International Workshop on Frontiers in
Electroweak Interaction of Leptons and Hadrons,
November 2-6 2016, Aligarh

Status and Prospects of T2K/T2K-II and Hyper-Kamiokande

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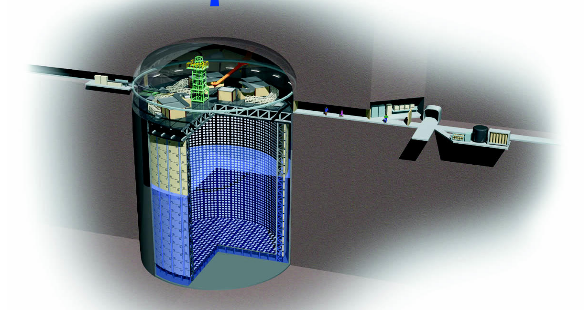
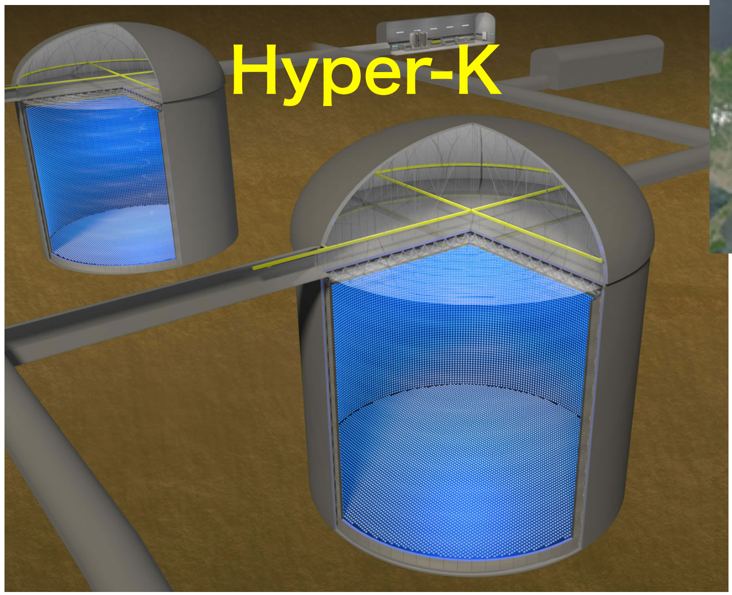
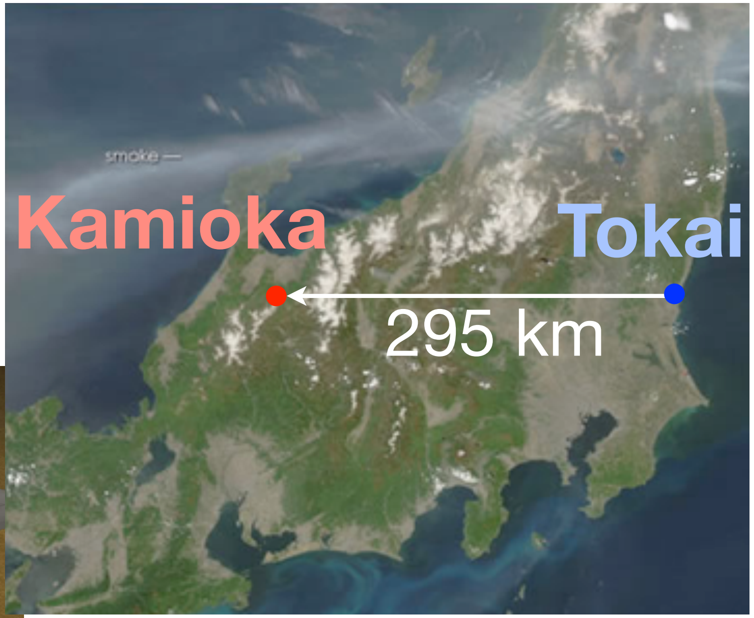
J-PARC Neutrino Beam and the detectors

Very Intense Neutrino Beam for $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ study

Super-K

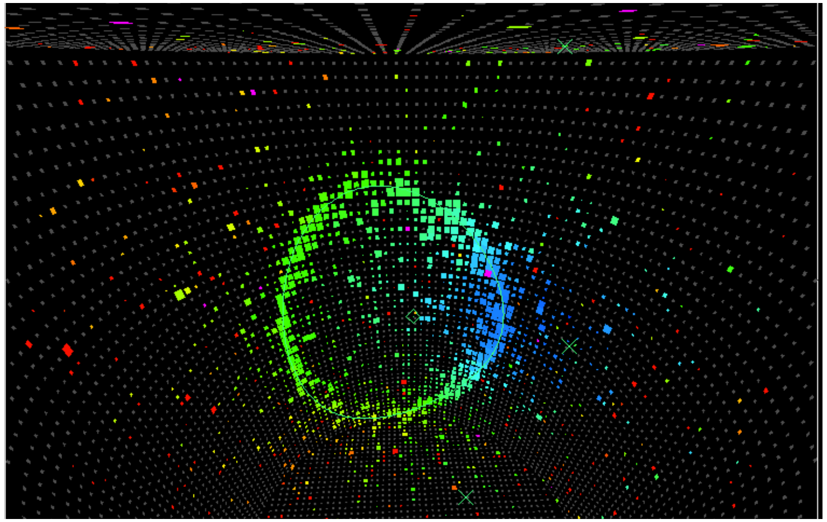






- 420 kW (today)
- ~1MW (2020)
- 1.3 MW (2025)

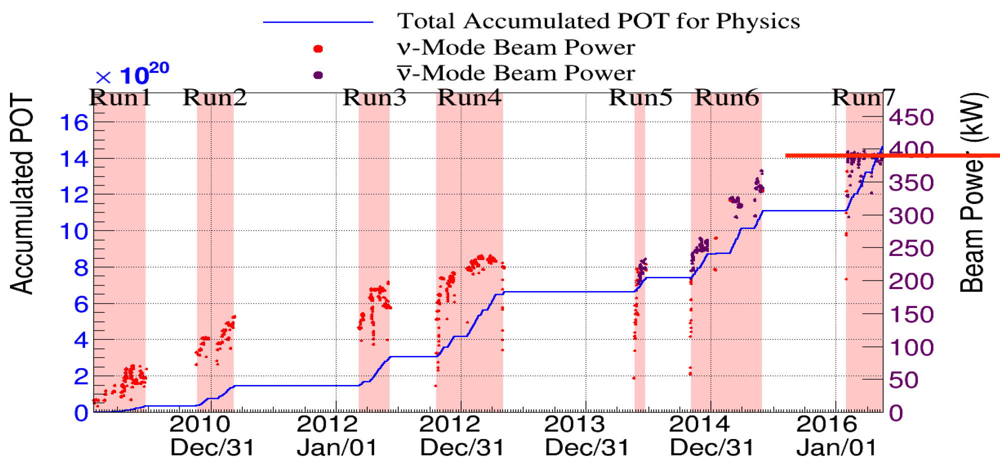
- 22.5 kton (Super-K, ~2026)
- 190(×2) kton (Hyper-K, 2026~)



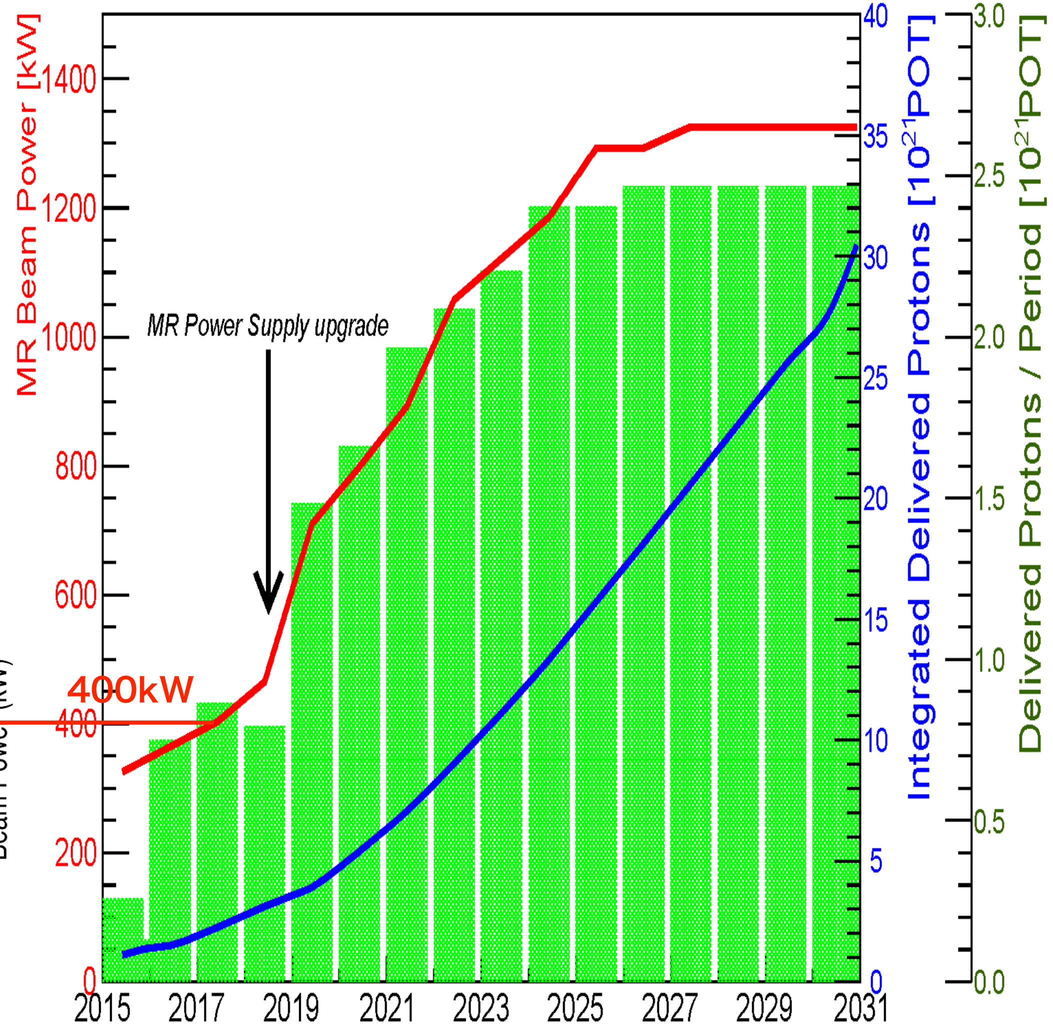
Accelerator Power Plan

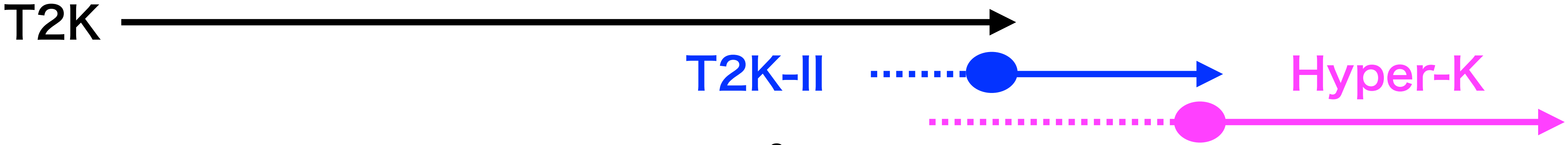
- J-PARC MR achieves **420 kW** operation
- **MR Power Supply Upgrade** is scheduled on 2018. [The upgrade is approved and the budget starts this year.]
- After the upgrade, aims at the power of **>1MW**.

Today

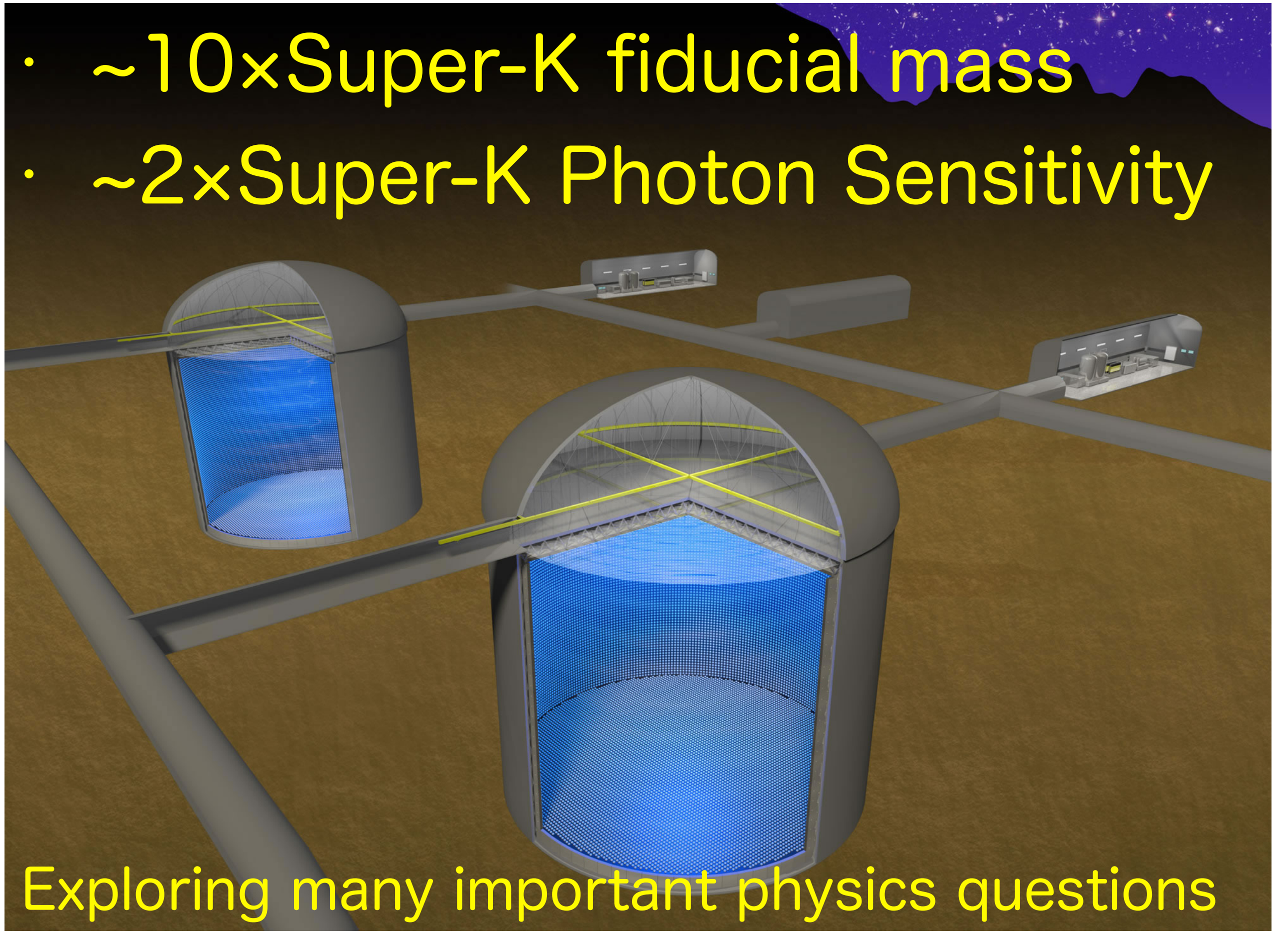


T2K-II to Hyper-K



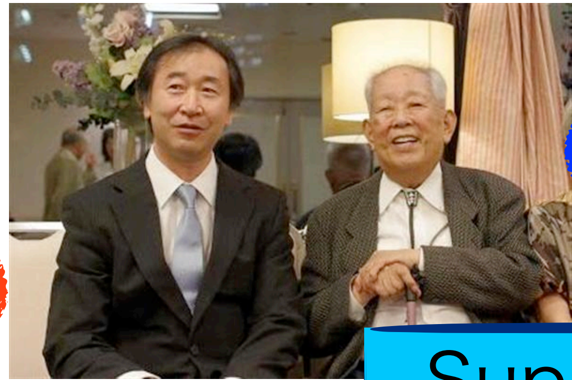


Hyper-Kamiokande
with Upgrade of J-PARC Neutrino Beam



- Neutrino particle-physics
- Neutrino astro-physics
- GUT
- more …

Neutrino Physics in Japan



ν osc.

ν astro

- Supernova ν
- Solar ν

- Atmospheric ν
- Solar ν

- 6 quark

CP

- Atmospheric ν
- Accelerator ν

T2K II

Hyper-K

Probing Neutrino CPV

- Neutrino Oscillations with CP violation
  - Weak (flavor) state ≠ Mass state
  - 3 generations ➡ Imaginary Phase in a mixing matrix
    - [Neutrino] MNS matrix ∼ [Quark] CKM matrix
  - Example: Prob.($\nu_\mu \rightarrow \nu_e$) ≠ Prob.($\overline{\nu}_\mu \rightarrow \overline{\nu}_e$)
- Heavy Majorana Neutrino (N) if exists
  - NOT easy to access (very very difficult)
  - The decay of N
    - Prob.($N \rightarrow \overline{l_L} + \phi$) ≠ Prob.($N \rightarrow l_L + \overline{\phi}$)
  - Or, the oscillations of N

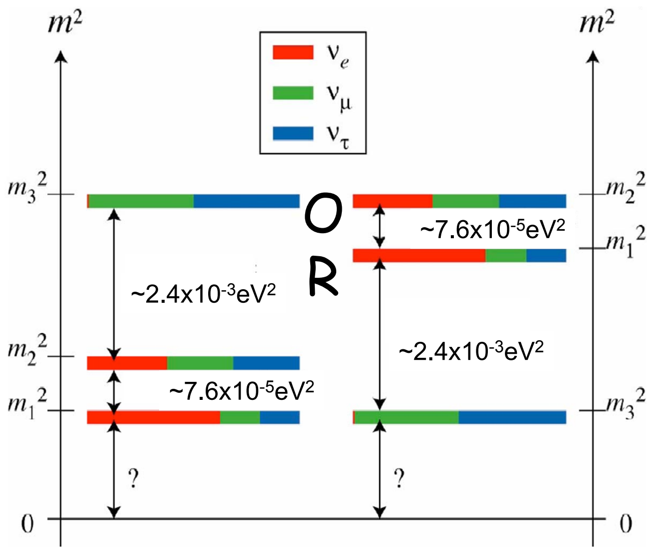
Leptogenesis and Neutrino CPV

- Saharov conditions for Baryon Asymmetry
  - [B] Baryon Number Violation
  - [CP] C and CP violation
  - [T] Interactions out of thermal equilibrium

- Leptogenesis and Low Energy CP violation in Neutrinos
  - [B] Sphaleron process for $\Delta(B+L)\neq 0$
  - [CP] Heavy Majorana Neutrino decay and/or Neutrino oscillations
    - [Phys. Rev. D75, 083511 (2007)] **$|\sin\theta_{13}\sin\delta|>0.09$** is a necessary condition for a successful "flavoured" leptogenesis with hierarchical heavy Majorana neutrinos when the CP violation required for the generation of the matter-antimatter asymmetry of the Universe is provided entirely by the Dirac CP violating phase in the neutrino mixing matrix.
      - $\sin\theta_{13}\sim 0.15$ ➡ **$|\sin\delta|>0.6$**

How to measure neutrino CPV?

- Measure $P(\nu_\mu \to \nu_e)/P(\overline{\nu}_\mu \to \overline{\nu}_e) \neq 1$
  - or $P(\nu_\mu \to \nu_\tau)/P(\overline{\nu}_\mu \to \overline{\nu}_\tau) \neq 1$ because of $P(\nu_\mu \to \nu_{all})/P(\overline{\nu}_\mu \to \overline{\nu}_{all}) = 1$
- Or, precisely measure $P(\nu_\mu \to \nu_e)$ with the assumption of 3 light neutrinos. Within the framework of 3 neutrinos, CP violation will be governed by the imaginary phase δ_{CP} in the neutrino mixing matrix.
- Matter effect can mimic the genuine CP violation. The measurement of the matter effect is equally important to study neutrino CP violation. The matter effect determine the neutrino mass ordering.



