DEEP UNDERGROUND NEUTRINO EXPERIMENT

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

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for the DUNE Collaboration
Fermilab Neutrino Seminar
May 28, 2020

Overview

- Long-Baseline Neutrino Oscillation
  - Introduction
- DUNE Experiment
  - Collaboration
  - Detectors
- **DUNE Long-Baseline Oscillation Sensitivity**
  - **Sensitivity analysis**
  - **Sensitivity results**
  - **Additional studies**
- Summary & Future Plans

Neutrino Mixing & Oscillation

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- Neutrinos have non-zero mass
- Mass states are not the same as the flavor states; flavor states may be written as linear combination of mass states (and vice versa) using a mixing matrix

$\nu_\alpha = \nu_e, \nu_\mu, \nu_\tau$ are the flavor states

$$|\nu_\alpha\rangle = \sum_k U_{\alpha k} |\nu_k\rangle$$

PMNS matrix

$\nu_k = \nu_1, \nu_2, \nu_3$ are the mass states

- Oscillation probability depends on the mixing angles, Δm^2 (mass differences), and L/E (baseline/energy)

2 neutrino case:

$$P_{\alpha\rightarrow\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

PMNS Matrix

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$$|\nu_\alpha\rangle = \sum_k U_{\alpha k} |\nu_k\rangle \quad \Rightarrow \quad U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}} \sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} \sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- **$\theta_{23} \approx 45^o$**
- Octant unknown (new symmetry?)

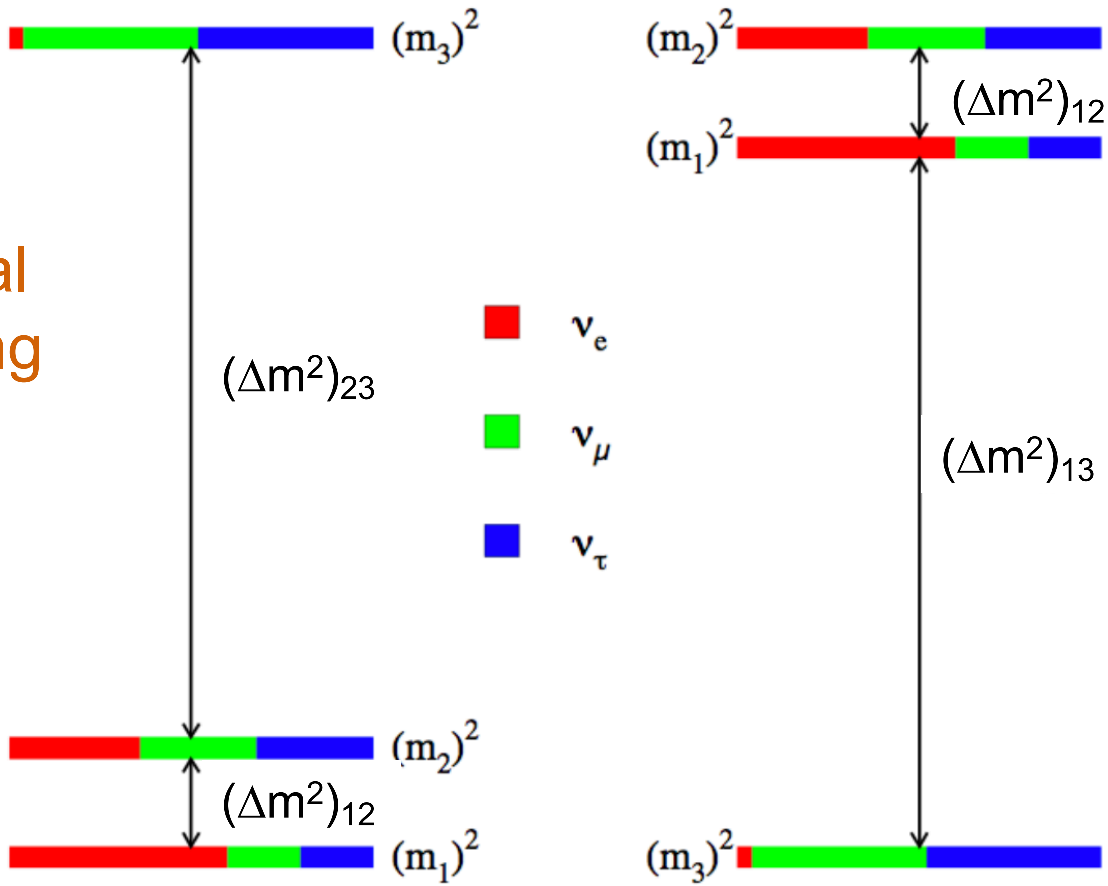
- **$\theta_{13} \approx 10^o$**
- Large uncertainty in δ_{CP} (CP violation?)

- θ_{12} **$\approx 35^o$**

Mass Ordering

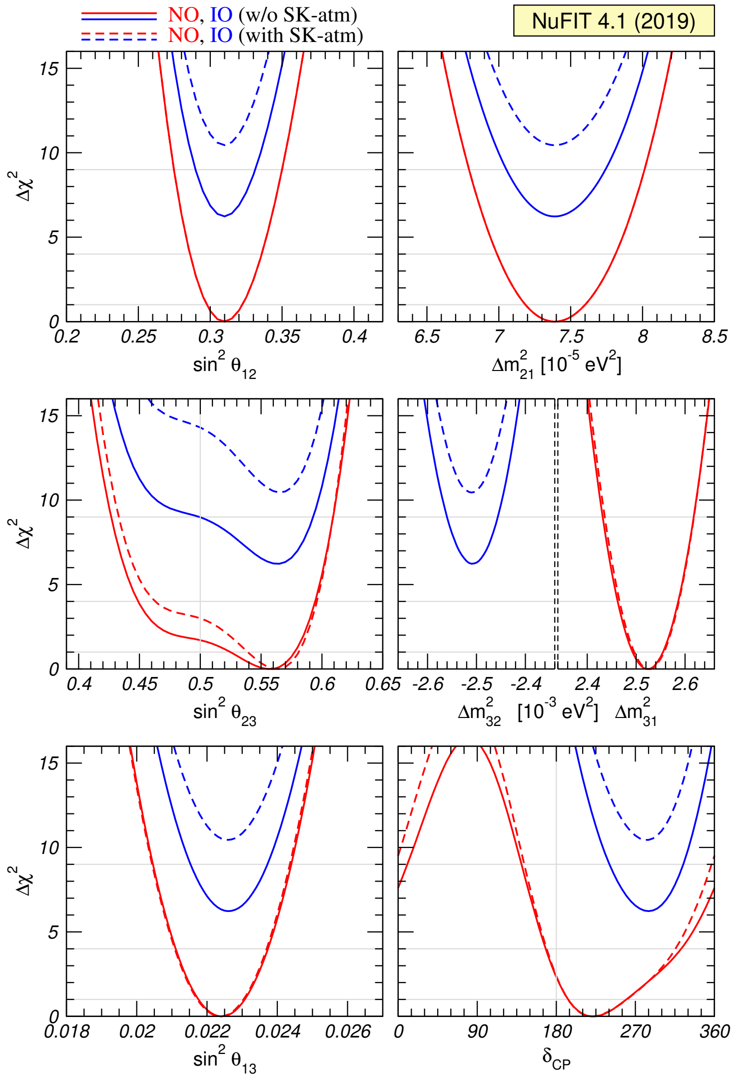
Neutrino mass "ordering" or "hierarchy" (sign of Δm^2_{23}) is unknown.

Normal ordering



Inverted ordering

Current Knowledge (NuFit 4.1)



JHEP 01 (2019) 106 (arXiv:1811.05487), www.nu-fit.org

- See last week's seminar
- Sign of larger mass splitting unknown; some preference for normal ordering
- θ_{23} octant unknown; some preference for upper octant
- δ_{CP} unknown; significant regions of possible phase space excluded at 3σ
- Currently running long-baseline experiments: T2K & NOvA
  - Recent result from T2K: *Nature* **580**, 339–344 (2020). https://doi.org/10.1038/s41586-020-2177-0
  - Latest result from NOvA: *Phys.Rev.Lett.* 123 (2019) 15, 151803. https://arxiv.org/abs/1906.04907
  - Expect updated results at Neutrino 2020 in June

Long-Baseline Experiment

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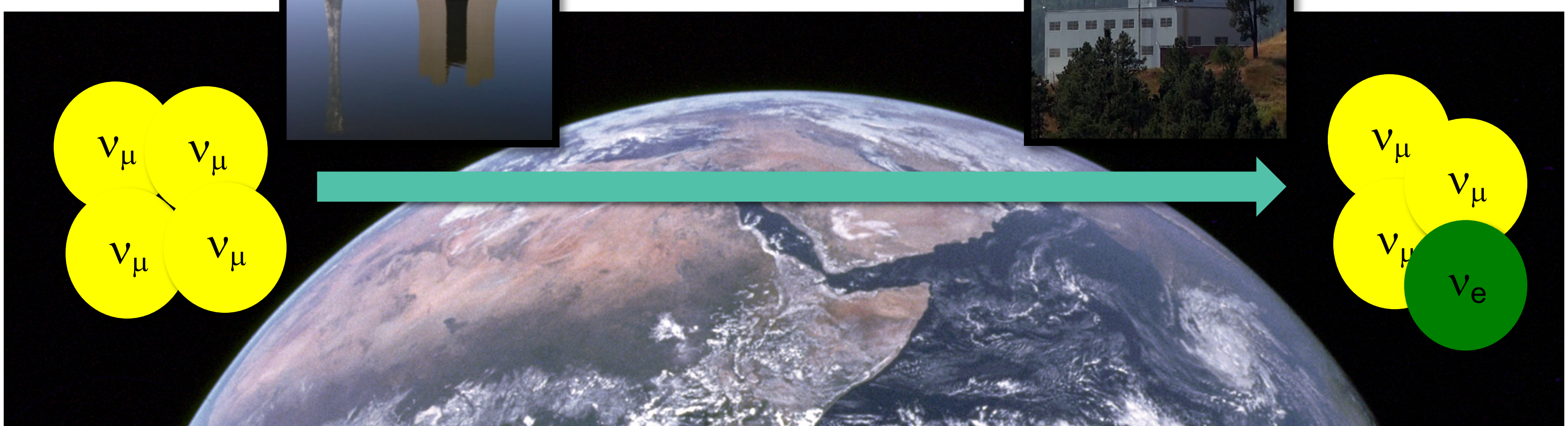
"Muon" neutrino beam created at accelerator complex → Composition of neutrino beam measured by near detector → Neutrinos travel 100s of kilometers through the Earth → Composition of neutrino beam after oscillation measured by far detector → Neutrino spectra analyzed to extract oscillation parameters

