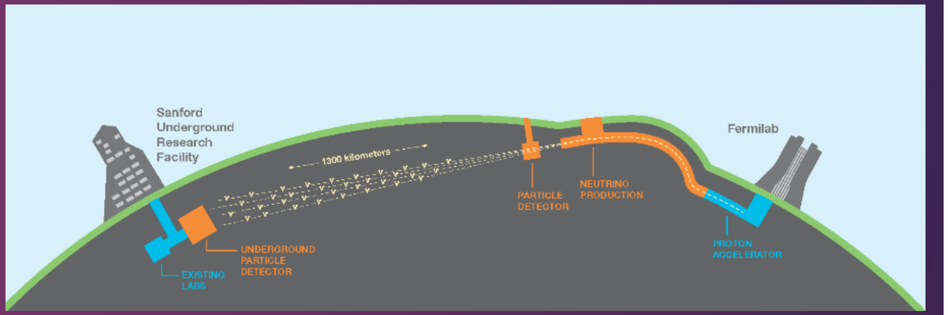
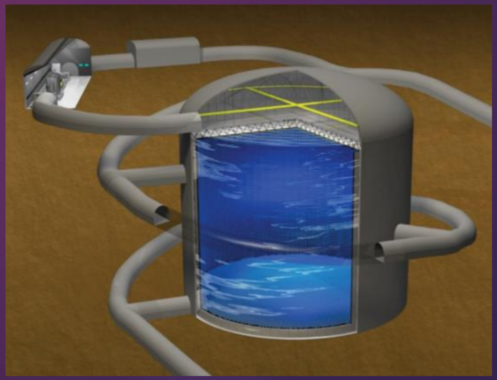
Long-Baseline Neutrino Experiments: The Future



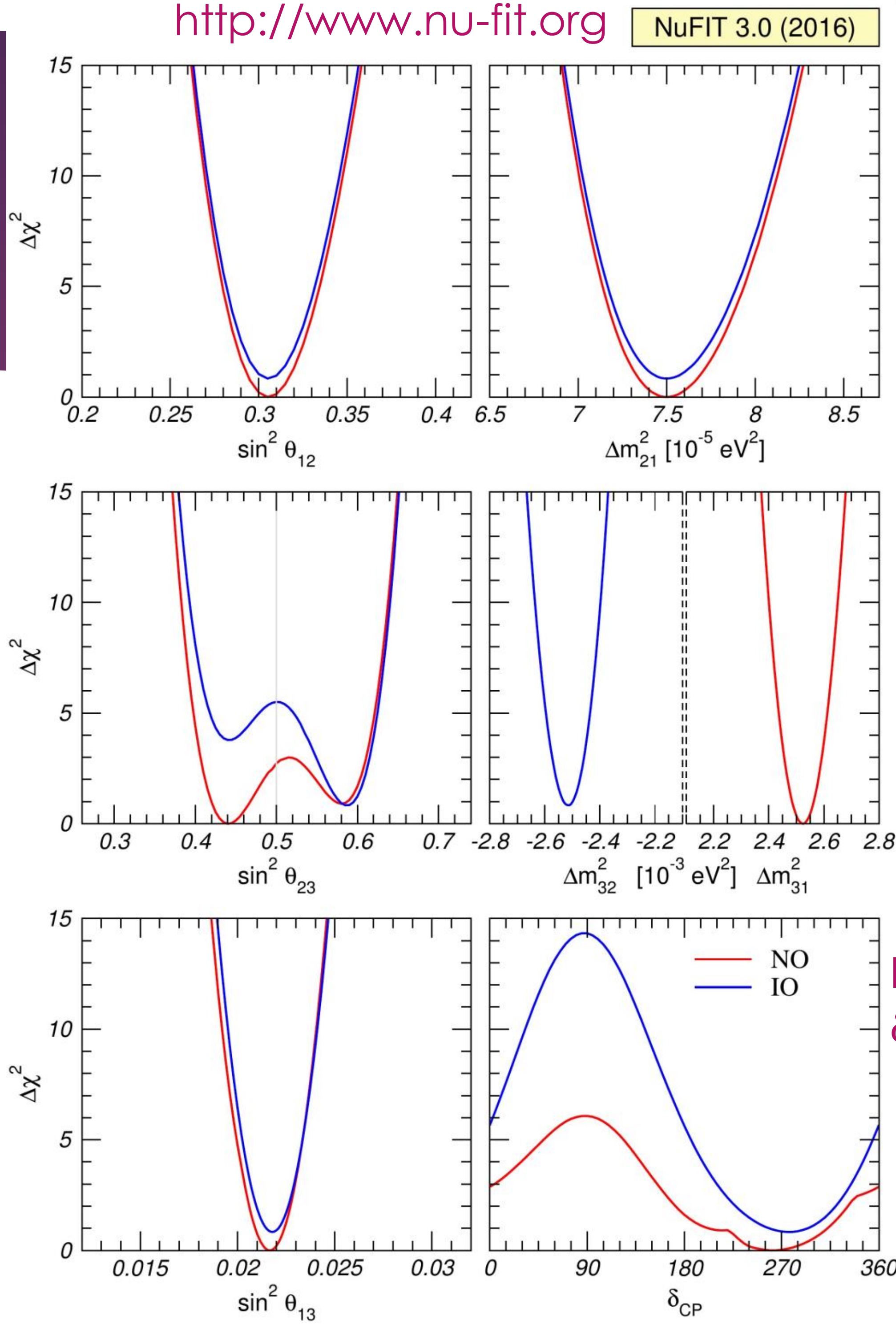
LISA WHITEHEAD KOERNER
UNIVERSITY OF HOUSTON
JULY 26, 2017



Introduction

- Some open questions in 3-neutrino mixing:
  - Is CP violated in neutrino oscillations ($\delta \neq 0, \pi$)?
  - Is θ_{23} maximal? (=π/4?)
  - What is the neutrino mass ordering?
- Or new physics?

http://www.nu-fit.org

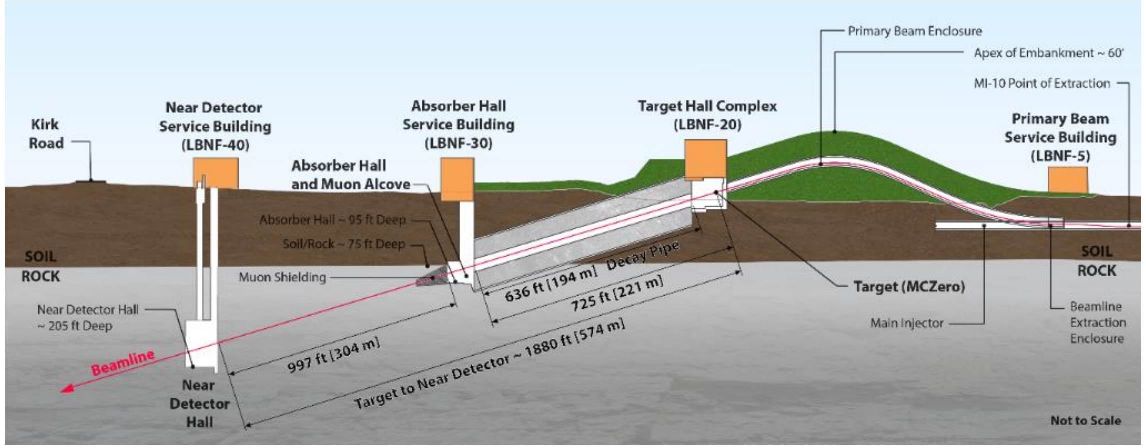


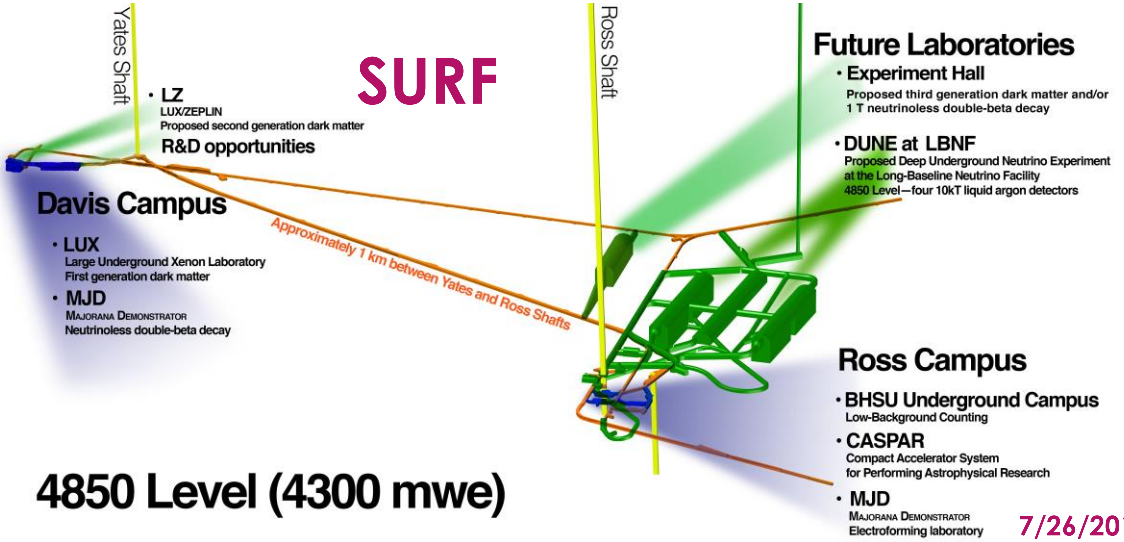
Recent global fit of neutrino oscillation data

Best fit $\delta_{CP} = 261°^{+51°}_{-59°}$ $(\approx -\pi/2)$

DUNE (**D**eep **U**nderground **N**eutrino **E**xperiment)

- Muon neutrino beam from from Fermilab (LBNF – Long Baseline Neutrino Facility)
  - On-axis broadband beam
  - Beam intensity 1.2 MW, upgradable to 2.4 MW (120 GeV primary protons)
- Far detector at SURF in South Dakota
  - 1300 km baseline
  - 4300 mwe overburden

