Deep Underground Neutrino Experiment: DUNE

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University of Cambridge
for the DUNE Collaboration

Interdisciplinary Developments in Neutrino Physics
Monday 28th March 2022

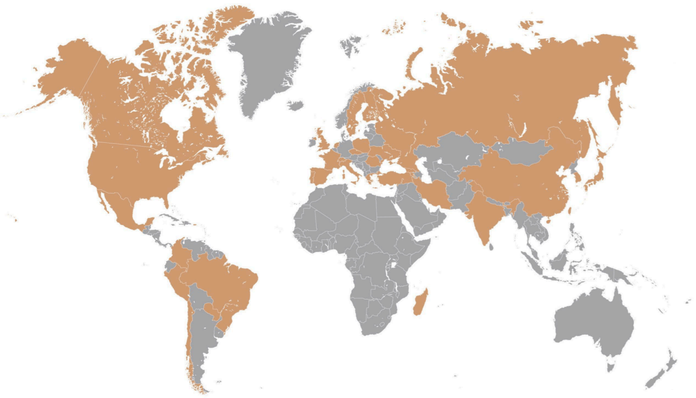
UNIVERSITY OF CAMBRIDGE

DUNE

Overview

- Introduction
- Long-baseline neutrino oscillations
- Other physics highlights
- Prototyping
- Summary

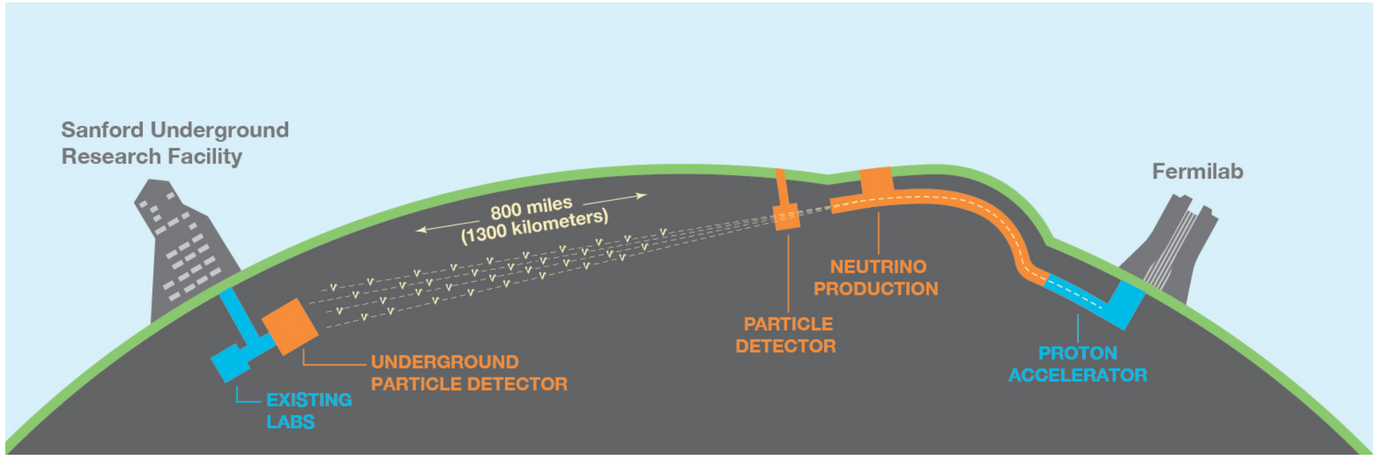
1300+ collaborators
200+ institutions
30+ countries and CERN



CERN, January 2020 - our last face-to-face collaboration meeting

Deep Underground Neutrino Experiment

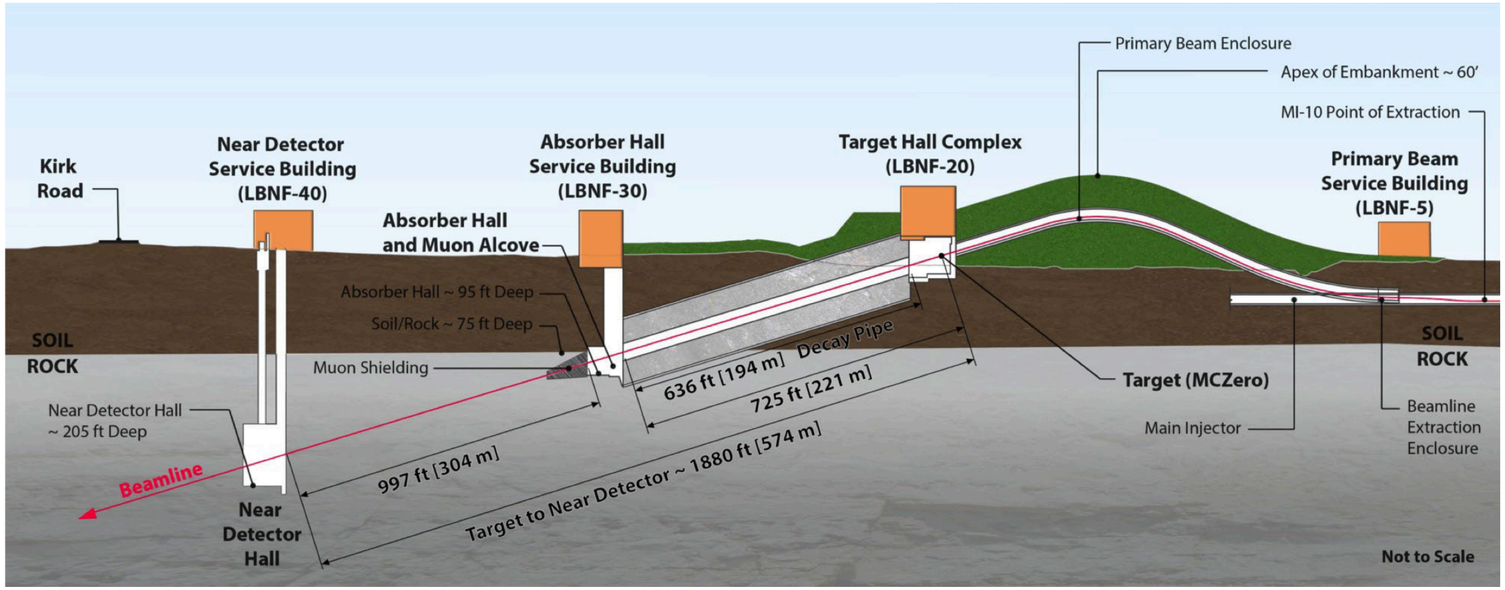
- Next-generation long-baseline neutrino oscillation experiment

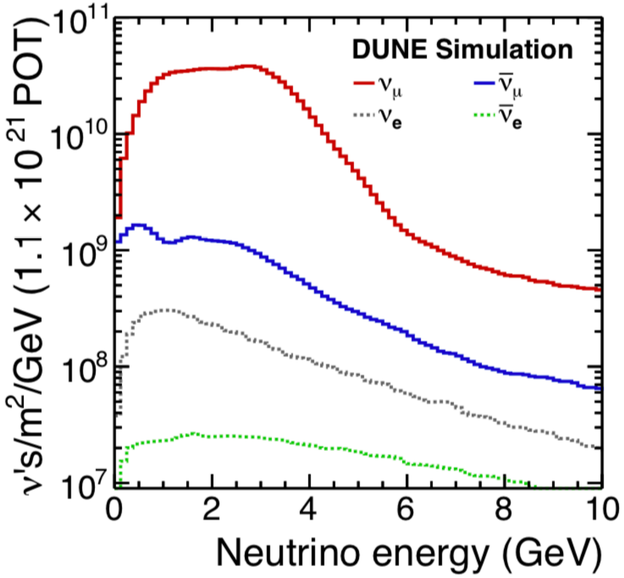


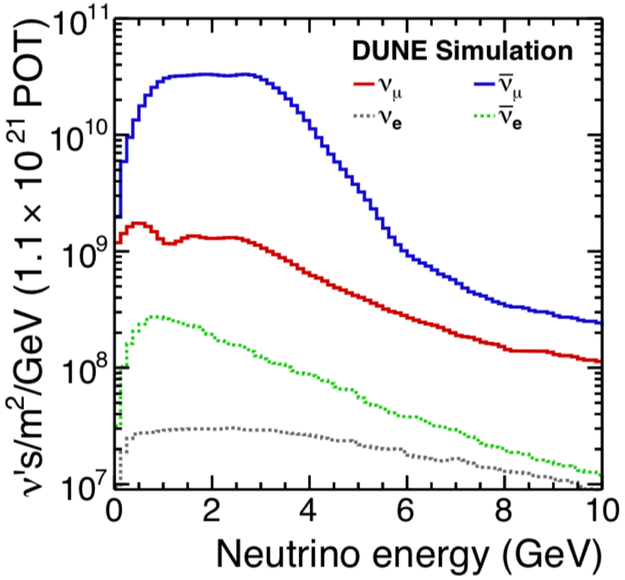
- High power (anti)neutrino beam produced at Fermilab
- 70kt liquid argon far detector at SURF formed from four modules
  - Approximately one mile underground
- Near detector at Fermilab
- Wide physics programme beyond long-baseline neutrino oscillation physics

LBNF Neutrino Beam

- New neutrino beam to be built at Fermilab
  - 120 GeV protons interact with a carbon target
  - Initial power of 1.2 MW, upgradable to 2.4 MW
  - Wideband beam
  - Runs in neutrino and antineutrino modes





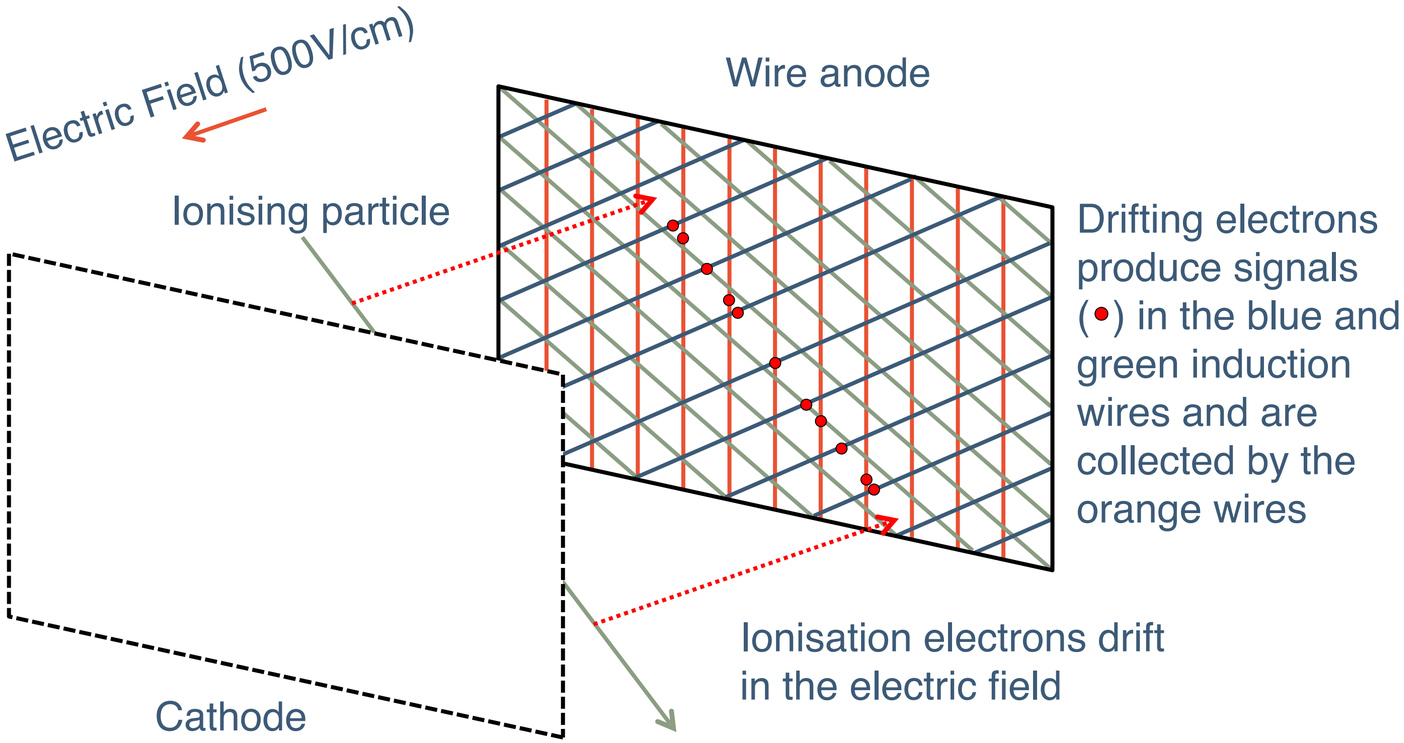


B. Abi, et al., (DUNE Collaboration), Long-baseline neutrino oscillation physics potential of the DUNE experiment *Eur. Phys. J. C* **80** 10, 978 (2020)

Liquid Argon TPCs

- The far detector and part of the near detector will be LArTPCs
- Ionisation electrons drift in the electric field to the readout planes

- Horizontal Drift (HD)
  - Electric field is horizontal
  - -180 kV on the cathode
  - 3.6m drift length
  - Similar to previous LArTPCs
  - Three wire readout planes
  - Photon detector system embedded in the wire planes (X-ARAPUCAs)



