Future Long-baseline Neutrino Oscillation Experiments and Technology

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Outline

- Introduction
  - Science questions and status of present results
- Future long-baseline ν-oscillation experiments
  - LBNF and DUNE Experiment
  - J-PARC and Hyper-K
  - Projected Physics Sensitivities
- Potential other projects
- Summary and Outlook

Neutrino Oscillations

Neutrinos change flavor while propagating in vacuum/matter

➔ Neutrinos have mass = evidence for physics beyond the Standard Model

Flavor

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

Mass

ν_e

ν_μ

ν_τ

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

atmospheric & **accelerator**

$\theta_{23} = (45 \pm 3)^o$

$|\Delta m^2_{32}| = (2.52 \pm 0.04)\times 10^{-3}\ eV^2$

reactor & **accelerator**

$\theta_{13} = (8.5 \pm 0.15)^o$

$|\Delta m^2_{31}| = (2.52 \pm 0.04)\times 10^{-3}\ eV^2$

solar & reactor

$\theta_{12} = (33.6 \pm 0.8)^o$

$\Delta m^2_{21} = (7.50 \pm 0.18)\times 10^{-5}\ eV^2$

CP violation phase: $\delta_{CP} \approx -90^o$?

PMNS (Pontecorvo, Maki, Nakagawa, Sakata) – matrix describes mixing between flavor and mass eigenstates

Neutrino Oscillations

Flavor

ν_e

ν_μ

ν_τ

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

Mass

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

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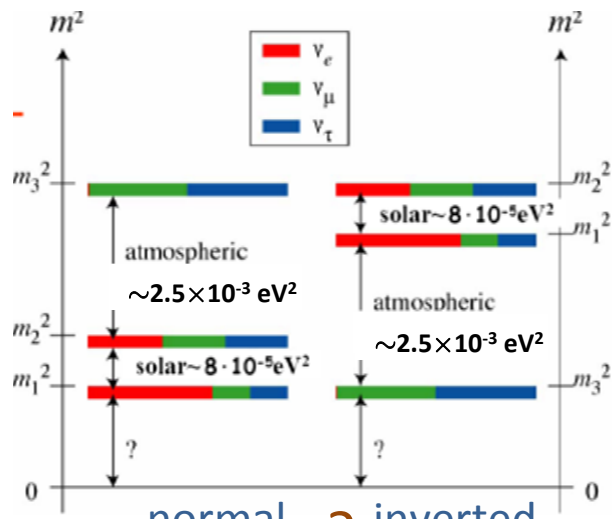
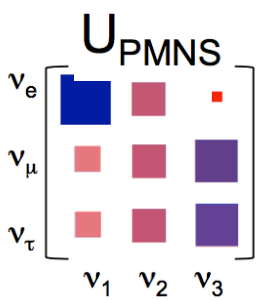


normal ? inverted

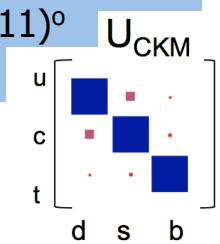
(NH) hierarchy (IH)

Key open questions in neutrino physics

- Is there CP violation in the lepton sector ?
- Which mass hierarchy is correct ?
- What are the precise values of the neutrino mixing parameters ?



Mixing	Neutrinos	Quarks
θ_{12}	$(33.6 \pm 0.8)^o$	$(13.04 \pm 0.05)^o$
θ_{23}	$(45 \pm 3)^o$	$(2.38 \pm 0.06)^o$
θ_{13}	$(8.5 \pm 0.15)^o$	$(0.201 \pm 0.011)^o$
δ_{CP}	$(-90^{+115}{}_{-122})^o$	$(67 \pm 5)^o$



→ Test 3 flavor paradigm
→ Measure symmetry between 2nd and 3rd generation
→ Search for new/unexpected physics

(Accelerator based) long-baseline ν experiments

- What is the absolute neutrino mass scale ?
- Are neutrinos Dirac or Majorana particles ?
- …

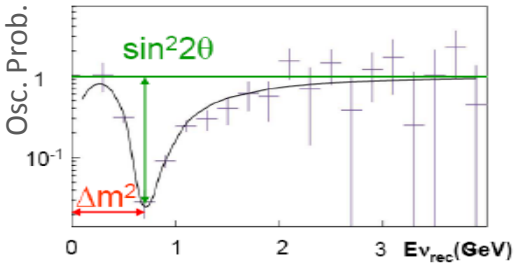
Neutrino Oscillation Probabilities

ν_μ disappearance:

$$P(\nu_\mu \to \nu_\mu) \approx 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23})\sin^2\frac{\Delta m^2_{32} L}{4E_\nu}$$

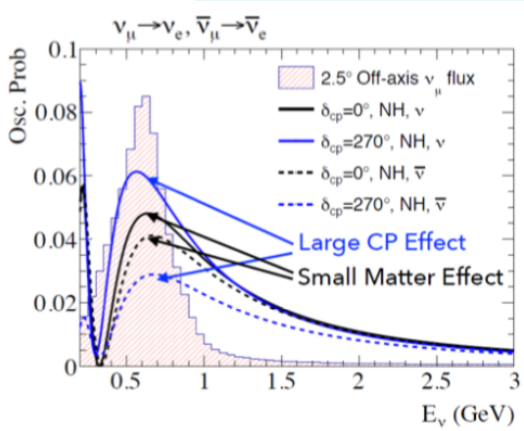
Leading term: ~ 0.95 next to leading term: ~ 0.05

yields sensitivity to θ_{23} octant



ν_e appearance:

$$P(\nu_\mu \to \nu_e) \sim \sin^2 2\theta_{13} \times \sin^2\theta_{23} \times \frac{\sin^2[(1-x)\Delta]}{(1-x)^2}$$
$$-\alpha\sin\delta \times \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23} \times \sin\Delta\frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)}$$
$$+\alpha\cos\delta \times \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23} \times \cos\Delta\frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)}$$
$$+\mathcal{O}(\alpha^2)$$



$$\alpha = \left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \sim \frac{1}{30} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E} \qquad x \equiv \frac{2\sqrt{2}G_F N_e E}{\Delta m^2_{31}}$$

θ_{13} sensitivity

θ_{23} octant sensitivity (θ_{23} >,<,= 45°)

δ_{CP} phase sensitivity : $P(\nu_\mu \to \nu_e) - P(\overline{\nu_\mu} \to \overline{\nu_e}) \neq 0$ for $\sin\delta \neq 0$

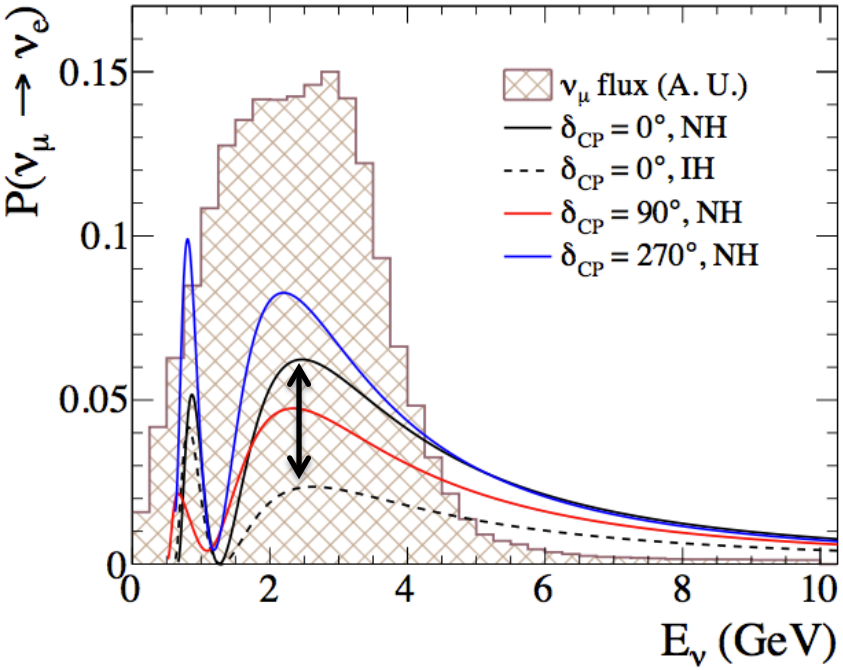
Matter effect sensitivity: ν_e enhanced in normal hierarchy

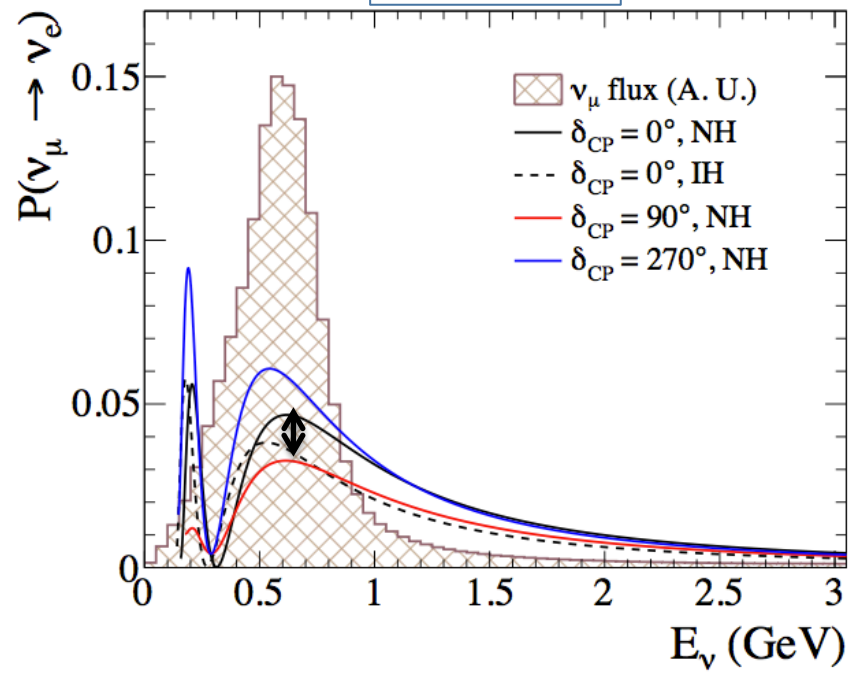
Neutrino Oscillation Probabilities

L = 1300 km

arXiv: hep-ex:1608.06237

L = 295 km





→ Obtain corresponding $P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$ by switching $\delta_{CP} \rightarrow -\delta_{CP}$ and NH → IH

→ CP effect ~ ±30%
→ large matter effects ~ ±40%

→ CP effect ~ ±30%
→ small matter effects ~ ±10%

Strategy:
use high intensity ν_μ ($\overline{\nu}_\mu$) beam to measure ν_e ($\overline{\nu}_e$) appearance and ν_μ ($\overline{\nu}_\mu$) disappearance

→ **require well matched values of L and E : L/E ≈ 500 km/GeV to maximize sensitivity**

Match E_ν over broad E range:
→ disentangle CP and mass hierarchy effects

Match E_ν in narrow E range:
→ measure CP

Measurement Parameters

Measure at far detector

$$N_{FD} = \int dE\ \Phi_{FD}(E) \times \sigma(E) \times \varepsilon_{FD}(E) \times P(\nu_\alpha \rightarrow \nu_\beta; E; \theta_{ij}, \Delta m^2_{ij}, \delta_{CP})$$

no. of ν events — flux — Cross section — efficiency — Oscillation probability

Primary physics interest

$$N_{ND} = \int dE\ \Phi_{ND}(E) \times \sigma(E) \times \varepsilon_{ND}(E)$$

Measure at near detector

Requires good understanding of:

- ν flux → separate hadro production experiments and simulations
- cross sections → near detector measurements and external data
  → Theoretical interaction models and generators
- detector efficiencies →atmospheric data and detector simulations

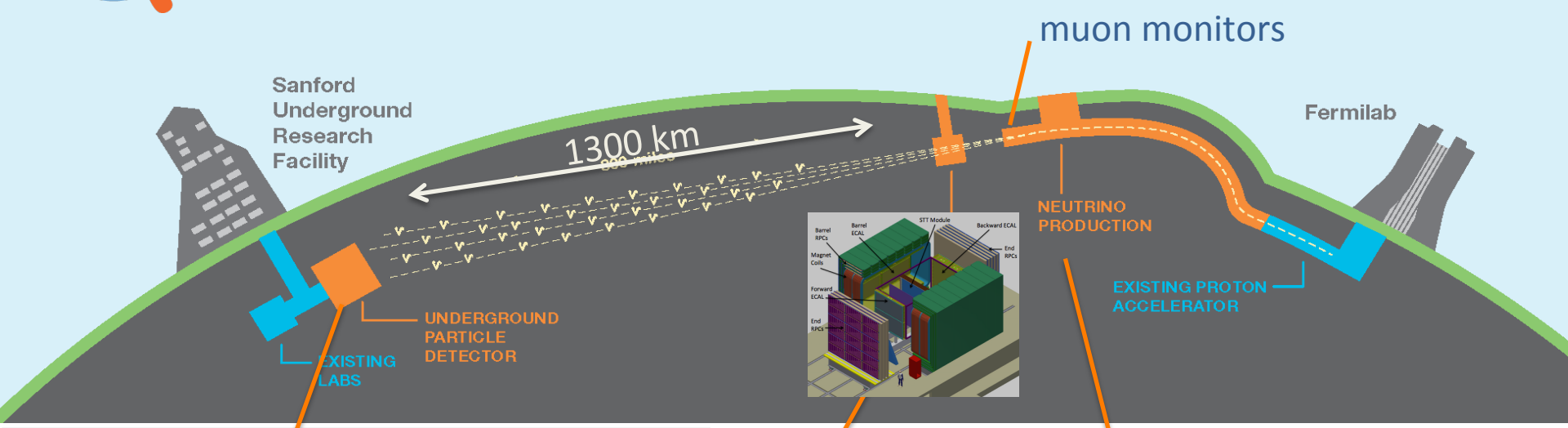
Far Detector needs to be **large** and requires good:

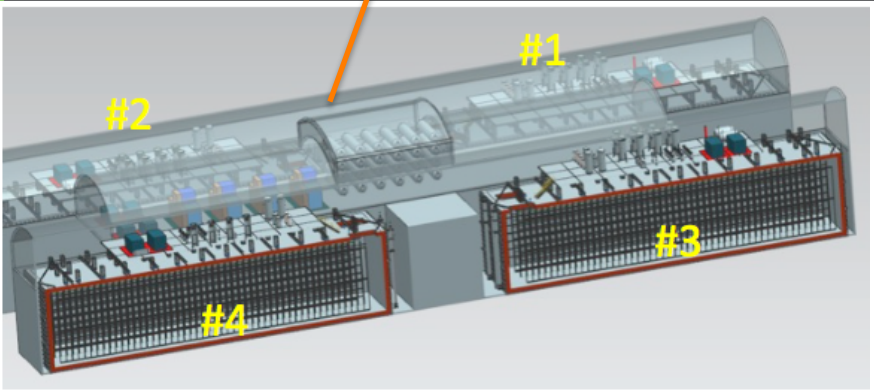
- particle identification
- energy resolution
- background rejection capabilities

DUNE and LBNF Overview

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Long-Baseline Neutrino Facility (LBNF)





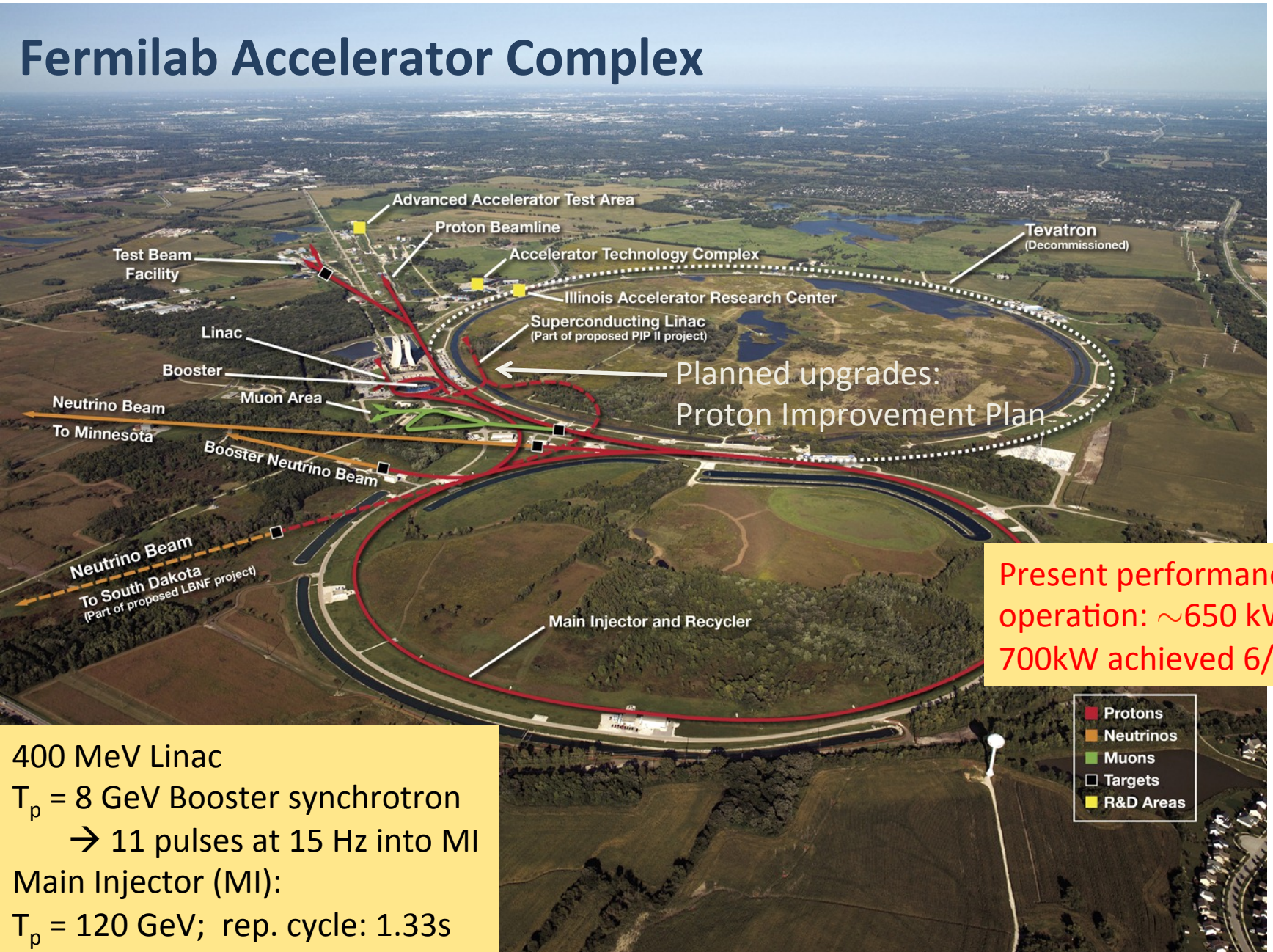
high precision near detector at 574m

Wide band, high purity ν_μ beam with peak flux at 2.5 GeV operating at $\sim$1.2 MW and upgradeable

- four identical caverns/cryostats deep underground
- staged approach to four independent 10 kt LAr detector modules
- Single-phase and dual-phase readout under consideration

also see J. Bian: 6/20 neutrino parallel session

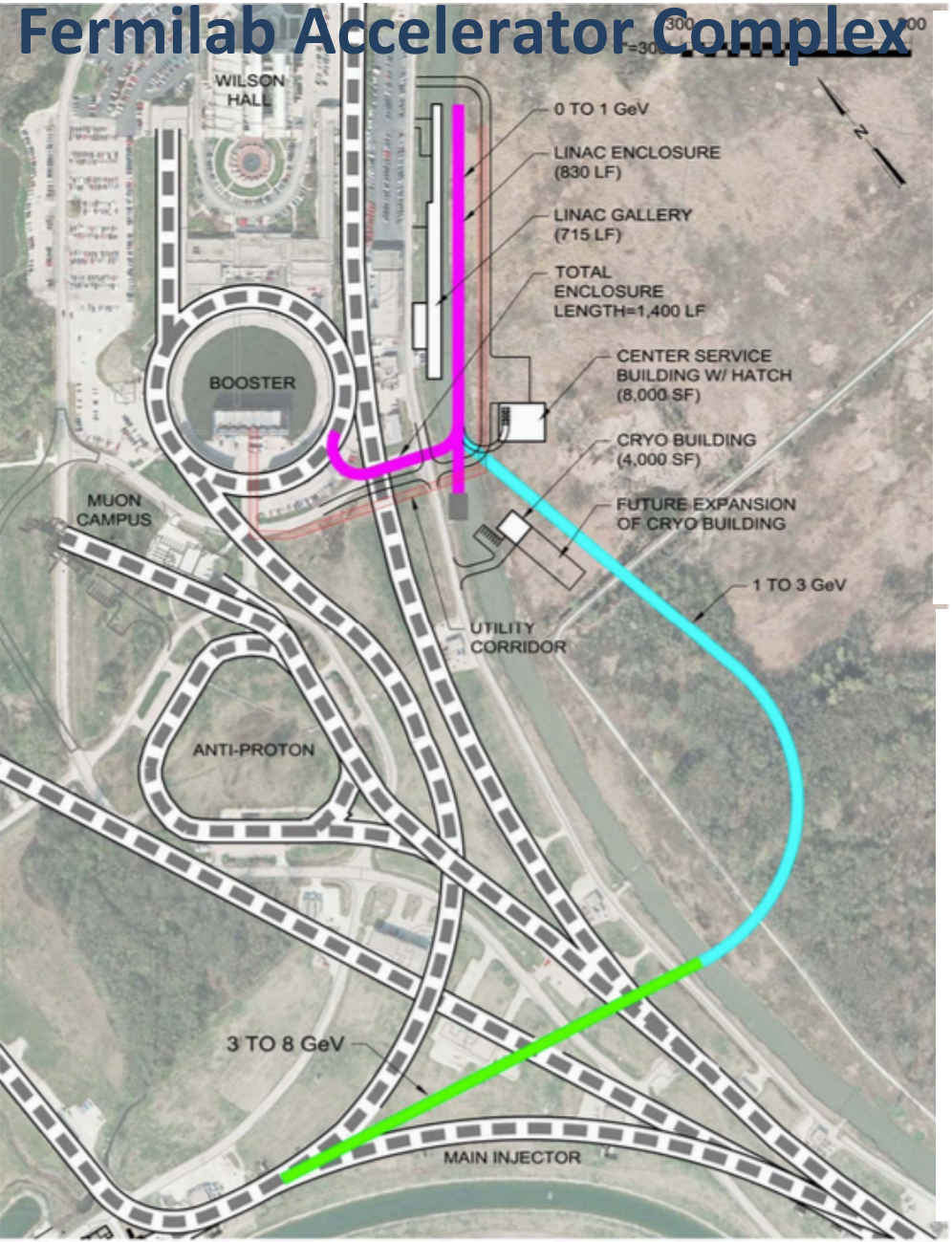
Long Baseline Neutrino Facility



Present performance:
operation: ~650 kW
700kW achieved 6/13/2016

400 MeV Linac
T_p = 8 GeV Booster synchrotron
→ 11 pulses at 15 Hz into MI
Main Injector (MI):
T_p = 120 GeV; rep. cycle: 1.33s

Proton Improvement Plan II and III



Upgrades to increase proton yield

PIP II : (ready by ~2025)

MI beam power → **1.2 MW**

- upgrade to superconducting (SC) 800 MeV linac
- Booster rep. rate: 15 → 20 Hz
- MI rep. cycle: 1.33 →1.2 s

PIP III : (> 2025)

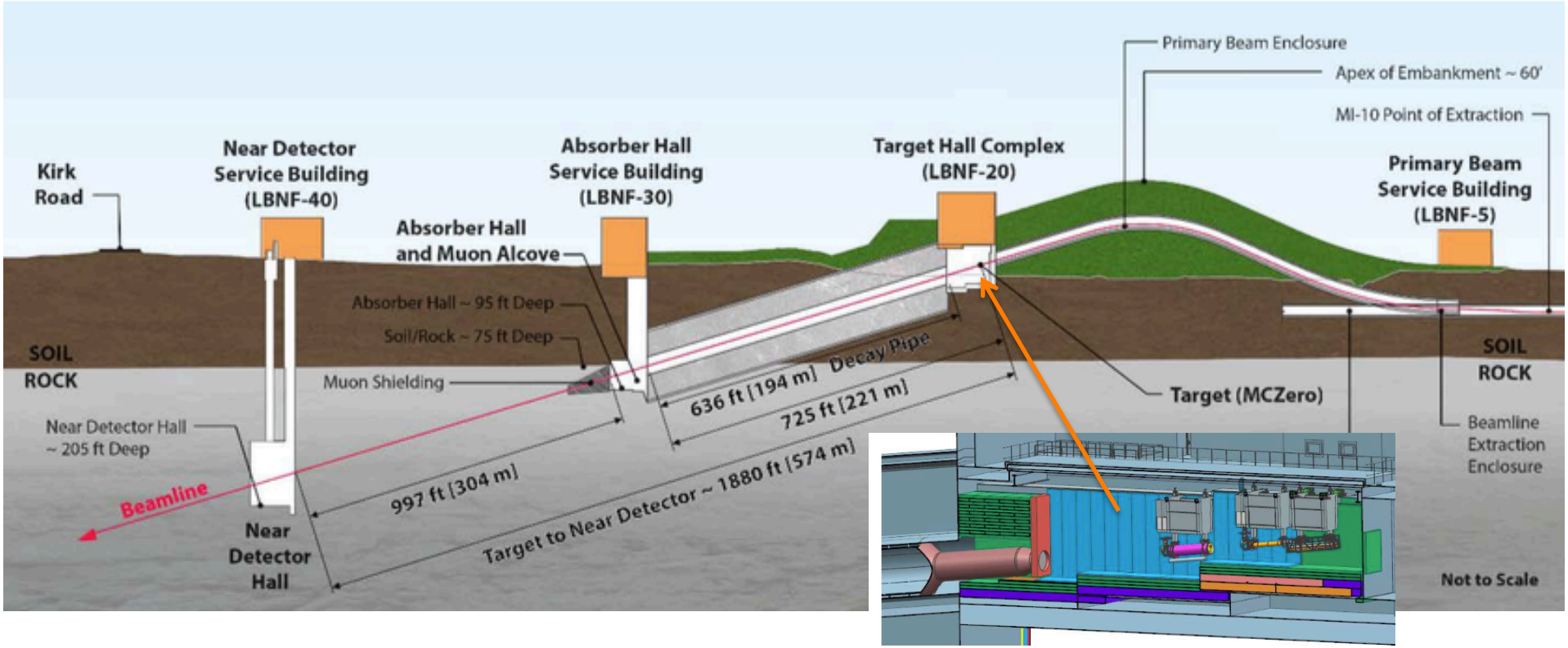
MI beam power → **2.3 MW**

- Upgrade to 8 GeV SC linac

OR

- Upgrade to 2 GeV SC linac and
- Replace booster with 8 GeV rapid cycling synchrotron (RCS)