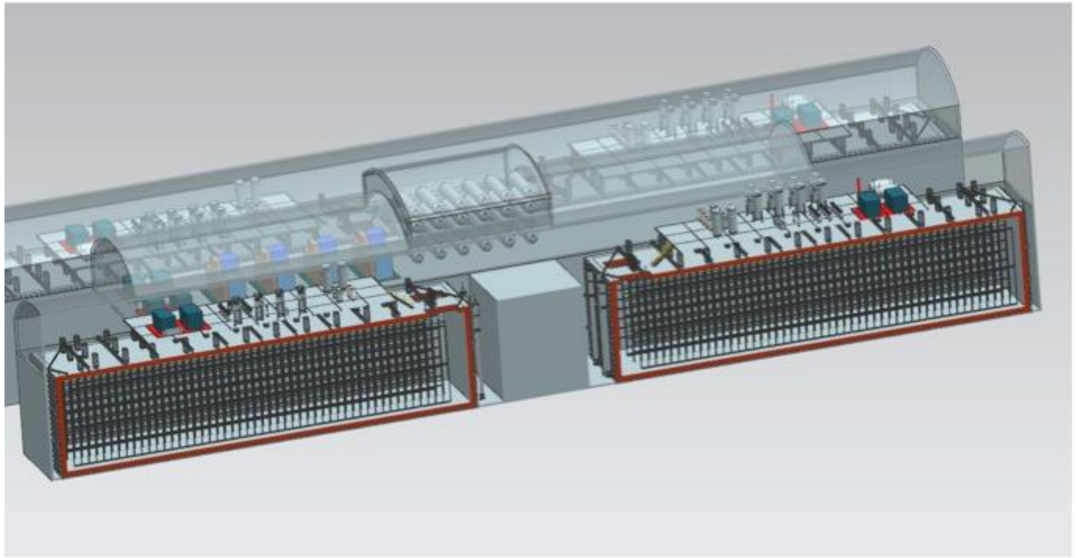




DUNE CDR arXiv:1512.06148
E. Worcester, APS April 2017

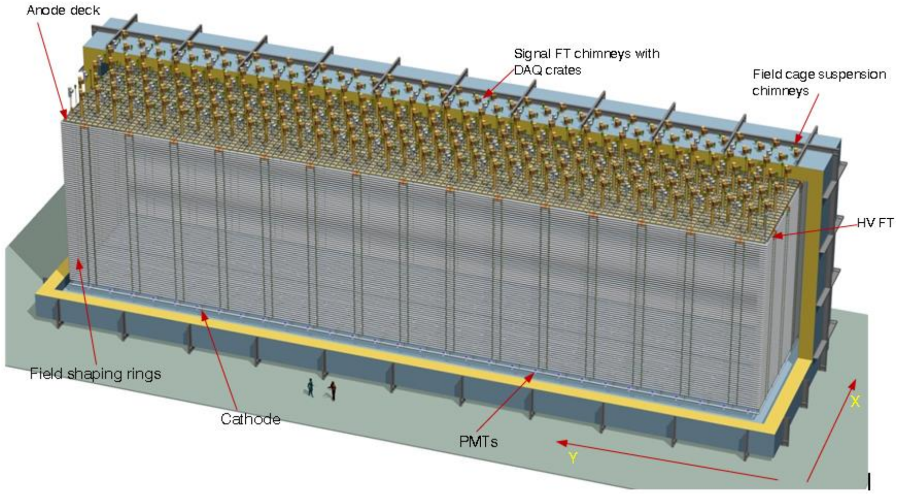
DUNE Far Detector

40 kt liquid argon (LAr) TPC
4 x 10 kt modules
(Modules not necessarily identical)



Dual-phase TPC

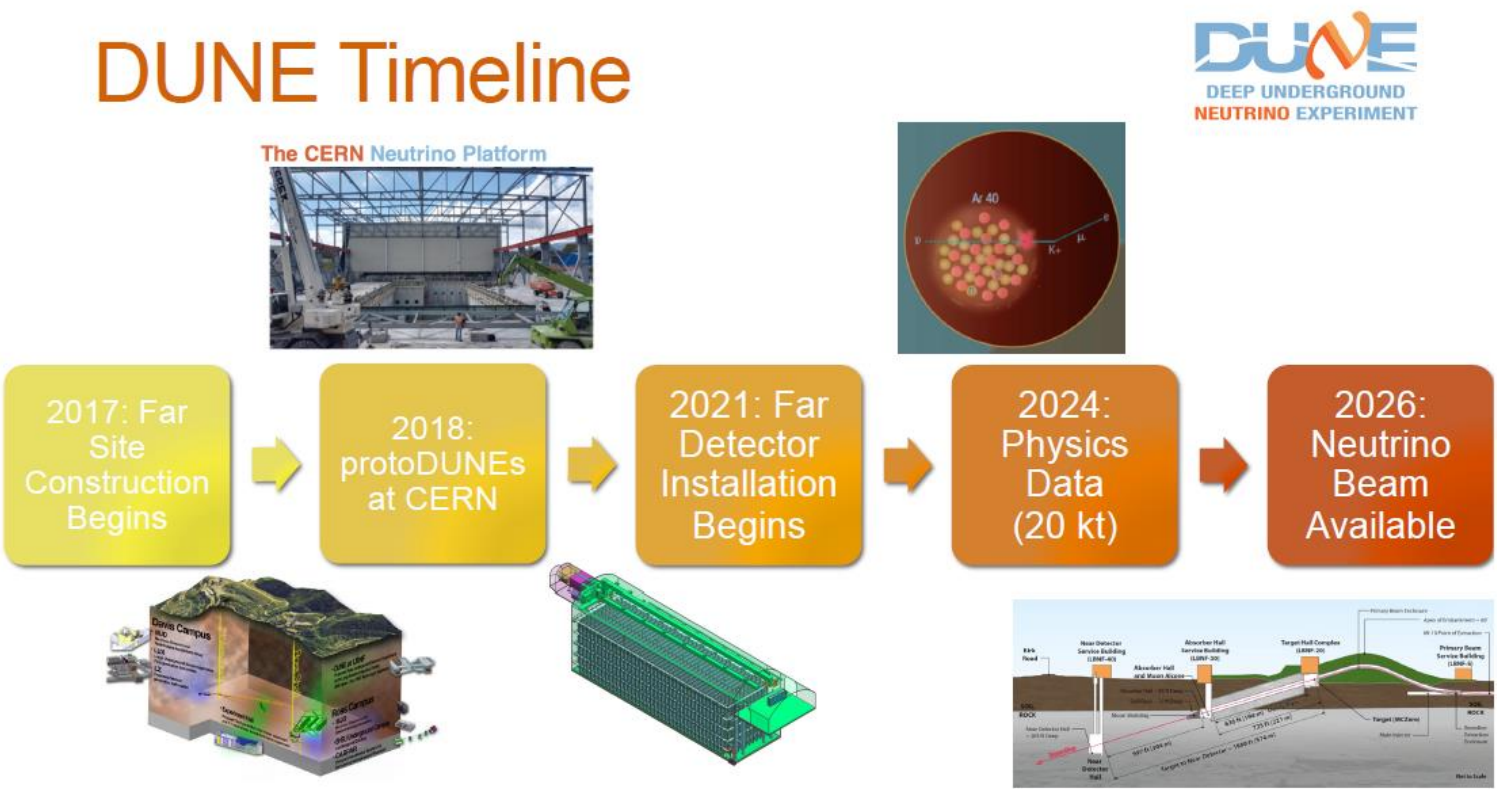
(single module with amplification in gas phase)



Single-phase TPC

Suspended anode (APA) and cathode (CPA) assemblies – 3.6 m spacing

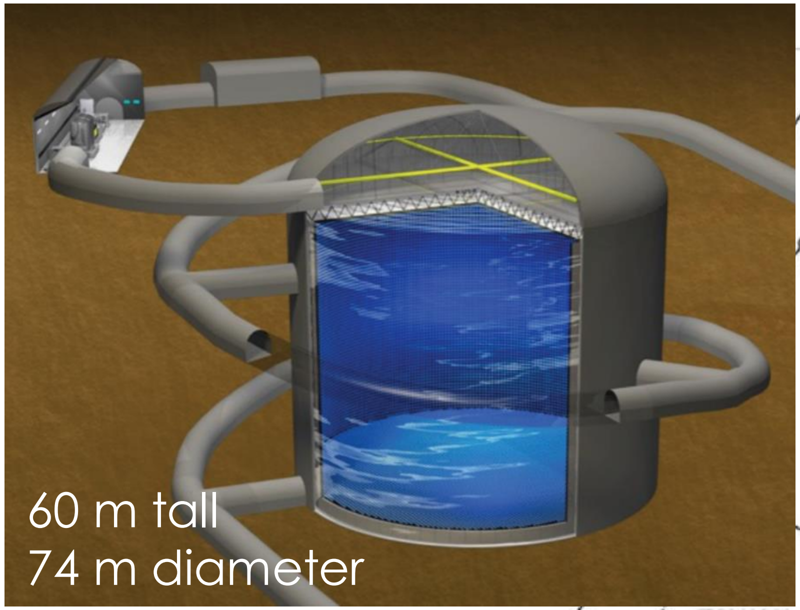
DUNE Status and Timeline

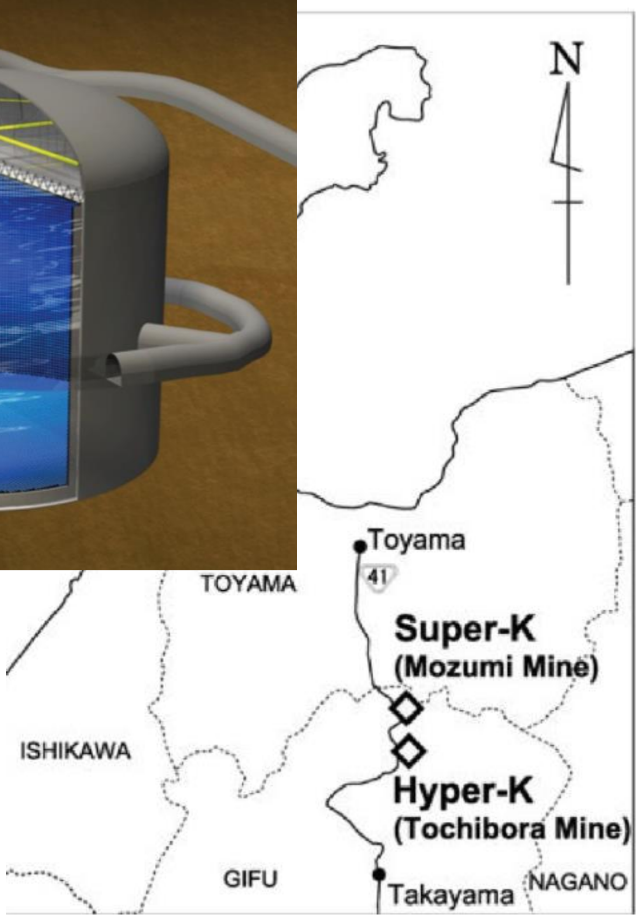


- International collaboration
  - Began in 2015
  - Nearly 1000 collaborators from 30 countries
- Far site ground breaking ceremony July 21!