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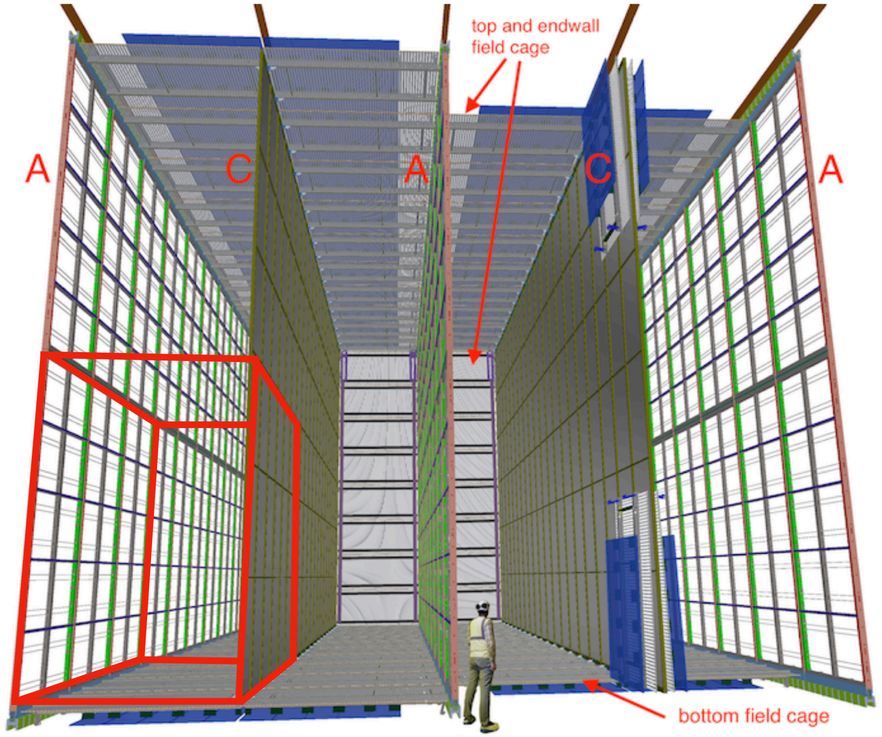
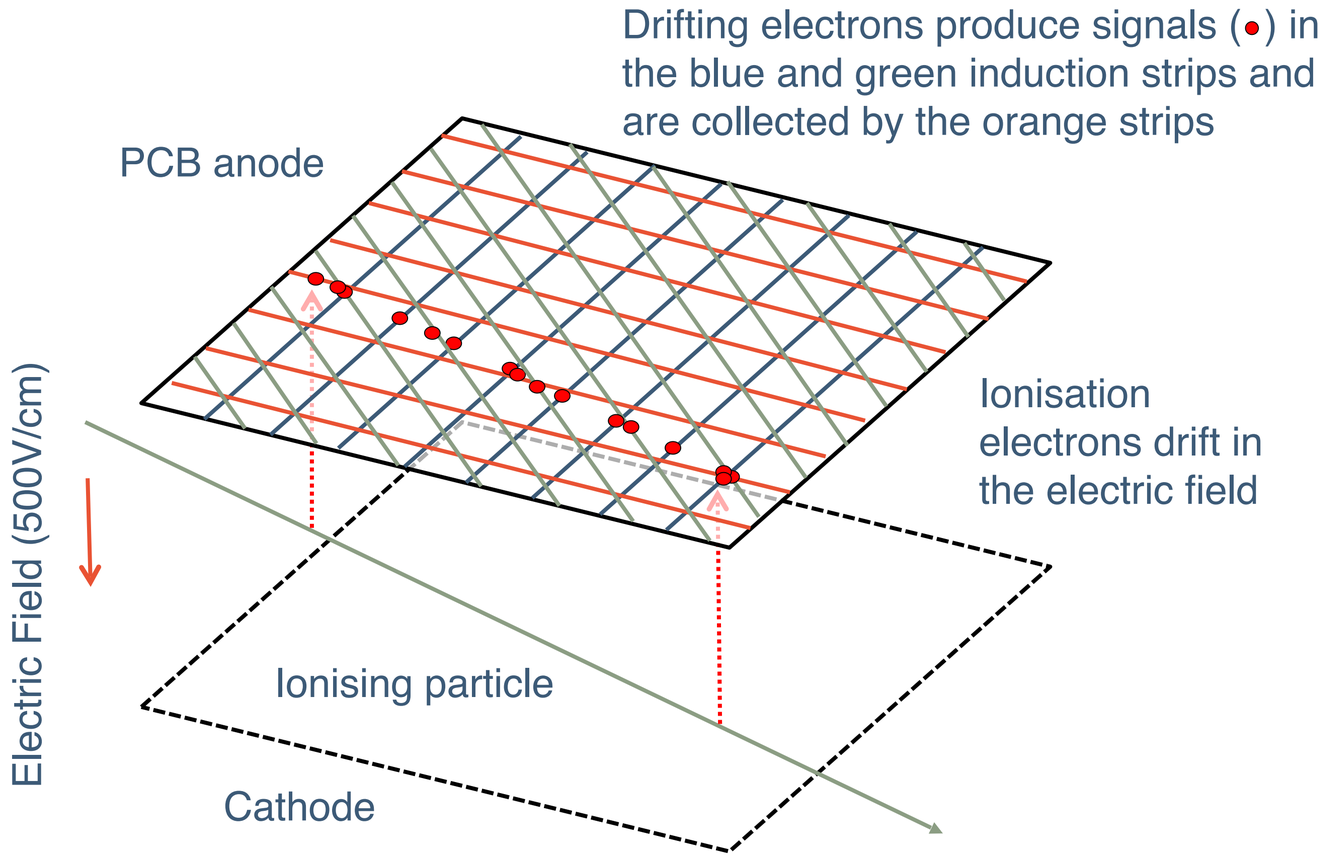


A = Anode, C = Cathode

Liquid Argon TPCs

- The far detector and part of the near detector will be LArTPCs
- Ionisation electrons drift in the electric field to the readout planes

- Vertical Drift (VD)
  - Electric field is vertical
  - 6.5 m drift length
  - -300 kV on the cathode
  - Perforated PCB with three readout views
  - Photon detector system on the cryostat walls and cathode (X-ARAPUCAs)



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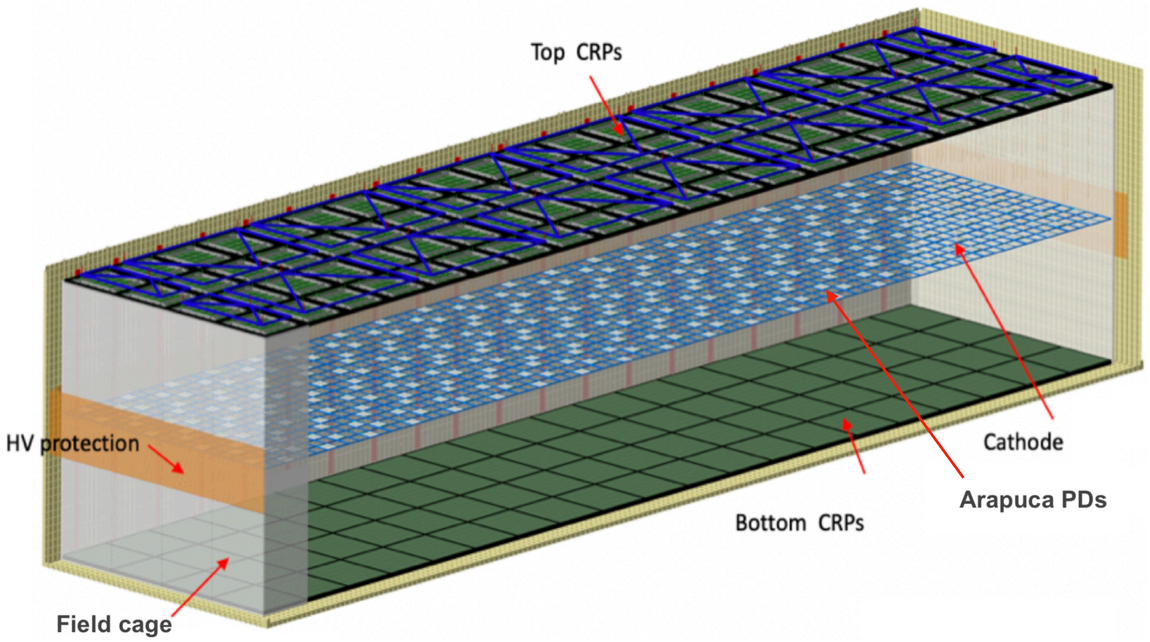
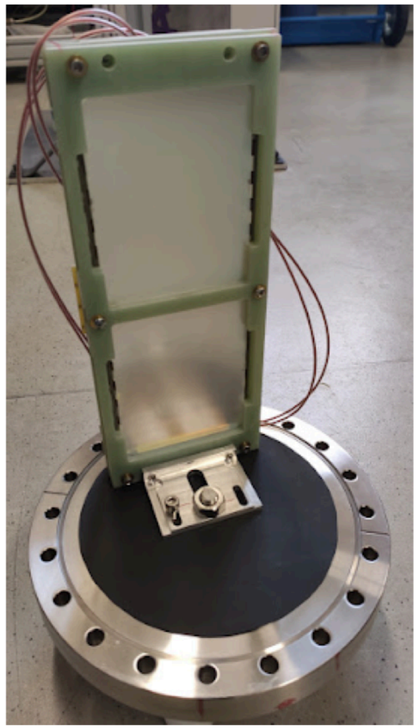
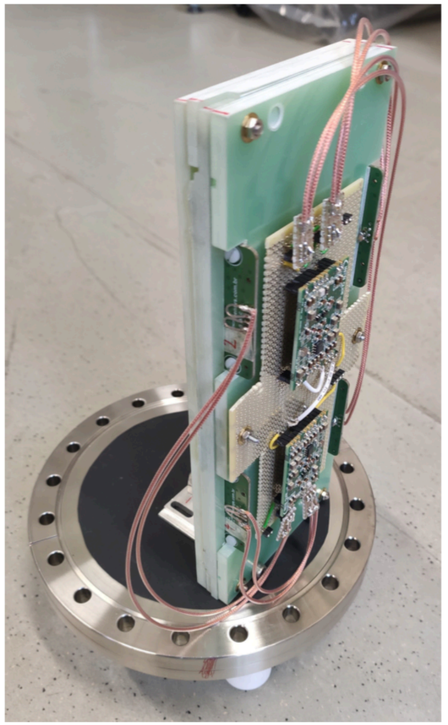


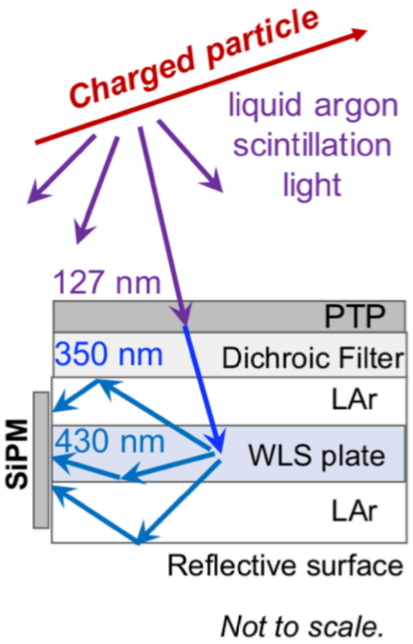
Photon detection system

- Use X-ARAPUCAs to measure the scintillation light from LAr
  - LAr scintillation light has a wavelength of ~127 nm (VUV)
- Hybrid between a light trap and a light guide
  - Light wavelength shifted to visible
  - Total internal reflection
- Silicon photomultiplier readout

- Evolution of the ARAPUCAs that were used in ProtoDUNE





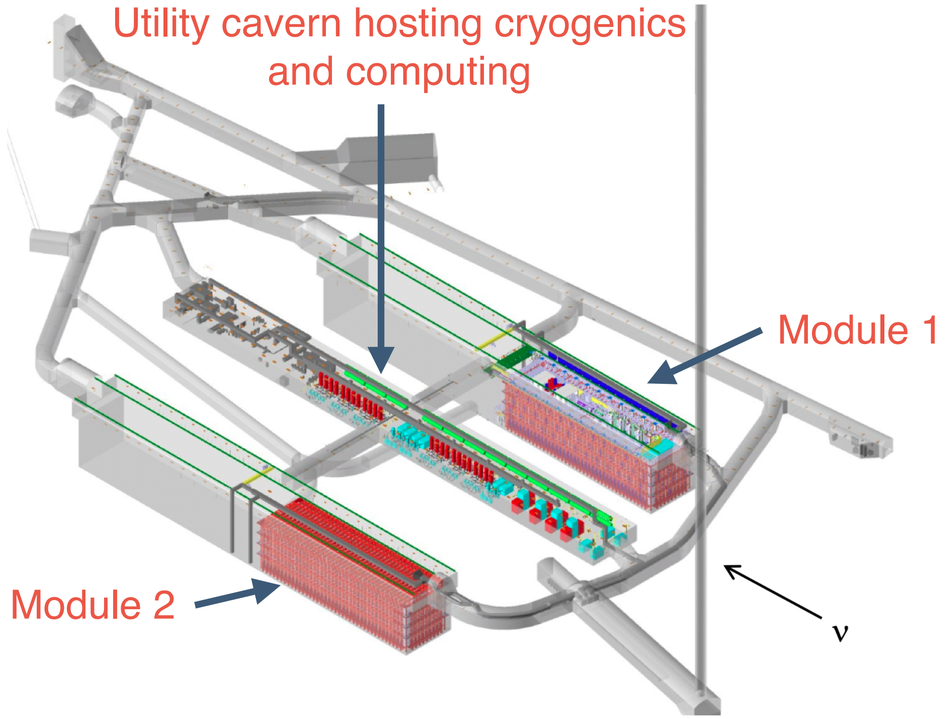


Far Detector

- Module 1 will be HD, Module 2 will be VD
  - Each have total LAr mass of ~17 kton
  - These two modules form Phase I

- Modules three and four complete the full FD
  - Choice of technology for these modules is currently undecided

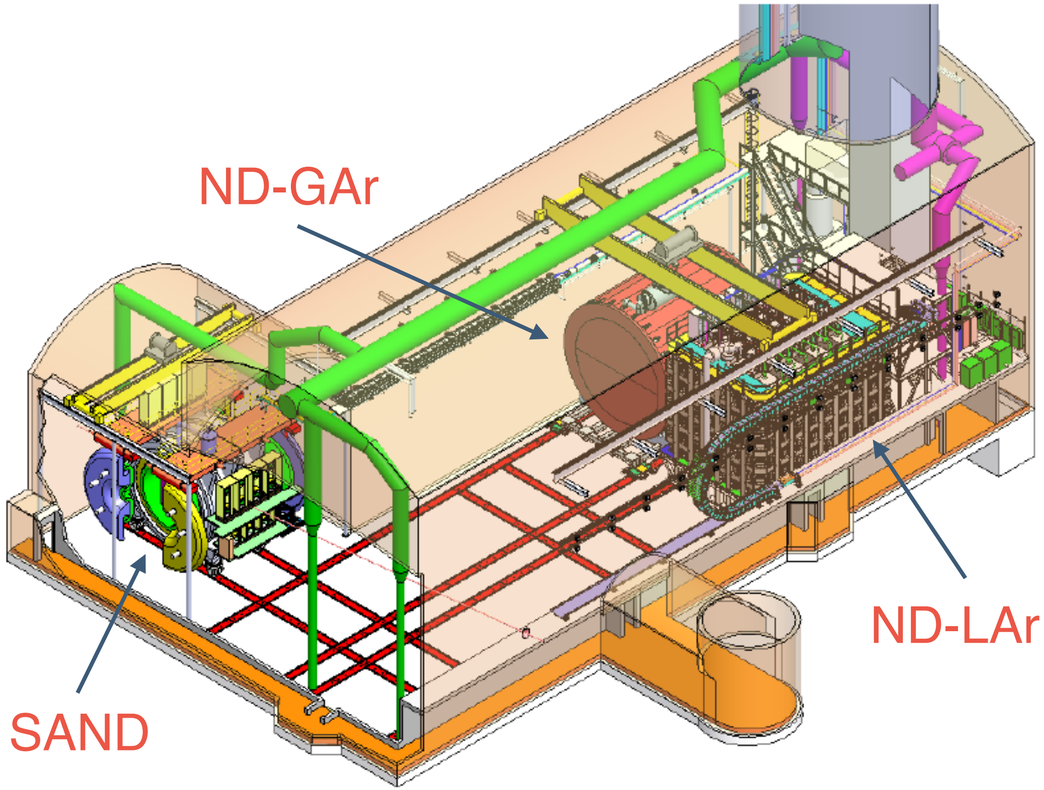
- Cavern excavations have begun at SURF
  - One mile underground
  - The FD is becoming a reality!



