LONG-BASELINE NEUTRINO OSCILLATION AT THE DEEP UNDERGROUND NEUTRINO EXPERIMENT (DUNE)

Elizabeth Worcester

BNL HET Lunch Discussion

August 28, 2020

Overview

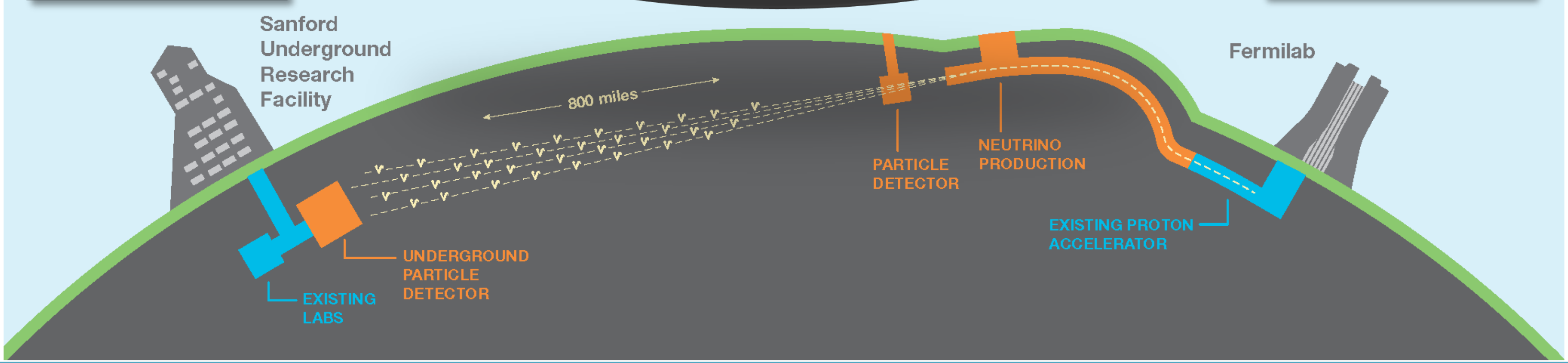
- No Introduction Needed
- DUNE Experiment
- **DUNE Long-Baseline Oscillation Sensitivity**
  - **Sensitivity analysis**
  - **Sensitivity results**
  - **Additional studies**
- DUNE Sterile Neutrino Sensitivity

Based on FNAL Neutrino Physics Seminar

Based on PROSPECT oscillation workshop talk

DUNE

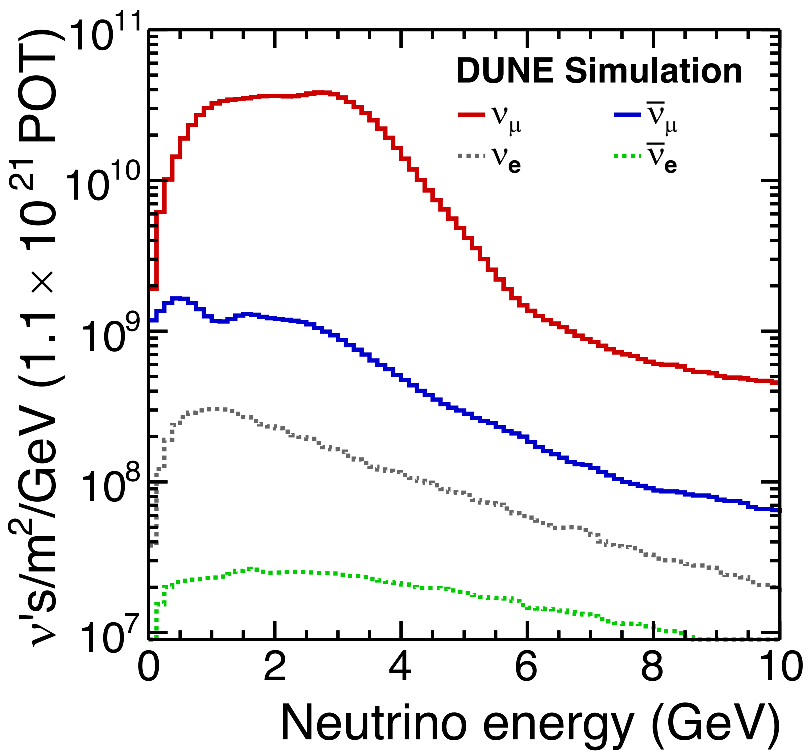
Measure ν_e appearance and ν_μ disappearance in a wideband neutrino beam at 1300 km to measure mass ordering, CP violation, and neutrino mixing parameters in a single experiment. Large detector, deep underground allows sensitivity to rare processes and low-energy physics.



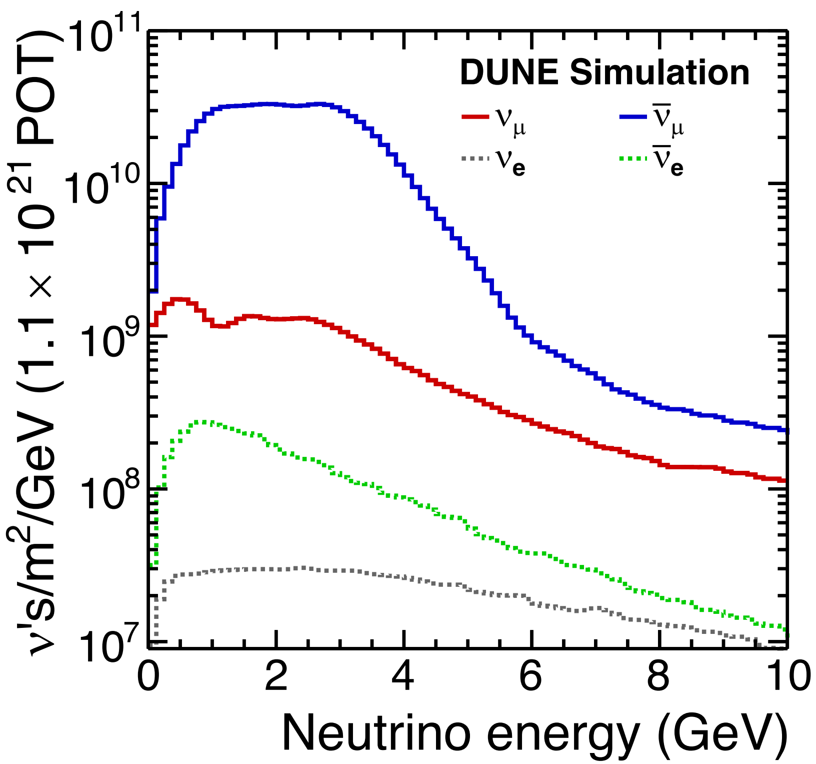
DUNE: Beam

- 120-GeV protons from FNAL accelerator complex
  - 1.2 MW beam power, upgradeable to 2.4 MW
- Neutrino beam line designed using genetic algorithm to optimize CPV sensitivity

Neutrino Mode:

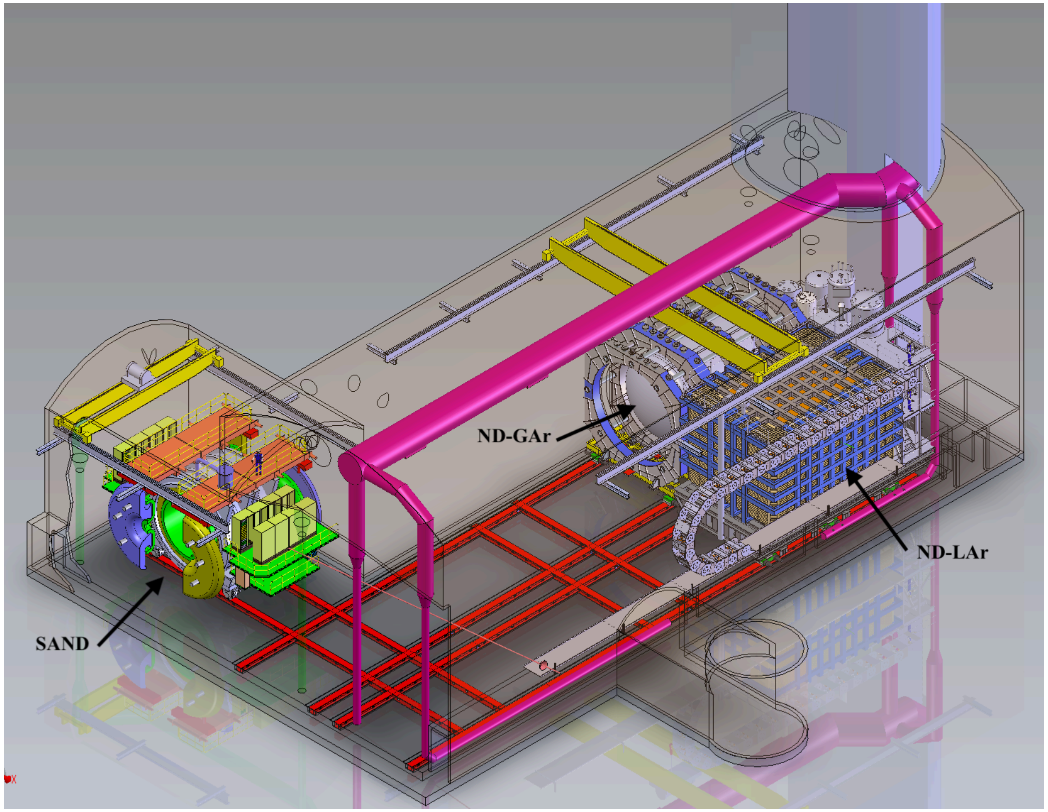


Antineutrino Mode:



DUNE Near Detector

- Located 574 m from neutrino beam target
- Primary purpose is to constrain systematic uncertainty for the long-baseline oscillation analysis



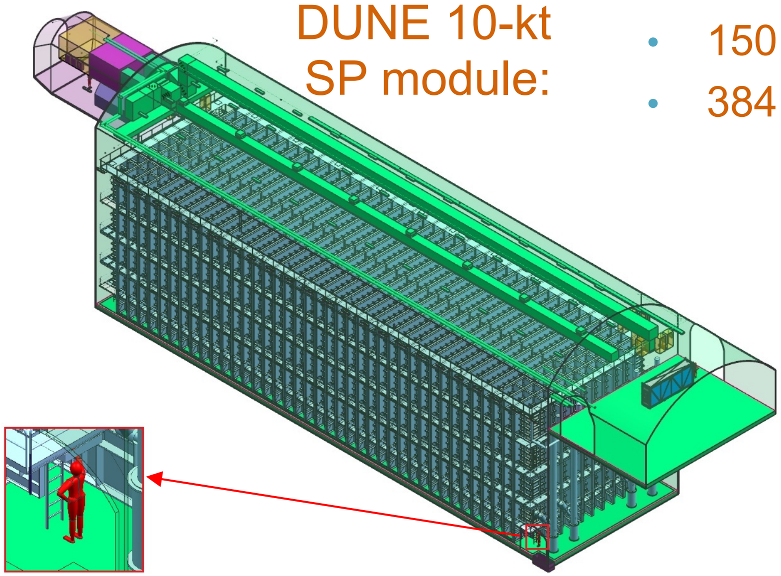
- ND-LAr: Modular, pixelized liquid argon TPC
  - Primary target
  - Most similar to FD
- ND-GAr: High pressure gaseous argon TPC surrounded by ECAL and magnet
  - Momentum analysis of muons from interactions in ND-LAr
  - Lower threshold
- ND-LAr & ND-GAr move off-axis to observe varied beam spectra (DUNE-PRISM)
- SAND: Tracker surrounded by ECAL and magnet
  - On-axis
  - Monitors beam spectrum

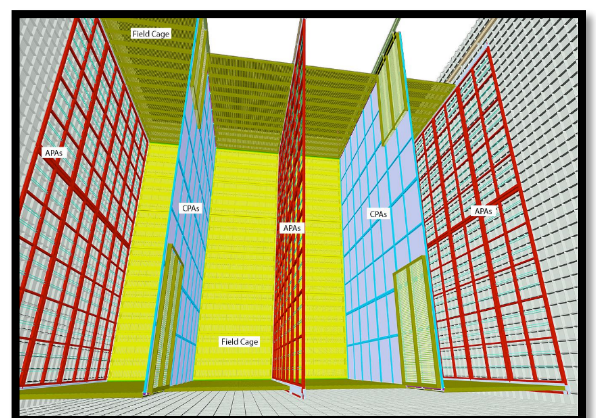
DUNE Far Detector

- 40-kt (fiducial) liquid argon TPC at 4850L of SURF with integrated photon detection
  - Four 17-kt (10 kt fiducial) modules
- Single- and dual-phase detectors being prototyped
  - First module will be a single phase LArTPC
- Modules installed in stages; modules will not be identical

DUNE 10-kt SP module:

- 12 m high x 15.5 m wide x 58 m long
- 150 individual anode plane assemblies (2.3 m x 6 m)
- 384,000 readout wires



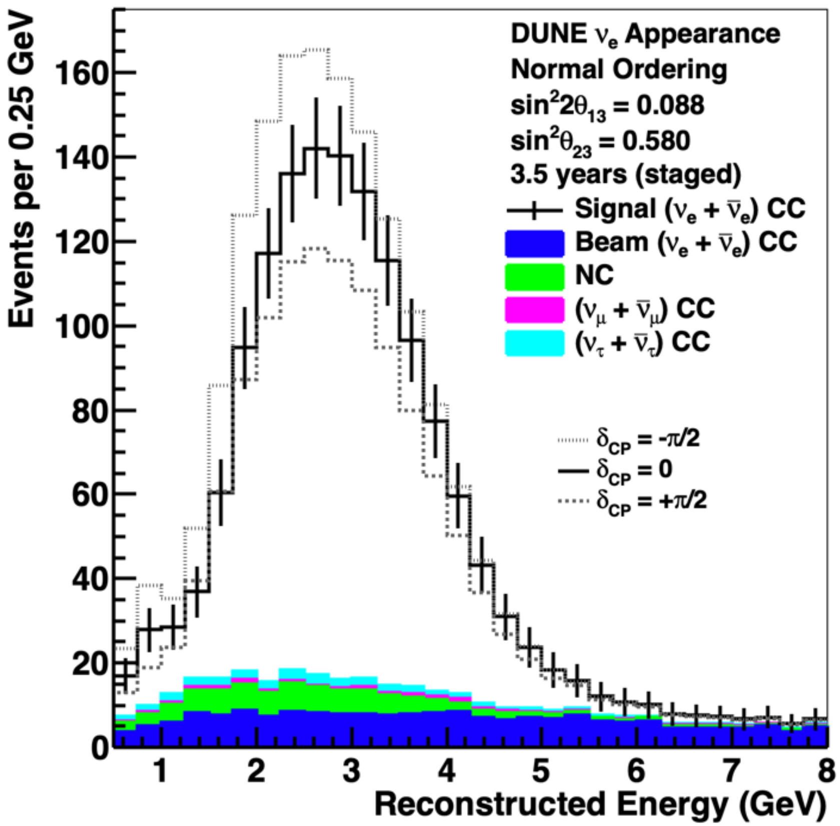


DUNE Physics Goals

- **Three-flavor long-baseline neutrino oscillation**
  - Precise measurement of all parameters governing long-baseline oscillation in a single experiment: θ_{23}, θ_{13}, Δm^2_{32}, δ_{CP}
  - Definitive measurement of neutrino mass ordering
  - Discovery potential for CP violation for wide range of δ_{CP} values
  - Significant potential for determination of θ_{23} octant
- Supernova burst neutrinos
  - Large sample of neutrinos for SNB in our galaxy (especially ν_e)
  - Measure flavor content, spectra, time evolution of SNB neutrinos
  - Quantitative measurements of SNB evolution, particle physics parameters
  - Early detection and pointing for multi-messenger astrophysics
- BSM processes
  - Baryon number violating processes, **sterile neutrinos**, non-unitarity of PMNS matrix, non-standard interactions, CPT violation, neutrino trident production, dark matter detection, ….

