Status and Prospects

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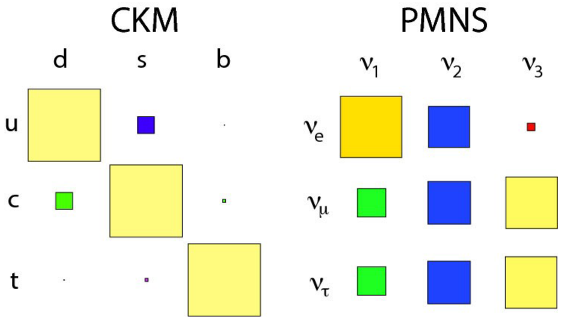
for the DUNE Collaboration.

NNN23

22nd International Workshop on Next Generation Nucleon Decay and Neutrino Detectors
Procida October 11-13, 2023

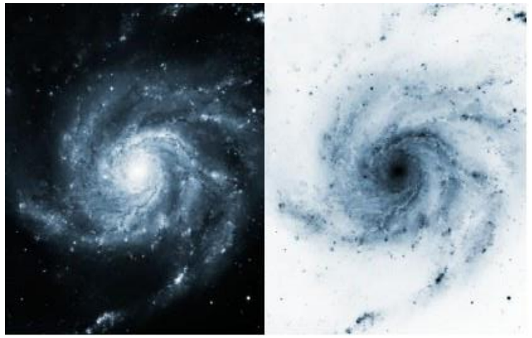
Fundamental Questions

- What is the origin of neutrino mixing?
  Is there an underlying **flavor symmetry**?

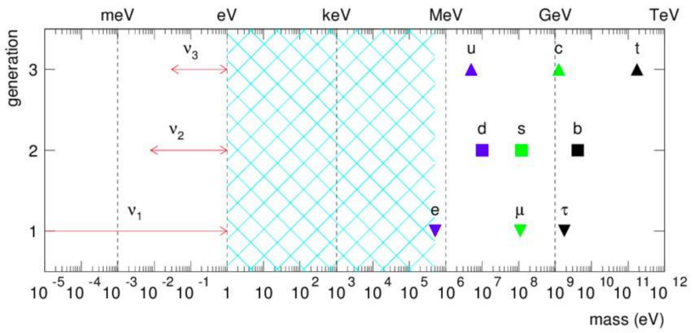


PoS(ICHEP2012)033

- Is **leptogenesis** a viable explanation
  to baryon asymmetry ?

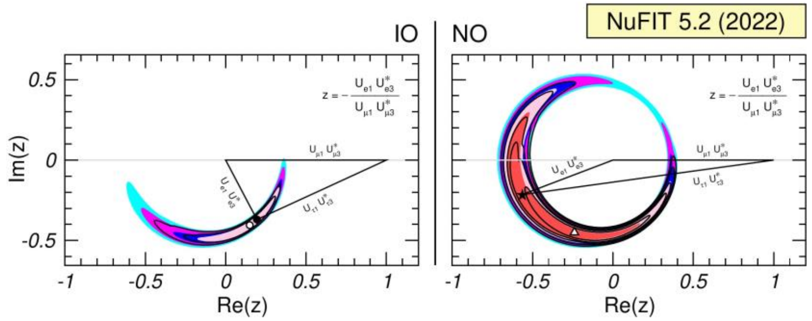


- What is the **origin of neutrino mass**?
  Why are the neutrinos so light?



arXiv:hep-ph/0411274

- Are there sterile neutrinos?
  Is the **PMNS matrix unitary**?



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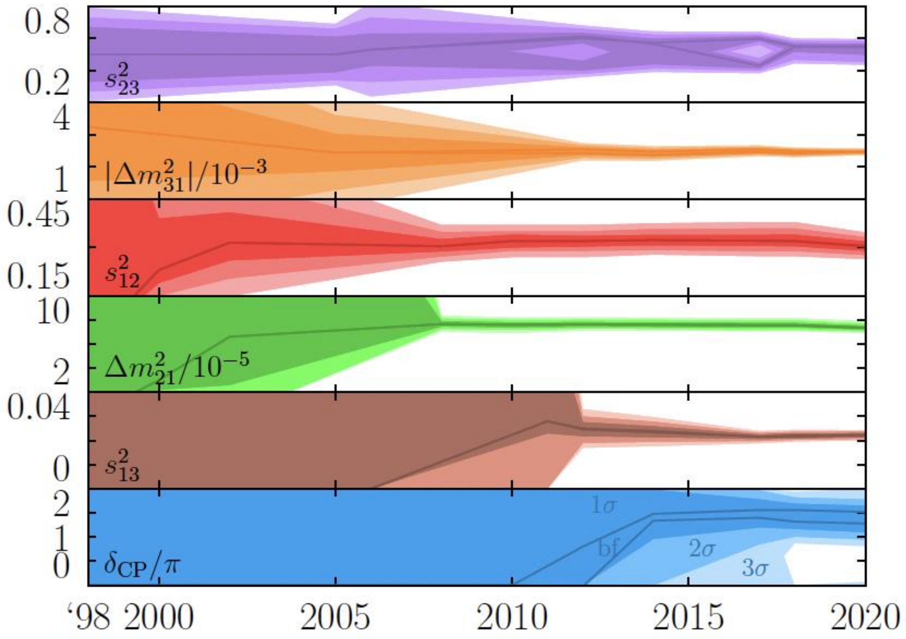
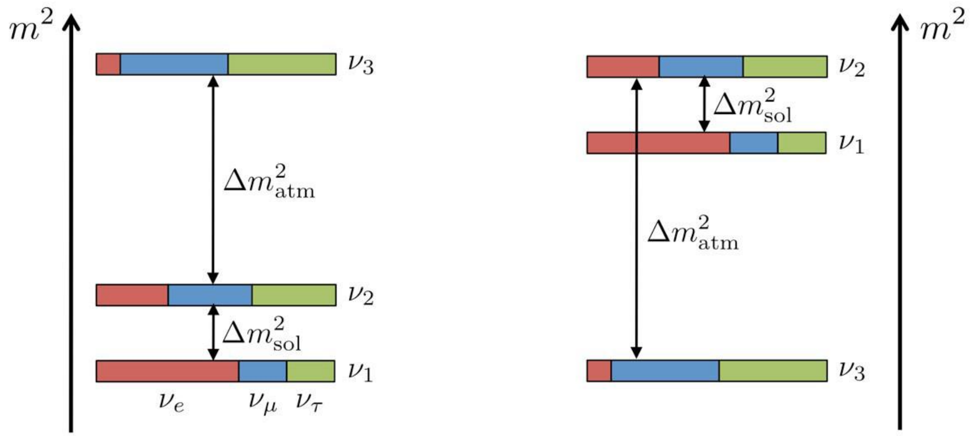
Neutrino Oscillations

Impressive progress since 1998

arXiv:2212.00809



normal hierarchy (NH) **inverted hierarchy (IH)**



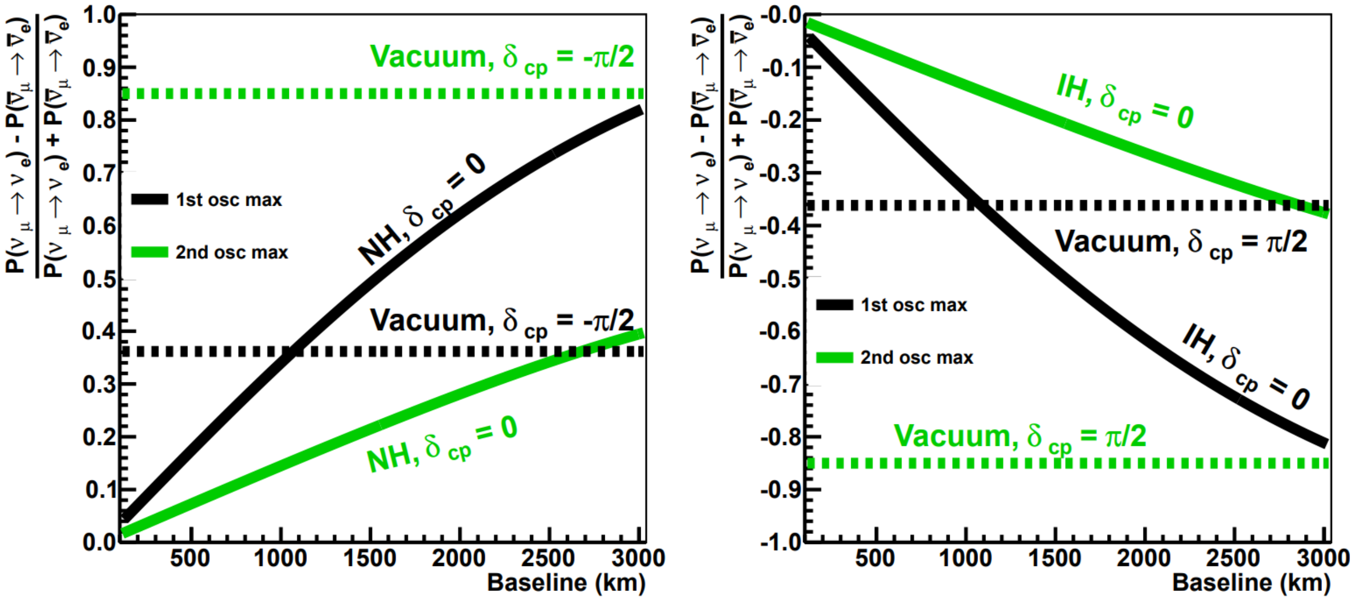
$$U_{\mathrm{PMNS}} = \underset{\sin^2\theta_{23} = 0.5 \pm 0.1}{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}} \begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\mathrm{CP}}} s_{13} \\ 0 & 1 & 0 \\ \underset{?}{-e^{i\delta_{\mathrm{CP}}}} \underset{2.7\%}{s_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & \overset{2.3\%}{s_{12}} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Experimental Strategy

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

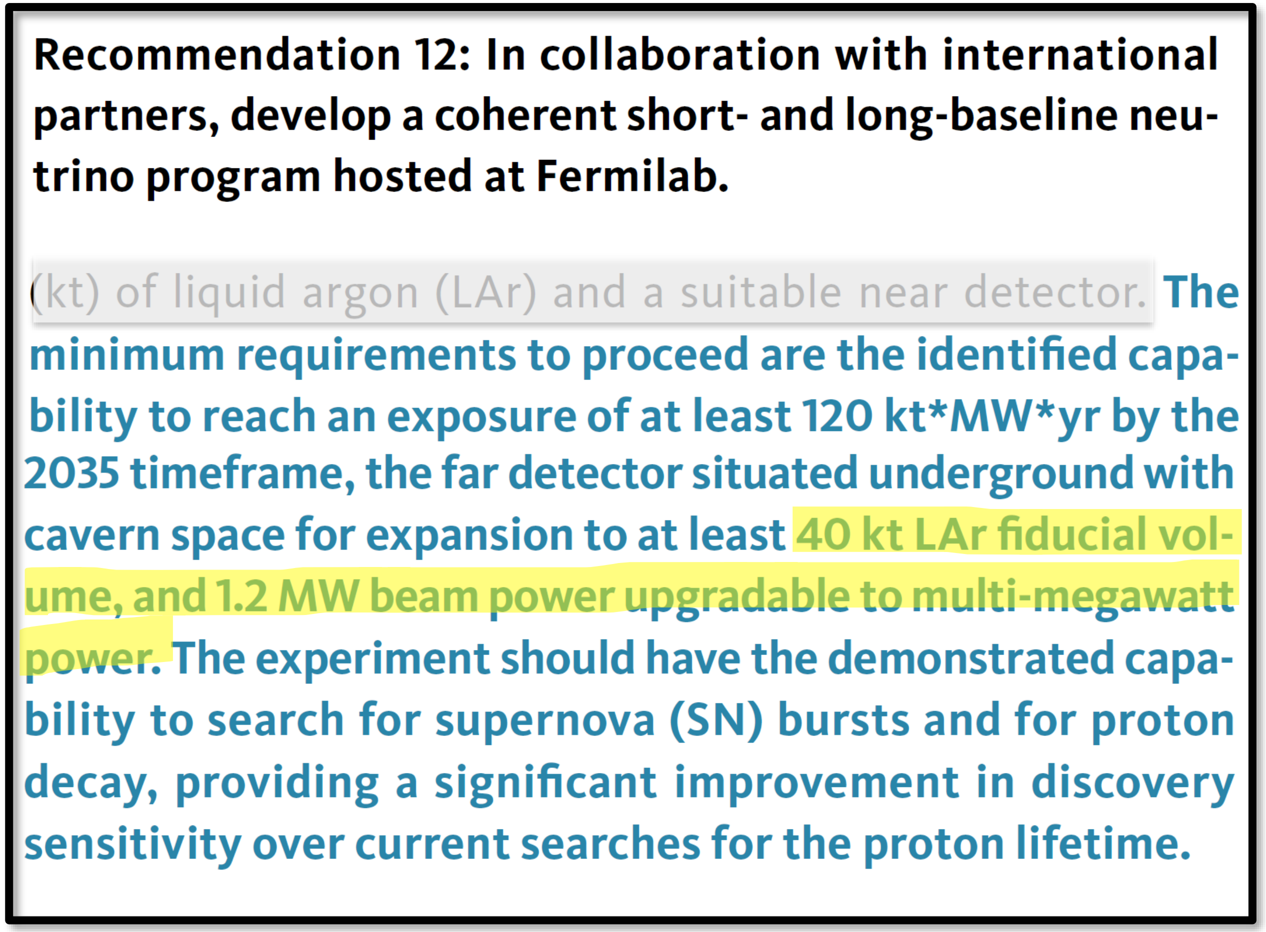
Long baseline + **wide-band beam**: unfold **CPV** and **matter effects** using information from the first and second oscillation maxima.

- Baseline ~ 1000 km
- 1st peak at ~ 2 GeV
- 2nd peak at ~ 0.5 GeV



Phys. Rev. D 91, 052015 (2015)

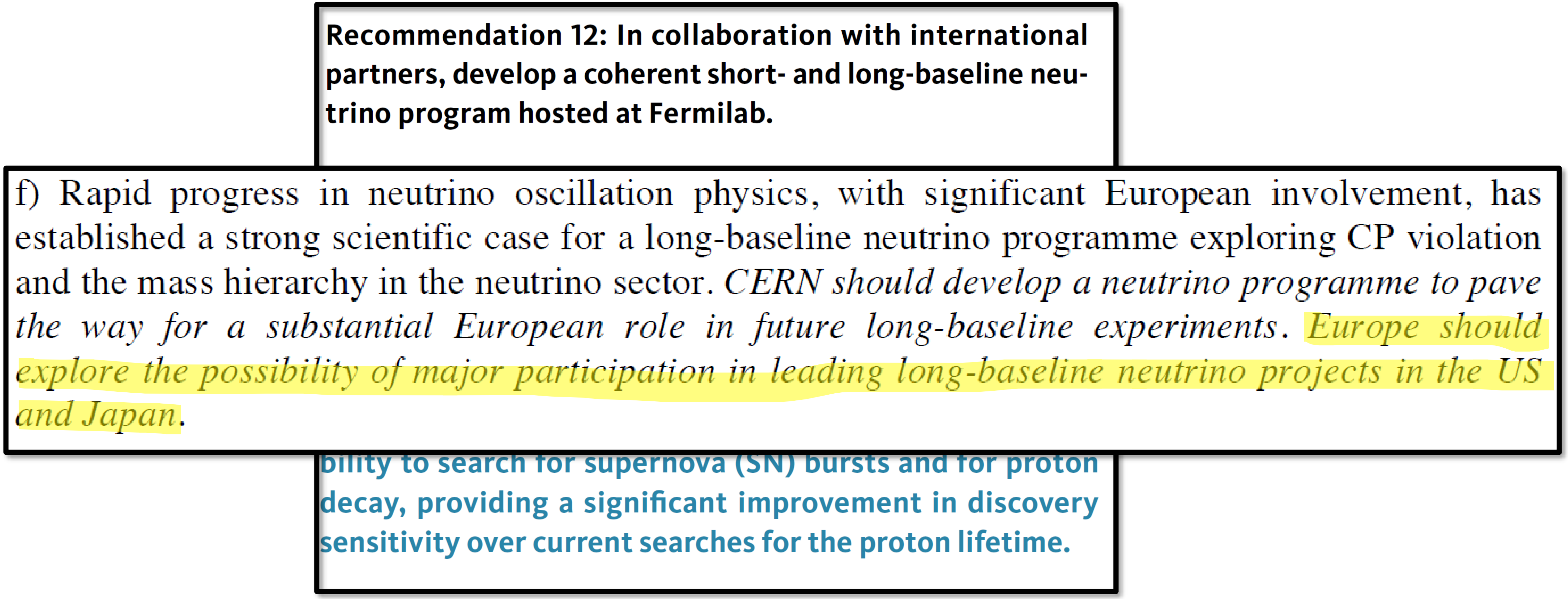
P5 & ESPP Recommendations



Recommendation 12: In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab.

(kt) of liquid argon (LAr) and a suitable near detector. **The minimum requirements to proceed are the identified capability to reach an exposure of at least 120 kt*MW*yr by the 2035 timeframe, the far detector situated underground with cavern space for expansion to at least 40 kt LAr fiducial volume, and 1.2 MW beam power upgradable to multi-megawatt power. The experiment should have the demonstrated capability to search for supernova (SN) bursts and for proton decay, providing a significant improvement in discovery sensitivity over current searches for the proton lifetime.**

P5 & ESPP Recommendations



Recommendation 12: In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab.

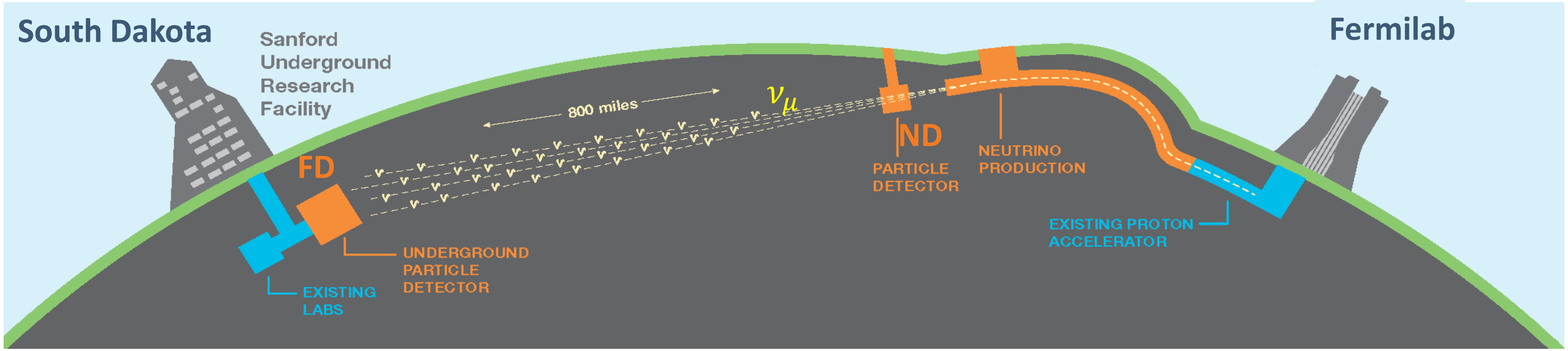
f) Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector. *CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan*.

bility to search for supernova (SN) bursts and for proton decay, providing a significant improvement in discovery sensitivity over current searches for the proton lifetime.

