DUNE: Long-Baseline Oscillation Sensitivity

Luke Pickering for The DUNE Collaboration
STFC Rutherford Appleton Lab
2023/08/25
NuFact 2023 – SNU, Seoul

Science and Technology Facilities Council

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Supported by URF\R1\211661
THE ROYAL SOCIETY

Long-Baseline Oscillations: Open Questions

What is the mass ordering of the neutrino mass states?

Is there significant CP violation in the neutrino sector?

What are the precise values of the remaining neutrino oscillation parameters?

Are standard PMNS oscillation able to explain observations?

Oscillation Programme Overview

Measuring Long-Baseline Oscillations with DUNE

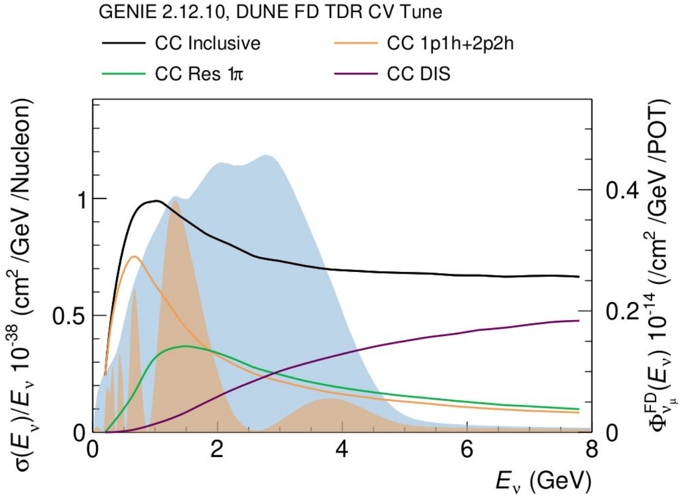
$$N_{\mathrm{near}}(E_{\mathrm{obs}}) = \int dE_\nu \, \Phi_{\mathrm{near}}(E_\nu) \cdot \sigma(E_\nu) \cdot \mathbf{D}_{\mathrm{near}}$$

Want to know

$$N_{\mathrm{far}}(E_{\mathrm{obs}}) = \int dE_\nu \, \Phi_{\mathrm{far}}(E_\nu) \cdot P_{osc}(E_\nu) \cdot \sigma(E_\nu) \cdot \mathbf{D}_{\mathrm{far}}$$

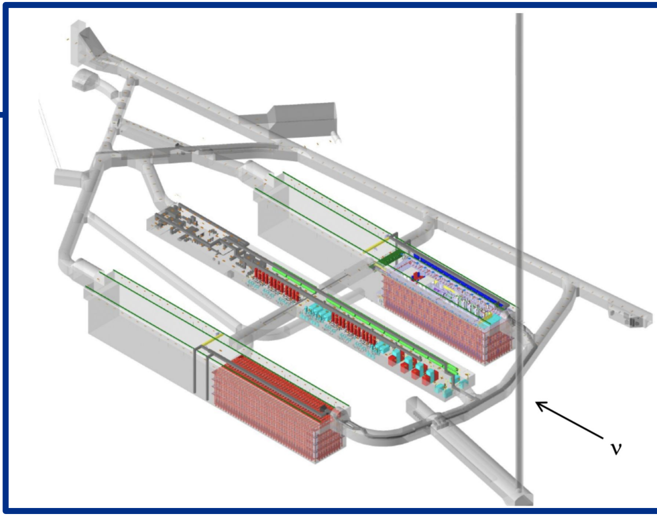
Observe

- Oscillation measurements **not** just near-to-far ratio:
  - Oscillation is not a function of E_{obs}
- Must use models to infer P_{osc}
- Degeneracies in the integral → limits on sensitivity
  - Design ND to minimise Flux and Cross Section degeneracy
  - Limited by Detector capability



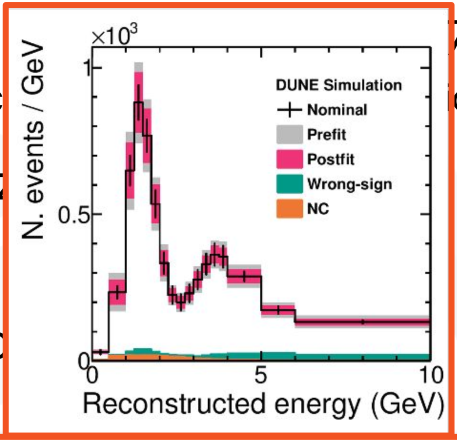
The Far Detectors

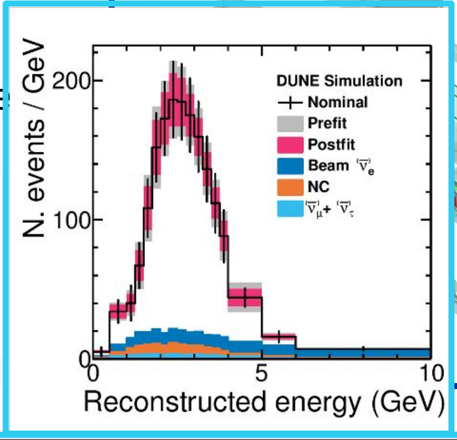
- Four caverns with space for 17 kt LAr TPCs
  - Unprecedented detector resolution for an LBL far detector
- FD-1 Horizontal Drift LAr TPC
- FD-2 Vertical Drift LAr TPC
- Rich prototype programme at CERN

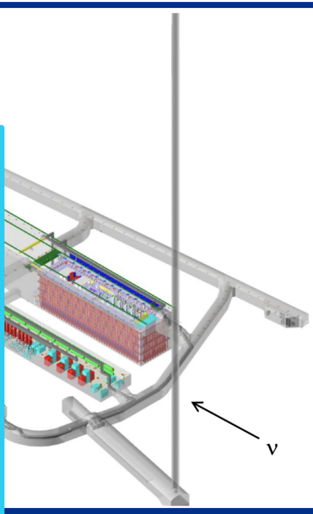


The Far Detectors

- Four cave 7 kt LAr TPCs
  - Unprec ion for an LBL far dete
- FD-1 Horiz
- FD-2 Vert
- Rich proto CERN



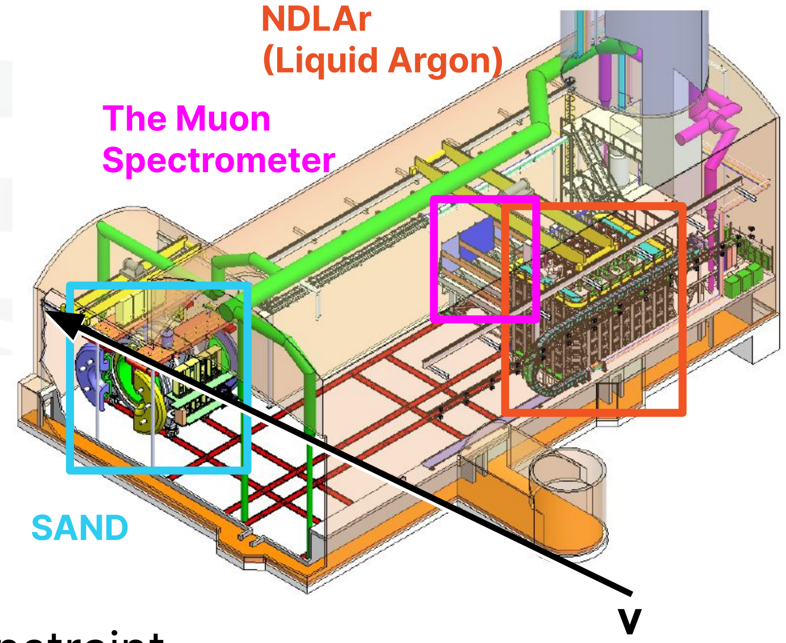




The Near Detectors

A. Furmanski's talk on Tuesday
for more information

- Constrain systematic uncertainties
  - Beam
  - Neutrino–argon interactions in few GeV region
- Monitor beam stability
- Function in high-rate environment

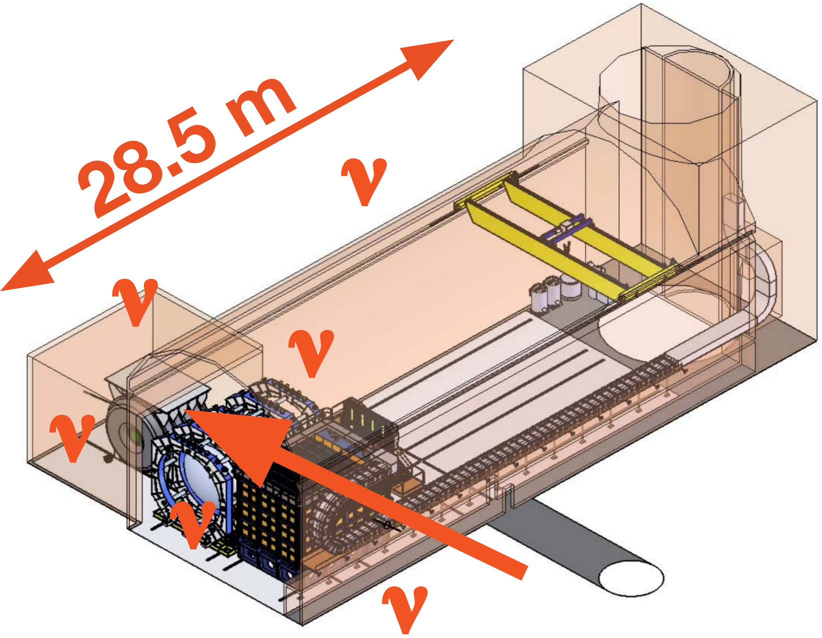


SAND: Beam Monitoring and C12-target physics

TMS: Muon momentum and sign-selection

NDLAr: Ar40-target physics, unoscillated rate constraint

Near Detector: On-the-move

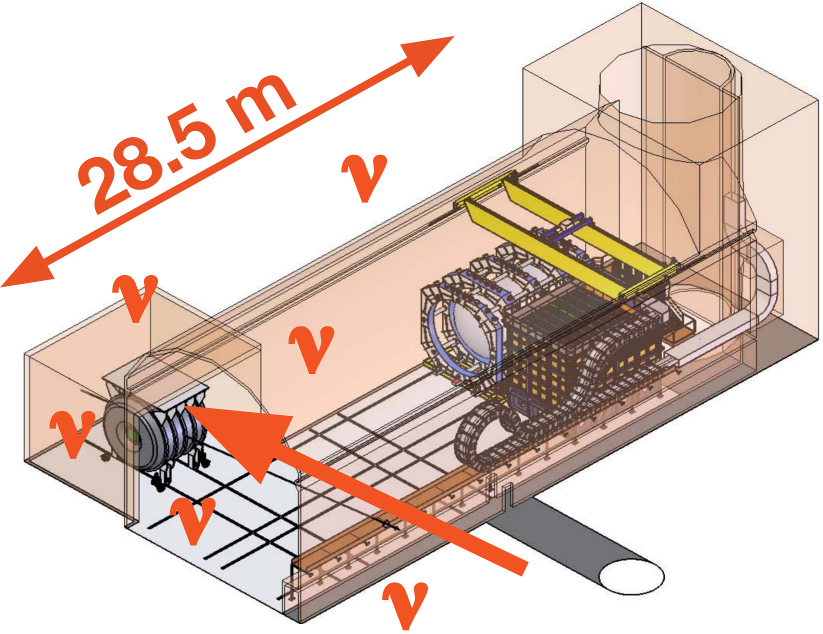


Excuse the out of date detector design in the graphic

A mobile near detector is one of the ways that DUNE is designed to constrain interaction uncertainties to the required level