LBL Oscillation Analysis

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \simeq\ & \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 \\
& + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{CP}) \\
& + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,
\end{aligned}
$$



- Compare FD data to FD predictions to measure oscillation parameters
  - Sensitivity analysis, so all “data” is simulated
- FD prediction comes from combination of flux model, neutrino interaction model, detector models, and ND data
- Individual sources of systematic uncertainty (flux, interactions, detector effects) included in analysis
  - Incorporate knowledge from existing experiments (MINERvA, NOvA, T2K, uBooNE)
  - Consider impact of “unknown unknowns”

Far Detector Analysis

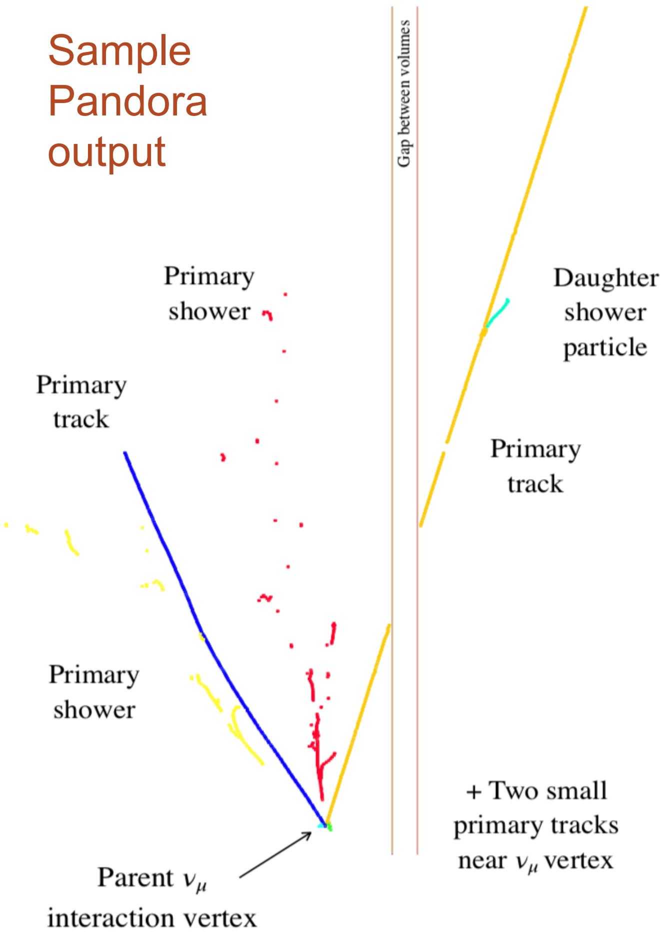
DEEP UNDERGROUND NEUTRINO EXPERIMENT

- GEANT4 simulation of neutrino beam design
- Full LArSoft Monte Carlo simulation
  - Shared framework among many LArTPC experiments
  - GENIE event generator
  - GEANT4 particle propagation
  - Detector readout simulation including realistic waveforms and white noise
- Automated reconstruction: signal processing and hit finding, clustering algorithms, energy reconstruction
- Event classification using convolutional visual network (CVN)
  - A convolutional neural network (CNN)

FD Reconstruction

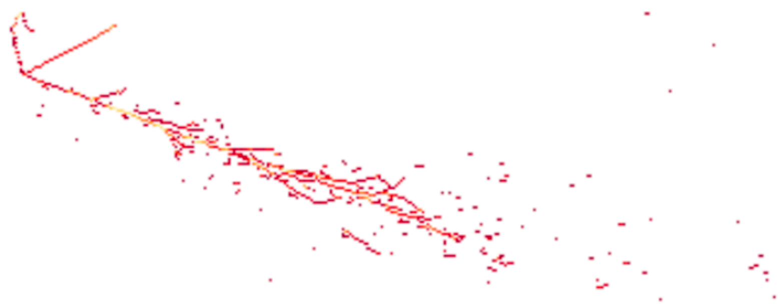
- High-level objects (tracks & showers) identified based on hit proximity in space and time
- Track energies determined using range (contained) or multiple Coulomb scattering (exiting)
- Shower (hadronic and EM) energies determined with calorimetry
- Corrections applied for recombination, electron lifetime, and missing energy
- Reconstructed neutrino energy is sum of lepton and hadron reconstructed energies
- Neutrino energy resolution: 15-20%
  - Dominated by hadron reconstruction

Sample Pandora output

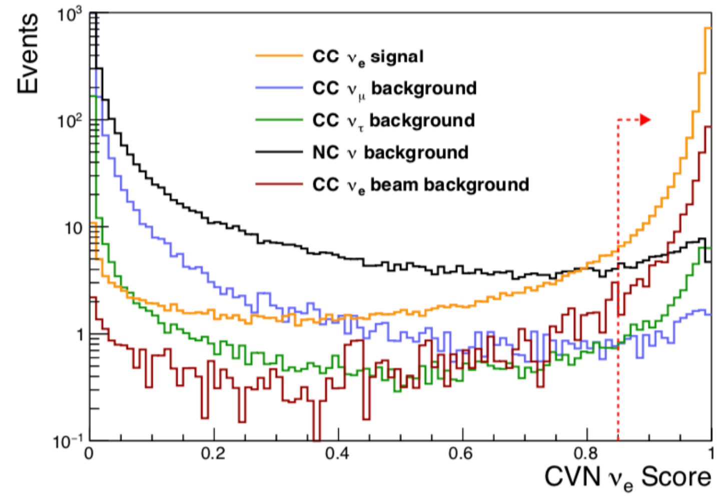


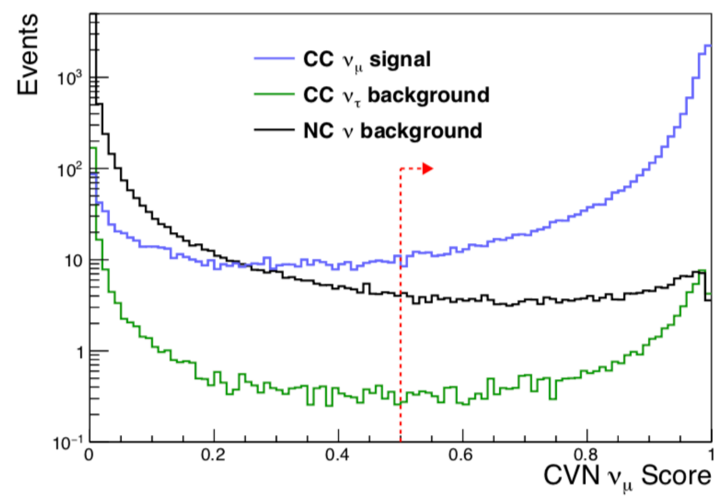
FD Event Classification

- Performed using convolutional visual network (CVN)
  - Three input images per event (time vs. wire number for each readout plane)



- Training performed on statistically independent MC sample
- Event selection criteria chosen to optimize CP violation sensitivity



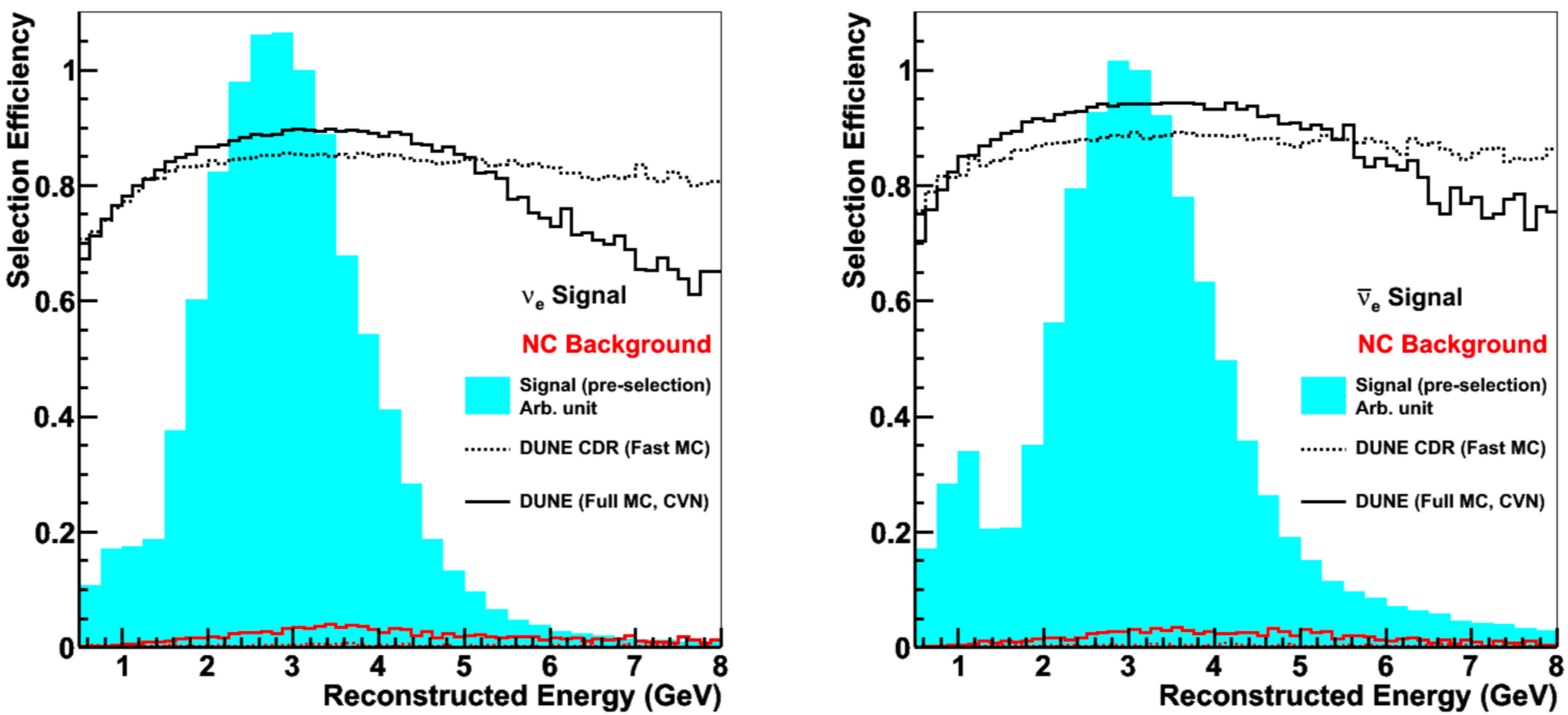


FD Event Selection Efficiency

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Neutrino Mode:

Antineutrino Mode:



>90% peak efficiency for both ν_e and ν_μ selection

Good efficiency for full energy range used in oscillation analysis

Analysis Input

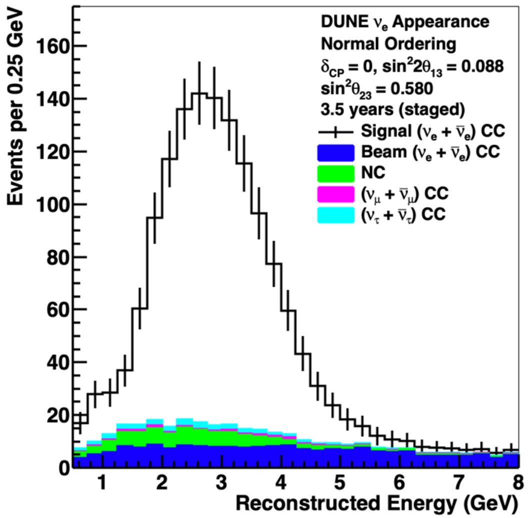
- Oscillation parameters: NuFit 4.0 (Nov 2018)
  - http://www.nu-fit.org/?q=node/177
  - True value of θ_{23} has significant impact on sensitivity
- Earth density: 2.848 g/cm^3
- Baseline: 1284.9 km
- Staging assumptions (technically limited schedule)
  - 1.2 MW × 20 kton at start
  - 1.2 MW × 30 kton after 1 yr
  - 1.2 MW × 40 kton after 3 yr
  - 2.4 MW × 40 kton after 6 yr
  - Equal running in neutrino/antineutrino mode
  - Standard "Fermilab year" = 56% accelerator uptime

