Lancaster University

DEEP UNDERGROUND NEUTRINO EXPERIMENT

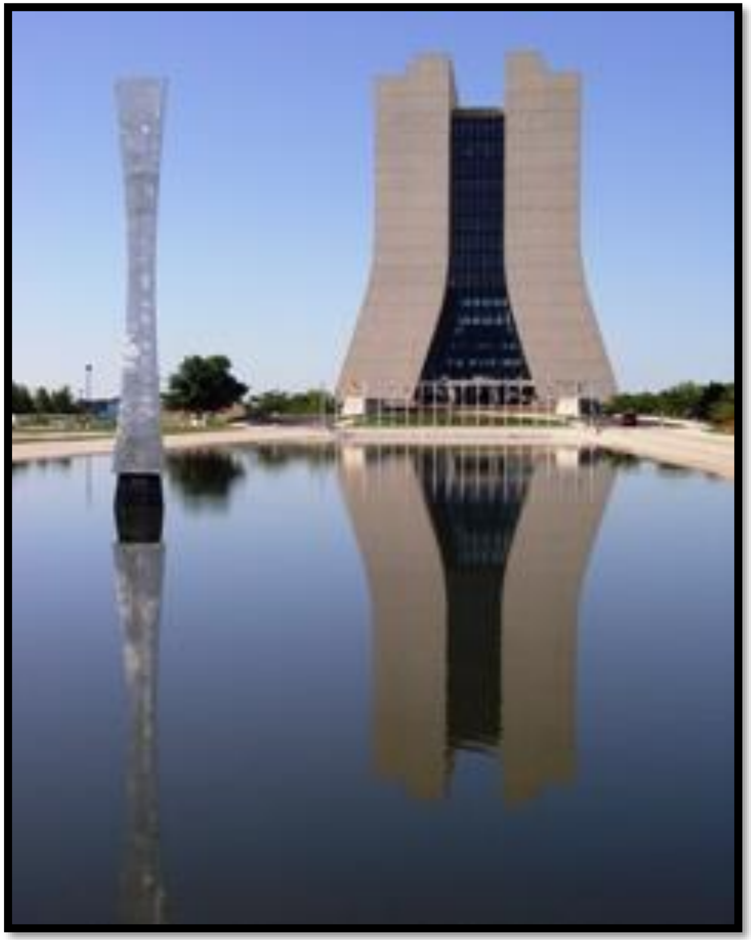
INTERACTIONS MODELING IN DUNE

Jarek Nowak for the DUNE Collaboration

Modeling neutrino-nucleus interactions, ECT-Villa Tambosi

July 12, 2018

ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS



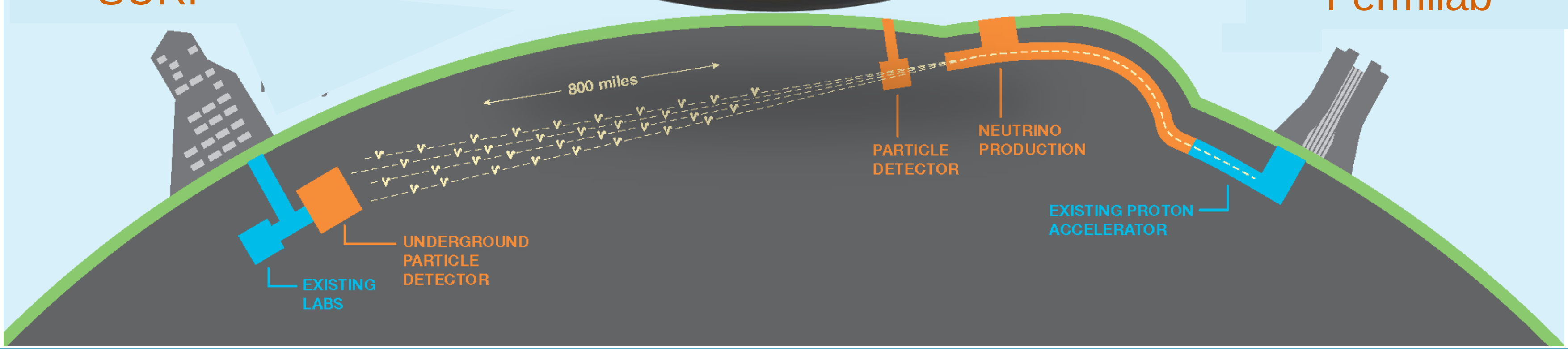
- DUNE Experiment: Detectors & Status
- DUNE Physics
- Interaction Monte Carlo generators @DUNE

DUNE Experiment

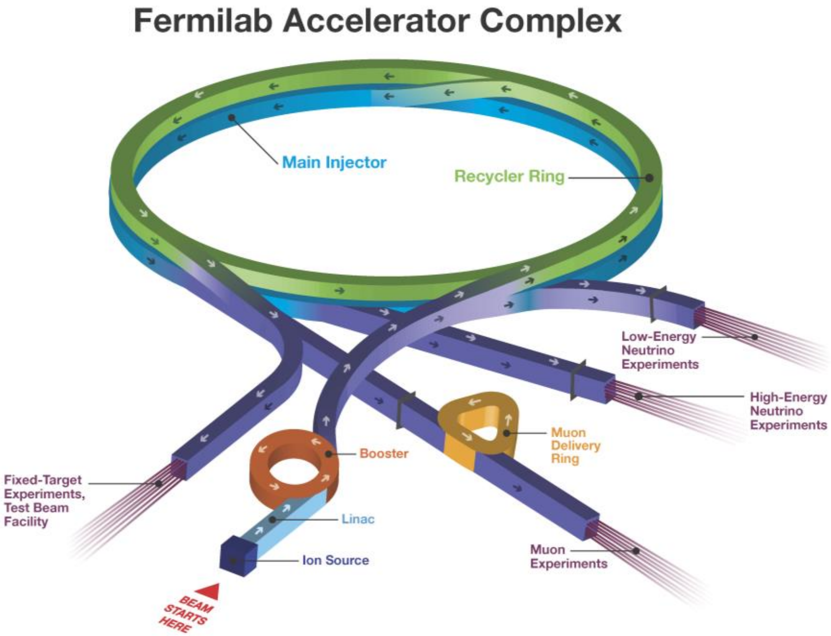
Observe ν_e appearance and ν_μ disappearance at long baseline in wideband beam to measure MH, CPV, and neutrino mixing parameters in a single experiment. Deep underground location reduces cosmogenic background and enables sensitivity to low-energy physics.

