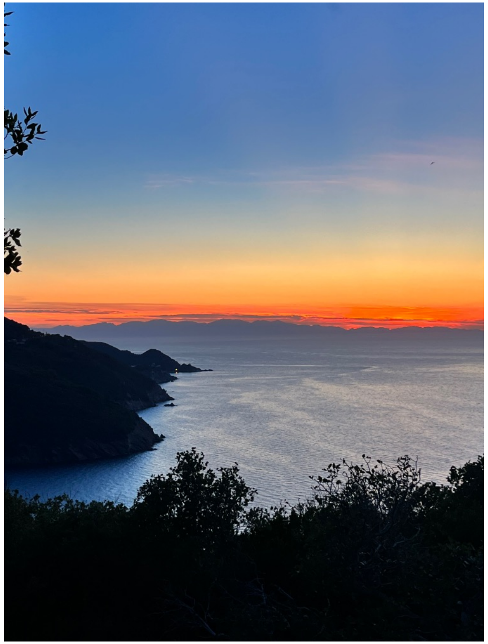
Brookhaven National Lab/Stony Brook University
SBND, ICARUS, and DUNE collaborations
She/her



DUNE Status and Science

Importance of neutrino interactions

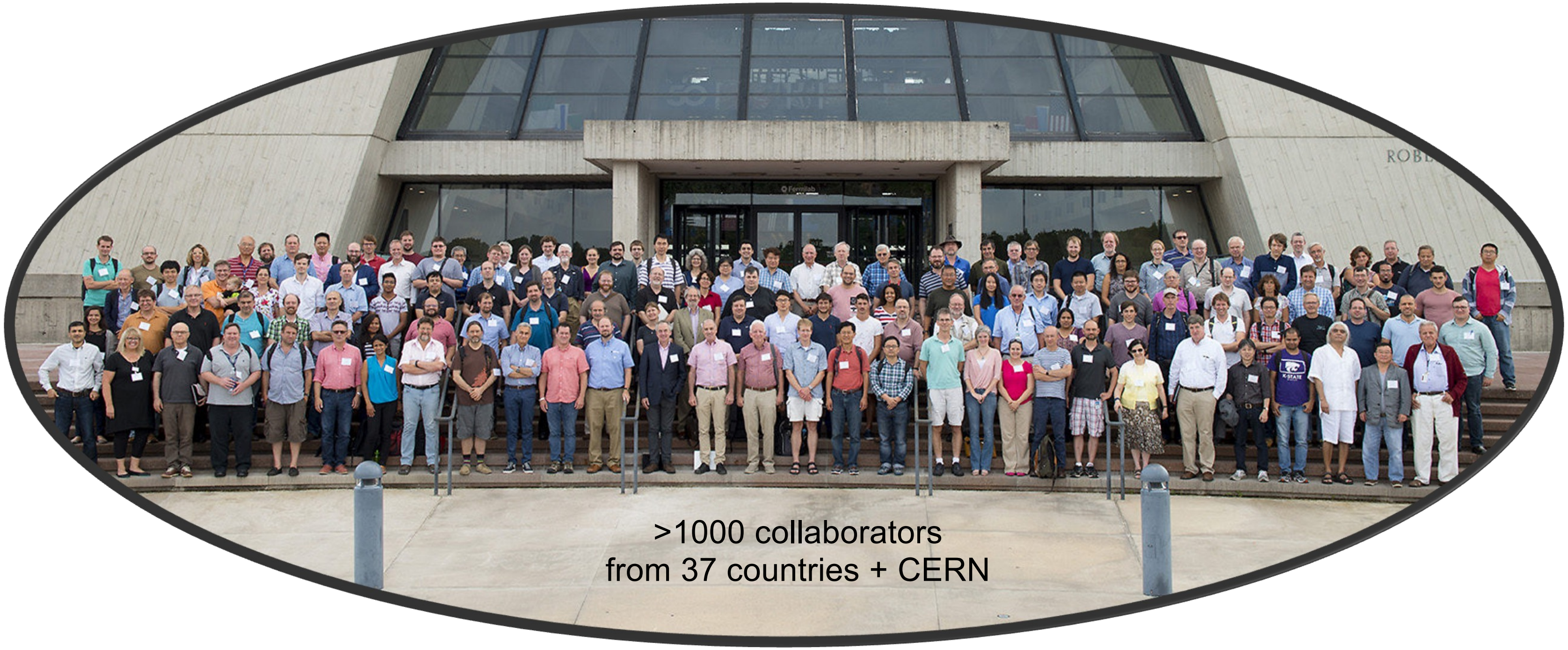
Elizabeth Worcester, for the DUNE collaboration

Marciana 2023 – Lepton Interactions with Nucleons and Nuclei

September 7, 2023

Deep Underground Neutrino Experiment (DUNE)

Measure ν_e appearance and ν_μ disappearance in a wideband neutrino beam at 1300 km to measure MO, CPV, and neutrino mixing parameters in a single experiment. Large detector, deep underground provides sensitivity to low energy neutrinos (supernova, solar) and baryon number violating processes.



>1000 collaborators
from 37 countries + CERN

Neutrino Mixing and Oscillation

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}\text{PMNS matrix}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

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

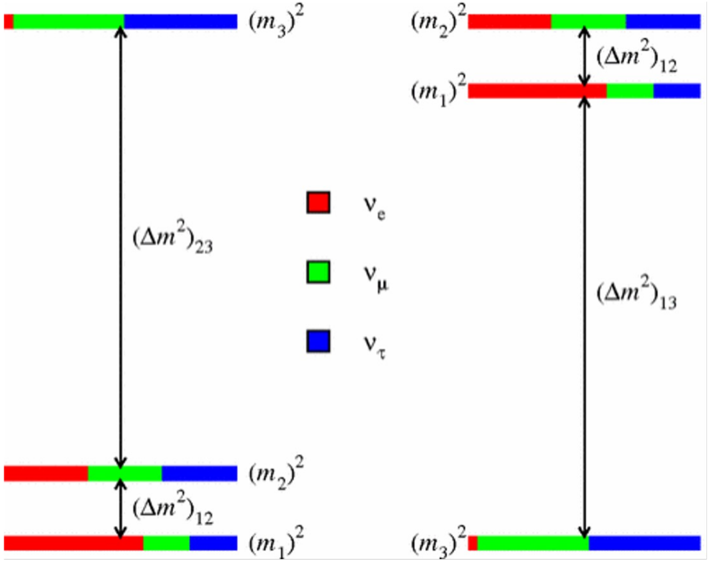
$\theta_{23} \approx 45^\circ$ $\theta_{13} \approx 9^\circ$ $\theta_{12} \approx 33^\circ$

$\delta_{CP} = ?$

Most parameters currently measured to ~3%

Open questions:

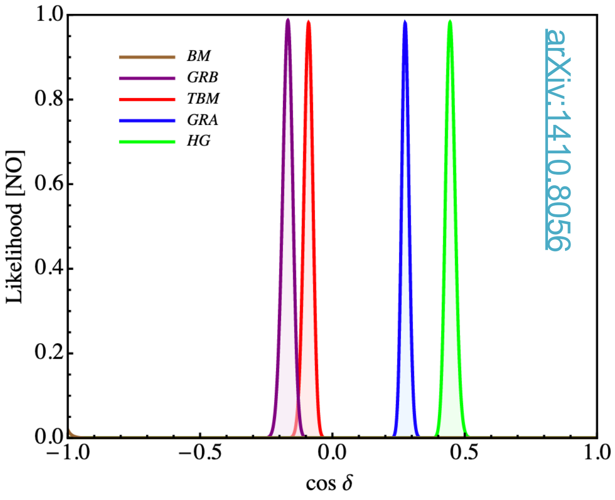
- Mass ordering ($\Delta m^2_{32} > 0$?)
- Octant ($\sin^2\theta_{23} = 0.5$?)
- CP violation ($\delta_{CP} \neq 0, \pi$?)
- PMNS unitary?



Normal Ordering Inverted Ordering

What Can We Discover with LBL Oscillations?

- LBL oscillation sensitive to θ_{13}, θ_{23}, Δm^2_{32}, δ_{CP}
- CP Violation
  - Symmetry and symmetry violation has been a major driver of discovery in particle physics
  - Leptogenesis requires CPV in high-energy Lagrangian (incl. right-handed neutrinos)
    - No model-independent connection between low-energy (PMNS) CPV and high-energy CPV required for leptogenesis
- Flavor structure
  - Why is the structure of the ν mixing matrix different from that of the quark mixing matrix
  - What flavor symmetry can produce this pattern of mixing and how is it broken?
  - Is $\nu_\mu \leftrightarrow \nu_\tau$ mixing symmetric? If so, why?
- Model discrimination
  - Many flavor and BSM models make specific predictions for values of oscillation parameters

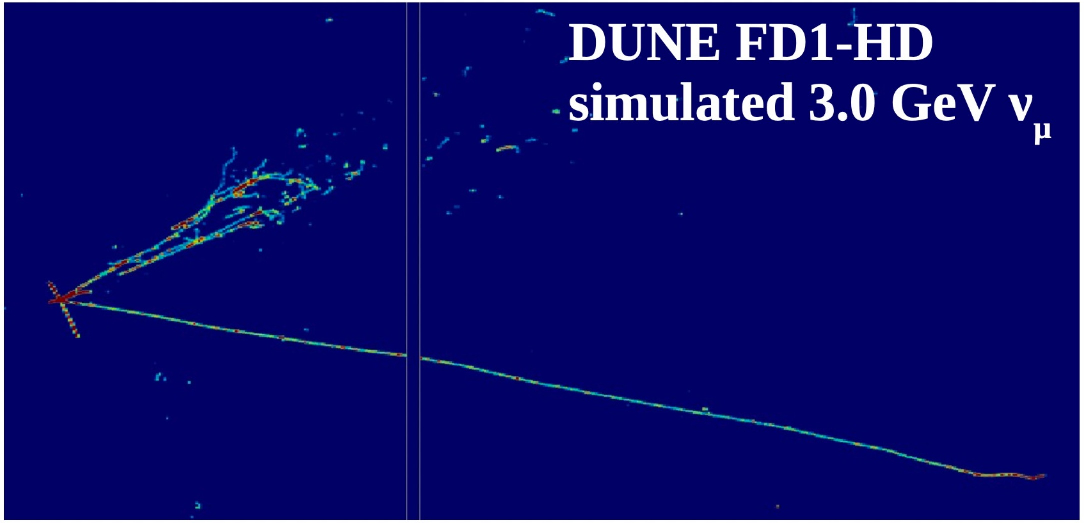


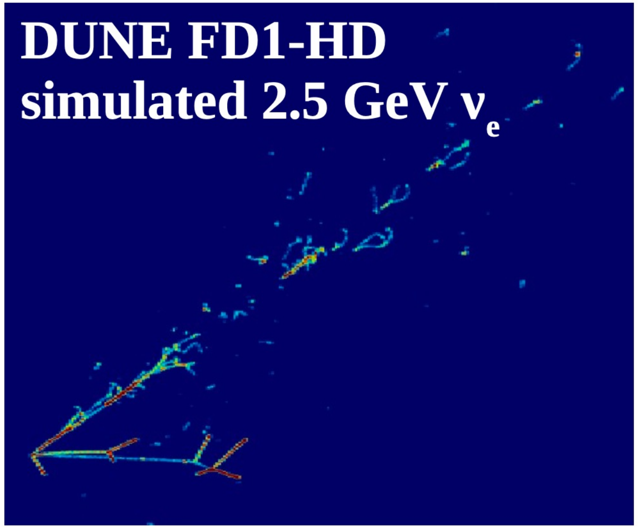
arXiv:1410.8056

- BSM physics in neutrino oscillation (additional particles or interactions)