LBNF Beamline



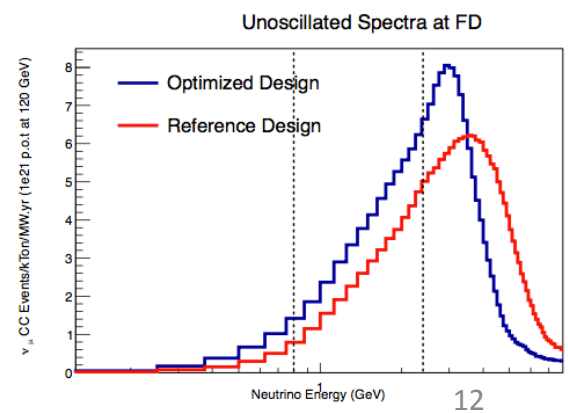
Extract 60 – 120 GeV primary proton beam onto 95cm graphite target

→ (1.1 – 1.9) $\times 10^{21}$ protons on target/yr

Focusing horns

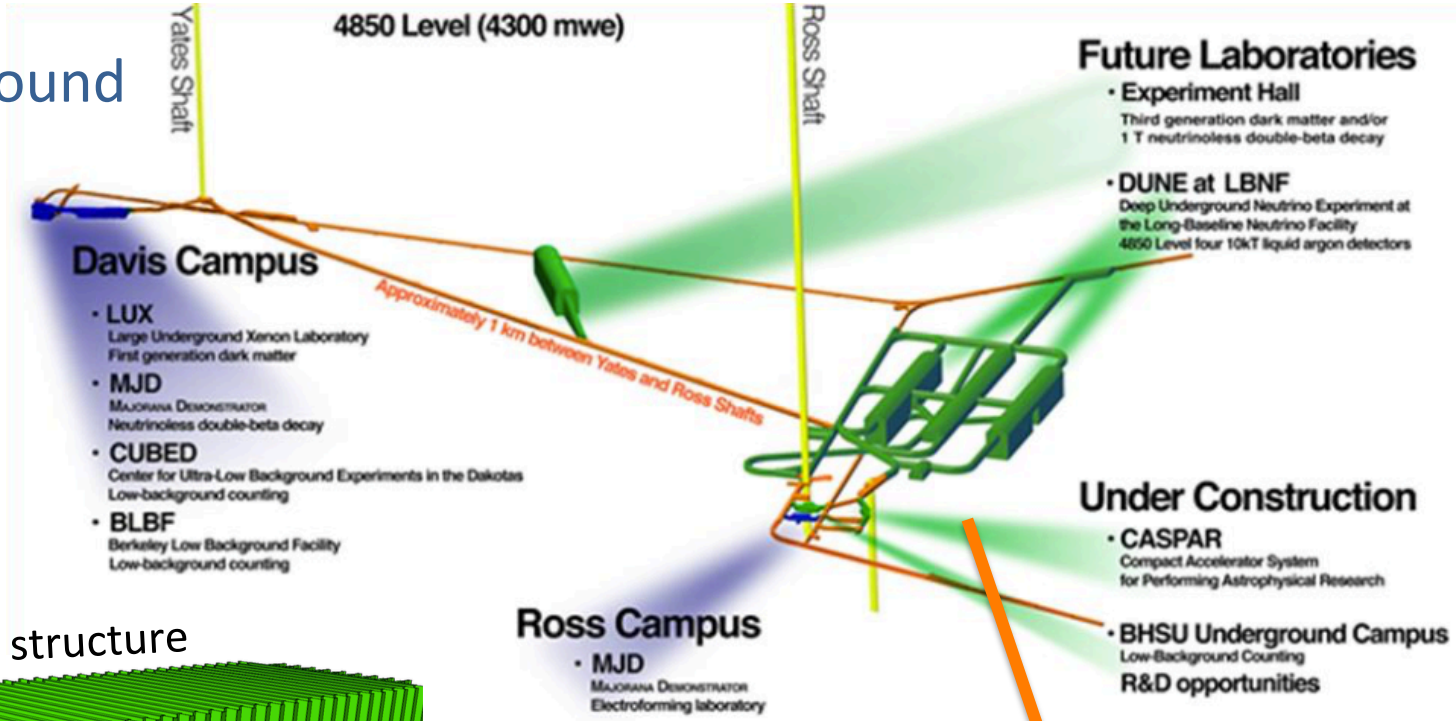
1) NuMI like horn (reference design)
2) optimized focusing design (genetic algorithm)

Decay pipe: 4m diameter ~200m long; He filled

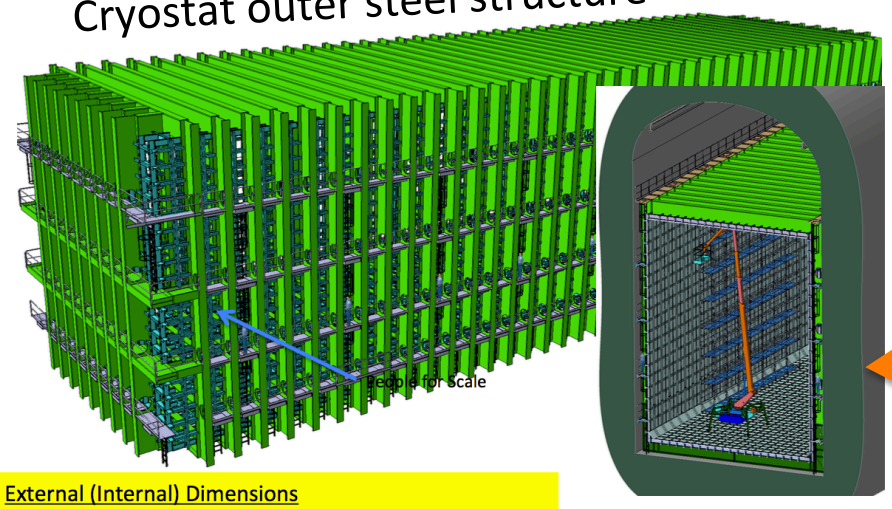


DUNE Far Detector at SURF

Location:
Sanford Underground Research Facility

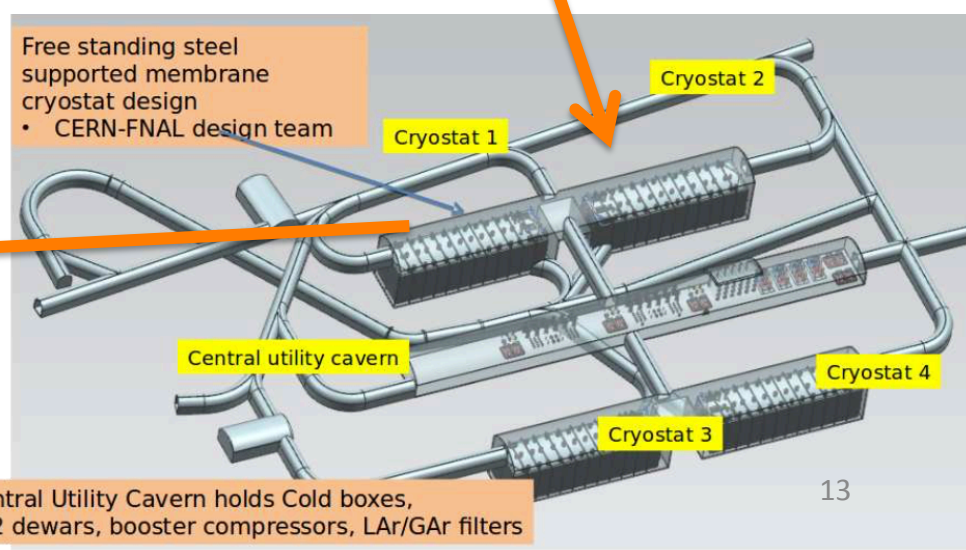


Cryostat outer steel structure



External (Internal) Dimensions
19.1m (16.9m) W x 18.0m (15.8m) H x 66.0m (63.8m) L

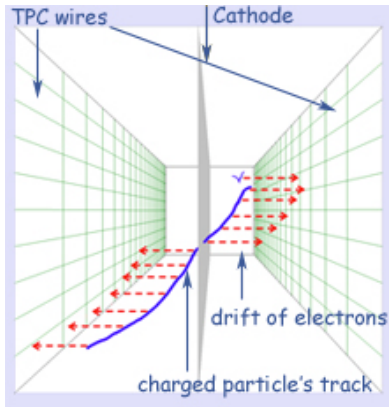
Can accommodate single and dual-phase LAr detectors

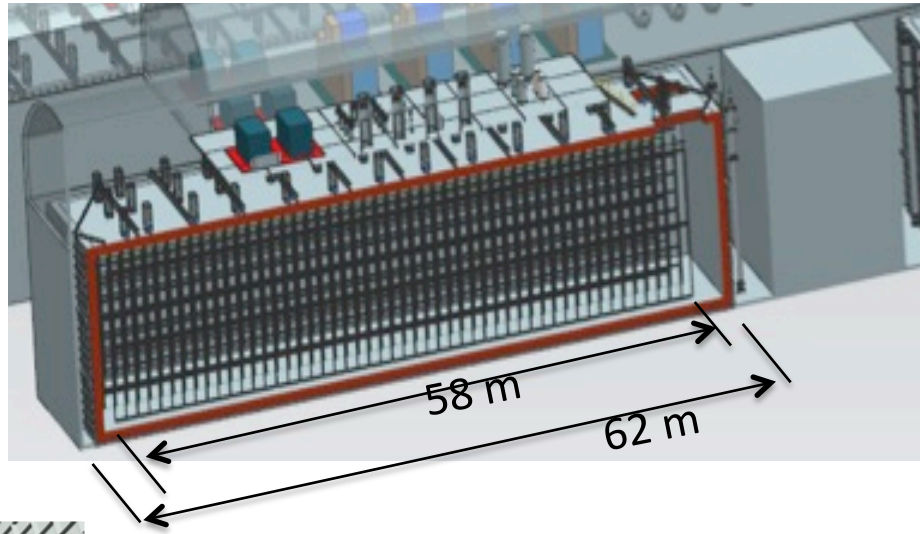


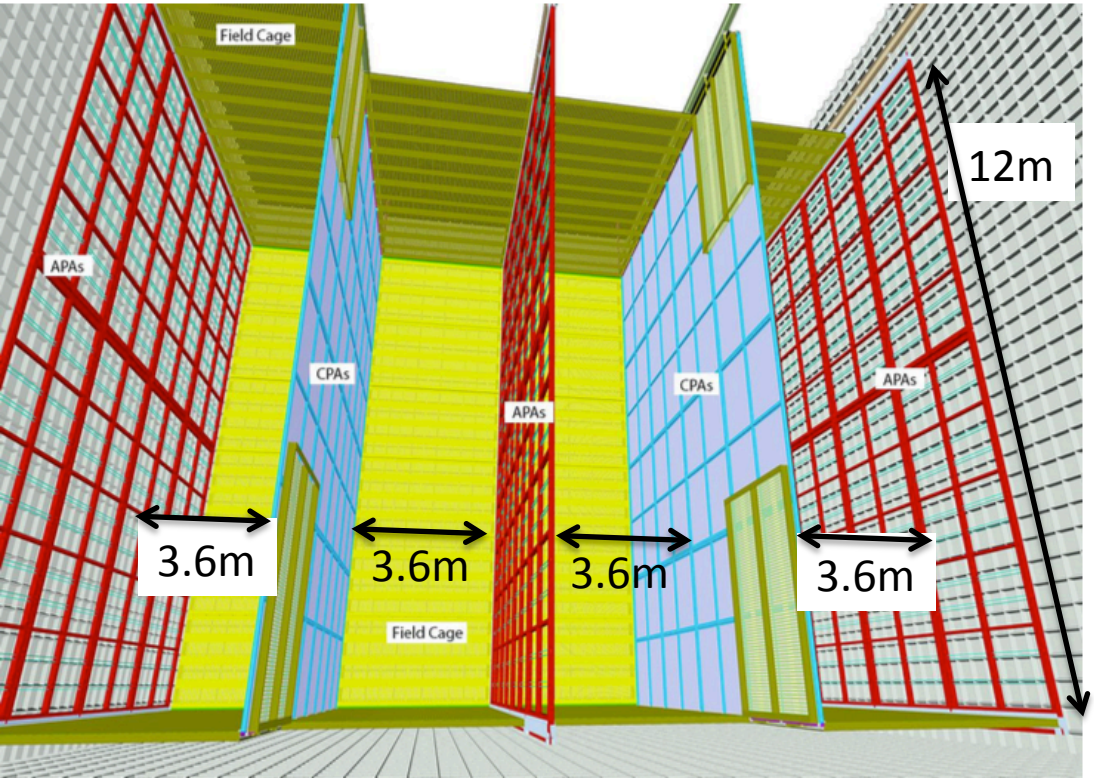
Single-Phase LAr Detector

Readout of
- Ionization charge and
- scintillation light

Detector mass [kt]	
total	17.1
active	13.8
fiducial	11.6







Time Projection Chamber:

3 wire Anode Planes (APAs)

[induction + collection wires]

