Neutrinos :
J-PARC neutrino facility upgrade for T2K and HK experiments

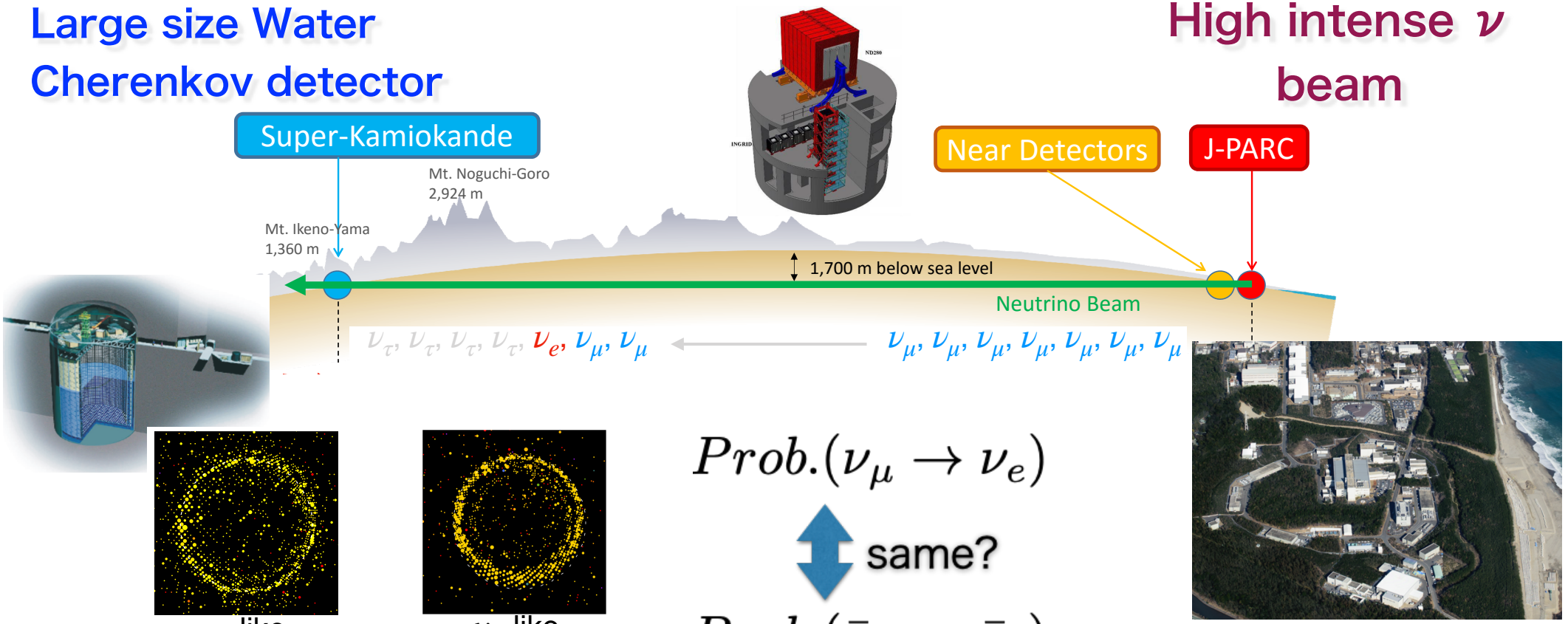
2023/3/20, Workshop at Argonne Lab.

Ken Sakashita (KEK/J-PARC neutrino group)

Accelerator-based long-baseline neutrino oscillation experiments at Japan

Large size Water Cherenkov detector

High intense ν beam



$$Prob.(\nu_\mu \rightarrow \nu_e)$$

same?

$$Prob.(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

Study neutrino oscillation :

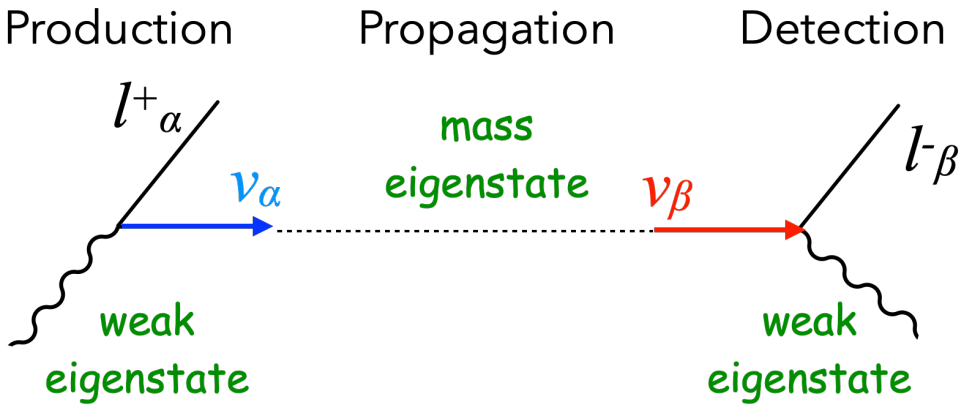
- major physics target is to explore **neutrino CP violation**

Neutrino oscillation

- Flavor changes during flight (quantum effect over macroscopic length)
- can evaluate the mass diff. and mixing

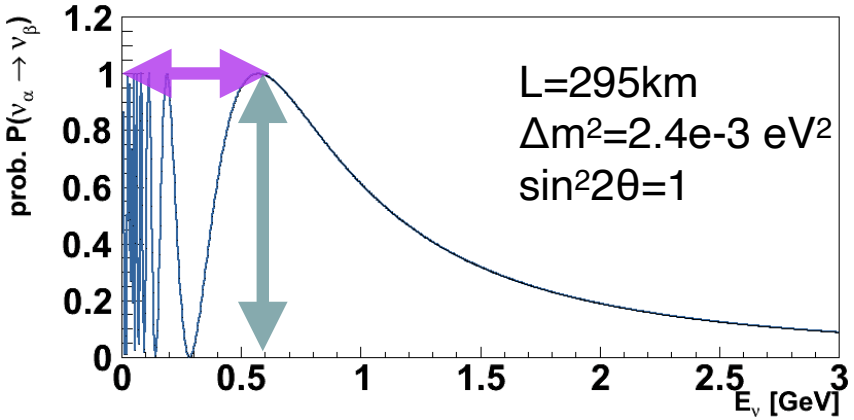
$$|\nu_\alpha> = \sum_{i=1}^{i=3} U^*_{\alpha i} |\nu_i>$$

Flavor eigenstate $\alpha = e,\mu,\tau$ *Mass eigenstate*



$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2\left[\frac{1.27\Delta m^2 L}{E_\nu}\right]$$

(in case of 2 flavor)



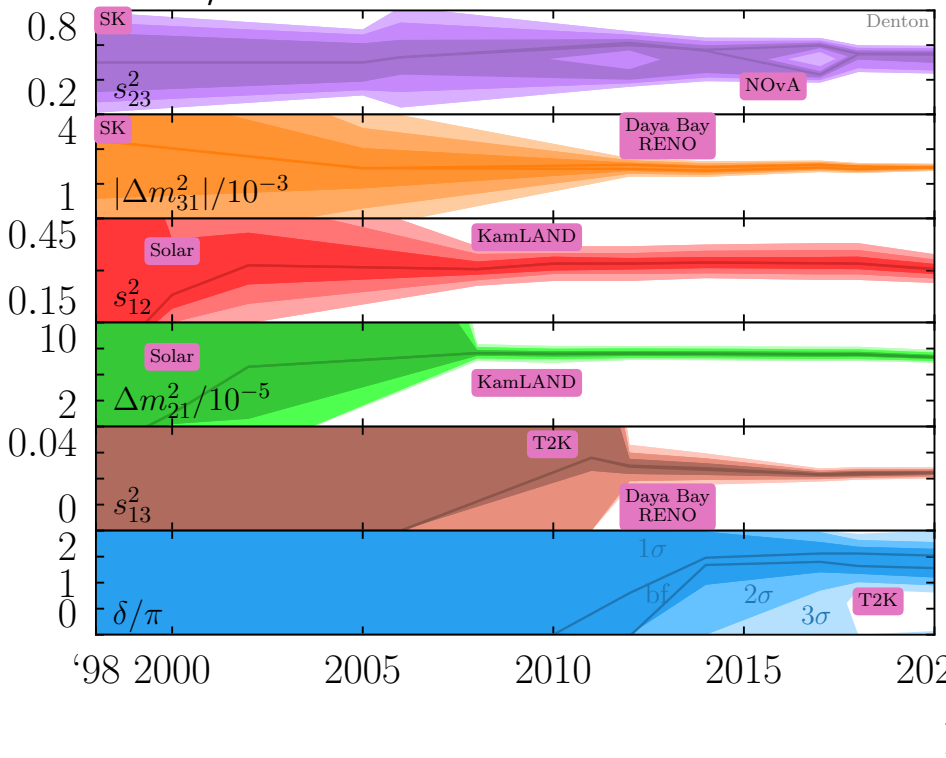
$\Delta m^2_{ij} = m_i^2 - m_j^2$, θij ： mixing angle, $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$,

- in 3 flavor case, there are three mixing parameters (θ_{12},θ_{23},θ_{13}) and two mass differences (Δm^2_{21}, Δm^2_{32}) and one complex phase (δ_{CP})