Formula of Oscillation Probability with CP violation

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \;=\; & 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31} \\
& +8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& -8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& +4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21} \\
& -8C_{13}^2 S_{132}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \\
& +8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{13}^2} (1 - 2S_{13}^2) \sin^2 \Delta_{31}
\end{aligned}
$$

Leading

CP violating (flips sign for $\bar{\nu}$)

Solar

Matter effect

Leading $\sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$

CPV

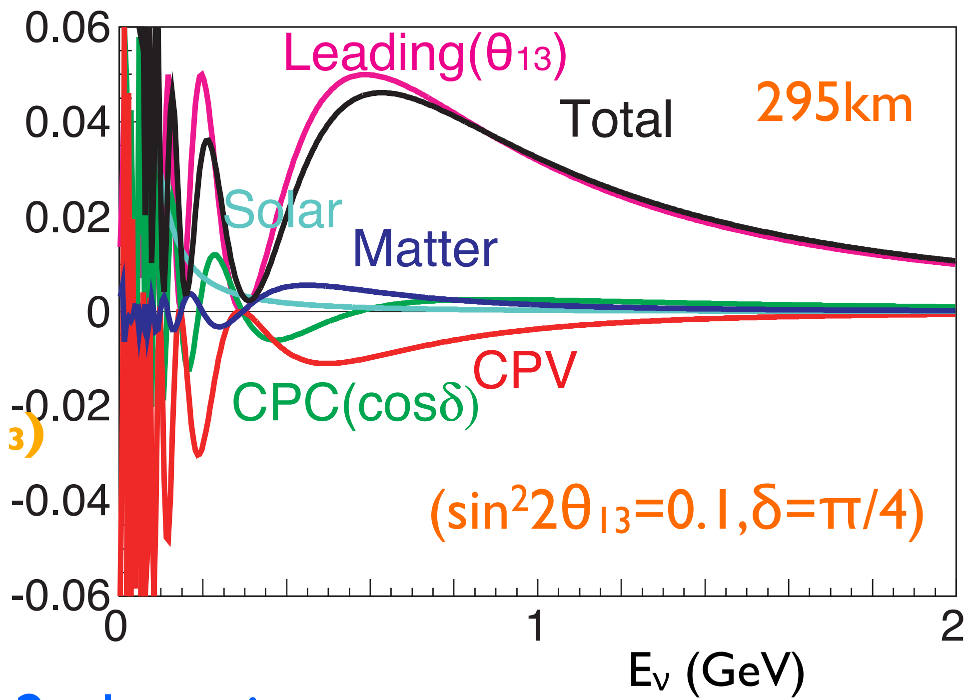
$$\frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2\sin\theta_{13}} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \sin\delta$$

~0.03 ~11.8 (6.4 from $1/\sin\theta_{13}$)

$$\sim \frac{\pi}{4} \frac{\Delta m_{21}^2}{\Delta m_{32}^2} \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{\sin^2\theta_{23} \sin\theta_{13}} \frac{E_{1st\,max}}{E} [leading] \sin\delta$$

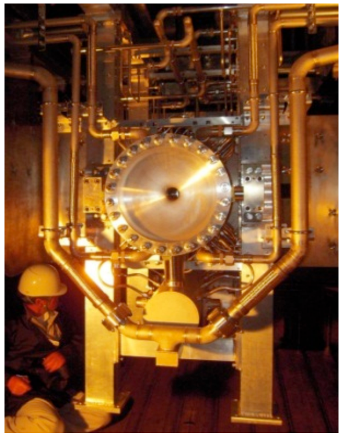
$$\sim 0.27 \times [leading] \times \frac{E_{1st\,max}}{E} \times \sin\delta$$

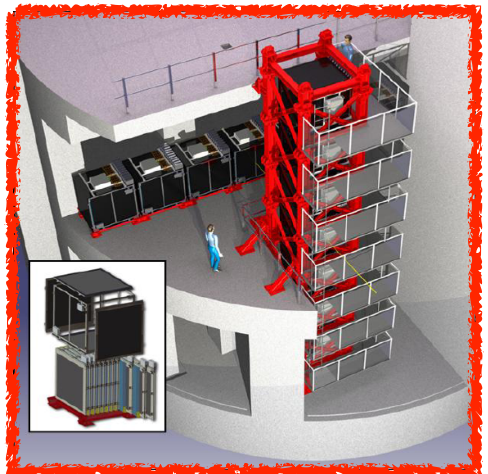
27%

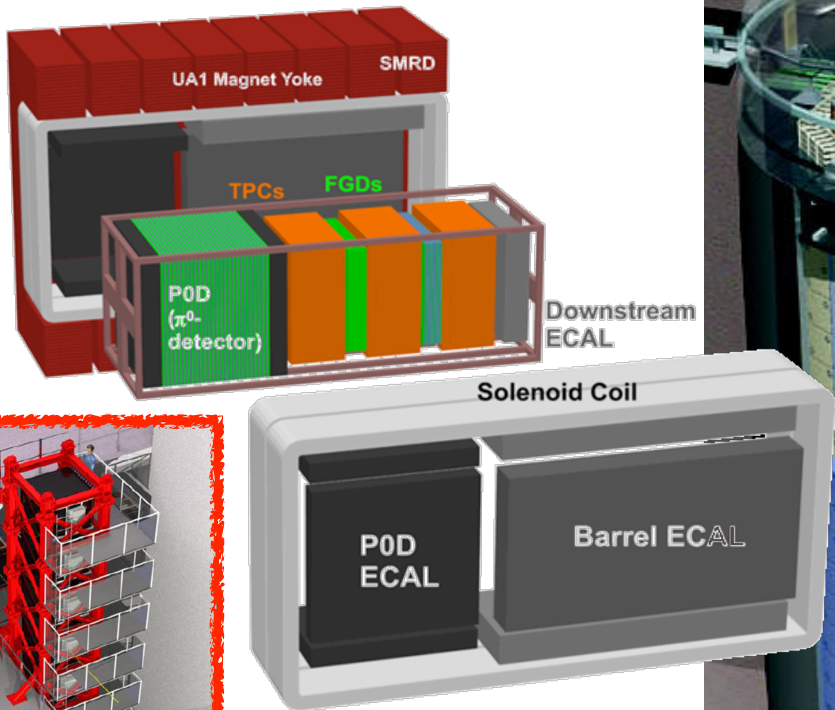


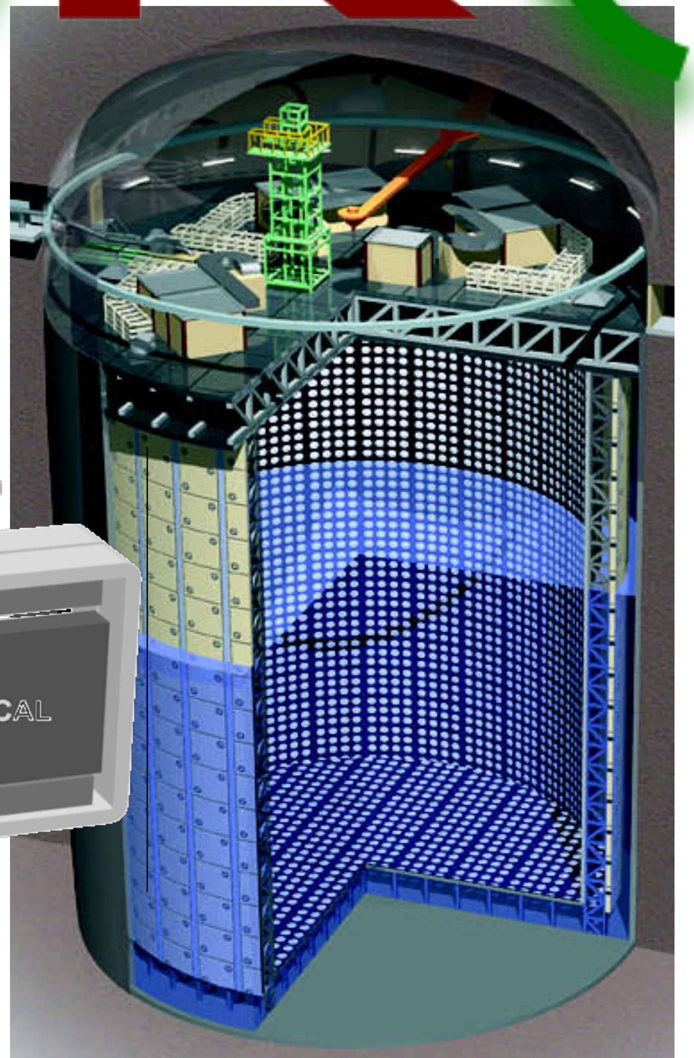
- No magic for the 2nd maximum.
- Energy dependence is important.

T2K

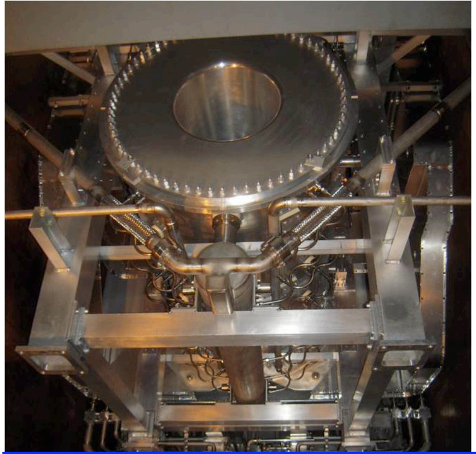




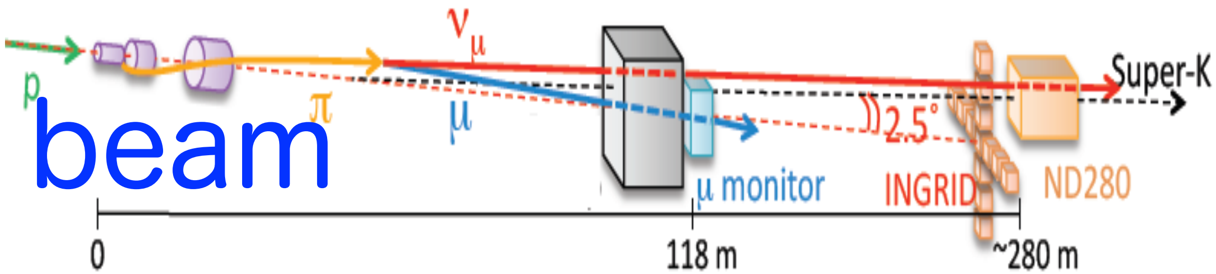

UA1 Magnet Yoke
SMRD
TPCs
FGDs
P0D
(π⁰-
detector)
Downstream
ECAL
Solenoid Coil
P0D
ECAL
Barrel ECAL



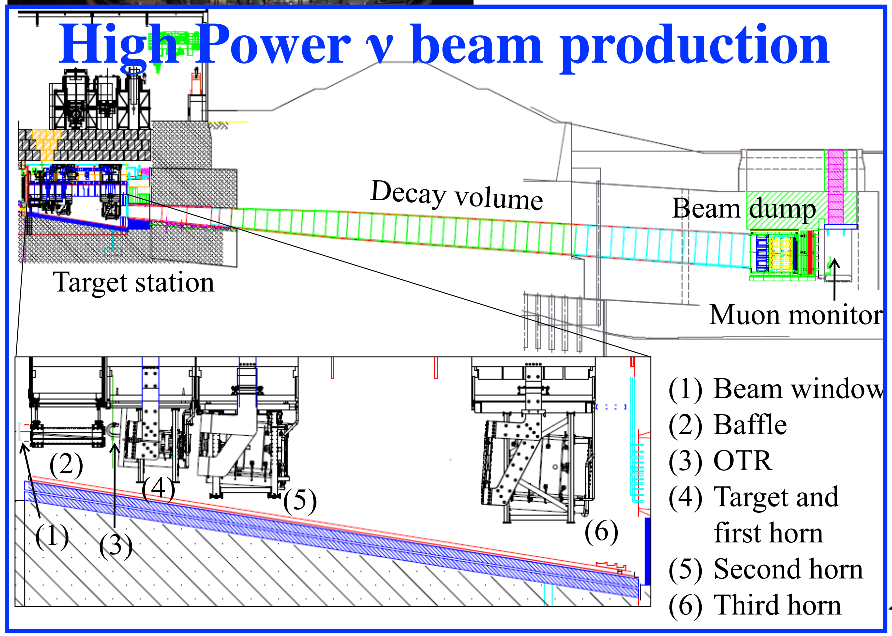
J-PARC
(Japan-Proton-Accelerator Research Complex)

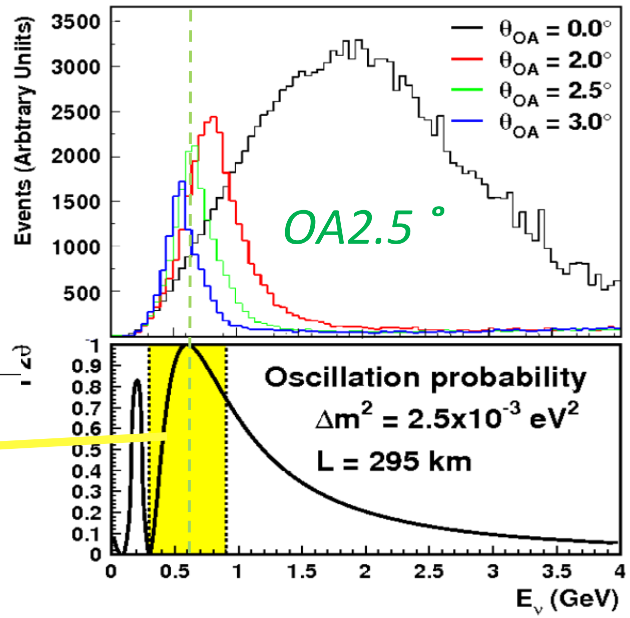


T2K ν beam

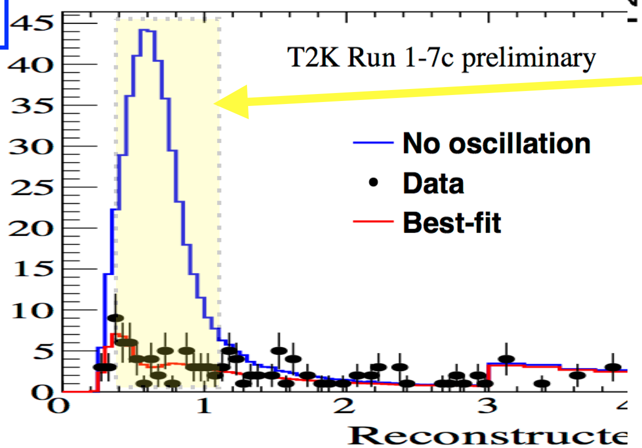


- **Off-axis (2.5 °) ν_μ beam**
  - Intense, low energy narrow-band
  - Peak E_ν tuned for oscillation max. (~0.6 GeV)
  - Reduce BG from high energy tail
  - 1mrad direction shift => ~2% energy shift at peak
  - Small ν_e fraction (~1%)





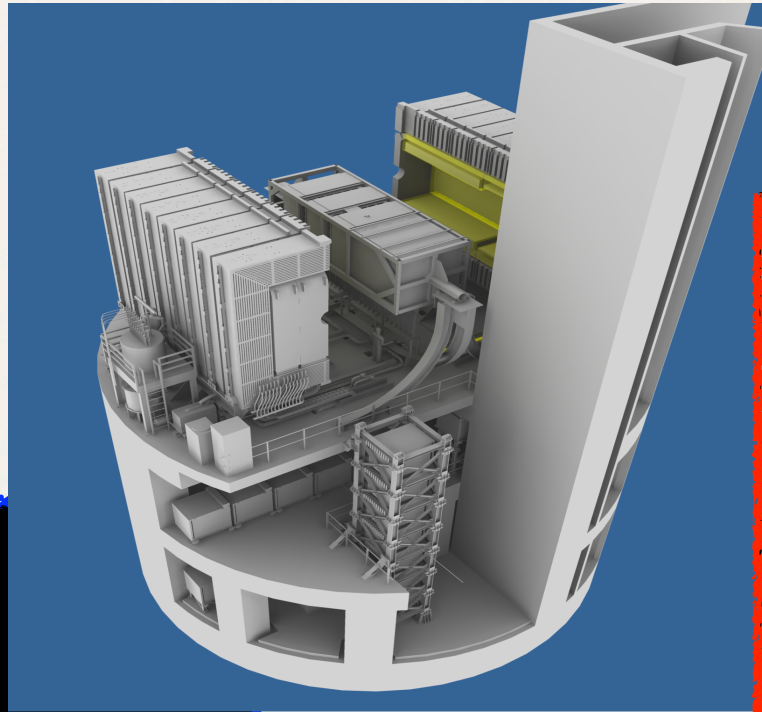
T2K 2016 ν_μ disappearance

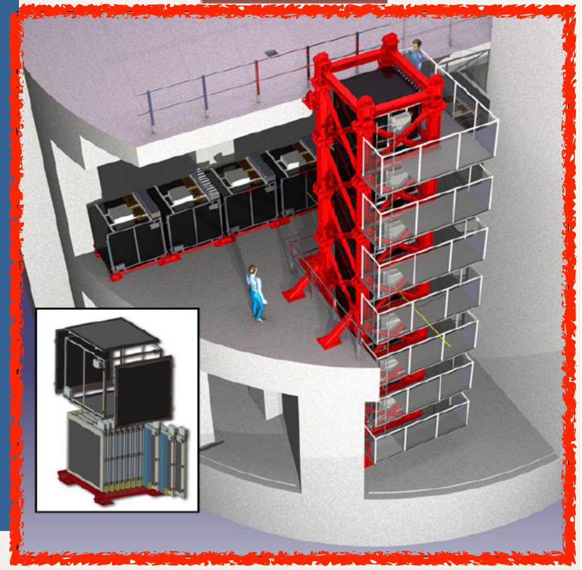


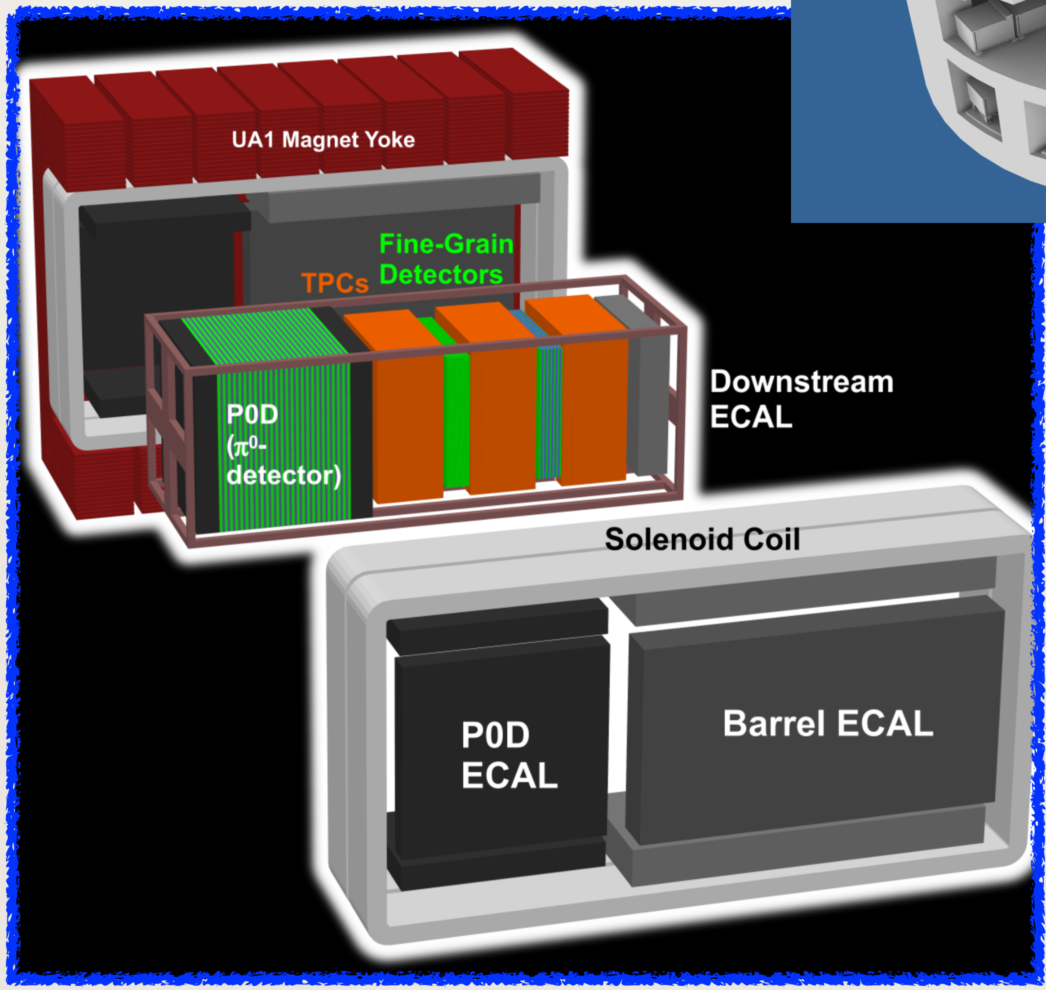
- 30 GeV **~1×10^14** protons extracted every 2.5/1.3 sec. directed to the carbon target.
- Secondary π^+(and K^+) focused by three electromagnetic horns (**250kA/320kA**)
- ν_μ from mainly $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - ν_e in the beam come from K and μ decays

