DUNE: Science & Status

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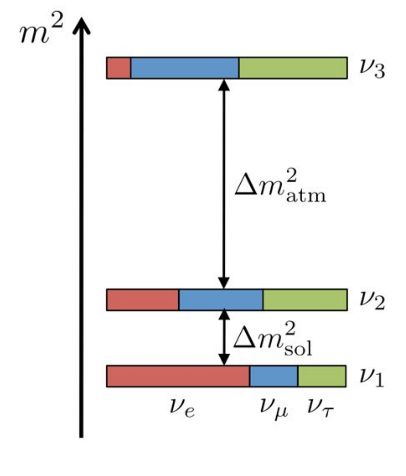
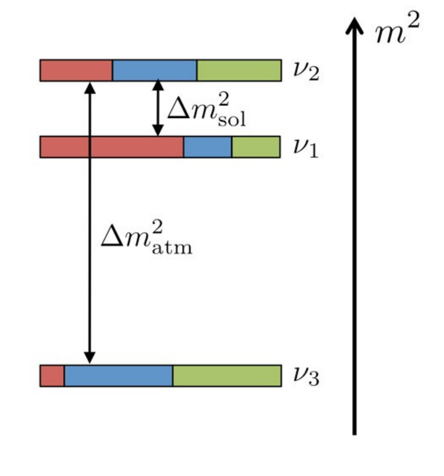
UNIVERSITY of ROCHESTER
U.S. DEPARTMENT OF ENERGY | Office of Science

Long-baseline neutrino oscillations: unknown PMNS parameters

$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\text{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\text{CP}}} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

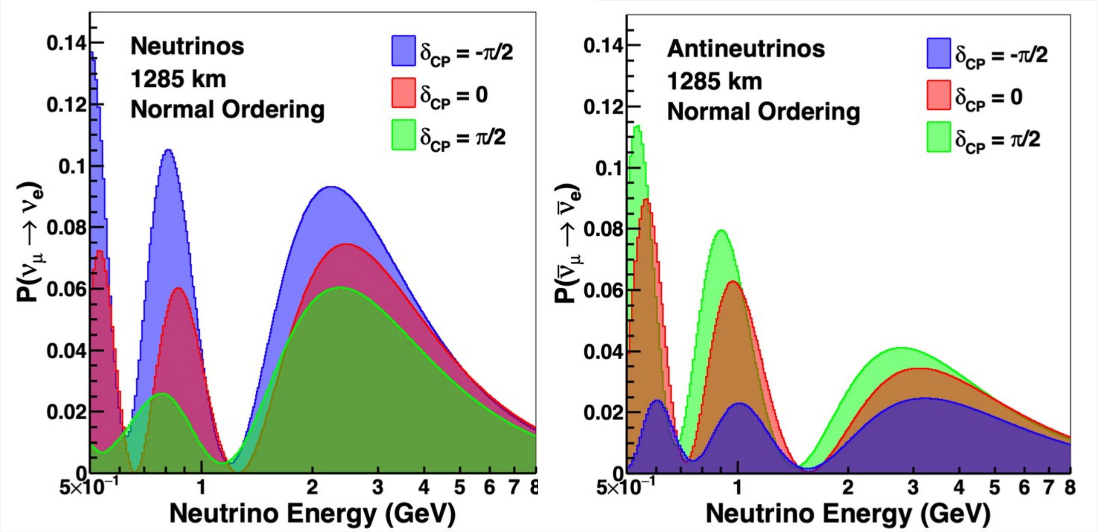
- Goals for next generation experiments are often stated as:
  - Determine the neutrino mass ordering
  - Measure δ_{CP} and determine if CP is violated
  - Determine the octant of θ_{23}





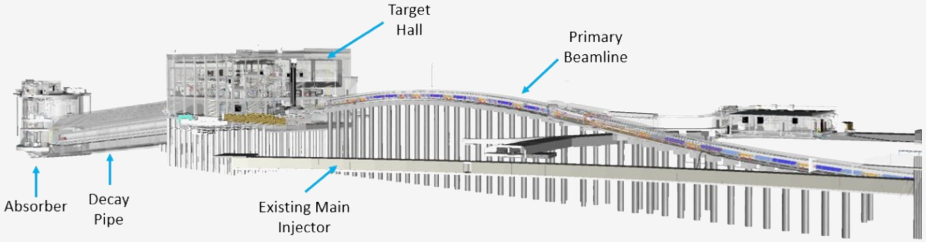
Long-baseline neutrino oscillations: Is the 3-flavor model correct?

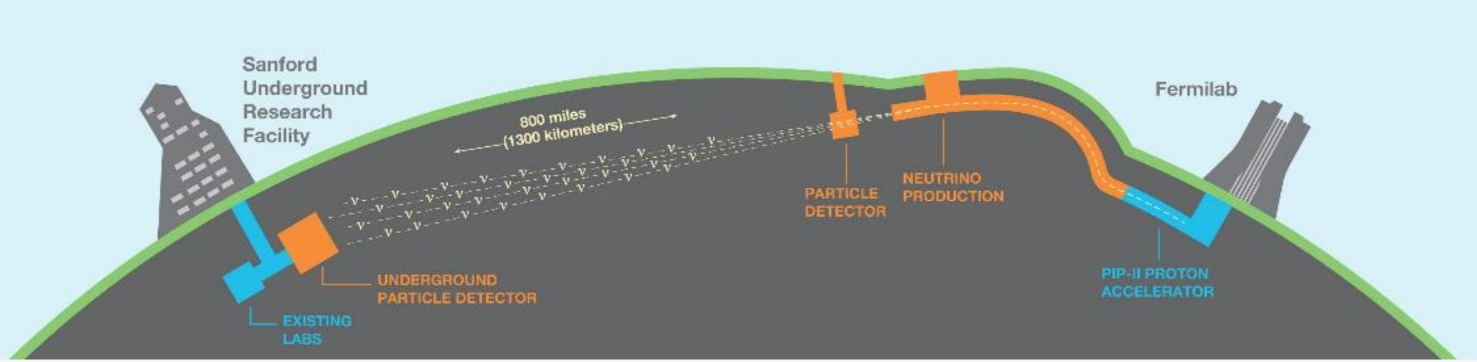
- Measure neutrino and antineutrino oscillation as a function of L/E
- Does the three-flavor model describe the data?
  - If yes: measure the mixing angles, mass splittings, and CP phase
  - If no: characterize the new physics
- Need for a global program: different energies, matter effects, systematics, etc.



Long-baseline oscillations as part of a broad physics program

- Large, sensitive underground detectors are excellent to:
  - Observe supernova burst neutrinos
  - Measure solar and atmospheric neutrinos
  - Search for new physics of cosmogenic origin
  - Search for nucleon decays and other rare processes
- Intense beams with capable near detectors are excellent to:
  - Search for new physics produced in the beamline
  - Search for new physics in rare interactions (i.e. neutrino tridents)