What we know up to now

P. B. Denton, Neutrino2022

measured with ~3% precision



θ_{23} ~45°

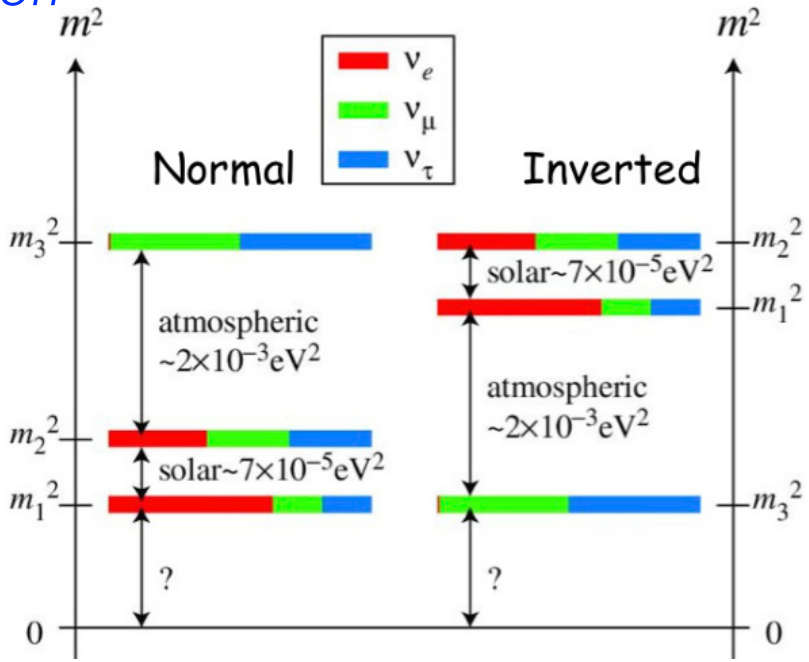
$|\Delta m^2_{32}|$

θ_{12} ~33°

Δm^2_{21}

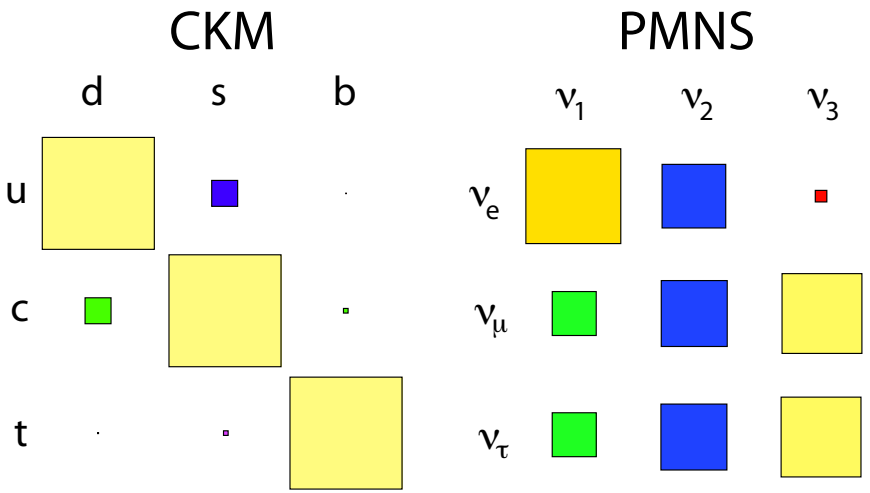
θ_{13} ~9°

δ_{CP} ?



Mass ordering :

$m_3 > m_2$ or $m_3 < m_2$?



Neutrino mixing looks stronger than quark (error of U is still large)

Area ~ U^2

S.Stone, PoS(ICHEP2012)933

Do neutrinos violate CP symmetry ?

- It is still unknown but the size of CP violation of neutrino (PMNS) could be O(10^3) larger than the quarks (CKM)

Jarlskog invariant (=size of CPV) : $J_{CP} = \sin\theta_{13}\cos^2\theta_{13}\sin\theta_{12}\cos\theta_{12}\sin\theta_{23}\cos\theta_{23}\sin\delta_{CP}$

$$J_{CP}^{CKM} \approx 3 \times 10^{-5} \quad \Leftrightarrow \quad J_{CP}^{PMNS} \approx 0.033 \times \sin\delta_{CP}$$

- Neutrino are the possible source of CP violation which can explain the matter-antimatter asymmetry in the universe

Leptogenesis

EW Baryogenesis

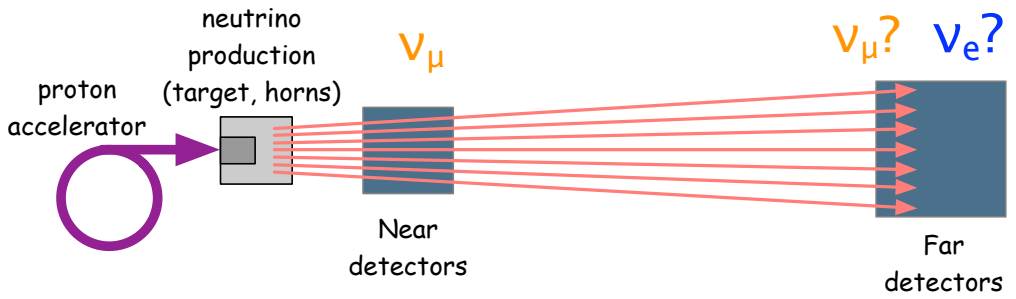
There are models in which only PMNS CP phase can generation the matter-antimatter asymmetry.

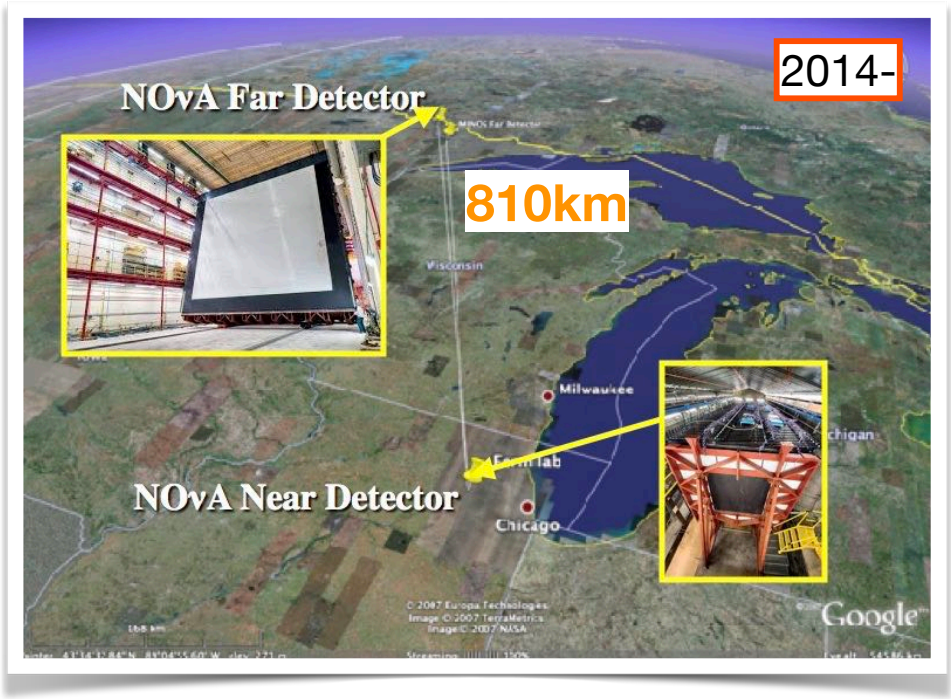
[Nucl. Phys. B774 (2007) 1], [JHEP 03, 034(2019)]
[arXiv:1609.05028. arXiv:1807.06582]

T2K collaboration

~528 members, 76 institutes, 14 countries

T2K and NOvA





- **L=295km** → matter eff. is negligible
- **Almost pure CPV measurement**
- Beam power : 500kW (soon >750kW)
- SK water Cherenkov detector

- **L=810km** → matter eff. is not negligible
- **Sensitive to mass ordering**
- ~900kW
- Segmented liquid scintillator detector (tracking, calorimetric)

