



DUNE Introduction

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University of Manchester

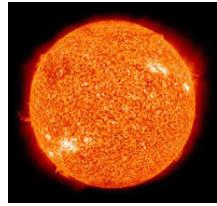
DUNE-UK/LA School
6 September 2022

Pontecorvo–Maki–Nakagawa–Sakata Matrix

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

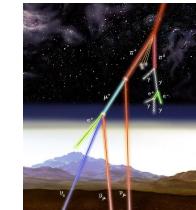
$$U_{\text{PMNS}} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

$c_{ij} = \cos \theta_{ij}; s_{ij} = \sin \theta_{ij}$



θ_{13} : mixes ν_e with ν_3
 δ : complex phase

- θ_{12} : “solar mixing angle”
- mixes ν_e with ν_1 and ν_2



- θ_{23} : “atmospheric mixing angle”
- mixes ν_μ with ν_τ

Pontecorvo–Maki–Nakagawa–Sakata Matrix

$$U_{\text{PMNS}} = \begin{pmatrix} \text{solar} & & \\ & & \\ & & \end{pmatrix} \begin{pmatrix} \text{"reactor"} & & \\ & & \\ & & \end{pmatrix} \begin{pmatrix} \text{atmospheric} & & \\ & & \\ & & \end{pmatrix}$$

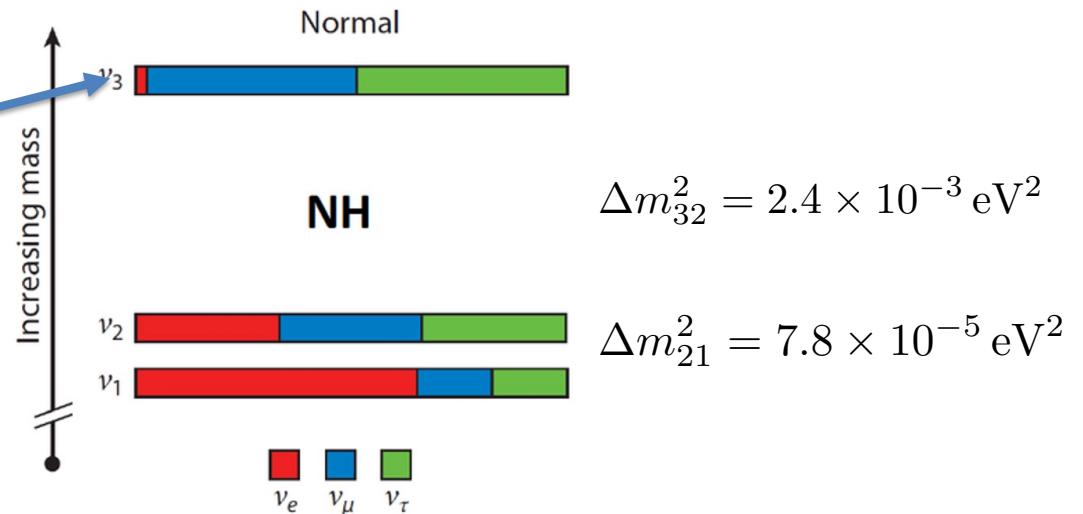
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$$\theta_{12} = 33.44^\circ {}^{+0.78^\circ}_{-0.75^\circ}$$

$$\theta_{23} = 49.0^\circ {}^{+1.1^\circ}_{-1.4^\circ}$$

$$c_{ij} = \cos \theta_{ij}; s_{ij} = \sin \theta_{ij}$$

- “Small” angle θ_{13} mixes ν_e with ν_3
- Look for ν_e mixing driven by Δm_{32}^2
- Reactor: anti- ν_e disappearance
- Accelerator: ν_e appearance in ν_μ beam
 \rightarrow sensitive to θ_{13} and δ (and MO).



The PMNS Matrix and CP violation

complex CP phase

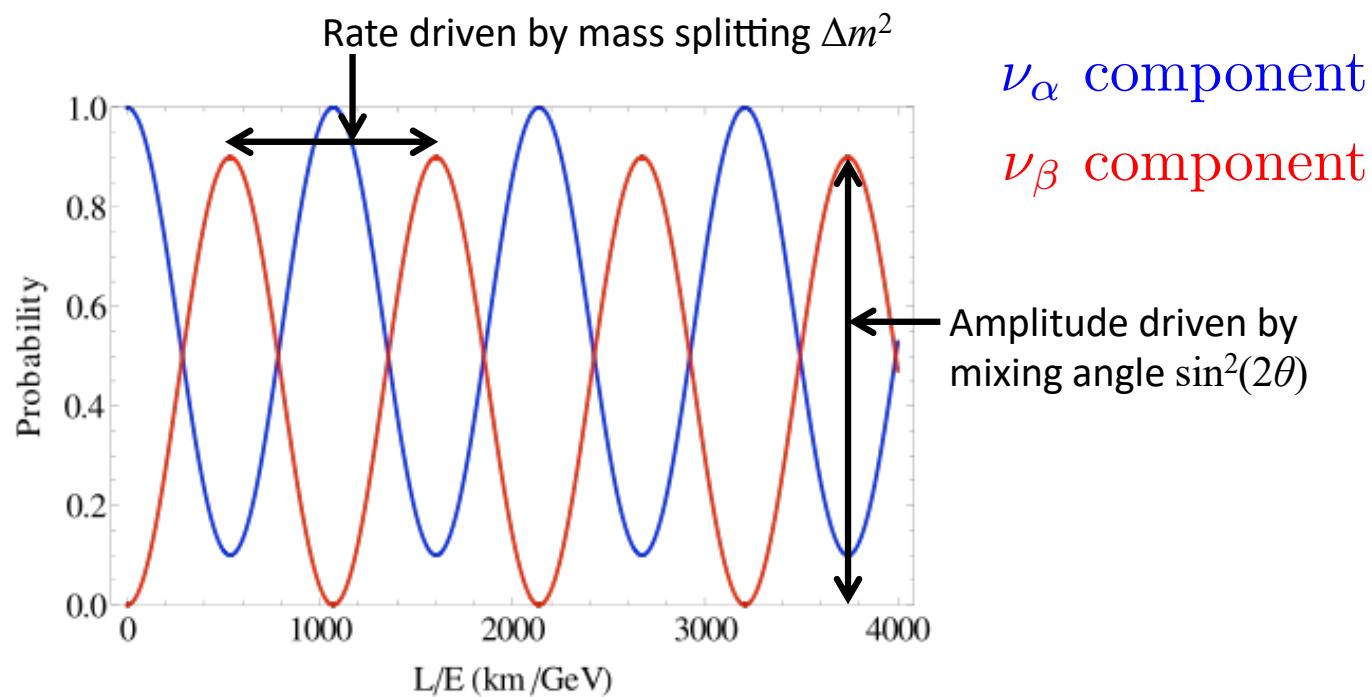
$$U_{\text{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$
$$\delta \neq \{0, \pi\} \quad s_{ij} = \sin \theta_{ij}; \quad c_{ij} = \cos \theta_{ij}$$

CP Violation involving neutrinos might provide support for Leptogenesis as mechanism to generate the Universe's matter-antimatter asymmetry.

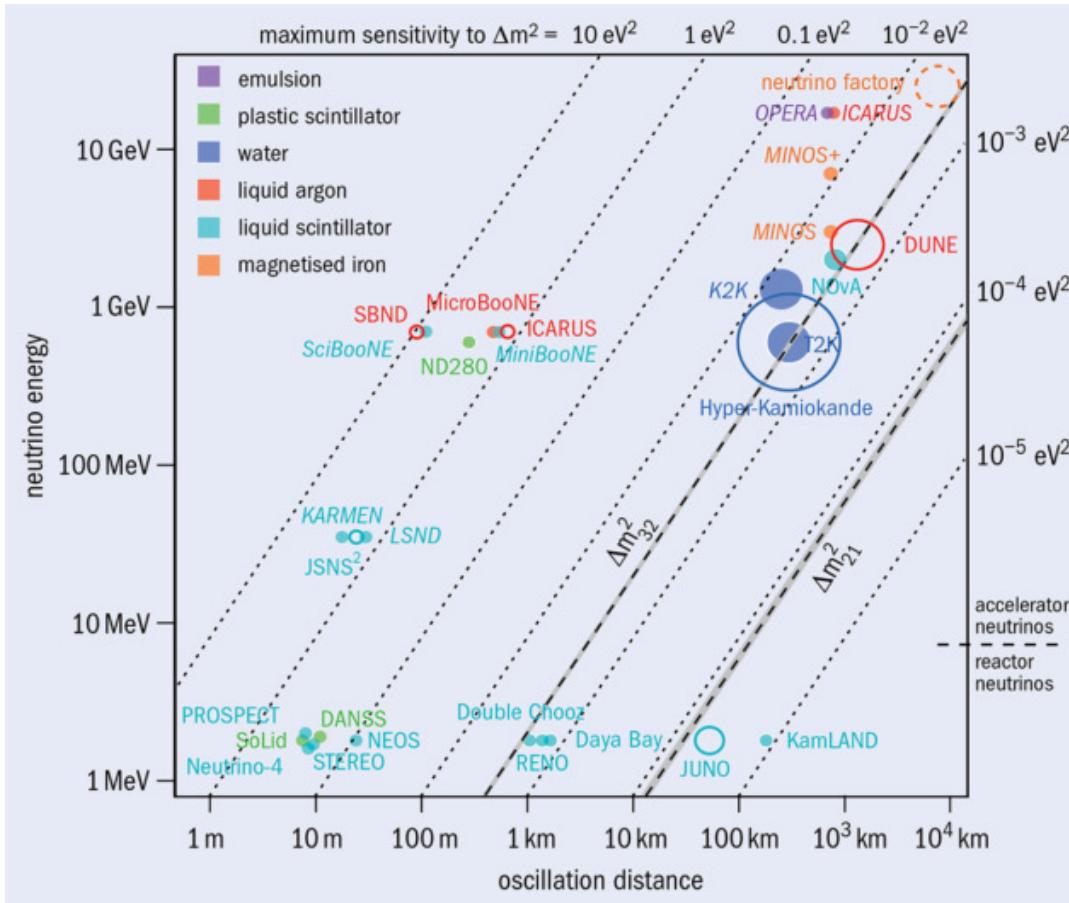


Neutrino flavour oscillations

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta) \sin^2 \left(1.27 \frac{\Delta m_{21}^2 [\text{eV}^2] L [\text{km}]}{E [\text{GeV}]} \right)$$



Baseline, energy, and frequency



CERN Courier, 2020

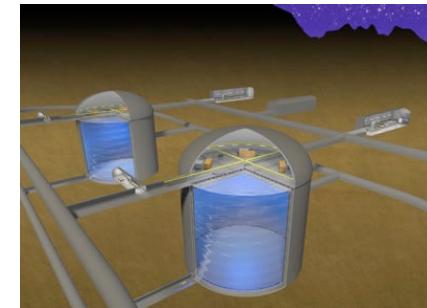
$$\frac{\Delta m^2 L}{4E}$$

Optimizing detectors for neutrino oscillations

$L \approx 300 \text{ km}$

$$\begin{aligned} L/E(1^{\text{st}} \text{ max}) &= 500 \text{ km/GeV} \\ L/E (2^{\text{nd}} \text{ max}) &= 1700 \text{ km/GeV} \end{aligned}$$

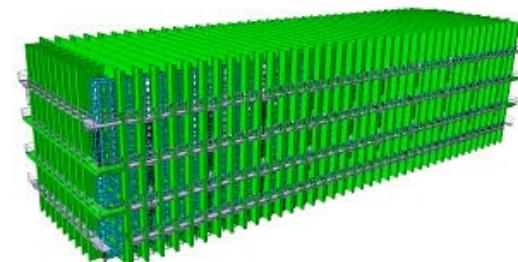
- no matter effects.
- use narrow width neutrino beam (off axis) with $E < 1 \text{ GeV}$
- observe first oscillation maximum
- “counting experiment”



Water Cherenkov (HK)

$L = 1300 \text{ km}$

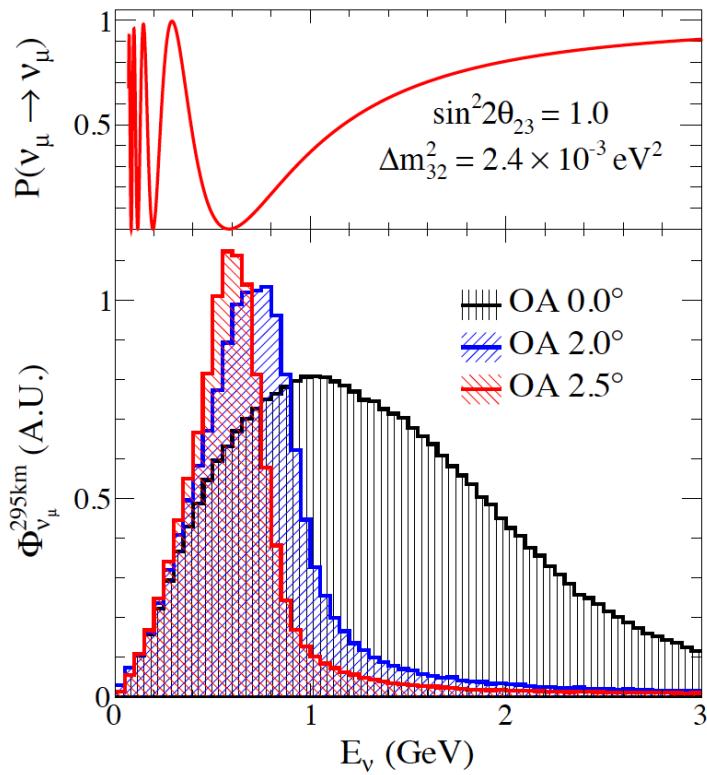
- matter effects
- use broad-band neutrino beam (on axis).
- observe first and second oscillation maximum.
- unfold CP and MO effects through energy dependence



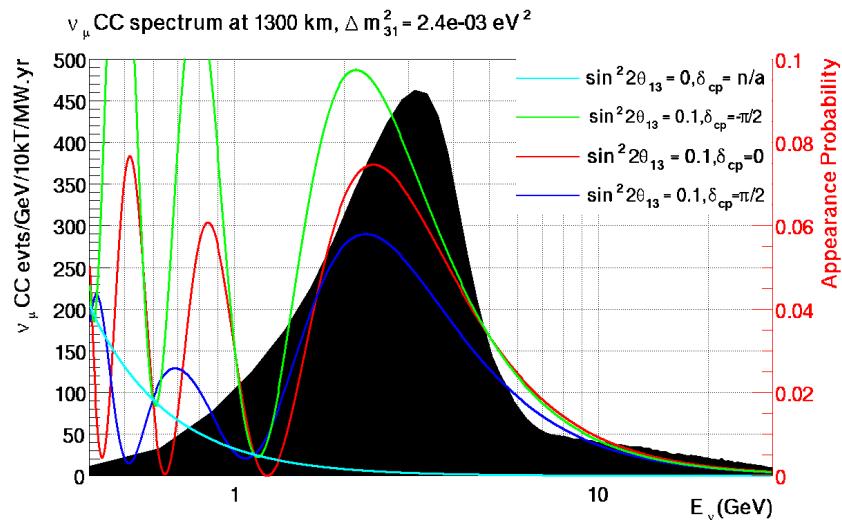
Liquid argon (DUNE)

Off-axis vs on-axis beams

T2K at 2.5 degrees



DUNE on-axis beam



ν_e appearance gives access to δ

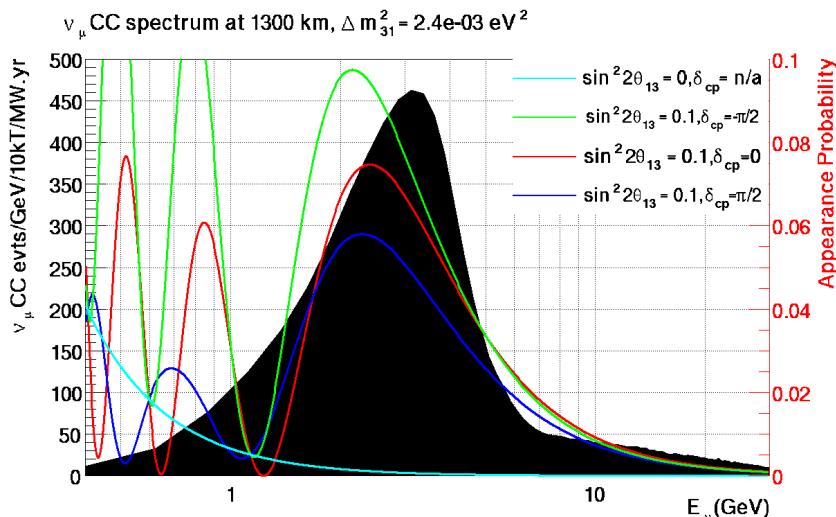
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2$$

$$+ \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31} \frac{\sin(aL)}{aL} \Delta_{21} \cos(\Delta_{31} - \delta)$$

$$+ \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin(aL)}{aL} \Delta_{21}^2$$

$$a = \frac{G_F N_e}{\sqrt{2}}$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$



- ν_e appearance amplitude depends simultaneously on θ_{13} , θ_{23} , δ_{CP} , and matter effects –
- Measurements of all four possible in a single experiment.