Precision Reaction-Independent Spectrum Measurement

Near Detector: On-the-move



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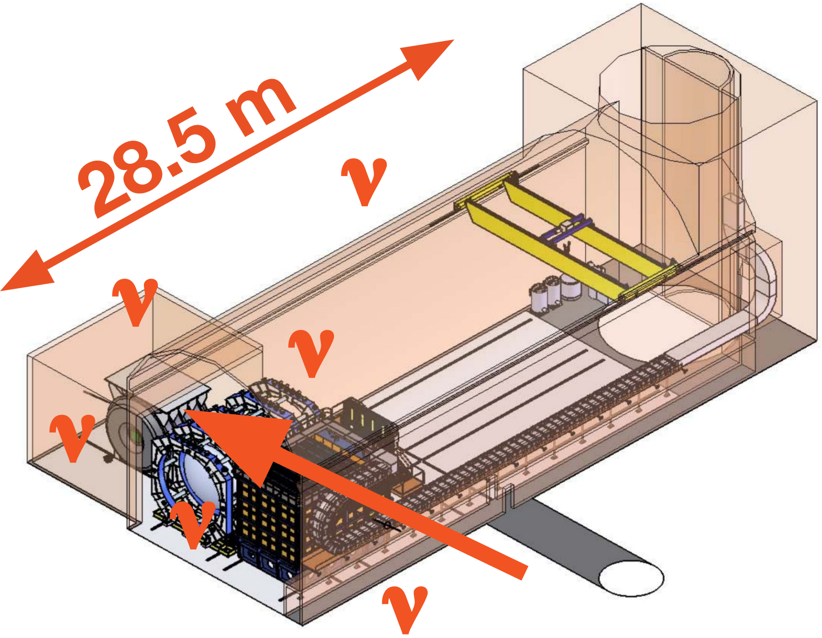
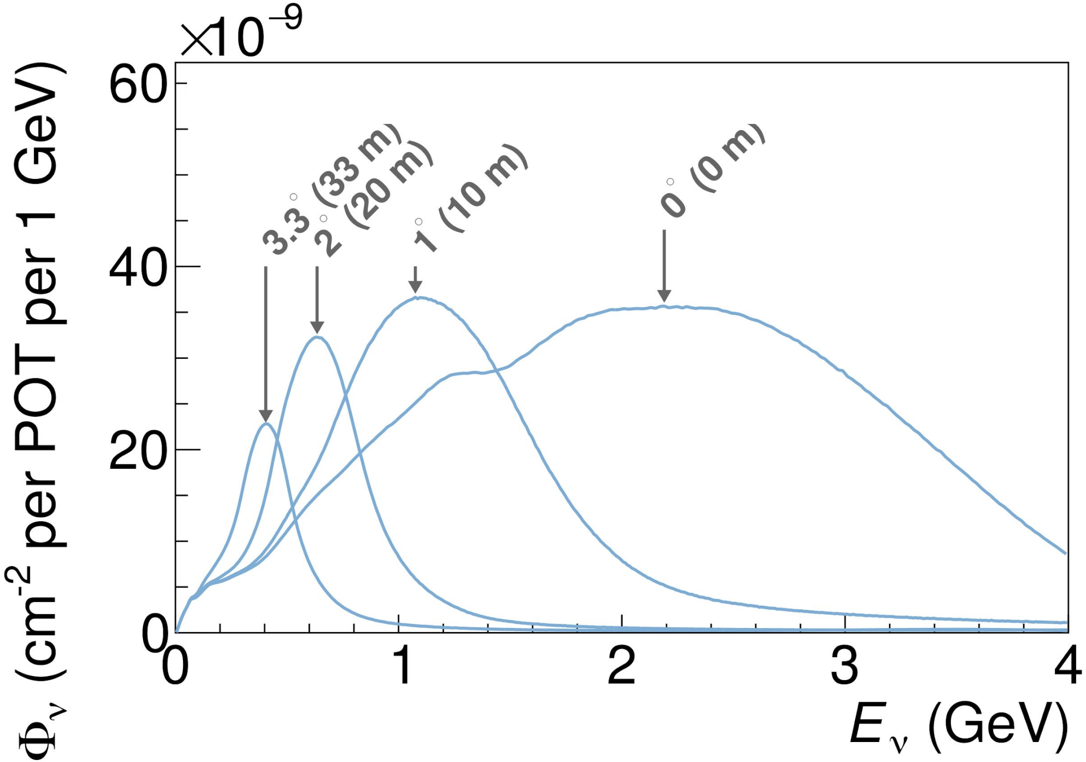
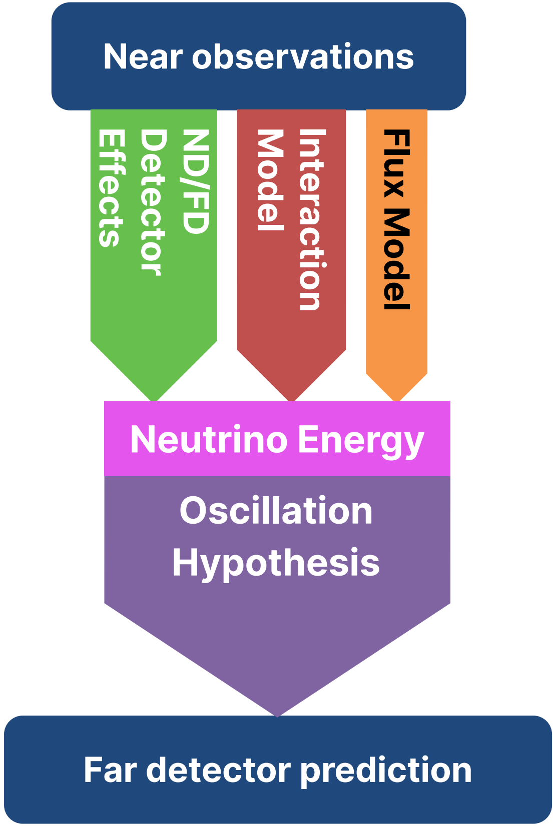




Oscillation Measurements in a Nutshell

- Existing Oscillation Analyses:
  - Use models to 'unfold' near detector observations to a neutrino energy spectrum (implicit or explicit)
  - Apply oscillation hypothesis
  - Compare to far detector observations



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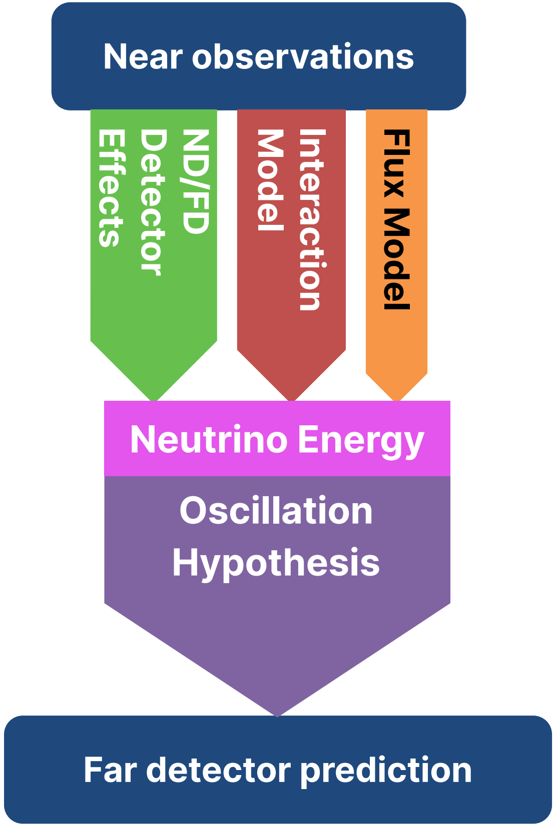
  - Simulate oscillation features at the wrong place in observables
  - Inflate errors → degrade sensitivity
  - Bias measurements



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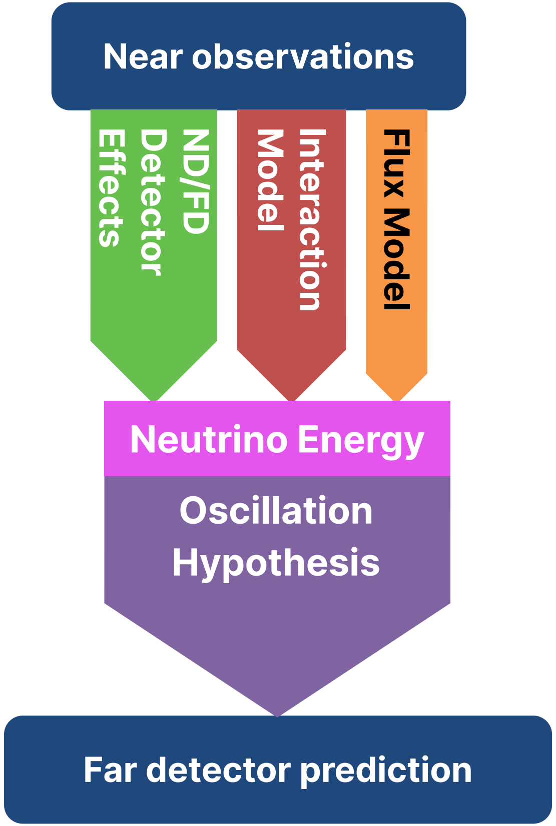
- What happens if the model is wrong?
  - Simulate oscillation features at the wrong place in observables
  - Inflate errors → degrade sensitivity
  - Bias measurements
- Current generation experiments are still largely statistically limited
  - The next generation hope not to be limited at the '5σ' level
  - Need to actively design the experimental programme to minimize systematic uncertainty in flux and interaction models



The Analysis Model-Dependence Axis

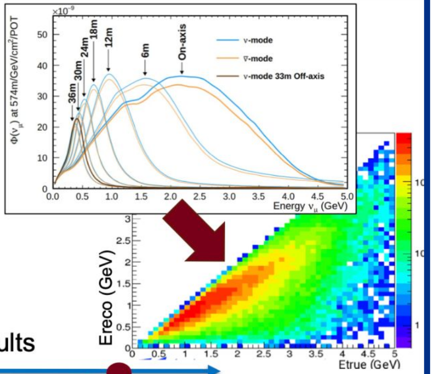
Analysis Choices

On-Axis-Only

- This analysis constrains flux and xsec parameters to predict the FD spectrum
- Results strongly depend on the flux and xsec model accuracy

Energy Response Fitting

- With PRISM data, we can empirically expand the cross section model
  - Can include normalization parameters in Ereco vs Etrue bins
- Still relies on modeling within the bins
  - e.g. correlations to other physics variables will be wrong
- However, this will mitigate biased fit results



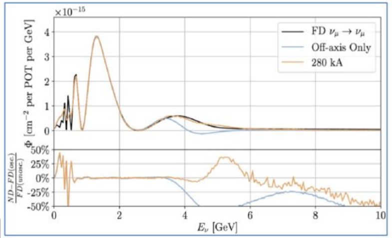
Constrained-Model Approach ⟷ Model-Insensitive Approach

Direct Comparison of ND & FD Data

("Linear Combination Analysis")

- The ND data in each off-axis slice can be linearly combined (based only on flux) to produce oscillated FD spectra
- Any unknown xsec effects will cancel in ND/FD data comparison
- Requires precise flux error cancelation

More Details in L. Pickering's Talk on Friday



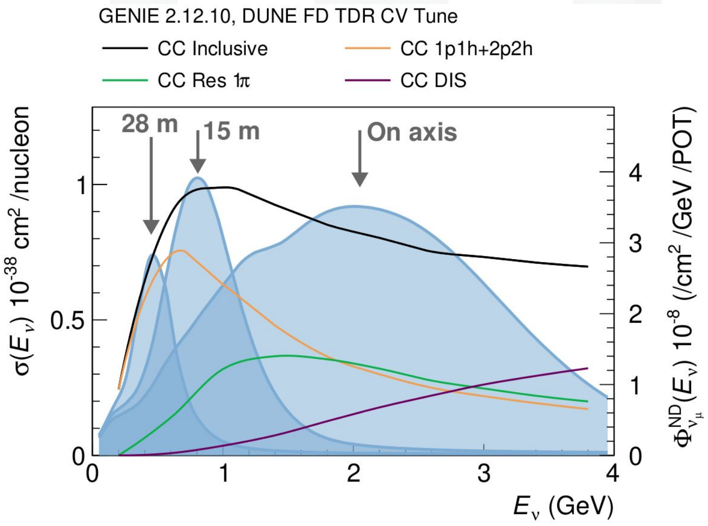
Remaining Model Dependence:

- **Background subtraction**
  - PRISM allows more precise bkgd measurements at ND
- **ND efficiency correction**
  - "Geometric Efficiency Correction" can mitigate this

12 Mike Wilking | The PRISM Technique for LBL ν Experiments NuFACT, Seoul, 2023/08/23

DUNE-PRISM: Two Uses

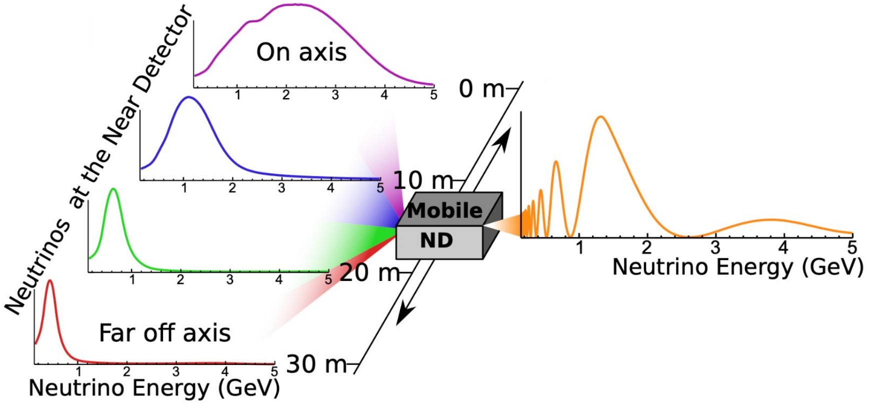
1) Over-constrain beam and interaction model in 'traditional' oscillation analysis with on- and off-axis observations



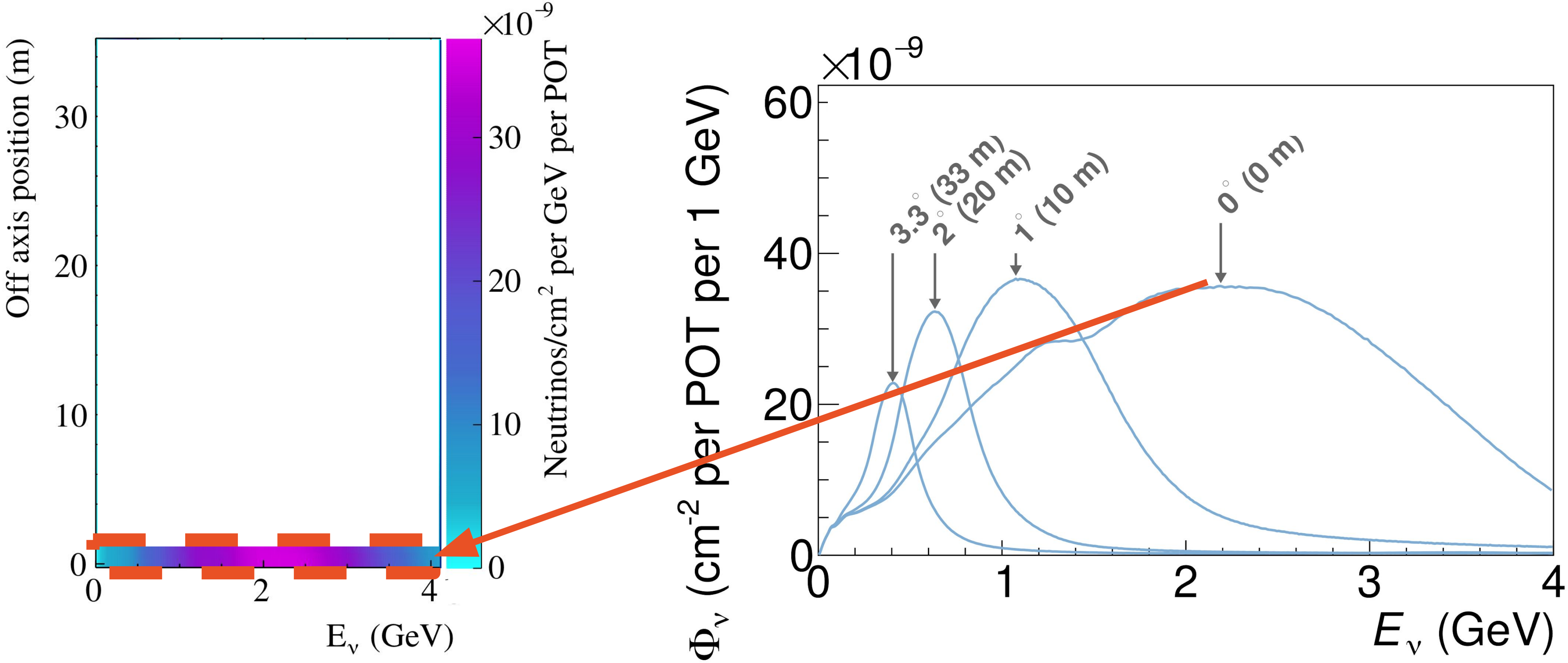
2) Synthesise the measurement of an oscillated flux with the near detector