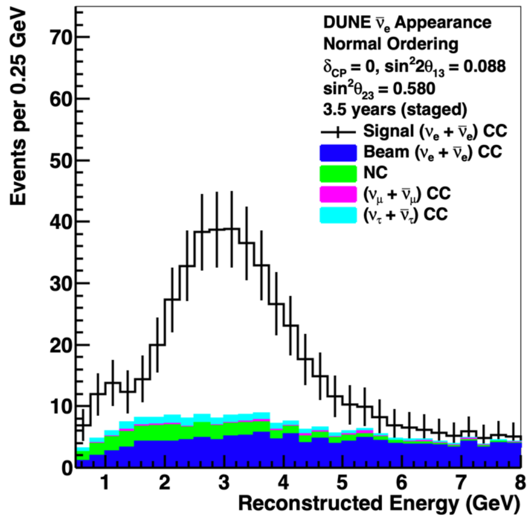
FD Selected Spectra

DEEP UNDERGROUND
NEUTRINO EXPERIMENT

Neutrino Mode | Antineutrino Mode

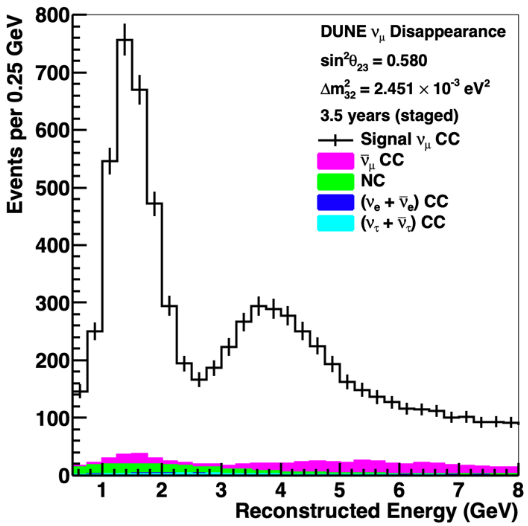
Appearance

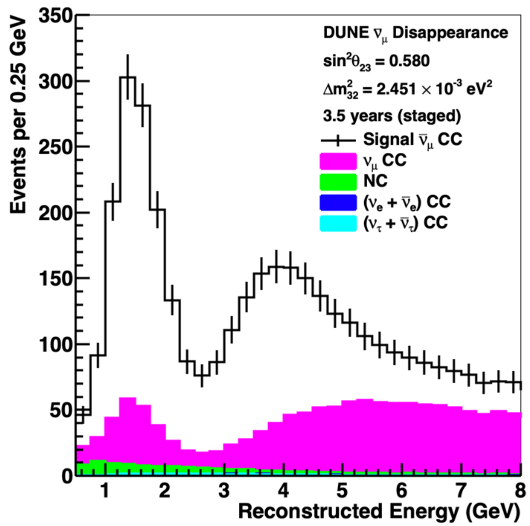




Order 1000 appearance events in 7 years

Disappearance

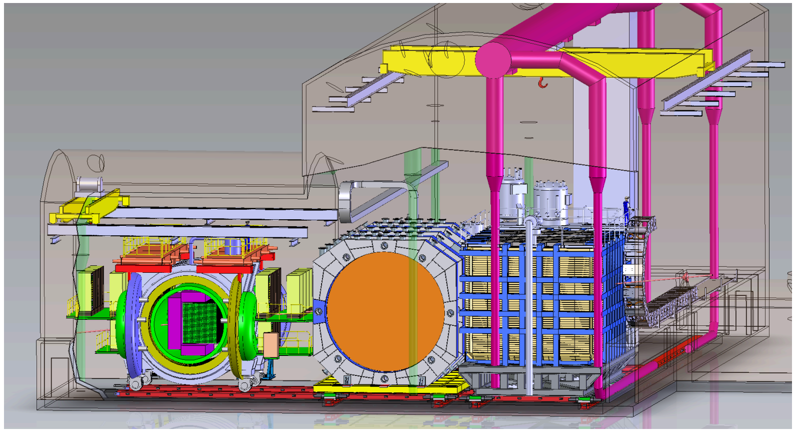




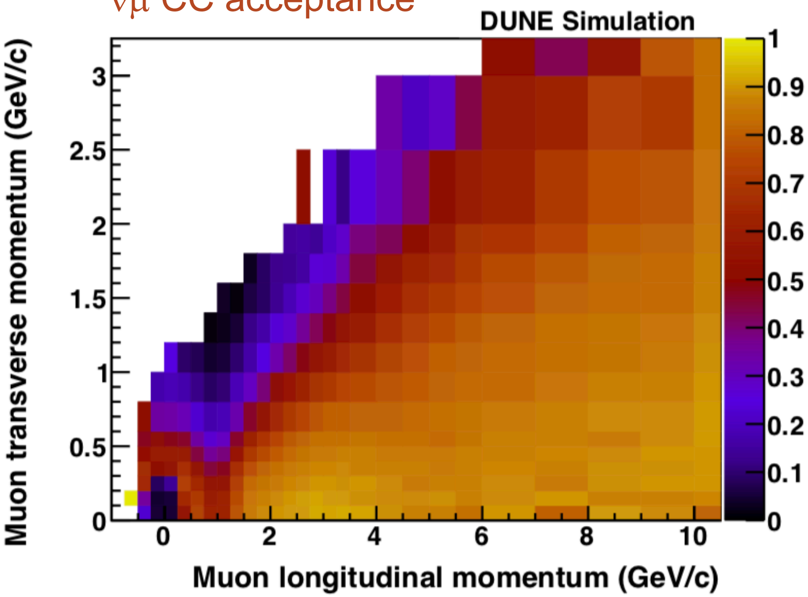
Order 10,000 disappearance events in 7 years

Near Detector Analysis

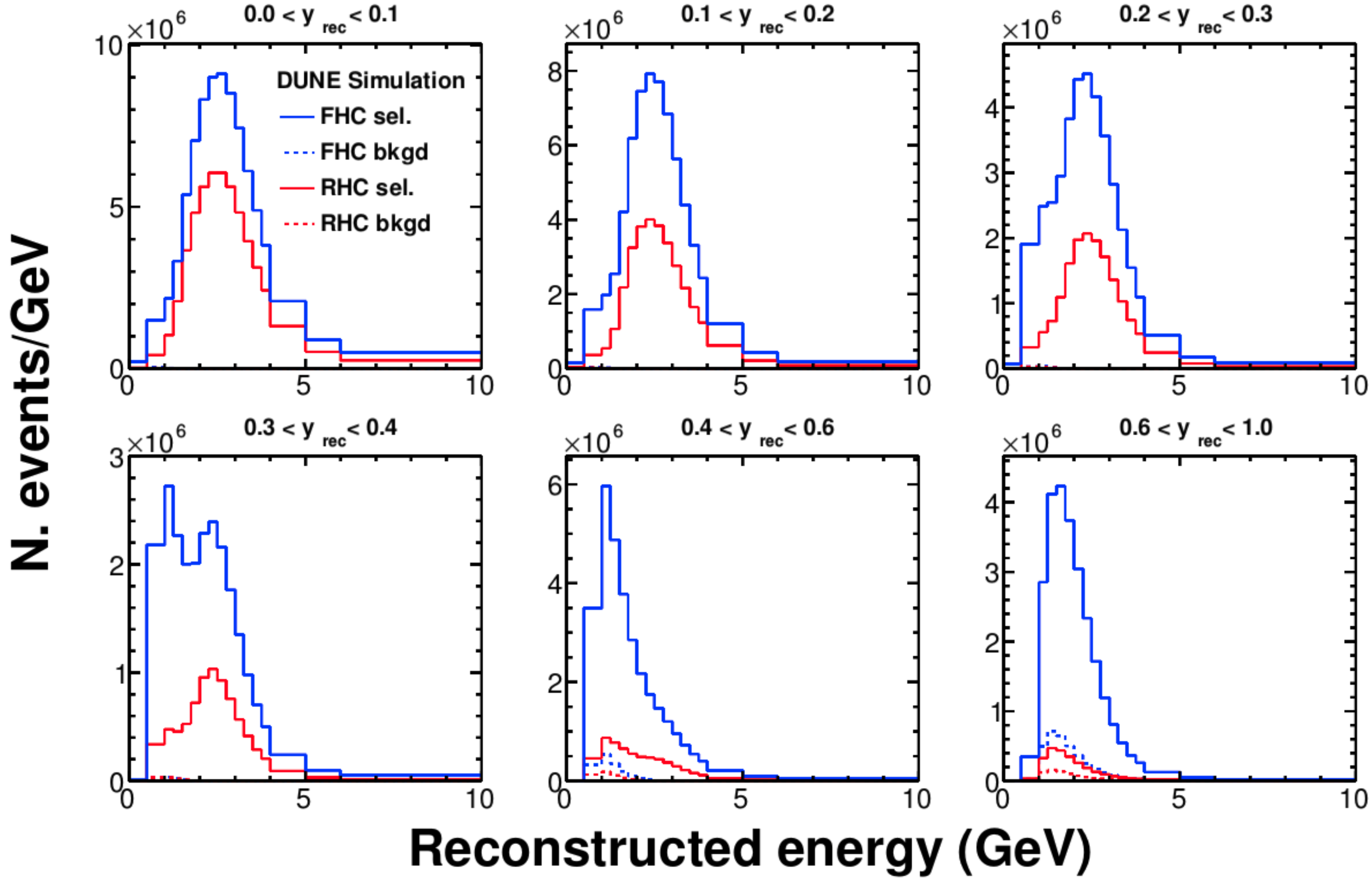
- For analysis presented here, only parameterized reconstruction (based on Geant4 simulation) of ν_μ CC sample in ND-LAr is included in fits **but** analysis assumes constraints from full ND
  - Parameterized muon reconstruction assumes momentum analysis in ND-GAr for tracks exiting ND-LAr, so acceptance is limited to tracks that stop in ND-LAr or are matched in ND-Gar
  - Tracks are selected as muons if they are at least 1 m long and the mean energy deposit per cm is <3 MeV
  - Events are required to have exactly one identified muon track
  - Hadronic energy is calculated calorimetrically (sum of energy deposits not associated with a track)
- For fit, ND samples binned in reconstructed energy and y_{rec}



νμ CC acceptance

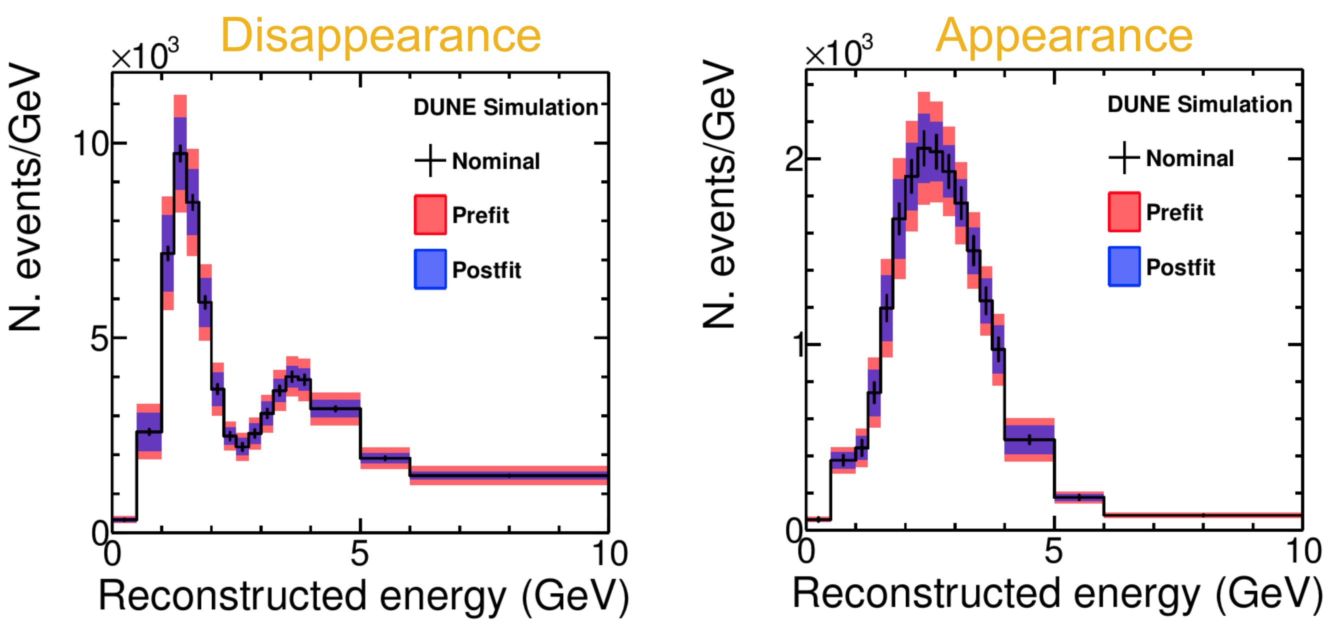


ND Selected Spectra



Systematic Uncertainties

- Analysis includes impact of individual sources of systematic uncertainty in both FD and ND samples
  - Flux, interaction model, detector effects

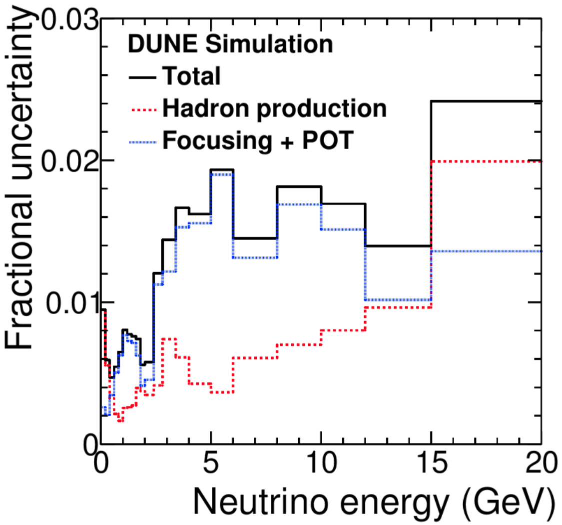


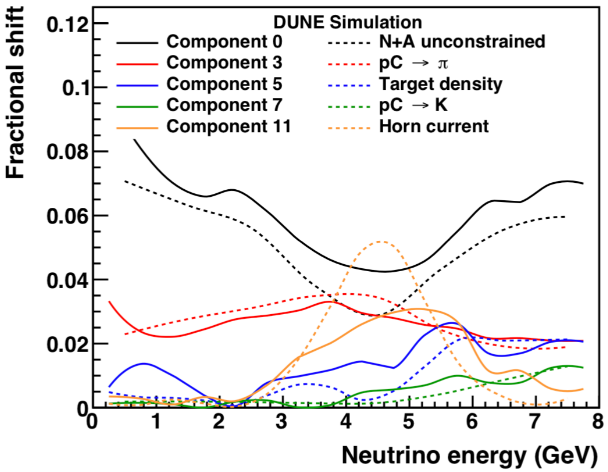
Note: Previous DUNE analyses did not attempt to evaluate impact of individual sources of systematic uncertainty. Overall effect of systematic uncertainty, after constraints from ND and FD sample-sample cancellations, was approximated using 2% uncorrelated signal normalization uncertainty. This approximation is replaced by the detailed treatment of individual sources of uncertainty in the analysis presented here.

