The Deep Underground Neutrino Experiment

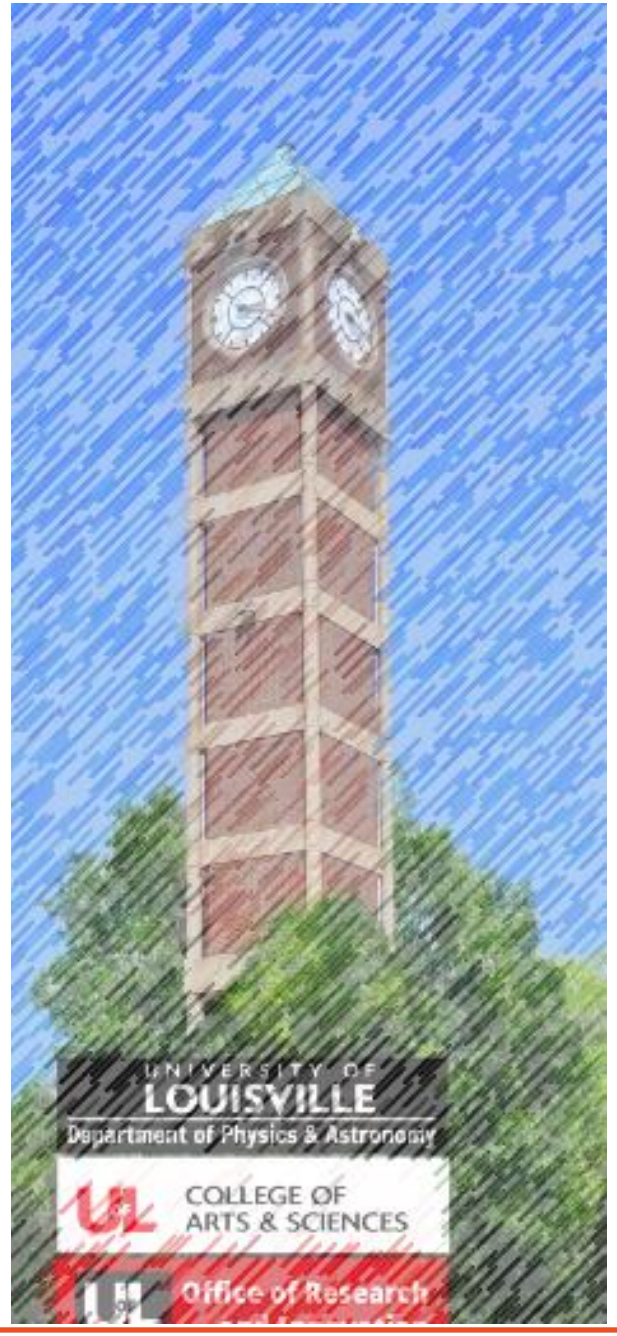
Status and Prospects

Martin Tzanov on behalf of the DUNE Collaboration
Louisiana State University

TAU 2023
Dec. 7th, 2023

Outline

- Neutrino Oscillations
- Scientific Reach
- The DUNE Experiment
- LBNF Beam
- DUNE Near Detector
- LBNF Far Site and DUNE Far Detector
- ProtoDUNE – DUNE prototype
- DUNE Physics.
- Conclusion and Future



Neutrino Oscillations

Phenomenon of neutrino flavor transmutation at a distance traveled. For 3-flavor model

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

- Neutrinos are produced as flavor eigenstates and propagate as mass eigenstates

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

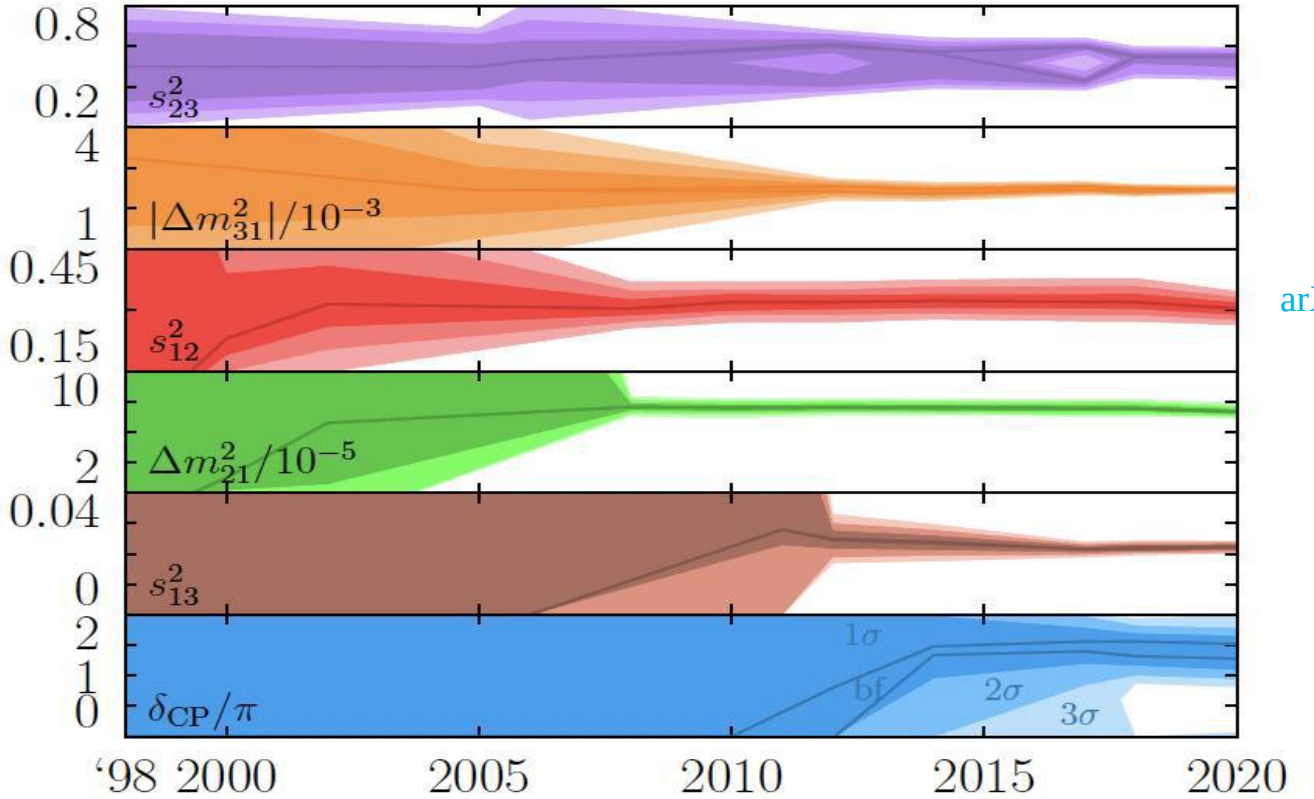
- PMNS matrix – transforms from mass to flavor eigenstates – 3 mixing angles and phases

$$P(\nu_\alpha \to \nu_\beta) \sim \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

- Two flavor oscillation probability depends on the distance L and neutrino energy E.
- Governed by the mixing angles and mass splitting.

Neutrino Oscillations Measurements

- Fast progress in 25 years.

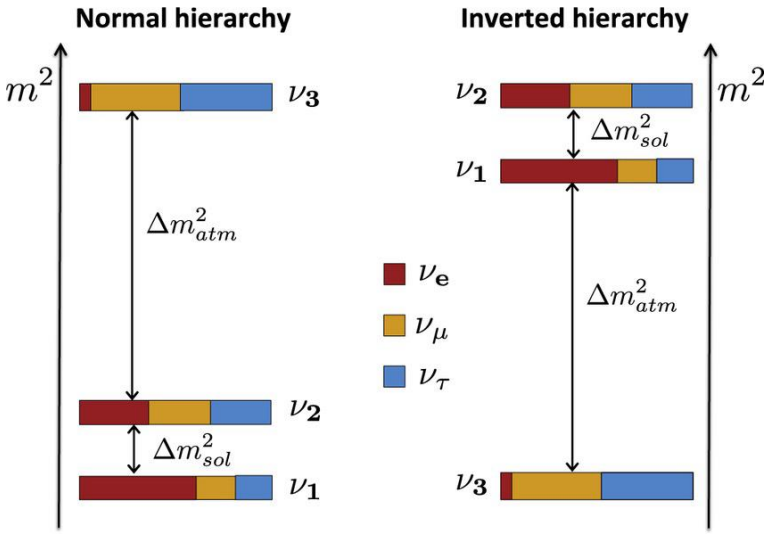


arXiv:2212.00809

- Neutrinos have non-zero masses and they are different.

Neutrino Oscillations – Open Questions

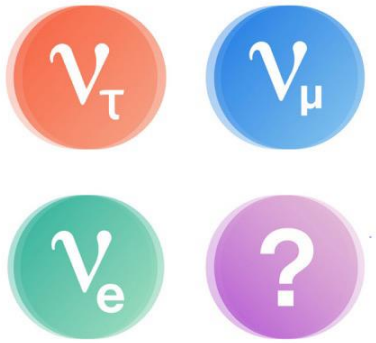
- How the mass eigenstates ordered?



- Is θ_{23} maximal?
  - $\theta_{23} \sim 45^o$
- Is PMNS unitary?

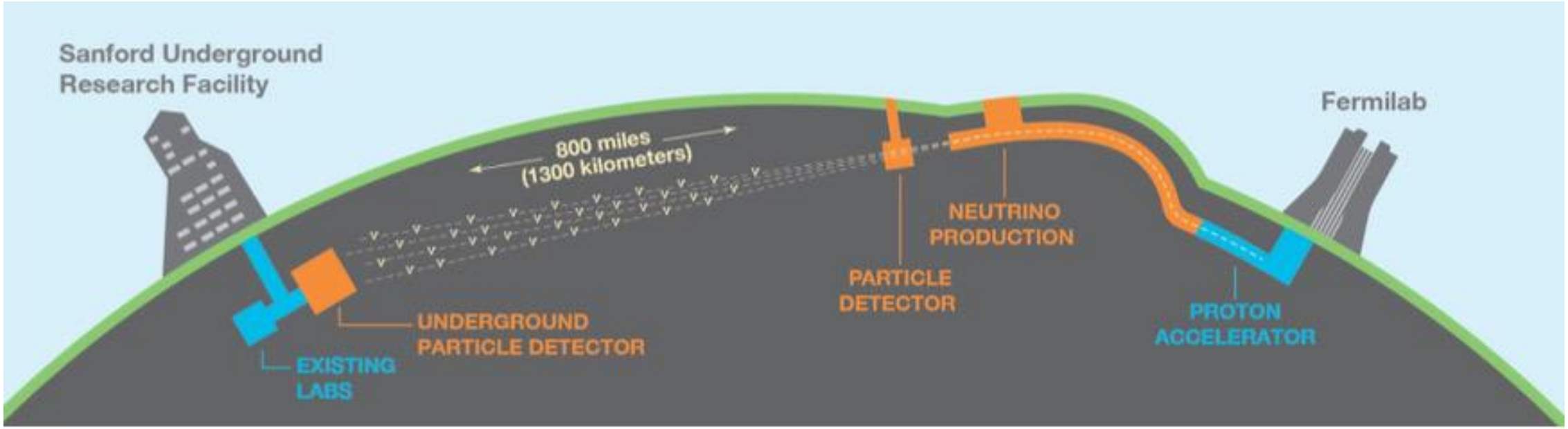
- Is CP symmetry violated?
  - $\delta_{CP}=0$?
- If yes, does it explain the matter anti-matter asymmetry?

- Are there sterile neutrinos?



Symmetry Magazine

DUNE/LBNF/SURF



- DUNE collaboration is an international team of 1400+ scientists and engineers.
- LBNF is the facility combining the beamline and the near detector complex at Fermilab and the far detector complex at SURF.
- SURF experimental facility at the far site.