ND280

Near Detector @ 280m from the target



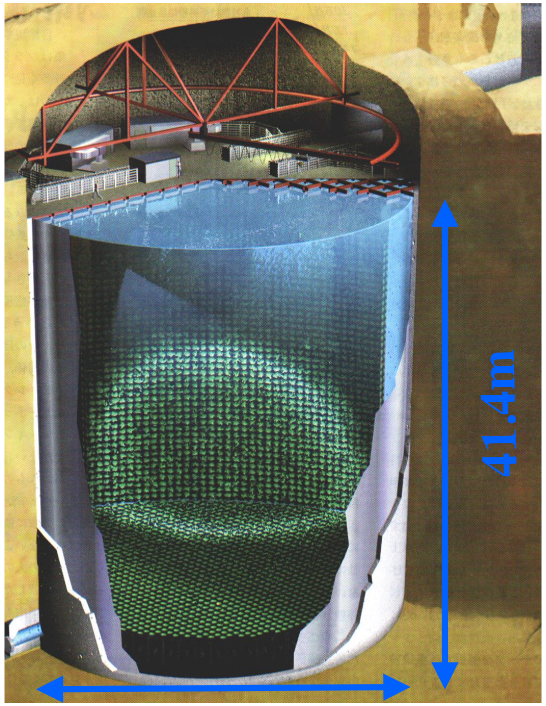


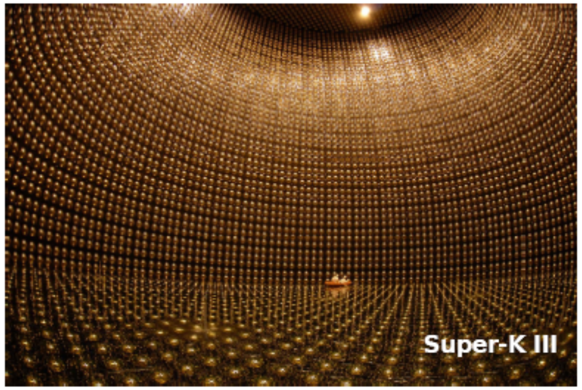


- **INGRID** @ on-axis (0 degree)
  - ν beam monitor [rate, direction, and stability]

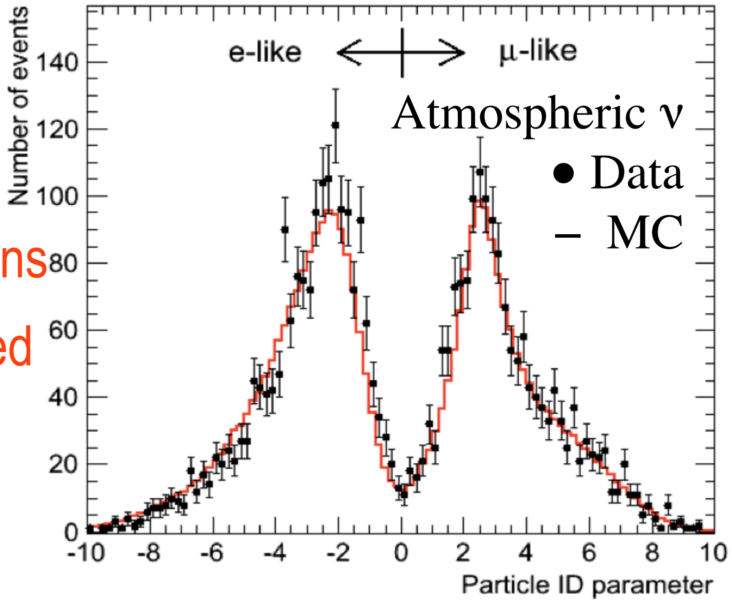
- **ND280** @ 2.5 degree off-axis
  - ✦ Normalization of Neutrino Flux
  - ✦ Measurement of neutrino cross sections.
    - Dipole magnet w/ 0.2T
    - **P0D:** π^0 Detector
    - **FGD+TPC:** Target + Particle tracking
    - **EM calorimeter**
    - **Side-Muon-Range Detector**

T2K-Far Detector: Super-Kamiokande



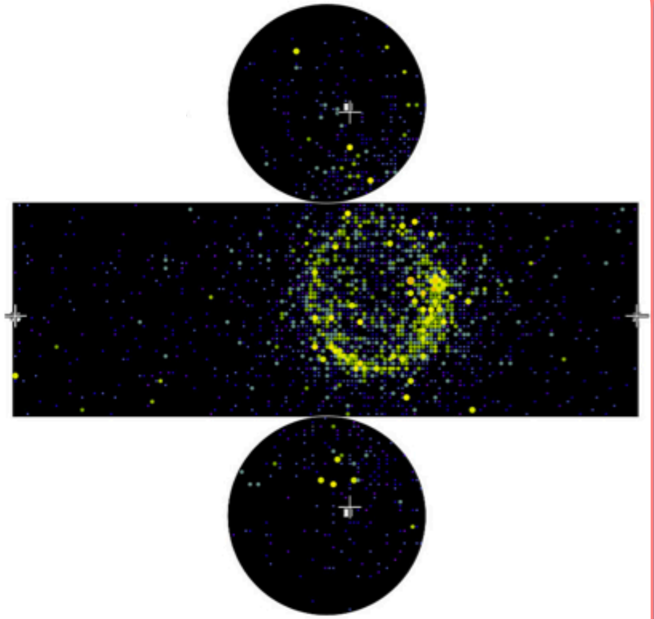


- Water Cherenkov detector with 50 kton mass (22.5 kton Fiducial volume) located at 1km underground
  - Good performance (momentum and position resolution, PID, charged particle counting) for sub-GeV neutrinos.
  - [Typical] 61% efficiency for T2K signal ν_e with 95% NC-1π^0 rejection
    - Inner tank (32 kton) :11,129 20inch PMT
    - Outer tank:1,885 8inch PMT
- Dead-time-less DAQ
- GPS timing information is recorded real-time at every accelerator spill
  - T2K recorded events: All interactions within a ±500μsec window centered on the the neutrino arrival time.

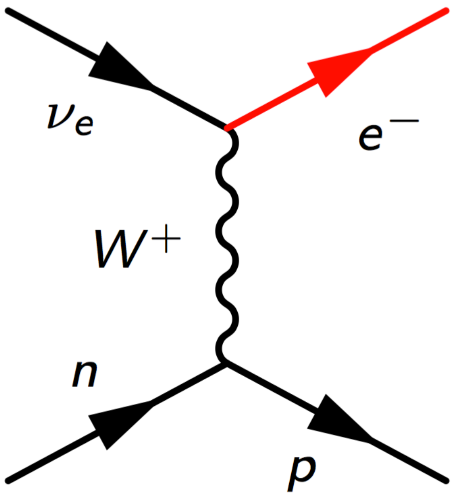


Neutrino Detection at SK Far Detector

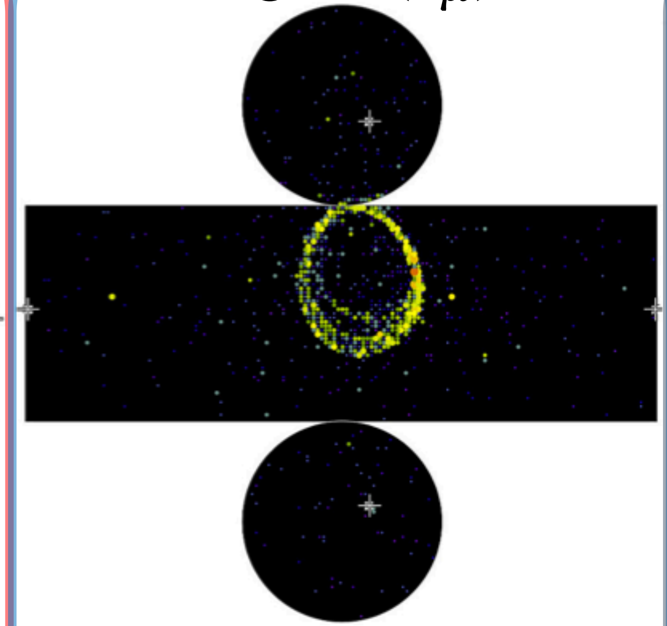
Signal (ν_e)



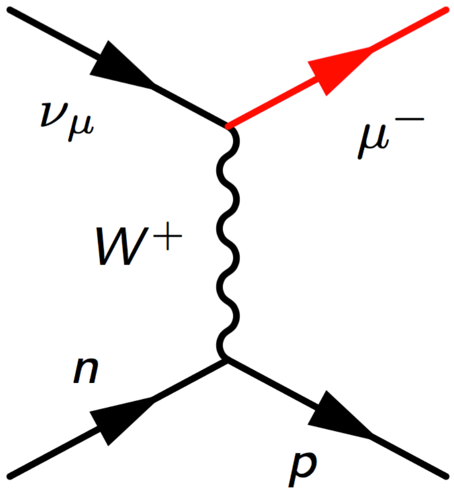
ν_e CCQE



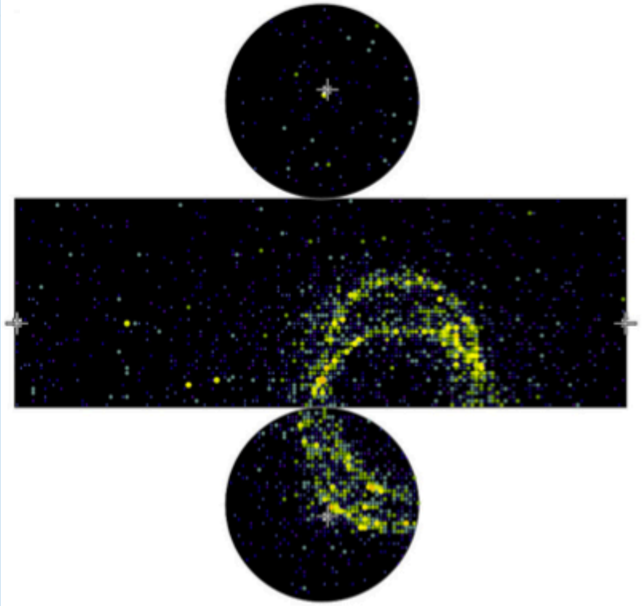
Signal (ν_μ)



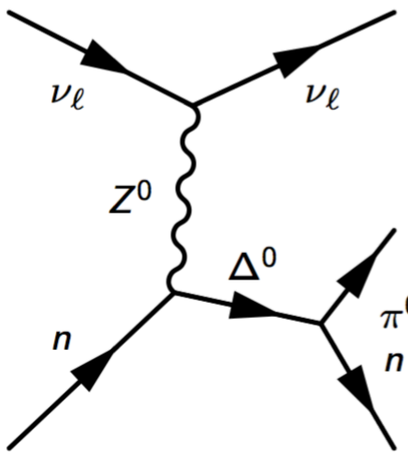
ν_μ CCQE



Background

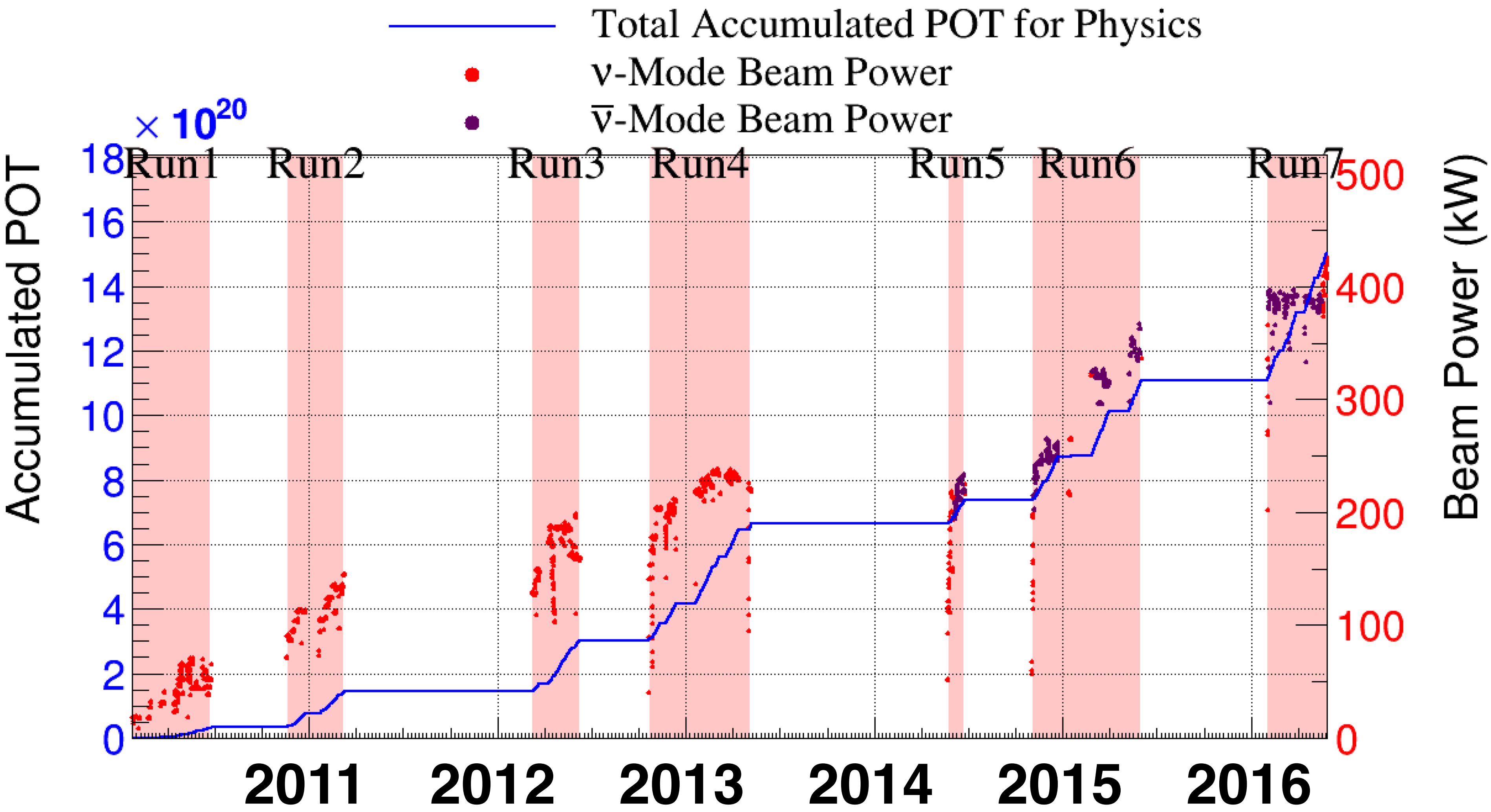


ν_ℓ NC1π^0



New Results
- this summer-

Data Set



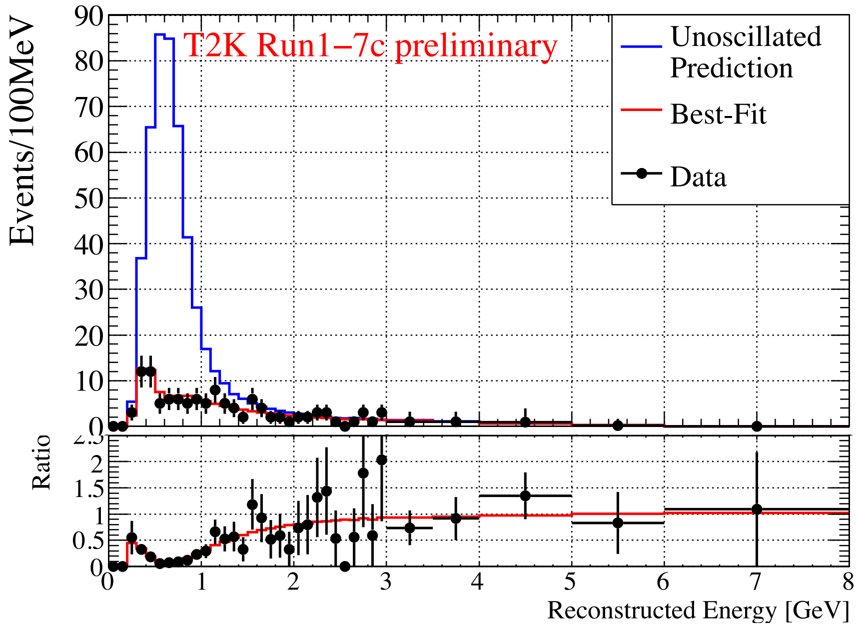
27 May 2016
POT total: 1.510×10^{21}

ν-mode POT: 7.57×10^{20} (50.14%)
ν̄-mode POT: 7.53×10^{20} (49.86%)

$\nu_\mu/\bar{\nu}_\mu$ Disappearance Analysis

- CPT test by comparing $(\nu_\mu \rightarrow \nu_\mu)$ and $(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$ modes

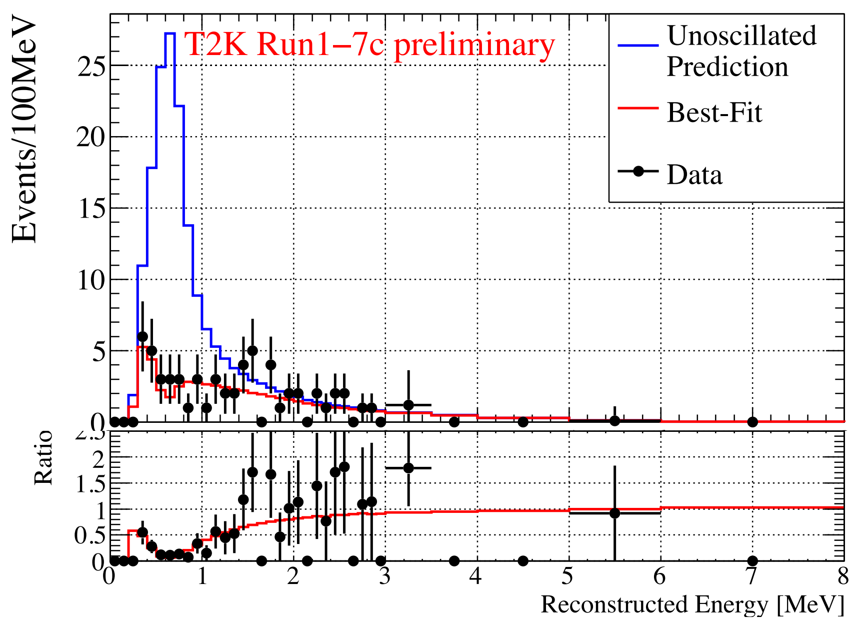
ν_μ



135 events observed

(135.8 events expected)

