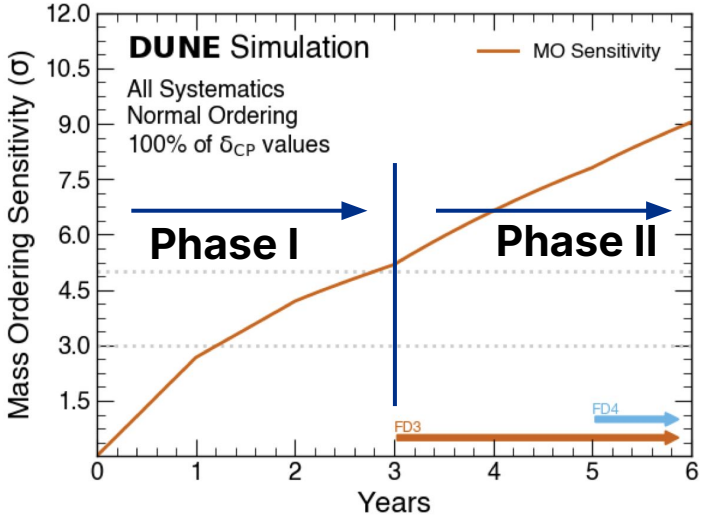
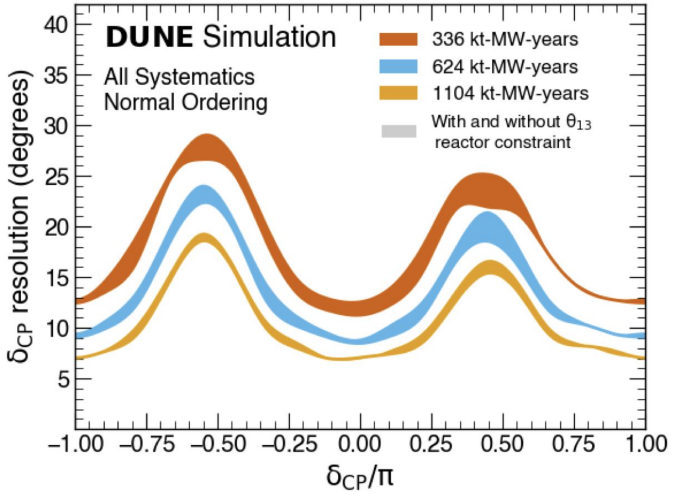
  - 5σ Mass ordering measurement independent of other mixing parameters
  - Exclude CP conservation at 3σ for true $\boldsymbol{\delta}_{CP} = \pm\pi$
- **Phase II:**
  - Measure $\boldsymbol{\delta}_{CP}$
  - Exclude CP conservation at:
    - > 3σ for 75% of $\boldsymbol{\delta}_{CP}$ values
    - > 5σ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

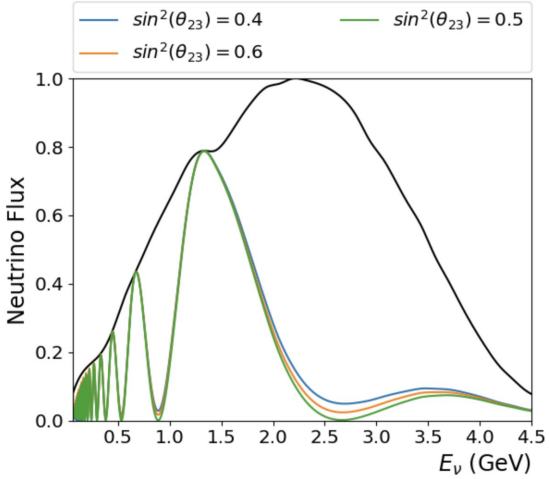


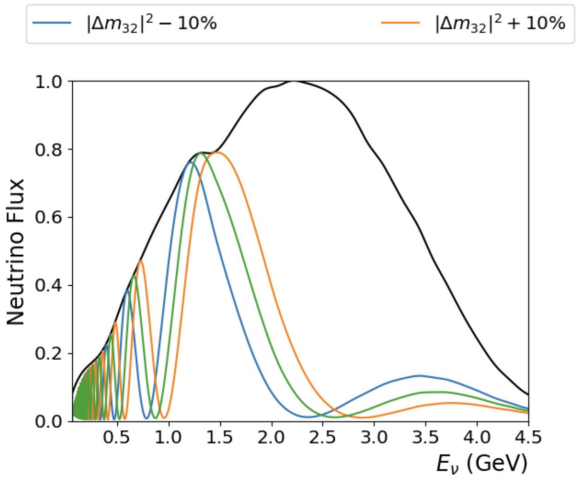


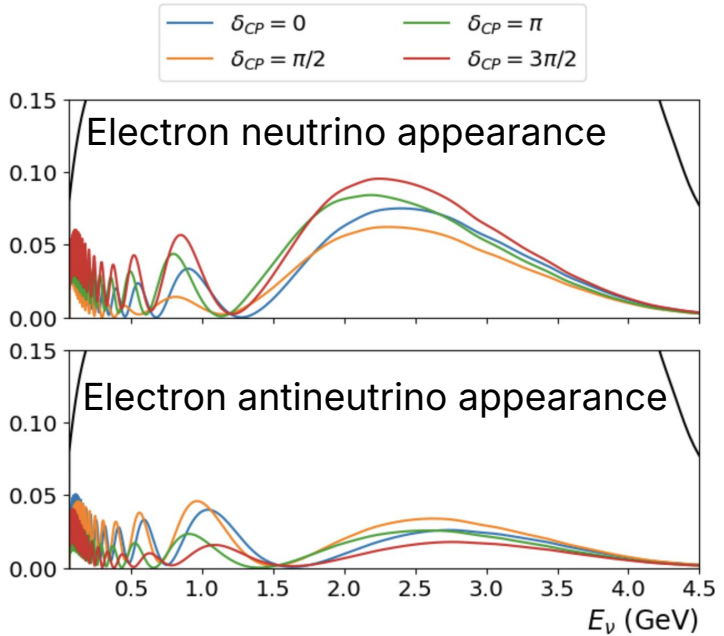
Design Features

- On-axis, wide-band beam:
  - **Observe more than a full oscillation period**
  - Higher energy → longer baseline → stronger matter effects
  - Appreciable rate above threshold for tau production

Muon neutrino disappearance







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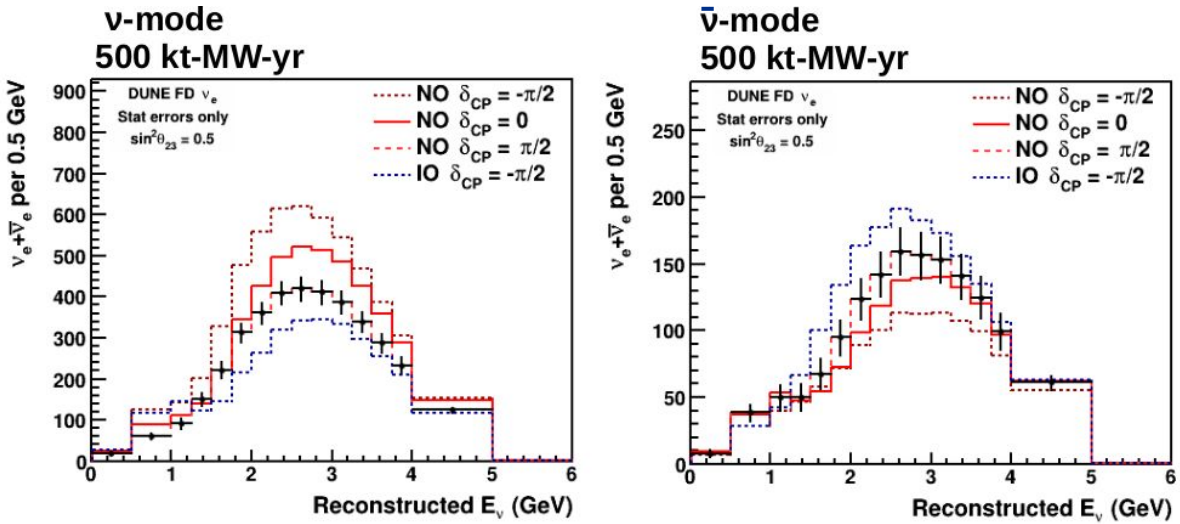

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- On-axis, wide-band beam:
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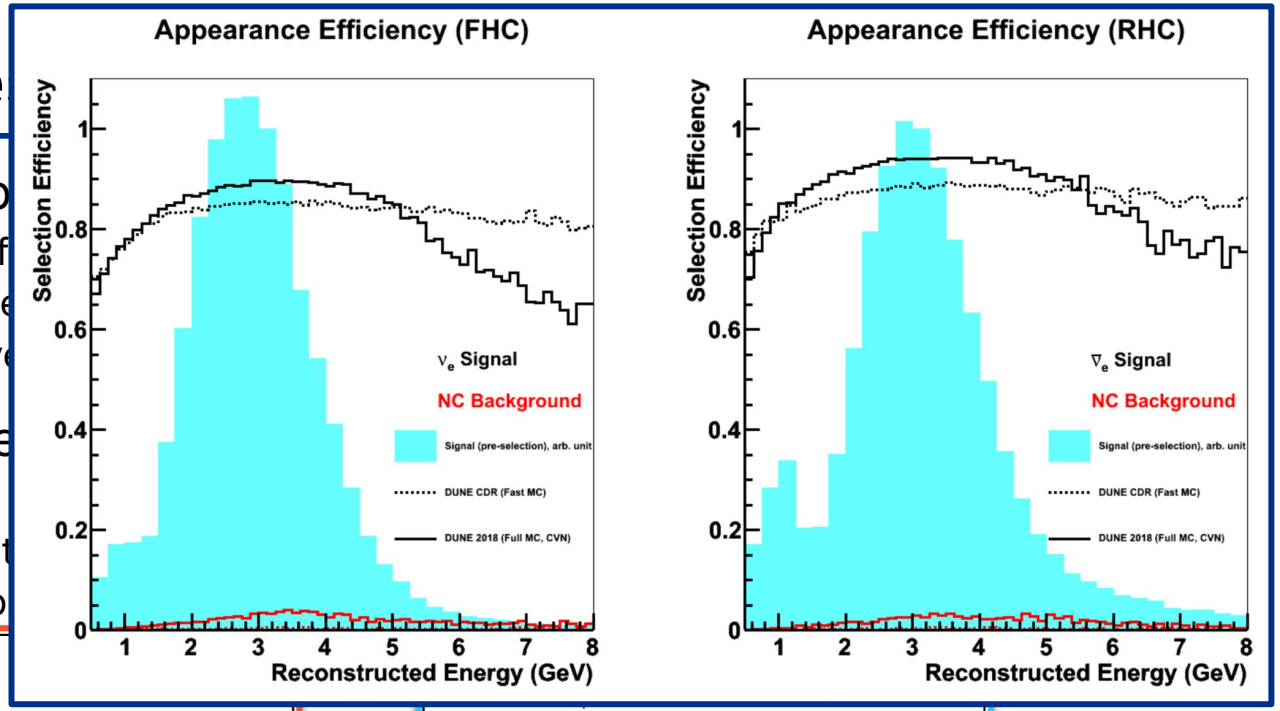