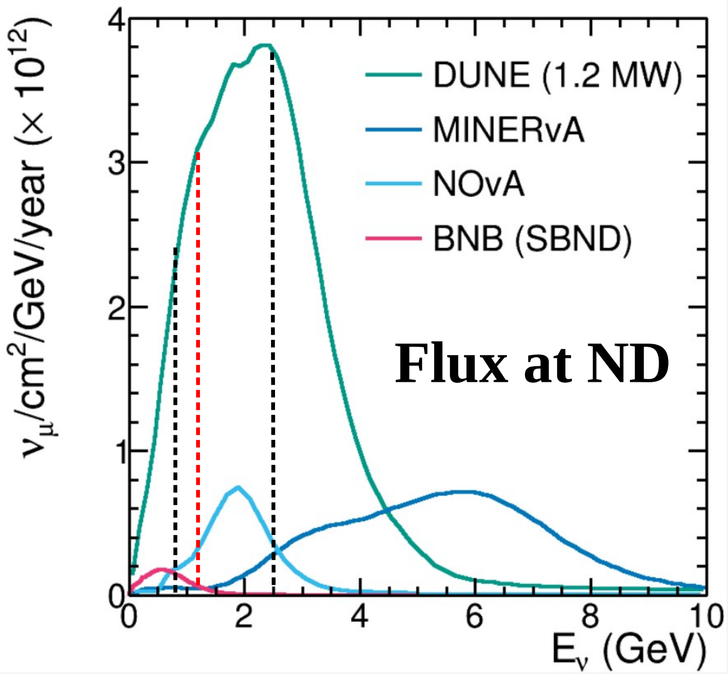




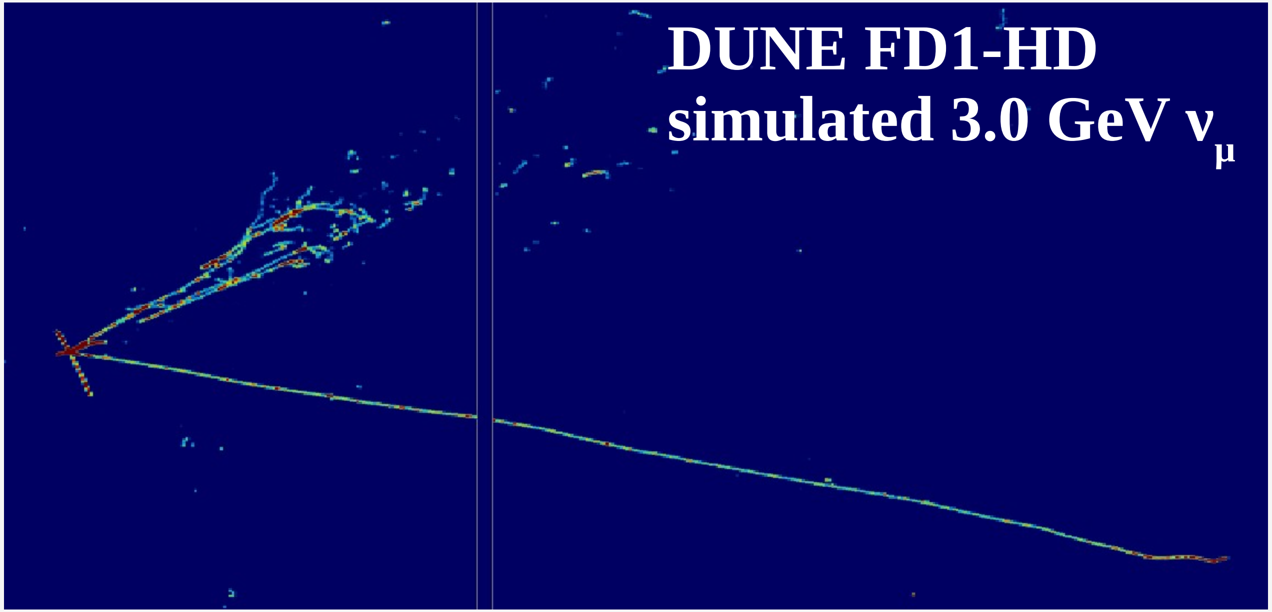
- Wideband (anti)neutrino beamline at with >2MW intensity
- Modular underground LArTPC Far Detector with ≥40 kt fiducial mass
- Movable LArTPC Near Detector with muon spectrometer + on-axis detector
- Global collaboration of >1400 scientists and engineers

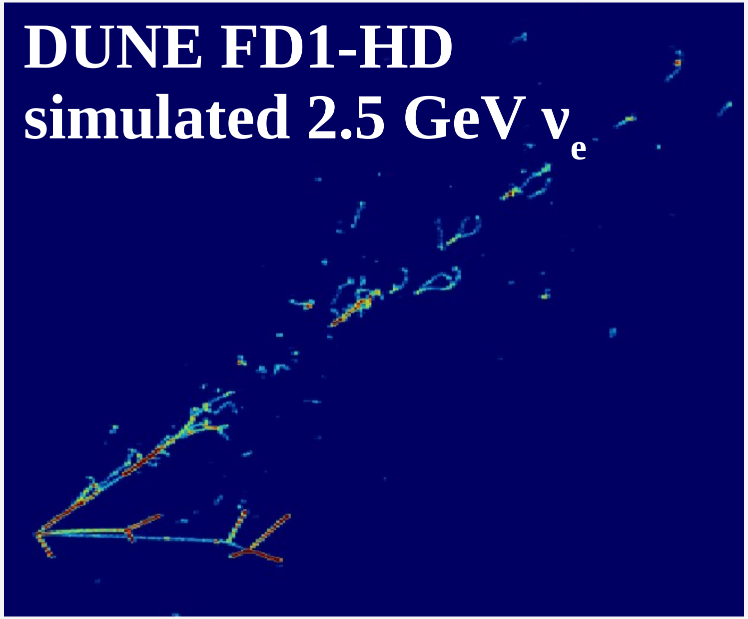
LBNF beamline: lots of neutrinos

- DUNE neutrino beam is far higher intensity than present-day experiments
- Very high flux between oscillation minimum (1.27 GeV) and maximum (2.54 GeV), with coverage of second maximum (0.8 GeV)
- Recent development: ACE-MIRT upgrades could increase beam intensity to >2 MW by decreasing the time between spills from 1.2s to 0.6s, can be achieved before DUNE operations begin
- More neutrinos sooner!



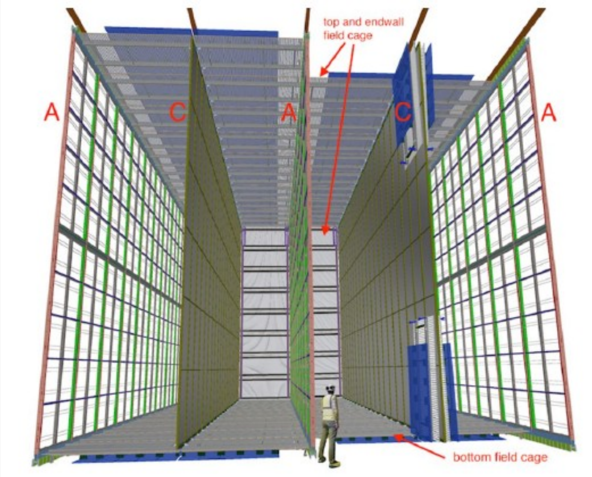
LArTPC: flavor & energy reco over a broad range of topologies

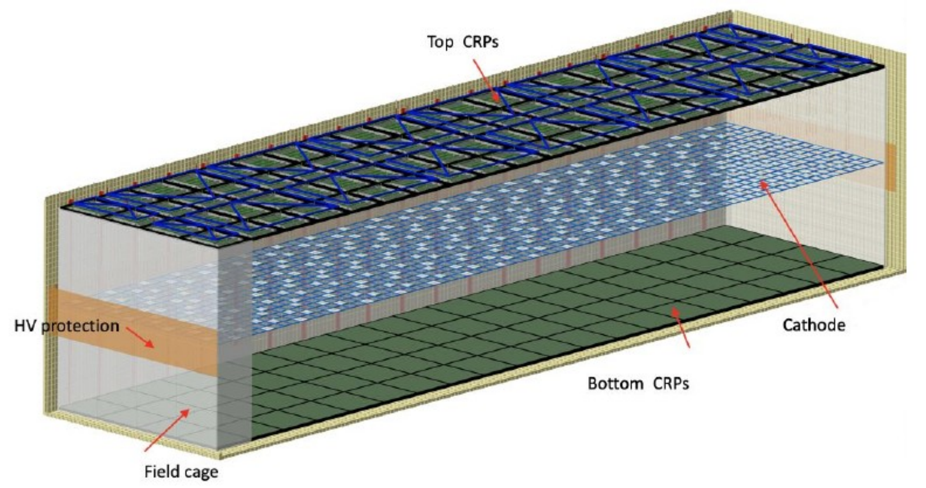




- 60% of interactions at DUNE energy have final state pions → LArTPC enables precise hadron reconstruction
- Excellent e/μ separation

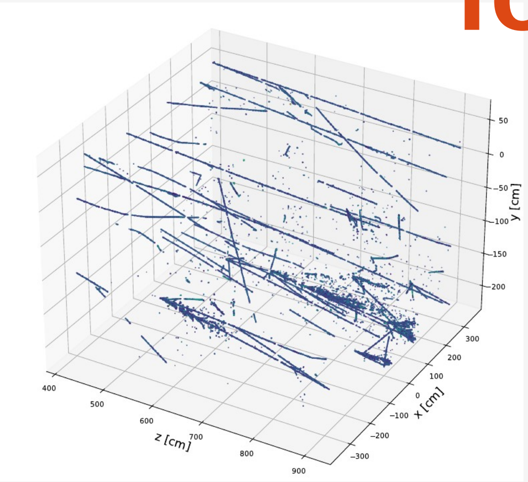
Far detector: two readout technologies

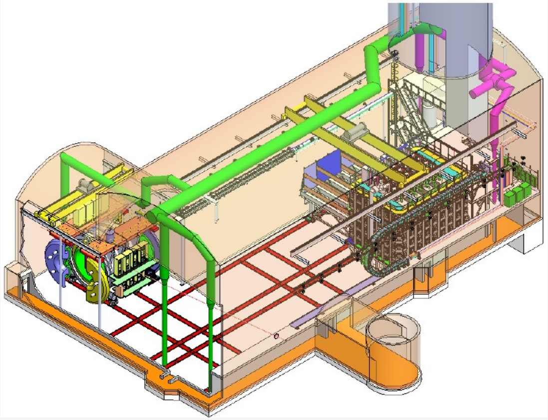




- Horizontal drift (HD) using wire readout planes, four drift regions
- Vertical drift (VD) using two larger 6.25m drift regions and central cathode
  - Simpler to install → first DUNE FD module will use vertical drift
  - Baseline design for modules 3 and 4