$\bar{\nu}_\mu$

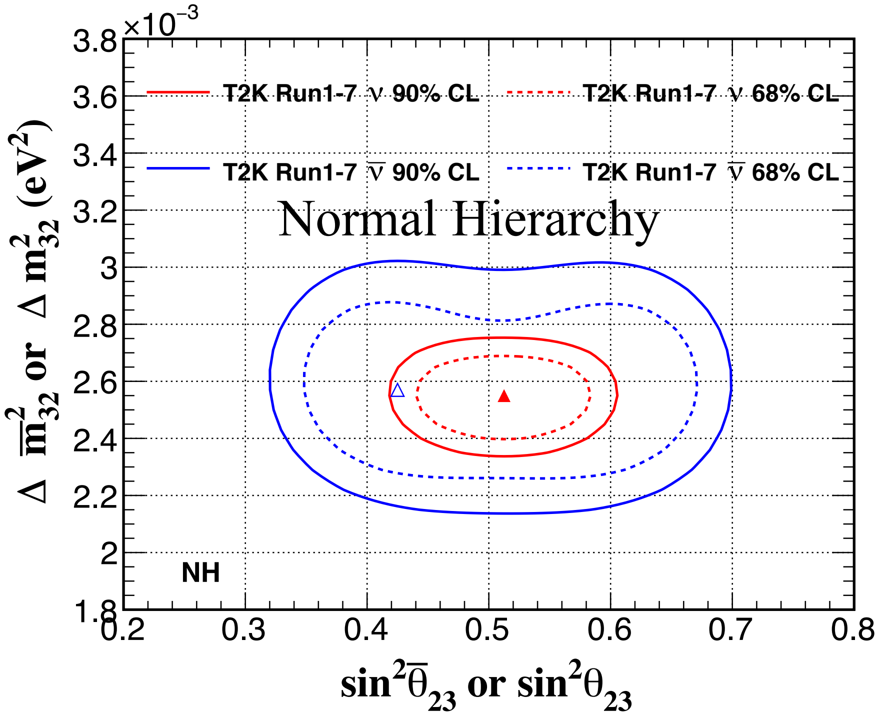


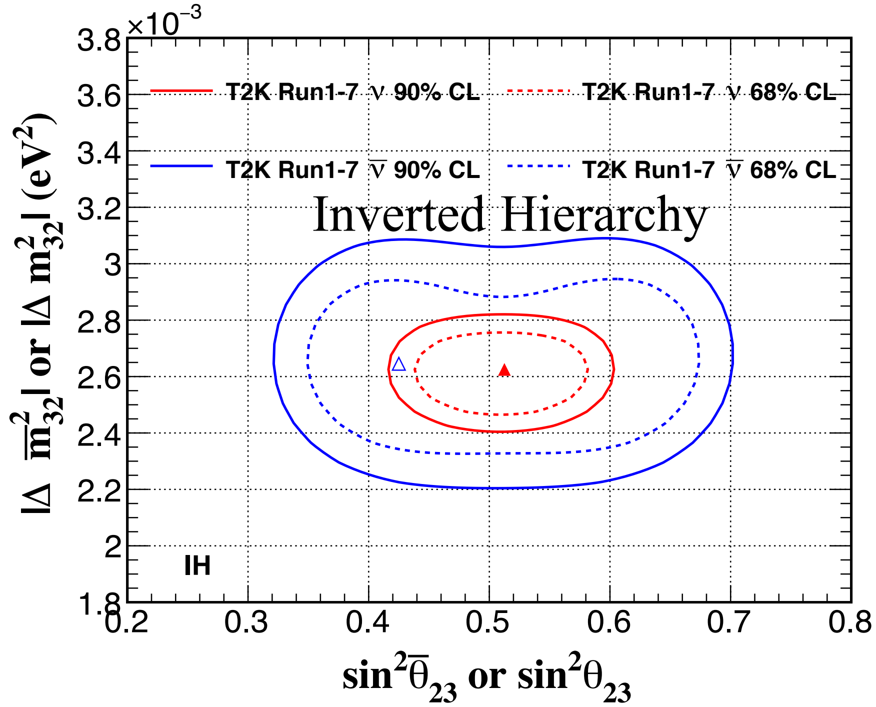
66 events observed

(64.2 events expected)

θ_{23} and Δm^2_{32} Comparison

- No hint of CPT violation





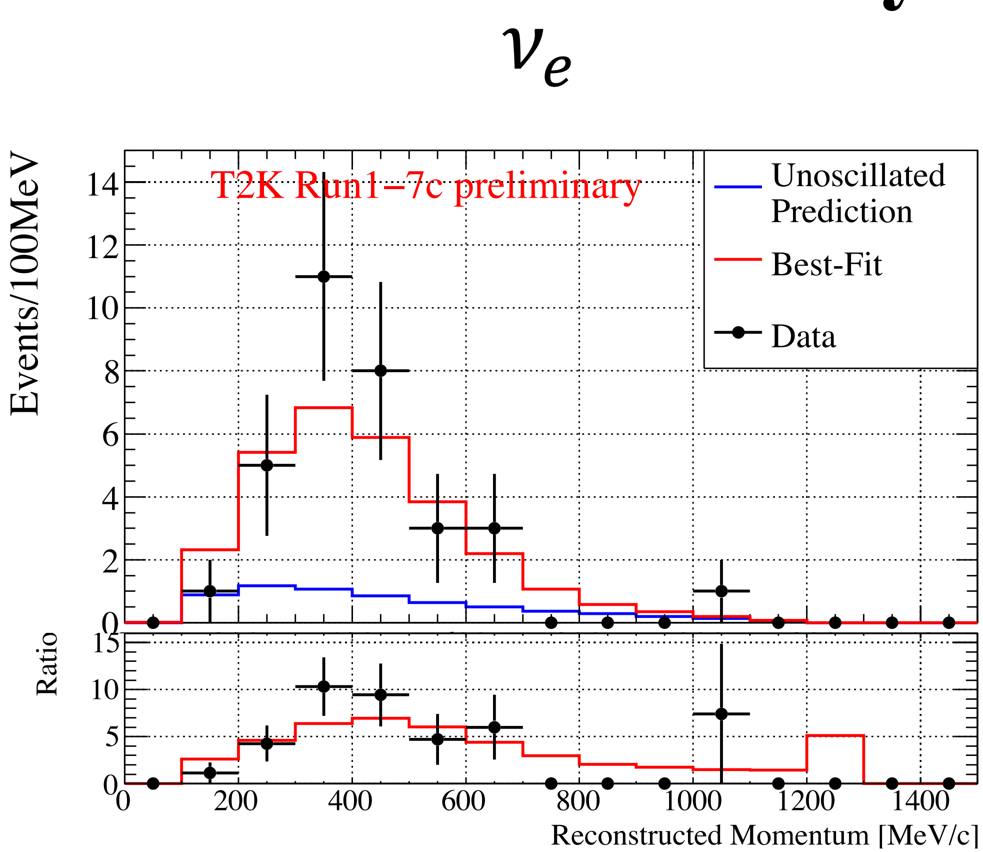
$\Delta\overline{m}^2_{32} = [2.16, 3.02]\times 10^{-3} eV^2 (NH)$ at 90% CL

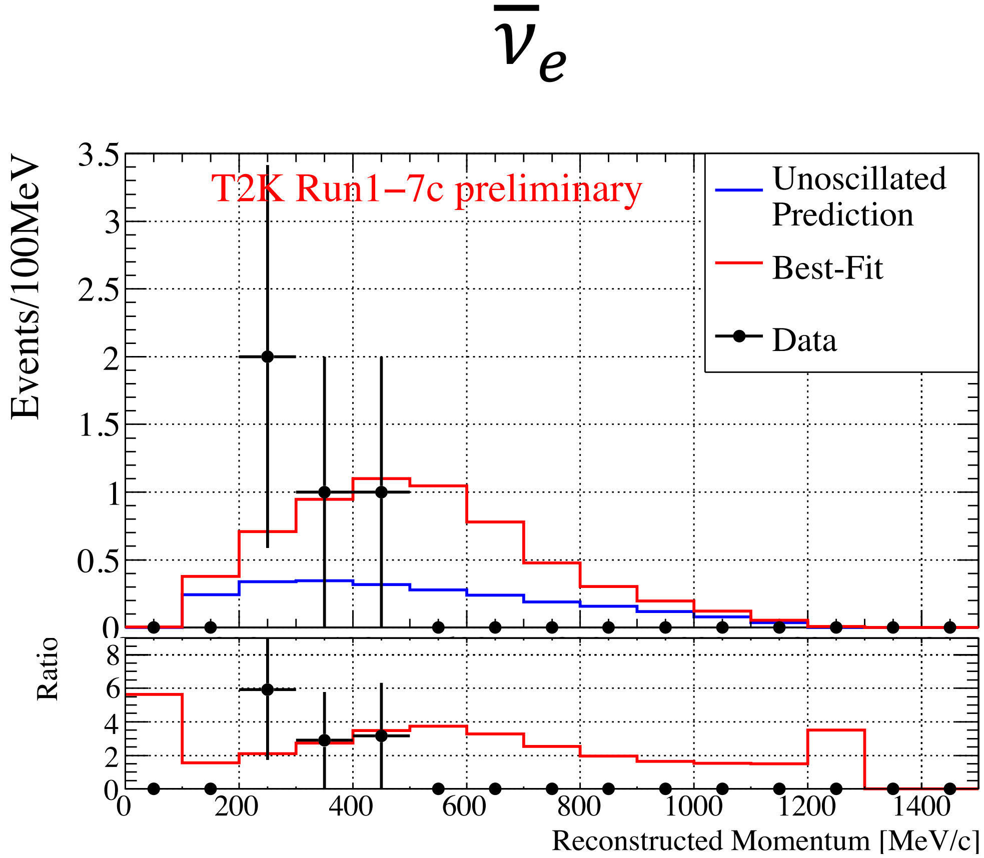
$\sin^2\overline{\theta}_{23} = [0.32, 0.70](NH)$ at 90% CL

$\Delta m^2_{32} = [2.34, 2.75]\times 10^{-3} eV^2 (NH)$ at 90% CL

$\sin^2\theta_{23} = [0.42, 0.61](NH)$ at 90% CL

Full Joint Fit Analysis





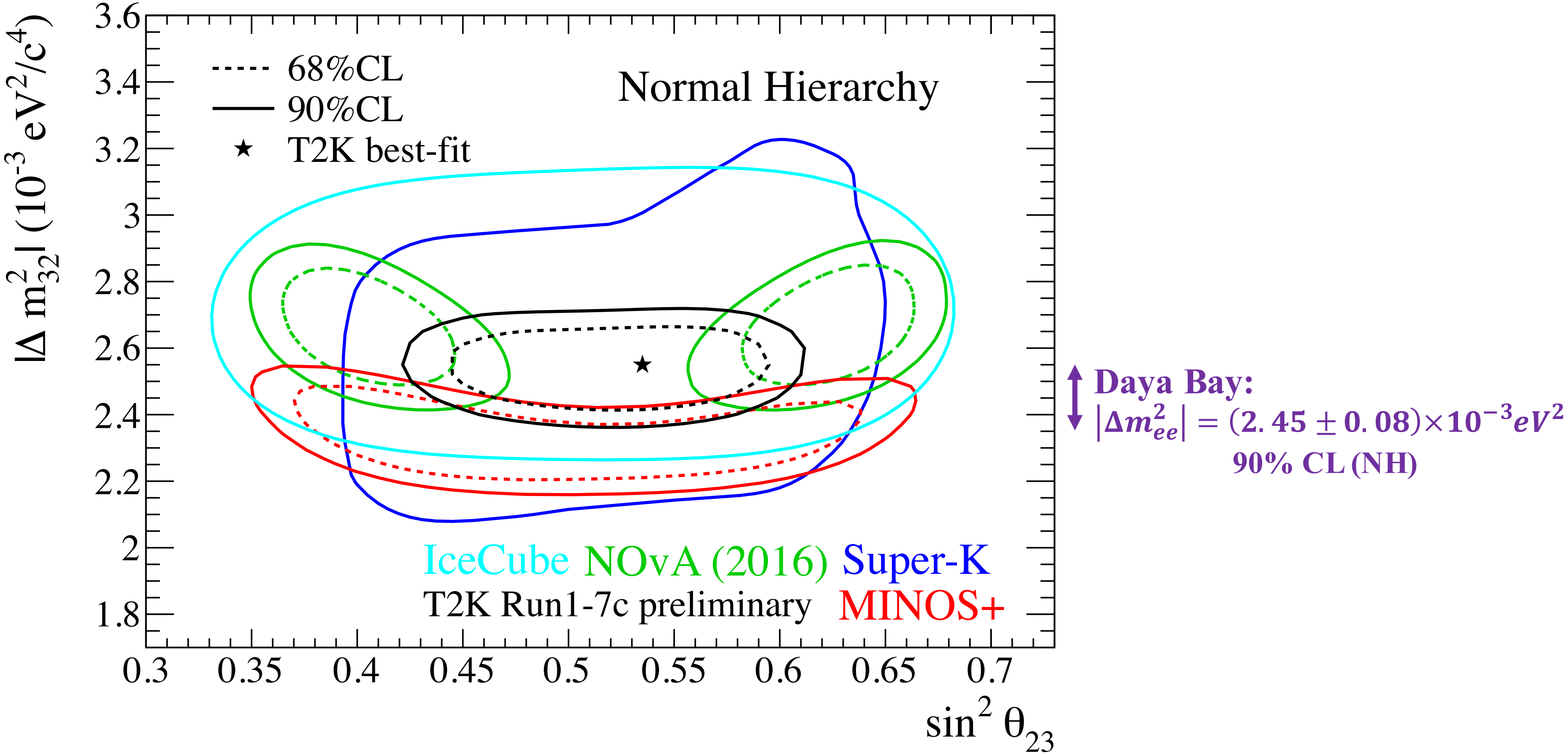
32 events observed

4 events observed

	$\delta_{cp} = -\pi/2$ (NH)	$\delta_{cp} = 0$ (NH)	$\delta_{cp} = +\pi/2$ (NH)	$\delta_{cp} = \pi$ (NH)	Observed
ν_e	28.7	24.2	19.6	24.1	32
$\bar{\nu}_e$	6.0	6.9	7.7	6.8	4

θ_{23} and Δm^2_{32}

- Consistent with maximal mixing

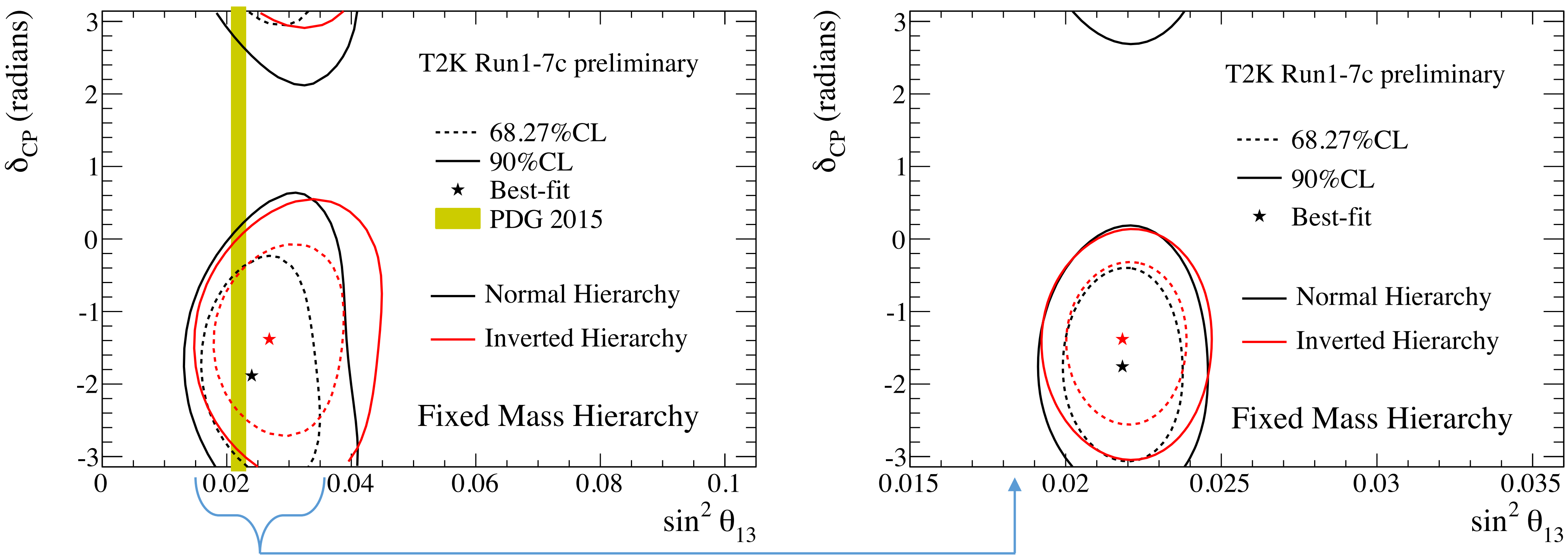


	NH	IH
$\sin^2\theta_{23}$	$0.532^{+0.046}_{-0.068}$	$0.534^{+0.043}_{-0.066}$
$\lvert\Delta m^2_{32}\rvert[10^{-3}eV^2]$	$2.545^{+0.081}_{-0.084}$	$2.510^{+0.081}_{-0.083}$

θ_{13} and δ_{cp}

T2K-Only

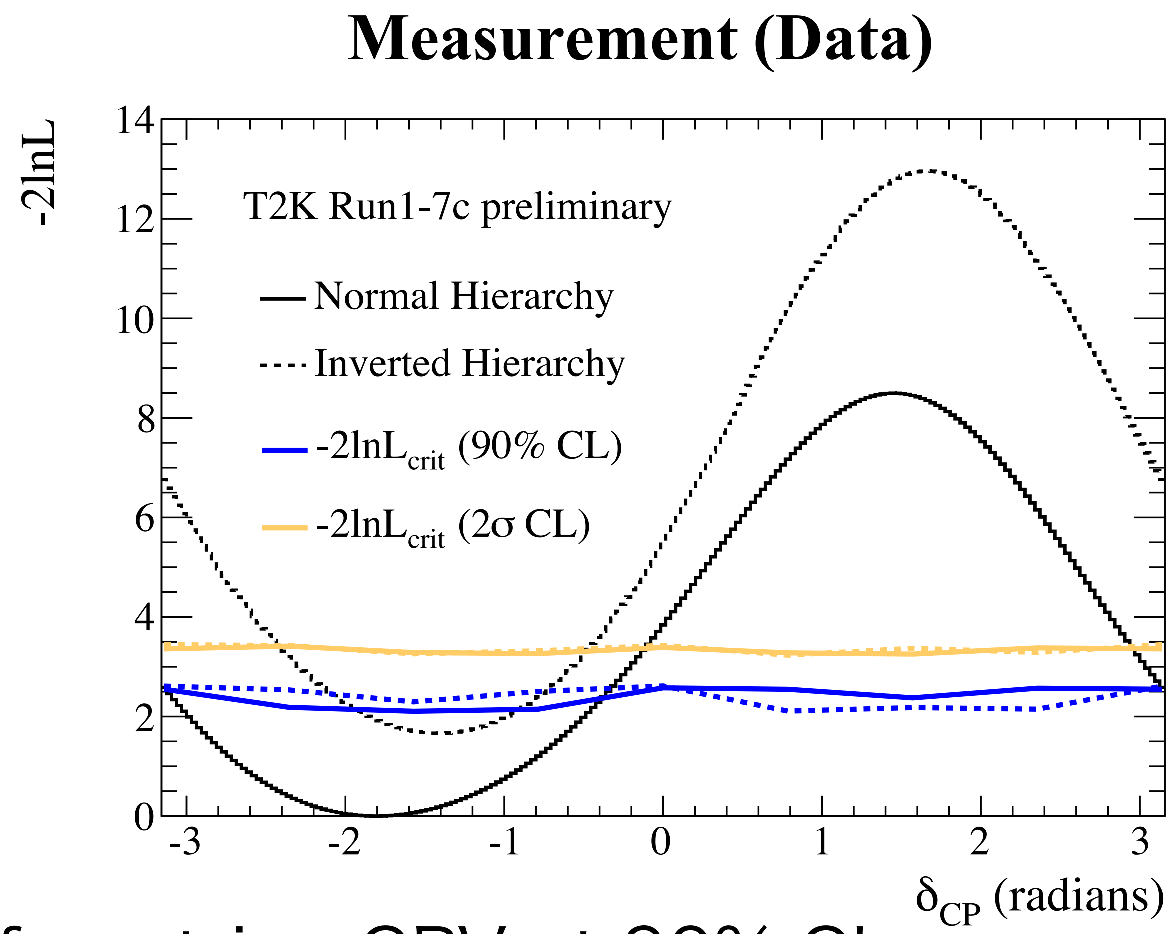
T2K Result with Reactor Constraint ($sin^2 2\theta_{13} = 0.085 \pm 0.005$)