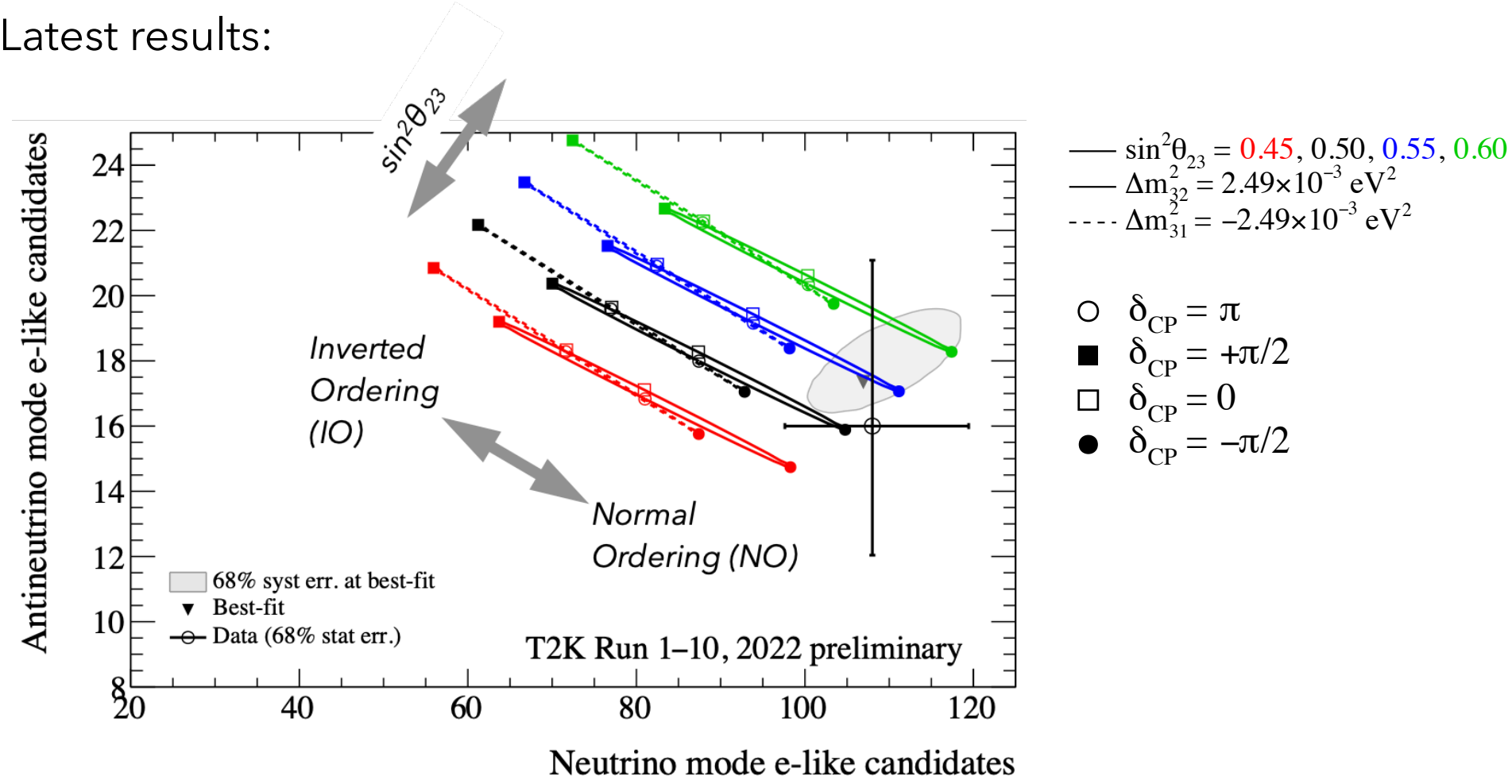
T2K and NOvA can provide complementary information

T2K : CPV results

- The first strong constraints on the δ_{CP} parameter using the data until 2019 published on Nature paper (2020)

DOI:10.1038/s41586-020-2177-0

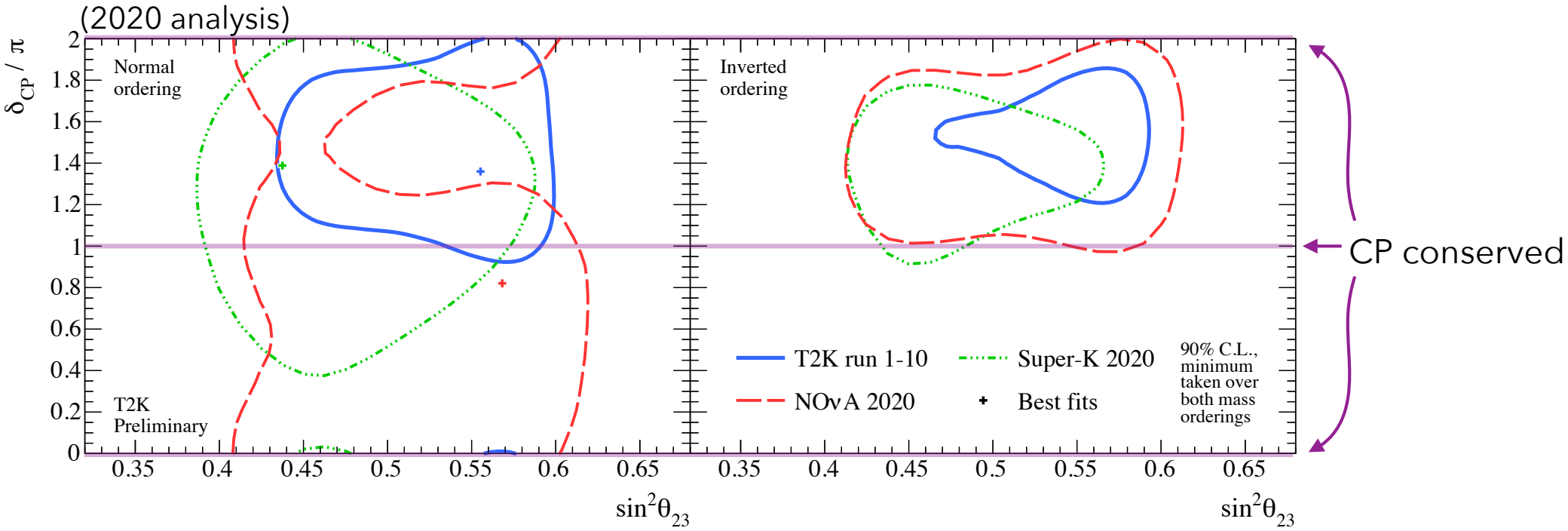
- Latest results:



T2K data prefers the maximal CP violation (δ_{CP}= -90°).
CP conservation is excluded at 90% C.L.

More statistics is needed

Comparisons among T2K, NOvA and SK

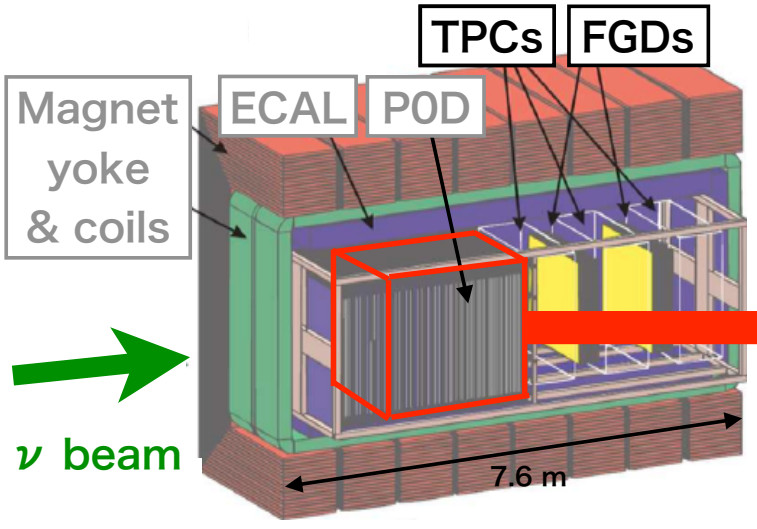


- **T2K-NOvA**, T2K-SK joint analysis are on-going : different energies, baselines and detector technologies
  - expect better sensitivity in mass ordering, δ_{CP} and θ_{23} octant due to resolved degeneracies and syst. constraints