The Dune Collaboration

- 1450 Collaborators
- 215 institutions
- 35 countries

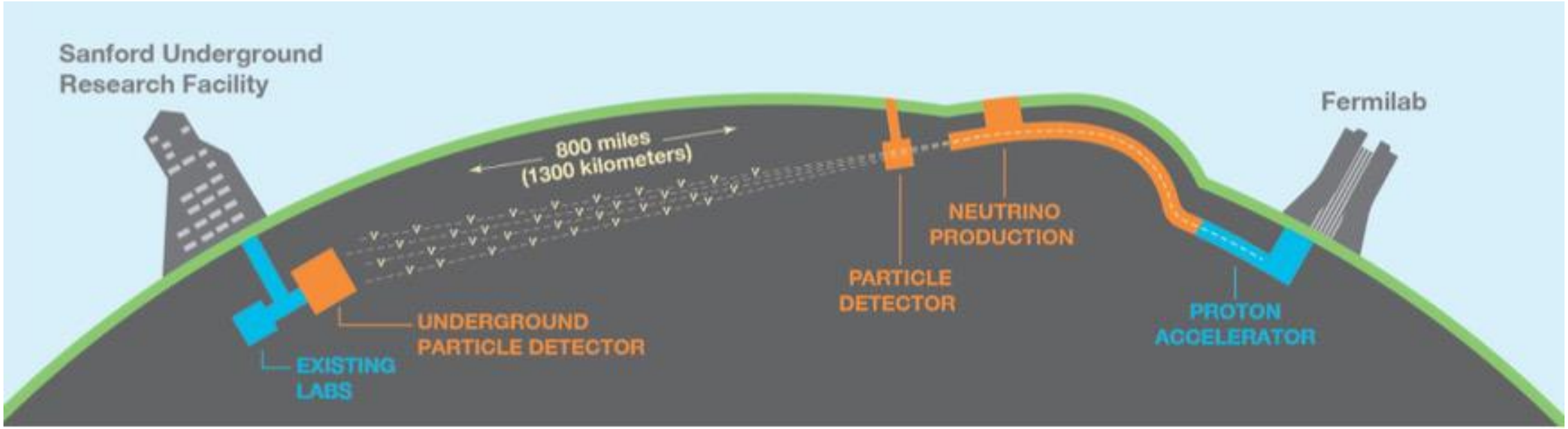

Mary Bishai


Sergio Bertolucci

DUNE'sspokespersons

January Collaboration Meeting at CERN

DUNE Concept



- Long baseline ~ 1300km

$$\mathcal{A}_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \sim \frac{\cos\theta_{23} \sin 2\theta_{12} \sin\delta_{\mathrm{CP}}}{\sin\theta_{23} \sin\theta_{13}} \left(\frac{\Delta m^2_{21} L}{4E_\nu}\right) + \text{matter effects}$$

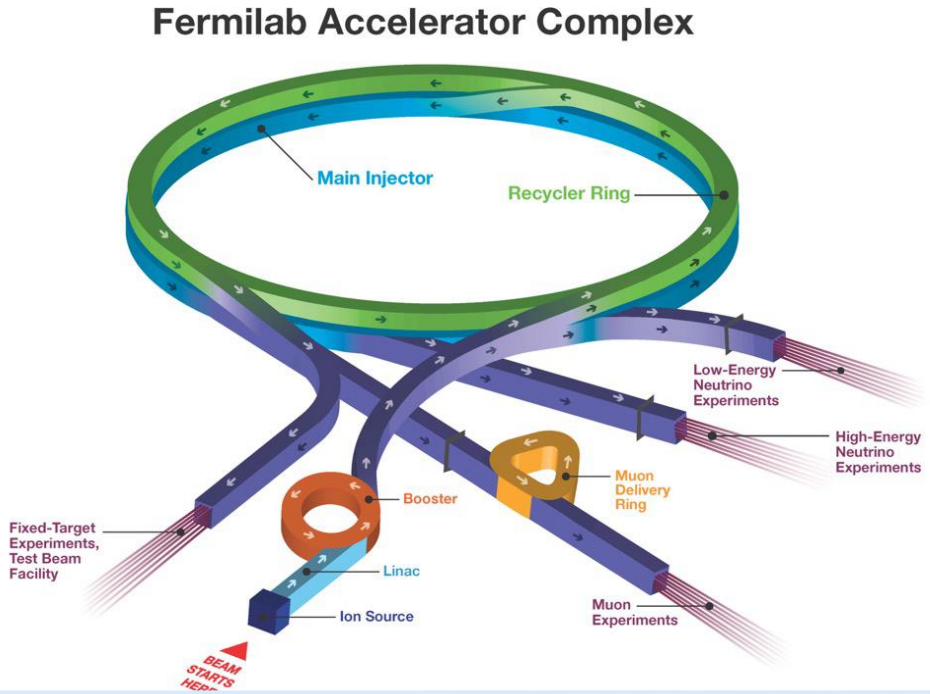
- Wide-band $\nu/\bar{\nu}$ beam ~ 2GeV peak with 1.2 MW power (2.4MW with upgrade)
- Near detector complex to analyze the beam and control systematics.
- 70 kt LArTPC far detector complex at SURF ~ 1.5km below the surface.

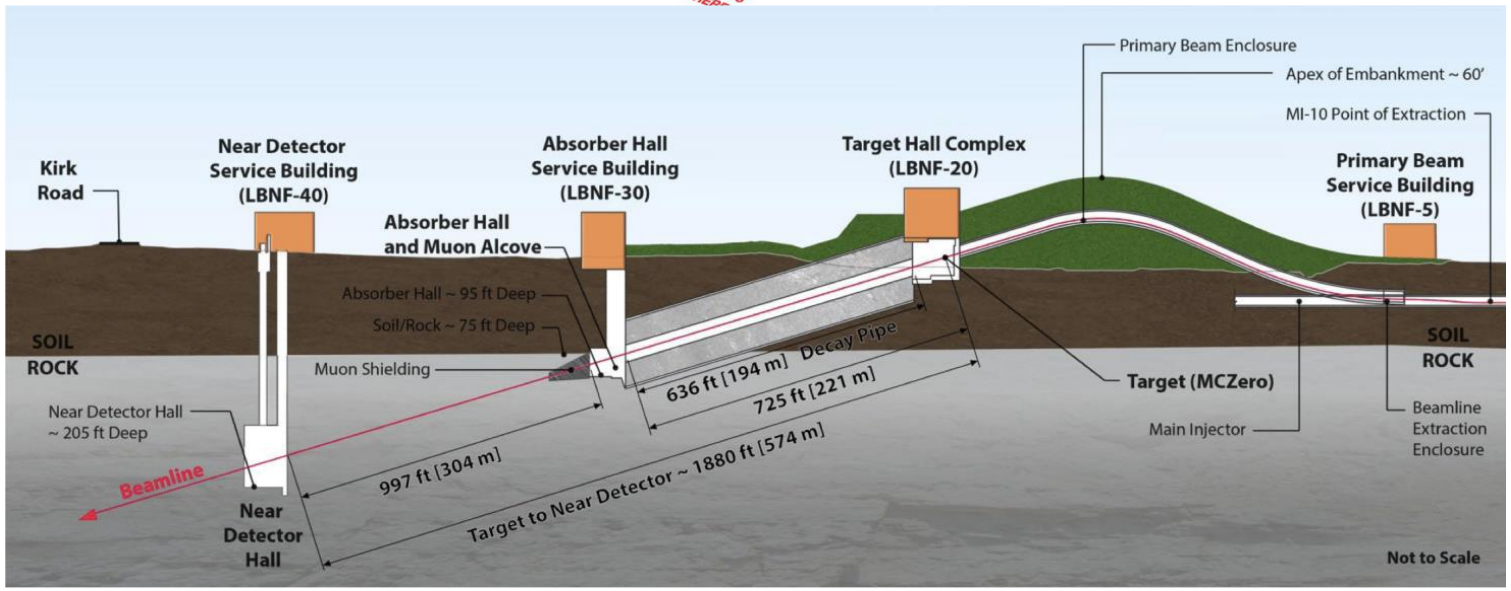
LBNF Beamline – PIP-II

- Proton Improvement Plan
- New proton source with 800MeV H^- at Fermilab
- LINAC line to inject into Booster
- MI with 1.2MW (phase-I) and

  up to 2.4MW (phase-II)

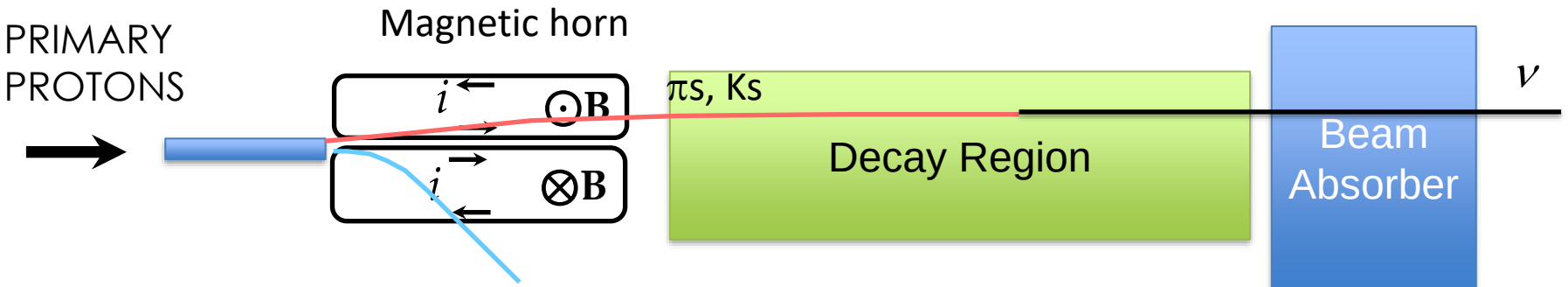
Eur. Phys. J. C **80** 10, 978 (2020)





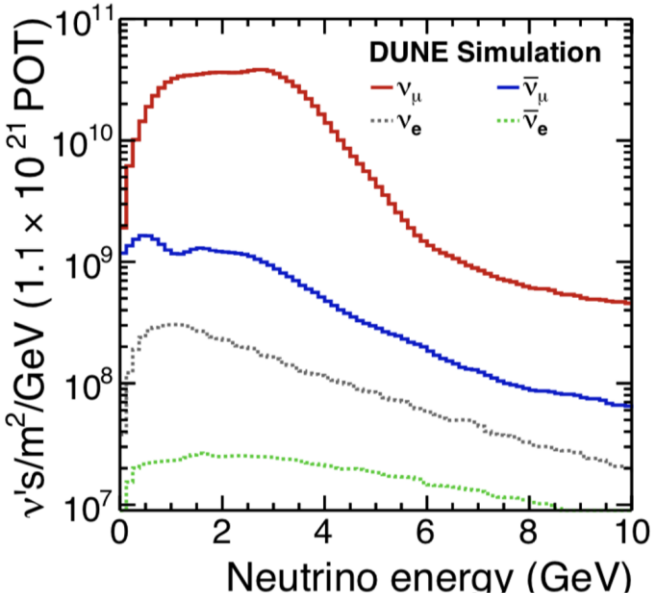
LBNF Neutrino Beam

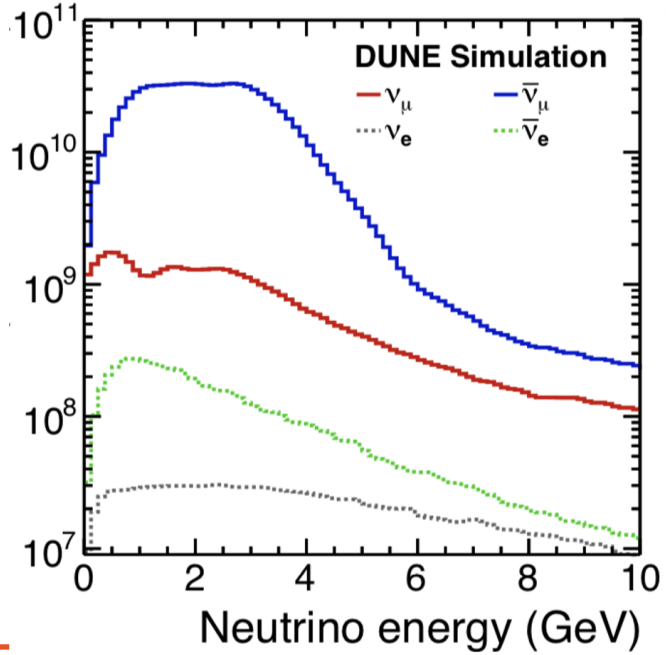
- Protons from MI impinging on a graphite target
- Magnetic focusing horns with reversible current to produce ν mode (FHC) and $\bar{\nu}$ mode (RHC).
- Beamline entering Earth at a 5.8° and pointing to the far site producing wide-band beam.



