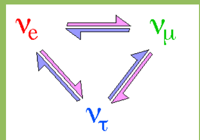

Review and Status of Neutrino Oscillation Studies from Long Baseline Accelerator Based Experiments

ICPPA 2022 December 1, 2022

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Outline*

- History and Motivation : ν's
- Present:T2K and NOvA Experiments
- Oscillation Results:
  - Muon (+Anti-)Neutrino Disappearance
  - Electron (+Anti-)Neutrino Appearance
  - Joint Fits
- Future Hyper-K and DUNE
- Prospects, Outlook and Summary

* Disclaimer: I am not officially representing T2K, NOvA, Hyper-K, or DUNE. I am summarizing public knowledge.

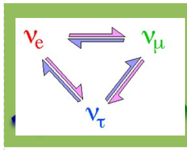
Neutrinos

"I have done a terrible thing, I have postulated a particle that cannot be detected…"

→ Wolfgang Pauli, 1930, after postulating the existence of the neutrino

Pauli was not too far off – They are hard to detect (first detected in late 1950's)
→ One needs lots of them and massive detectors.

Presently we know of three active neutrinos: ν_e, ν_μ, ν_τ



Neutrino Masses and Mixing

- 1969-90s Ray Davis Measures Solar ν_e Flux at Homestake Deep Underground Mine ~1/3 Expected! Gallex, Sage, SuperK, SNO, Kamland (Reactor)
  - Interpretation: solar $\nu_e \rightarrow 1/3\ \nu_e + 1/3\nu_\mu + 1/3\nu_\tau$ (roughly)

- 1980s IMB, Kamioka, measure atm. ν_μ flux, less than expected. SuperK; K2K, MINOS (Accelerators) Confirm
  - Interpretation: atm. $\nu_\mu \rightarrow 1/2\nu_\mu + 1/2\nu_\tau$

What's going on… Neutrino Oscillations Established:
→ Neutrinos are not mass eigenstates
→ Neutrino Masses & Mixing Measurements Era Began

→ Evidence for physics beyond the Standard Model

3-Flavor Mixing (PMNS Matrix)

- 3-flavor mixing describes (almost) all neutrino oscillation phenomena (3 mixing angles, 2 independent mass splittings, 1 CPV phase)

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\boxed{\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{+i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\boxed{\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

<u>Atmospheric & accelerator:</u>
$\theta_{23} \sim 45^\circ$
$\Delta m^2_{23} \sim 2.4\times10^{-3}\ \mathrm{eV}^2$

<u>Interference:</u>
$\Theta_{13} \sim 8.4^\circ$ and δ_{CP}=??

<u>Solar & reactor:</u>
$\theta_{12} \sim 34^\circ$
$\Delta m^2_{12} \sim 8\times10^{-5}\ \mathrm{eV}^2$

Muon neutrino disappearance ($\nu_\mu \rightarrow \nu_\mu$) :

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - (\cos^2\theta_{13}\sin^2 2\theta_{23})\sin^2\left(\Delta m^2_{32}\frac{L}{4E}\right)$$

→ **Sensitive to:**
θ_{23}, $|\Delta m^2_{31}|$ ($\sim|\Delta m^2_{32}|$)
($\Delta m^2_{32} = m^2_3 - m^2_2$)

Electron neutrino appearance ($\nu_\mu \rightarrow \nu_e$):

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\left(1+\frac{2a}{\Delta m^2_{31}}(1-2\sin^2\theta_{13})\right)$$

Leading term

$$-\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}\sin\delta\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\sin\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)$$

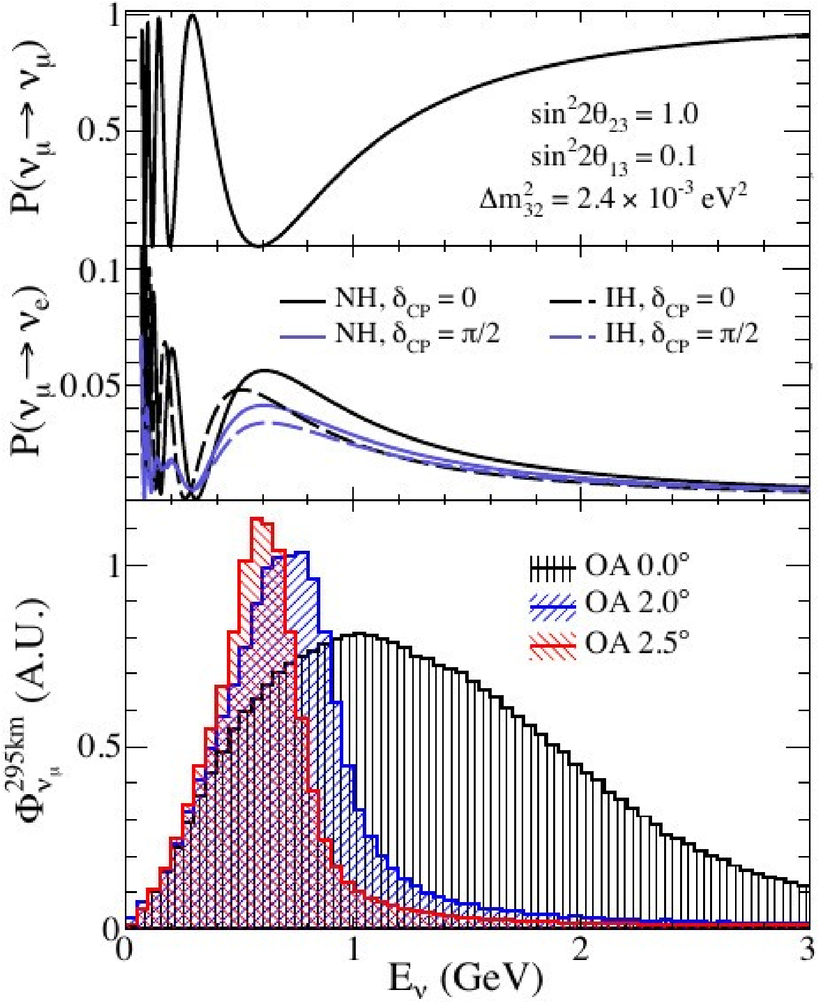
CP violating

→ **Sensitive to:**
θ_{13}, δ_{CP}, θ_{23}, Δm^2_{31}

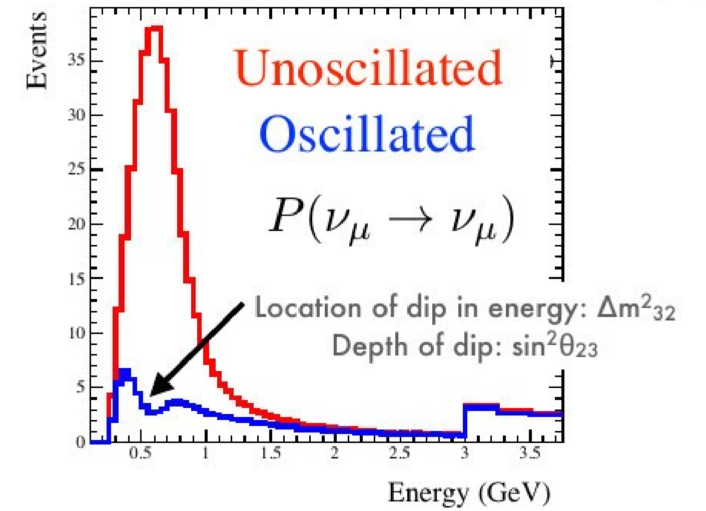
Depends on sign of mass difference: *i.e.* Mass Ordering

[($P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ δ_{CP} turns into - δ_{CP} and a to -a (“a” matter effect term)]

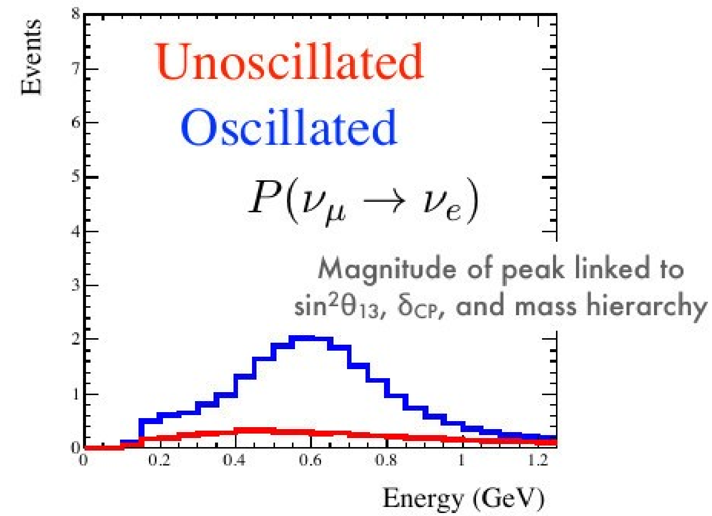
Oscillation Primer:
Common to All Accelerator Based Oscillation Experiments



Disappearance



Appearance

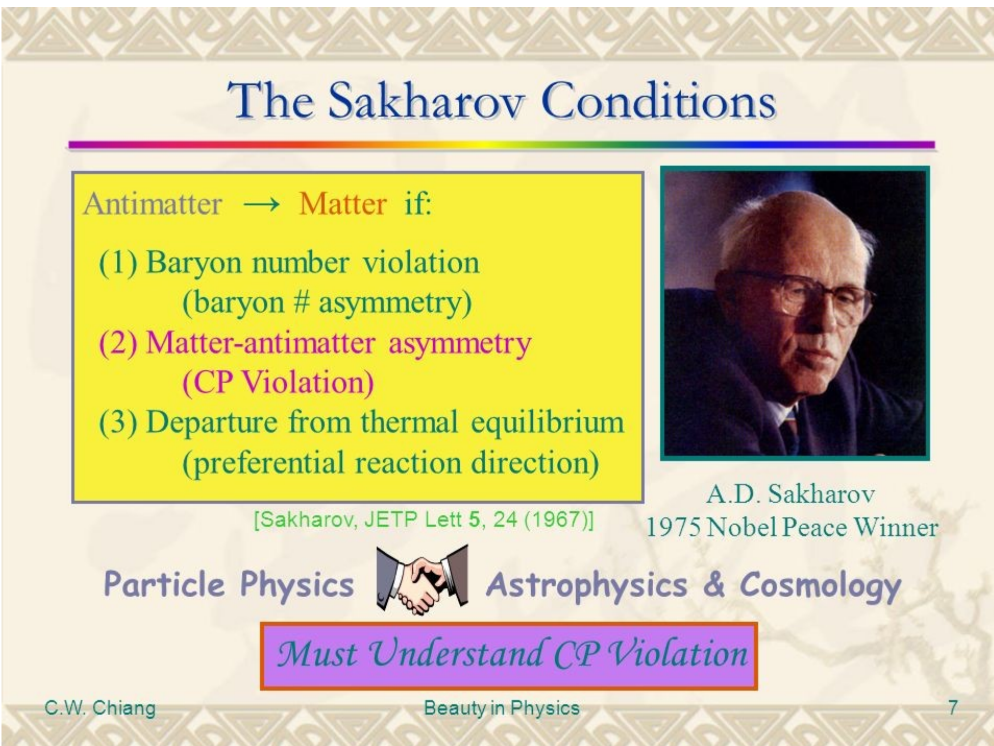


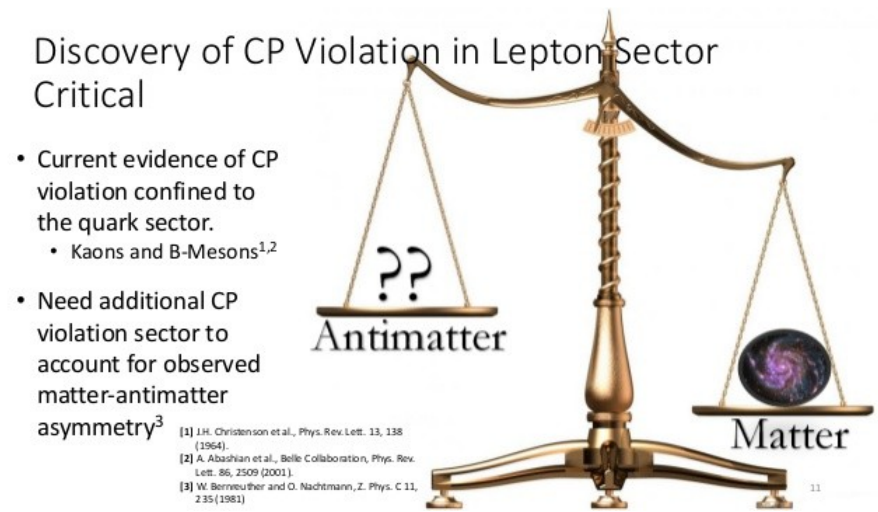
→ P obtained by measuring ratio of un-oscillated (Near Detector) to oscillated spectra (Far Detector)

Motivation

The matter-antimatter asymmetry problem:

The Big Bang should have created equal amounts of matter and antimatter.
So why is there far more matter than antimatter in the universe?





What Do We Know?

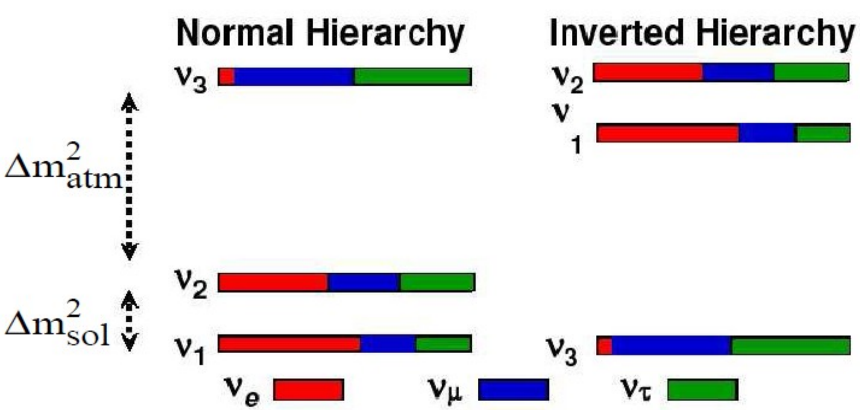
Solar+KamLAND → $\theta_{12} \sim 34^0$

SK, MINOS, T2K, NOνA → $\theta_{23} \sim 45^0$

Daya Bay, Reno, Double Chooz → $\theta_{13} = \sim 8.4^0$

(T2K: $\theta_{13} \neq 0 \rightarrow$ In Appearance Channel)

(NO) (IO)



$\Delta m^2_{21} = (7.65 + \pm 0.23) \times 10^{-5}$ eV^2

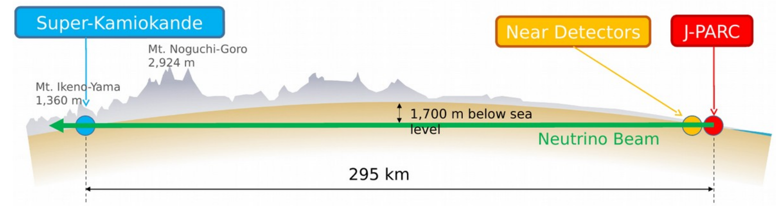
sign of the mass difference, $\Delta m^2_{21} > 0$.