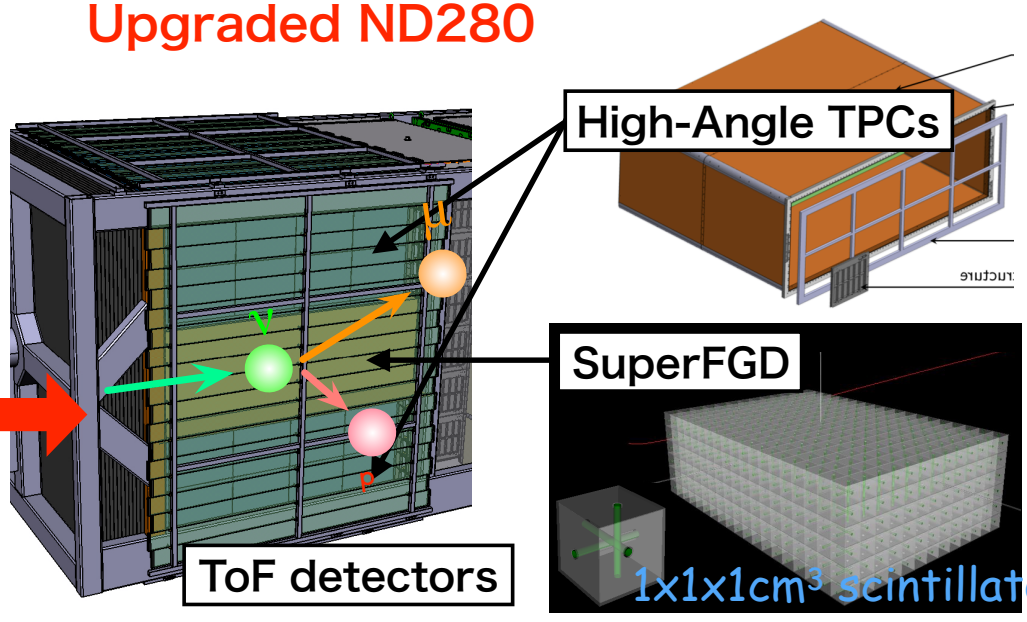
ND280 upgrade for T2K

To better constrain neutrino interaction systematic errors

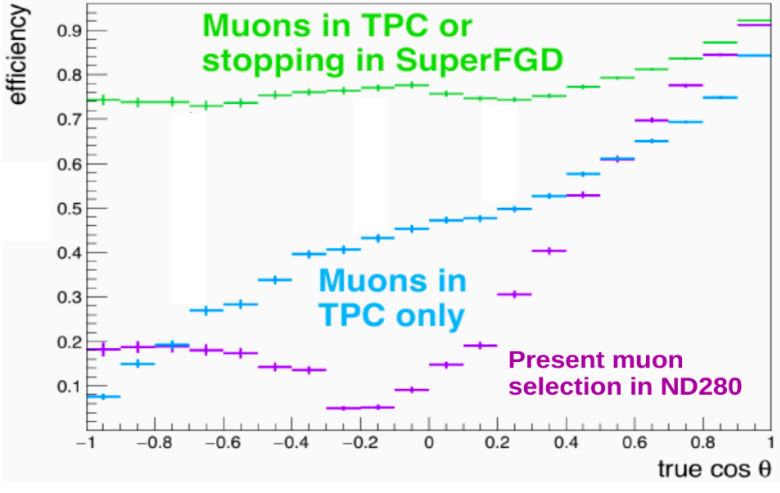
Current ND280



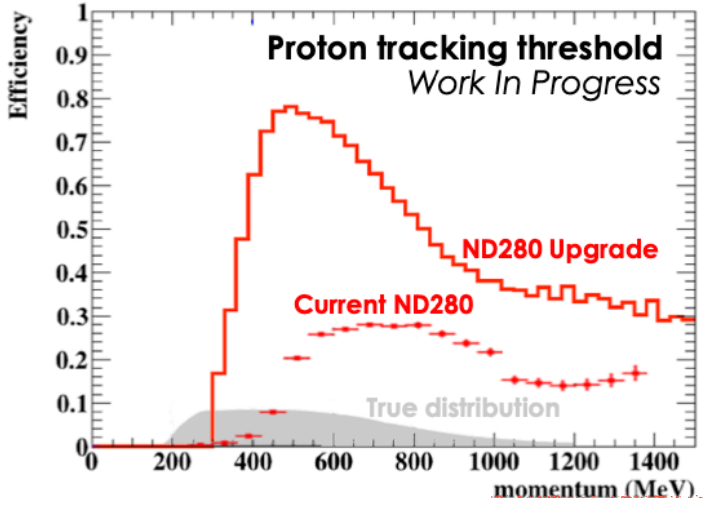
Upgraded ND280



Improved acceptance for high angle tracks



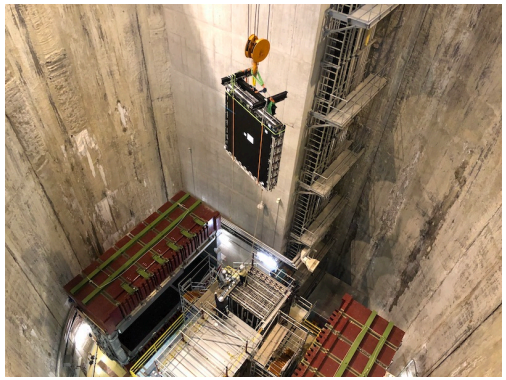
Protons → threshold down to 300 MeV/c (>500/c MeV with current ND280)



Status of ND280 upgrade

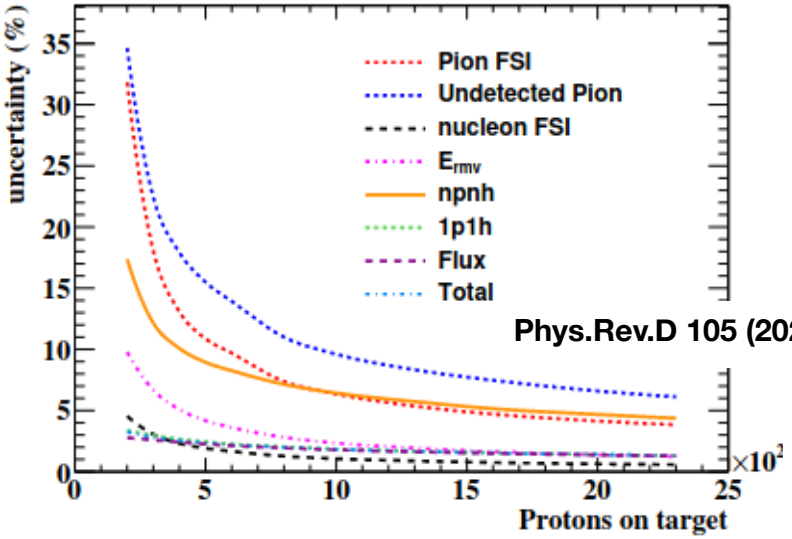
- Construction status
  - SFGD: Assembly is on-going at J-PARC.
  - HA-TPC : Production of the field cage, mass production of ERAM in progress
  - P0D detector removal was completed

International collaboration incl. US



Plan to start T2K data taking with the ND280 upgrade in 2023

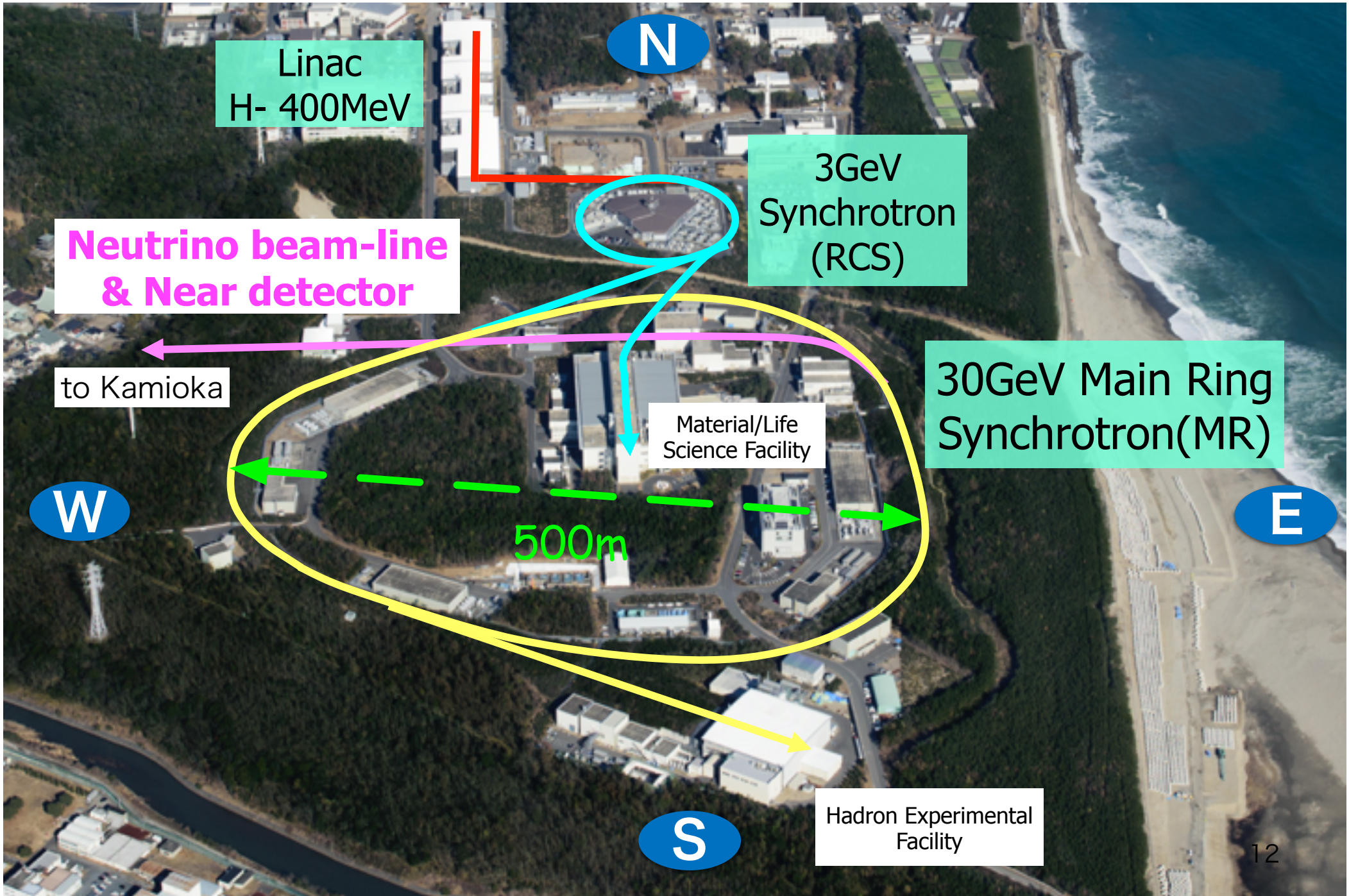
ν : μ– + proton analysis



Phys.Rev.D 105 (2022) 3, 032010

- ✤ Unprecedented sensitivity of neutrino interaction measurements w/ upgraded ND280
- ✤ This is also beneficial for future experiments (Hyper-K, DUNE)

J-PARC accelerators at Tokai



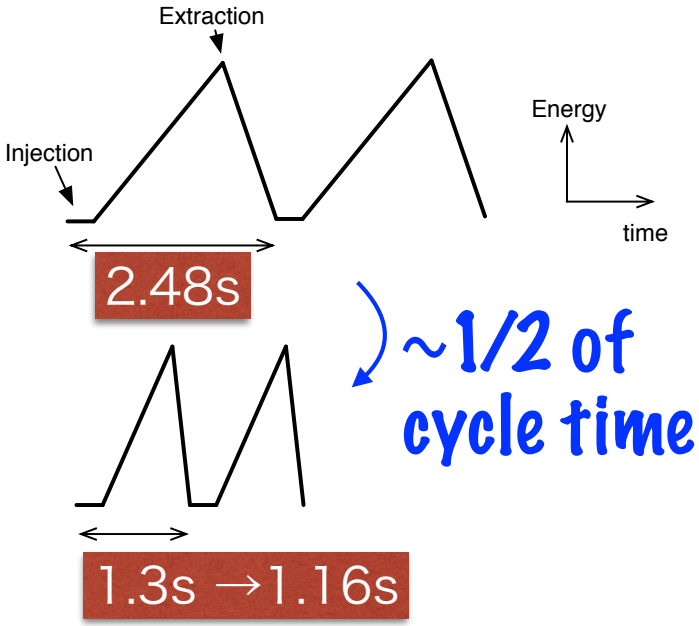
How can we increase beam power ?