→ More direct extrapolation of near-detector observations

→ Reduce reliance on accuracy of interaction model predictions



Off Axis at the Near Detector



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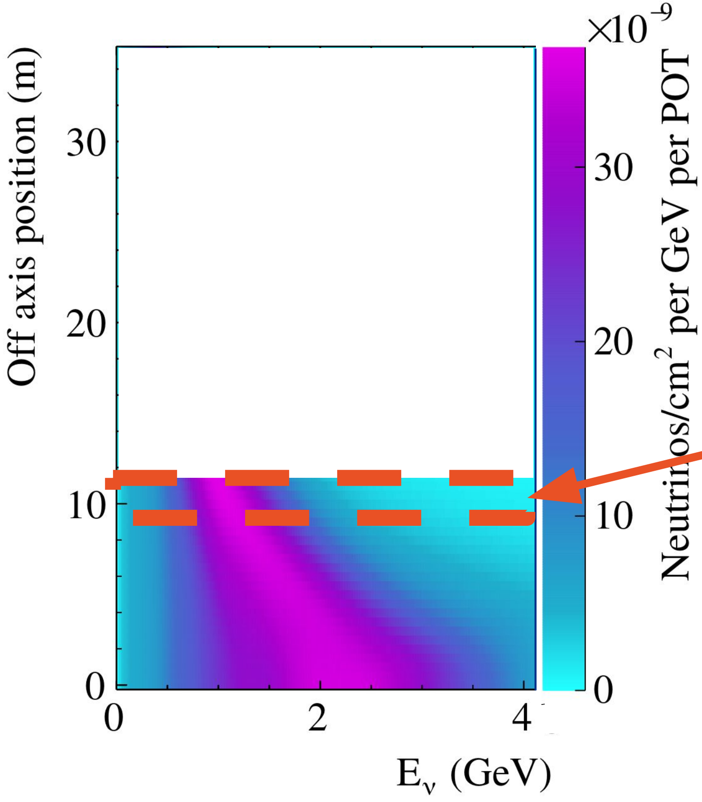

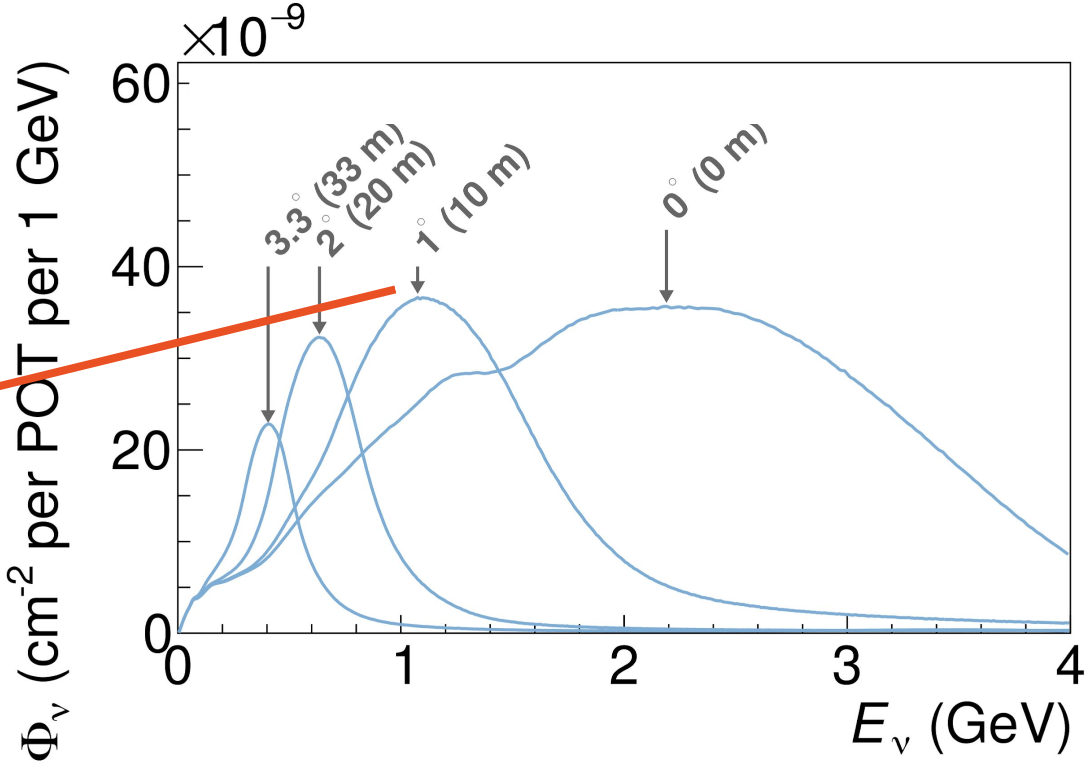

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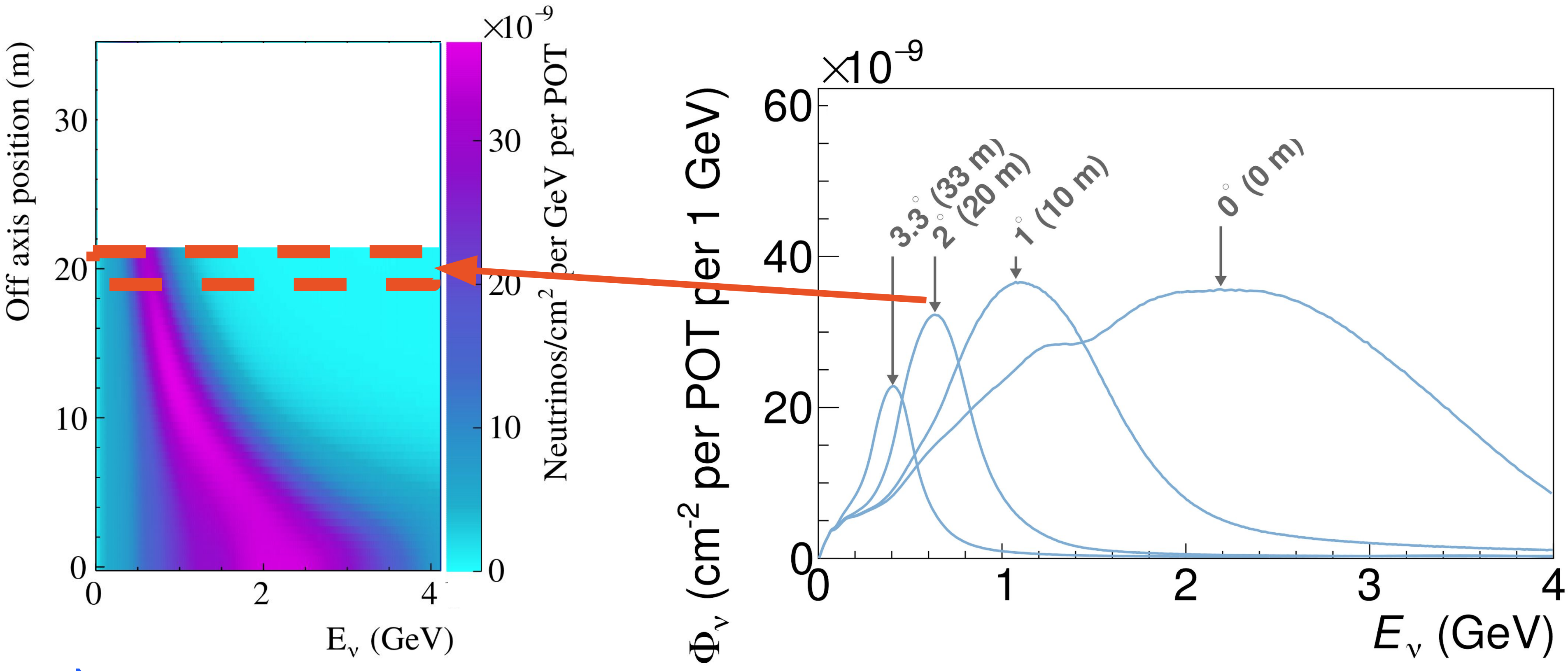

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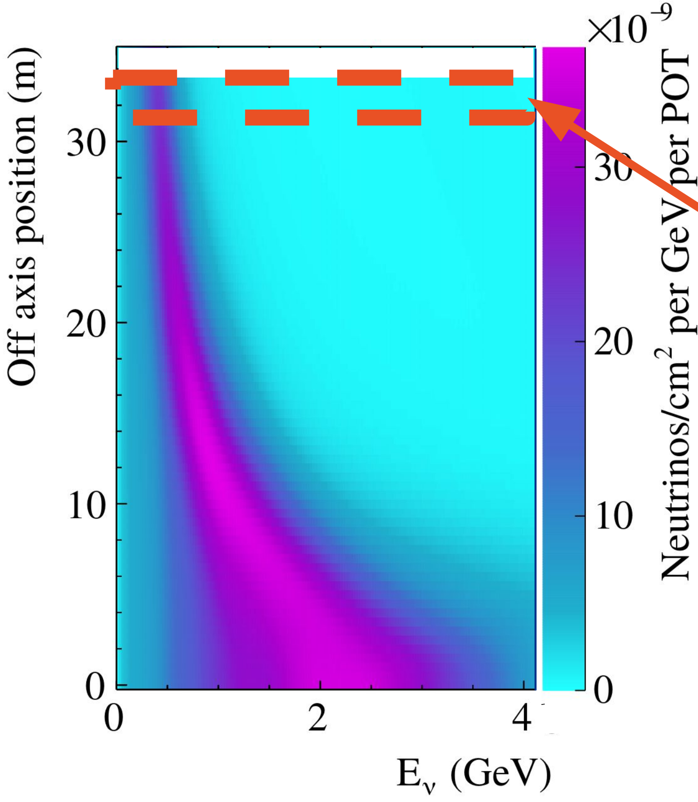
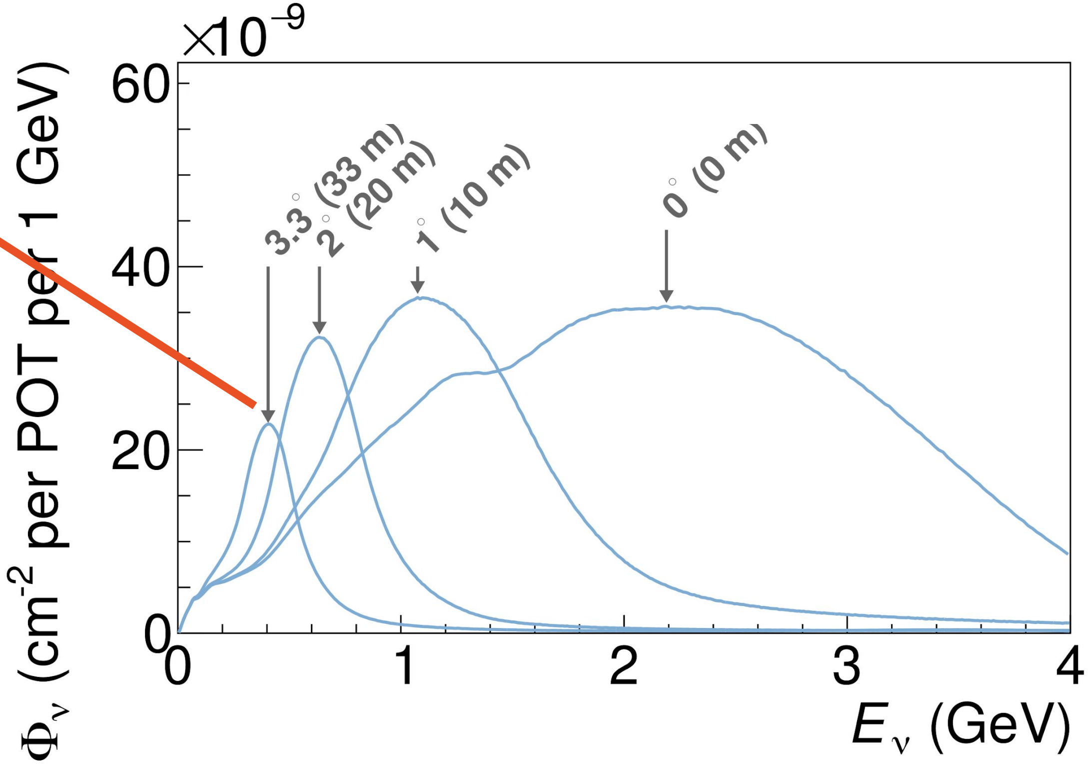
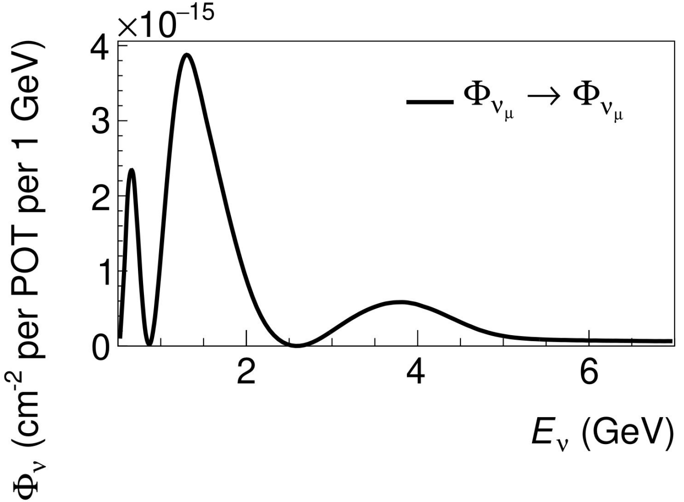