SURF

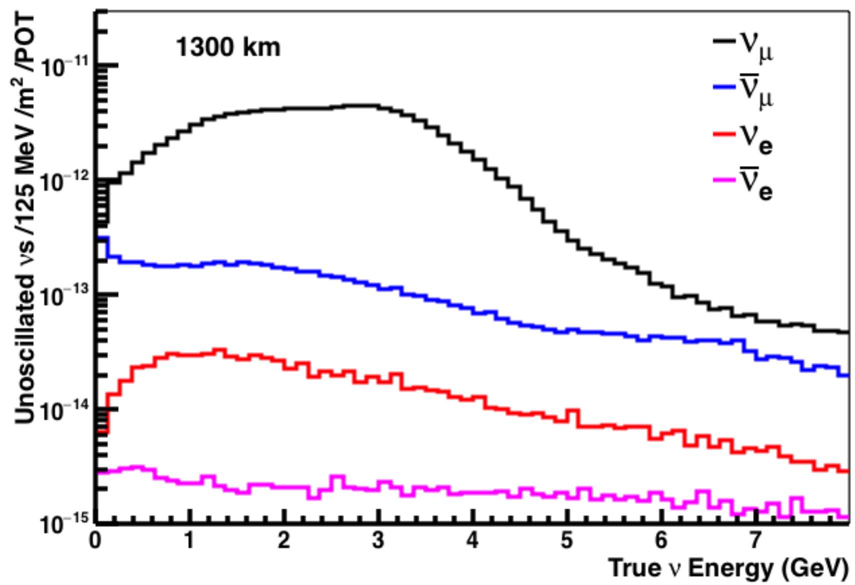
Fermilab



LBNF Beam



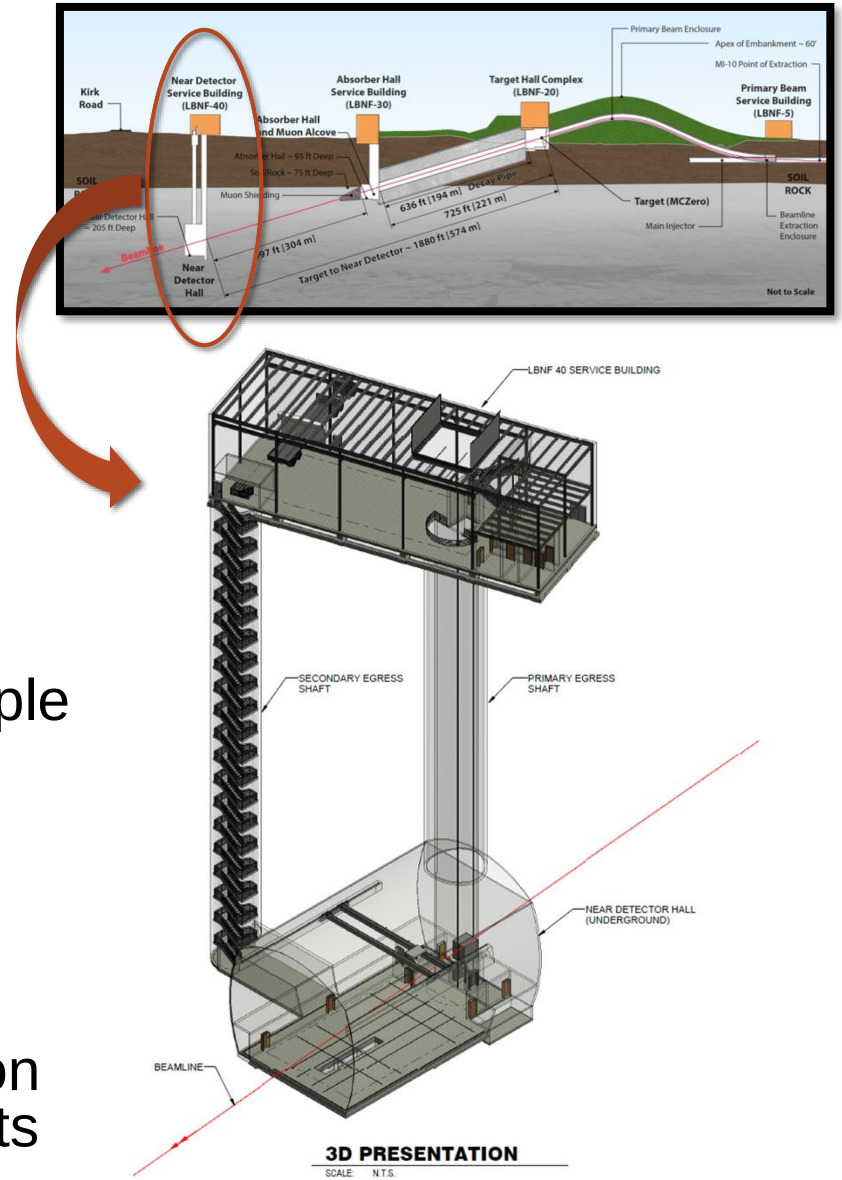
Neutrino Flux at 1300 km
(CDR Optimized Beam)



- 60-120 GeV proton beam
- 1.2 MW, upgradeable to 2.4 MW
- Horn-focused neutrino beam line optimized for CP violation sensitivity using genetic algorithm
  - Engineering design of 3-horn focusing system based on optimized parameters in progress
- Neutrino (FHC) and antineutrino (RHC) modes

DUNE Near Detector

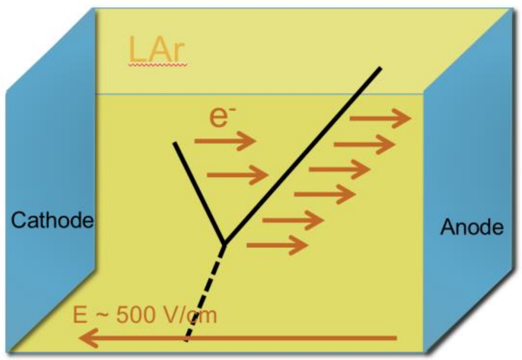
- Primary purpose is to **constrain systematic uncertainty** for long-baseline oscillation analysis
  - Constrain flux, cross-section, and detector uncertainties
- DUNE ND design concept near final
  - Active ND Design Group
  - ND Conceptual Design Report (CDR) planned for 2019
- DUNE ND design concept is an integrated system composed of multiple detectors:
  - Highly segmented LArTPC
  - Magnetized multi-purpose tracker
  - Electromagnetic calorimeter
  - Muon chambers
- Conceptual design will preserve option to move ND for off-axis measurements

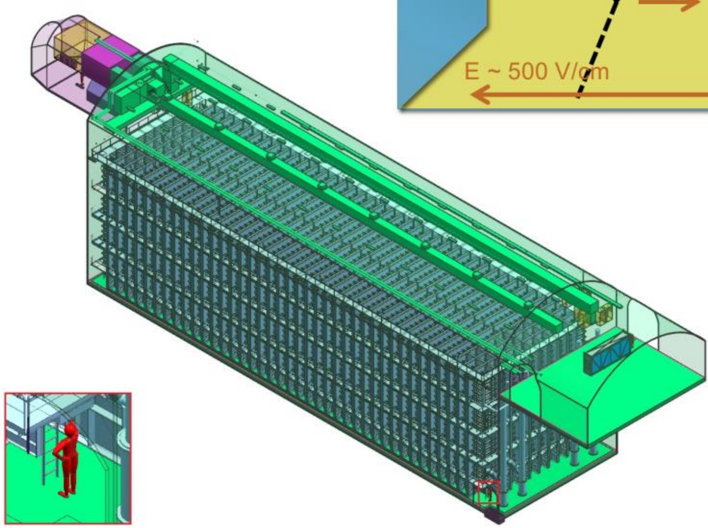


DUNE Far Detector

- 4 10-kt (fiducial) liquid argon TPC modules
- **Single-** and **dual**-phase detector designs (1st module will be single phase)
- Integrated photon detection
- Modules will not be identical

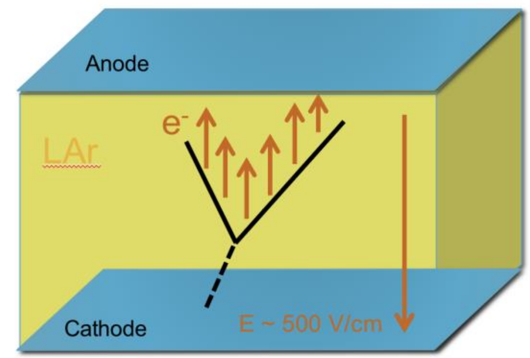
Single phase: modular wire-plane readout

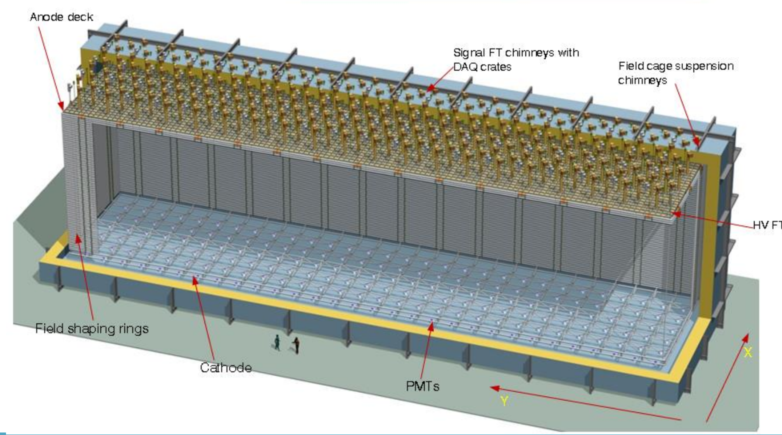




12 m high
15.5 m wide
58 m long

Dual phase: signal extracted; amplified in gas phase

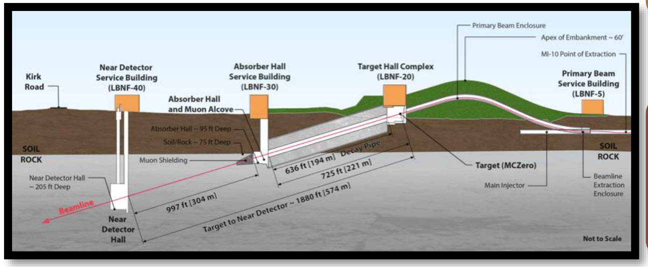




Timeline

Physics data as soon as 1st module complete

- Atmospheric νs
- SNB and solar νs
- Baryon number violation
- Detector calibration



2018: protoDUNEs at CERN

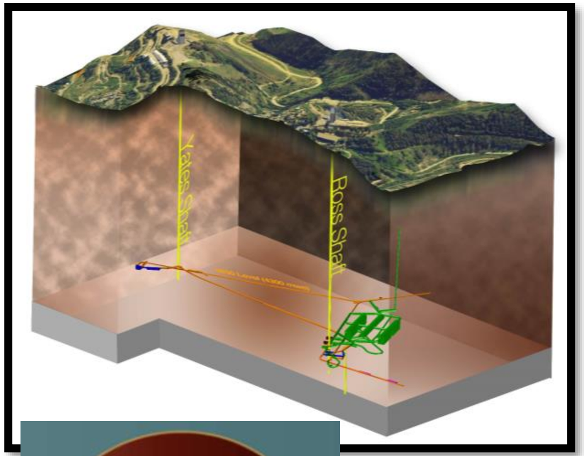
2019: Technical Design Report

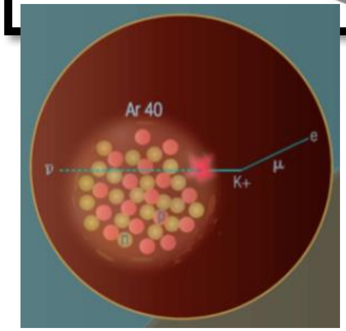
2019: Far Site Primary Excavation Begins