ν_e appearance gives access to δ

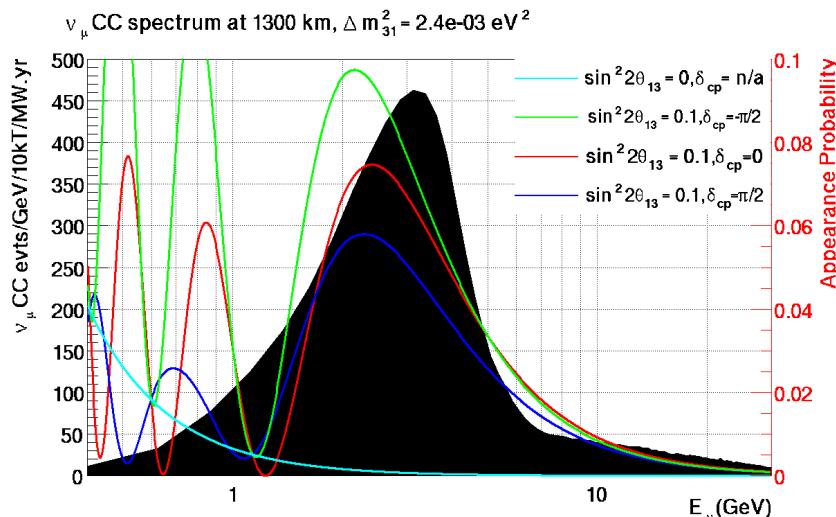
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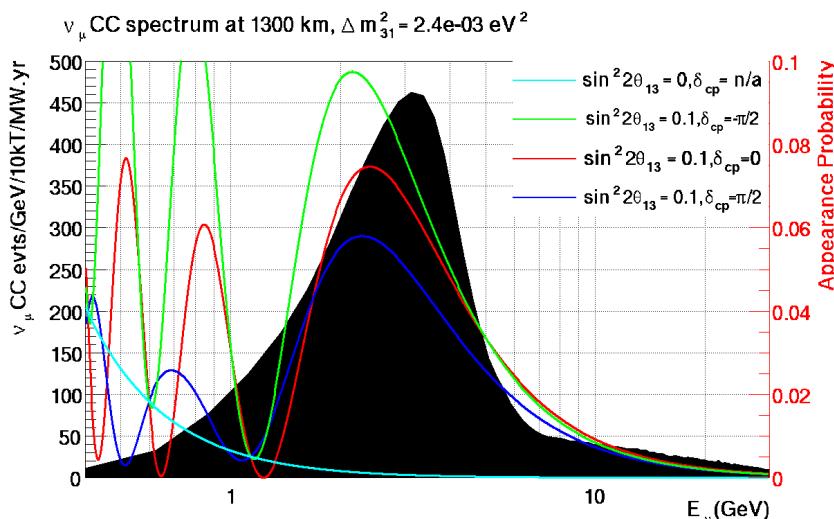
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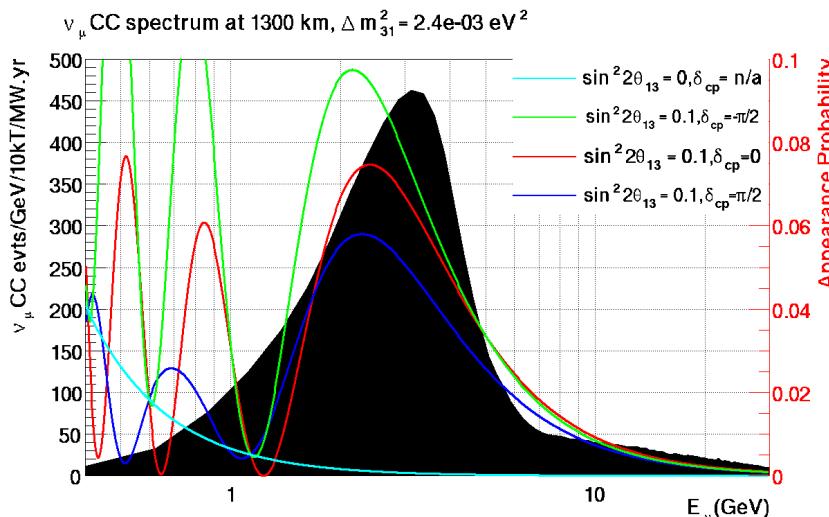
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- ν_e appearance amplitude depends simultaneously on θ_{13} , θ_{23} , δ_{CP} , and matter effects –
- Measurements of all four possible in a single experiment.
- Need to resolve degeneracies (e.g., MO vs. CP).

ν_e appearance gives access to δ

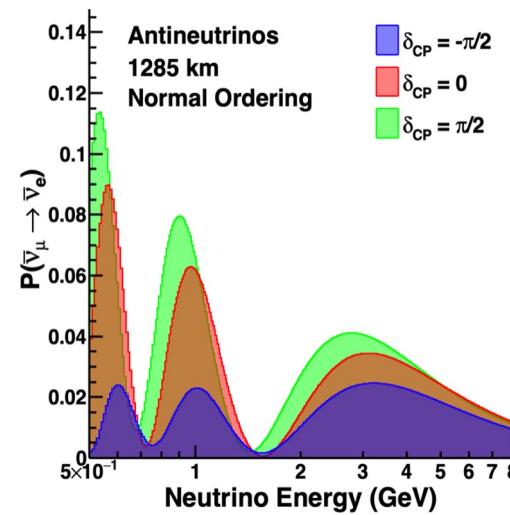
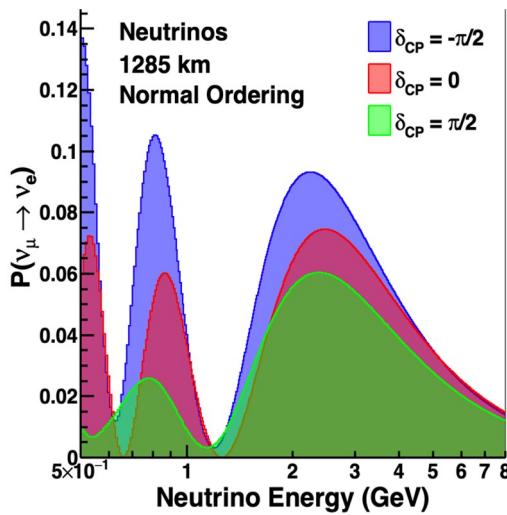
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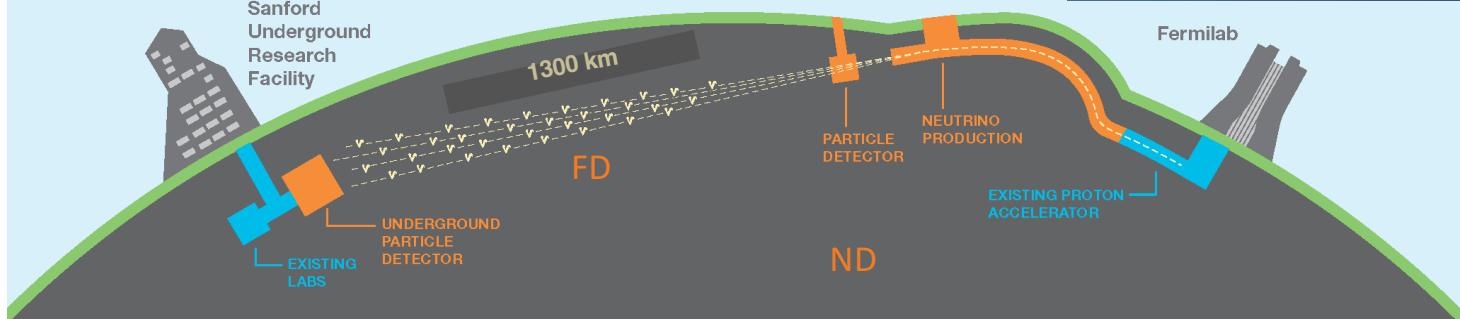
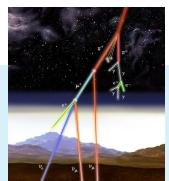


How to measure LBL neutrino oscillations

- Measure flavour change as a function of energy over a long distance.
- Starting with a muon-neutrino beam, we observe muon-neutrino disappearance and electron-neutrino appearance.
- Measure event rates and not the flux directly.
- Measurement is a convolution of the oscillation probabilities P , the neutrino flux Φ , the cross sections σ , and the detector response T .

$$\frac{N_{\nu_i}^{\text{FD}}}{N_{\nu_\mu}^{\text{ND}}}(E_{\text{rec}}) = \frac{\int \Phi_{\nu_\mu}^{\text{FD}}(E_\nu) \cdot P_{\nu_\mu \rightarrow \nu_i}(E_\nu) \cdot \sigma_{\nu_i}^{\text{Ar}} \cdot T_{\nu_i}^{\text{FD}}(E_\nu, E_{\text{rec}}) \, dE_\nu}{\int \Phi_{\nu_\mu}^{\text{ND}}(E_\nu) \cdot \sigma_{\nu_\mu}^X \cdot T_{\nu_\mu}^{\text{ND}}(E_\nu, E_{\text{rec}}) \, dE_\nu}$$

DUNE in a Nutshell



1. A high-power, wide-band **neutrino beam** (\sim GeV energy range).
2. A ≈ 70 kt **liquid-argon Far Detector** in South Dakota, located 1478 m underground in a former gold mine.
3. A **Near Detector** located approximately 575 m from the neutrino source at Fermilab close to Chicago.

Making a neutrino beam

Pion decay at rest:

$$E_\nu^* = \frac{m_\pi^2 - m_\mu^2}{2m_\pi} = 29.8 \text{ MeV}$$

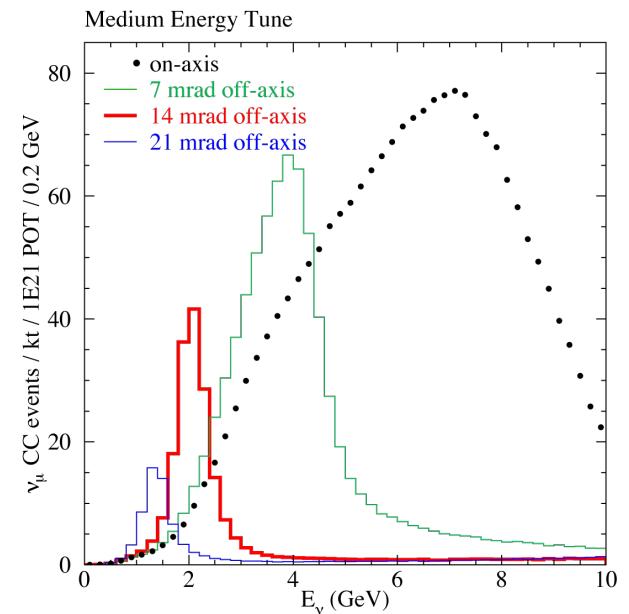
Boost into lab system:

$$\begin{aligned} E_\nu &= \frac{m_\pi E_\nu^*}{E_\pi - p_\pi \cos \theta} \\ &= \frac{E_\nu^*}{\gamma_\pi (1 - \beta_\pi \cos \theta)} \end{aligned}$$

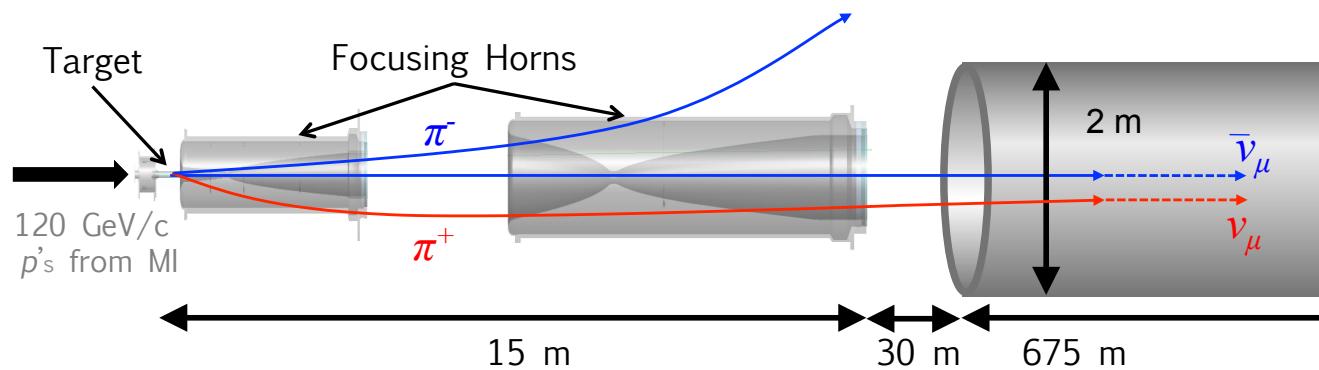
$E_\pi = 9 \text{ GeV}$ at $\theta = 0$:

$$\gamma_\pi = 64.5 \implies E_\nu = 3.8 \text{ GeV}$$

$$\bar{\nu}_l \leftarrow \pi^+ \rightarrow l^+$$

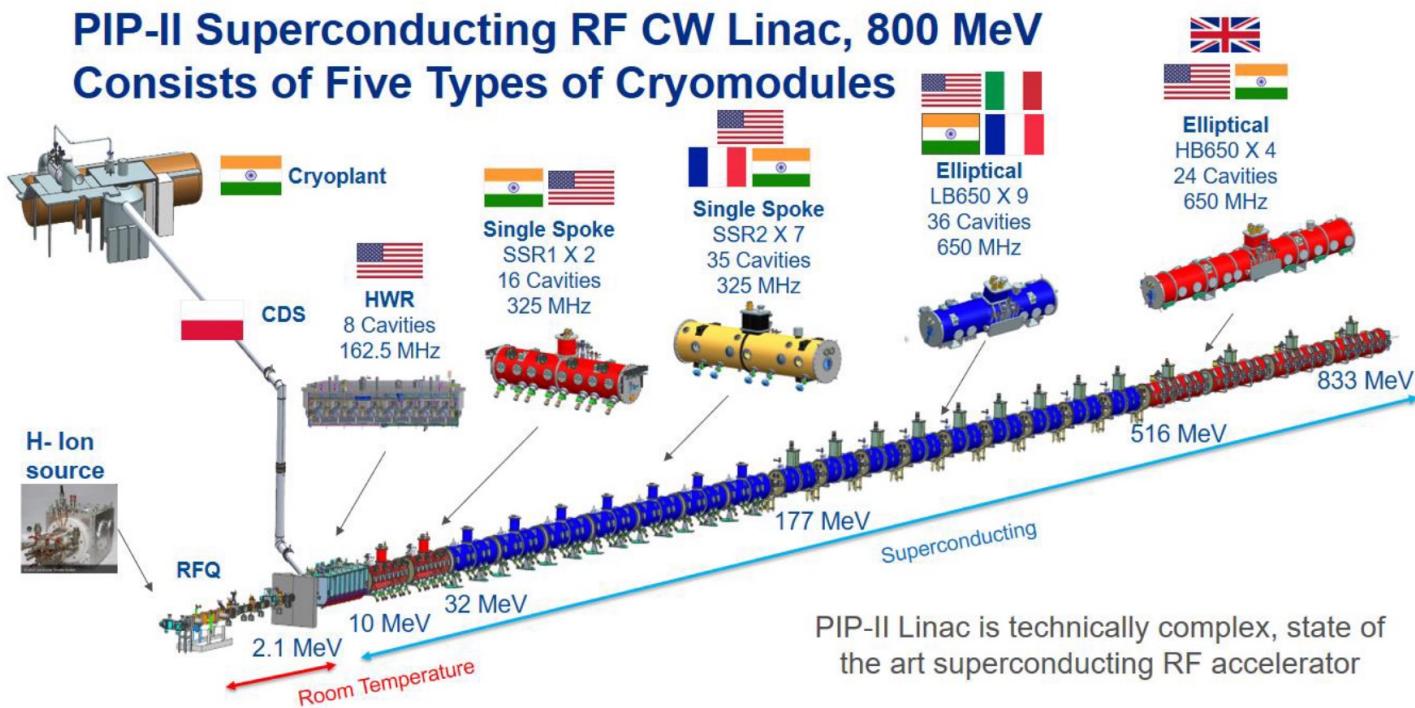


Making a neutrino beam



- As neutrinos are neutral, they cannot be focused, and a magnetic horn is thus used to focus the pions.
- Invented by Simon van der Meer at CERN.