- Positive particles focused
- Negative particles defocused

Making a neutrino beam

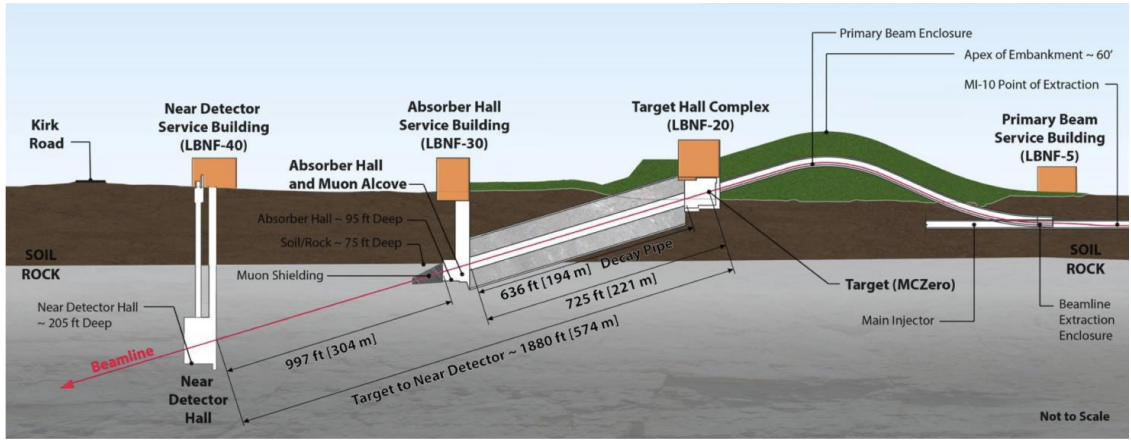


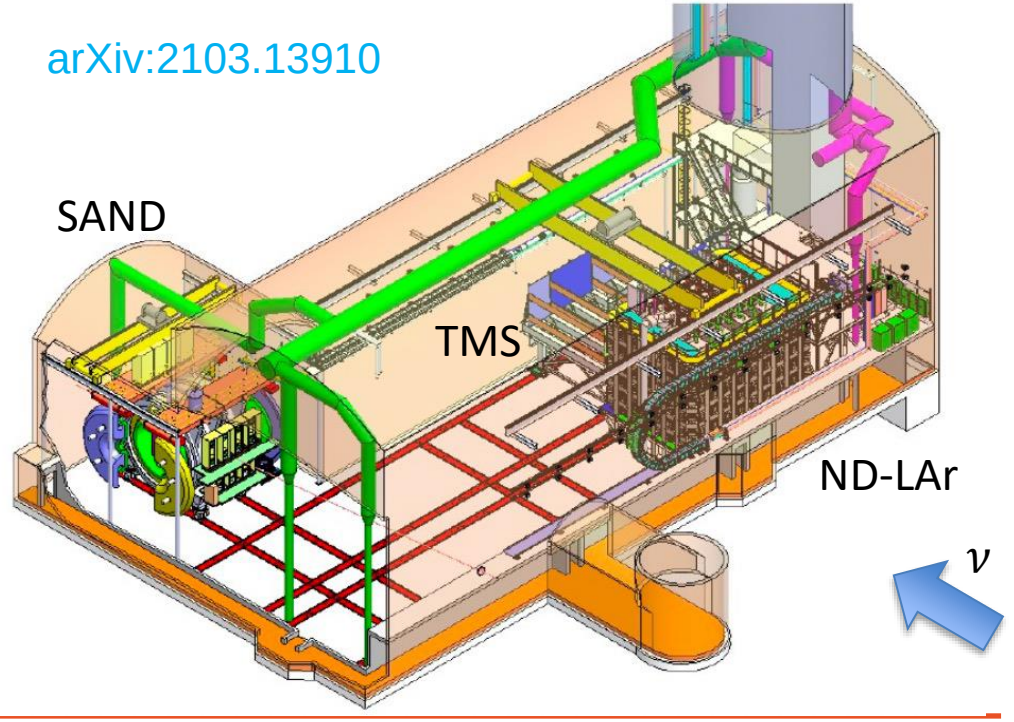


Near Detector Complex

Versatile complex tasked with neutrino beam characterization and control of systematic uncertainties. Comprise of

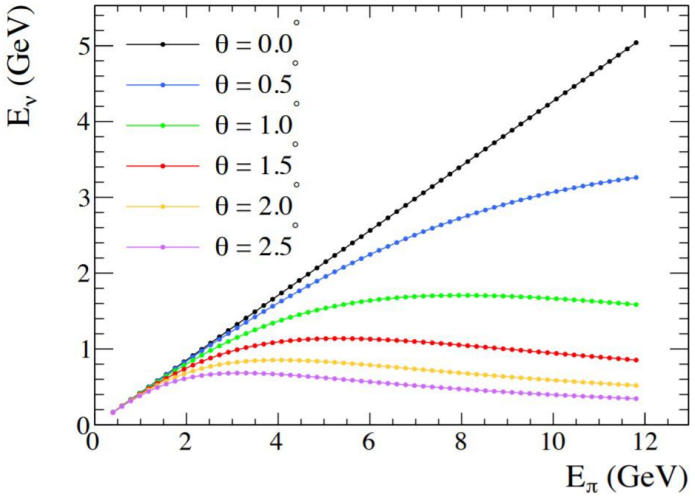
- ND-LAr – same target and detection technology as the far detector modified for higher rate
- TMS – The Muon Spectrometer – magnetized spectrometer to analyze muons produced in ν_μ CC interactions.
- DUNE-PRISM – moving ND-LAr and TMS to 30m off axis.
- SAND – on-axis tracking spectrometer with Ar target GRAIN and STT with ECAL utilizing the KLOE magnet.

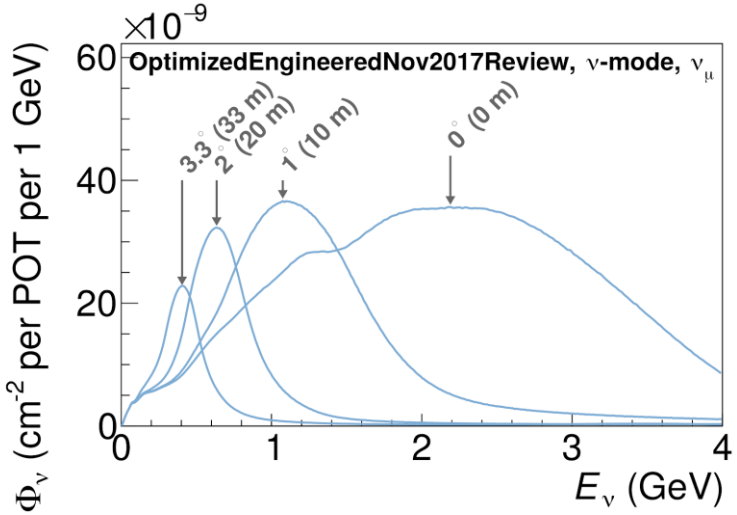




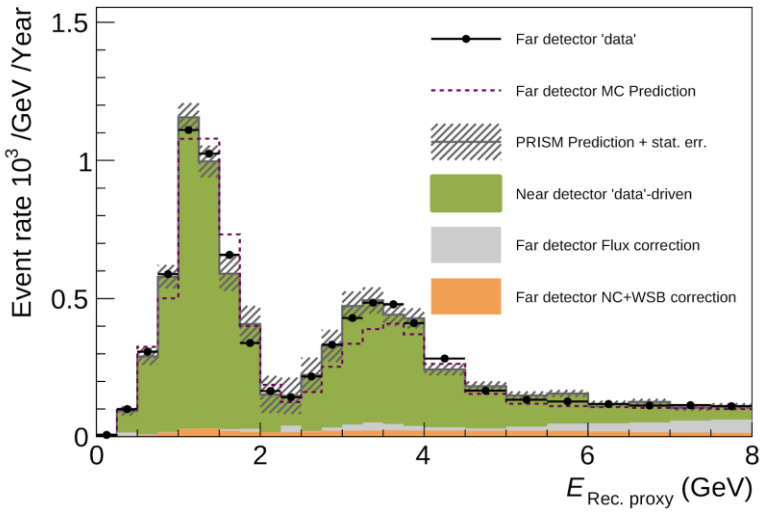
DUNE PRISM Concept

- Different off-axis angles result in different neutrino beam spectra.
- Linear combination for different angles can reproduce the far detector oscillated flux.
- Similarly, it can be used to get a Gaussian narrow beam for cross section measurements.



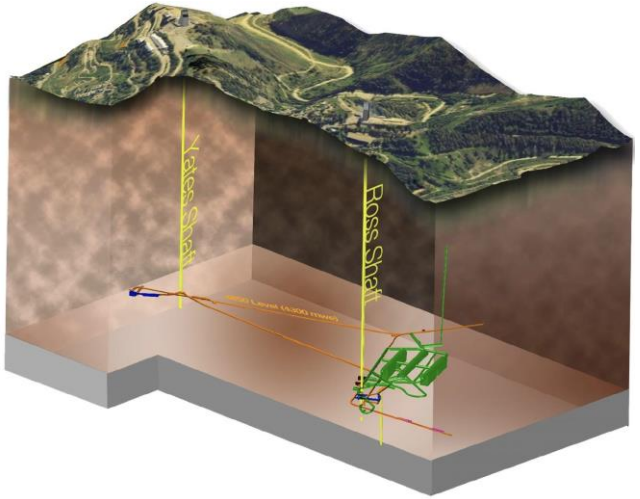


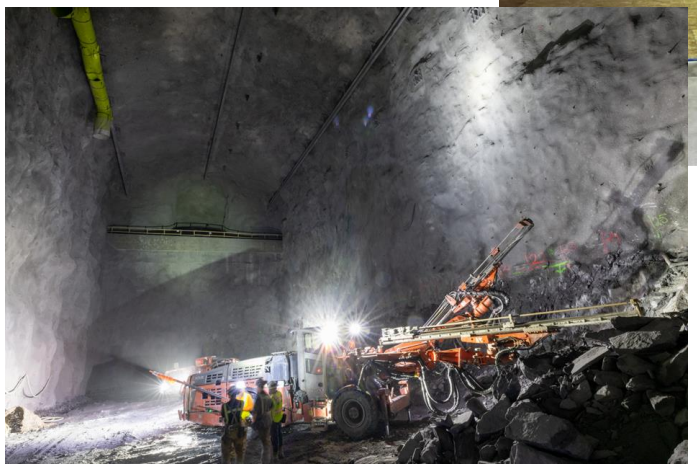
NuFit 4.1, $\Delta|M^2|_{32} = 2.52\times10^{-3}$ eV, $\sin^2(\theta_{23}) = 0.525$