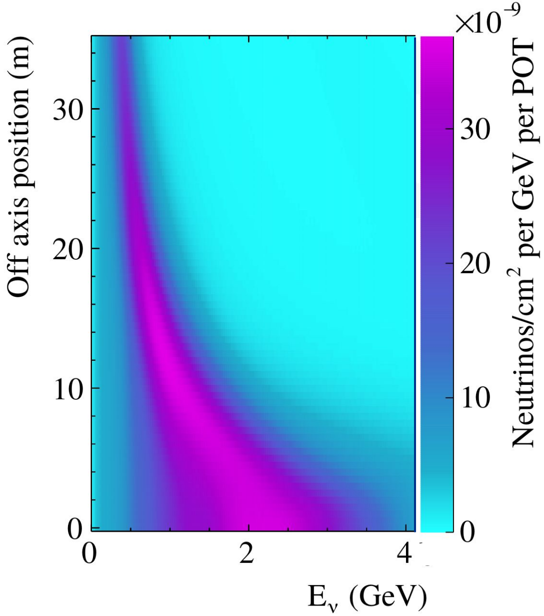
Predicting Oscillations with the Near Detector

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



Predicting Oscillations with the Near Detector

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



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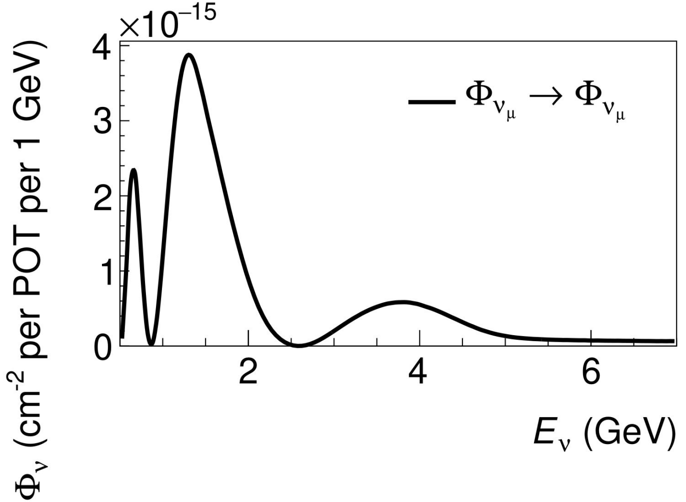

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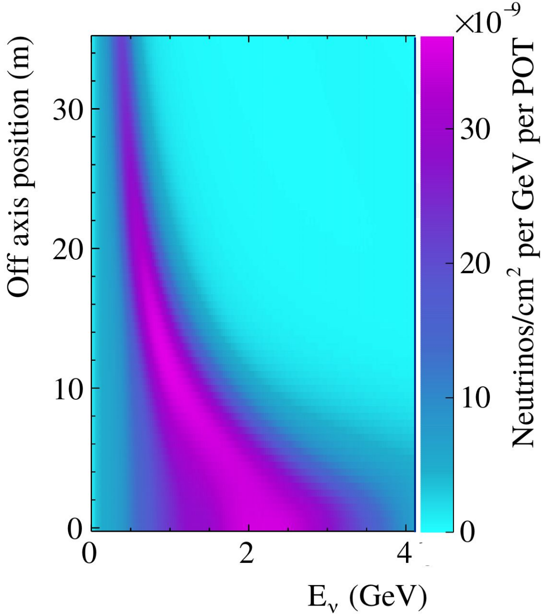
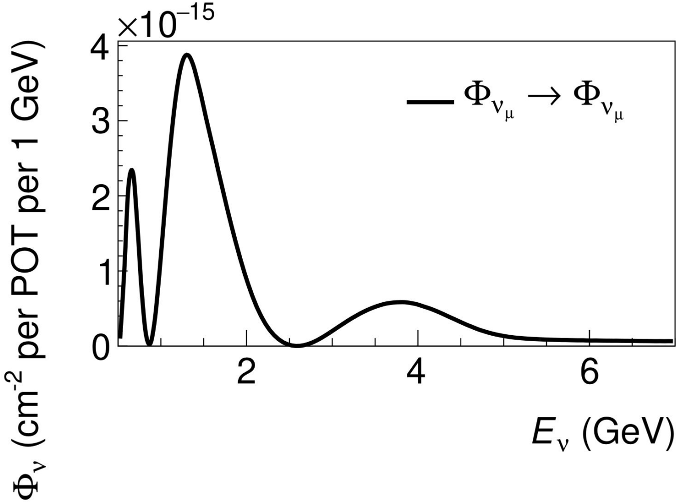
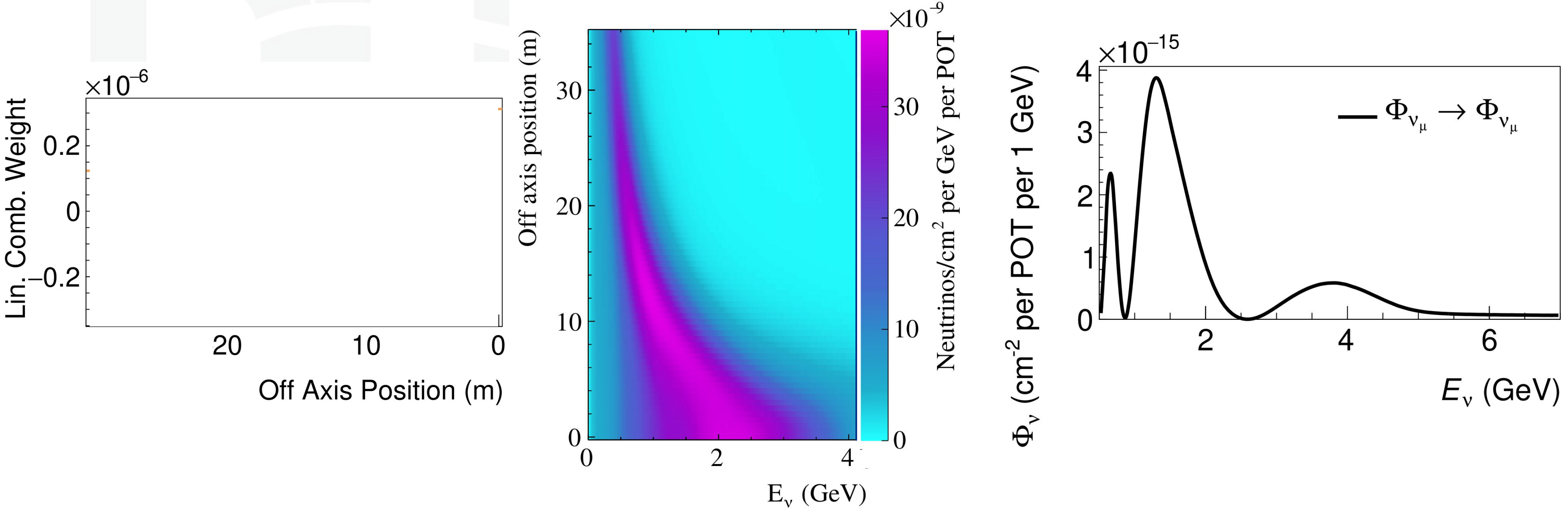


$$\vec{\Phi}^{\nu}_{\mathrm{Far}} \cdot P^{\mathcal{H}}_{\mathrm{Osc}}$$



Predicting Oscillations with the Near Detector

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



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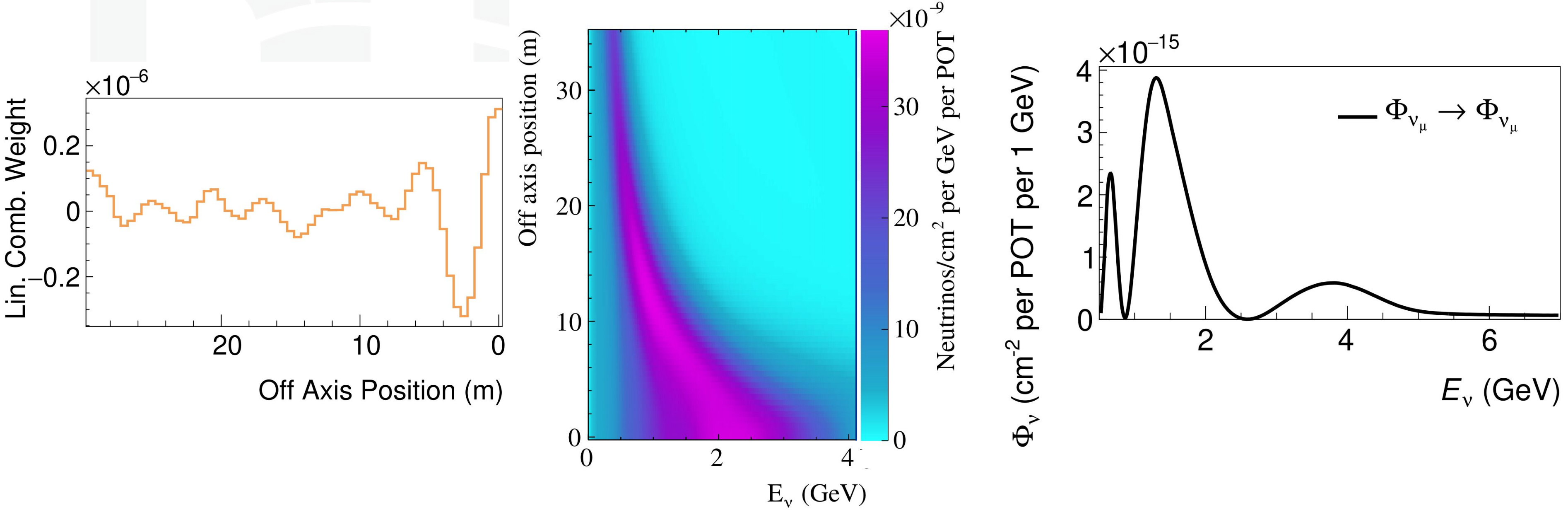

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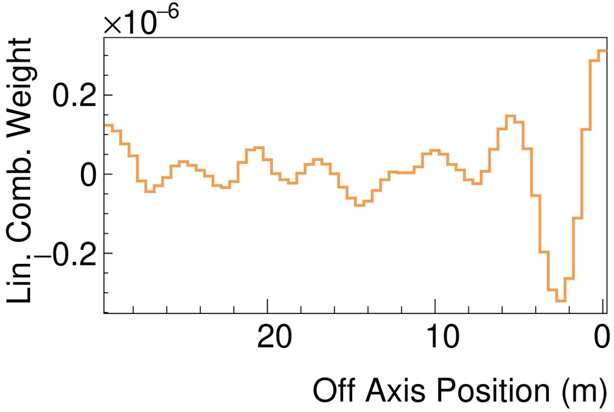
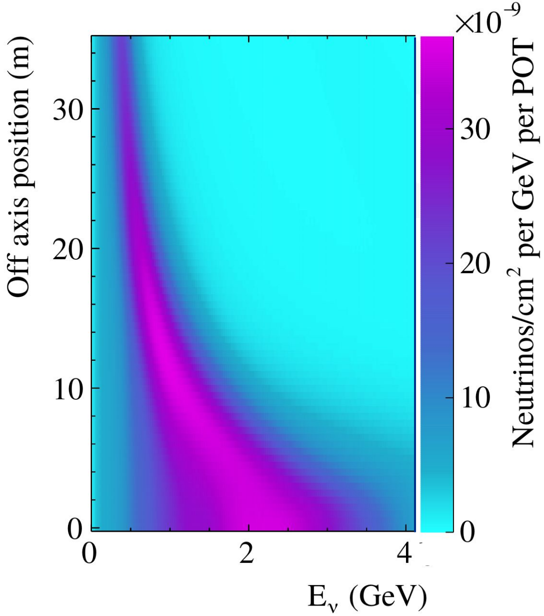
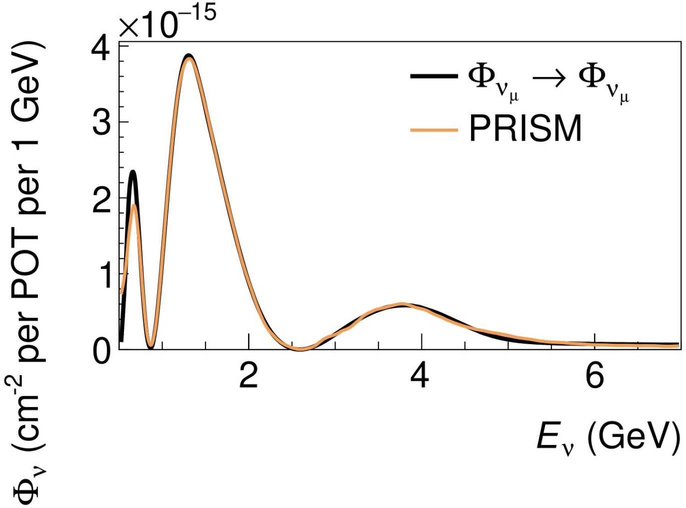
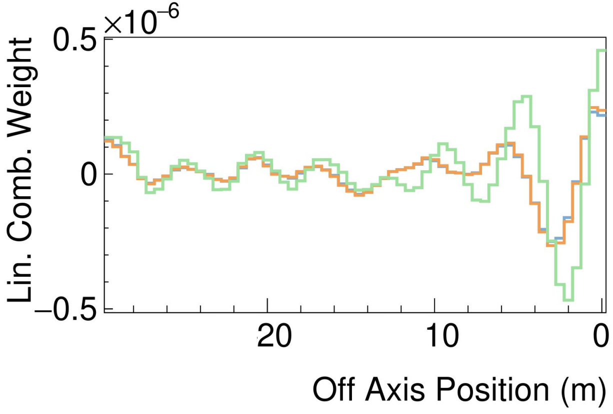