Flux Systematics

- Flux prediction from Geant4 simulation
- Flux uncertainties include hadron production, beam focusing, and alignment effects
  - Uncertainty analysis informed by experience with the NuMI beam
  - ~8% at peak of appearance spectrum
- Flux uncertainties largely cancel in ND/FD ratio
  - ~1% at peak of appearance spectrum
- Flux uncertainty implemented in analysis via principle component analysis of flux covariance matrix
  - Include 30/208 principle components

Uncertainty in ND/FD Ratio





Interaction Model Systematics

- Neutrino interactions are simulated with GENIE version 2.12.10, with default physics list except for Valencia 2p2h model
- LBL analysis uses "DUNEInt"
  - Implementation of interaction model & uncertainties developed by neutrino interaction experts based on experience from MINERvA, NOvA, T2K, uBooNE
  - Makes extensive use of GENIE's reweighting framework
    - Supports kinematic shifts in addition to reweighting
  - Adds additional freedom inspired by lack of measurements on argon and informed by modeling uncertainties in running experiments
- Model uncertainty implemented in the analysis by allowing individual model parameters to vary, constrained by a penalty term proportional to pre-fit uncertainty
  - ~40 individual parameters included
- Implicit assumption that model fully describes the physics and only the parameters of the model are uncertain (more later)

Detector Systematics

- Detector systematics defined using **post-calibration** expectation of detector performance, based on experience with previous experiments and prototypes
- Detector systematics treated as uncorrelated between ND & FD
- Energy scale uncertainties defined separately for four particle types: muons (1-2%), charged hadrons (5%), neutrons (20-30%), EM showers (2.5%)
  - Parameterized to allow significant freedom as a function of energy

$$E'_{rec} = E_{rec} \times (p_0 + p_1\sqrt{E_{rec}} + \frac{p_2}{\sqrt{E_{rec}}})$$

  - Resolution uncertainty also applied separately for the four particle types
- Far detector parameters allowed to vary individually in the fit, constrained by a penalty term proportional to pre-fit uncertainty
- Near detector parameters not allowed to vary in the fit
  - Impact of ND uncertainty included by adding an additional penalty term extracted from a covariance matrix generated by “throws” of ND detector uncertainty parameters
  - Prevents over-constraint from ND sample based on parameterized analysis

Fitting

- Fits performed using CAFAna
  - Originally developed for NOvA
  - Produces expected event rates given input MC samples, oscillation parameters, systematic uncertainties
  - Systematics implemented using 1D response functions
  - Oscillation weights calculated in fine bins of true neutrino energy
  - Minimization performed with MINUIT
- θ_{13} constrained by NuFit uncertainty in nominal fits
- All other long-baseline oscillation parameters vary freely

$$\chi^2(\boldsymbol{\vartheta}, \mathbf{x}) = -2\log\mathcal{L}(\boldsymbol{\vartheta}, \mathbf{x})$$

$$= 2\sum_{i}^{N_{\text{bins}}}\left[M_i(\boldsymbol{\vartheta}, \mathbf{x}) - D_i + D_i \ln\left(\frac{D_i}{M_i(\boldsymbol{\vartheta}, \mathbf{x})}\right)\right]$$

→ Compare predicted spectra to mock data

$$+ \sum_{j}^{N_{\text{systs}}}\left[\frac{\Delta x_j}{\sigma_j}\right]^2$$

→ Penalty for varied systematics parameters

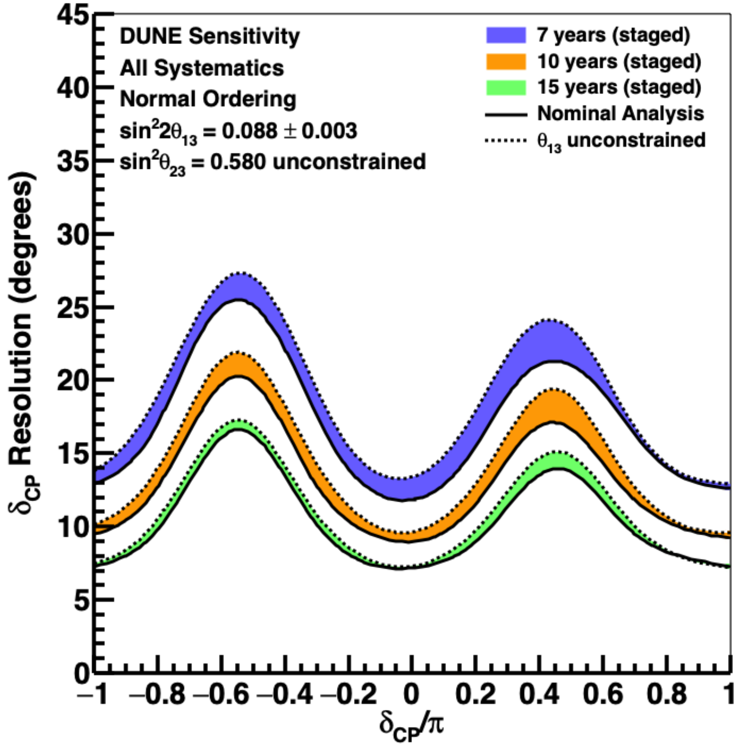
$$+ \sum_{k}^{N_{\text{bins}}^{\text{ND}}}\sum_{l}^{N_{\text{bins}}^{\text{ND}}}\left(M_k(\mathbf{x}) - D_k\right) V_{kl}^{-1}\left(M_l(\mathbf{x}) - D_l\right),$$

→ Penalty for (fixed) ND systematics

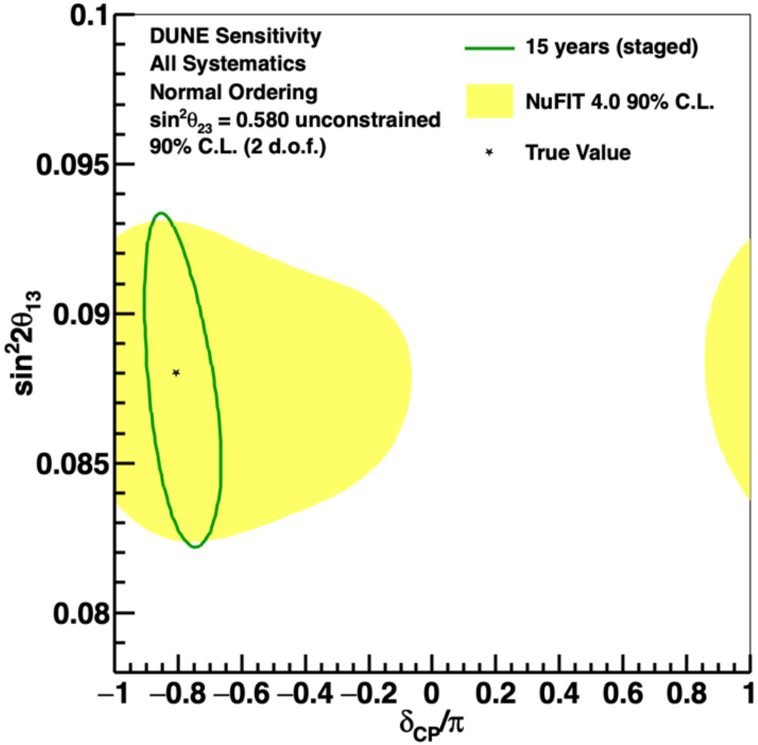
Precision δ_{CP} Measurement

DEEP UNDERGROUND NEUTRINO EXPERIMENT

δ_{CP} Resolution



θ_{13} vs δ_{CP}



Width of band represents difference between sensitivity with and without external constraint on θ_{13}

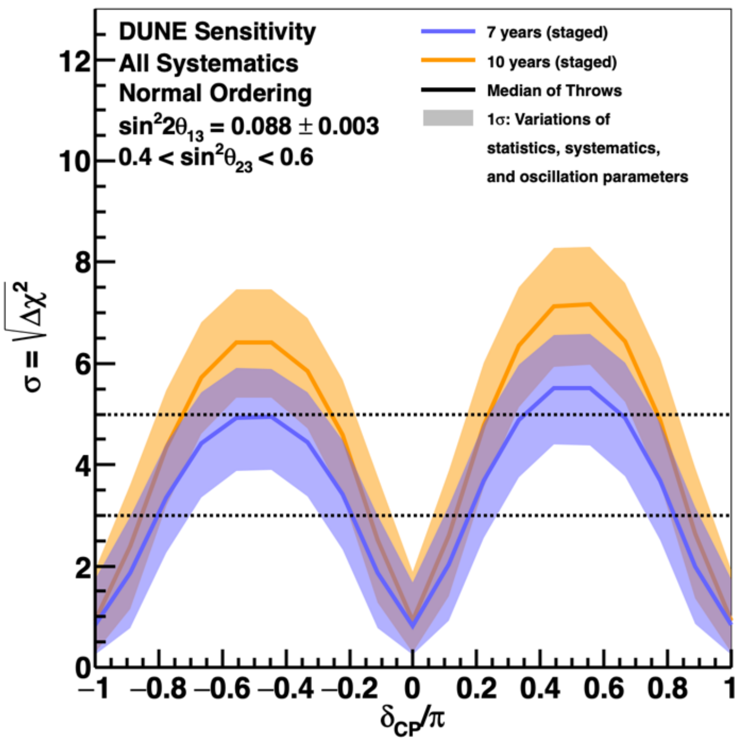
Ultimate goal is precise measurement of δ_{CP}: < 17 degrees after 15 years