Hyper-Kamiokande Detector

- Water Cherenkov detector
  - 260 kton ultra pure water (Fiducial mass 187 kton)
  - New 50 cm photo sensors with improved single photon deection efficiency (2x Super-K PMTs)
  - 40% photocathode coverage
  - 650 m (1750 mwe) depth
- Aiming for a quick start with one tank
  - Second tank under consideration (time, design, location…)

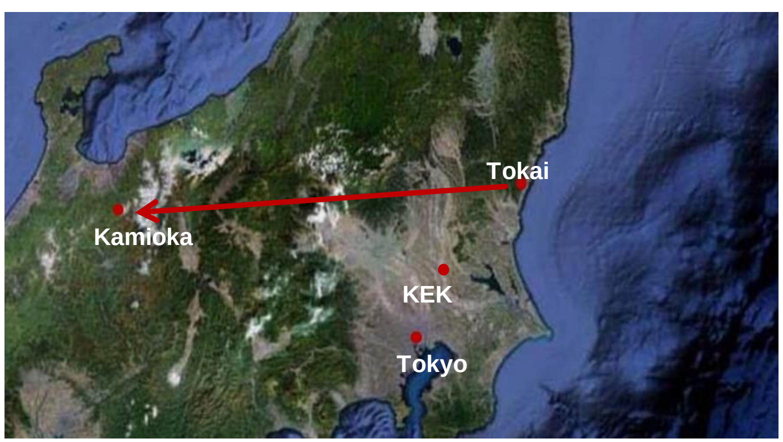


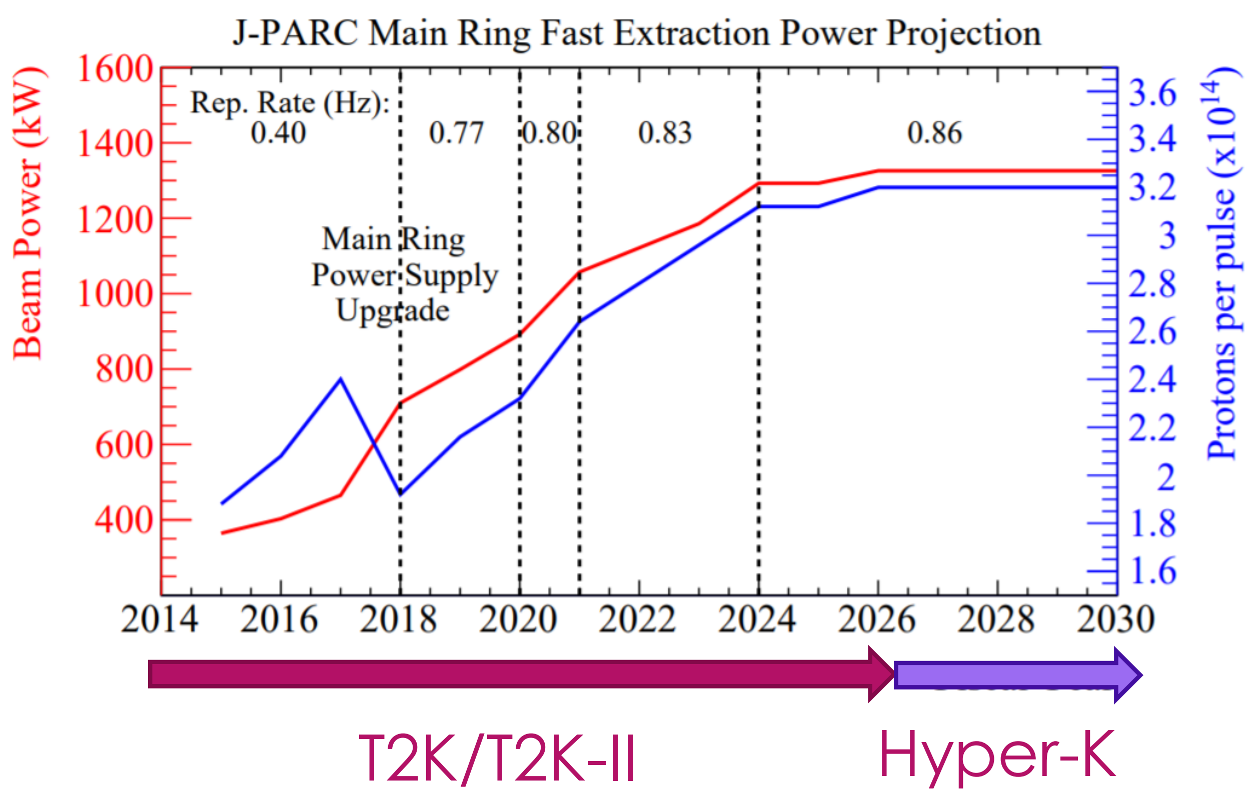


S. Nakayama WIN 2017
"Hyper-Kamiokande Design Report"
https://lib-extopc.kek.jp/preprints/PDF/2016/1627/1627021.pdf

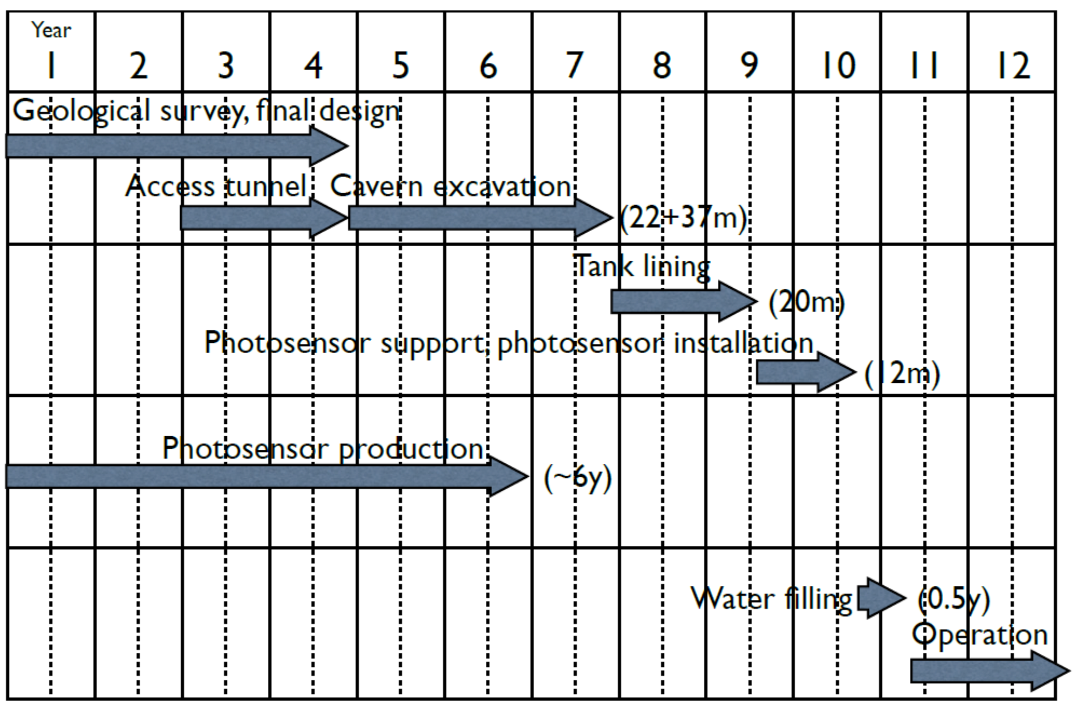
Hyper-K Long-Baseline Program

- Muon neutrino beam from J-PARC (currently being used for T2K)
  - Same 295 km baseline, 2.5° off-axis angle
  - Beam power of 1-1.3 MW achievable after upgrades





Hyper-K Status and Timeline



- International Collaboration
  - Began in 2015
  - As of April 2017, 300 members from 15 countries
- Just last week, a draft of the MEXT (funding agency) Roadmap for Large Projects was released and includes Hyper-K as an important component
- Budget request to start construction in JFY2018
  - Aim to begin operation in 2026

Sensitivity Assumptions

DUNE

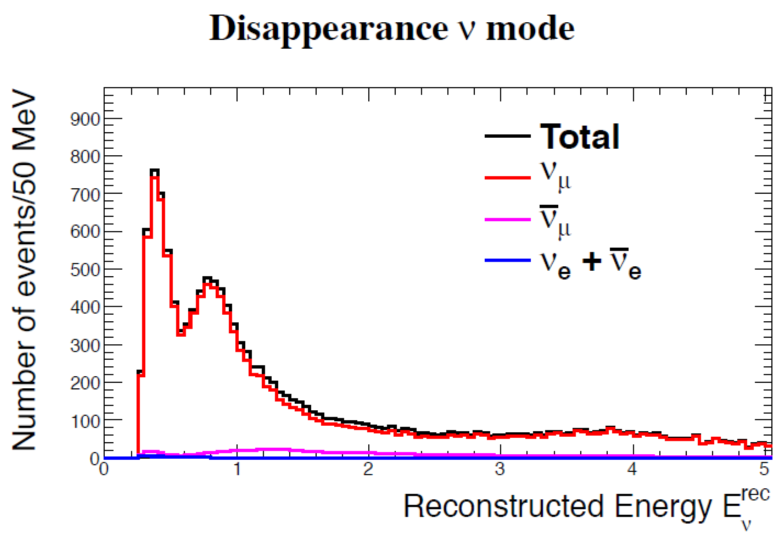
- Staging: Begin with 20 kton, 1.07 MW beam; 40 kton in year 4, 2.14 MW in year 7
- Neutrino: Antineutrino = 1:1
- θ_{23} from global fit (non-maximal)

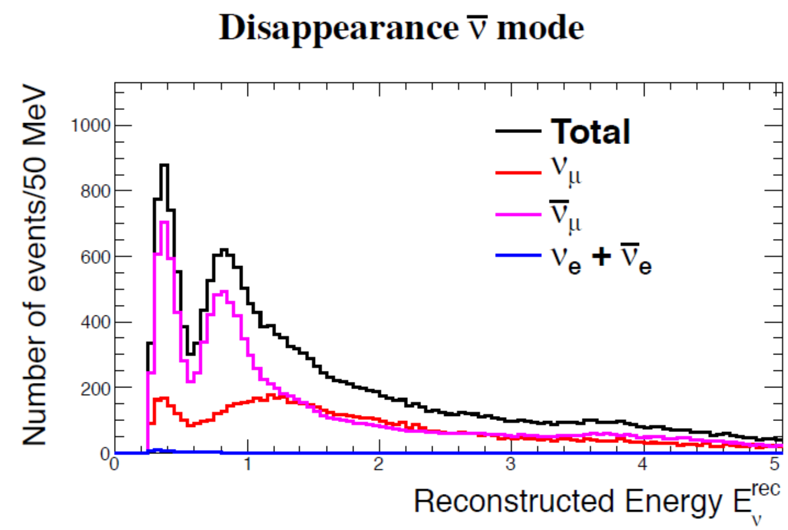
Hyper-K

- Staging: Begin with single 187 kton fiducial tank and 1.3 MW beam; second tank in year 7
- Neutrino: Antineutrino = 1:3
- θ_{23} maximal