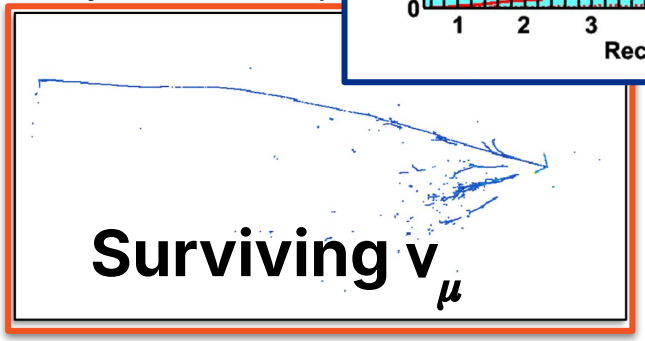

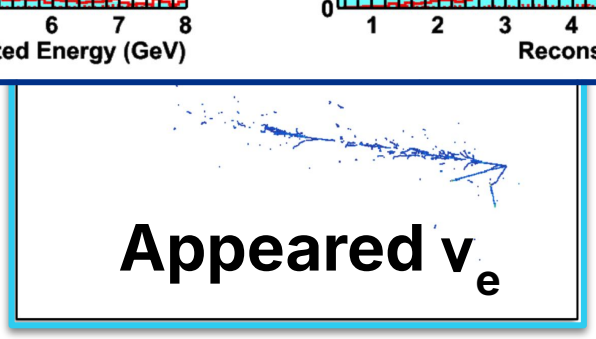

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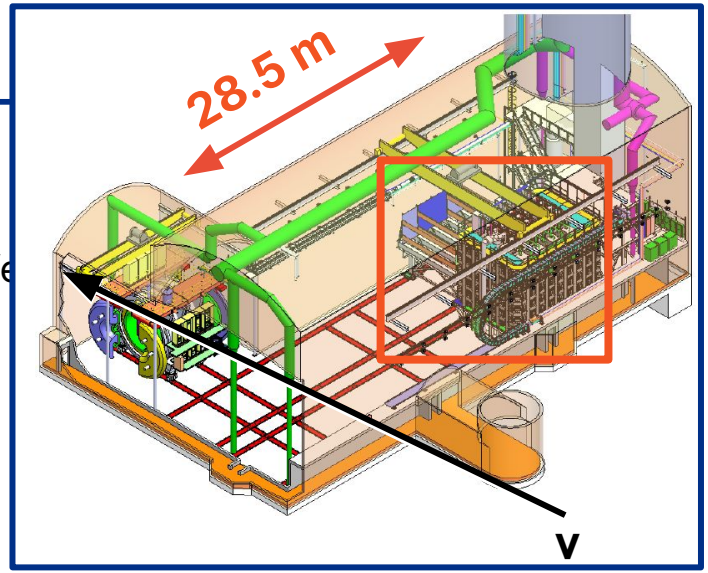
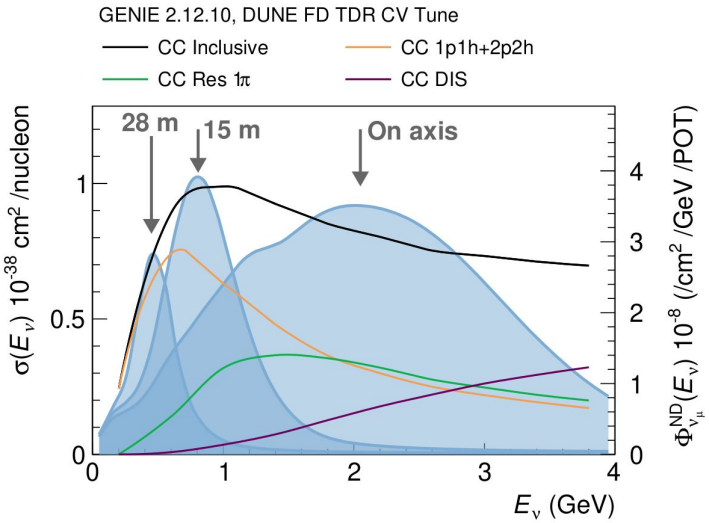
- Mobile near detector with the same target material:
  - Reduced reliance on model for target scaling
  - Use off axis data to 'over constrain' flux & cross section models



DUNE PRISM

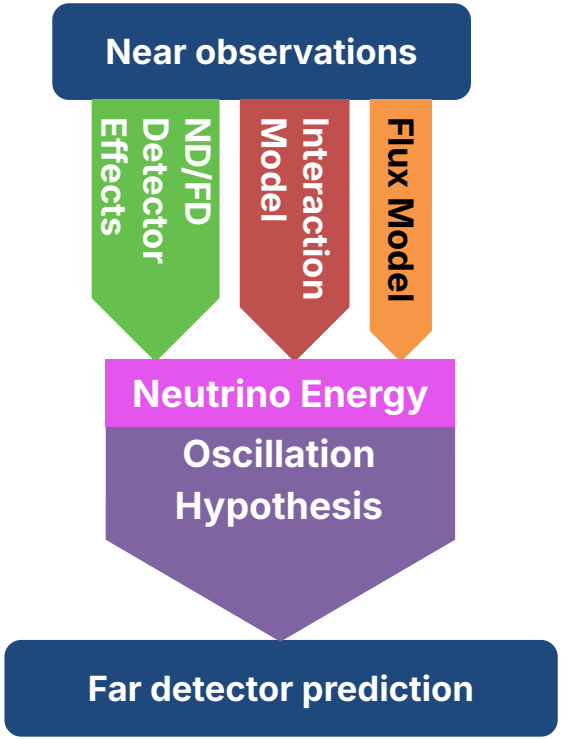
DUNE-PRISM: A Tale of Two Analyses

1) 'Over-constrain' flux and interaction model in 'traditional' oscillation analysis with on- and off-axis observations



DUNE-PRISM: A Tale of Two Analyses

Model-based Extrapolation



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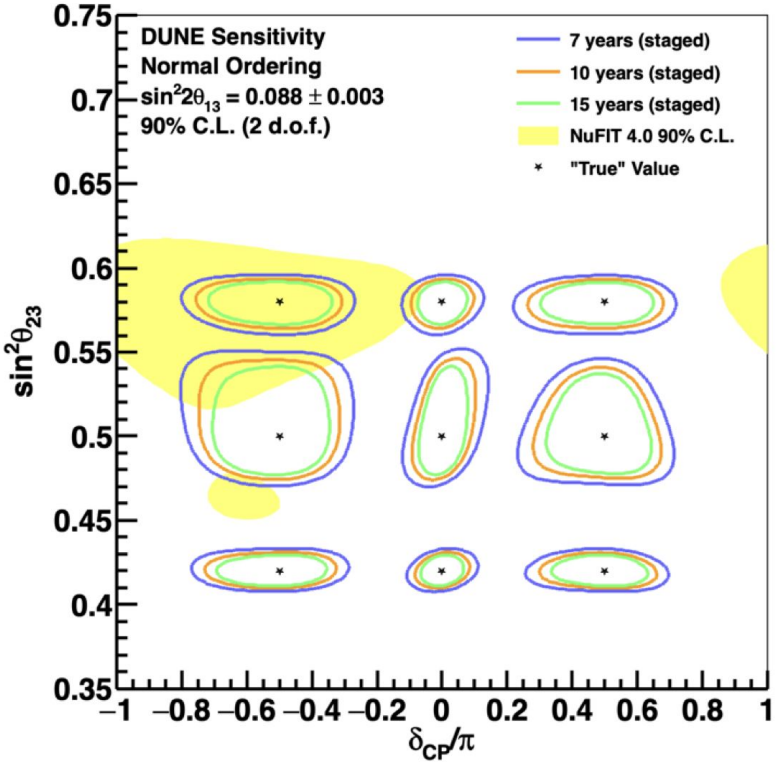
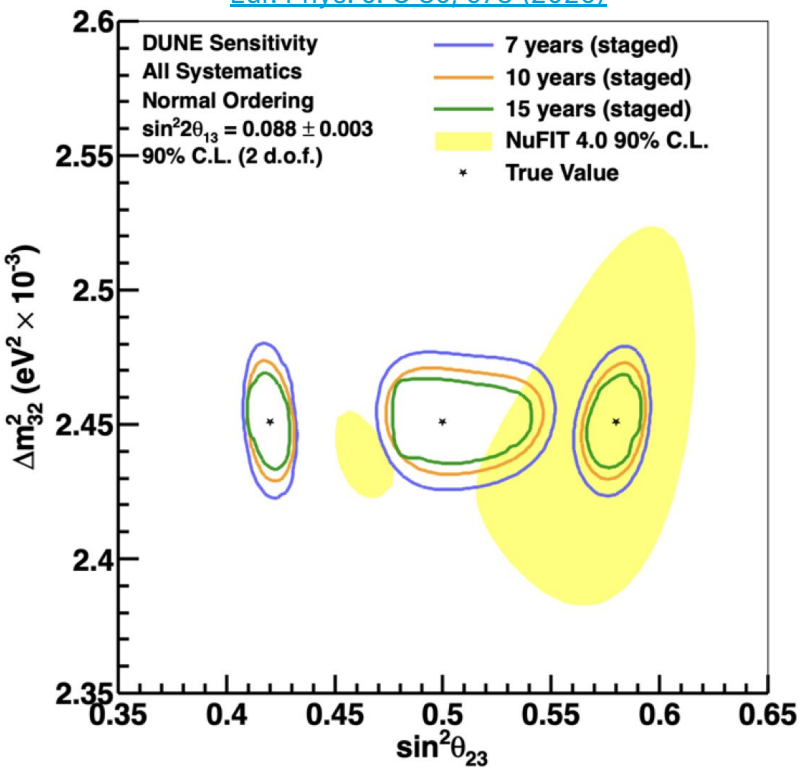


Eur. Phys. J. C 80, 978 (2020)



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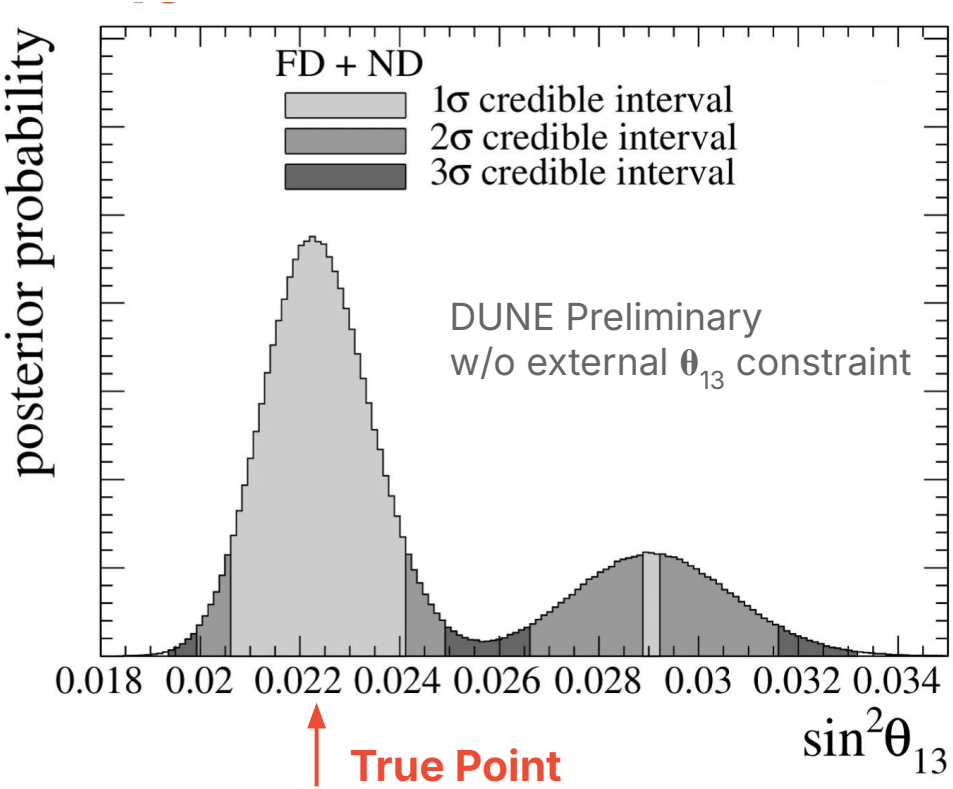