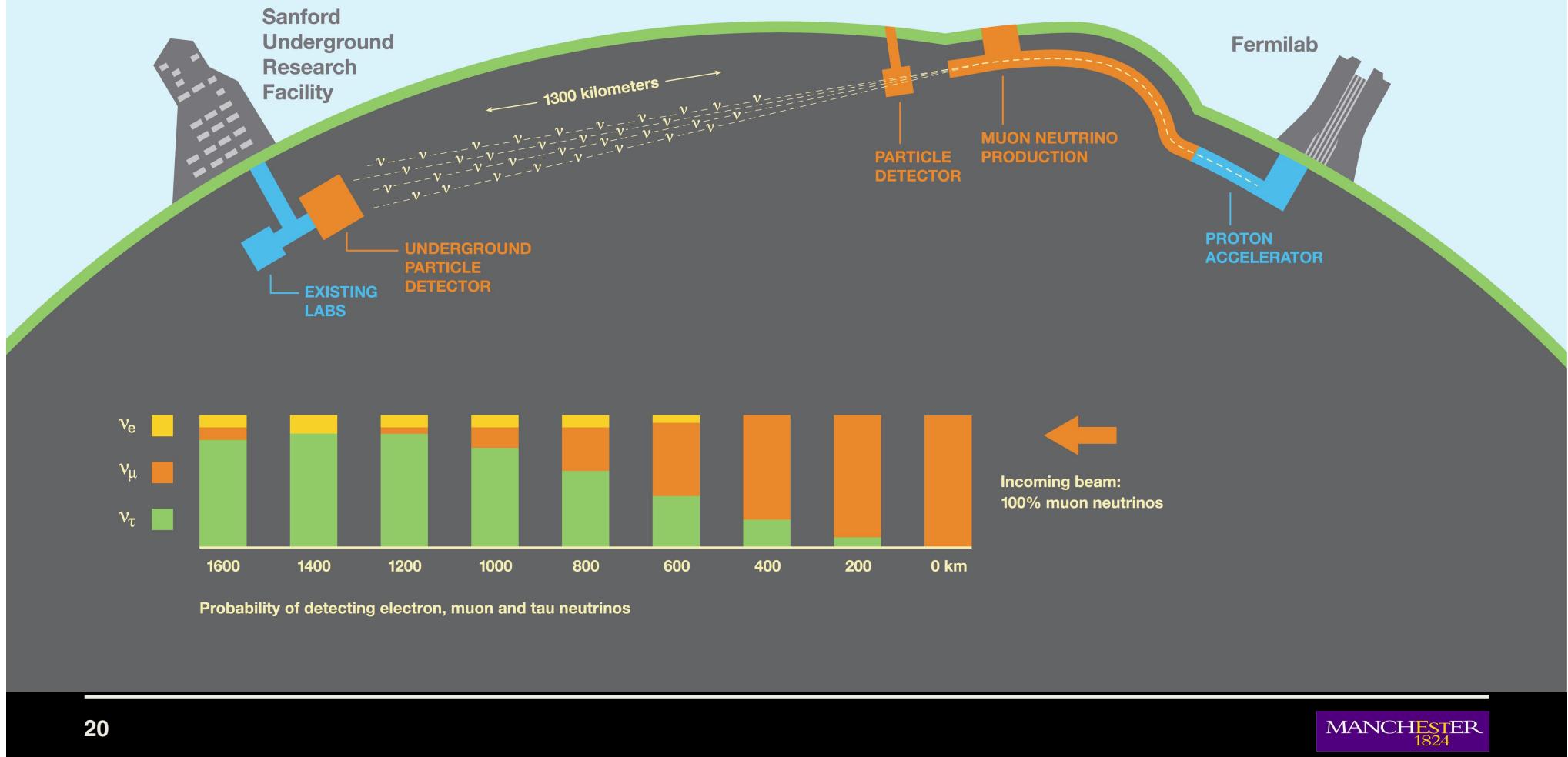
Proton Improvement Plan (PIP-II)

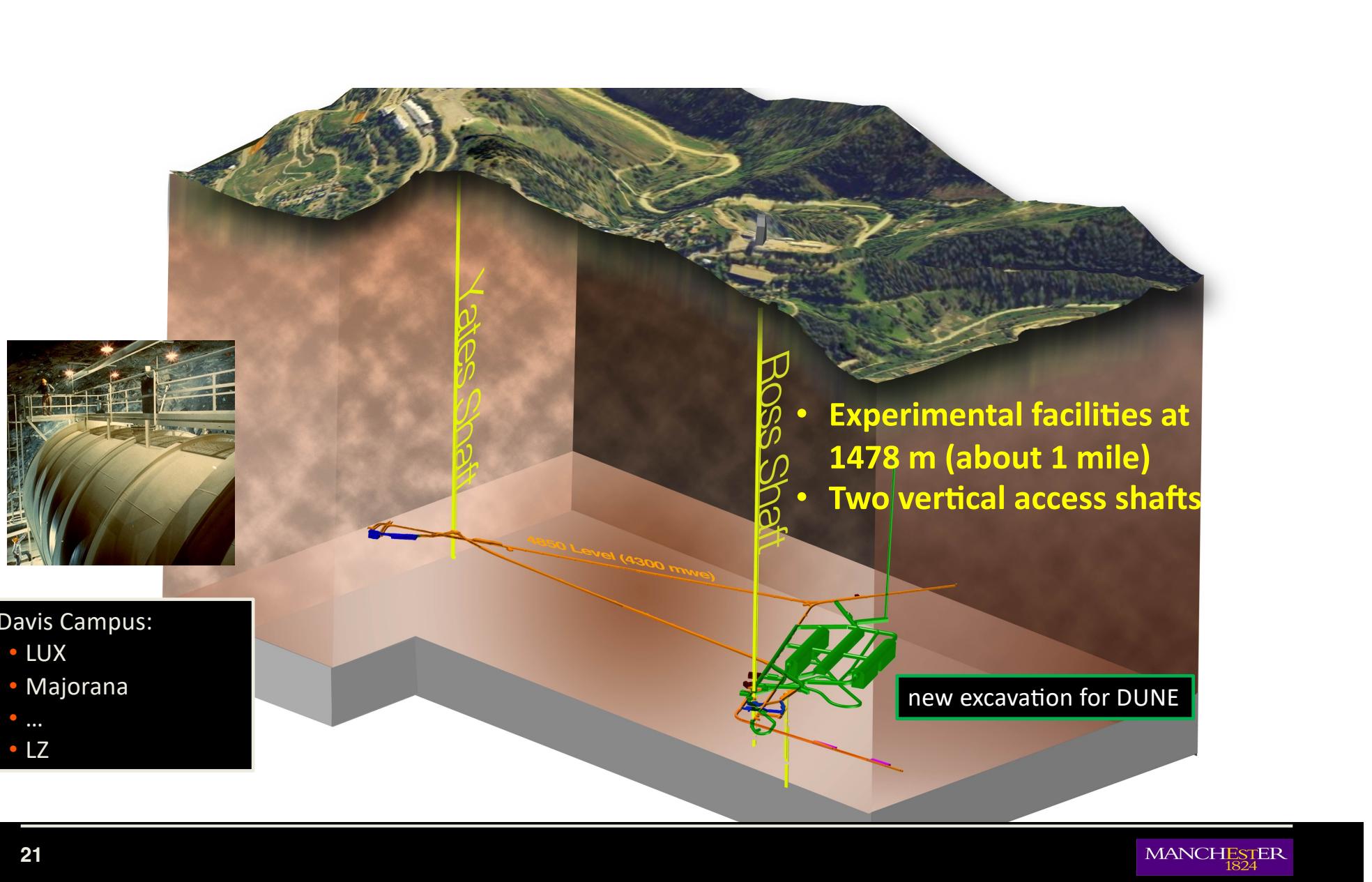


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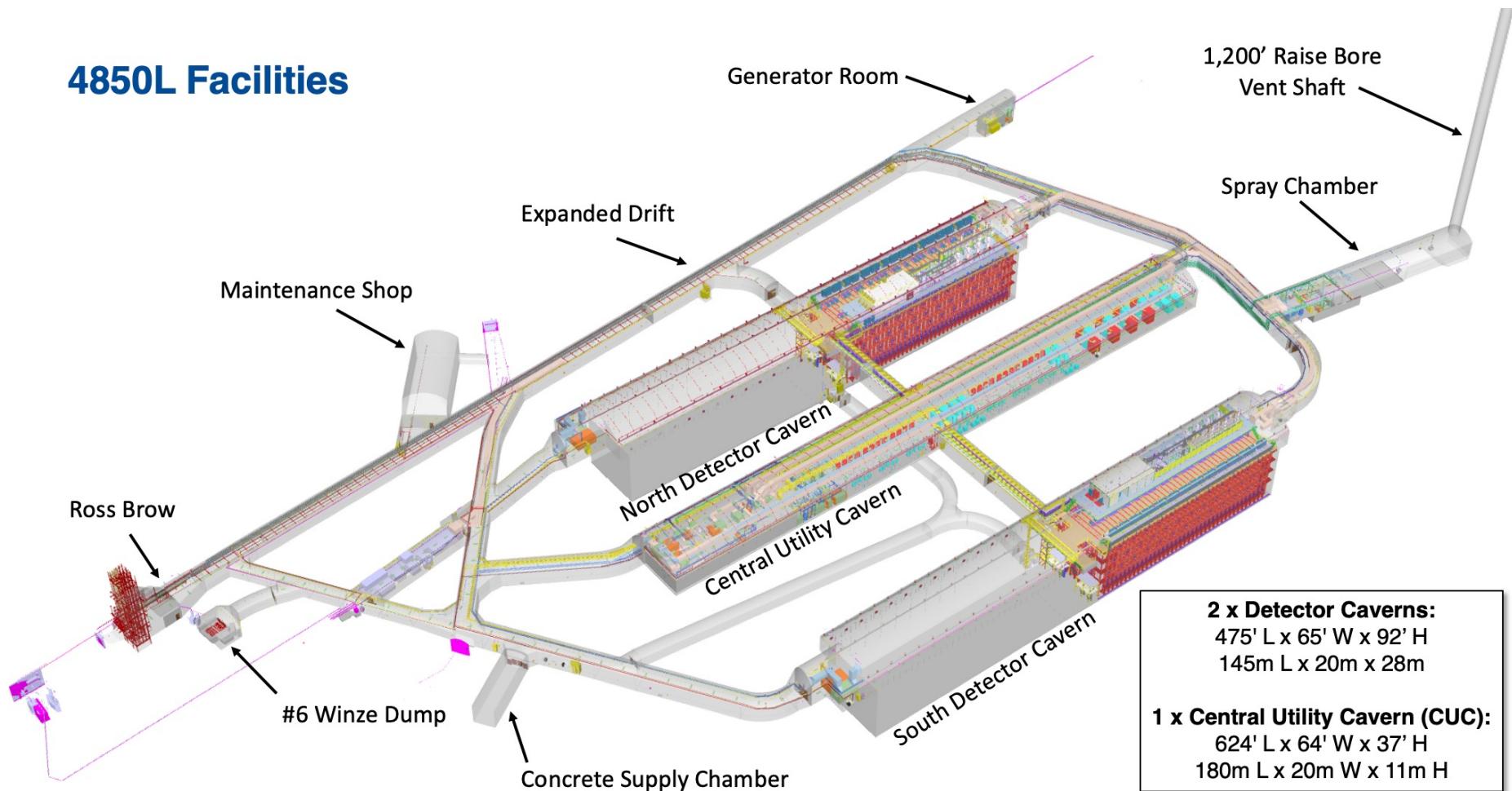


Deep Underground Neutrino Experiment





4850L Facilities



12 Feb 2022

Central Utility Cavern Pilot Drift Breakthrough



Cavern is being constructed



Nigel Lockyer
@Nigel_Lockyer

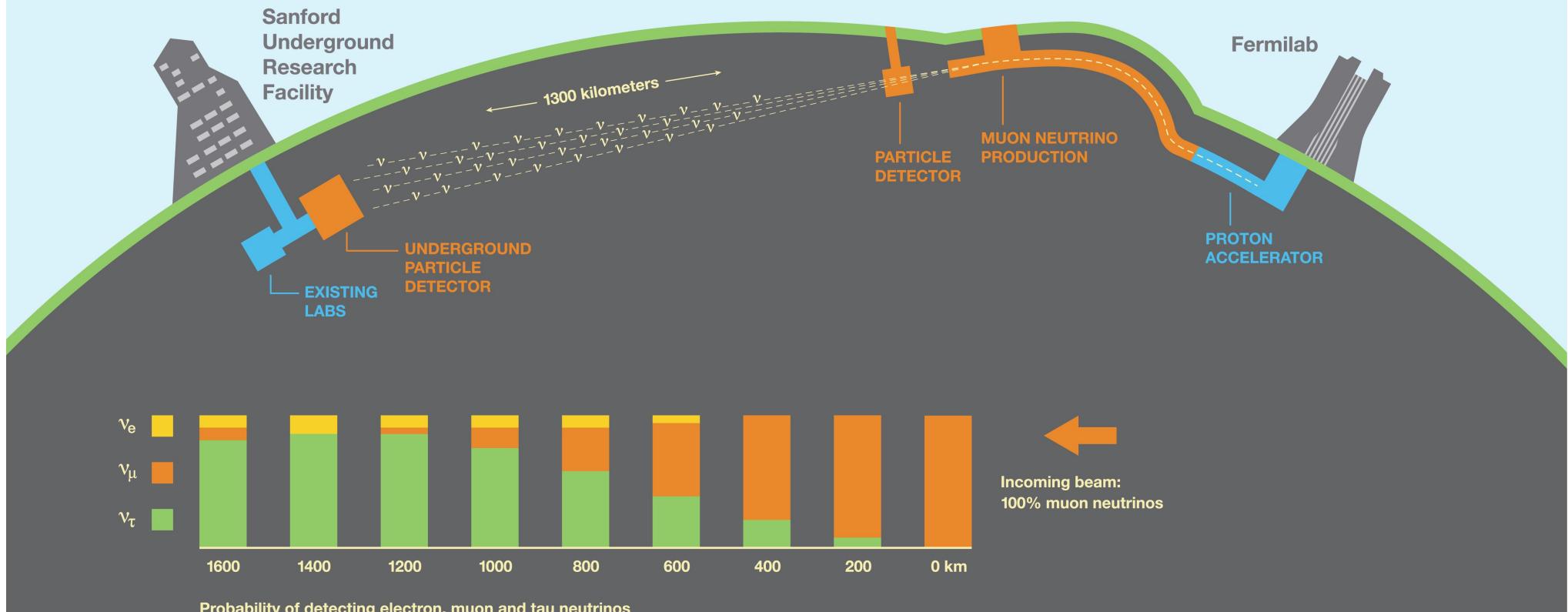
...

Look carefully, the construction worker says he has just started excavating this cavern. The final enormous size is hard to comprehend. All for neutrinos.

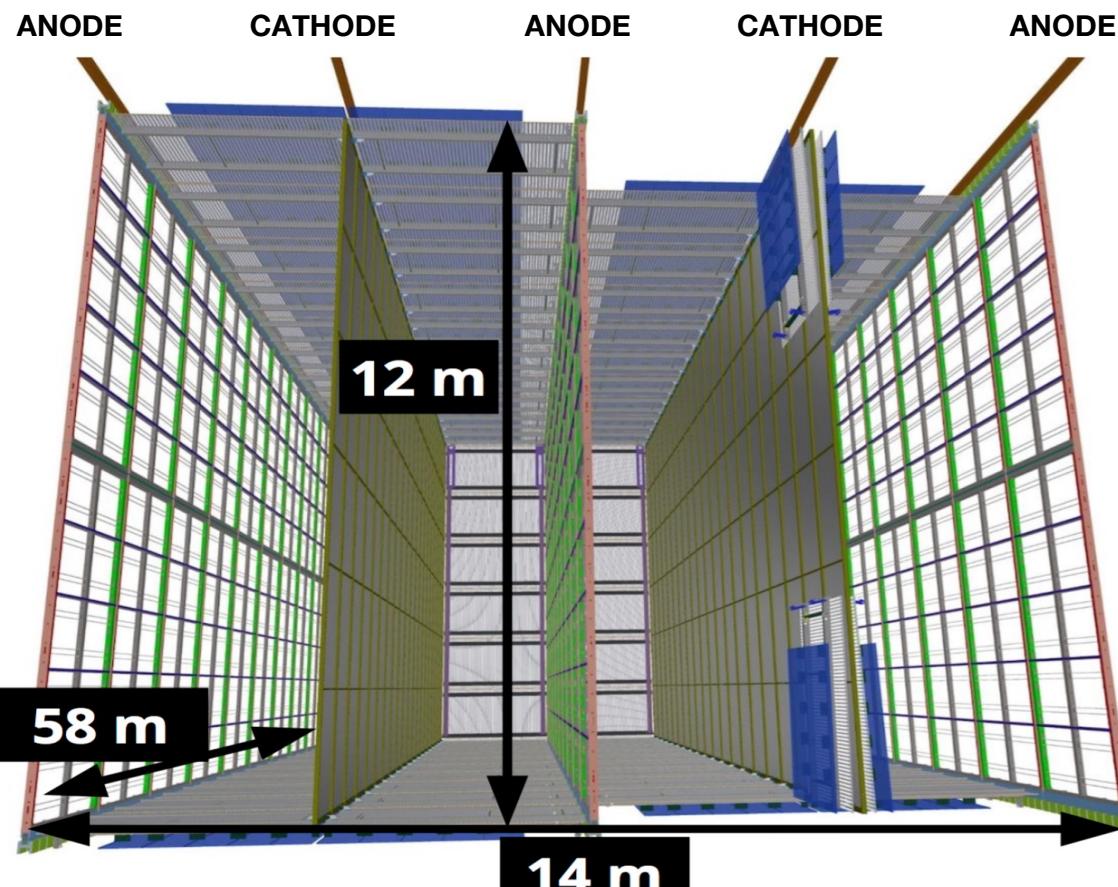
2:27 pm · 2 Jul 2022 · Twitter for iPhone



Deep Underground Neutrino Experiment



Horizontal Drift Detector (FD Module 1)



Module 1: Horizontal Drift



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UK scientists build core components of global neutrino experiment