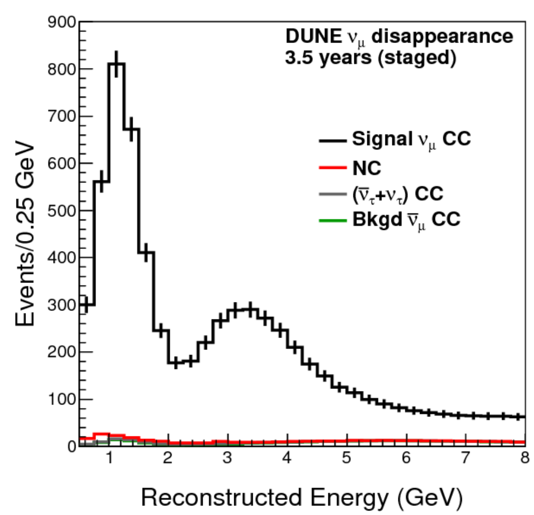
Disappearance Spectra

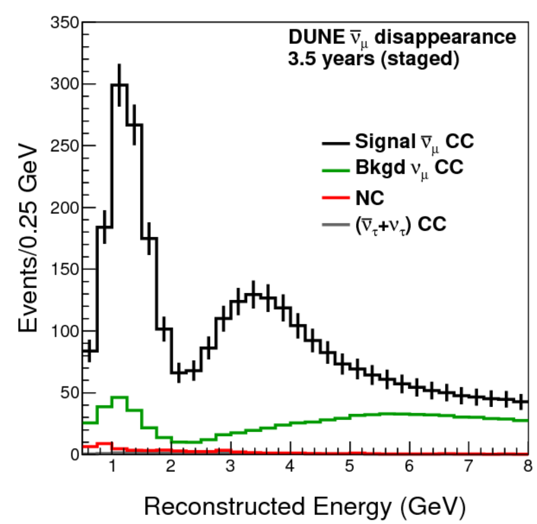
Hyper-K
(10 yrs total)





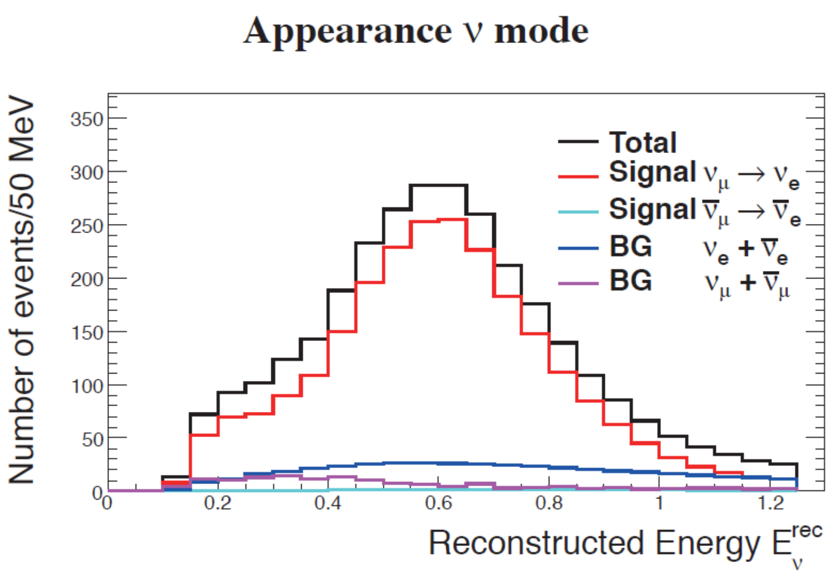
DUNE
(7 yrs total)

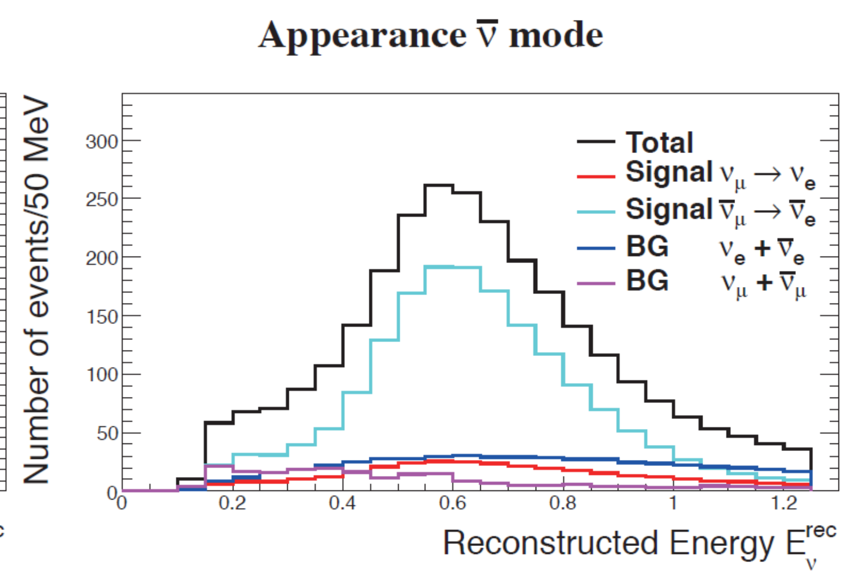




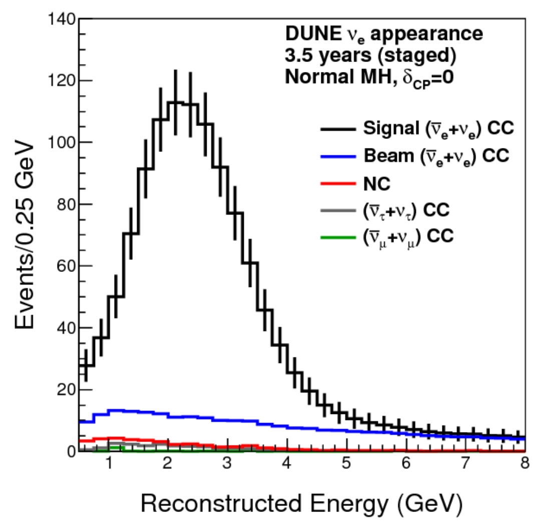
Appearance Spectra

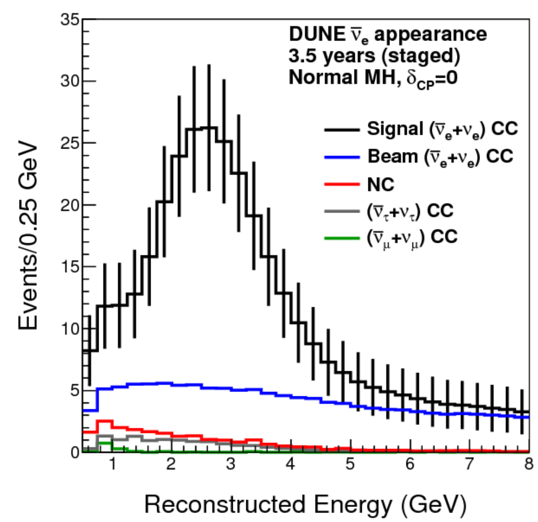
Hyper-K
(10 yrs total)





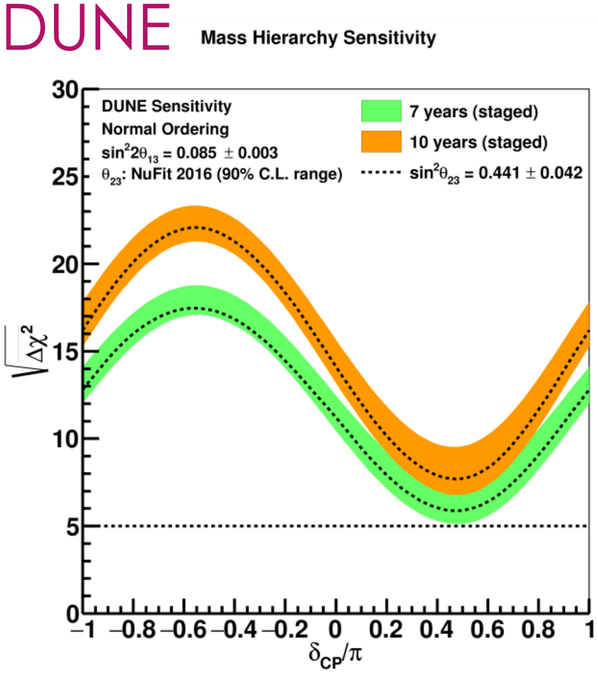
DUNE
(7 yrs total)





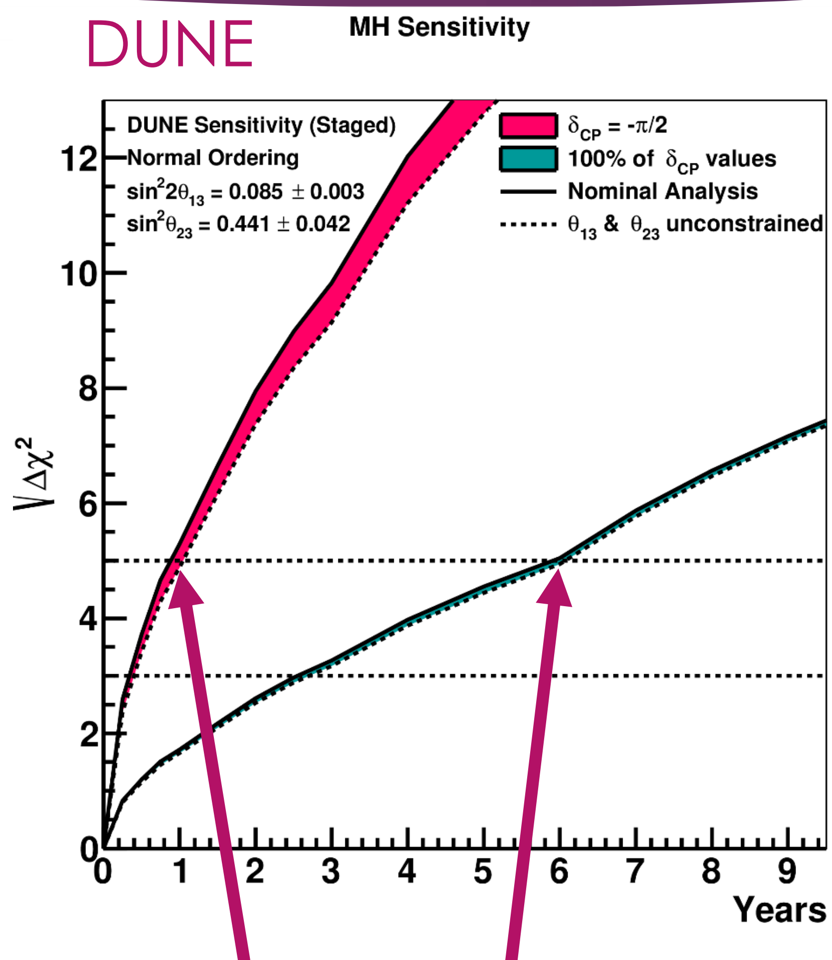
Mass Hierarchy

DUNE



Width of band indicates variation in sensitivity for θ_{23} values in the NuFit 2016 90% C.L. range