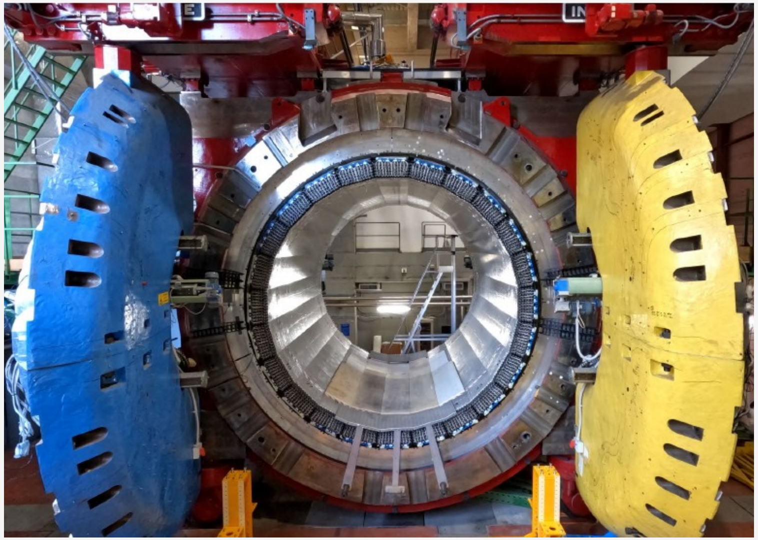
Near detector: systematic constraints for precision physics





- ND is a (movable) LArTPC + muon spectrometer, and a (fixed) magnetized tracker + calorimeter
- Off-axis data in different neutrino fluxes constrains energy dependence of neutrino cross sections
- Same target, same technology → inform predictions of reconstructed E_ν in Far Detector
- Neutrino pile-up → modular design with pixelated, natively 3D readout to isolate activity from individual neutrinos

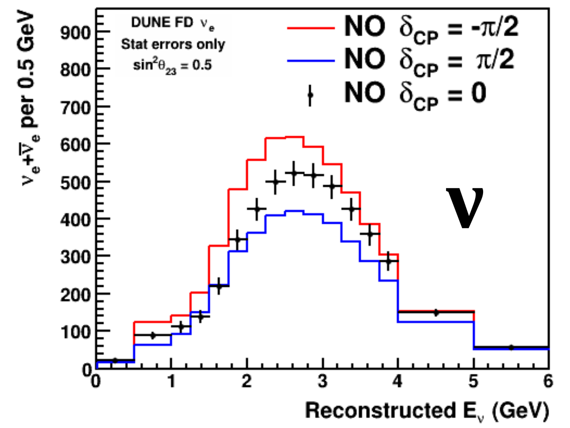
SAND: on-axis detector using KLOE magnet and calorimeter

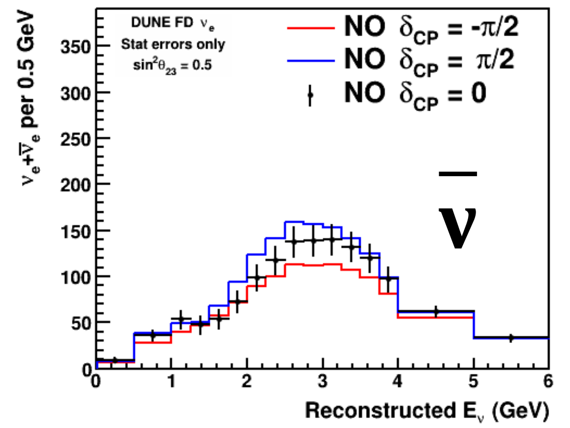


Event display from Matteo

- Fixed component of ND repurposes existing solenoid magnet and ECAL from KLOE
- Plan is to build a collider-like detector in a neutrino beam: low-density straw tube tracker with thin targets, surrounded by calorimetry
- Fine-grained, particle-by-particle reconstruction with very low rescattering, excellent for highly exclusive neutrino-nucleus measurements
- Being (carefully) taken apart at Frascati for the move to the US

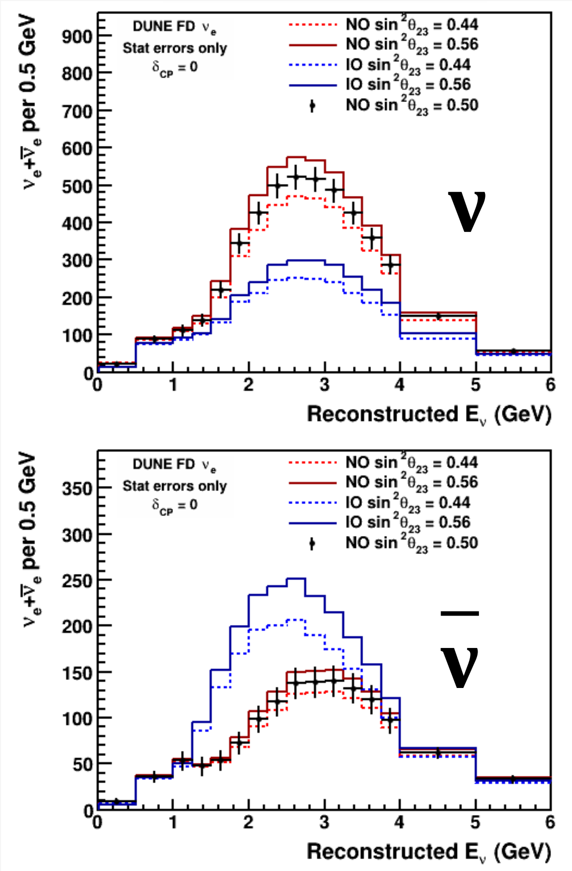
Far Detector energy spectra are sensitive to CP violation





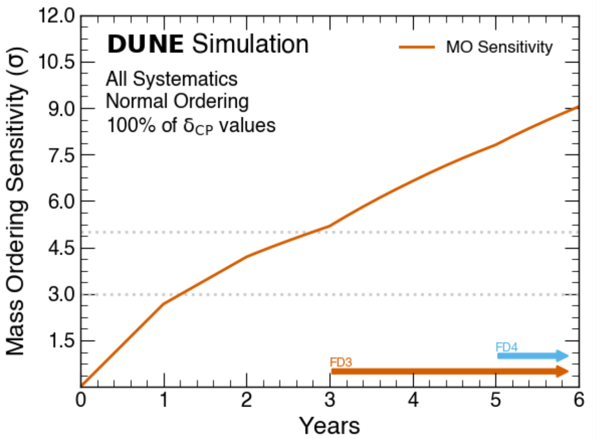
- If δ_{CP} ~ $-\pi/2$, DUNE will measure an enhancement in electron neutrino appearance, and a reduction in electron antineutrino appearance

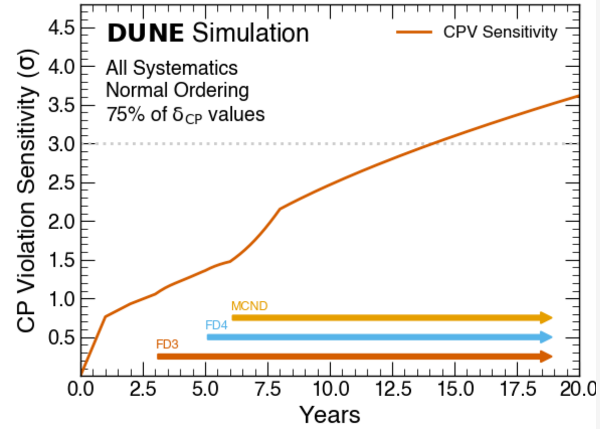
Far Detector energy spectra are sensitive to CP violation