Two operational modes make either neutrino or antineutrino dominated beam

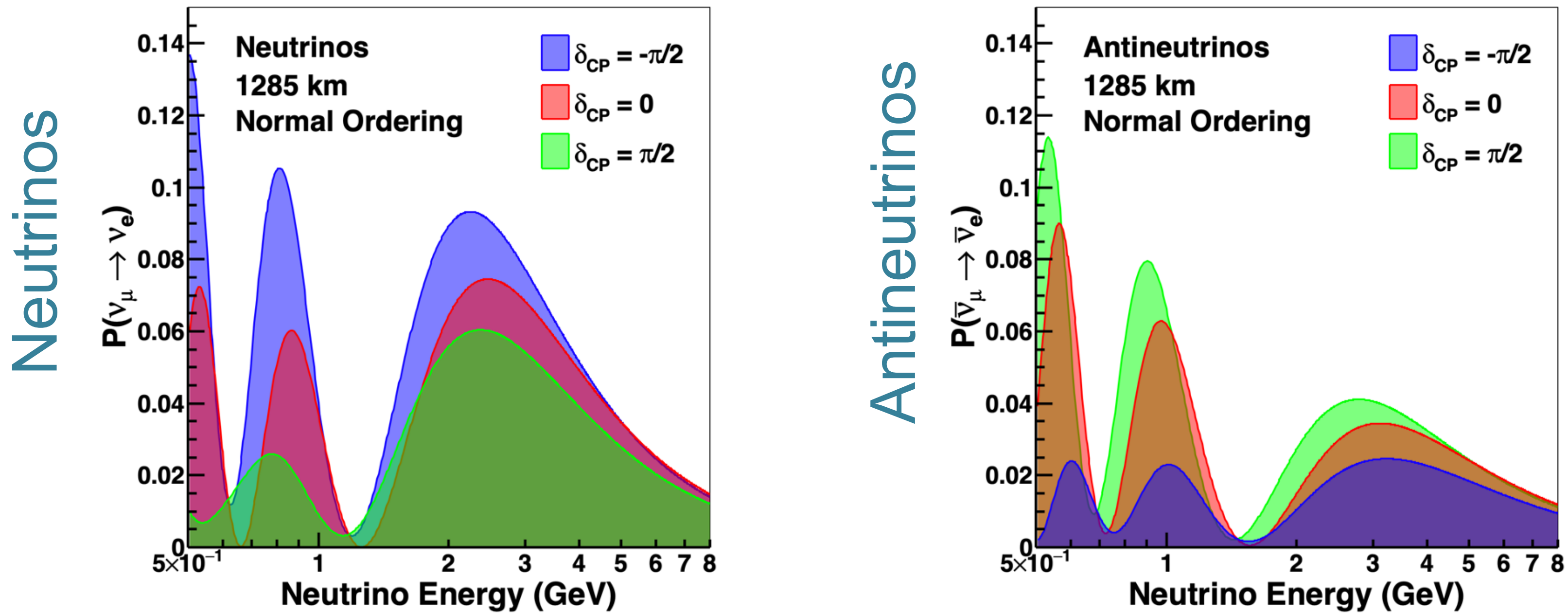


ν_e Appearance

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

$$a = G_F N_e / \sqrt{2}$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$



DUNE

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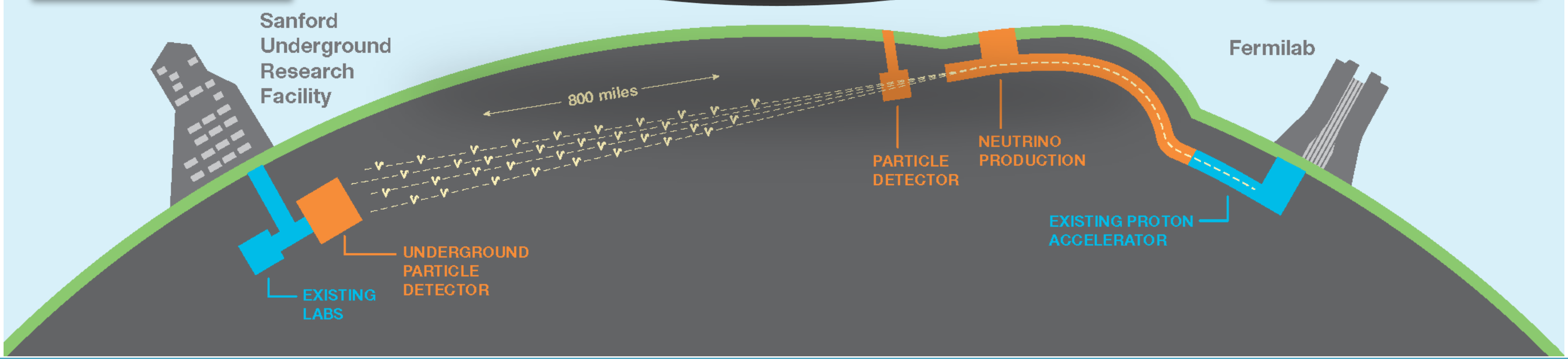
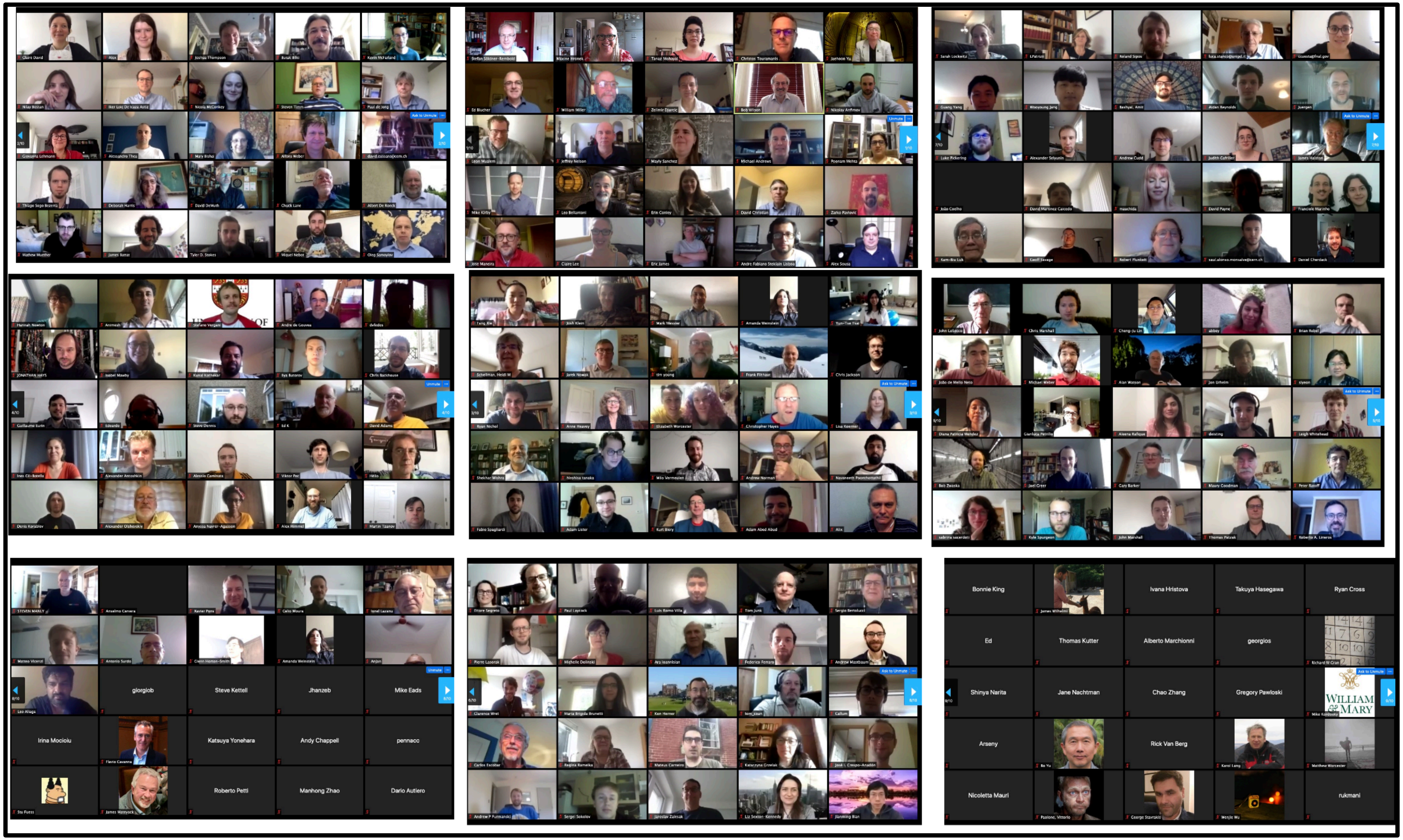
Measure ν_e appearance and ν_μ disappearance in a wideband neutrino beam at 1300 km to measure mass ordering, CP violation, and neutrino mixing parameters in a single experiment. Large detector, deep underground allows sensitivity to rare processes and low-energy physics.



May 2020 Collaboration Photo

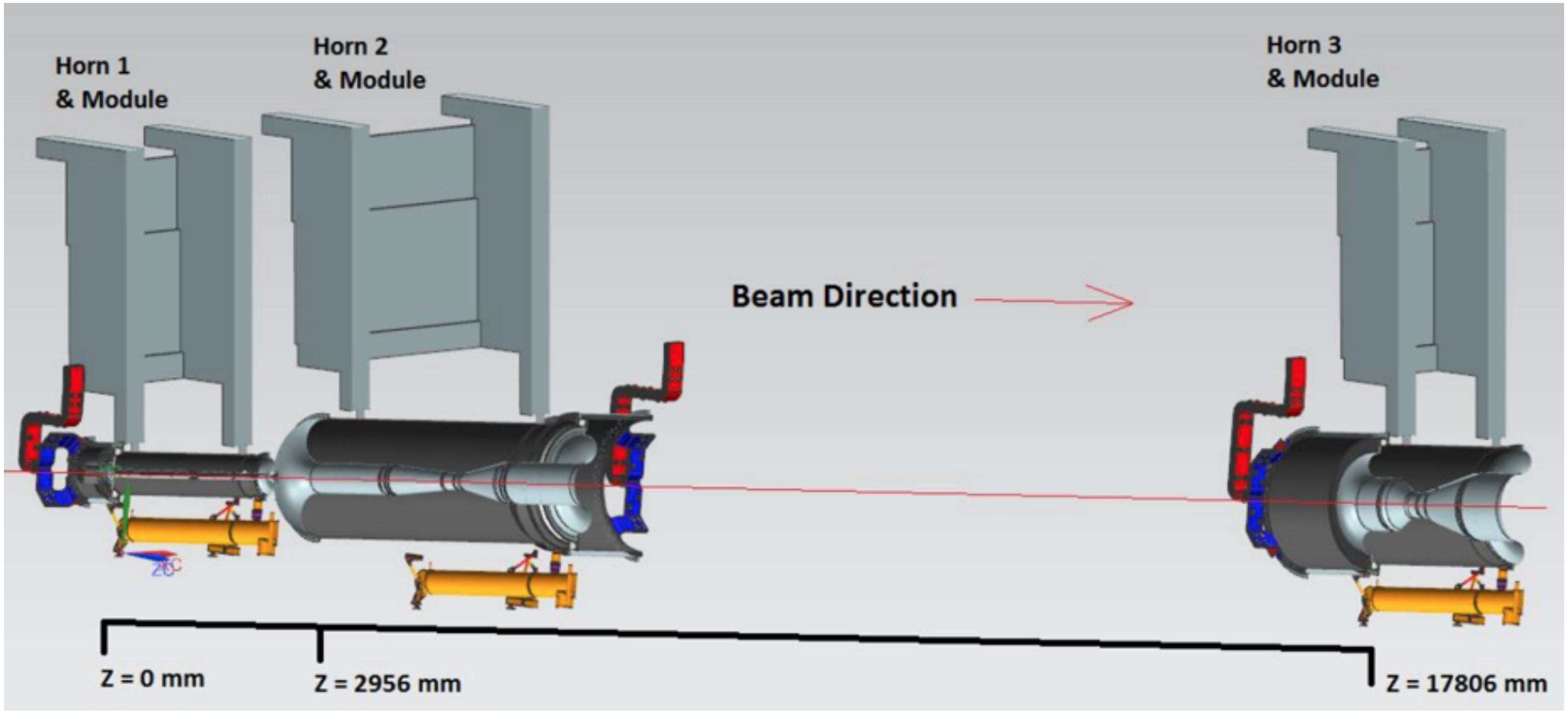
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

~250 participants!



LBNF Neutrino 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 CP violation sensitivity



Neutrino Flux

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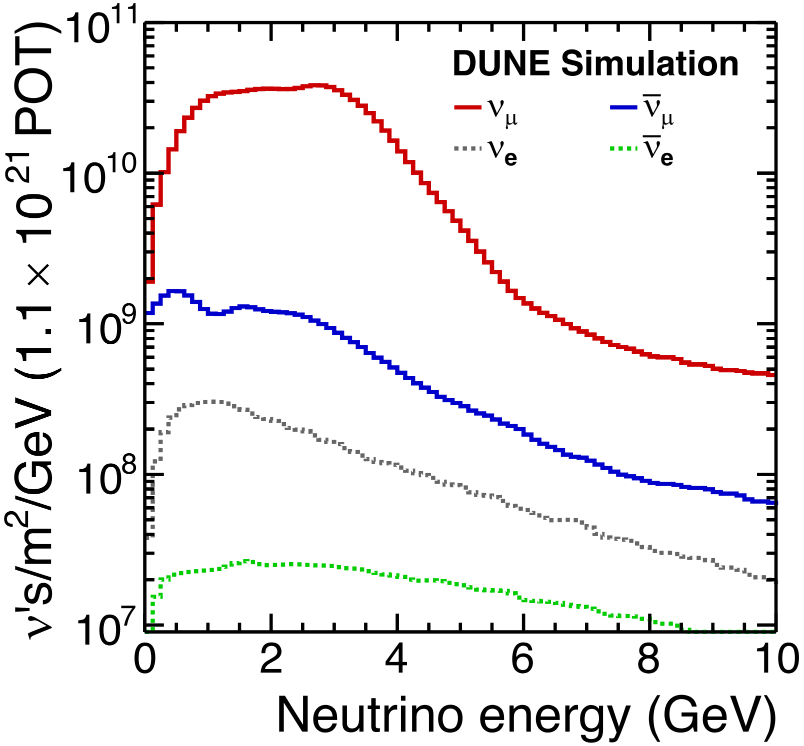
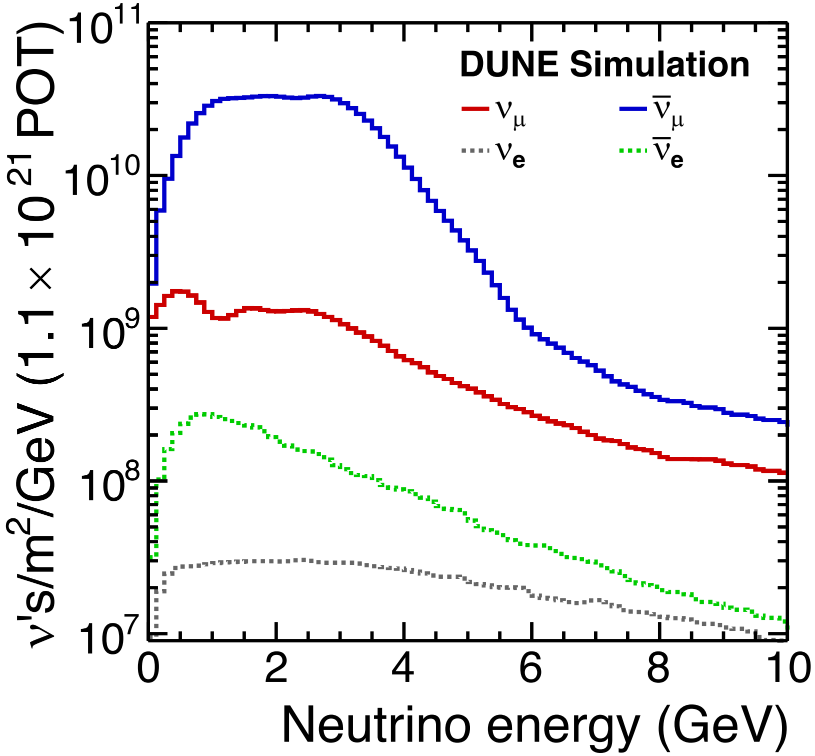
Neutrino Mode:

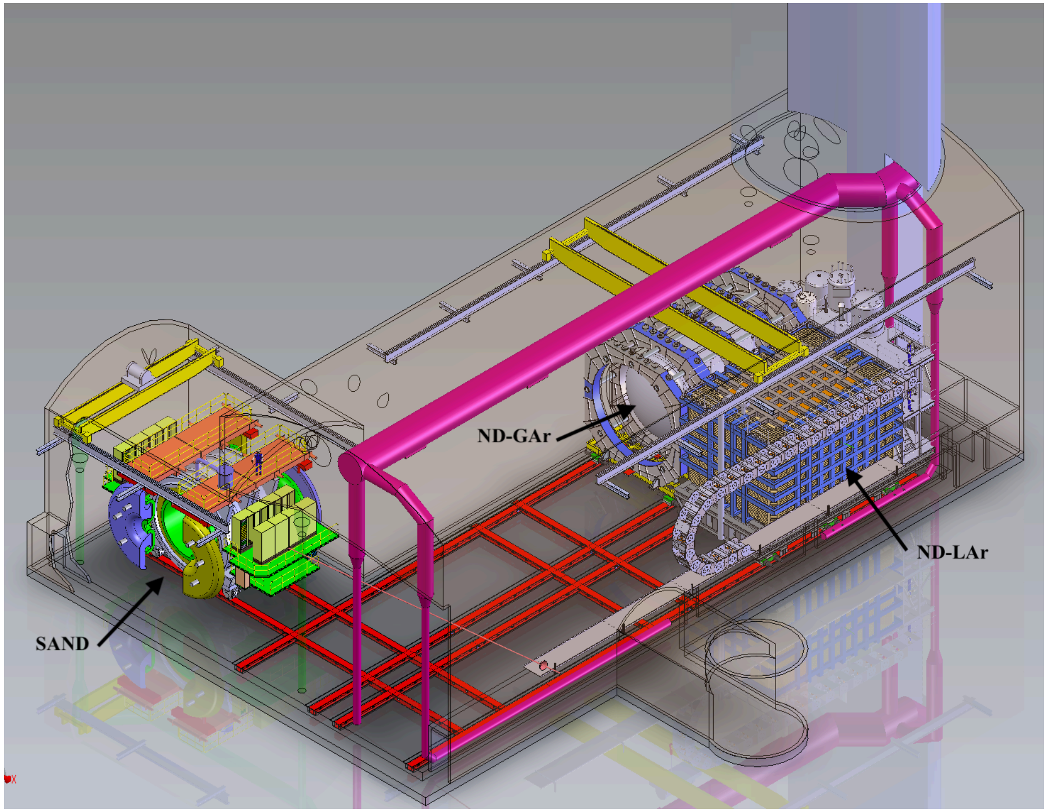


Antineutrino Mode:



DUNE Near Detector

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



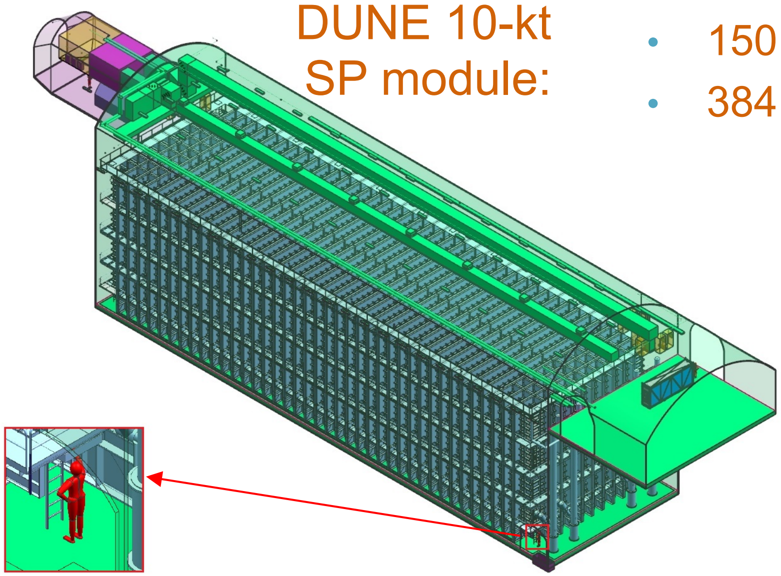
- ND-LAr: Modular, pixelized liquid argon TPC
  - Primary target
  - Most similar to FD
- ND-GAr: High pressure gaseous argon TPC surrounded by ECAL and magnet
  - Momentum analysis of muons from interactions in ND-LAr
  - Lower threshold
- ND-LAr & ND-GAr move off-axis to observe varied beam spectra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

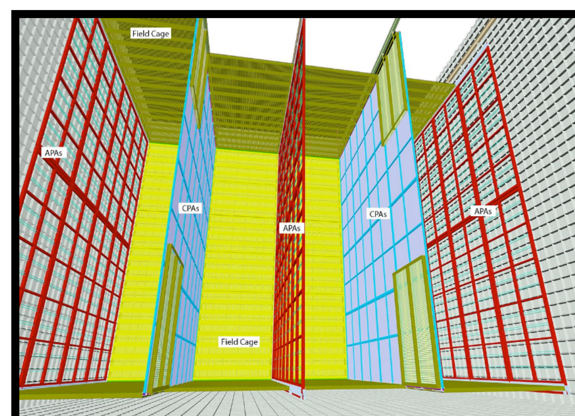
DUNE Far Detector

- 40-kt (fiducial) liquid argon TPC at 4850L of SURF with integrated photon detection
  - Four 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





SURF

Sanford Underground Research Facility (Lead, SD)

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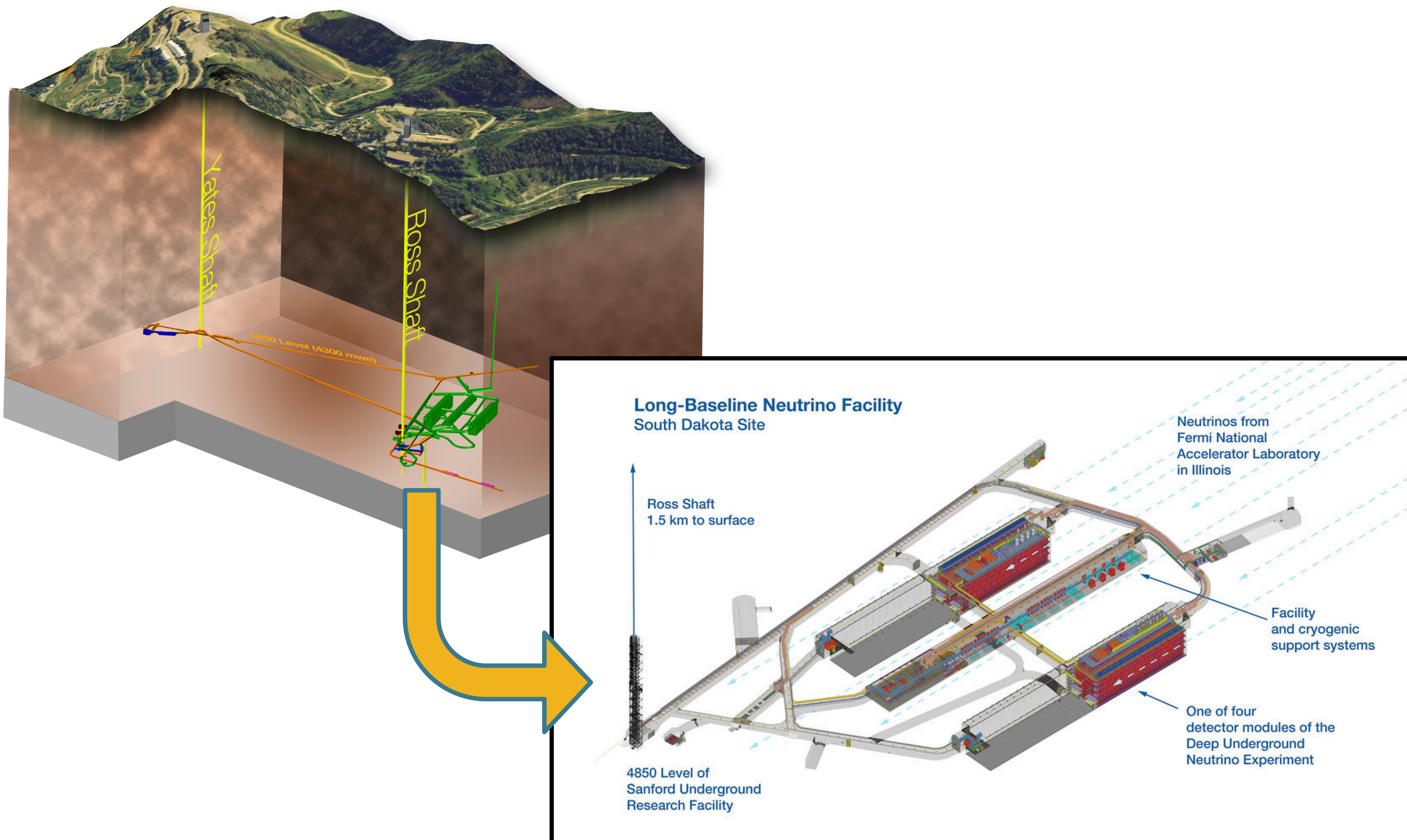

DUNE Physics Goals

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- 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, ….

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- BSM pro…
  - Baryon …umber violating processes, sterile neutrinos, non-unitarity of PMNS matrix, non-standard interactions, CPT violation, neutrino trident production, dark matter detection, ….

Another talk…

LBL Oscillation Analysis

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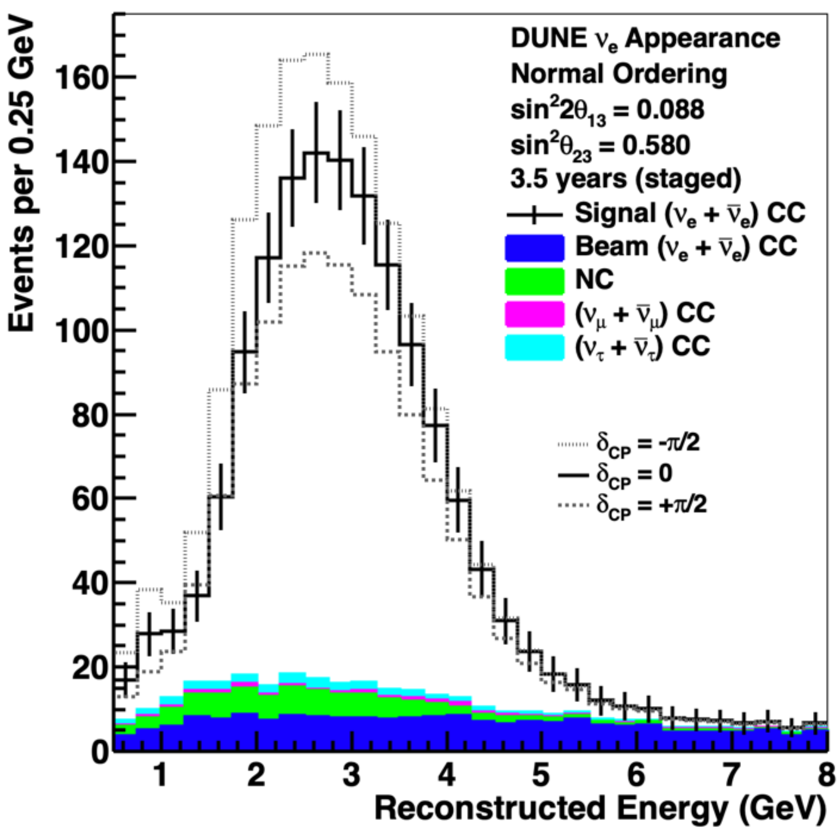
$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,$$



- 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"