DUNE



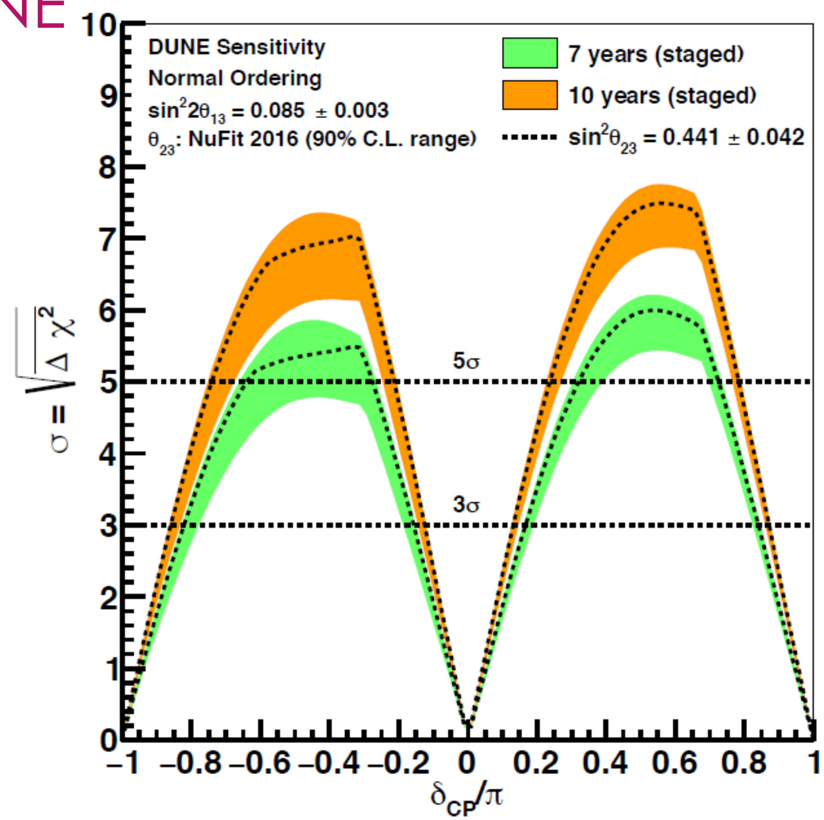
~1 yr

~6 yrs

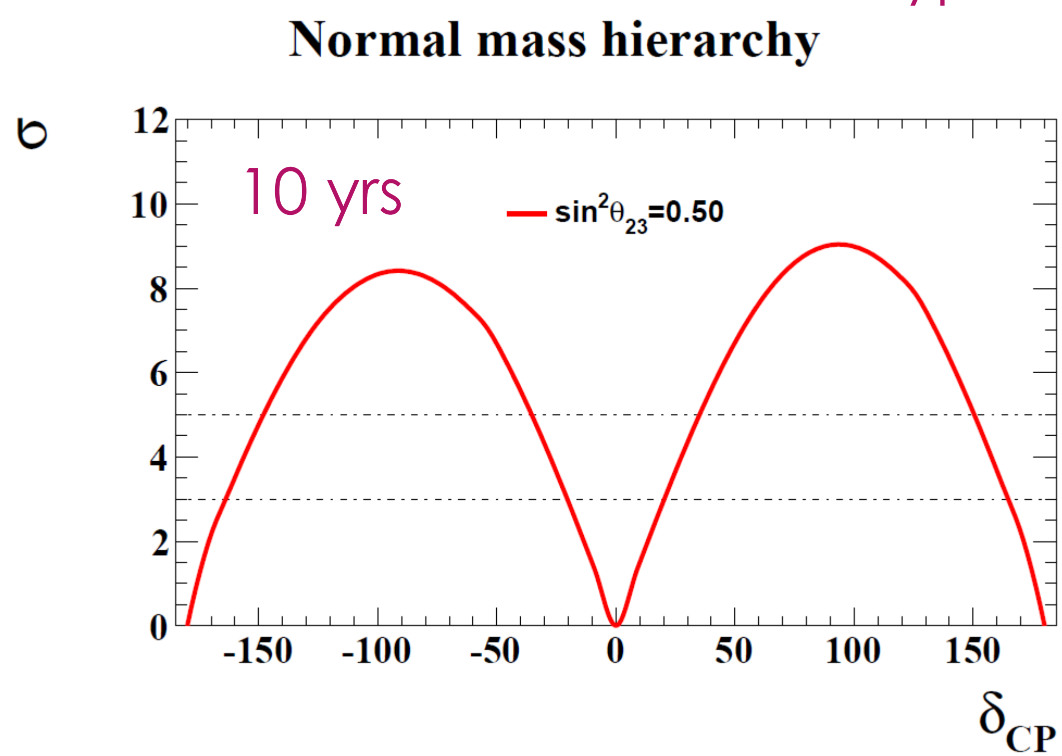
- DUNE should be able to make a relatively quick determination of the mass hierarchy
- Hyper-K is less sensitive due to the shorter baseline
  - Combined analysis with beam and atmospheric neutrinos leads to >3σ determination in about 5 years with one tank Hyper-K

CP Violation

DUNE



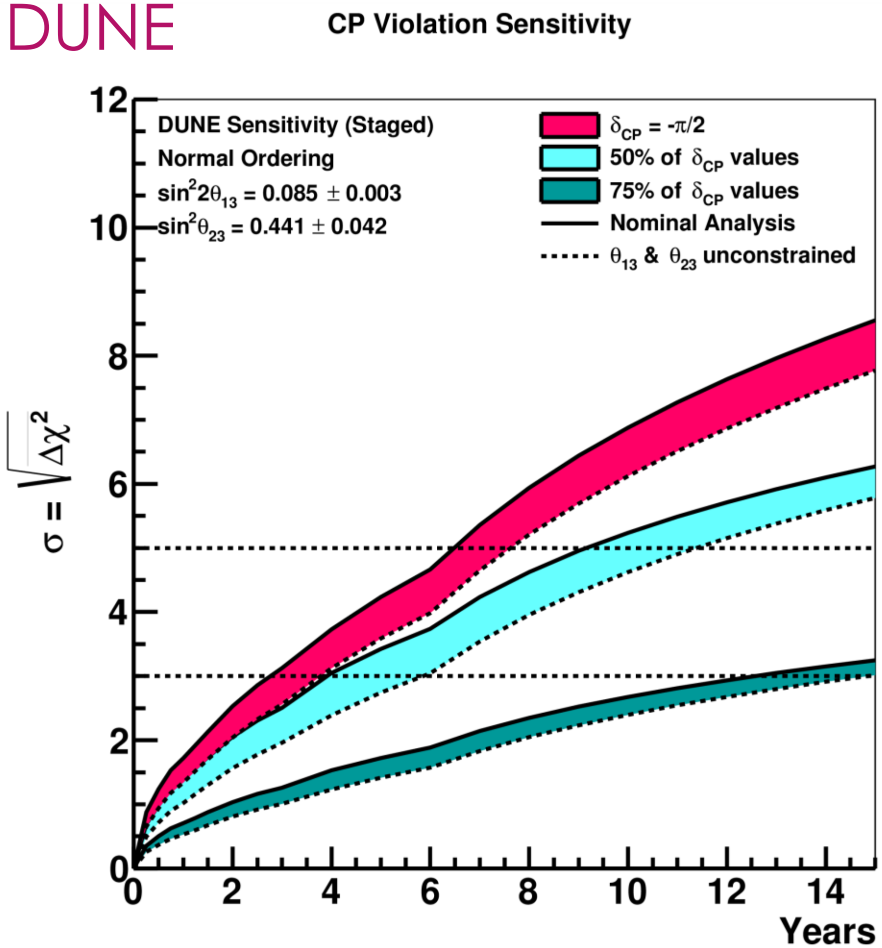
Hyper-K



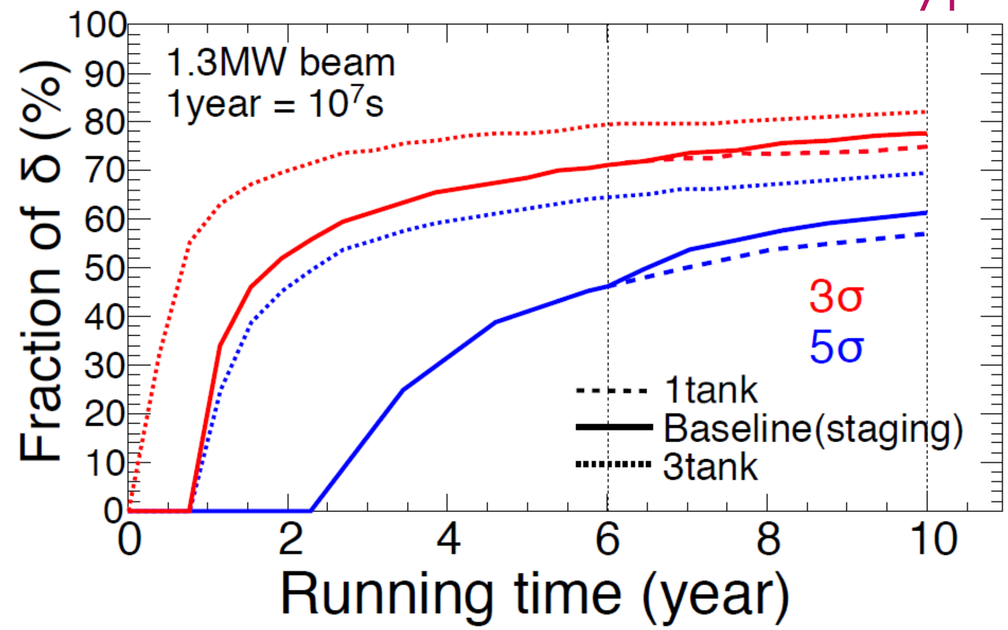
Width of band indicates variation in sensitivity for θ_{23} values in the NuFit 2016 90% C.L. range