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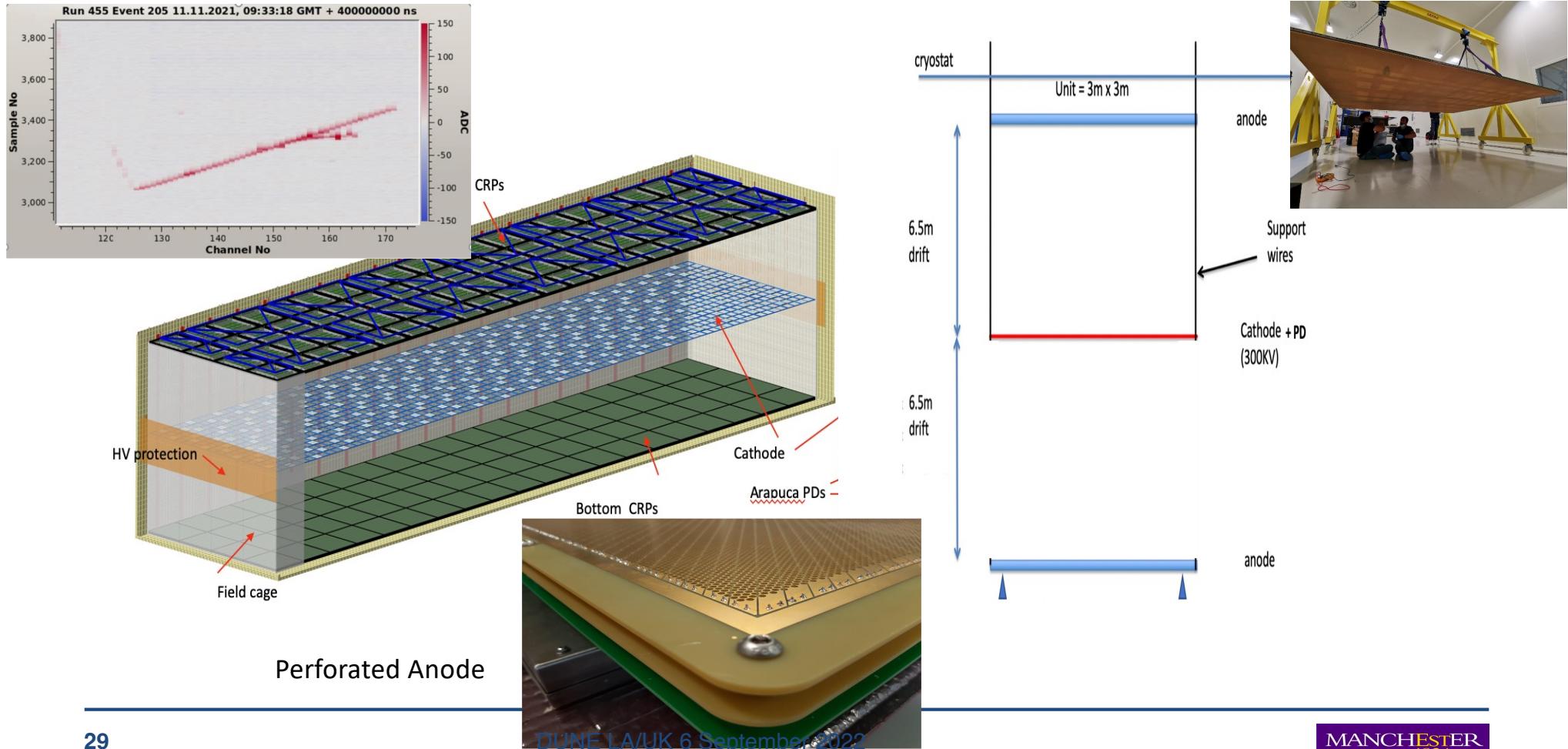
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- 150 Anode Plane Assemblies (APA)
- 130 in UK and 20 in US

ProtoDUNE at CERN

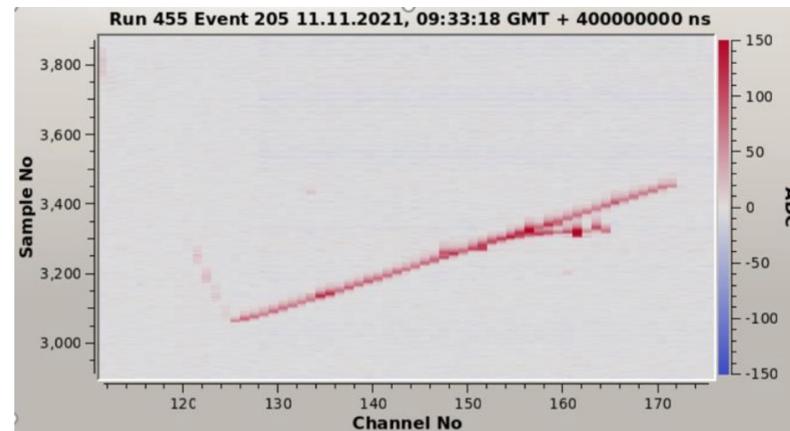


Vertical Drift Detector (FD Module 2)

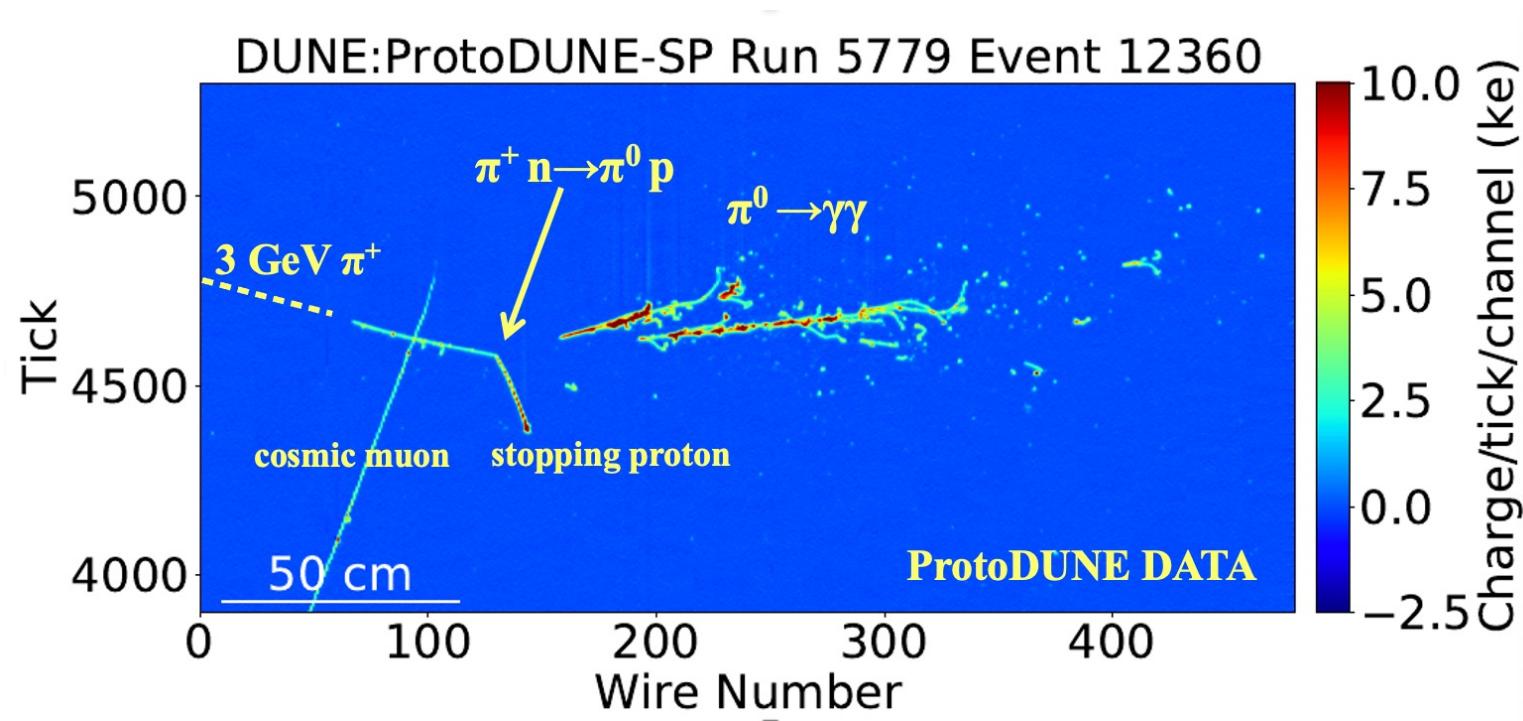


Module 2: Vertical Drift

Successful tests at CERN,
leading to design of ProtoDUNE
Module-0 for Vertical Drift.



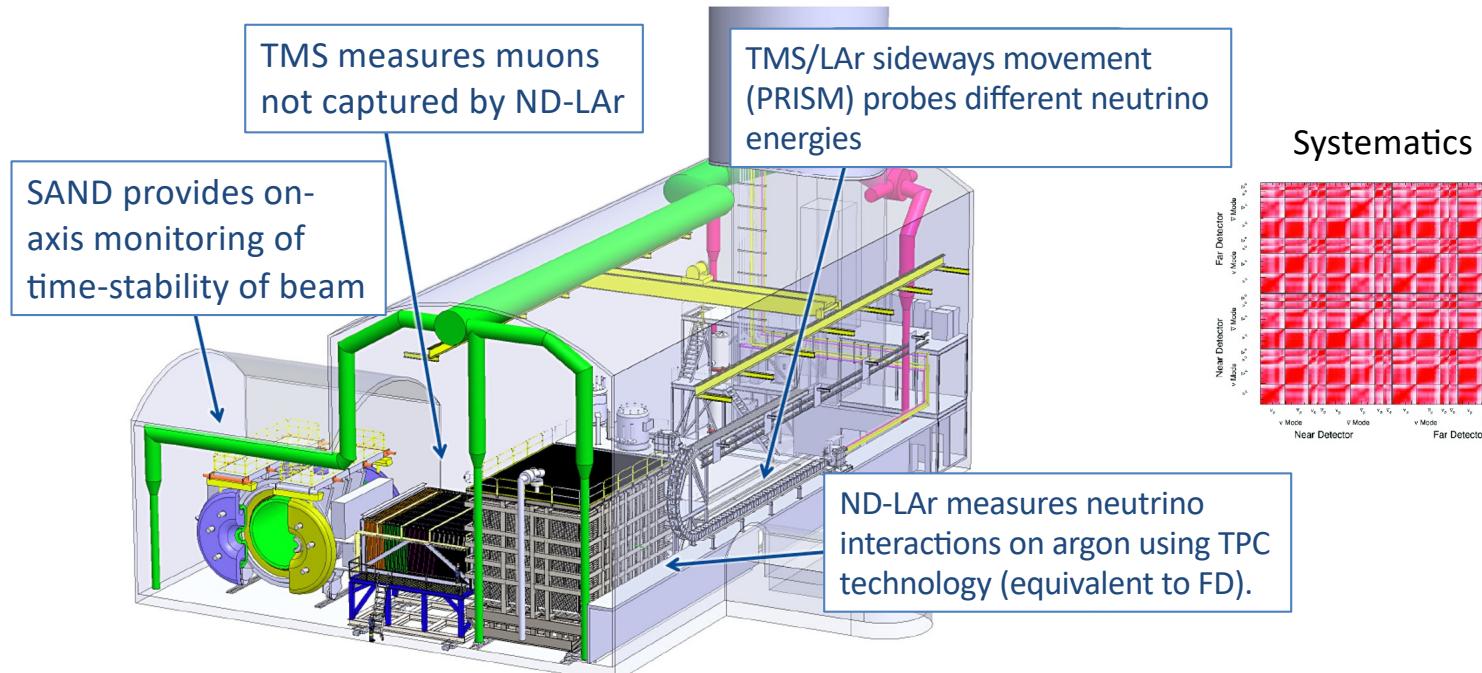
A ProtoDUNE-HD Data Event



Reconstruction of events performed by PANDORA framework
with the use of Grid computing resources, both areas UK-led.

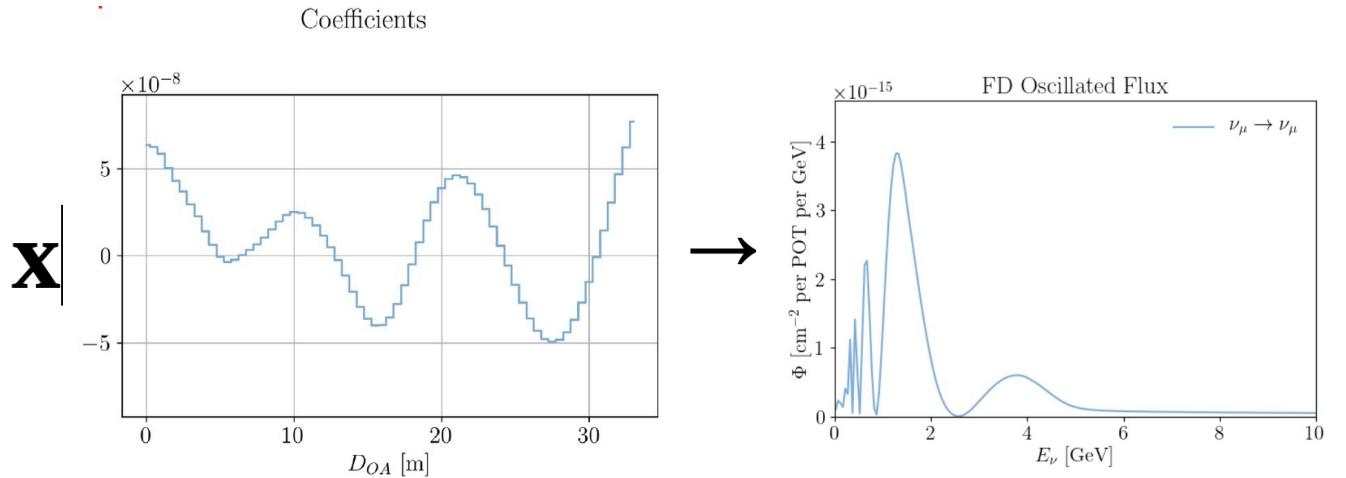
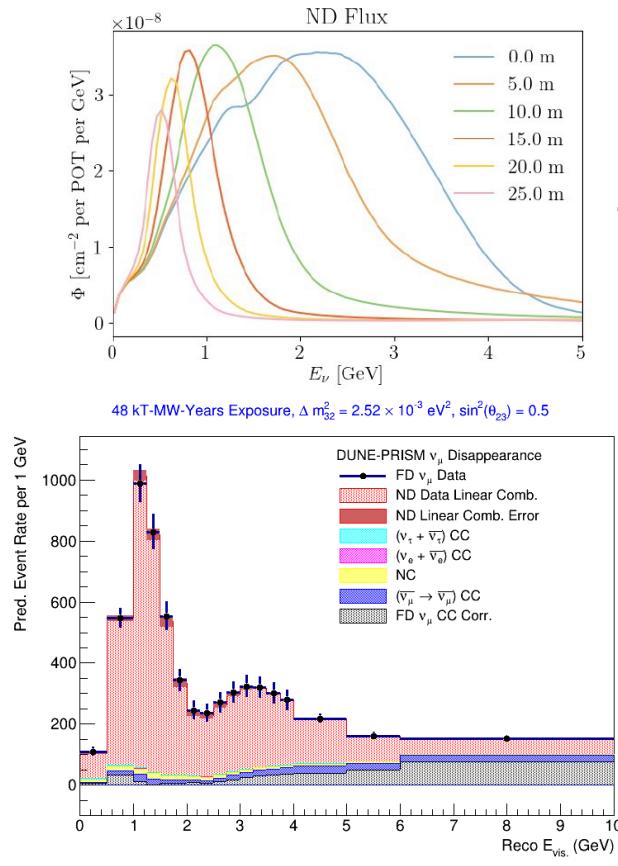
DUNE Phase I Near Detector

We expect to replace TMS by a gas-argon TPC for Phase-II.



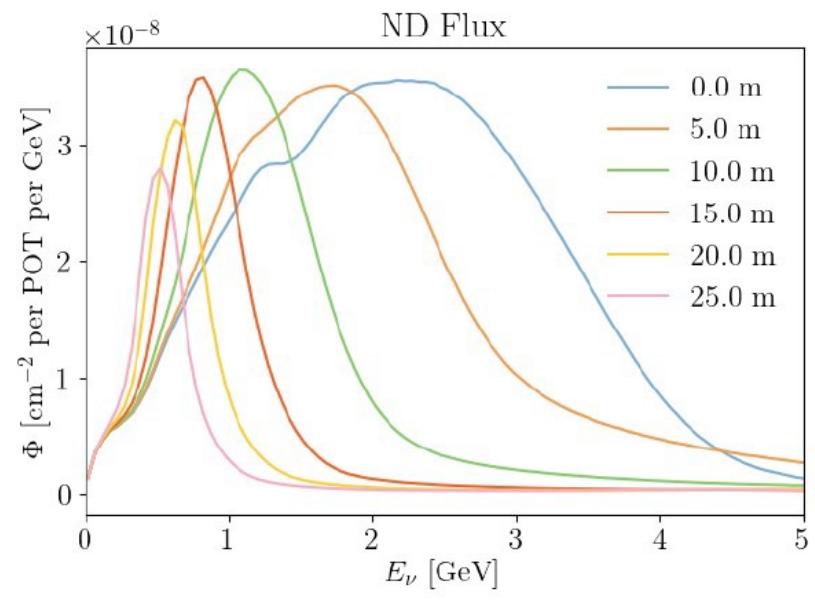
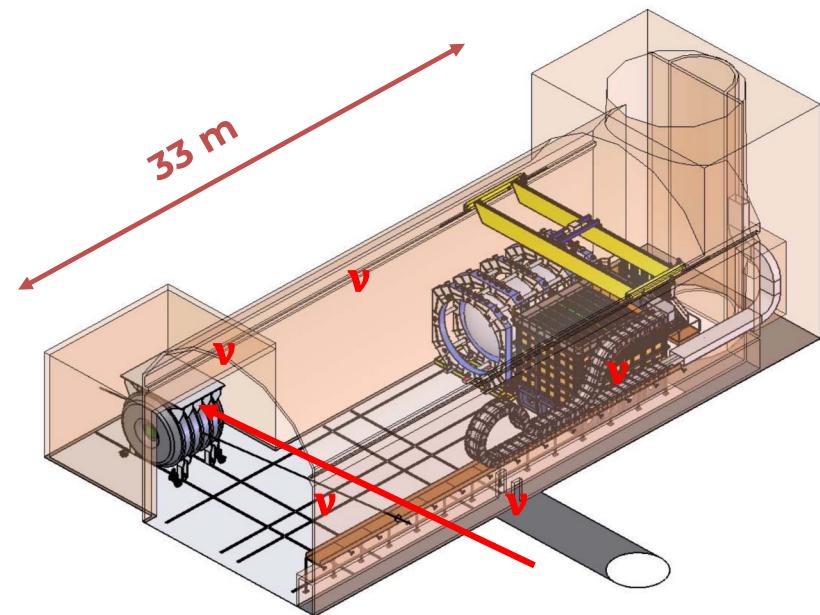
- Near Detectors constrain systematic uncertainties for long-baseline oscillation analysis
Neutrino flux & cross-section, and detector systematics
- In addition, >100 million interactions will also enable a rich non-oscillation physics programme (e.g. BSM).