- T2K-only result consistent with the reactor measurement
- Favors the $\delta_{cp} \sim -\frac{\pi}{2}$ region

δ_{CP} with reactor θ_{13}

with $\sin^2 2\theta_{13}$=0.085±0.005



- A hint of neutrino CPV at 90% CL
  - δ_{CP} = [-3.13, -0.39] (NH), [-2.09, -0.74] (IH) at 90% CL

Prospect

CP Violation Sensitivity in T2K-II

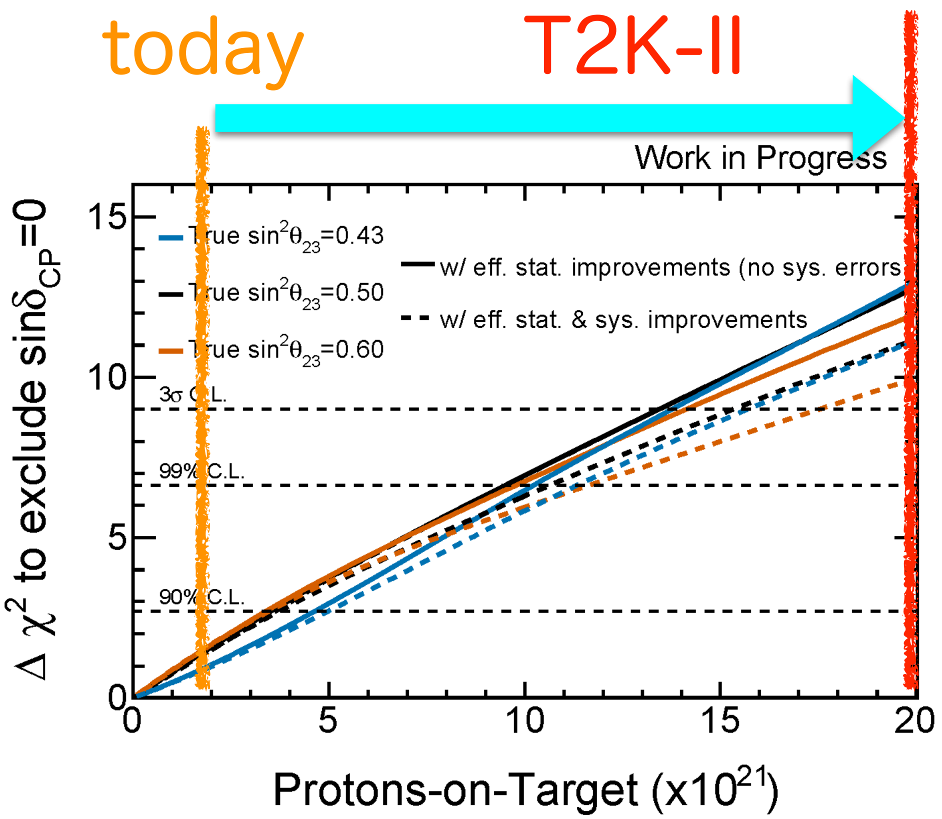
T2K-II w/ improved stat. (10E21 POT for nu and 10E21 POT for anti-nu)

	True δ_{CP}	Total	Signal $\nu_\mu \to \nu_e$	Signal $\bar{\nu}_\mu \to \bar{\nu}_e$	Beam CC $\nu_e + \bar{\nu}_e$	Beam CC $\nu_\mu + \bar{\nu}_\mu$	NC
ν-mode	0	454.6	346.3	3.8	72.2	1.8	30.5
ν_e sample	$-\pi/2$	545.6	438.5	2.7	72.2	1.8	30.5
$\bar{\nu}$-mode	0	129.2	16.1	71.0	28.4	0.4	13.3
$\bar{\nu}_e$ sample	$-\pi/2$	111.8	19.2	50.5	28.4	0.4	13.3

3σ sensitivity to CP violation for favorable parameters based on

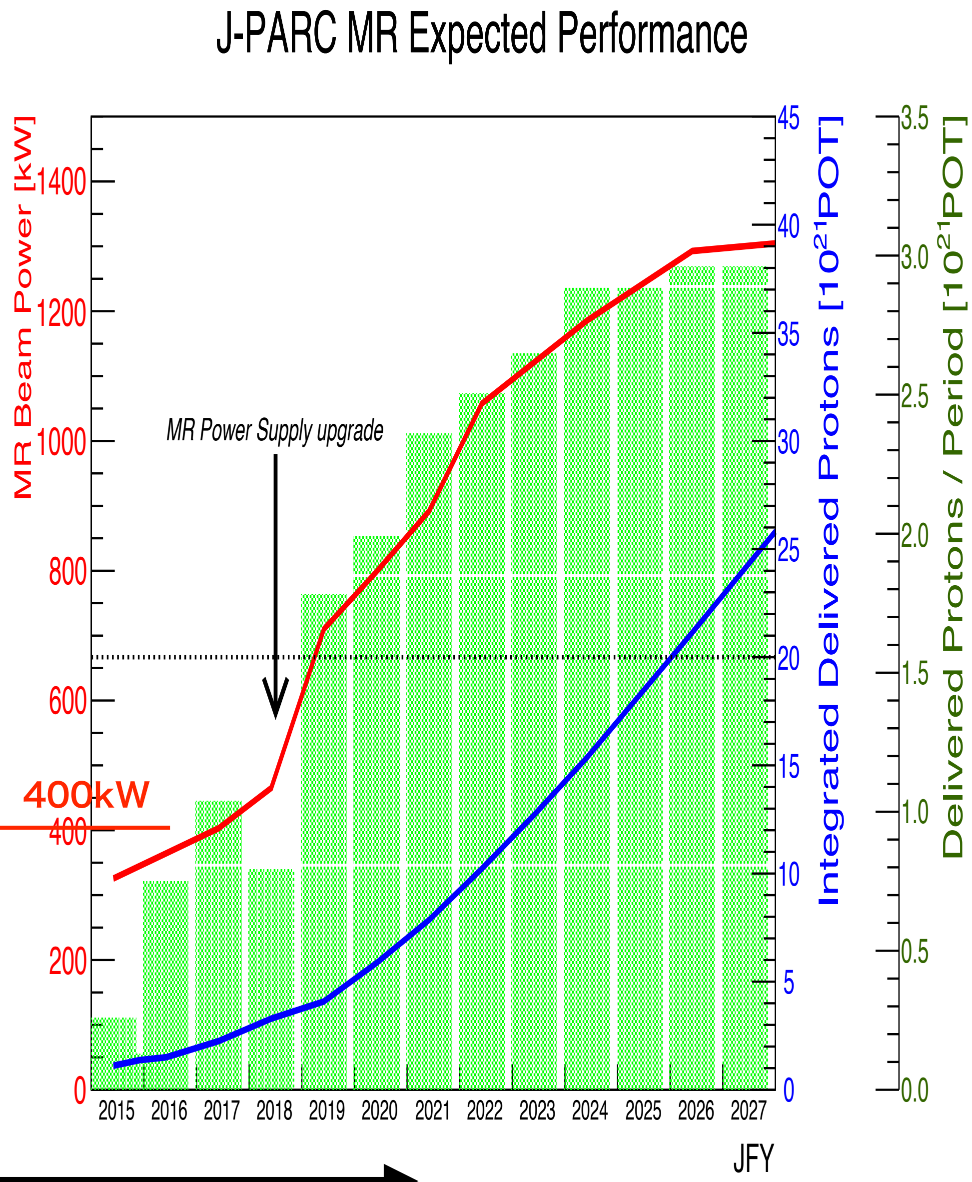
- 20×10^{21} Protons on Target with the upgrade of J-PARC to 1.3MW (~10 year long run) before year 2026.
- 50 % more events with improvements of the beam line and event reconstructions.
- ~2/3 smaller systematic uncertainties.

J-PARC PAC gives Stage 1 approval. We are preparing the Technical Design Report.

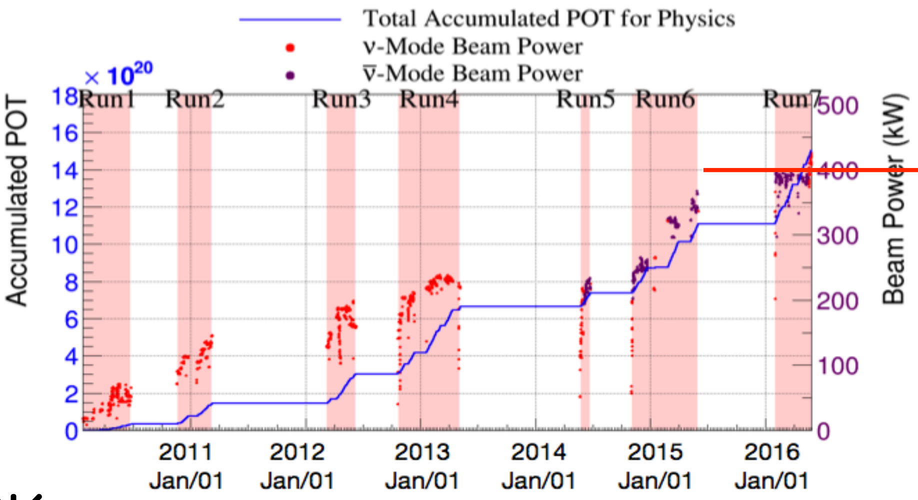


Accelerator Upgrade

- J-PARC MR has achieved 420 kW operation
- MR Power Supply Upgrade is scheduled in 2018.
- J-PARC demonstrated 3.41E13 ppb operation [1 MW equivalent] (see the accelerator reports in the previous J-PARC PAC).
- After the upgrade, the aim is 1.3MW or higher.



Today

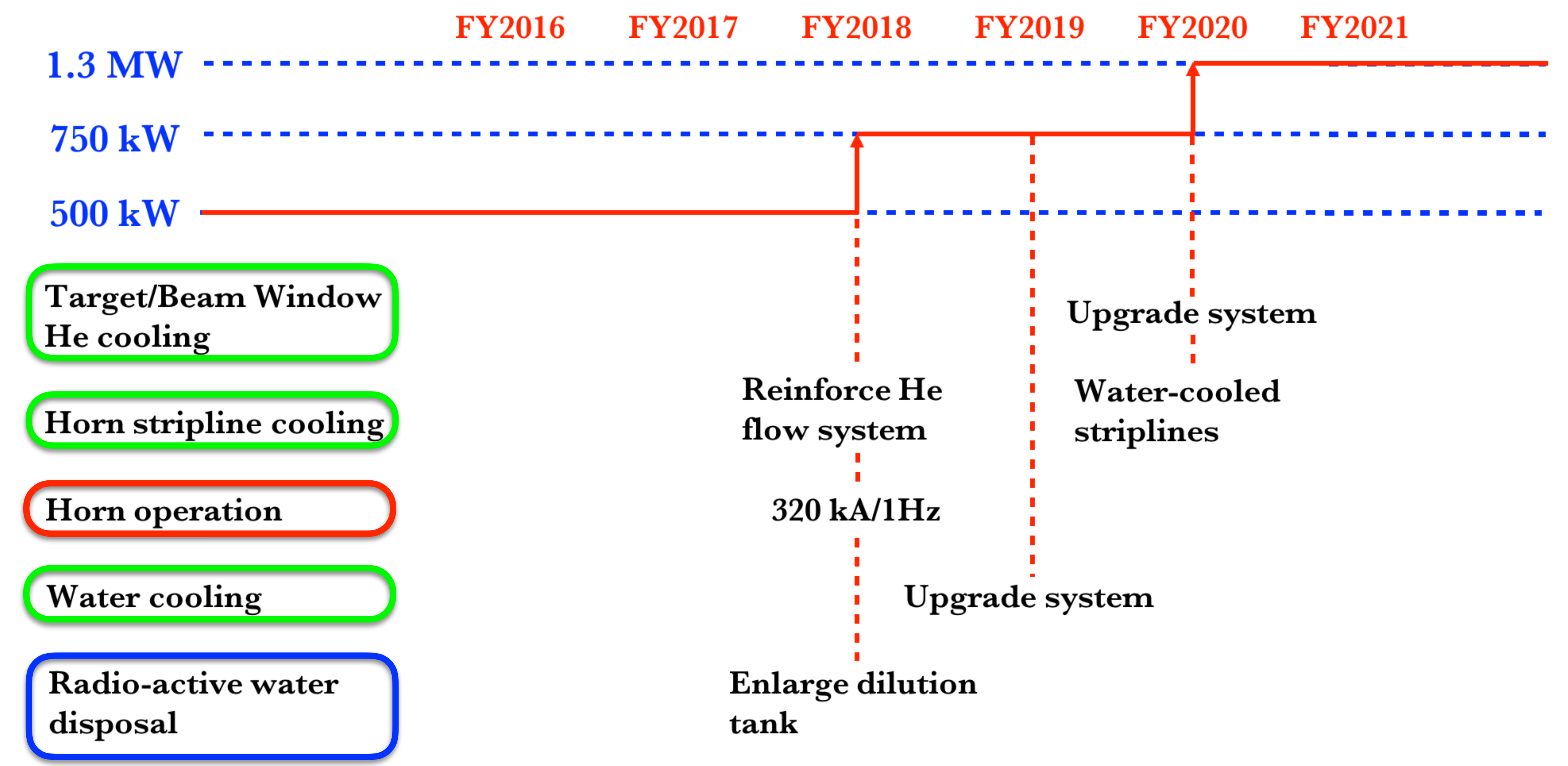


T2K

Extension

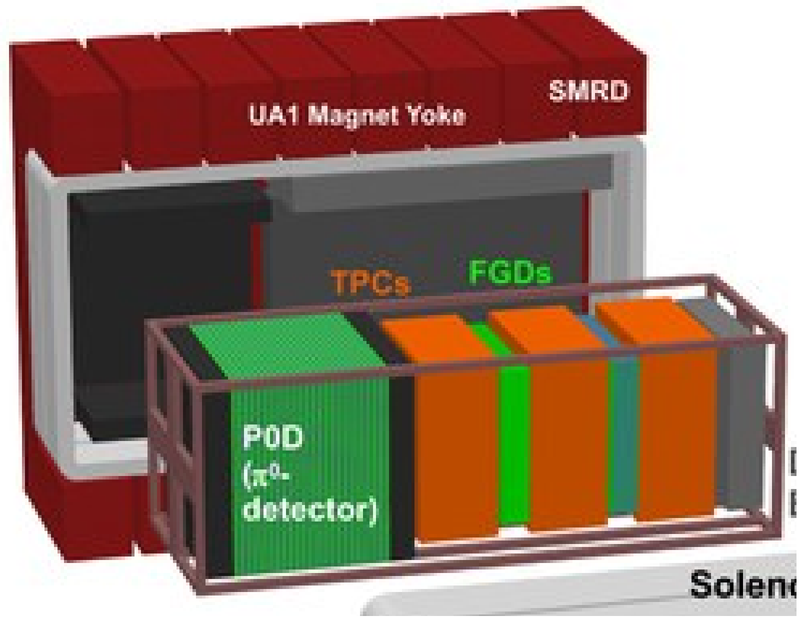
Improvement of Neutrino Flux with Upgrade

- 320kA horn current, Radio-active water disposal, cooling, cooling, and cooling
  - +10% more neutrino flux expected

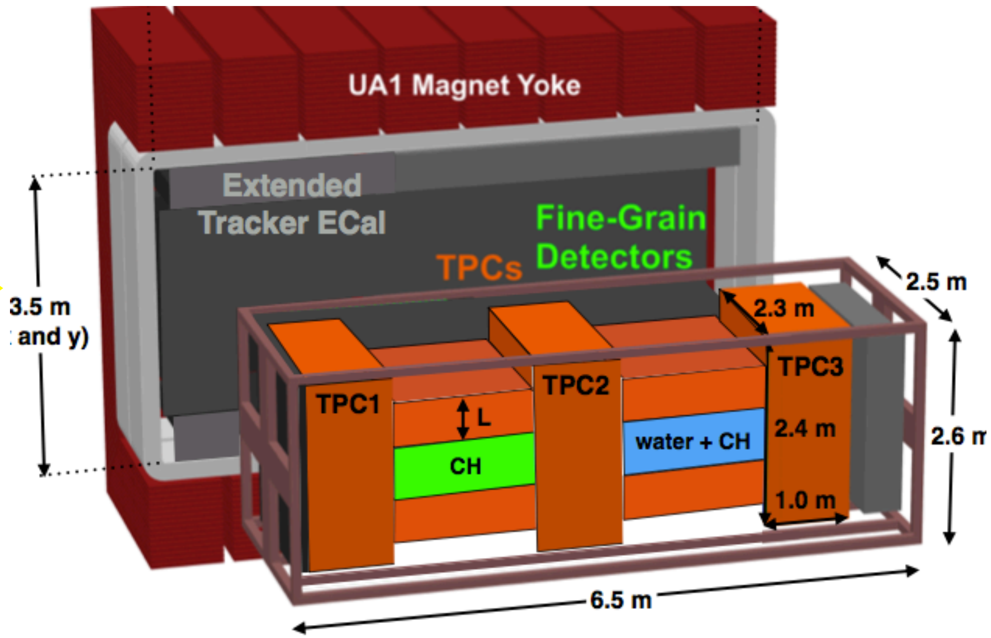


Near Detector Upgrade

ND280 (NOW)



ND280 (Upgrade)



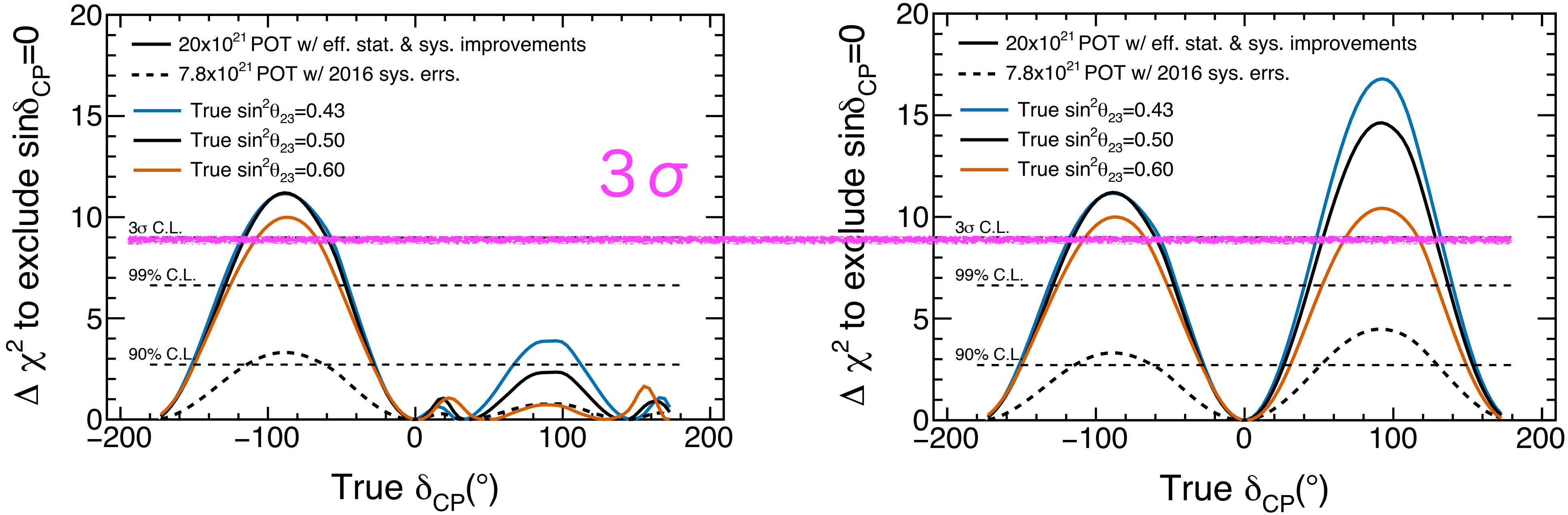
This is just an image, and the details are under discussions in the T2K collaboration.

- T2K steadily improves the systematic uncertainty.
  - ~18% (2011) → ~9% (2014) → ~6% (2016) [→ ~3% (2020)]
- Understanding of Neutrino Interactions is essential for future experiments (T2K-II and Hyper-K)

T2K-II Physics Sensitivity

- For which true δ_{CP} values can we find CP violation assuming true $\sin^2\theta_{23}$=0.43, 0.50, 0.60?
  - The fractional region for which $\sin\delta_{CP}$=0 can be excluded at the 99% (3σ) C.L. is 49% (36%) of possible true values of δ_{CP} assuming the MH is known.