$\Delta m^2_{32} (\approx \Delta m^2_{31}) = (2.40 \pm 0.12) \times 10^{-3}$ eV^2

What We Don't Know?

- **Value CP-Violating Phase: δ**
- θ_{23} **Maximal? Octant? (< or > 45^0)**
- **Sign of the mass difference (MO):** $\Delta m^2_{32} = m^2_3 - m^2_2$
  - **Normal Ordering (NO) > 0**
  - **Inverted Ordering (IO) < 0**
- **Above items accessible with LBL**
- **Are there any more ν's? (sterile)**
- **Are Neutrinos Dirac or Majorana?**
- **Absolute Mass Scale**

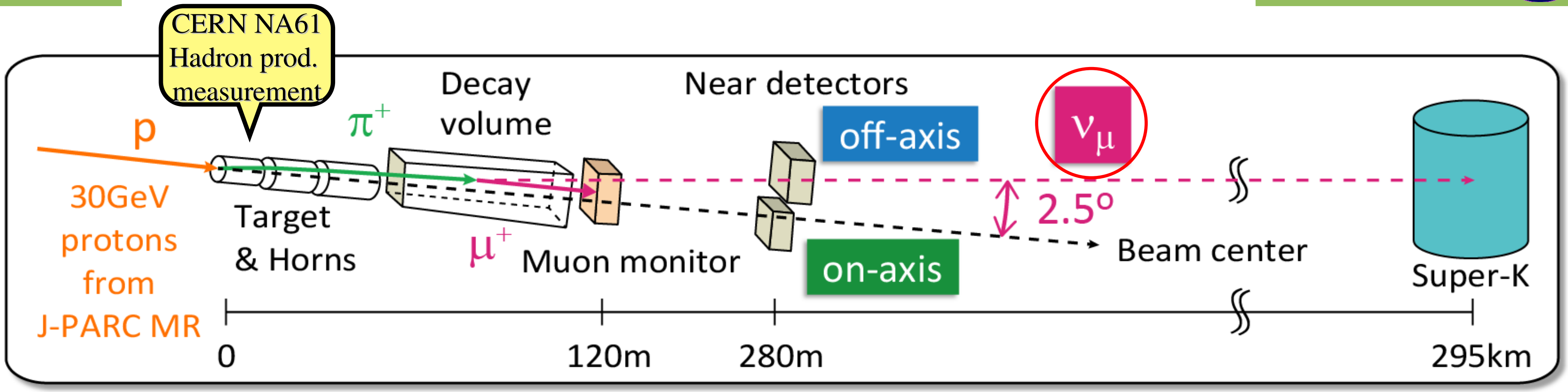
The T2K Experiment
(Tokai to Kamioka)



Goals:

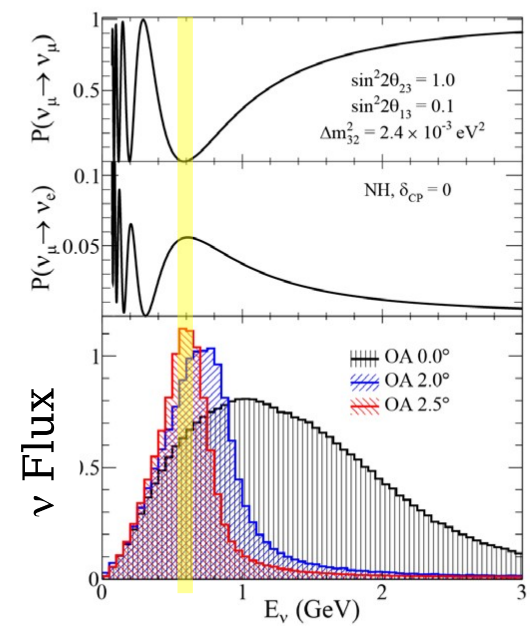
- Study ν_e and $\bar{\nu}_e$ appearance $(\nu_\mu \rightarrow \nu_e, \bar{\nu}_\mu \rightarrow \bar{\nu}_e)$: Explore δ_{CP} and $\theta_{13,\,23}$
- Precision measurement of ν_μ and $\bar{\nu}_\mu$ disappearance: Explore θ_{23} and Δm^2_{32}

Overview of T2K: Beam

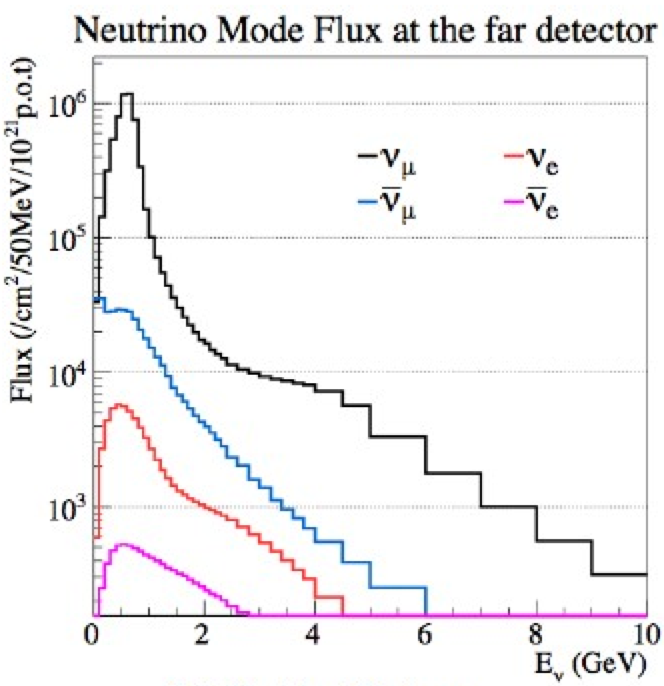


First Use of Off-axis ν_μ Beam:

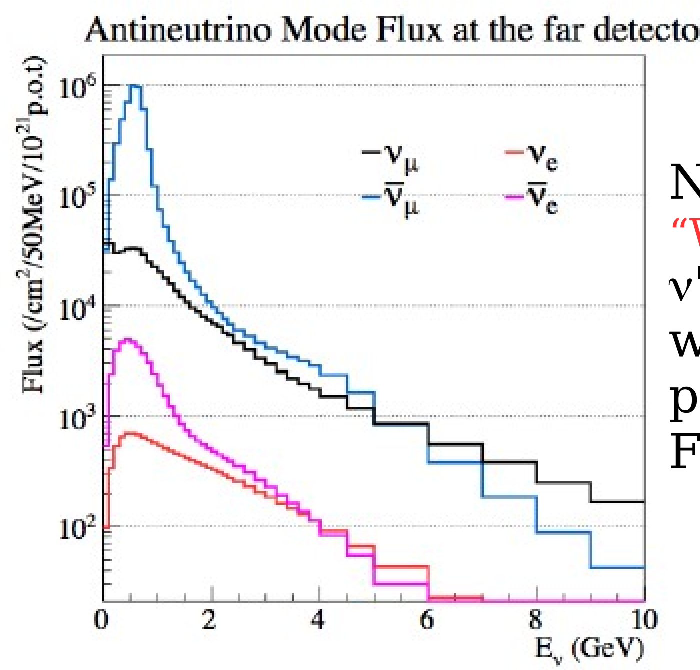
- Intense & high-quality beam (Beam direction stability < 1mrad)
  - ~1 mrad shift corresponds to ~2% energy shift at peak
- Low-energy narrow-band beam
- Can choose between ν and $\bar{\nu}$ by changing current direction in horns
- E_ν peak around oscillation maximum (~0.6 GeV)
- Small high-energy tail → reduces feed-down background events
- π,K production at target was measured using CERN NA61 exp.



Beam Configurations (T2K)



SK: Neutrino Mode, ν_μ



SK: Antineutrino Mode, $\bar{\nu}_\mu$

Note: More "Wrong Sign" ν's in RHC when compared to FHC

ν - mode known as "forward horn current" (FHC) or "positive focusing" (PF)
$\bar{\nu}$ - mode known as "reverse horn current" (RHC) or "negative focusing" (NF)

→ Mean energy sub-GeV→ Present flux uncertainties smaller than 6% (at peak)

Main systematics due to the hadron interactions modeling →
With NA61/SHINE measurements using T2K replica target

At These Energies Neutrino Cross-sections are Poorly Known

- **ν oscillations:**

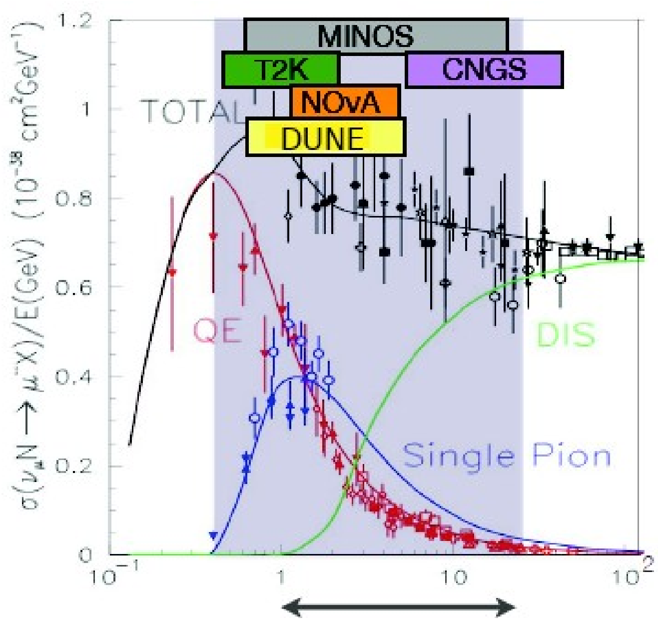
→ We are now in a period of precision neutrino oscillation measurements

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta_{32})\sin^2((1.27\Delta m^2_{32}L)/E_\nu)$$

(ν_τ appearance example)

→ **Note oscillation probability depends on E_ν**

- However Experiments Calculate E_{rec}
- E_{rec} depends on Flux, σ, detector response, interaction multiplicities, target type, particle type produced and final state interactions: E_{rec} not equal to E_ν



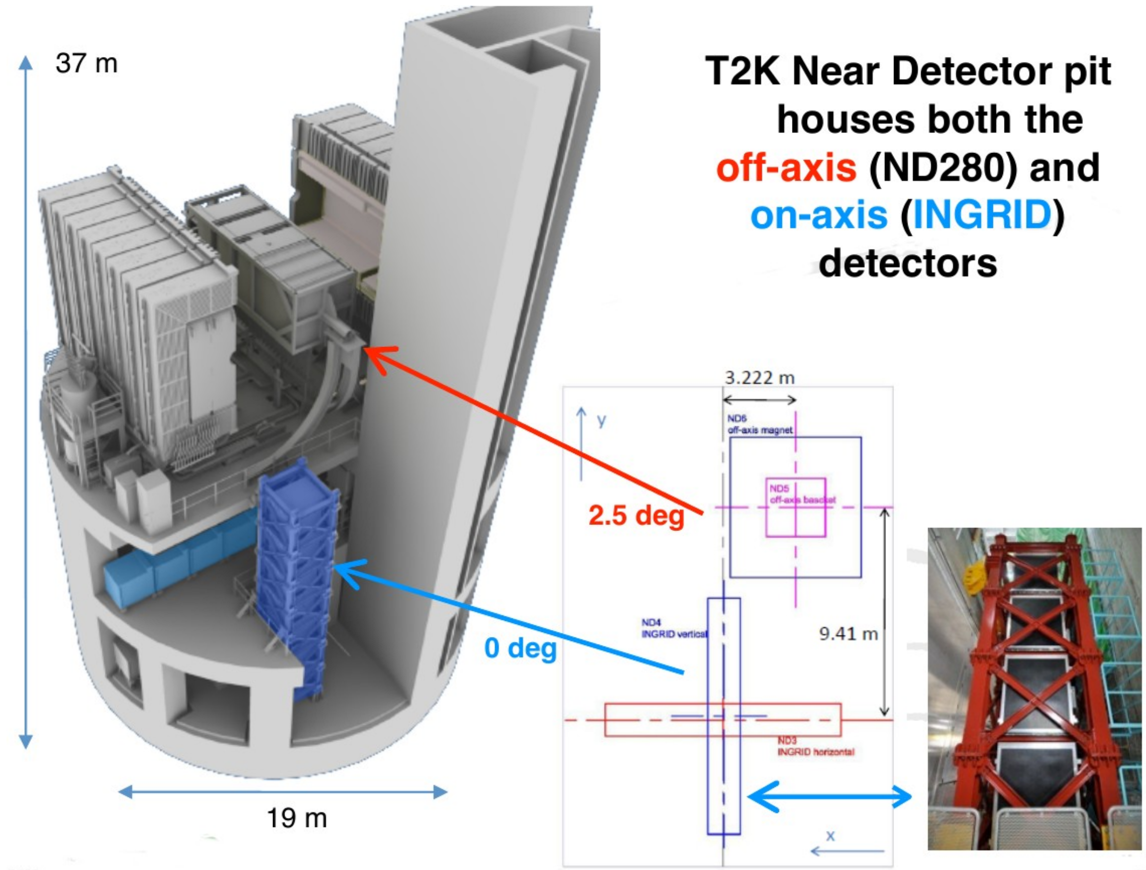
→ Appearance Oscillation Measurements:

- Large Θ_{13} and CP violation - systematics important
- Need to understand backgrounds to ν_e searches:

- **Need Precision understanding of Low energy (Few GeV) ν_μ & $\bar{\nu}_\mu$ cross sections to improve models.**

→ T2K and NOvA have rich programs in non-oscillation physics (ν cross sections)

Overview of T2K: Near Detectors(ND280)

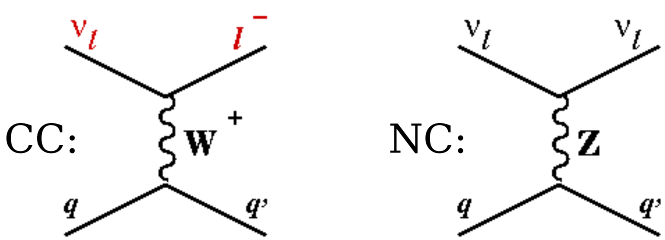


On-Axis Detector (INGRID) Monitor ν:

- **Beam direction**
- **Beam Intensity**

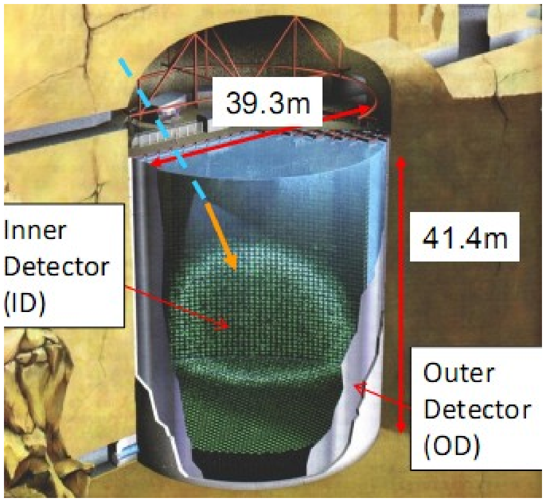
Off-Axis Detector:

- **In SK Direction**
- **Measure:**
  - **ν flux**
  - **Cross-section measurements using water targets to reduce systematic errors on oscillation parameters**