LArTPC Detectors

- Detailed images of final state particle trajectories
- Clean separation of ν_μ and ν_e interactions
- Good energy reconstruction over broad energy range
- Low threshold (few MeV)





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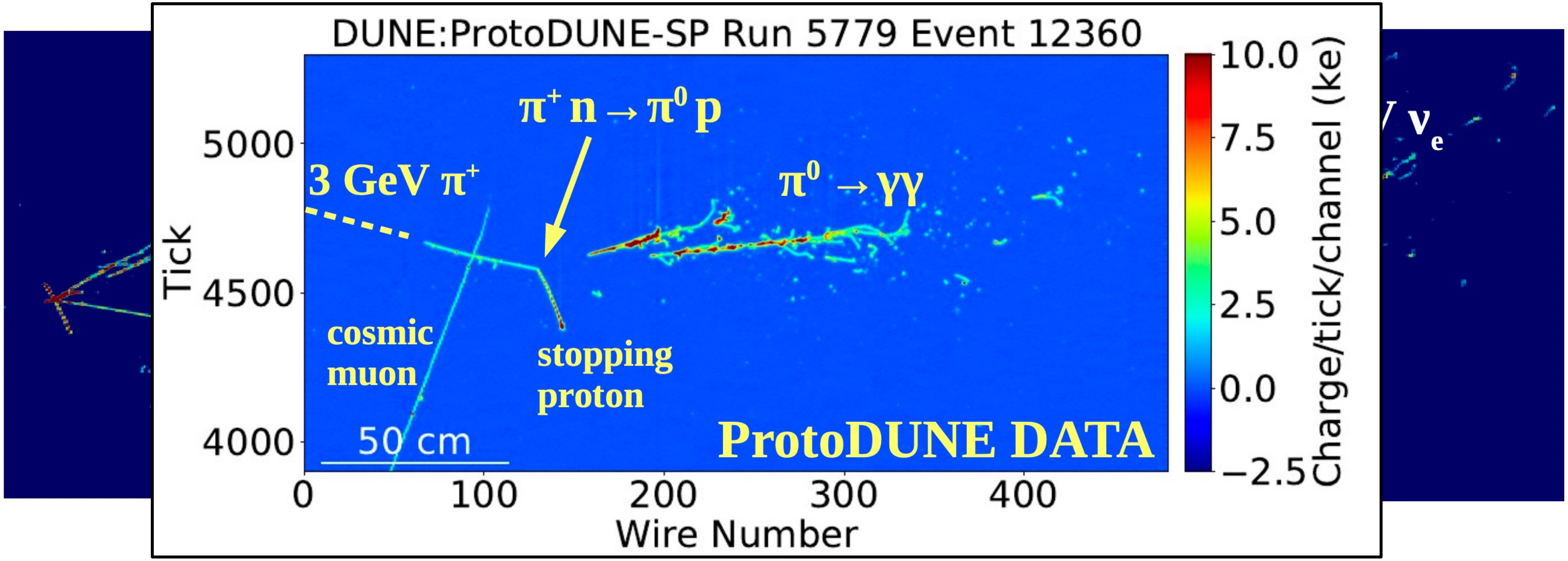
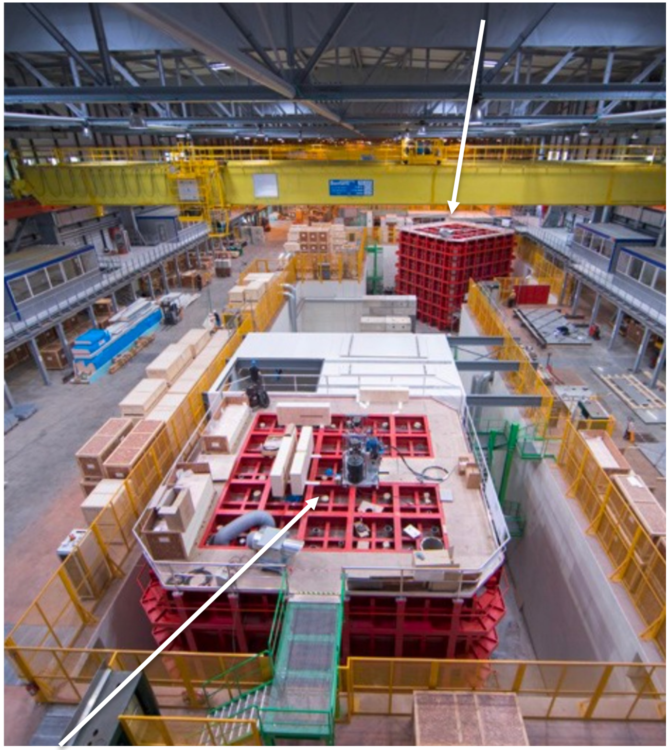


ProtoDUNE

- ProtoDUNE ran from 2018-2020 at CERN
  - Full-scale DUNE components
  - Successful long-term operation
  - Data taken in charged test beam and with cosmic rays analyzed to evaluate detector performance and for physics measurements
- 2nd ProtoDUNE run in 2024 will validate final DUNE detector components for first two far detector modules

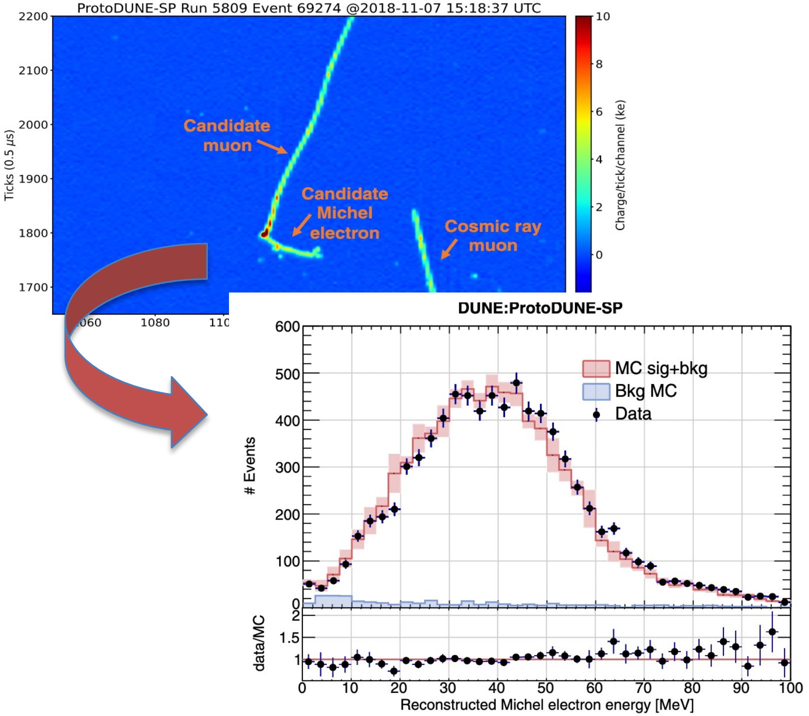
protoDUNE-DP



protoDUNE-SP

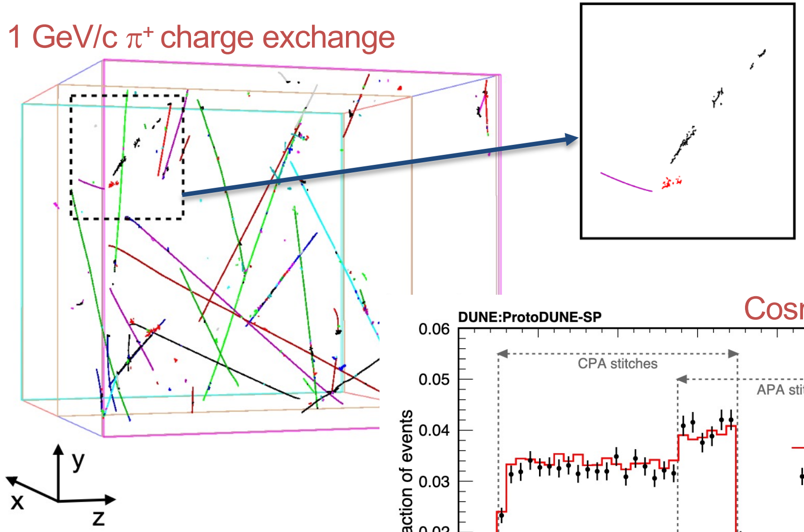
New ProtoDUNE Results!

Identification and reconstruction of Michel electrons from stopping muons:
Phys. Rev. D 107, 092012 (2023)
arXiv:2211.01166

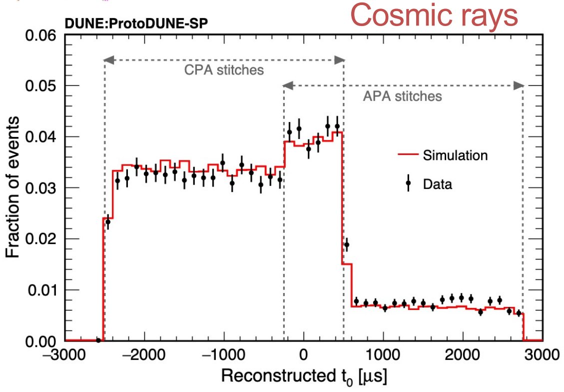


Pandora reconstruction performance for cosmic rays and beam particles:
Eur. Phys. J. C 83, 618 (2023)
arXiv:2206.14521