2 cathode planes at -180 kV

4 drift regions: 3.6m drift each

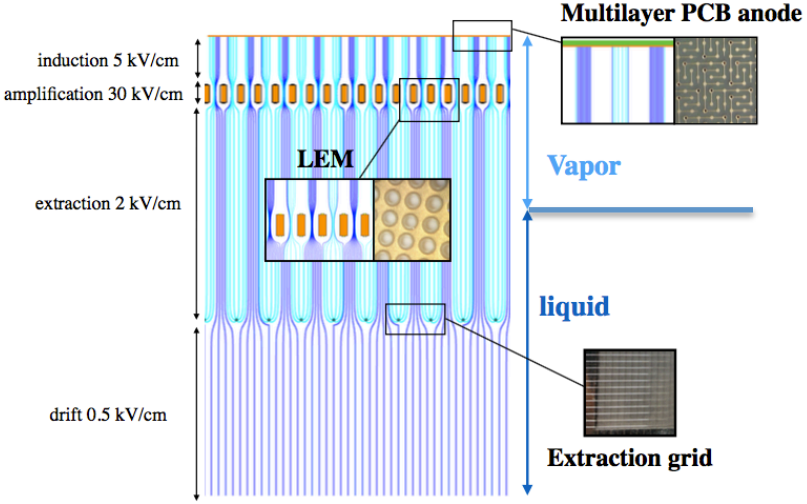
Photon Detection System

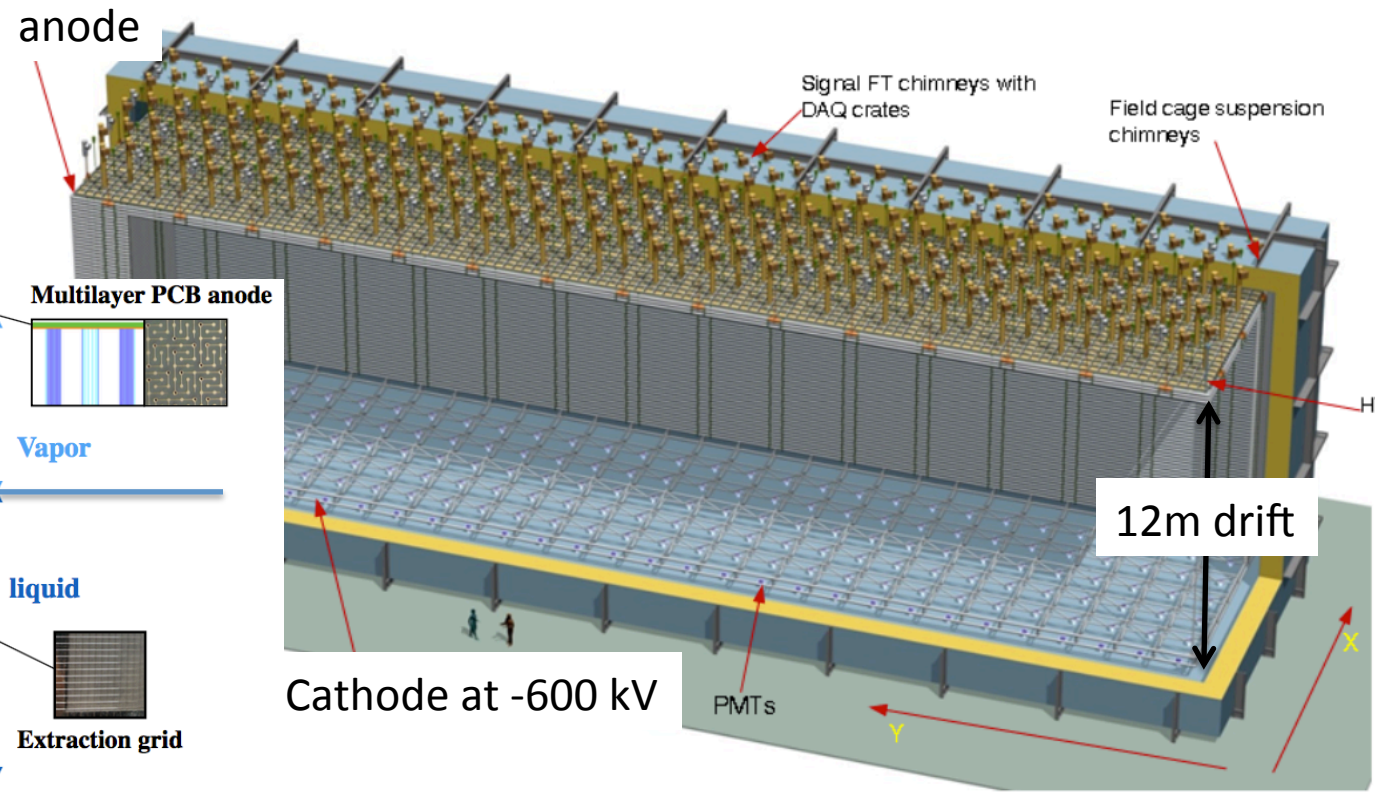
integrated in APAs to measure non-beam event timing

Dual-Phase LAr Detector

Readout of

- Ionization charge
- scintillation light





Ionization charge extracted into Ar gas phase
charge amplification via large electron multipliers (LEM) before readout
[2 dimensional charge collection]

→ If demonstrated, could be used as alternative design for 2nd or subsequent 10 kt far detector modules

DUNE Near Detector

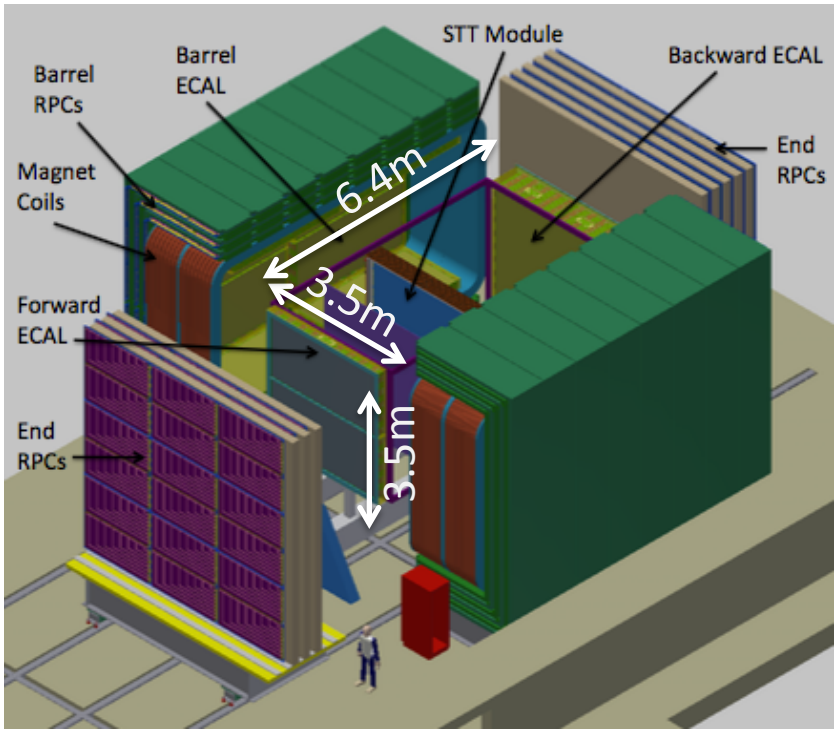
Measure :

CC ν_μ events (normalization, spectrum)
CC ν_e , NC π^0 events (backgrounds)
Neutrino interaction properties

$\sim 10^7$ interactions/yr
→ high precision

Reference design:

Fine Grained Tracker inside 0.4 T magnetic field : straw-tube tracker
Surrounded by lead-scintillator ECal and RPC muon tracker



Multiple nuclear targets:
Ar, C, Ca, Fe, …

Active work on other designs:

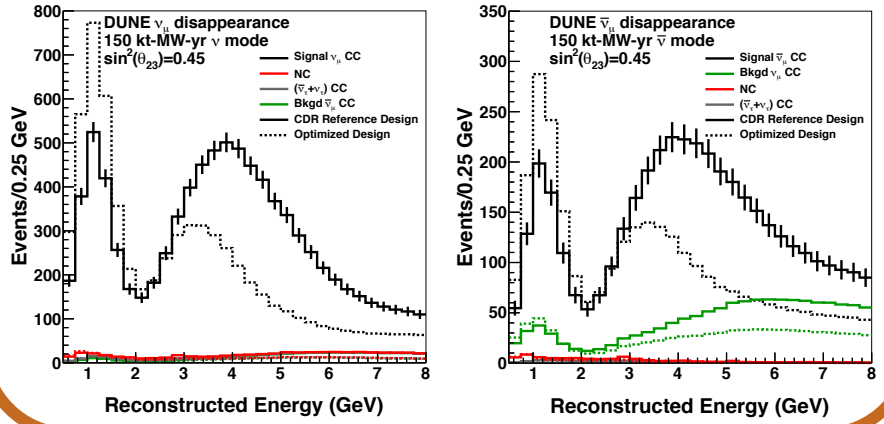
- LAr TPC
- Magnetized high-pressure GAr TPC
- Hybrid designs

Neutrino Oscillation Prospects

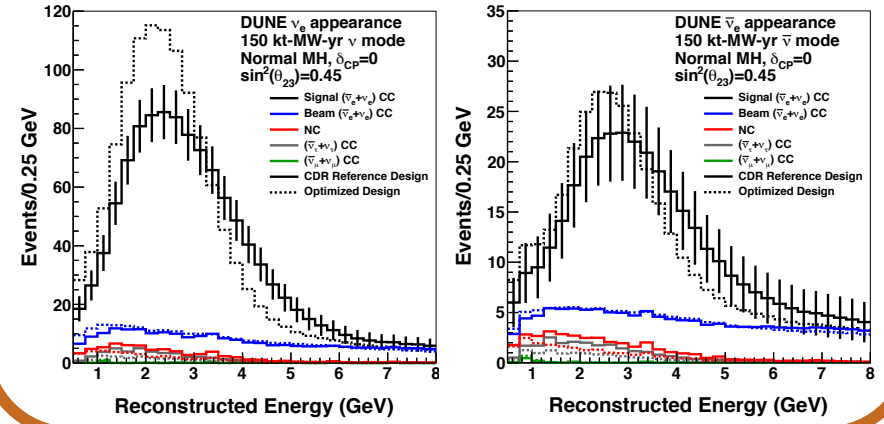
Exposure: 150 kt MW yr

Assumes: $\sin^2 2\theta_{13} = 0.084$, $\sin^2\theta_{23} = 0.45$, $\Delta m^2_{31} = 2.47\times10^{-3}$, $\delta_{CP} = 0$

$\nu_\mu / \bar{\nu}_\mu$ disappearance



$\nu_e / \bar{\nu}_e$ appearance



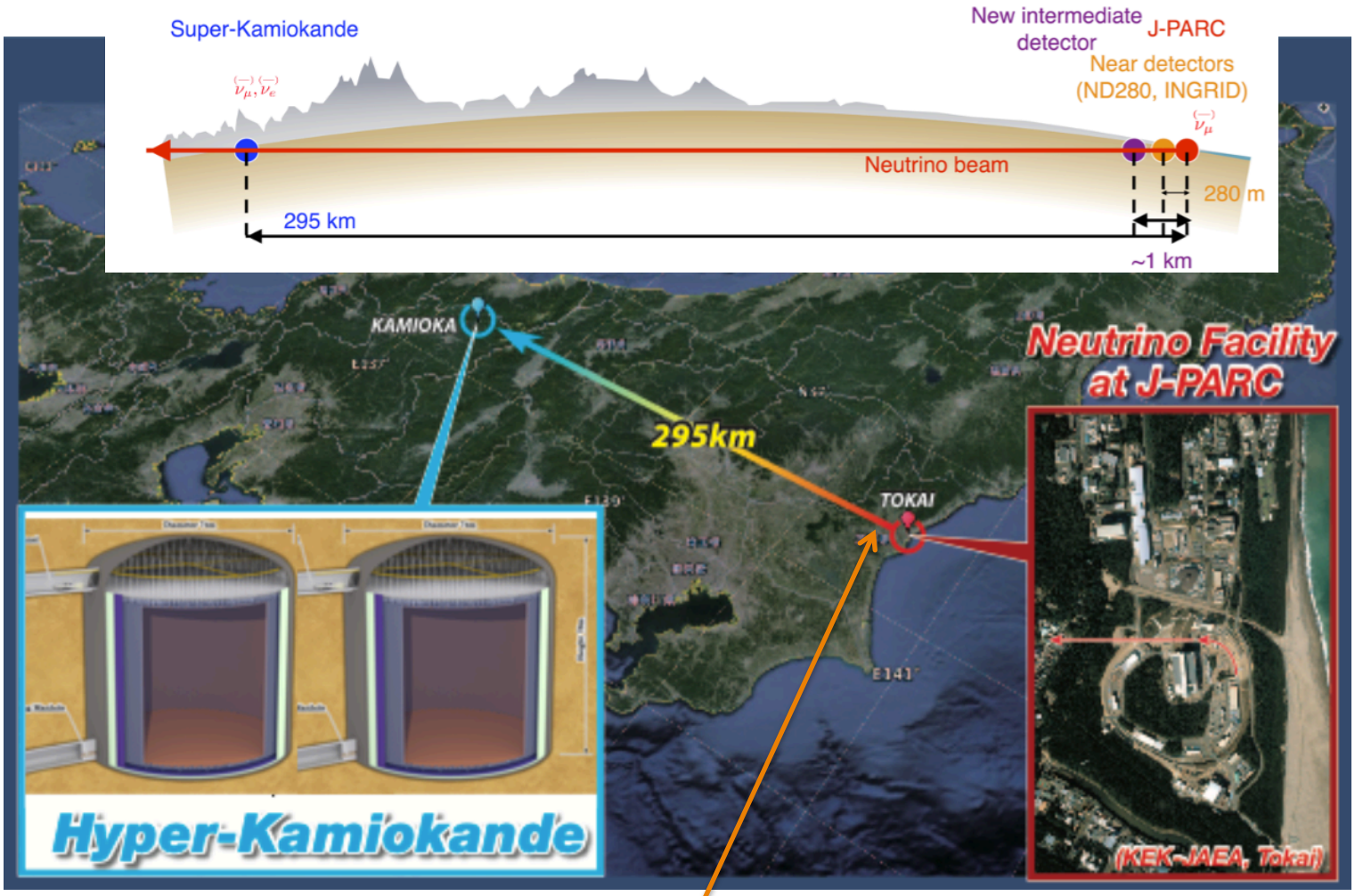
→ Simultaneous fit to all 4 samples to determine oscillation parameters