- **1440 collaborators**
- **37 countries**
- **208 institutions including CERN**

DUNE Collaboration Meeting, CERN January 2023

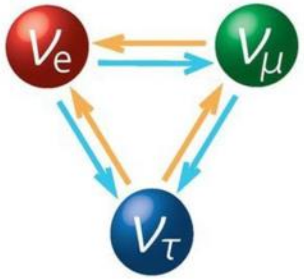
The Deep Underground Neutrino Experiment (DUNE)

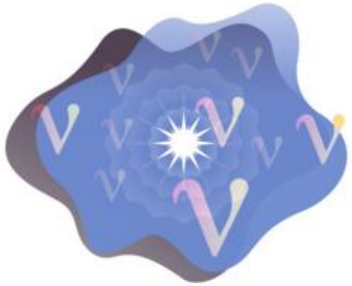


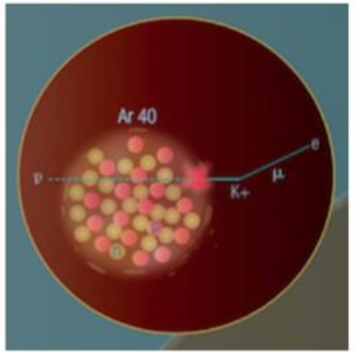
A new generation Long-Baseline – 1300 km – neutrino oscillation experiment based on

- a wide band high intensity (1.2 MW upgradable to 2.4 MW) $\nu/\bar{\nu}$ neutrino beam produced at Fermilab
- a large total mass (~70 kton) Far Detector at the Sanford Underground Neutrino Facility (SURF) 1.5 km underground exploiting the Liquid Argon Time Projection Chamber (LArTPC) technology
- a Near Detector complex (ND) at Fermilab providing control of systematic uncertainties, enabling a rich physics program

DUNE and its Physics Program in one slide







- **Long-baseline wide-band neutrino beam**
  - Measurement of CP violation phase and determination of the neutrino mass ordering in a single experiment using spectral information
- **Underground location → access to astrophysical neutrinos**
  - Supernova neutrino burst detection – sensitive to the ν_e component
  - Atmospheric neutrino – capability of ν_τ identification
  - Solar neutrinos – potential for detection of hep flux
- **Massive detectors with tracking and calorimetric information**
  - Search for baryon number violating processes – $p \rightarrow \nu K^+$, $n\ \bar{n}$
- **Long baseline + higher energy neutrino beam**
  - ν_τ appearance, NSI searches
- **Capable Near Detector Complex**
  - Precise neutrino physics (cross sections, nuclear effects)
  - BSM searches

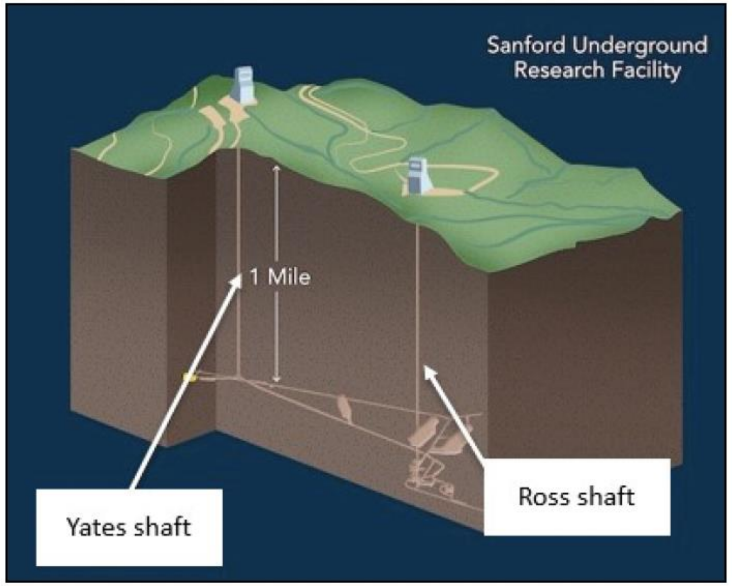
arXiv 1807.10334

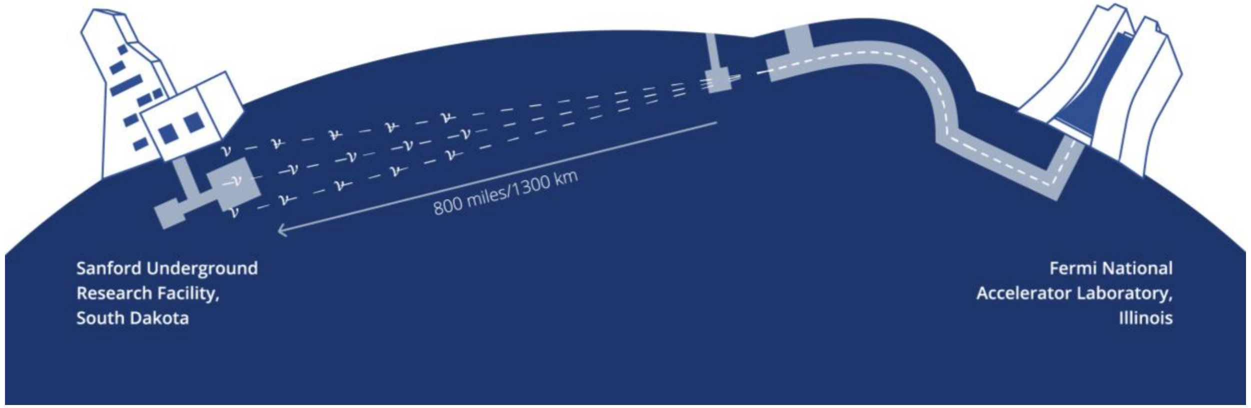
The Long-Baseline Neutrino Facility (LBNF) and DUNE

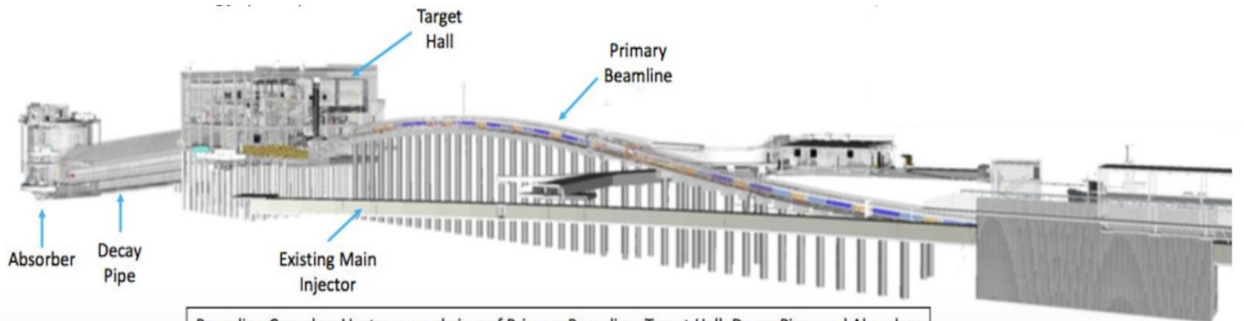
LBNF → Facility
DUNE → Experiment

DUNE experiment is enabled by LBNF providing

- a high intensity wide-band neutrino beam
- a deep underground lab in South Dakota and Near Detector infrastructures

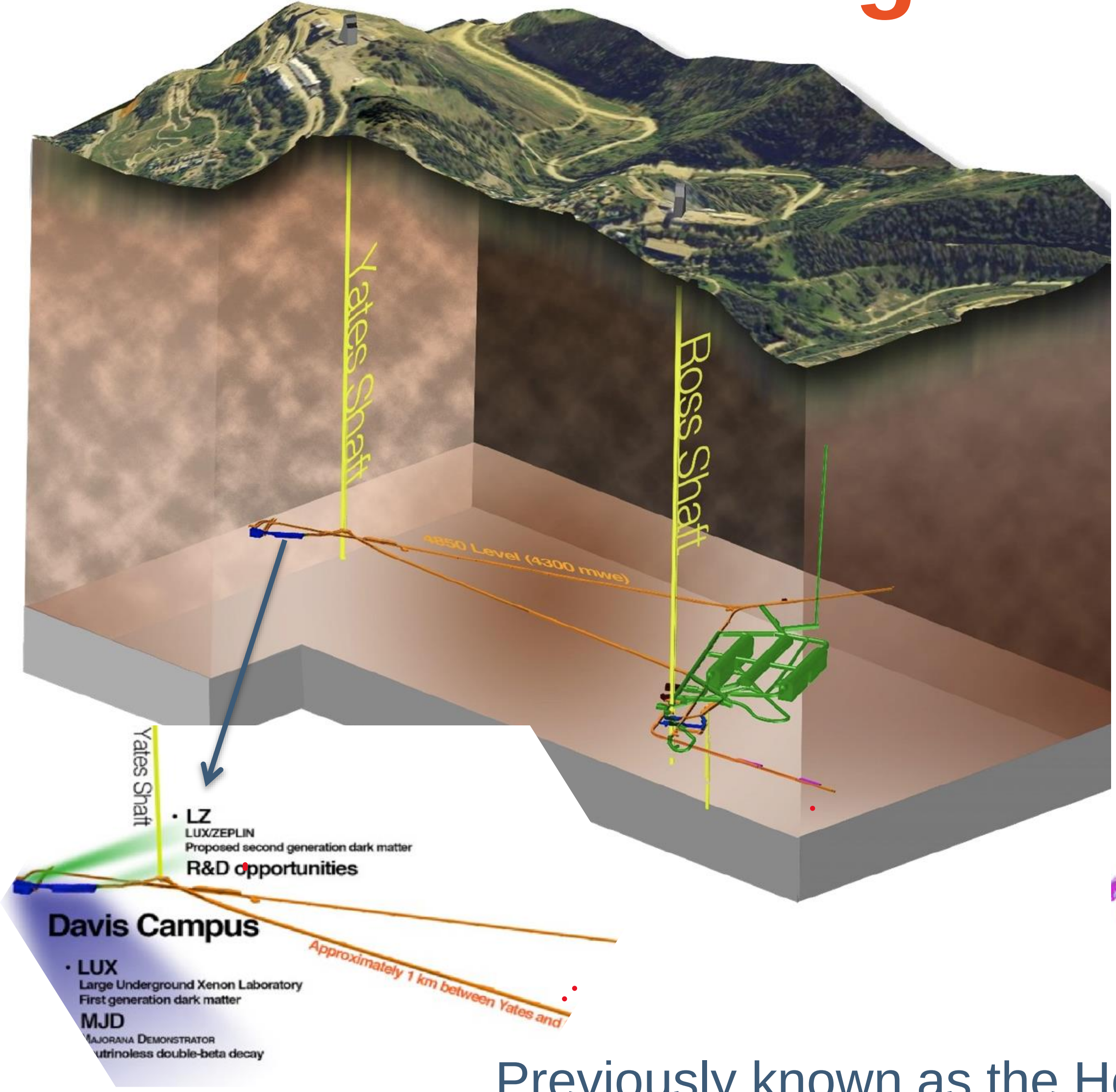


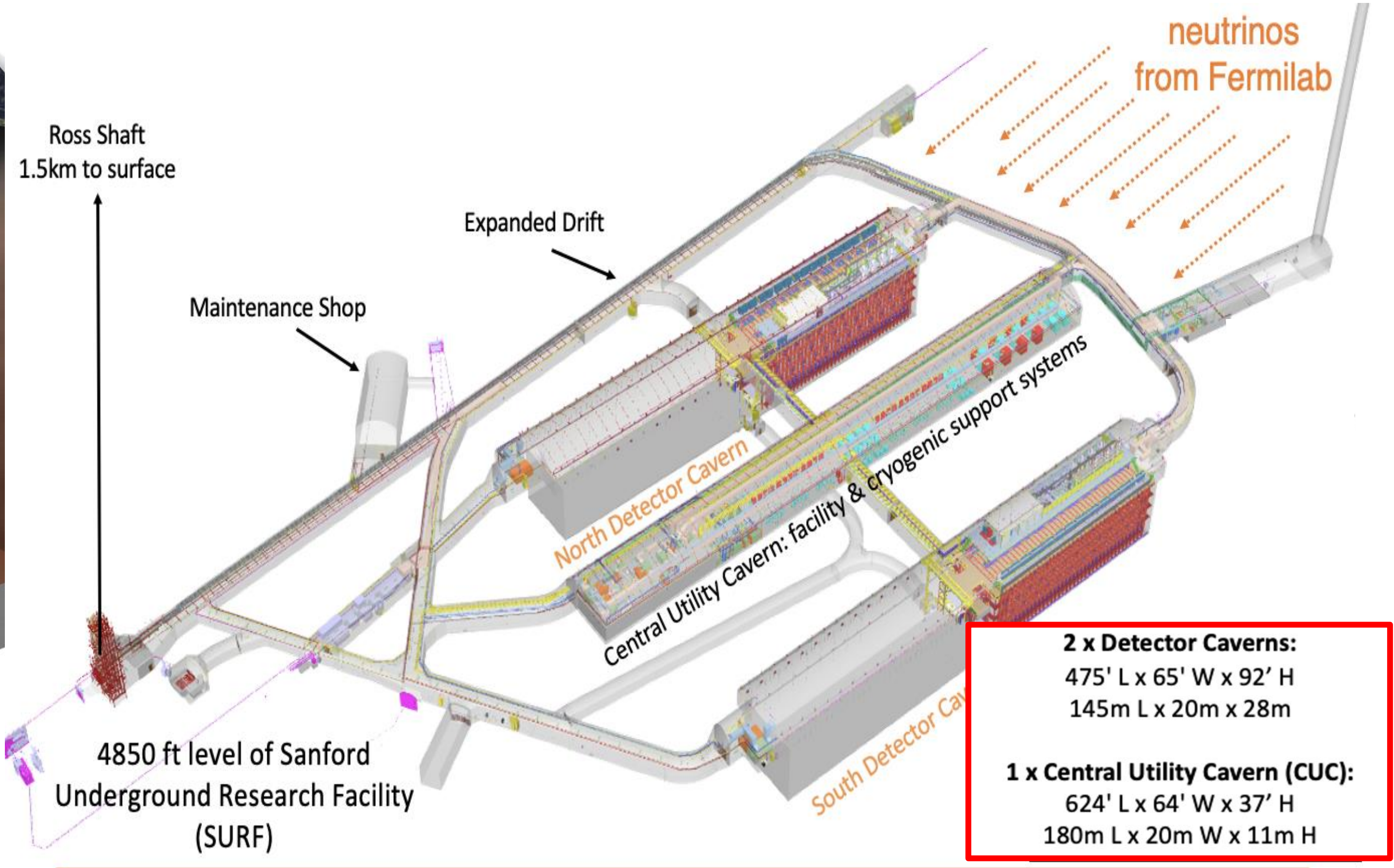




Beamline Complex: Upstream end view of Primary Beamline, Target Hall, Decay Pipe, and Absorber

Sanford Underground Research Facilities



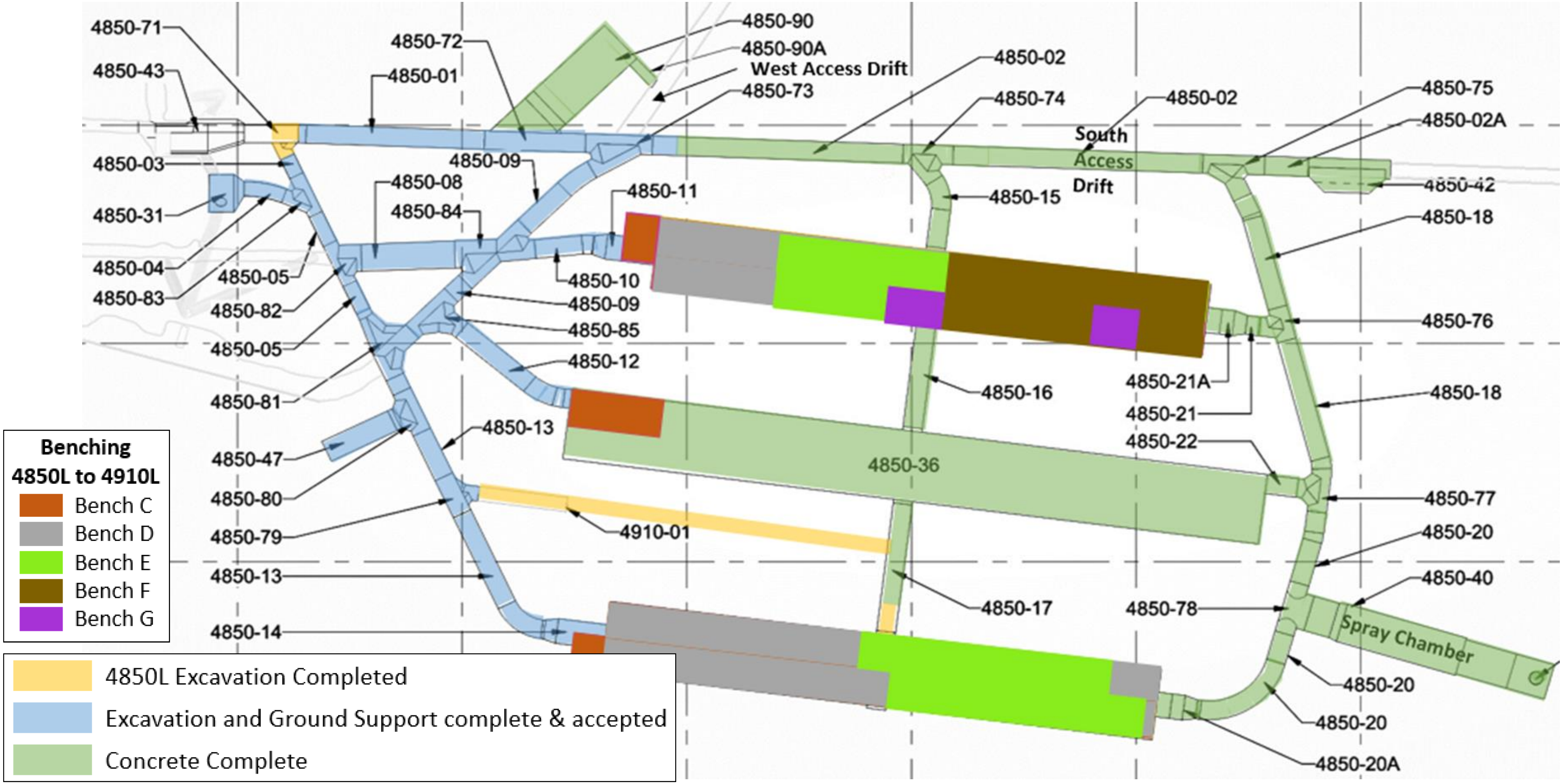


2 x Detector Caverns:
475' L x 65' W x 92' H
145m L x 20m x 28m

1 x Central Utility Cavern (CUC):
624' L x 64' W x 37' H
180m L x 20m W x 11m H

Previously known as the Homestake (gold) Mine in the Black Hills

Excavation Progress – Reached 80% on 25 September 2023



North Detector Cavern

- View of east end of cavern
- 12’ of additional benching to be performed when this photo was taken
- 3D VR photos available

Photo by
Matt Kapust, SDSTA
Aug 2023

Central Utility Cavern

- Excavation of Central Utility Cavern is complete!
- 90% of cavern concrete slab is in place

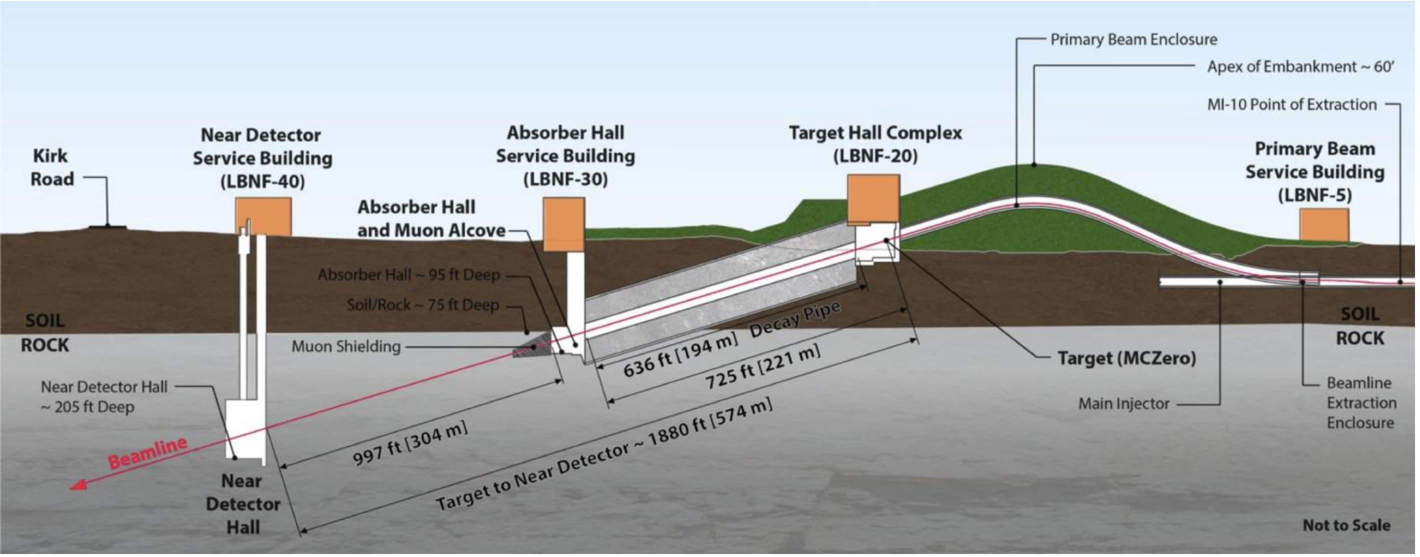
The LBNF beamline at FNAL

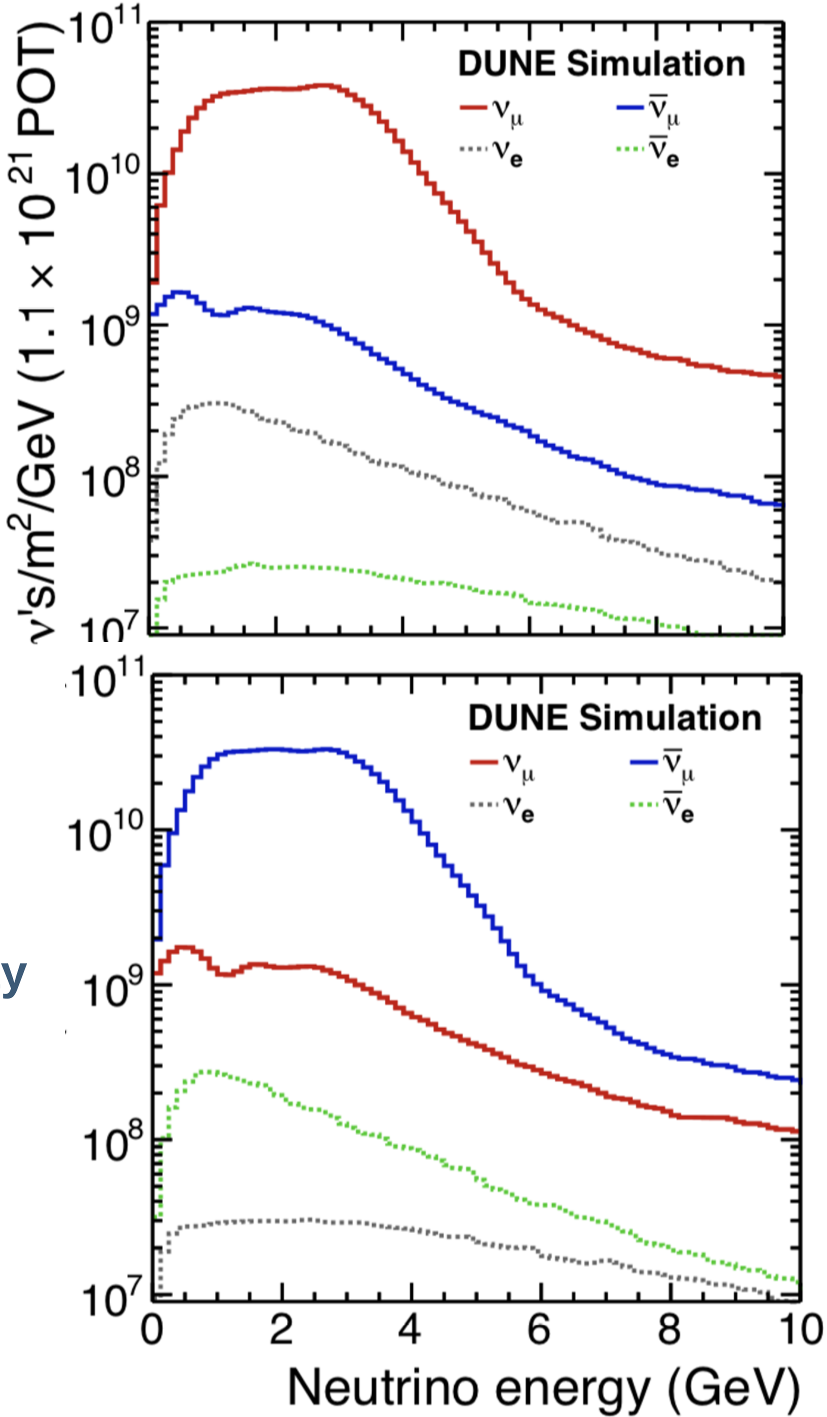
LBNF will use protons from the Main Injector