1 GeV/c π^+ charge exchange

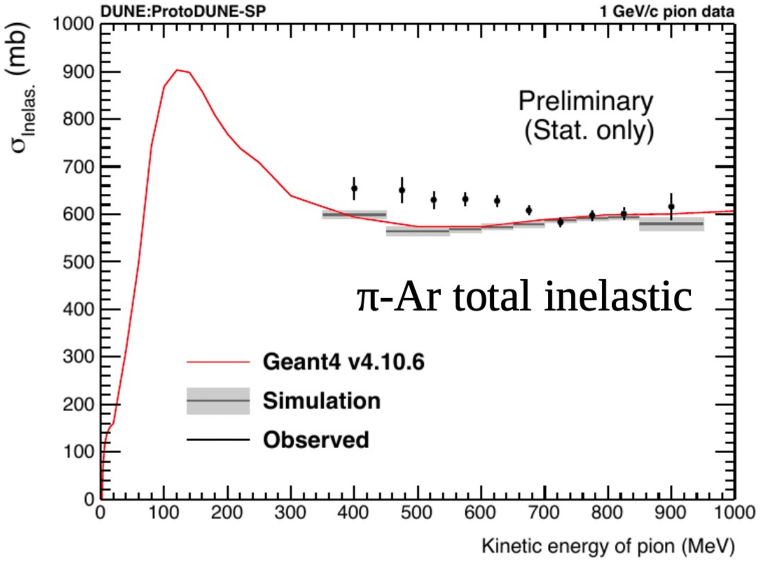


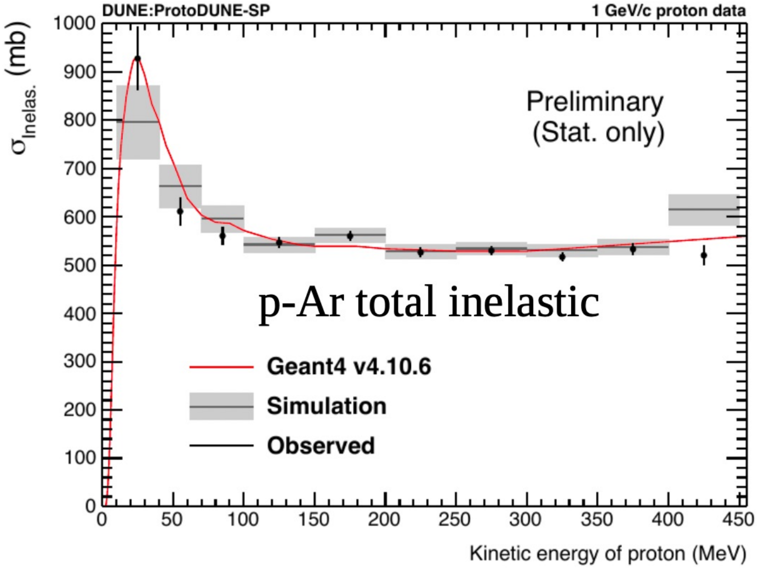
Cosmic rays



Upcoming ProtoDUNE Results

- Many hadron-argon cross section analyses in progress

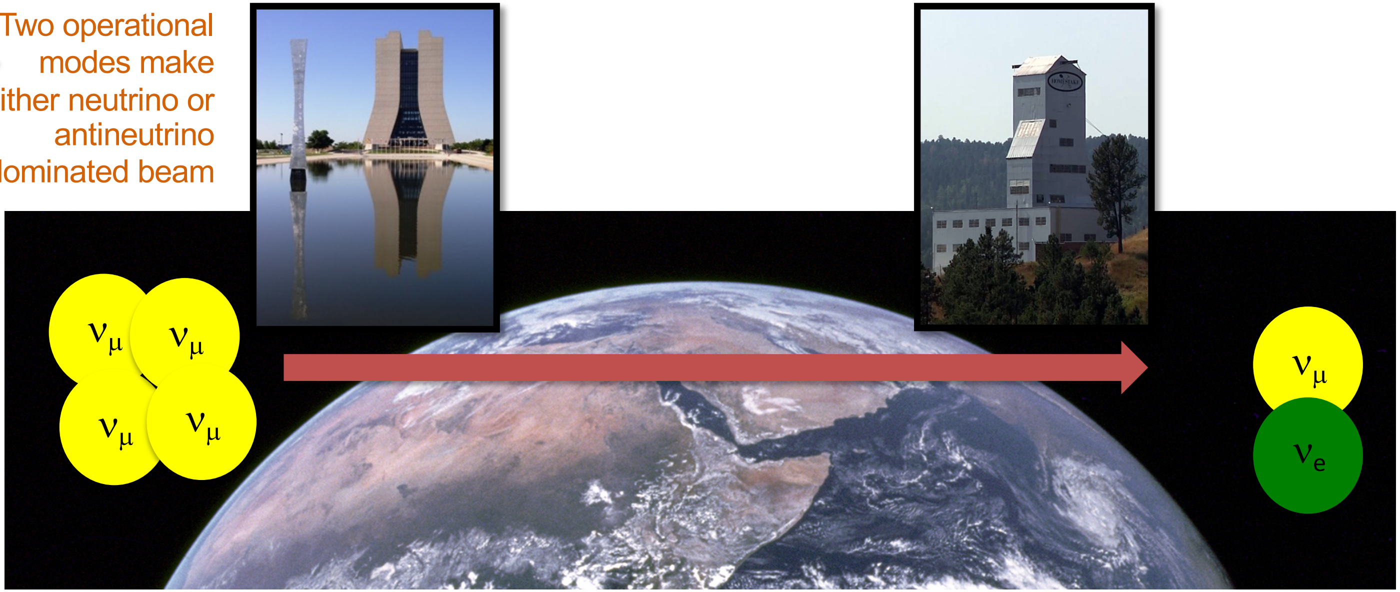




Sketch of Long-Baseline Oscillation Experiment

“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



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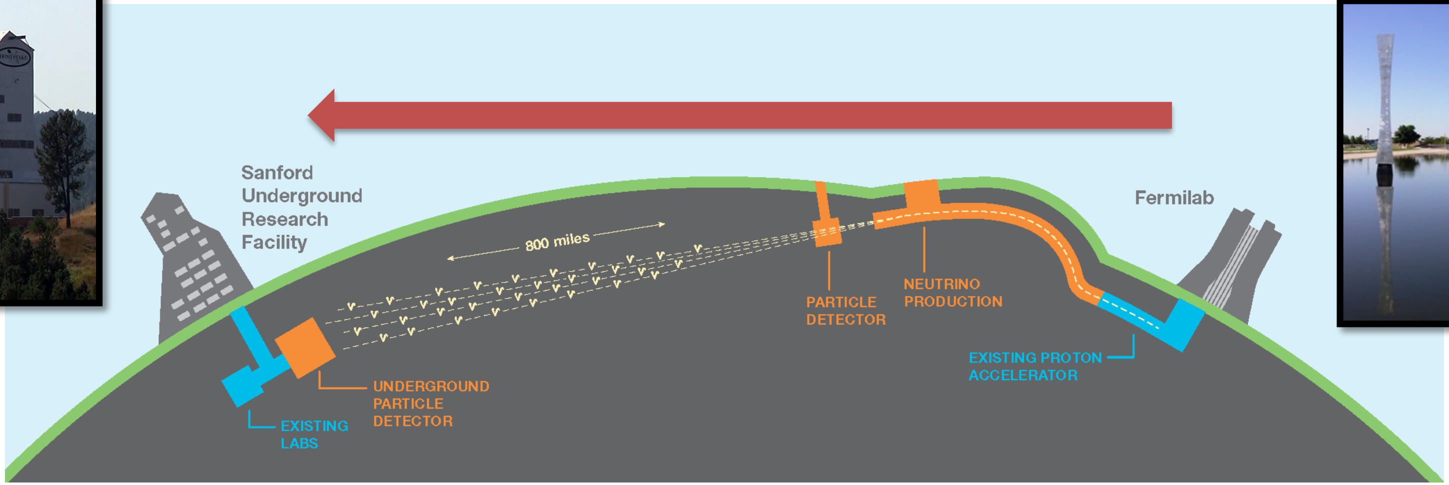
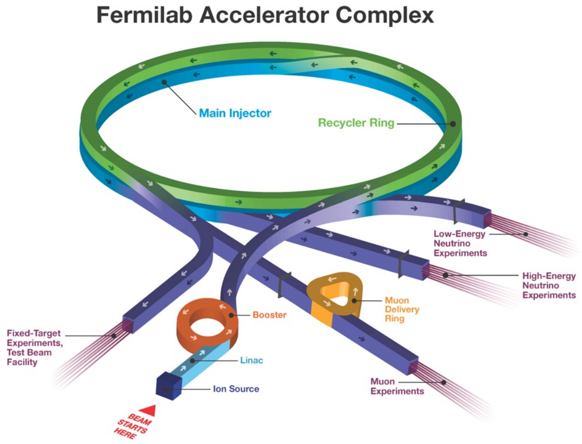


LBNF Neutrino Beam

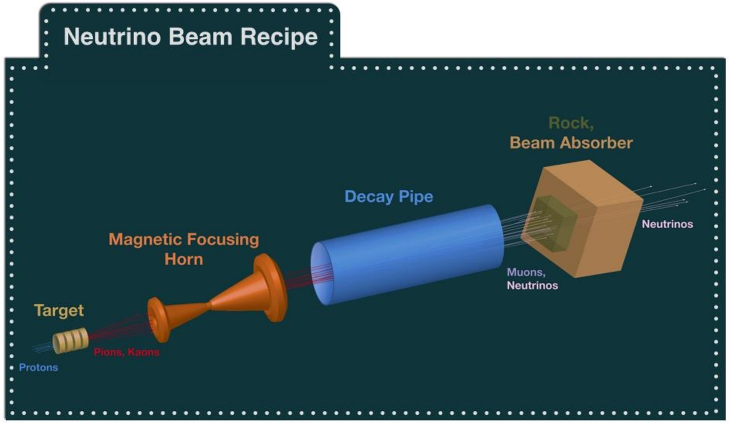
LBNF: Long Baseline Neutrino Facility
(beam, underground facilities, infrastructure)

- 120-GeV protons from FNAL accelerator complex
  - Up to 2 MW beam power in Phase I (PIP-II, ACE)
  - Booster replacement (increased power, reliability, protons for other projects) prior to Phase II
- Neutrino beam line designed using genetic algorithm to optimize CP violation sensitivity
  - Broadband beam with large flux between 1st and 2nd oscillation maxima

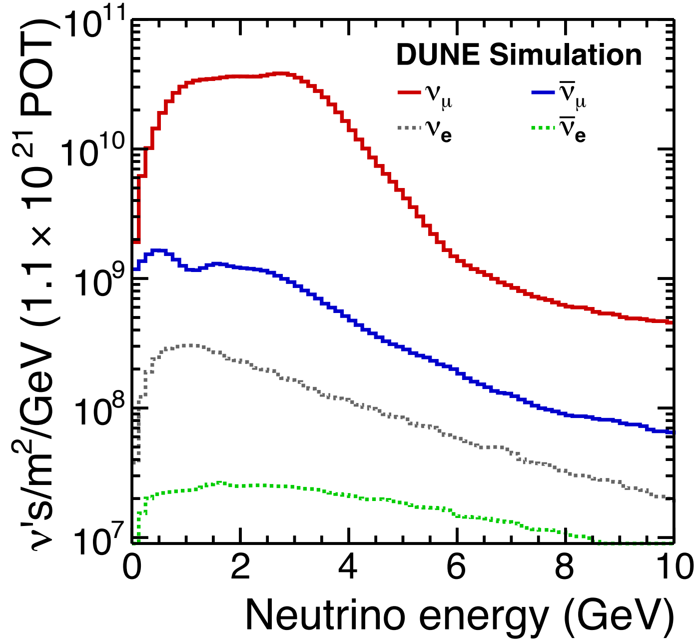
Proton Beam:



Neutrino Beam:



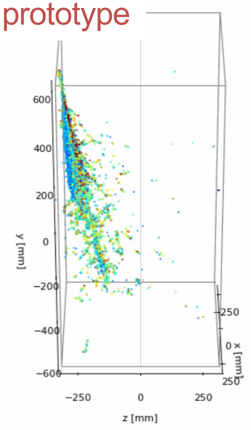
Neutrino Mode Flux:

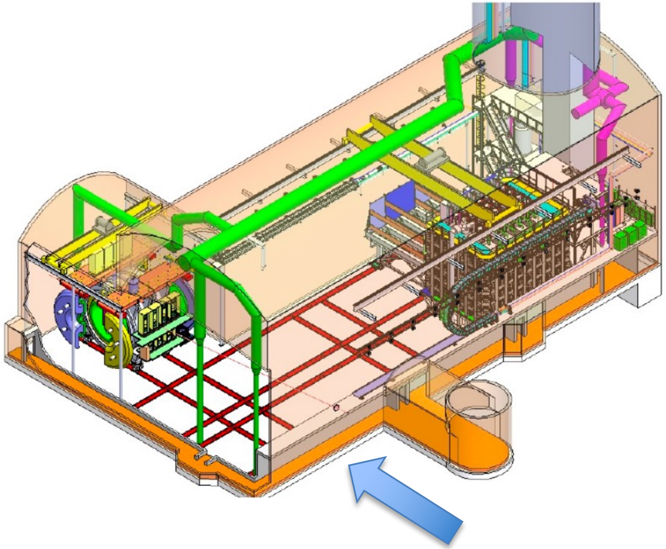


DUNE Near Detector arXiv:2103.13910

- Suite of ND components are designed to provide constraint on systematic uncertainty from flux, neutrino interaction modeling, and detector effects
- **LArND**
  - Same nuclear target and detection technology far and near
  - Differences in ND design required to handle higher rate environment
- The Muon Spectrometer (**TMS**)
  - Serves as "muon catcher" for LArTPC
  - Upgradable to "more capable ND" (**MCND**) such as a high-pressure gaseous argon TPC for improved systematics constraints in Phase II
- **PRISM**
  - LArTPC and TMS move up to 30m off axis to facilitate measurements in different neutrino fluxes
- **SAND**
  - On-axis magnetized low-density tracker and spectrometer, re-using magnet and ECAL from KLOE