- If δ_{CP} ~ -π/2, DUNE will measure an enhancement in electron neutrino appearance, and a reduction in electron antineutrino appearance
- If the mass ordering is normal, DUNE will measure a *much larger* enhancement in electron neutrino appearance, and a reduction in electron antineutrino appearance
- MO, δ_{CP}, and θ_{23} all affect spectra with different shape → additional handle on resolving degeneracies
- If new physics is present, there may be no combination of MO, δ_{CP}, and θ_{23} that fits data

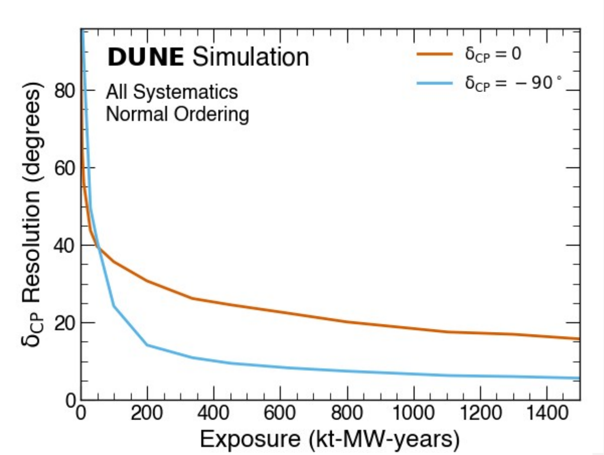
Long-baseline sensitivity

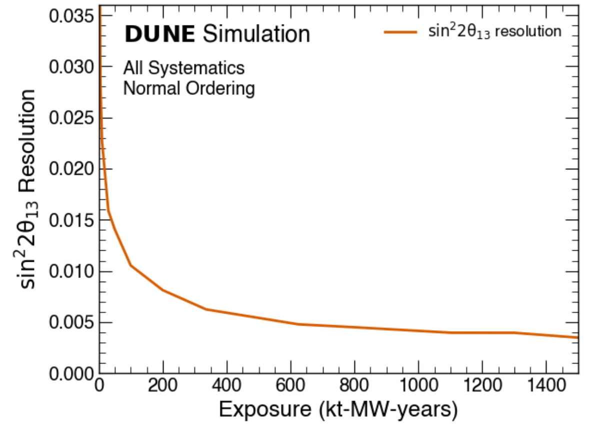




- Mass ordering at >5σ in <3 years, no matter the value of δ_{CP} or any other parameter
- Long-term: DUNE can establish CP violation at >3σ for >75% possible values of δ_{CP}

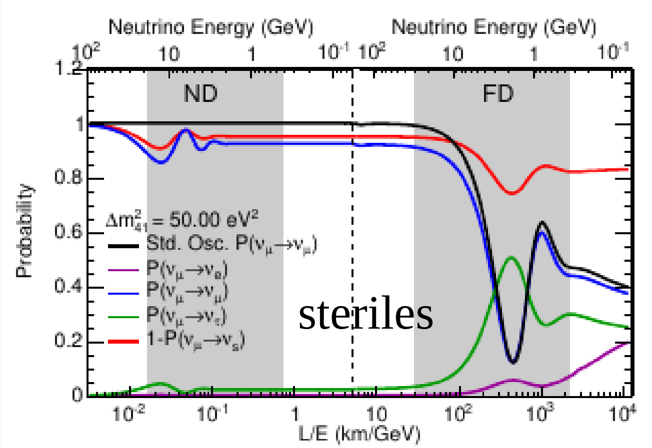
Precision measurements

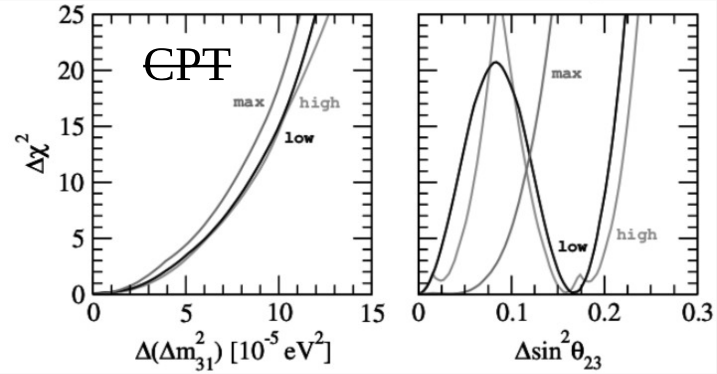


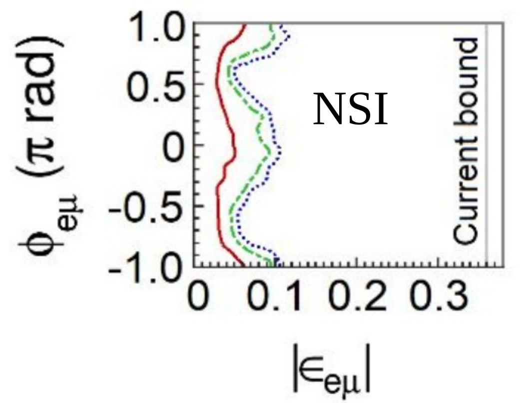


- Mass ordering at >5σ in <3 years, no matter the value of δ_{CP} or any other parameter
- Long-term: DUNE can establish CP violation at >3σ for >75% possible values of δ_{CP}
- 6-16° precision in δ_{CP}
- World-leading precision (for long-baseline experiment) in θ_{13} and Δm^2 → comparisons with reactor measurements are sensitive to new physics

Beyond three flavors

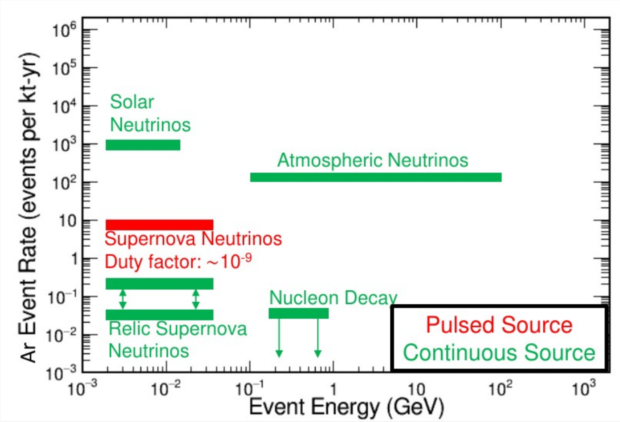


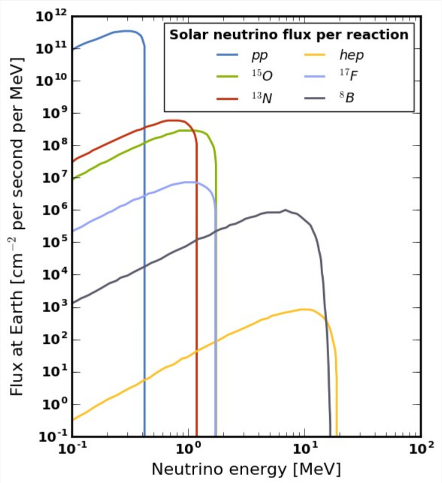


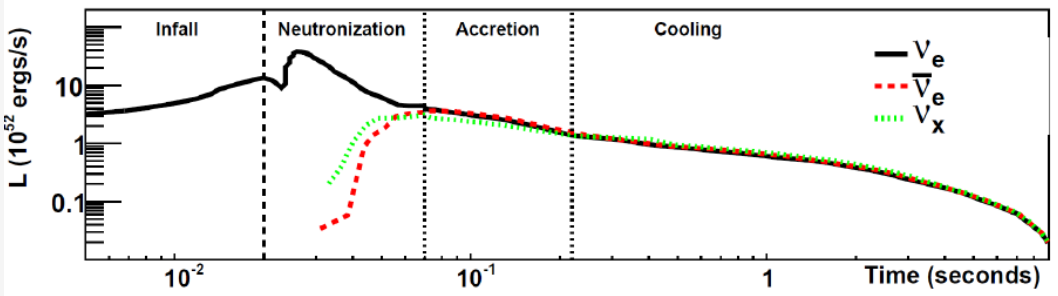


- Broad range of L/E at ND and FD → search for non-SM oscillations
- High statistics neutrino and antineutrino measurements → search for CPT violation
- Very large matter effect → uniquely sensitive to some NSI