θ_{13} precision comparable to that of reactor experiments after 15 years

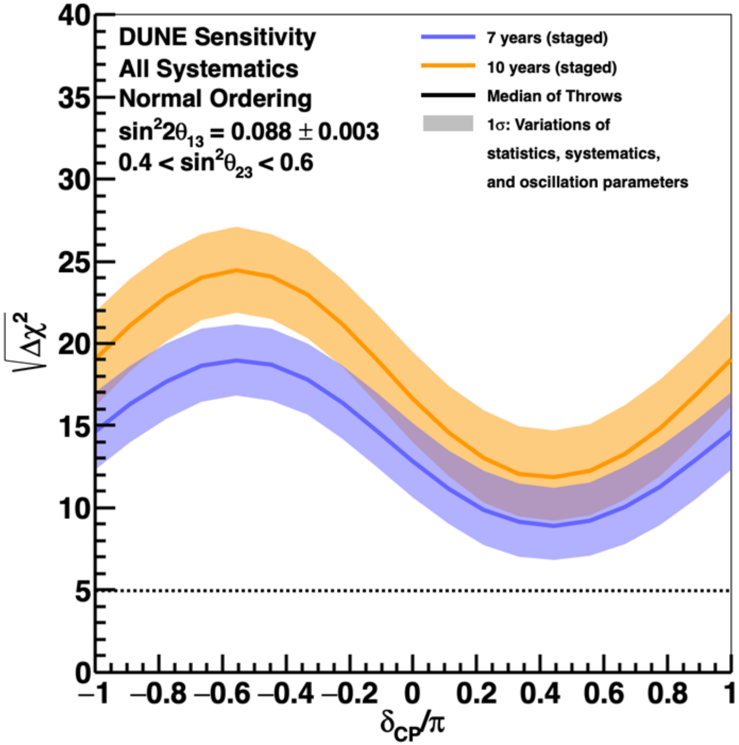
CPV & MO Sensitivity

DEEP UNDERGROUND NEUTRINO EXPERIMENT

CP Violation



Mass Ordering

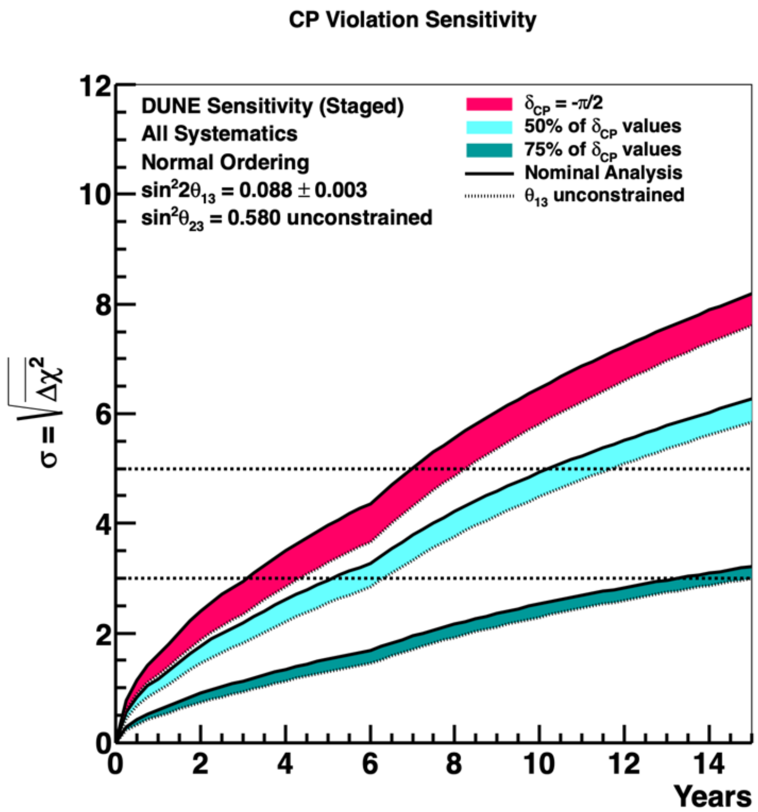


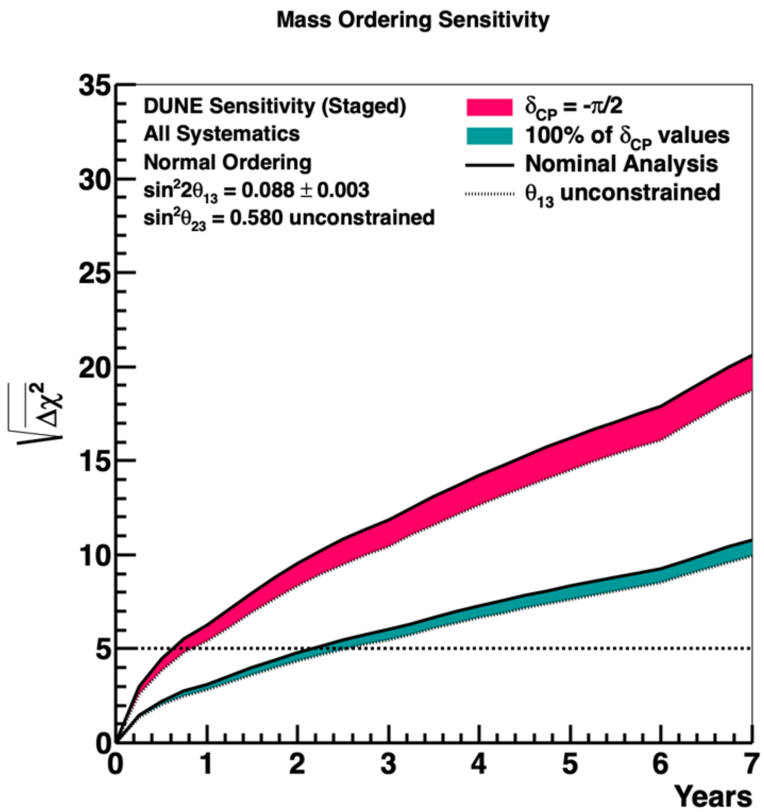
Width of band represents 68% of throws (stats, systematics, oscillation parameters)

Significant CP violation discovery potential over wide range of δ_{CP} space in 7-10 years

Sensitivity Over Time

DEEP UNDERGROUND NEUTRINO EXPERIMENT



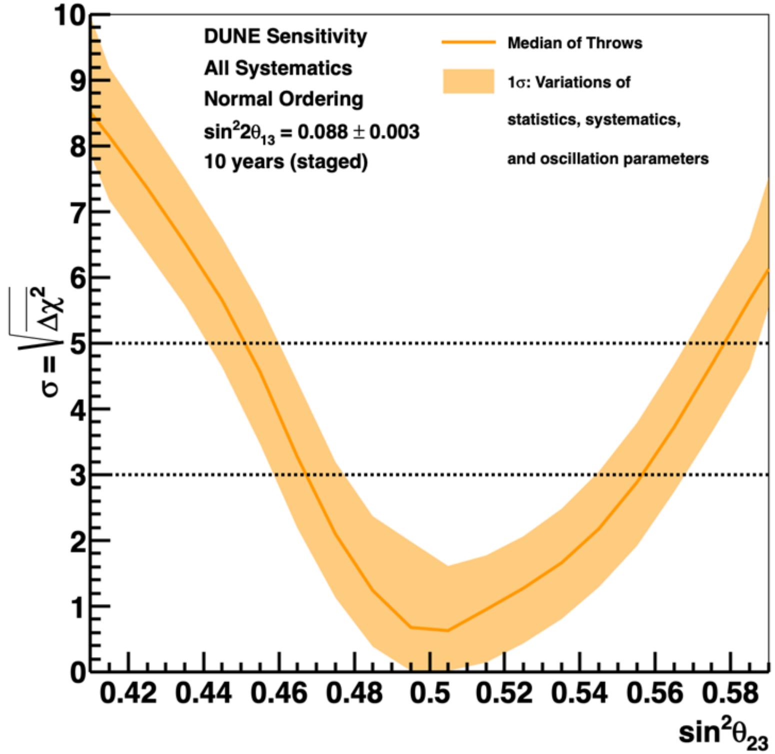


Width of band represents difference between sensitivity with and without external constraint on θ_{13}

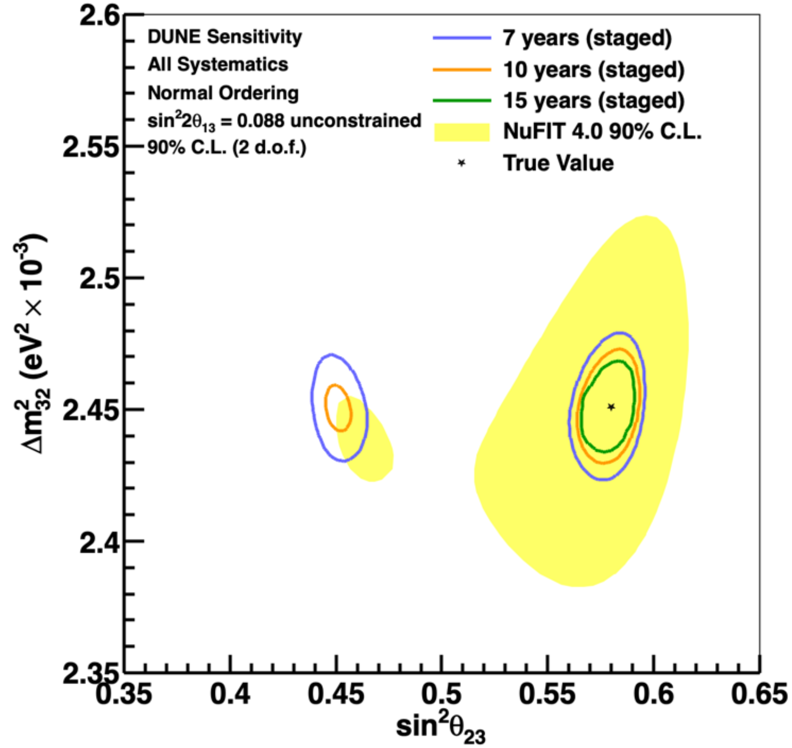
Unambiguous determination of neutrino mass ordering within first few years. Significant milestones throughout the beam physics program.

Other Parameters

Octant determination



Δm^2_{32} vs $\sin^2\theta_{23}$



Width of band represents 68% of throws (stats, systematics, oscillation parameters)

Significant improvement in precision measurement of atmospheric mixing parameters

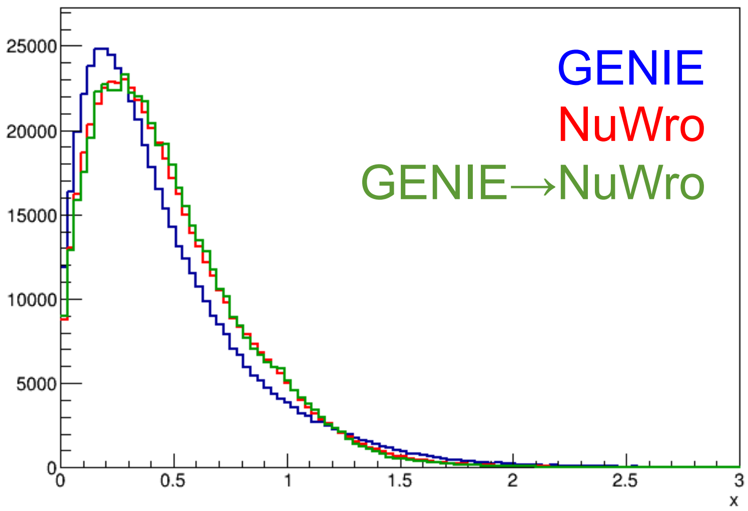
Further Studies

- Ability to detect and resolve model deficiencies is implicit in the sensitivities in the preceding slides
- By definition, we don't know exactly how our model might be insufficient → "unknown unknowns"
- Study experimental capacity for handling unknown unknowns by creating alternative simulated datasets drawn from a different, plausible underlying model than that used in the nominal analysis, eg:
  - GENIE→NuWro
  - Redistribute energy between final state protons and neutrons

NuWro Bias Study

- Use BDT to reweight GENIE→NuWro in a space of 18 kinematic variables
- FD fit χ^2/d.o.f. < 1, but produces bias in fit for δ_{CP}
- ND-FD fit has χ^2/d.o.f. > 30
- Without ND to validate interaction model, would have to include possibility of this kind of bias as systematic uncertainty
- Exclusive final state samples in ND-GAr may be used to reduce this bias

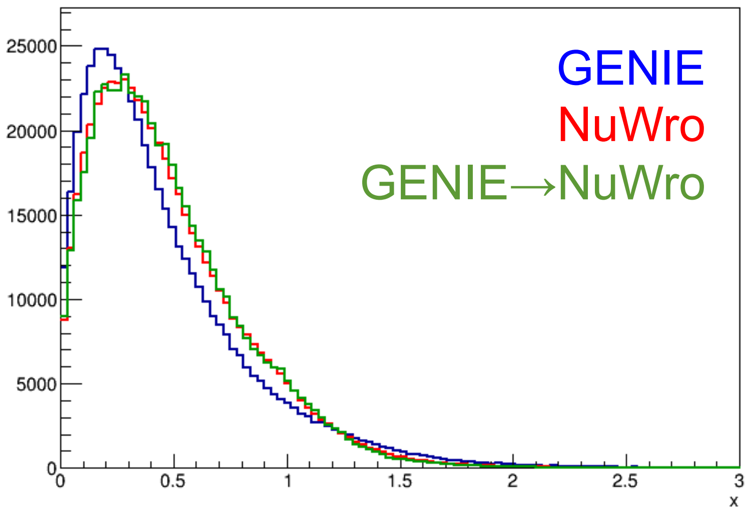
x distribution, FD FHC ν_e

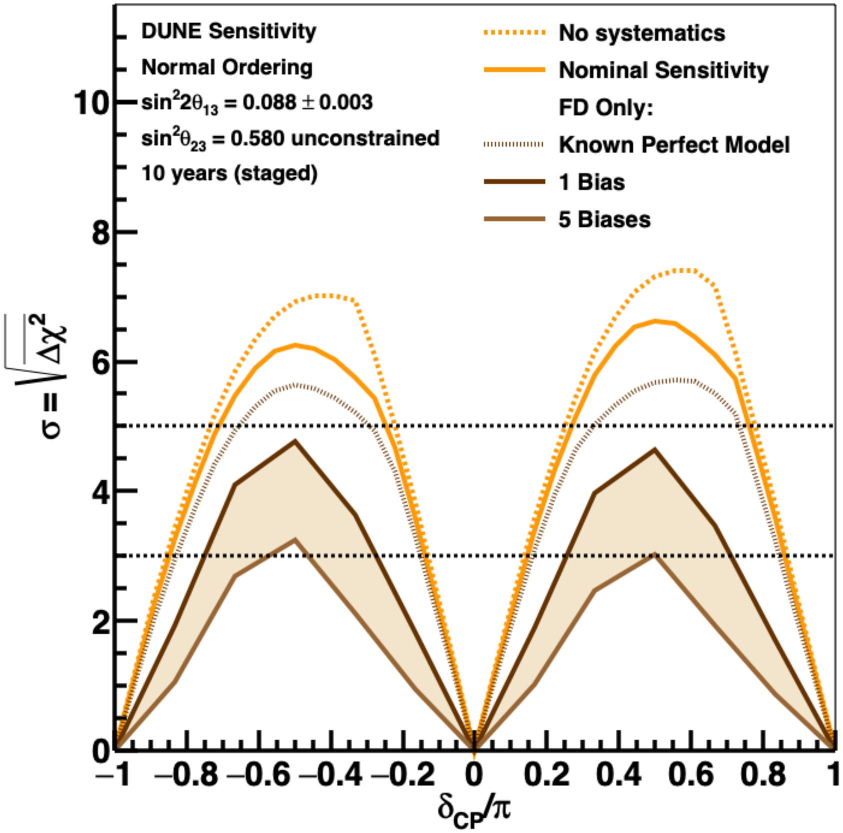


NuWro Bias Study

- Use BDT to reweight GENIE→NuWro in a space of 18 kinematic variables
- FD fit χ^2/d.o.f. < 1, but produces bias in fit for δ_{CP}
- ND-FD fit has χ^2/d.o.f. > 30
- Without ND to validate interaction model, would have to include possibility of this kind of bias as systematic uncertainty
- Exclusive final state samples in ND-GAr may be used to reduce this bias