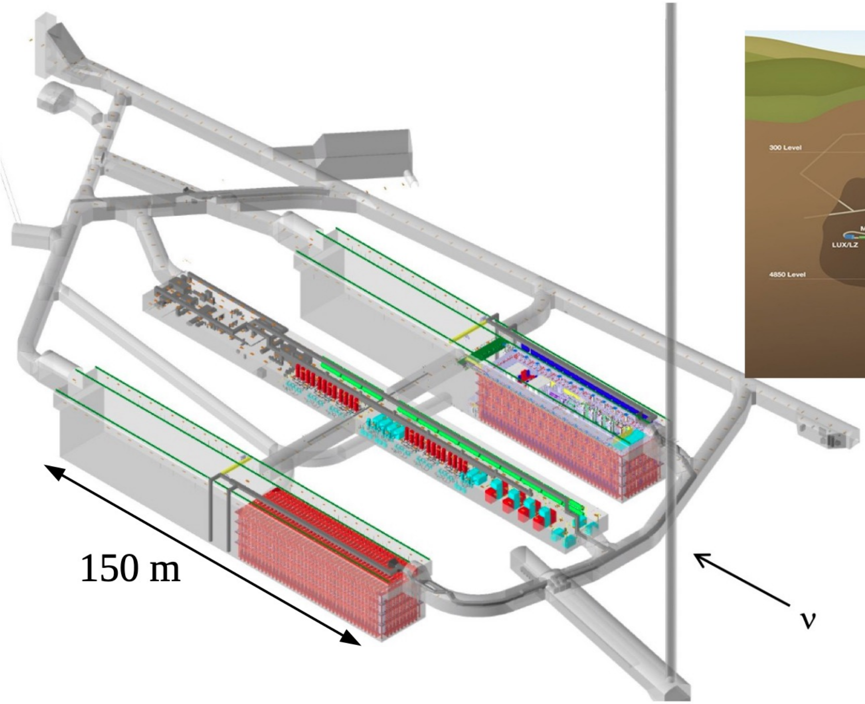
LAr-ND prototype

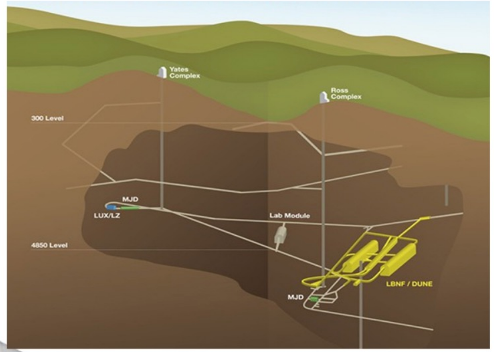




DUNE Far Detector at SURF

SURF: Sanford Underground Research Facility (Lead, SD)





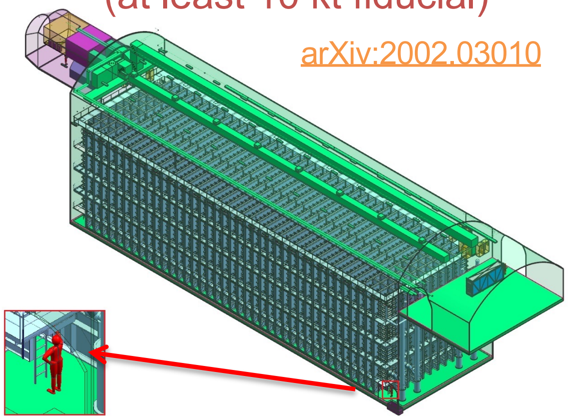
4850 level of SURF

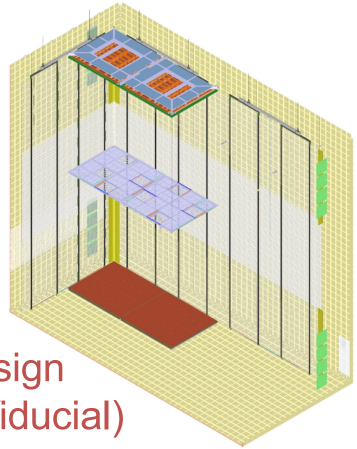
Far Detector Modules

- Excavation includes space for four 17-kt LArTPC modules: 70 kt total (>40 kt fiducial), integrated photon detection
- First two modules will be installed before Phase I operations:
  - FD1: Horizontal drift LArTPC
    - 3.2 m drift distance
    - Wire plane readout (150 APAs, 6 x 2.3 m)
  - FD2: Vertical drift LArTPC
    - 6.5 m drift distance
    - PCB plane readout (160 CRPs, 3 x 3.4 m)
- Far detector will be completed for Phase II with installation of FD 3&4
  - Details TBD
  - Potential opportunity for expanded physics scope

DUNE FD1 module
(at least 10 kt fiducial)

arXiv:2002.03010





DUNE FD2 design
(at least 10 kt fiducial)

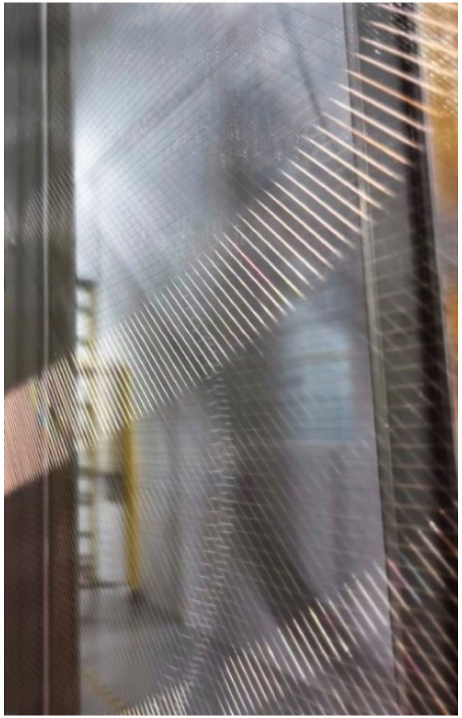
DUNE is under construction now

Excavation is 75% complete by rock volume!
10 APAs already complete, production will ramp to 40/year by 2026

North cavern

Central utility cavern

FD1 APA Production



Phased Construction

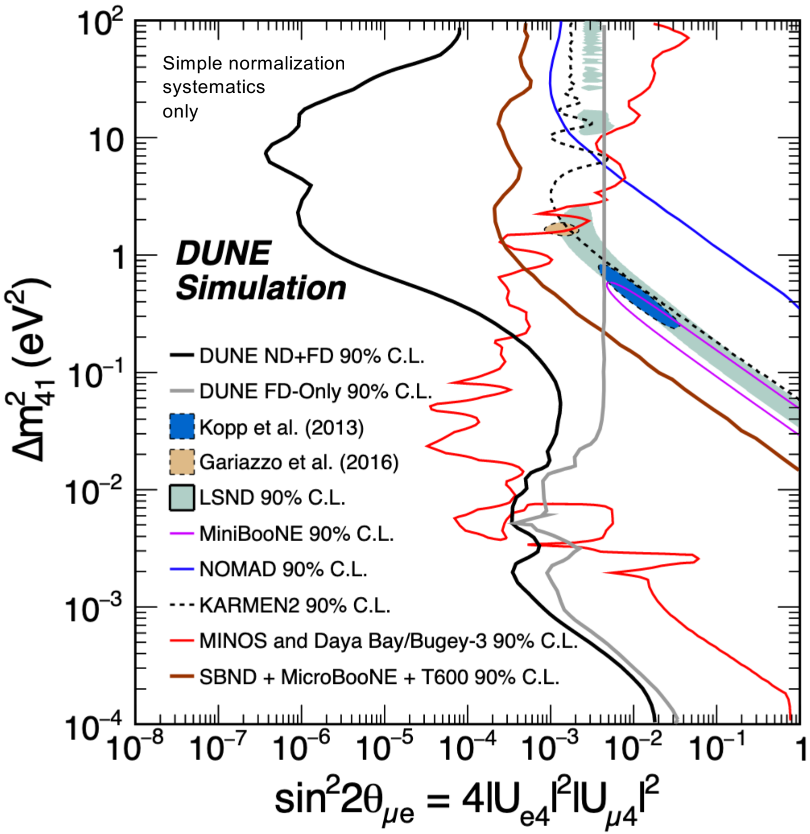
- **Phase I**
  - Includes full near & far site facilities and infrastructure (incl. caverns for 70 kt FD)
    - Excavation complete: 2024
  - Upgraded proton beam and new neutrino beamline: 2031
  - Two 17 kt LArTPC modules
    - FD1 installation begins: 2026
    - Commissioning, begin physics: 2028
    - FD2 installation: 2029
  - Moveable LArND w/ TMS: 2031
  - On-axis near detector: 2031
- **Phase II**
  - Two additional far detector modules
    - Full required fiducial mass
    - Potential opportunity for expanded physics scope!
  - Beam upgrade
    - Improved reliability and increased statistics
    - More protons for broader FNAL program
  - More capable near detector
    - Improved control of systematic uncertainty from neutrino interaction modeling

DUNE Physics

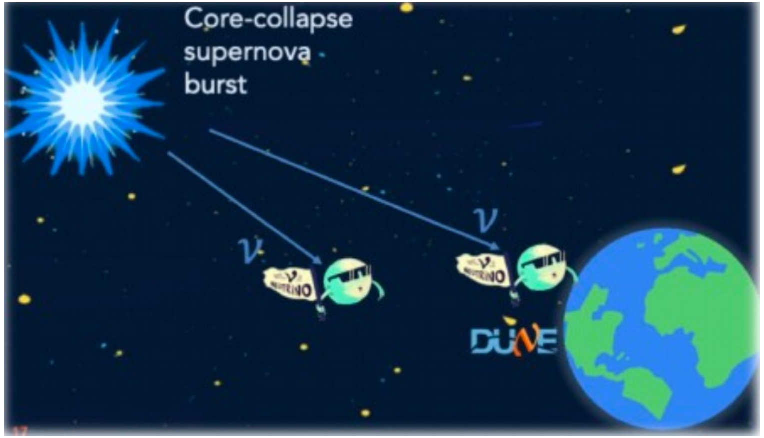
- Primary physics goals
  - make precise measurements of the parameters governing $\nu_1 - \nu_3$ and $\nu_2 - \nu_3$ mixing in a single experiment, including the neutrino mass ordering and the CP-violating phase δ_{CP}, and test the three-flavor paradigm
  - make astrophysics and particle physics measurements with supernova burst neutrinos and other low-energy neutrinos
  - search for physics beyond the Standard Model, including baryon number violating processes