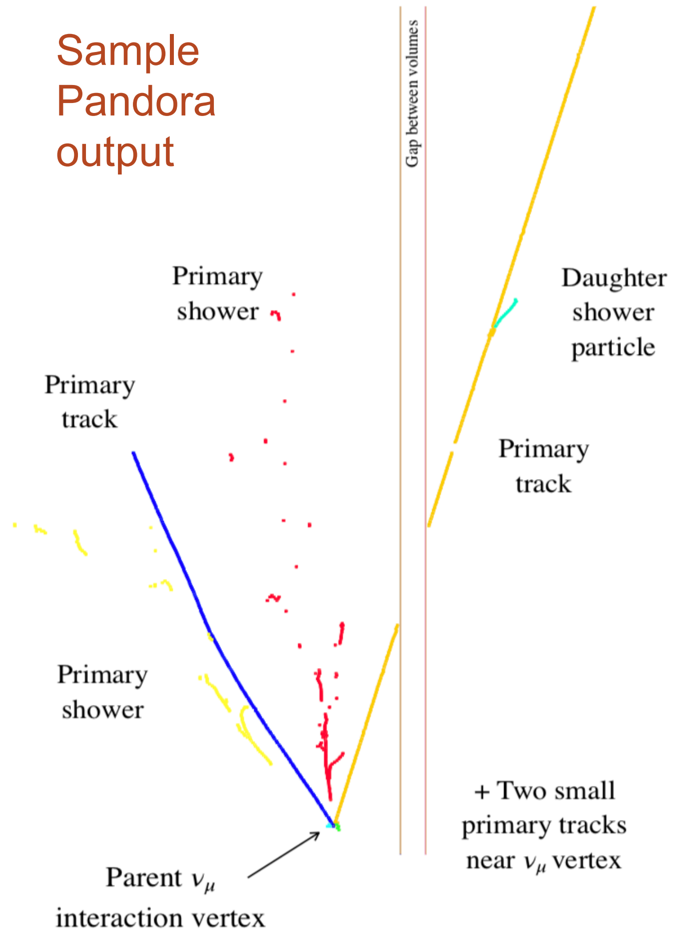
Far Detector Analysis

- 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

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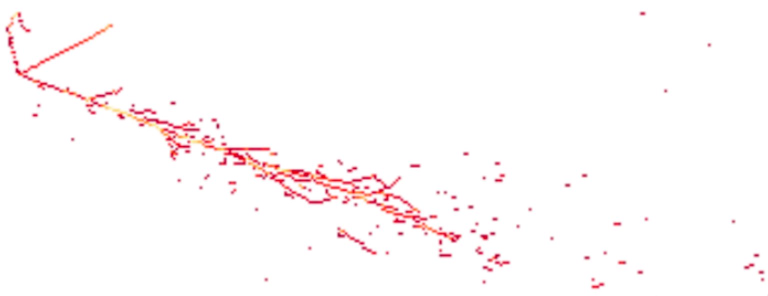
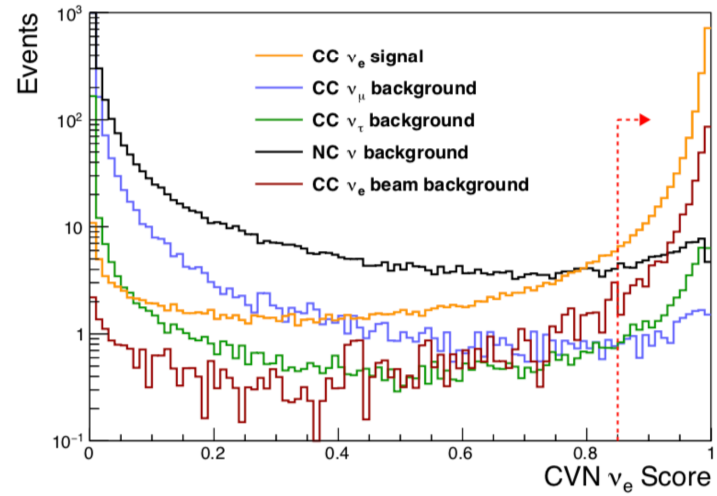
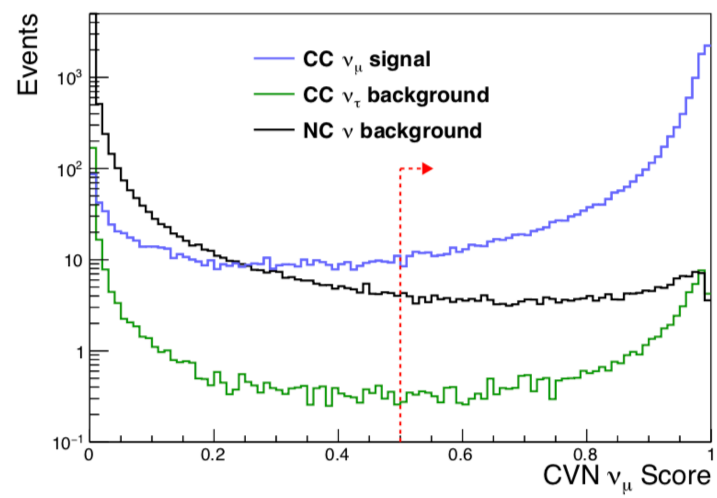
- Performed using convolutional visual network (CVN)
  - Three input images per event (time vs. wire number for each readout plane)



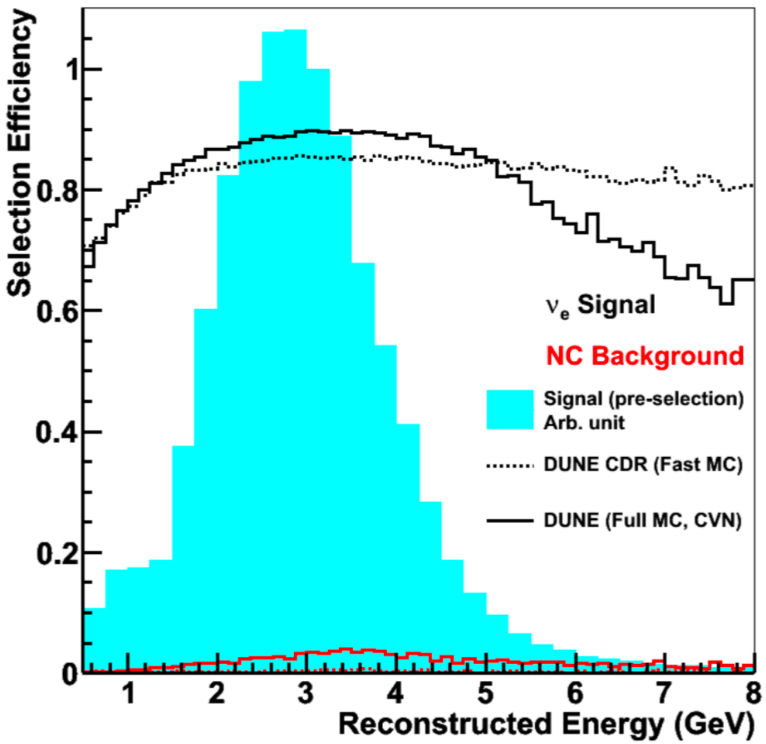
- Training performed on statistically independent MC sample
- Event selection criteria chosen to optimize CP violation sensitivity



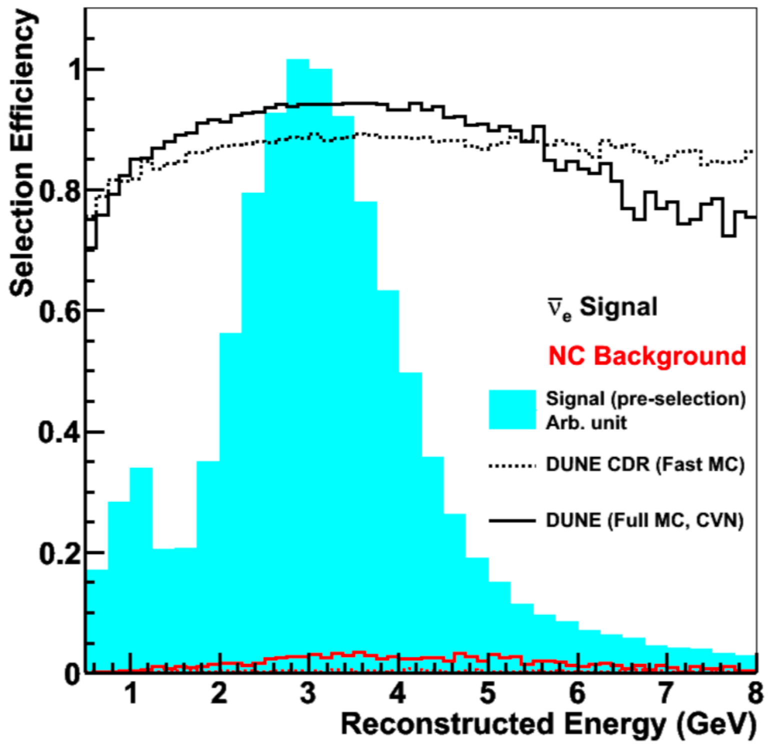


FD Event Selection Efficiency

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

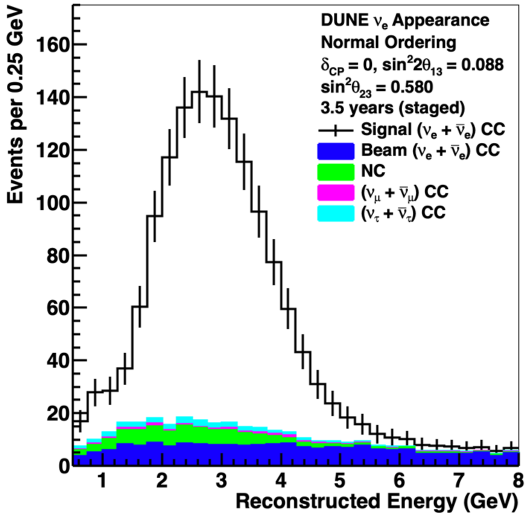
Analysis Input

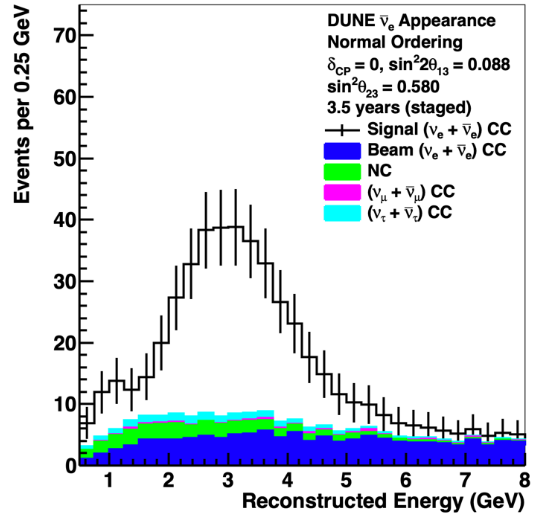
- Oscillation parameters: NuFit 4.0 (Nov 2018)
  - http://www.nu-fit.org/?q=node/177
  - True value of θ_{23} has significant impact on sensitivity
- Earth density: 2.848 g/cm^3
- Baseline: 1284.9 km
- Staging assumptions (technically limited schedule)
  - 1.2 MW × 20 kton at start
  - 1.2 MW × 30 kton 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