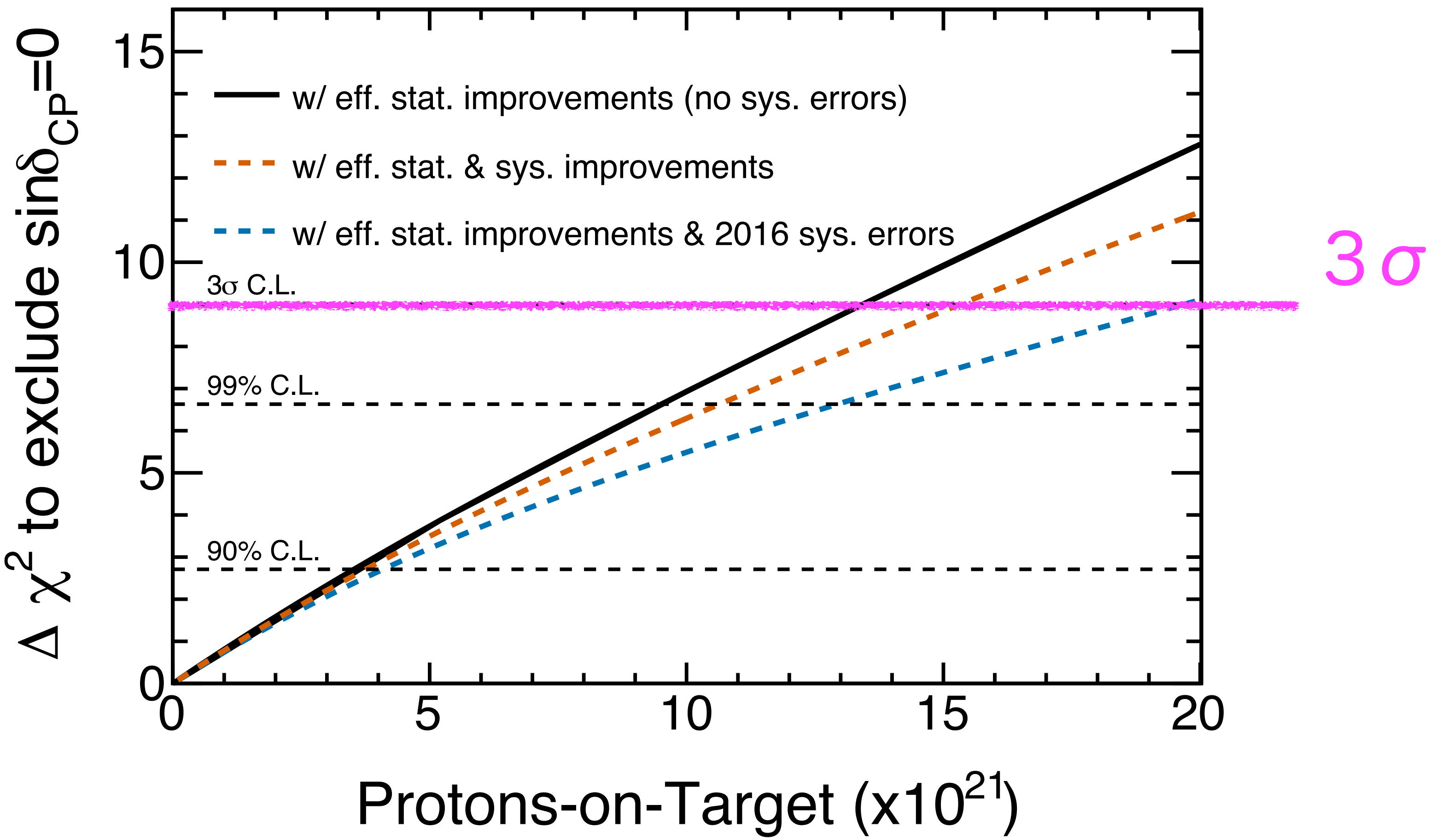
assuming MH unknown　　　　　　　　　　assuming MH known



(Note) Although T2K alone can't measure MH, we can help with the MH measurement by, ie, combining T2K + NOVA

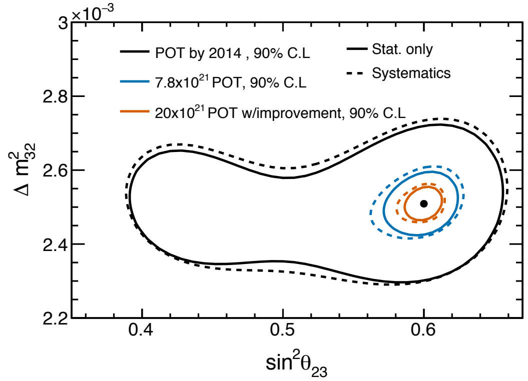
T2K-II Physics Sensitivity

- As a function of POT in the case of $\sin^2\theta_{23}$=0.5, δ_{CP}=-π/2 and normal MH

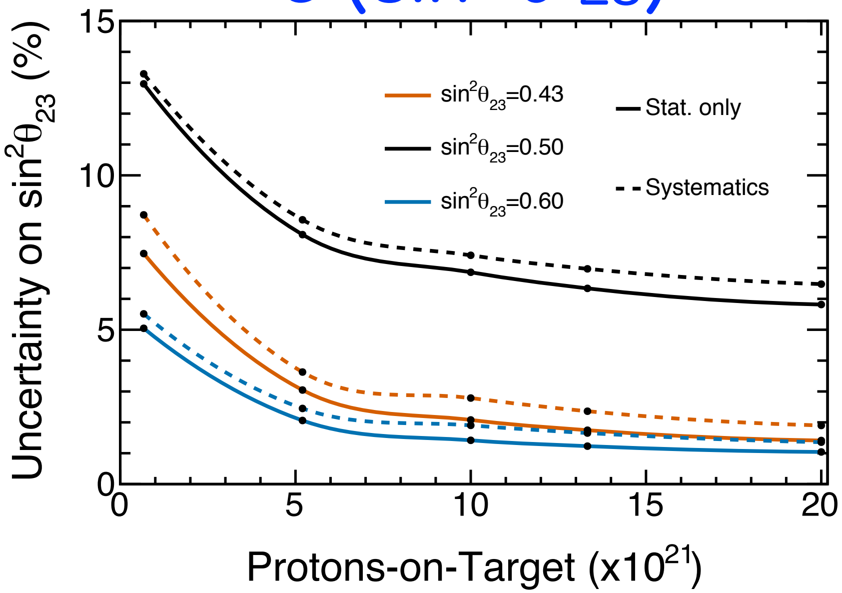


T2K-II Physics Sensitivity

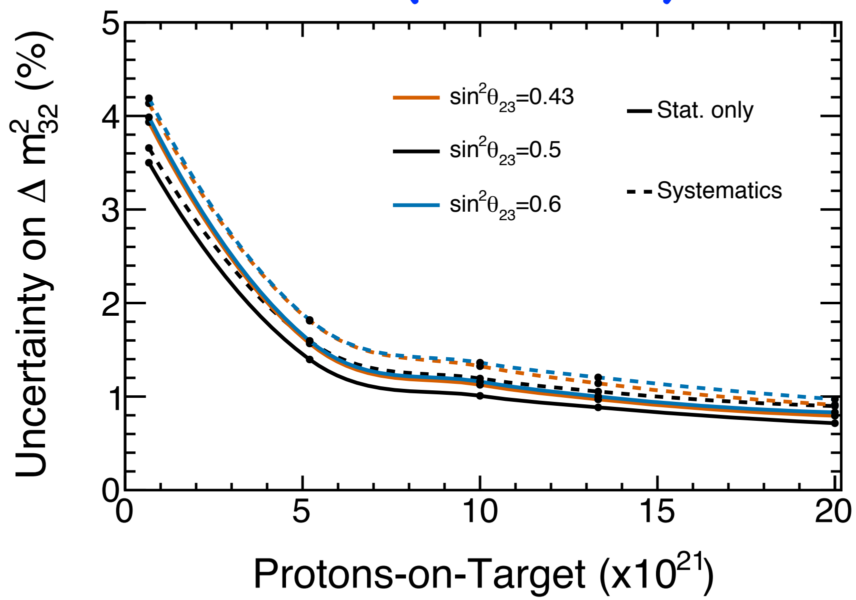
- Precisions of $\sin^2\theta_{23}$ and Δm_{32}^2



$\delta(\sin^2\theta_{23})$



$\delta(\Delta m_{32}^2)$

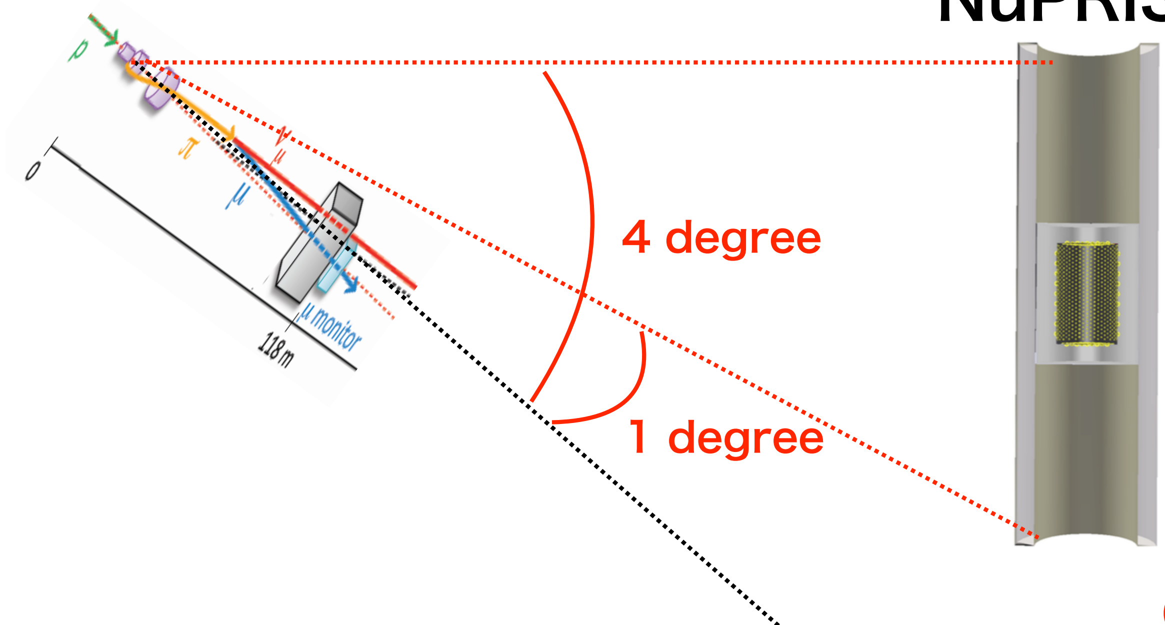


- More physics for Neutrino Interactions and non-standard models

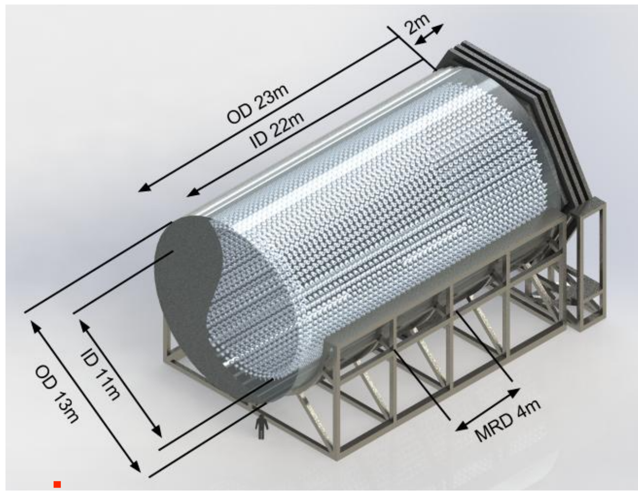
Intermediate Detector

- Because of the intense neutrino beam, a Water Cherenkov detector can be only operable in the intermediate distance (> ~1km from the target).
  - Good Near/Far flux ratio to predict the neutrino events at Kamioka (TITUS)
  - A new technique to predict the neutrino events at Kamioka (NuPRISM).
- **Under design intensively!**

NuPRISM

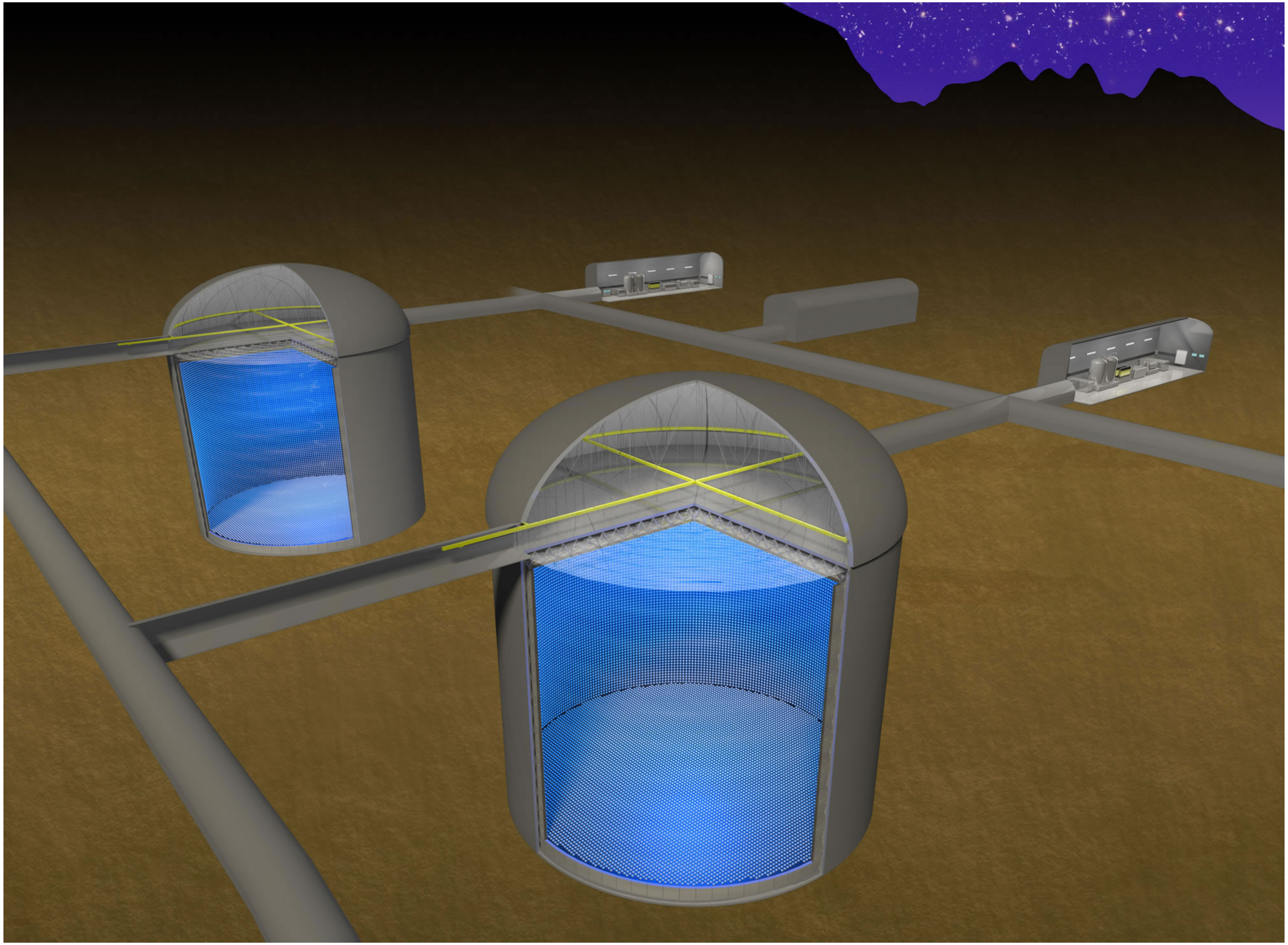


TITUS



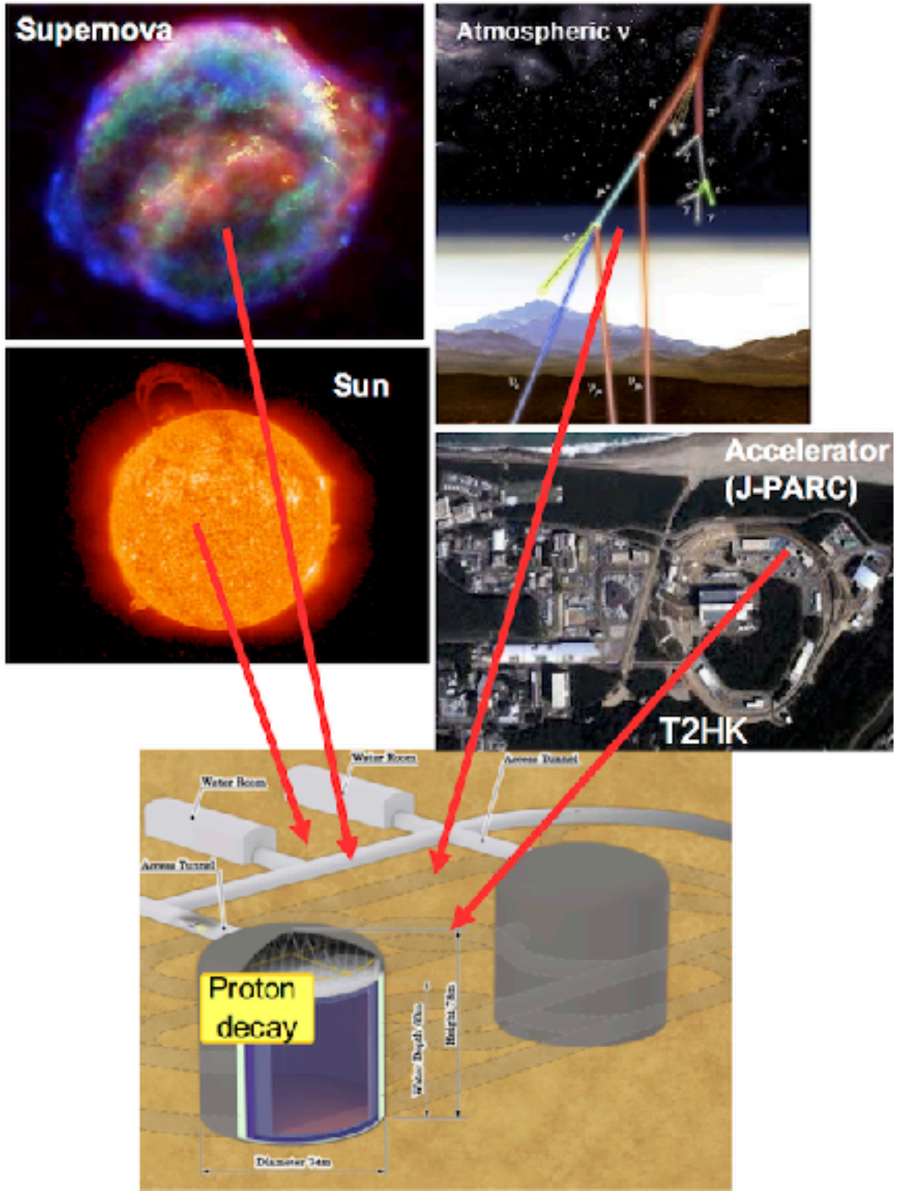
+ combining

Hyper-Kamiokande

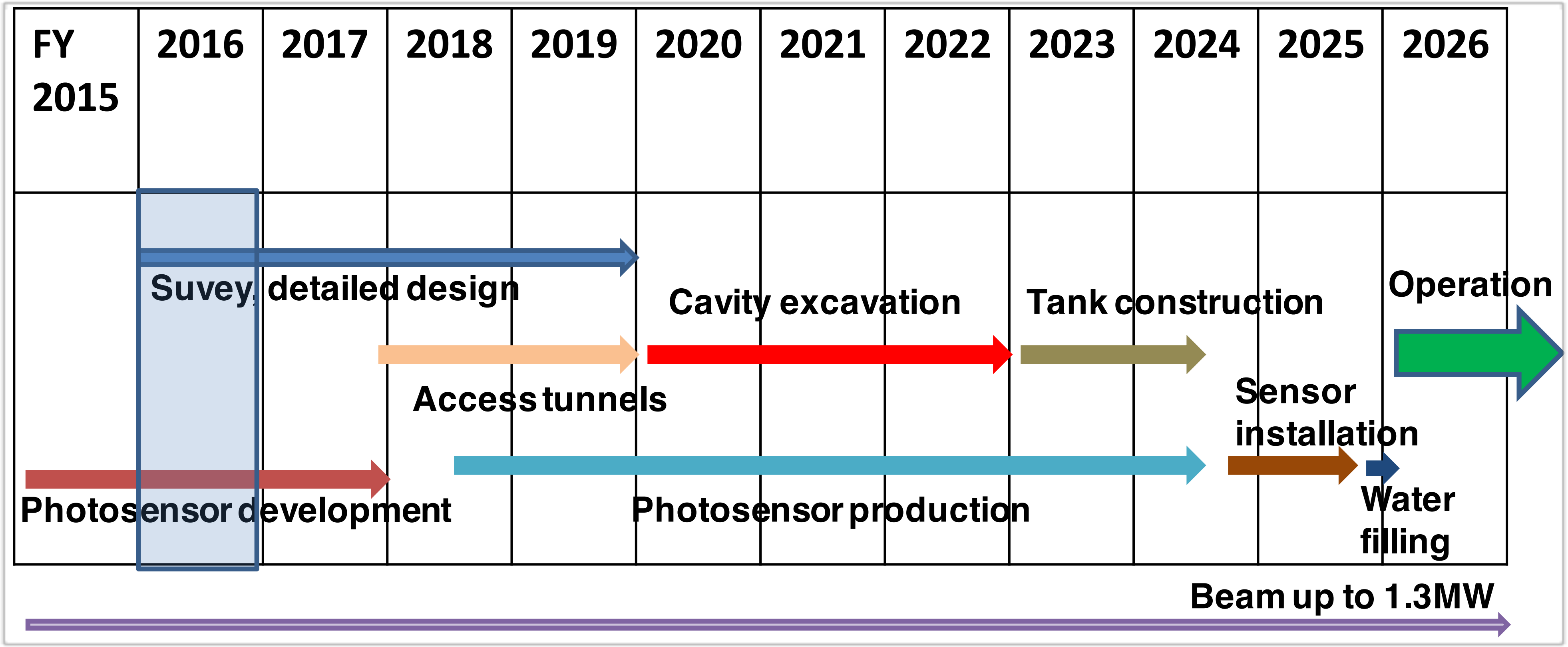


Broad science program with Hyper-K

- Neutrino oscillation physics
  - Comprehensive study with beam and atmospheric neutrinos
- Search for nucleon decay
  - Possible discovery with ~×10 better sensitivity than Super-K
- Neutrino astrophysics
  - Precision measurements of solar ν
  - High statistics measurements of SN burst ν
  - Detection and study of relic SN neutrinos
- Geophysics (neutrinography of interior of the Earth)
- Maybe more (unexpected)