2022: First Module Installation Begins

2026: Neutrino Beam Available

DUNE Far Detector Interim Design Report (2018)
Will be made public soon…

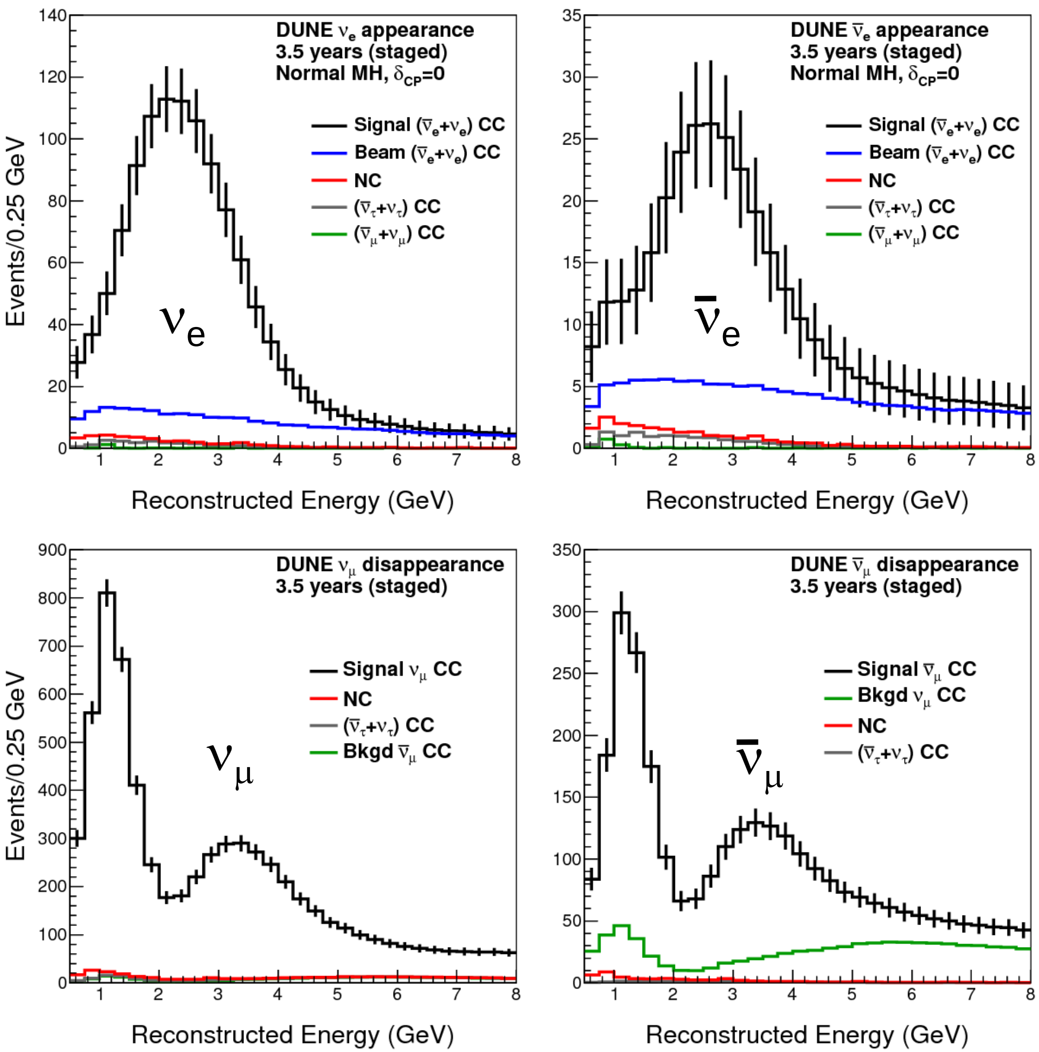




DUNE SCIENCE

Oscillation Sensitivity Calculations

DUNE Conceptual Design Report (CDR)
arXiv:1512.06148



- Reconstructed spectra based on GEANT4 beam simulation, GENIE event generator, and Fast MC using detector response parameterized at the single particle level
  - Efficiency tuned using hand scan results
- Order 1000 ν_e appearance events in ~7 years of equal running in neutrino and antineutrino mode
- Simultaneous fit to four spectra to extract oscillation parameters

DUNE CDR Systematics

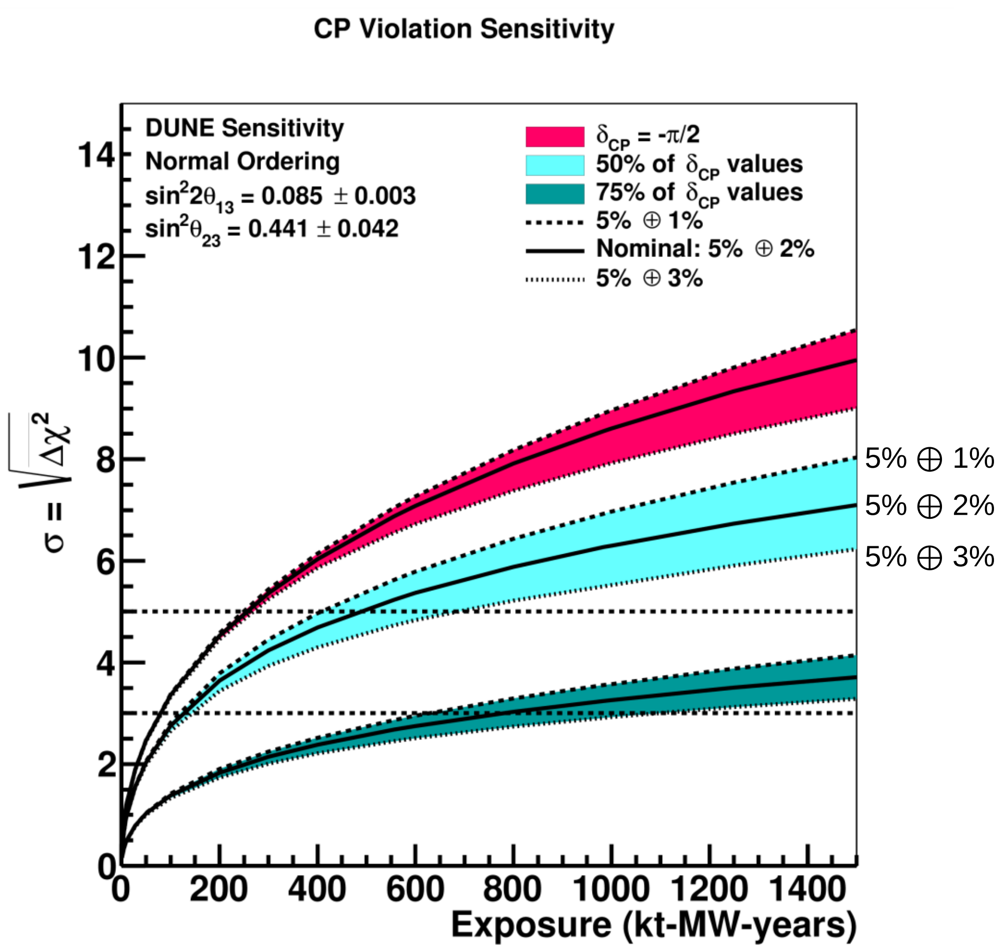
- Sensitivities in DUNE CDR are based on GLoBES calculations in which the effect of systematic uncertainty is approximated using signal and background normalization uncertainties.

Spectral uncertainty not included in this treatment.

- Signal normalization uncertainties are treated as *uncorrelated* among the modes (ν_e, $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$) and represent the **residual uncertainty** expected after constraints from the near detector and the four-sample fit are applied.
  - $\nu_\mu = \bar{\nu}_\mu = 5\%$ → Flux uncertainty after ND constraint
  - $\nu_e = \bar{\nu}_e = 2\%$ → Residual uncertainty after ν_μ and $\nu/\bar{\nu}$ constraint

- Oscillation parameter central values and uncertainties are taken from NuFit 2016 (arXiv:1611.01514). Parameters are allowed to vary constrained by 1/6 of the $\pm 3\sigma$ range in the global fit.

Effect of Normalization Uncertainty



Statistically limited for ~100 kt-MW-years.