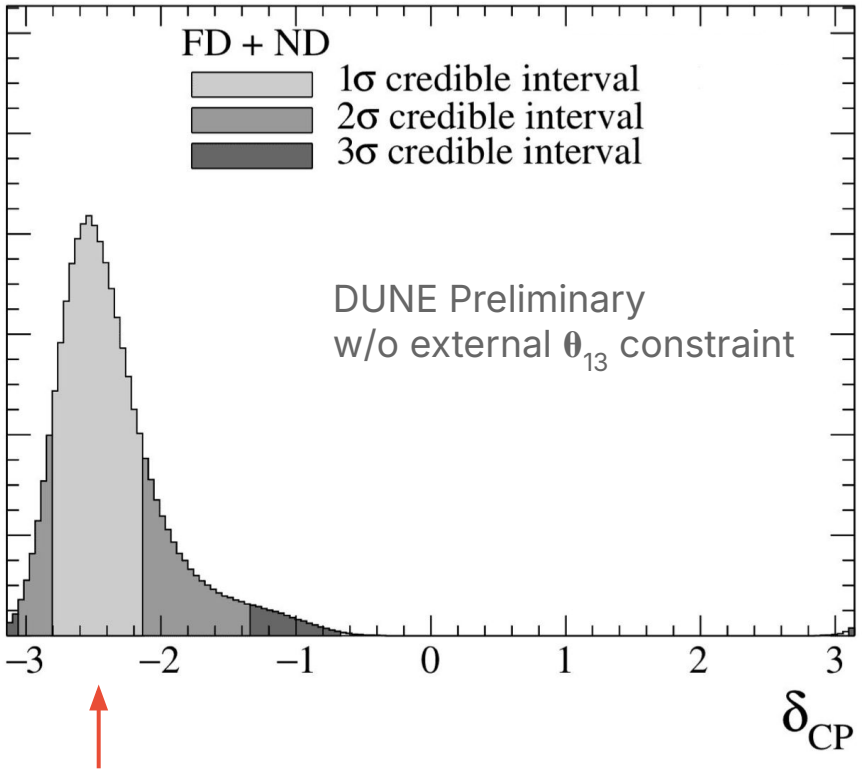

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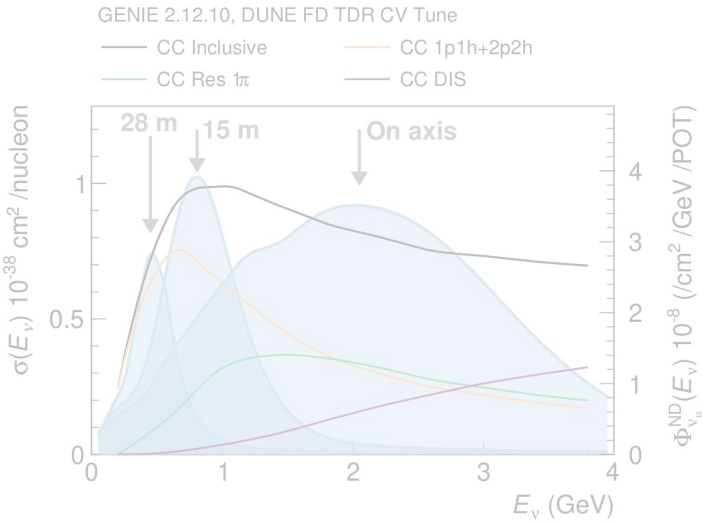
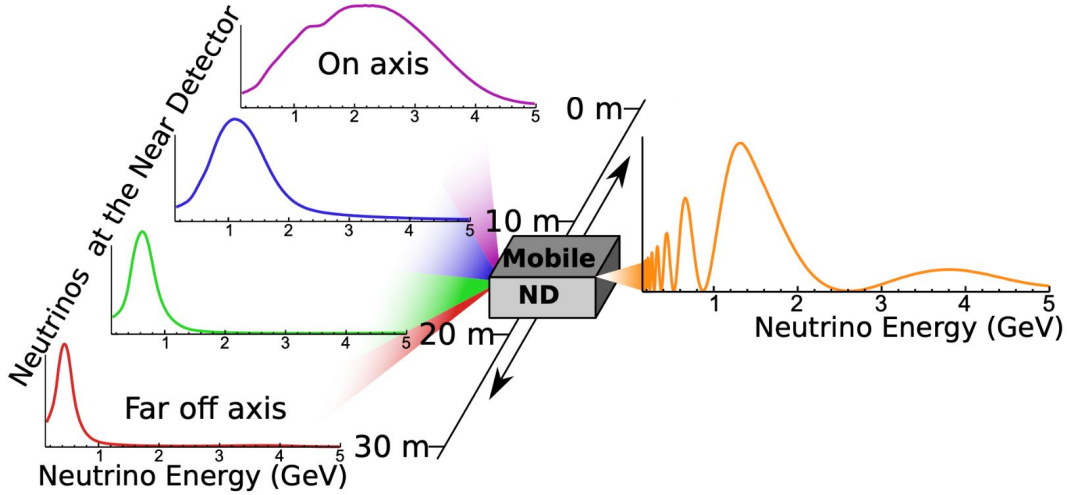


2) Synthesise the measurement of an oscillated flux with the near detector

→ More direct extrapolation of ND observations

→ Reduce reliance on precise interaction model



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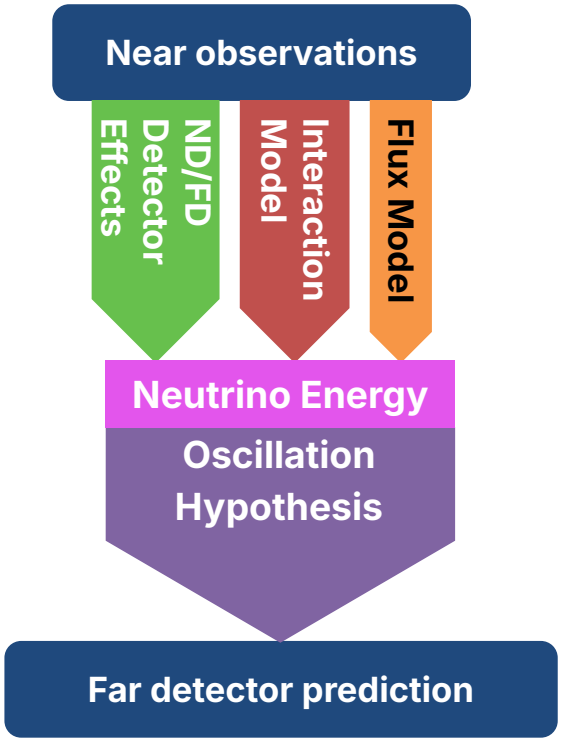
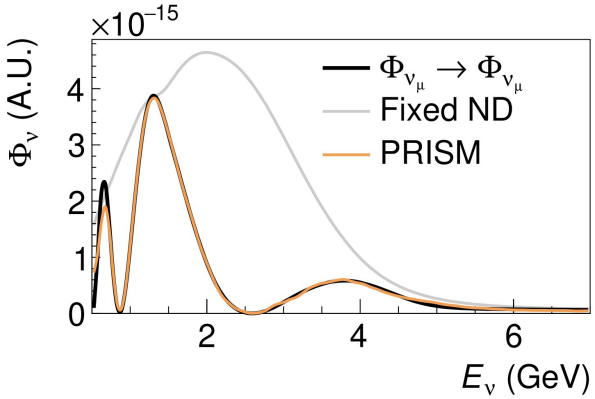




- Off axis measurements enable more direct near-to-far extrapolation
  - Reduce dependence on signal interaction model for disappearance

PRISM Linear Combination

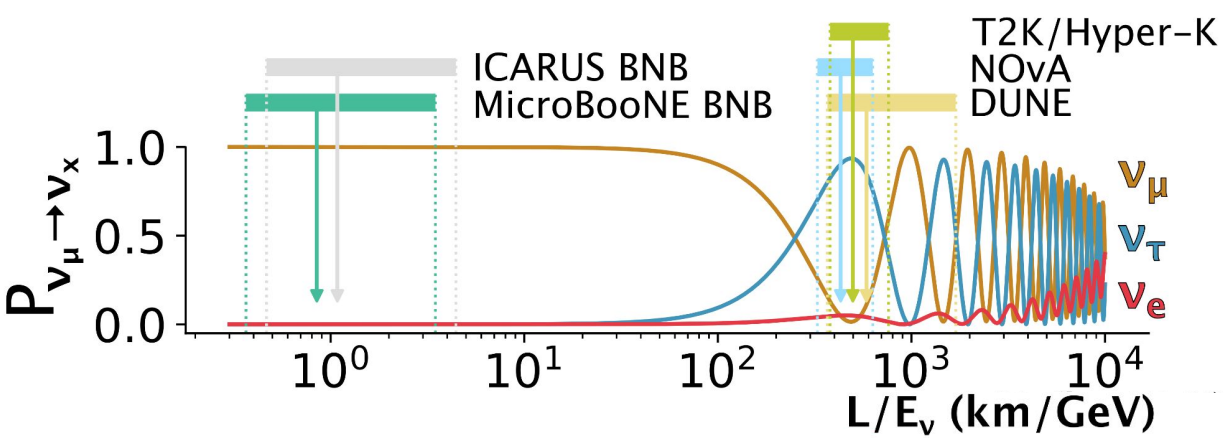
DUNE Talks This Week

DUNE LBL talks this week:

- Liban: DUNE long-baseline oscillation physics sensitivity
  - Tuesday 14:45 WG1 parallel
- Ciaran: DUNE-PRISM: Removing neutrino interaction model dependence with a movable neutrino detector
  - Friday 14:25 WG1 parallel
- Meghna: DUNE Status
  - Friday 16:45 plenary

Exploiting Complementarity

- Compare measurements with different:
  - **Baselines/energies (beam + Atmospheric)**
  - Systematics: Targets, dominant interaction channels, detector and flux



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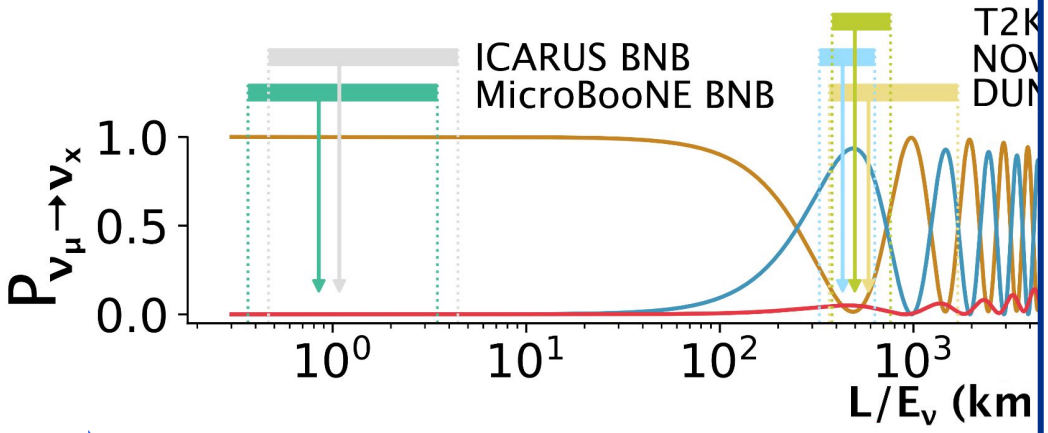

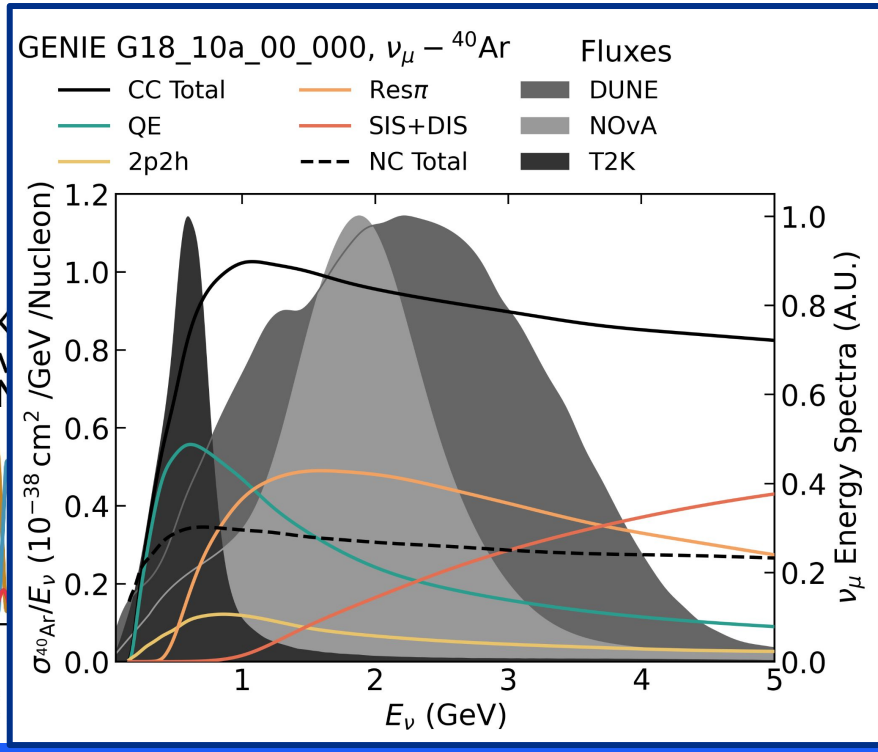

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  - IWCD/DUNE-PRISM enable measurements in very similar fluxes, in different beamlines, on same & different targets