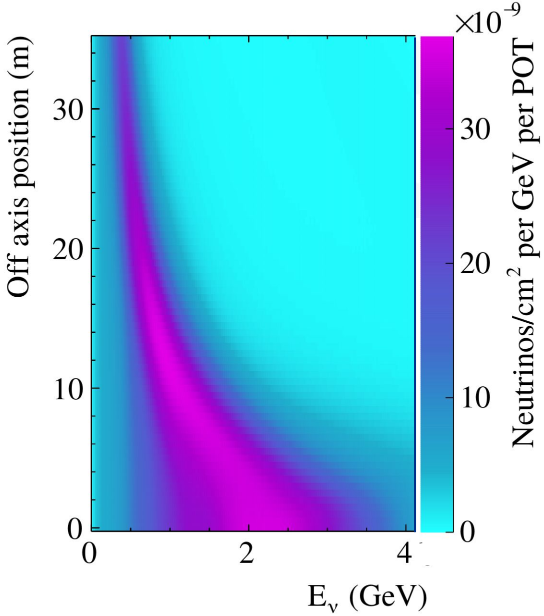


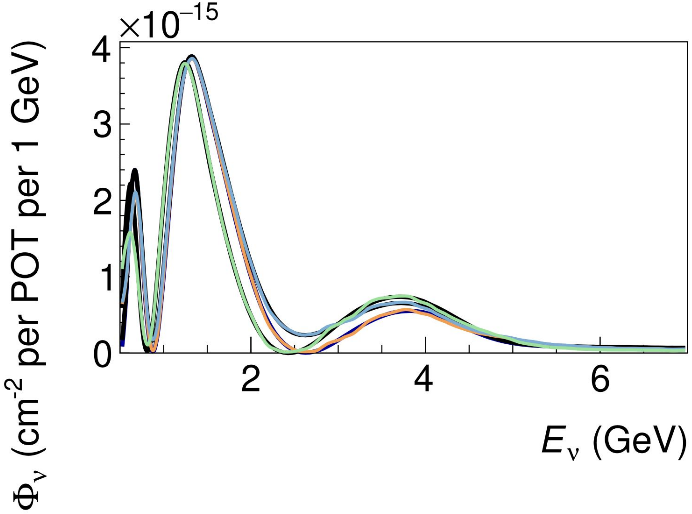


Predicting Oscillations with the Near Detector

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

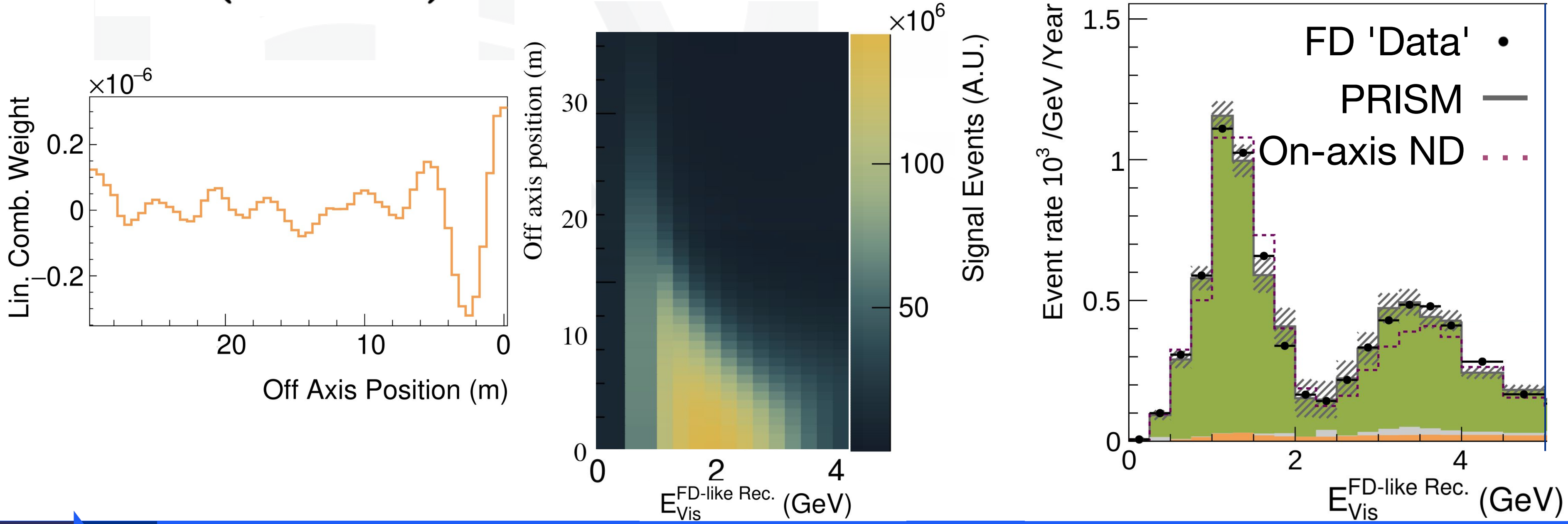




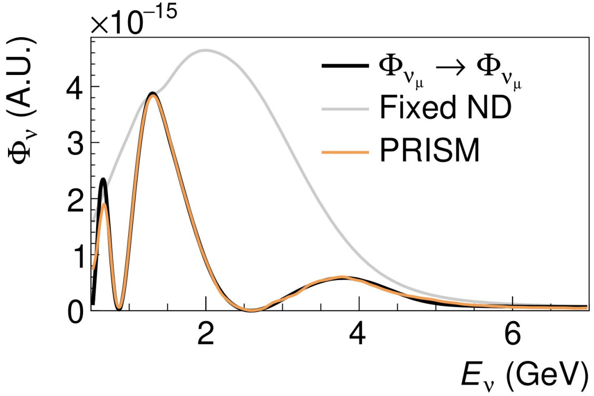


Predicting Oscillations with the Near Detector

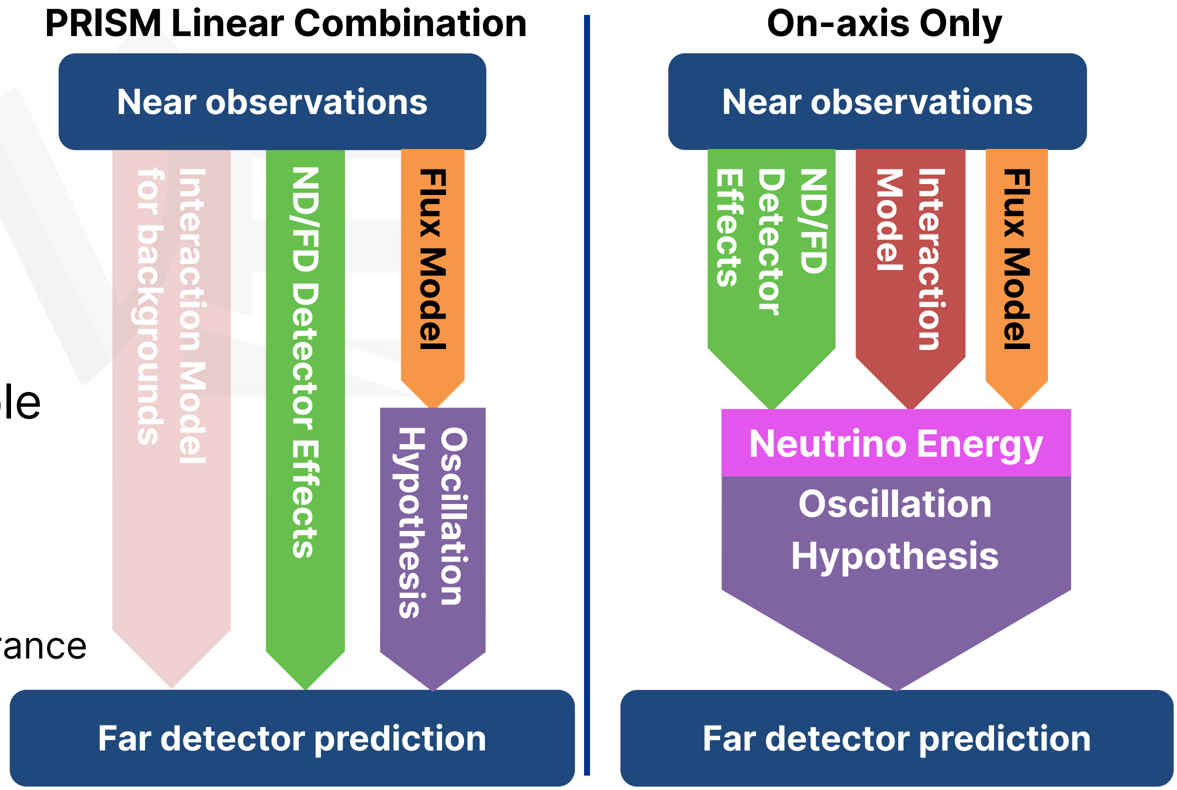
$$\vec{\mathcal{C}}\left(P^{\mathcal{H}}_{\mathrm{Osc}}\right) \cdot \begin{matrix}\mathbf{R}^{\nu}_{\mathrm{Near}} \\ \left(= \Phi^{\nu}_{\mathrm{Near}} \cdot \sigma^{\nu}\right)\end{matrix} = \begin{matrix}\vec{\mathrm{R}}^{\nu}_{\mathrm{Far}} \\ \left(= \vec{\Phi}^{\nu}_{\mathrm{Far}} \cdot P^{\mathcal{H}}_{\mathrm{Osc}}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



Complementary Approaches



- Off axis measurements enable more-direct near-to-far extrapolation
  - Reduce dependence on signal interaction model for disappearance
- But, expect lower sensitivity for LC analysis



Oscillation Sensitivities

FD Event Samples

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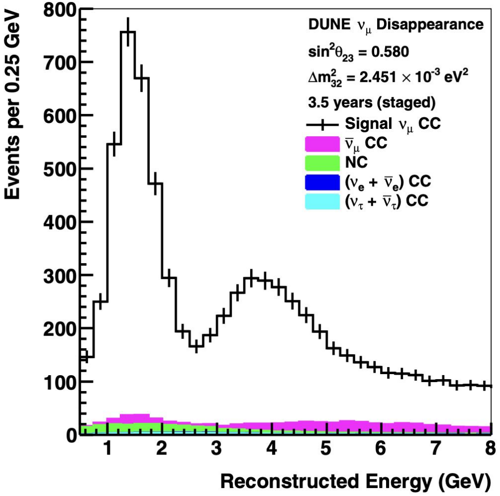
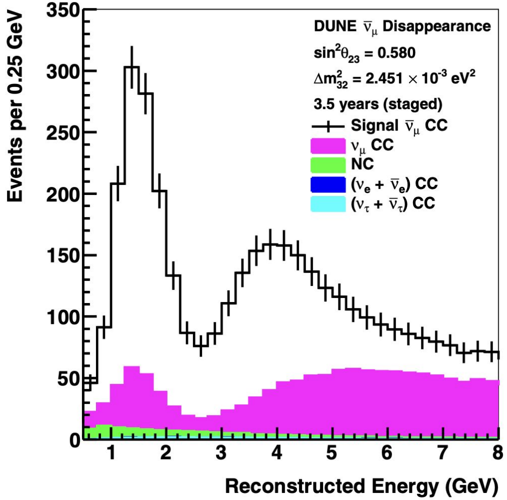
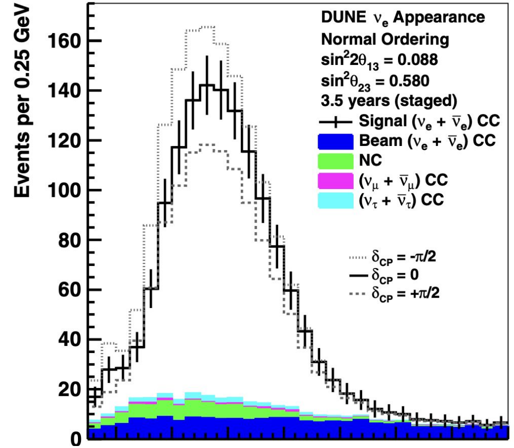
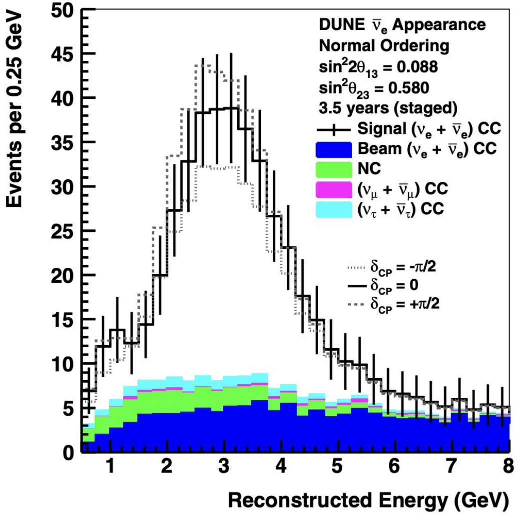