Uncertainty in ν_e appearance sample normalization must be ~5% ⊕ 2% to discover CPV in a timely manner.

STRATEGY FOR CONSTRAINING SYSTEMATIC UNCERTAINTIES

- The uncertainty could be categorised into three groups.
  - Flux - will be constrained using near detector and external data
  - Detector response - will be constrained using prototype detectors, SBN detectors, test beam experiments, near detector)
  - Interaction modelling (discussed here)

Strategy for Interaction Model

- Prospects for improved interaction models:
  - Improved models becoming available
  - Intermediate neutrino program measurements in LAr TPCs
- ND constraint:
  - High precision near detector designed to constrain cross-section and hadronization uncertainties, resolving many individual particles produced by resonance and DIS interactions
  - Argon nuclear targets in ND allows significant cancellation of cross section uncertainties common to near and far detectors
- FD constraint:
  - Four FD samples allow cancellation of uncertainties that are correlated between ν_e/ν_μ or $\nu/\bar{\nu}$

Improving Interaction Models

- Worldwide effort that will benefit DUNE!
- Alternative models being implemented in GENIE include:
  - Long- and short-range correlations among nucleons
  - Effect of random phase approximations
  - Meson exchange currents
  - Effective spectral functions
  - Coherent pion production
  - Updated PDFs for DIS interactions
- Variation of tunable parameters within existing models
- Comparisons among generators
- Neutrino interaction data available or coming soon from:
  - ArgoNeuT, MINERvA, NOvA-ND, T2K-ND280, μBooNE, SBND, ICARUS, …
- Electron-argon scattering data coming from JLab

DUNE Monte Carlo Generator

- In the DUNE CDR neutrino interactions were simulated using GENIE 2.8.4.

- The newest Monte Carlo production uses GENIE 2.12.8
  - configuration DefaultPlusMECWithNC (https://cdcvs.fnal.gov/redmine/projects/nutools/wiki/GENIE_Configuration_Files)
  - This is rather “old” configuration with Rein-Sehgal models for pion production interactions and experimental MEC model (by S. Dytman)

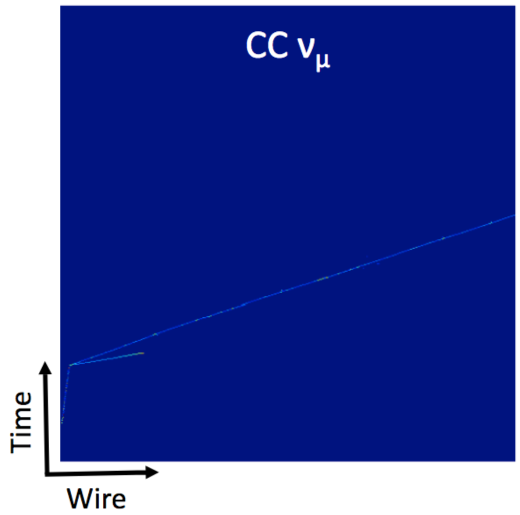
- Dune collaboration is now in the process of defining modern GENIE configuration/tune.
  - I will report opinions from this workshop to the working group.
  - The new configuration will be used for the Technical Design Report (2019).

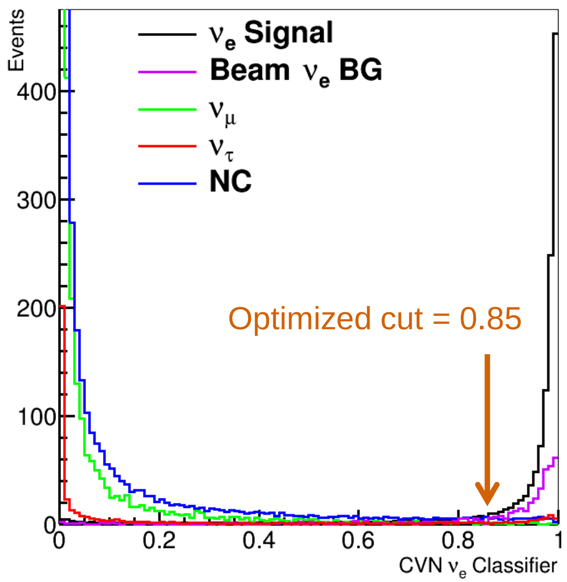
Monte Carlo Analysis (New!)

- GEANT4 beam simulation of updated 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 signal processing and hit finding
- Automated energy reconstruction
  - Muon momentum from range (contained) or multiple Coulomb scattering (exiting)
  - Electron and hadron energy from calorimetry
- Event selection using convolutional visual network (CVN)
- Oscillation analysis using CAFAna fitting framework
  - Shared framework with NOvA
- CDR-style systematics analysis (update coming in 2019)
- Results shown here are for single phase; dual phase analysis in progress

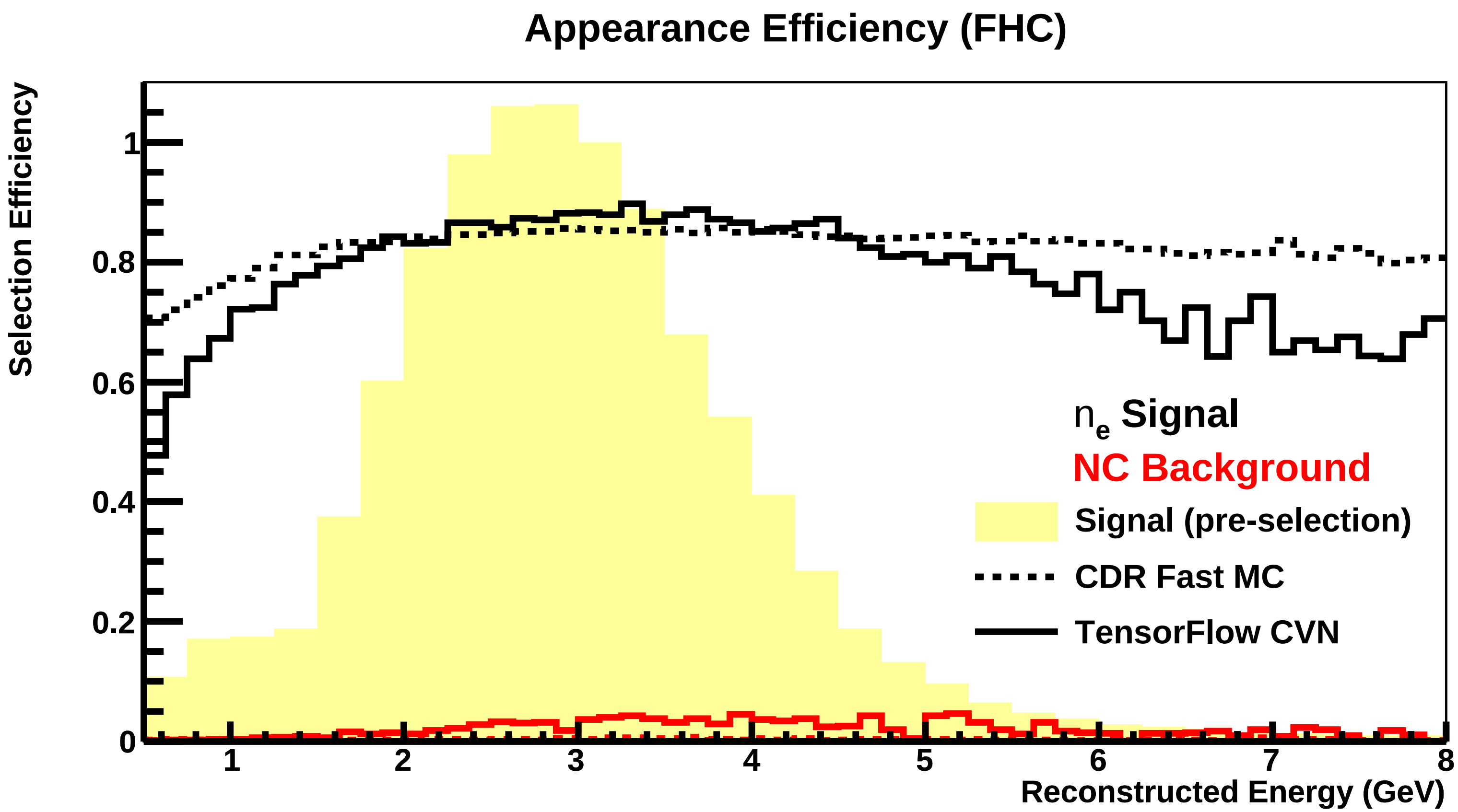
CVN Event Selection

- ResNet architecture implemented in TensorFlow (arXiv:1605.07678)
- Training performed on sets of 500 x 500 DUNE MC images
- DUNE MC images classified into categories
  - ν_eCC, ν_μCC, ν_τCC, NC
- Event selection performed by applying cuts on ν_eCC-like and ν_μCC-like CVN classifiers
  - ν_eCC-like cut chosen by optimizing CPV sensitivity