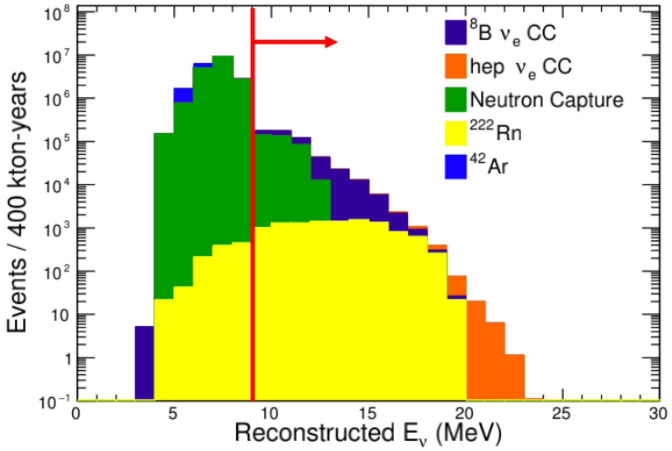
Physics Beyond the Standard Model [arXiv:2008.12769]

- Sensitivity to many new physics scenarios being investigated both by the collaboration and phenomenologists
- Deviations from 3-flavor oscillation (sterile ν, NSI, PMNS non-unitarity, CPT violation, etc)
- Complementary measurements at both DUNE and HK may help disentangle degeneracy between BSM signatures and 3-flavor oscillation parameters.
- Other (non-neutrino) new physics signatures (neutrino trident rate, dark matter, baryon number violation, etc – both ND and FD)



Astrophysical Neutrino Sources arXiv:2008.06647





- Thousands of neutrinos will be observed by DUNE for a typical galactic supernova burst
  - Probe core collapse mechanism, supernova evolution, etc.
- Flux complementary to other detectors: CC absorption (ν_e) dominates
- Pointing capability (multi-messenger astrophysics)

- DUNE will see ~100 solar neutrinos per day
  - Large background at low energies due to neutron capture
- DUNE can observe hep solar flux at >5σ (first time!)
- Measurements of solar oscillation parameters can be compared with JUNO (arXiv:1808.08232)

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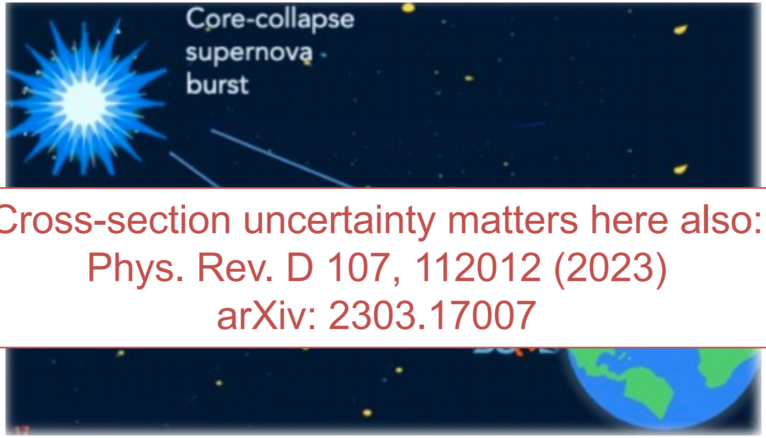
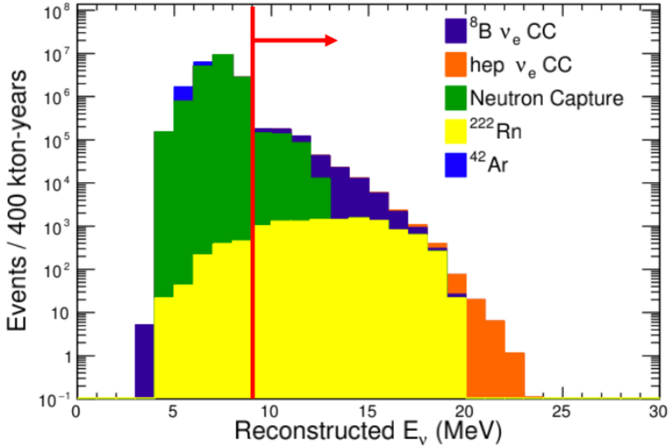


Cross-section uncertainty matters here also:
Phys. Rev. D 107, 112012 (2023)
arXiv: 2303.17007



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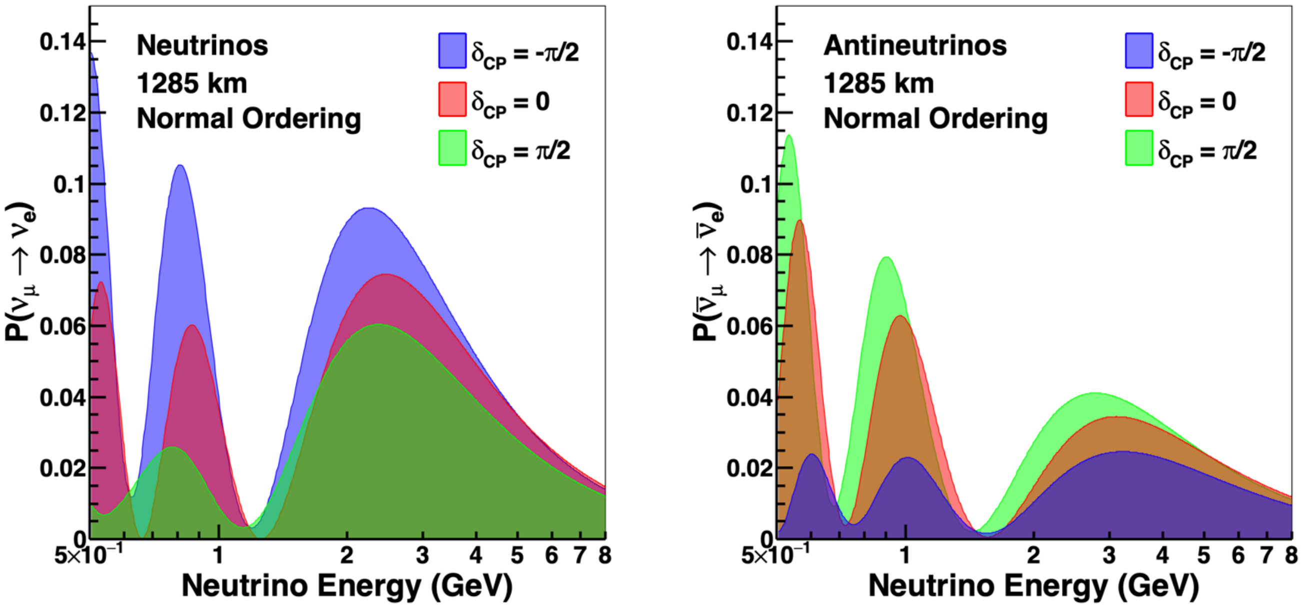
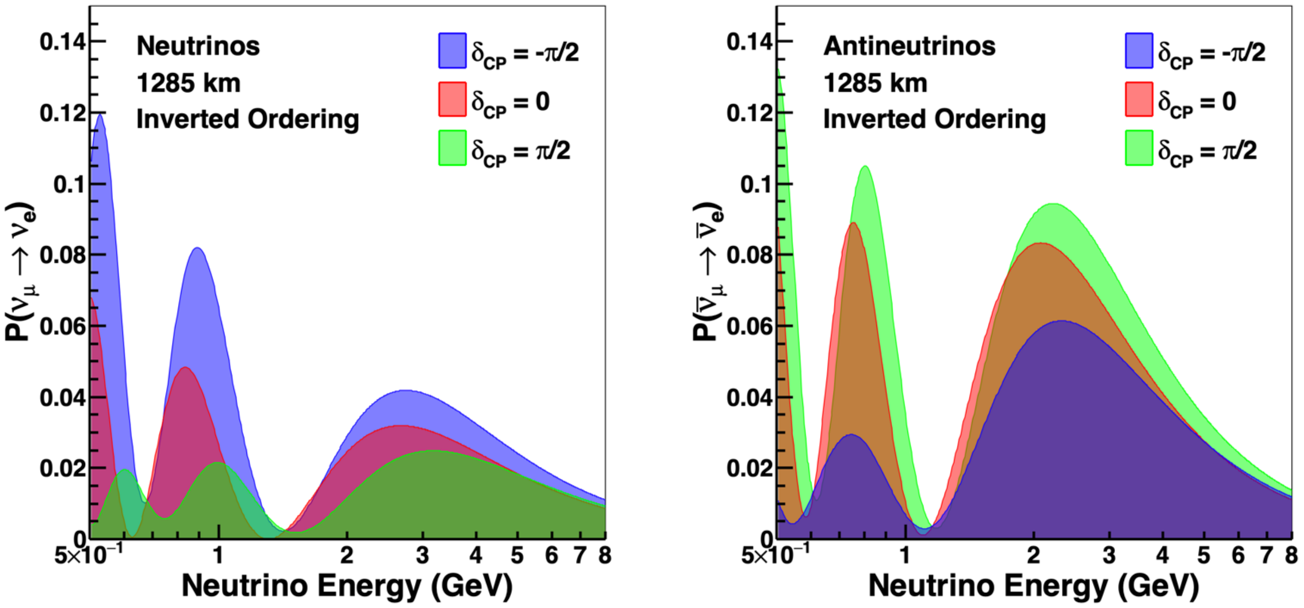
3-Flavor Neutrino Oscillation at DUNE



- Value of δ_{CP} affects both rate and shape of appearance probability, with asymmetric impact on neutrinos and antineutrinos
- Matter effect enhances appearance probability for neutrinos and reduces it for antineutrinos if ordering is <u>normal</u>

3-Flavor Neutrino Oscillation at DUNE



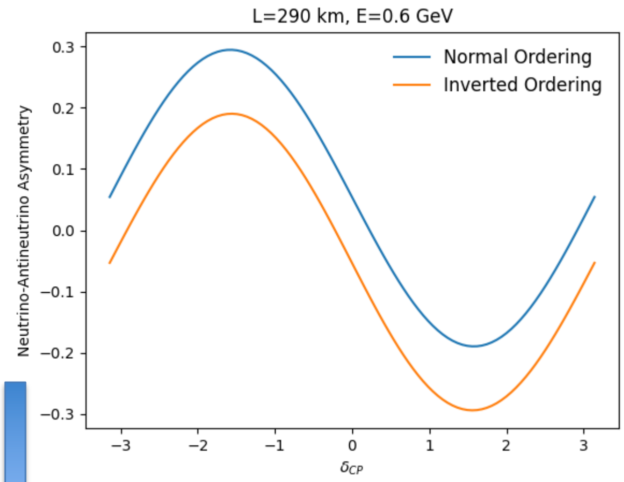
- Value of δ_{CP} affects both rate and shape of appearance probability, with asymmetric impact on neutrinos and antineutrinos
- Matter effect reduces appearance probability for neutrinos and enhances it for antineutrinos if ordering is inverted

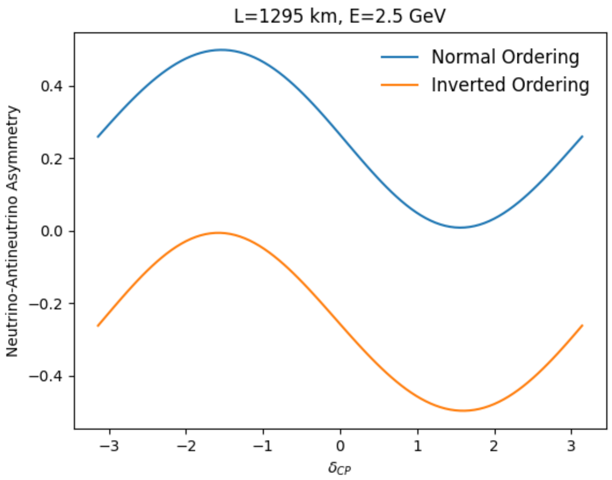
Both matter effect and δ_{CP} induce matter-antimatter asymmetry!