Natural neutrino sources at DUNE FD



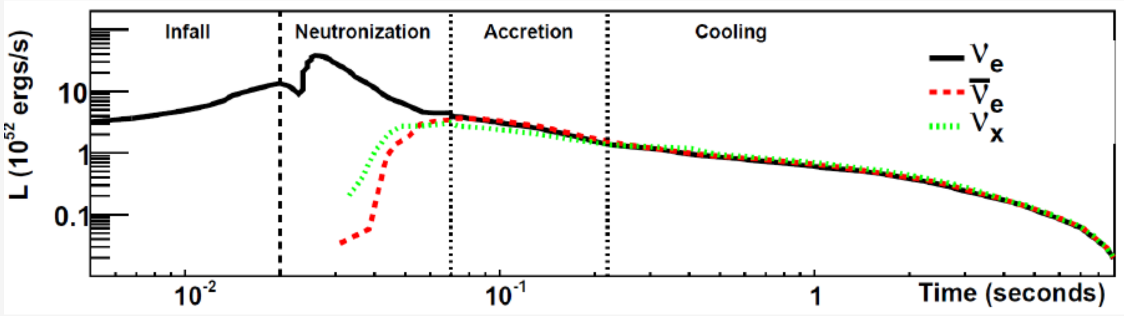


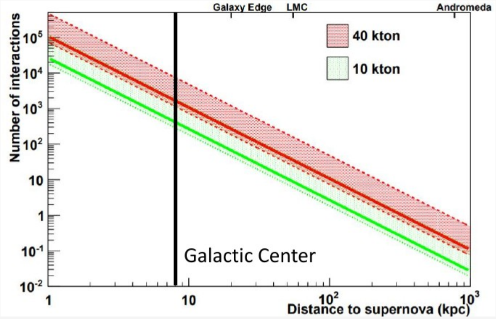


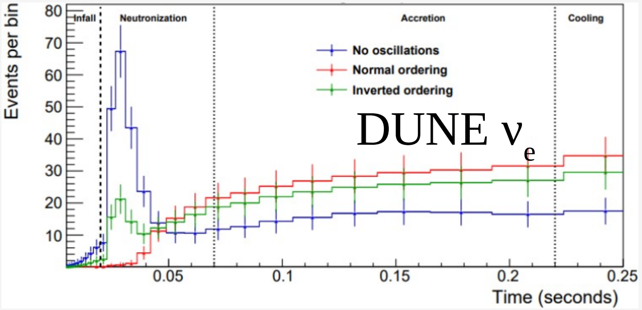
- DUNE FD will observe atmospheric, solar, and supernova neutrinos
- Argon target gives unique sensitivity to MeV-scale electron neutrinos
  - $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$ ($E_\nu > 1.5$ MeV)
  - $\bar{\nu}_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^*$ ($E_\nu > 7.5$ MeV)
  - $\nu_x + e^- \rightarrow \nu_x + e^-$ (pointing)
- Highly complementary to other experiments (Hyper-K, JUNO) that predominantly see $\bar{\nu}_e$ via IBD

Particle astrophysics with supernova burst neutrinos

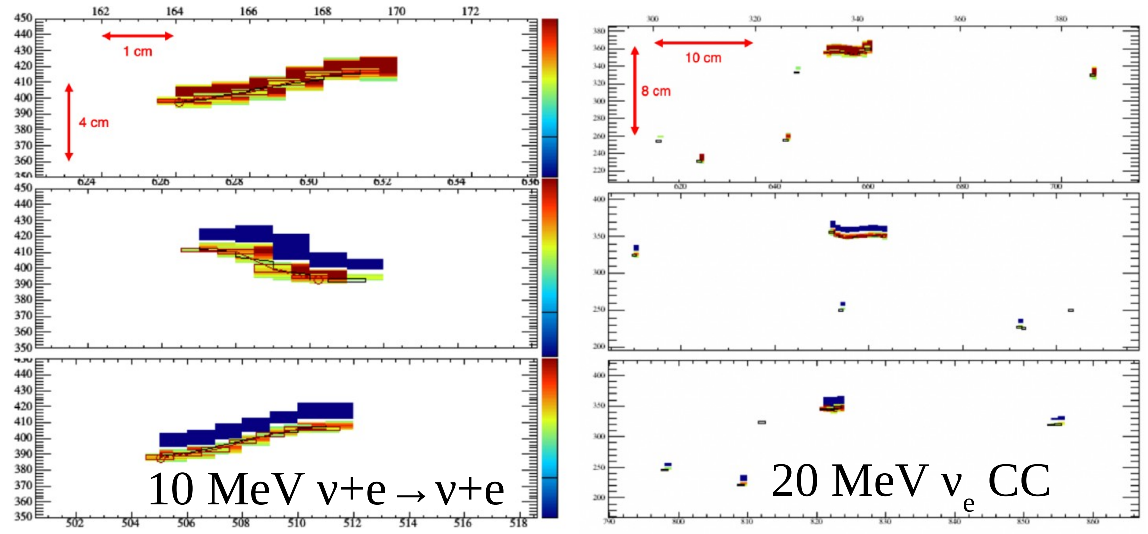
- DUNE will observe ~thousands of neutrino interactions from a galactic supernova burst
- Time and energy spectra are sensitive to core collapse mechanism and stellar evolution
  - Neutronization through electron capture in the core (unique to DUNE → determine neutrino mass ordering)
  - Dominated by matter falling into core during accretion
  - Emission cools as neutrinos diffuse

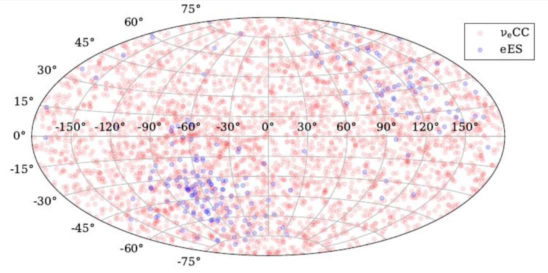


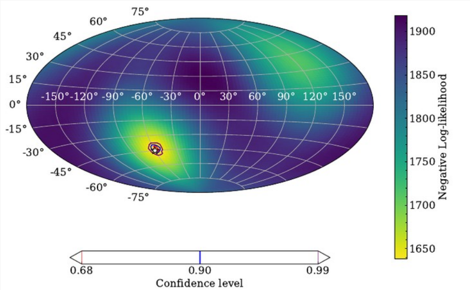




Supernova pointing and multi-messenger astronomy

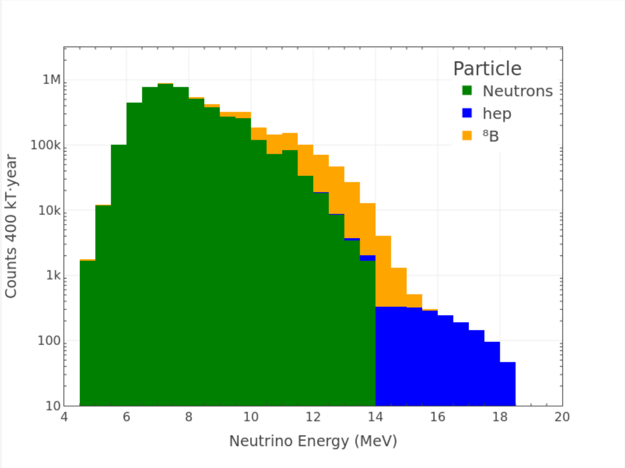


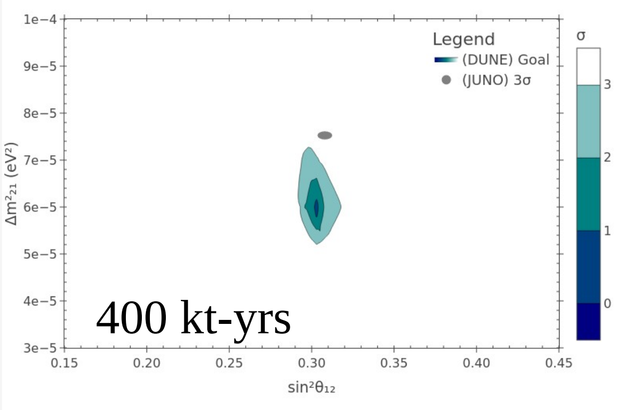




- DUNE can identify elastic scatters by the absence of nuclear de-excitation photons
- Enables pointing resolution as good as ~5° depending on location
- Paper just submitted to arXiv (or maybe not yet, update this)