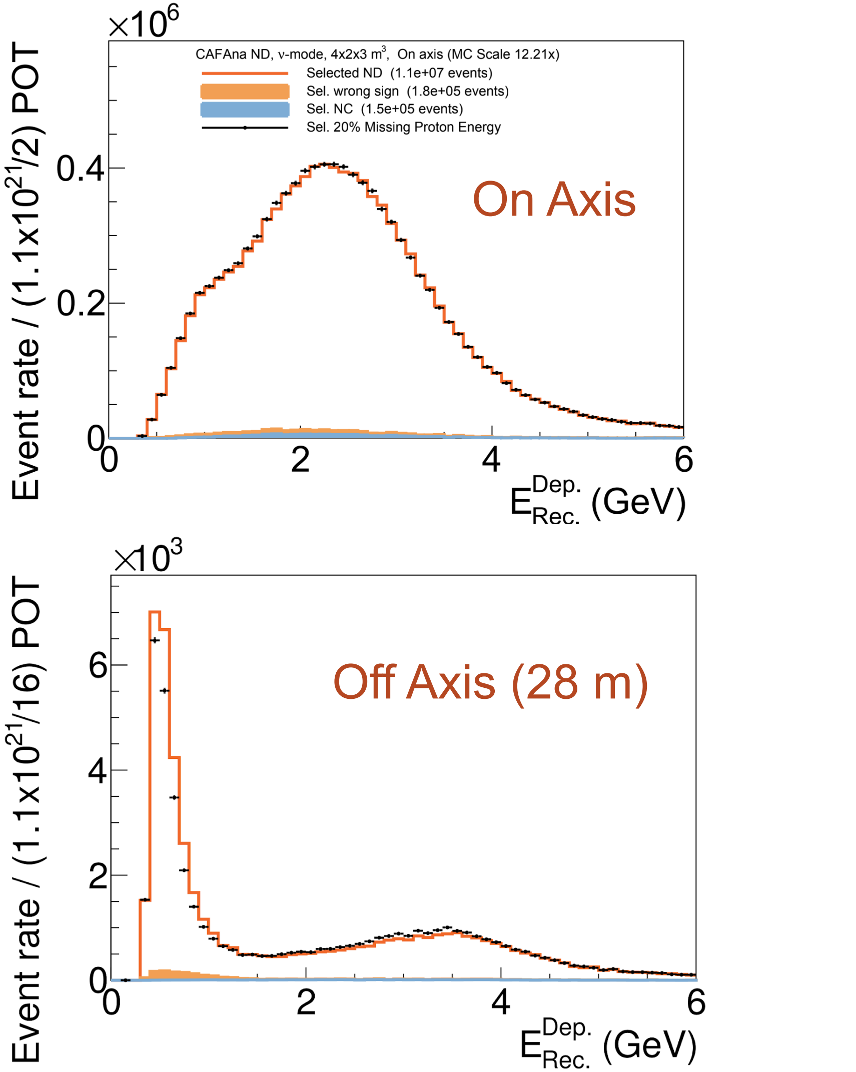
x distribution, FD FHC ν_e





Energy Bias Study

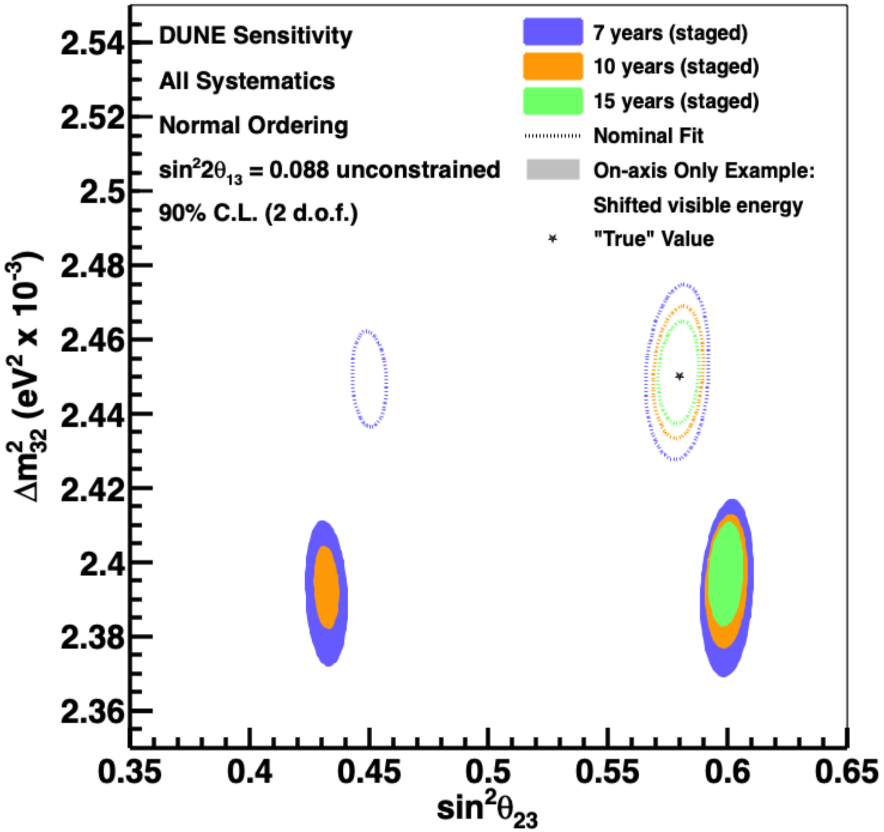
- 20% of proton energy is removed and added to (largely invisible) neutrons
  - Significant modification to relationship between reconstructed and true energy
  - An artificial but plausible example of a way in which the interaction model could be off
- Use BDT to adjust model parameters such that **on-axis** ND reconstructed distributions agree with the nominal sample



Energy Bias Study

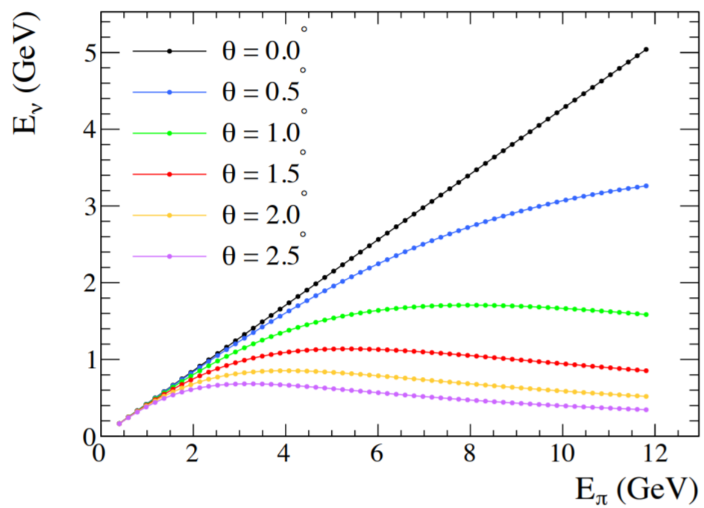
- 20% of proton energy is removed and added to (largely invisible) neutrons
  - Significant modification to relationship between reconstructed and true energy
  - An artificial but plausible example of a way in which the interaction model could be off
- Use BDT to adjust model parameters such that **on-axis** ND reconstructed distributions agree with the nominal sample
- Mismatch leads to significant bias in measured oscillation parameters

Δm^2_{32} vs $\sin^2\theta_{23}$

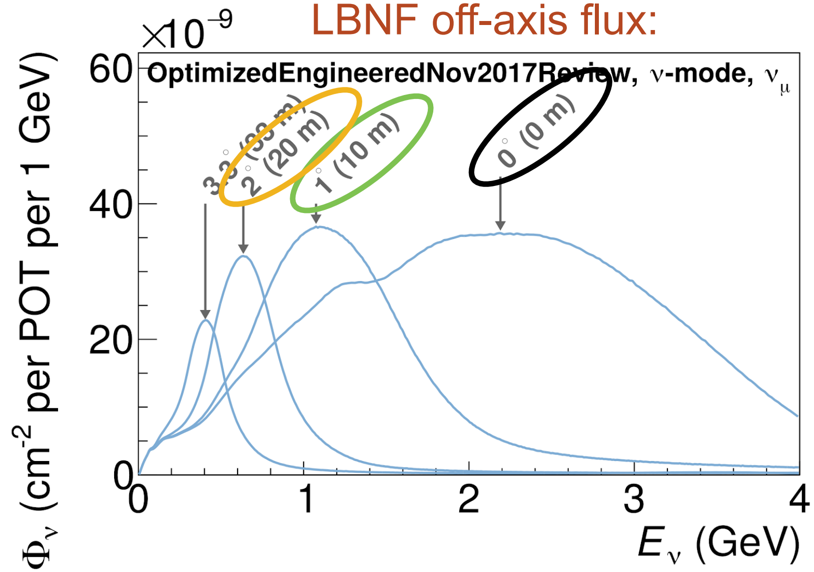


DUNE PRISM

Off-axis neutrino energy:



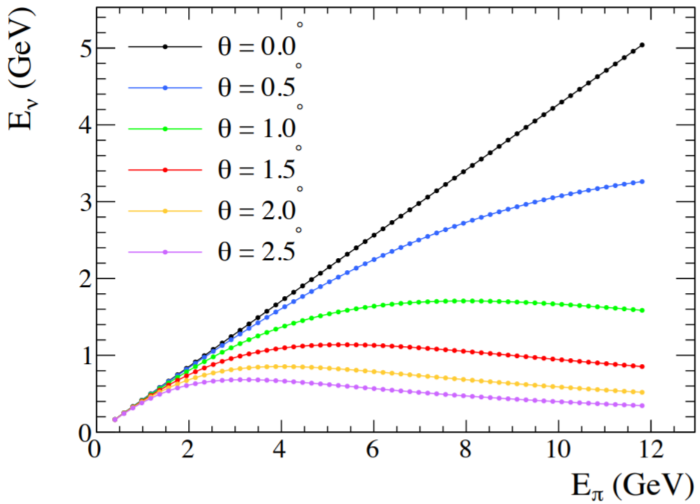
LBNF off-axis flux:



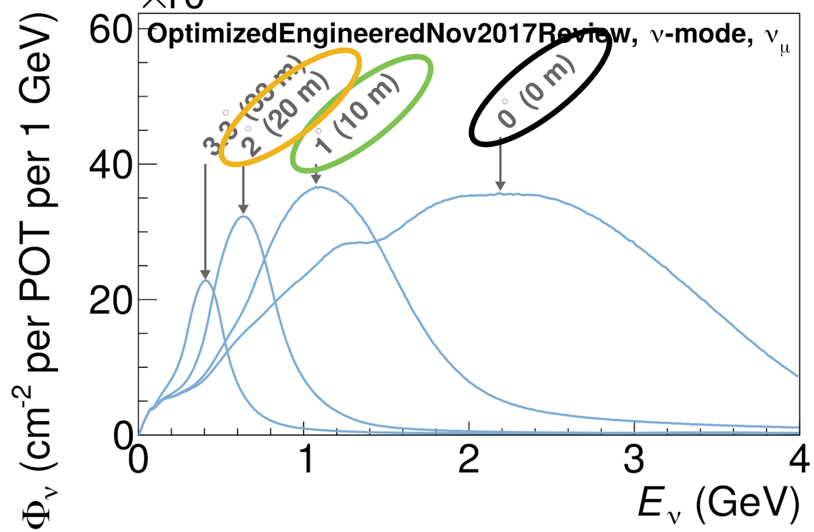
DUNE PRISM

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Off-axis neutrino energy:



LBNF off-axis flux:

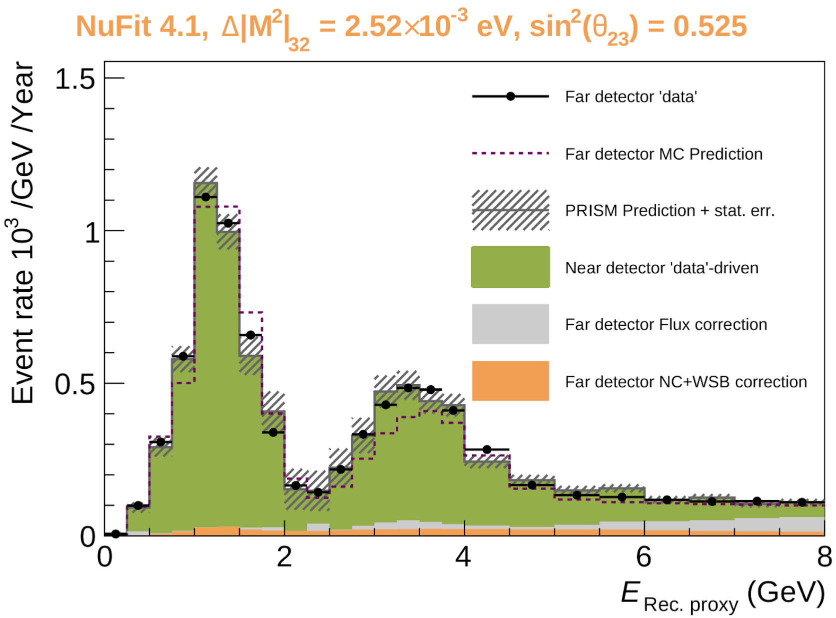


PRISM (Precision Reaction-Independent Spectrum Measurement) concept is to use linear combinations of off-axis fluxes to construct any flux: can ~reproduce FD flux prediction or Gaussian flux at a given energy. Same weights can then be applied to ND data to construct a “data driven” predicted event rate for a given flux.

