Search of neutrino CPV:
the T2K experiment and the Hyper-Kamiokande project

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Article

Constraint on the matter–antimatter symmetry-violating phase in neutrino oscillations

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Check for updates

The T2K Coll

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CP violation
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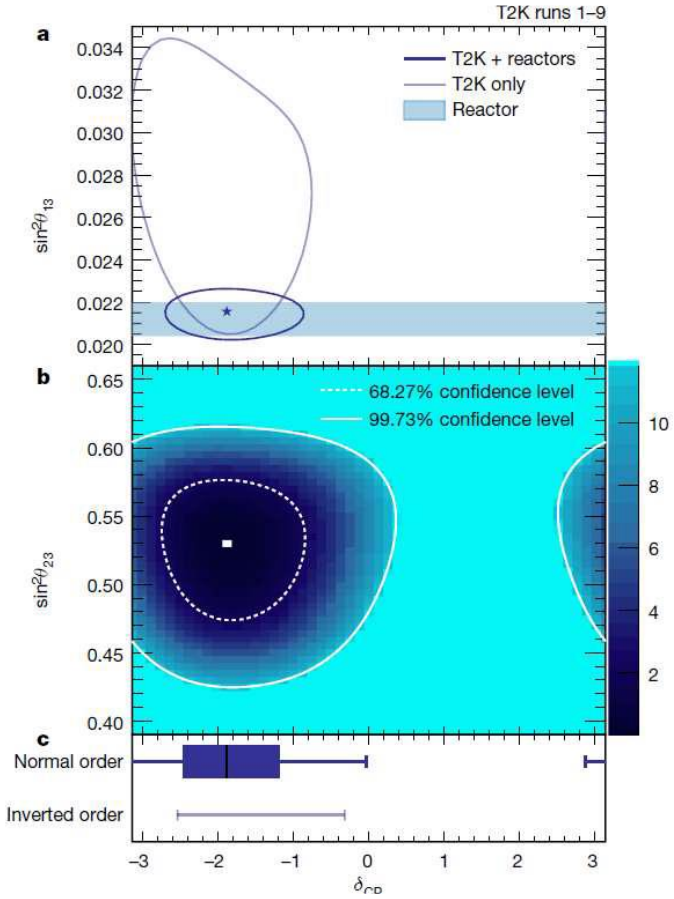
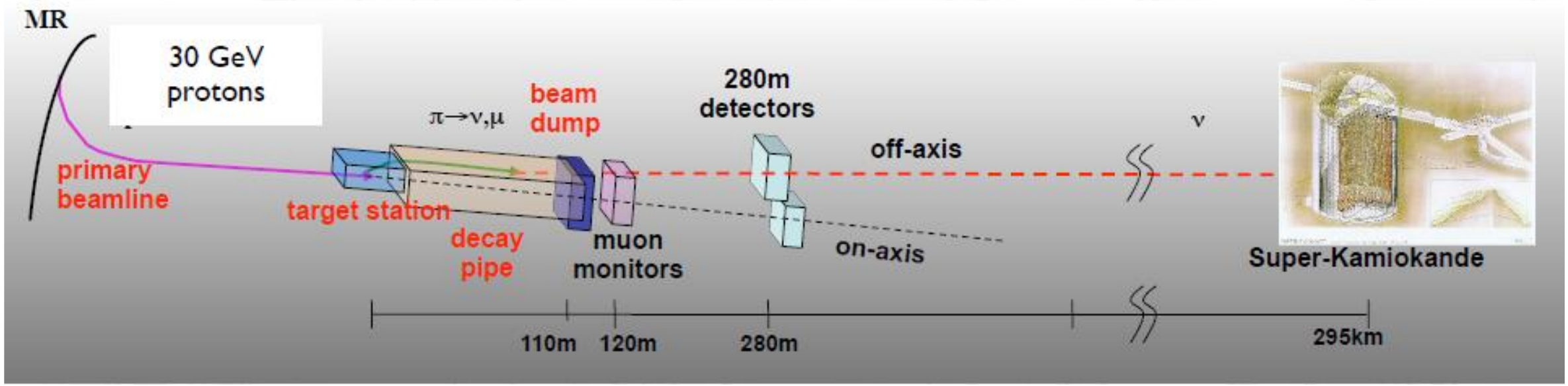