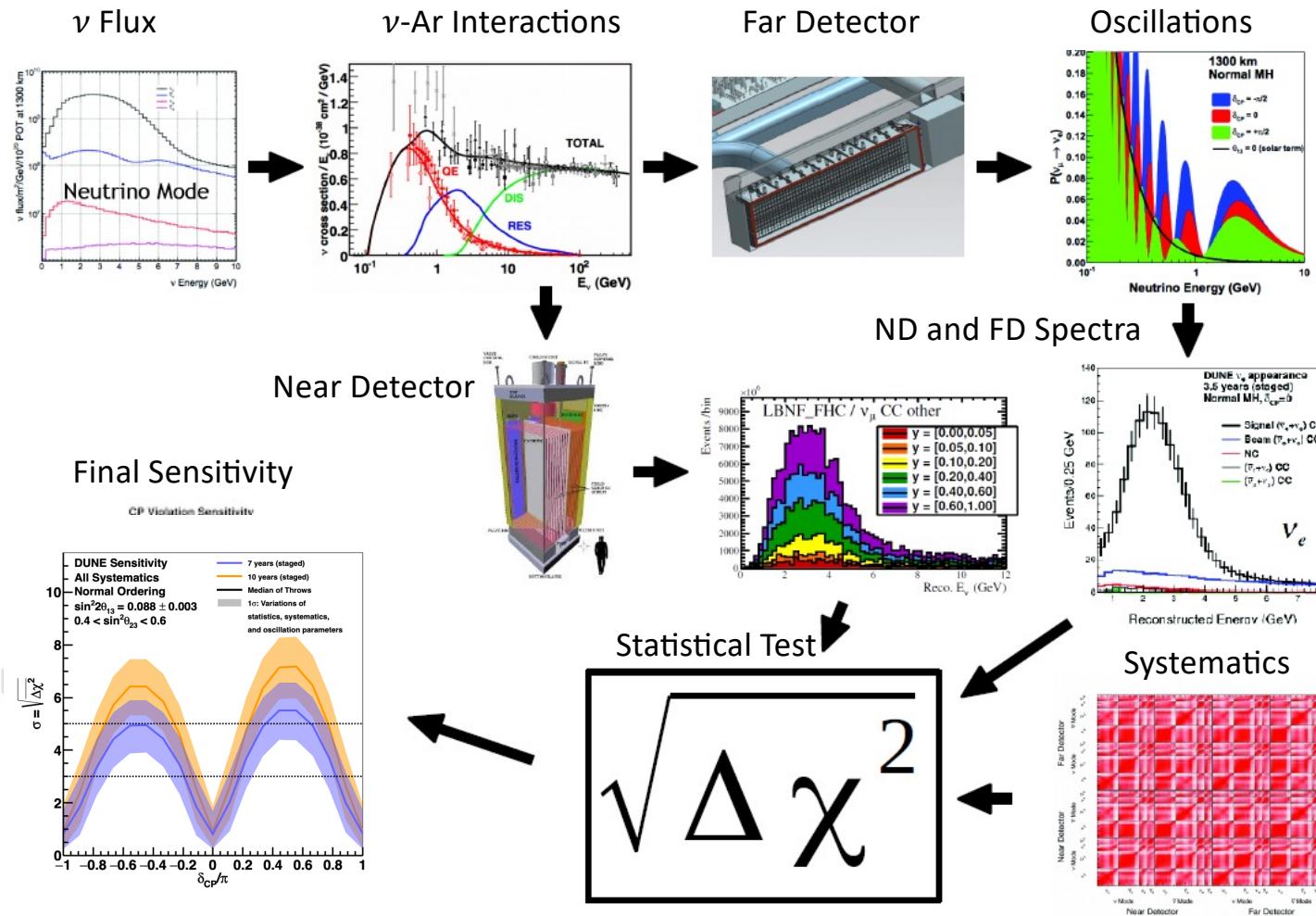
DUNE PRISM



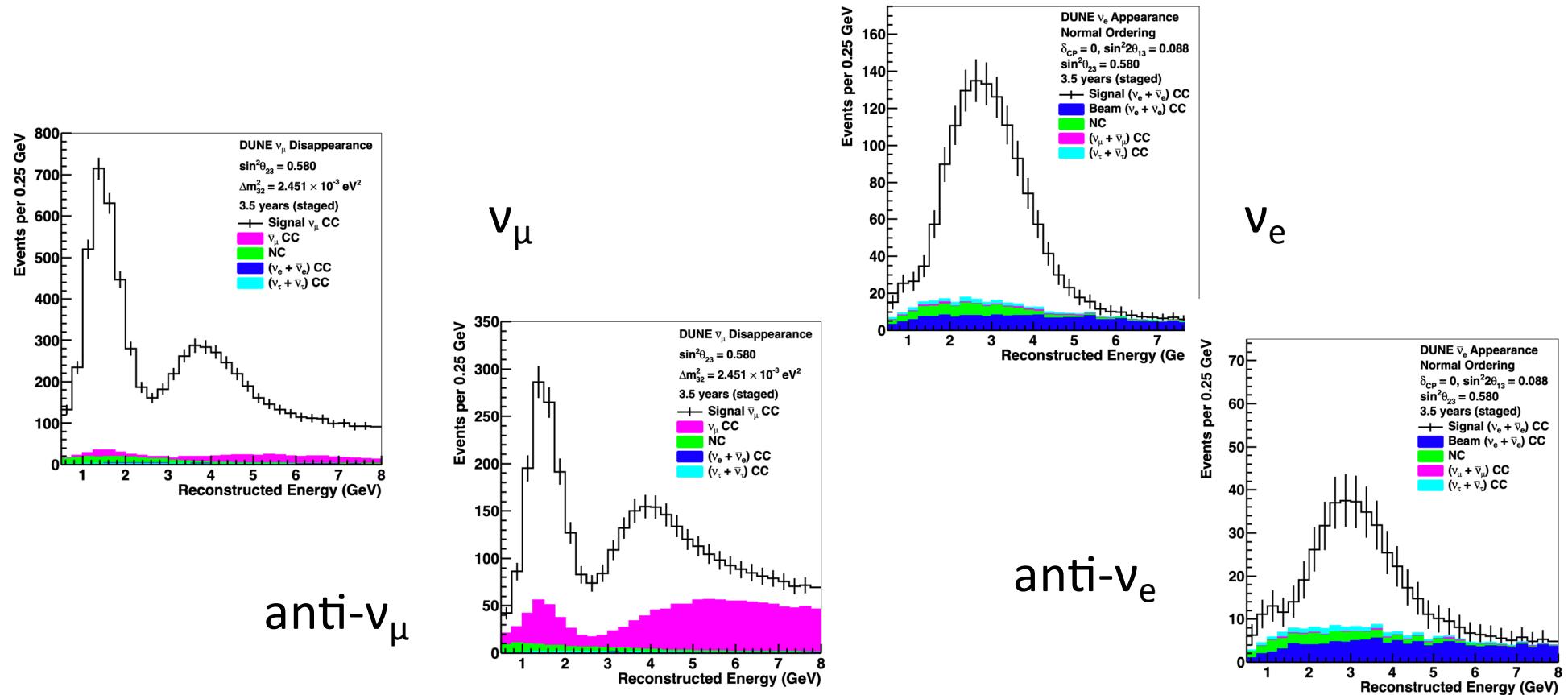
- FD flux \neq ND flux \rightarrow uncertainties in energy extrapolation
- ND flux changes with angle due to pion decay kinematics
- Take ND data in different fluxes \rightarrow build linear combination to match FD oscillated spectra
- Robust analysis approach with very minimal \times dependence on interaction modeling

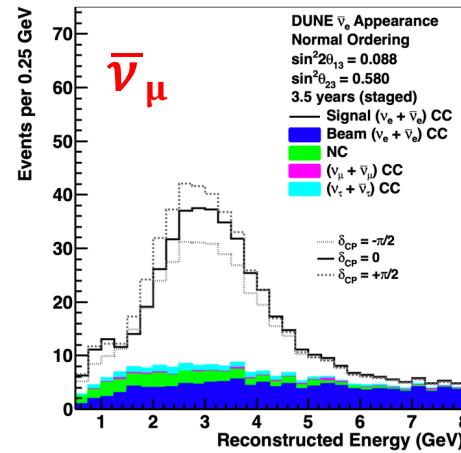
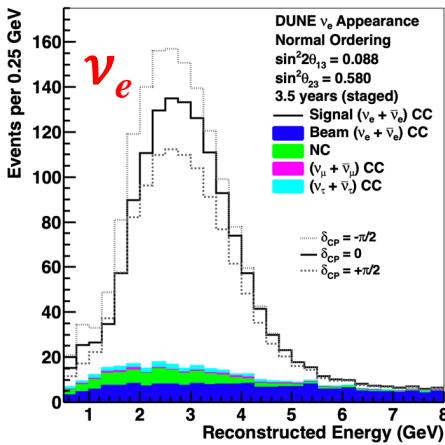
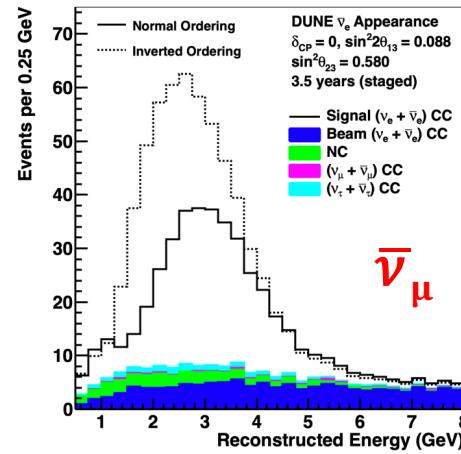
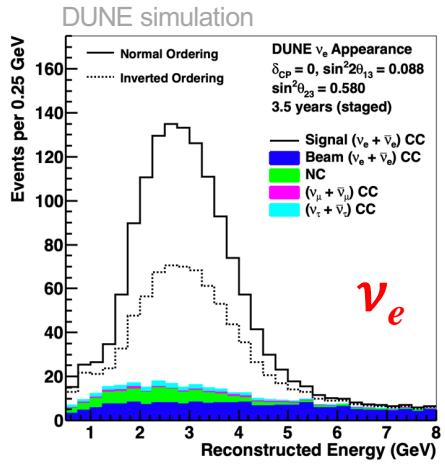
DUNE PRISM





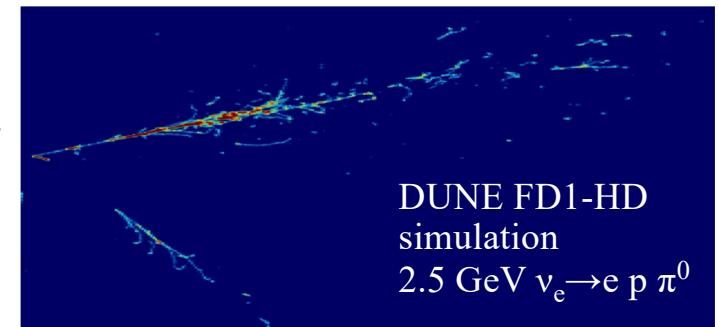
DUNE ν_μ disappearance & ν_e appearance





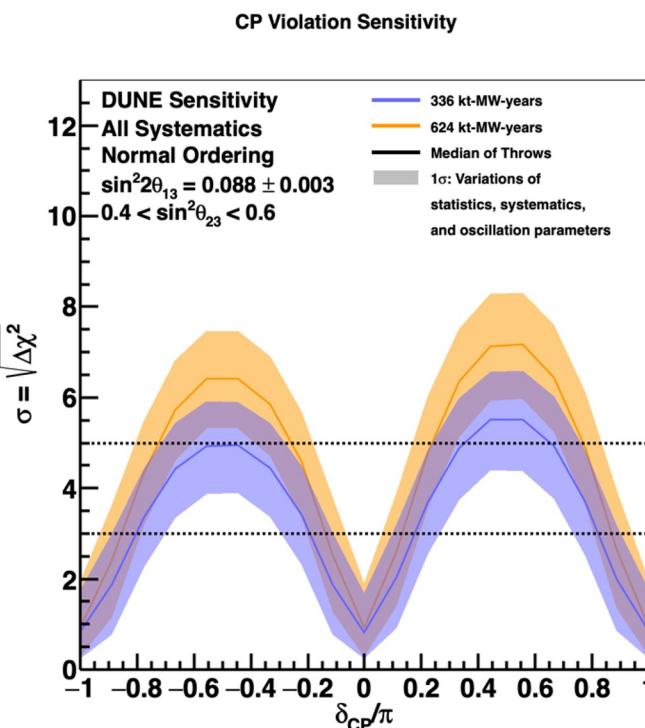
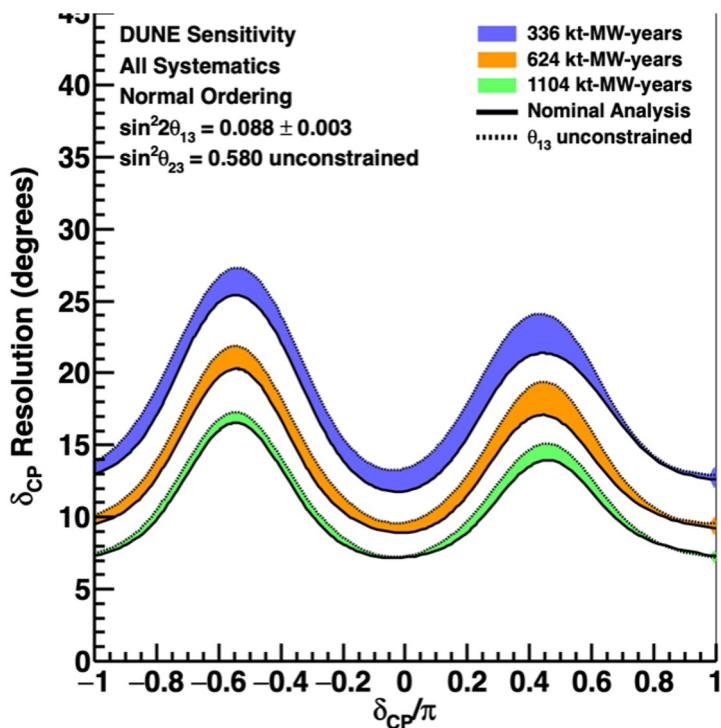
7 years