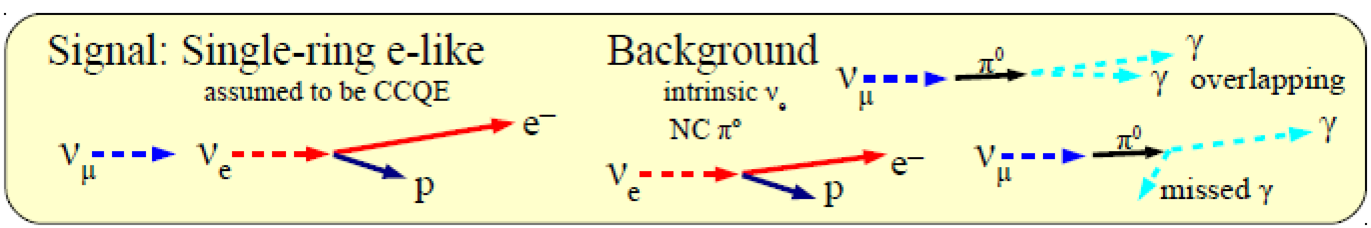


→ Used for monitoring of beam, flux constraints and systematic error reduction

The T2K Far Detector: Super-Kamiokande

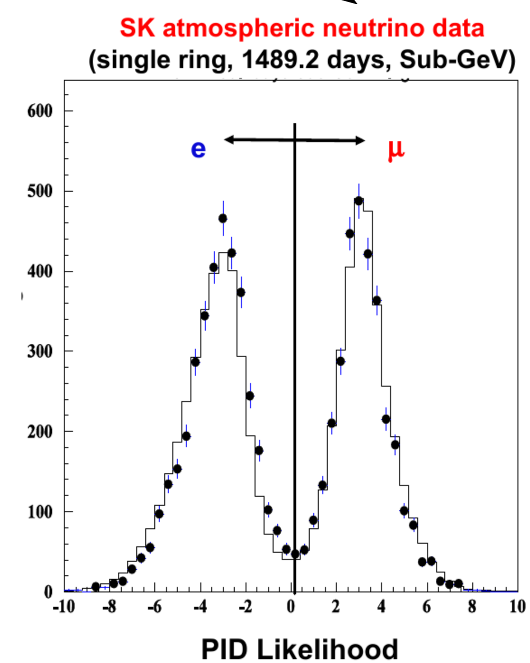


- 50 kiloton Water Cherenkov detector 1 km underground
- Performance well matched to sub-GeV neutrinos
- High ν_e signal efficiency plus high π^0 rejection
  - Fiducial cut (*i.e.* cut on vertex distance to wall) optimized for each interaction type.
- Probability to misidentify muon as electron is small
- GPS time recorded in real-time for every spill
  - Associate events with J-PARC (beam)



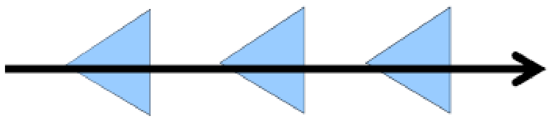
Signal (ν_e)

Background

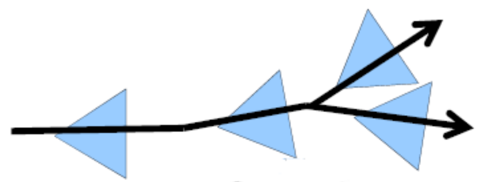


Far Detector (WC): Particle ID

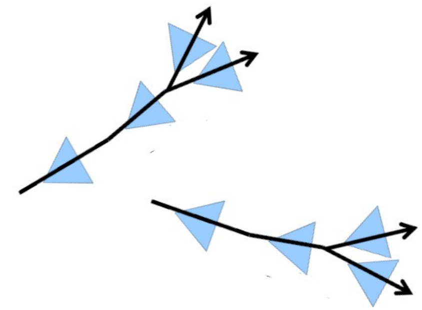
MS Small:
Sharp Ring

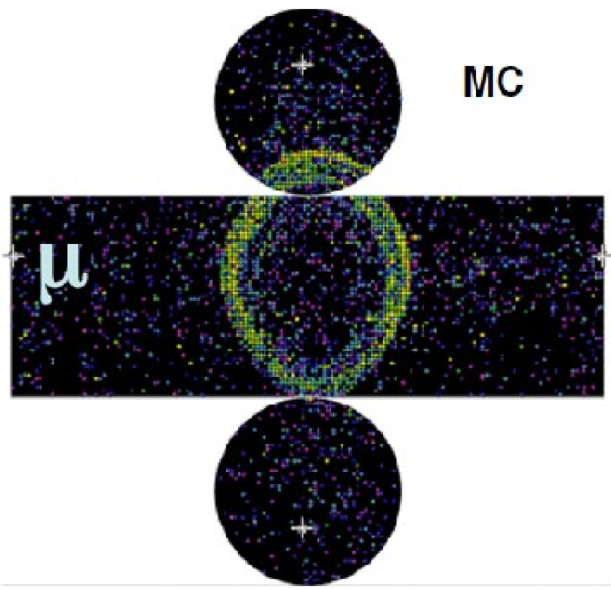


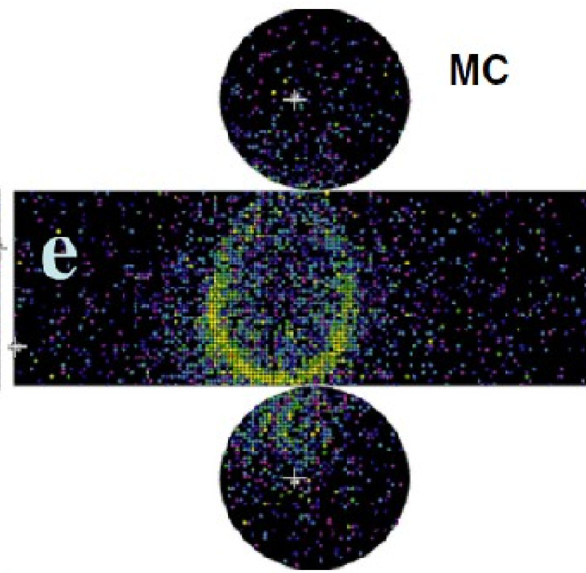
EM Shower:
Fuzzy Ring

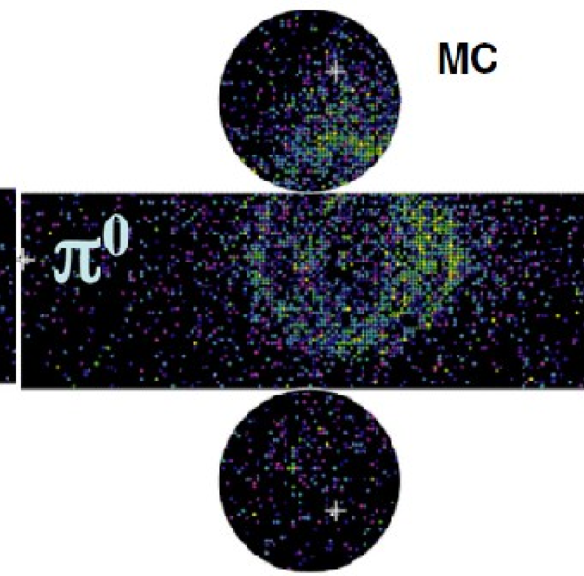


2 EM Showers:
> 1 Fuzzy Ring

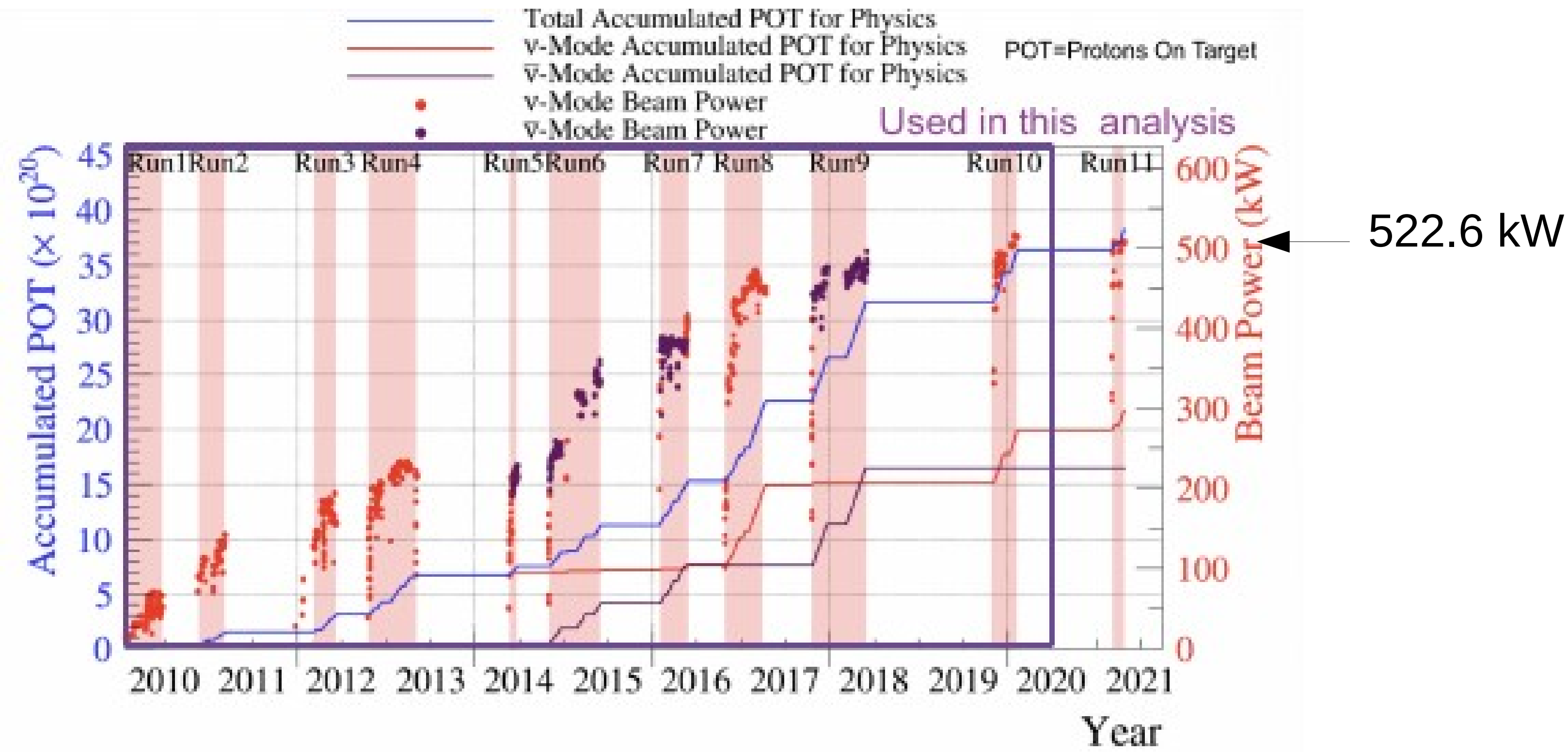








Analyzed Data (T2K)



Analyzed data:

→ ν-mode: 21.7 $\times 10^{20}$ POT → $\bar{\nu}$-mode: 16.3 $\times 10^{20}$ POT

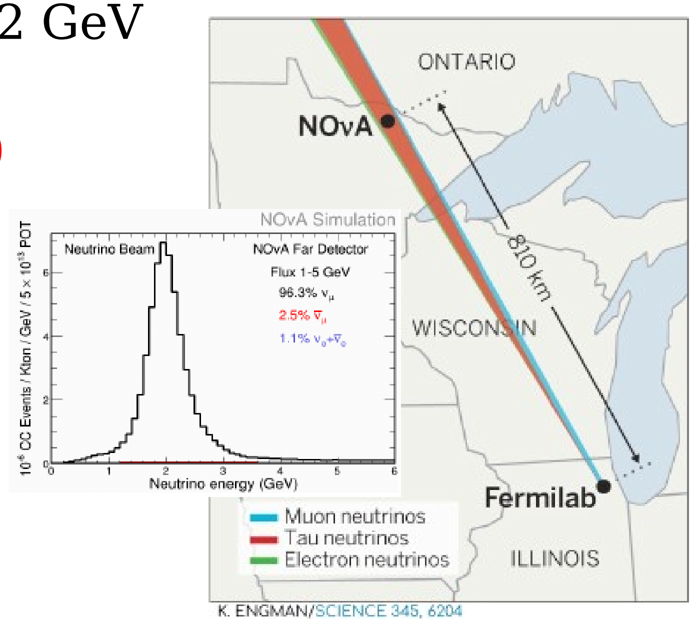
→ Total: 38.2 $\times 10^{20}$ POT (POT – Protons on Target)

→ Required beam direction stability also achieved (< 1mrad)

The NOvA Experiment:

23.2×10^{20} POT ν mode
12.7×10^{20} POT $\bar{\nu}$ mode

- **US based Long-baseline neutrino oscillation experiment:**
- FNAL neutrino beam to Ash River, MN (on surface, BL ~810 km)
  - Off-axis narrowband neutrino beam: $<E_\nu>\sim 2$ GeV
    - > 890 kW beam achieved
- Functionally identical near/far detectors (~~T2K~~)
  - **Segmented liquid scintillator bars**
    - → Different technology than T2K
  - Far: 14 kton total mass (65% active mass)
- Data analysis based on:
  - Event classification with CNN



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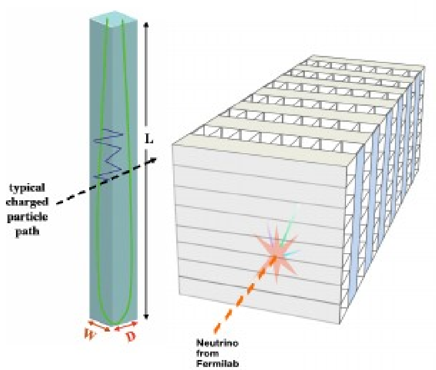
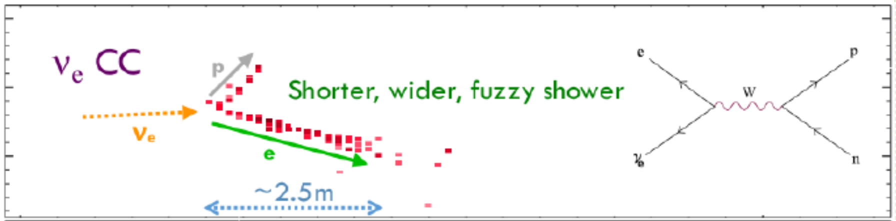
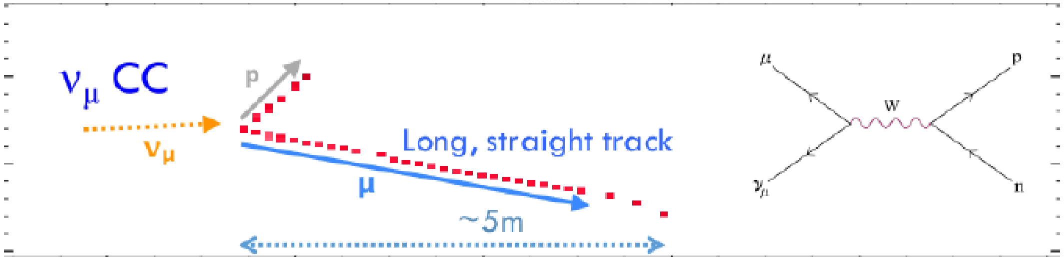
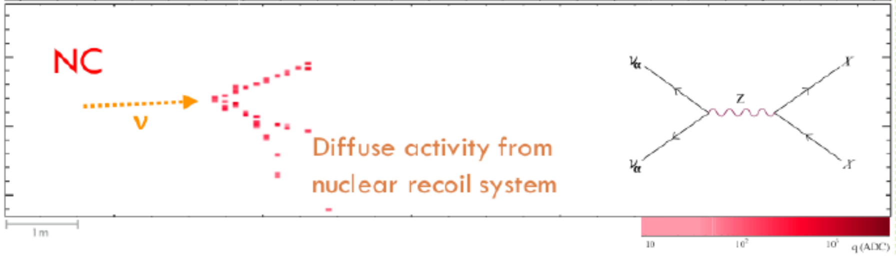