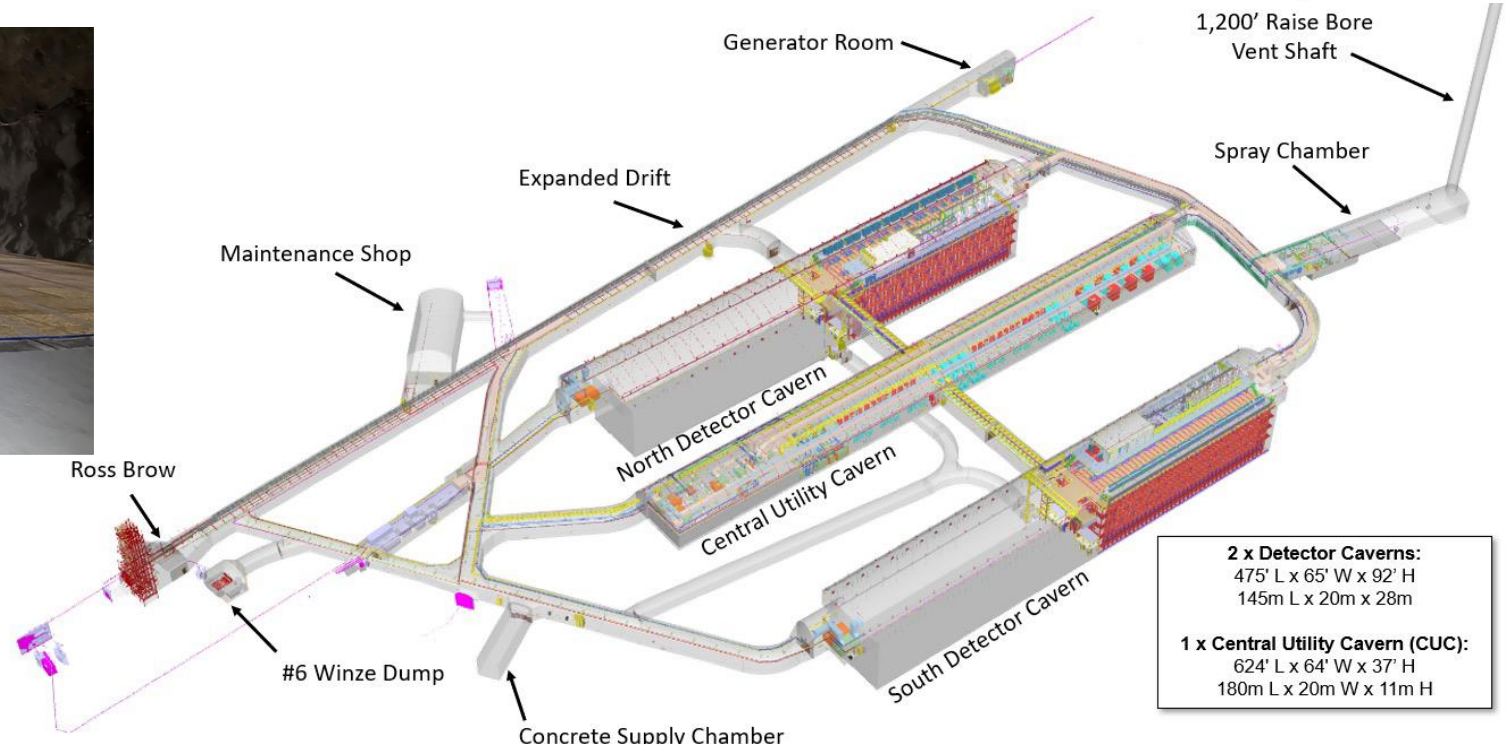


DUNE Far Site

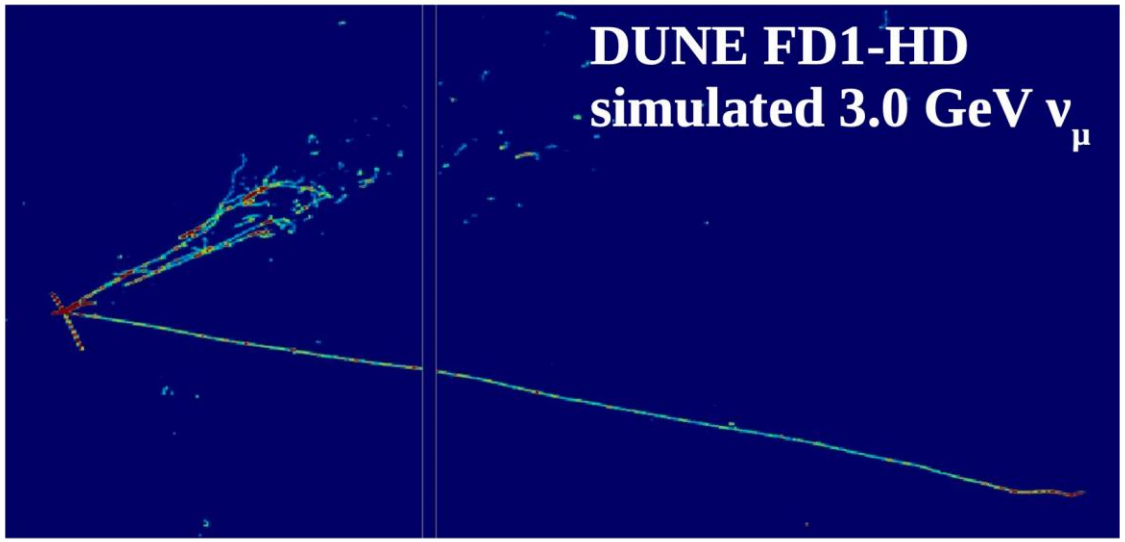
- Excavation expected to finish in 2024
- 80% done.
- Facility to be completed in 2025

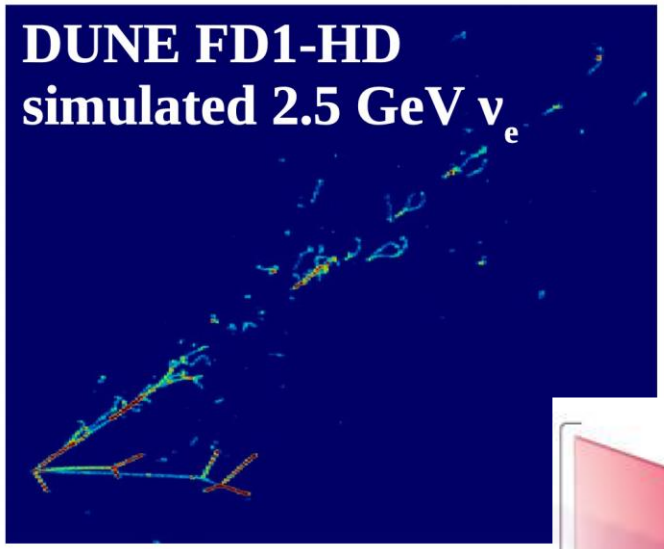


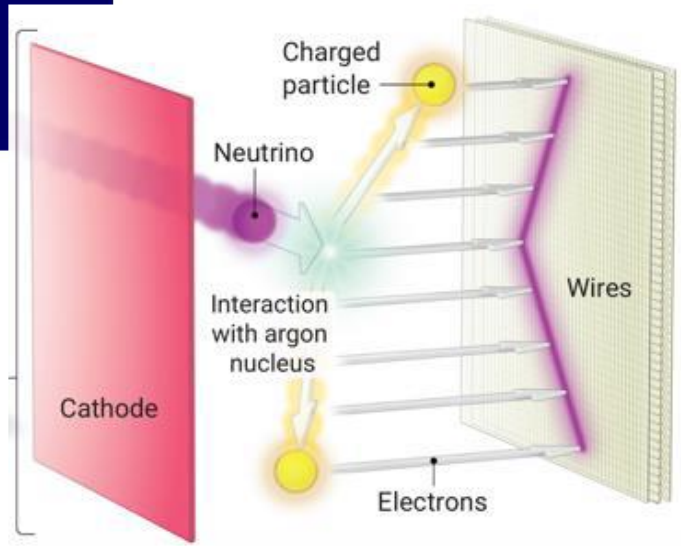




DUNE Far Detector - LArTPC





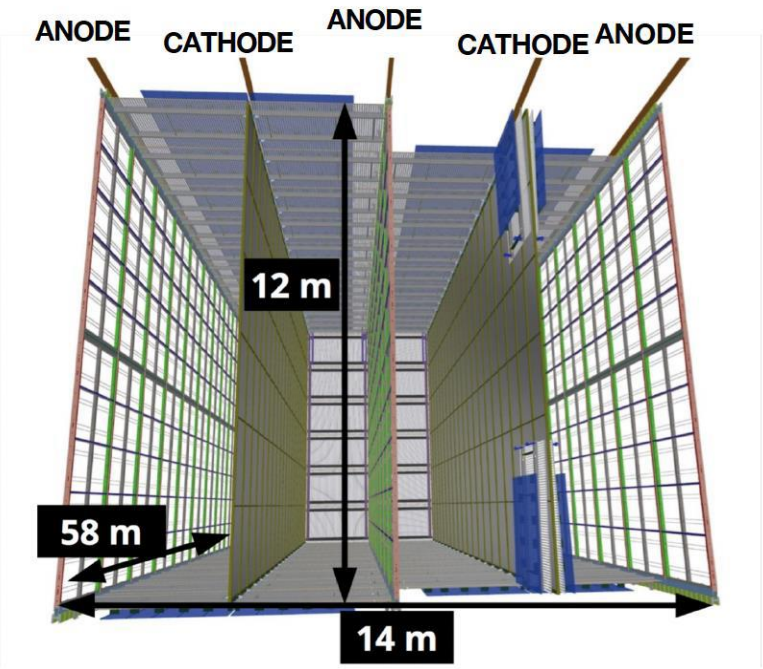


- Liquid Ar Time Projection Chamber
- Low detection threshold ~MeV
- High resolution (mm) tracking
- Energy reconstructed for calorimetry -
- Particle ID – good separation between ν_μ and ν_e events

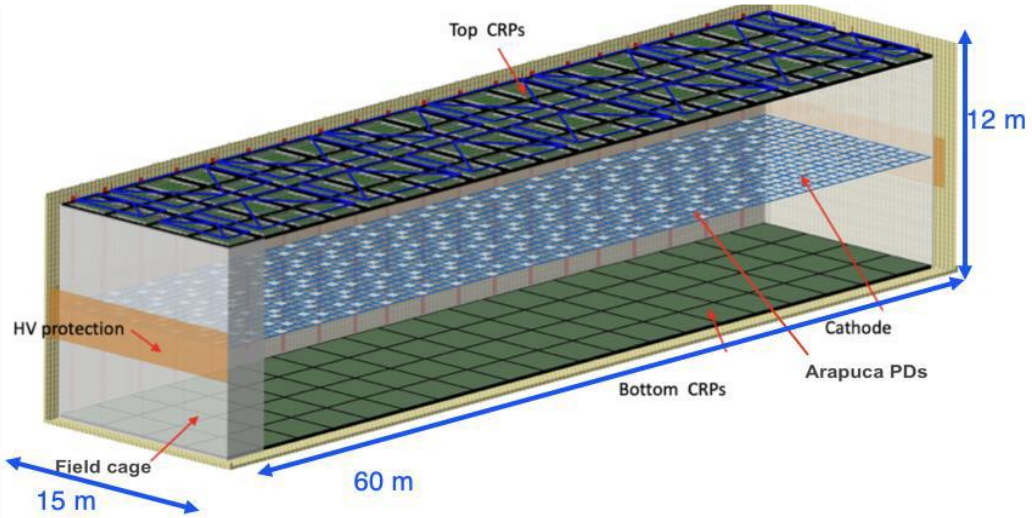
DUNE Far Detector

Module 1 - Horizontal drift.

- 150 wire APAs – total of 384k channels
- About 180kV on the cathode
- Max drift distance of 3.5m (CPA->APA)
- Photo detection system (PDS) – 6000 PDS



APAs construction



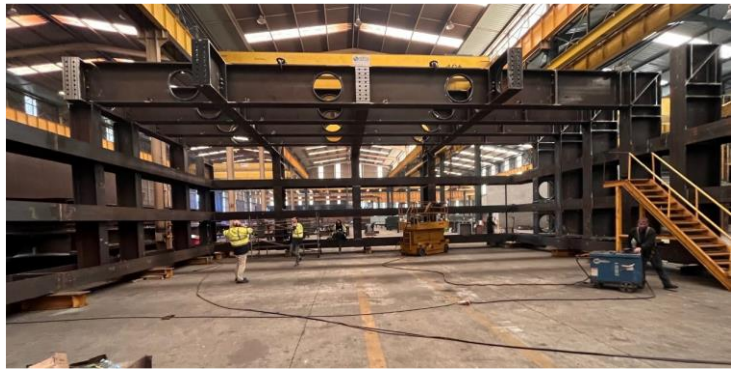
Module 2 - Vertical drift.