Near Detector

- Full ND suite will consist of three detectors
  - LArTPC called ND-LAr
  - Gaseous argon TPC: ND-GAr
  - A hybrid tracker called SAND

- The ND provides key constraints
  - Measure the neutrino flux
  - v-Ar and $\bar{\nu}$-Ar interaction cross sections
    - Also other target nuclei
  - Constrain LArTPC detector response



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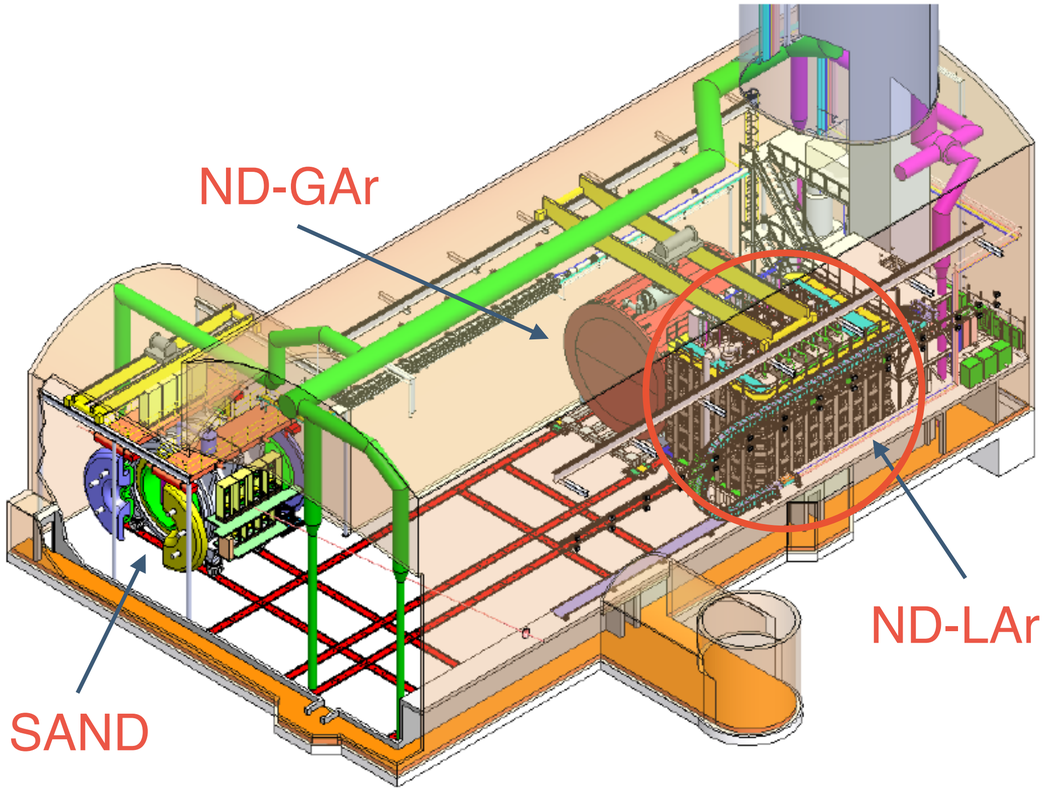
- ND-LAr is a modular LArTPC
  - 50t fiducial mass
  - Pixel readout
  - Based on the ArgonCube design
  - 2x2 module demonstrator will shorty begin testing in the NuMI beam



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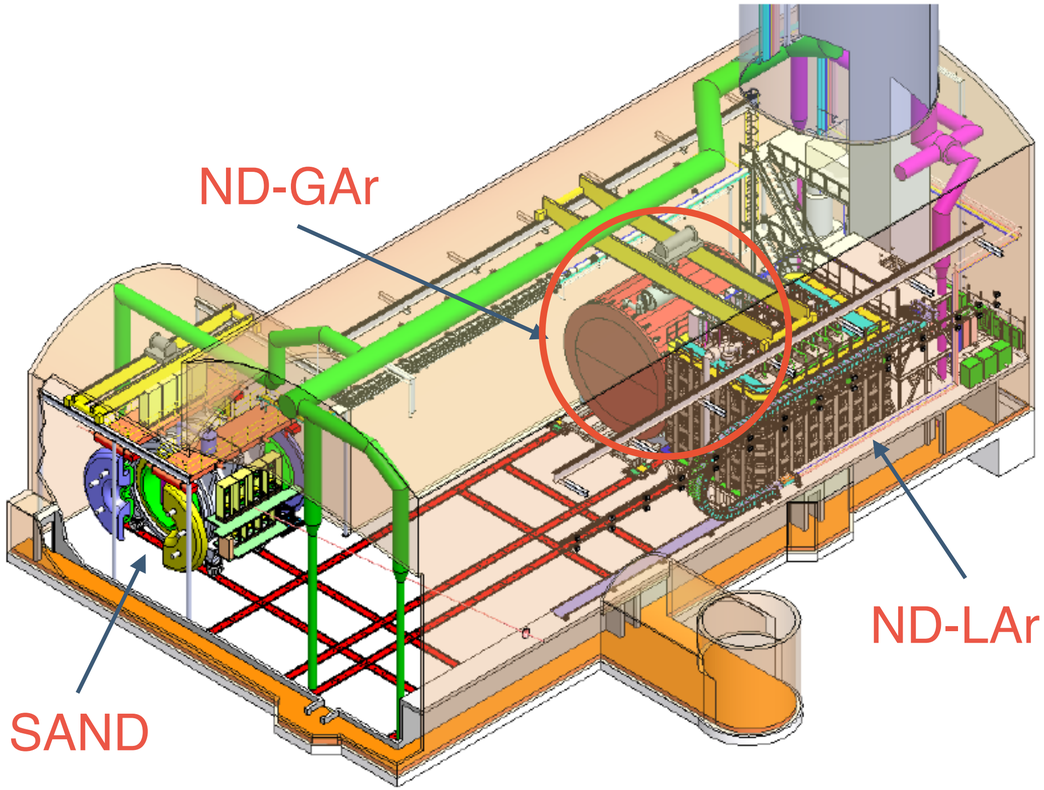
- ND-GAr magnetised GArTPC
  - Very low detection threshold
  - 4π tracking capability for cross-section measurements
  - Measure muons from ND-LAr
    - Momentum and charge



Near Detector

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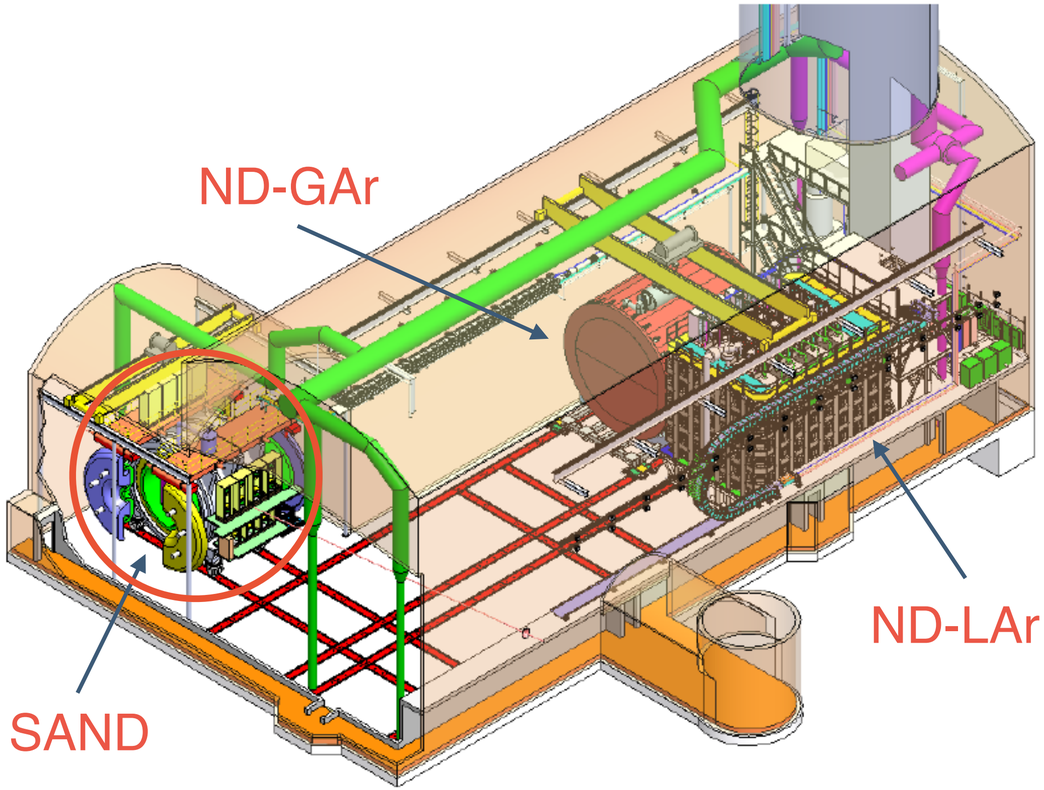
  - Gaseous argon TPC: ND-GAr
  - A hybrid tracker / ECAL: SAND

- SAND
  - Tracker surrounded by ECAL
  - 0.6T magnet from KLOE
  - Monitors the neutrino beam on-axis
  - Measures ν and $\bar{\nu}$ cross sections



Near Detector

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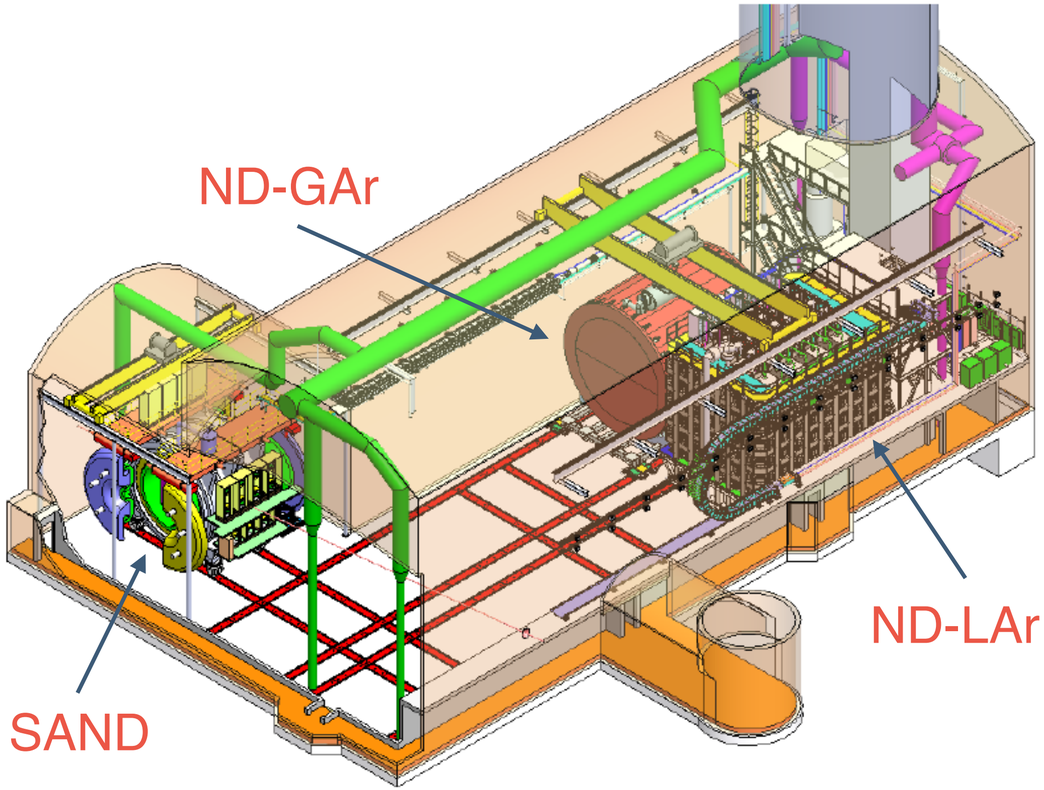
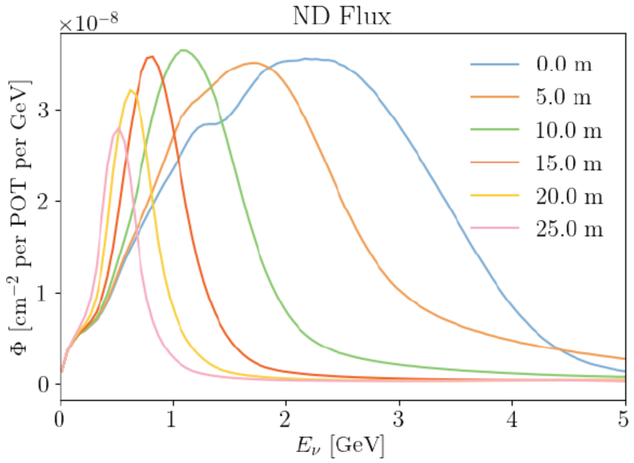


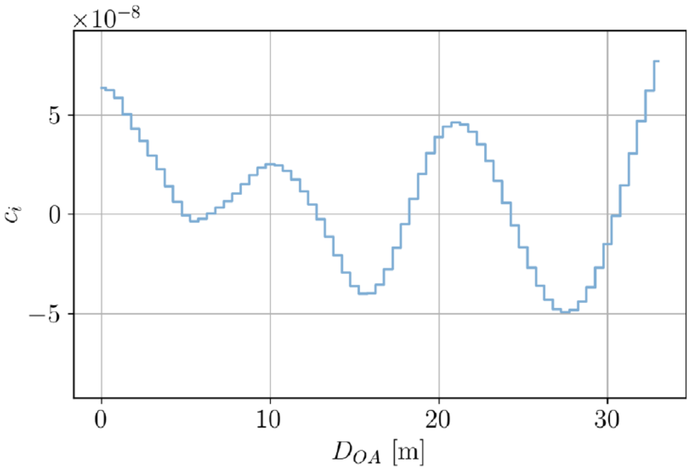
- ND-LAr and ND-GAr can move from on-axis to 33m off-axis
  - Directly probes energy dependence of interactions
- A temporary muon spectrometer (TMS) will stand-in for ND-GAr initially
  - MINOS-like magnetised scintillator tracker to measure muons exiting ND-LAr