T2K:
a major step forward in the study of difference between matter and antimatter

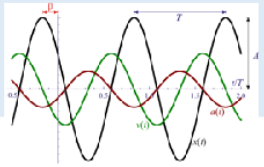
T2K experiment



Neutrinos produced in a particle accelerators or nuclear reactors.

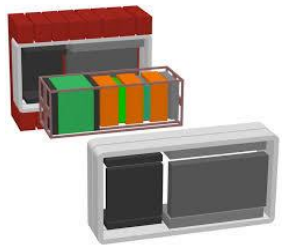
Neutrino flux properties

ν oscillations

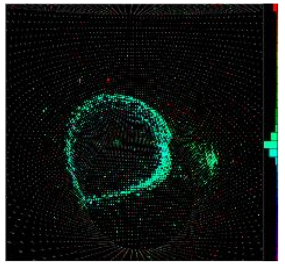


Neutrino flux & flavour

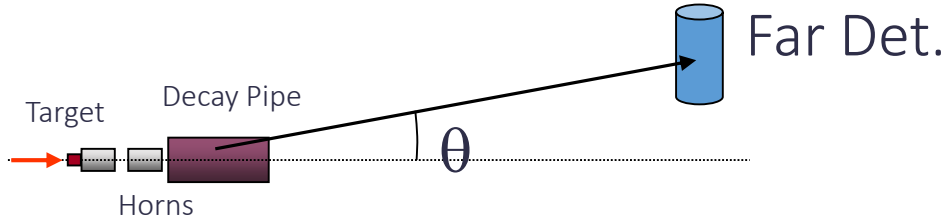
$\nu_\mu / \bar{\nu}_\mu$

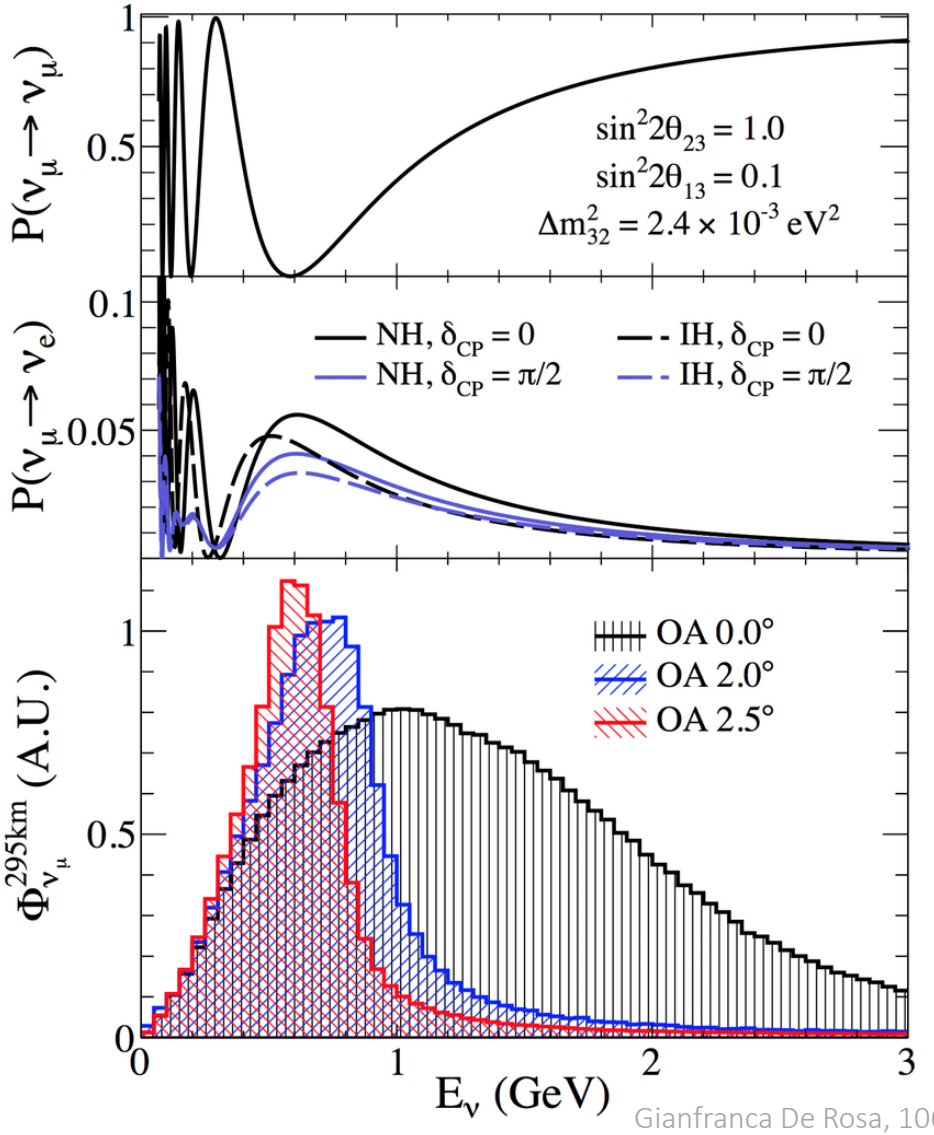


$\nu_\mu / \bar{\nu}_\mu$ » $\nu_e / \bar{\nu}_e$



Off-axis beam





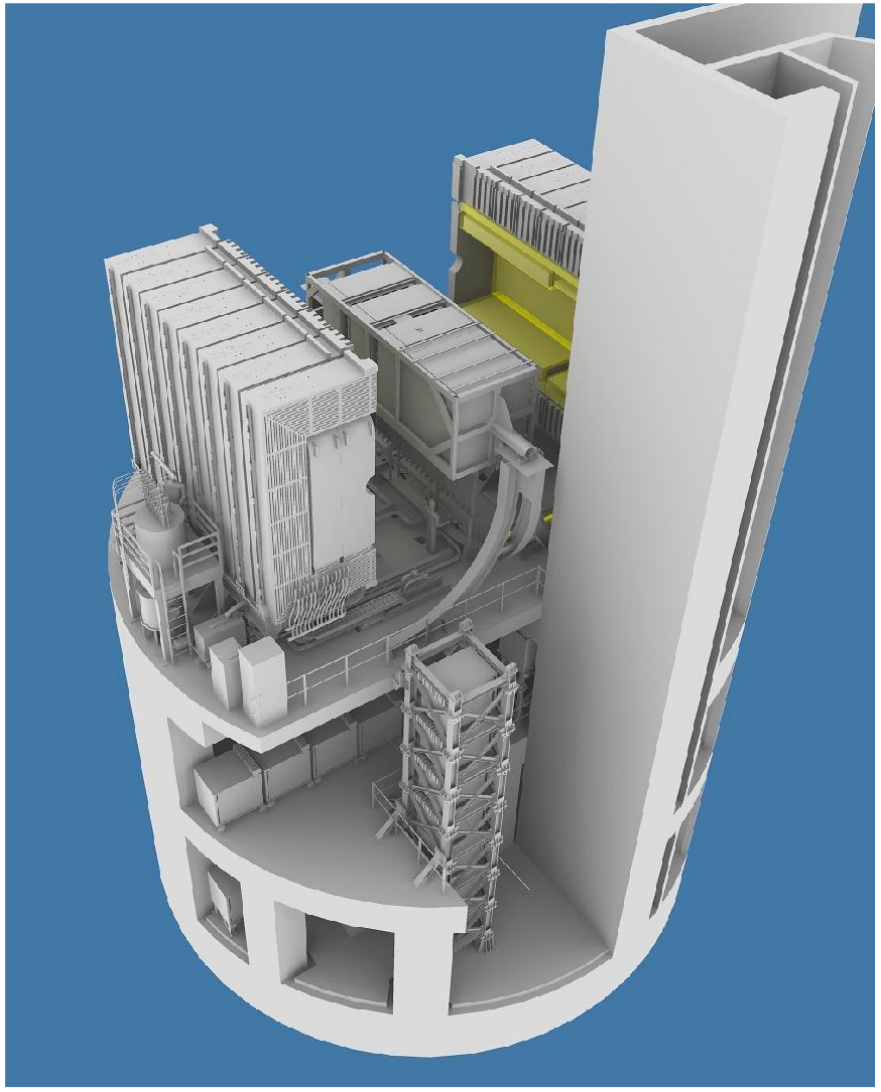
Off axis:

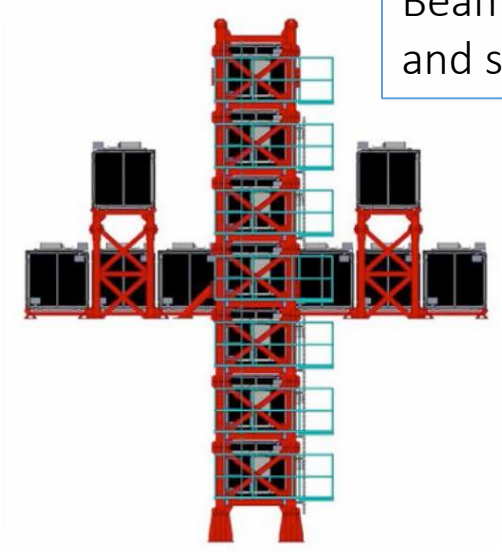
- Off-axis optimises the flux at the maximum of the oscillation.
- Only one oscillation maximum can be measured at a fixed distance.
- Narrow beam less dependent on beam uncertainties but more on beam pointing.
- Lower energies achieved.

On axis:

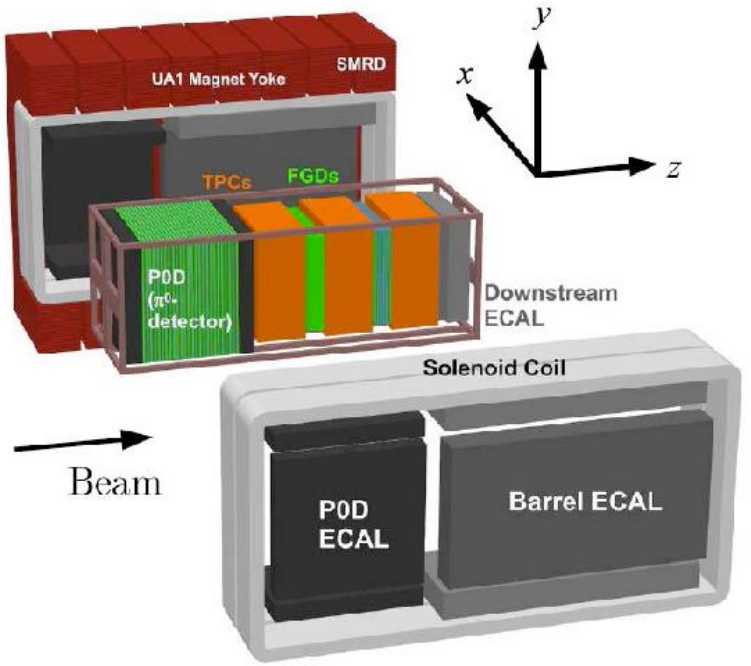
- On-axis optimises the total integrated flux.
- Spectrum with higher neutrino energy (longer oscillation distances)
- If broad enough, more than one oscillation maximum can be measured at a fixed distance.