T2K and NOνA Comparisons

- Both T2K and NOνA are studying the same physics
  - However they are using different detection technologies
    - This is a good thing

- As mentioned both measure $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ but…
  - In the PMNS framework these are functions of several parameters
    - *i.e.* Baseline for NOνA is 810km and 295km for T2K
      - Longer baselines have greater sensitivity to the Mass Ordering

- The joint measurements of T2K and NOνA important in untangling the physics parameters embedded in $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$, specifically δ_{CP}
  - Joint working group

Oscillation Results

Disappearance (anti-)neutrino results…
(Test for CPT Violation or a search for non-standard ν interactions)

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

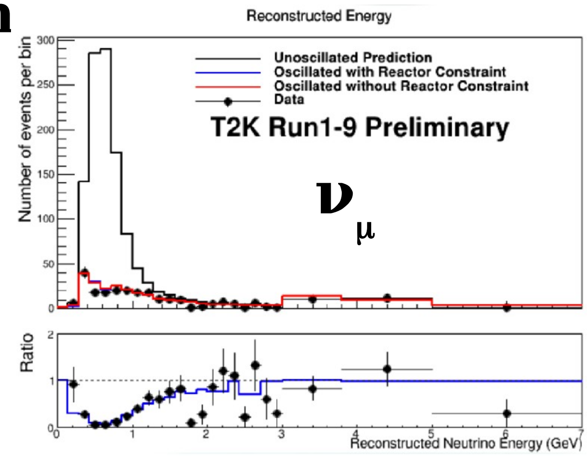
Sensitive to:
θ_{23}, $|\Delta m^2_{31}|$ ($\sim|\Delta m^2_{32}|$)

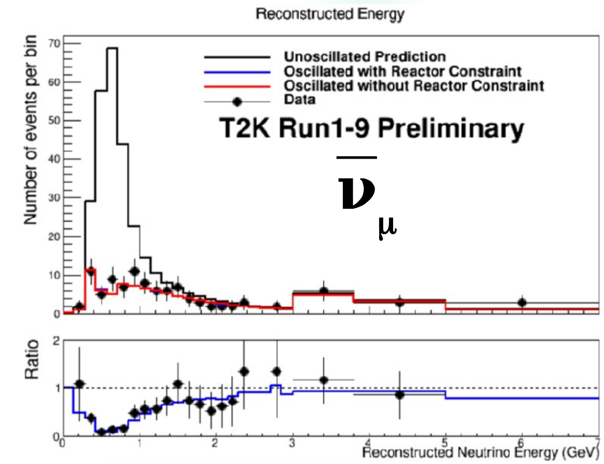
- θ_{23} **Maximal? Octant? (< or > 45^0)**

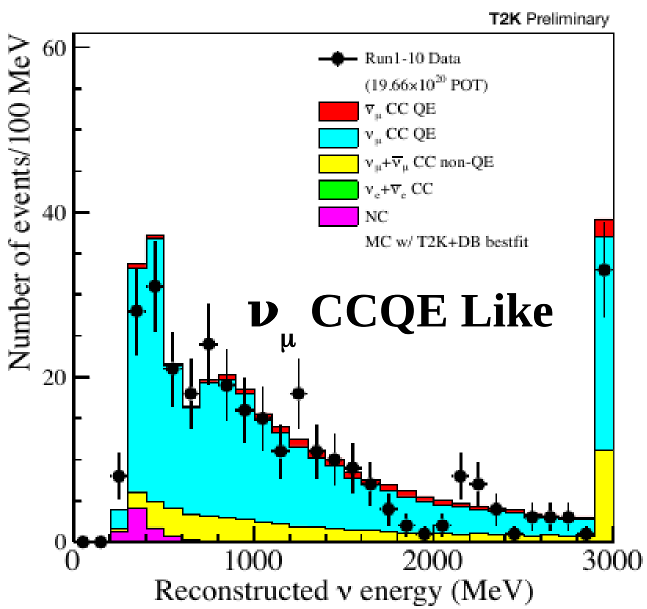
T2K: Disappearance Event Selection

ν_μ ($\bar{\nu}_\mu$) CC event selection (Disappearance):

- Fully contained fiducial volume
- Single-ring μ-like event (Multi Ring not shown)
- $p_\mu > 200$ MeV/c
- # of decay electron ≤ 1



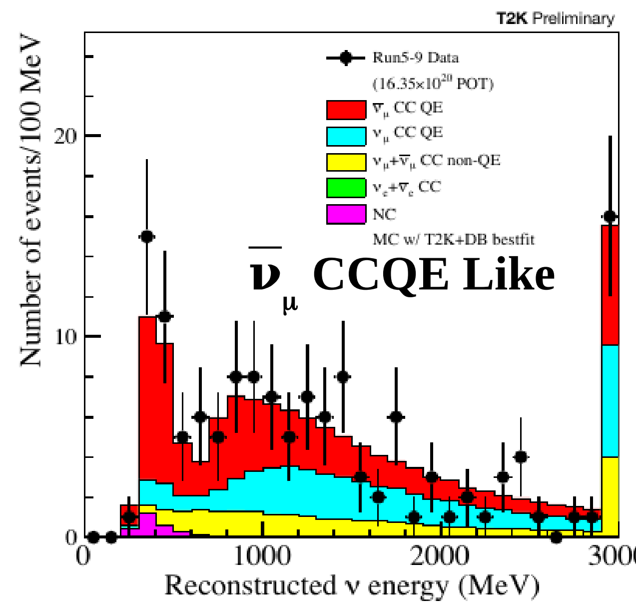




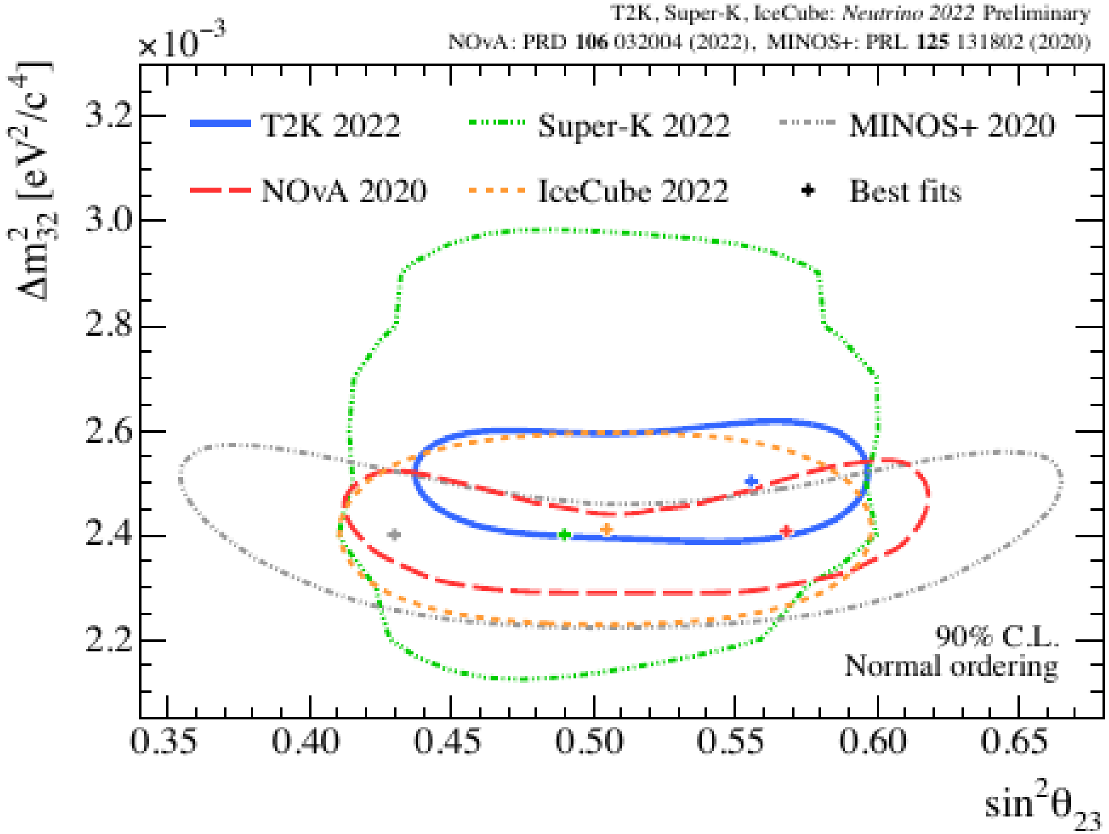
318 events

(Runs 1-10)

137 events



Disappearance



→ Reactor constraints on Θ_{13} used (T2K)

→ Consistent with maximal mixing (Θ_{23}=45°) – but best fit in upper octant

→ In addition no obvious difference observed between ν and $\bar{\nu}$

For ν's (T2K best fit):
$\sin^2\theta_{23} = 0.53^{+0.03}_{-0.04}$ (UO-2020)
$\Delta m^2_{32} = (2.45)\cdot 10^{-3}$ eV^2
(New interaction model and ND samples cause largest change compared to 2020)

Best fit (NOvA): Prefers Normal Ordering
$\sin^2\theta_{23} = 0.57^{+0.03}_{-0.04}$ (UO)
$\Delta m^2_{32} = (2.41\pm 0.07)\cdot 10^{-3}$ eV^2

Oscillation Results

Appearance (anti-)neutrino results…

$$P(\nu_\mu \to \nu_e) \approx \underline{\sin^2\theta_{23}}\,\underline{\sin^2 2\theta_{13}}\,\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\left(1+\frac{2a}{\Delta m^2_{31}}\left(1-2\sin^2\theta_{13}\right)\right)$$

$$-\underline{\sin 2\theta_{12}}\,\underline{\sin 2\theta_{23}}\,\underline{\sin 2\theta_{13}}\cos\theta_{13}\,\underline{\sin\delta}\,\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\sin\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)$$

[(P($\bar{\nu}_\mu \to \bar{\nu}_e$) δ turns into – δ and a to -a (“a” matter effect term)]

Sensitive to:
θ_{13}, δ_{CP}, θ_{23}, Δm^2_{31}

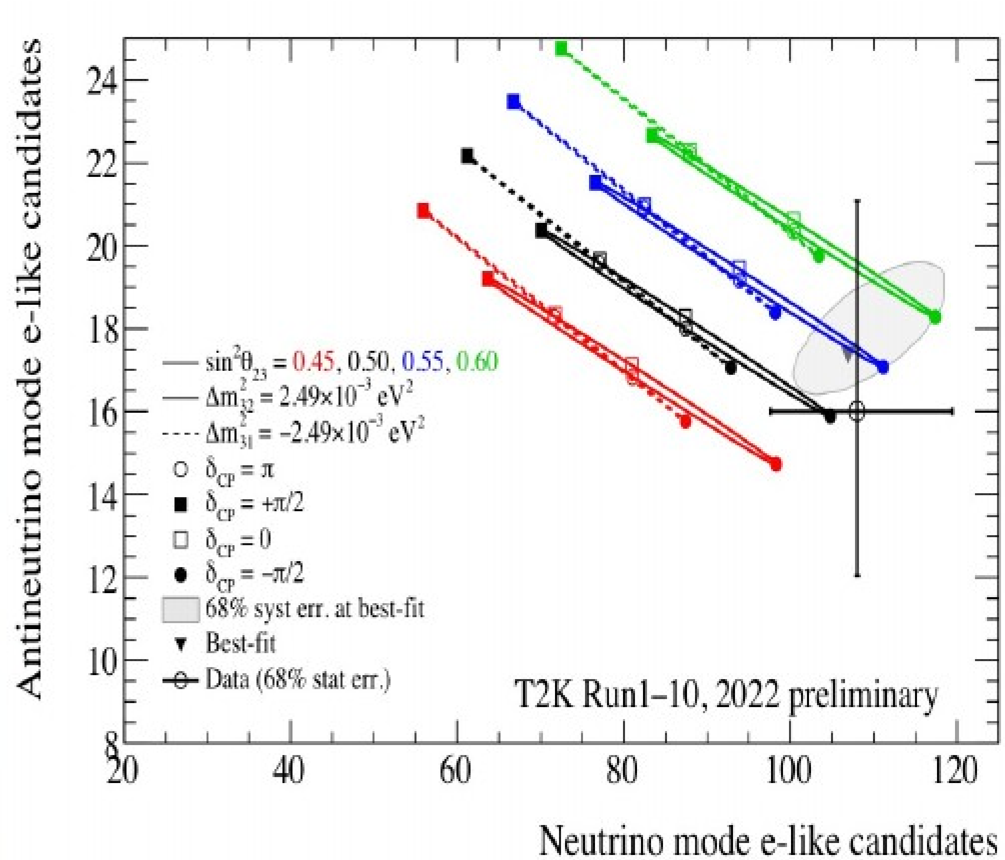
We measure “P” → Degeneracies…

- **CP-Violating Phase: δ**

Oscillation probabilities as a function of parameters

- θ_{23} → ν_e and $\bar{\nu}_e$ appearance probabilities are affected in the same way
- δ_{CP} = -π/2 → maximize ν_e appearance, minimize $\bar{\nu}_e$ (~30%)
- δ_{CP} = π/2 → maximize $\bar{\nu}_e$ appearance, minimize ν_e (~30%)
- Normal hierarchy → same as δ_{CP}=-π/2 but smaller effect in T2K (~10%)
- Inverted hierarchy → same as δ_{CP}=π/2 but smaller effect in T2K (~10%)

T2K:



Expected # of events($\nu_\mu,\bar{\nu}_\mu,\nu_e,\bar{\nu}_e$):

(1(M)R → 1(Multi) Ring)