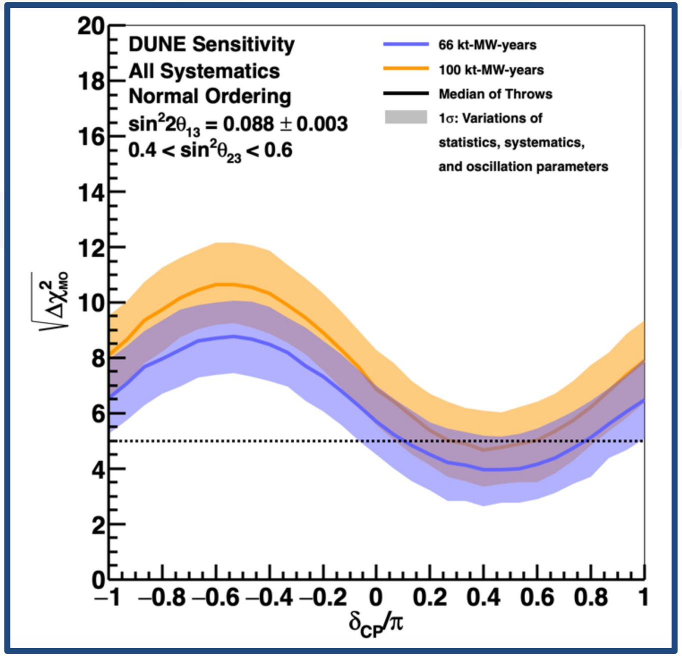


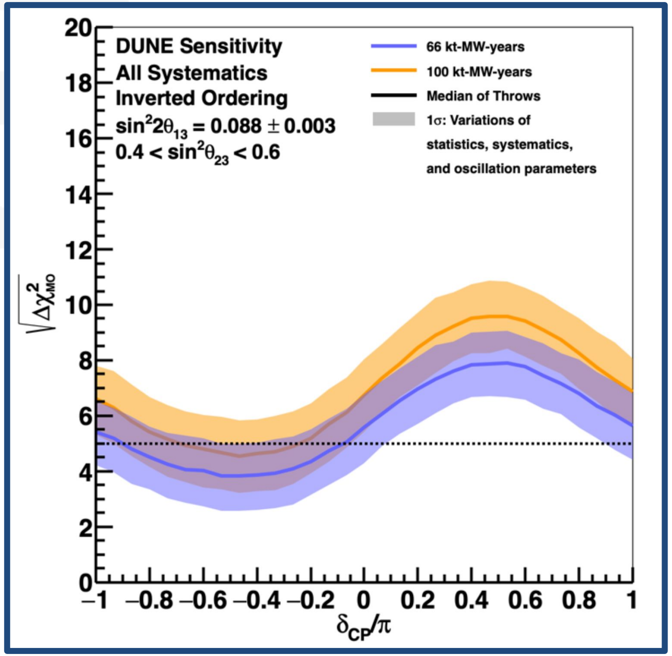


- 2019 Studies:
  - CC-Inclusive, mu- & e-like in nu and nubar mode
- Future:
  - Investigate impact of more granular event selection & projection Near and Far

Mass Ordering: Short Exposures

- Strong MO sensitivity, even with short exposures [O(3-5 years)]
  - P < 0.01 to prefer wrong ratio after 66 kt-MW-yrs





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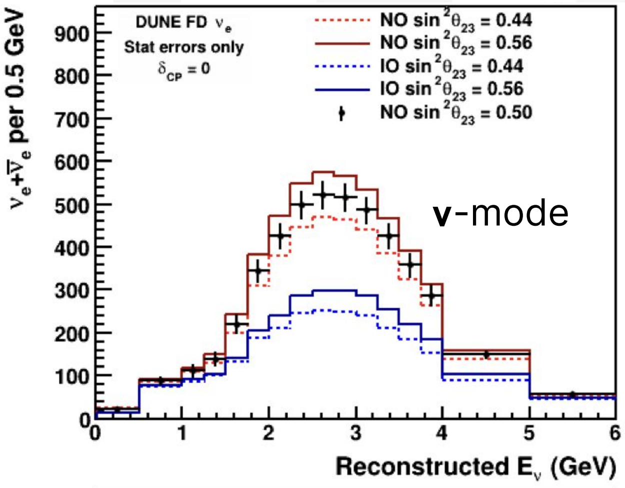
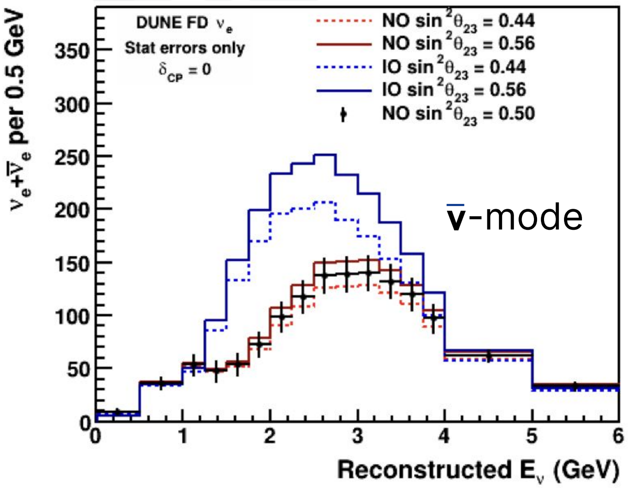
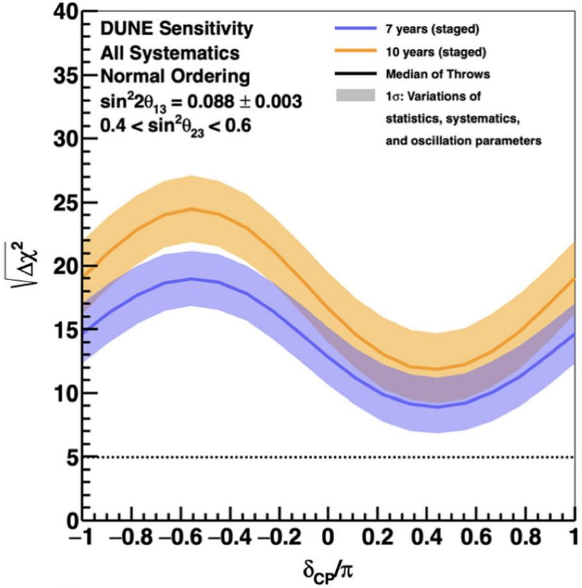
Mass Ordering: Ultimate Sensitivity

- Ultimate MO determination is unambiguous
  - Not dependent on precision measurement of other oscillation parameters
  - Requires no external oscillation parameter input







[EPJC 80 (2020) 978]

World-Leading Sensitivities

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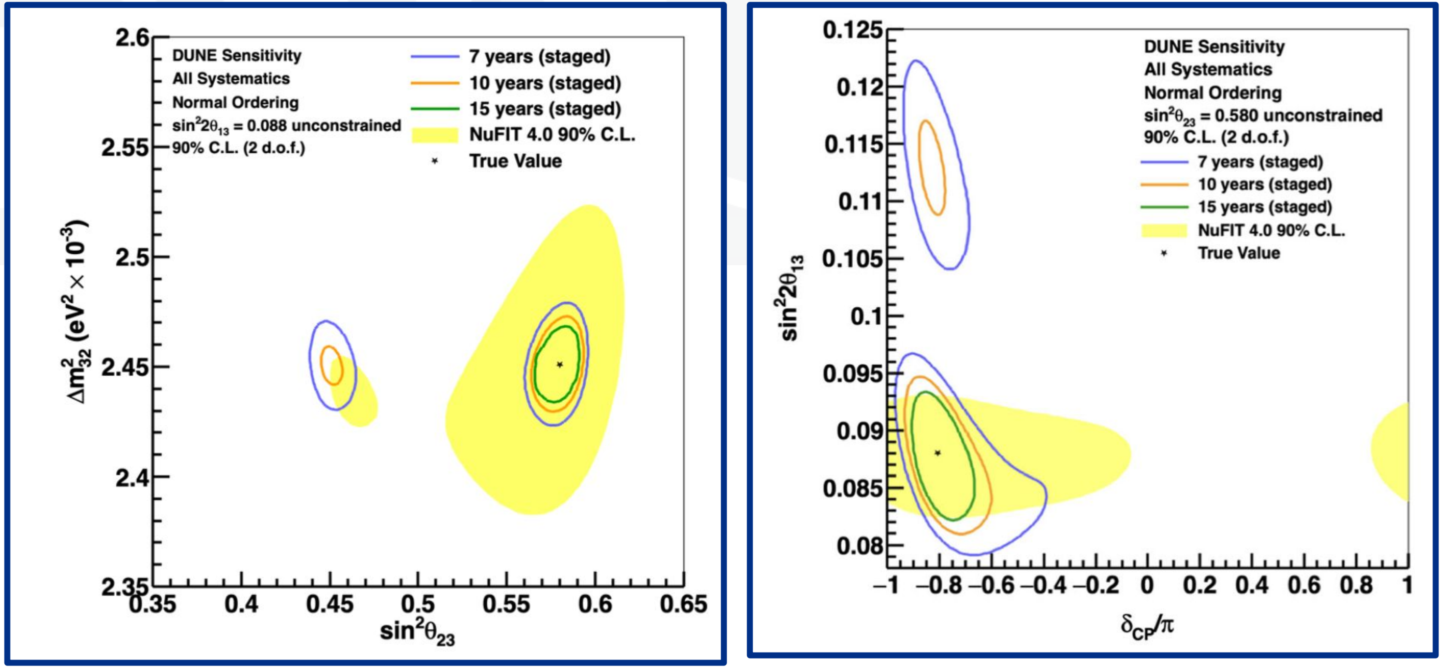
- Assume DUNE-PRISM has been used to minimize and account for significant deviations from interaction model predictions.



Precision Measurements

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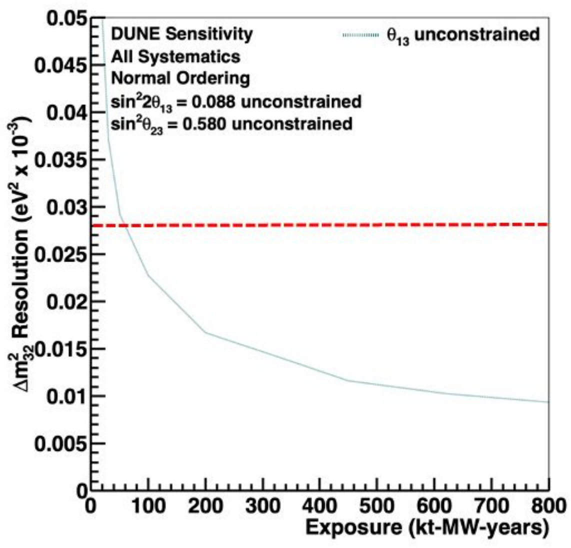
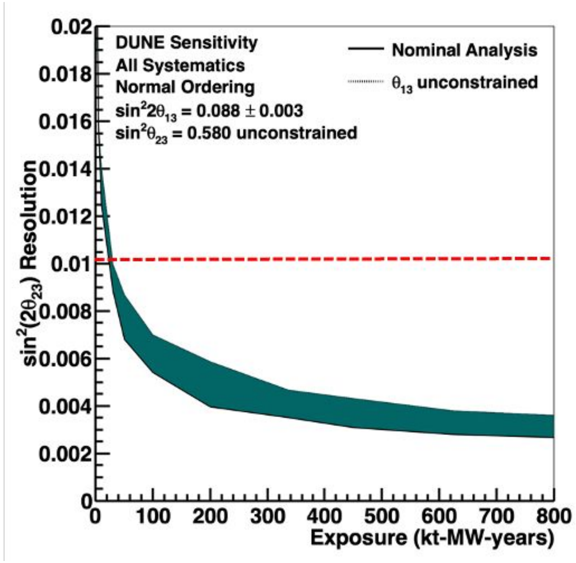
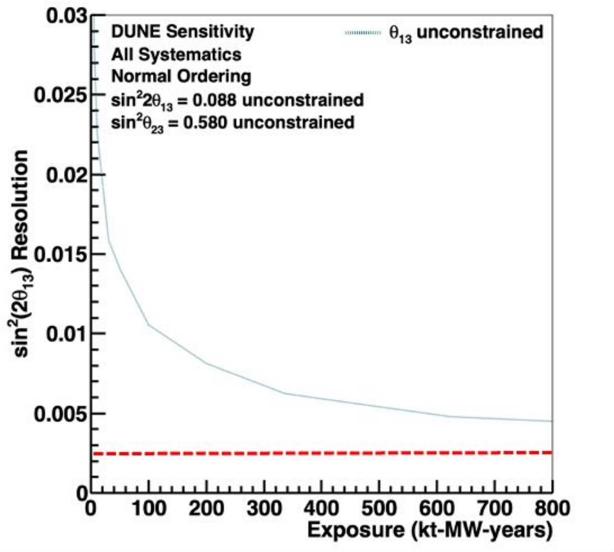
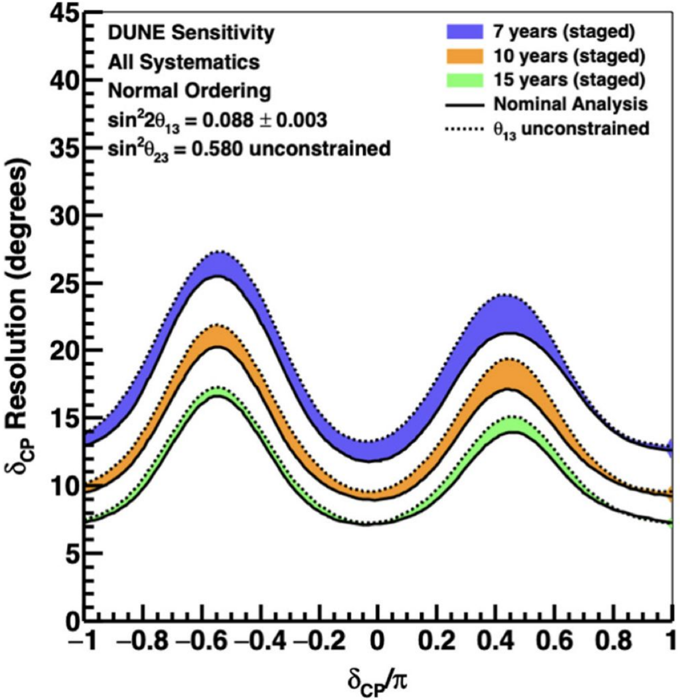


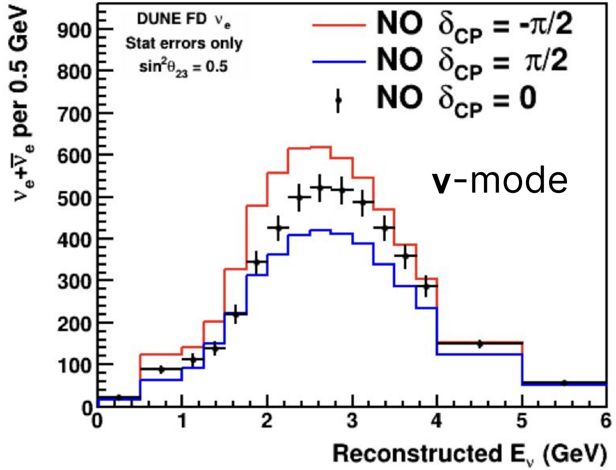


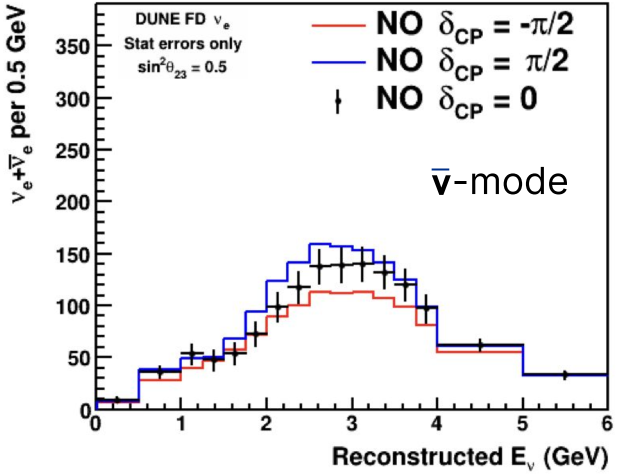


- Expected DUNE sensitivity v.s. current world-averages from NuFit 5.0 (JHEP 09 (2020) 178))
- Ultimate θ_{13} sensitivity approaches reactor constraint
- Precision Osc. measurements, especially joint w/ HK & JUNO, will stress-test PMNS: Different energies/detectors/PMNS matrix elements!