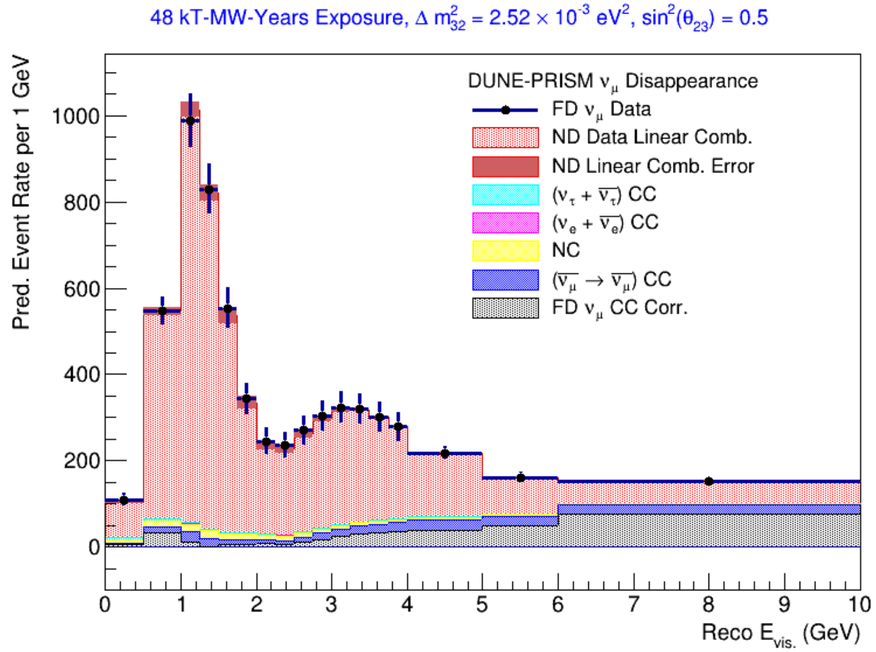
PRISM approach

- The ND flux isn't identical to the FD flux
  - Changes as a function of angle due to pion decay kinematics
- Take linear combinations of ND spectra at different off-axis angles to match the oscillated spectrum seen at the FD
- Robust method with minimal dependence on interaction modelling / cross sections



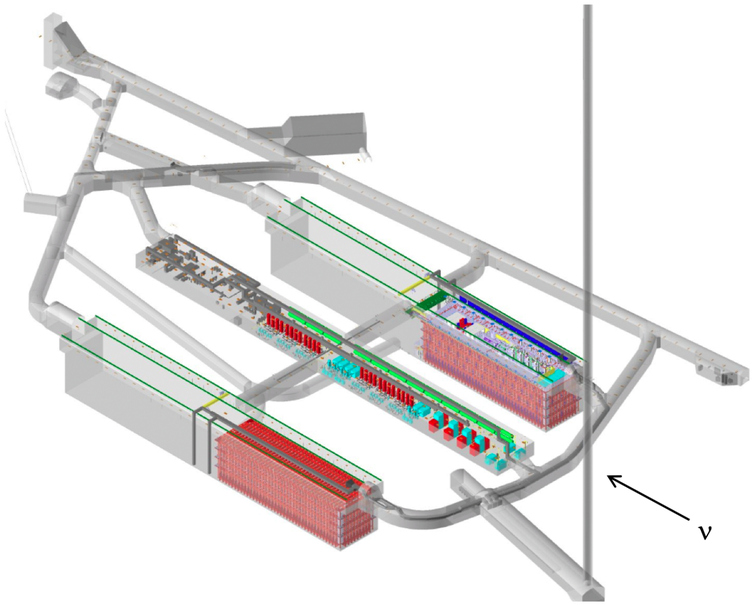
X

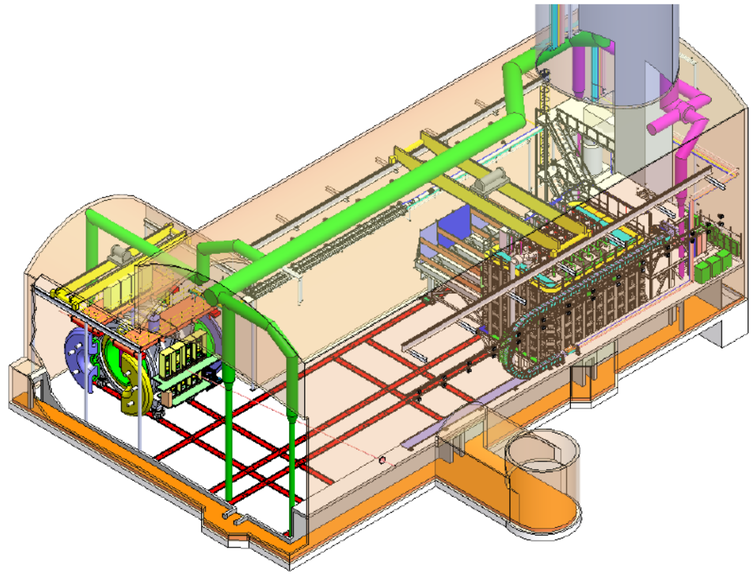




DUNE Construction: Phase I

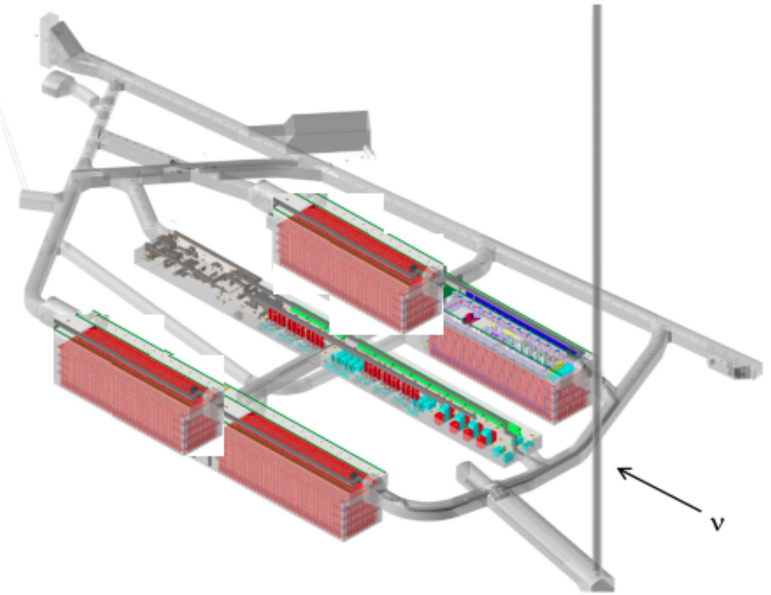
- Neutrino beam running at 1.2 MW beam power
- Two 17kt LArTPC Far Detector Modules
- Near detector:
  - ND-LAr + TMS (movable PRISM concept)
  - SAND

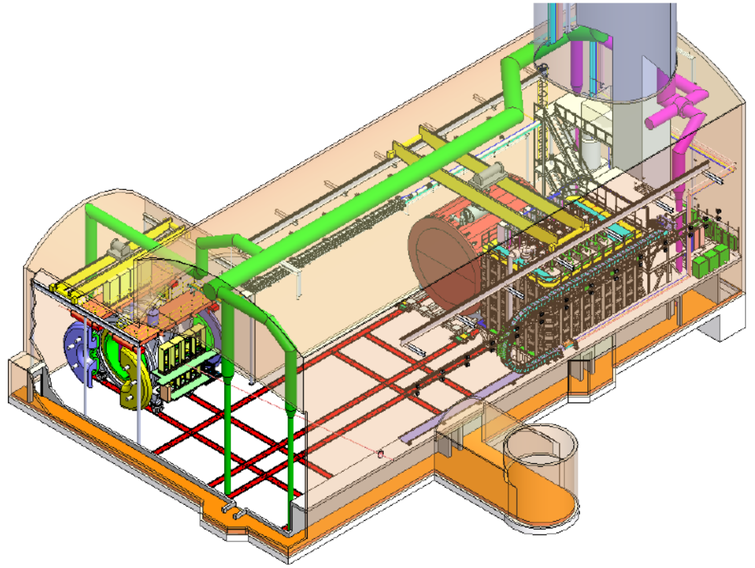




DUNE Construction: Phase II

- Neutrino beam upgraded to 2.4 MW beam power
- Four 17kt LArTPC Far Detector Modules
- Near detector:
  - ND-LAr + ND-GAr (movable PRISM concept)
  - SAND
  - Replacement of TMS by ND-GAr is driven by the enhanced physics capability of ND-GAr
- Allows us to reach the long-term physics goals





The DUNE Physics Programme

- Three-flavour long-baseline neutrino oscillations
  - Search for neutrino-sector CP-violation
  - Precise measurement of θ_{13}
  - Measure the neutrino mass hierarchy
  - Precise measurement of θ_{23}
- Supernova neutrinos
- Solar neutrinos
- Beyond the Standard Model physics
  - Baryon number violation
  - Dark matter
  - Non-standard interactions
  - Sterile neutrinos
  - Large extra dimensions
- Neutrino interaction cross-section measurements

Three-flavour neutrino oscillations

- We can write the PMNS matrix as the product of three matrices $c_{jk} = \cos\theta_{jk}, s_{jk} = \sin\theta_{jk}$

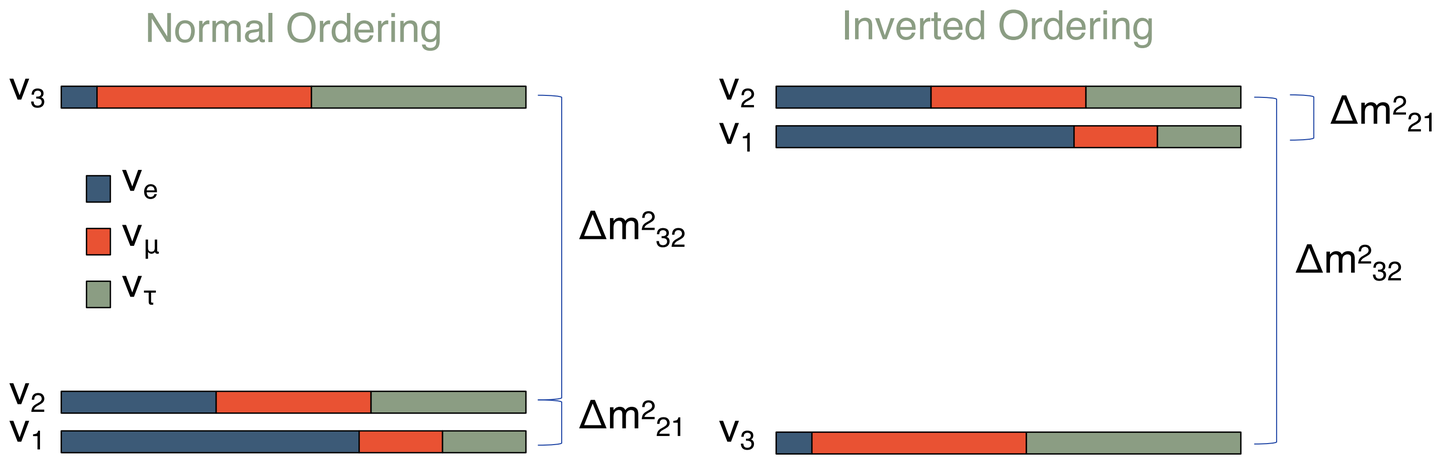
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

ν_μ and $\bar{\nu}_\mu$ disappearance (accelerator and atmospheric)

$\bar{\nu}_e$ disappearance (reactor)
ν_e and $\bar{\nu}_e$ appearance (accelerator)

ν_e and $\bar{\nu}_e$ disappearance (solar and reactor)

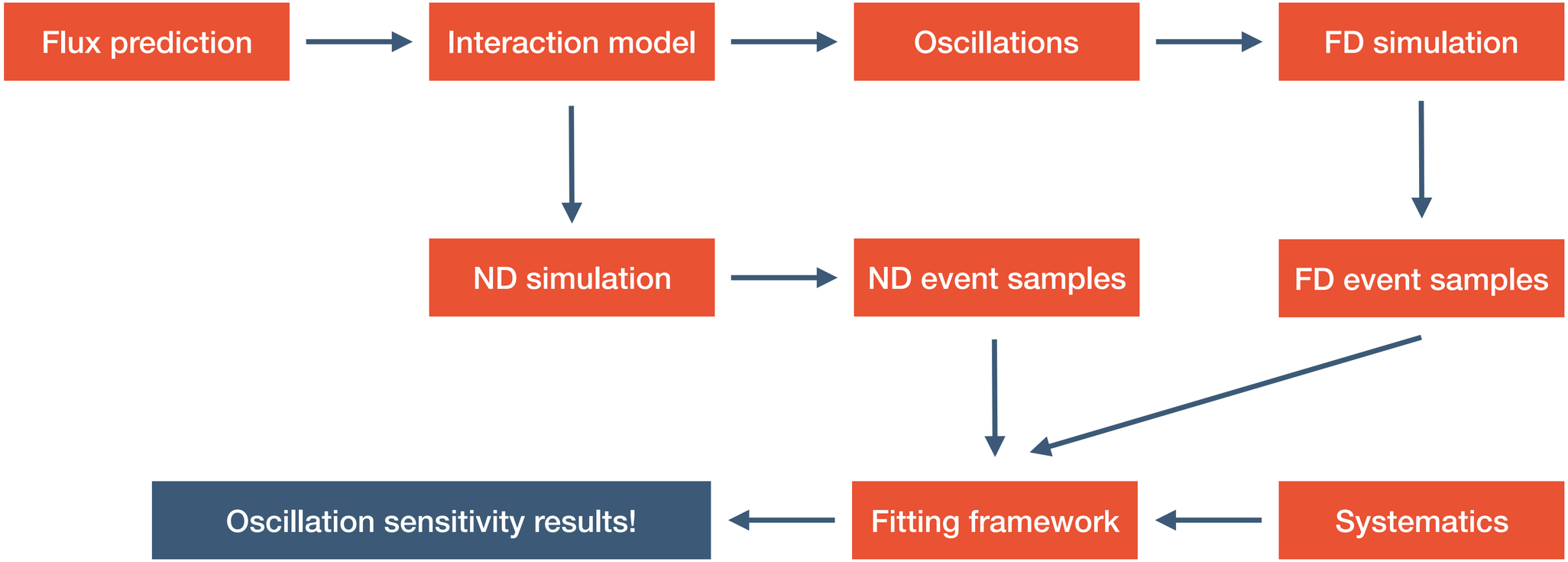
- DUNE will accurately measure four of these parameters
  - θ_{13}, θ_{23}, δ_{CP}, and Δm^2_{32}
  - Measure the sign of Δm^2_{32}
  - Discover CP-violation(?)