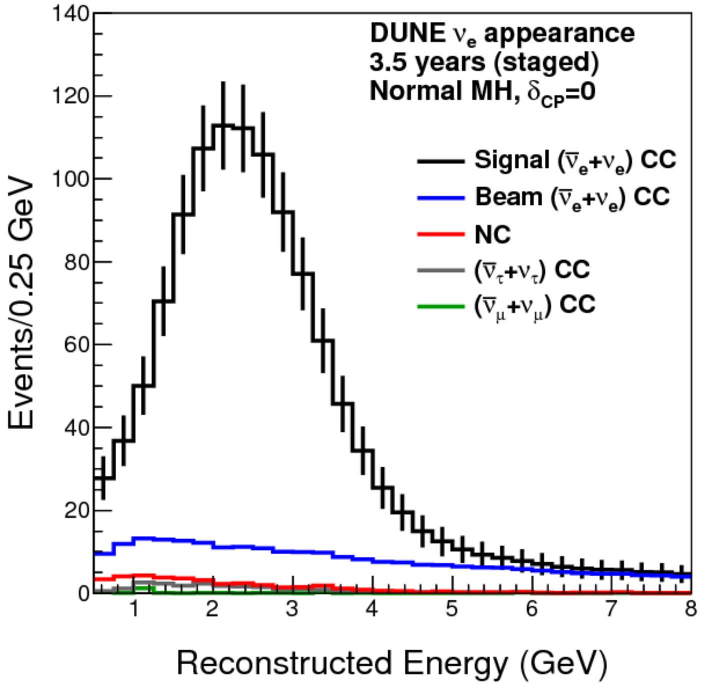
Selection Efficiency



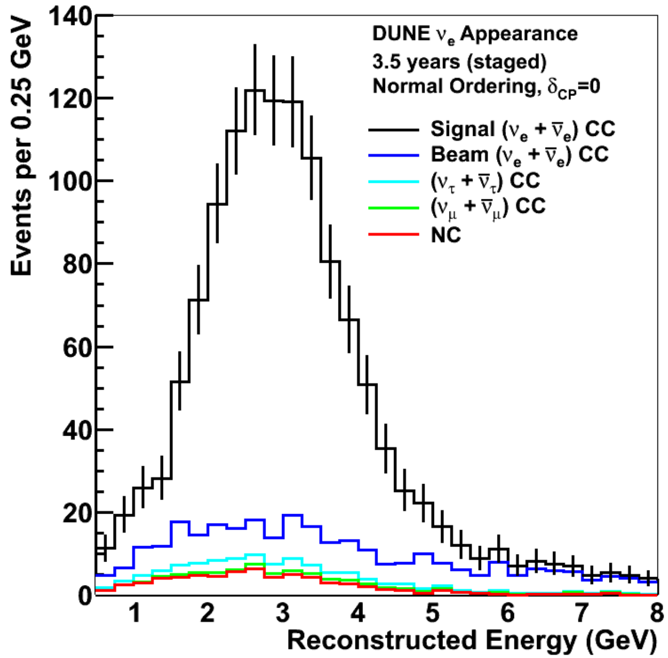
CVN ν_e event selection efficiency similar to that from CDR Fast MC

Monte Carlo Analysis Results

CDR



New!

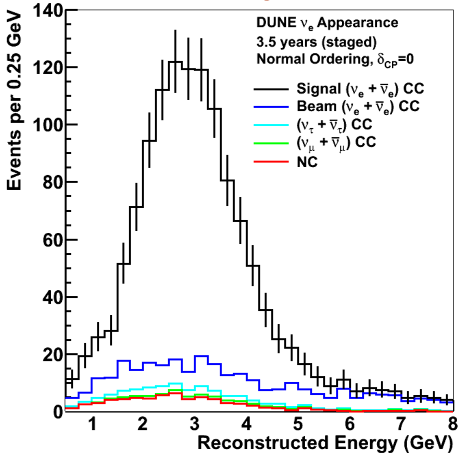


Good agreement between CDR and New MC-based analysis

Full update of sensitivity plots with detailed systematics planned for TDR in 2019

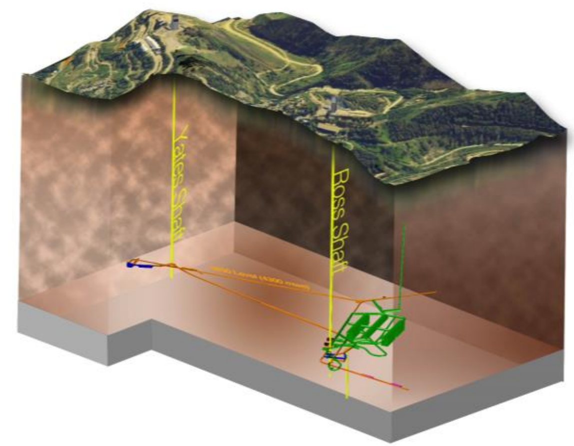
Summary

New Analysis



protoDUNE

Coming Soon…

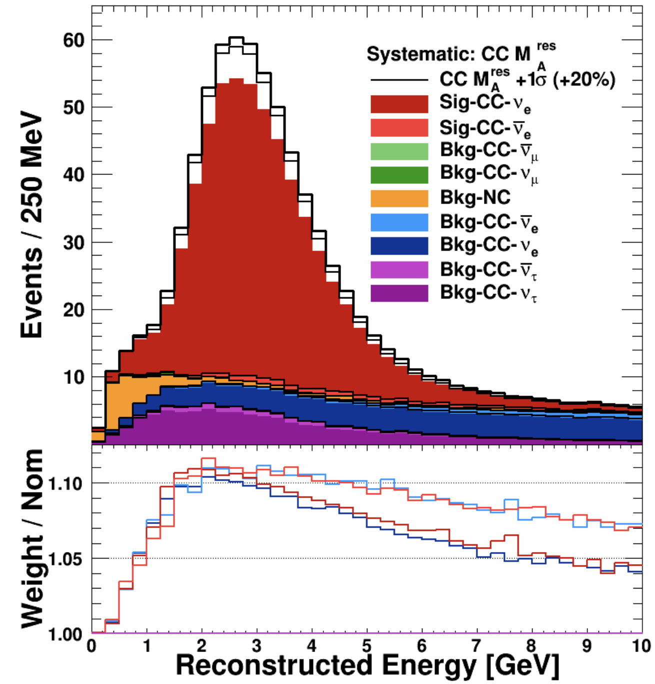


- LBNF and DUNE making rapid progress on facility construction, detector design, and physics analysis
- New MC-based analysis is ready for sensitivity studies.
- The neutrino interactions modeling in DUNE MC will be updated for the Technical Design Report in 2019!
- Expect first DUNE FD data in ~2024…

Extra Slides

Fast MC/MGT Details

- Fast MC = Flux simulations + GENIE + parameterized detector response
- Detector response parameterization based on inputs from LArSoft simulations, GEANT4, and ICARUS
- Reconstructed quantities and selection criteria based on realistic kinematics
- MGT fitter includes statistical limitations on constraints from four-sample fit and uncertainty in sample-sample correlation



Single particle detector response.
Many values quite conservative.

Particle type	Detection Threshold (KE)	Energy/Momentum Resolution	Angular Resolution
$\mu^{\pm}$	30 MeV	Contained track: track length Exiting track: 30%	1°
$\pi^{\pm}$	100 MeV	μ-like contained track: track length π-like contained track: 5% Showering or exiting: 30%	1°
$e^{\pm}/\gamma$	30 MeV	$2\% \oplus 15\%/\sqrt{E}$[GeV]	1°
p	50 MeV	p<400 MeV/c: 10% p>400 MeV/c: $5\% \oplus 30\%/\sqrt{E}$[GeV]	5°
n	50 MeV	$40\%/\sqrt{E}$[GeV]	5°
other	50 MeV	$5\% \oplus 30\%/\sqrt{E}$[GeV]	5°

Example: ν_e appearance spectrum showing variation that is induced by changing the value of M_A^{RES} by +1σ in the simulation.