variation with
mass ordering



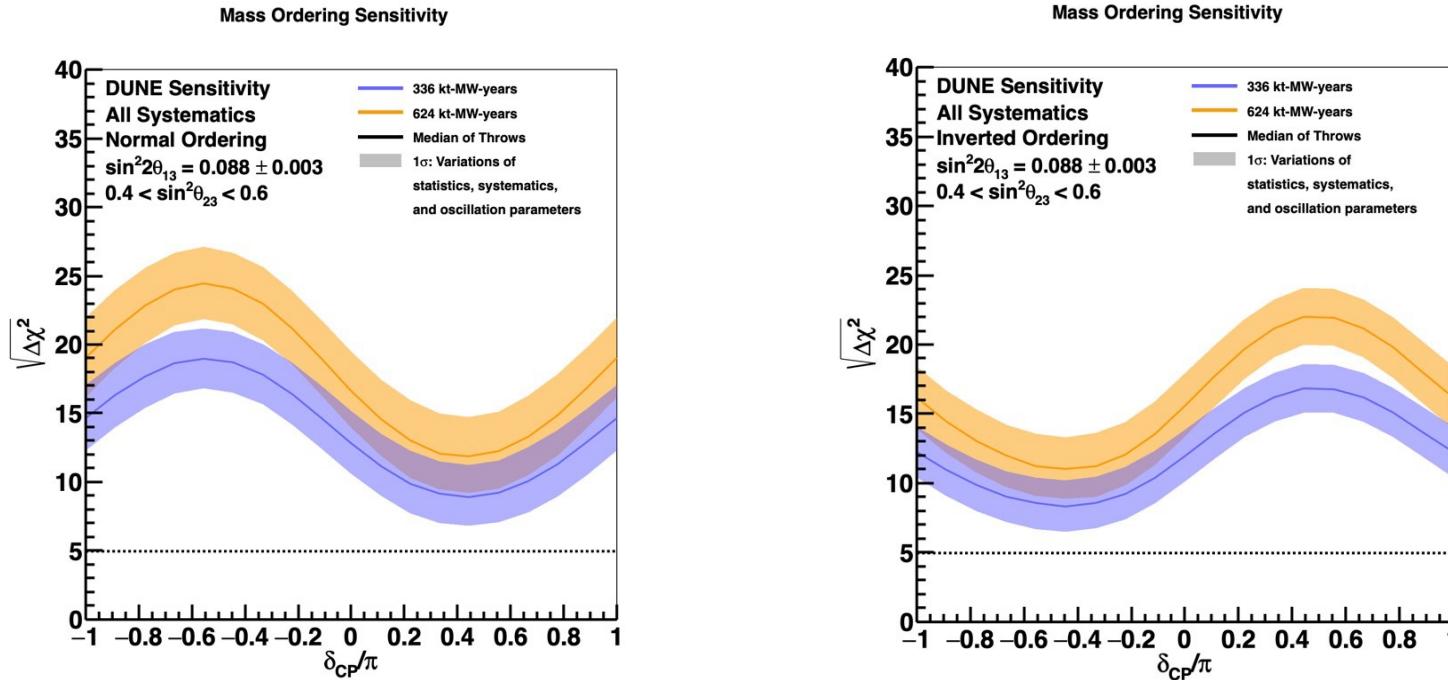
variation with δ_{CP}

DUNE: Sensitivity to CP Violation



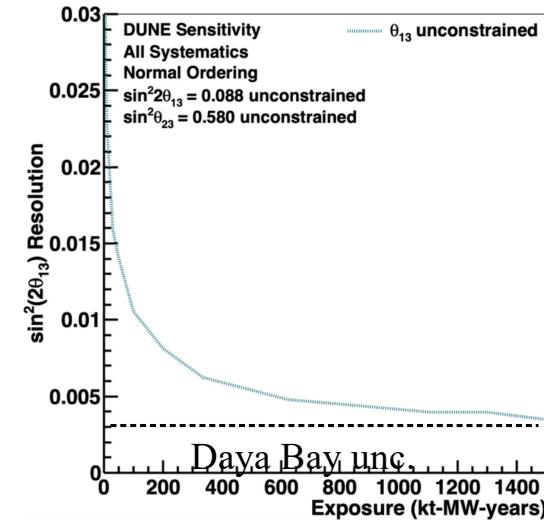
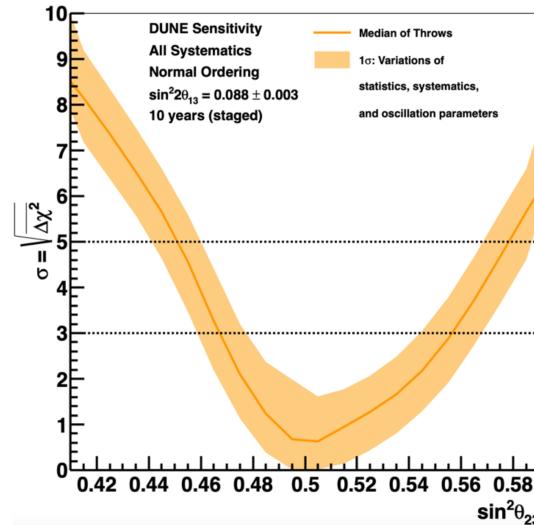
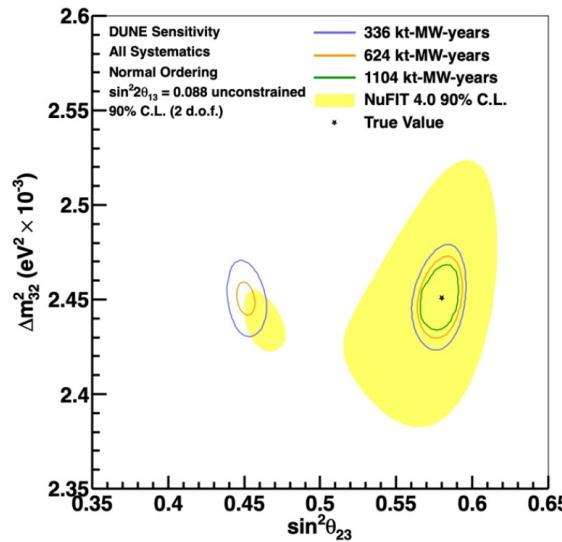
- 5 σ discovery potential for CP violation over >50% of δ_{CP} values
- 7-16° resolution to δ_{CP} , *without reliance on other experiments*

DUNE: Sensitivity to Mass Ordering



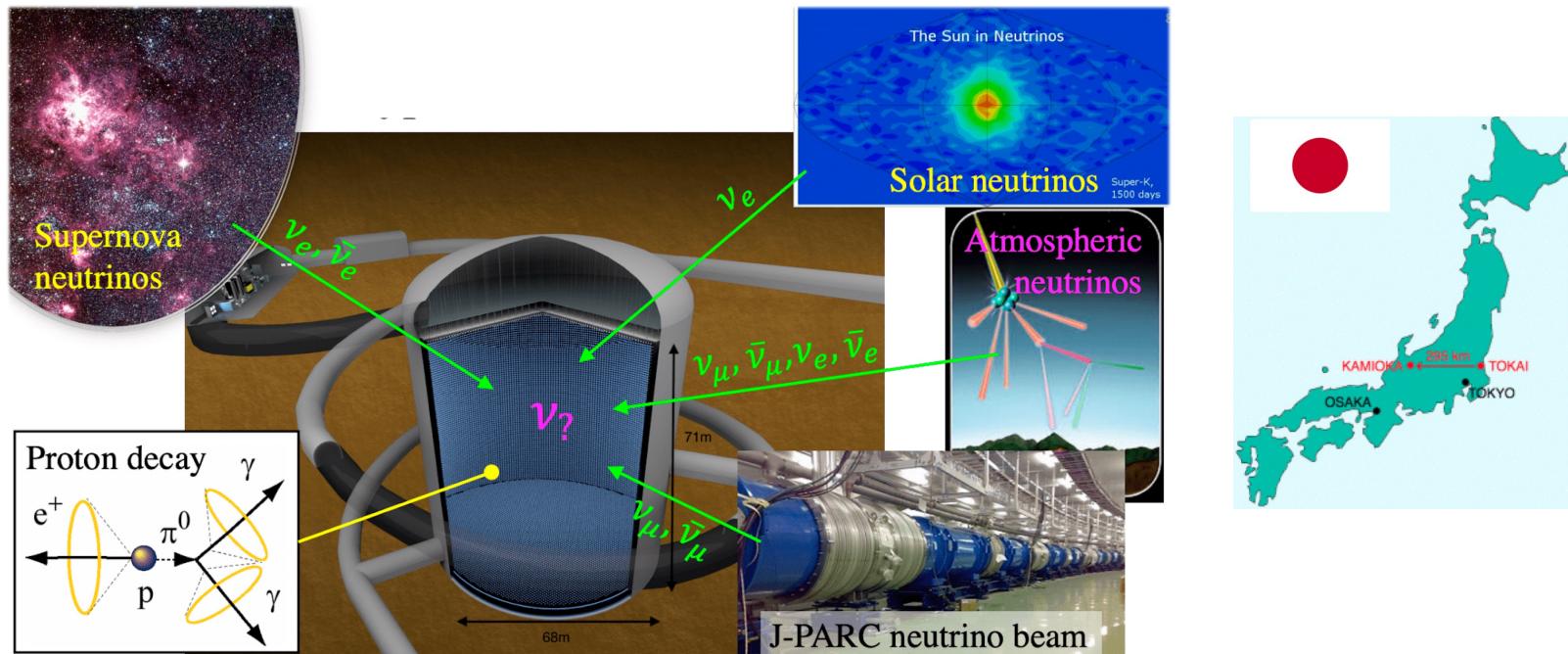
Regardless of the values of other parameters, and without dependence on other experiments, DUNE has unprecedented and unrivaled ability to definitively resolve the mass ordering

DUNE: Unitarity tests



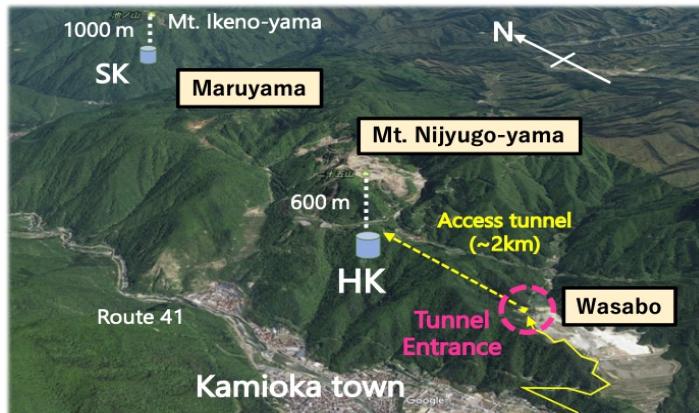
- World-leading precision on Δm^2_{32} and θ_{23} , including octant, and novel PRISM technique that is less sensitive to systematic effects
- Ultimate reach does not depend on external θ_{13} measurements, and comparison with reactor data directly tests PMNS unitarity

HyperKamiokande in a Nutshell



- **8.4 times larger fiducial mass** (190 kiloton) than SK with **double-sensitivity PMTs**
- New (IWCD) and upgraded (@280m) Near Detectors to control systematic uncertainties.
- J-PARC neutrino beam to be upgraded from 0.5 to 1.3 MW

HK Access Tunnel

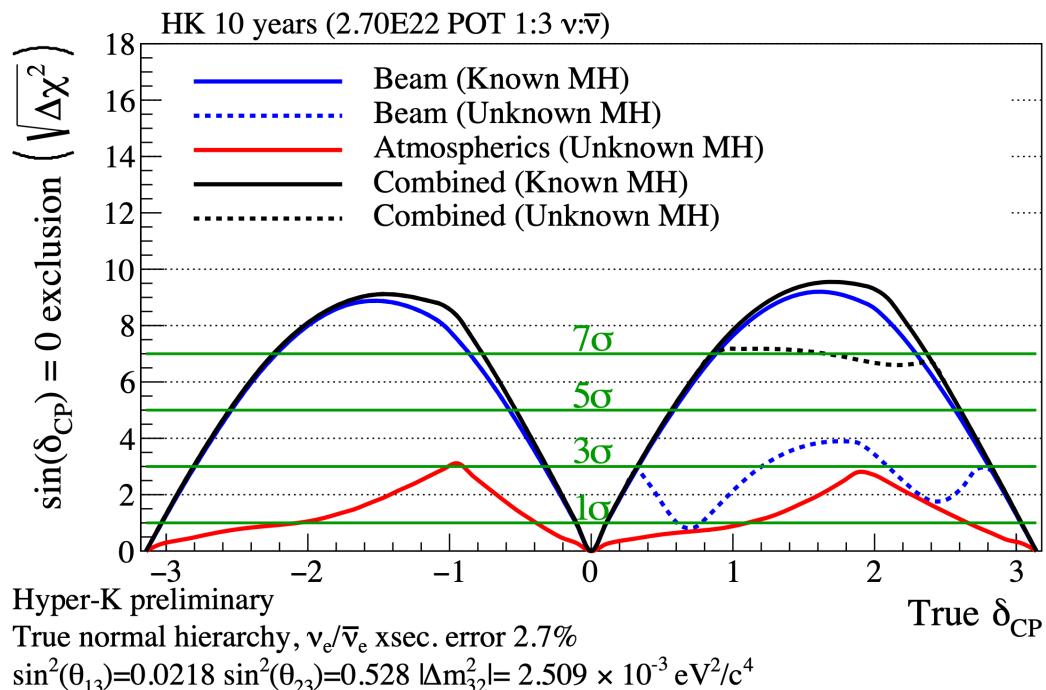


Commissioning 2026
Far Detector operation in 2026



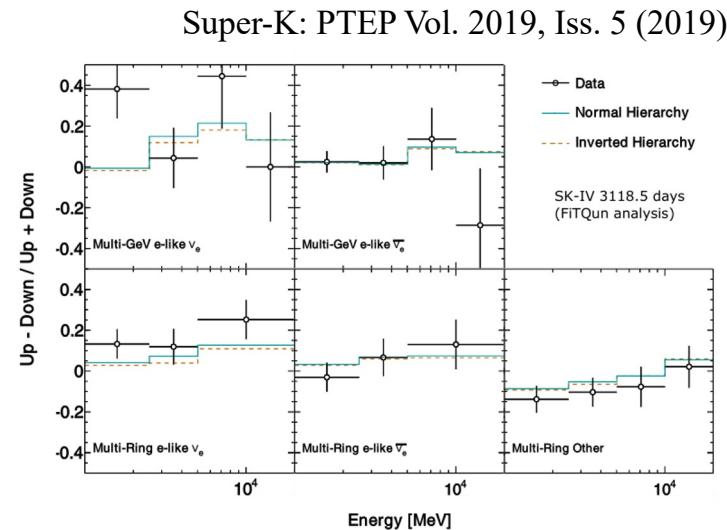
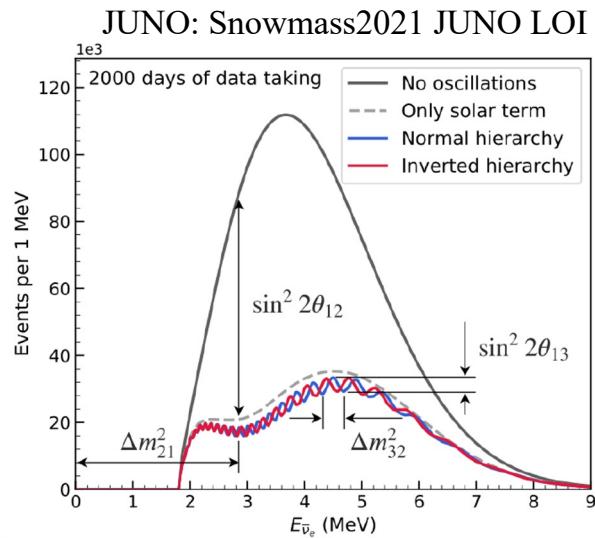
Access tunnel (1873 m) completed in February 2022 and work on approach tunnel has started.

HK: Sensitivity to CP Violation



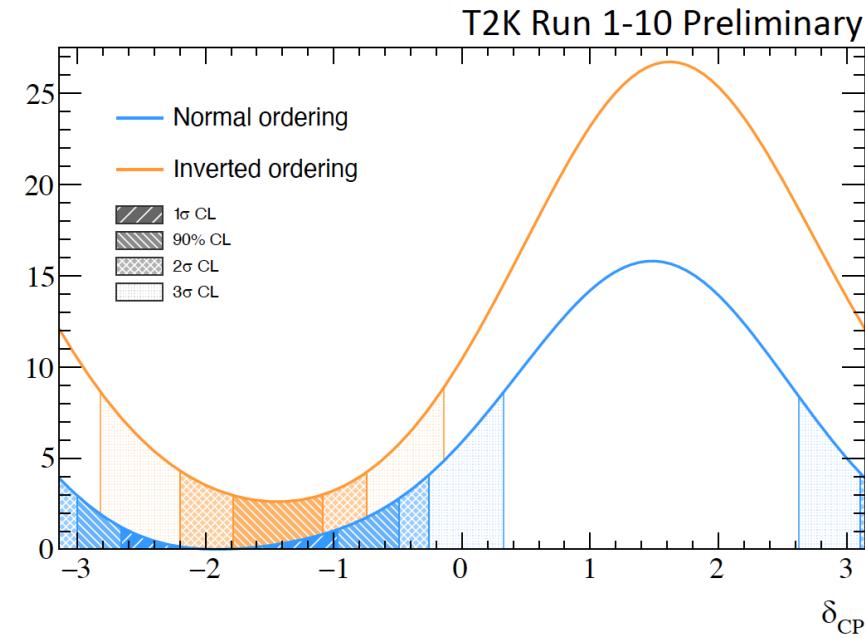
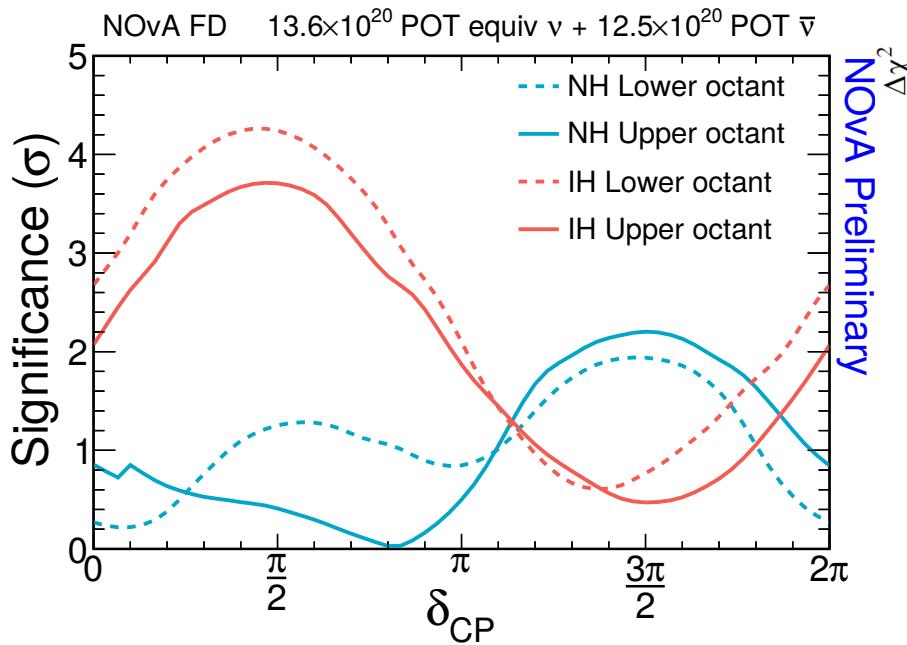
- Due to short baseline HK cannot resolve MO/CP degeneracy.
- If MO unknown, beam analysis less sensitive for some values of δ .
- Joint atmospheric and beam analysis increases sensitivity.