- Large matter effect from very long baseline gives high sensitivity to mass ordering

Oscillation analysis strategy

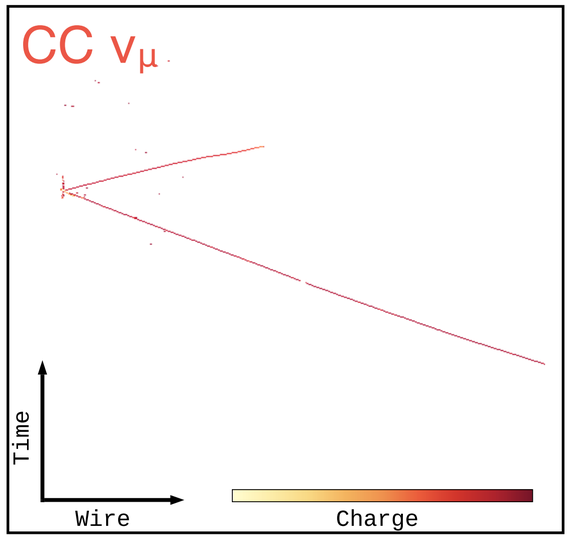
- There are many steps to get to the oscillation parameter sensitivities



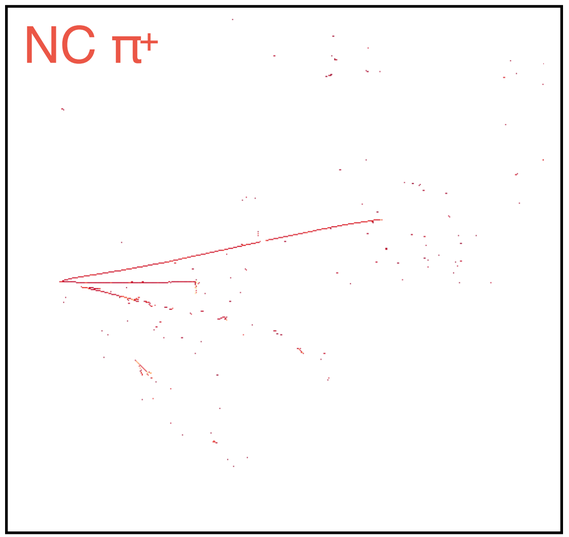
FD: neutrino flavour classification

- A key component of the event selections is selecting CC ν_e and CC ν_μ interactions
  - Important to reject NC backgrounds
- Use a convolutional neural network (CVN) to predict the neutrino flavour
  - Returns scores for how likely events are to be CC ν_μ and CC ν_e

ν_μ disappearance analysis

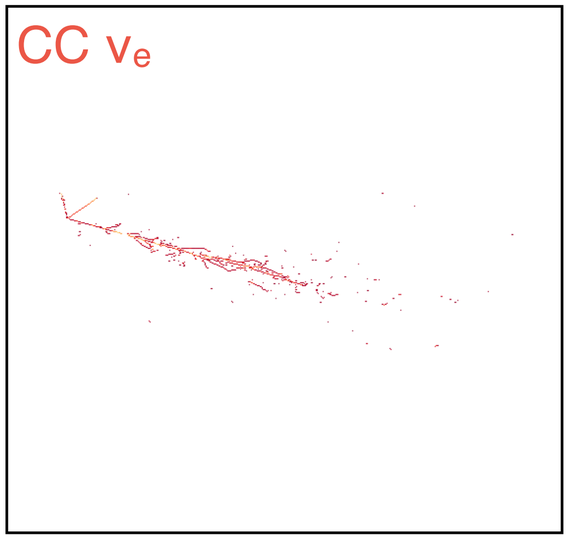


Signal



Primary Background

ν_e appearance analysis



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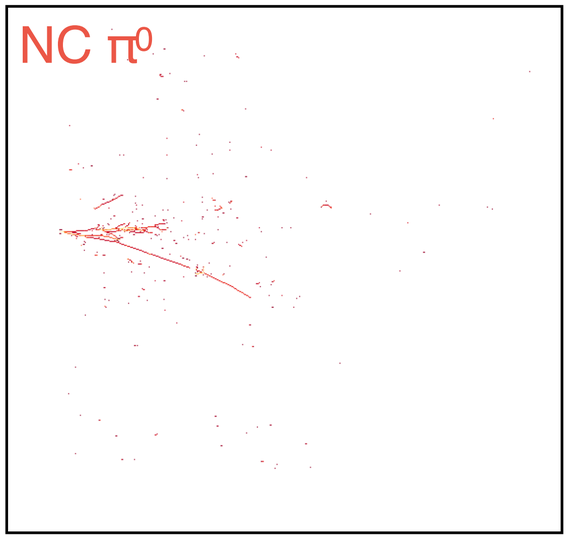


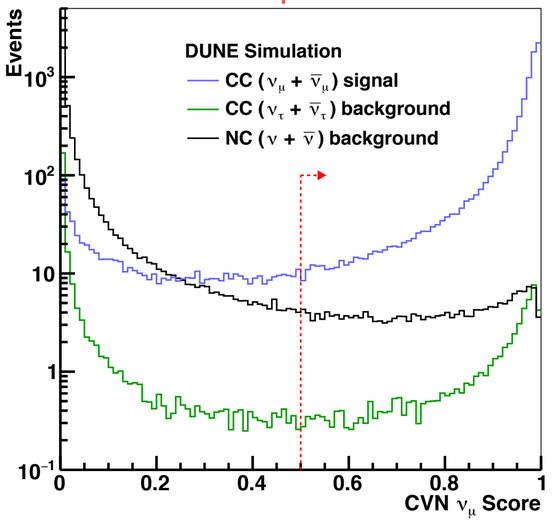
Primary Background

B. Abi, et al., (DUNE Collaboration), Neutrino interaction classification with a convolutional neural network in the DUNE far detector, *Phys. Rev. D* **102**, 092003 (2020)

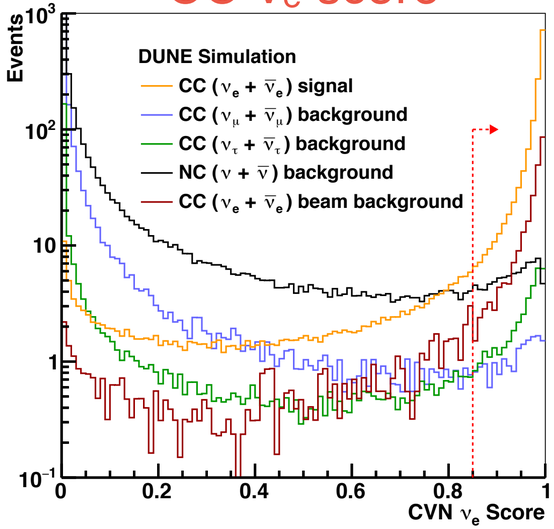
FD: neutrino flavour classification

- The CC ν_μ and CC ν_μ scores give strong separation of signal and backgrounds interactions
- The technique allows for highly efficient and pure event selections
  - CC ν_μ score > 0.5 for CC ν_μ selection
  - CC ν_e score > 0.85 for CC ν_e selection
- Performance in antineutrino mode is slightly better

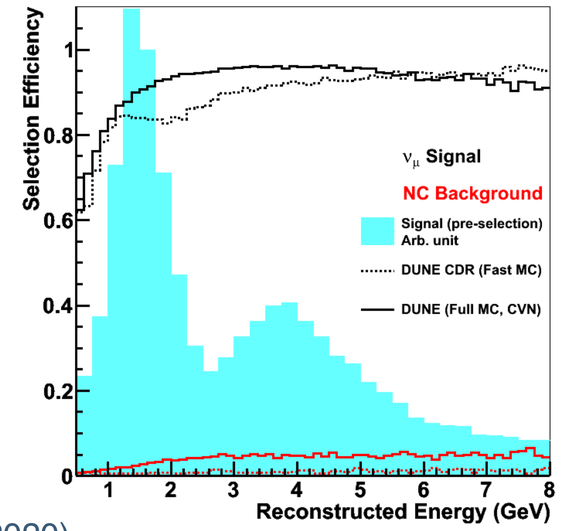
CC ν_μ score



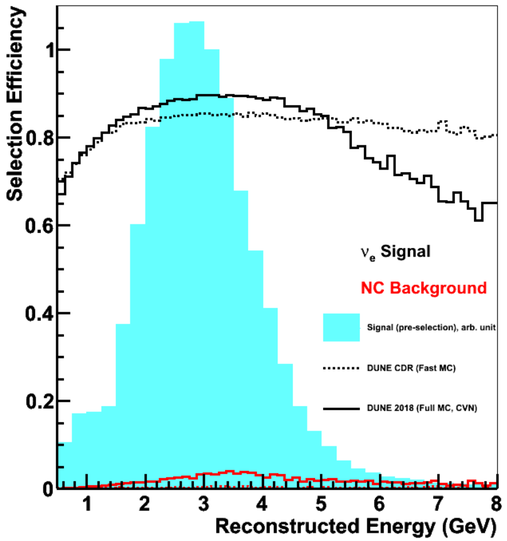
CC ν_e score



Disappearance Efficiency (FHC)



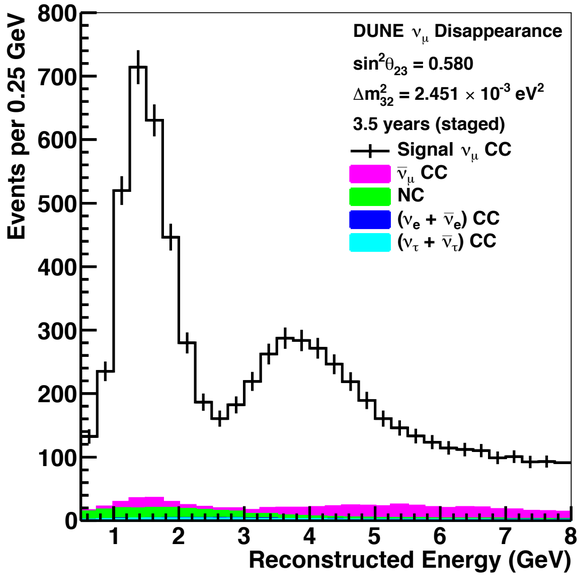
Appearance Efficiency (FHC)

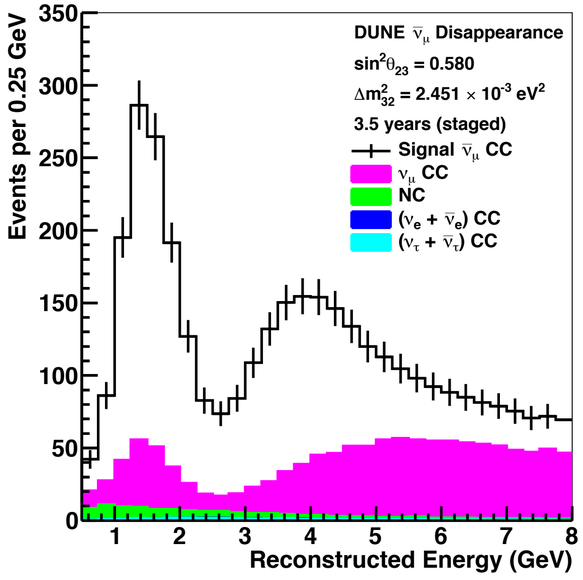


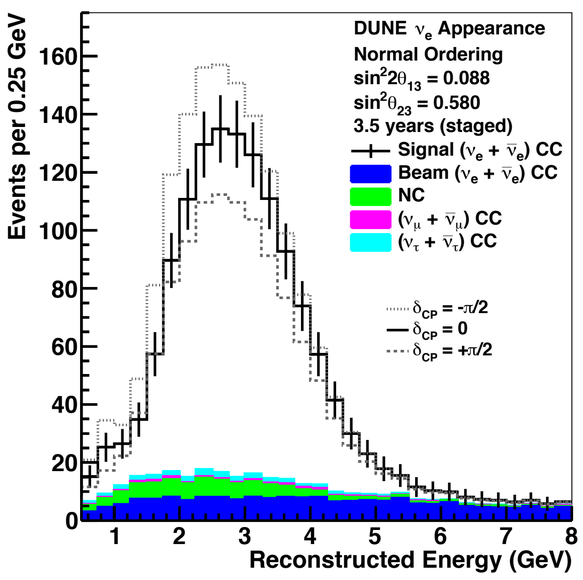
B. Abi, et al., (DUNE Collaboration), Neutrino interaction classification with a convolutional neural network in the DUNE far detector, *Phys. Rev. D* **102**, 092003 (2020)

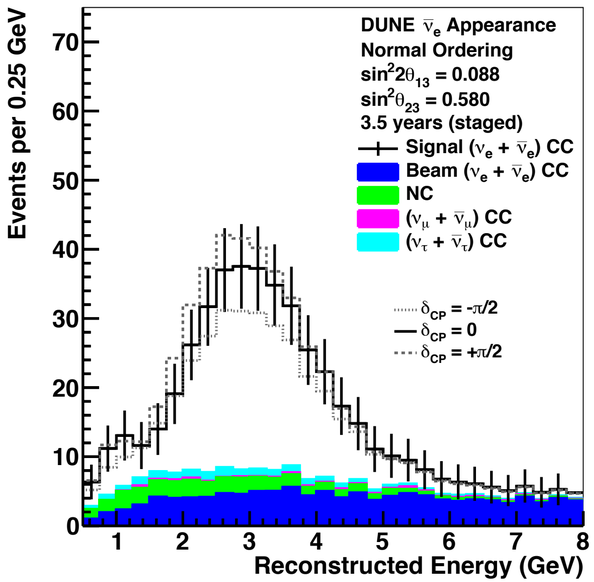
FD: selected events

- We obtain four samples of interactions
  - Figures below assume the normal mass ordering