DUNE CDR

Normalization uncertainties

- Estimate uncertainties after ND and external data constraints
- Understand advantages of LArTPC, and cancellations in FD 4-sample fits
- Consider experience from T2K and MINOS
  - MINOS similarities
    - Flux shape, ν energies
    - Longer baseline
    - Similar cross sections
  - T2K similarities
    - Different near and far detector technologies
    - Similar analysis strategies
- Strategies to address required increase in precision

Source of Uncertainty	MINOS ν_e	T2K ν_e	DUNE ν_e
Beam Flux after N/F extrapolation	0.3%	3.2%	2%
Interaction Model	2.7%	5.3%	$\sim 2\%$
Energy scale (ν_μ)	3.5%	included above	(2%)
Energy scale (ν_e)	2.7%	2.5% includes all FD effects	2%
Fiducial volume	2.4%	1%	1%
Total	5.7%	6.8%	3.6 %
Used in DUNE Sensitivity Calculations			$5\% \oplus 2\%$

Background Uncertainties

Table 3.9: Normalization uncertainties and correlations for background to the ν_e, $\bar{\nu}_e$, ν_μ, and $\bar{\nu}_\mu$ data samples

Background	Normalization Uncertainty	Correlations
For $\nu_e/\bar{\nu}_e$ appearance:		
Beam ν_e	5%	Uncorrelated in ν_e and $\bar{\nu}_e$ samples
NC	5%	Correlated in ν_e and $\bar{\nu}_e$ samples
ν_μ CC	5%	Correlated to NC
ν_τ CC	20%	Correlated in ν_e and $\bar{\nu}_e$ samples
For $\nu_\mu/\bar{\nu}_\mu$ disappearance:		
NC	5%	Uncorrelated to $\nu_e/\bar{\nu}_e$ NC background
ν_τ	20%	Correlated to $\nu_e/\bar{\nu}_e$ ν_τ background

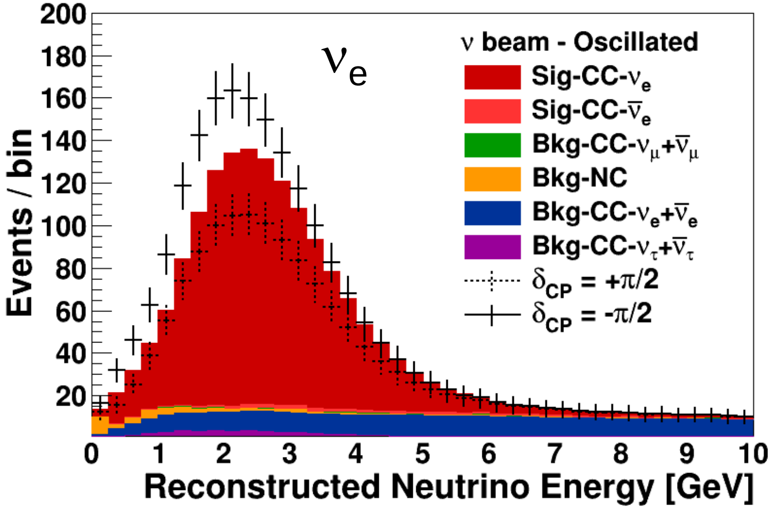
The DUNE Experimental Setup

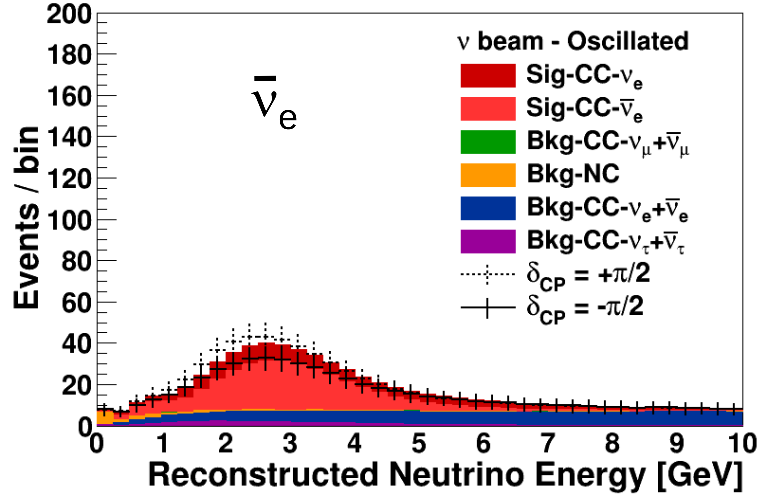
	CDR Reference Design	Optimized Design
ν mode (150 kt · MW · year)		
ν_e Signal NH (IH)	861 (495)	945 (521)
$\bar{\nu}_e$ Signal NH (IH)	13 (26)	10 (22)
Total Signal NH (IH)	874 (521)	955 (543)
Beam $\nu_e + \bar{\nu}_e$ CC Bkgd	159	204
NC Bkgd	22	17
$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd	42	19
$\nu_\mu + \bar{\nu}_\mu$ CC Bkgd	3	3
Total Bkgd	226	243
$\bar{\nu}$ mode (150 kt · MW · year)		
ν_e Signal NH (IH)	61 (37)	47 (28)
$\bar{\nu}_e$ Signal NH (IH)	167 (378)	168 (436)
Total Signal NH (IH)	228 (415)	215 (464)
Beam $\nu_e + \bar{\nu}_e$ CC Bkgd	89	105
NC Bkgd	12	9
$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd	23	11
$\nu_\mu + \bar{\nu}_\mu$ CC Bkgd	2	2
Total Bkgd	126	127