CP Violation

DUNE



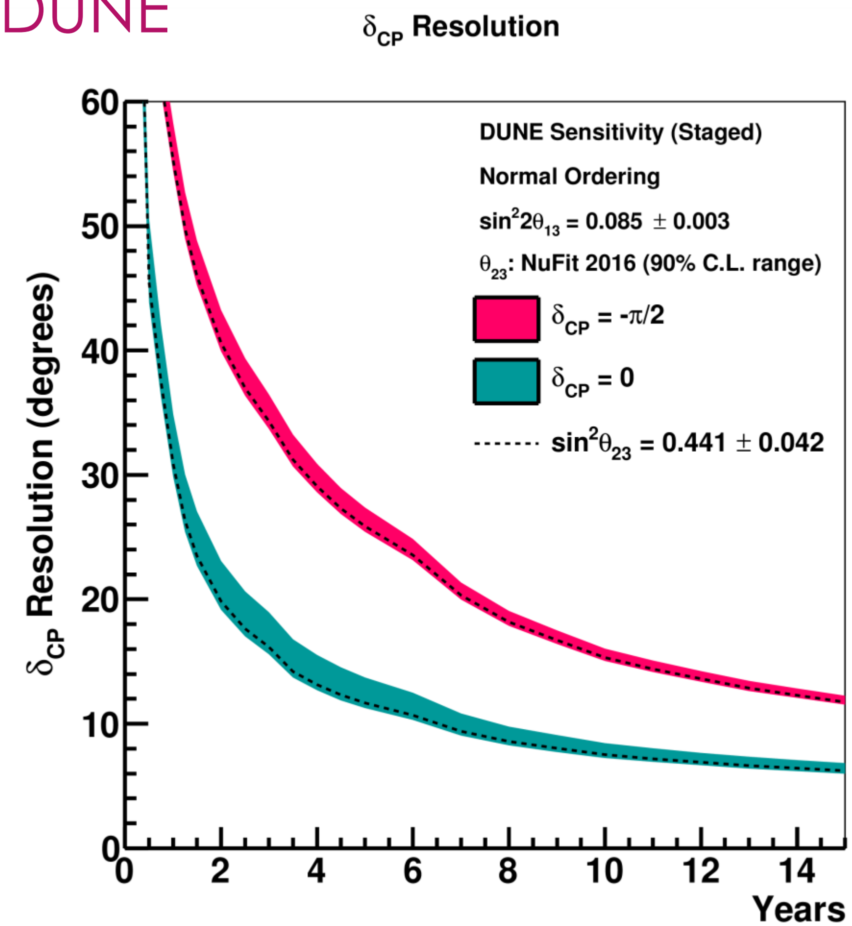
Hyper-K



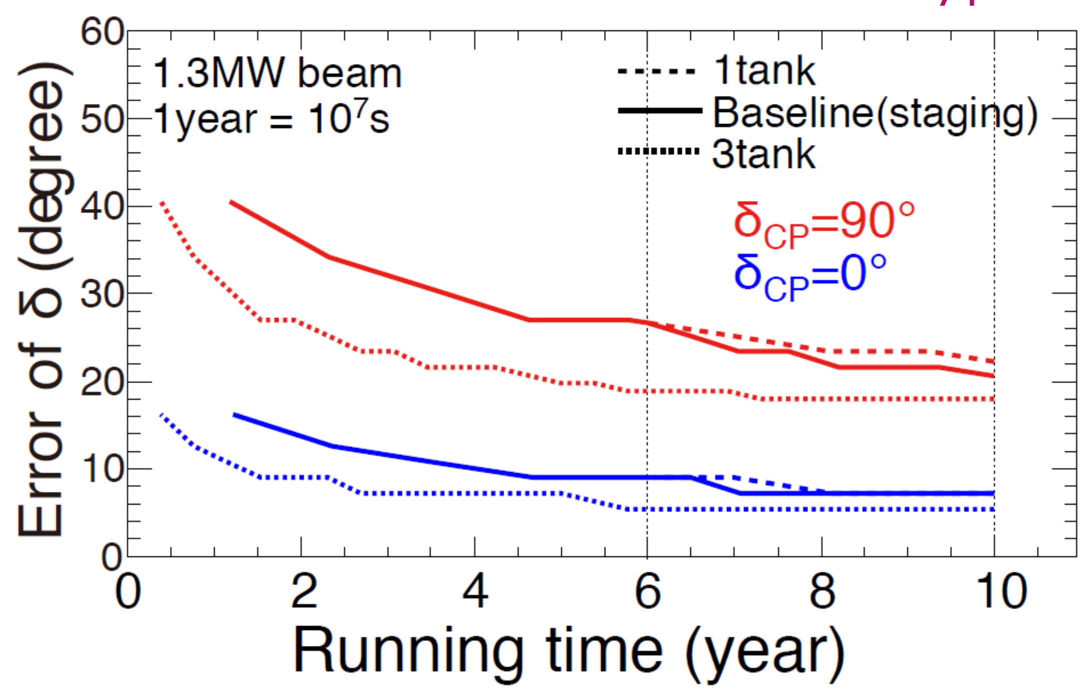
- Ultimately sensitivities of 5σ with 50% CP coverage and 3σ 75% CP coverage