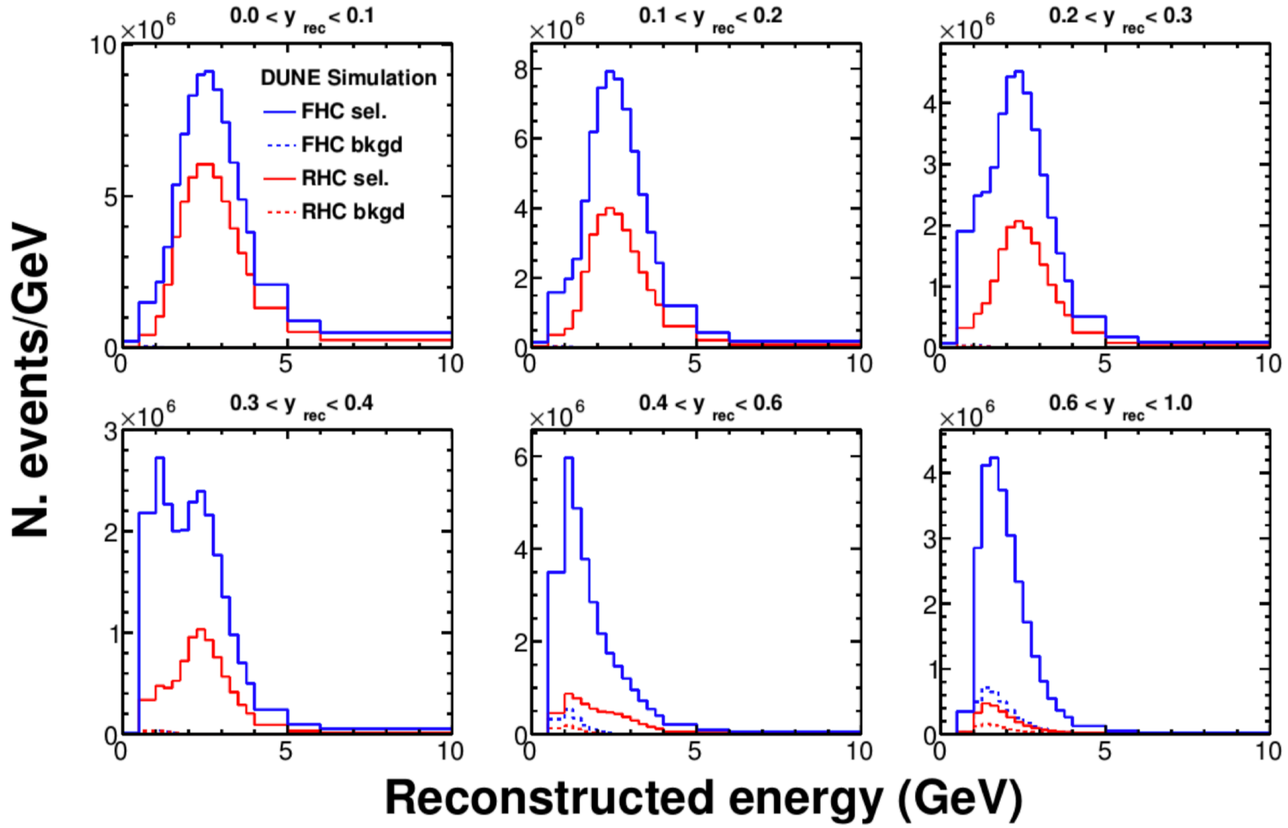
O(10000) disappearance events in seven years

O(1000) appearance events in seven years

B. Abi, et al., (DUNE Collaboration), Long-baseline neutrino oscillation physics potential of the DUNE experiment *Eur. Phys. J. C* **80** 10, 978 (2020)

ND: selected events

- In this analysis, consider CC ν_μ interactions as a function of energy and inelasticity
  - There are many other samples that the ND could provide in the future



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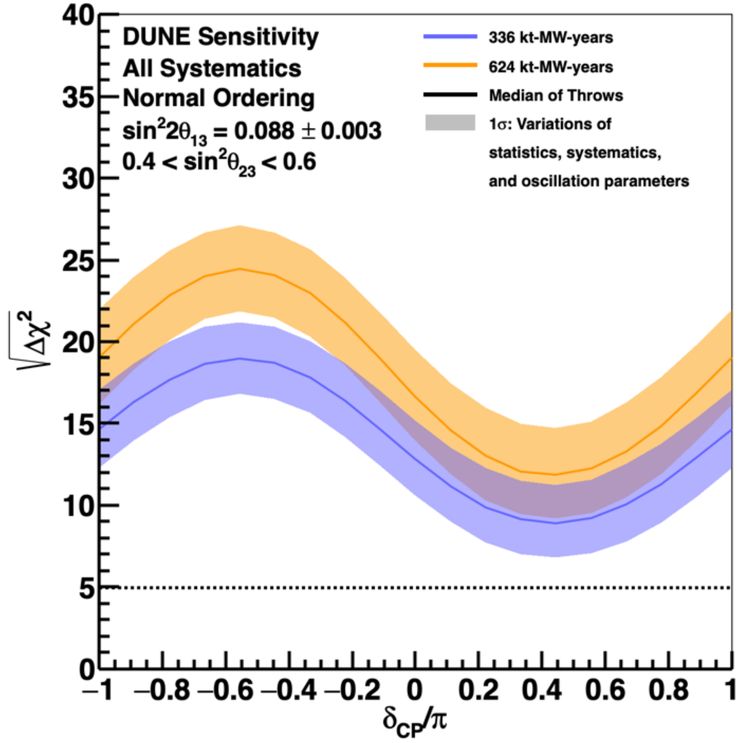
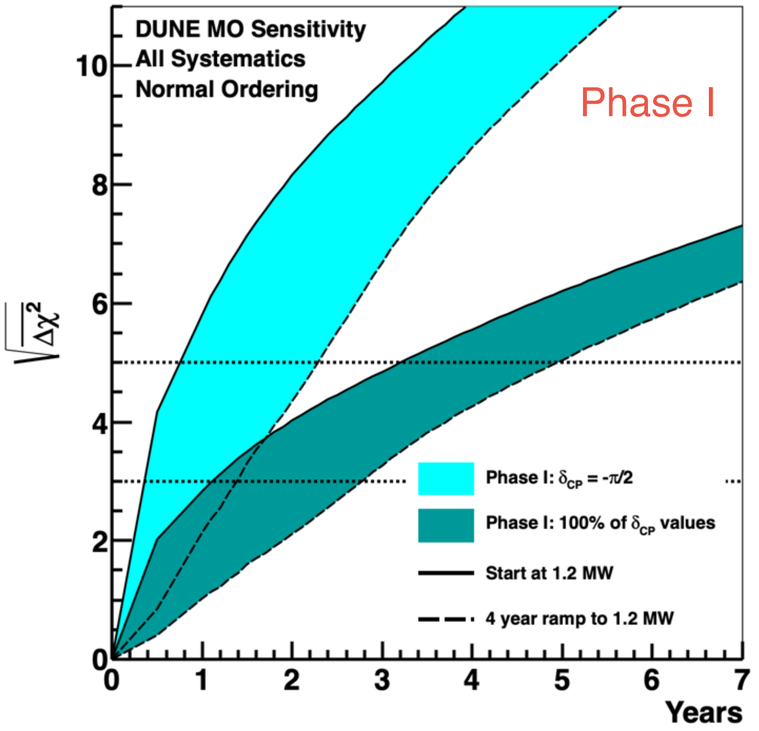
Oscillation sensitivities: Mass Ordering

- A joint fit where the four FD and twelve ND spectra are fit simultaneously
  - Detailed treatment of flux, cross section and detector systematic uncertainties
    - These are constrained by the ND samples
- Definitively resolve the mass ordering
  - No dependence on other experiments or other parameter values
  - Unrivalled ability of DUNE
- Discovery possible in Phase I
  - World-leading precision on Δm^2_{32} measurement

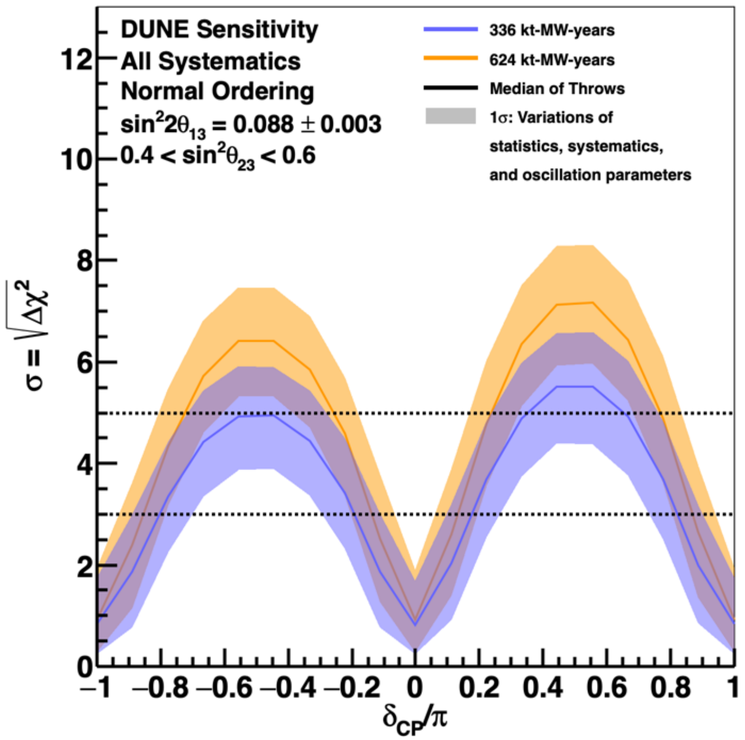


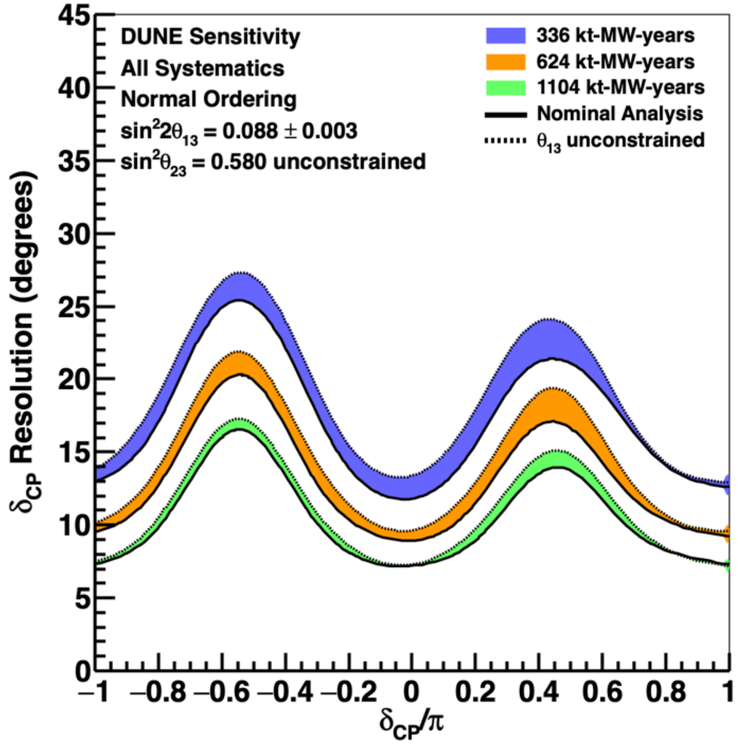


B. Abi, et al., (DUNE Collaboration), Long-baseline neutrino oscillation physics potential of the DUNE experiment *Eur. Phys. J. C* **80** 10, 978 (2020)

Oscillation sensitivities: CP-violation

- A joint fit of the four FD and twelve ND spectra are fit simultaneously
  - Detailed treatment of flux, cross section and detector systematic uncertainties
    - These are constrained by the ND samples
- 5σ discovery potential for > 50% of δ_{CP} values
- 7-16 degree resolution on δ_{CP} with no reliance on other experiments



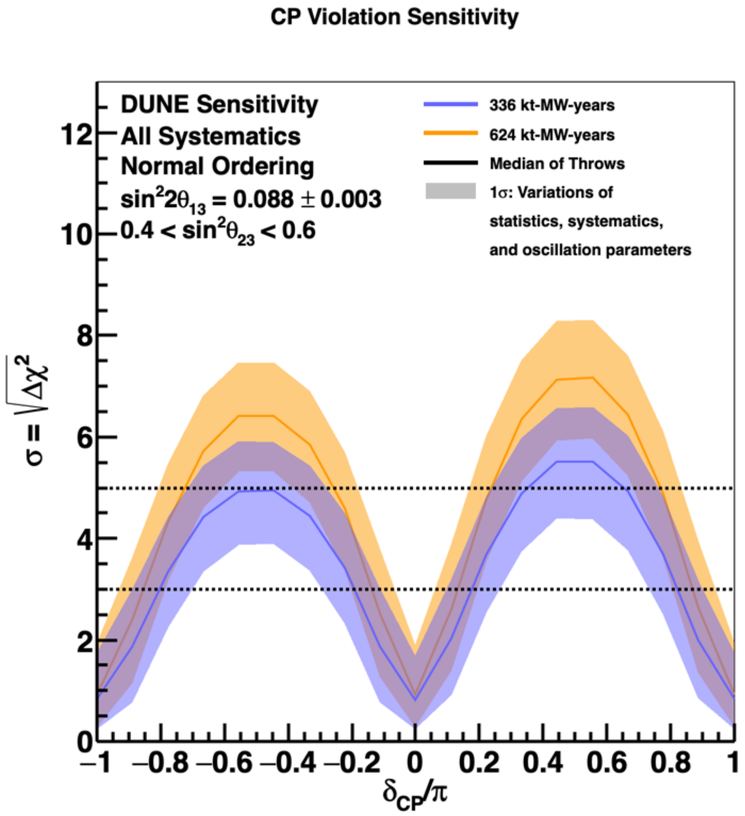


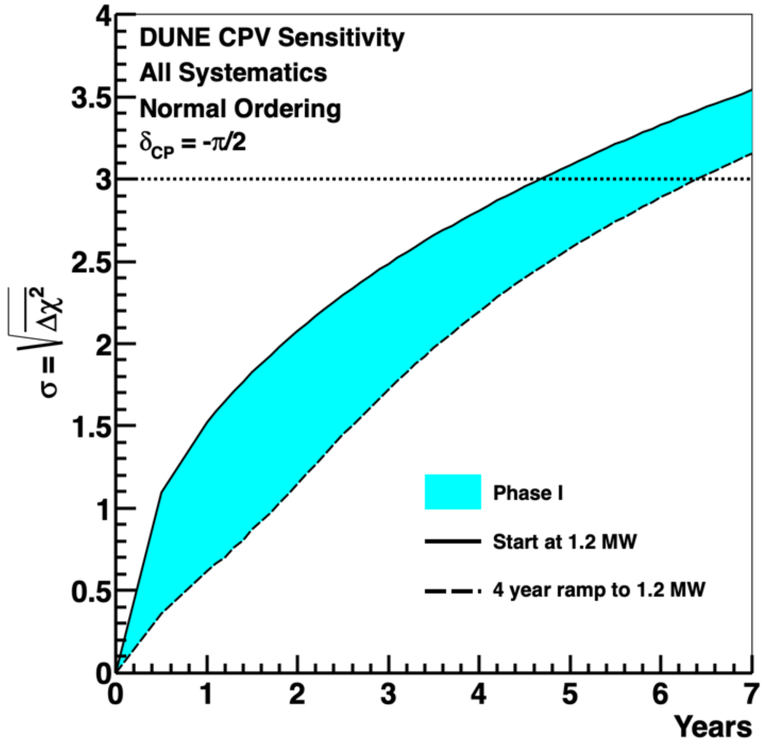
B. Abi, et al., (DUNE Collaboration), Long-baseline neutrino oscillation physics potential of the DUNE experiment *Eur. Phys. J. C* **80** 10, 978 (2020)