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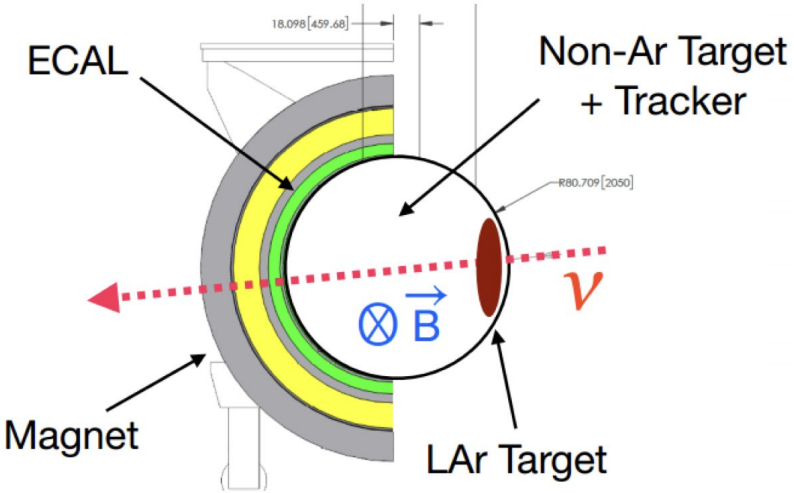

(b) Sketch of SAND vertical cross-section

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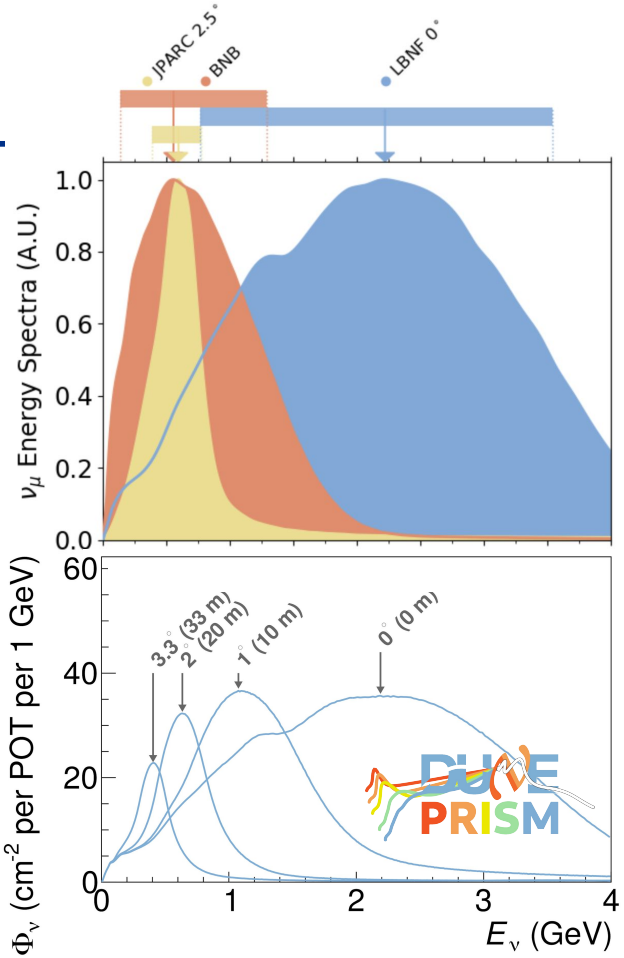

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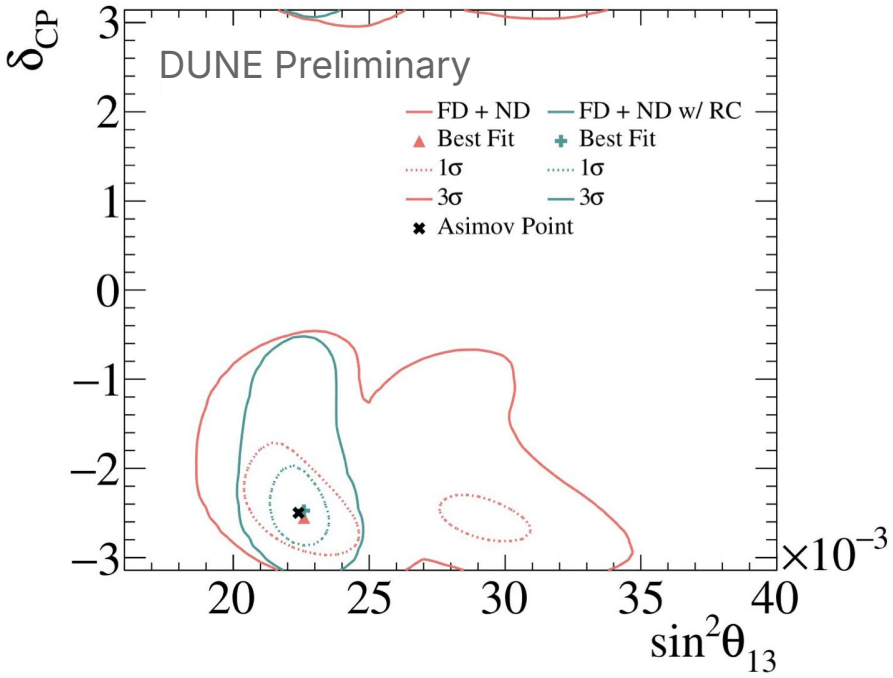

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- Incorporating parameter constraints:
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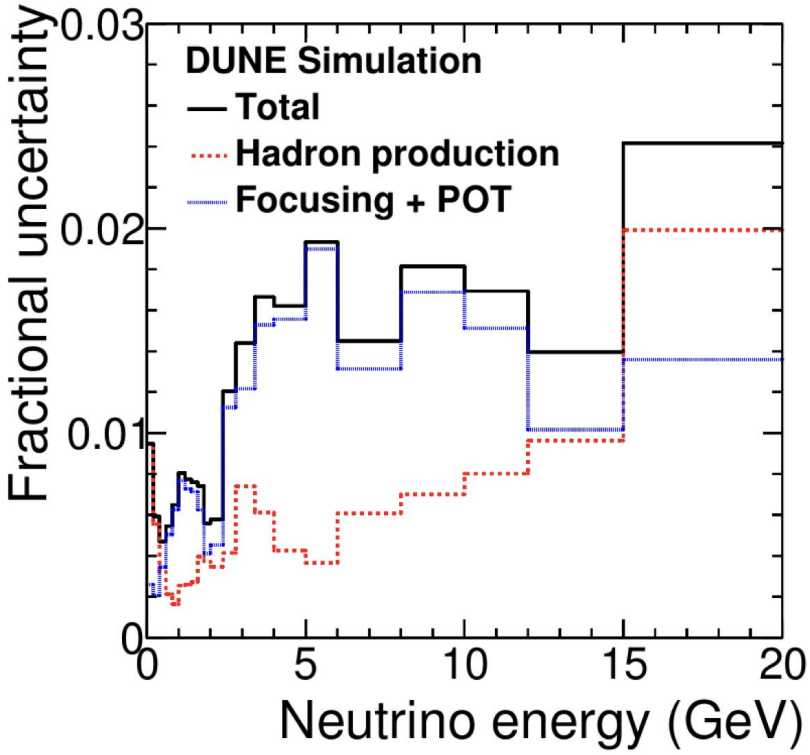
- Flux Predictions:
  - **J-PARC/LNBF/Atmospherics different energies, but may be able to motivate correlations in hadron production models**



Technical Considerations: Flux

LBNF, J-PARC, Atmospheric flux correlations

- Traditionally written off as too difficult to correlate, but people are talking again...
- We need to organize to actively support this talking!
  - What do we need from NA61/EMPHATIC?
  - Would new measurements/experiments help?
  - →Dedicated workshops?
  - →Supporting funding/fellowship/beamtime applications for useful work?
- Ignoring correlations *has* been reasonable in current-generation joint analyses
  - May not be with next-generation uncertainty budgets

Technical Considerations: Cross Sections

Energy, target, neutrino species scaling:

- To meet uncertainty budget, continued engagement of theorists is essential:
  - May generate more engagement if coordinated across collaborations
  - Allows theorists to point to more 'impact' for their funders
  - ... we're going to be relying on predictions of **nue/numu** at some level for appearance even if far off axis measurements offer some constraint.

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  - … we're going to be relying on predictions of **nue/numu** at some level for appearance even if far off axis measurements offer some constraint.
- Significant overlap in physics across experiments, even if peak energies and targets differ
  - What new measurements may help?
    - Vector constraint via E4nu?
    - Hadron rescattering measurements with targeted energy. *e.g.* 250 MeV pion beam…

Technical Considerations: Cross Sections

Energy, target, neutrino species scaling:

- To meet uncertainty budget, continued engagement of theorists is essential:
  - May generate more engagement if coordinated across collaborations
  - Allows theorists to point to more 'impact' for their funders
  - … we're going to be relying on predictions of **nue/numu** at some level for appearance even if far off axis measurements offer some constraint.
- Significant overlap in physics across experiments, even if peak energies and targets differ
  - What new measurements may help?
    - Vector constraint via E4nu?
    - Hadron rescattering measurements with targeted energy. *e.g.* 250 MeV pion beam…
- Work underway to improve interoperability of interaction simulations and uncertainties, but this is a trivial technical step that just requires a bit of will:
  - Other 'irreducible' concerns need new measurements/inputs!

Technical Considerations: Misc

- Host lab support could be transformative:
  - Computing support for designing/debugging interfaces and long-term institutional support for common tools
  - Existing common tools efforts are driven by small group and institutional support, where it exists is largely incidental
  - Support for open data storage spaces
  - Support for shared documents/meeting infrastructure
- Seems mundane, but can reduce many barriers that dramatically lengthen development cycles (days → weeks → months...)
- Needs to be actively pushed for by experiment upper management.

DUNE: Long Baseline Sensitivities and Multi-Experiment Complementarities

Luke Pickering ~~for the DUNE Collaboration~~
NuFact24, Argonne National Laboratory
2024/09/15

Science and Technology Facilities Council

Supported by URF\R1\211661

THE ROYAL SOCIETY

Personal Parting Thoughts

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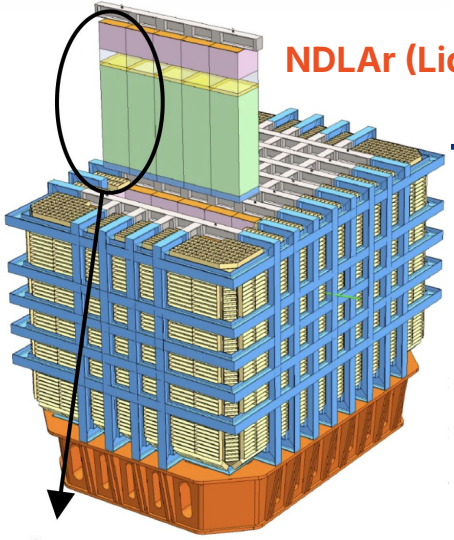
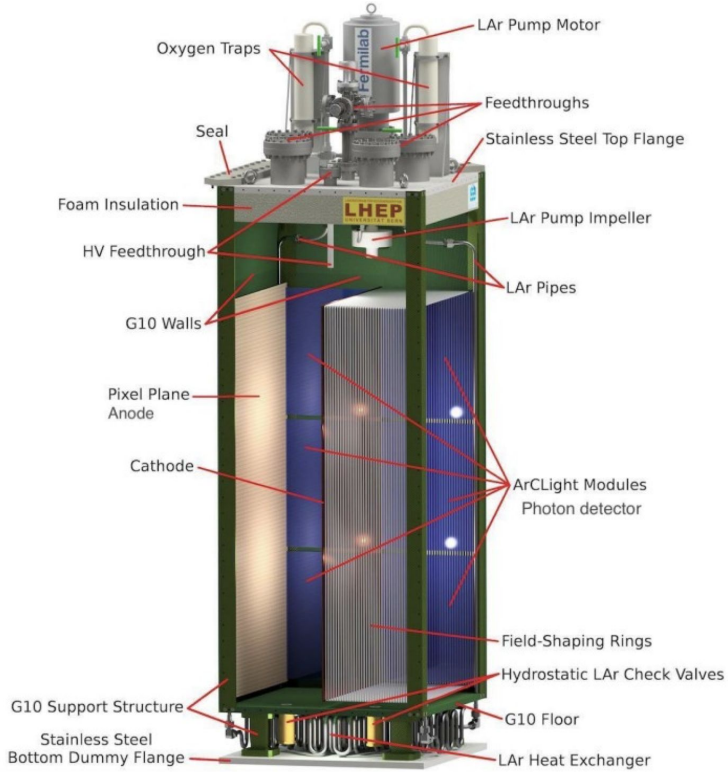
- I emphatically believe we should plan for the maximal long-term global exploitation of the data we're going to take over the next tens of years
  - Ultimate physics reach of the field can only be achieved with multi-experiment analysis
- Working together on shared features soon:
  - **WILL** strongly benefit each individual programme and the wider community
  - **WILL** lay groundwork that makes future multi-experiment analysis possible
  - **WILL NOT** compromise the important and healthy scientific competition, experimental independence, or the impact and reproducibility of individual results.