Neutrino Mode | Antineutrino Mode

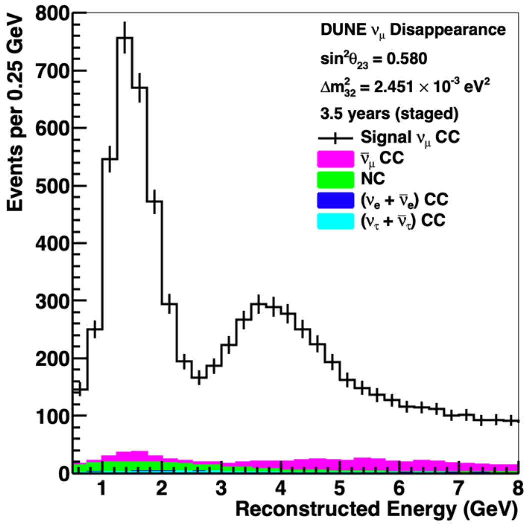
Appearance

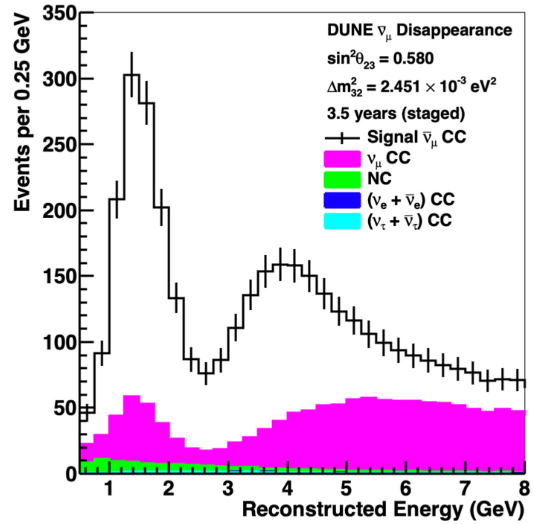




Order 1000 appearance events in 7 years

Disappearance





Order 10,000 disappearance events in 7 years

Near Detector Analysis

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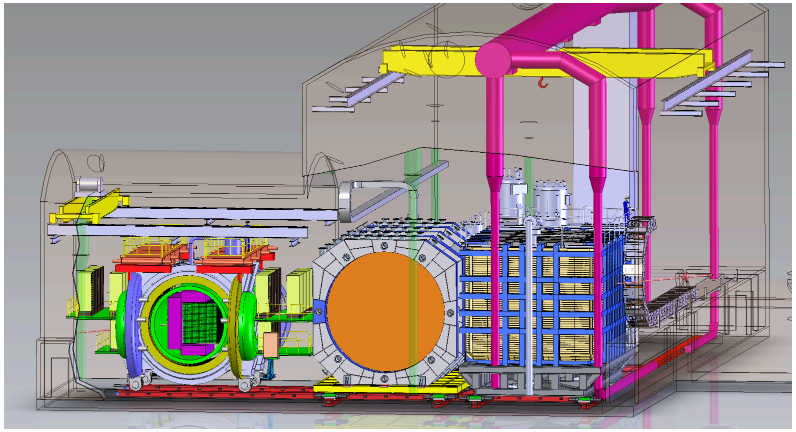
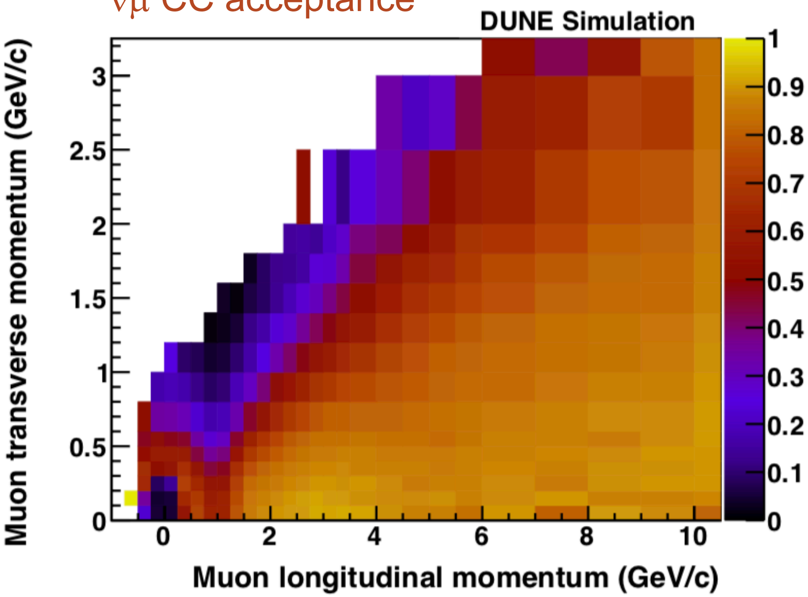
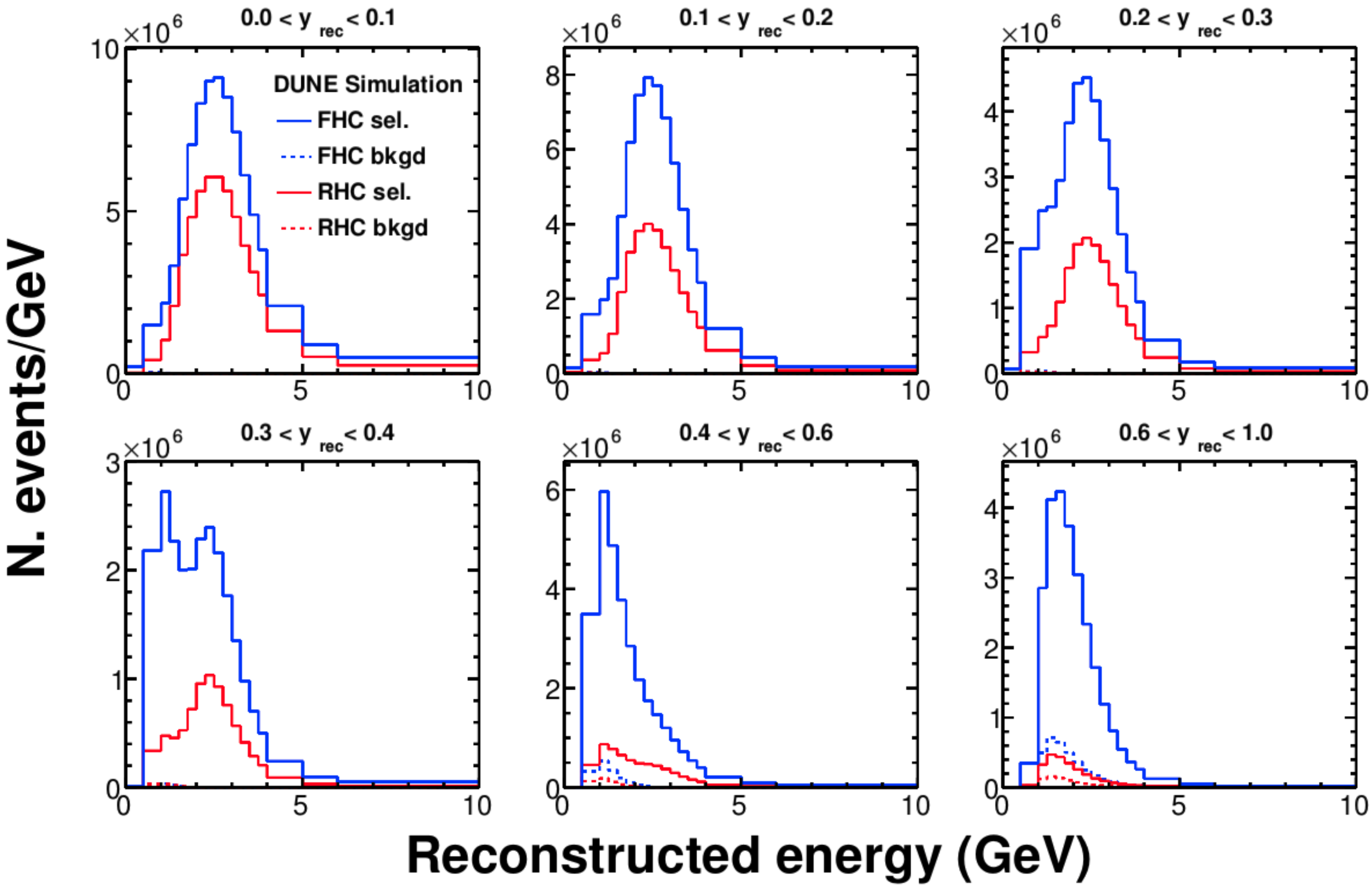
- For analysis presented here, only parameterized reconstruction (based on Geant4 simulation) of ν_μ CC sample in ND-LAr is included in fits **but** analysis assumes constraints from full ND
  - Parameterized muon reconstruction assumes momentum analysis in ND-GAr for tracks exiting ND-LAr, so acceptance 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}



$\nu\mu$ CC acceptance

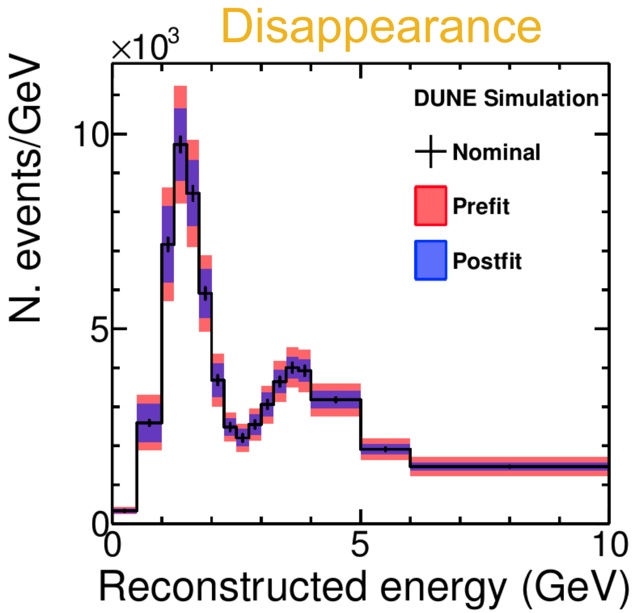


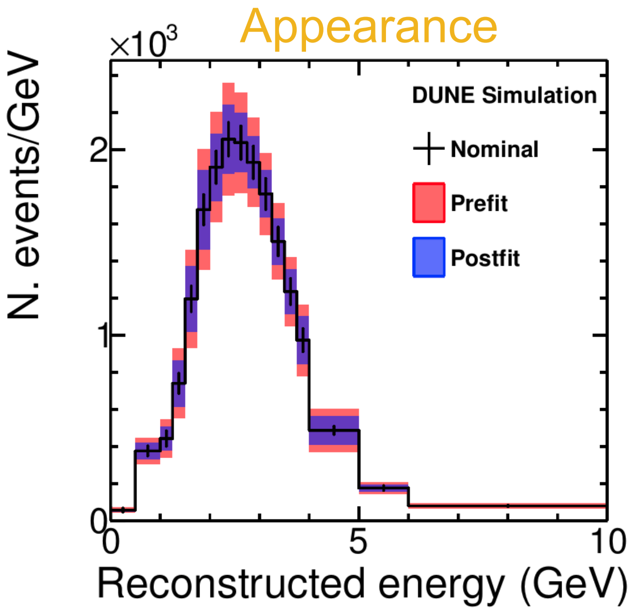
ND Selected Spectra



Systematic Uncertainties

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



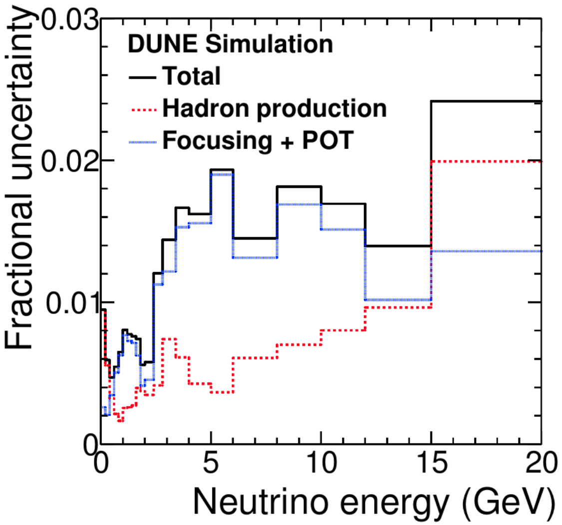


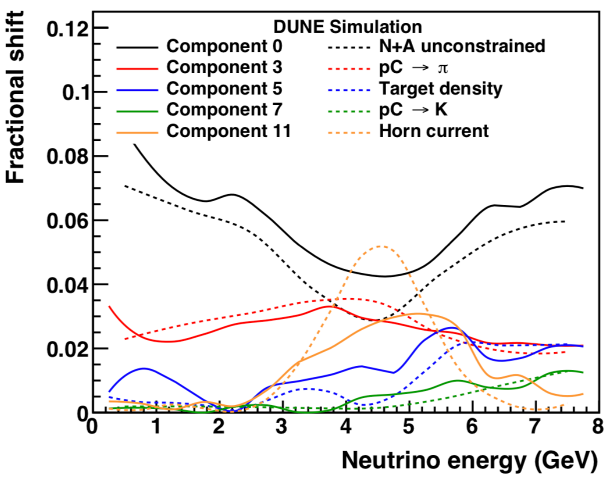
Note: Previous DUNE analyses did not attempt to evaluate impact of individual sources of systematic uncertainty. Overall effect of systematic uncertainty, after constraints from ND and FD sample-sample cancellations, was approximated using 2% uncorrelated signal normalization uncertainty. This approximation 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

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- 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