Power ∝ 30GeV x # of protons x $1/T_{rep.}$

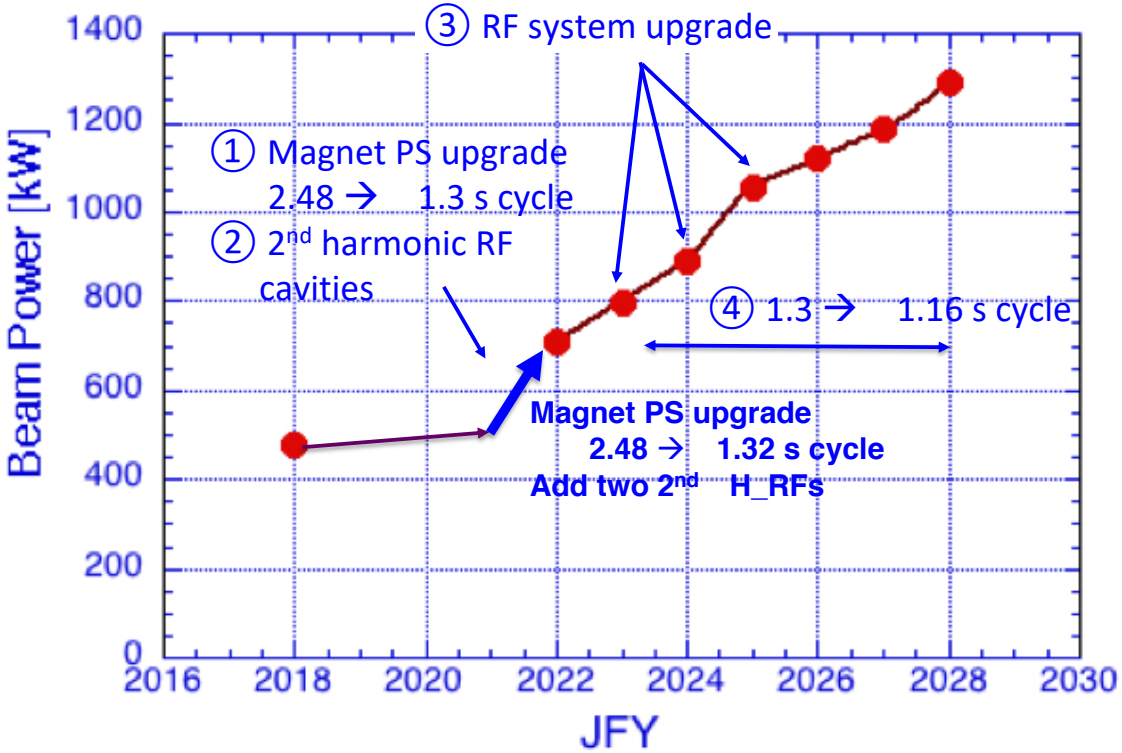
now 0.5MW 2.5×10^{14}

+30% protons per pulse

target 1.3MW 3.2×10^{14}

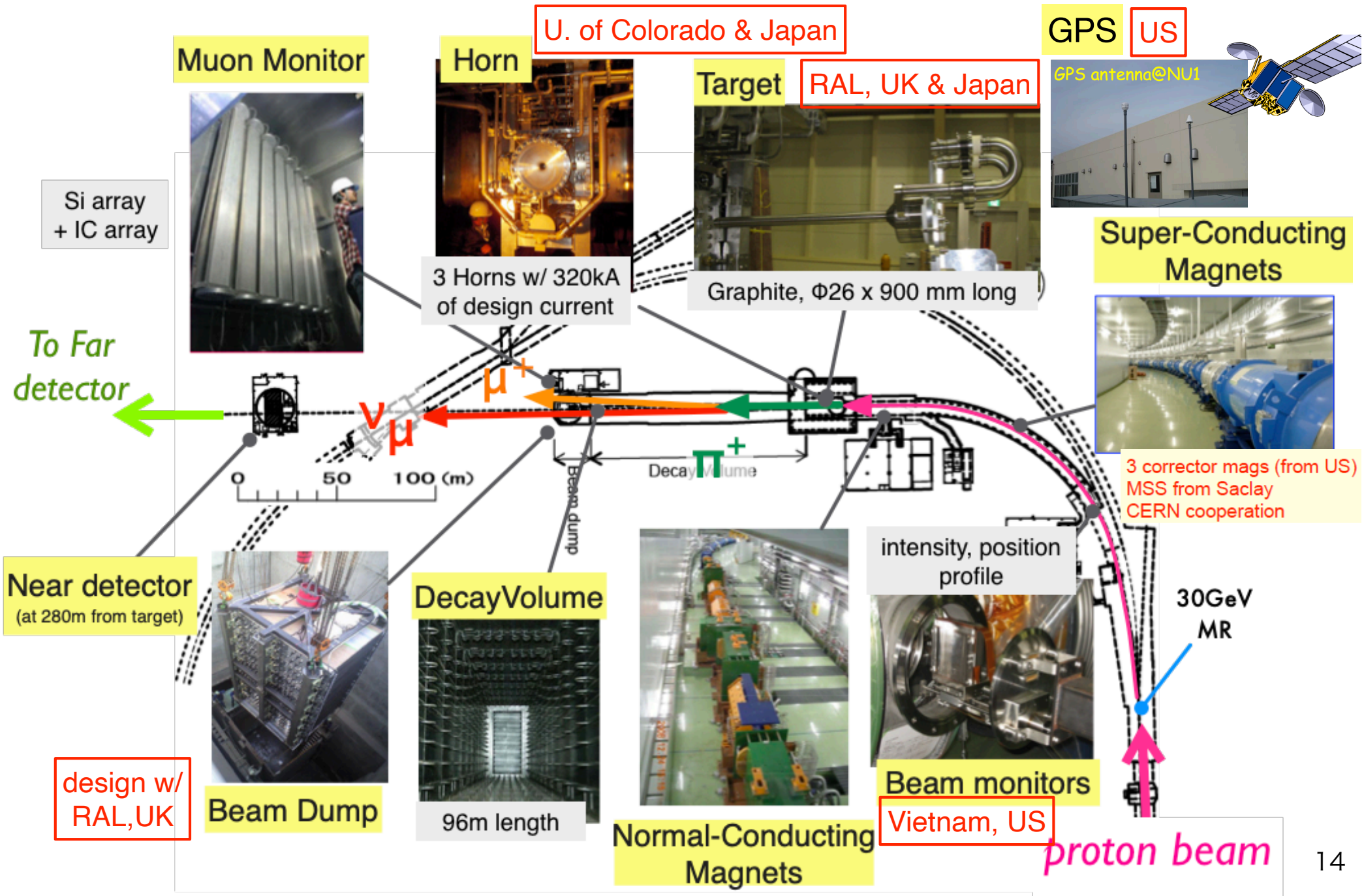


❖Upgrade of magnet power supply and RF



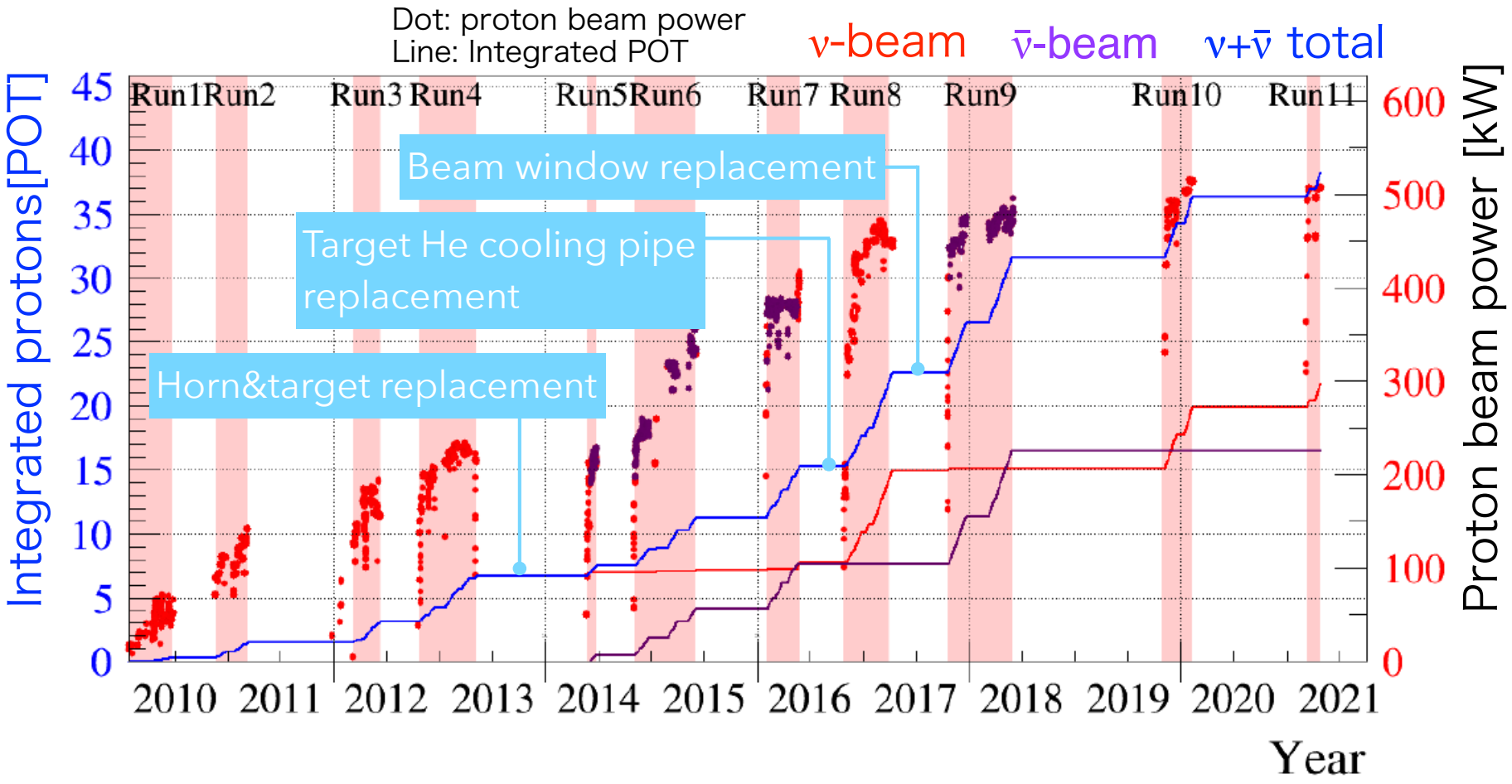
Beam commissioning after 2021-2022 upgrade is in progress

J-PARC neutrino beamline



Neutrino beamline operation

- Accumulated 3.82×10^{21} Protons On Target (2010 Jan. ~ 2021 Apr.)
- Replacement of radio-activated equipments(*) were successfully performed several times
- Stable operation at 515kW has been achieved with no major issues

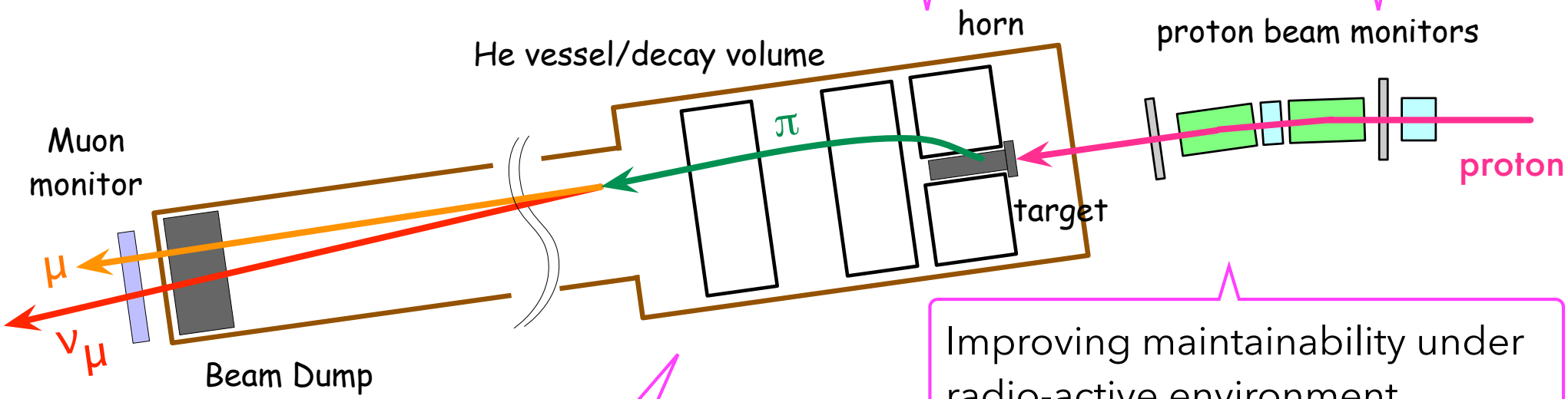


(*) horn,target and beam window are assumed to be periodically replaced

How can we realize 1.3MW operation ?