- CRP based on perforated PCB
- About 300kV on the cathode
- Max drift distance of 6.4m
- Photo detection system (PDS) – on cathode

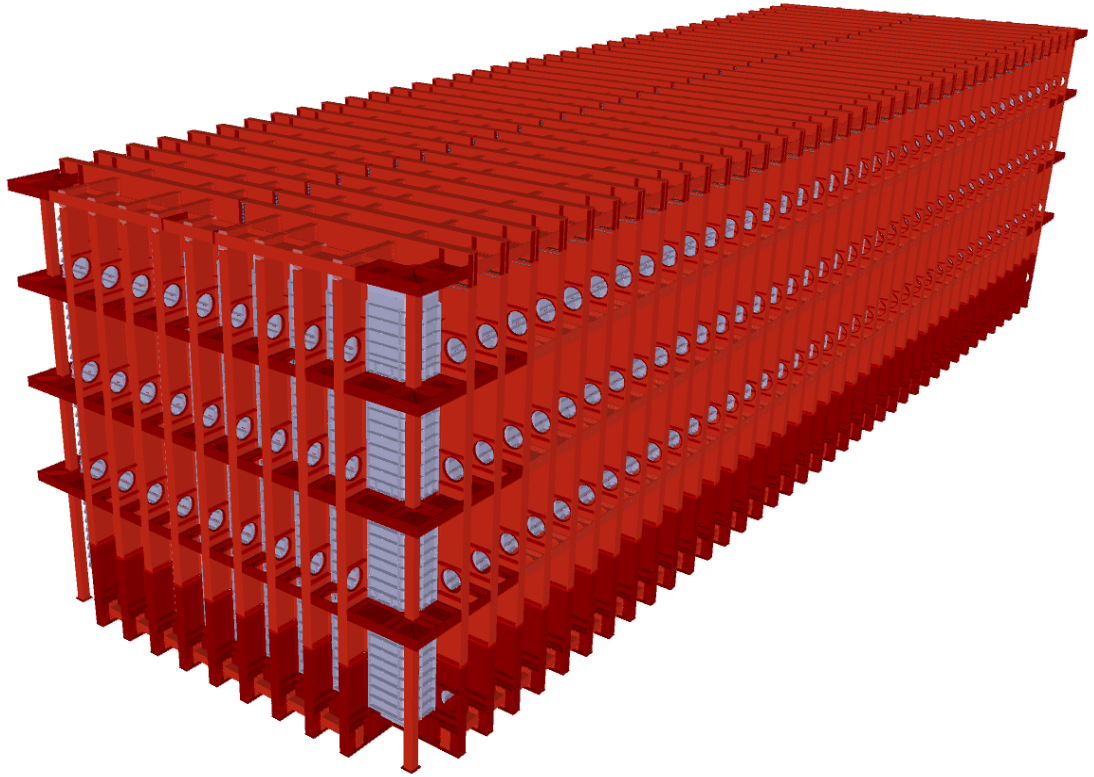
DUNE Far Detector

- Two 17kt LArTPC modules – 1 each of horizontal and vertical drift.
- 17.8m(H)x19m(W)x65.9m(L) Cryostat with internal volume of 28’500 m^3
- 17.5kt of LAr when filled.
- Membrane with passive insulation.

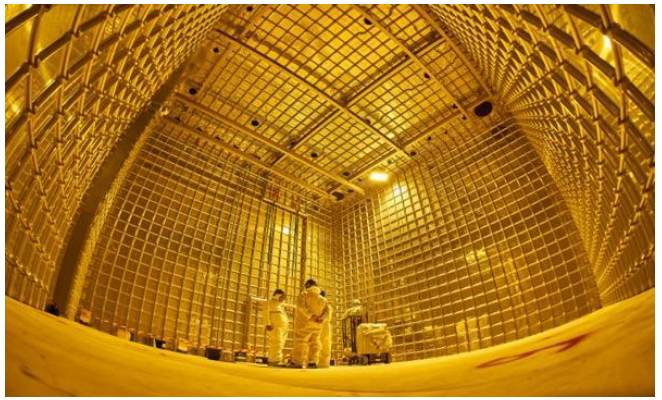
  Design by CERN and GTT



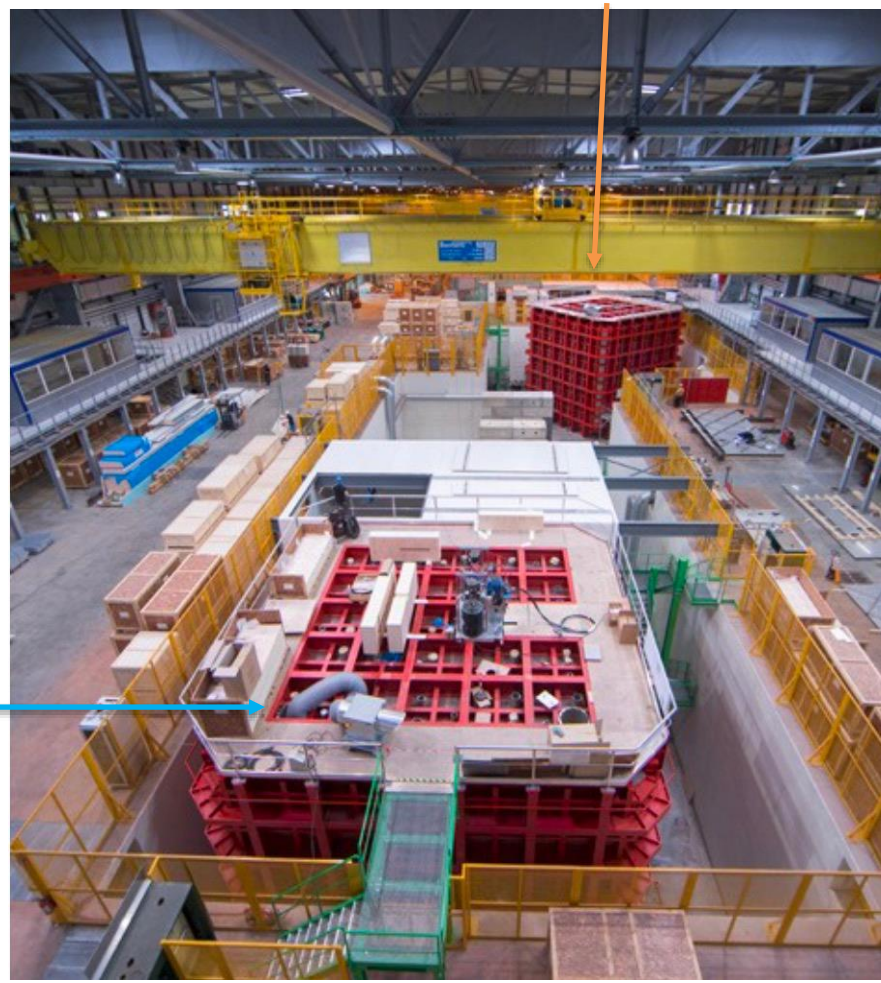
Cryostats construction happening now



Comprehensive R&D Program - ProtoDUNE



ProtoDUNE-DP

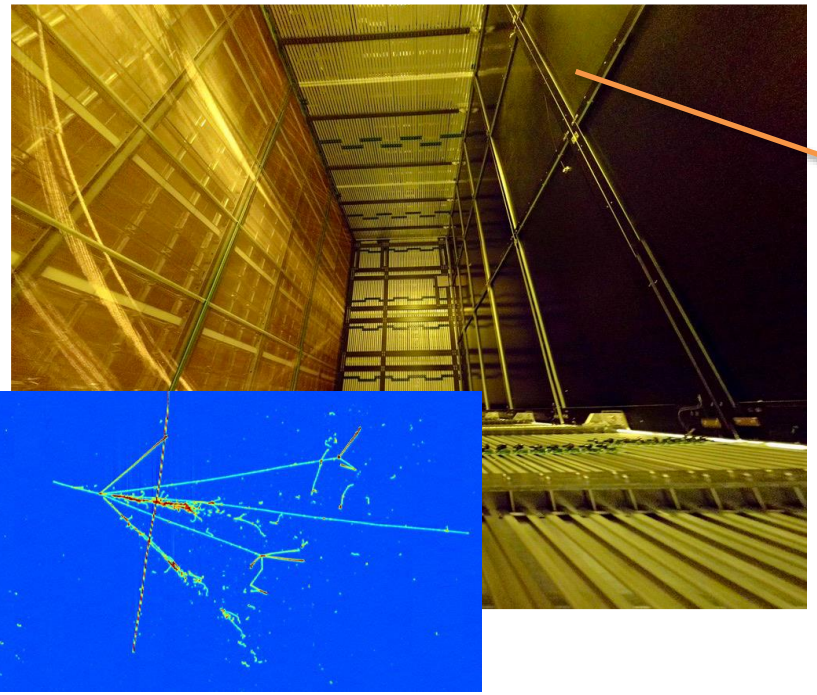


ProtoDUNE-SP

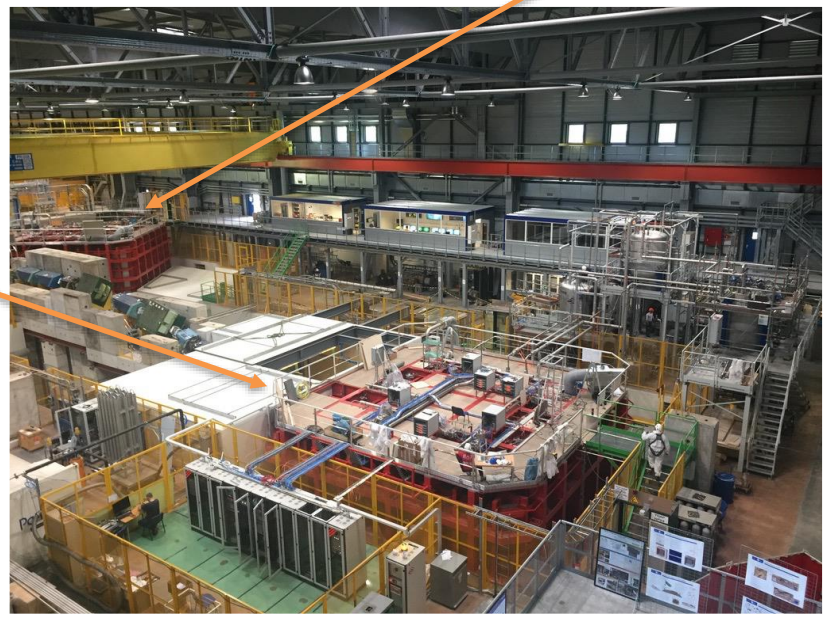
- Two Prototypes at CERN – 770t
- 1/25th of DUNE
- DUNE size components 8mx8mx8m cryostat
- Test beam with muons, pions, protons, kaons, etc.
- Multiple beam momenta.
- Characterization of detector components performance and detector response.
- Development and tuning of reconstruction.
- Physics measurements.