δ_{CP} Resolution



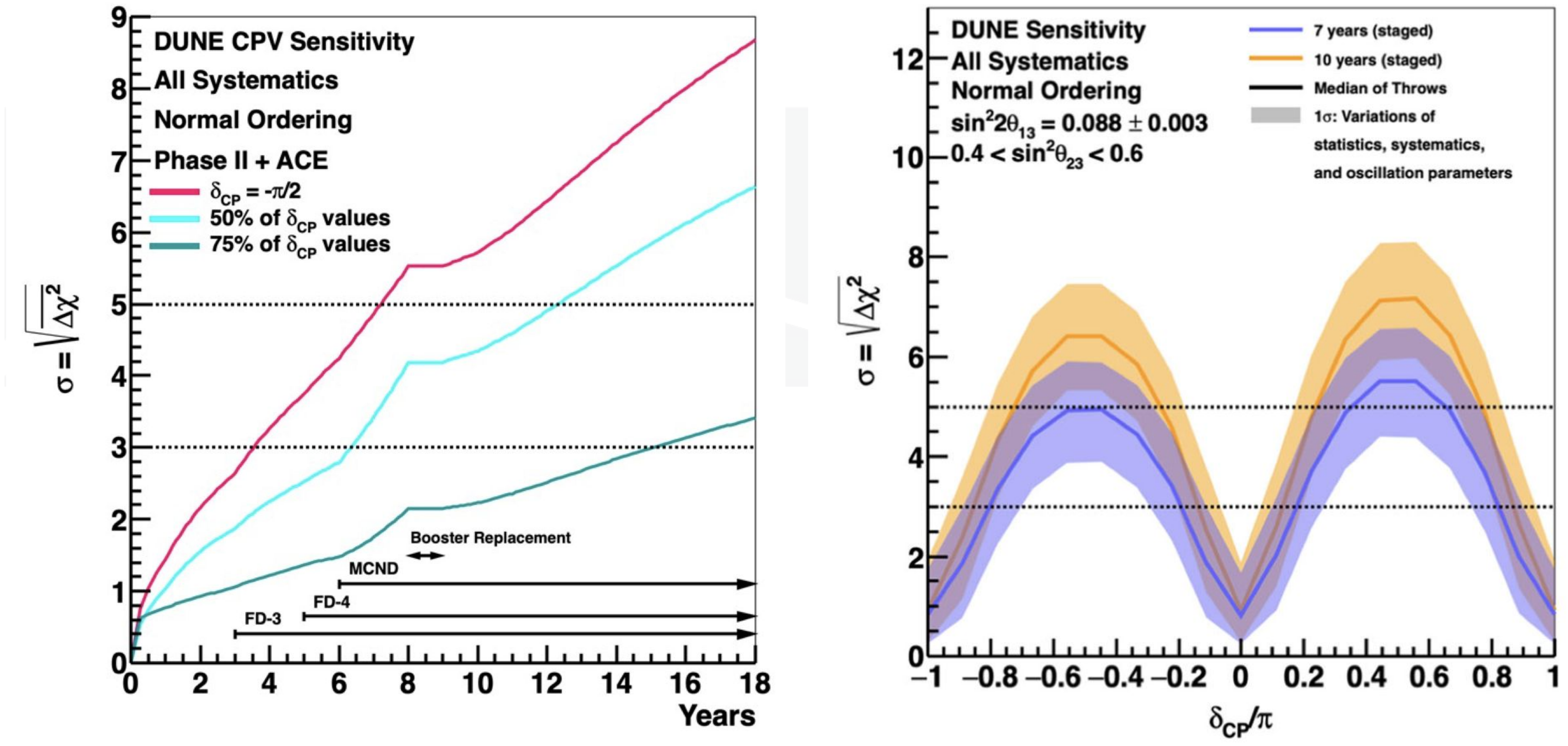




- 7–16° δ_{CP} resolution regardless of true value

CPV Sensitivity

C. Marshall Wednesday Plenary

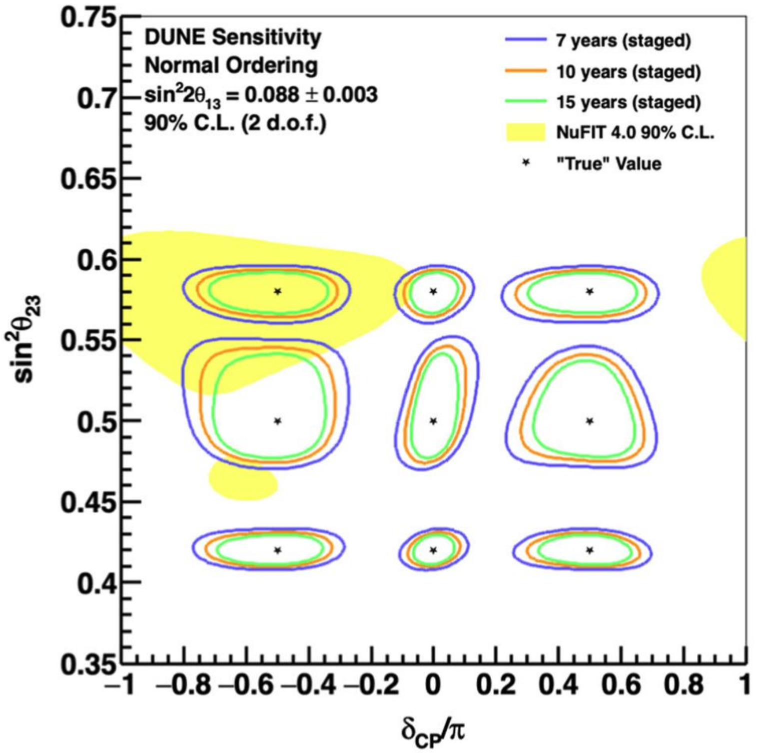


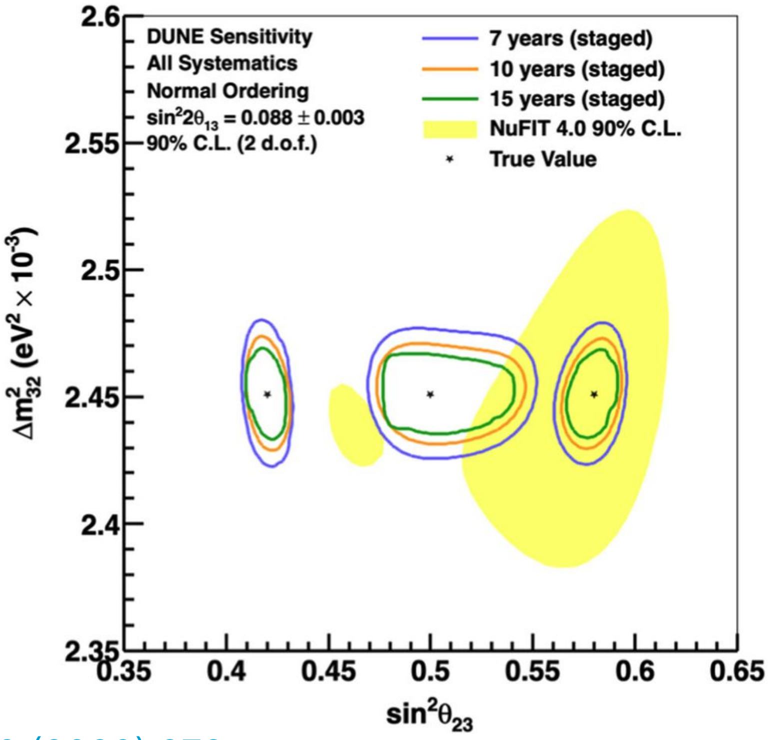
Summary

- Unprecedented sensitivity to PMNS oscillations with DUNE
  - Constrain δ_{CP}, $|\Delta m^2_{32}|$, θ_{23}, θ_{13} and MO with a single experiment!
- PRISM helps insure against small interaction uncertainty budget

Backups

Sensitivities for Different Scenarios





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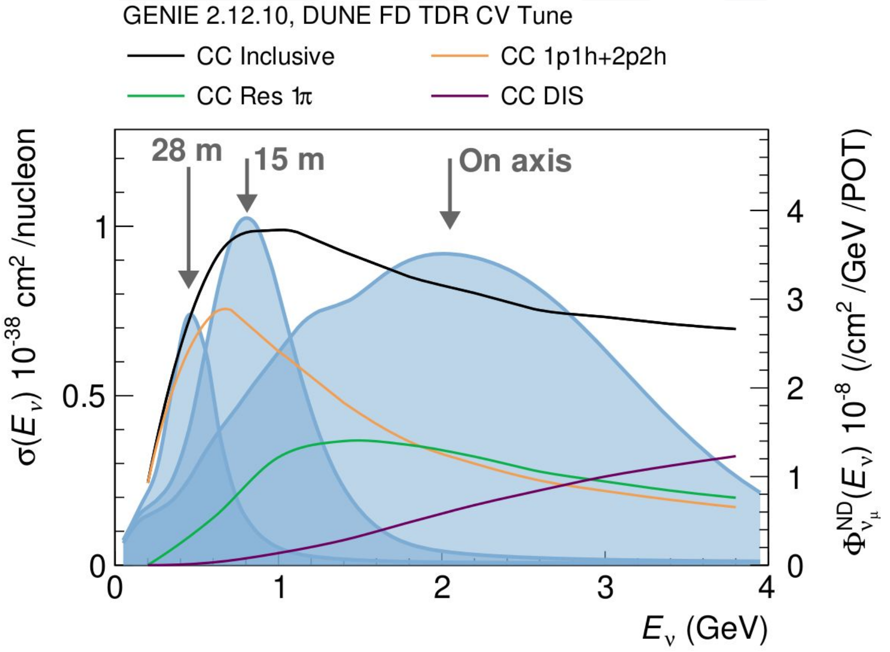
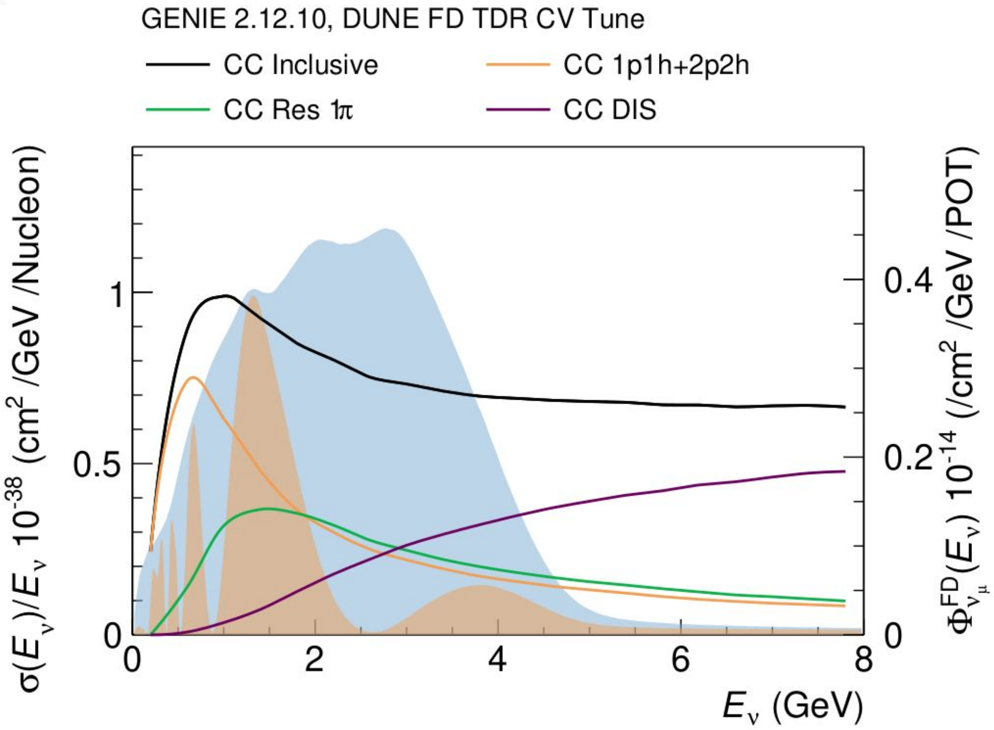
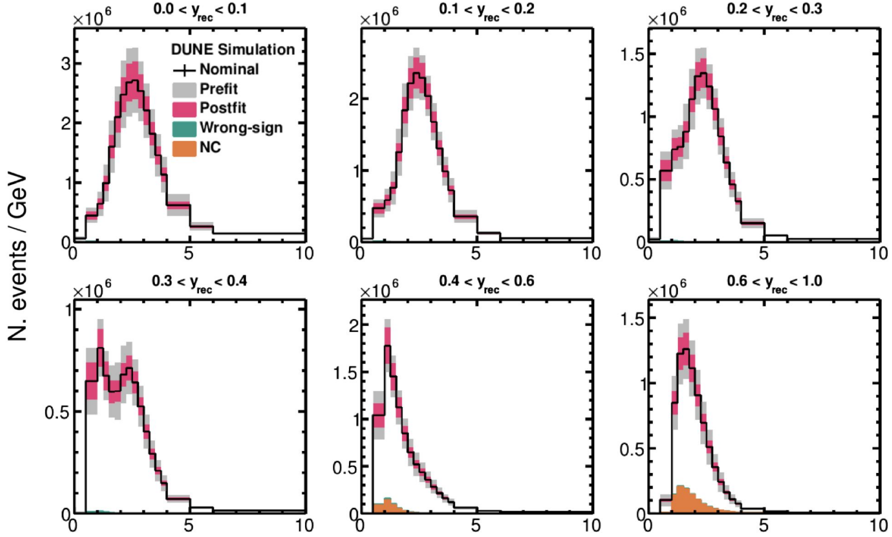
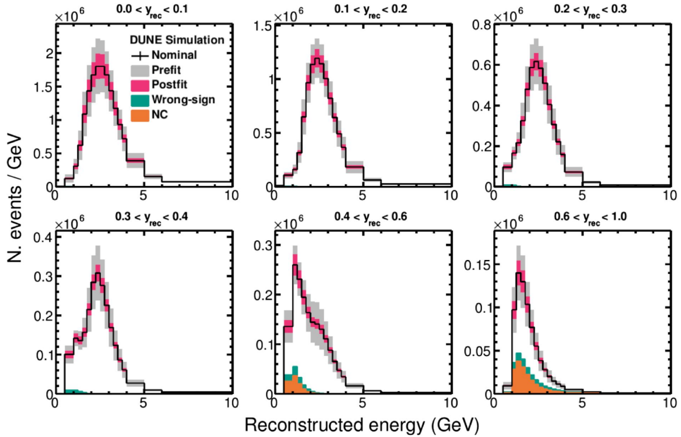
Cross-section Energy Evolution