Oscillation sensitivities: CP-violation

- A joint fit of the four FD and twelve ND spectra are fit simultaneously
  - The ND samples act to constrain many of the systematic uncertainties

- 5σ discovery potential for > 50% of δ_{CP} values
- 7-16 degree resolution on δ_{CP} with no reliance on other experiments
- Phase I: 3σ discovery if CP-violation is large

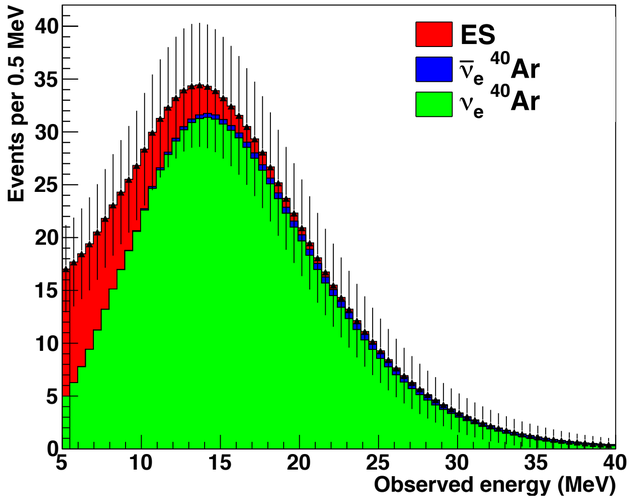


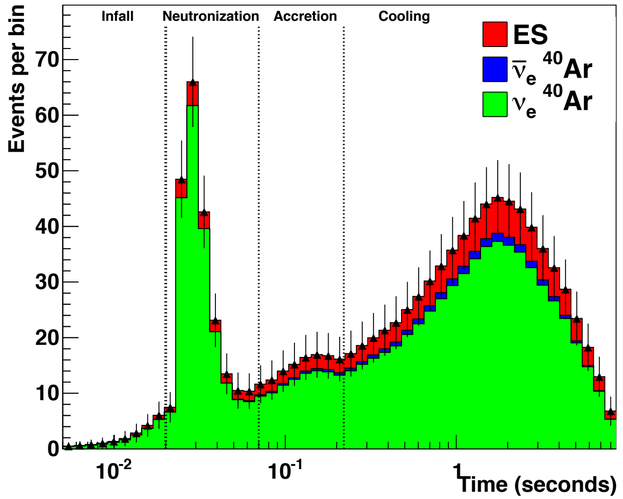


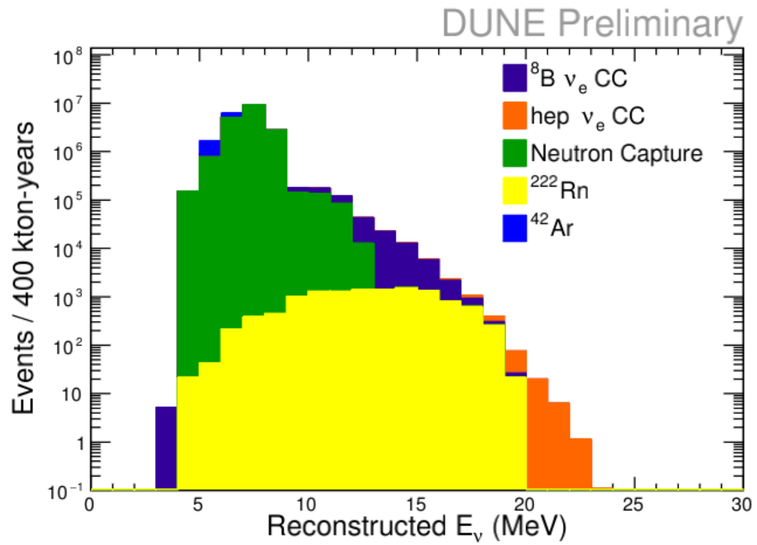
B. Abi, et al., (DUNE Collaboration), Long-baseline neutrino oscillation physics potential of the DUNE experiment *Eur. Phys. J. C* **80** 10, 978 (2020)

MeV-scale physics with electron neutrinos

- Sensitive to ν_e produced in supernovae including neutronisation burst
  - Unique for DUNE and complementary with HK
  - O(1000)s of events for a galactic supernova burst
- On-going work on solar neutrinos
  - Sensitive to ^{8}B and hep fluxes
  - Measure oscillation parameters
- Some proposals for the 4th module to enhance low energy physics programme



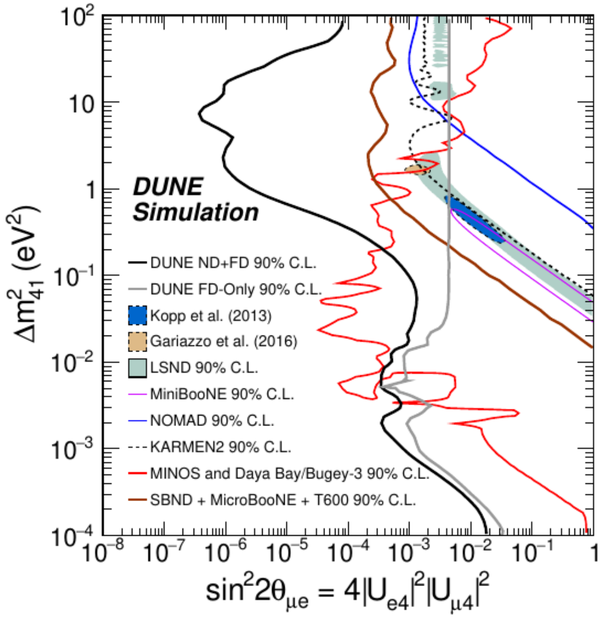




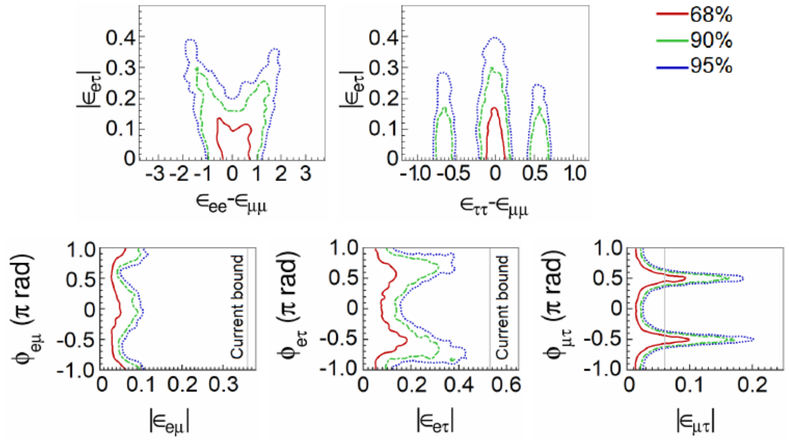
B. Abi, et al., (DUNE Collaboration), Supernova neutrino burst detection with the Deep Underground Neutrino Experiment, *Eur. Phys. J. C* **81** 5, 423 (2021)

Beyond the Standard Model

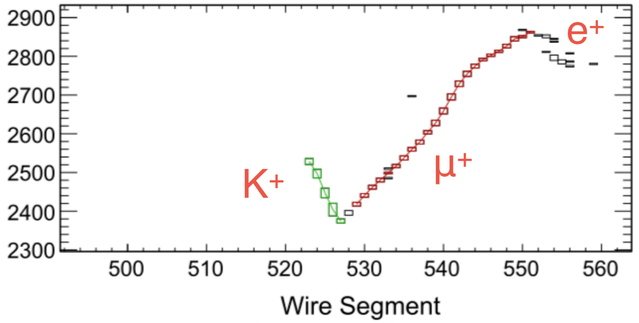
- Wide search for BSM physics using both ND and FD



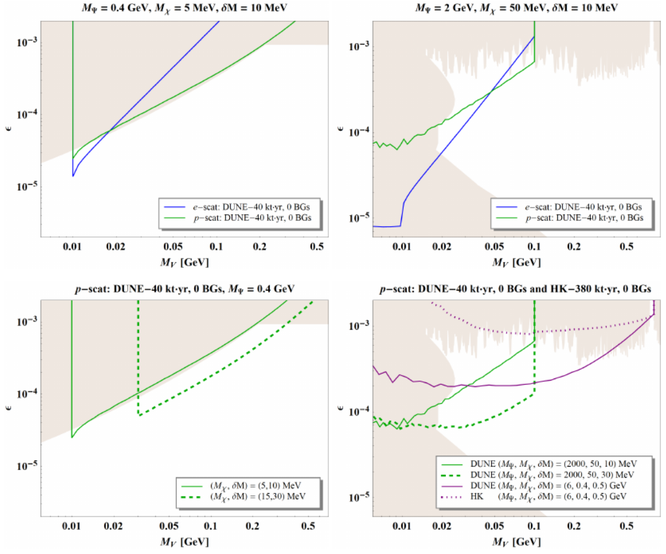
Sterile neutrino search



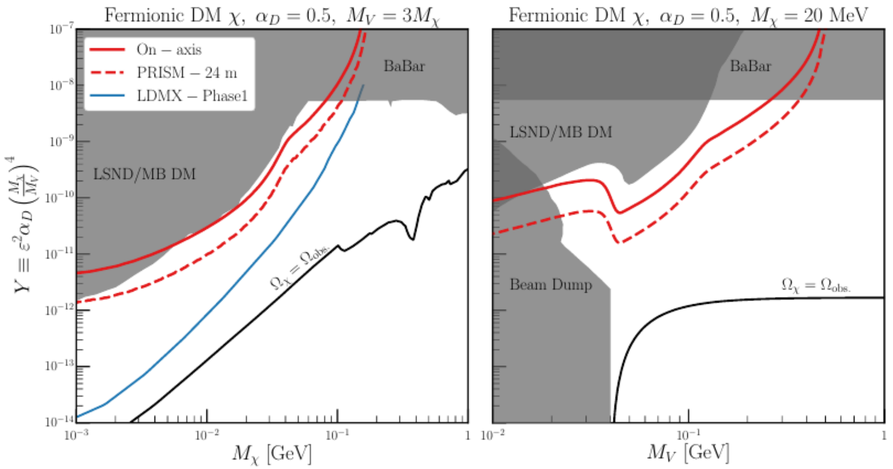
Non-standard interactions



Proton decay



Inelastic boosted dark matter at the FD (cosmic origin)



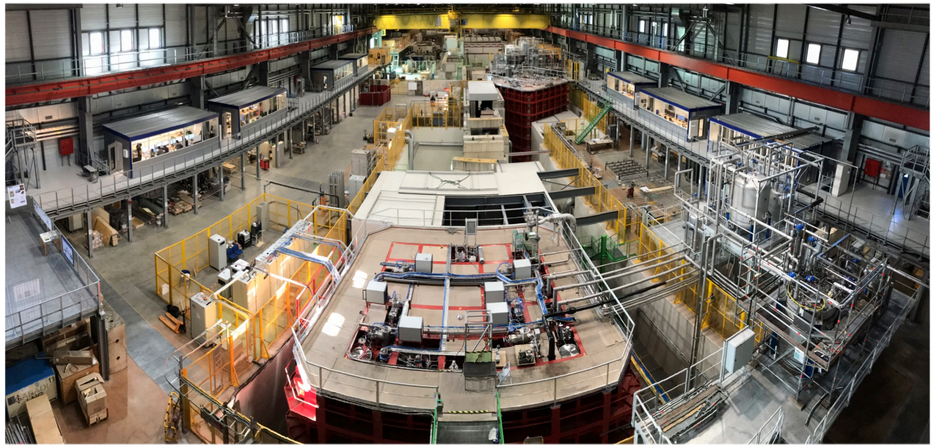
Light dark matter at the ND (produced in the beam line)

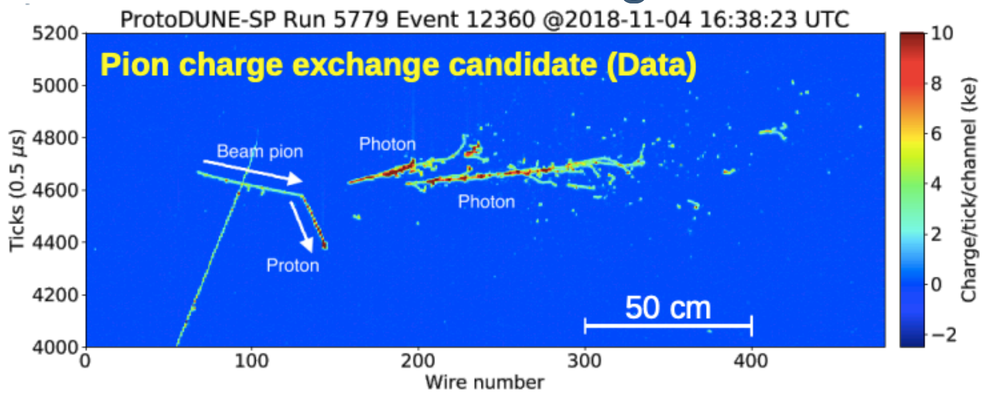
- Plus lots more!