Other mass hierarchy measurements



- JUNO can determine mass ordering by differentiating rapid wiggle with unprecedented energy resolution.
- Large water Cherenkov detectors can model $\nu_e/\bar{\nu}_e$ flux and cross sections and look for a small differences in the up/down asymmetry

CP Violation Phase

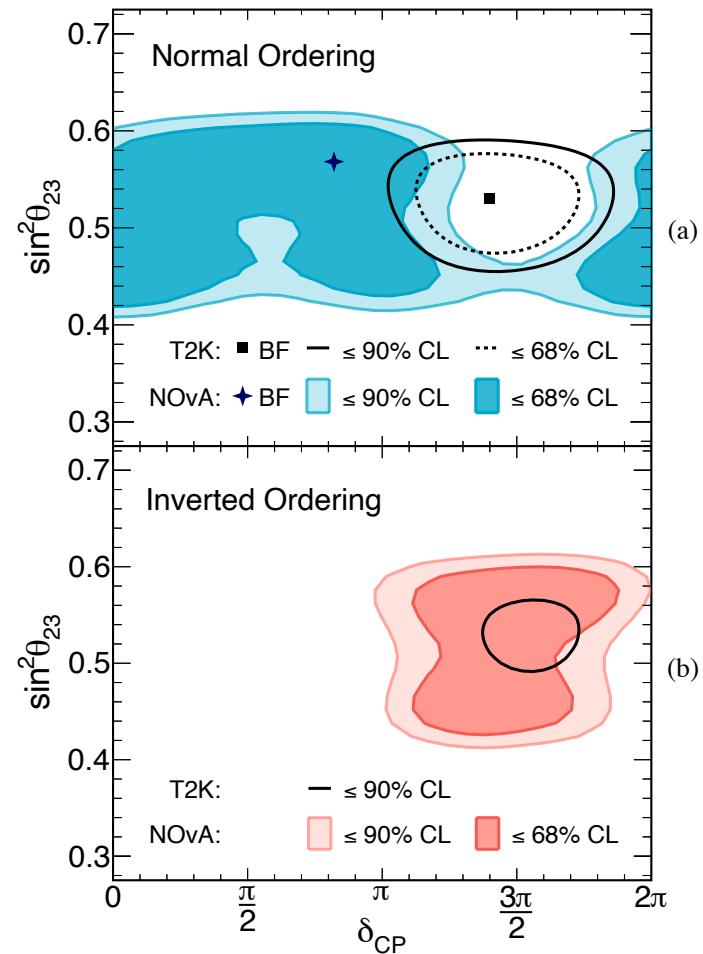


- Sensitivity to combination of CP phase and MO
- Normal ordering slightly preferred (1σ)
- Exclude IO, $\delta = \pi/2$ at $> 3\sigma$
- Disfavour NO, $\delta = 3\pi/2$ at $\sim 2\sigma$

- Using θ_{13} from reactor experiments
- CP conversation $(0, \pi)$ excluded at 90% confidence level
- Normal ordering preferred

NOvA and T2K

- NOvA does not see strong neutrino/antineutrino asymmetry in electron neutrino appearance.
- T2K observes more electron neutrino appearance than electron antineutrino appearance.
- Current data are inconclusive – expect some improvements with further running.
- Need next-generation experiments to discover CPV and resolve mass ordering.

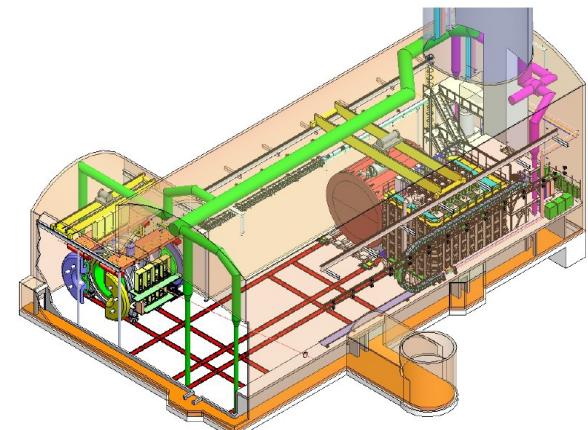


DUNE Phases

DUNE Phase I:

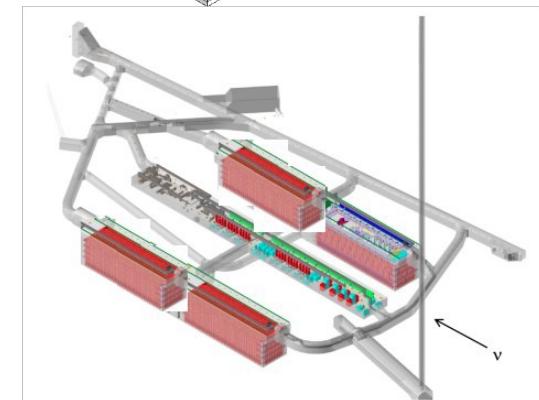
- Ramp up to 1.2 MW beam intensity
- Two 17kt LAr TPC FD modules
- Near detector: ND-LAr + TMS (movable) + SAND

Phase II – full DUNE

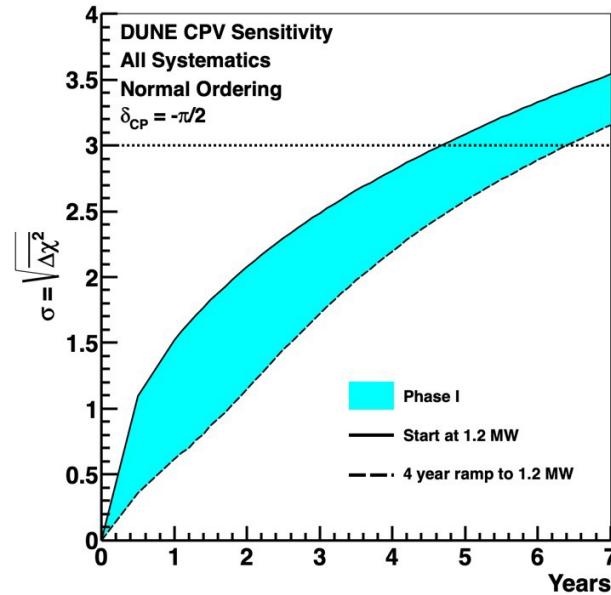
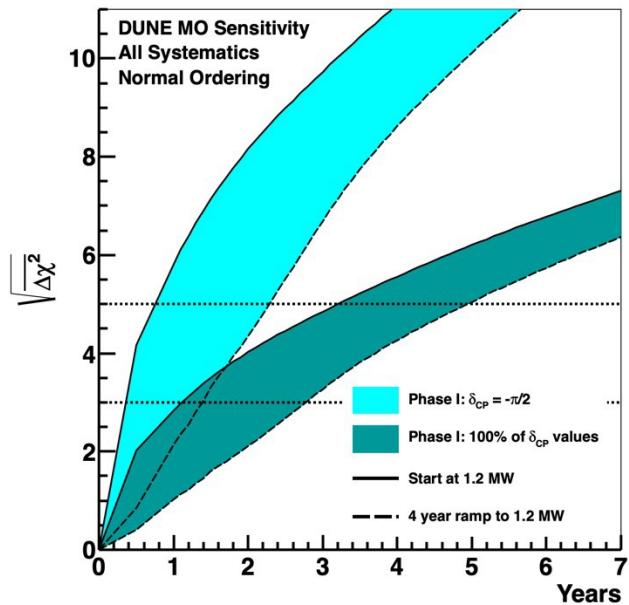


DUNE Phase II:

- Fermilab proton beam upgrade to 2.4 MW
- Four 17kt LAr TPC FD modules
- Near detector: ND-LAr + ND-GAr (movable) + SAND

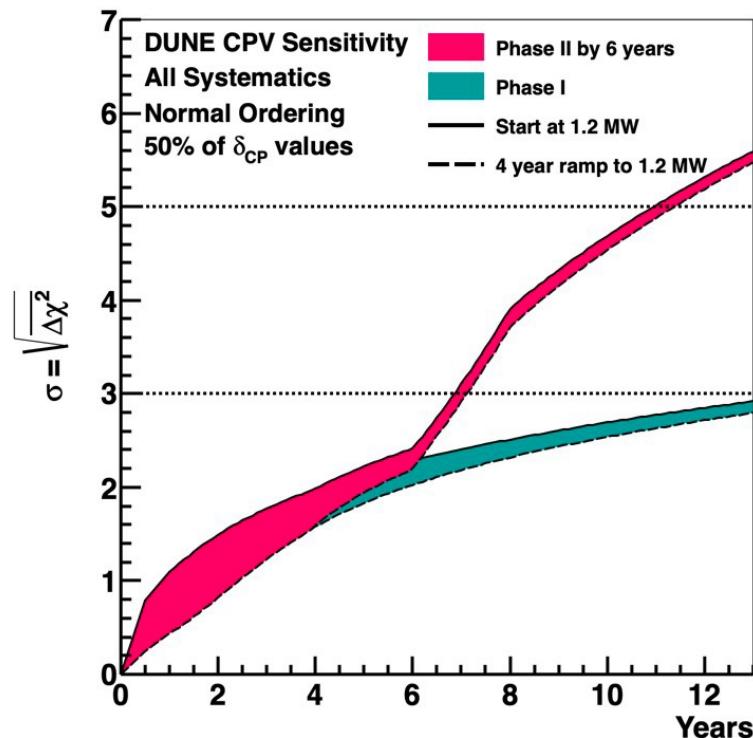


DUNE Phase I



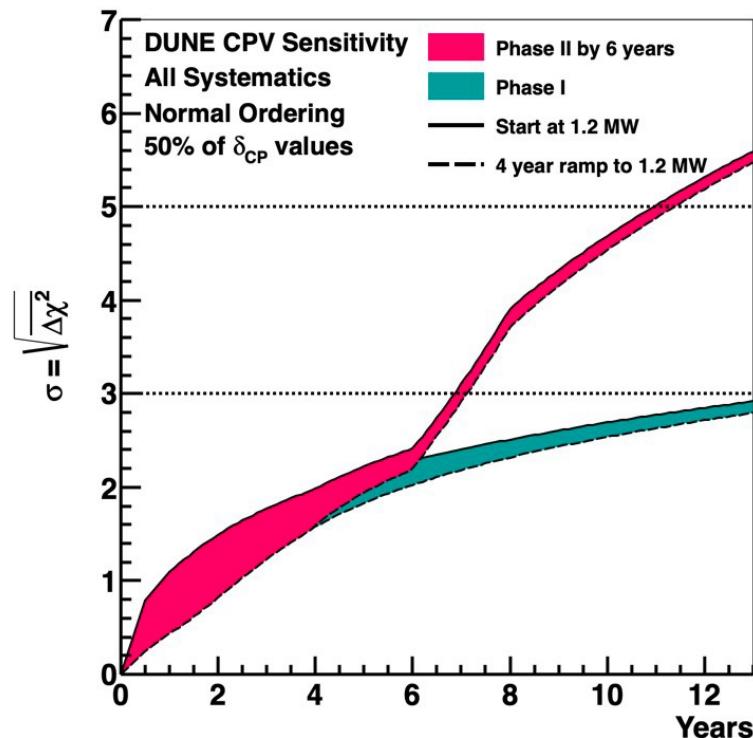
- Only experiment with 5σ mass ordering capability regardless of true parameters
- Discovery of CPV at 3σ if CP violation is large
- World-leading precision on Δm^2_{32} , and other oscillation measurements

DUNE Phase II



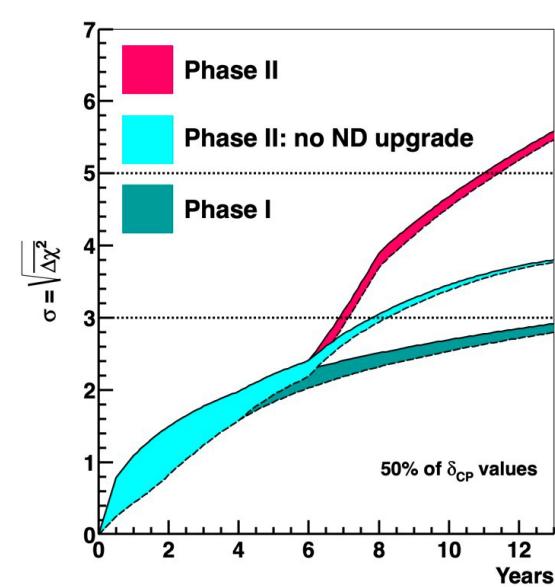
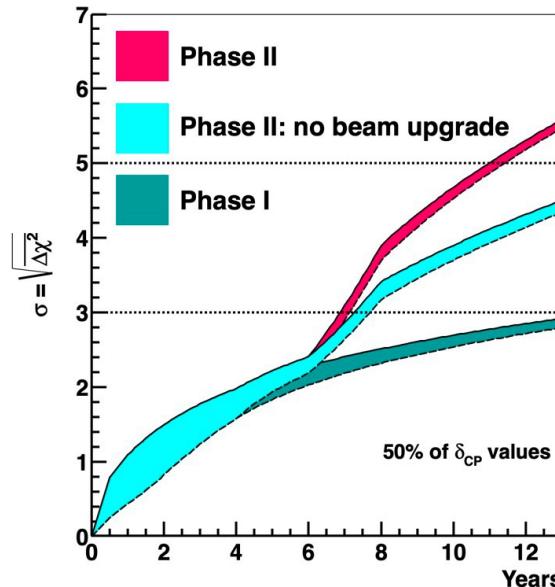
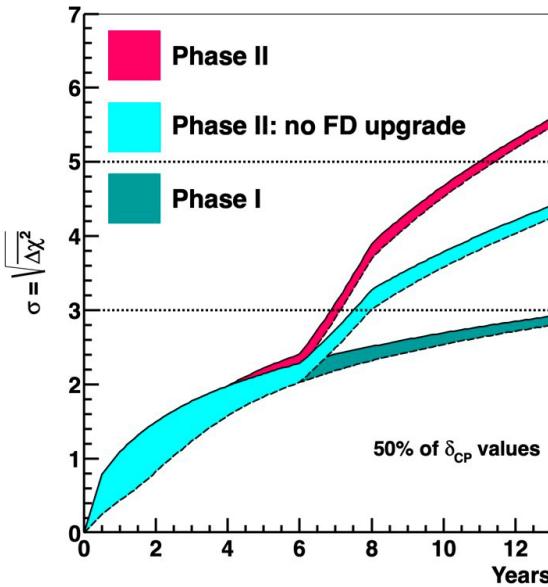
- DUNE needs full Phase II scope to achieve precision physics goals defined in P5 report
- Timescale for precision physics is driven by achieving full scope on aggressive timescale, early ramp-up is not as relevant
- A second phase of DUNE (Modules 3 and 4) can also extend physics capabilities, e.g. solar neutrinos or neutrinoless DBD.

DUNE Phase II



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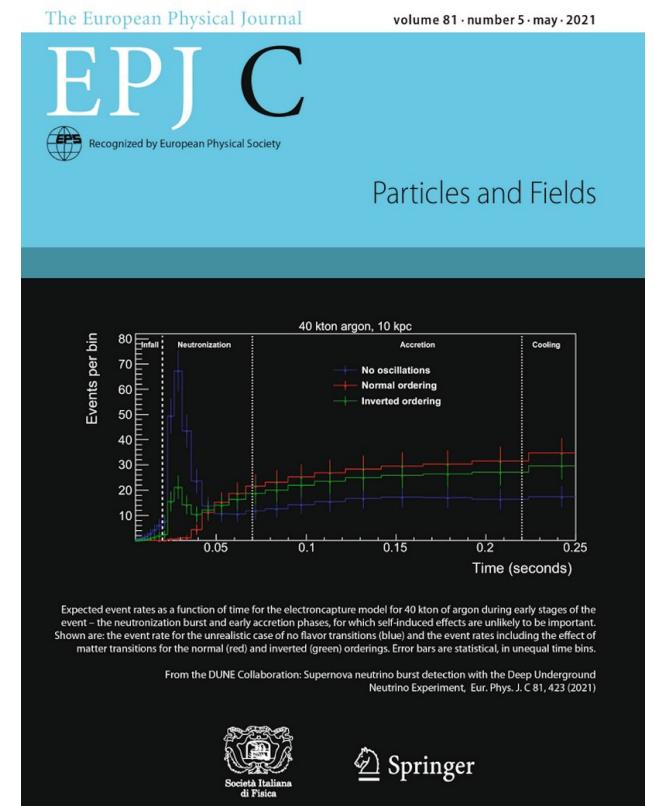
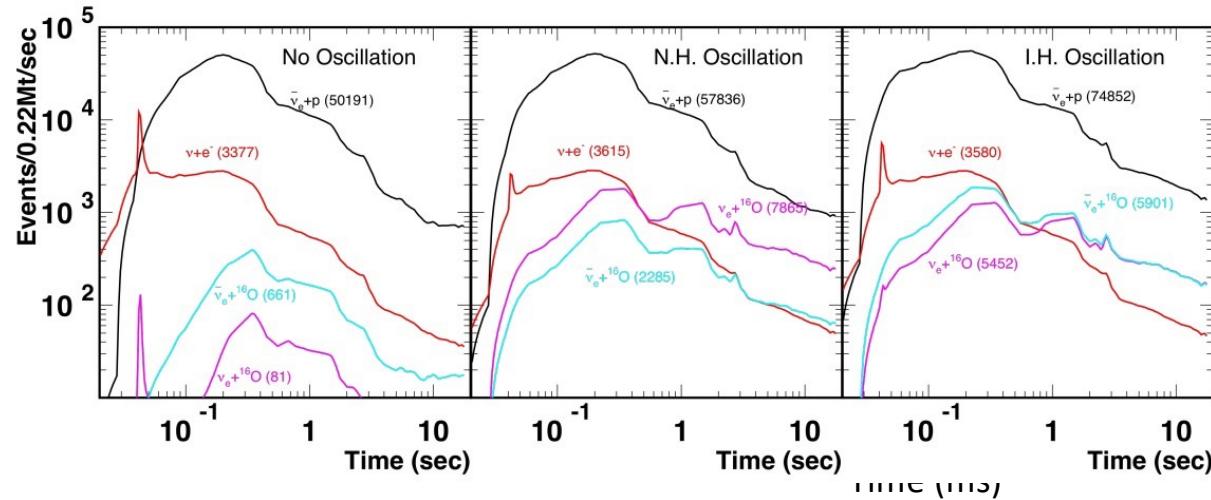
DUNE Phase II



- To achieve the precision physics goals, including CPV sensitivity for a broad range of δ_{CP} values, all three upgrades are required
- Plots show the effect of removing one of them, resulting in a significant loss of sensitivity

Neutrino Observatories

- Rich non-accelerator physics programme studying neutrinos from a supernova, solar, atmospheric neutrinos..
- Measurement at early times tests mass ordering and supernova burst model.
- HK and DUNE are complementary in their sensitivity.
- Detector requirements different from beam physics.