DUNE sensitivity to solar neutrinos

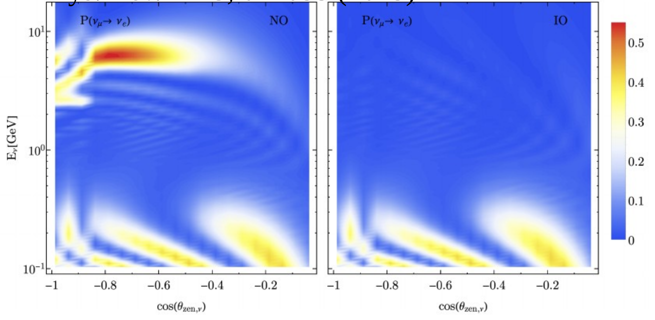


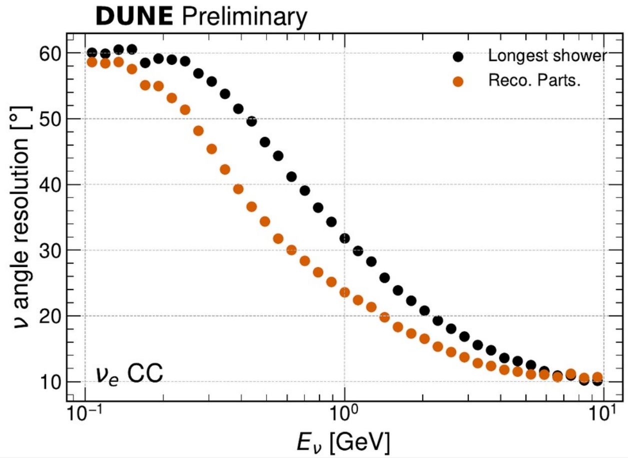


- Despite a large neutron background at low energies, DUNE has excellent sensitivity to ^{8}B solar neutrinos above ~10 MeV, and discovery sensitivity to the hep solar flux
- DUNE can improve upon existing solar oscillation measurements via day-night asymmetry induced by matter effects → comparison with JUNO
- Current analysis assumes dedicated trigger and flash matching (needed for fiducialization)

Atmospheric neutrinos: angle reconstruction including hadrons

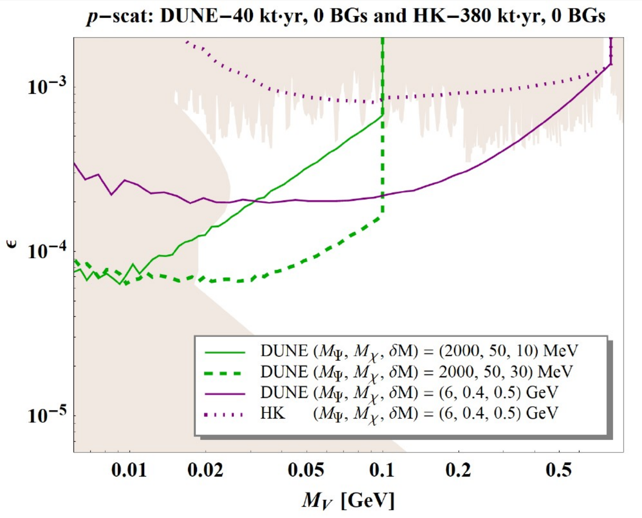
Phys. Rev. X 13, 041055 (2023)

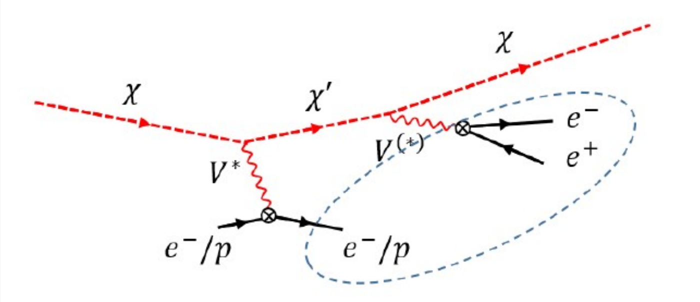




- Main advantage of DUNE for atmospheric neutrinos is the reconstruction of the neutrino direction
- Including reconstructed hadrons substantially improves angle resolution, especially at lower neutrino energies
- Potential to extend to low energies has been studied phenomenologically, see Phys. Rev. Lett. 123, 081801 (2019)
- DUNE analysis in progress

BSM searches with the Far Detector

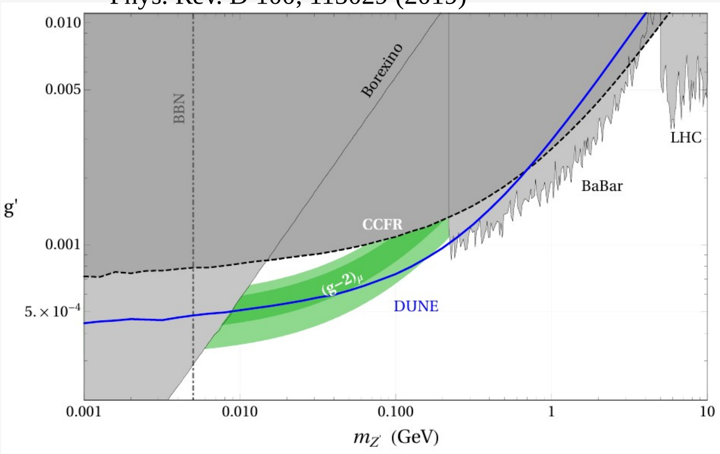


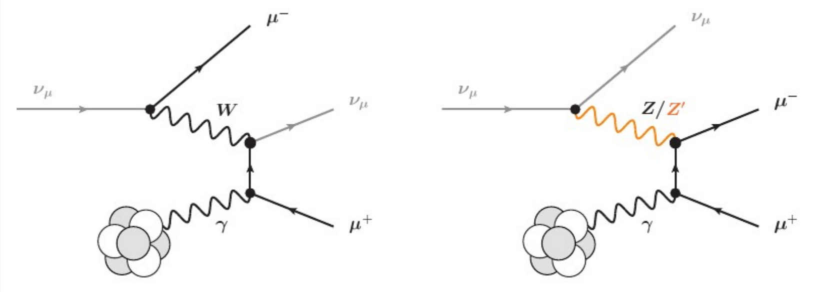


- DUNE Far Detector is sensitive to rare processes (nucleon decay, n-n̄ oscillation, etc.) and new physics of cosmogenic origin
- Key strengths of DUNE:
  - Ability to detect low-energy particles (for iBDM, signal is a soft e/p and spatially proximate e+/e- pair)
  - Ability to reconstruct direction including hadrons (i.e. for BDM produced in Sun or Galactic Center)

BSM searches with the Near Detector

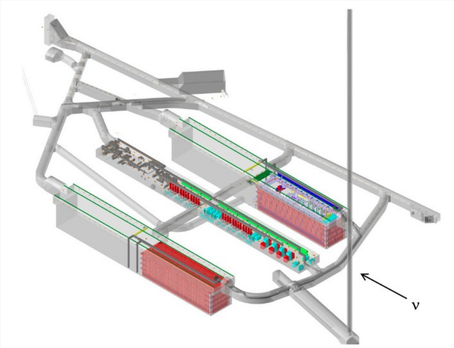
Phys. Rev. D 100, 115029 (2019)

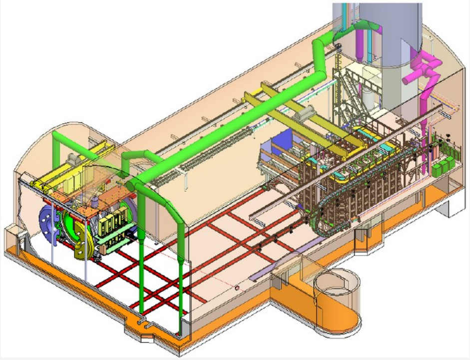




- DUNE Near Detector is sensitive to rare processes in the beamline (HNL, LDM) and to BSM contributions to neutrino interactions (ν tridents)
- Key strengths of DUNE:
  - 120 GeV proton beam and very high intensity
  - LAr ND with 50-70t fiducial mass
  - Low density ND (SAND) → increased S/B for decays in ND volume

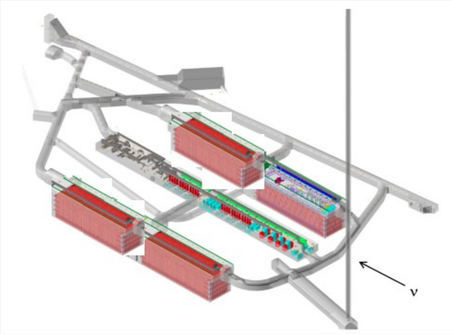
DUNE construction: Phase I

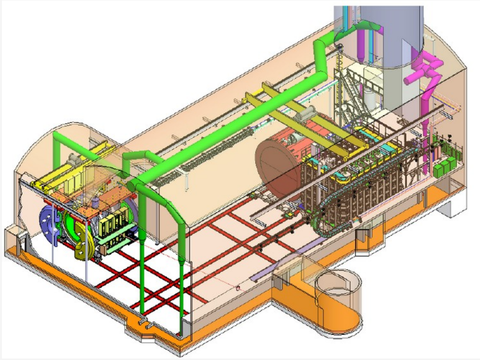




- Full Near and Far Site facility
- Two LArTPC modules (VD & HD), each 17 kt Ar
- 1.2 MW upgradeable neutrino beamline
- Movable LArTPC ND+muon catcher, SAND

DUNE construction: Phase II





- Two additional FD modules
- Beamline upgrade to >2MW (could happen before operations begin)
- More capable Near Detector (ND-GAr)

P5 report in the US strongly endorses DUNE Phase I & II

Recommendation 1: As the highest priority independent of the budget scenarios, complete construction projects and support operations of ongoing experiments and research to enable maximum science.

b. The first phase of DUNE and PIP-II to open an era of precision neutrino measurements that include the determination of the mass ordering among neutrinos.