Increasing cooling capability for the heat generated by beam

Improving performance of beam monitors



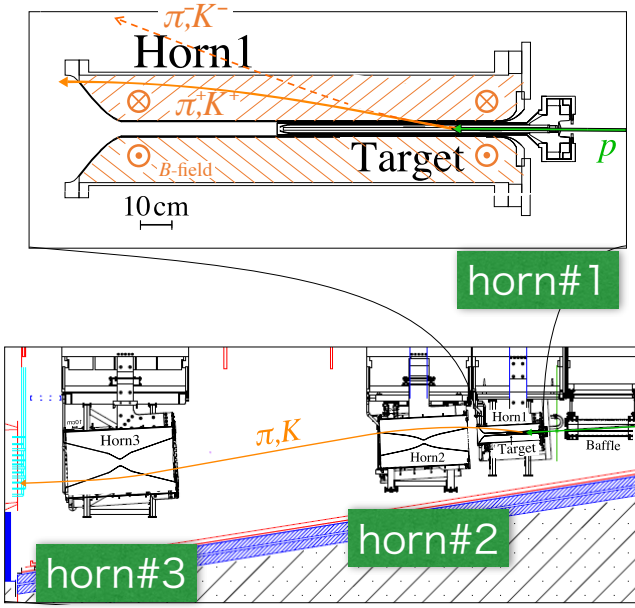
Improving maintainability under radio-active environment

Increasing capability of radio-active waste handling

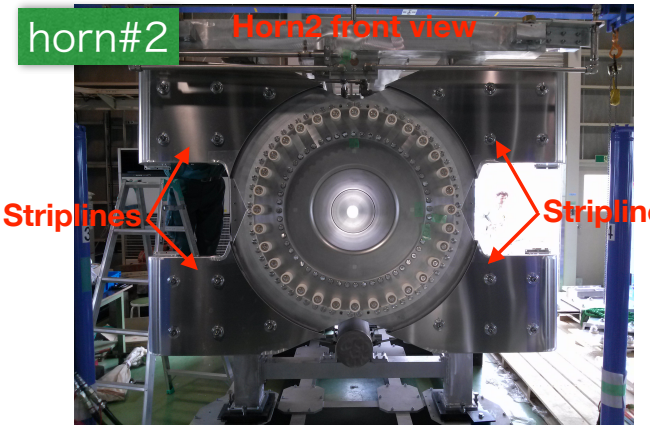
+ Increase horn current for better focusing
+ Accepting high repetition rate (~1Hz) beam

Horn PS upgrade
DAQ improvement

Electromagnetic horn upgrade

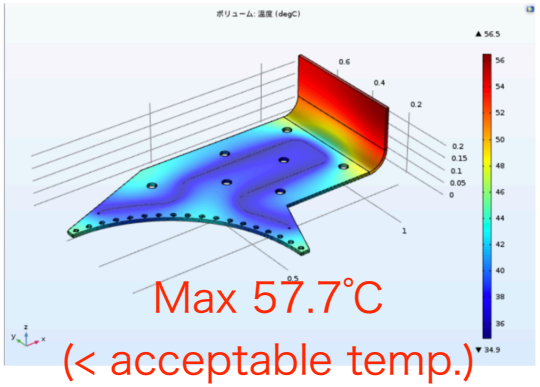


(Previous) the He gas cooling method limits acceptable power to 750kW



Developed a new **water cooled stripline** which can accept up to 2.1MW

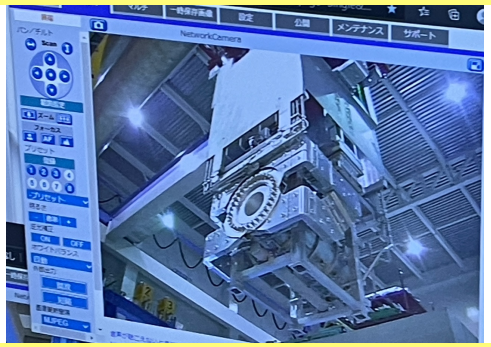
water tube embedded in striplines using Friction-Stir-Welding(FSW) method



Max 57.7℃ (< acceptable temp.)