3-Flavor Neutrino Oscillation at DUNE

Baseline of 290 km
(very little matter effect)

Baseline of 1295 km
(large matter effect)



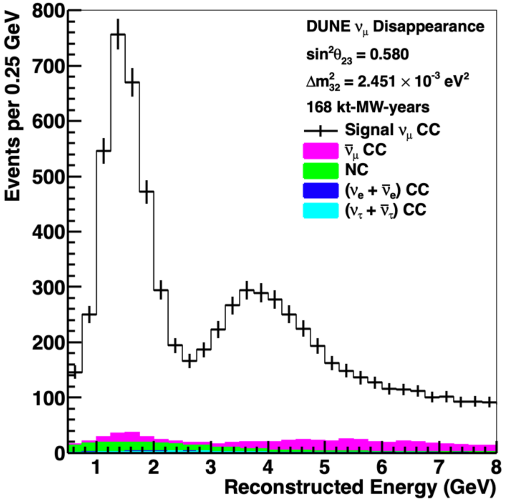


Degeneracy between δ_{CP} and matter effects is lifted for baselines greater than ~1000 km because matter effect produces larger asymmetry: DUNE can measure mass ordering unambiguously

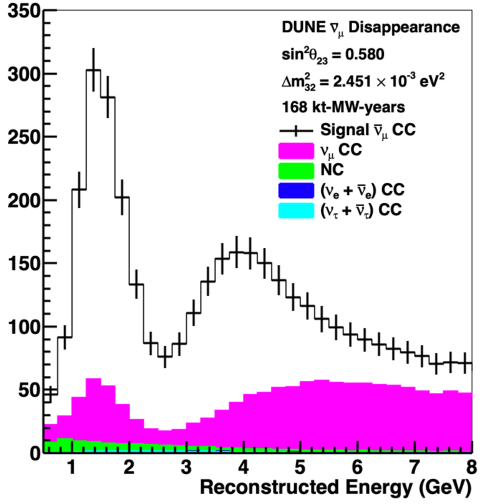
Matter-antimatter asymmetry

DUNE Spectra (~7 years)

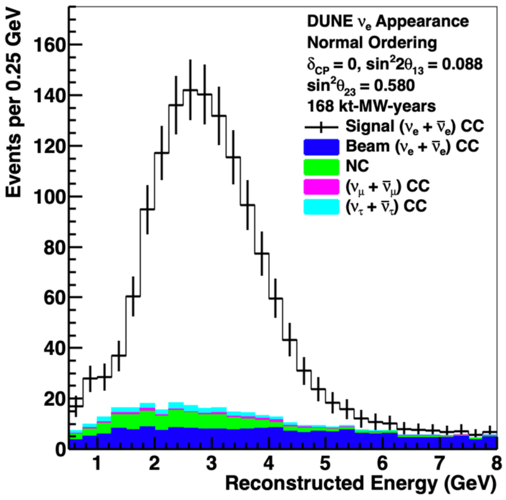
Neutrinos



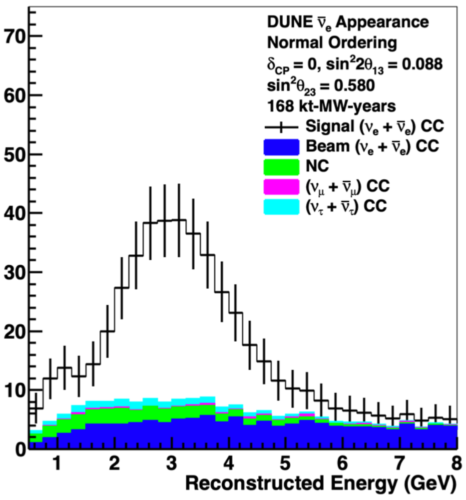
Antineutrinos



Neutrinos



Antineutrinos



ν_μ Disappearance

Order 10,000 events

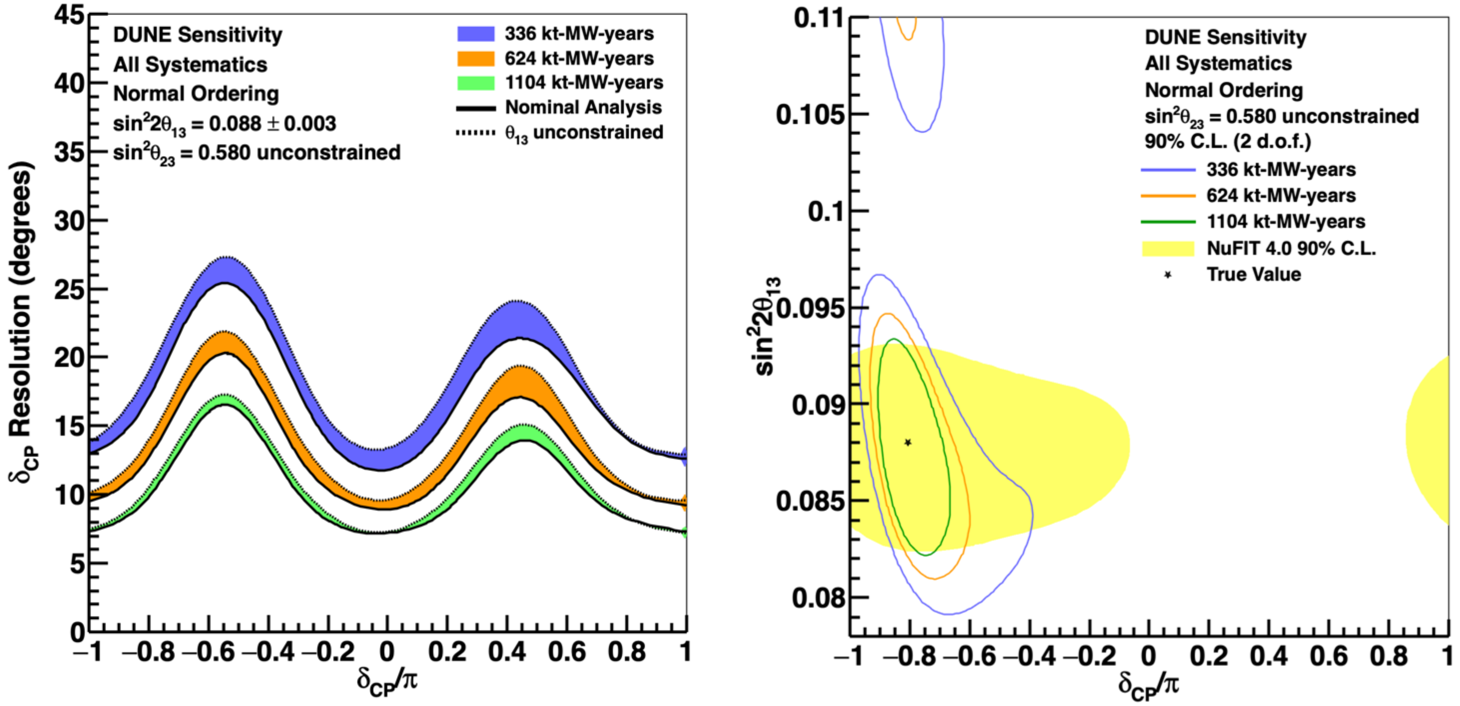
ν_e Appearance

Order 1000 events

DUNE Sensitivity

arXiv:2006.16043
arXiv:2109.01304

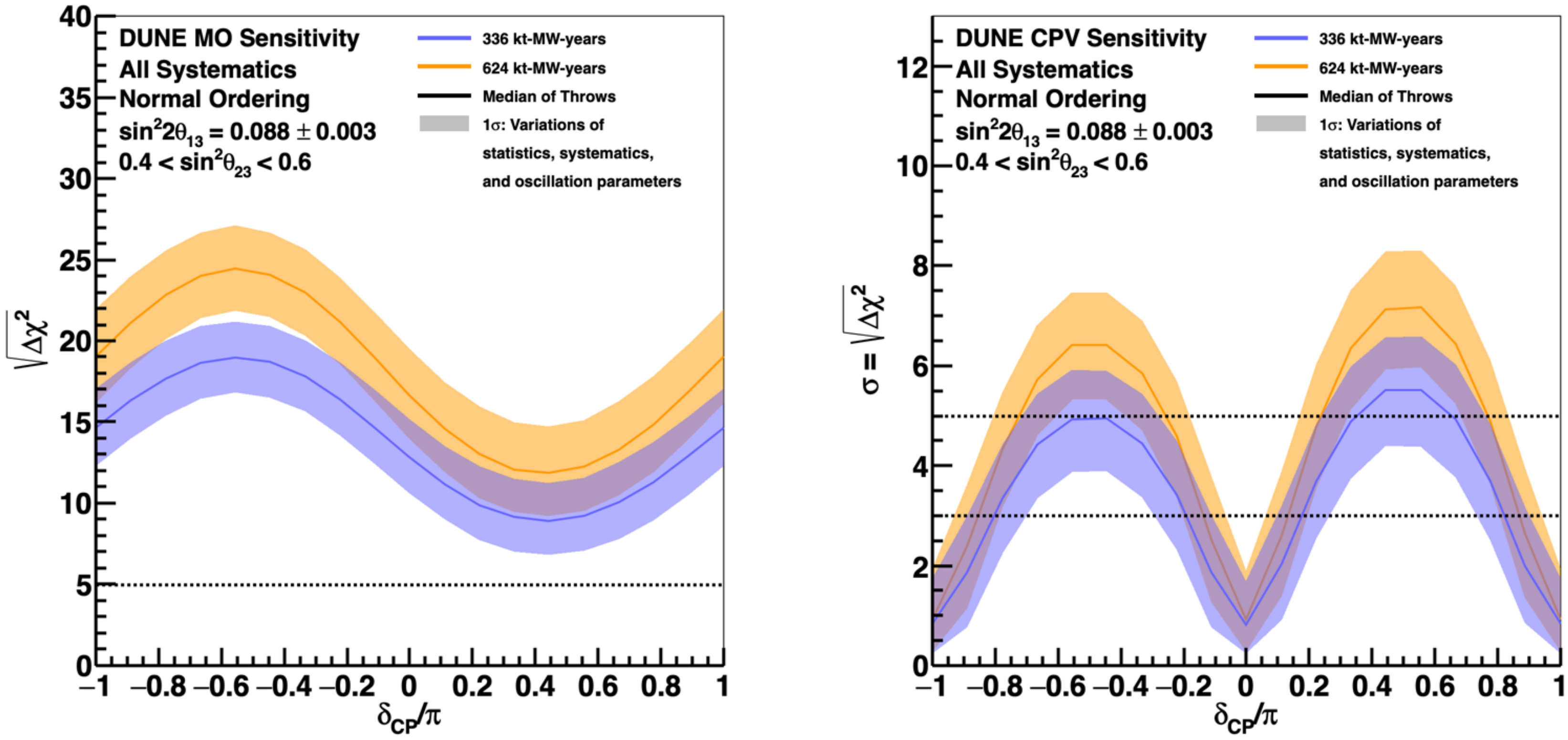
Precision Measurements:



Width of band represents difference between sensitivity with and without external constraint on θ_{13}
θ_{13} precision comparable to that of reactor experiments for large exposures

DUNE Sensitivity

arXiv:2006.16043
arXiv:2109.01304

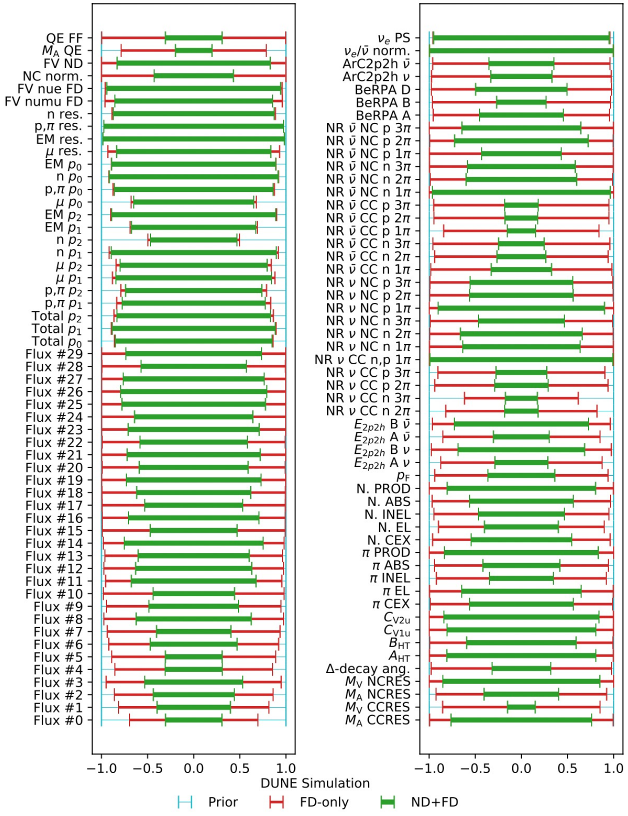


Width of band shows 1σ variations of statistics, systematic parameters, and oscillation parameters.
Unambiguous determination of neutrino mass ordering and 5σ sensitivity to δ_{CP} for a large range of parameter space.

Systematic Uncertainty

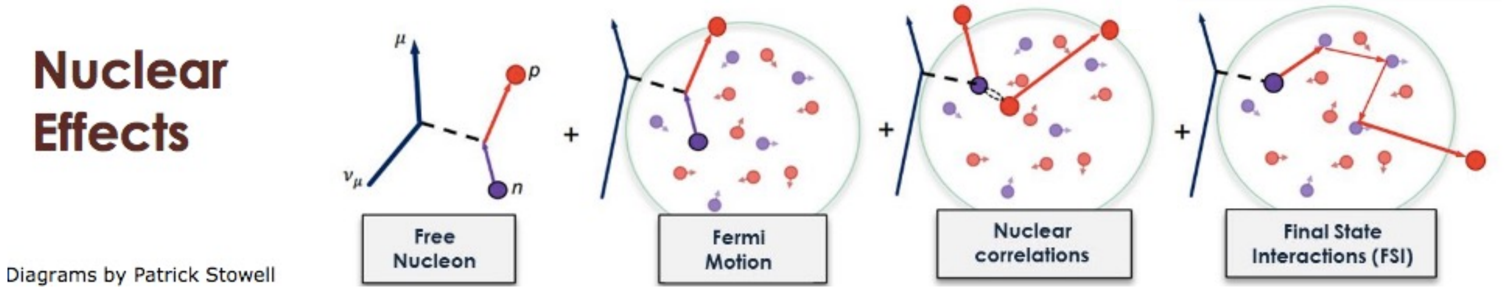
- Order few percent uncertainty required for precision measurements
- Sources of uncertainty:
  - Neutrino flux
  - Neutrino interaction model
  - Detector effects
- Sensitivity projections include detailed analysis of impact from individual source of systematics
- Impact of biases due to shortcomings in the interaction model is large
- Near detectors are critical to achieve precision measurement goals!

Systematics included in sensitivity projections ([arXiv:2006.16043](https://arxiv.org/abs/2006.16043)):



Neutrino Interaction Modeling

Neutrinos in DUNE are not interacting with bare nucleons…structure of the nucleus matters!

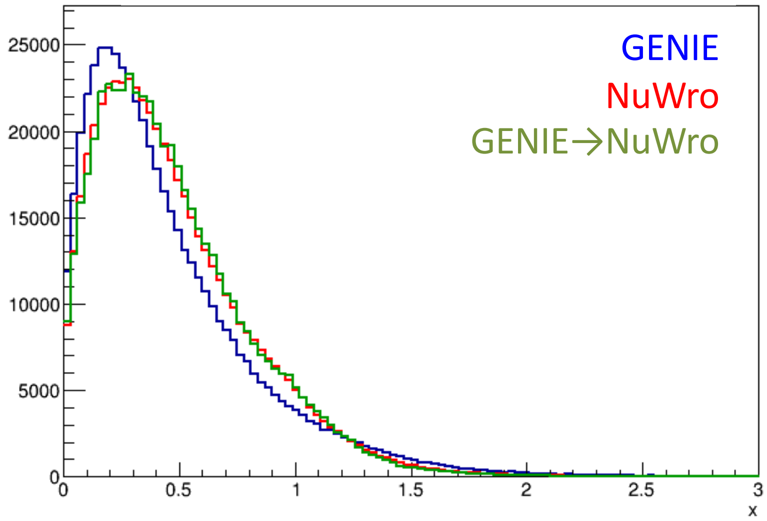


- Modeling neutrino interactions requires detailed modeling of complex nuclei!
- Interaction model affects energy reconstruction – mis-reconstructed energy can significantly bias results
- Neutrino-nucleus interaction model does not currently describe world neutrino interaction data → program of neutrino interaction experiments, model-building, and event generator development very important for precision measurements in neutrino physics
- Long-baseline experiments are being designed to provide experimental solutions to imperfect interaction model
  - Improve model constraints by making precise measurements of final states
  - Reduce sensitivity to details of model by making data-driven predictions

Studies of Interaction Model Systematics

- 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 MCND may be used to reduce this bias

Example: ν x distribution, FD FHC ν_e



More on multivariate reweighting:
C. Vilela at NPML 2020

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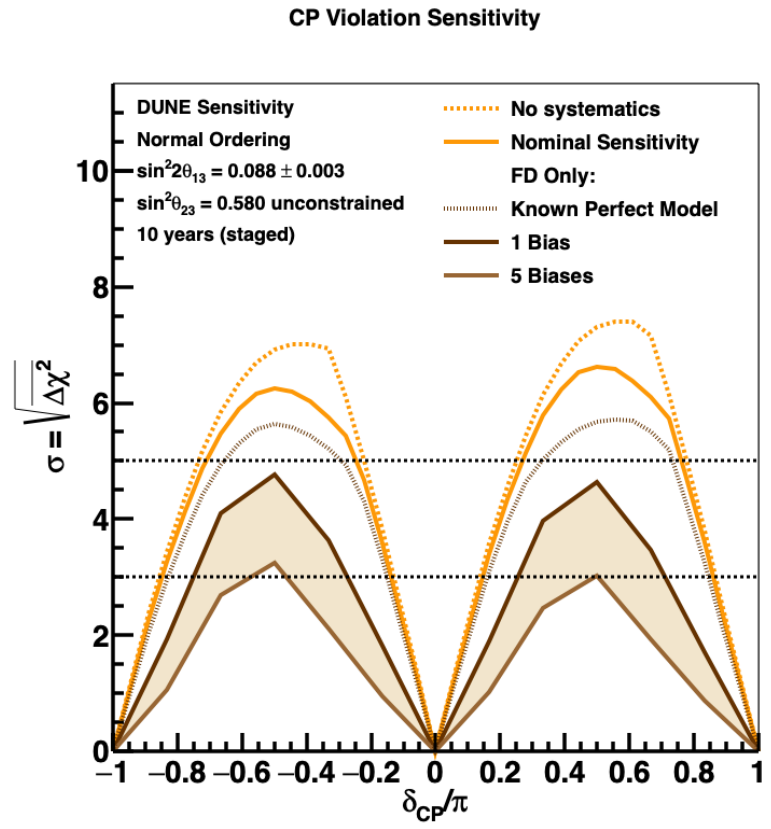
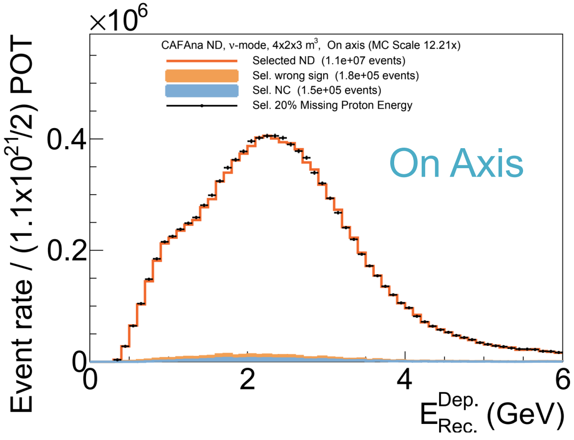
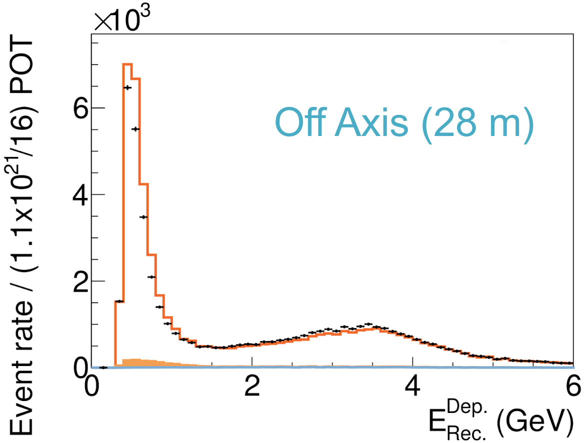
- FD fit χ^2/d.o.f. < 1, but produces bias in fit for d_{CP}
- ND-FD fit has χ^2/d.o.f. > 30
- Without ND to validate interaction model, would have to include possibility of this kind of bias as systematic uncertainty
- Exclusive final state samples in MCND may be used to reduce this bias