ProtoDUNE II

ProtoDUNE-HD (NP04)

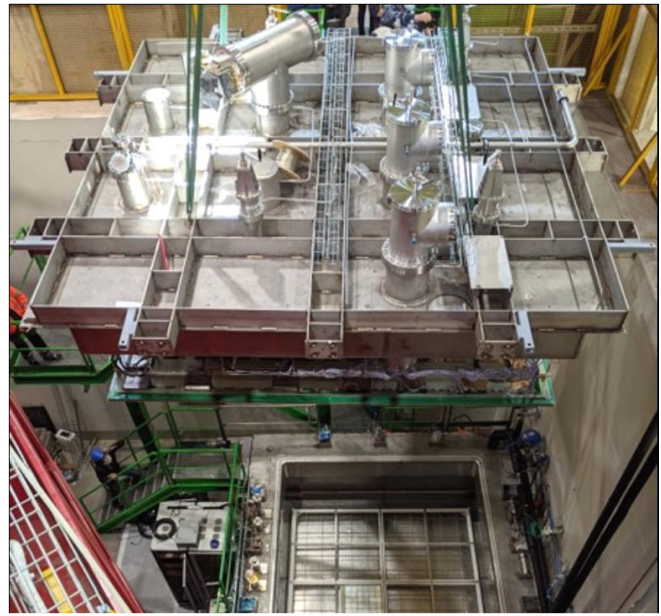


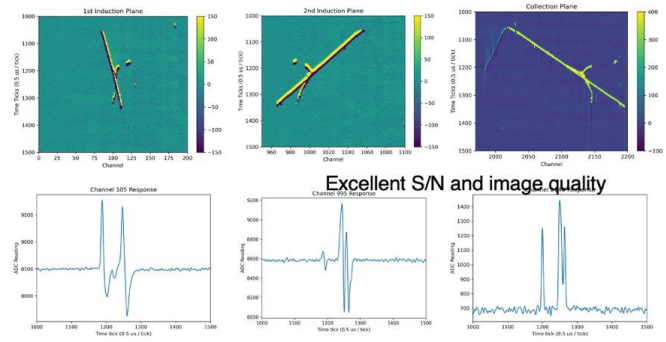
- ProtoDUNE-HD is installed
- Module – 1 components



- Expected to take data later in 2024

ProtoDUNE-VD (NP02)

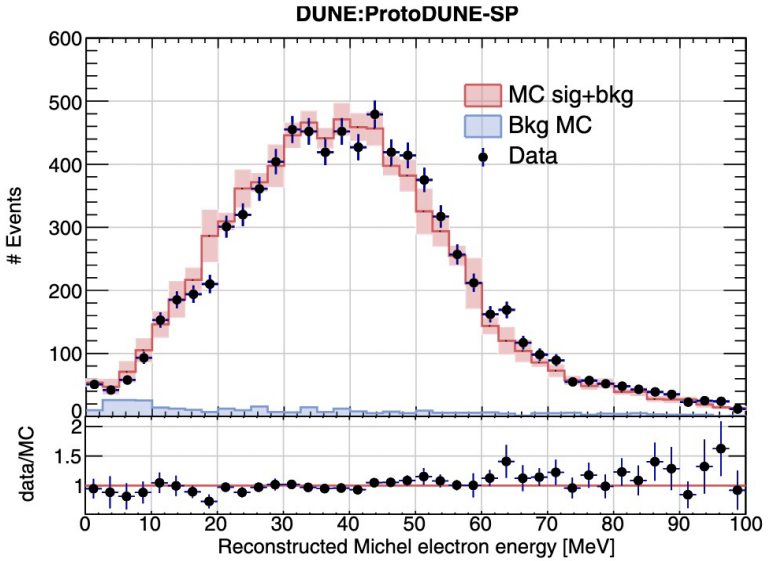




- ProtoDUNE-VD is being installed
- Module – 2 components

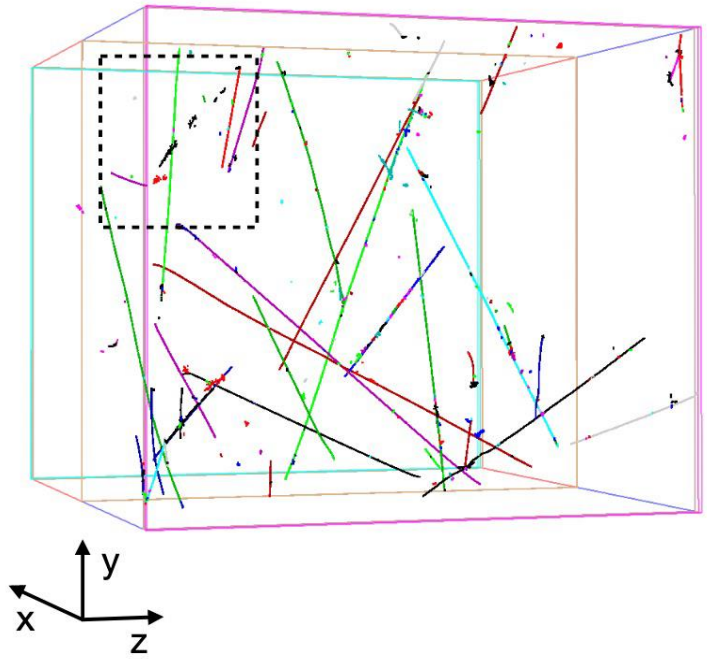
ProtoDUNE I Physics – 2018/20 Run

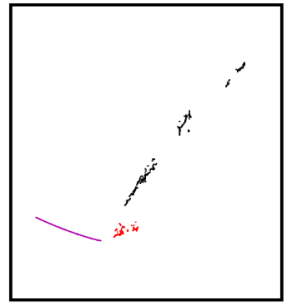
- ProtoDUNE single phase beam and cosmics.
- Successful long-term run.
- Evaluate the performance of first version of DUNE's components and reconstruction tools.
- Physics results are already coming out.



Michel energy reconstruction

Phys. Rev. D 107, 092012 (2023)
arXiv:2211.01166



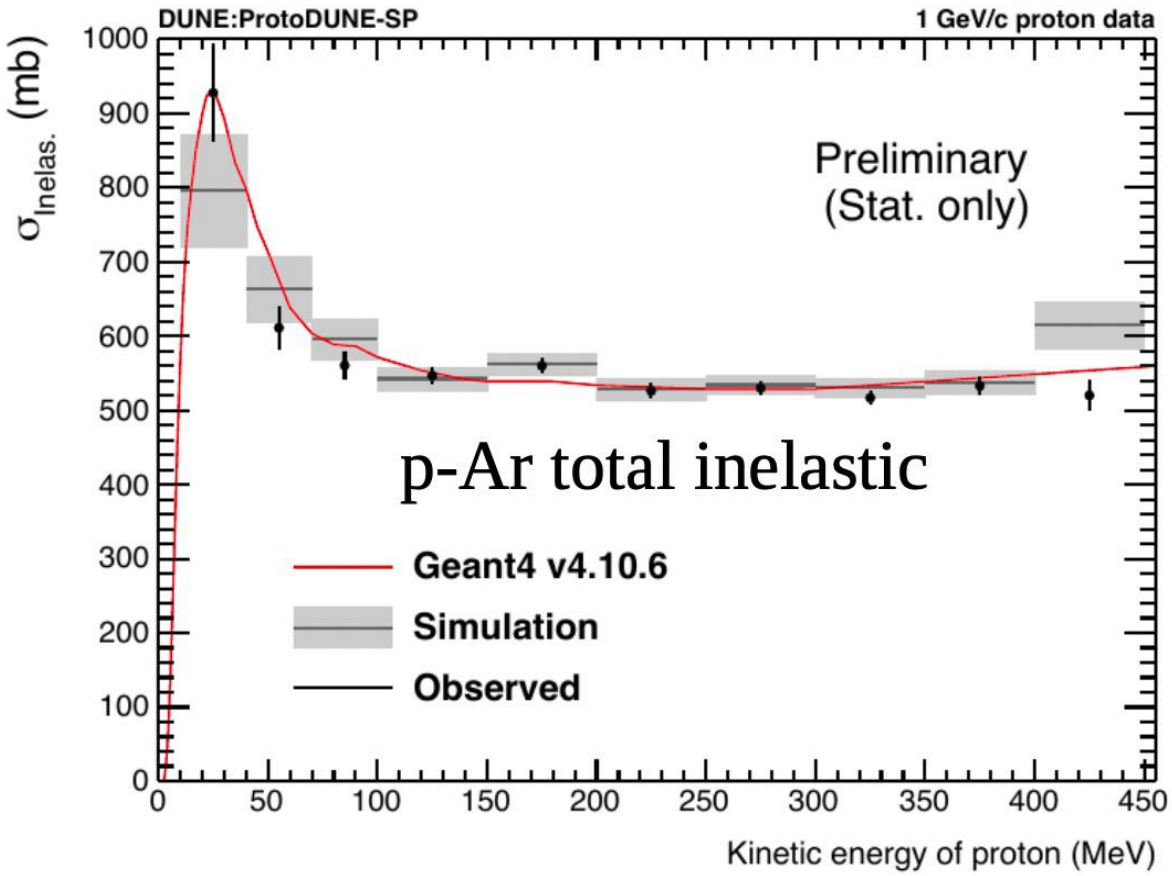


Pandora reconstruction validation with beam and cosmic muons

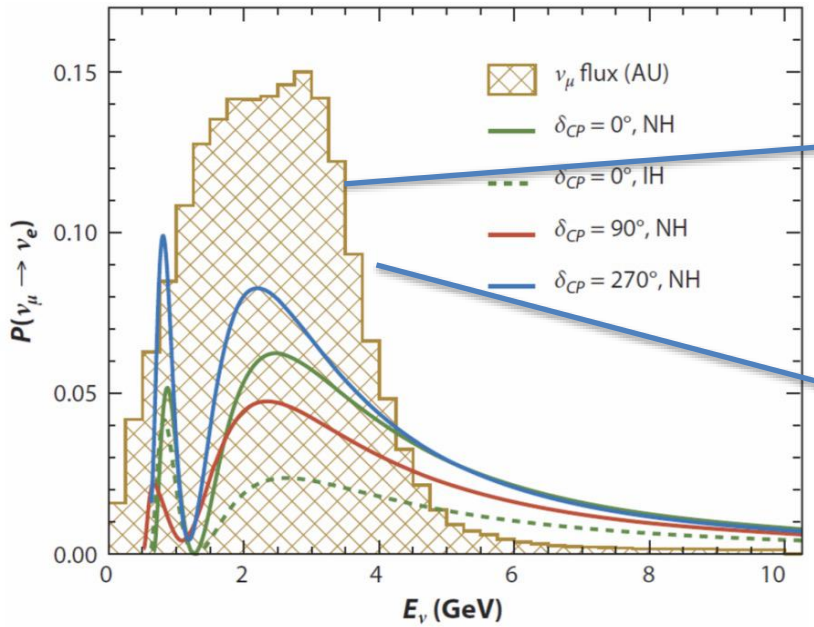
Eur. Phys. J. C 83, 618 (2023)
arXiv:2206.14521

Physics Results in the Works

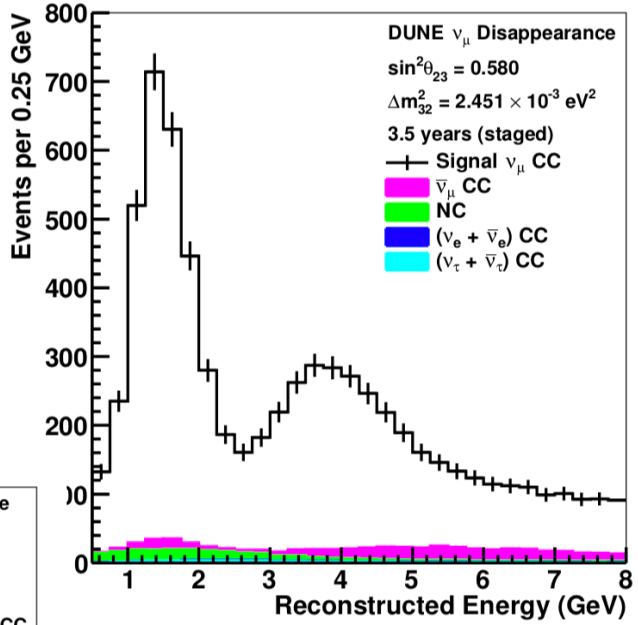
- Number of hadron cross section results for pion, proton, and kaons
- Important input to neutrino event generators
- Used to tune the modeling of nuclear effects in neutrino interactions.