New horn production/construction under cooperation w/ **Colorado U. and FNAL**

New horn2 was successfully installed

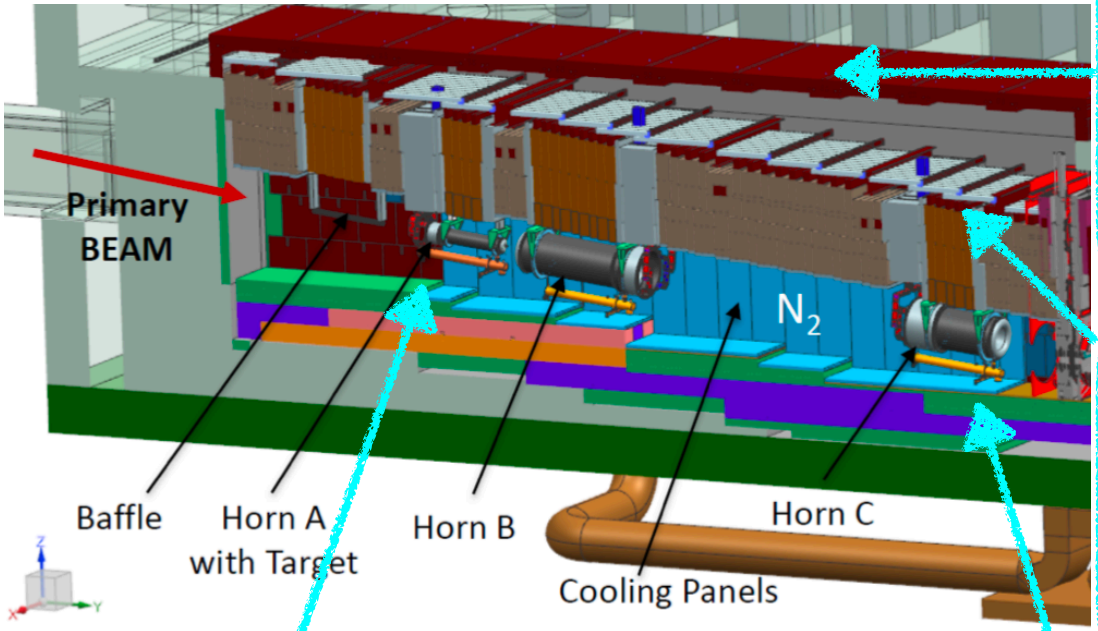


Control room for remote operation

Plan to resume beamline operation for T2K in April 2023

KEK/J-PARC - FNAL cooperation

LBNF neutrino beamline

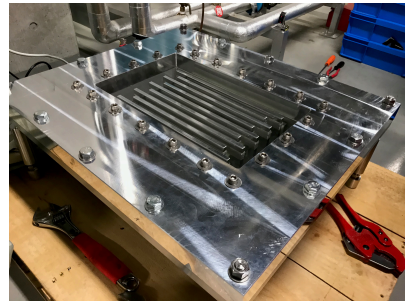


Air-Tightness Hatch cover

- Performance test with Fermilab engineers in J-PARC
- Requirement of 10^{-6} Pa・m^3/s satisfied

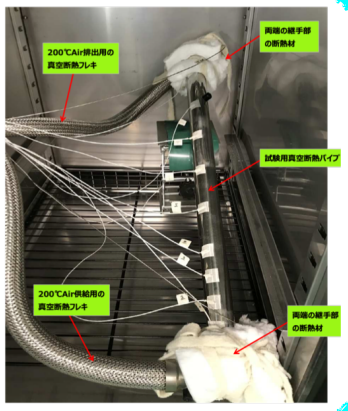
Feedthrough for stripline of Horn magnet

- Performance test and requirement satisfied
- Current testing prototype under development



He circulation system for target cooling

- Thermal insulation for high temperature He gas line under development
- Proof-of-principle test of vacuum insulation pipe revealed a promising result



Hydrogen removal for Horn cooling water

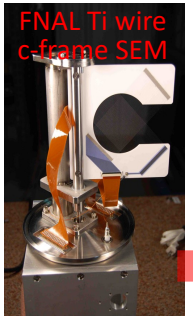
- Critical component for high-power beam operation
- Hydrogen recombination sufficiently remove H_2 from 5%→0.1%/day
- Additionally introduced new ion-exchanger and O_2 de-gasifier for safer operation.

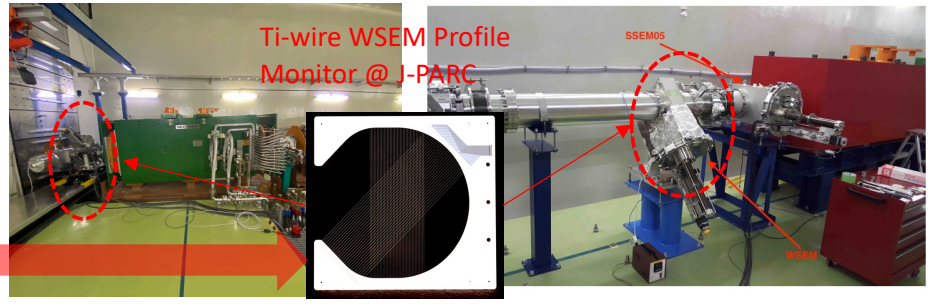
some of these are common technical challenges toward high intensity facility

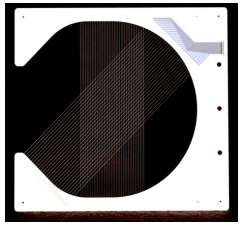
Based on over 10 years experience and R&D at J-PARC, we promote KEK-FNAL cooperation for LBNF

◉ Advances in Proton Instrumentation

- Extracted Beam Monitoring: FNAL→ J-PARC
  - Assemble WSEM with Carbon-nano-tube wire (low-Z) at FNAL (2022), and test at J-PARC neutrino beam-line (2023~)





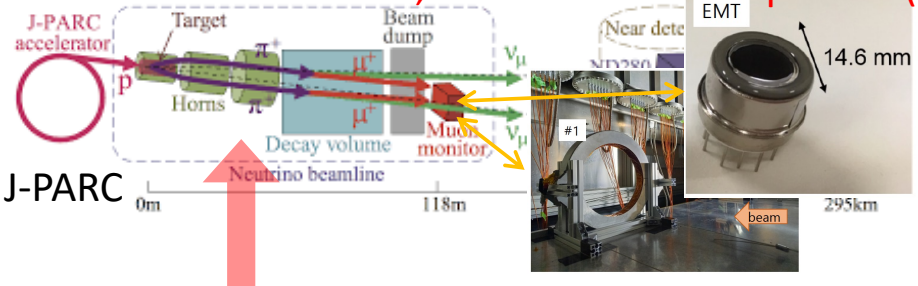


WSEM w/ CNT
Will be developed.

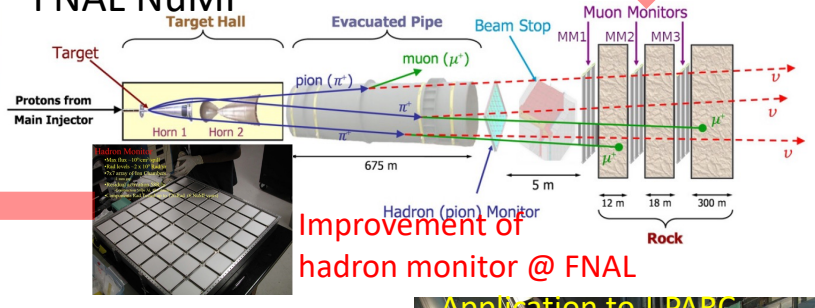
◉ High-power target facility issues

- Radiation hardened beam instrumentation

EMT, CT is under development (beam test : ~FY2021, …)



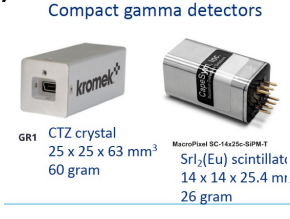
Test, Application@ NuMI

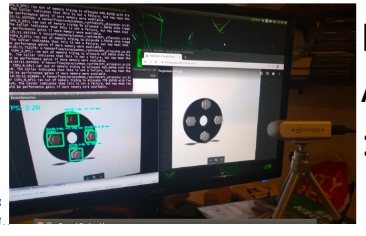


Study on application@ J-PARC

Improvement of hadron monitor @ FNAL

- Autonomous Robotics and Remote Handling

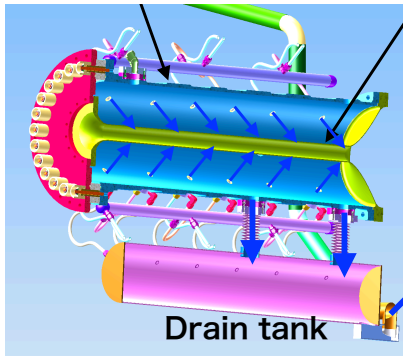


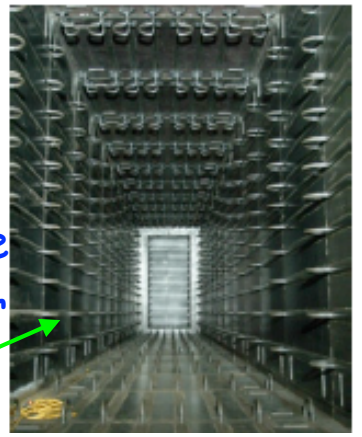


Non-GPS drone,
AI image recognition, etc
: Under development
@ FNAL

How to reduce "Tritium" ?