DUNE PRISM Example

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Energy bias study with PRISM:



Far detector 'data'
Has proton → neutron energy shift applied

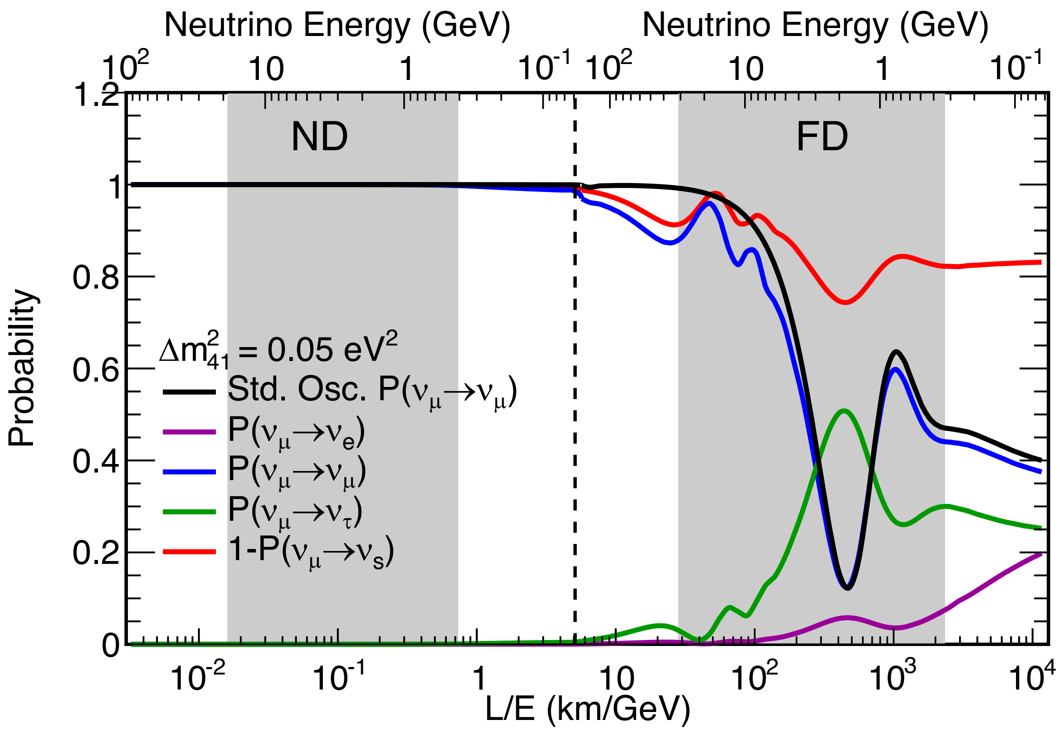
Far detector MC Prediction
Nominal MC (no shift)

PRISM Prediction + stat. err.
Based on ND MC (shift included) + corrections

- With nominal MC, prediction badly mismatched to data, leading to biased measurement of oscillation parameters
- PRISM prediction is well-matched to data and no bias in parameter measurement is observed!

Sterile ν in DUNE

- 3+1 model: 6 additional parameters Δm^2_{41}, θ_{i4} (3), δ_{14}, δ_{24}
- Depending on the value of the mass splitting, DUNE will be:
  - **Sensitive to disappearance at FD in NC & CC channels**
  - Sensitive to ν_e appearance at FD (degenerate w/ PMNS)
  - Sensitive to ν_μ disappearance and ν_e appearance at ND



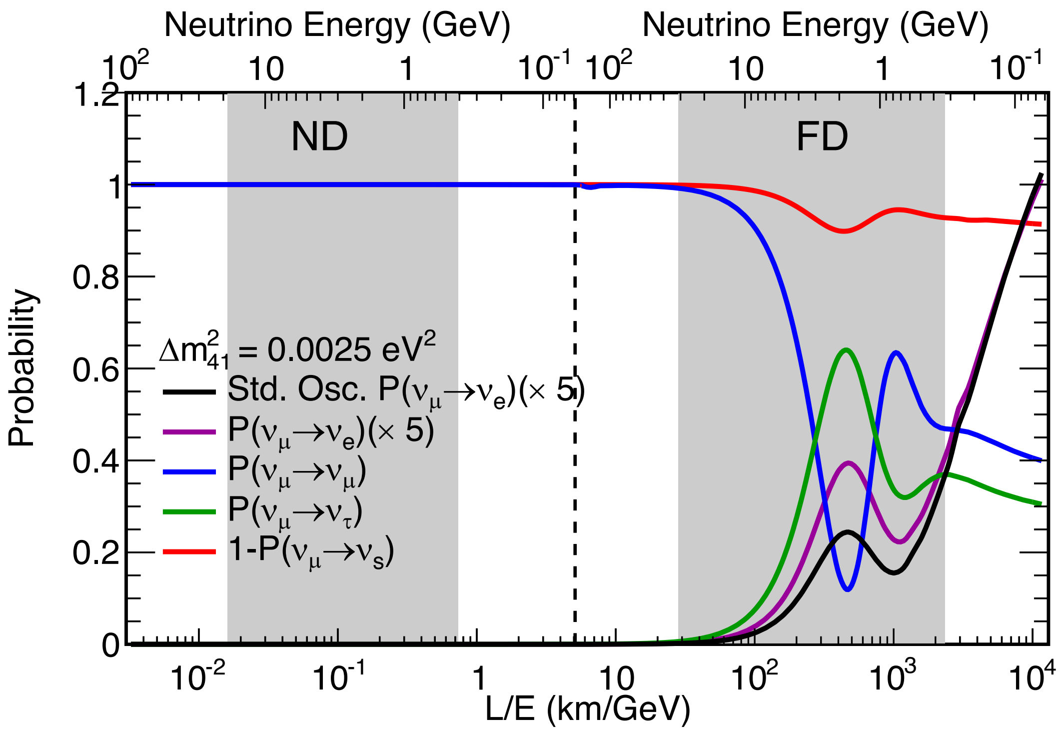
NC disappearance

3-flavor ν_μ CC disappearance

Distortion to ν_μ CC disappearance

Sterile ν in DUNE

- 3+1 model: 6 additional parameters Δm^2_{41}, θ_{i4} (3), δ_{14}, δ_{24}
- Depending on the value of the mass splitting, DUNE will be:
  - Sensitive to disappearance at FD in NC & CC channels
  - **Sensitive to ν_e appearance at FD (degenerate w/ PMNS)**
  - Sensitive to ν_μ disappearance and ν_e appearance at ND



3-flavor ν_e CC appearance

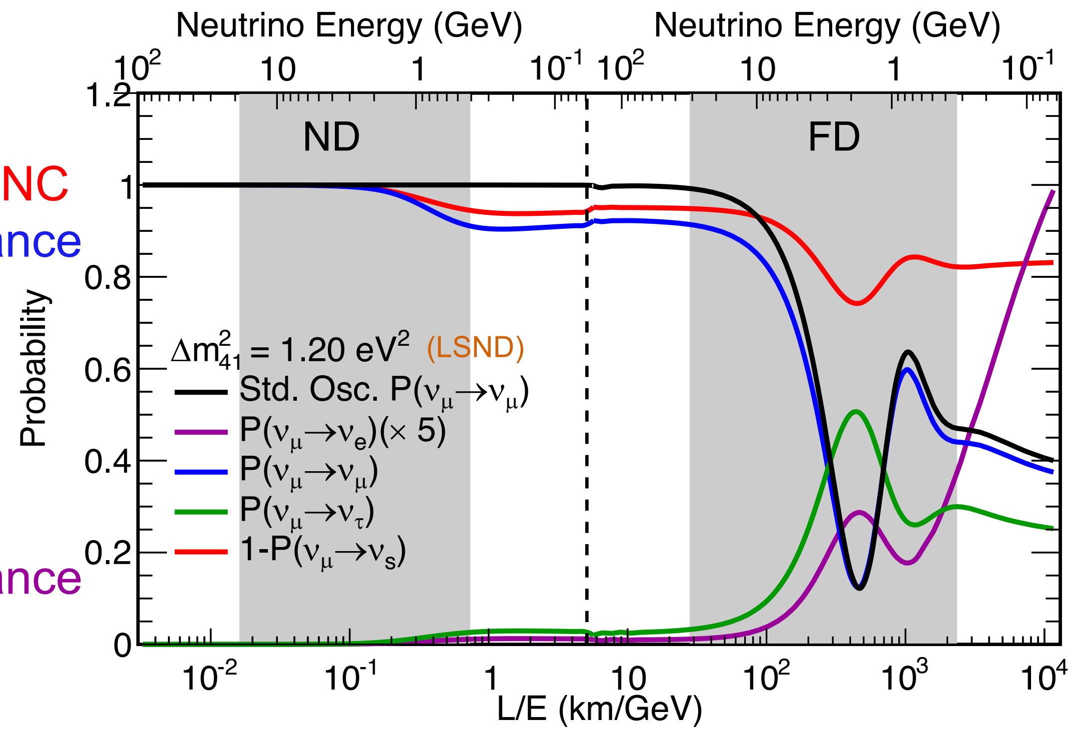
3+1 ν_e CC appearance

Sterile ν in DUNE

- 3+1 model: 6 additional parameters Δm^2_{41}, θ_{i4} (3), δ_{14}, δ_{24}
- Depending on the value of the mass splitting, DUNE will be:
  - Sensitive to disappearance at FD in NC & CC channels
  - Sensitive to ν_e appearance at FD (degenerate w/ PMNS)
  - **Sensitive to ν_μ disappearance and ν_e appearance at ND**

ν_μ CC and NC disappearance at ND

ν_e CC appearance at ND

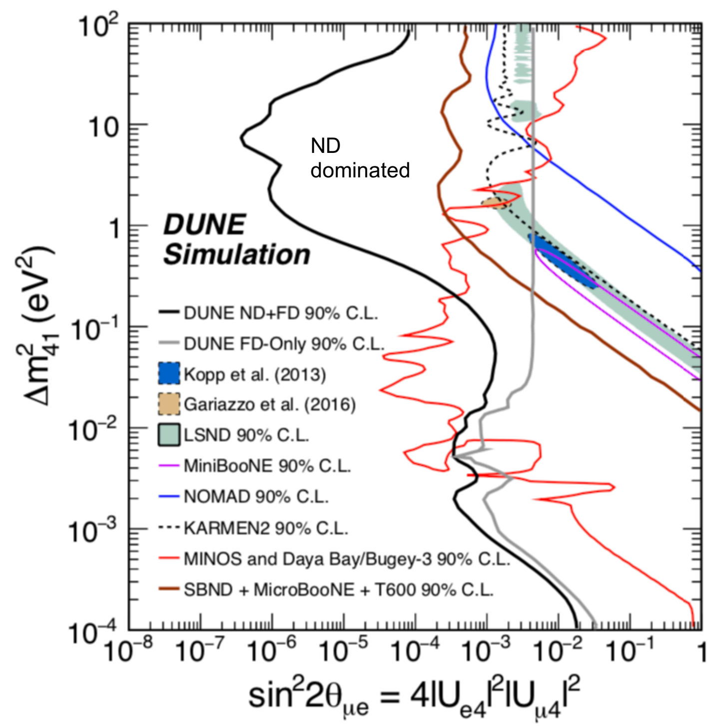


Sterile Sensitivity Analysis

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Fit using GLoBES:
- FD inputs from DUNE TDR LBL analysis
- ND assumed to be a scaled-down version of the FD
- Systematics implemented as **normalization uncertainties** on signal and background modes, correlated appropriately between ND and FD
- **Important caveat**: difficult to implement realistic shape systematics in GLoBES → show both FD-only and ND+FD with norm. uncertainties only to bound this effect
- Additional energy smearing included as proxy for uncertainty in neutrino production point
- Suppress very fast oscillations to avoid aliasing effects (low-pass filter at 0.125 GeV)
- Profile over phases
- Results shown for 7 years of exposure

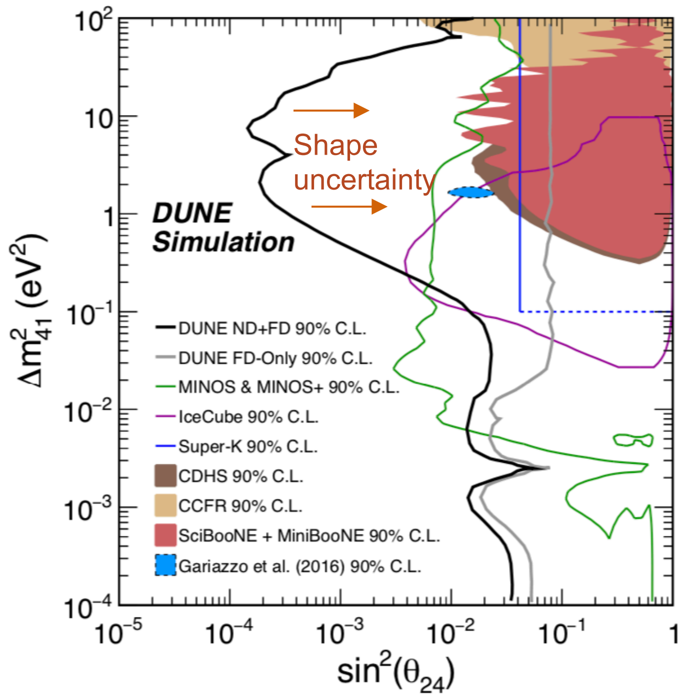
Example:
$\sin^2 2\theta_{\mu e}$ sensitivity
All samples



DUNE BSM Paper on arxiv this week

Shape Effects

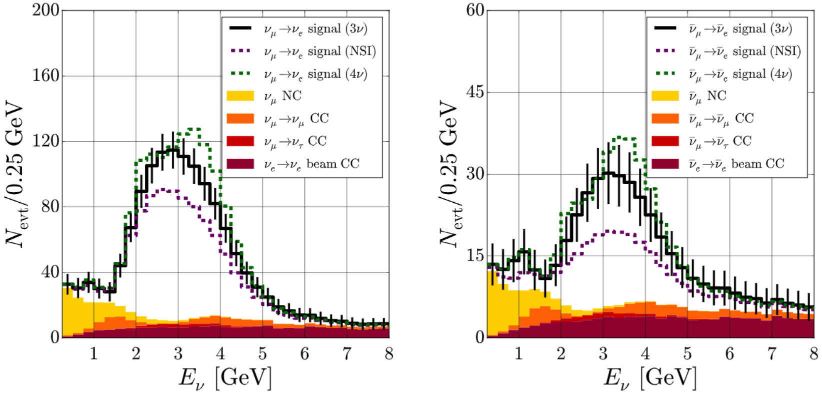
- DUNE ND (especially in parameterized form) is incredibly powerful
  - Huge statistics mean that without realistic shape uncertainties from the neutrino interaction model, detector effects, and possible interplay among these, the ND can overconstrain almost any model
  - This is an ongoing technical challenge for the 3ν analysis even in the full framework
  - Capabilities within GLoBES to implement shape uncertainties are limited – nominal sensitivity include normalization uncertainties
- GLoBES studies implementing arbitrary shape systematics have significant impact on ND-dominated part of DUNE sterile sensitivity
  - An internal study shows significant degradation in sensitivity for the 1 eV^2 part of phase space with a 10% (arbitrary & artificial) shape uncertainty
  - Need full framework for realistic uncertainties → In progress