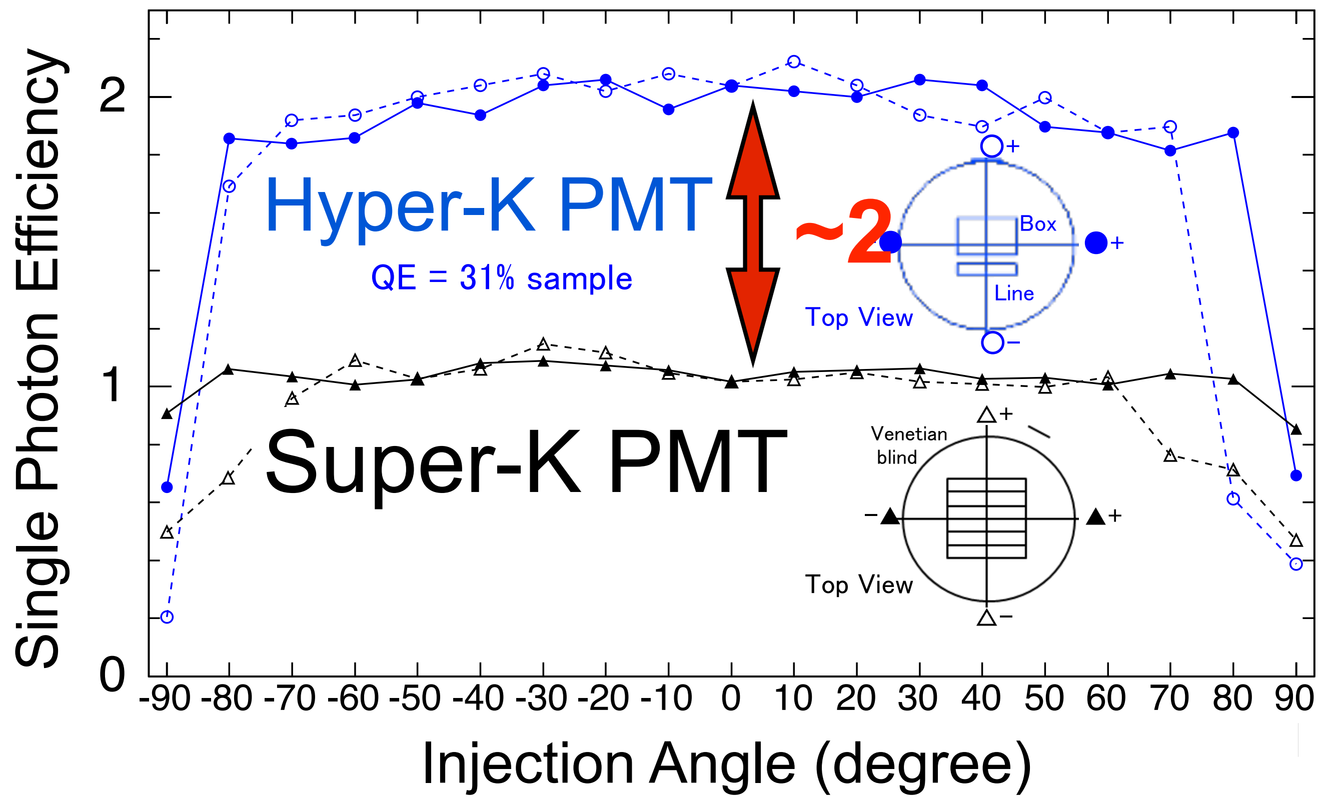


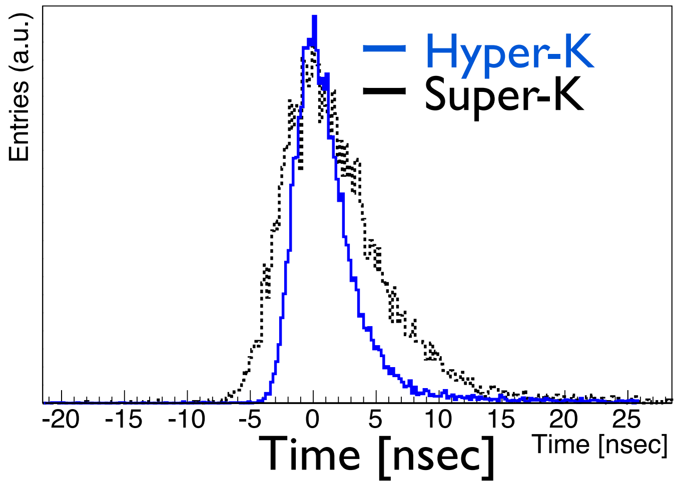
Hyper-K construction timeline

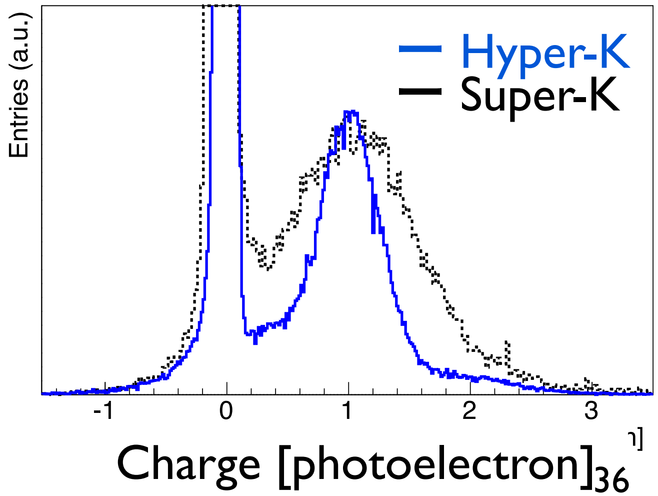


- Assuming funding from 2018
- The 1st detector construction in 2018~2025
  - Cavern excavation: ~5 years
  - Tank (liner, photosensors) construction: ~3 years
  - Water filling: 0.5 years

Hyper-K New Technology



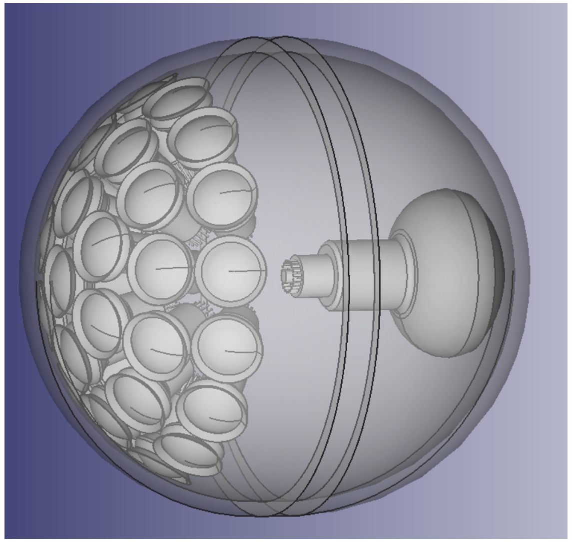




- Single Photon Efficiency: **x2**
- Time Resolution: **x2**
- Charge Resolution: **x2**
- Better Physics Sensitivity with the improved detector performance

Hyper-K with KM3NET and IceCube

There are several common features among Hyper-K, KM3NET and IceCube projects



- Physics
  - Neutrino Interactions
  - Atmospheric Neutrinos
  - Cosmic Neutrinos
- Detectors
  - **A Large Novel Photo-Sensors are KEY**
  - Simulation/Calibration of the Cherenkov detectors

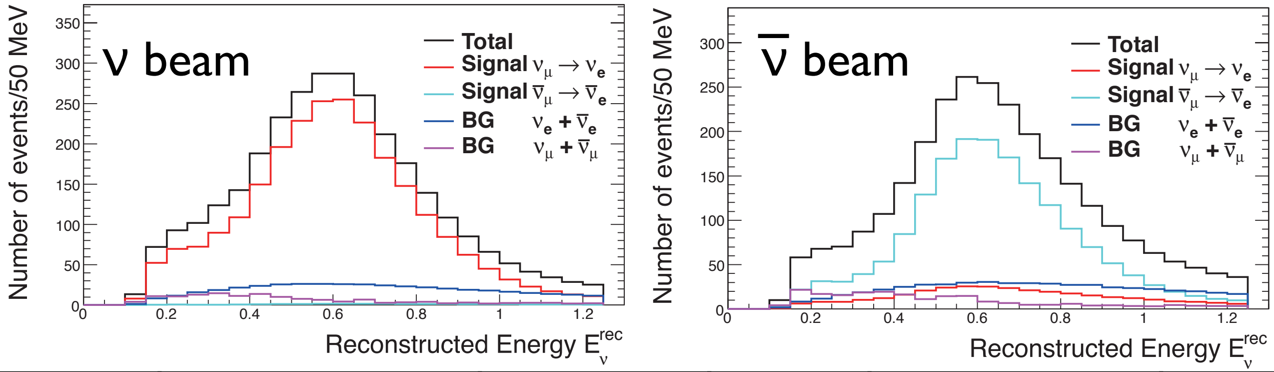
- It is important to move the Project and Science forward together with collaborative efforts.
  - Hyper-K and KM3NET make MOU to develop the projects together.

Expected events

1.3MW, 10×10^7sec, $\nu:\bar{\nu}$=1.3

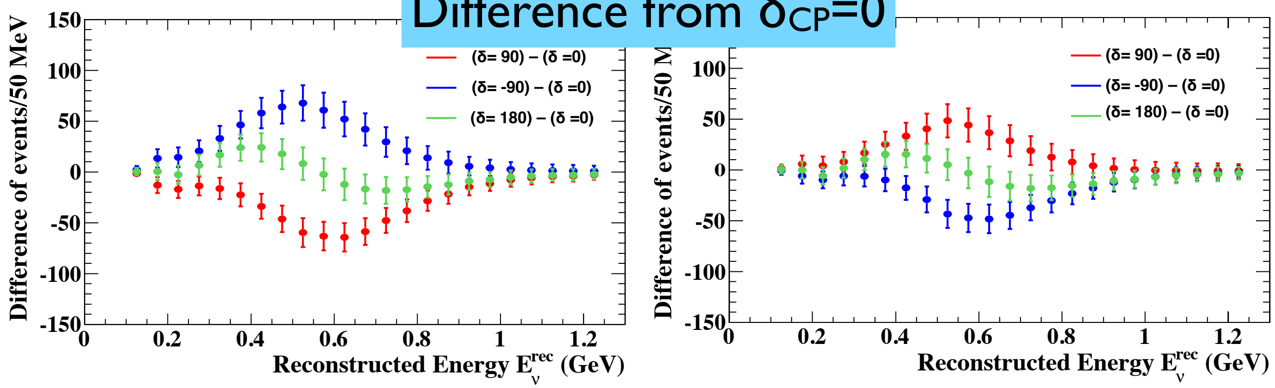
ν_e candidates

Using fiTQun for π^0 rejection



for δ=0	Signal ($\nu\mu \to \nu e$ 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



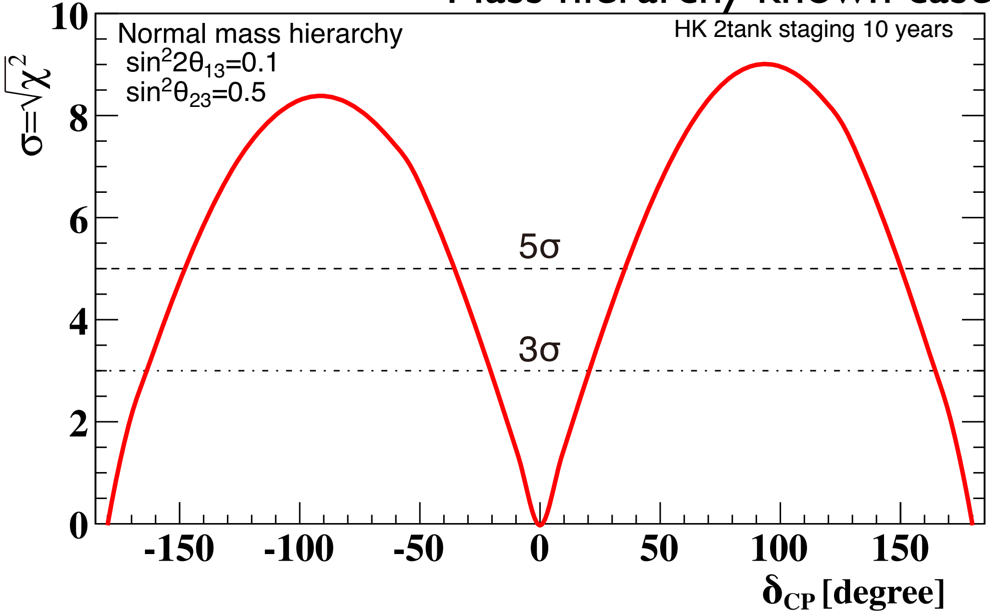
δ=0 and 180° can be distinguished using shape information

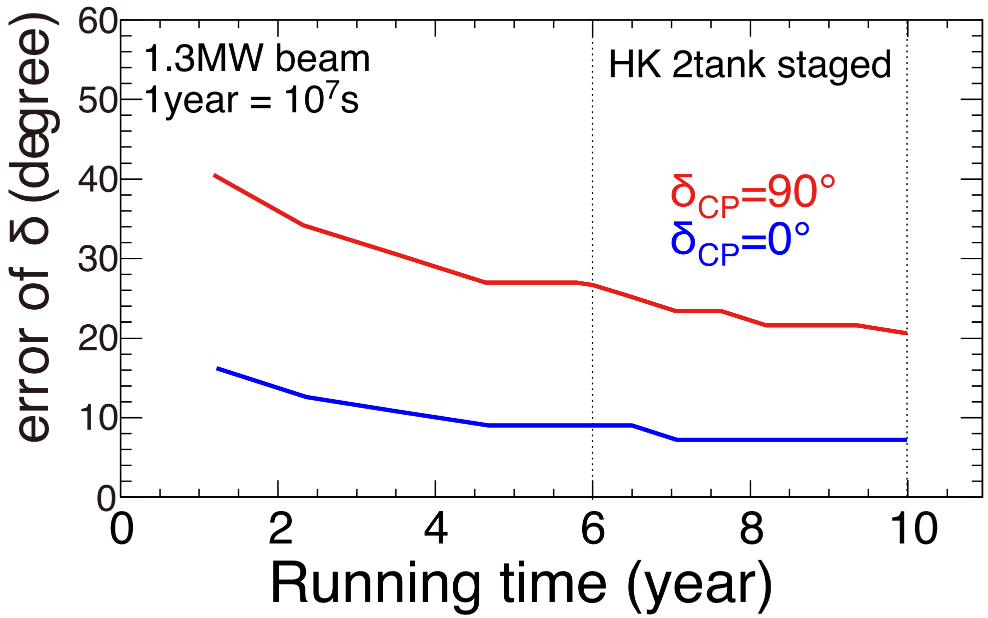
CPV sensitivity

- Exclusion of $\sin\delta_{CP}=0$
  - >8σ(6σ) for δ=-90°(-45°)
  - ~80% coverage of δ parameter space with >3σ
- From discovery to δ_{CP} measurement:
  - ~7° precision possible

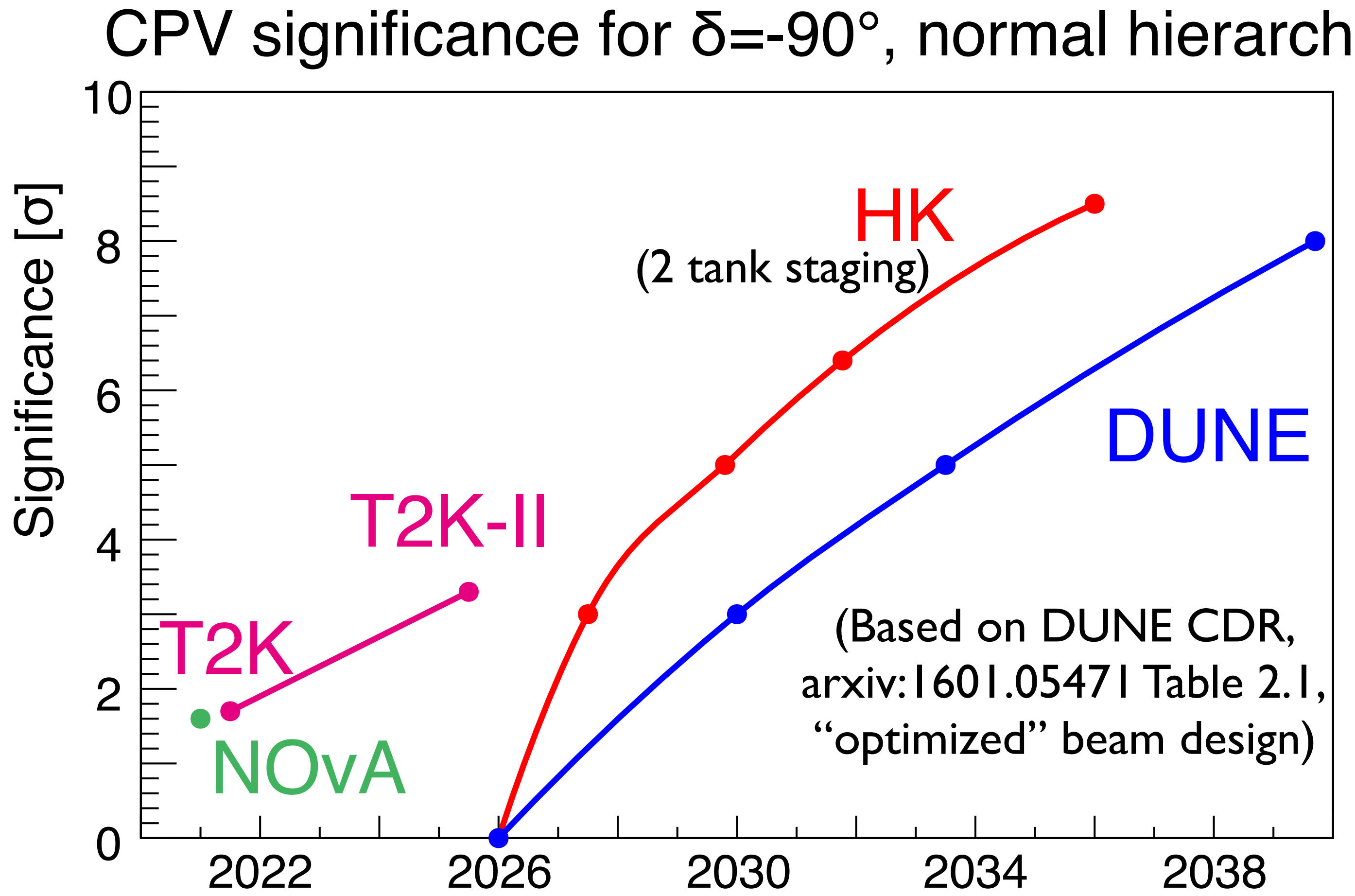
sinδ=0 exclusion		error	
>3σ	>5σ	δ=0°	δ=90°
78%	62%	7.2°	21°