Studies of Interaction Model Systematics

- 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

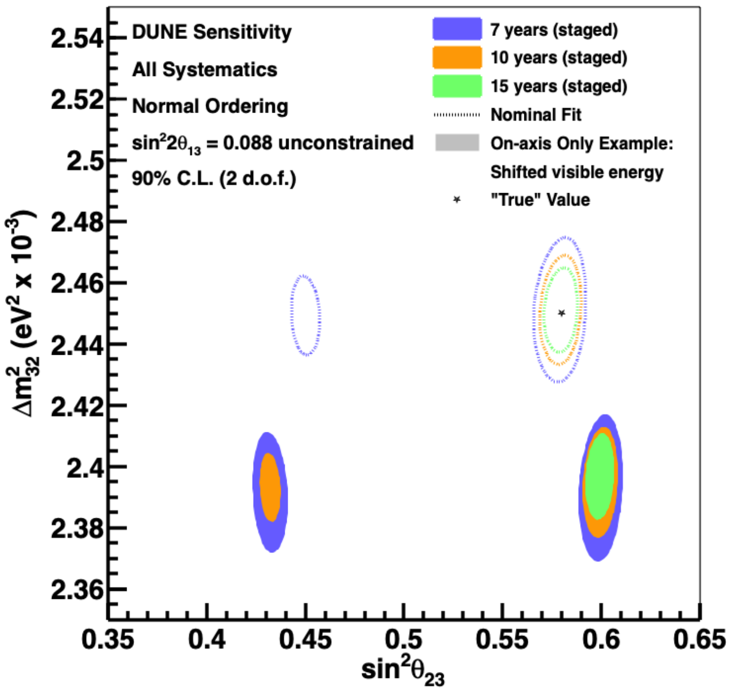




Studies of Interaction Model Systematics

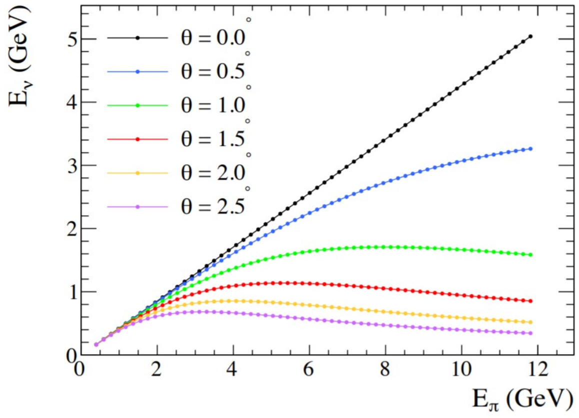
- 20% of proton energy is removed and added to (largely invisible) neutrons
  - Significant modification to relationship between reconstructed and true energy
  - An artificial but plausible example of a way in which the interaction model could be off
- Use BDT to adjust model parameters such that **on-axis**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

Δm^2_{32} vs $\sin^2\theta_{23}$

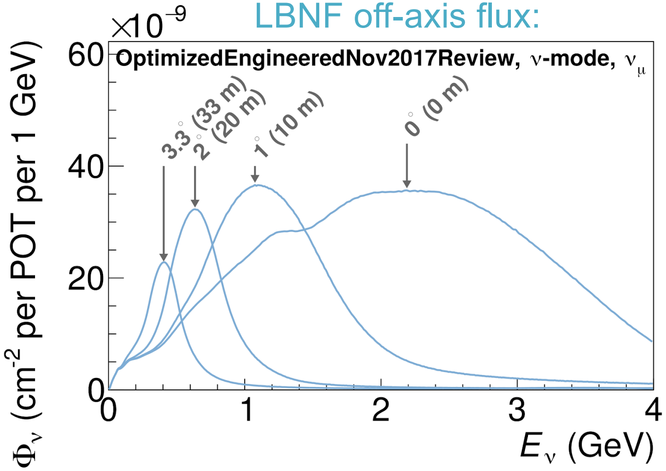


DUNE PRISM

Off-axis neutrino energy:



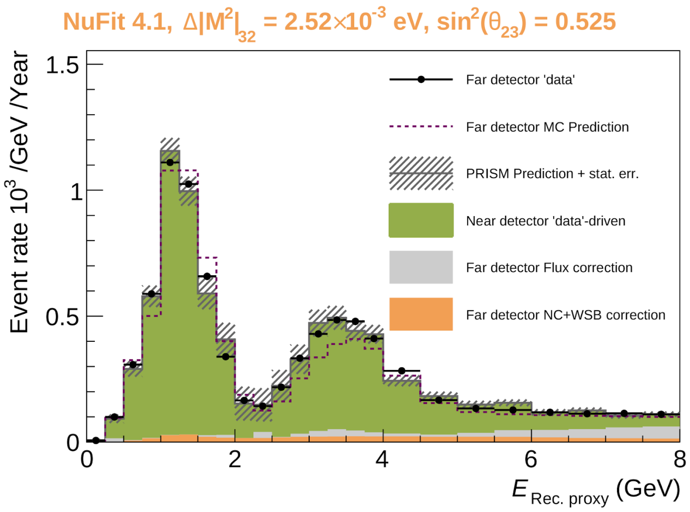
LBNF off-axis flux:

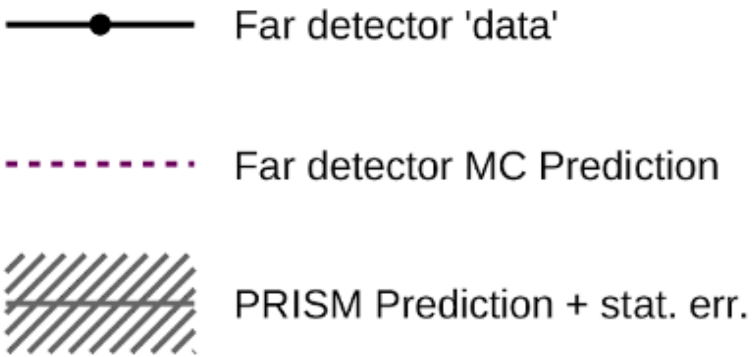


PRISM (Precision Reaction-Independent Spectrum Measurement) concept is to use linear combinations of off-axis fluxes to construct any flux: can ~reproduce FD flux prediction or Gaussian flux at a given energy. Same weights can then be applied to ND data to construct a "data driven" predicted event rate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

DUNE PRISM Example

Energy bias study with PRISM:



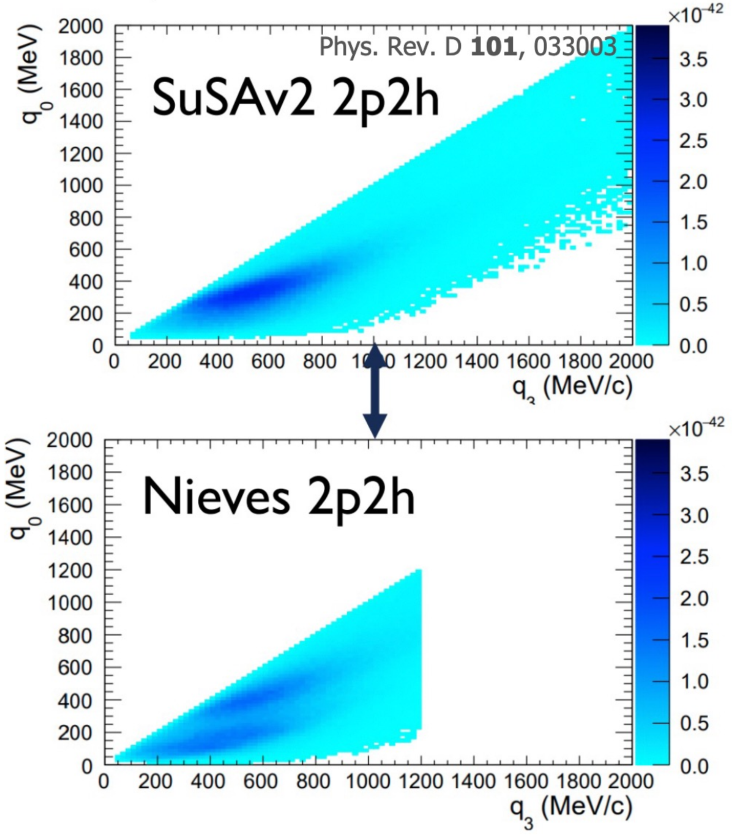


- With nominal MC, prediction badly mismatched to data, leading to biased measurement of oscillation parameters
- PRISM prediction is well-matched to data and no bias in parameter measurement is observed!

Interactions Baseline Model

- GENIE version 3.4.0, release Ar23_20i (2023)
- Common among DUNE and SBN (ICARUS and SBND)
  - Facilitates collaboration on development of systematics variations and any future constraints from SBN program measurements
- Guiding principle in model choice is flexibility for future studies: covers large phase space to allow for reweighting
- Updates include:
  - Updated nuclear ground state model
  - Z-expansion for CCQE axial form factor
  - SuSAv2 2p2h
  - Simulation of de-excitation photons for Argon

SuSAv2 2p2h covers more phase space: can reweight from SuSA to Nieves but not vice-versa



Interaction Measurements Program

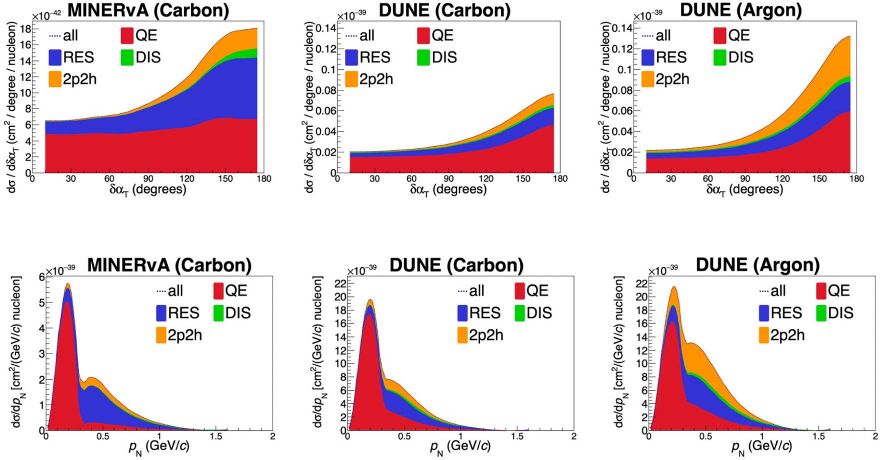
DUNE ND CDR (arXiv:2103.13910):

Table 6.2: Events per year (1.1×10^{21} POT) in the forward horn-current (ν_μ-favoring) mode. The rates were computed with GENIE 2.12.10. The rates assume a 50 t fiducial volume of liquid argon and a 1 t fiducial volume of argon gas.

	Interaction Channel		Event Rate	
			ND-LAr	ND-GAr
CC	ν_μ		8.2×10^{7}	1.64×10^{6}
		0π	2.9×10^{7}	5.8×10^{5}
		$1\pi^{\pm}$	2.0×10^{7}	4.1×10^{5}
		$1\pi^{0}$	8.1×10^{6}	1.6×10^{5}
		2π	1.1×10^{7}	2.1×10^{5}
		3π	4.6×10^{6}	9.3×10^{4}
		other	9.2×10^{6}	1.8×10^{5}
	$\bar{\nu}_\mu$		3.6×10^{6}	7.1×10^{4}
	ν_e		1.45×10^{6}	2.8×10^{4}
NC			5.3×10^{5}	5.5×10^{5}
$\nu+e$			8.3×10^{3}	1.7×10^{2}

Massive rate of neutrino interactions at ND!

Example TKI measurements:



DUNE phase space and momentum acceptance, combined with heavy target nucleus with isospin T=2 allows access to different regions of parameter space, in some cases with added sensitivity to FSI

Summary

- DUNE represents a major experimental advance for long-baseline oscillation experiments: thousands of events, unambiguous determination of the mass ordering, 5σ-level sensitivity to CPV, precision measurements of oscillation parameters, including δ_{CP}, significant sensitivity to physics beyond the Standard Model
- [Interaction] Systematics are critical for precision measurements!
- DUNE has a broad physics program beyond 3-flavor oscillation physics
  - Supernova ν physics, solar ν physics, baryon number non-conservation, BSM searches…
  - Neutrino interactions measurements program
  - Opportunities to expand the physics reach with new detector ideas in Phase II
  - DUNE and HyperK design strategies complement each other and will help disentangle any observed BSM effects from 3-flavor oscillation
- DUNE is being built now – the next decade will be very busy and exciting!