T2K

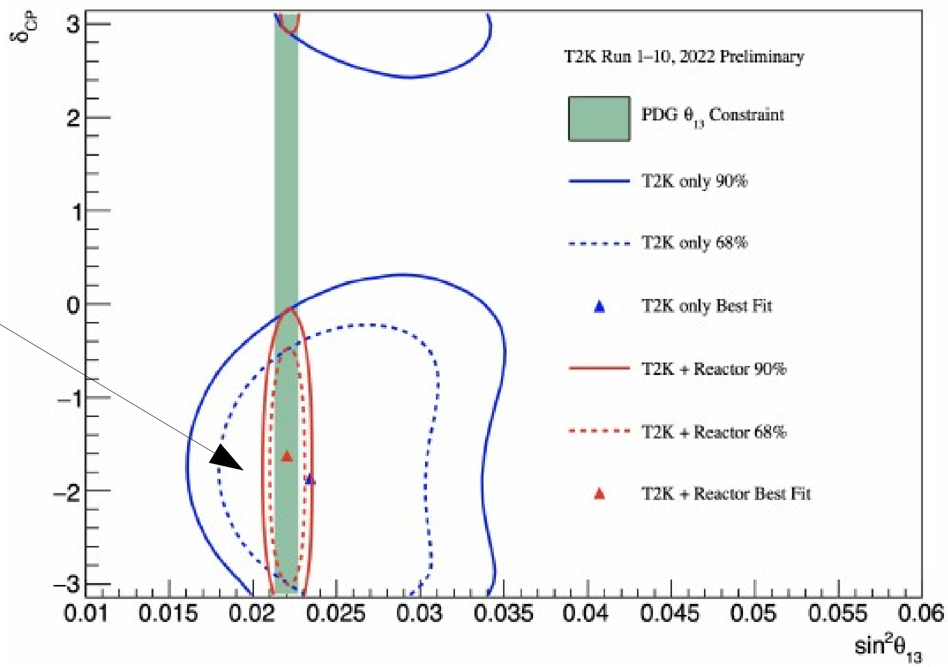
Mode	Sample	$\delta=-\pi/2$ MC	$\delta=0$ MC	$\delta=\pi/2$ MC	$\delta=\pi$ MC	Data
ν	1Re	102.7	86.7	71.1	87.1	**94**
	1Re CC1π^+	10.0	8.7	7.1	8.4	**14**
	1Rμ	379.1	378.3	379.1	380.0	**318**
	MRμ CC1π^+	116.5	116.0	116.5	117.0	**134**
$\bar{\nu}$	1Re	17.3	19.7	21.8	19.4	**16**
	1Rμ	144.9	144.5	144.9	145.3	**137**

- **Preference for $\delta_{CP}=-\pi/2$ → maximize ν_e appearance probability, minimize $\bar{\nu}_e$ appearance**

Joint Fits ($\nu_\mu,\bar{\nu}_\mu,\nu_e,\bar{\nu}_e$): δ_{CP} *vs* Θ_{13}

T2K

T2K Result with Reactor Constraint



- T2K results consistent with reactor results
- Data prefer close to maximal CPV: **δ_{CP}=-π/2**
  - With reactor constraints: stronger preference for values of δ_{CP} ~ -π/2
  - Even though statistics are small $\bar{\nu}_e$ results reinforce maximal CPV observed for ν_e data

δ_{CP}: NOvA Recent Results

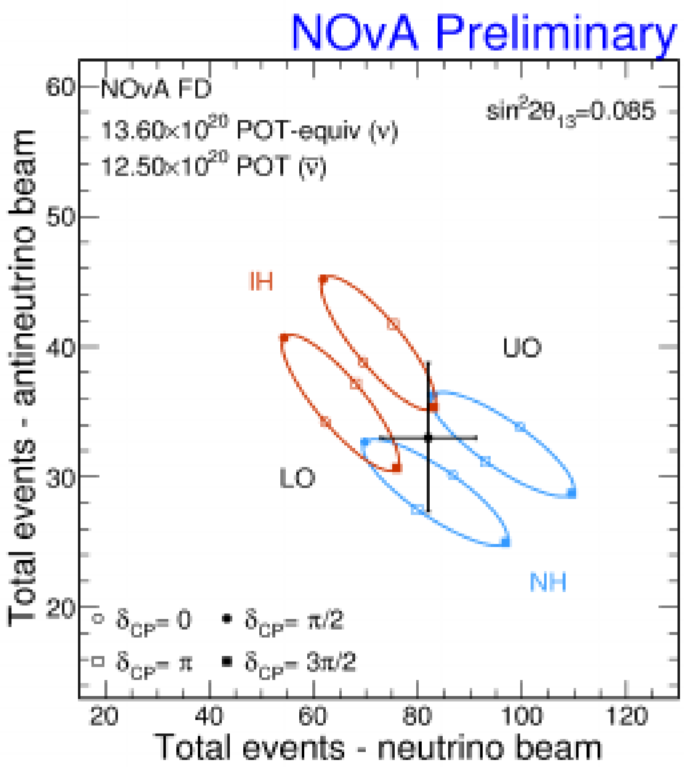
J. Wolcott @NuFact2022

Best fit: Prefers Normal Ordering

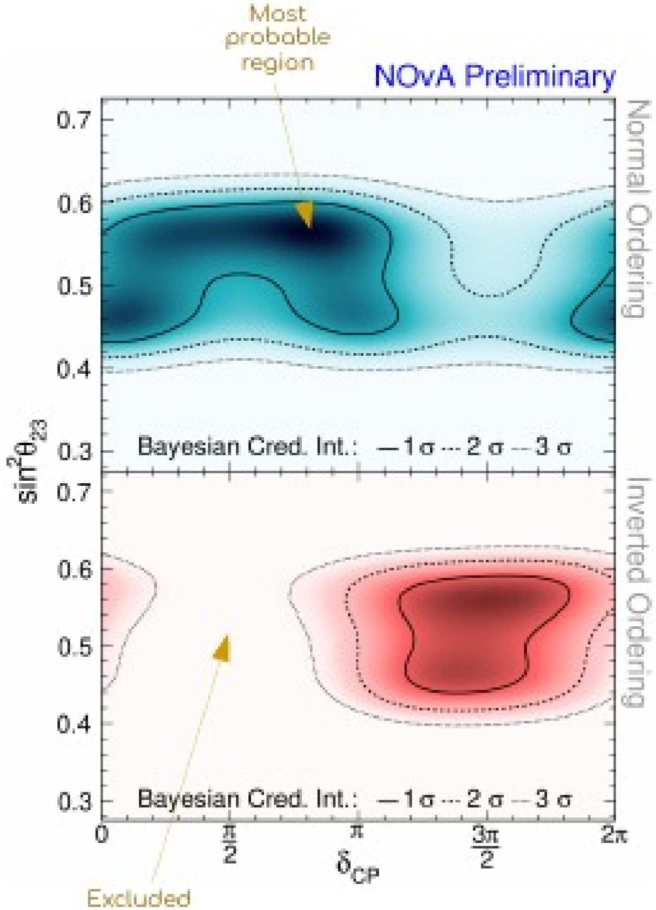
$\sin^2\theta_{23} = 0.57^{+0.03}_{-0.04}$ (UO)

$\Delta m^2_{32} = (2.41 \pm 0.07)\cdot 10^{-3}\ \mathrm{eV}^2$

NOνA Observes:
~83 events in ν
~33 events in $\bar{\nu}$:



New Bayesian analysis:
Phys. Rev. D 106 (2022) 032004



Future

→ Upgrade to T2K (→ Hyper-K)

→ Hyper-K

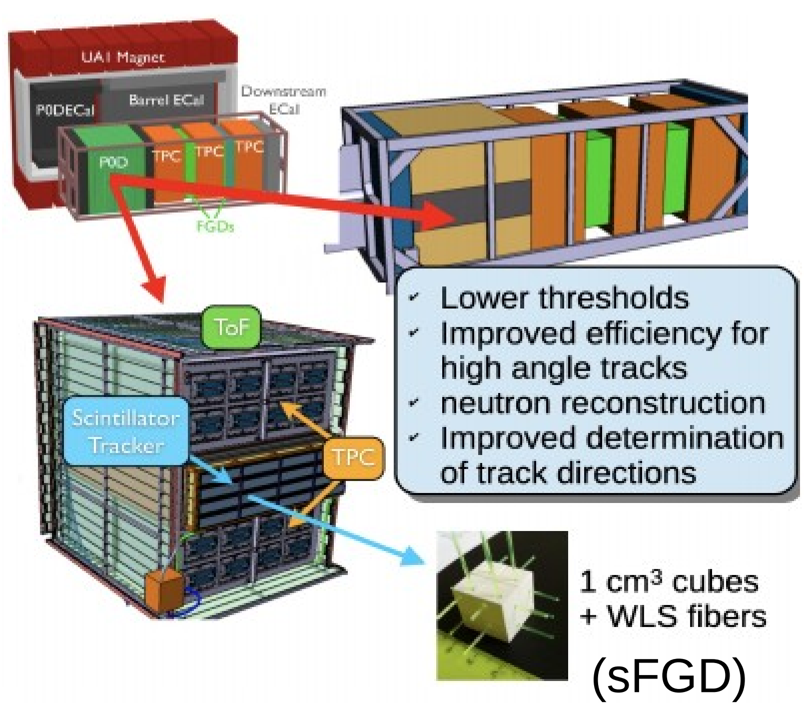
→ DUNE Project

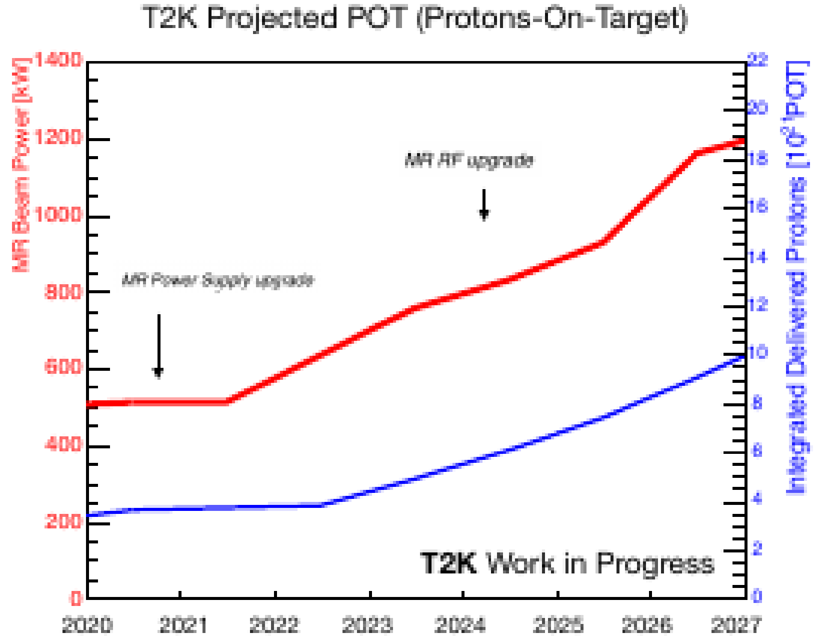
Upgrade to T2K(ND280)

→ Improved proton and neutron tracking.

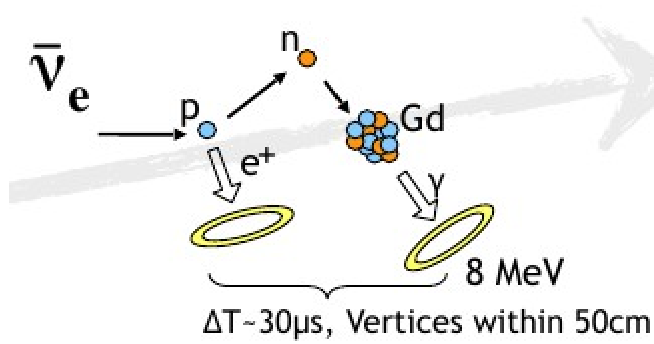
→ Improved muon Angular acceptance.

ND280 upgrade





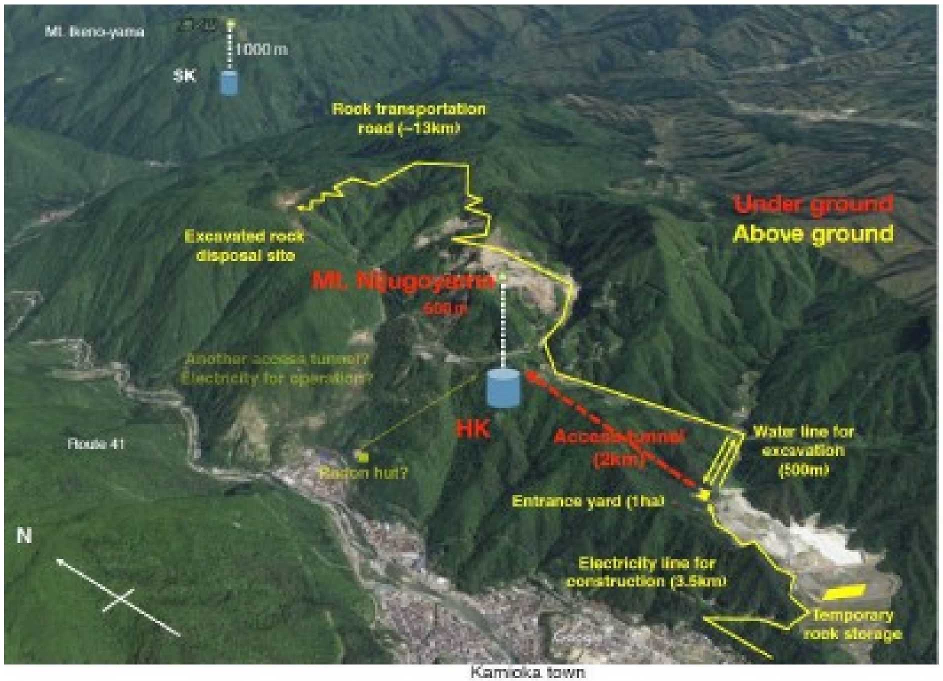
Increased power Proton beam→ Higher intensity: reduced rep. rate, higher horn current, ready early 2023
> 1 MW by 2027 (Hyper-K)



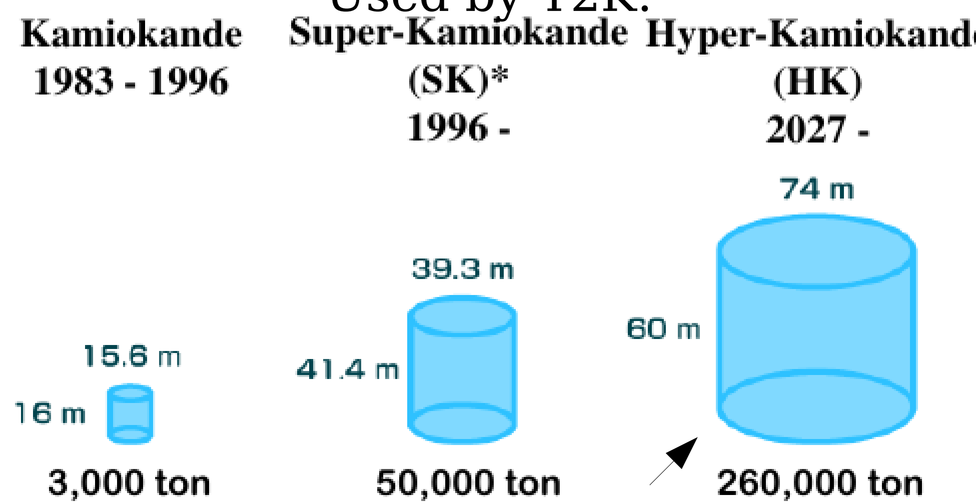
SK upgrade Gd now added to SK → $\bar{\nu}_e$ detection