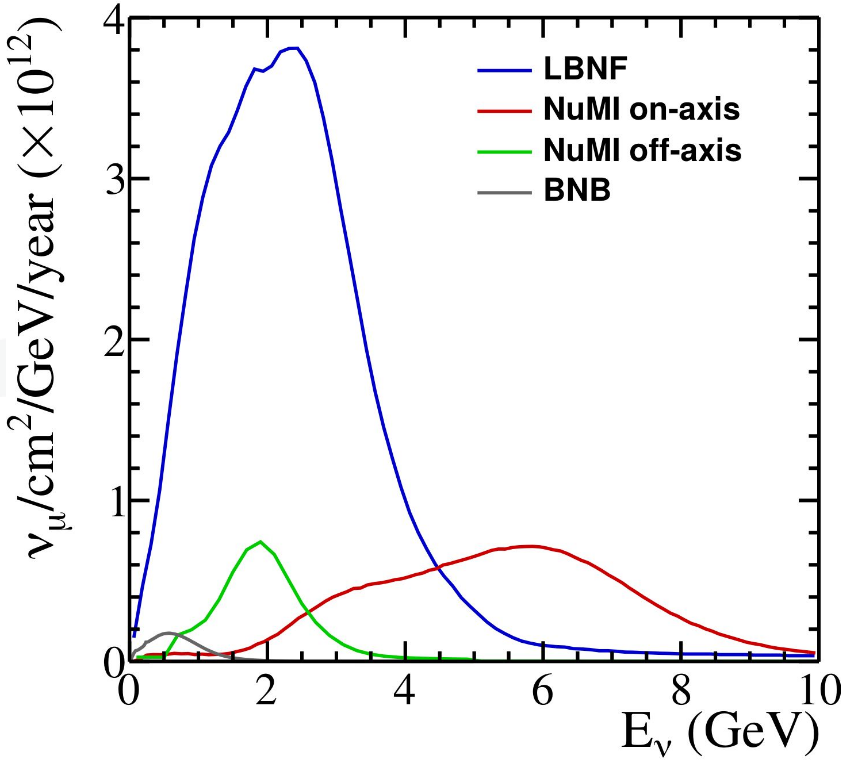





N. events / GeV
0.0 < y_rec < 0.1
0.1 < y_rec < 0.2
0.2 < y_rec < 0.3
0.3 < y_rec < 0.4
0.4 < y_rec < 0.6
0.6 < y_rec < 1.0
DUNE Simulation
Nominal
Prefit
Postfit
Wrong-sign
NC

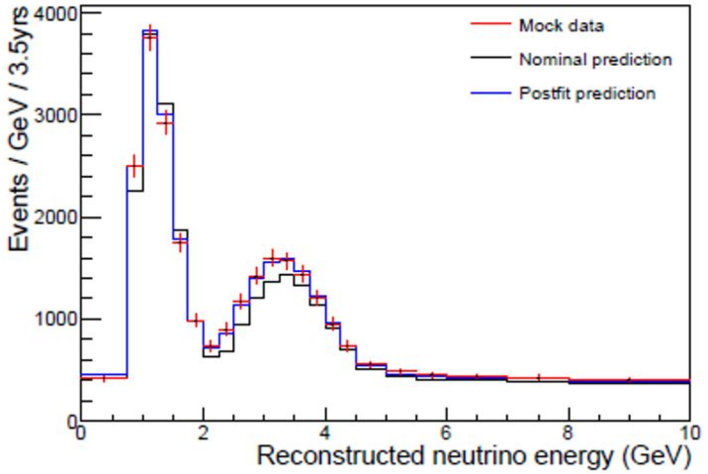

N. events / GeV
0.0 < y_rec < 0.1
0.1 < y_rec < 0.2
0.2 < y_rec < 0.3
0.3 < y_rec < 0.4
0.4 < y_rec < 0.6
0.6 < y_rec < 1.0
DUNE Simulation
Nominal
Prefit
Postfit
Wrong-sign
NC
Reconstructed energy (GeV)

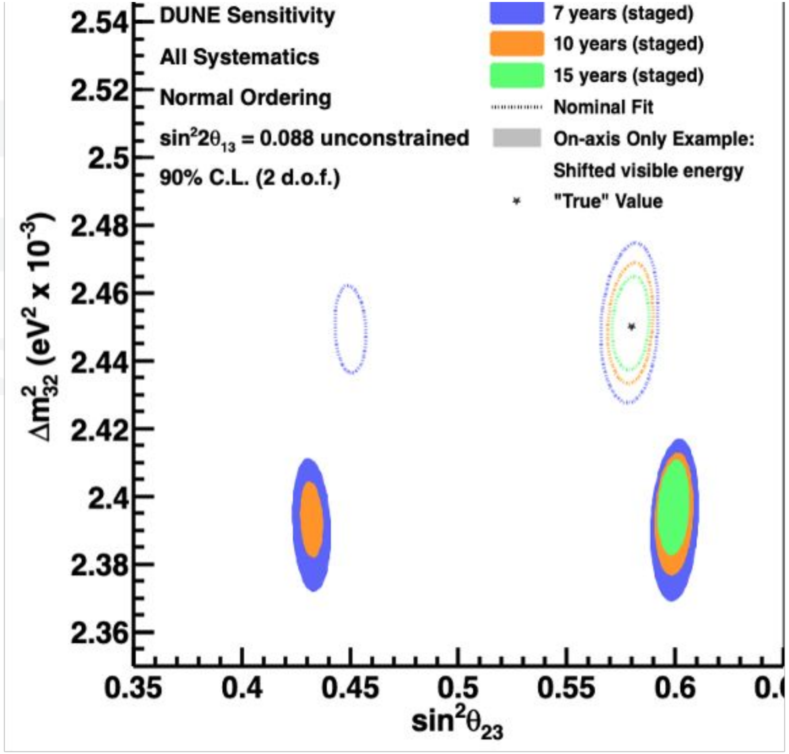
DUNE Beam in Context

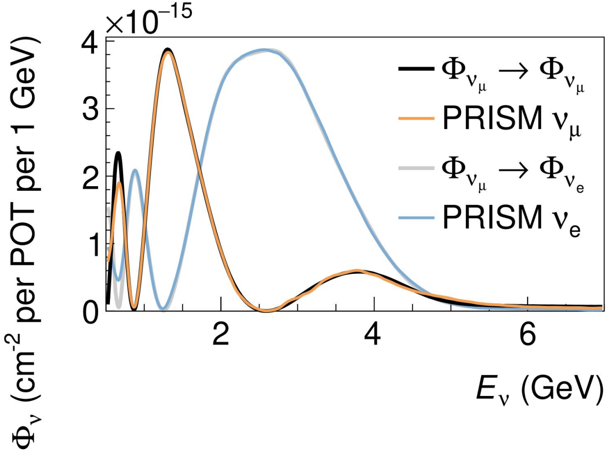


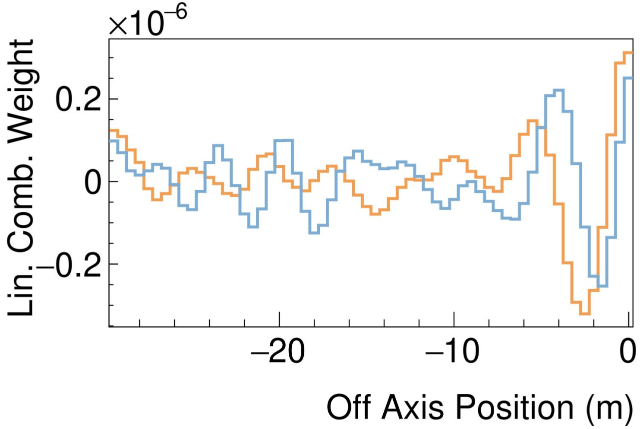
Missing Proton FDS

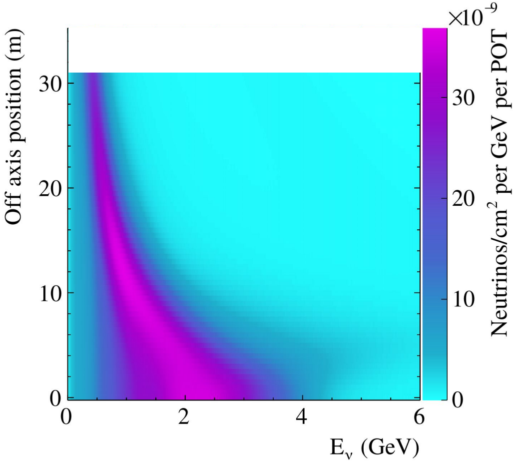
- Move 20% of proton energy to neutrons.
- Vary Cross-section model to minimize ND observables
- Effect unacceptable Osc. bias






×10^−15
4
3
2
1
0
2
4
6
$\Phi_{\nu_\mu} \rightarrow \Phi_{\nu_\mu}$
PRISM ν_μ
$\Phi_{\nu_\mu} \rightarrow \Phi_{\nu_e}$
PRISM ν_e
Φ_ν (cm^{-2} per POT per 1 GeV)
E_ν (GeV)


×10^−6
Lin. Comb. Weight
0.2
0
−0.2
−20
−10
0
Off Axis Position (m)


Off axis position (m)
30
20
10
0
0
2
4
6
E_ν (GeV)
×10^−9
30
20
10
0
Neutrinos/cm^2 per GeV per POT

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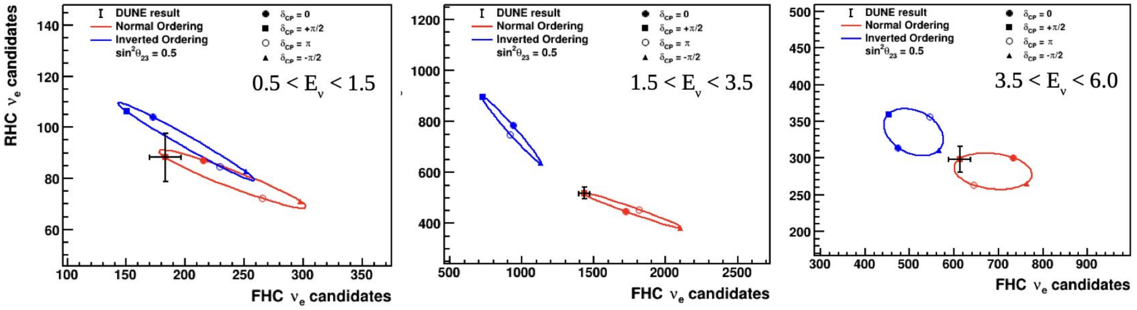
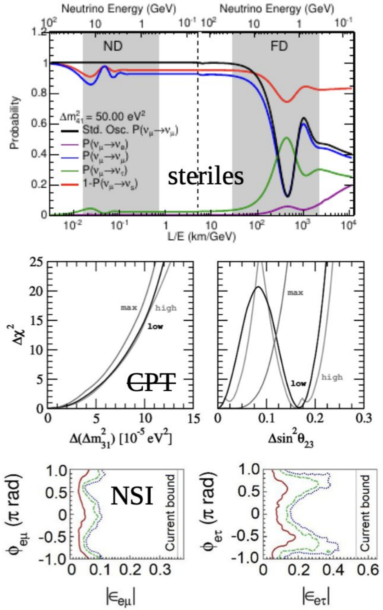
DUNE bi-event plots



- Single flux-integrated event count is a bad way to represent DUNE data, even separating into several bins undersells what DUNE can do with the spectrum
- Very long baseline → no overlap between mass ordering and CPV effects in the energy peak
- Ellipses have very different shape above the oscillation max → resolve degeneracies
- Search for consistency with a particular oscillation parameter in many energy bins → search for new physics

DUNE is sensitive to new physics in neutrino oscillations



- If ν and $\bar{\nu}$ spectra are inconsistent with three-flavor oscillations, it could be due to sterile neutrinos (top), CPT violation (middle), or NSI (bottom)
  - DUNE covers a very broad range of L/E at both the ND and FD
  - DUNE can measure parameters like Δm^2_{32} with neutrinos and with antineutrinos
  - DUNE has unique sensitivity to NSI matter effects due to long baseline
- Characterizing new physics will be challenging: precise measurements with small matter effect in Hyper-K **and** large matter effect in DUNE Phase II likely required