MI will start at 1.2 MW (Phase 1) and be upgraded to 2.4 MW (Phase 2)

Proton Improvement Plan (PIP II): upgrade of LINAC to reach 1.2 MW

The LBNF beam





FHC
(ν-mode)

RHC
($\bar{\nu}$-mode)

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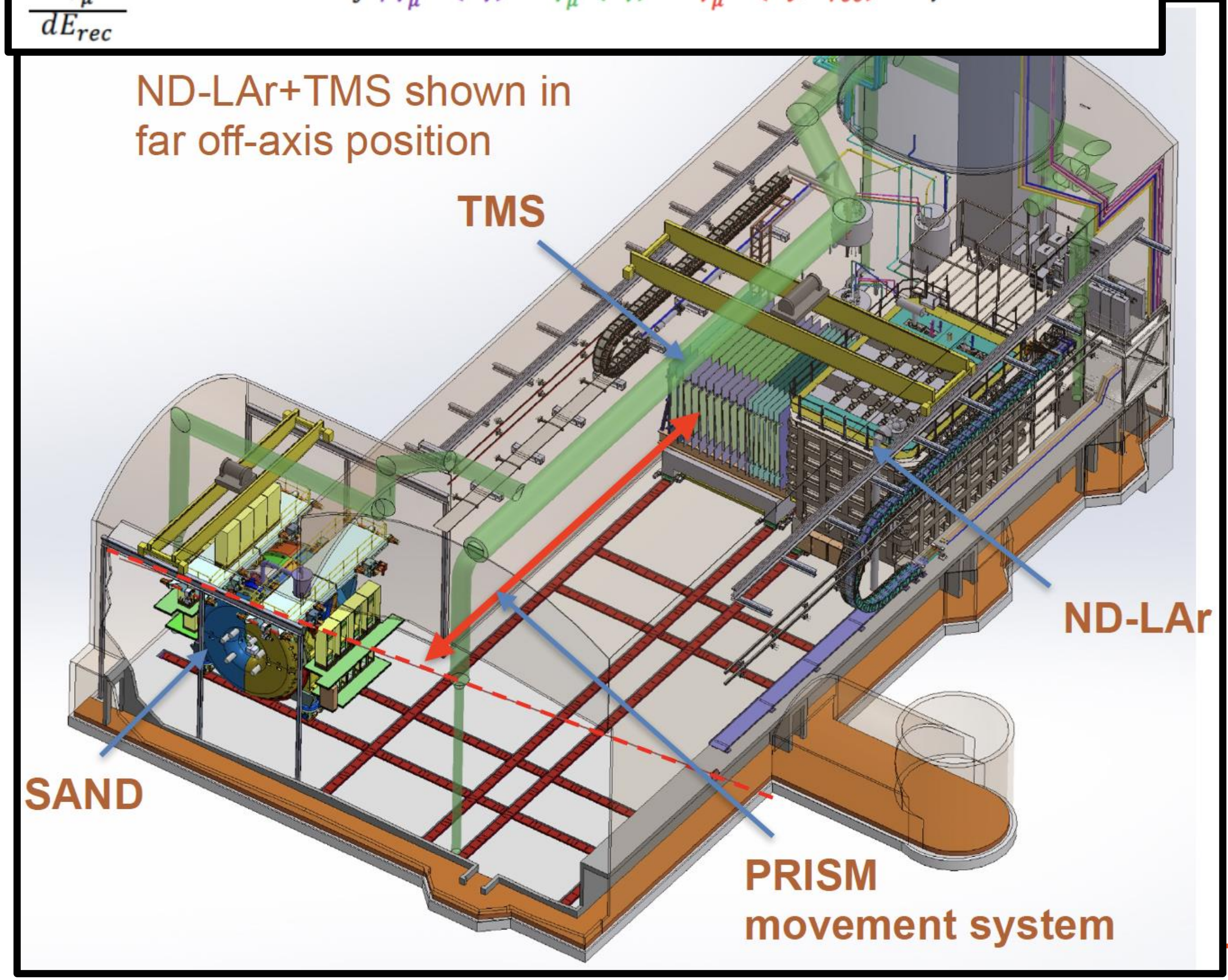
- **Neutrino beamline at a slope of 5.8°**
- **Primary proton beam (60-120 GeV) on a graphite target (1.1 – 1.9)10^{21} pot/yr**
- **Horns/beam line designed to maximize CP violation sensitivity**
- **Pulse duration: 10 μs**
- **Forward/Reverse Horn Current (FHC/RHC) $\nu/\bar{\nu}$-enhanced,**
- **Wide band beam**

The Near Detector Complex

$$\frac{\frac{dN^{far}_{\nu_e}}{dE_{rec}}}{\frac{dN^{near}_{\nu_\mu}}{dE_{rec}}} = \frac{\int P_{\nu_\mu\rightarrow\nu_e}(E_\nu) * \phi^{near}_{\nu_\mu}(E_\nu) * F_{far/near}(E_\nu) * \sigma^{Ar}_{\nu_e}(E_\nu) * D^{far}_{\nu_e}(E_\nu, E_{rec})\ dE_\nu}{\int \phi^{near}_{\nu_\mu}(E_\nu) * \sigma^{Ar}_{\nu_\mu}(E_\nu) * D^{near}_{\nu_\mu}(E_\nu, E_{rec})\ dE_\nu}$$



- Measures the neutrino beam rate and spectrum to predict un-oscillated event rates in the far detector
- Constrains systematic uncertainties (flux, cross sections, detector response) for oscillation measurements
- Additional physics program

Configuration (Phase I):

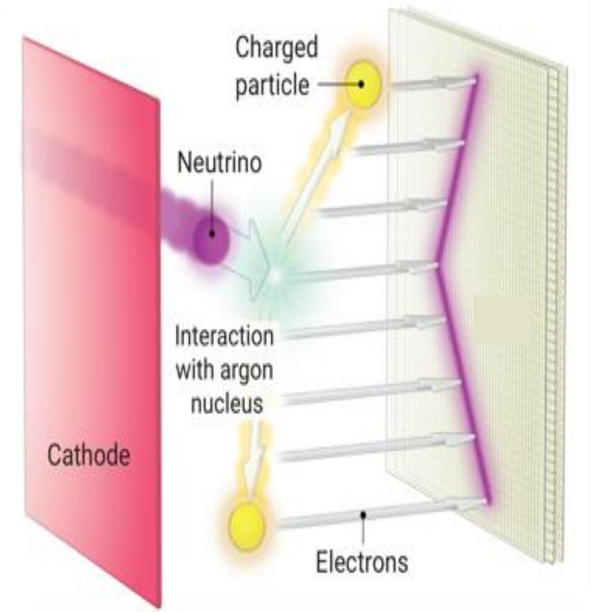
- **ND-LAr:** 7 x 5 array of modular 1x1x3 m^3 LArTPCs with pixel readout
- **TMS:** Magnetized steel range stack for measuring muon momentum/sign from ν_μ CC interactions in ND-LAr
- **DUNE-PRISM: ND-LAr** + **TMS** move up to 28.5 m off-axis

SAND:

- On-axis magnetized neutrino detector with LAr target (GRAIN), tracking (STT), and calorimeter (ECAL)

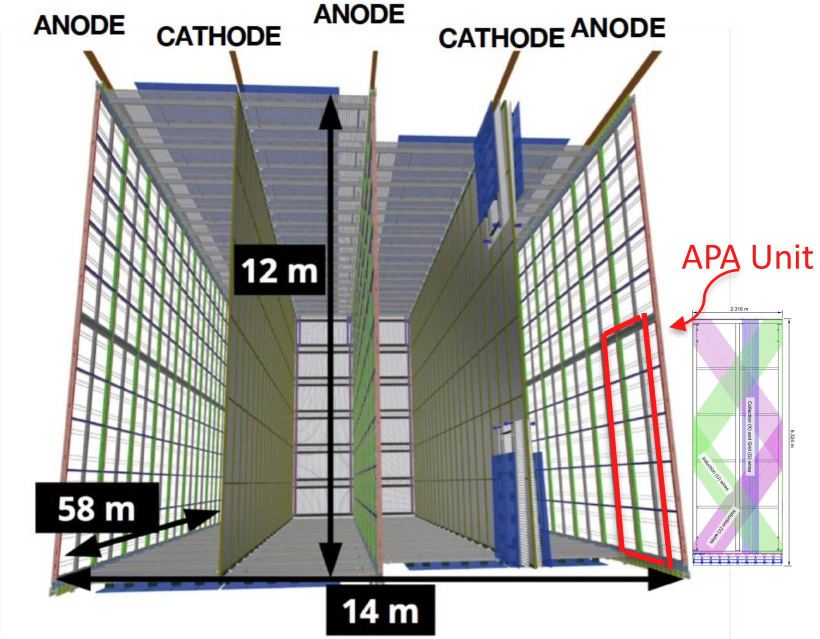
DUNE - Far Detector Modules 1&2

LAr TPC



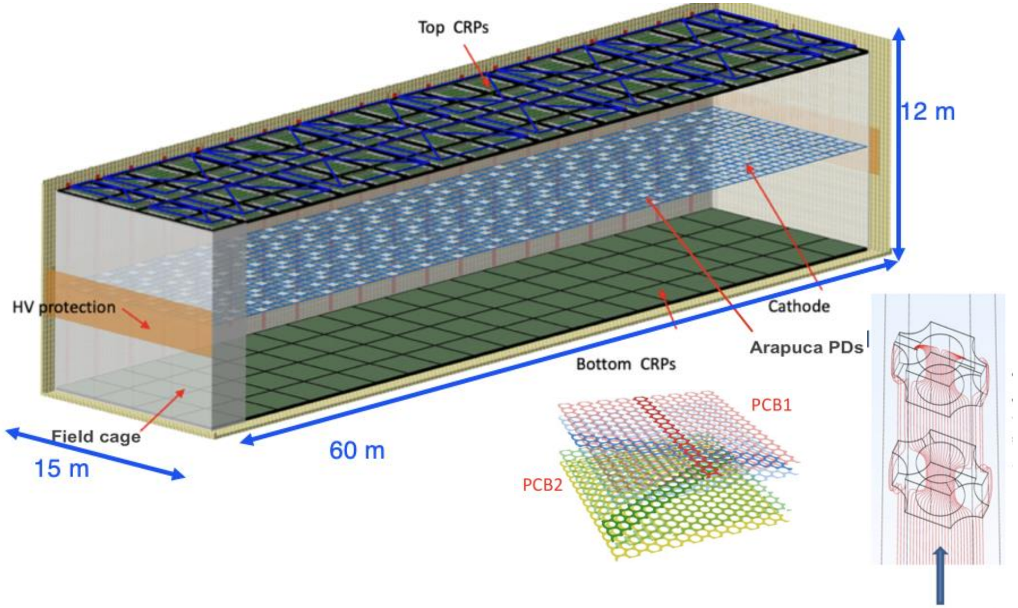
Liquid Argon TPC (C. Rubbia, 1977) is the technique with the best particle imaging capability at kton scale:

FD1-HD «Horizontal drift»



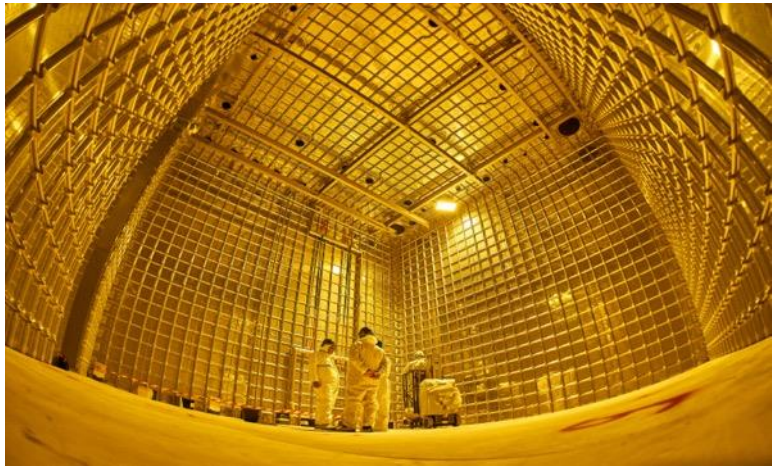
- 150 Anode Plane Assemblies (APAs)
- 384,000 readout wires
- Anode-Cathode 3.5 m drift;
- 500 V/cm field; cathode at -180 kV;
- 6000 photon detection system (PDS) channels
- PDS X-Arapuca modules embedded in APA

FD2-VD «Vertical drift»

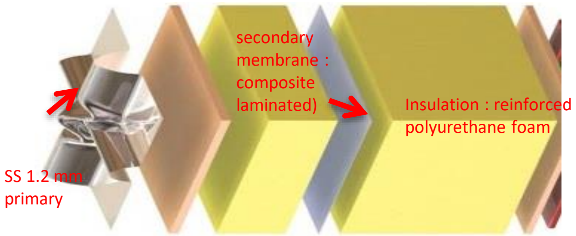


- Charge Readout Planes : perforated PCB's with segmented electrodes (strips)
- CRPs at the top and bottom
- Cathode (-300 kV) in the middle
- two 6.5 m drift chambers 450 V/cm field
- X-Arapuca modules integrated on cathode and on cryostat walls.

The Cryostats



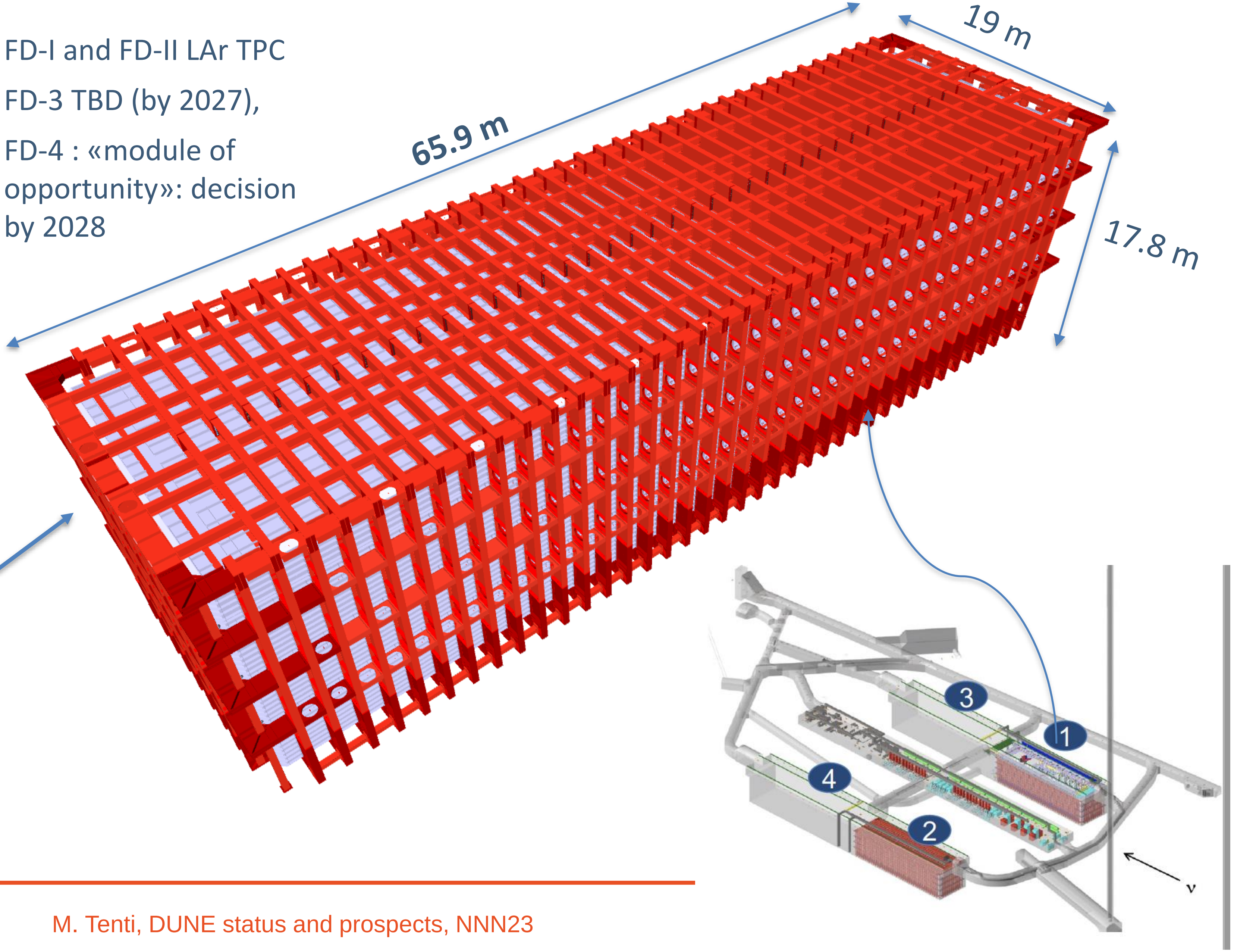
4 vessels already constructed (protoDUNE, SBND,..)