Backups

DUNE



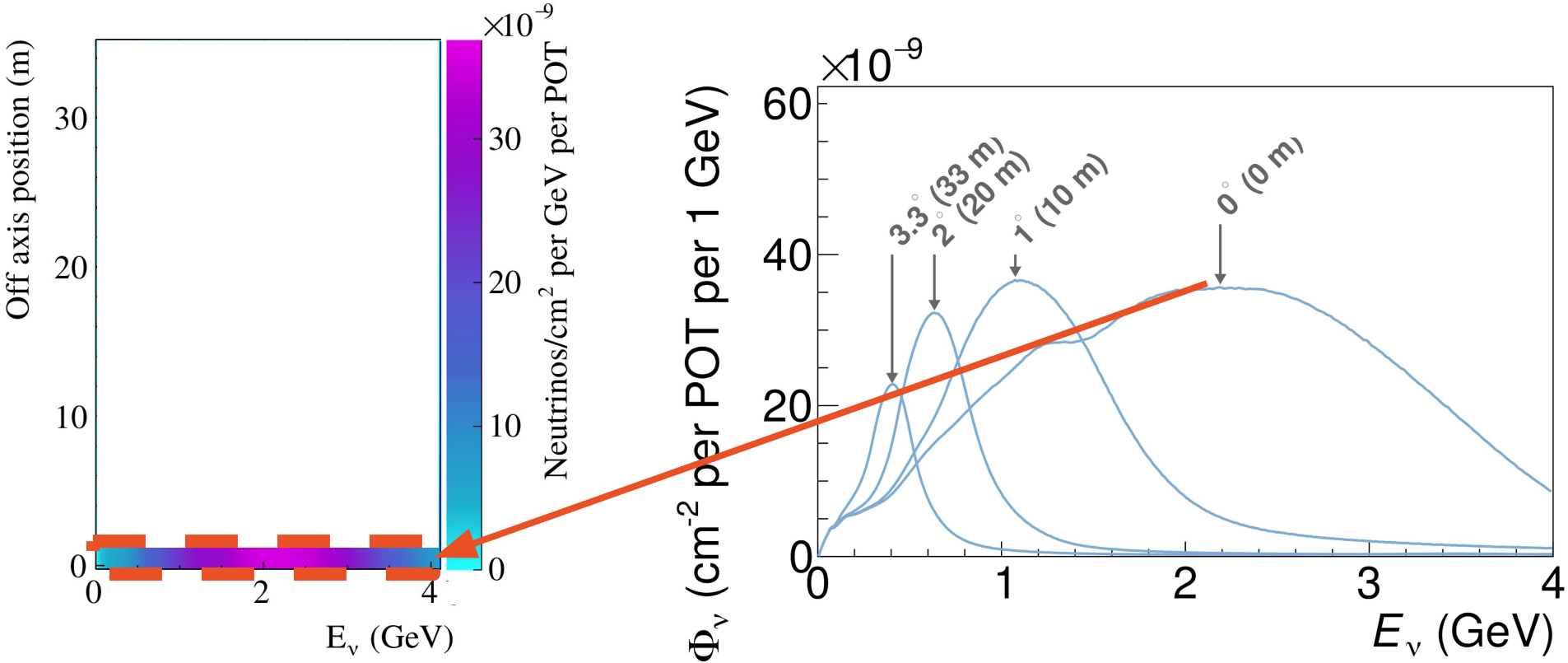
NDLAr (Liquid Argon)



Phase I

- 2×17 kt active LAr far detectors
  - Atmospheric data from ~2029 with FD1
- 1.2 MW on-axis beam, peaking at 2.3 GeV
  - 1300 km baseline
- **Modular** LAr + muon system near detector
  - Moveable through 0–3° off axis
- On-axis beam monitor

Off Axis at the Near Detector



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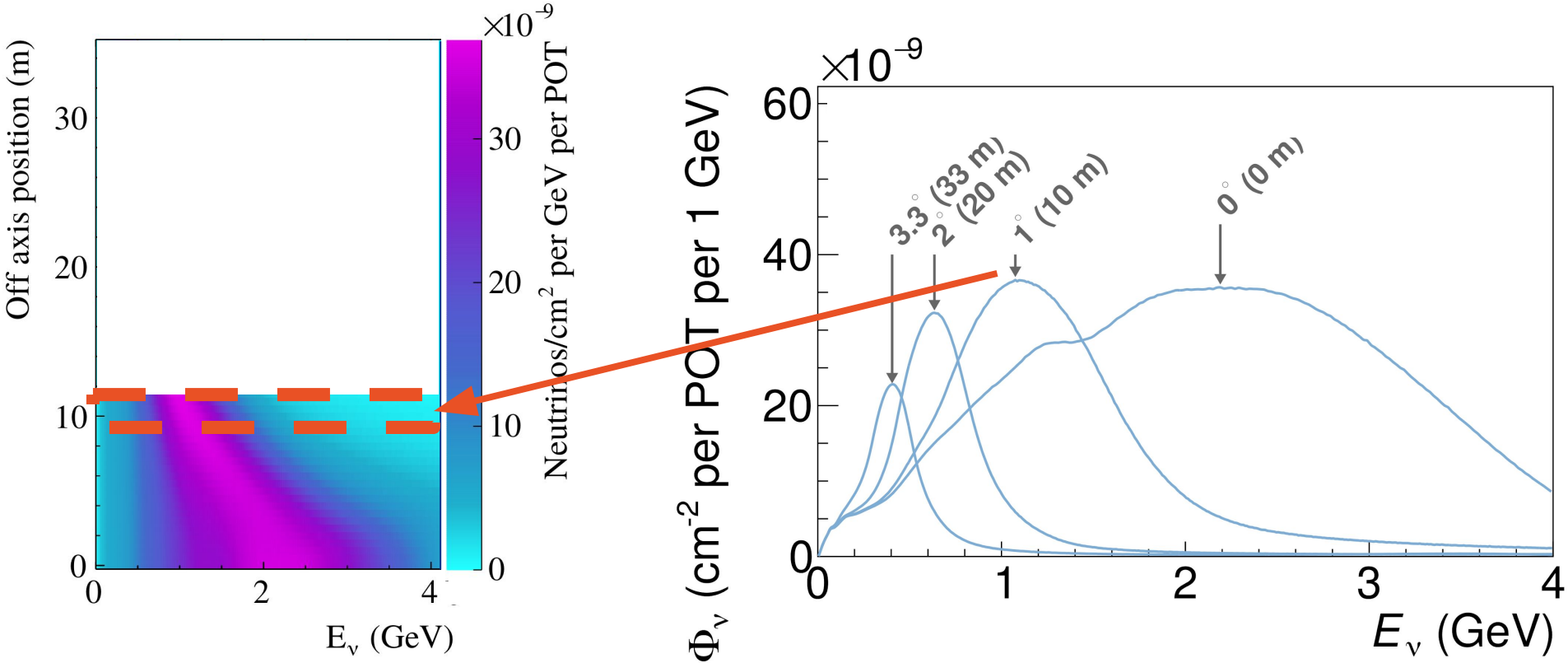

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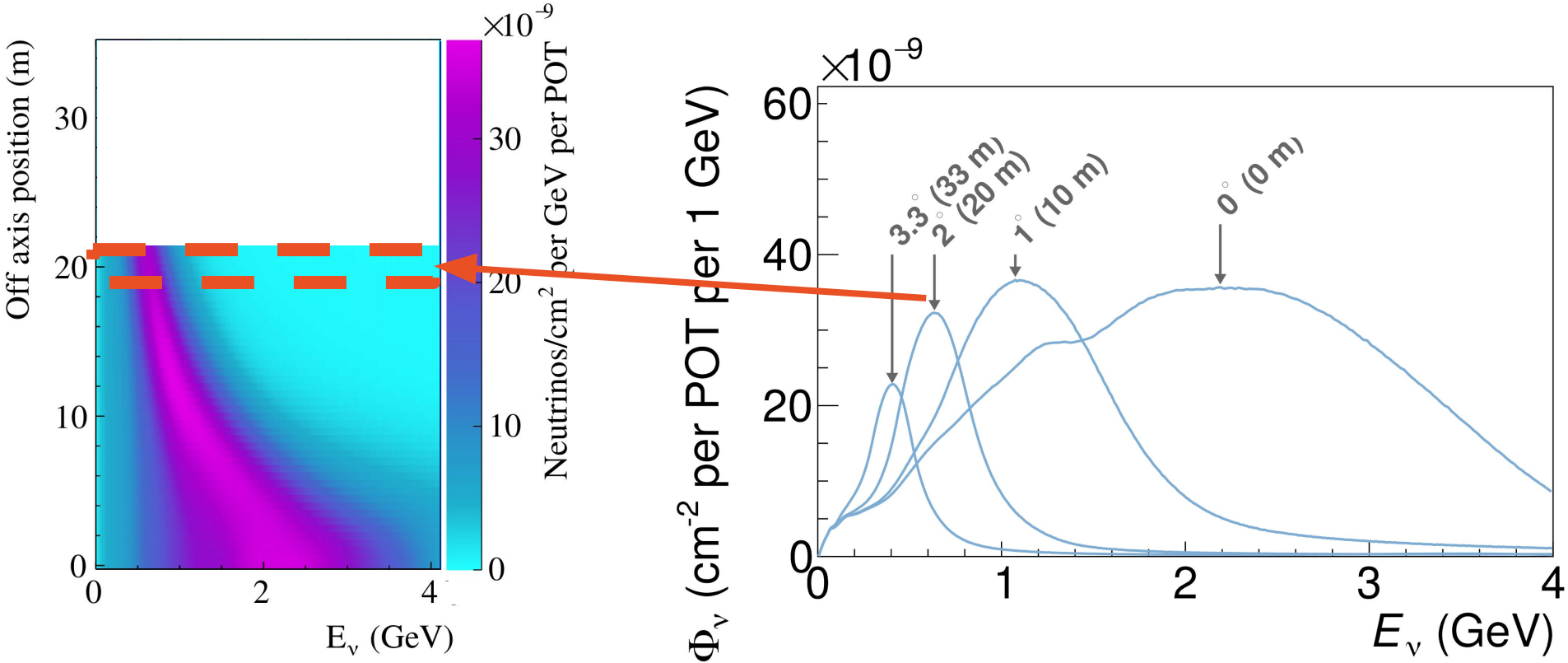