Mass hierarchy known case





Towards leptonic CP asymmetry



Strategy of Japan-based program

~3σ indication with T2K→T2K-II,

>5σ discovery and measurement with HK

Note: "exact" comparison sometimes difficult due to different assumptions

θ_{23} and Δm^2_{32}

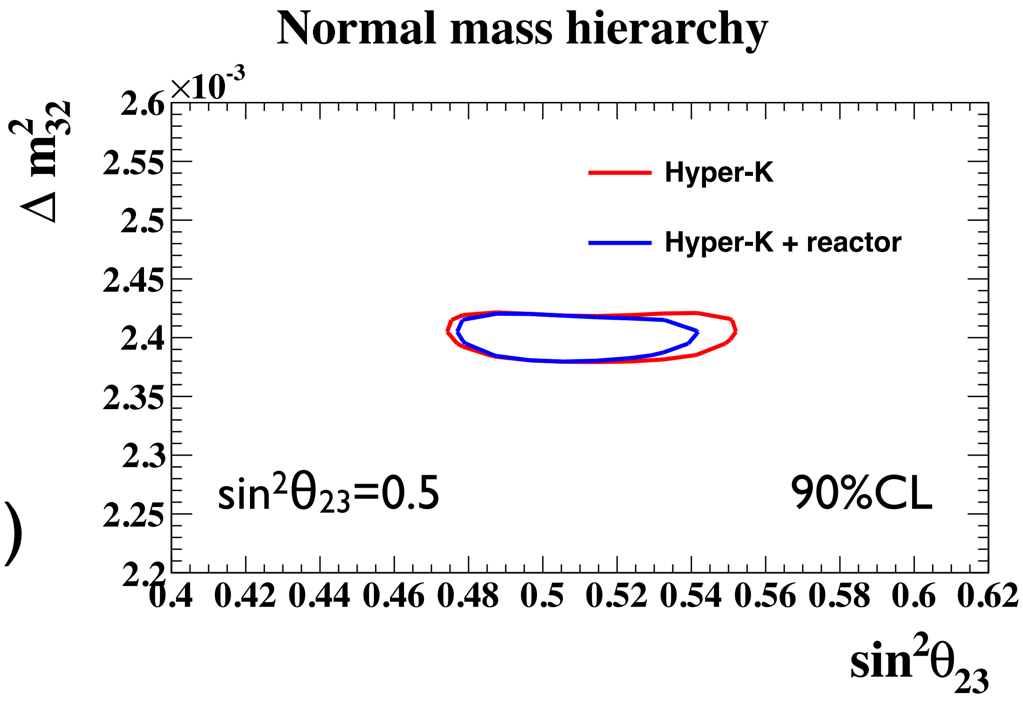
$\delta(\Delta m^2_{32})$~$1.4\times10^{-5}eV^2$

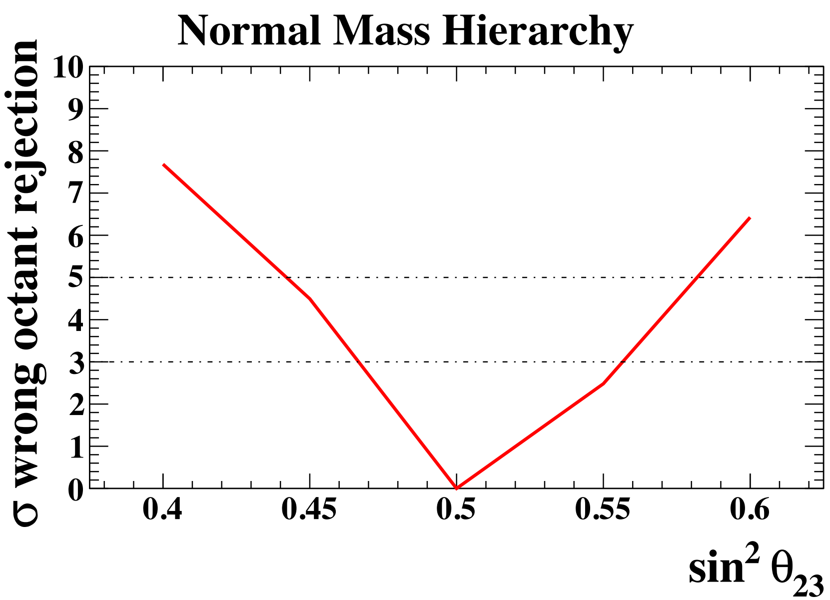
→ Mass hierarchy sensitivity in combination with reactor

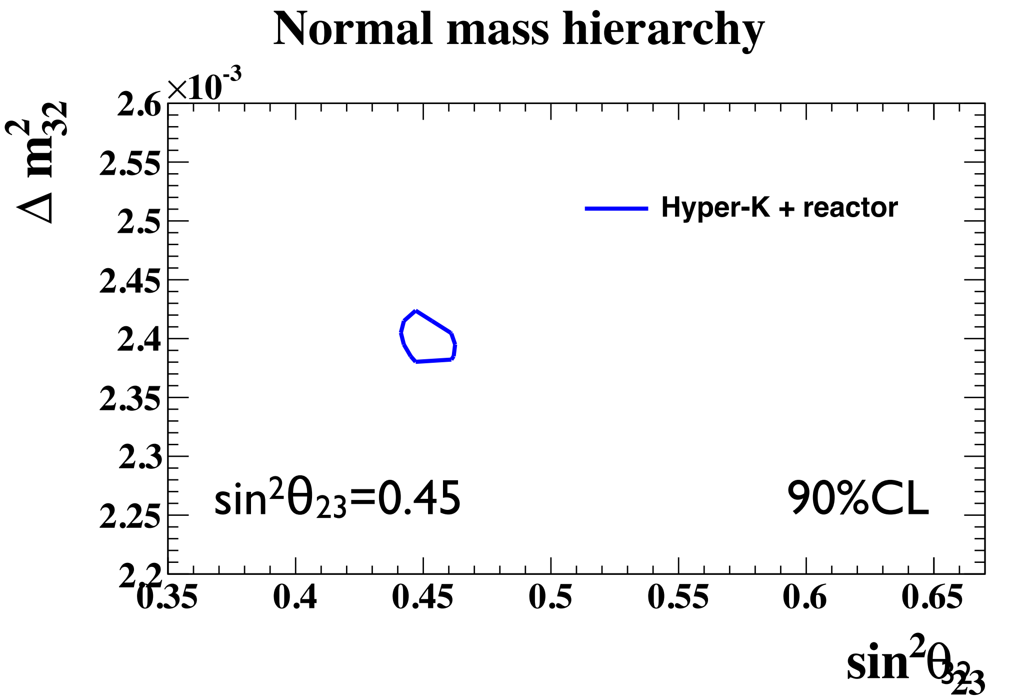
$\delta(\sin^2\theta_{23})$~0.015 (for $\sin^2\theta_{23}$=0.5)

~0.006 (for $\sin^2\theta_{23}$=0.45)

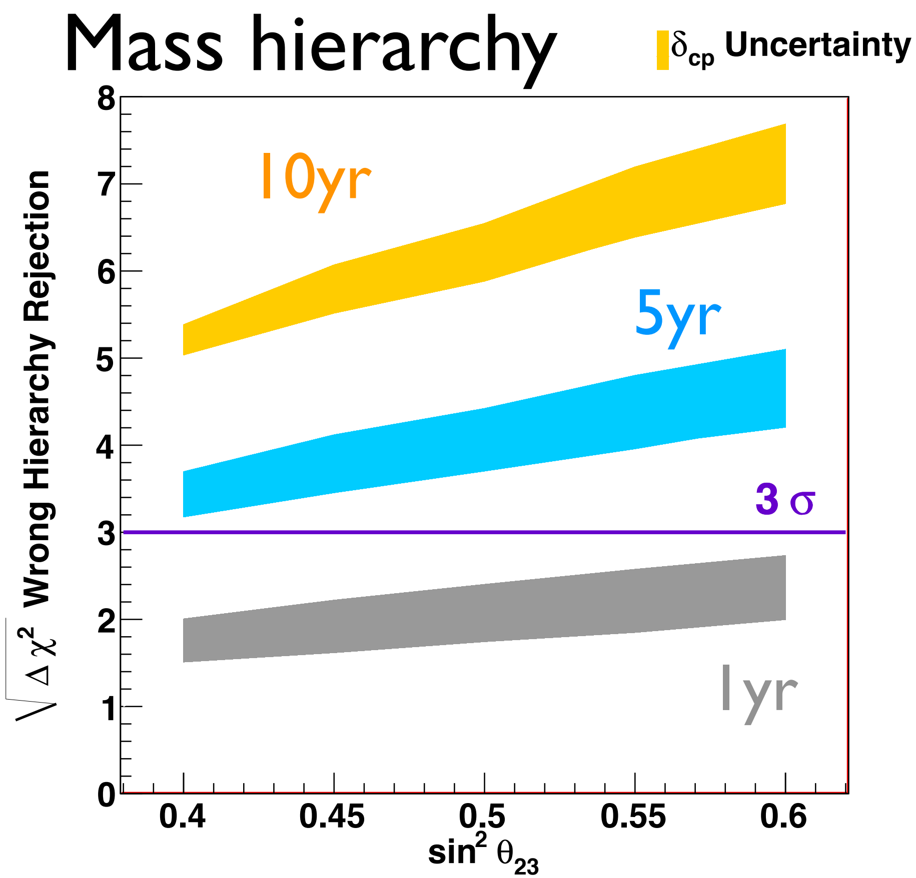
→Octant determination, input to models

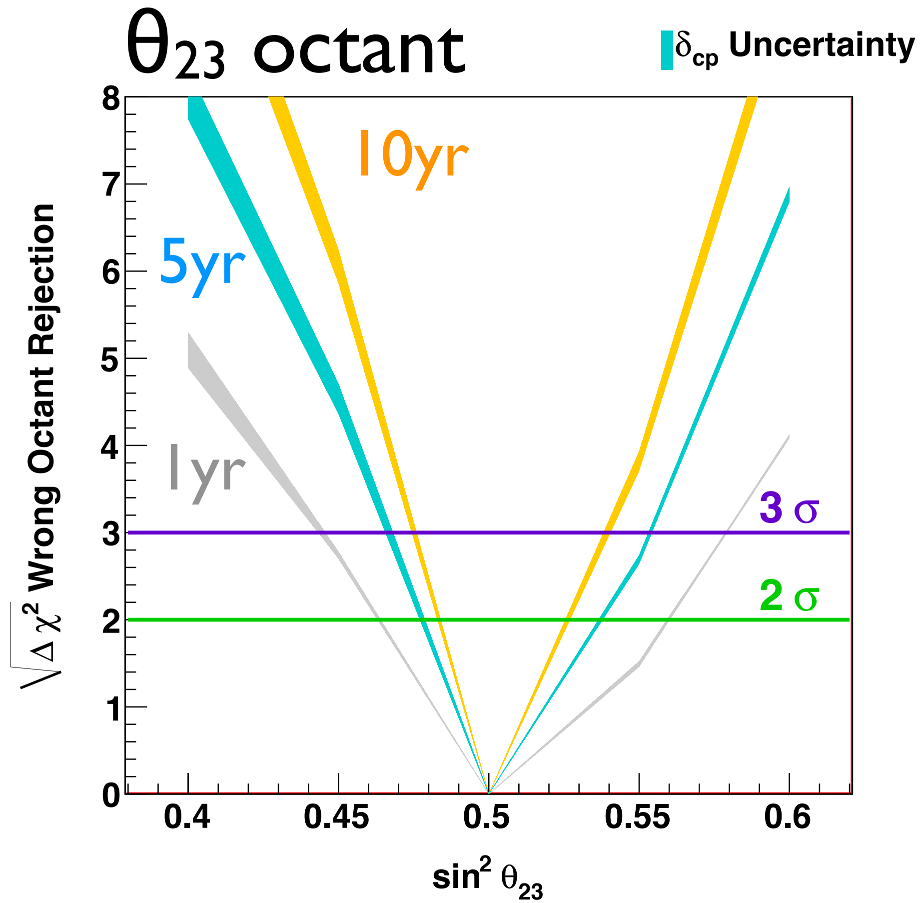






Beam + Atm ν combination



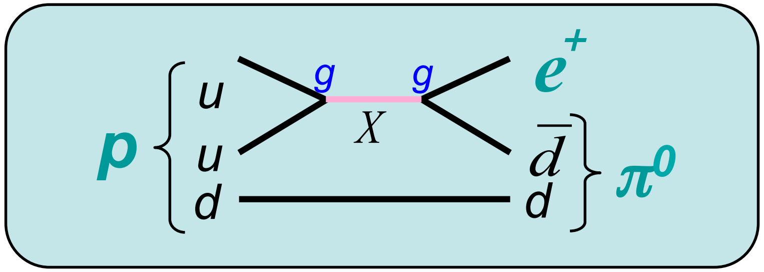


- Complementary information from beam and atm ν
- Sensitivity enhanced by combining two sources!

Proton Decay

- **Keep looking for GUT with neutrinos.**
- Example: $p \to e^+ \pi^0$ in Hyper-K

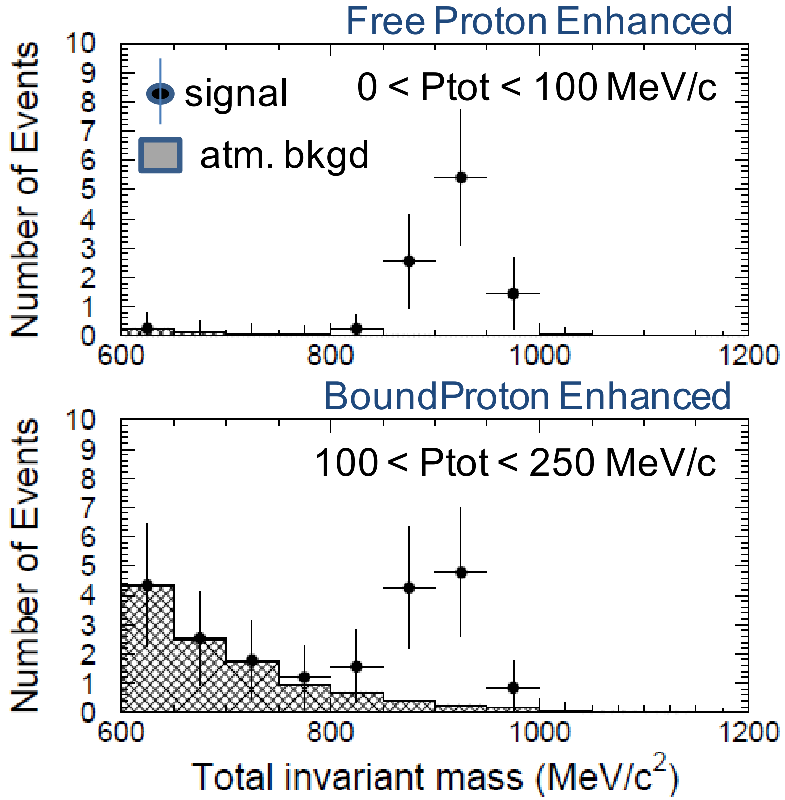
Mediated by gauge bosons

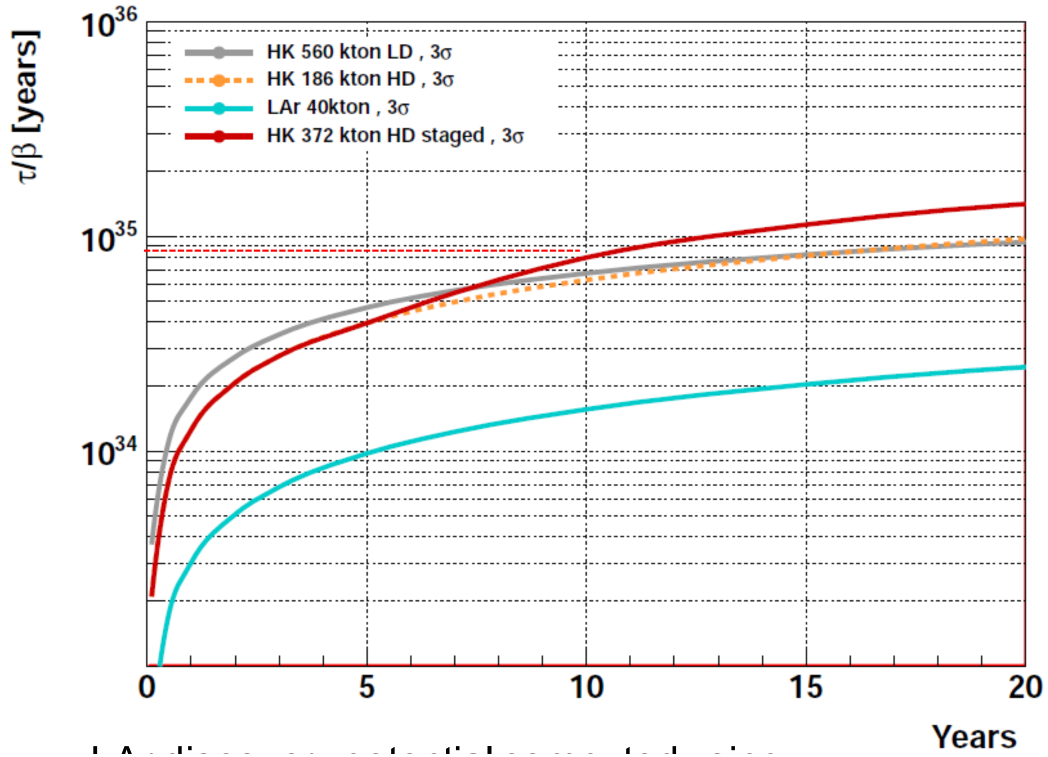


$p \to e^+ \pi^0$

$$\Gamma(p \to e^+ \pi^0) \sim \frac{g^4 m_p^5}{M_X^4}$$

$\tau_{proton} = 1.4\times10^{34}$ years (SK 90% CL limit)





Summary

- Discovery of Neutrino Oscillation opens the window to explore neutrinos science further including CP violation.
- CP violation in lepton sector is within the reach by using these facilities.
- T2K, T2K-II and Hyper-K are running, being upgraded and being proposed.
  - T2K produces many interesting results about neutrino oscillations.
  - T2K-II aims for the discovery of neutrino CP violation with 3σ or higher significance with the extension of running to 20×10^{21} POT for the next 10 years (by ~2026).
  - Hyper-K is planned to start taking data in 2026. In addition to the precise measurements of neutrino CP violation, we are also looking for the evidence of GUT, proton decay.