Recommendation 2: Construct a portfolio of major projects that collectively study nearly all fundamental constituents of our universe and their interactions, as well as how those interactions determine both the cosmic past and future.

b. A re-envisioned second phase of DUNE with an early implementation of an enhanced 2.1 MW beam—ACE-MIRT—a third far detector, and an upgraded near-detector complex as the definitive long-baseline neutrino oscillation experiment of its kind

Recommendation 4: Invest in a comprehensive initiative to develop the resources—theoretical, computational, and technological—essential to realizing our 20-year strategic vision. This includes an aggressive R&D program that, while

e. Conduct R&D efforts to define and enable new projects in the next decade, including detectors for an e^+e^- Higgs factory and 10 TeV pCM collider, Spec-S5, DUNE FD4, Mu2e-II, Advanced Muon Facility, and line intensity mapping

Elucidate the Mysteries of Neutrinos

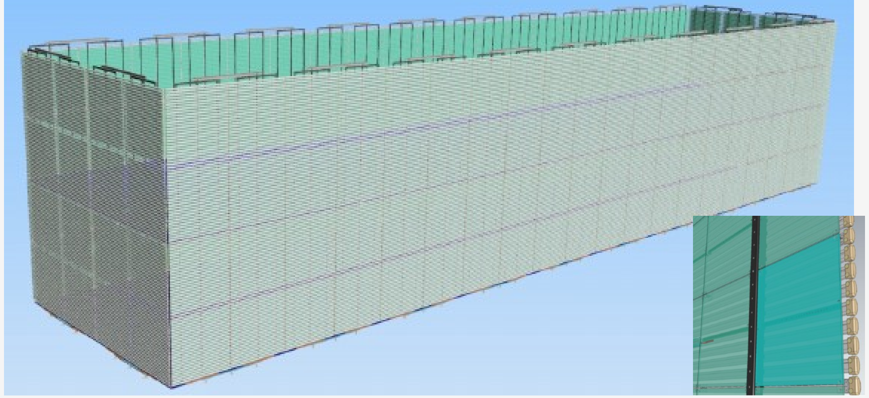
- During the next decade (2024-2034), P5 recommended:
  - Highest priority: Complete DUNE Phase I and begin operations
  - Implement ACE-MIRT accelerator/beamline upgrades before operations begin
  - Design and build FD3 and MCND
  - Perform R&D toward FD4

Building DUNE: construction schedule

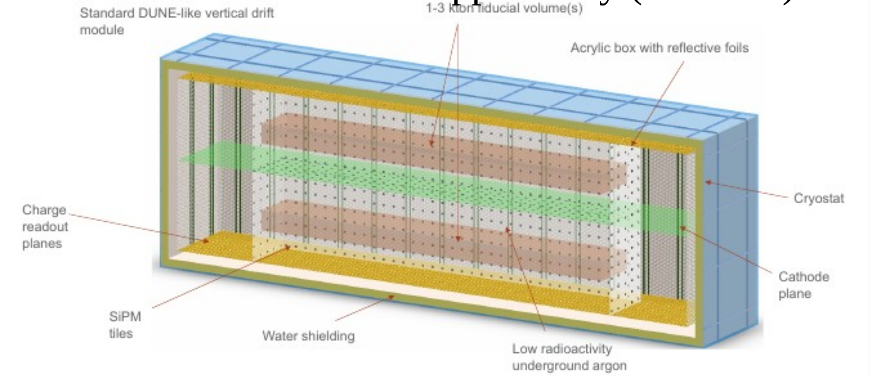
- Far site excavation is complete
- Next: Building & Site Infrastructure work until mid-2025
- Cryostat warm structure is on its way to US from CERN to be installed in 2025-26
- Detector installation in 2026-27
- Purge and fill with argon in 2028
- Physics in 2028 or early 2029
- Beam physics with Near Detector 2031

Phase II FD: additional mass + opportunities to expand physics reach

APEX for FD3

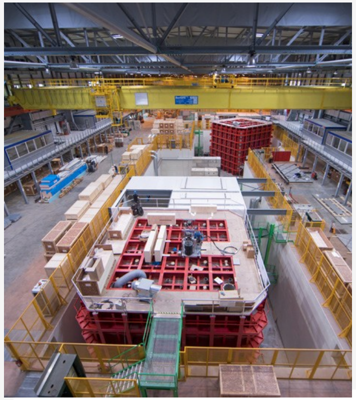


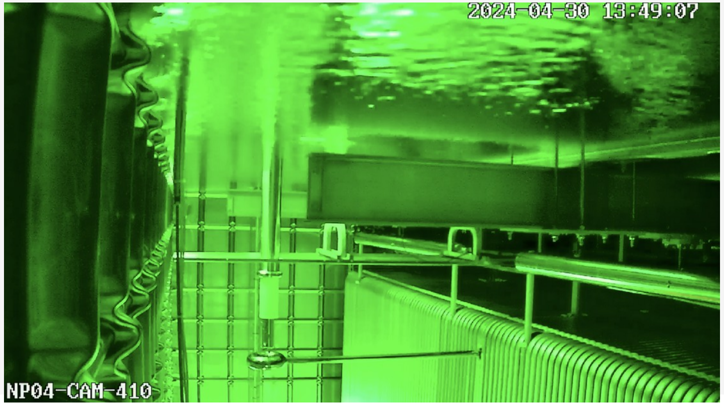
Possible FD4 Module of Opportunity (SLOMO)

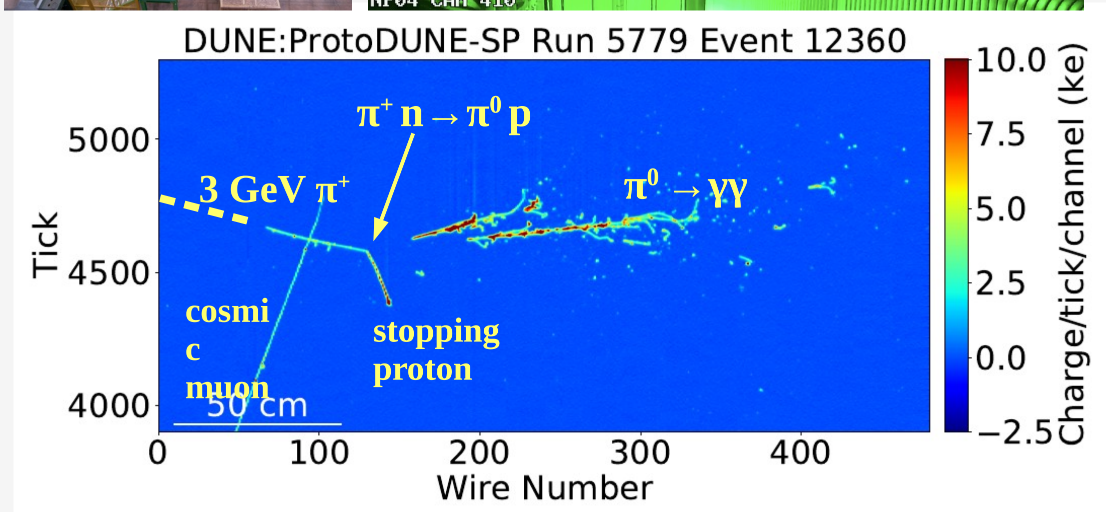


- Vertical Drift module is the baseline design for Phase II FD modules
- Pursuing low-hanging improvements to light collection for FD3, including Aluminum Profiles with Embedded X-ARAPUCA, essentially integrating light detectors into field cage
- FD4 is the “Module of Opportunity”, and more ambitious designs are being considered, including a very low background module, additional Xe doping, pixel readout, and non-LAr technologies