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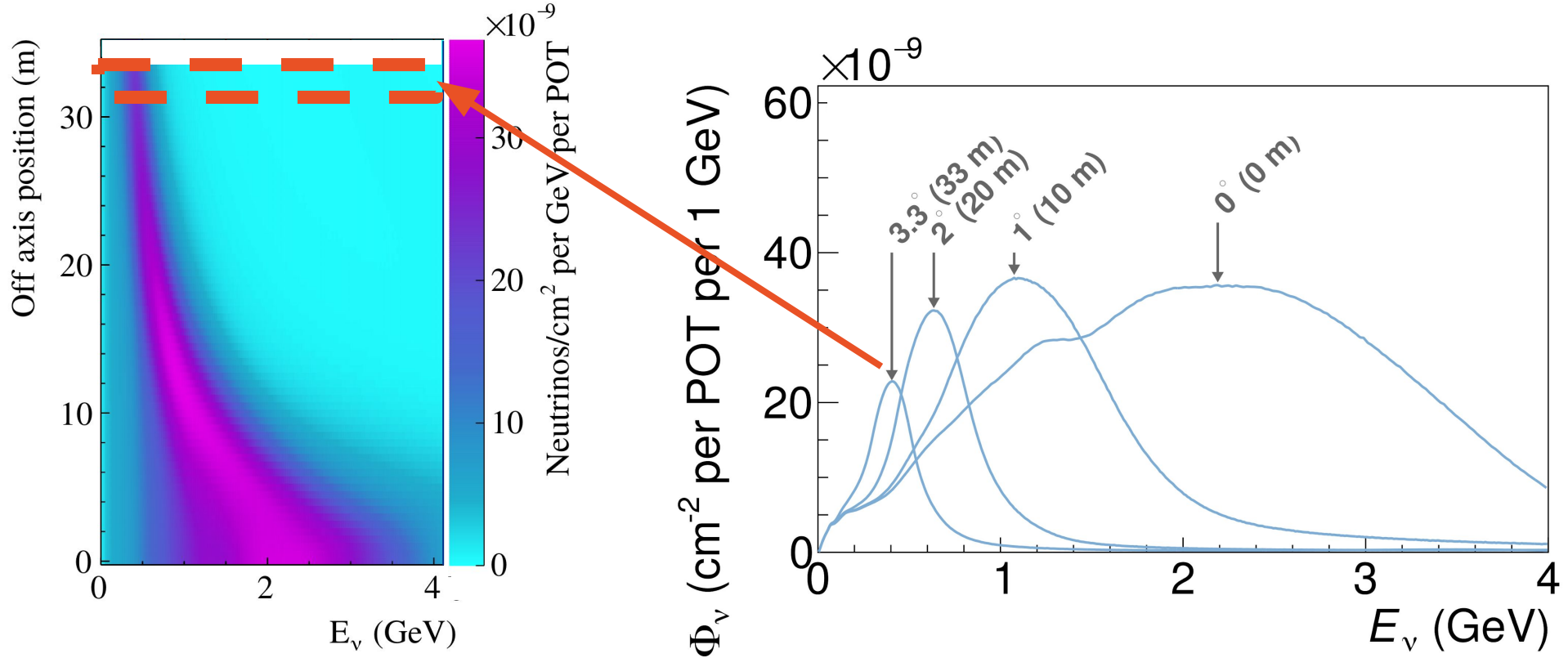
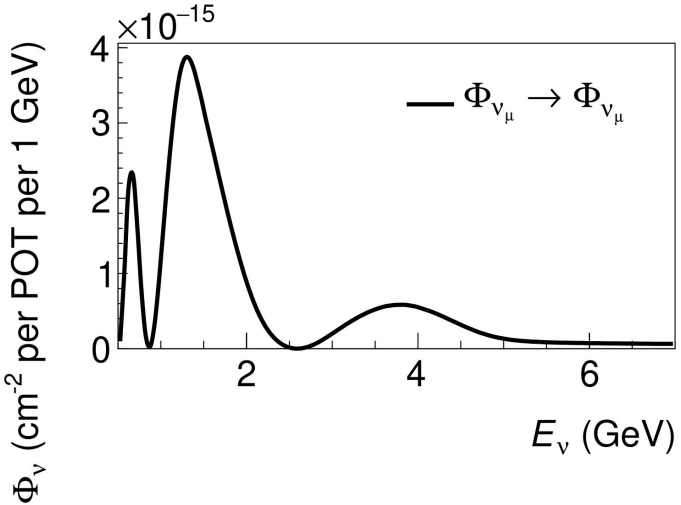


Predicting Oscillations with the Near Detector

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



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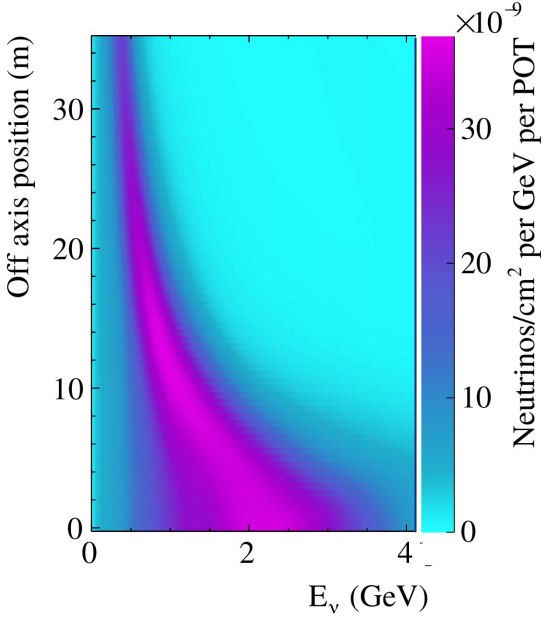
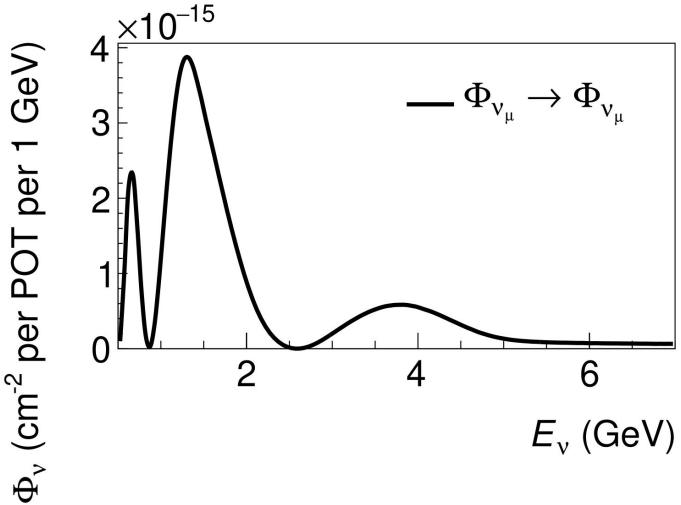
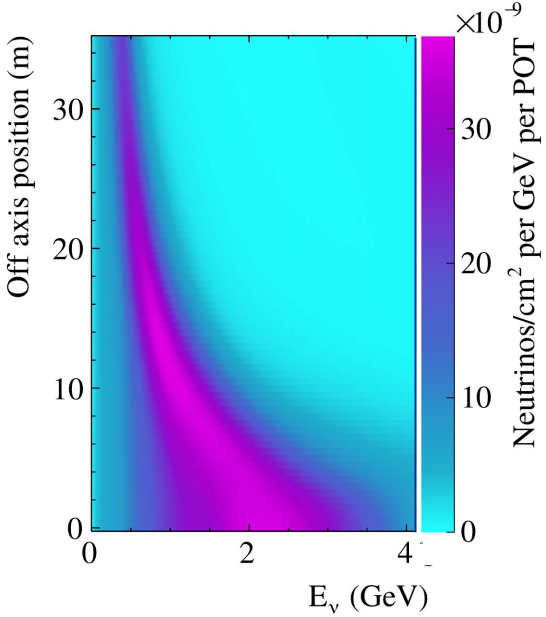
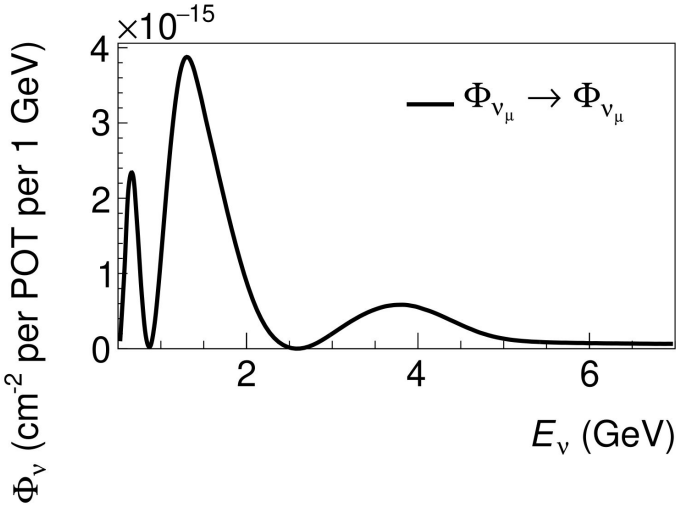




Predicting Oscillations with the Near Detector

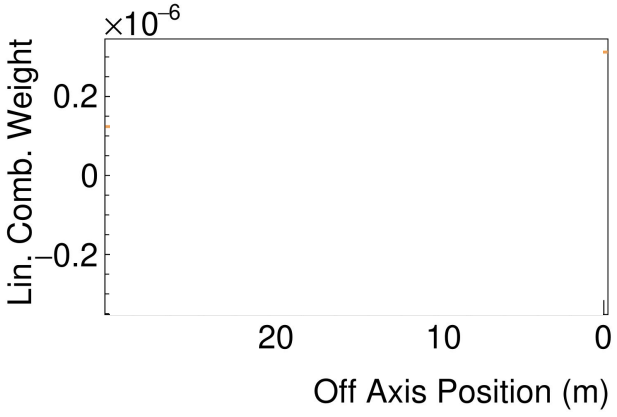
$$\Phi^{\nu}_{\text{Near}} \qquad \vec{\Phi}^{\nu}_{\text{Far}} \cdot P^{\mathcal{H}}_{\text{Osc}}$$