Integrated events 0.5 – 20 GeV

	CDR Reference Design	Optimized Design
ν mode (150 kt · MW · year)		
ν_μ Signal	10842	7929
$\bar{\nu}_\mu$ CC Bkgd	958	511
NC Bkgd	88	76
$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd	63	29
$\bar{\nu}$ mode (150 kt · MW · year)		
$\bar{\nu}_\mu$ Signal	3754	2639
ν_μ CC Bkgd	2598	1525
NC Bkgd	50	41
$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd	39	18

	CDR Reference Design	Optimized Design
ν mode (150 kt · MW · year)		
ν_e Signal NH (IH)	861 (495)	945 (521)
$\bar{\nu}_e$ Signal NH (IH)	13 (26)	10 (22)
Total Signal NH (IH)	874 (521)	955 (543)
Beam $\nu_e + \bar{\nu}_e$ CC Bkgd	159	204
NC Bkgd	22	17
$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd	42	19
$\nu_\mu + \bar{\nu}_\mu$ CC Bkgd	3	3
Total Bkgd	226	243
$\bar{\nu}$ mode (150 kt · MW · year)		
ν_e Signal NH (IH)	61 (37)	47 (28)
$\bar{\nu}_e$ Signal NH (IH)	167 (378)	168 (436)
Total Signal NH (IH)	228 (415)	215 (464)
Beam $\nu_e + \bar{\nu}_e$ CC Bkgd	89	105
NC Bkgd	12	9
$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd	23	11
$\nu_\mu + \bar{\nu}_\mu$ CC Bkgd	2	2
Total Bkgd	126	127

Hyper-K and J-PARC Overview

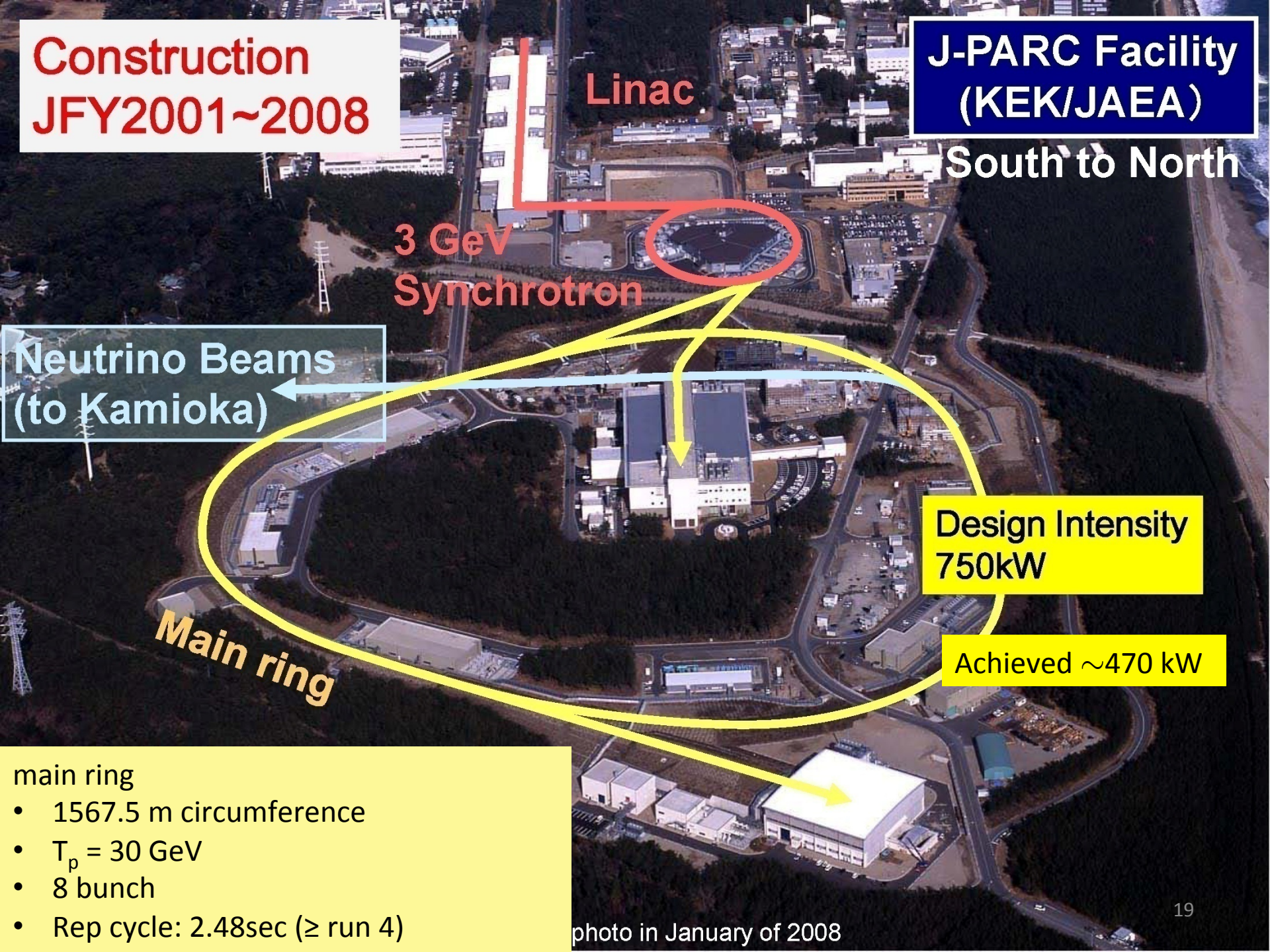


Two water Cherenkov detectors (staged approach)

Near (280m) and Intermediate (1km) detectors

narrow band, high purity ν_μ beam with peak flux at 0.6 GeV operating at $\sim$1.3 MW

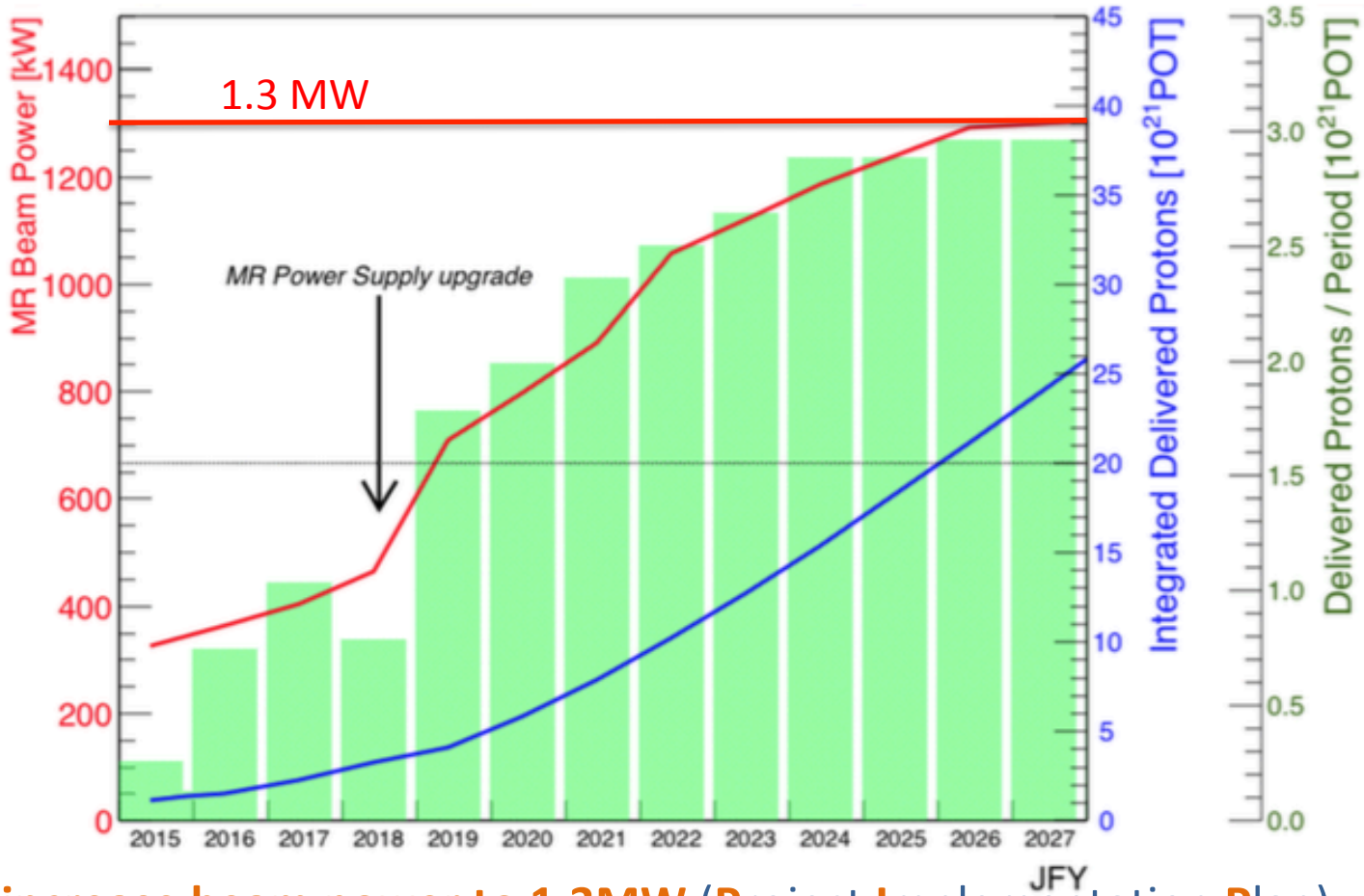
Also see S. Nakayama: 6/20 neutrino parallel session



main ring

- 1567.5 m circumference
- T_p = 30 GeV
- 8 bunch
- Rep cycle: 2.48sec (≥ run 4)

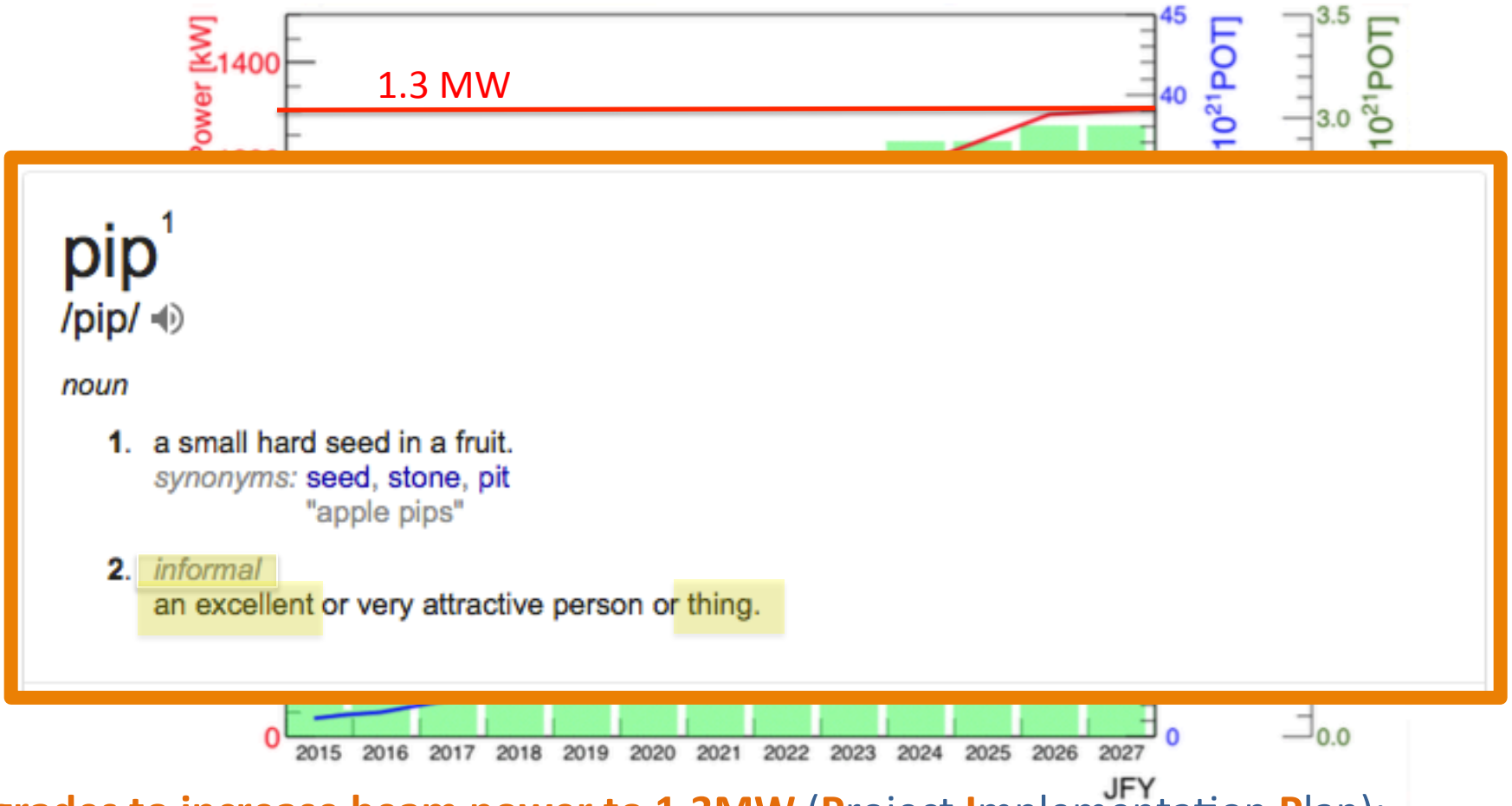
J-PARC beam power



Upgrades to increase beam power to 1.3MW (**P**roject **I**mplementation **P**lan):

- New power supply (~2019)
- Main ring rep. rate: 2.48s → 1.3s (2019) →1.25s →1.2s → 1.16s
- RF system upgrades
- KEK PIP highest priority: J-PARC upgrade for HK

J-PARC beam power



pip[1]
/pip/

noun

1. a small hard seed in a fruit.
   synonyms: seed, stone, pit
   "apple pips"

2. *informal*
   an excellent or very attractive person or thing.