Hyper-Kamiokande Experiment

Neutrino Detection Method: Water Cerenkov Detector



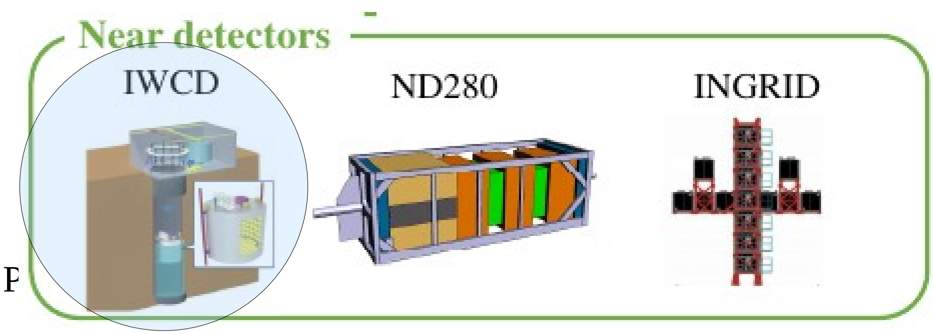
Used by T2K:



Access tunnel excavation: Finished on schedule
Cavern excavation is ongoing

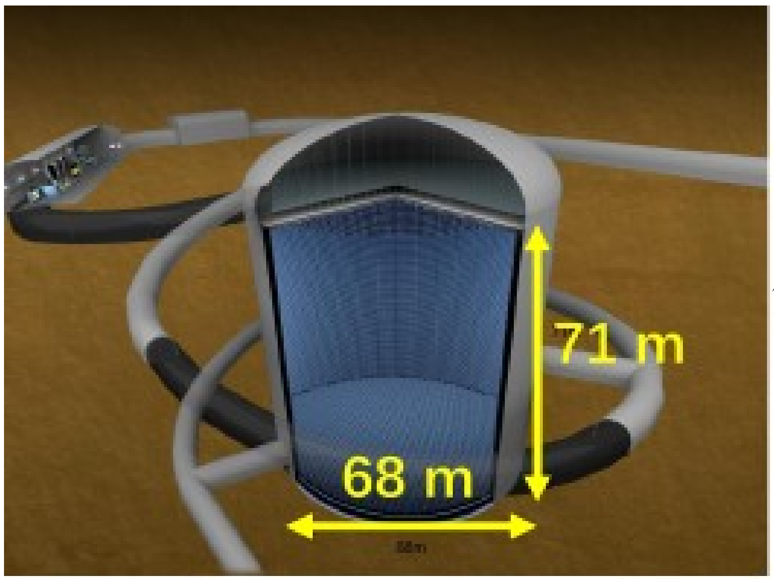
8 times fiducial volume of Super-Kamiokande (SK)

Far Detector HK, Near Detector (ND280 - mostly) from T2K:
(Beam JPARC - same as for T2K)



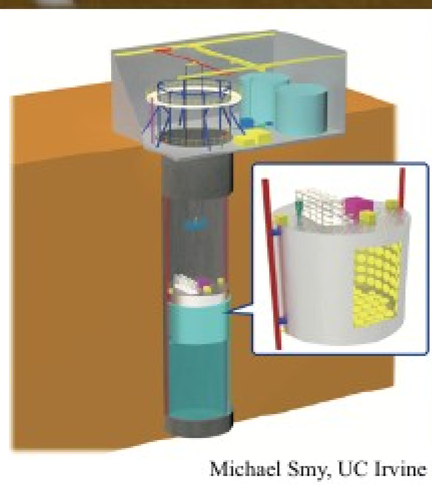
Hyper-Kamiokande:Detector Details

Hyper-K



- Cavern diameter 69m, height 73m + dome on top
- Tunnel construction completed, cavern excavation has commenced
- Tank construction: 2024/2025
- PMTs to be installed: 2025/2026
- Data collection starts in 2027
- Gd doping not included in present Hyper-K baseline design

IWCD

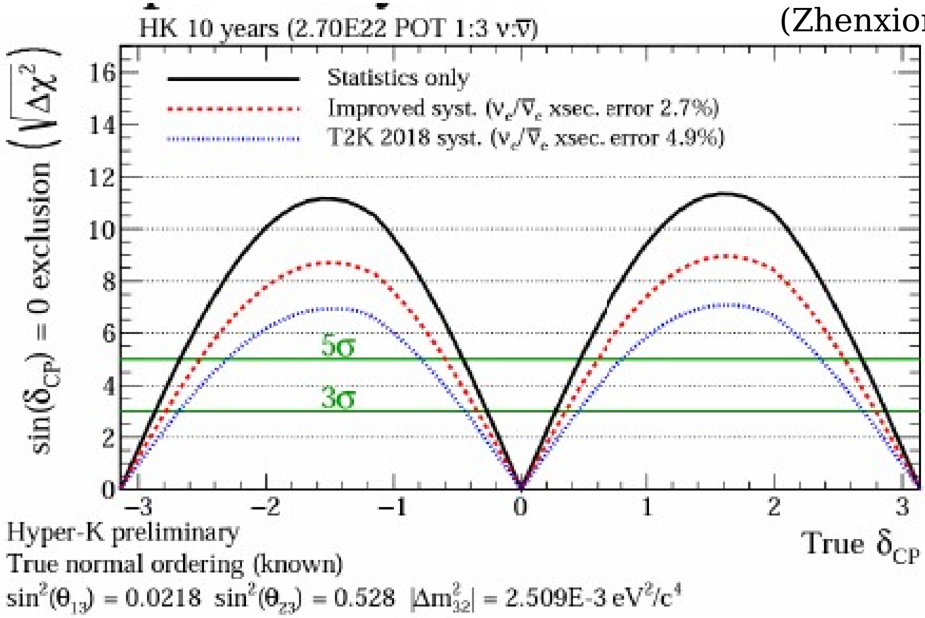


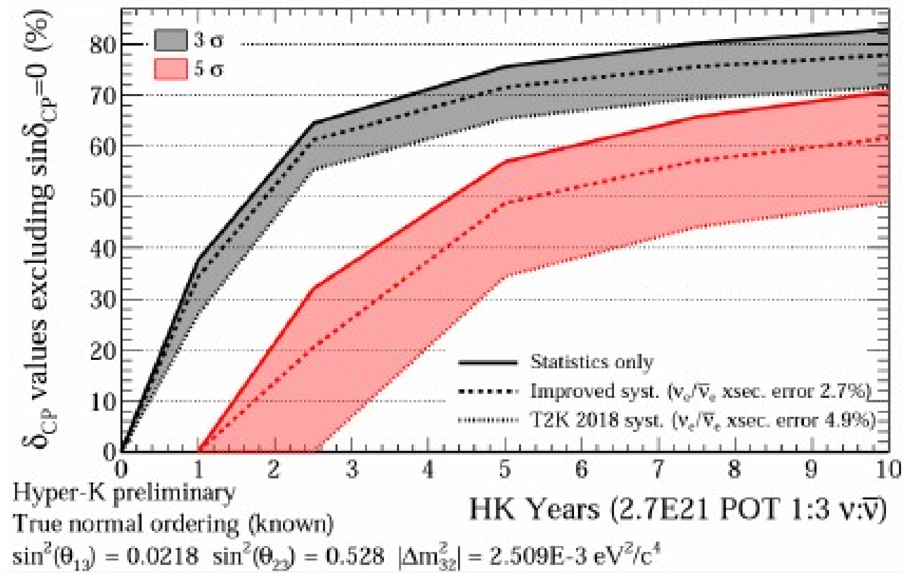
- Addition to T2K Near Detector Suite
  - IWCD: ~1kt scale Gd-doped water Cerenkov detector with little overburden
  - Diameter ~8m, height ~6m
  - Uses multi-PMT modules (19 3” PMTs)

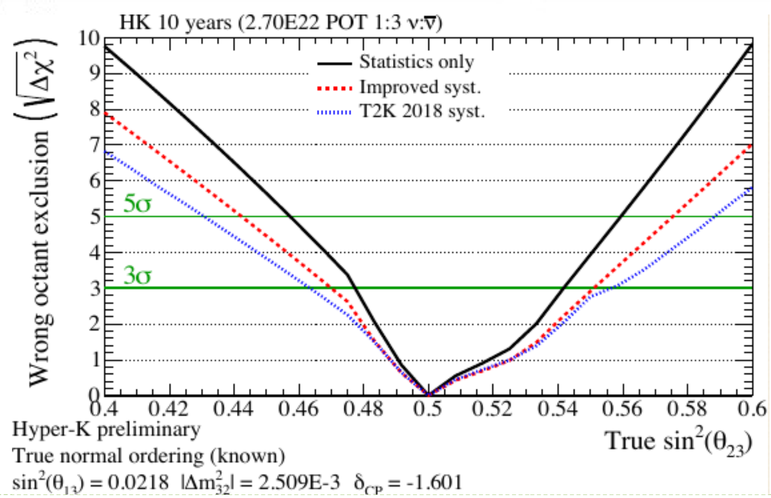
Hyper-Kamiokande: Sensitivity

δ_{CP} Sensitivity: With 10 HK-yrs, ~60% of δ_{CP} values can be explored at 5-σ (assuming MO known).

(Zhenxiong Xie/NOW2022)

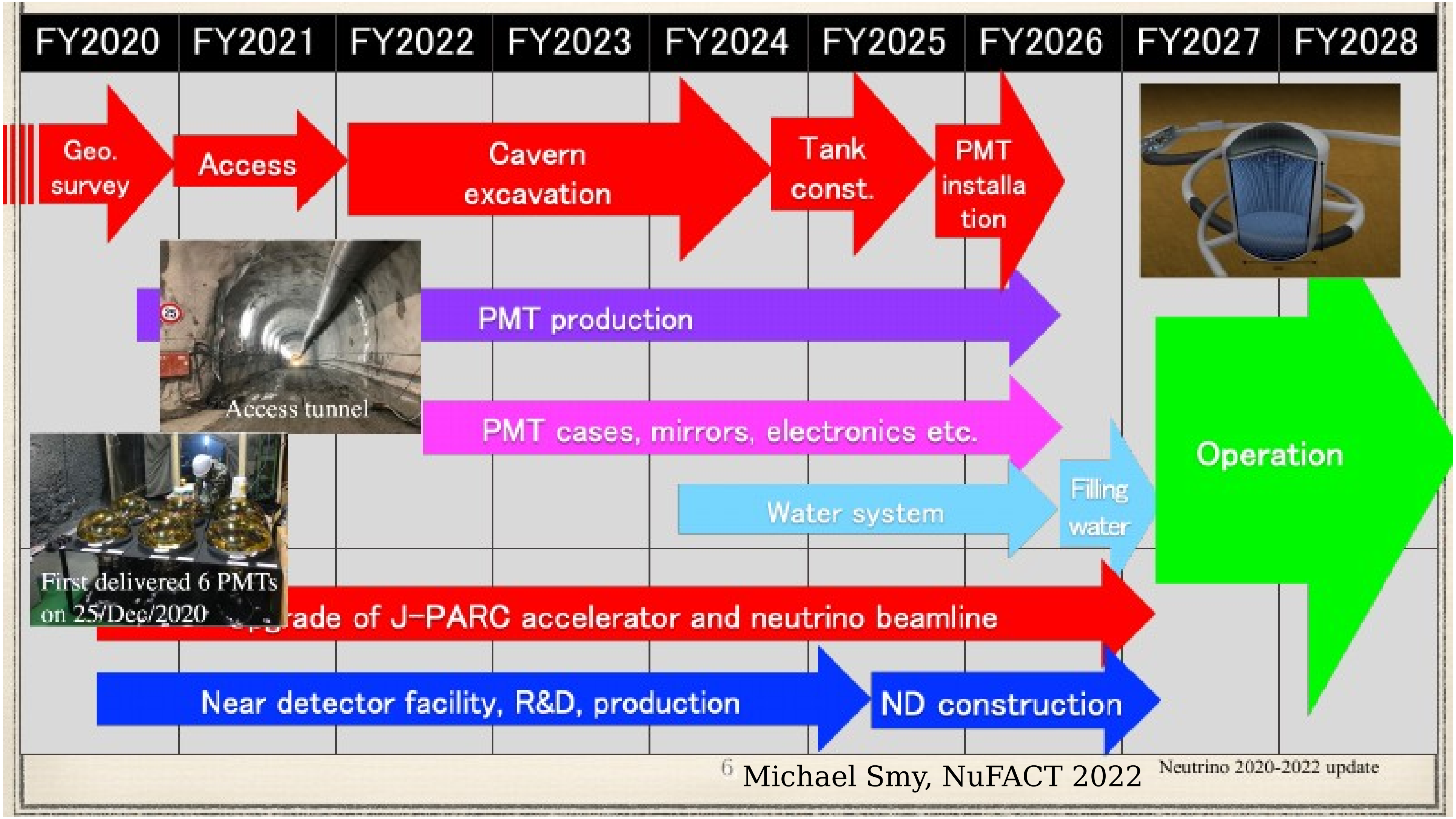




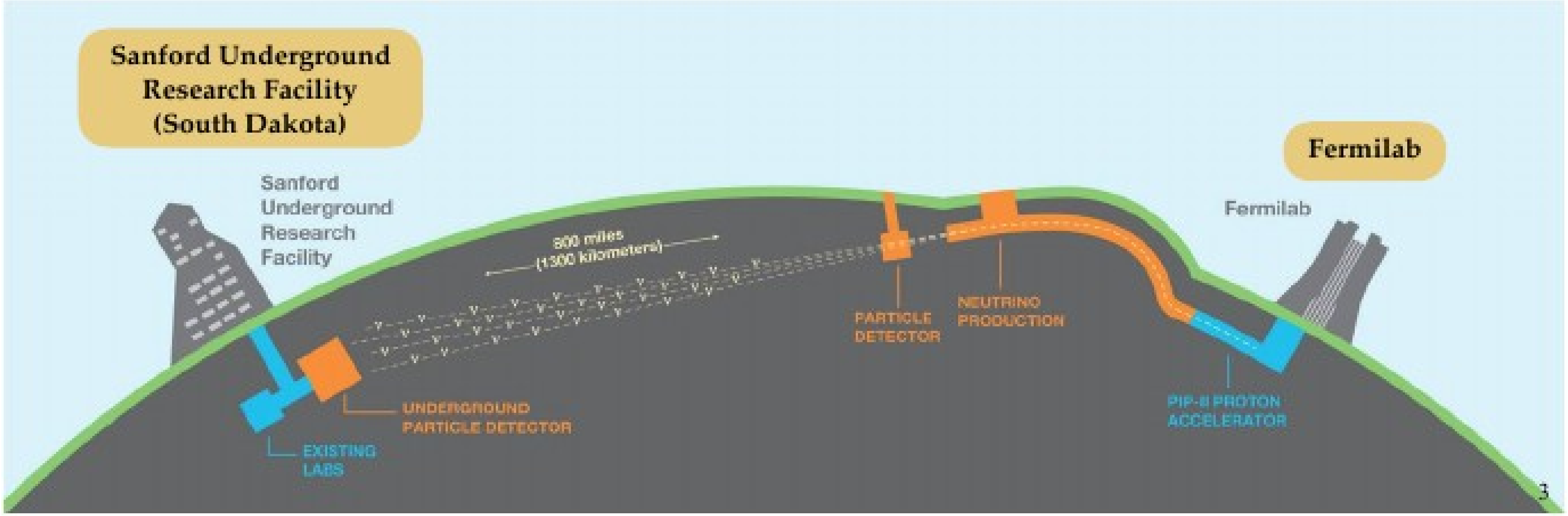


→ For true $\sin^2\theta_{23}$ < 0.47 and > 0.55 the wrong octant can be excluded at the 3-σ level