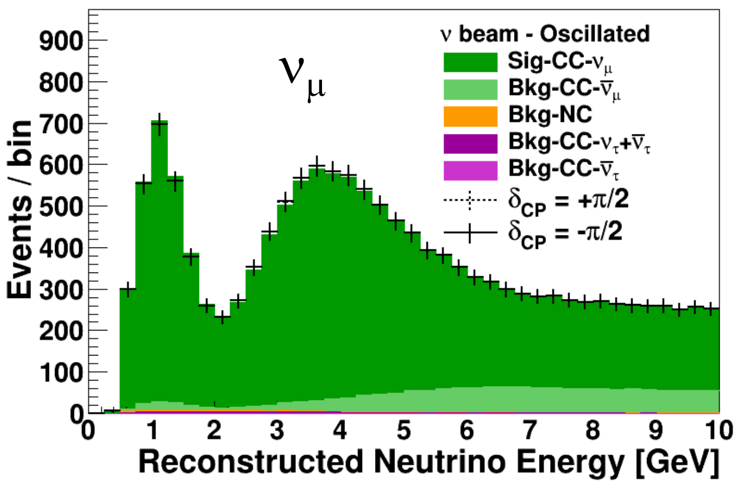
neutrinos

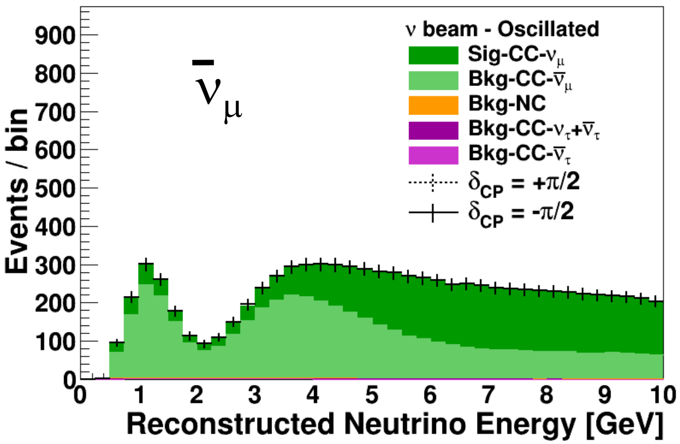
antineutrinos

Expected FD Spectra

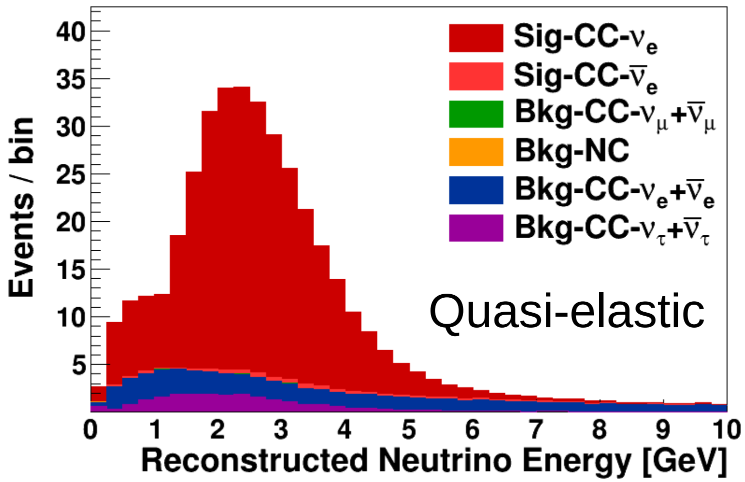


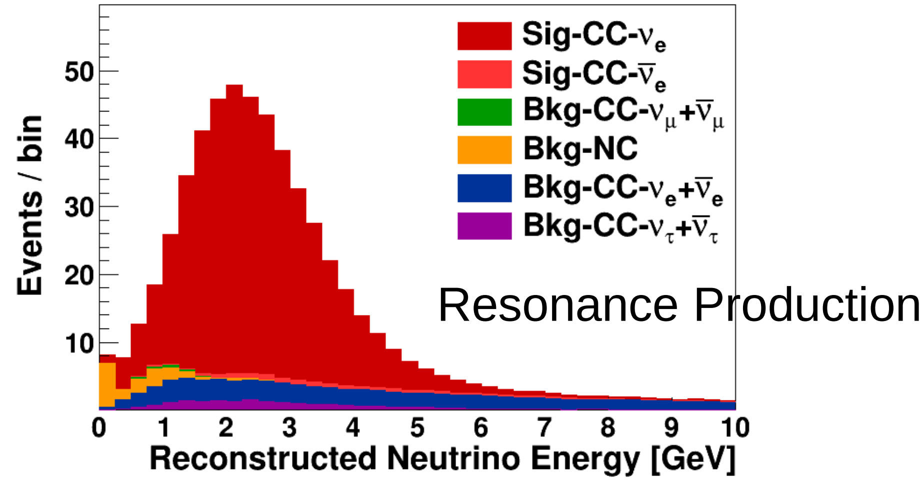


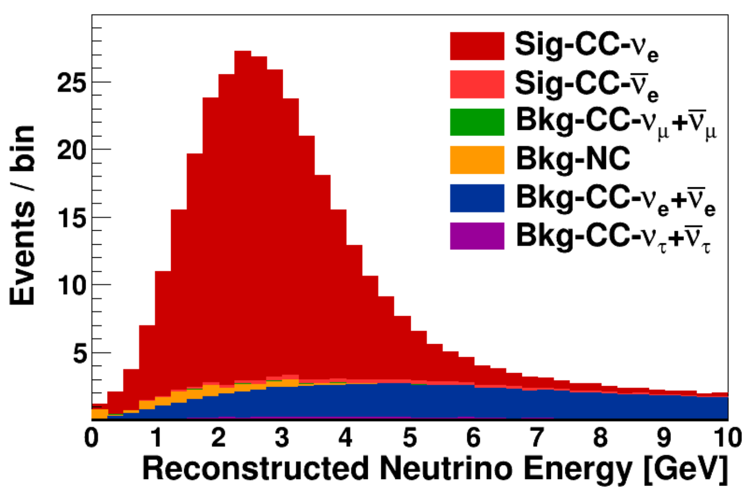




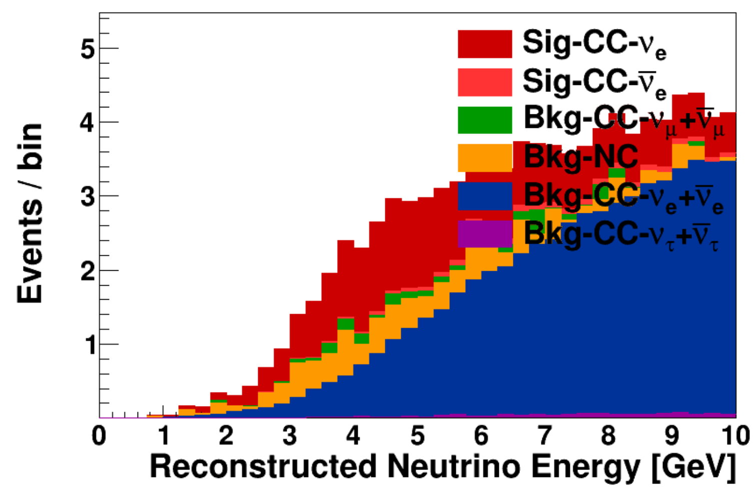
Spectra By Cross Section Model







DIS (W < 2.7 GeV)

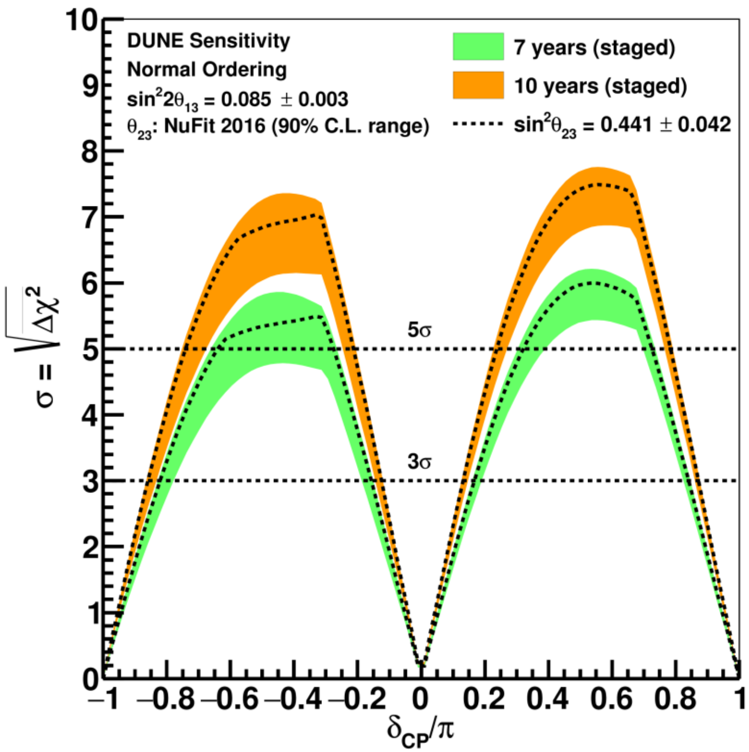


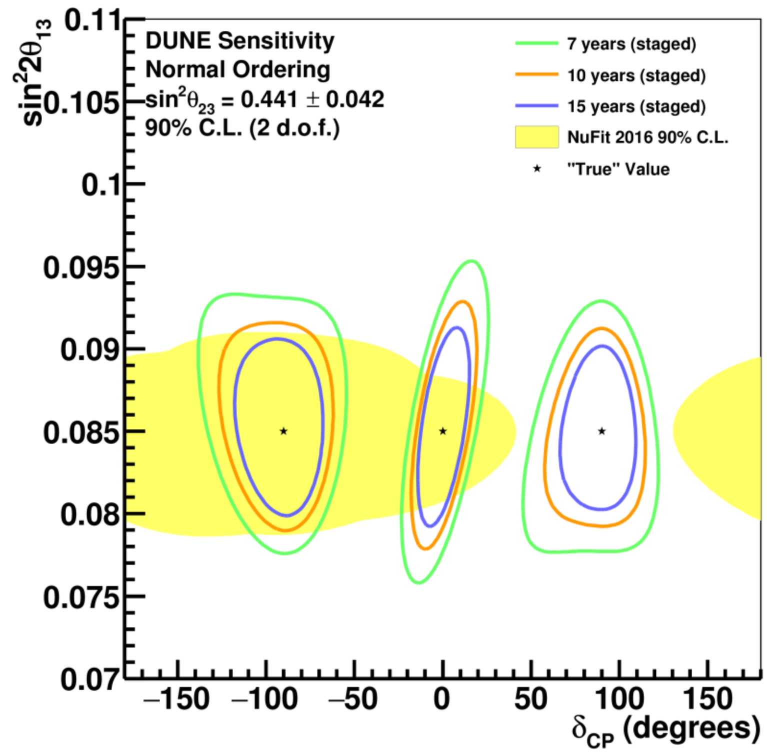
DIS (W > 2.7 GeV)

CP Violation Sensitivity

DUNE CDR:

CP Violation





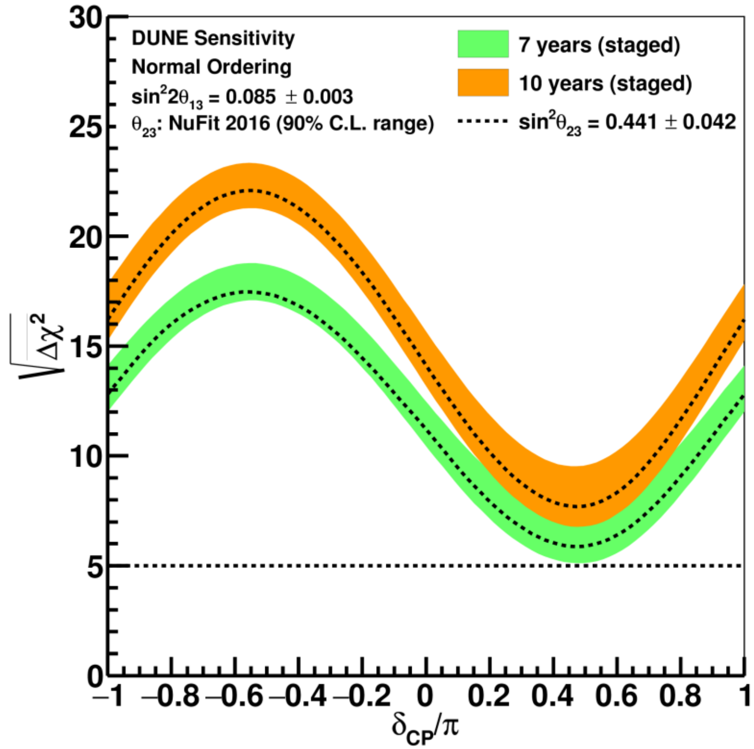
Width of band indicates variation in possible central values of θ_{23}