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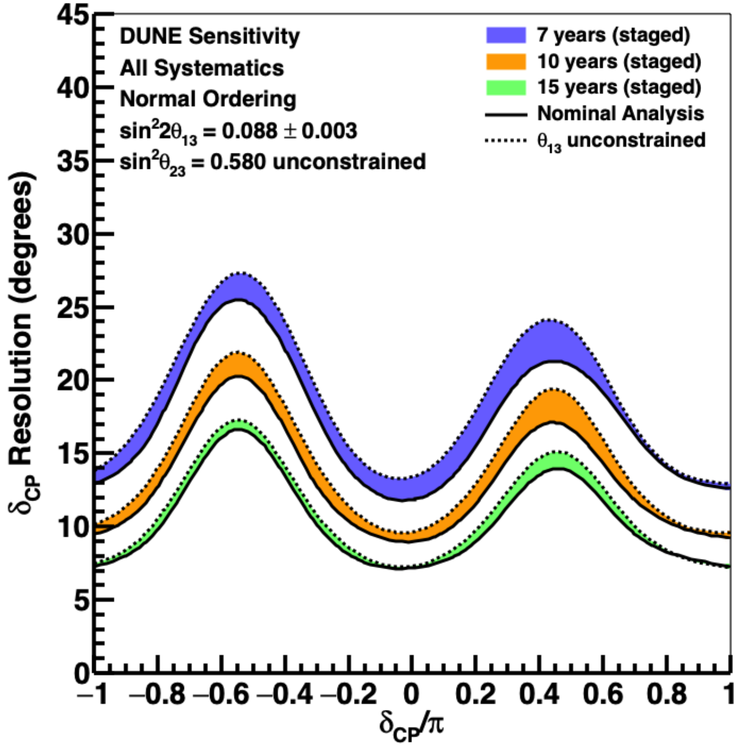
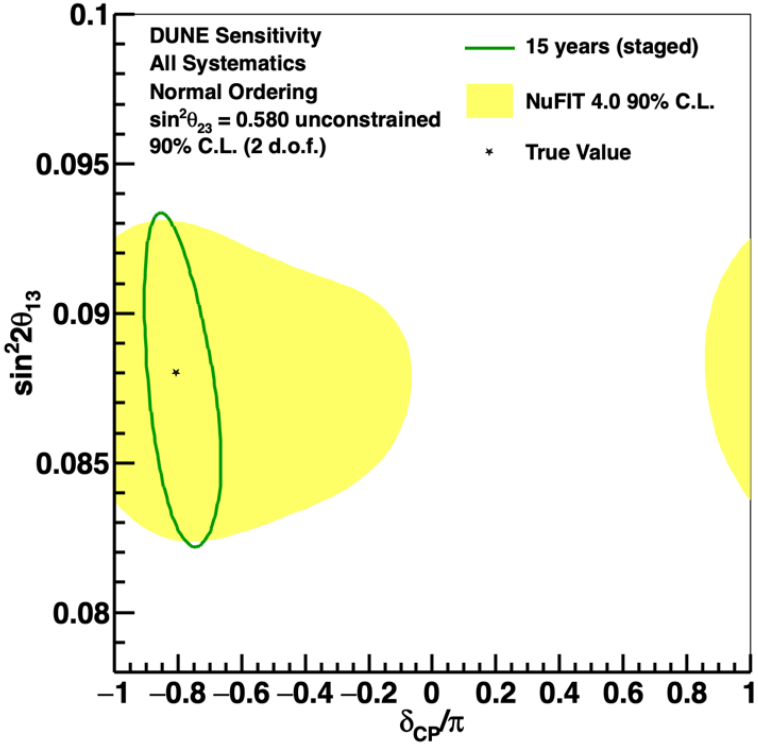
δ_{CP} Resolution



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

CP Violation Sensitivity

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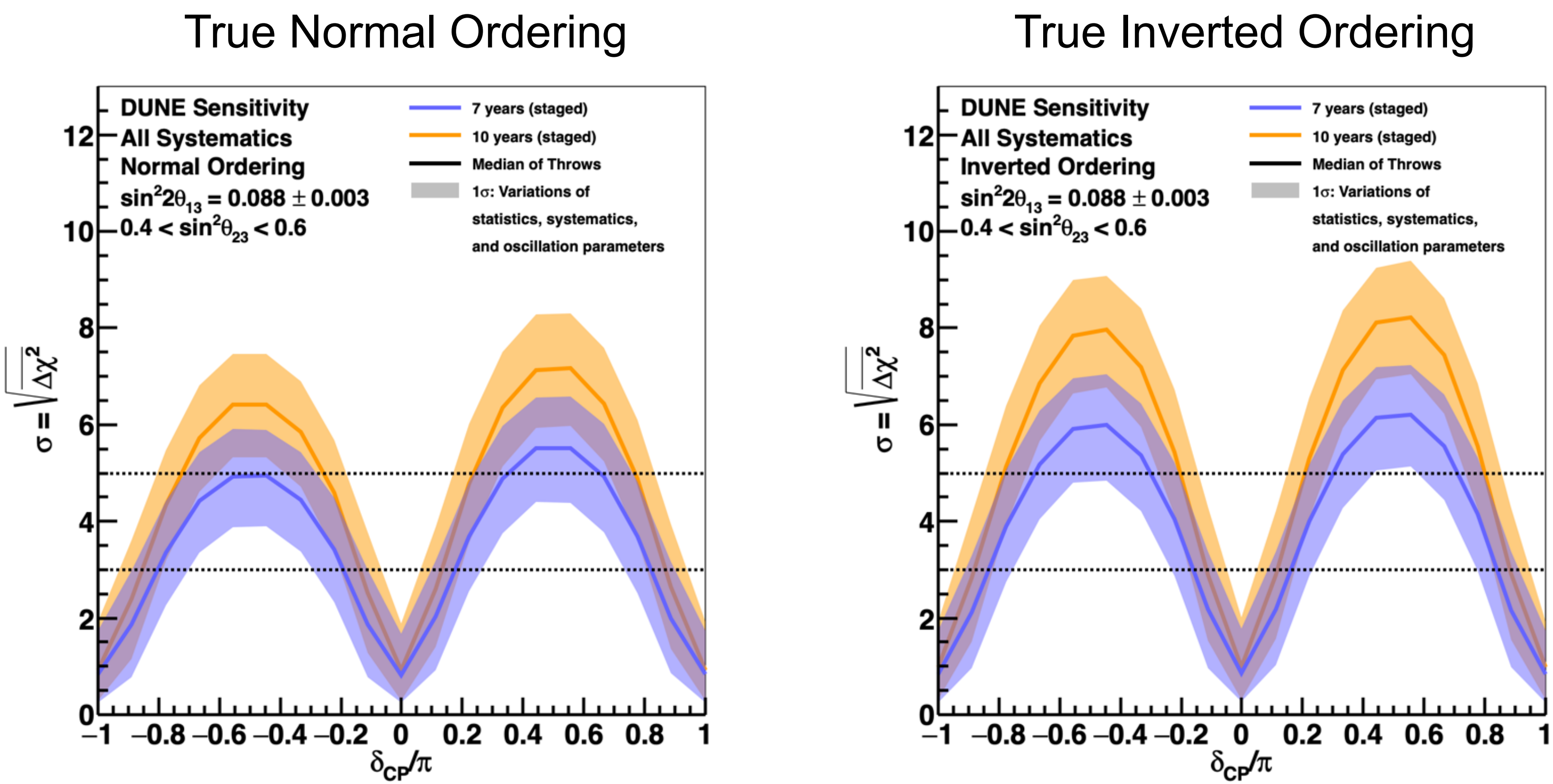
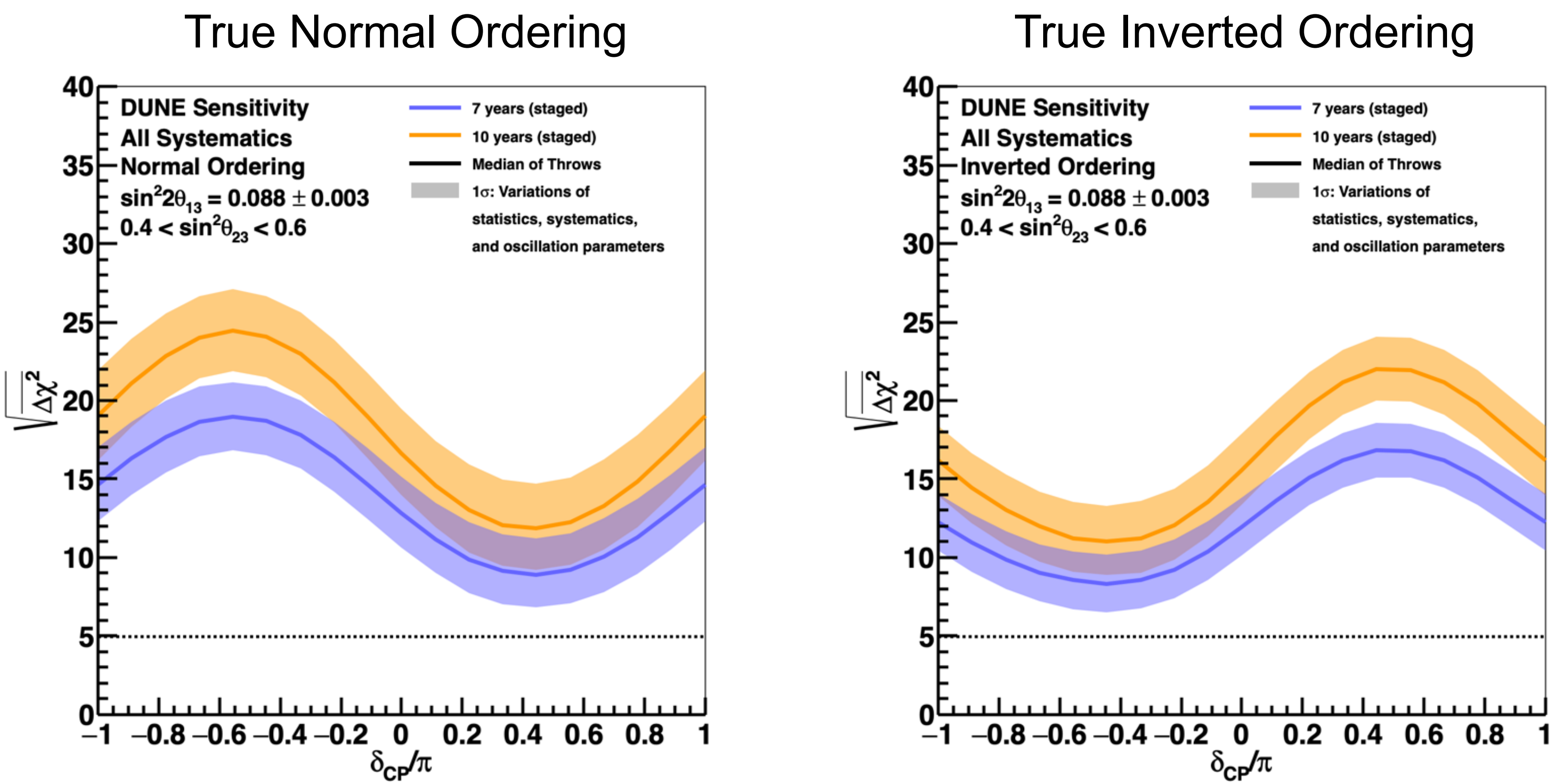


Width of band represents 68% of throws (stats, systematics, oscillation parameters)

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

Mass Ordering Sensitivity

DEEP UNDERGROUND NEUTRINO EXPERIMENT

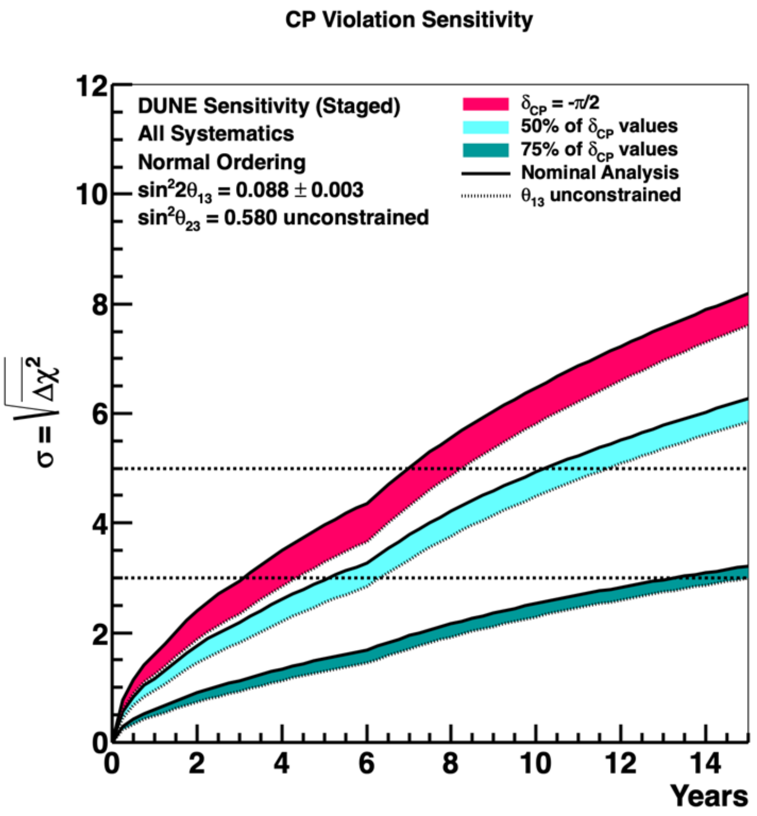


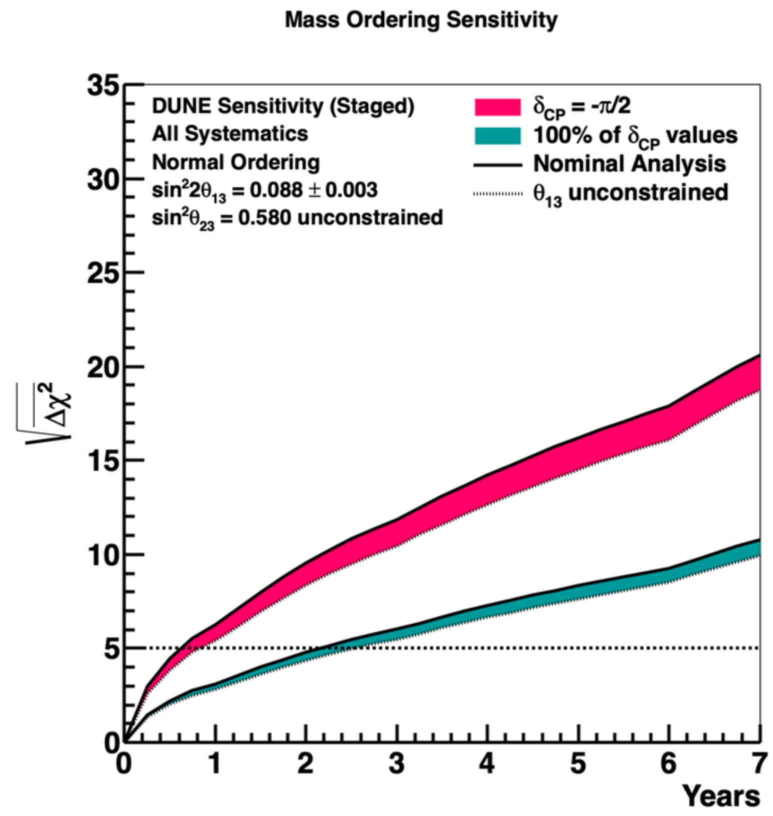
Width of band represents 68% of throws (stats, systematics, oscillation parameters)