Supernova 1987A

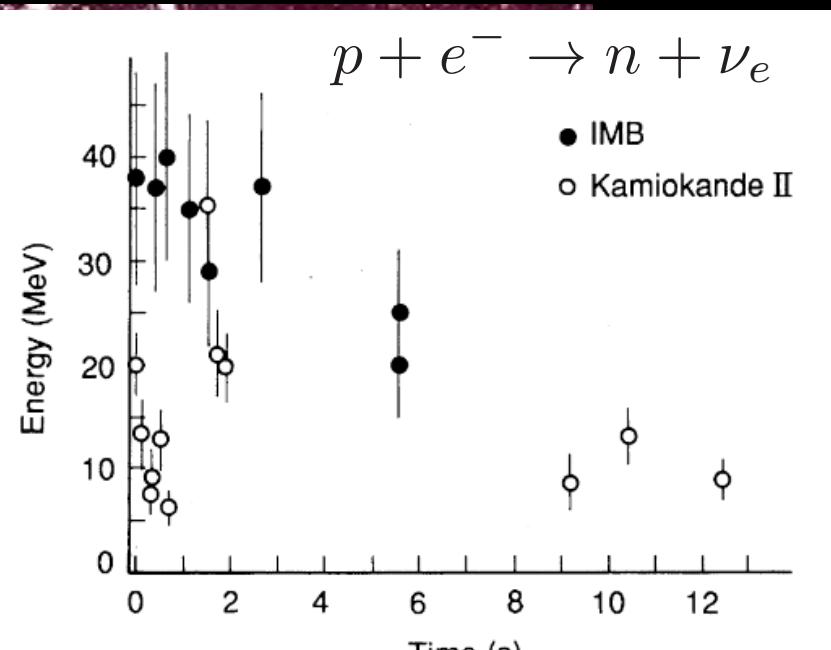
in the Large Magellanic Cloud (55 kpc away)



For comparison: the Milky Way is about 34 kpc across

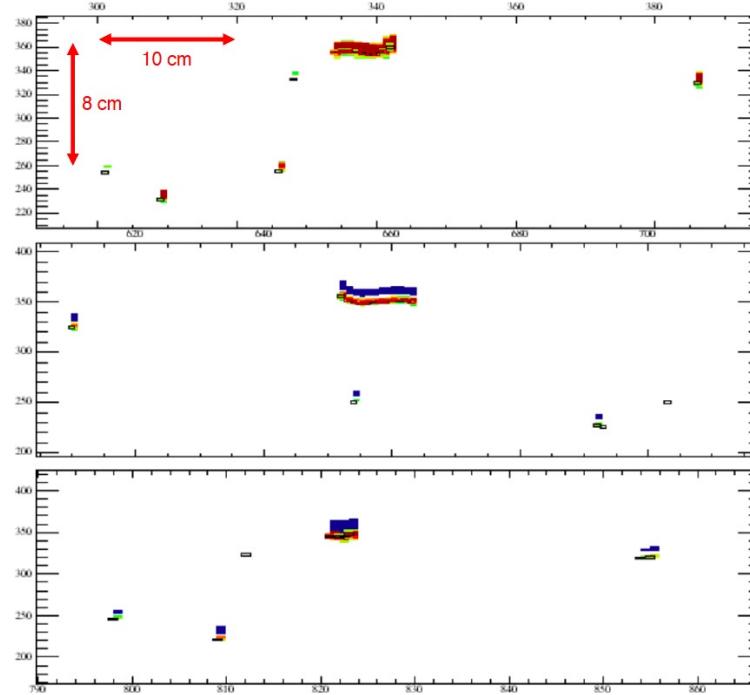
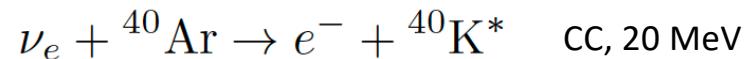
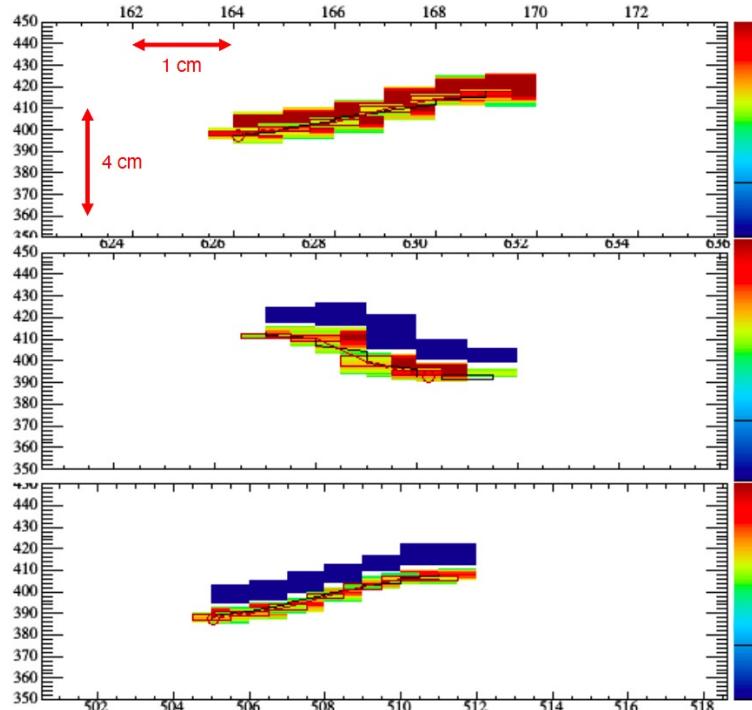
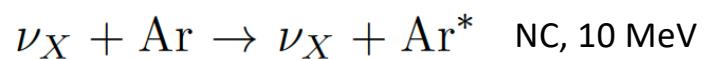
Supernova 1987A in the Large Magellanic Cloud (55 kpc away)

SN1987A, about 24 neutrinos
observed, 3 hours before photons.

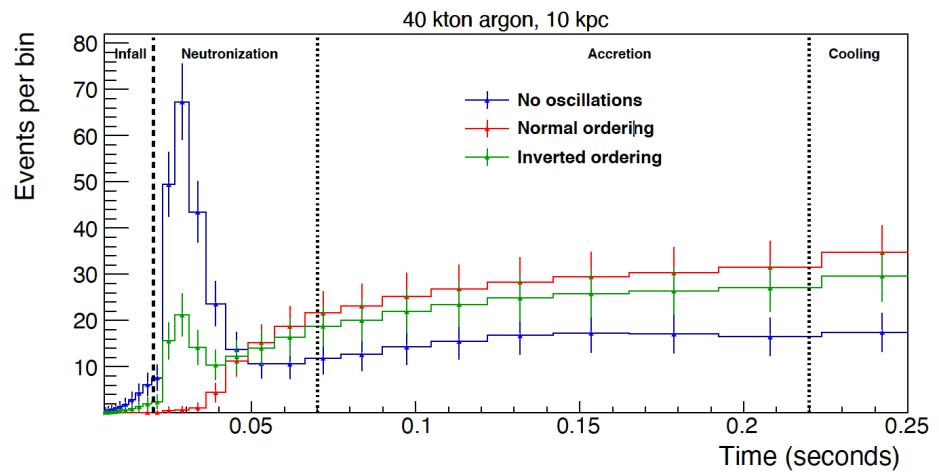
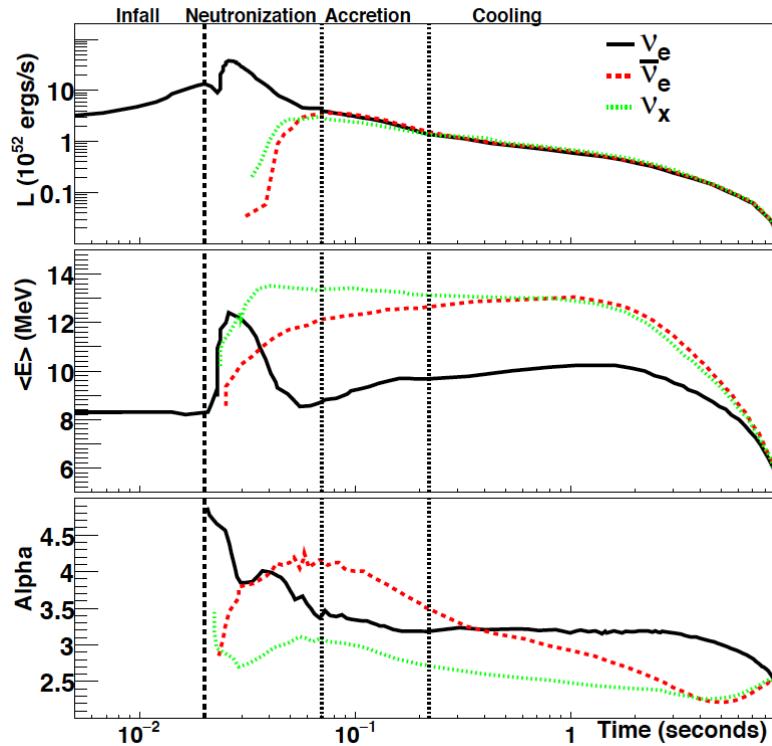


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Supernova neutrinos in DUNE

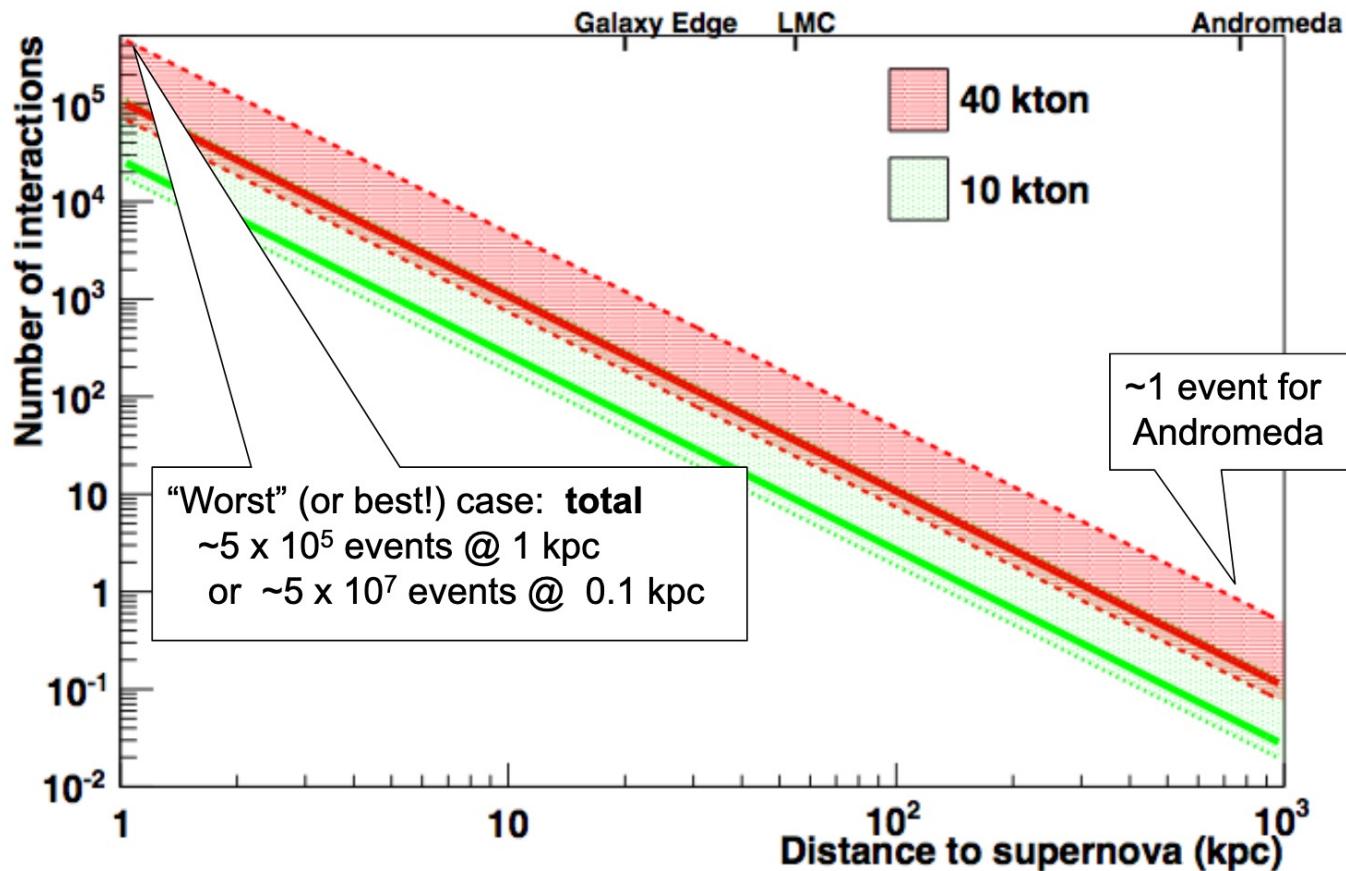


Supernova signal in DUNE



- Neutrinos arrive before the light and can trigger observation by optical telescopes.
- Potentially a signal of 1000s of neutrinos in DUNE.
- Signal will teach us both about neutrinos and about the supernova mechanism.

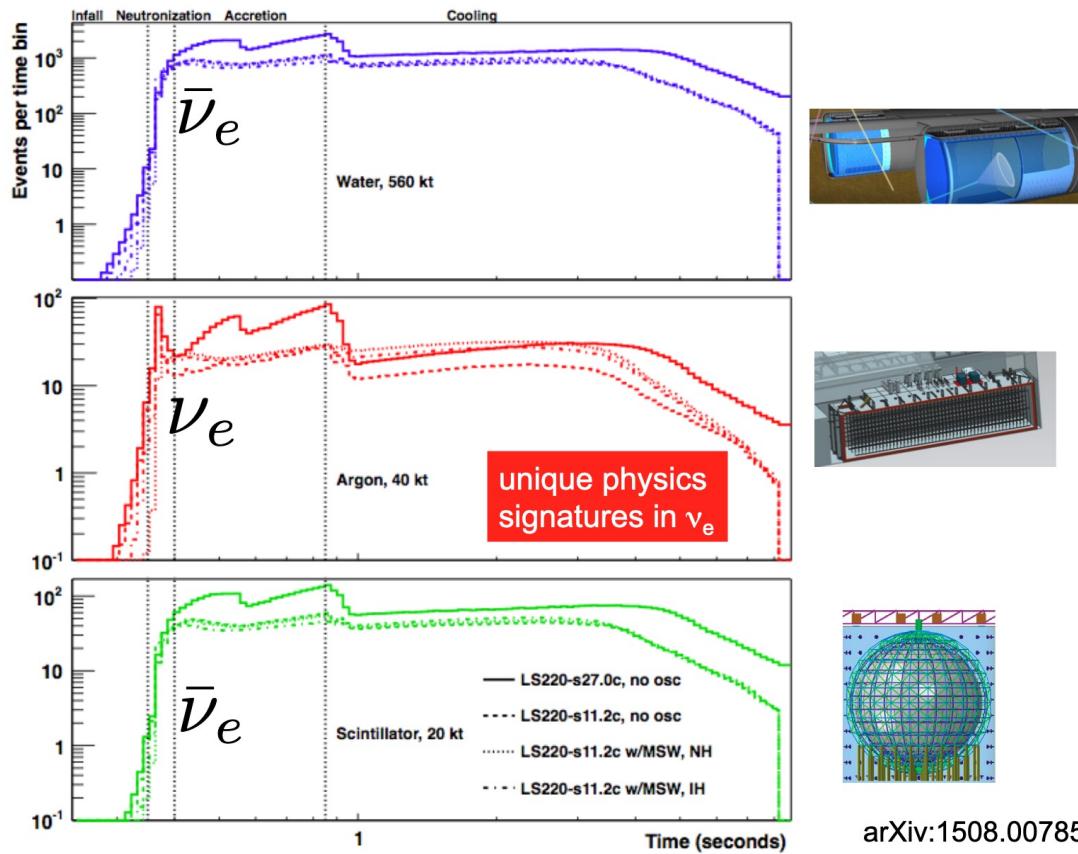
Supernova signal in DUNE



Complementarity

Two models (11.2 and 27.0 solar masses, NH/IH for former)

Kate Scholberg



arXiv:1508.00785

Summary

- DUNE Phase I (start operation in 2029):
 - Two modules (HD/VD)
 - Beam (1.2 MW) in 2030
 - Near Detector (SAND, TMS+NDLAr, PRISM) in 2031
- DUNE Phase II (needed to reach physics goals)
 - Modules 3 and 4 (ongoing R&D)
 - Beam upgraded to 2.4 MW
 - Upgrade to Near Detector (ND-GAr)