CP Phase

DUNE



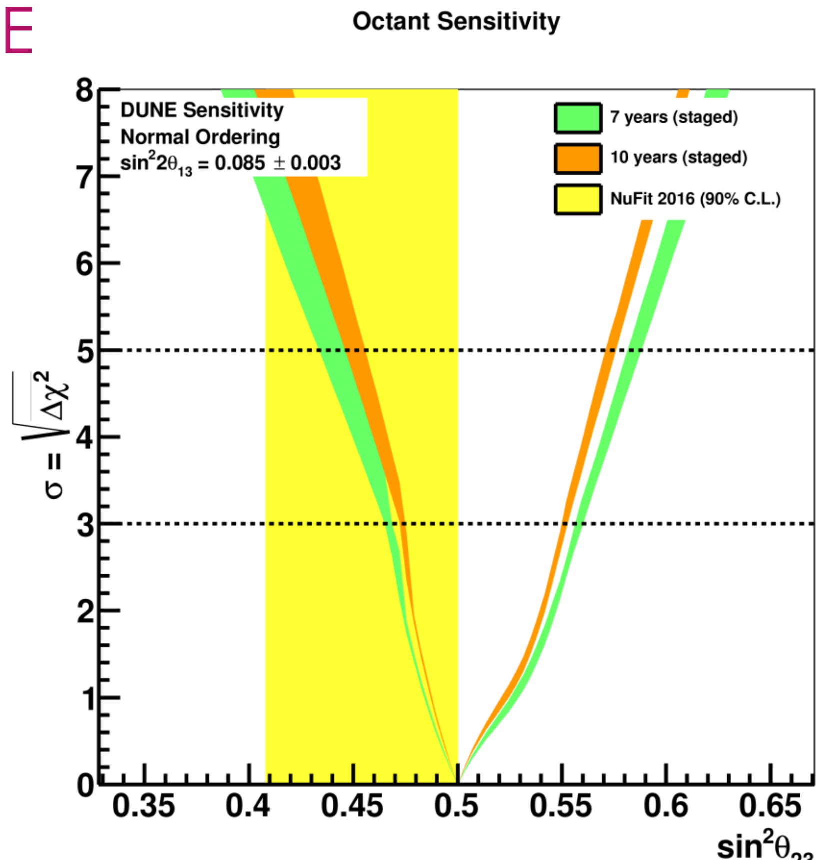
Hyper-K



- Resolution on measurement of δ_{CP} of ~10-20°

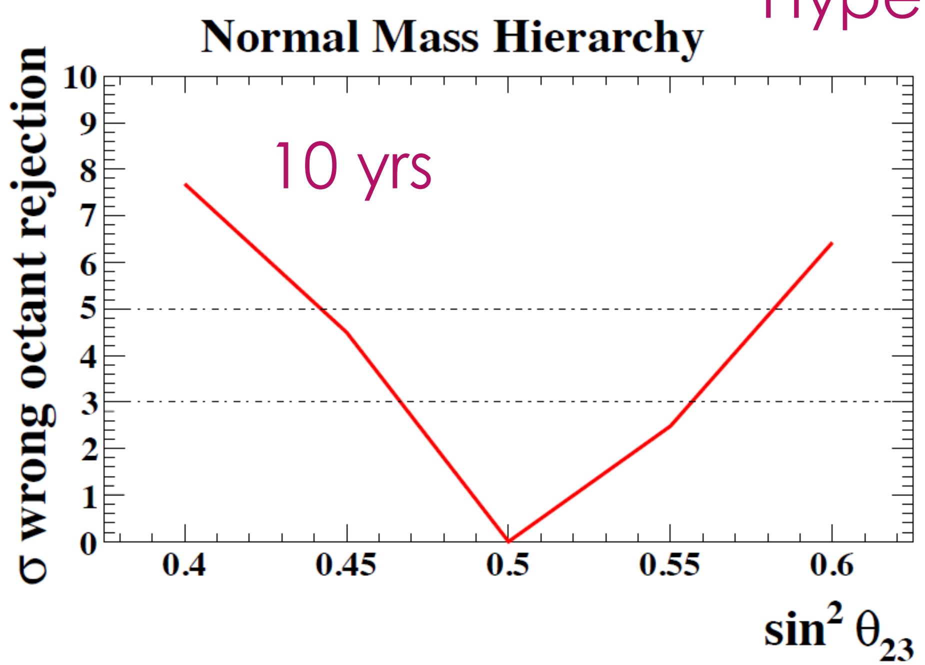
Octant

DUNE



Width of band indicates variation in sensitivity for different δ_{CP} values

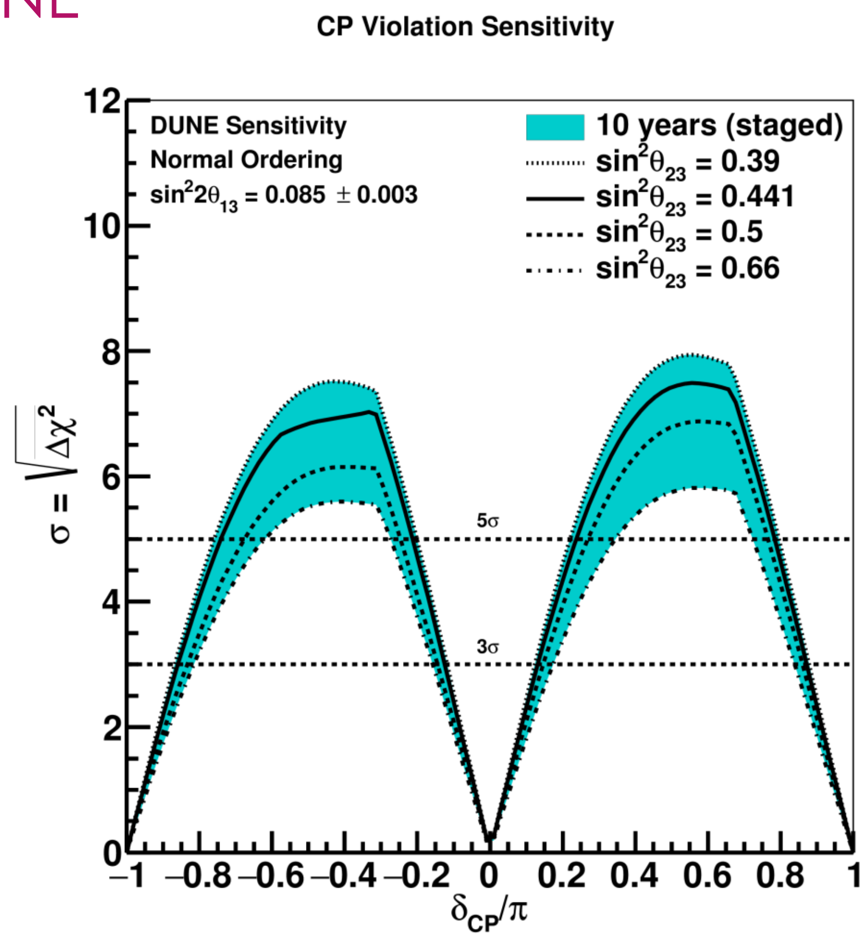
Hyper-K



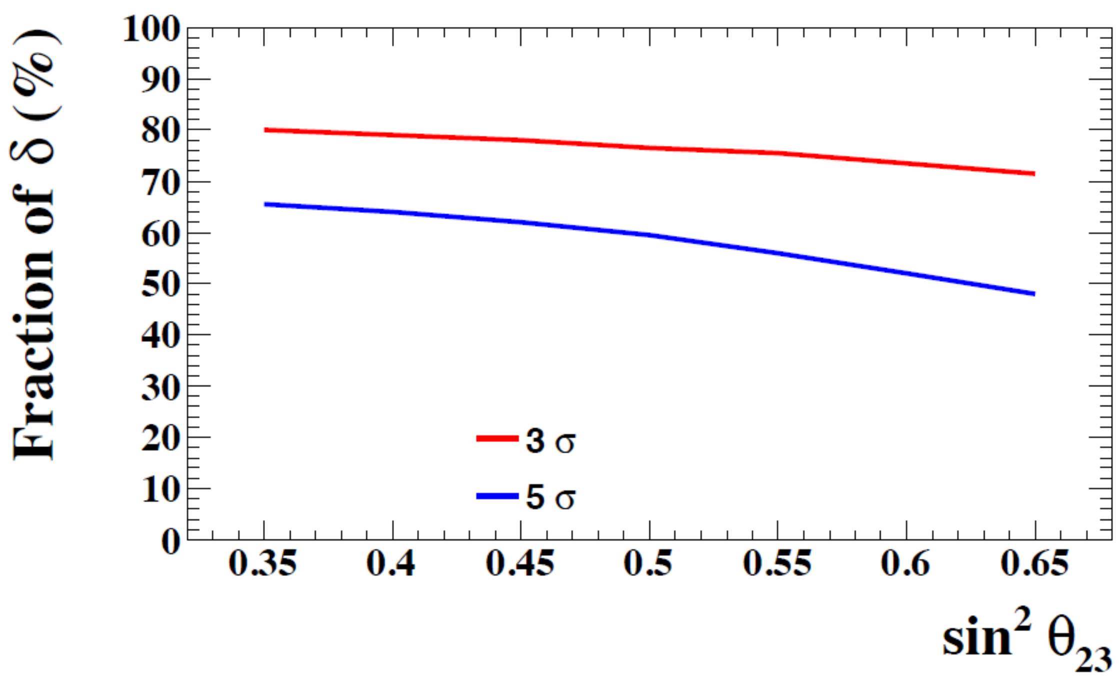
- Potential to reject maximal mixing at 3σ or 5σ in the range of the current global best fit
- Enhanced sensitivity with combined beam and atmospheric neutrino data

Effect of θ_{23} on CP

DUNE

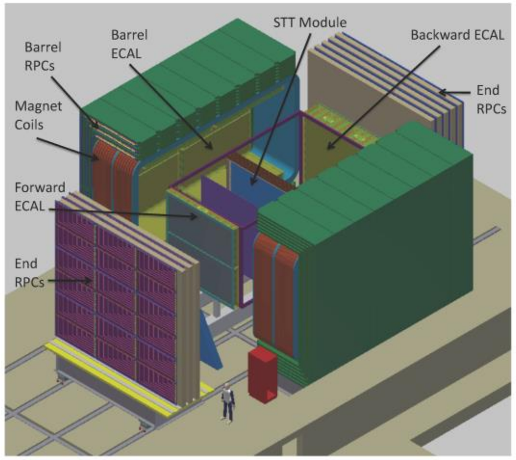


Hyper-K

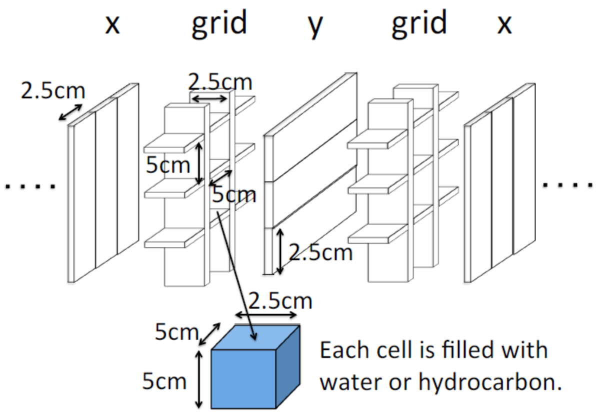


How do we get there?

- Near detectors
  - DUNE near neutrino detector design is on-going
    - Fine-grained tracker with multiple targets including argon gas
    - LAr-TPC + fine-grained tracker
  - Hyper-K near neutrino detector development
    - Possible upgrades to T2K ND280
    - WAGASCI
    - Intermediate (1-2 km baseline) water Cherenkov detector
  - Both will have muon monitors

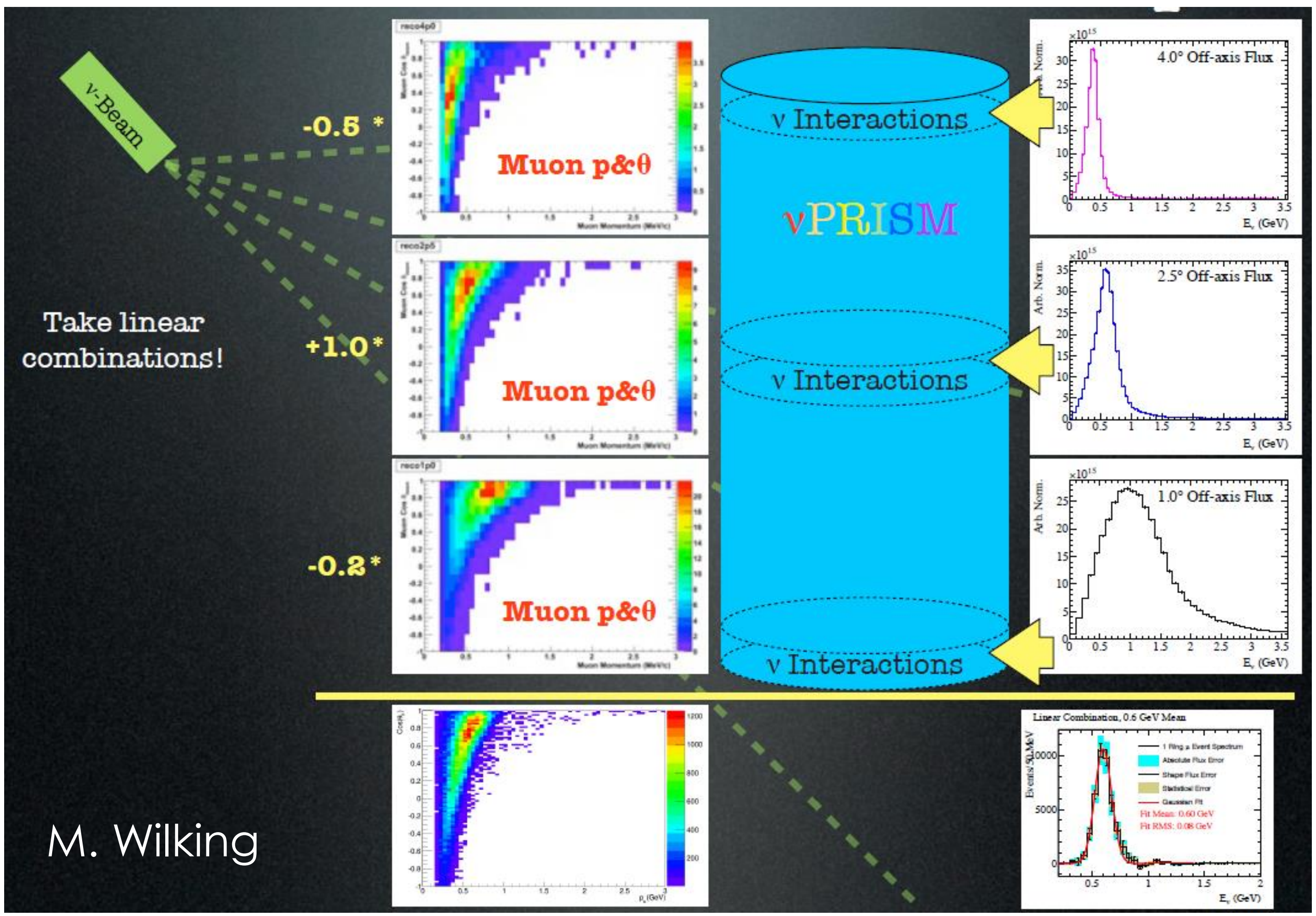


DUNE CDR Design



WAGASCI

NuPRISM Concept



- Status: NuPRISM and TITUS collaborations have merged to form E61 collaboration
- An intermediate distance water Cherenkov detector with Gd loading
- 50 m tall, 8m diameter , movable instrumented portion
- In the proposal stage with J-PARC PAC
- "Phase 0" date 2021

B. Jamieson, NuInt2017

How do we get there?

- Program of supporting measurements
  - Hadron production measurements: NA61/SHINE considering possibilities for running after the CERN 2019-2020 shutdown
  - Neutrino Interaction data: ArgoNeuT, MINERvA, NOvA ND, T2K ND280, MicroBooNE, SBND, ICARUS, NuPRISM, …
  - Improved models for neutrino interaction generators (GENIE, NuWro, NEUT, …)
  - Detector prototypes and calibration measurements (LArIAT, Mini-CAPTAIN, DUNE 35t, ProtoDUNE, ANNIE, …)

Supporting Measurements

ANNIE

- 26 ton Gd-loaded water Cherenkov detector located 100m from the Fermilab Booster Neutrino Beam (BNB) target
- Will measure final state neutron multiplicity as a function of topology and kinematics in the 0.5 - 3 GeV range
- First application of LAPPDs (Large Area Picosecond Photo Detectors) in particle physics
- Physics data in 2018

M. O'Flaherty, NuInt2017

CAPTAIN

- CAPTAIN is a liquid argon TPC (LArTPC) designed to make measurements relevant for the DUNE experiment
- Mini-CAPTAIN (400 kg instrumented LAr) taking data with Los Alamos neutron beam now
- Goal is to measure neutron-argon cross section up to 800 MeV

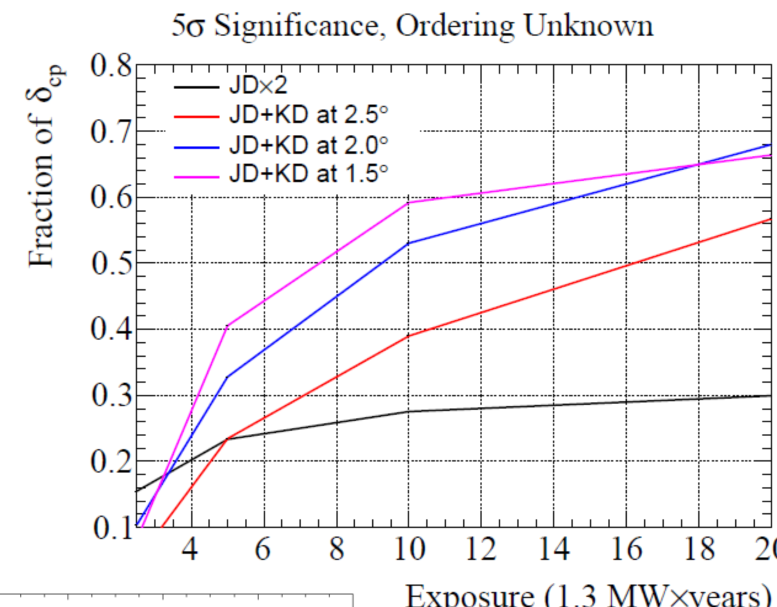
LArIAT

- Designed to characterize LArTPC performance and measure charged particle interactions in an energy range relevant for current and future LArTPC neutrino experiments
- 0.25 tons of LAr at Fermilab's Test Beam Facility
- Just completing its 3rd physics run