Simultaneous measurement of neutrino mixing angles and δ_{CP}

Other Oscillation Physics

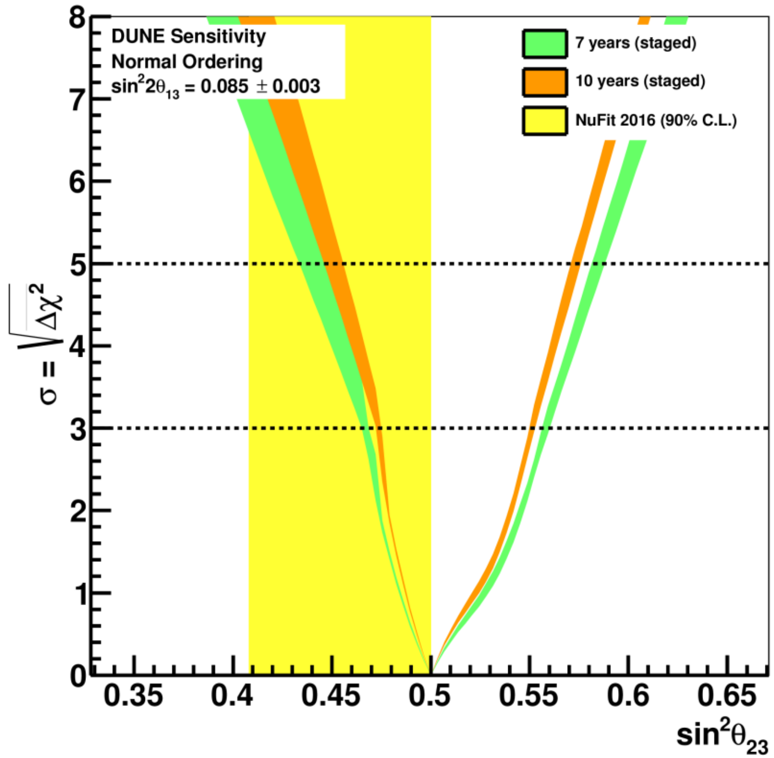
DUNE CDR:

Mass Ordering



Width of band indicates variation in possible central values of θ_{23}

Octant

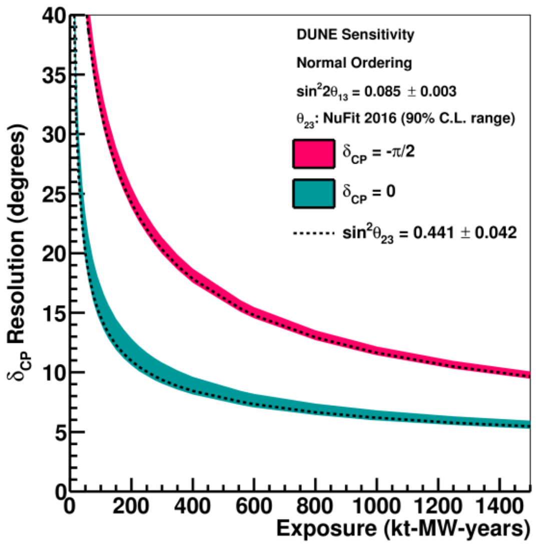


Width of band indicates variation in possible true value of δ_{CP}

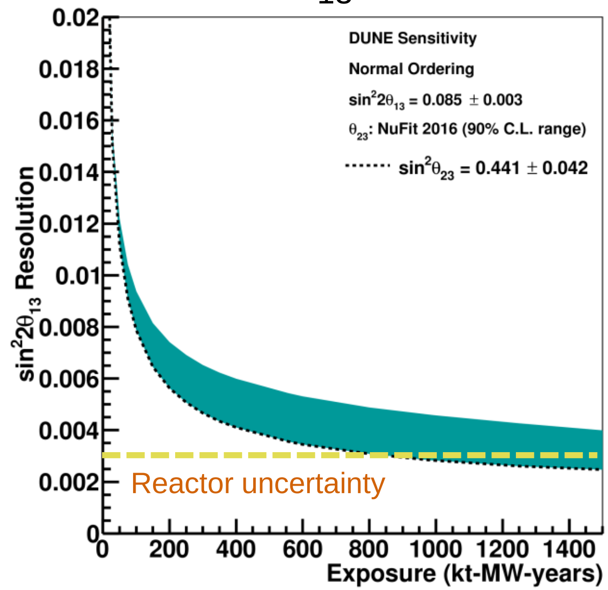
Oscillation Parameter Sensitivity

DUNE CDR:

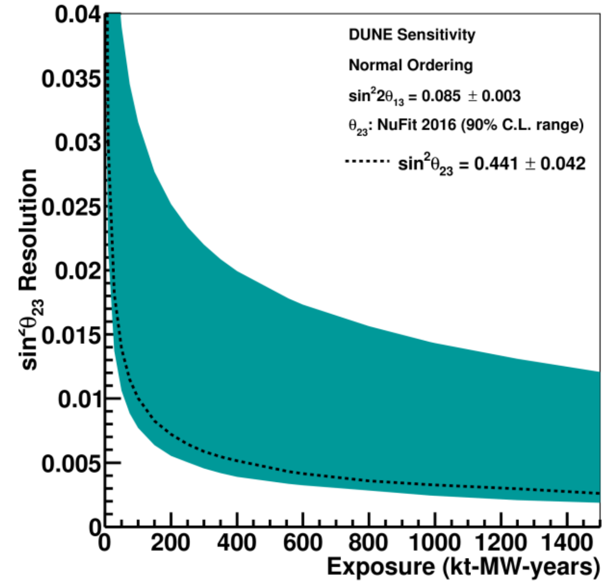
δ_{CP} Resolution



$\sin^2 2\theta_{13}$ Resolution



$\sin^2\theta_{23}$ Resolution



Staging Assumptions

- Year 1 (2026): 20-kt FD with 1.07 MW (80-GeV) beam and initial ND constraints
- Year 2 (2027): 30-kt FD
- Year 4 (2029): 40-kt FD and improved ND constraints
- Year 7 (2032): upgrade to 2.14 MW (80-GeV) beam (technically limited schedule)

Exposure (kt-MW-years)	Exposure (Years)
171	5
300	7
556	10
984	15

NuFit 2016

NuFIT 3.0 (2016)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 0.83$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.271 \to 0.345$
$\theta_{12}/^\circ$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$31.38 \to 35.99$
$\sin^2\theta_{23}$	$0.441^{+0.027}_{-0.021}$	$0.385 \to 0.635$	$0.587^{+0.020}_{-0.024}$	$0.393 \to 0.640$	$0.385 \to 0.638$
$\theta_{23}/^\circ$	$41.6^{+1.5}_{-1.2}$	$38.4 \to 52.8$	$50.0^{+1.1}_{-1.4}$	$38.8 \to 53.1$	$38.4 \to 53.0$
$\sin^2\theta_{13}$	$0.02166^{+0.00075}_{-0.00075}$	$0.01934 \to 0.02392$	$0.02179^{+0.00076}_{-0.00076}$	$0.01953 \to 0.02408$	$0.01934 \to 0.02397$
$\theta_{13}/^\circ$	$8.46^{+0.15}_{-0.15}$	$7.99 \to 8.90$	$8.49^{+0.15}_{-0.15}$	$8.03 \to 8.93$	$7.99 \to 8.91$
$\delta_{CP}/^\circ$	261^{+51}_{-59}	$0 \to 360$	277^{+40}_{-46}	$145 \to 391$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.03 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.524^{+0.039}_{-0.040}$	$+2.407 \to +2.643$	$-2.514^{+0.038}_{-0.041}$	$-2.635 \to -2.399$	$\begin{bmatrix} +2.407 \to +2.643 \\ -2.629 \to -2.405 \end{bmatrix}$

For 1σ uncertainty in DUNE sensitivity calculations, we take 1/6 of the ±3σ range, to account for non-Gaussian PDFs in NuFit.

DUNE Systematics: TDR

- Systematics analysis building on expertise developed in MINERvA, T2K, and NOvA
  - “DUNEResponse” ← “T2KReweight”
- CAFAna fitting framework facilitates more sophisticated treatment of systematic uncertainty than was possible for CDR
  - Systematic uncertainties in TDR will be based on detailed evaluation of flux, neutrino interaction, and detector uncertainties
  - Sensitivity calculations will be based on fits combining information from near and far detectors
- Flux and interaction systematics evaluated using reweighting technique (including GENIE and non-GENIE reweights)
  - Impact of systematic variations propagated through full analysis chain
  - Ability to consider systematics impacting kinematic distributions as well as normalization
- Detector systematics evaluated within the fit
  - Detector calibration task force evaluating magnitude and sources of detector uncertainty