Hyper-Kamiokande: Schedule



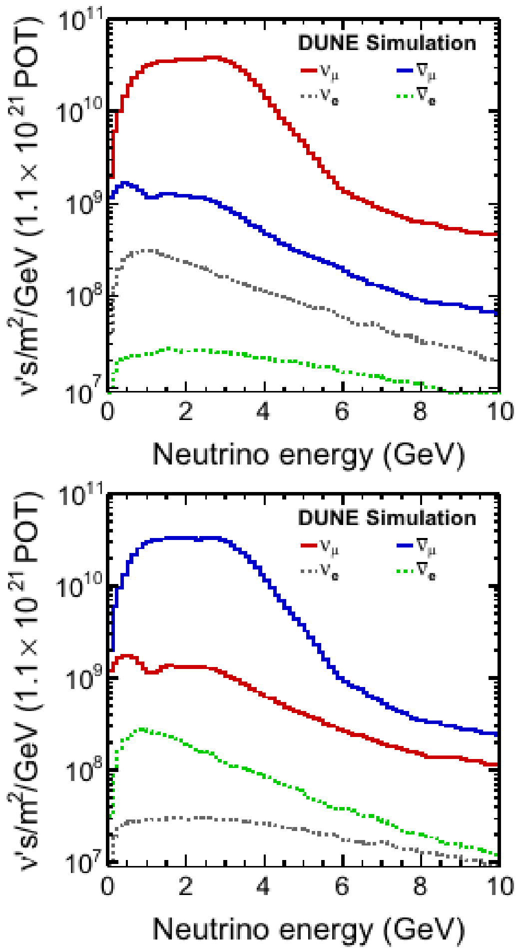
DUNE Experiment



- MegaWatt neutrino beam generated at FNAL to SURF(South Dakota, US) over 1300 km
- Near Detector complex (ND) at FNAL (multiple technologies will be employed)
- Far Detector site at SURF will accommodate 3+1 17 kt far detector (FD) modules (LArTPC)
- Long-Baseline Neutrino Facility (LBNF) responsible for the beam-line and Near/Far facilities
- Goals: Precision neutrino oscillation physics, MeV-scale physics (SuperNOVA detection), Nucleon decay searches, and extended BSM searches

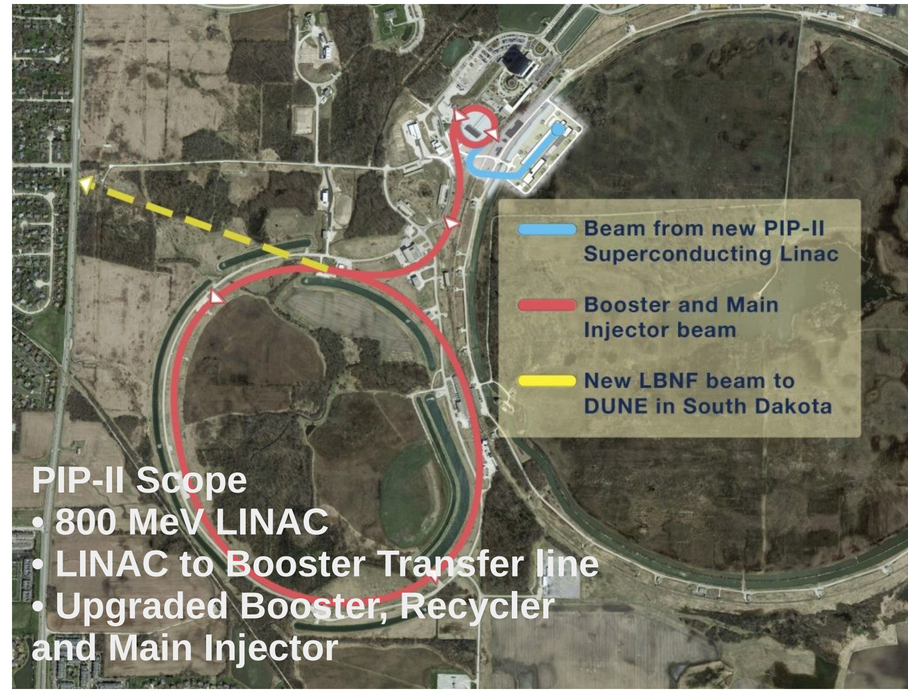
DUNE Beamline

Wideband Beam



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

FNAL Beamline Facility

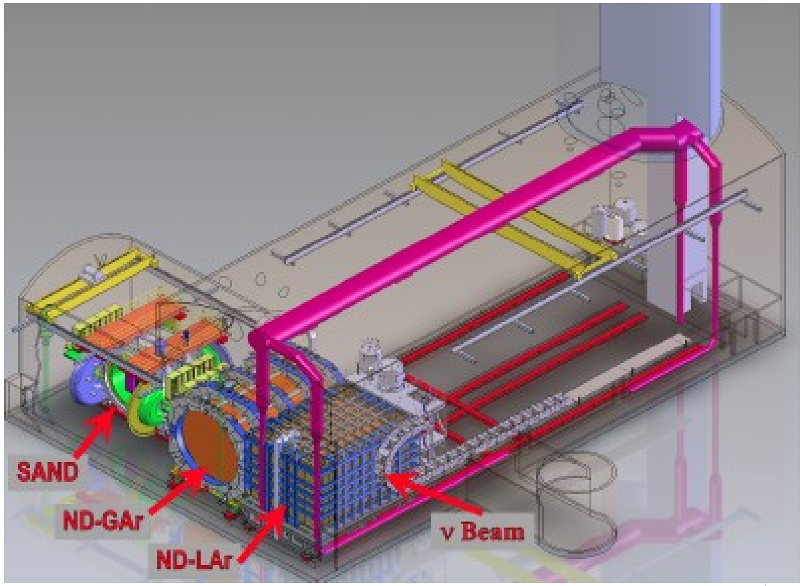


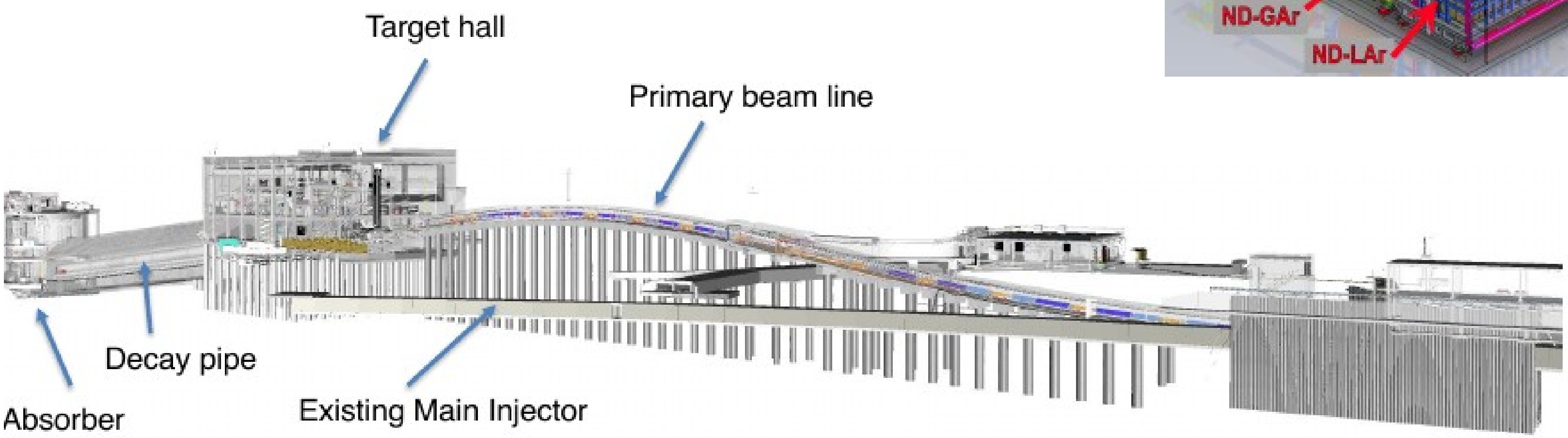
Proton Improvement Plan (PIP-II): critical element for DUNE's intense neutrino beam

- 1.2 MW beam intensity, up-gradable to 2.4 MW
- Goal: MW-scale to DUNE by 2031

DUNE: Near Detector

- Positioned 574m from beam target
  - Measure neutrino beam properties and constrain cross-sections
    - Reduce uncertainties for neutrino oscillation measurements
- Consists of multiple complementary systems:
  - ND-LAr: modular, pixelated LArTPC
    - Primary target (similar detector to FD)
  - High-pressure GArTPC, surrounded by ECAL and magnet (1st stage Temp. μ spectro. (TMS))
    - Muon spectrometer; nuclear interaction model constraints
  - SAND: tracker surrounded by ECAL and magnet
    - On-axis beam spectrum/time-stability monitor

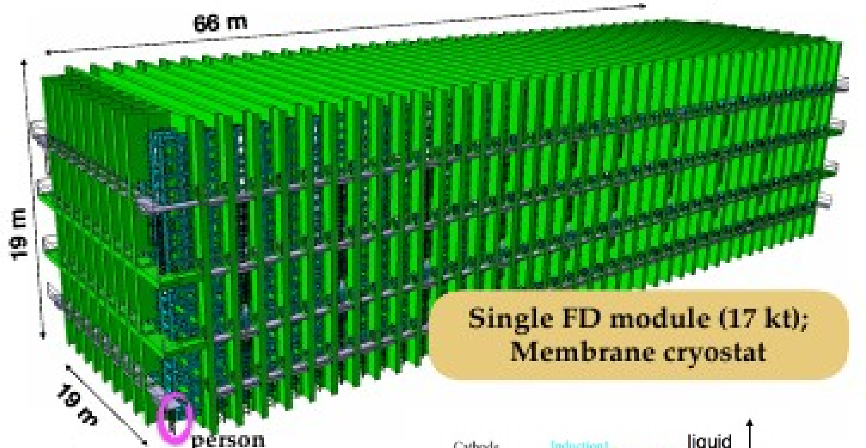


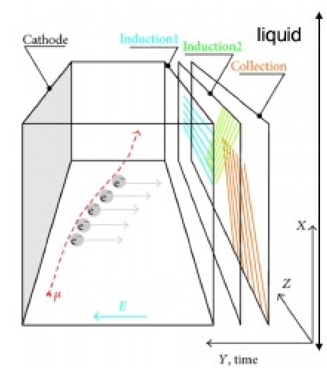


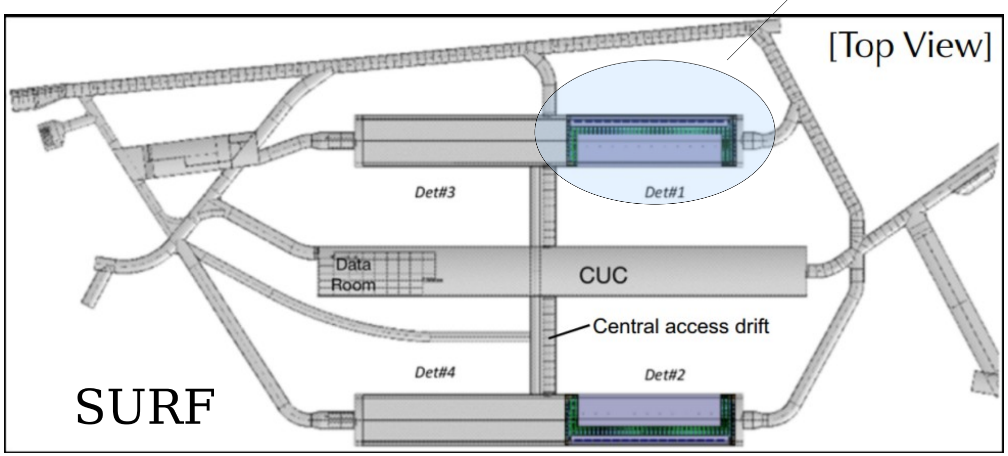
DUNE: Far Detector

- **Detection Method: Liquid Argon Time Projection Chamber (LArTPC)**
- Imaging Detectors: Excellent energy reconstruction and high resolution
  - Details of interactions are clearly seen
    - Allows separation Signal (υ_e CC) from background (NC π^0)
  - Low energy thresholds: MeV-scale physics
  - Scalable → massive detectors
- History of successful operation
  - MicroBooNE, ICARUS...

JINST 15 T08010



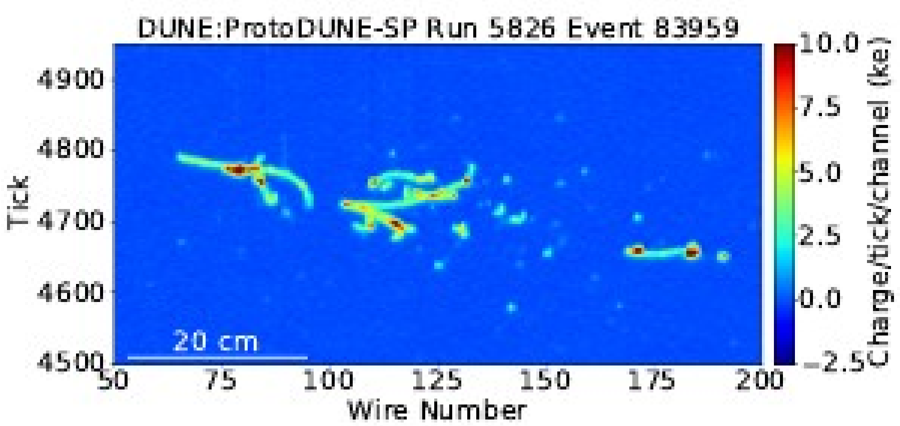




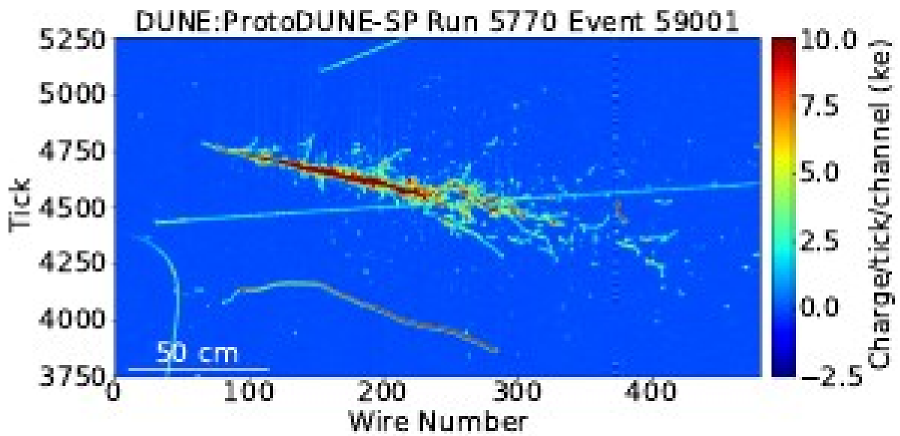
- The first two DUNE FD modules: LArTPC (17 kt mass each)
  - FD#1: Horizontal Drift (HD)
  - FD#2: Vertical Drift (VD)
  - FD#3: LAr technology TBD
  - FD#4: TBD (R&D ongoing)

Why LArTPC? Resolution!