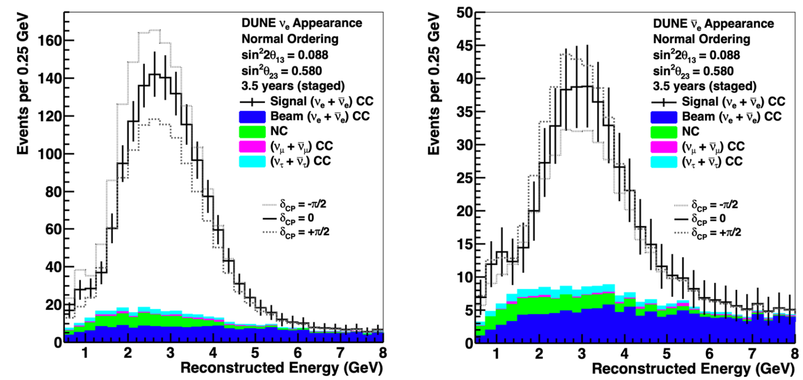
Impact on 3ν Sensitivity

- Example: generate spectra with 3+1 model but analyze assuming 3ν (1605.09376)

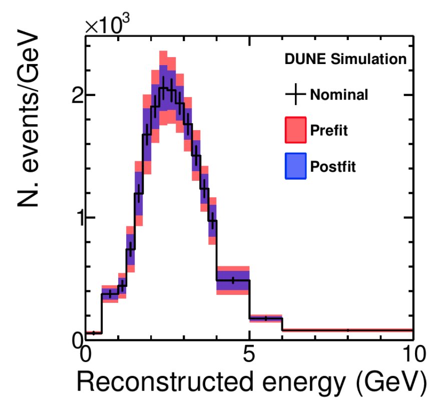
Appearance spectra with NSI and 3+1



DUNE appearance spectra with δ_{CP} variation



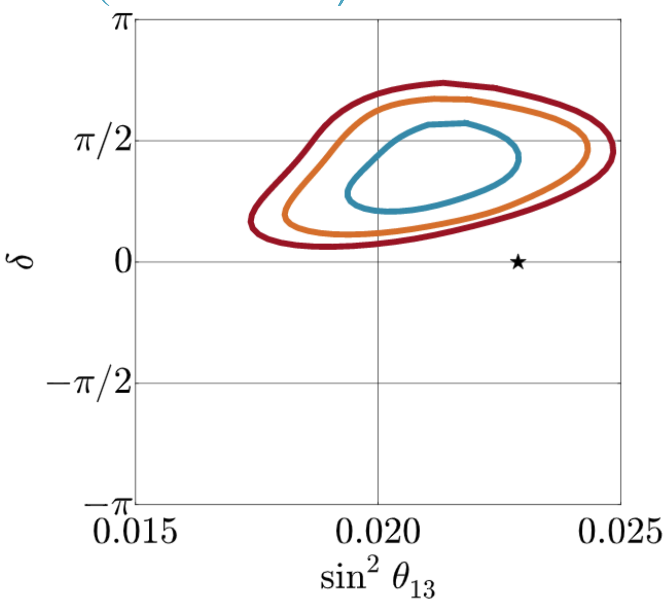
- Scenarios that shift the spectra in similar ways for neutrinos and antineutrinos are easier to distinguish from CPV
  - Octant does not have this handle
- Systematics affecting shape important in evaluating sensitivity to BSM



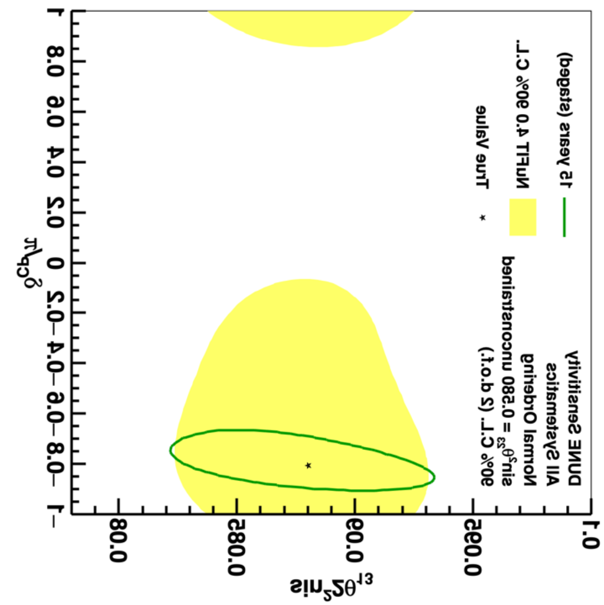
DUNE appearance spectrum (neutrino mode) with systematic variations

Impact on 3ν Sensitivity

Fit to data generated with CP-conserving 4ν model (6 yrs)
(1605.09376)



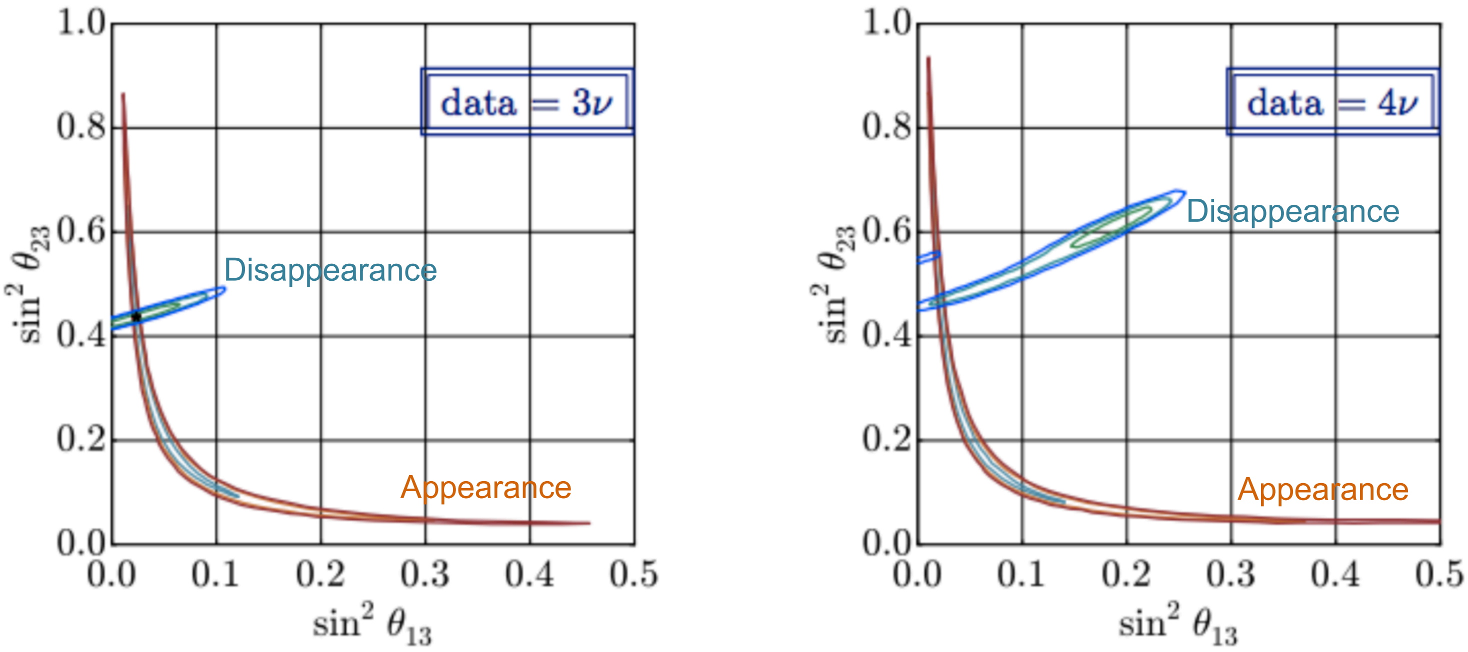
DUNE Nominal Sensitivity (15 yrs)



- One DUNE strategy to detect BSM is disagreement with reactor measurement of $\sin^2(2\theta_{13})$ – comparable precision after long exposures
- DUNE 15-year resolution on $\sin^2 2\theta_{13} \sim 0.004$ ($\sin^2\theta_{13} \sim 0.001$)
- Current global fit uncertainty on $\sin^2\theta_{13} \sim 0.0007$ (dominated by reactor)

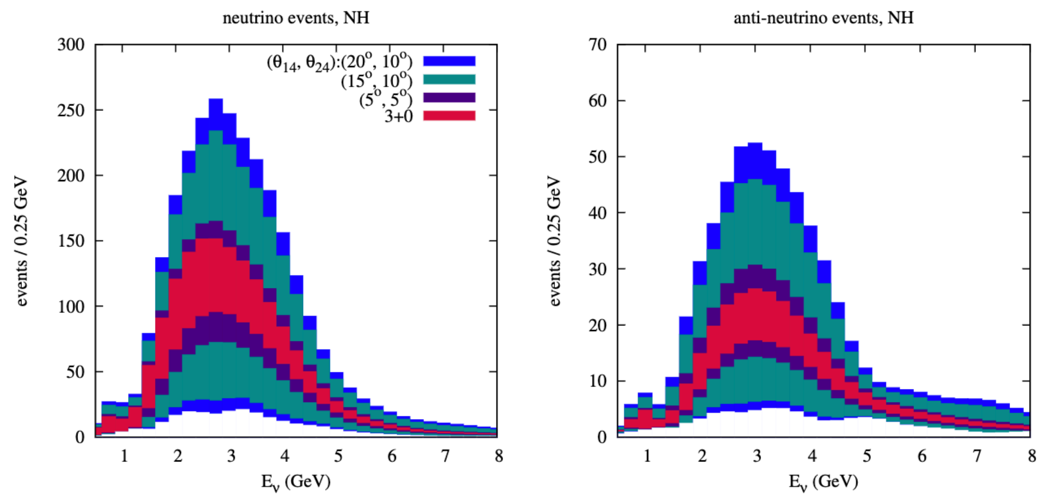
Internal Consistency

- "A Sterile Neutrino at DUNE", arxiv:1507.03986
- For cases where fit quality is poor, consider analyzing appearance and disappearance data separately – inconsistent results can point to inconsistency with 3ν paradigm



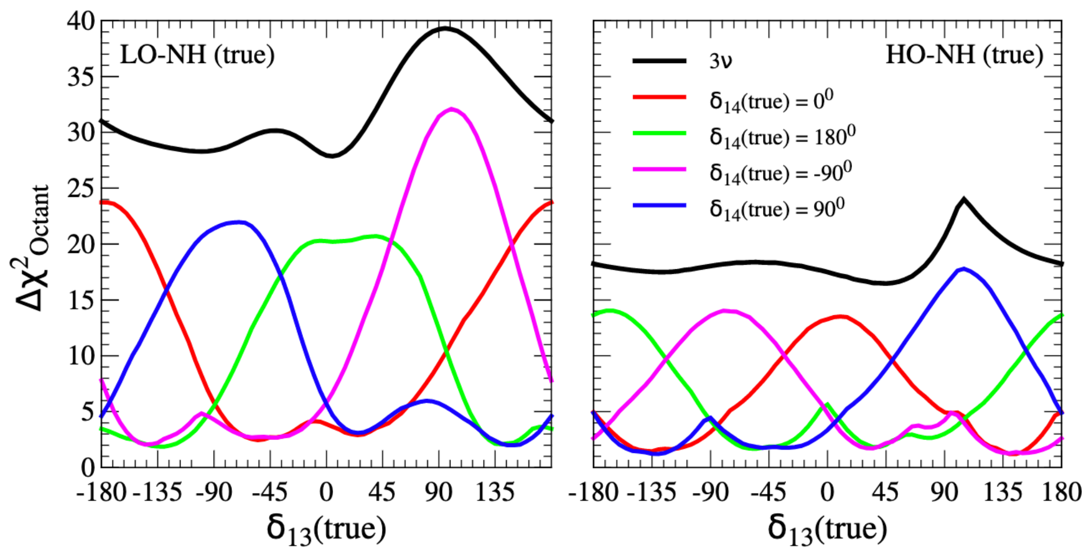
A Few More Theory Examples

DEEP UNDERGROUND NEUTRINO EXPERIMENT



Event rate degeneracy

- arxiv:1508.06275
- Impact of varying sterile parameters compared to varying δ_{CP} in 3ν case



Octant Sensitivity

- arxiv:1605.04299
- Impact of varying δ_{14} for a chosen set of θ_{i4} values
- $\sin^2\theta_{23}$=0.42 for LO, 0.58 for HO

Summary

- DUNE's primary physics goals include precise measurement of all parameters governing long-baseline oscillation in a single experiment: θ_{23}, θ_{13}, Δm^2_{32}, δ_{CP}
- DUNE analysis of sensitivity to long-baseline oscillation physics has been updated to include:
  - Full simulation, reconstruction, and CVN-based event selection for far detector Monte Carlo
  - Parameterized analysis of near detector Monte Carlo
  - Detailed treatment of individual sources of systematic uncertainty
  - Study of robustness to modeling deficiencies
- DUNE sensitivity to sterile neutrinos (and other BSM physics impacting oscillations) has been evaluated by the collaboration using GLoBES
  - Sensitivity with full analysis framework including realistic shape systematics in progress
  - Many outside phenomenology papers addressing impact of BSM models on DUNE sensitivity

More DUNE Information

- DUNE Technical Design Report
  - Volume 1, Introduction to DUNE, arXiv:2002.02967
  - Volume 2, DUNE Physics, arXiv:2002.03005
  - Volume 3, Far Detector Technical Coordination, arXiv:2002.03008
  - Volume 4, Far Detector Single-phase Technology, arXiv:2002.03010
- Paper on long-baseline analysis: https://arxiv.org/abs/2006.16043
- Paper on CVN event classification: https://arxiv.org/abs/2006.15052
- Paper on BSM analyses: In preparation