Membrane cryostat with passive insulation (CERN/GTT design)
internal volume : ~28’500 m^3
~17’500 tons of LAr

4 modules of **17 kt active mass**

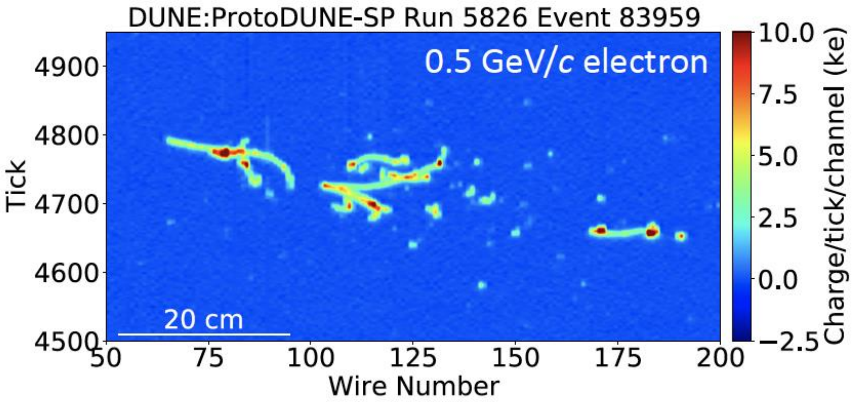
- FD-I and FD-II LAr TPC
- FD-3 TBD (by 2027),
- FD-4 : «module of opportunity»: decision by 2028

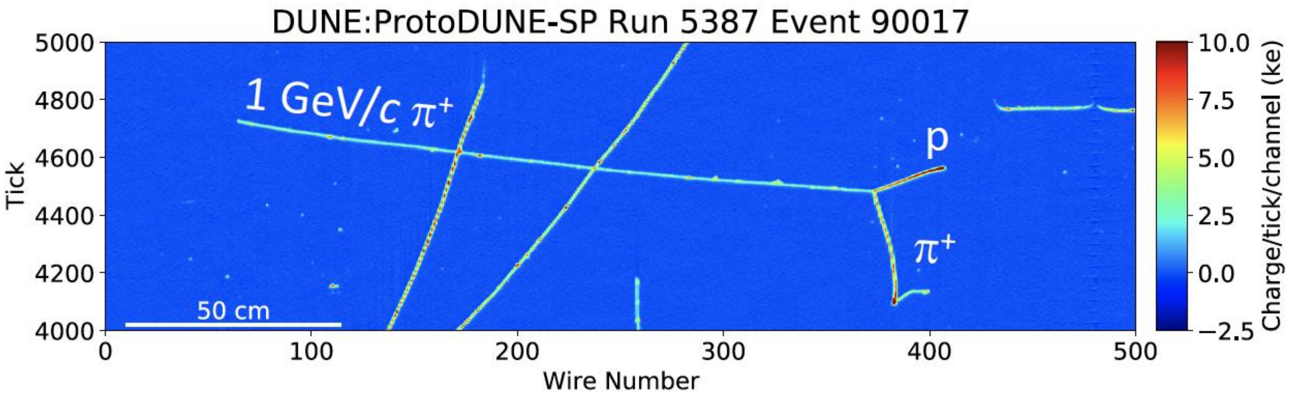


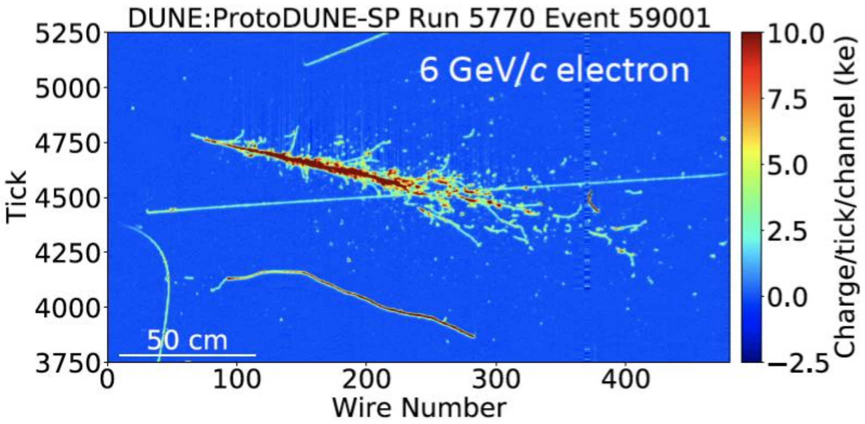
ProtoDUNE's @ the CERN Neutrino Platform

- Two 750 t prototypes ~8 x 8 x 8 m^3
- Design validation of all FD components at full scale
- ProtoDUNE Single-Phase Horizontal Drift:
  - Charged particle beam + cosmic rays runs (2018-2020)
  - Event reconstruction, full analysis
  - Excellent performance
  - **New run in 2024**
- ProtoDUNE Dual-Phase evolved to Single Phase Vertical Drift late 2020
  - SP-VD charged beams + CRs in 2024

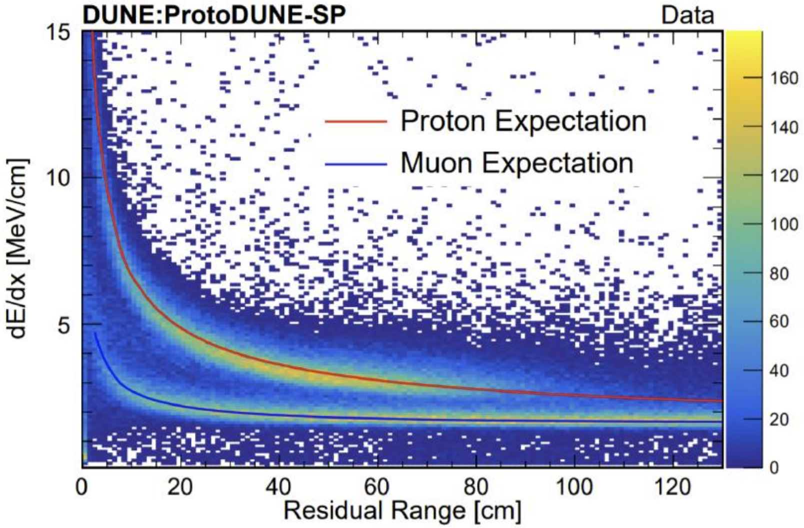
ProtoDUNE SP-HD Performance

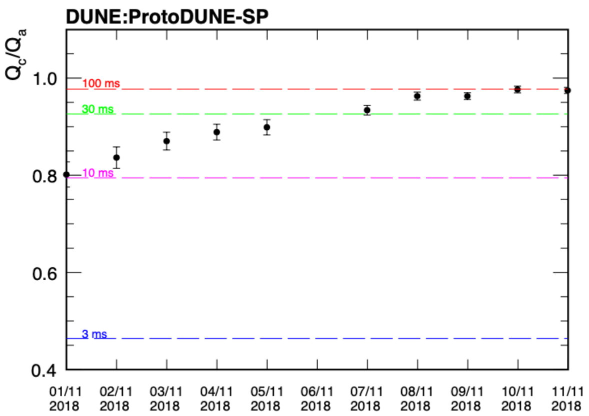






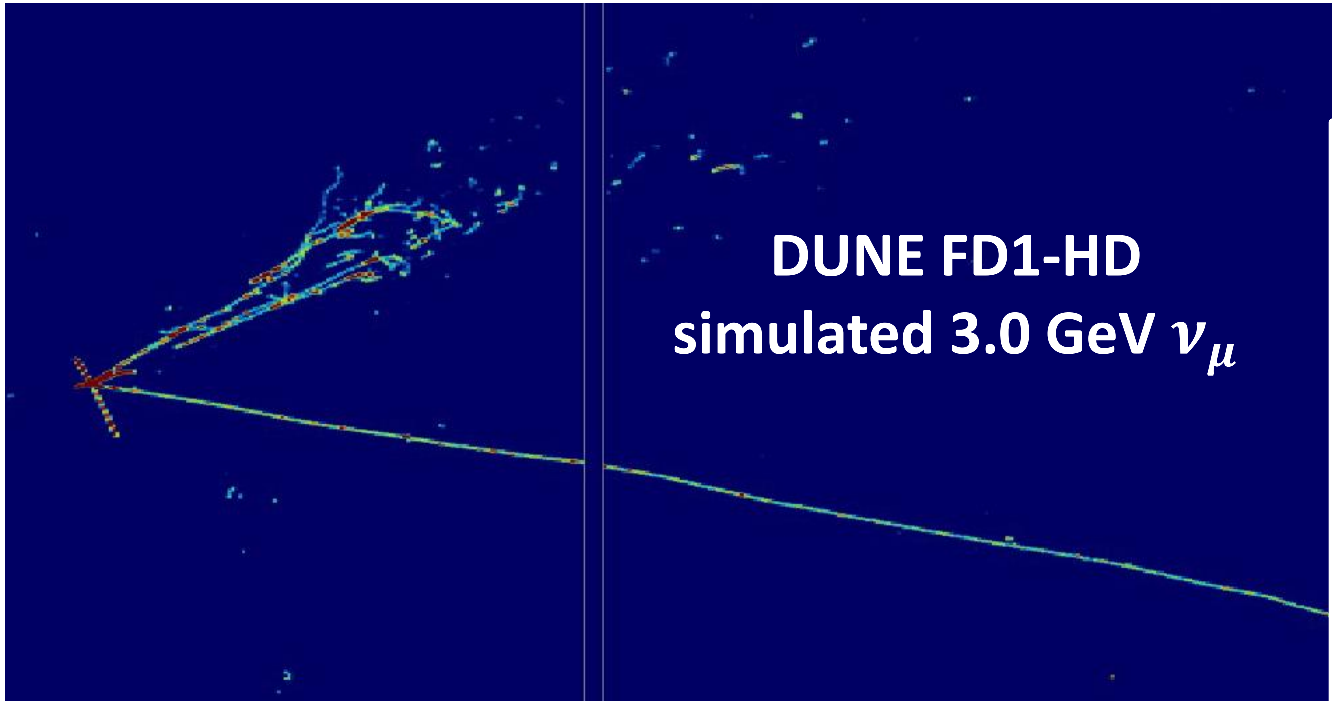
Eur. Phys. J. C82, 903 (2022)



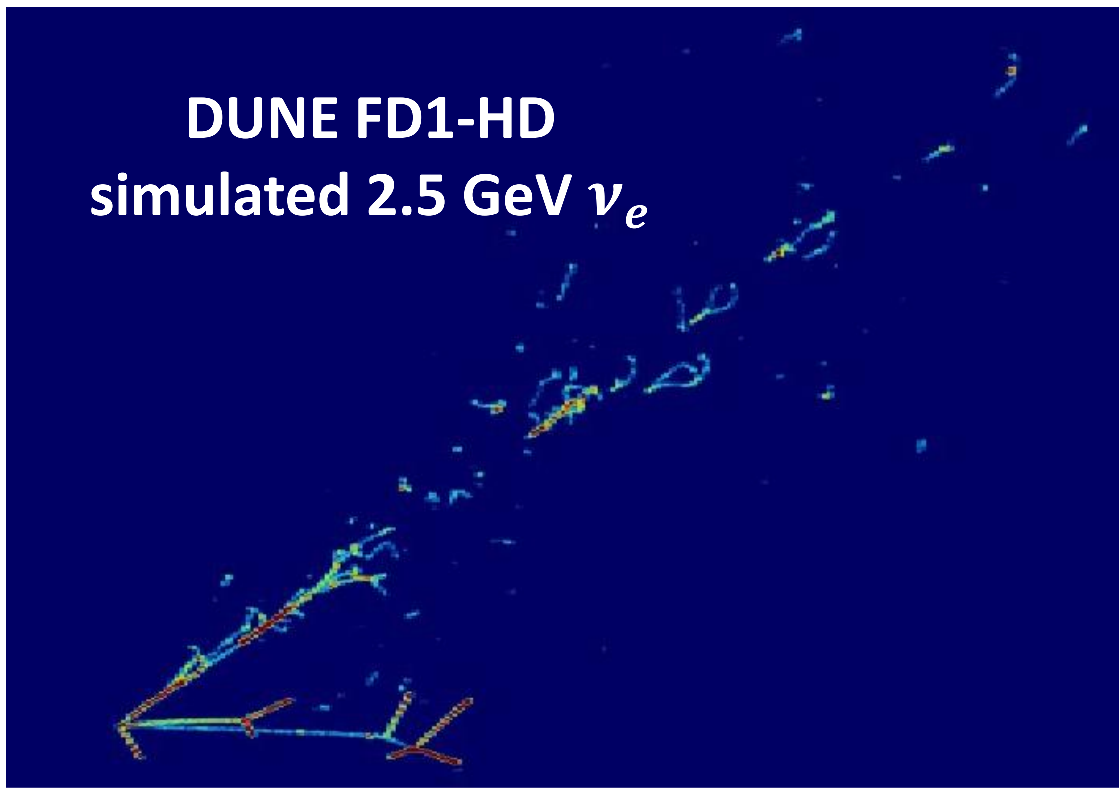


JINST, P12004 (2020)

LArTPC performances



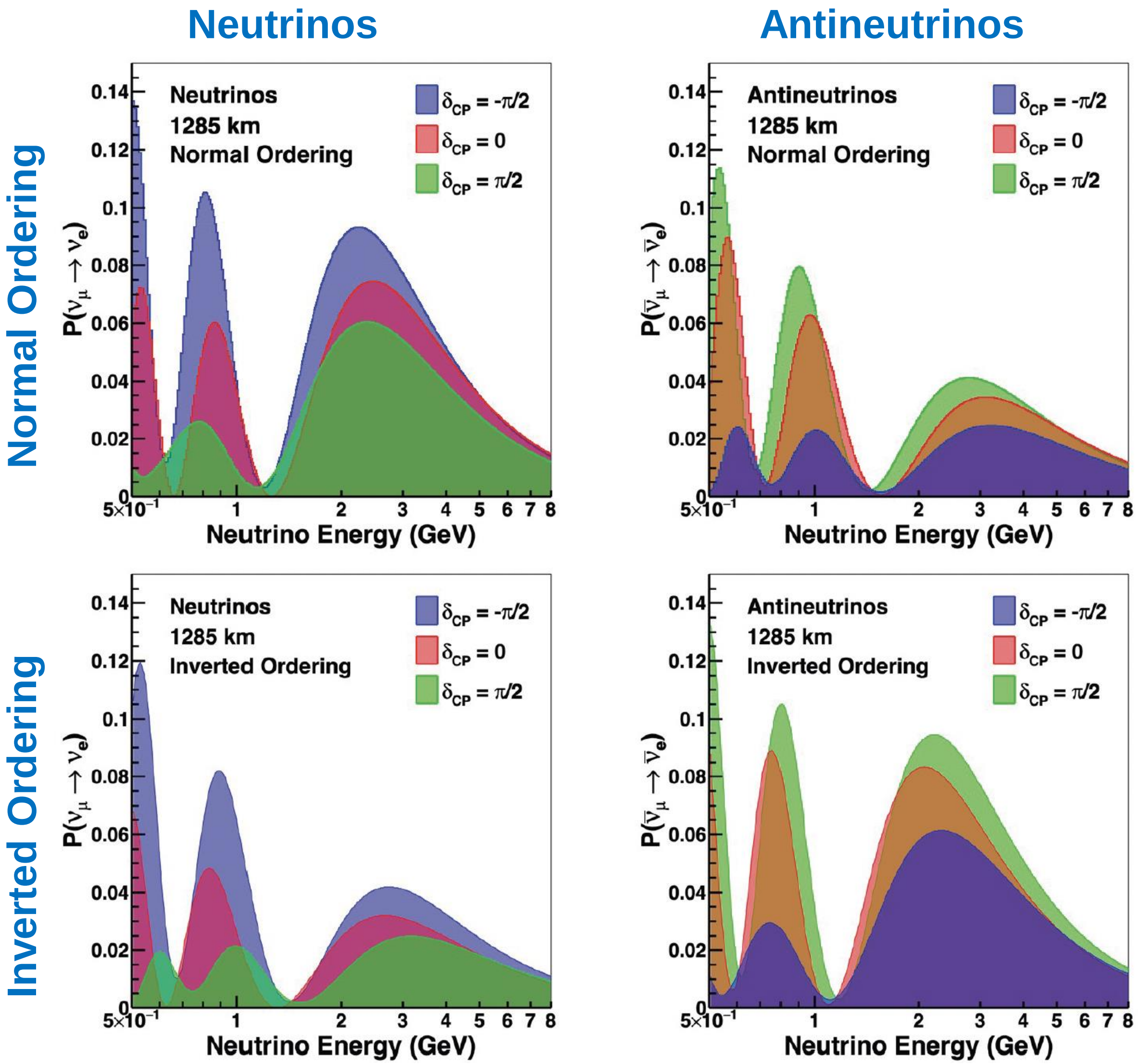
DUNE FD1-HD
simulated 3.0 GeV ν_μ



DUNE FD1-HD
simulated 2.5 GeV ν_e

- Clean separation of ν_μ and ν_e charged currents
- Low thresholds for charged particles
  $\rightarrow$ precise reconstruction of lepton and hadronic energy
  $\rightarrow$ E_ν reconstruction over broad energy range

ν_e , $\bar{\nu}_e$ oscillation shapes



$P(\nu_\mu \to \nu_e)$ vs $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

Mass ordering and CP violation induce different shapes in ν_e , $\bar{\nu}_e$ oscillation probabilities

DUNE's unique capability: with a wide band beam measures these shapes over more than a full period, resolving degeneracies

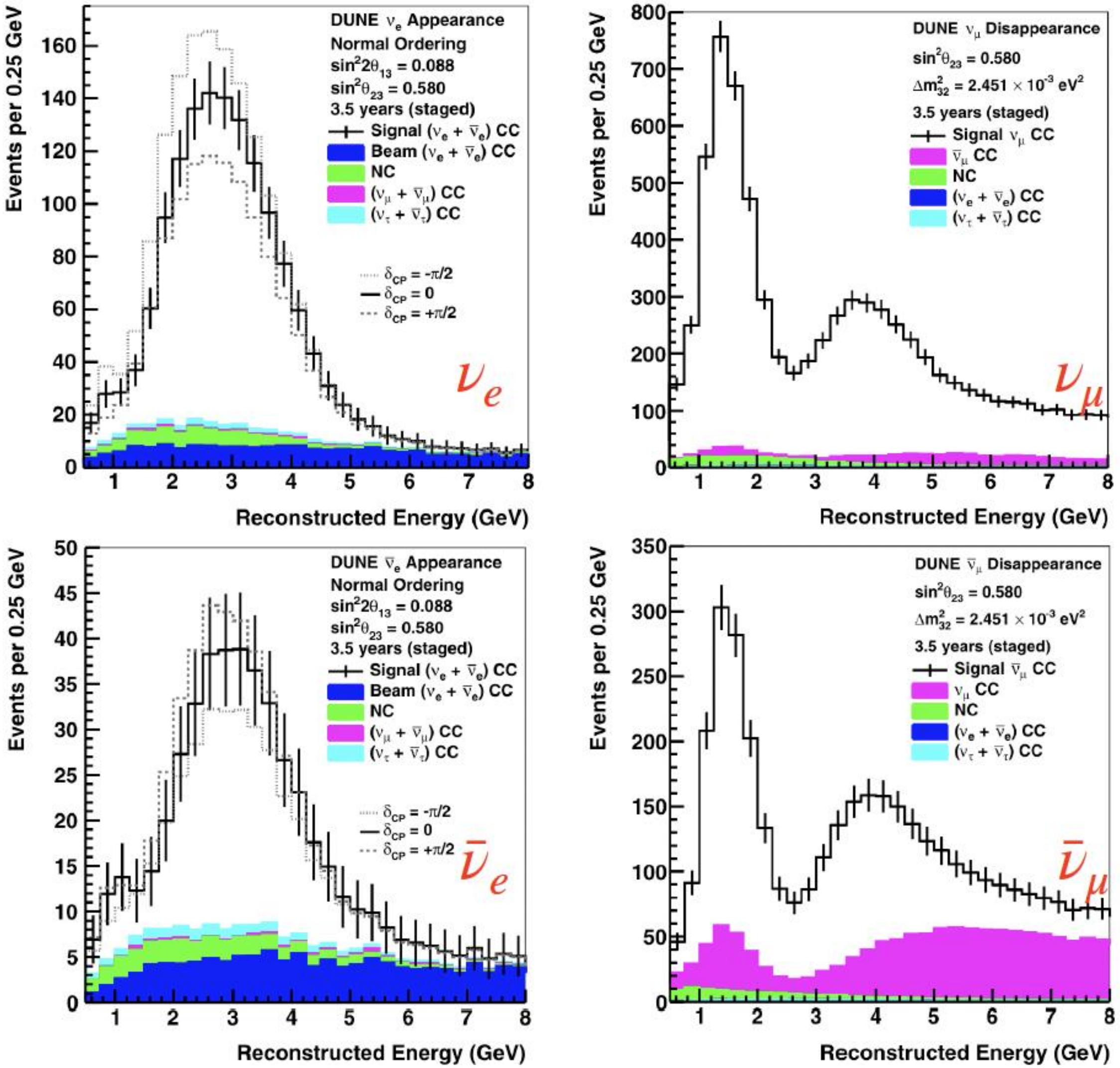
- **mass ordering**
- **CP violation**
- **θ_{23} octant**

with a single experiment

DUNE FD Data

FHC - ν

RHC - $\bar{\nu}$



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Convolution of oscillation probabilities with neutrino beam flux & cross-sections & detector response

Oscillation sensitivities: simultaneous fit over four components of FD data (disappearance and appearance spectra) with ND constraints

DUNE sensitivities - *Phase I*

DUNE will unambigously resolve the neutrino mass ordering at 3σ (5σ) level with a 66 (100) kt-MW-yr exposure