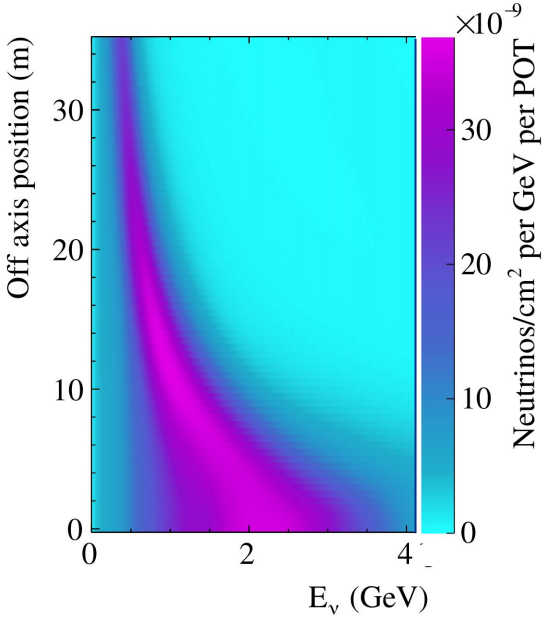


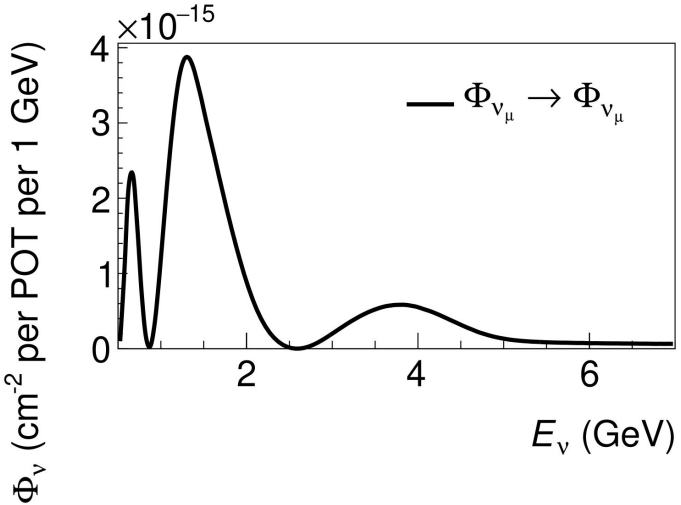


Predicting Oscillations with the Near Detector

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

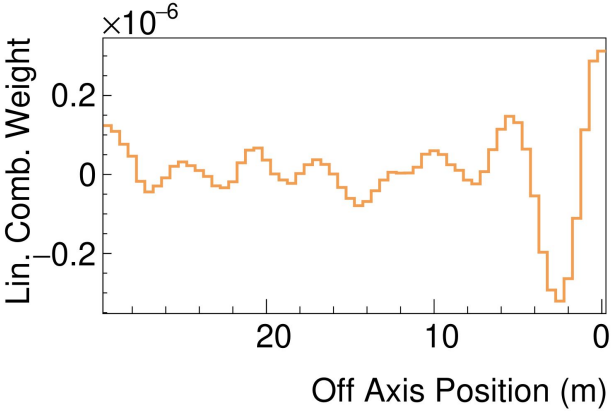


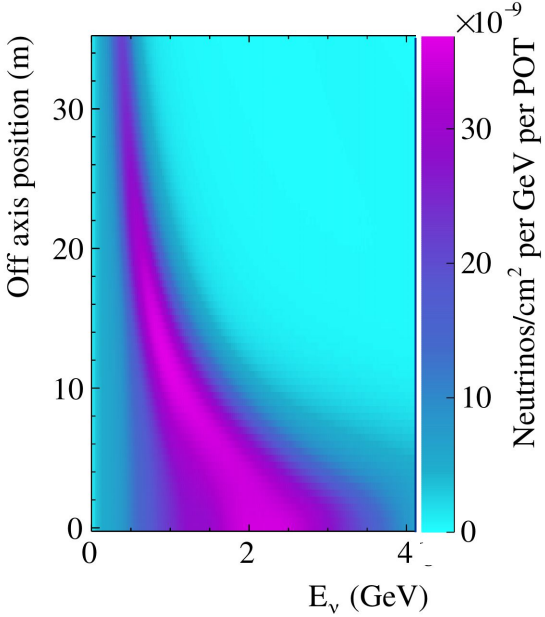


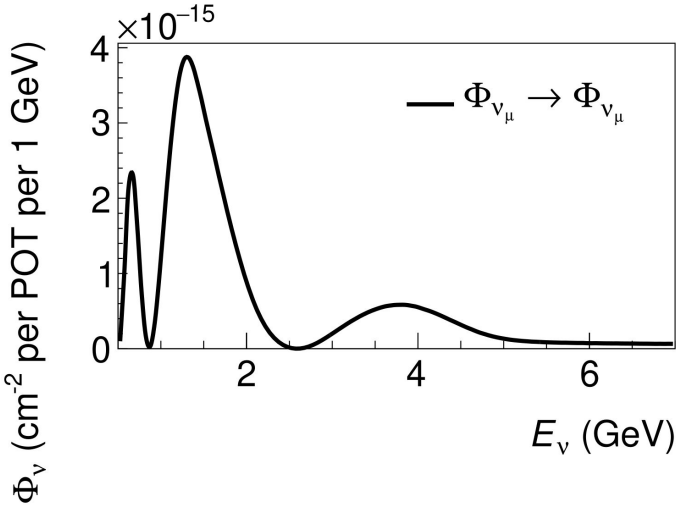


Predicting Oscillations with the Near Detector

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







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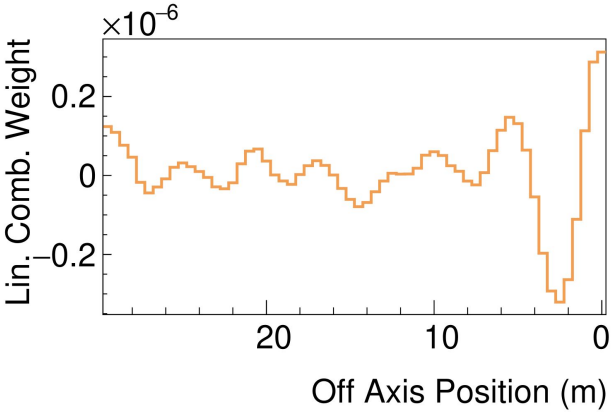
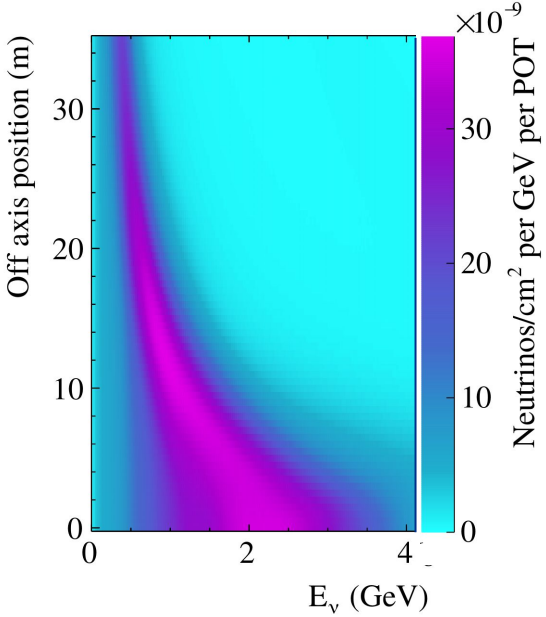
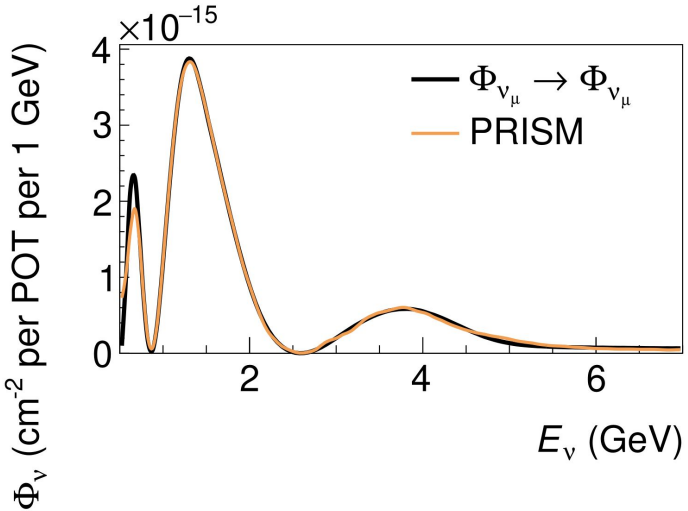
$$\vec{C} \cdot \Phi^{\nu}_{\text{Near}} = \vec{\Phi}^{\nu}_{\text{Far}} \cdot P^{\mathcal{H}}_{\text{Osc}}$$

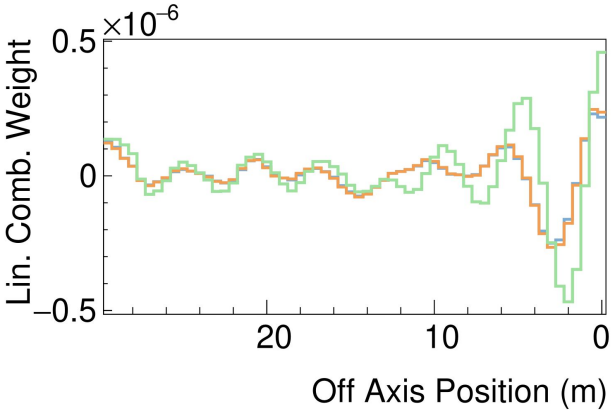


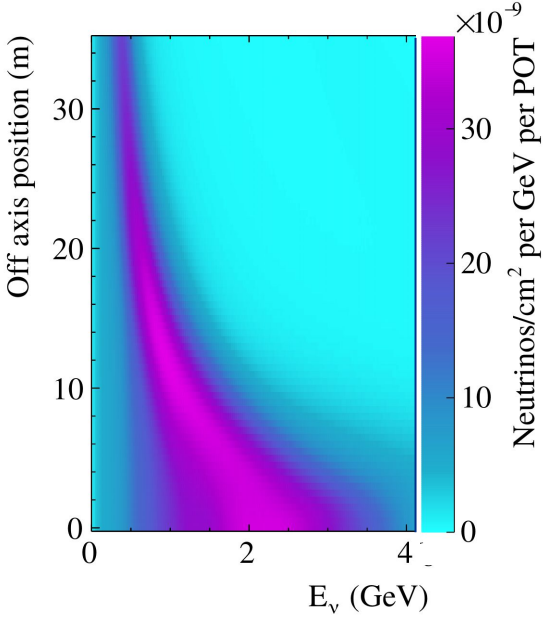


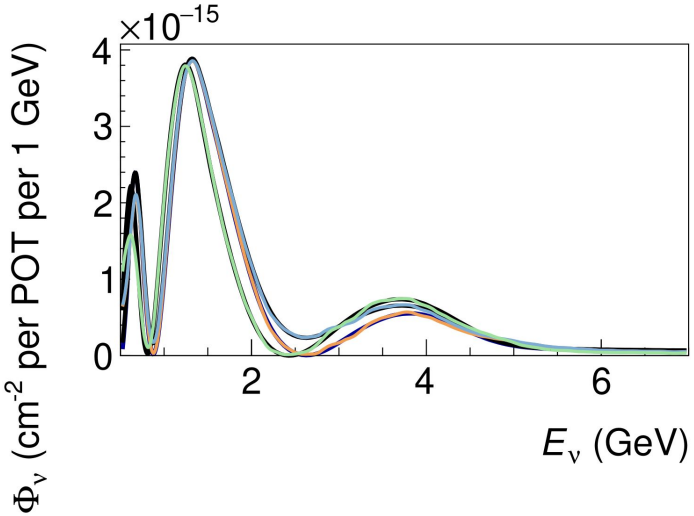


Predicting Oscillations with the Near Detector

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

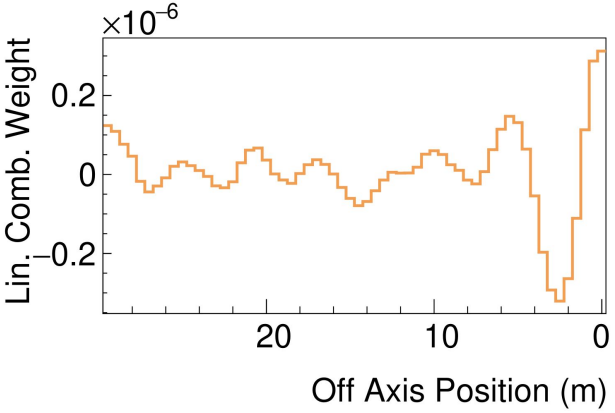


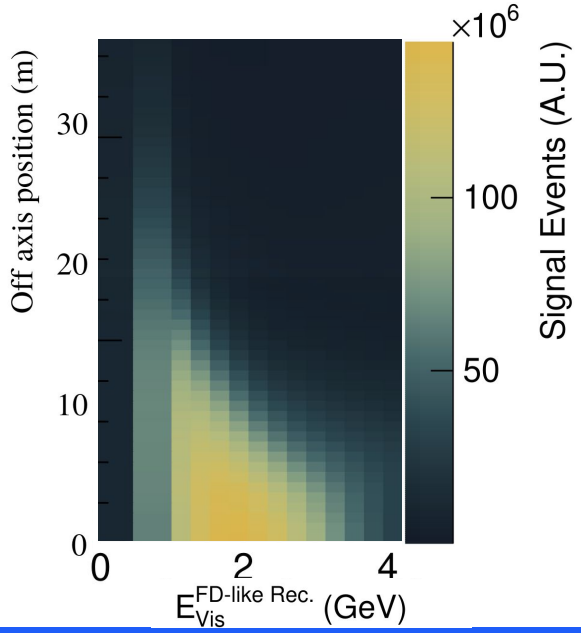


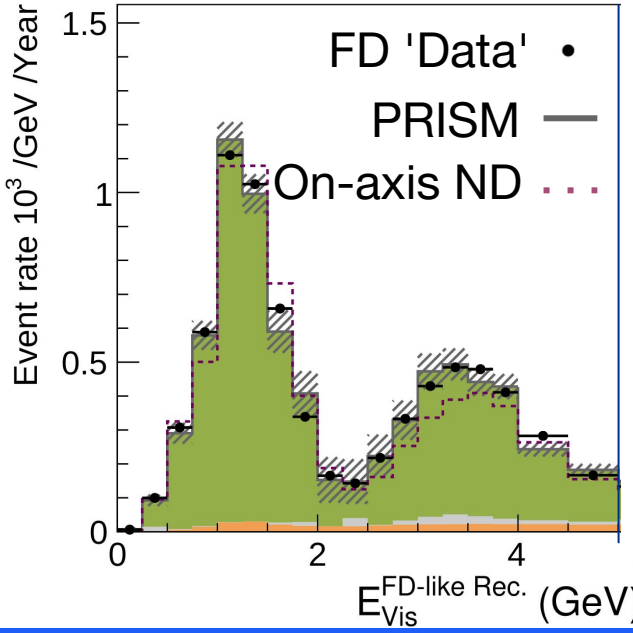


Predicting Oscillations with the Near Detector

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

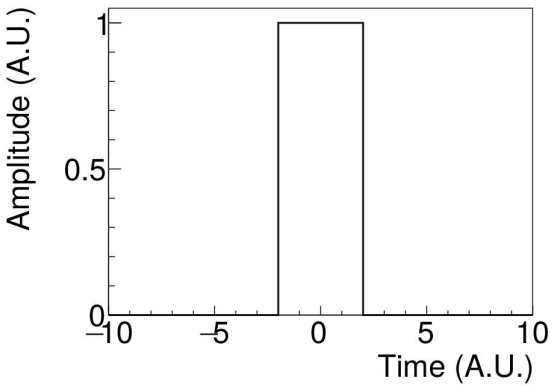






Discrete Fourier Transforms

- Approximate function as a linear sum of sines and cosines



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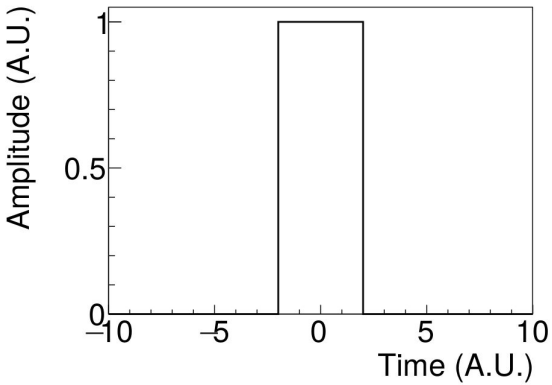