Definitive determination of mass ordering for all possible parameters

Sensitivity Over Time

DEEP UNDERGROUND NEUTRINO EXPERIMENT



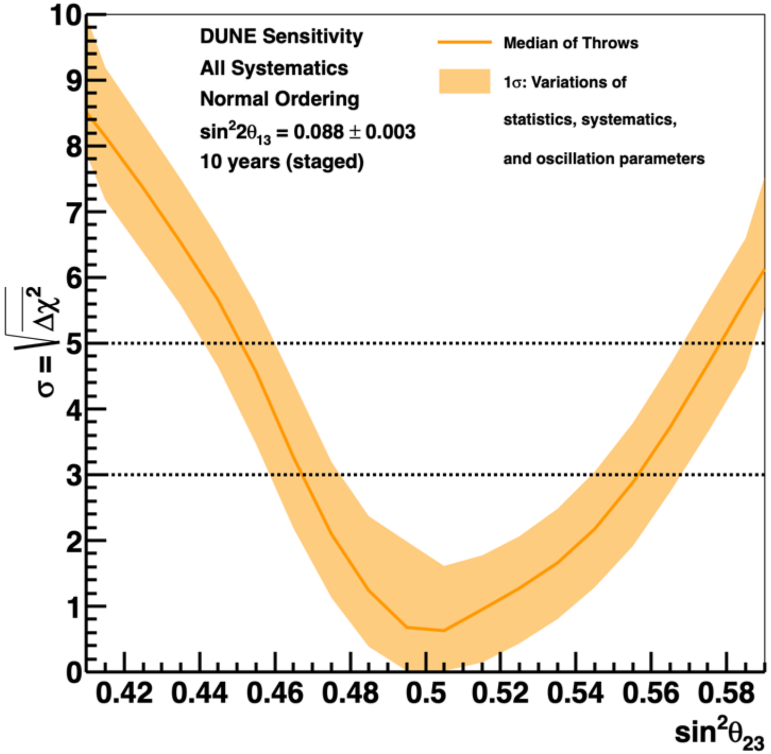


Width of band represents difference between sensitivity with and without external constraint on θ_{13}

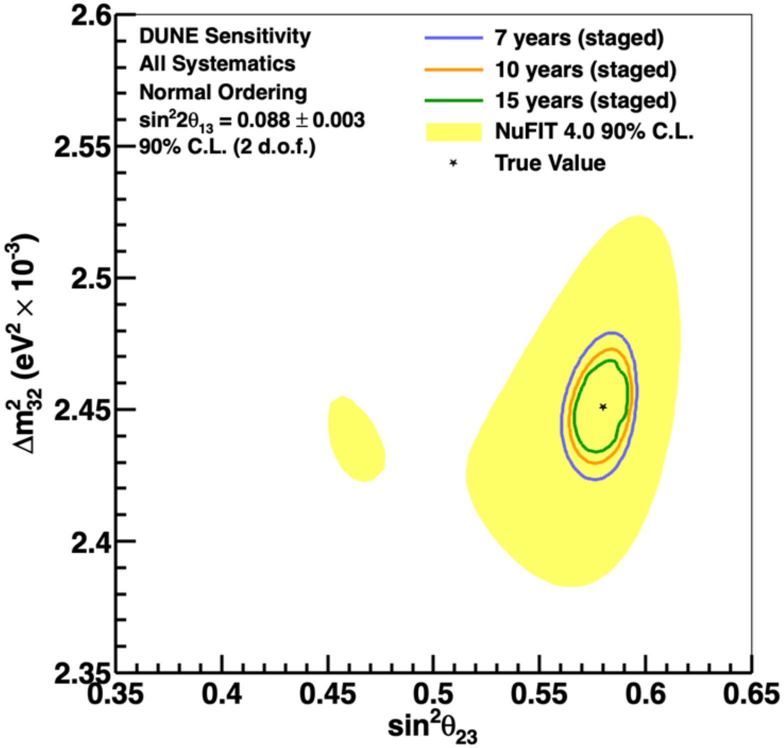
Unambiguous determination of neutrino mass ordering within first few years.
Significant milestones throughout the beam physics program.

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

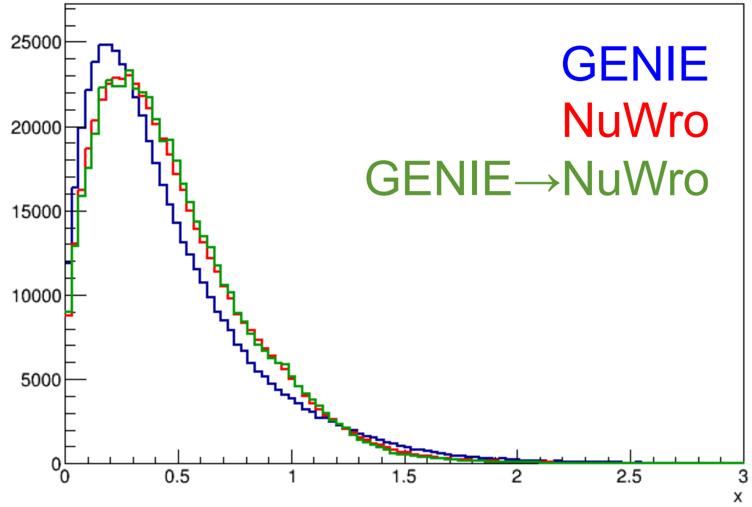
Further Studies

- 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

DEEP UNDERGROUND NEUTRINO EXPERIMENT

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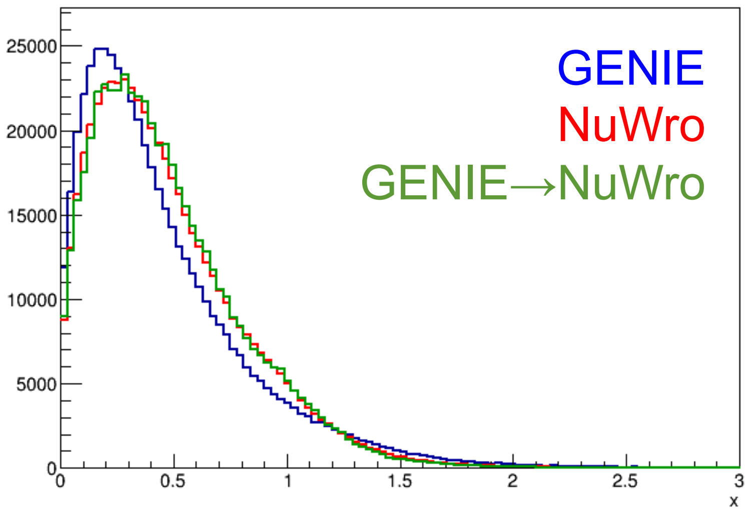
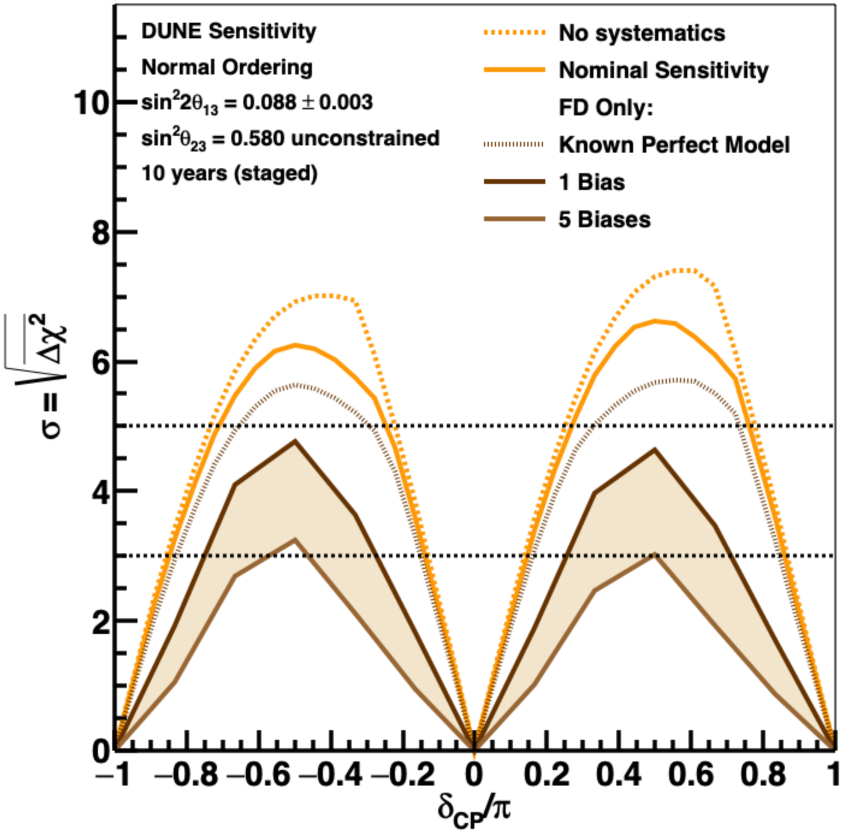
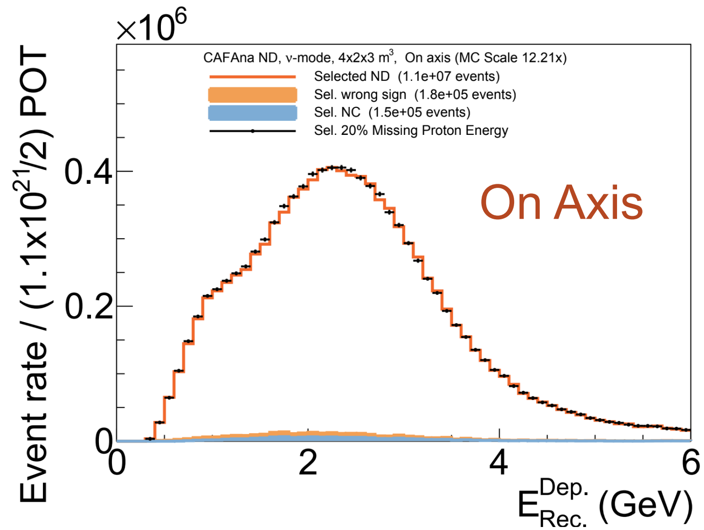
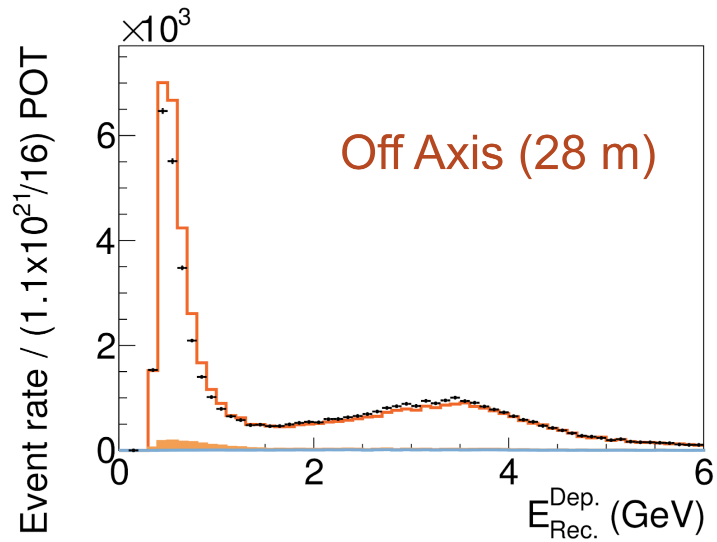