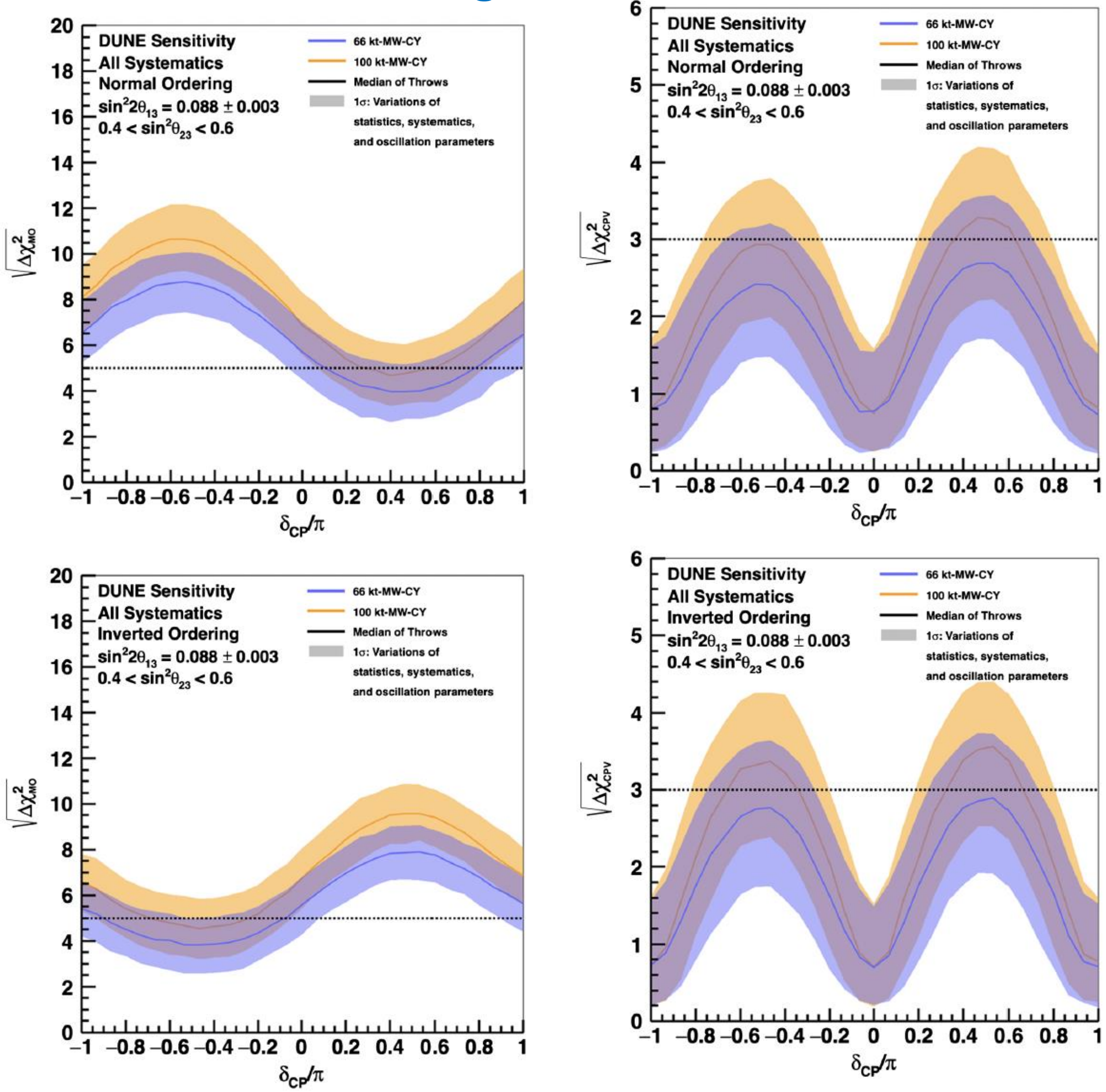
DUNE can measure CPV at 3σ level with a 100 kt-MW-yr exposure for the maximally CP-violating values $\delta_{CP} = \pm\pi/2$

Mass Ordering

CPV

Normal Ordering

Inverted Ordering



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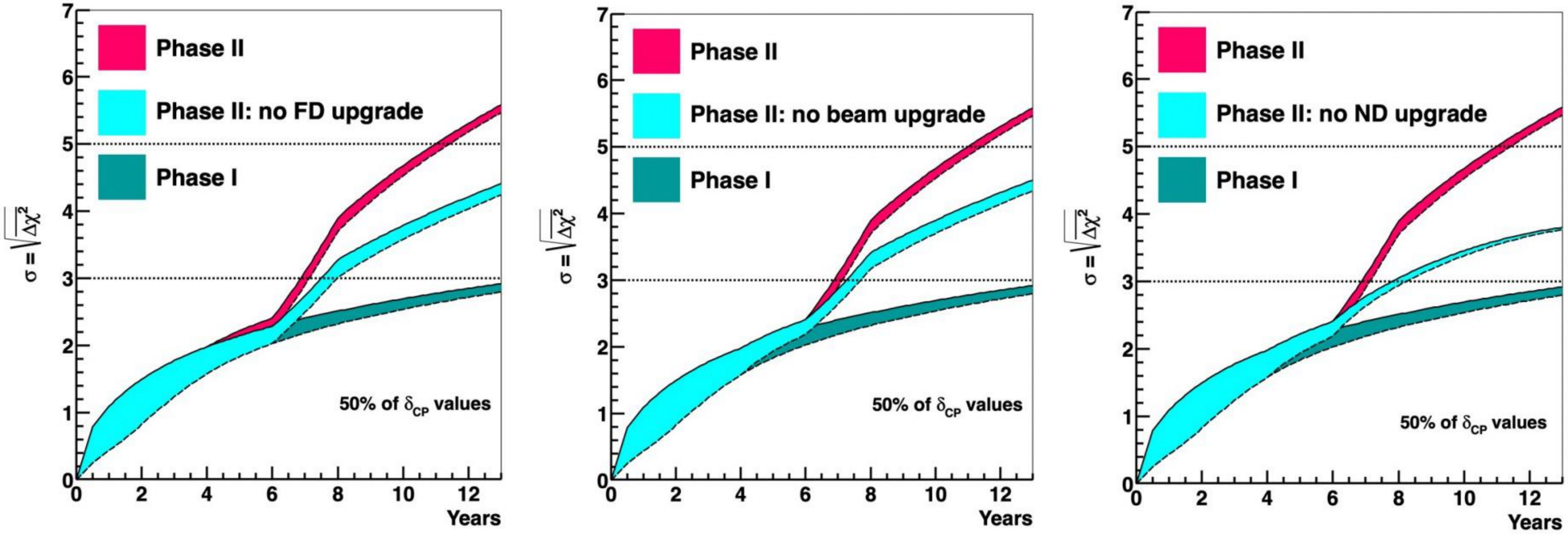
DUNE sensitivities at higher exposures (Phase II)

To achieve all P5 goals it is need : Detector Mass 40 kton (4 modules) + Beam power upgrade to 2.4MW + Improved Systematics (Near detector upgrade)



If $\delta_{CP} = \pm 90°$, CP violation at 3σ in Phase I

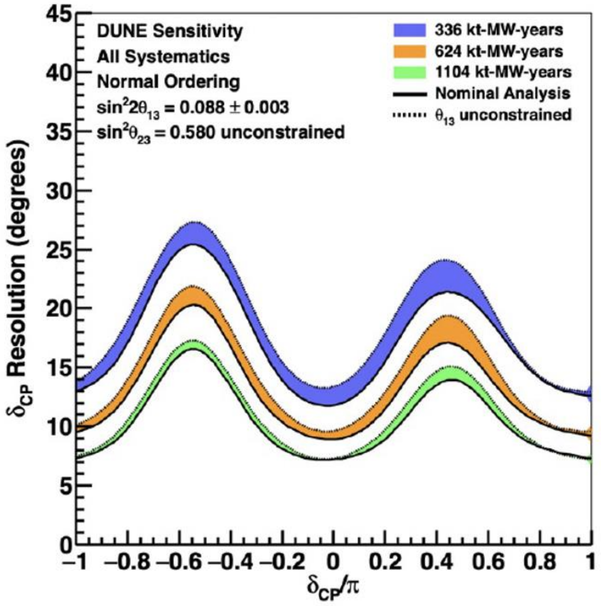
Phase II: If $\delta_{CP} = \pm 90°$ 5σ in 7 years

For 50% of δ_{CP} values 5σ CPV in 12 years

DUNE resolution

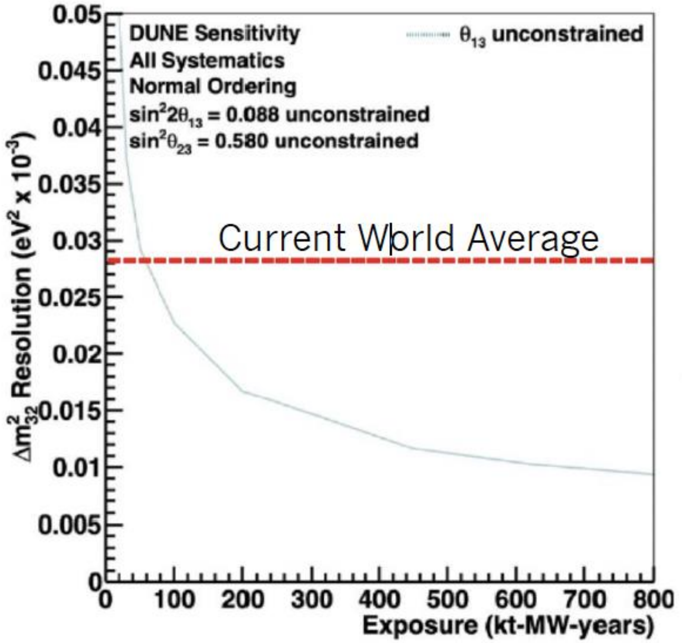
Δm^2_{32}, δ_{CP}, θ_{23} and θ_{13}

measured with high precision
with a single experiment

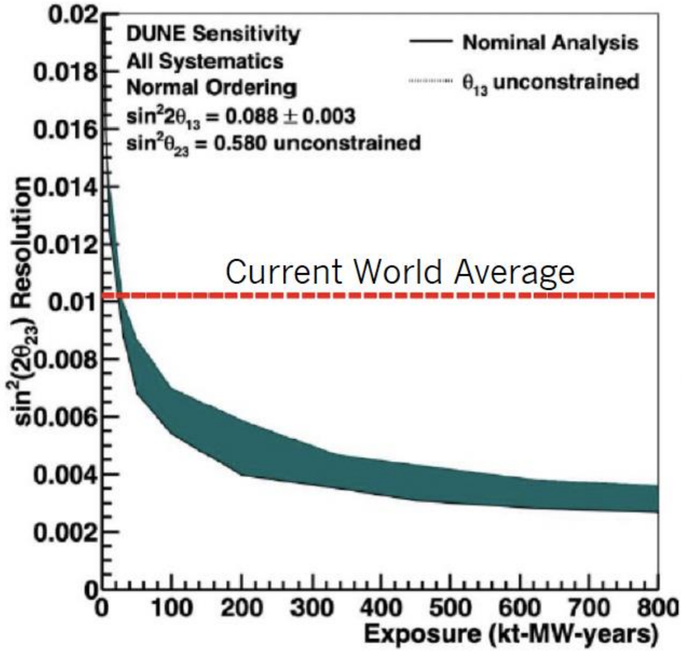


δ_{CP} resolution 6° ÷16°

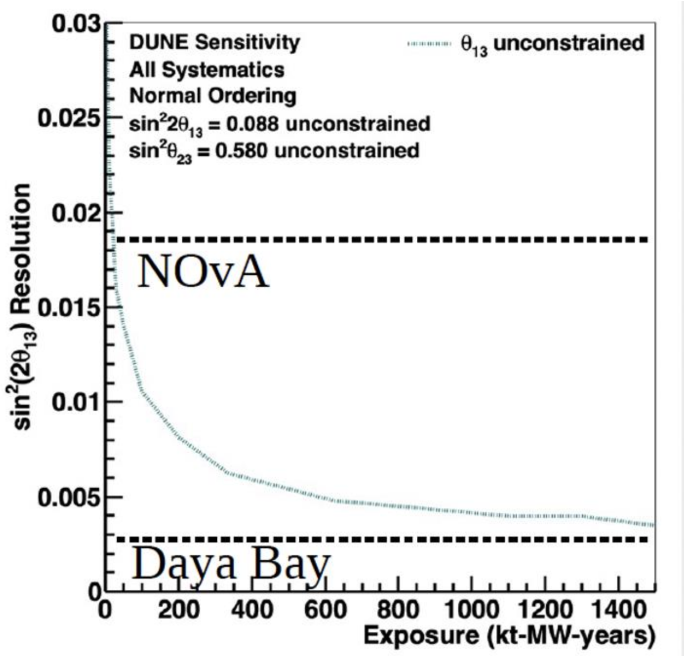
Δm^2_{32}



θ_{23}

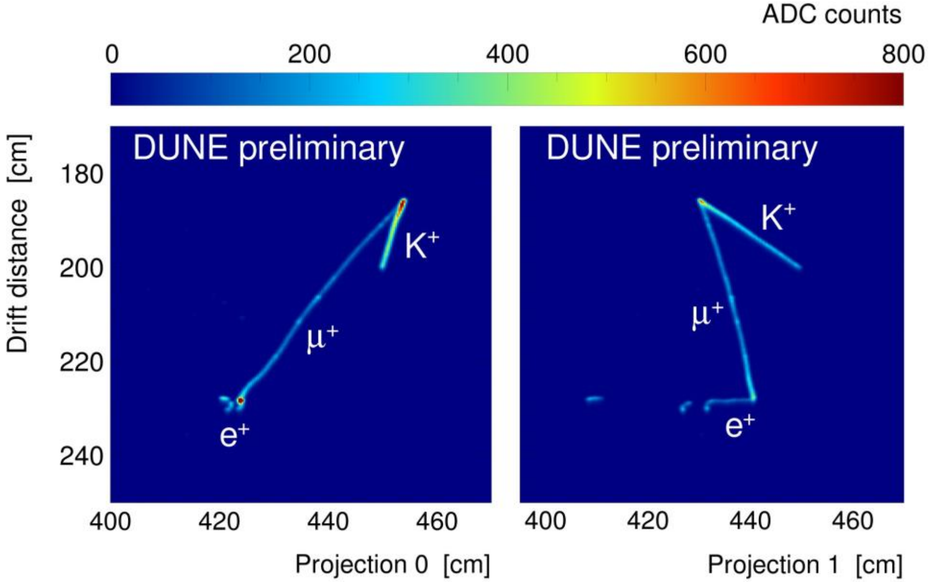


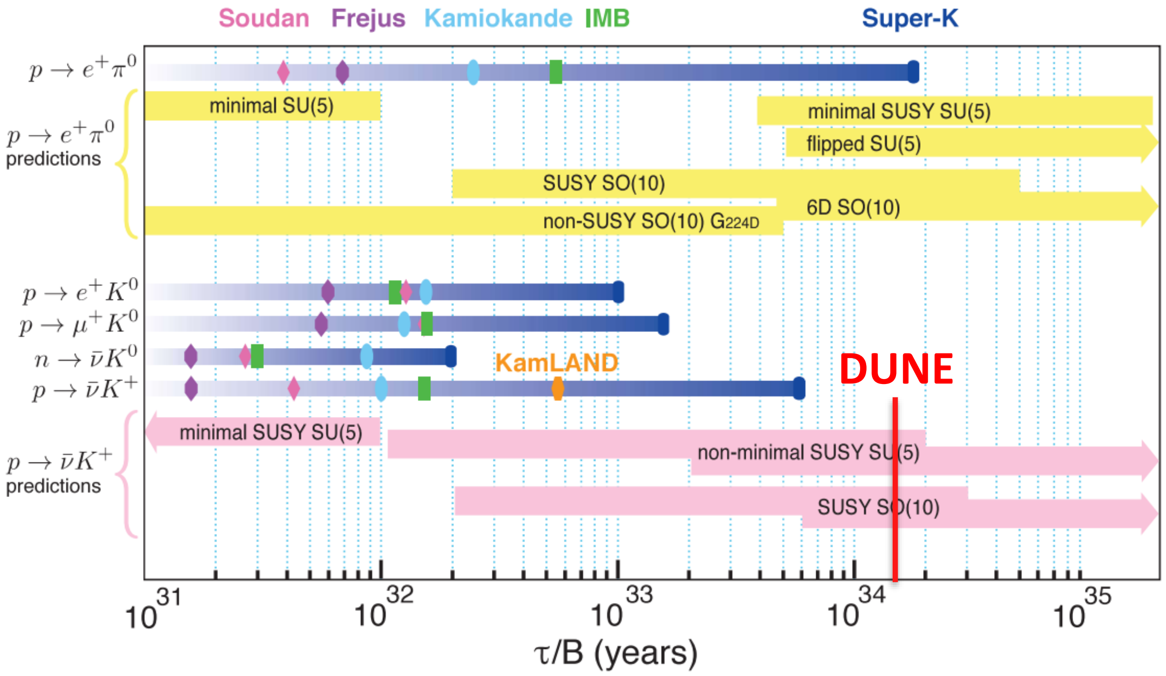
θ_{13}



Proton Decay Search

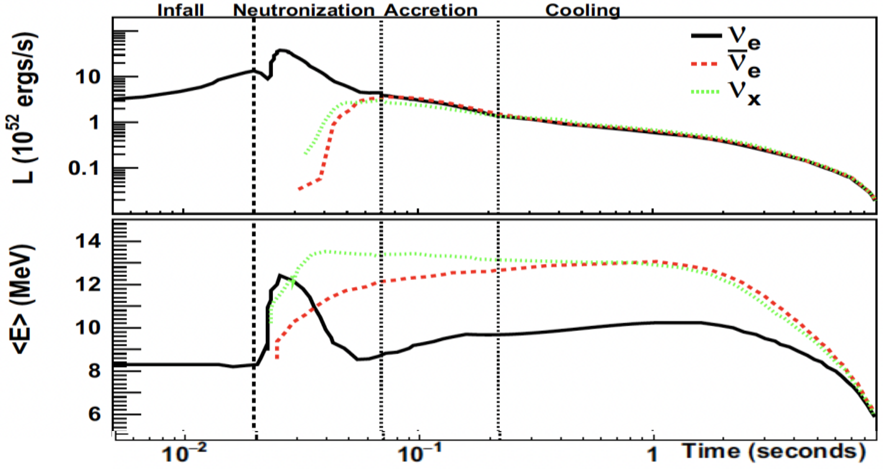
- $p \rightarrow K^{+}\overline{\nu}$ dominant in SUSY GUT models
- LArTPC technology has the **unique capability** to observe the entire decay chain for proton decays into charged kaons
- Identify isolated kaon by dE/dx and decay products $\rightarrow$ main background: atmospheric neutrinos
- **BDT** exploiting energy deposition topology and supported by **CNN** provides
  - Signal: **15% efficiency**
  - Background: **~ 1 ev/Mk-year**
- Sensitivity:
  - Assuming no signal in 10 y, 40 kt FV and an improved 30% signal efficiency:
    - **1.3×10^{34} years (90% C.L.)**





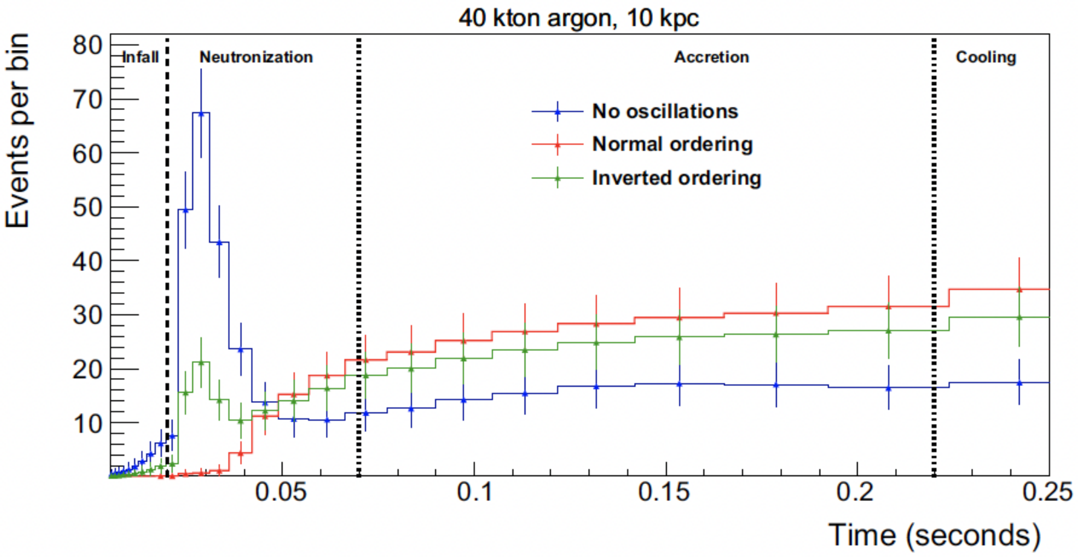
SN burst neutrinos

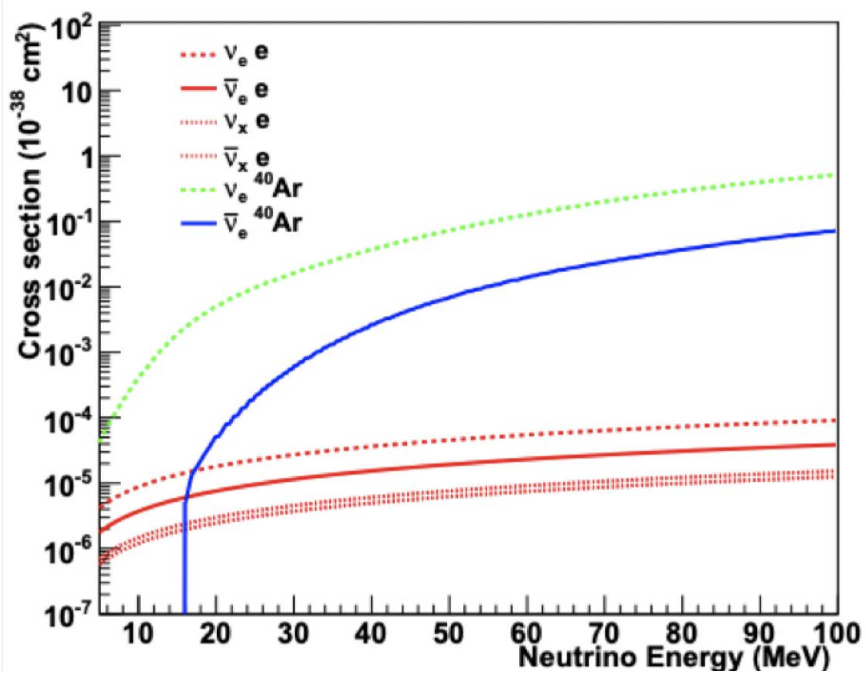
Eur. Phys. J. C (2021) 81



DUNE sensitive to ν_e CC events by $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$ exploiting the Ar target and to ν ES on electrons thanks to its large mass

SNEWS
SUPERNOVA EARLY WARNING SYSTEM





Solar neutrinos

DUNE sensitive to

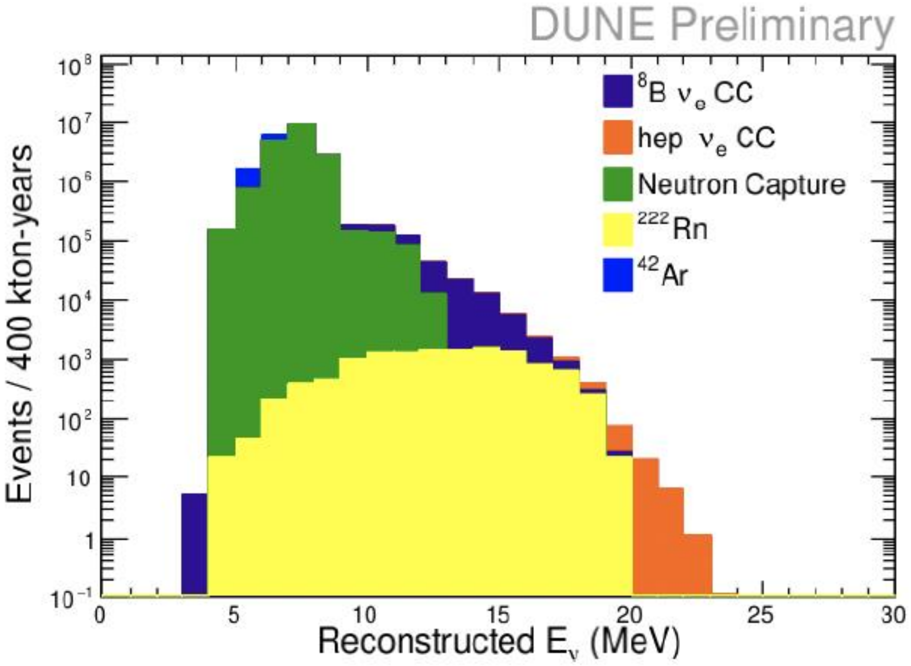
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

- observable sensitive only to electron neutrino flavor

$$\nu_{e,\mu,\tau} + e^- \rightarrow \nu_{e,\mu,\tau} + e^-$$

- observable sensitive to all neutrino flavors.