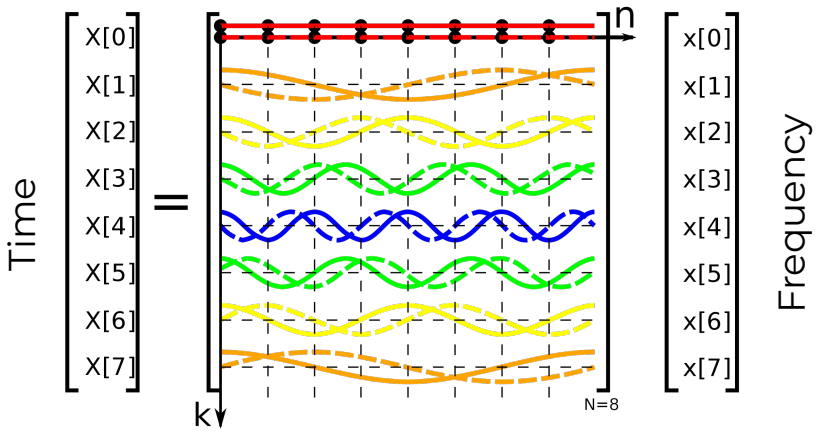

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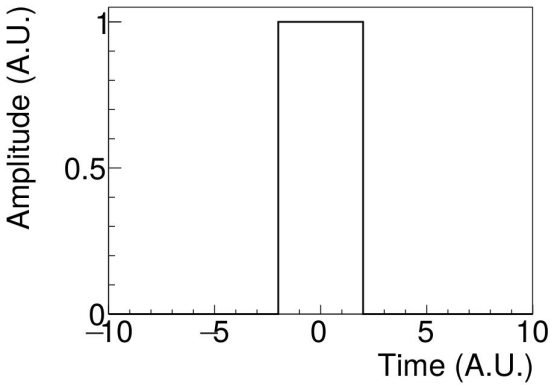

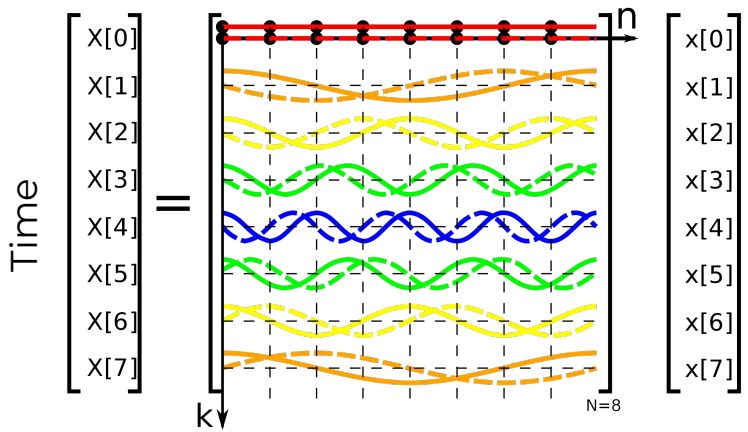

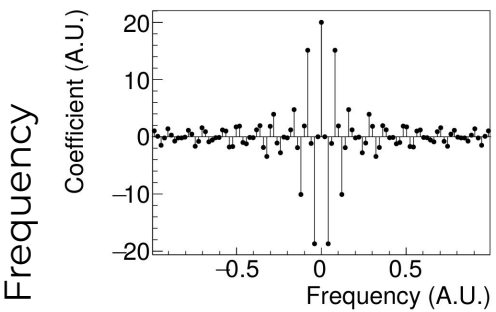

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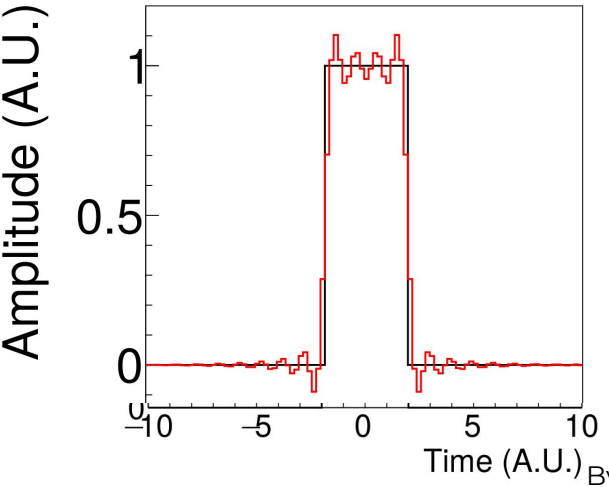

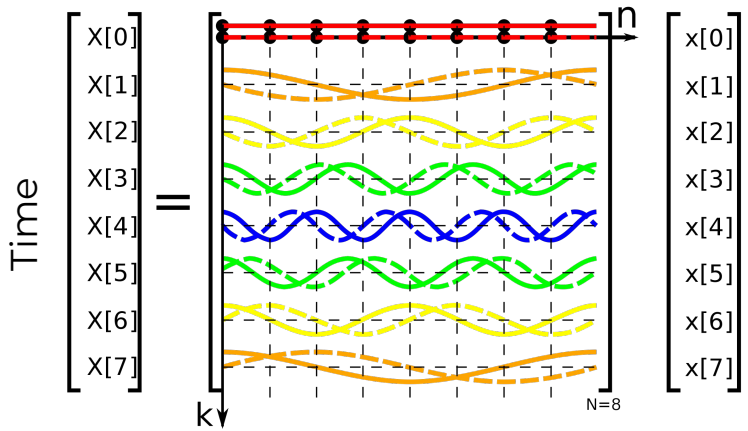

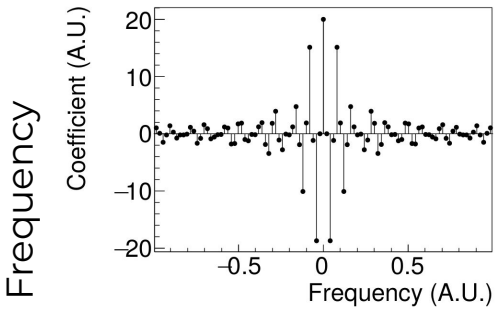

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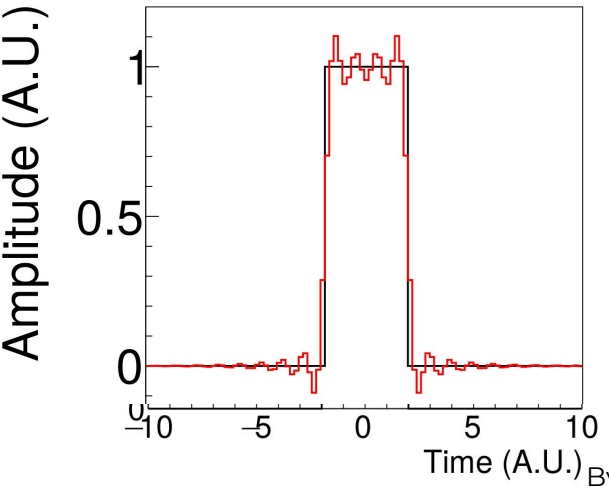

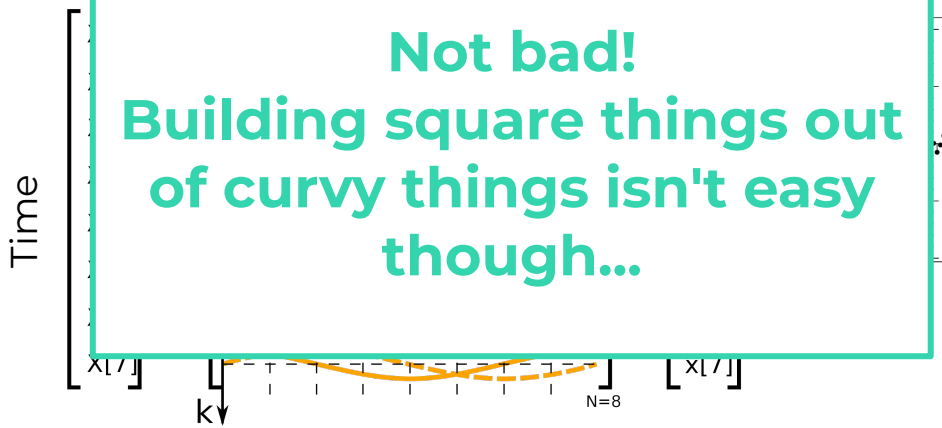

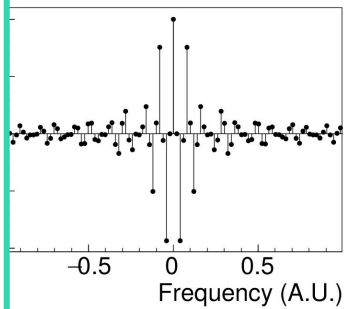

Not bad!
Building square things out of curvy things isn't easy though...

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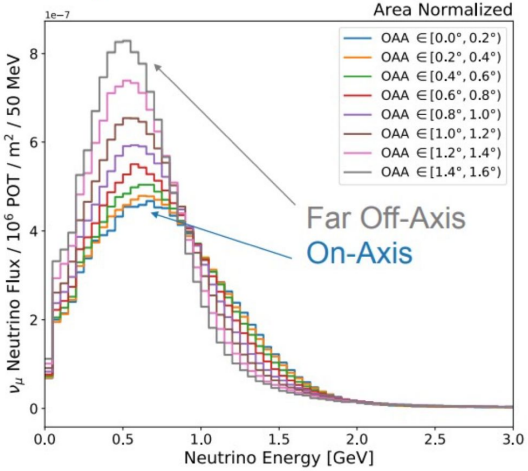
SBND PRISM

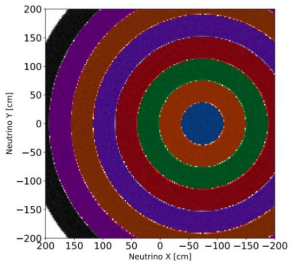
A. Furmanski NuFact23

SBND-PRISM

ν_μ flux in each of the OAA regions

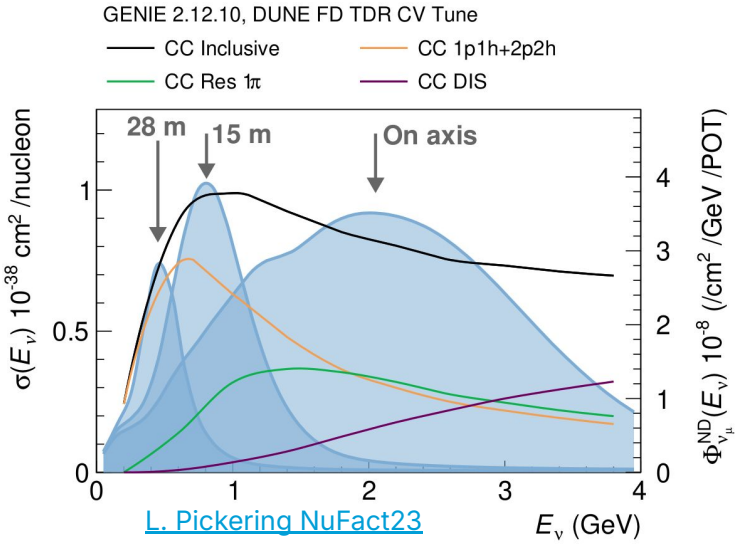


Beam view



Vary energy dependence by scanning position in detector

Directly determine energy dependence of cross sections



L. Pickering NuFact23