- Cooling water activated by ^{3}H (Tritium)
- Radio-active water should be diluted and drained
- We recently increased the size of the dilution tank to increase the capability of water disposal
- Tritium contamination increases as increasing beam exposures → need to consider appropriate treatment of the ^{3}H
- **R&D to understand Tritium production and knowledge sharing on Tritium treatment are in progress among US-Japan collaboration**





~25GBq HTO produced per 1x10^{20}POT
In Horn/TS He Vessel/Decay Volume Cooling Water

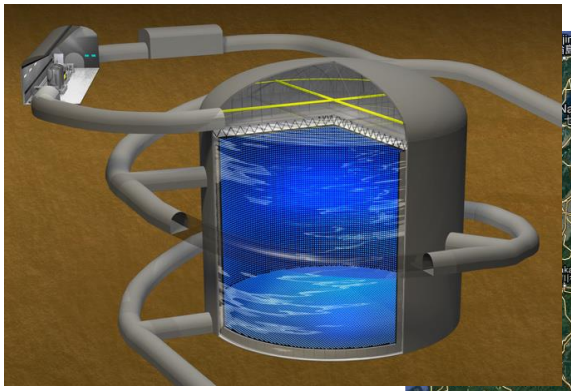
~6 times larger dilution tank has been newly constructed

Hyper-K experiment

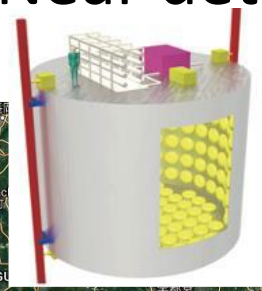
~520 members, 101 institutes, 20 countries

- New 260 kton water Cherenkov detector
  (Fiducial vol. = 190kton which is 8.4 times larger than Super-K)
- Upgrade of J-PARC neutrino beam (0.5→1.3MW)
- Upgrade of neutrino near detectors

Far detector



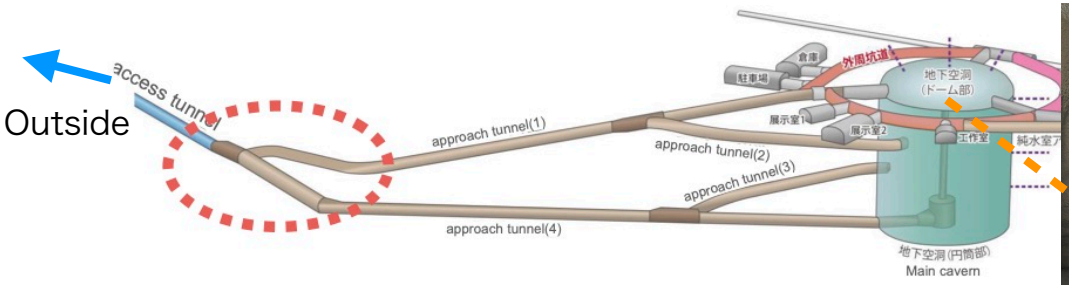
Neutrino Near detectors



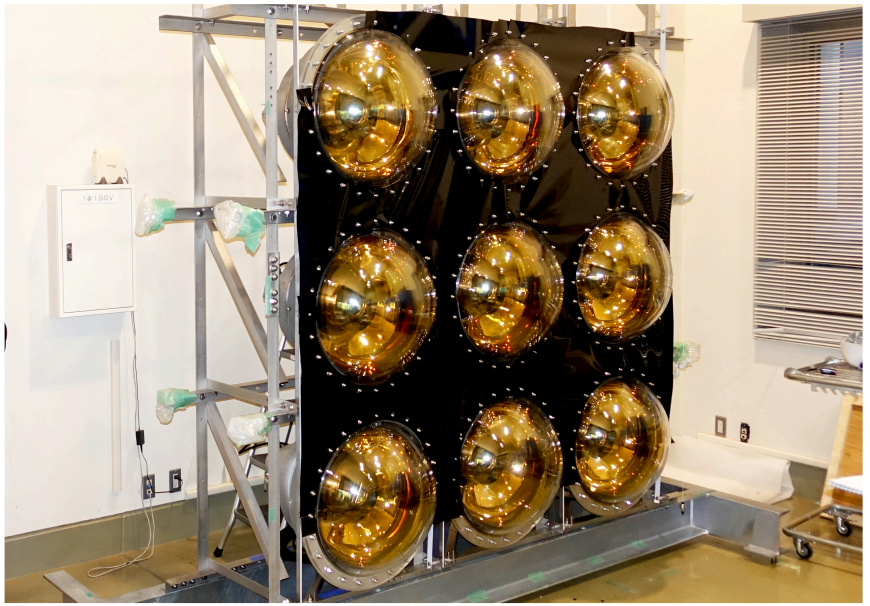
J-PARC accelerator & neutrino beamline

Construction on-going. Plan to start data taking in 2027

✤ Status of excavation



✤ Status of PMT production and delivery



Visual inspection & Testing signal for all the PMT is on-going

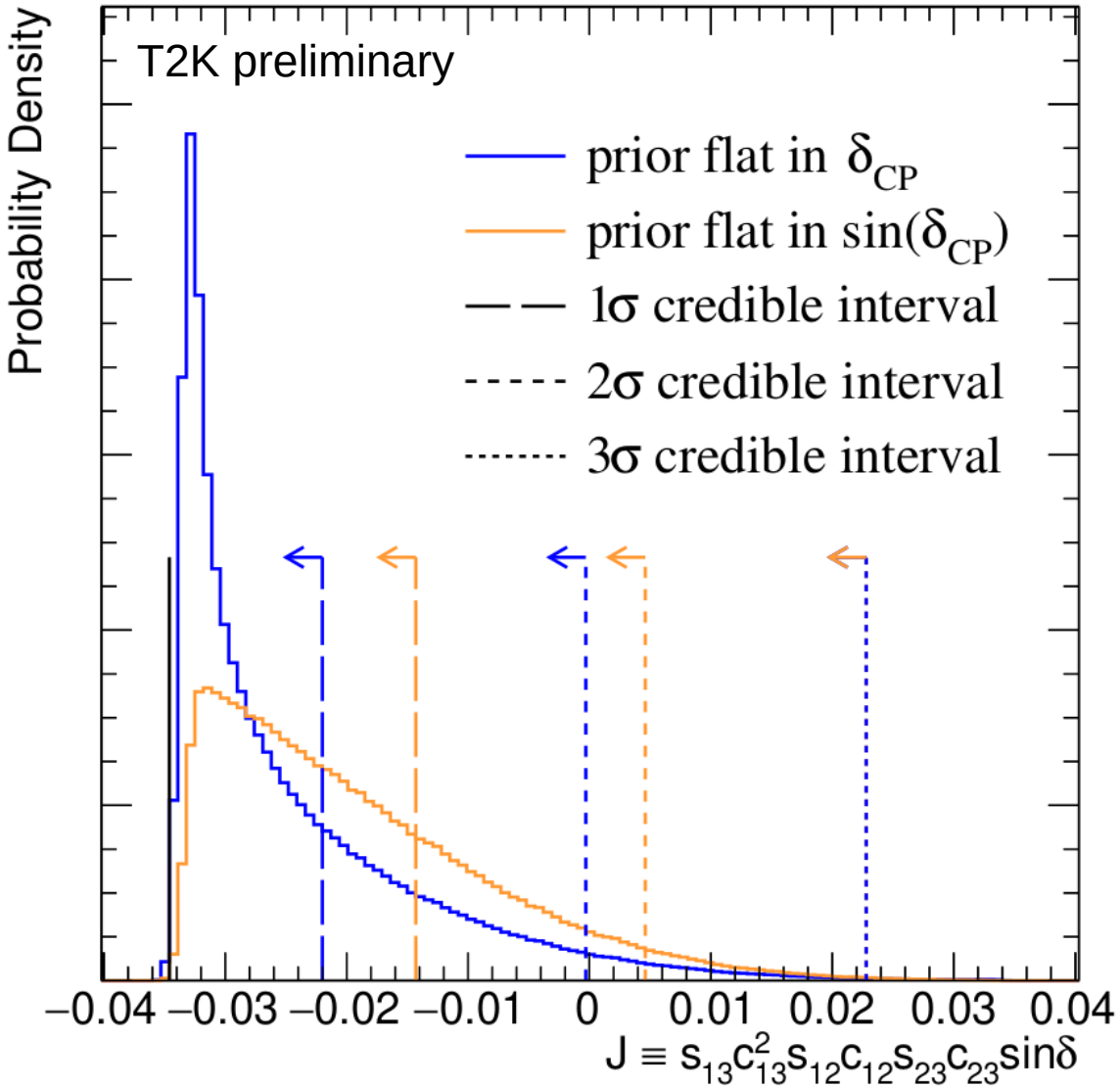
Summary

- J-PARC neutrino facility and its upgrade works for T2K and HK experiments are introduced
- Some of upgrade works are performed under strong international and domestic collaboration
- We will continue the US-Japan joint R&D to realize a Mega-Watt class high intensity neutrino beam fro long baseline neutrino oscillation experiments (T2K,NOvA,HK and DUNE)

backup

T2K results on Jarlskog invariant

$J_{CP} = \sin\theta_{13}\cos^2\theta_{13}\sin\theta_{12}\cos\theta_{12}\sin\theta_{23}\cos\theta_{23}\sin\delta_{CP}$



T2K data prefers largest (negative) CP violation.

sign is also sensitive to Leptogenesis models

[arXiv:2005.01039]

Understanding of Tritium behavior

- We observed ^{3}H from steel wall to water at J-PARC neutrino beamline.
- Discussion started among FNAL, CERN, J-PARC (also muon facility) for similar issues.
- To understand ^{3}H release from materials, need to evaluate diffusivity and solubility of the ^{3}H.