(*) F. Capozzi et al PRL 123 (2019) 13



On-going work on solar neutrinos

Sensitive to ^{8}B and hep fluxes

Measure oscillation parameters

Proposals for the 4th module to enhance low energy physics programme

Conclusions

- LBNF/DUNE: the ultimate neutrino facility/observatory
- DUNE will enable very rich physics program in the next decades (LifeCycle 20 years):
  - Neutrino oscillations
  - Studies of MeV-scale neutrinos
  - Several BSM searches
- LBNF and DUNE making rapid progress on facility construction, detector design, and physics analysis + ProtoDUNE run 2 in 2024

2029
Start Data Taking
@Far Detector

atmospheric ν,
astrophysics

2031
Start of Phase I

oscillation physics
atmospheric ν,
astrophysics

2037-2038
Start of Phase II

full physics scope

Thank You!

DUNE's attracting the world

- 1440 collaborators
- 37 countries
- 208 institutions including CERN

DUNE Collaboration Meeting, Fermilab, May 2023

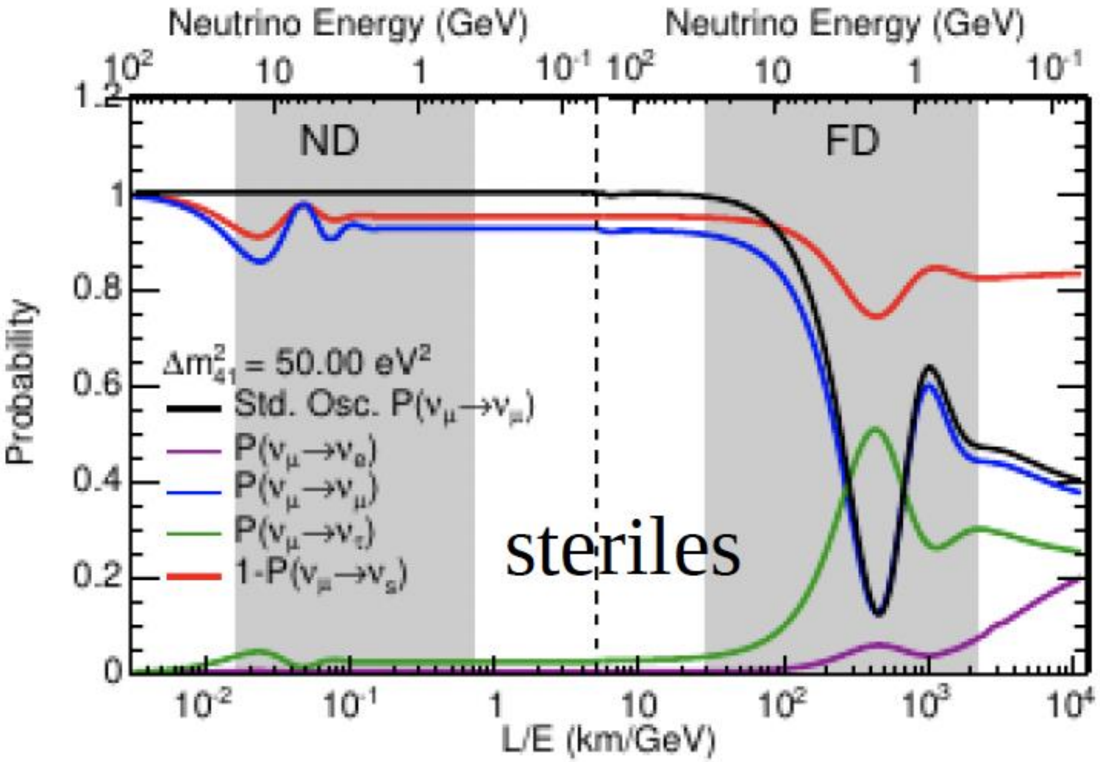
Mary Bishai

Sergio Bertolucci

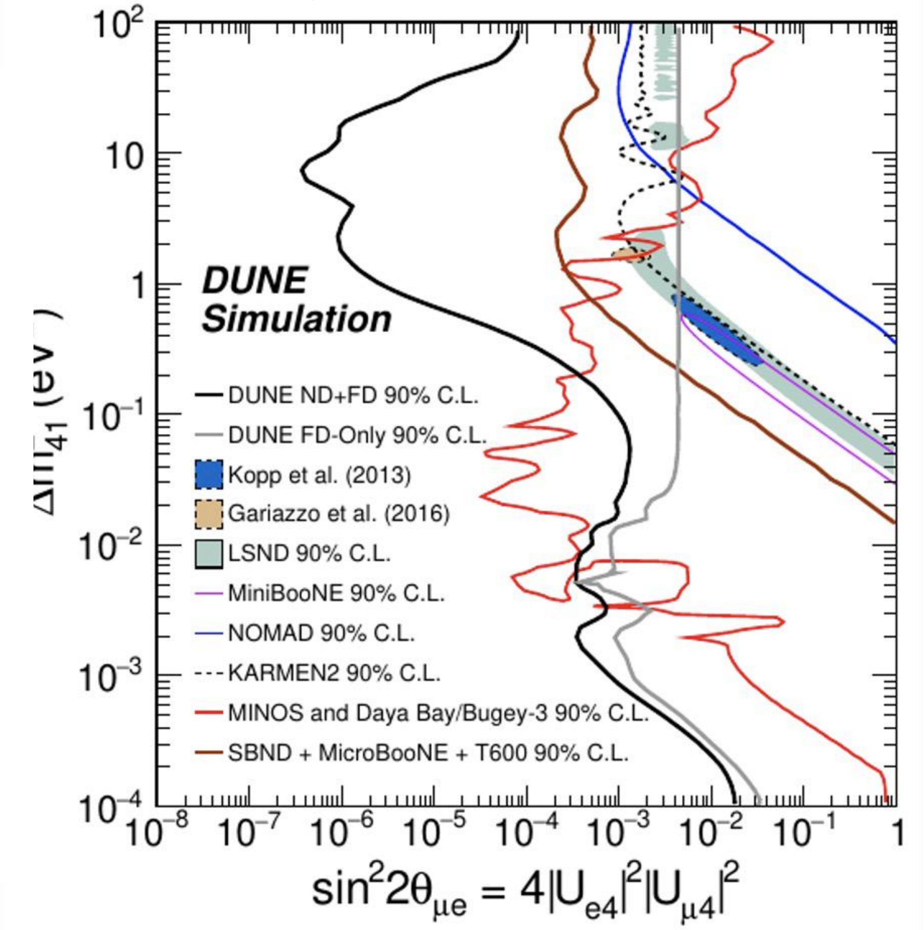
DUNE's spokespersons

Backup

Sterile Neutrinos



Sterile Neutrino Sensitivity
(ν_e CC appearance at ND)



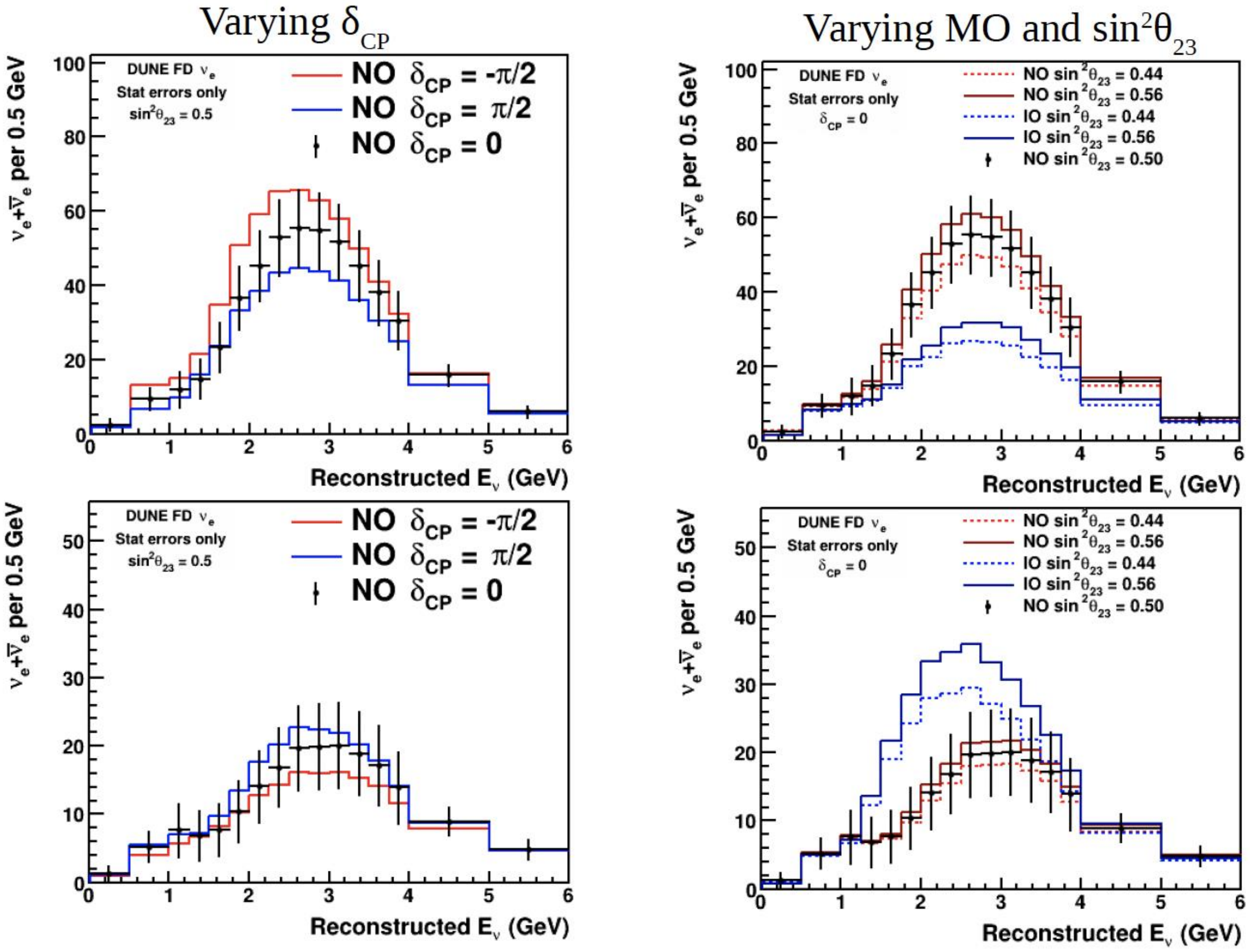
DUNE ν_e , $\bar{\nu}_e$ spectra can distinguish Mass Ordering in Phase I

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

Neutrino mode

Phase I

Antineutrino mode



DUNE ν_e , $\bar{\nu}_e$ spectra can measure δ_{CP}, θ_{23} octant in Phase II

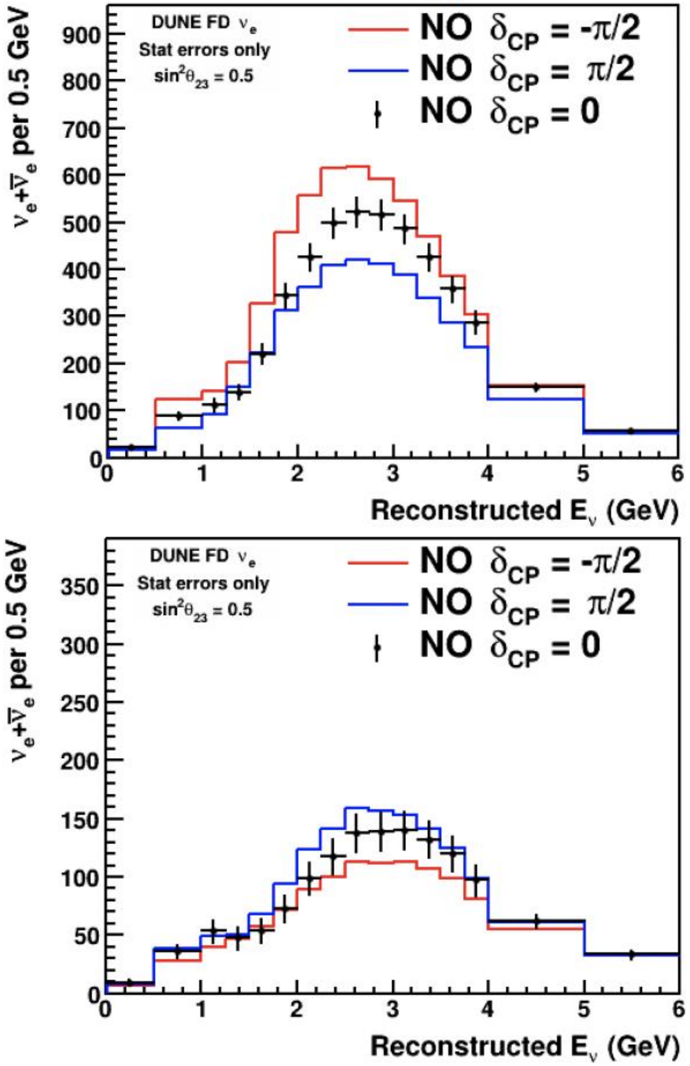
Data points show NO, $\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$