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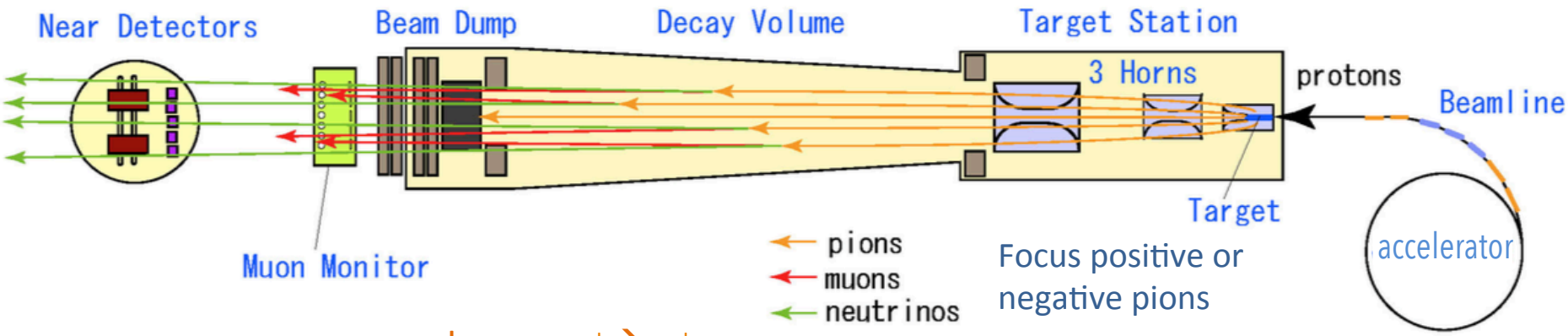
J-PARC accelerator and ν beam



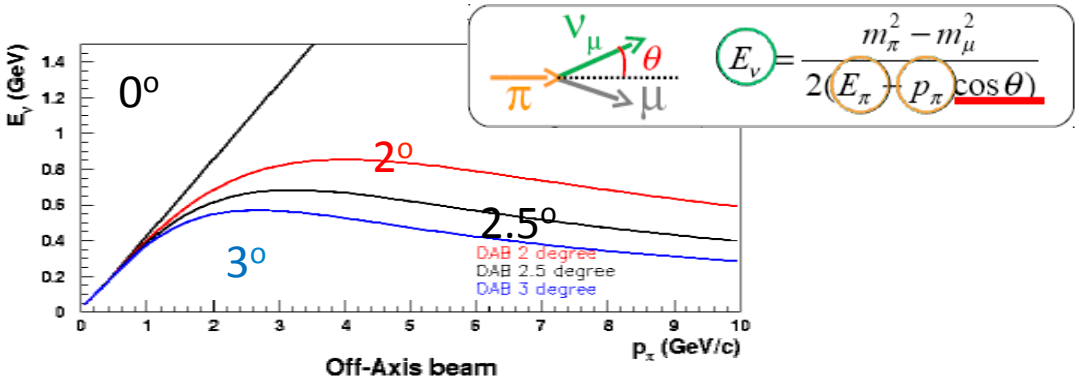
Focus positive or negative pions

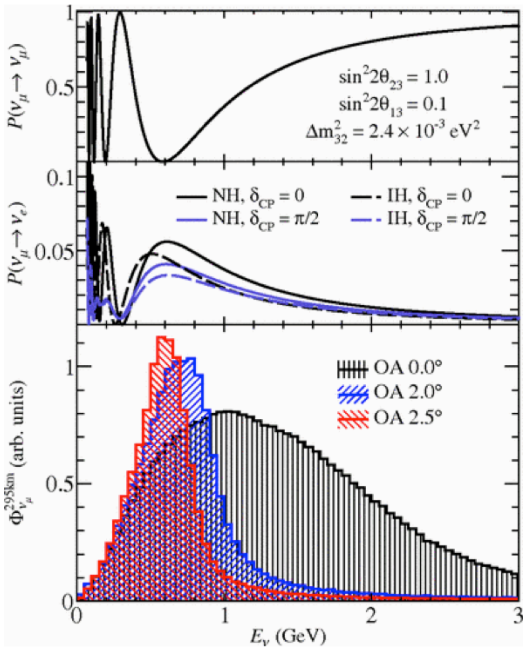
ν beam: $\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\bar{\nu}$ beam: $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

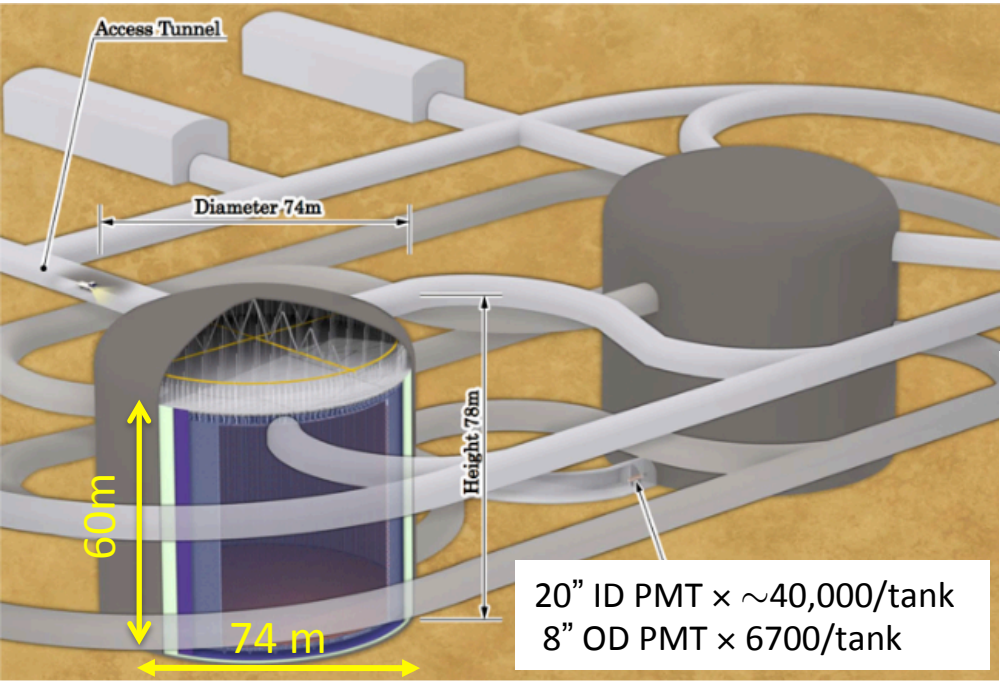
Muon monitors
Near ν detectors

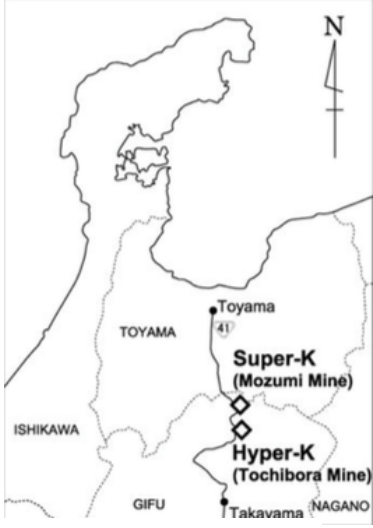
to measure ν beam (composition), backgrounds and ν cross sections





Hyper-Kamiokande Design

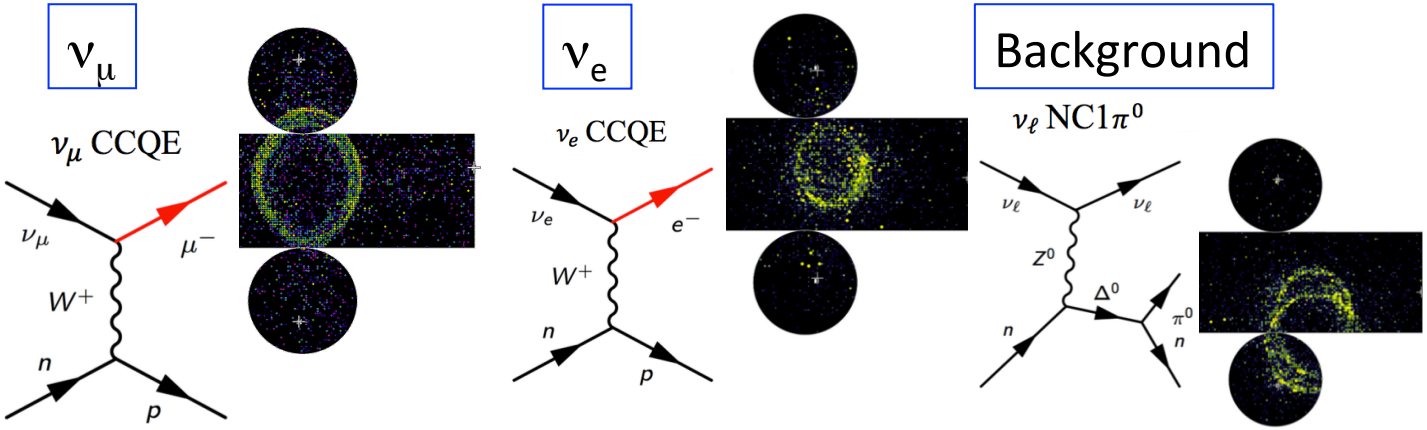


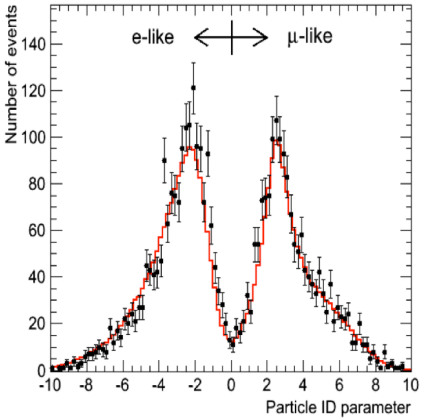


2x 260 kt Water-Cherenkov detector
(Fiducial : 2x 190 kt)
→ Staged approach (+ ~6yrs)

40% Photo coverage; high QE PMTs

Good energy resolution



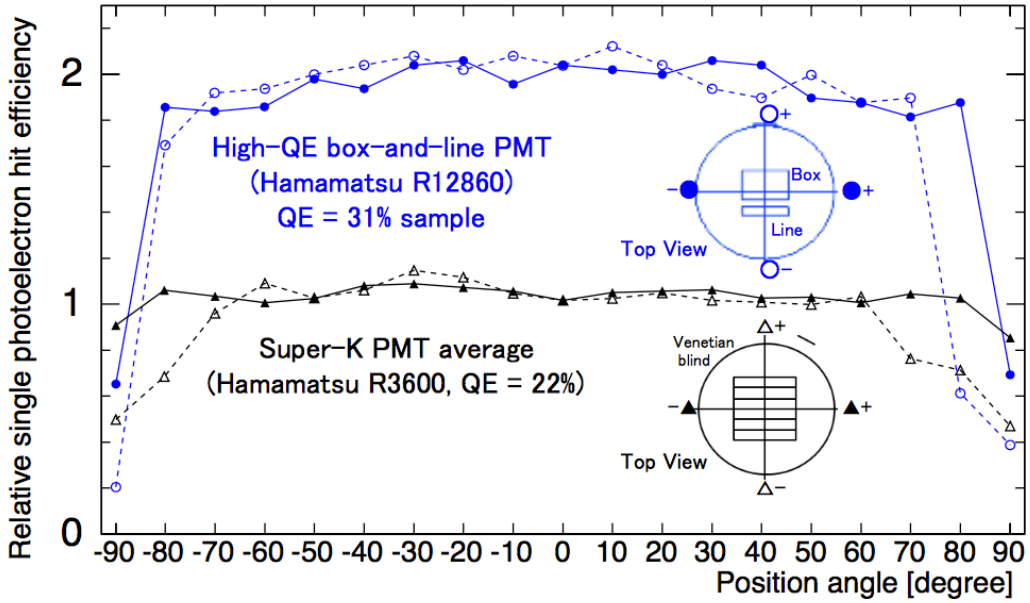


Good e/μ separation:
mis-idendification < 1%

Photosensor R&D

20“ HQE
Box and line PMT

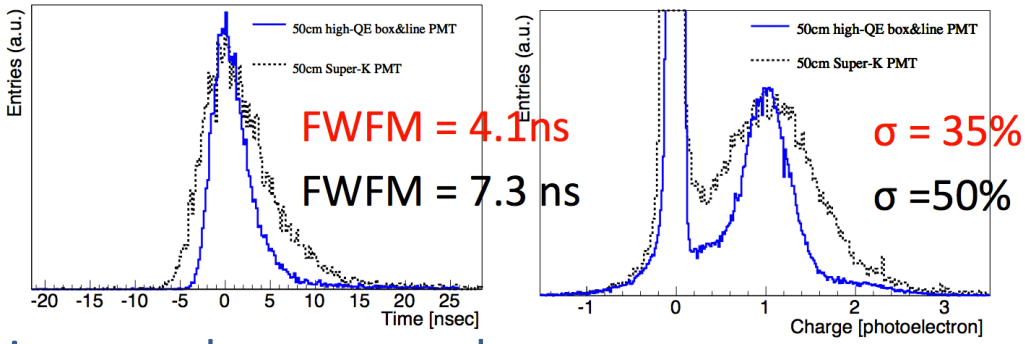
SK 20” PMT



2x light
detection efficiency

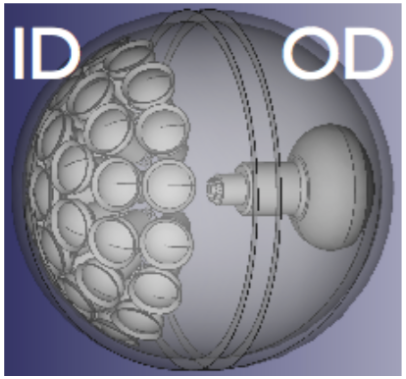
Developed with Hamamatsu:

- improved photocathode and dynode structure
- improved timing and photoelectron resolution



- improved pressure tolerance

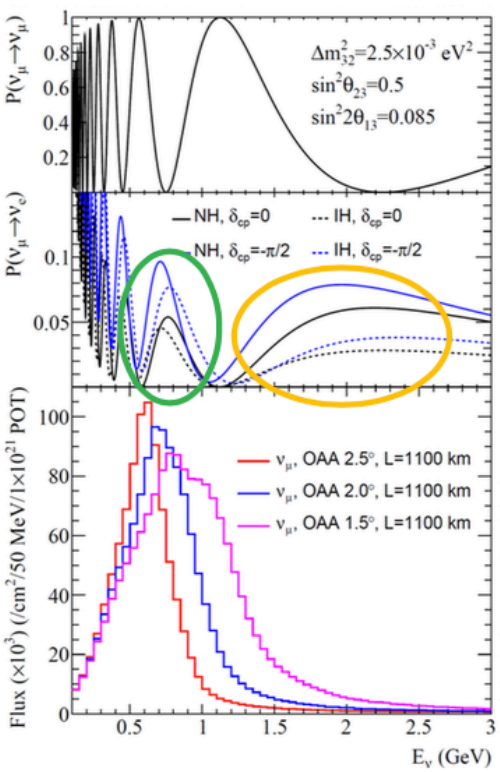
Studies of alternate solutions
in progress (with KM3NeT):



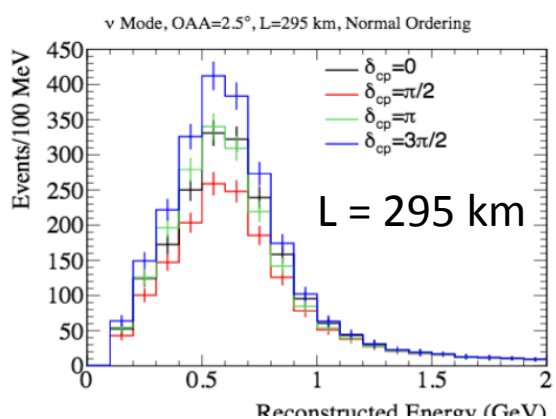
Option: 2nd Far Detector in South Korea

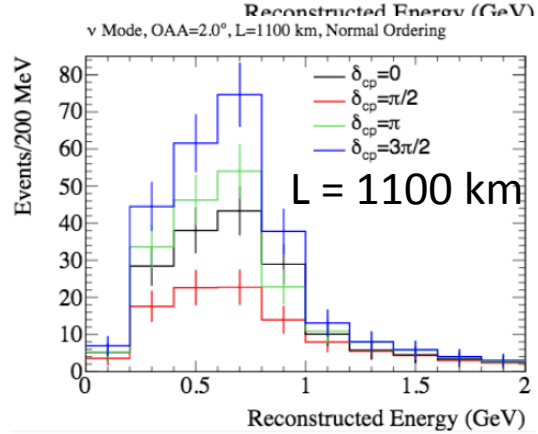
Key features:

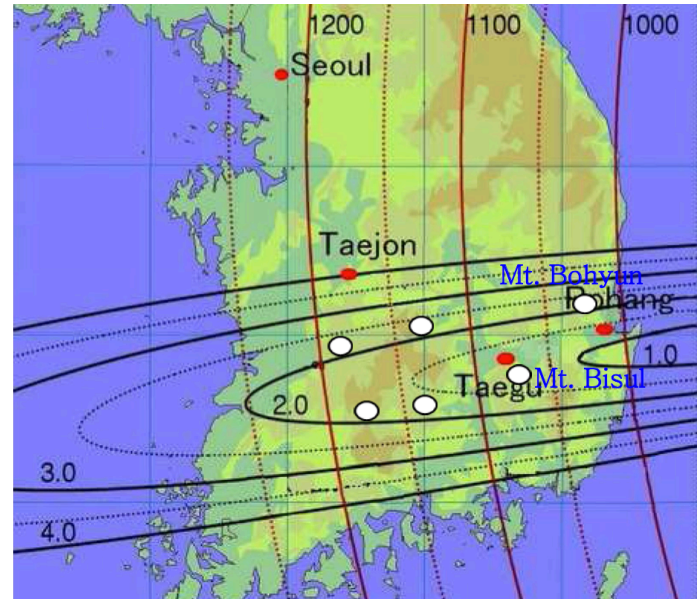
- Coverage of 2nd oscillation maximum (CP effect ~3x larger)
- Baseline: ~1100 km → mass hierarchy sensitivity
- Larger overburden relative to Japanese site



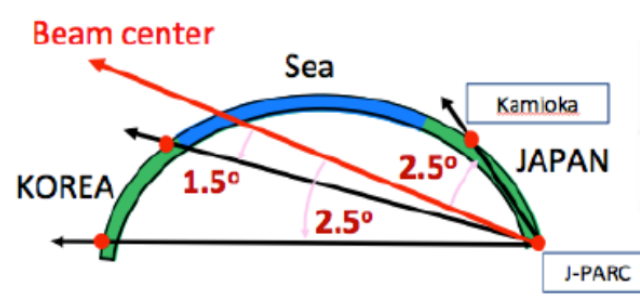
ν_e appearance event spectra







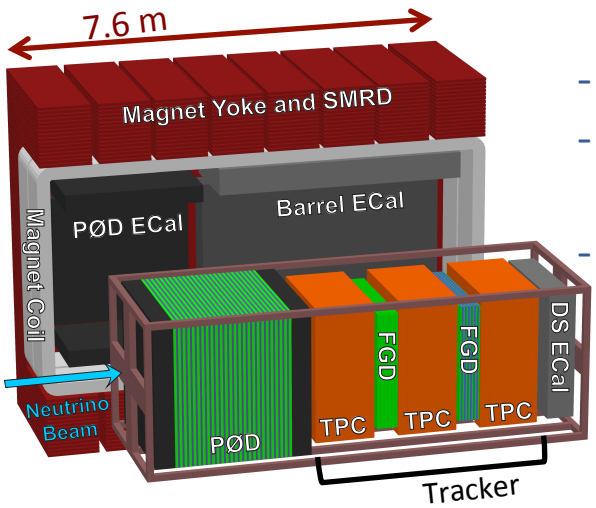
location	Baseline [km]	angle [°]	depth [km w.e.]
Bisul	1088	~ 1.3	2.2
Bohyun	1040	~ 2.2	2.2



White paper in preparation

Near + intermediate detectors

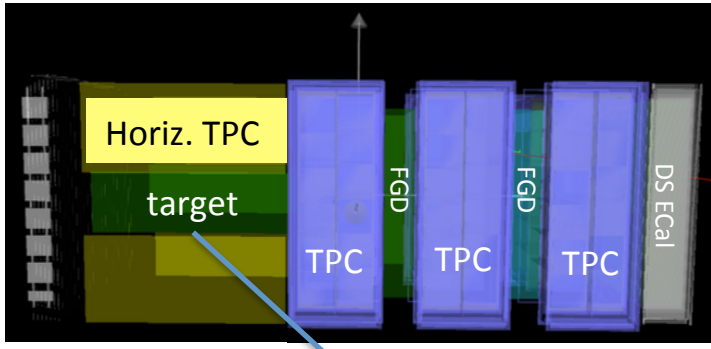
Off-axis near detector (ND280)

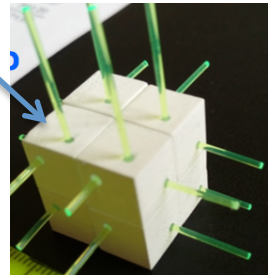


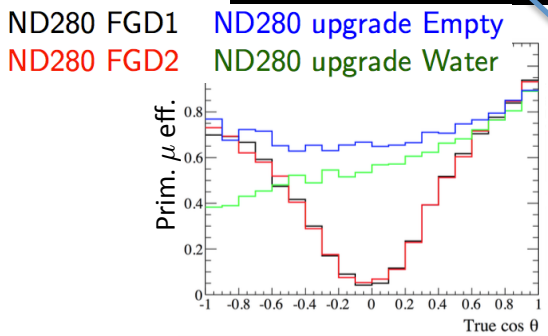
Key Improvements:

- Increase angular acceptance
- distinguish forward/backward tracks: ~ ns timing
- lower $p_{threshold}$: ~ 200 MeV/c
  - few tons of mass

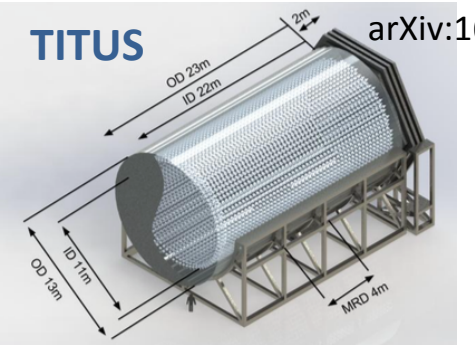
ND280 **upgrade (R&D in progress)**







Intermediate water Cherenkov detector



arXiv:1606.08114

Capture high momentum muons

Gd loaded

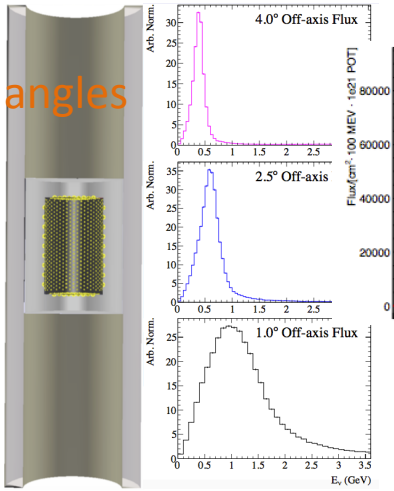
Magnetized muon range detector

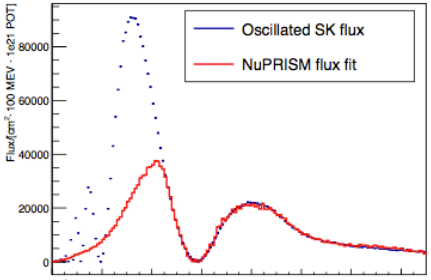
Work in progress to merge efforts

NuPRISM

Span multiple off-axis angles

arXiv:1412.3086





match oscil. flux with ND flux fit

Neutrino Oscillation Prospects

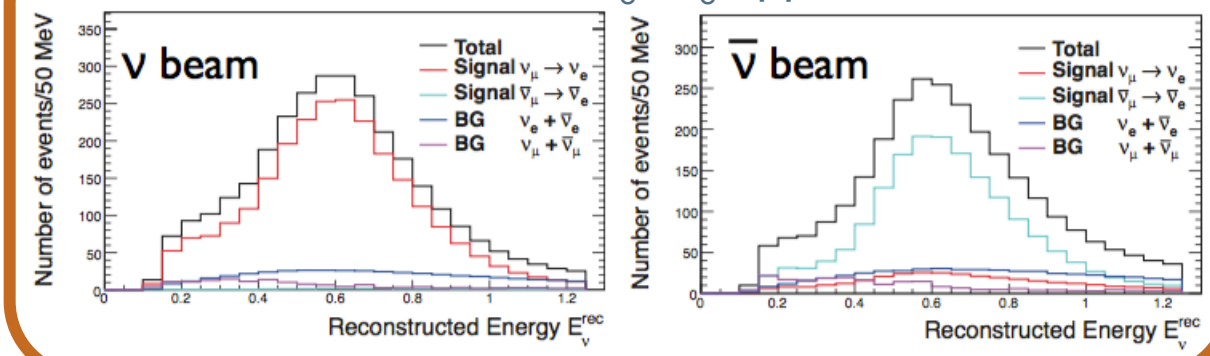
Exposure: 1.3 MW, 10 yrs

$\nu/\overline{\nu}$ = 1:3

1st detector

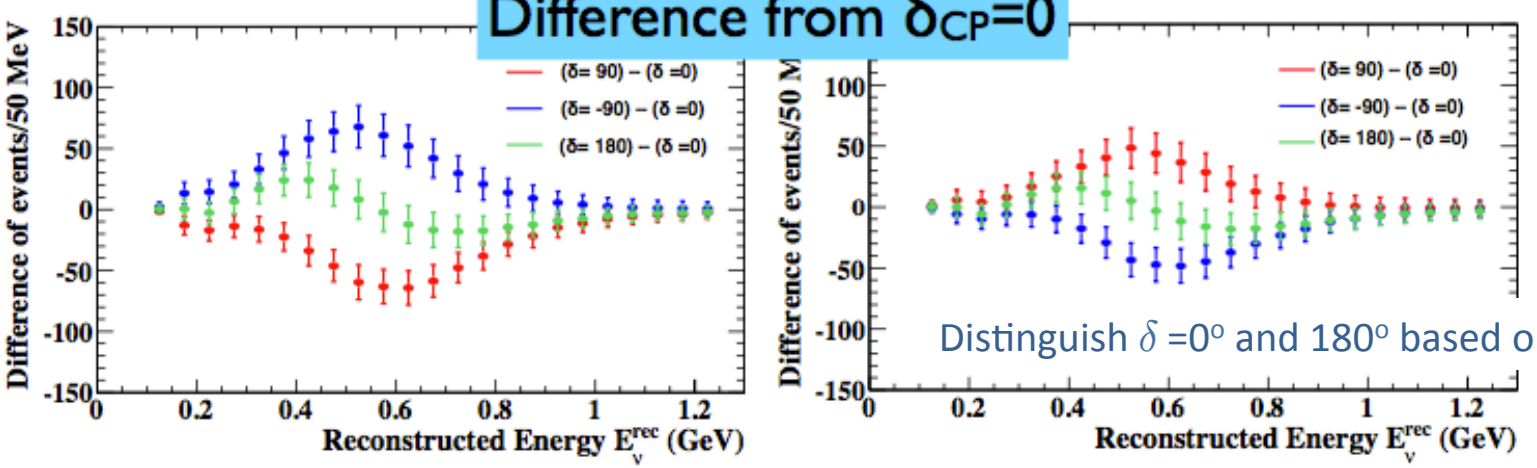
+ 2nd detector after 6 yrs

ν_e / $\overline{\nu}_e$ appearance



for δ=0	Signal (νμ→νe CC)	Wrong sign appearance	$\nu_\mu/\bar{\nu}_\mu$ CC	beam $\nu_e/\bar{\nu}_e$ contamination	NC
ν beam	2,300	21	10	362	188
$\bar{\nu}$ beam	1,656	289	6	444	274