ProtoDUNE: preparing for second runs

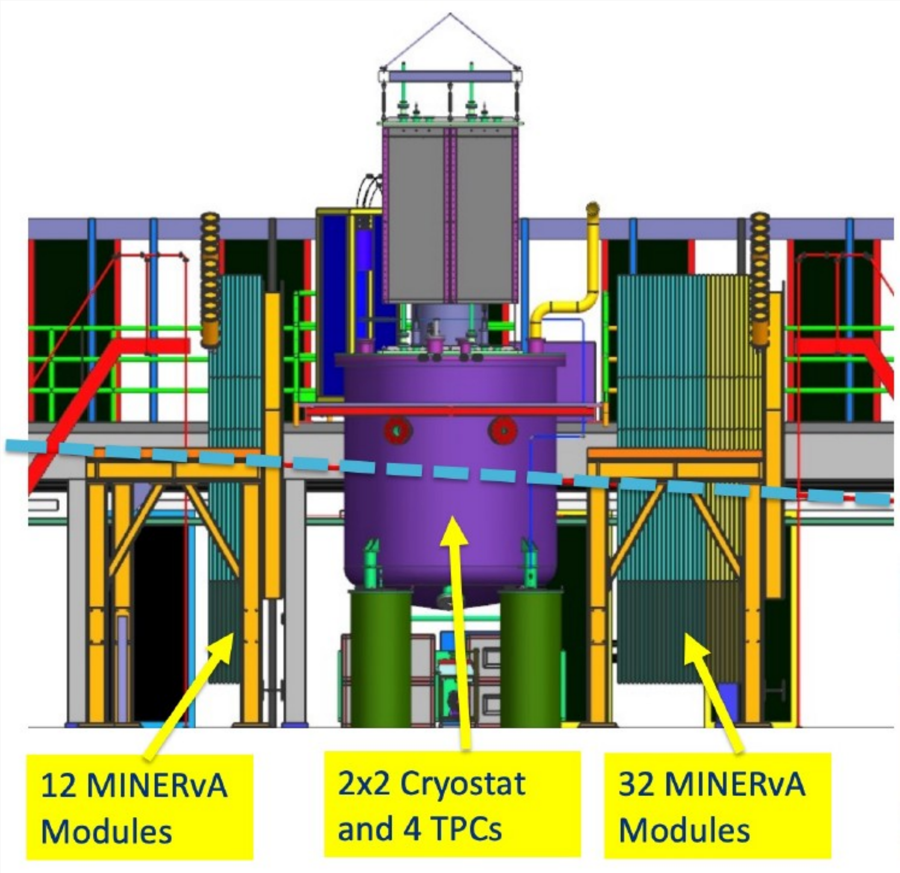






- Successful prototype of hoizontal drift in 2018 (ProtoDUNE-SP)
- ProtoDUNE-HD completed filling 30th April, running since May, with beam coming this week
- LAr will be transferred to ProtoDUNE-VD in October for running starting in early 2025

ND-LAr 2x2 prototype: DUNE's first neutrino detector in a beamline



- Individual ND-LAr prototype modules have been operated with cosmics at Bern
- "2x2" is a four-module integration test in the Fermilab NuMI beam
- Re-purposed MINERvA scintillator and calorimeter planes mimic the role of TMS in the DUNE ND
- Will demonstrate reconstruction with natively 3D readout in a neutrino beam with similar event rate to DUNE

ND-LAr 2x2 prototype: DUNE’s first neutrino detector in a beamline

more

photos

- Filling completed on some day
- Some statement about status to be determined

Summary

- DUNE is a long-baseline oscillation experiment and neutrino observatory
  - Unique and complementary reach in oscillations, MeV-scale neutrinos, and BSM searches
- DUNE has an active prototyping program, with excavation complete and components under construction → start of science before the neutrino turns 100
- See also 33 DUNE posters!

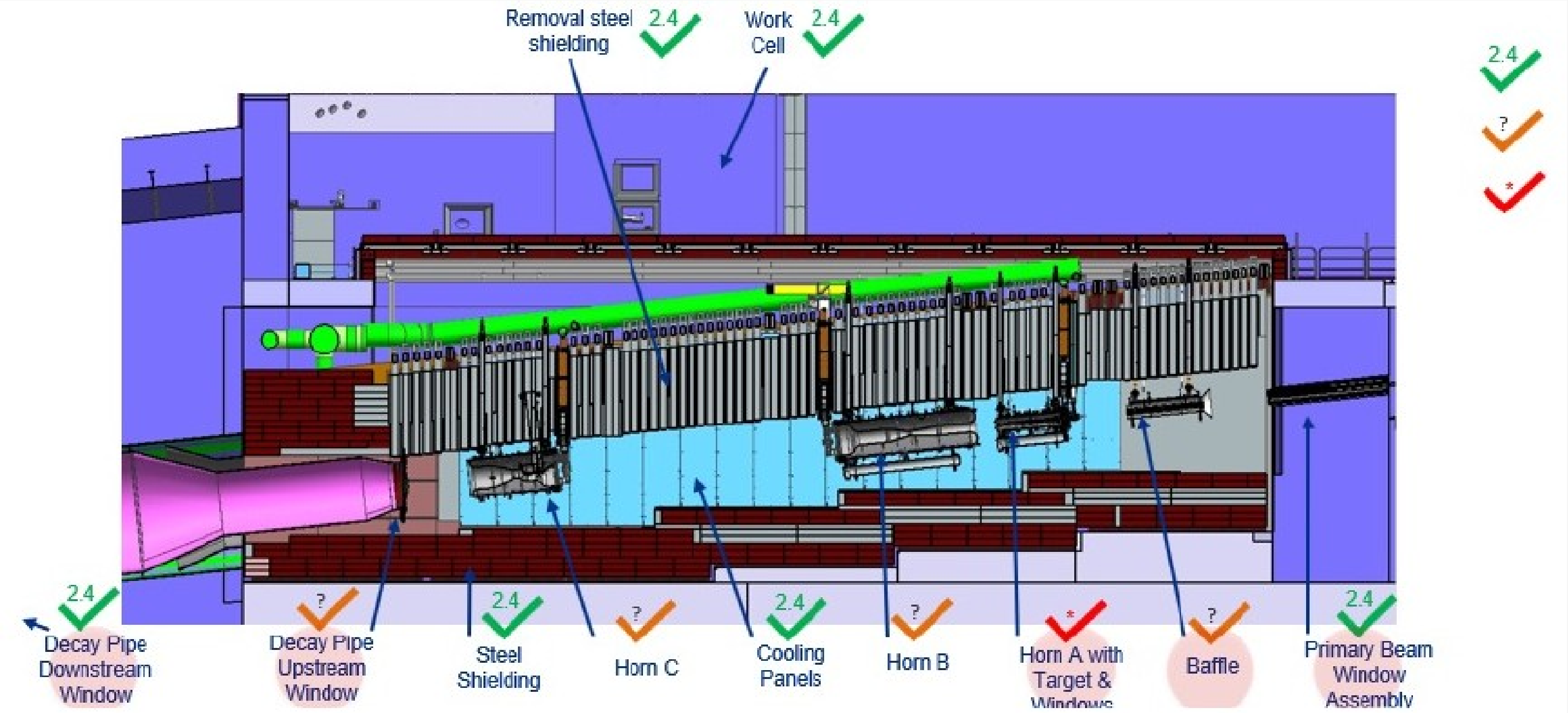
DEEP UNDERGROUND NEUTRINO EXPERIMENT

Backup Slides

Accelerator Complex Evolution: Main Injector Ramp & Target

		PIP-II Booster			
Operation scenario	**Present**	**PIP-II**	**ACE (a)**	**ACE (b)**	**units**
MI 120 GeV cycle time	**1.13**	**1.2**	**0.9**	**0.7**	s
Booster intensity	**4.7**	**6.5**			10^{12} p
Booster ramp rate	15	**20**			Hz
MI power	**0.96**	**1.2**	**1.7**	**2.1**	MW
cycles for 8 GeV	**6**	**12**	**6**	**2**	
Available 8 GeV power	30	83	56	24	kW

Accelerator Complex Evolution: Main Injector Ramp & Target



- Many beamline components are designed for 2.4 MW
- Others can likely be operated to 2 MW with minor modifications
- Target is the most critical component