Neutrino mode

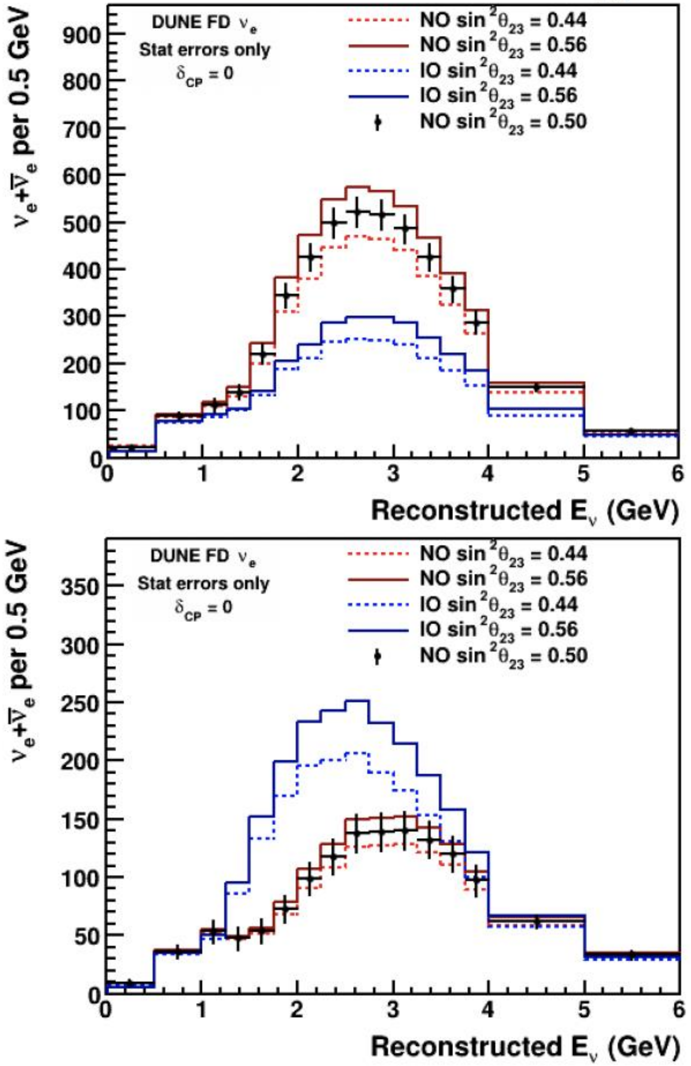
Phase II

Antineutrino mode

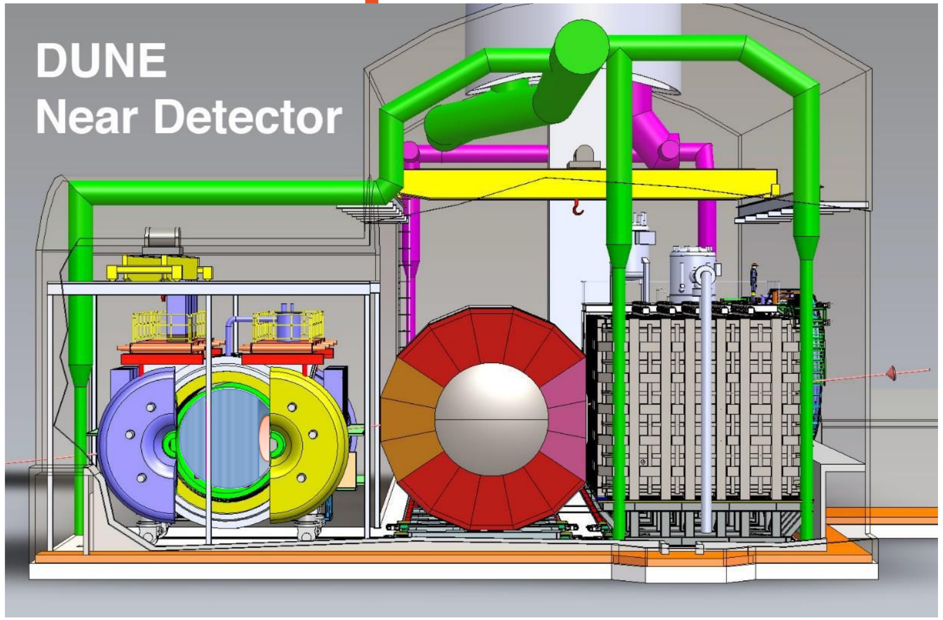
Varying δ_{CP}



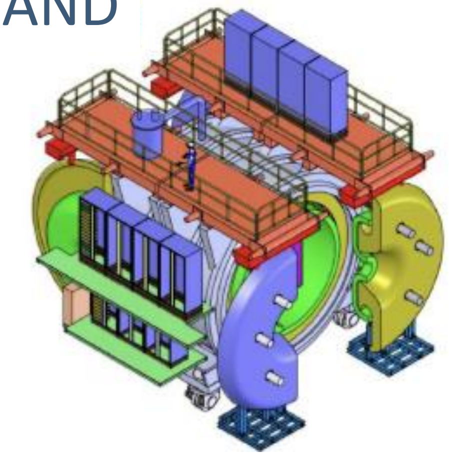
Varying MO and $\sin^2\theta_{23}$



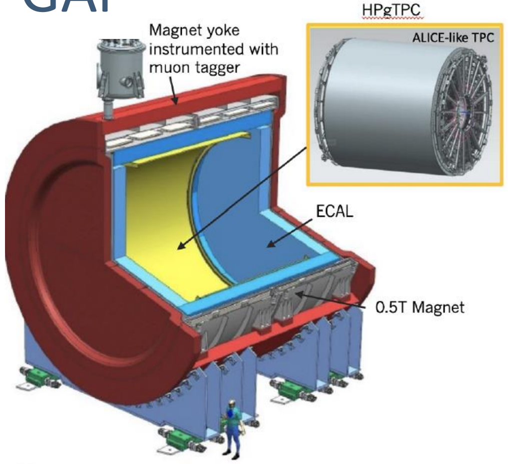
The Near Detector Complex – Phase II



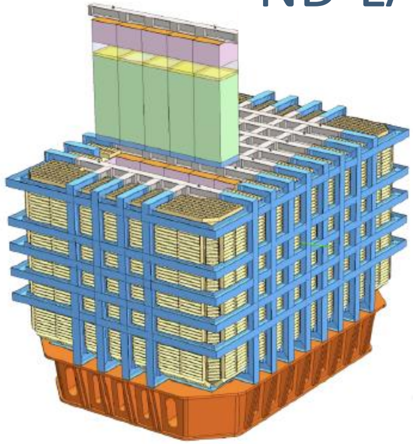
SAND



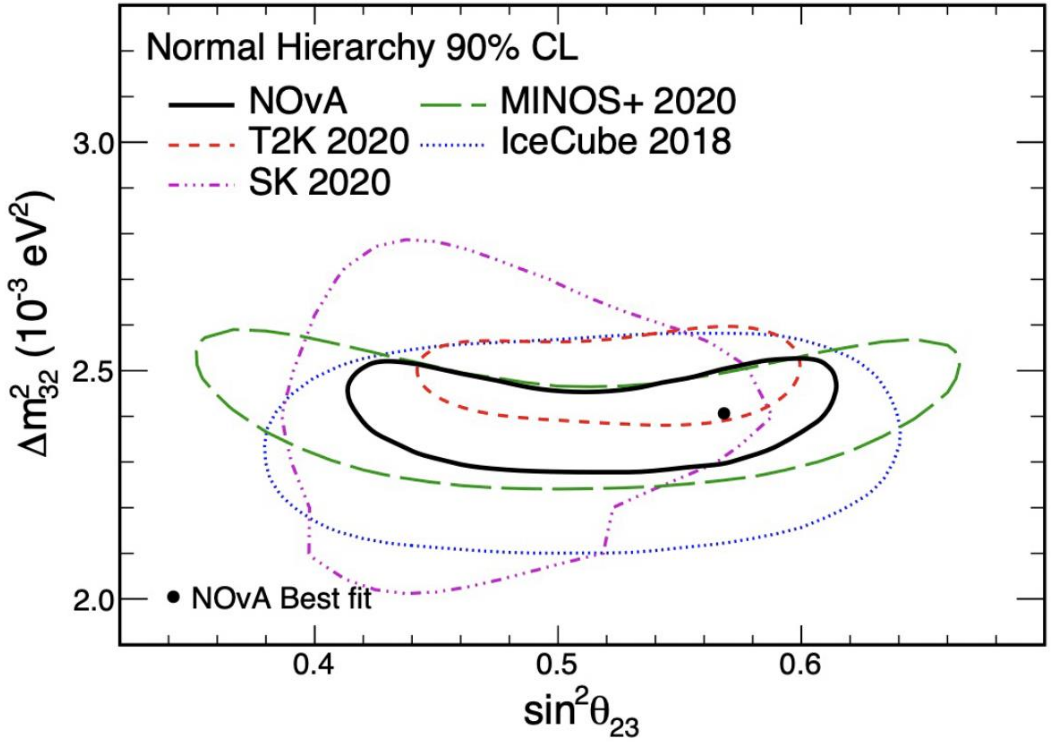
ND-GAr

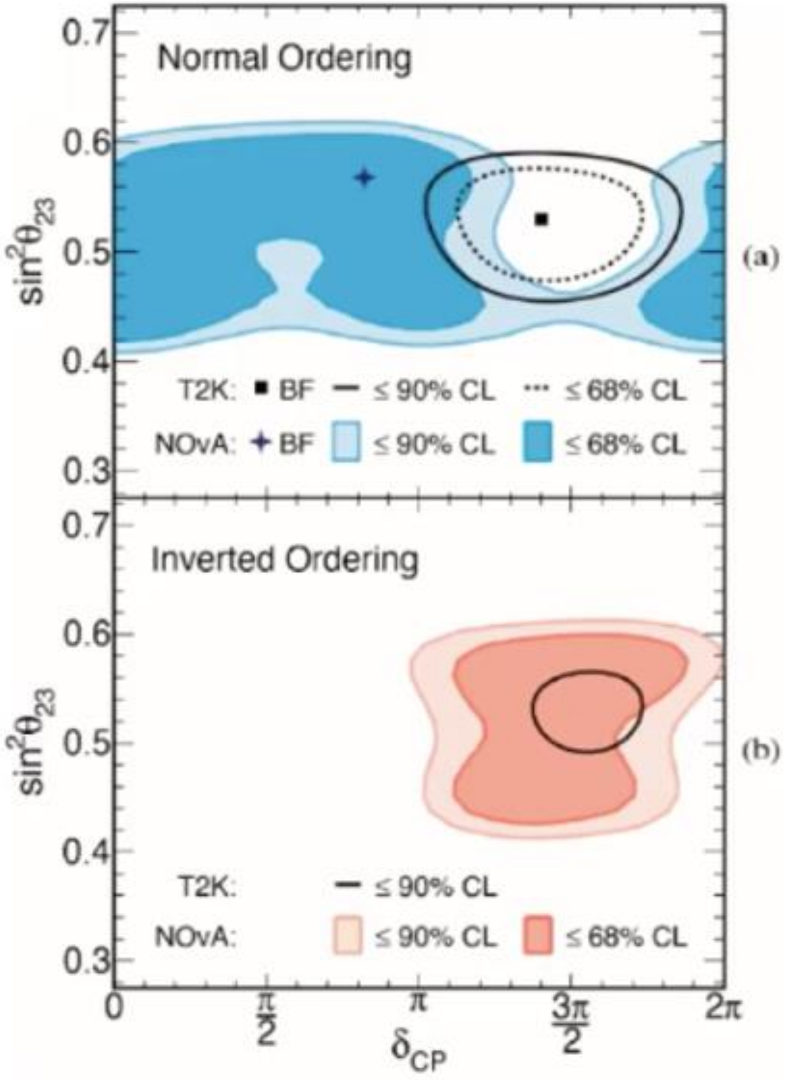


ND-LAr



… not a complete clear picture yet

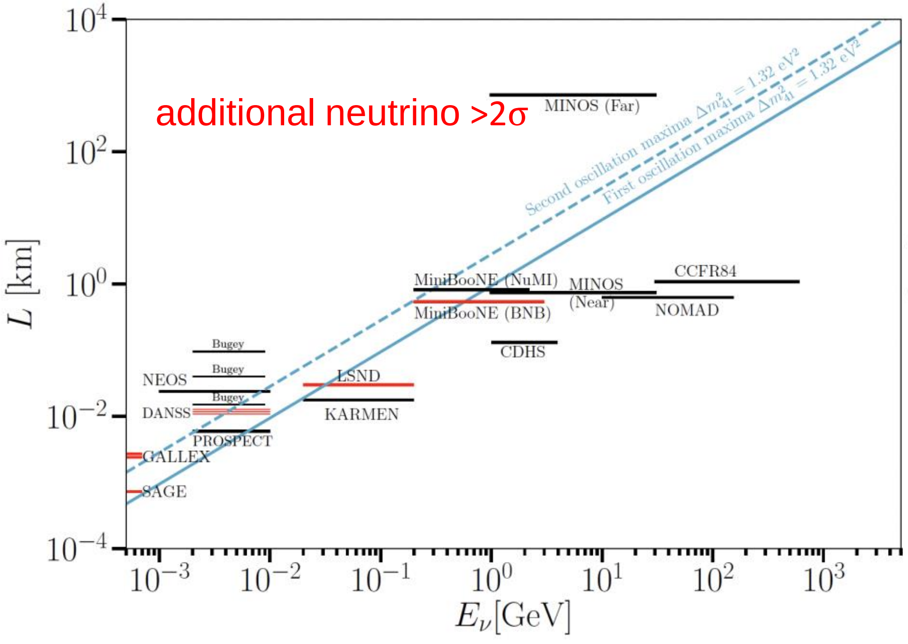




Phys Rev D 106, 032004 (2022)

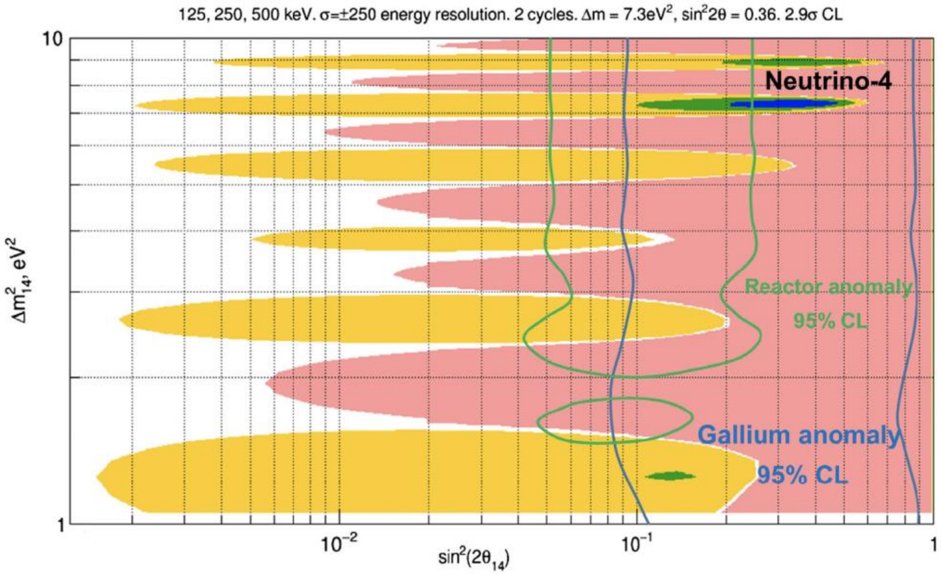
ref. ICARUS at FNAL

The «anomalies»

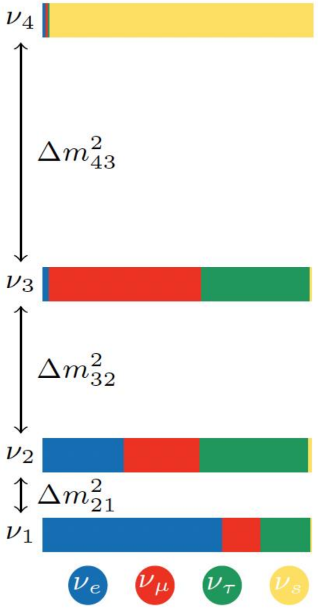


additional neutrino >2σ

arXiv:1906.00045

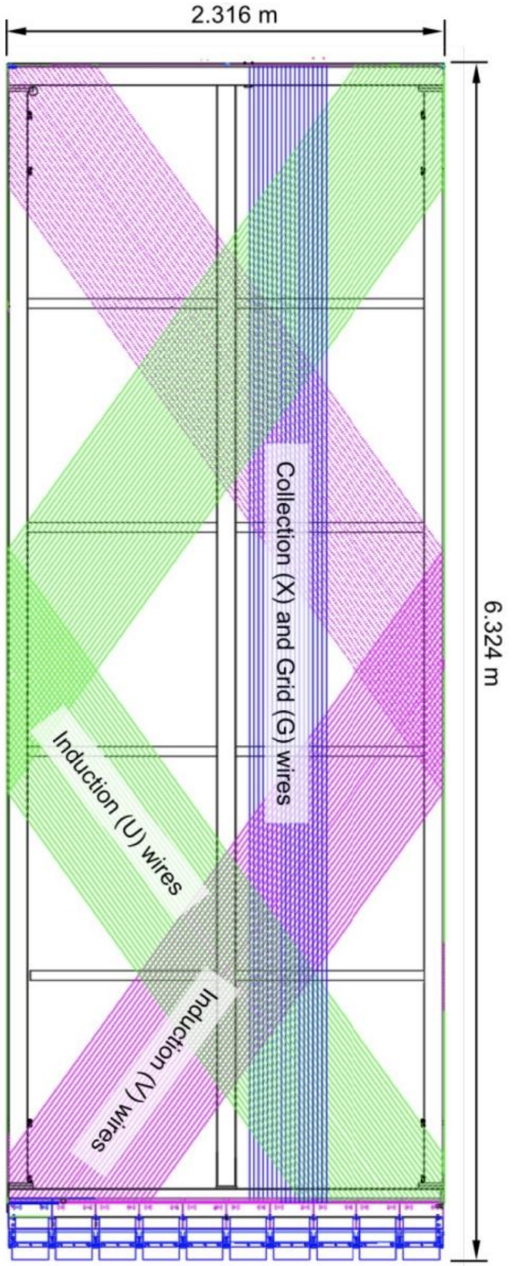


Phys.Rev.D 104, 032003 (2021)

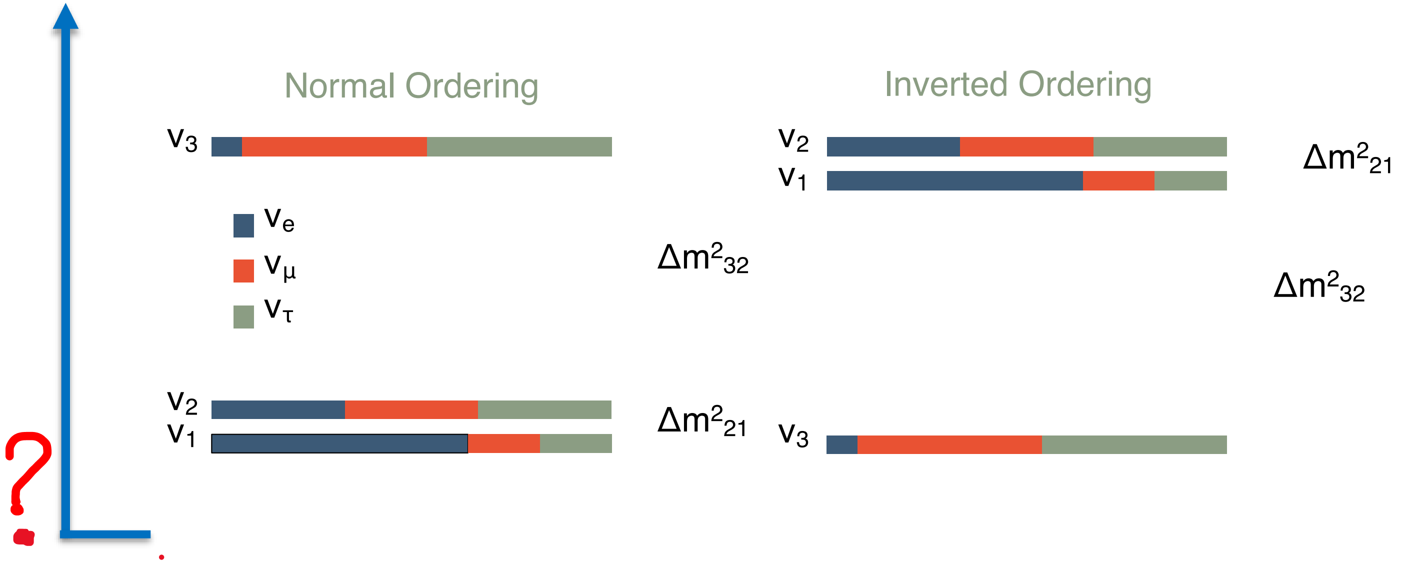


?

Construction of APAs



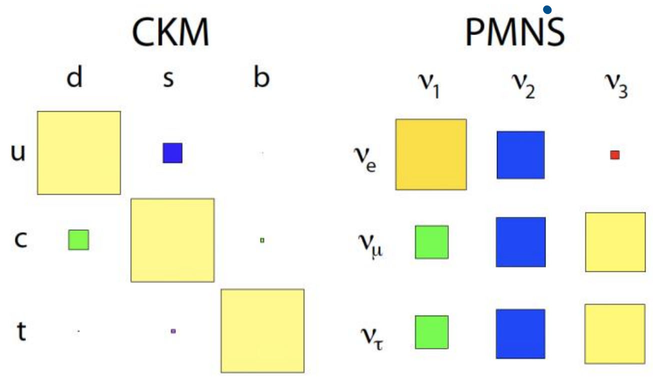
Neutrinos: Open Questions



	θ_{23}	θ_{13}	θ_{12}	δ
Leptons	$\sim 45°$	$8.5°$	$34°$	?
Quarks	$2.4°$	$0.20°$	$13°$	$69°$

Is the θ_{23} mixing maximal?

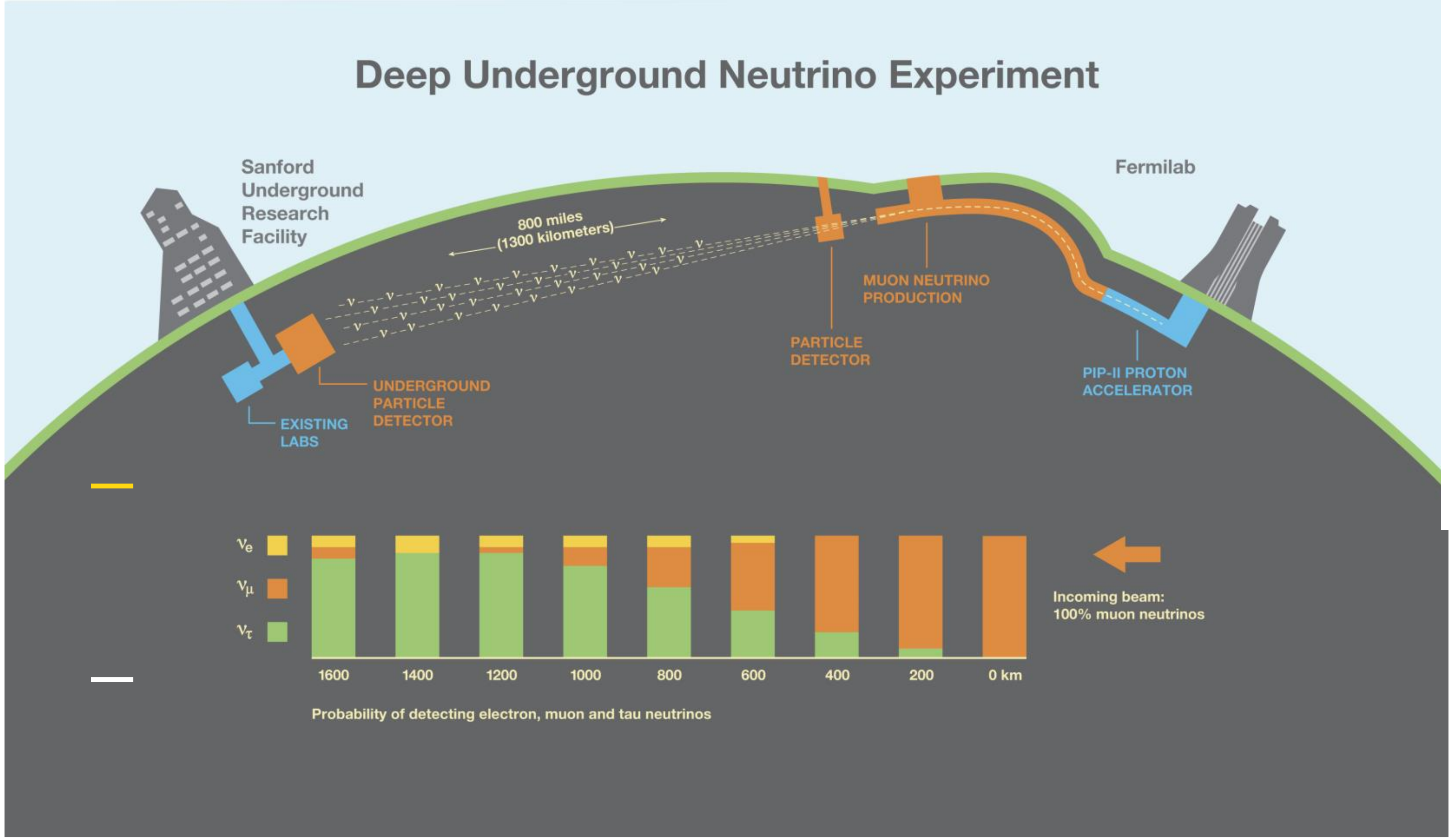
$\theta_{23} = 45° \rightarrow |U_{\mu 3}| = |U_{\tau 3}|$

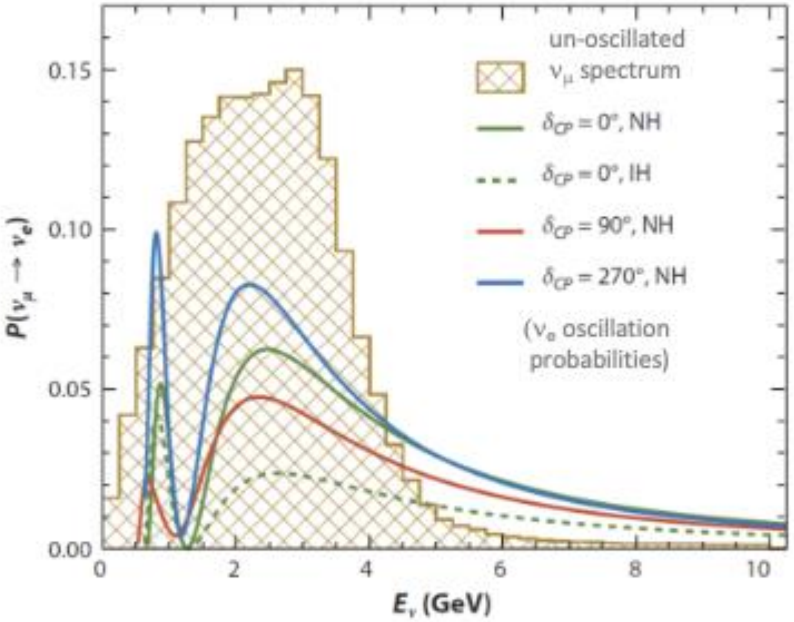


- What is the neutrino mass ordering? (Is Δm^2_{32} positive or negative?)
- Is there leptonic CP violation?
- Is θ_{23} mixing maximal?
- Is the PMNS matrix unitary?