Difference from δ_{CP}=0

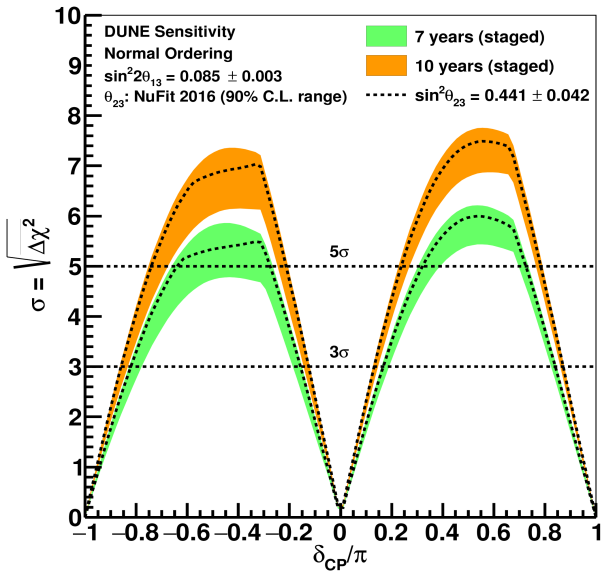


Distinguish δ =0° and 180° based on shape

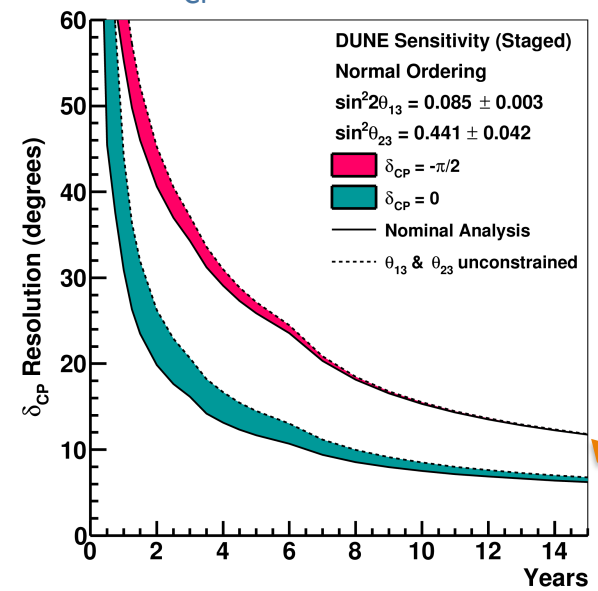
Projected CP Performance

DUNE

CP violation sensitivity

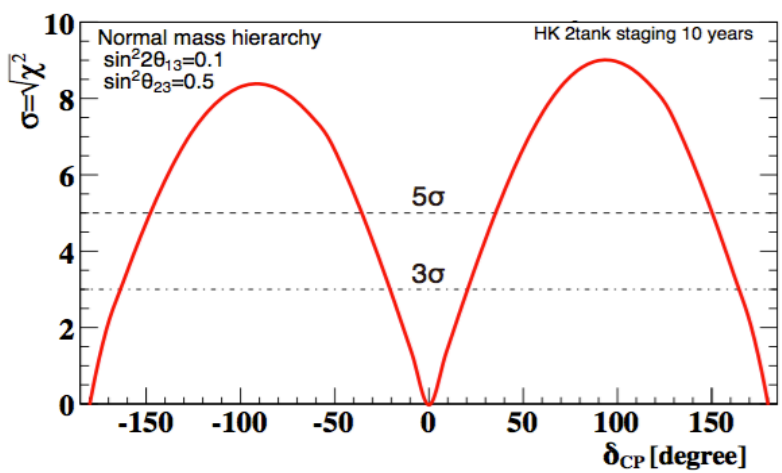


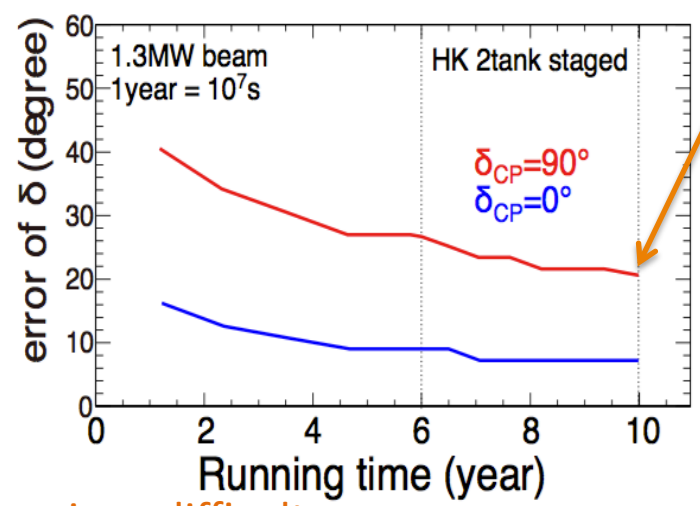
δ_{CP} resolution



Worst precision for presently favored value !

HK





Caveat: differences in assumptions → detailed comparison difficult

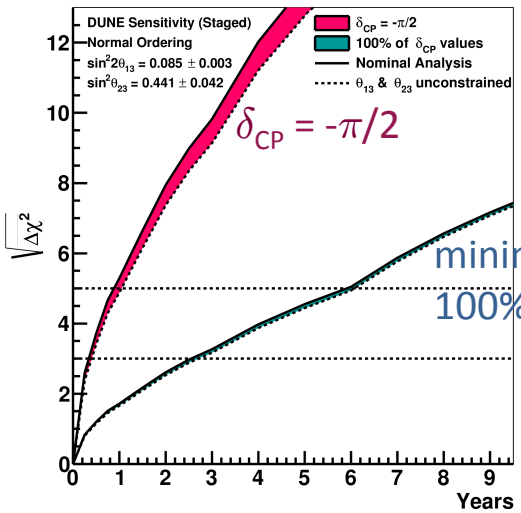
Overall: similar performance projections

Projected Performance

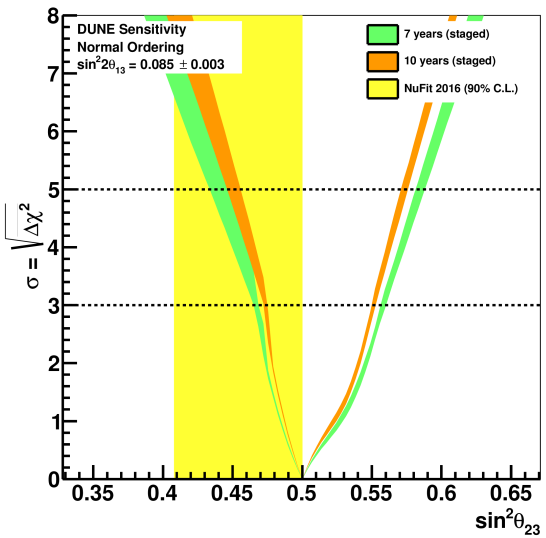
Mass hierarchy sensitivity

Octant sensitivity

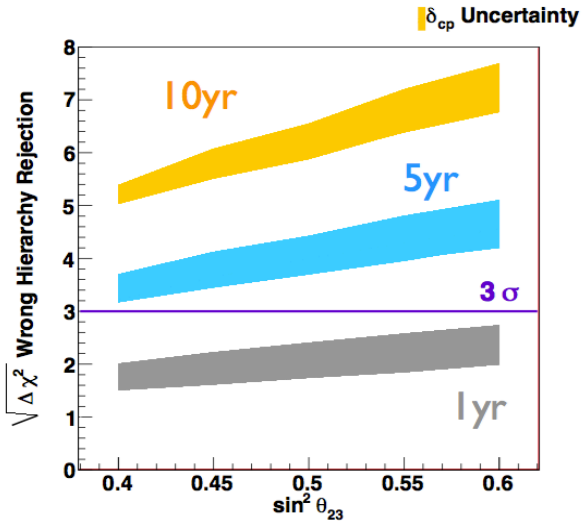
DUNE
beam only

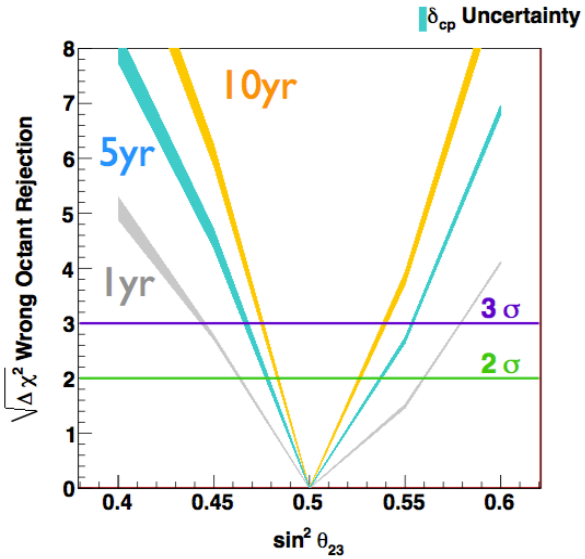


minimum for
100% of δ_{CP} values



HK
beam and
atmospherics





→ definitive determination
of neutrino mass hierarchy

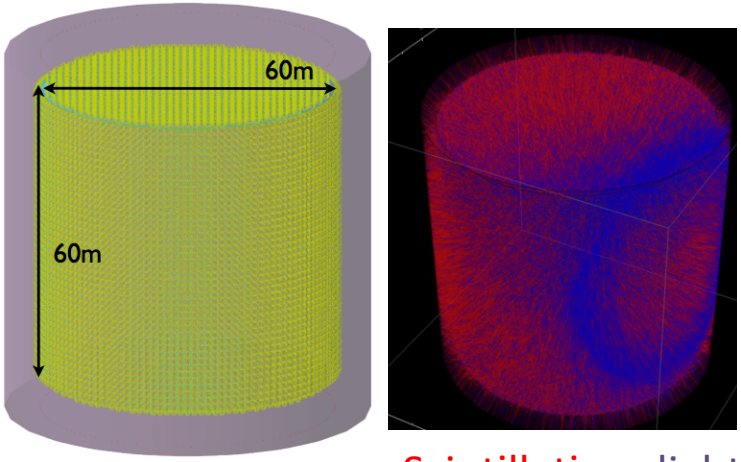
→ **Similar performance projections**

Potential Other Projects

THEIA : Advanced Scintillation Detector Concept

arXiv: 1409.5864

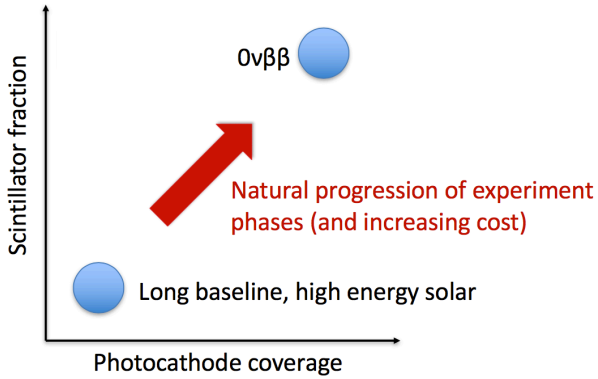
Water based liquid scintillator
high light yield
→low threshold, good energy resolution
combined with fast + efficient photon detectors



Scintillation light
Cherenkov
→Improved particle ID

Potential Physics program:

- Long-baseline physics
- Nucleon decay
- SNe burst neutrinos and DSNB
- Source based sterile searches
- Geo-neutrinos
- Solar neutrinos
- Neutrinoless double beta decay



Farther future and less certain possibilities not discussed here (apologies):

- ESSnuSB, Nu factory, Nu storm, …

also see M. Dracos: 6/20 neutrino parallel session

Summary and Outlook

- Reiterated some of the key questions in neutrino physics
  - Long-baseline neutrino oscillations: CP violation, mass hierarchy, precision measurements of neutrino oscillation parameters

- **LBNF/DUNE** will employ a 1.2 MW (and upgradable) broadband neutrino beam, near detector and modular 40kt LAr far detector at 1300km from Fermilab and located at SURF

- **J-PARC/Hyper-K** plans to use a 1.3 MW narrow band neutrino beam, near and intermediate detectors and one or possibly two far water Cherenkov detectors located at a distance of 295km (1100 km)

- Both programs have similar sensitivities (and timelines)
  - are complementary in technology
  - → Both experiments are needed for best precision