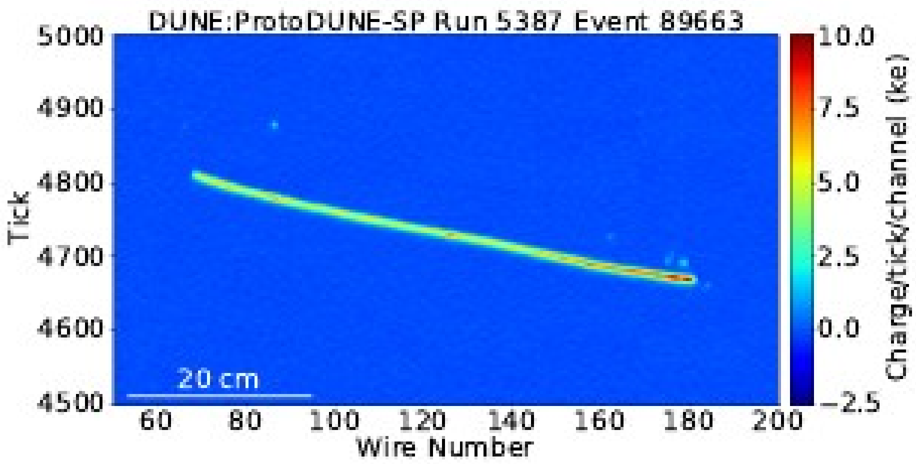
JINST 15 P12004 (2020) – ProtoDUNE @CERN



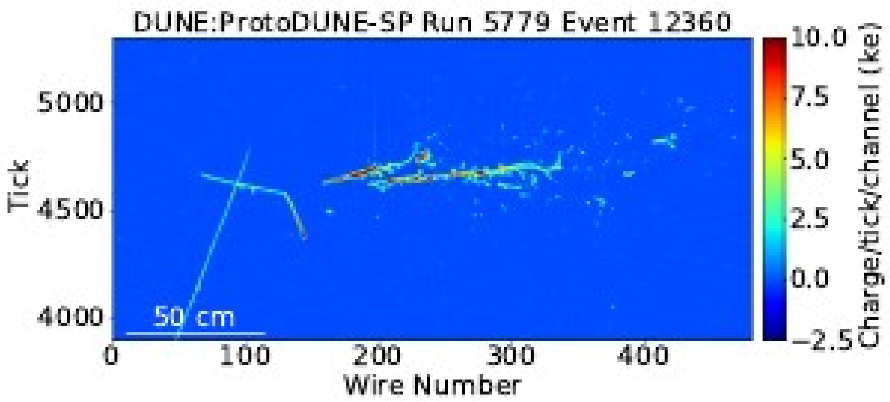
0.5 GeV/c electron candidate.



6 GeV/c electron candidate.



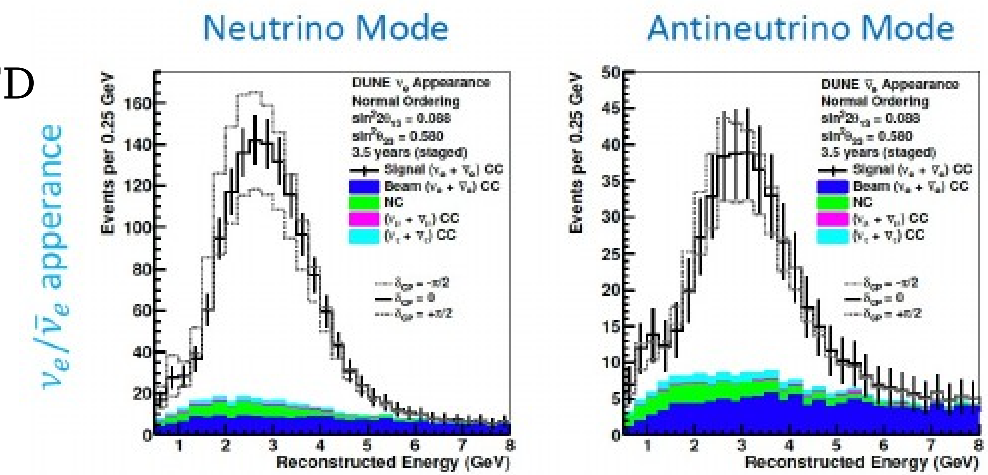
1 GeV/c stopping proton candidate.

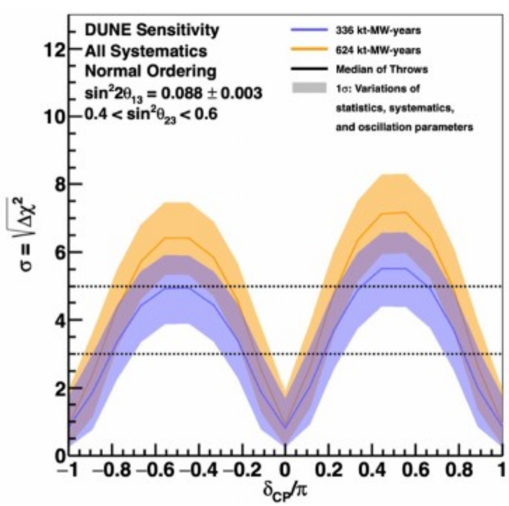


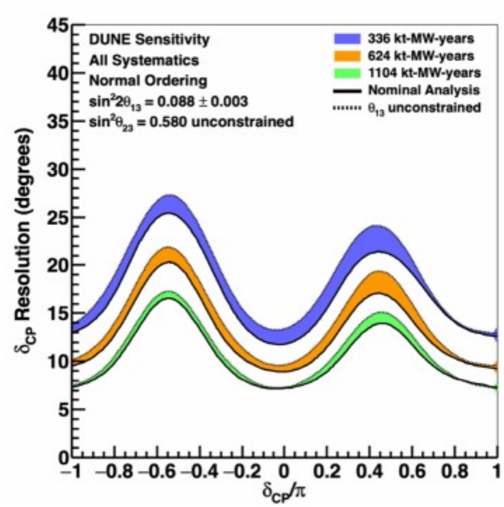
2 GeV/c pion charge exchange candidate.

DUNE: Physics Sensitivities

- Details [Eur. Phys. J. C 80 (2020) 10, 978]
- Using reconstructed spectra, includes full FD systematics
  - 3.5 years neutrino beam mode
  - 3.5 years anti-neutrino beam mode
- Expect:
  - ~1000 ν_e/ν_e–bar events in 7years
  - ~10,000 ν_μ /ν_μ-bar events in 7years

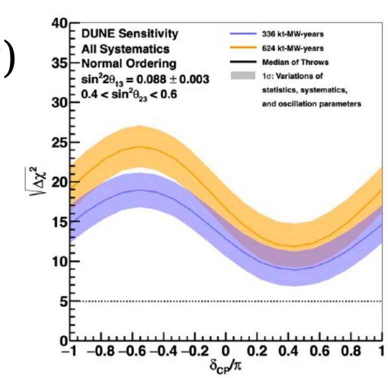




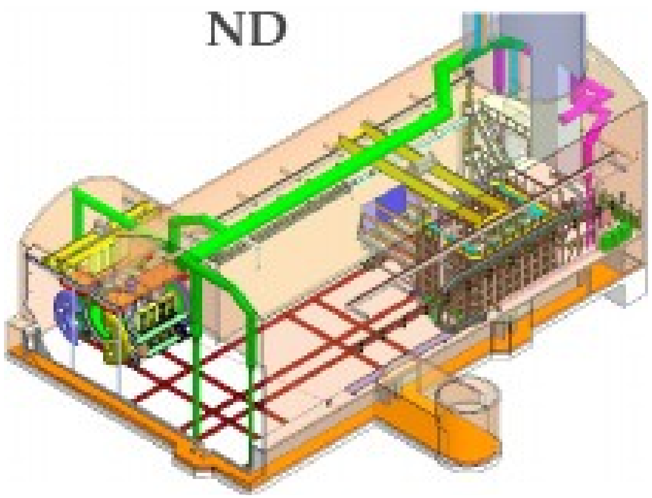


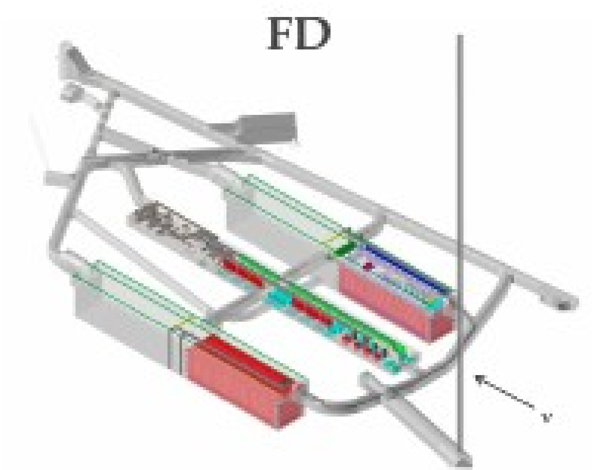
- 5σ discovery potential: CP violation over >50% of δ_{CP} values
  - 7-16° resolution to δ_{CP} (using input for solar parameters only)
  - Simultaneous measurement of neutrino mixing angles and δ_{CP}
- MH sensitivity (> 5σ) regardless of parameter choices

Mass Ordering Sensitivity



DUNE: Schedule

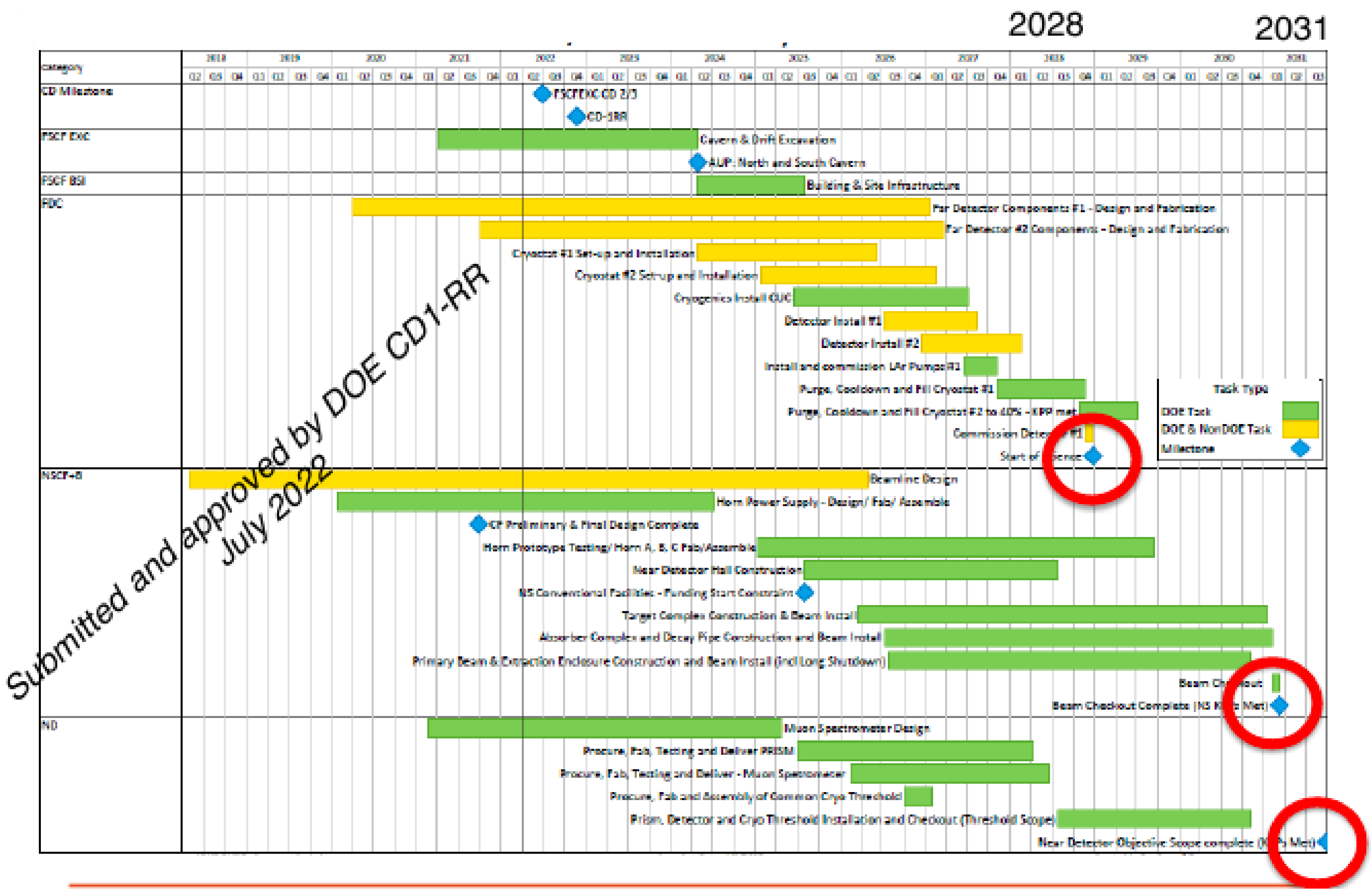




- **Phase I**
  - FD: 2 x 17 kt LArTPC modules
    - FD turns on late 2020s
  - ND: ND-LAr+TMS (with PRISM) + SAND
  - 1.2 MW capable beam-line and ND By 2031

- **Phase II**
  - FD: 4 x 17 kt modules
  - ND: ND-LAr+ND-GAr (with PRISM) + SAND
  - Proton beam 1.2 MW to 2.4 MW

DUNE: Schedule Summary



DUNE and Hyper-K Comparisons

- Similar to T2K/NOvA Comparisons

- **DUNE** long baseline (~1300 km, compared to Hyper-K BL (~295km)) will be more sensitive to matter effects (correlation with CPV)
  - Wide-band beam (multi-GeV energies) to measure multiple oscillation maxima for neutrinos and anti-neutrinos
  - High resolution detector (LArTPC) allows use of all (CC) cross section channels

- **Hyper-K** with shorter baseline will reduce correlation between CPV and matter effects
  - Low energy (sub-GeV), narrow-band beam to focus on CCQE
  - Inexpensive and well understood water Cerenkov detector with limited tracking ability but can employ larger fiducial masses

→ The joint measurements of DUNE and Hyper-K important to untangle the physics parameters embedded in $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$, specifically δ_{CP}

Summary and Outlook

- Both T2K and NOvA have accumulated significant POT
  - Joint analysis across all modes of oscillation $\nu_{\mu,e}/\bar{\nu}_{\mu,e}$ disappearance, appearance
  - Constraints from near detector measurements important to reduce systematic errors
  - These data show a preference for close to maximal θ_{23} mixing maybe upper octant, NO, and reduced the allowed δ_{CP} phase space

- Healthy competition and complementary between T2K and NOνA
  - Joint analysis in the works

- DUNE and Hyper-K have a similar complementary
  - It is important to determine the details of CPV using different baselines and detector technologies

→ Stay Tuned: More oscillation results to come – However to get definitive answers will take several years…