Energy Bias Study

- 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

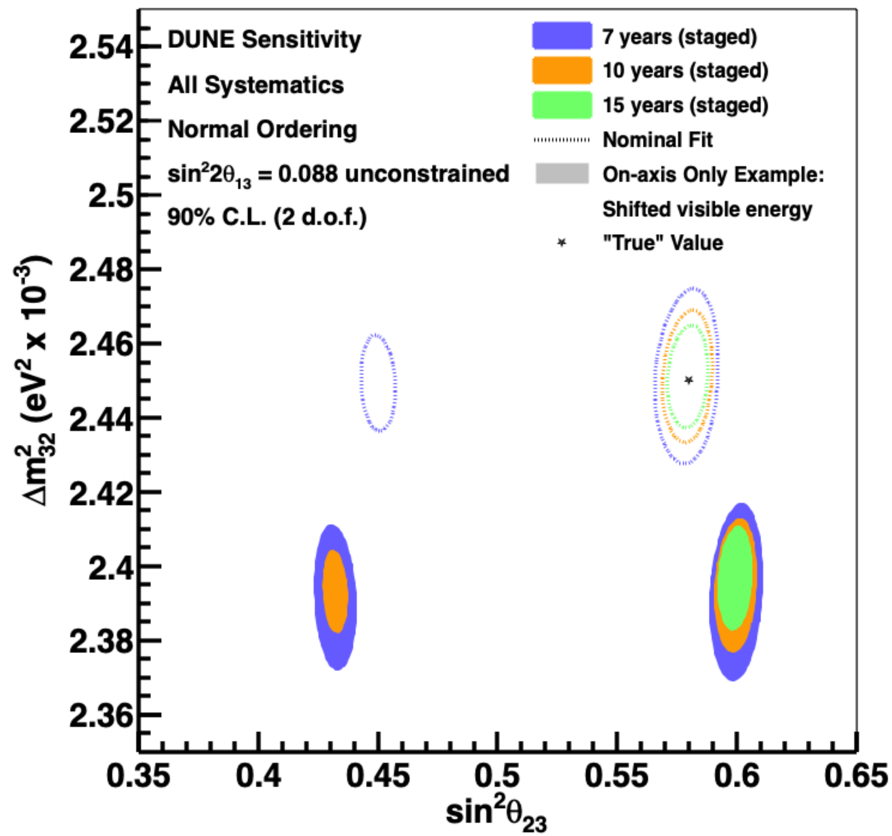




Energy Bias Study

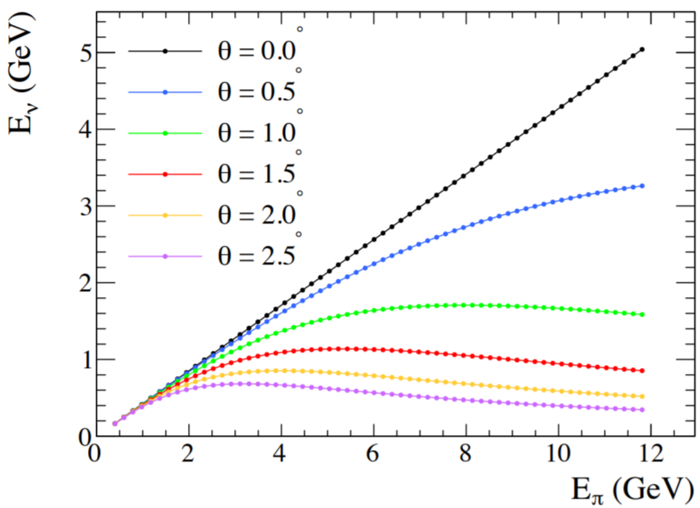
- 20% of proton energy is removed and added to (largely invisible) neutrons
  - Significant modification to relationship between reconstructed and true energy
  - An artificial but plausible example of a way in which the interaction model could be off
- Use BDT to adjust model parameters such that **on-axis**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

Δm^2_{32} vs $\sin^2\theta_{23}$

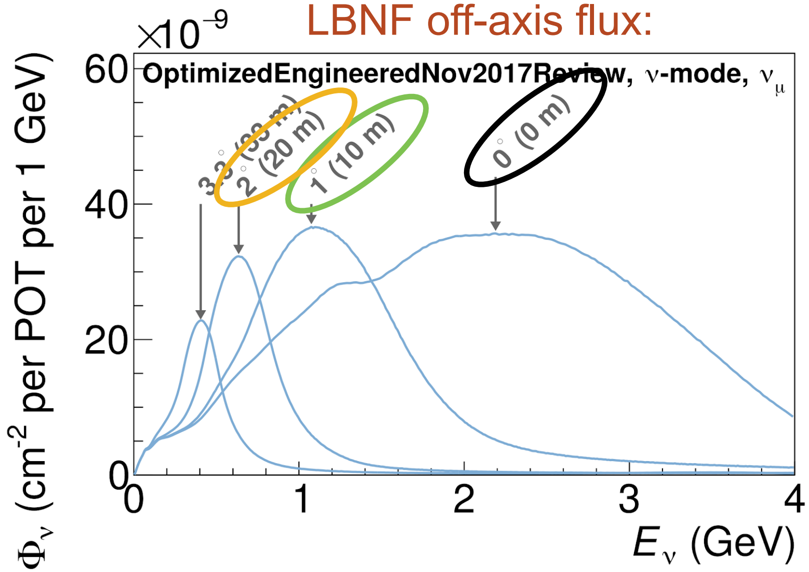


DUNE PRISM

Off-axis neutrino energy:



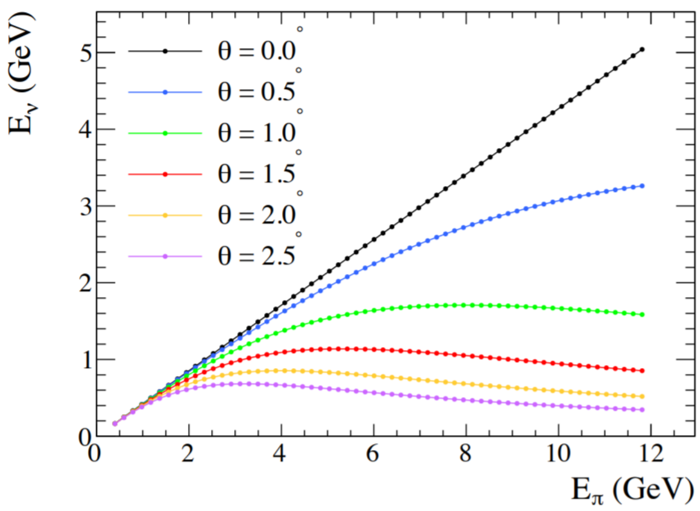
LBNF off-axis flux:



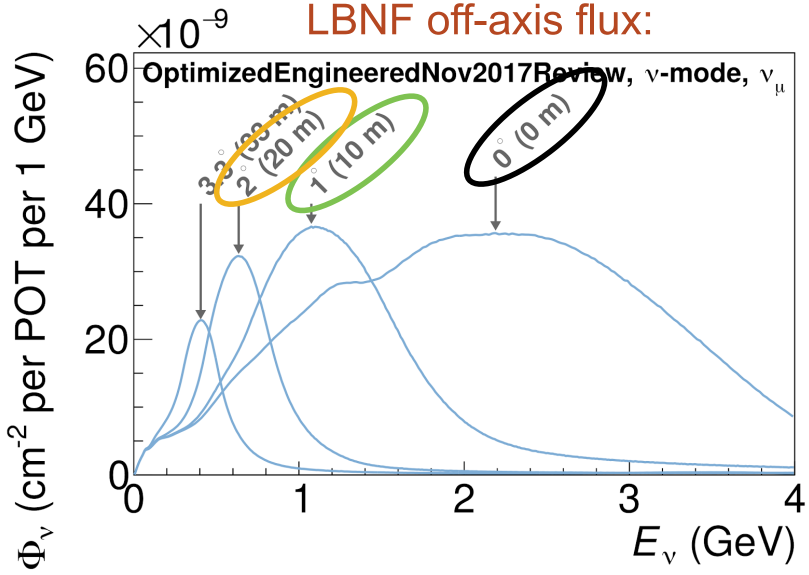
DUNE PRISM

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Off-axis neutrino energy:



LBNF off-axis flux:

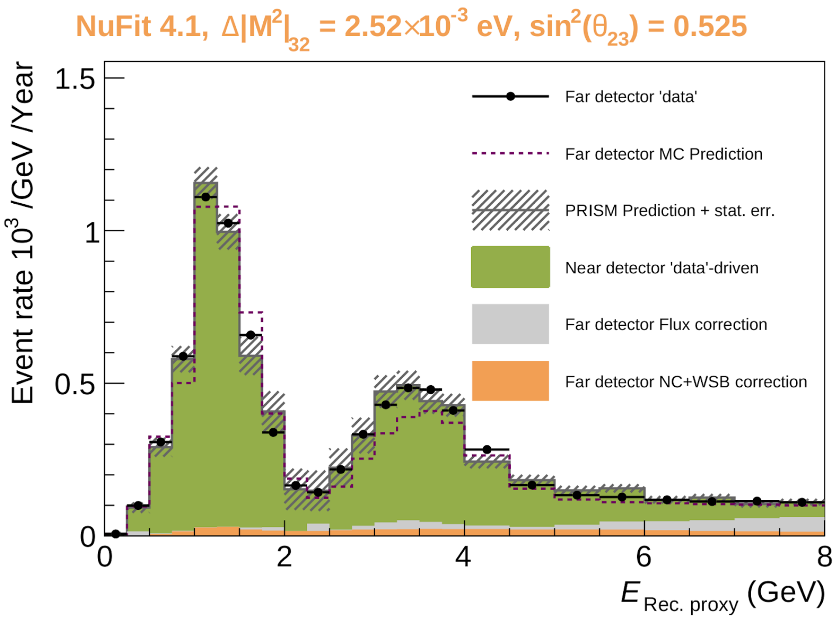


PRISM (Precision Reaction-Independent Spectrum Measurement) concept is to use linear combinations of off-axis fluxes to construct any flux: can ~reproduce FD flux prediction or Gaussian flux at a given energy. Same weights can then be applied to ND data to construct a “data driven” predicted event rate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

DUNE Timeline & Plans

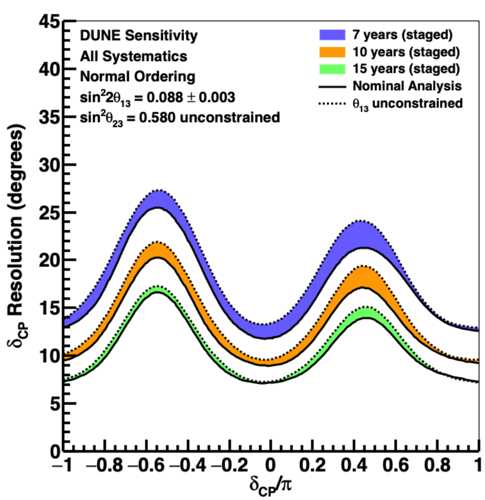
DEEP UNDERGROUND NEUTRINO EXPERIMENT

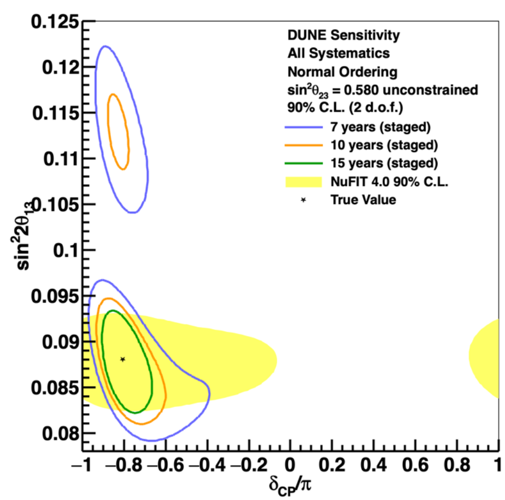
- Far site construction underway
- Near site preparation underway
- protoDUNEs (large scale FD prototypes at CERN Neutrino Platform) taking data now
- Far detector physics data expected in late 2020s
- Neutrino beam expected to be available on similar timescale
- Details of timeline will be finalized when project is baselined (expected this year)

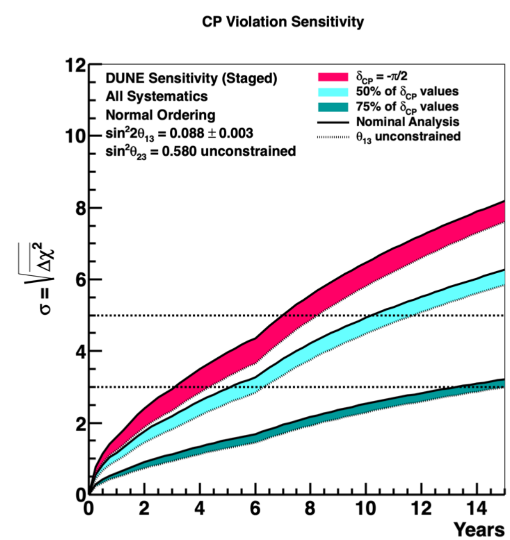
Summary

DEEP UNDERGROUND NEUTRINO EXPERIMENT

- 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







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 to be submitted to EPJC
- Paper on CVN event classification to be submitted to PRD