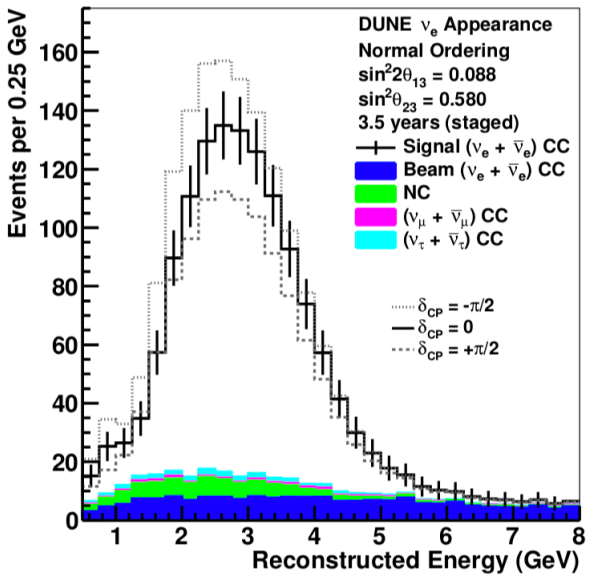
DUNE Physics – Neutrino Oscillations



ν_μ disappearance



ν_e appearance

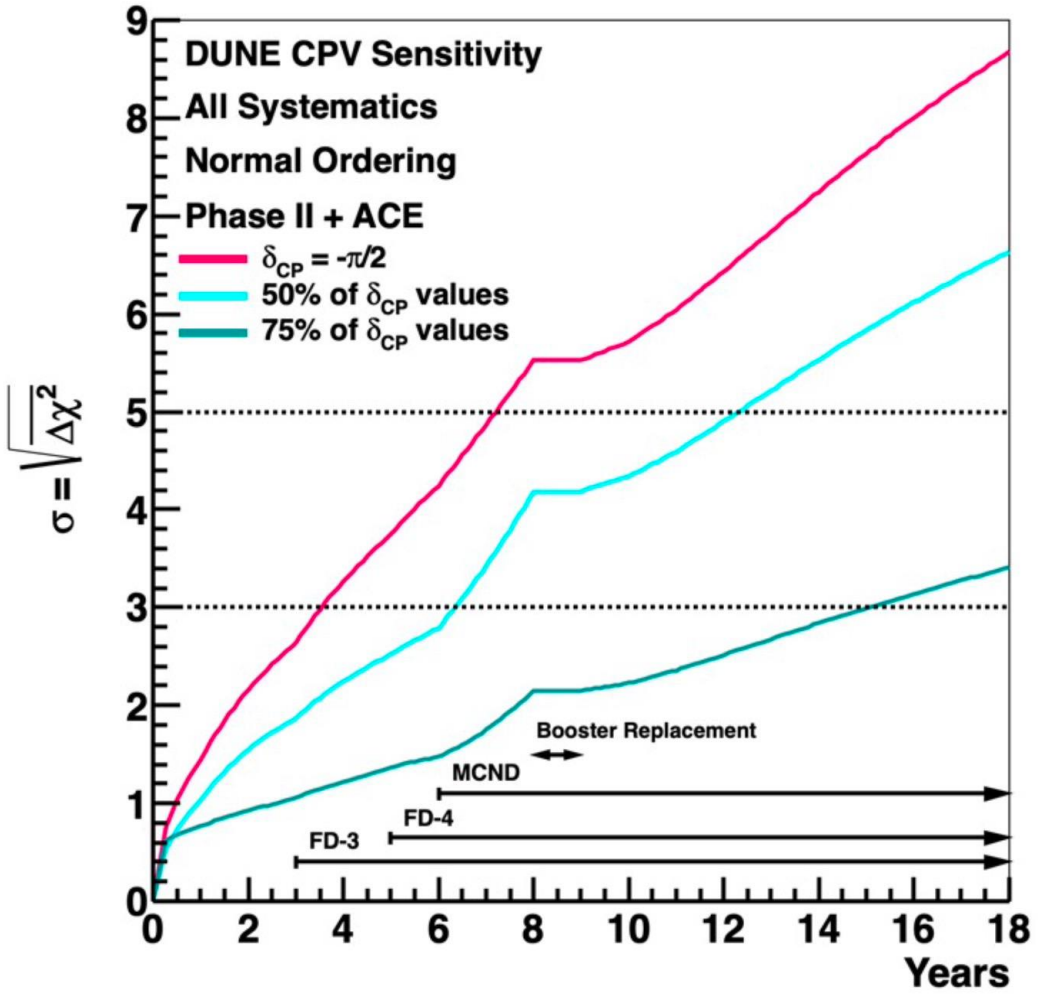


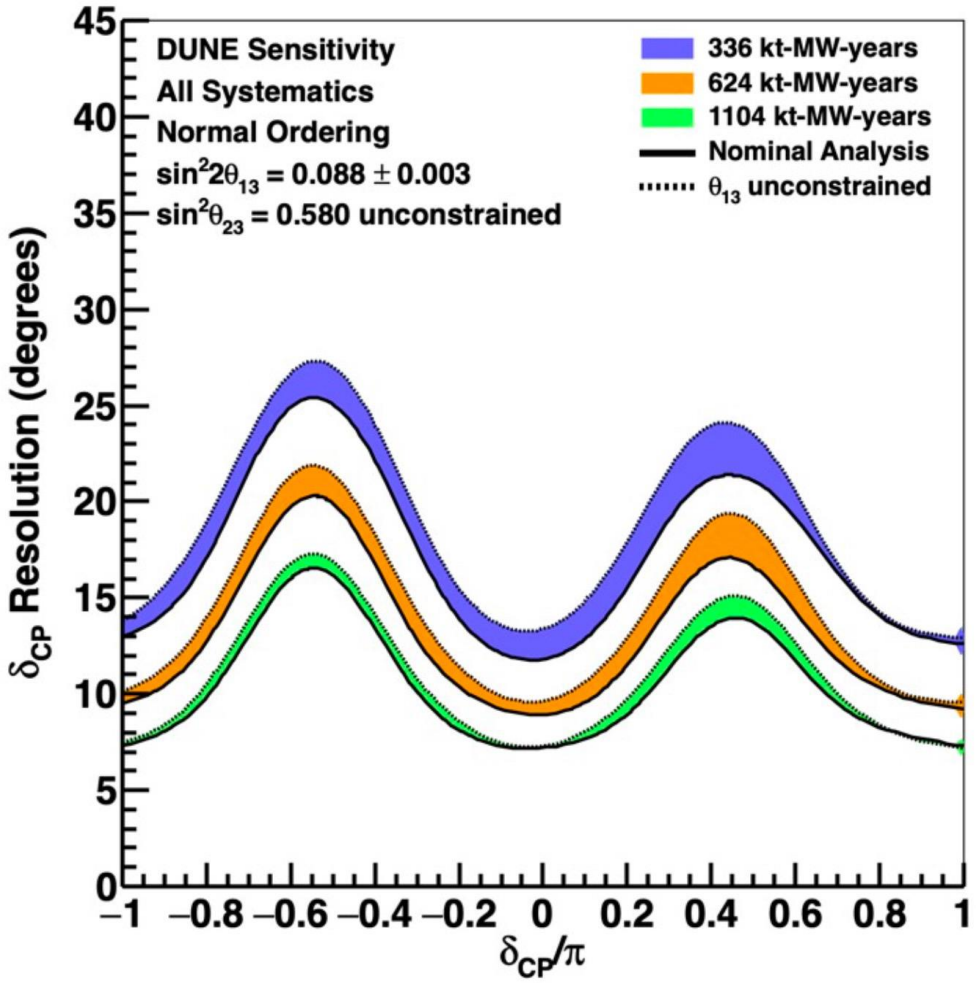
In about 7 years of running we expect

- ~10,000 disappearance events
- ~1,000 appearance events

Eur. J. Phys. C80, 978 (2020)

DUNE Physics – CP Violation Sensitivity





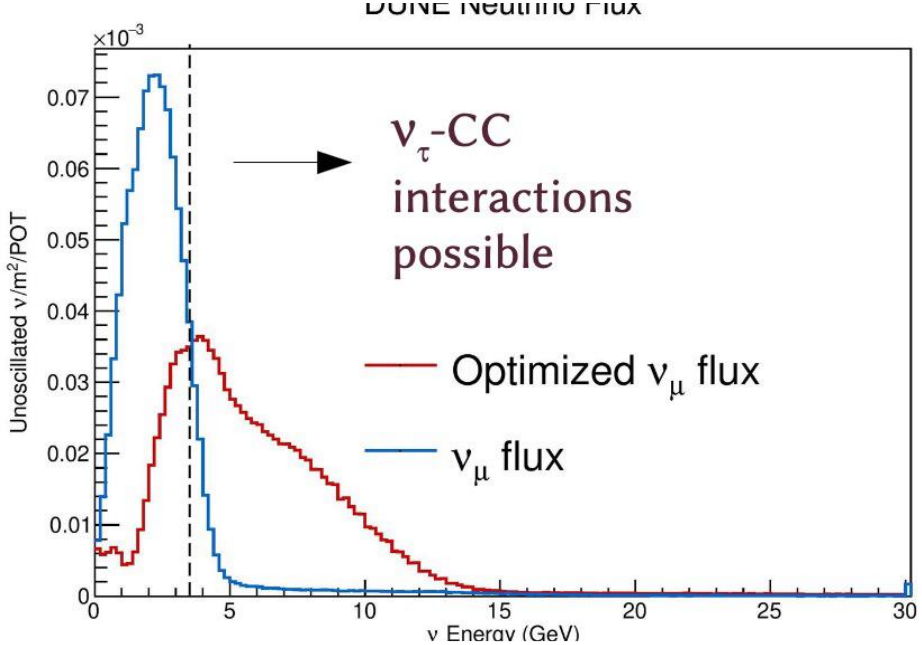
Rich Physics Program

- Precise measurement of 3-flavor neutrino oscillation parameters with both neutrinos and anti-neutrinos
  - Would be competitive to Daya Bay θ_{13} measurement with complete data set
- Neutrino interaction cross sections.
- SN physics – detect ν_e from galactic super-novae with ~5° pointing capability.
- HEP solar flux observation at more that 5σ and measurement of solar oscillation parameters.
- Test of 3-flavor oscillation limits – search for sterile n, PMNS non-unitarity, NSI, CPT violations
- Proton decay and GUT model tests. Search for $p \rightarrow K^+\bar{\nu}$.
- Other BSM physics.
- LArTPC can reconstruct ν_τ interactions as the beam is above τ production threshold.

Tau Neutrinos

- Configurable beam allows for high energy tune (phase-II)
- Needed to overcome the 3.5 GeV τ production threshold
- Achieved by moving the magnetic horns.
- Expected ν_τ statistics per year:
  - 130 with default beam
  - 800 with high energy tune.
- For $\bar{\nu}_\tau$ the rate is about 30events/year in low energy mode.

Phys. Rev. D 102, 053010 (2020)



Decay mode	Branching ratio
Leptonic	35.2%
$e^-\bar{\nu}_e\nu_\tau$	17.8%
$\mu^-\bar{\nu}_\mu\nu_\tau$	17.4%
Hadronic	64.8%
$\pi^-\pi^0\nu_\tau$	25.5%
$\pi^-\nu_\tau$	10.8%
$\pi^-\pi^0\pi^0\nu_\tau$	9.3%
$\pi^-\pi^-\pi^+\nu_\tau$	9.0%
$\pi^-\pi^-\pi^+\pi^0\nu_\tau$	4.5%
other	5.7%

Conclusions and Future

- DUNE is a next generation long-baseline neutrino oscillation experiment with rich physics program
  - Precise measurement of neutrino oscillation parameters
  - Astrophysical measurements with SN and other ~MeV energy neutrinos
  - BSM physics both neutrino and non-neutrino.
- ProtoDUNE is a successful testbed with many physics results right around the corner.
- LBNF construction is progressing rapidly with expectation to have occupancy at the far site at the end of 2024.
- First module starts taking data in 2028.
- First beam is expected to start in 2031.