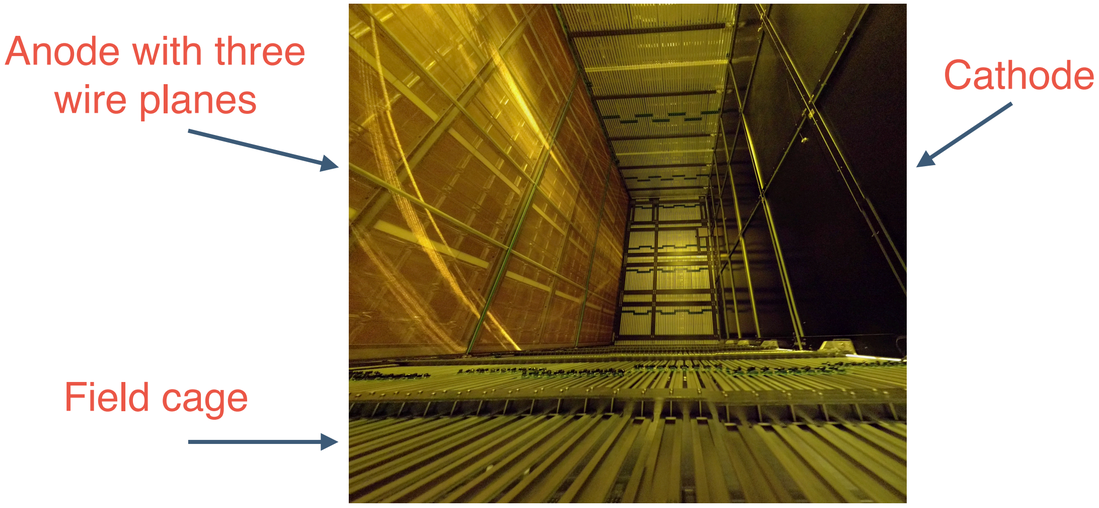
B. Abi, et al., (DUNE Collaboration), Prospects for beyond the Standard Model physics searches at the Deep Underground Neutrino Experiment *Eur. Phys. J. C* **81** 4, 322 (2021)

Prototyping

- ProtoDUNE-SP (HD prototype) collected charged particle beam data at CERN in 2018
- Very successful operation at design parameters
  - 500 V/cm electric field, > 99% channels active
  - High signal-to-noise ratio
- Broad hadron-argon cross-section programme
  - First results soon!
- Refitted detector to run again from Autumn 2022



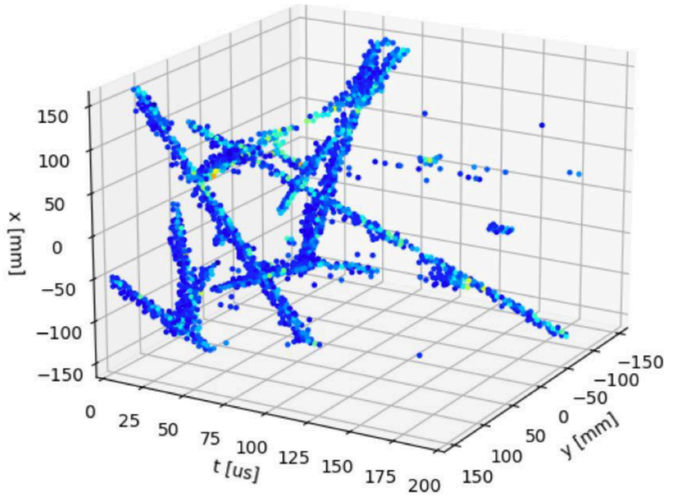




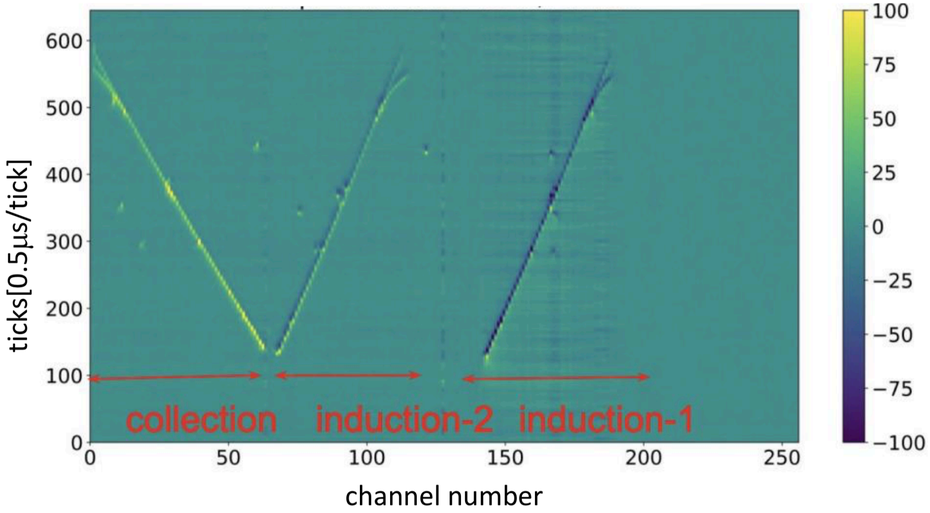
B. Abi, et al., (DUNE Collaboration), First results on ProtoDUNE-SP liquid argon time projection chamber performance from a beam test at the CERN Neutrino Platform, JINST **15** 12, P12004 (2020)
B. Abi, et al., (DUNE Collaboration), Design, construction and operation of the ProtoDUNE-SP Liquid Argon TPC, *JINST* **17** 01 P01005 (2022)

Prototyping

- A 2x2 demonstrator for ND-LAr at Fermilab
  - Each module is 0.7m x 0.7m x 1.4m
  - Collecting data in the NuMI neutrino beam as ProtoDUNE-ND
  - First neutrinos for DUNE equipment



- A dual-phase LArTPC ProtoDUNE-DP collected cosmic data at CERN
  - This design evolved into the VD option
  - 3-view VD PCB readout tested
  - ProtoDUNE-VD will be constructed at CERN



Summary

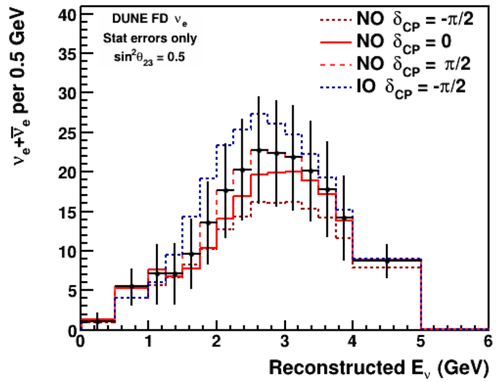
- DUNE has a wide and strong physics programme
  - Unique but complementary to Hyper-K

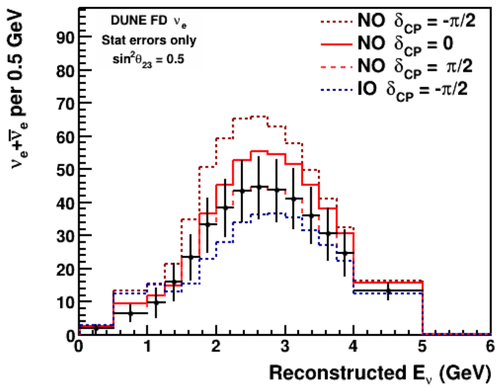
- It can measure the mass ordering and CP-violation in a single experiment with no dependence on constraints from other experiments

- Excellent progress towards realising DUNE has been made
  - Very successful ProtoDUNE programme demonstrating that the designs will work
  - Excavation of the FD caverns
  - Preparation for beam line and ND facilities underway

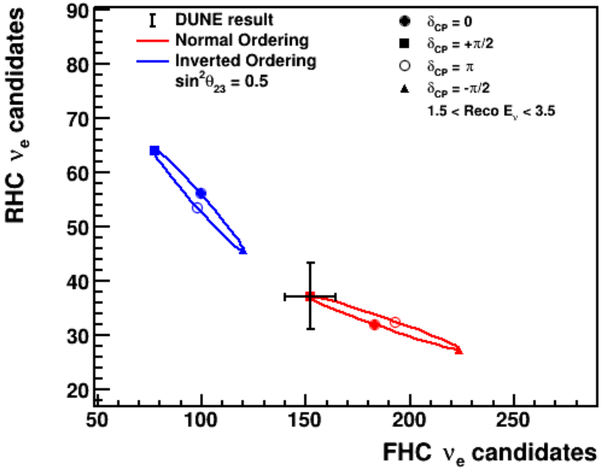
Mass ordering

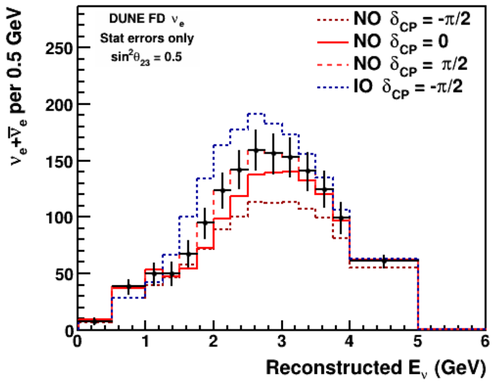
- Larger difference between normal and inverted ordering due to long baseline
  - Expectations derived directly from ND

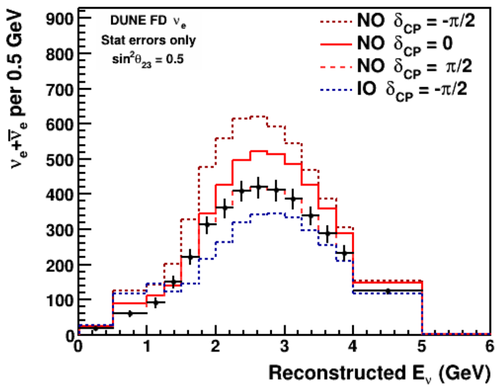




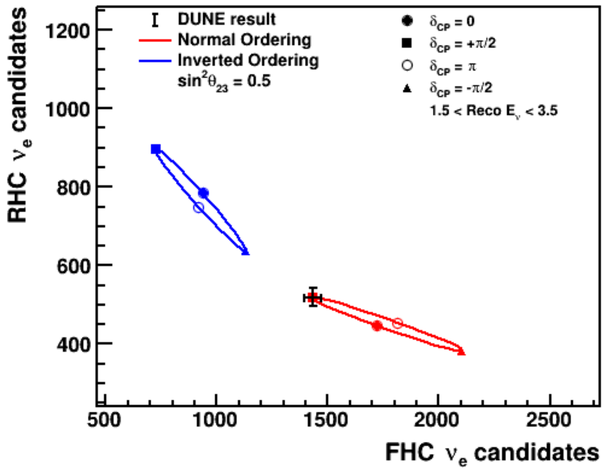
4 years with 20kt





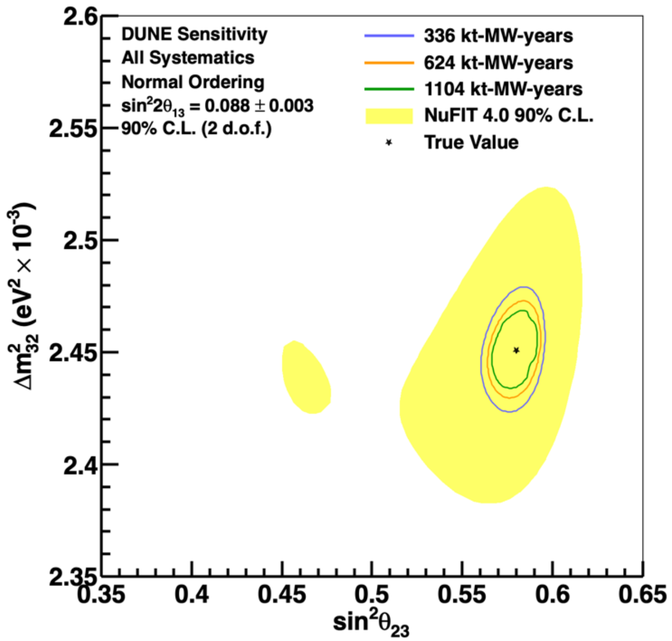


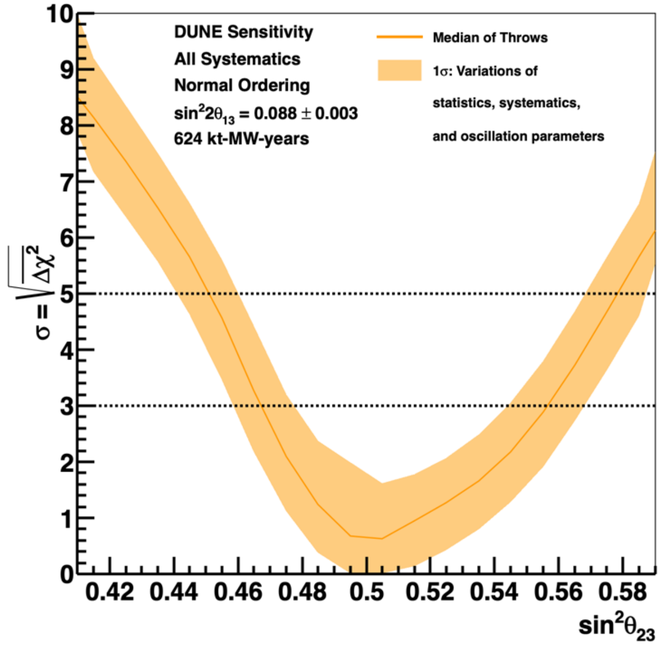
Long term

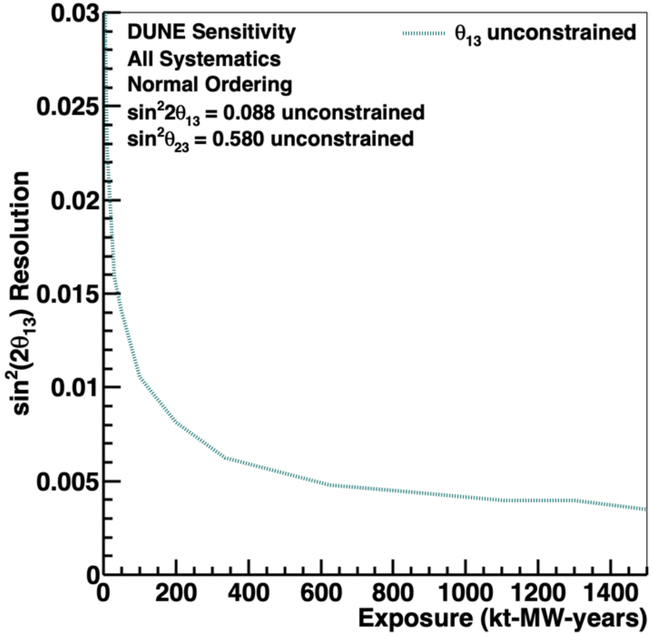


Oscillation parameter measurements

- DUNE will make very precise measurements of the oscillation parameters







- World leading precision on θ_{23} and Δm^2_{32}
  - Includes octant determination
- At full exposure the θ_{13} resolution approaches that of the reactor experiments
  - DUNE's physics reach does not depend on external measurements