- Can neutrinos explain the matter-antimatter asymmetry in the Universe?
- What is the neutrino absolute mass scale?
- Are neutrinos Majorana particles?

Neutrino Oscillations in DUNE





beam spectrum covers the full neutrino oscillation curve

not simply a counting experiment

BSM Physics

Baryon number violation, dark matter searches, sterile neutrinos, etc.

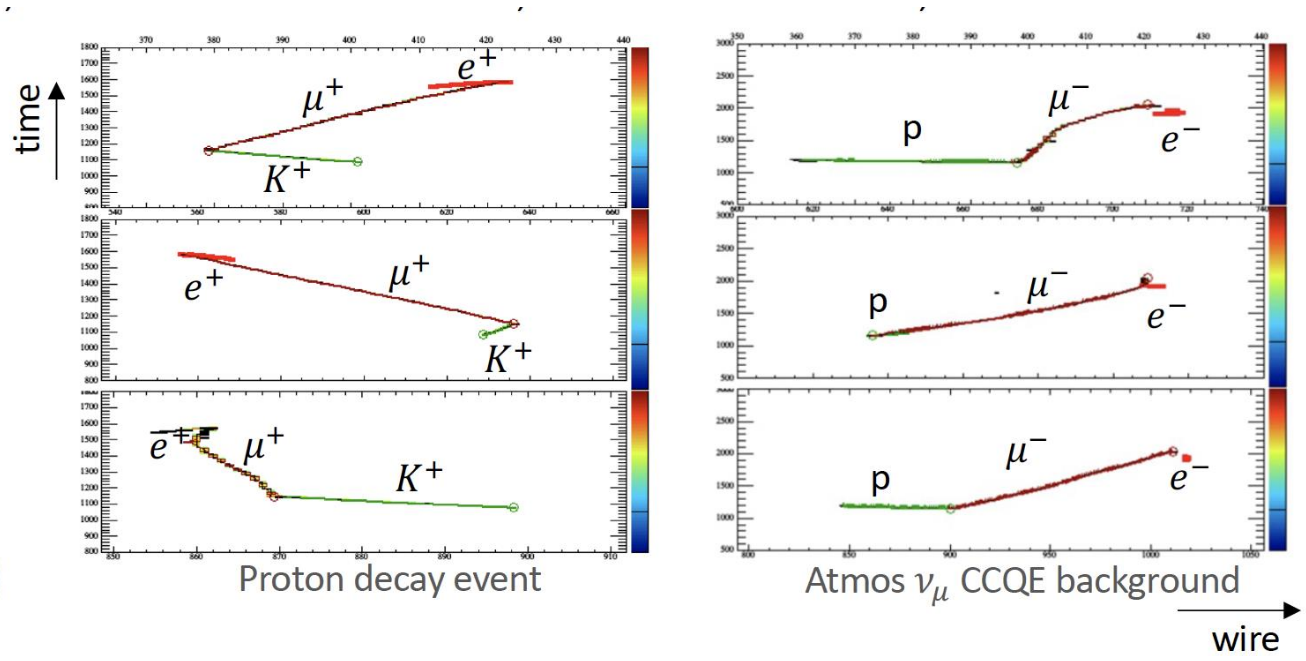
Example: proton decay

- Underground location
- Large fiducial mass
- Imaging capabilities

$p \rightarrow K^+ \bar{\nu}$

dominant SUSY GUT model

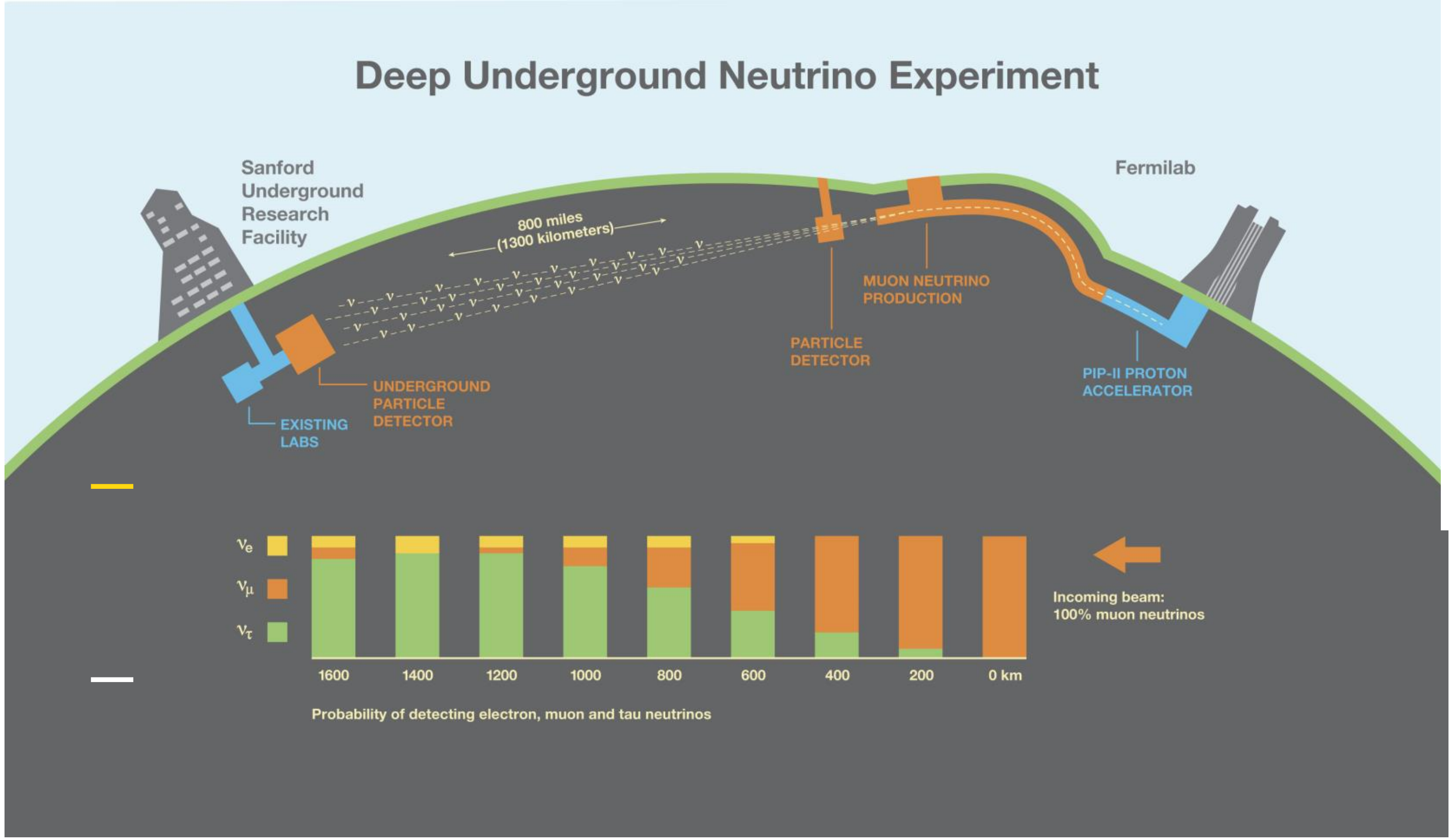
- **Identify kaon by dE/dx and decay products**
- **Main background: atmospheric neutrinos**

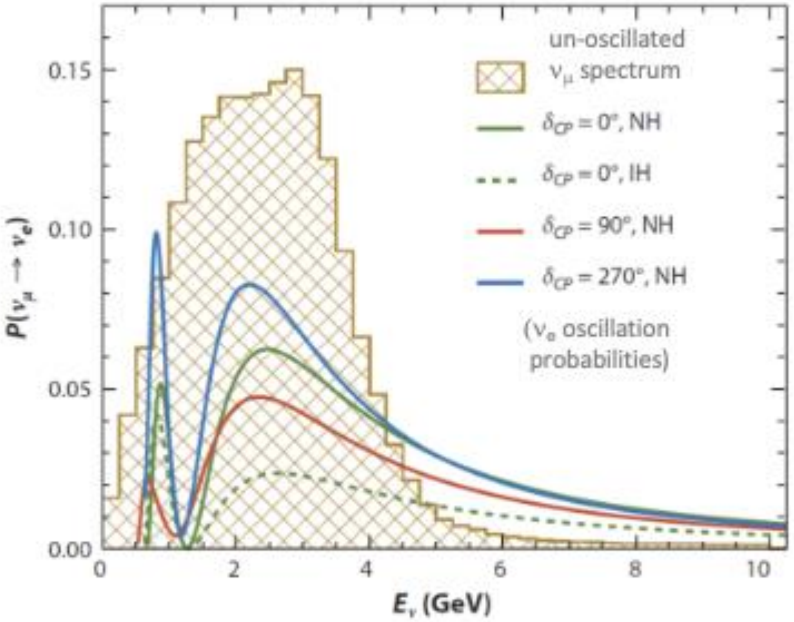


Proton decay event

Atmos ν_μ CCQE background

Neutrino Oscillations in DUNE





beam spectrum covers the full neutrino oscillation curve

not simply a counting experiment

Neutrino oscillations in the 3-neutrino framework

PMNS Matrix

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

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

$c_{ij} = \cos\theta_{ij}$

$s_{ij} = \sin\theta_{ij}$

PDG 2022

ν_e appearance : mass ordering, δ_{CP} , octant of θ_{23}

$$P_{\nu_\mu\to\nu_e,(\bar\nu_\mu\to\bar\nu_e)} \approx 4\,\sin^2\theta_{13}\,\sin^2\theta_{23}\frac{\sin^2\Delta}{(1-A)^2} + \alpha^2\sin^2 2\theta_{12}\,\cos^2\theta_{23}\frac{\sin^2 A\Delta}{A^2}$$
$$+\,8\,\alpha\,J_{CP}^{\max}\boxed{\cos(\Delta\pm\delta_{CP})}\frac{\sin\Delta A}{A}\,\frac{\sin\Delta(1-A)}{1-A}$$

for $\bar\nu$

- «minus» sign
- V→ -V

ν_μ disappearance: $|\Delta m^2_{32}|$, $\sin\vartheta^2_{23}$, constrain octant

$$J_{CP}^{\max} = \cos\theta_{12}\sin\theta_{12}\cos\theta_{23}\sin\theta_{23}\cos^2\theta_{13}\sin\theta_{13}$$

$$\Delta \equiv \frac{\Delta m^2_{31}L}{4E_\nu} \qquad A \equiv \frac{2E_\nu V}{\Delta m^2_{31}} \qquad \alpha \equiv \Delta m^2_{21}/\Delta m^2_{31} \qquad V_C = \sqrt{2}G_F n_e\,.$$

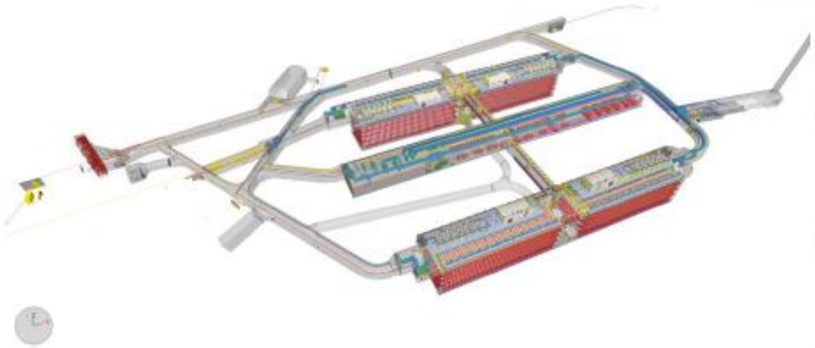
α, Δ , A are sensitive to the sign of Δm^2_{31}

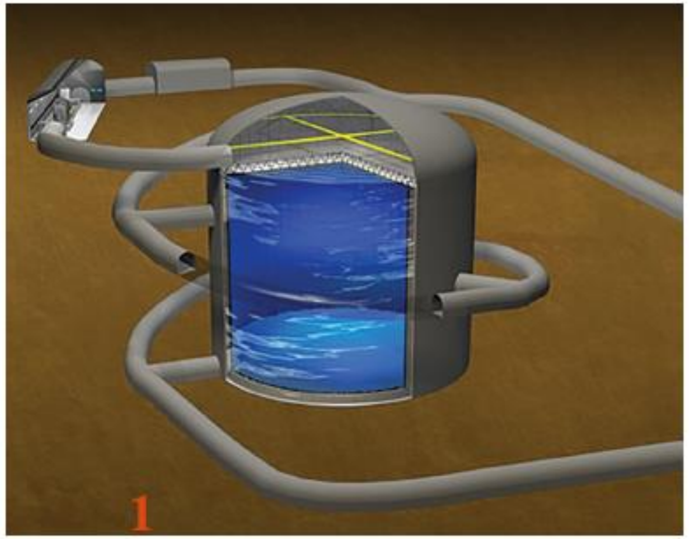
A Phased Approch

- **Two** Far Detector modules
- **1.2 MW** proton beam
- Three near detectors including temporary muon spectrometer (**TMS**)

- **Four** Far Detector modules
- **2.4 MW** proton beam upgrade (most intense neutrino beam in the world)
- Full Near Detector suite (**TMS replaced**)

DUNE and Hyper-K: different detectors, different strategy

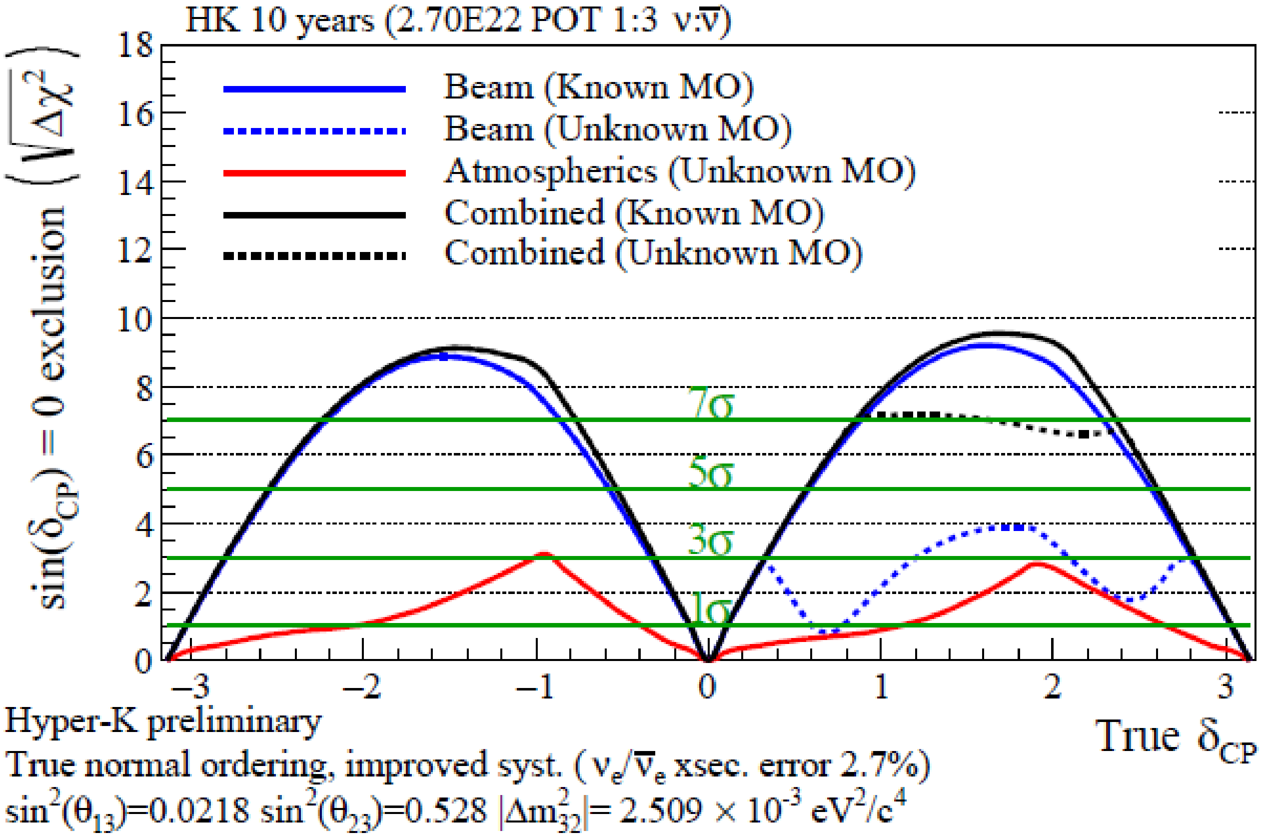




- DUNE:
  - Very long baseline → large matter effect
  - Broadband neutrino beam → high statistics over full oscillation period
  - LArTPC → imaging + calorimetry for ν-Ar interactions at ~2.5 GeV
  - Highly-capable near detector to constrain systematic uncertainties
- Hyper-K:
  - Shorter baseline → small matter effect
  - Off-axis location creates narrow beam → very, very high statistics at oscillation maximum, less feed-down
  - Water Cherenkov → kinematic measurement of E_ν from ν-O interactions at ~0.6 GeV
  - Highly-capable near detector to constrain systematic uncertainties

CPV Sensitivities

Michael B. Smy on behalf of the
Hyper-Kamiokande Collaboration
Phys. Sci. Forum 2023, 8(1), 41



arXiv:2002.03005

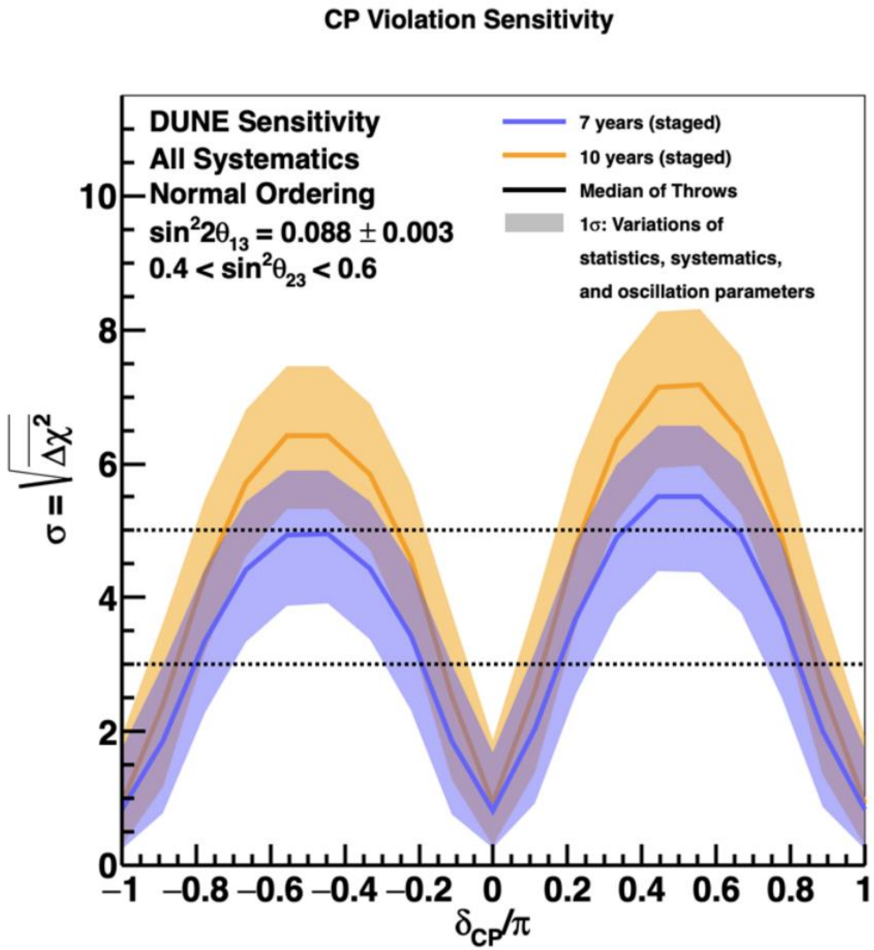


Figure 5.17: Significance of the DUNE determination of CP-violation (i.e.: $\delta_{CP} \neq 0$ or π) as a function of the true value of δ_{CP}, for seven (blue) and ten (orange) years of exposure. True normal ordering is assumed. The width of the transparent bands cover 68% of fits in which random throws are used to simulate statistical variations and select true values of the oscillation and systematic uncertainty parameters, constrained by pre-fit uncertainties. The solid lines show the median sensitivity.

CPV Sensitivities