DUNE Talk on **3D-Reconstruction of Tau Neutrinos in LArTPC Detectors**

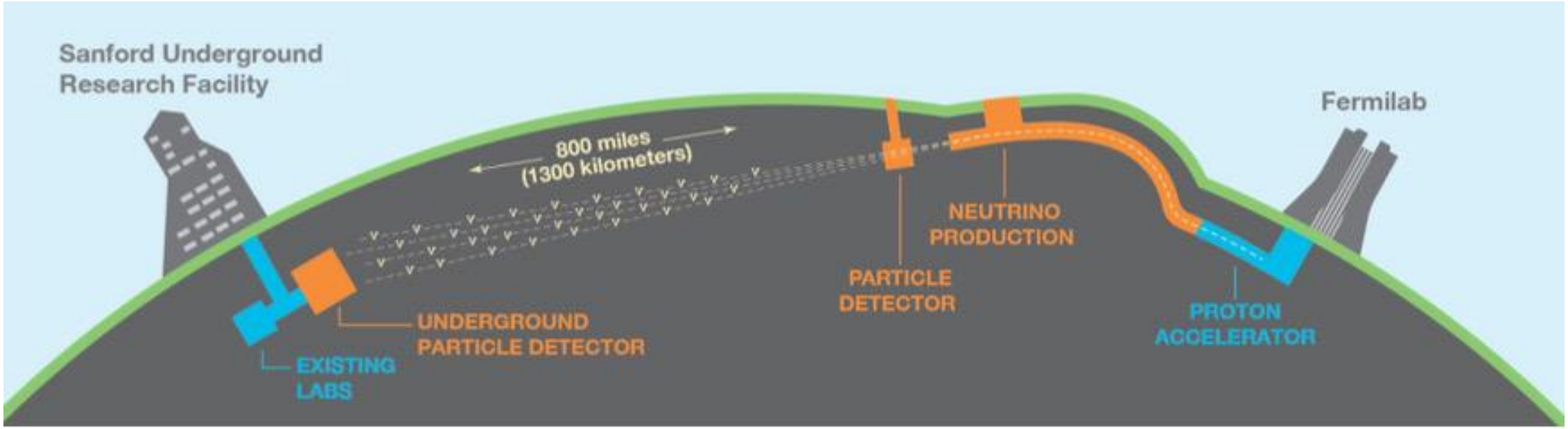
By Barbara Yaeggy Alvarez

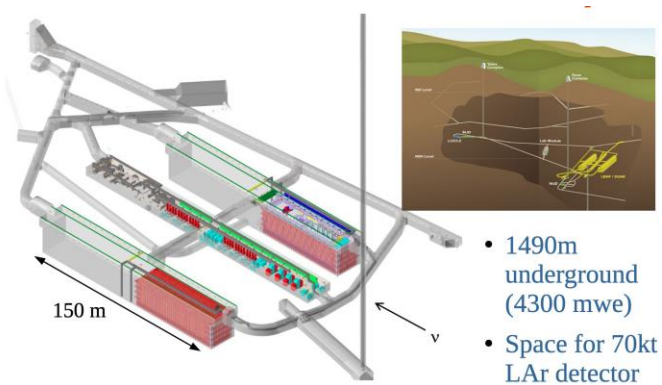
Thursday, Dec 7th, at 5:40PM.

Thank you!

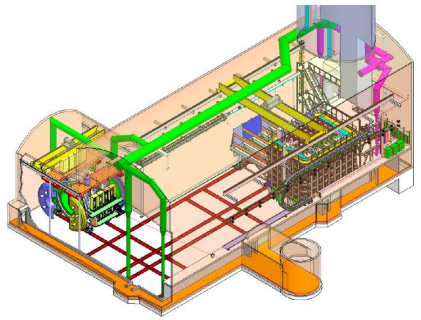
Backups

DUNE Concept





- 1490m underground (4300 mwe)
- Space for 70kt LAr detector



- Near detector

Beamline

DUNE Timeline and Phasing

DUNE phase-I:

- LBNF completed
  - PIP-II and neutrino beamline by 2031
  - full near detector site and facilities by 2028
  - far site with facilities and caverns for 2 modules – total of 70kt FD complete by the end of 2024
- Two FD modules – 17kt LArTPC each of HD and VD
  - HD starts installation in 2026, complete and commissioned by 2028
  - VD starts installation in 2029
- LAr-ND w/ TMS and on-axis SAND by 2031

DUNE phase-II:

- Fermilab beamline: Booster and other upgrade allowing for 2.1MW
- ND – additional sub-detectors – ND-Gar, calorimeter
- FD – FD3 and FD4 – technology TBD.

DUNE Physics – $\nu_e/\bar{\nu}_e$ Phase-I Statistics

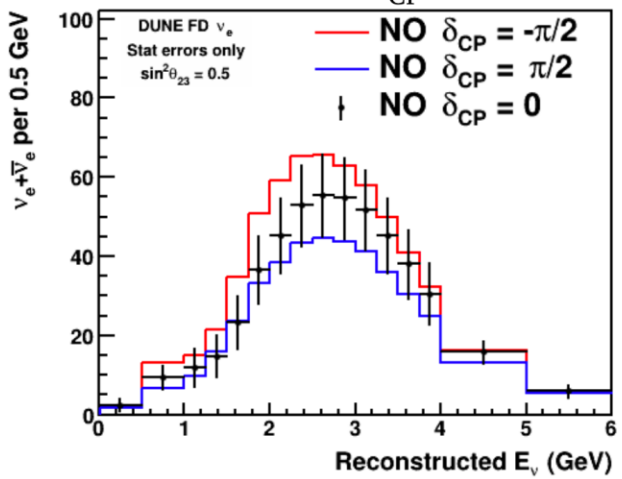
Data points show NO, $\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$

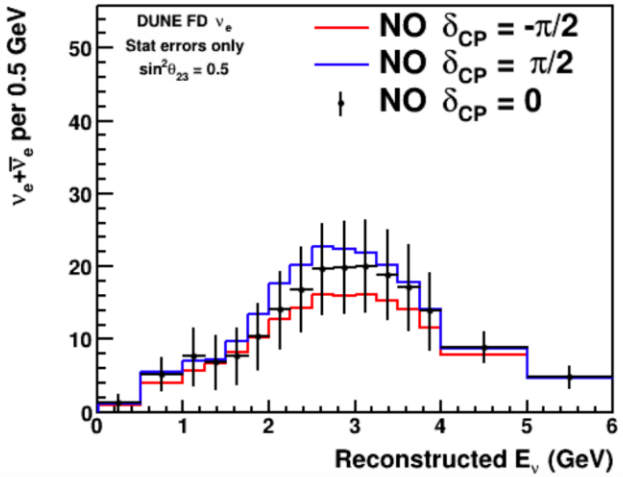
Neutrino mode

Phase I

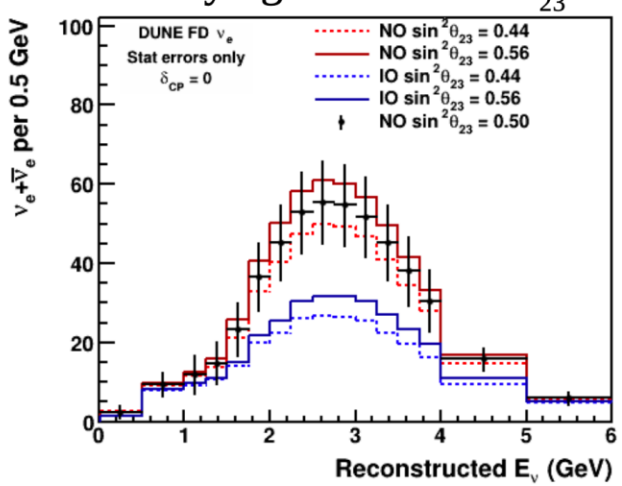
Antineutrino mode

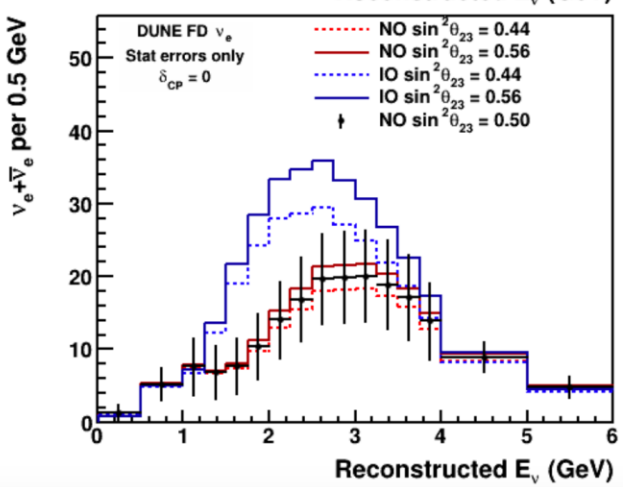
Varying δ_{CP}





Varying MO and $\sin^2\theta_{23}$





DUNE Physics – $\nu_e/\bar{\nu}_e$ Phase-II Statistics

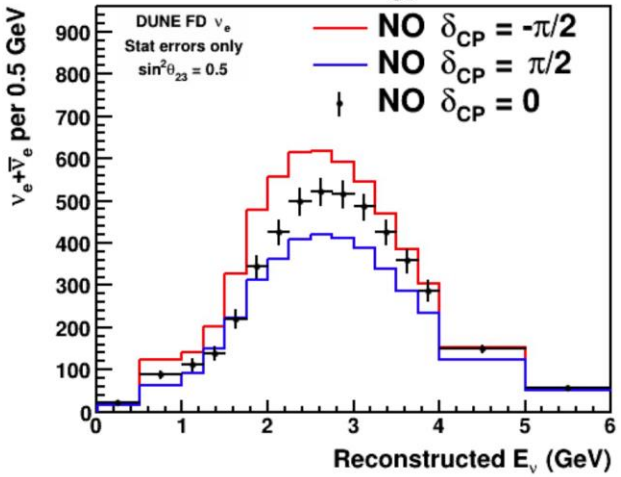
Data points show NO, $\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$

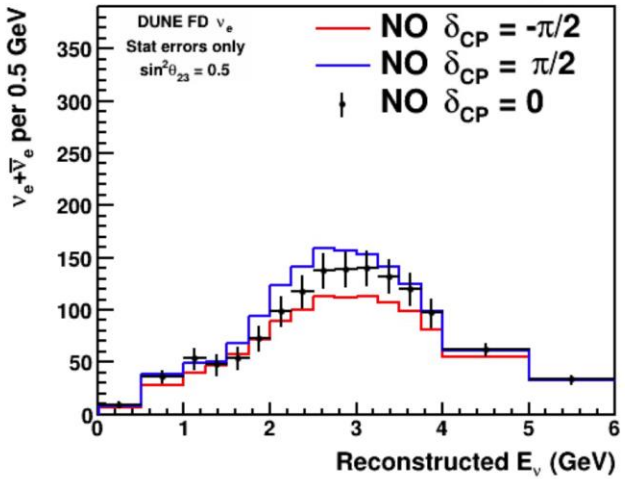
Neutrino mode

Phase II

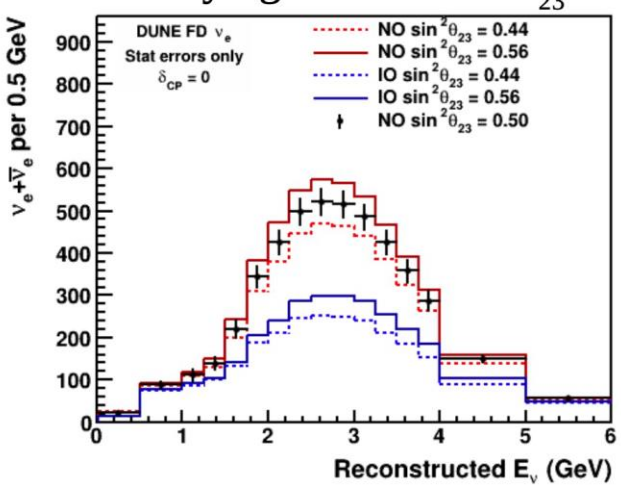
Antineutrino mode

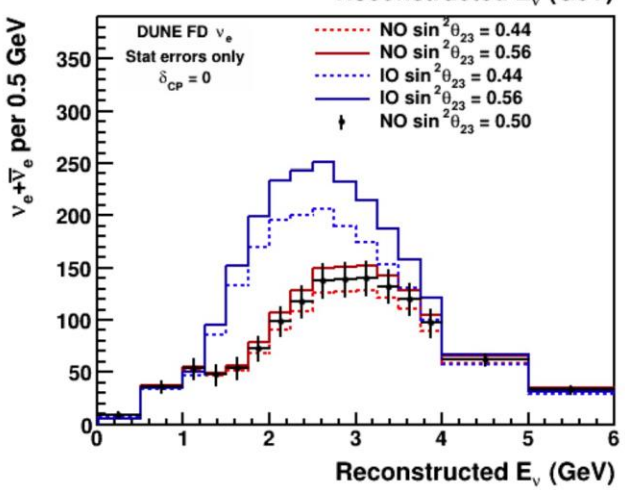
Varying δ_{CP}





Varying MO and $\sin^2\theta_{23}$





LBNF Far Site

- Excavation expected to finish 2024
- 80% done.
- Facility to be completed in 2025