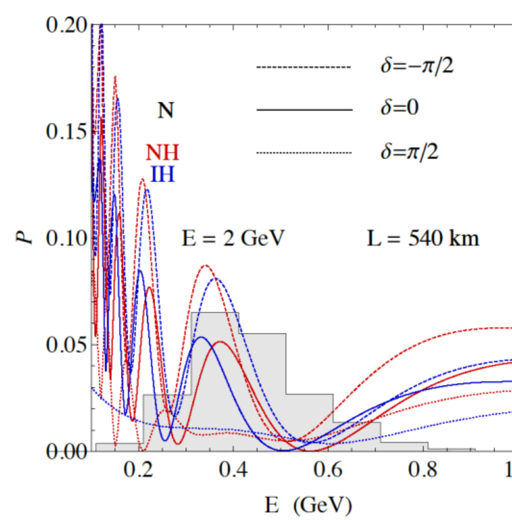
J. Asaadi, NuInt2017

Other future possibilities

- T2HKK
  - Second Hyper-K tank placed in Korea, at a 1100-1300 km baseline and 1-3 degree off-axis angle from J-PARC
  - Improves sensitivity to leptonic CP violation, neutrino mass ordering as well as nonstandard neutrino interactions.
- European Spallation Source Neutrino Super Beam
  - 5 MW, 2 GeV proton beam by 2023
  - Coverage of 2nd oscillation maximum
  - Design Study is needed



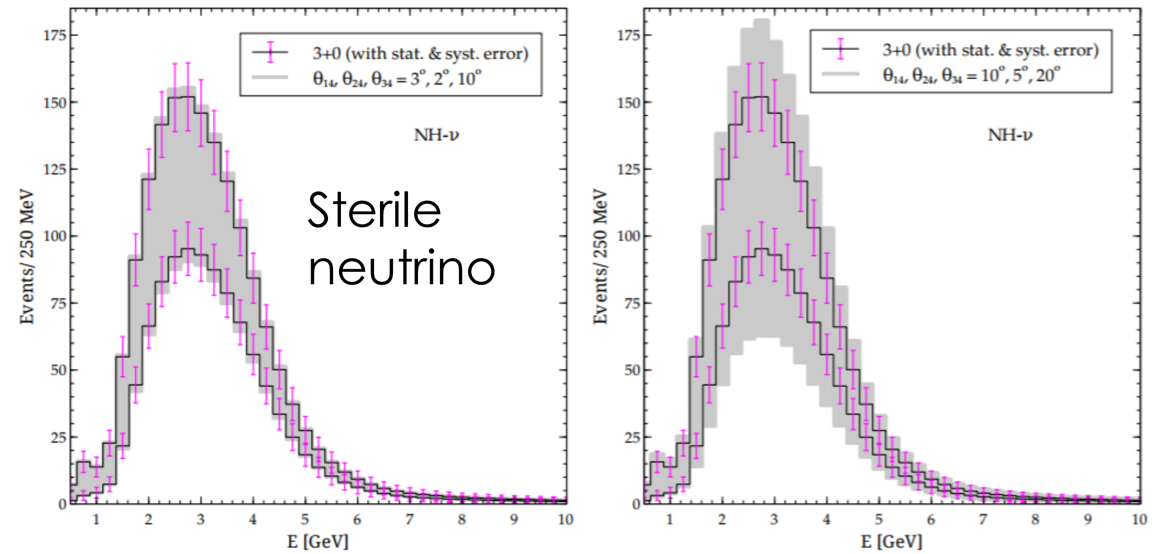
arXiv:1611.06118v1 [hep-ex]



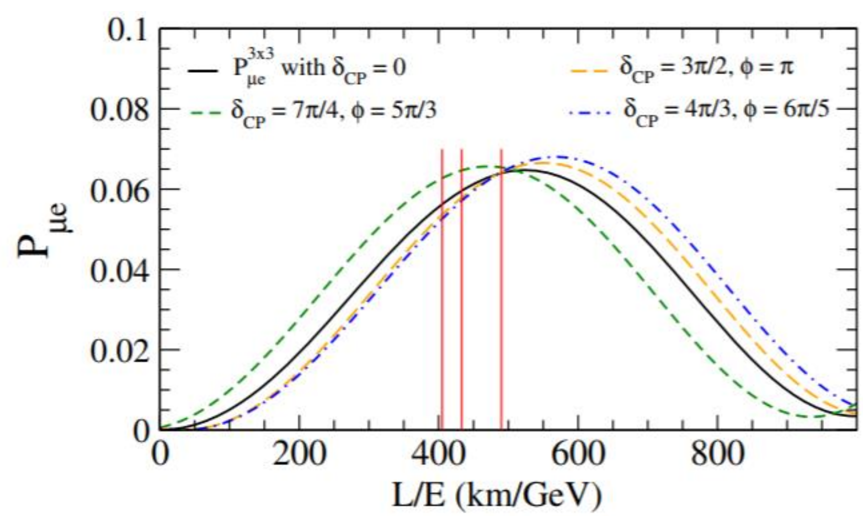
M. Dracos, WIN 2017

What about new physics?

- Future LBL experiments will explore beyond-the-standard model topics such as
  - Sterile neutrinos
  - Non-standard interactions
  - Lorentz and CPT-violation
  - And more…
- And new physics could introduce ambiguities of the measurements of CP violation



JHEP11(2016)122



PRL 117, 061804 (2016)

Non-unitary mixing matrix

Related talks

- CAPTAIN: Current Neutron and Future Stopped Pion Neutrino Measurements (me)
- Hyper-Kamiokande (H. Tanaka)
- The 2nd Hyper-Kamiokande detector in Korea (Seon-Hee Seo)
- The DUNE Far Detector (E. Kemp)
- The Hyper-K near detector programme (J. Wilson)
- Sensitivity of the DUNE Experiment to CP Violation (me)
- Measurements of the Neutrino Flux Using the DUNE Near Detector (J. Sinclair)
- Results from ANNIE Phase 1 and Plans for Phase 2 (R. Svoboda)
- (Apologies if I missed any!)

Summary

- Future long-baseline neutrino experiments will address the remaining questions about 3-neutrino mixing, including the neutrino mass ordering, CP violation, and maximal mixing
  - DUNE: Far site construction and detector prototypes are underway this year
  - Japan: Program of beam, detector, and analysis upgrades to go from T2K era to Hyper-K era
  - Different baselines, neutrino energy range, and detector technology make the measurements complementary
- Program of supporting measurements underway to support every aspect of these experiments
- Stay tuned!

Check out related talks in the parallel sessions!

Backup

Neutrino Mixing

3x3 mixing between flavor states and mass states

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

Three mixing angles and one phase that affect neutrino oscillations

T2K (arXiv:1701.00432)

$\sin^2\theta_{23} = 0.532^{+0.046}_{-0.068}$

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}\ e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\sin^2\theta_{23} = 0.404^{+0.030}_{-0.022}$

$\sin^2\theta_{23} = 0.624^{+0.022}_{-0.030}$

NOvA (arXiv:1701.05891)

$\sin^2 2\theta_{13} = 0.0841 \pm 0.0033$

Daya Bay (arXiv:1610.04802)

$\delta = ?$

$\tan^2\theta_{12} = 0.443^{+0.030}_{-0.025}$

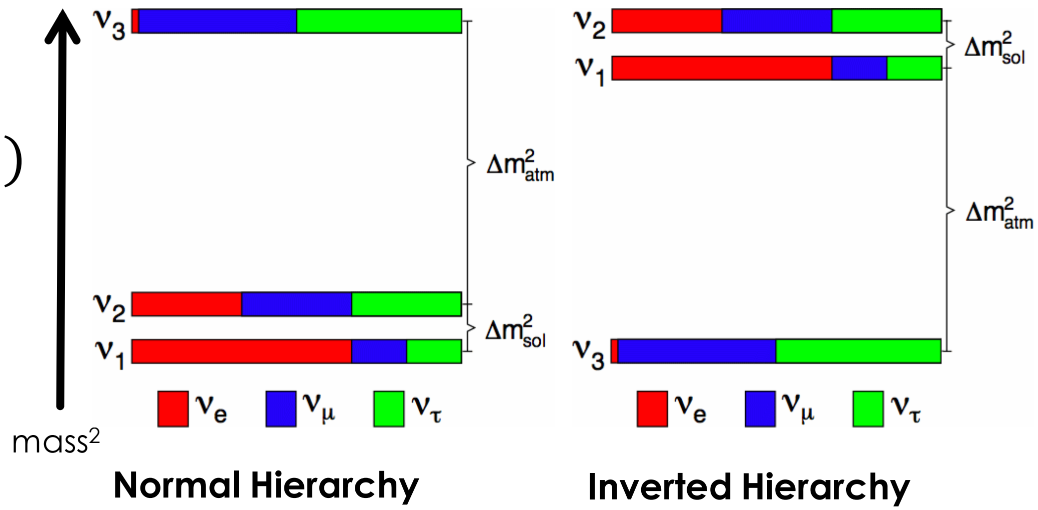
Solar + KamLAND (PRC 88, 025501 2013)

Neutrino Oscillations

Probability of flavor change (2-flavor approximation):

$$P_{\alpha\to\beta} = \sin^2 2\theta \, \sin^2(1.27\, \Delta m^2 L/E)$$

L **= baseline**
E **= neutrino energy**
$\Delta m_{ij}^2 = m_i^2 - m_j^2$



Color represents $|U_{\alpha j}|^2$

$\Delta m_{21}^2 = 7.46^{+0.20}_{-0.19} \times 10^{-5}\text{eV}^2$
Solar + KamLAND
PRC 88, 025501 2013

$|\Delta m_{32}^2| = 2.45^{+0.08}_{-0.08} \times 10^{-3}\text{eV}^2$
Daya Bay (arXiv:1610.04802)
$|\Delta m_{32}^2| = 2.545^{+0.081}_{-0.084} \times 10^{-3}\text{eV}^2$
T2K (arXiv:1701.00432)

(Assuming NH)

Muon Neutrino to Electron Neutrino Oscillations in Matter

Oscillations in matter with constant density:

H. Nunokawa, S. J. Parke, and J. W. Valle, Prog.Part.Nucl.Phys. 60, 338 (2008), arXiv:0710.0554 [hep-ph].

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

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

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

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

For antineutrinos, a → -a and δ → -δ

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

Matter effect: electron neutrinos have CC interactions with electrons in the Earth, while other flavors don't

$$\cos(\Delta_{31}+\delta_{CP}) = \cos\Delta_{31}\cos\delta_{CP} - \sin\Delta_{31}\sin\delta_{CP}$$

CP-violation