Near Detector Site

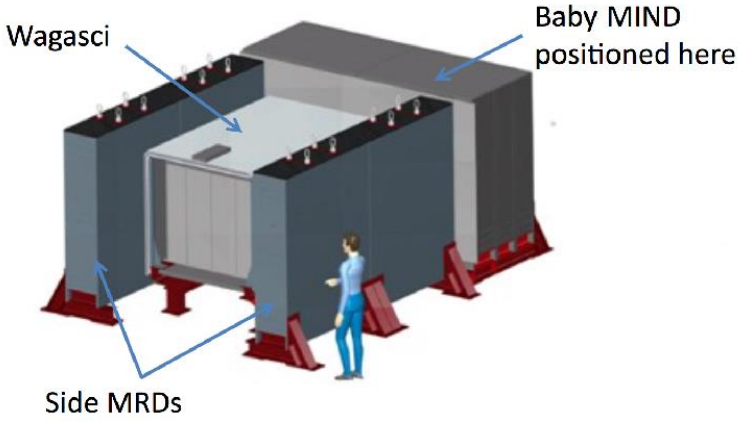




INGRID: On-axis
Beam direction and stability

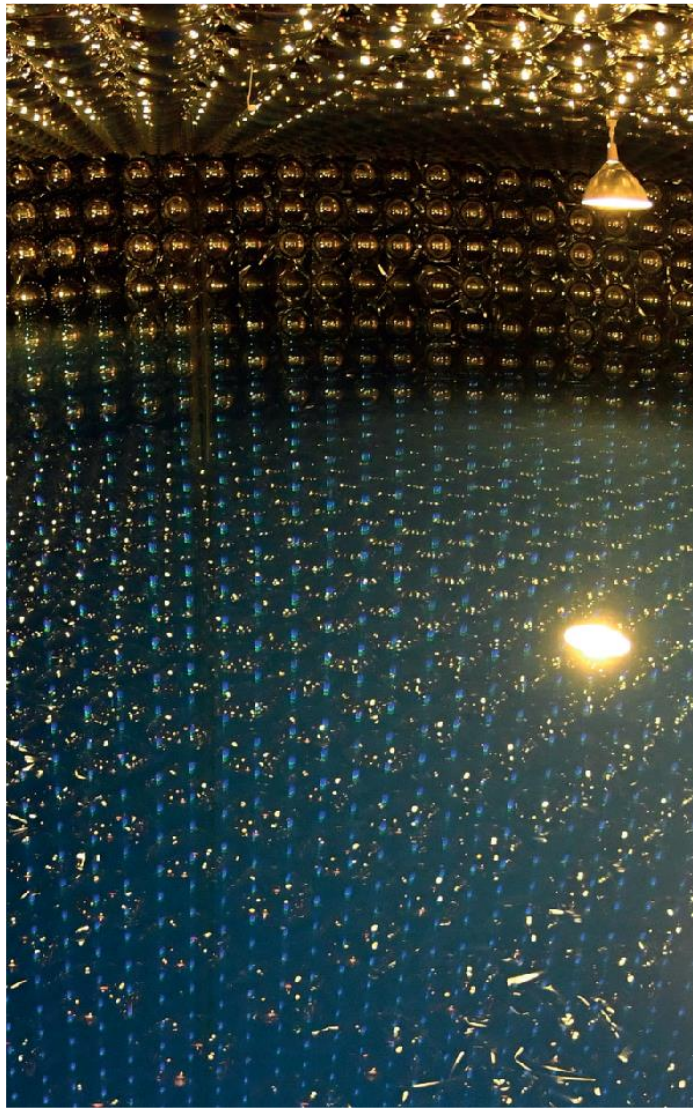


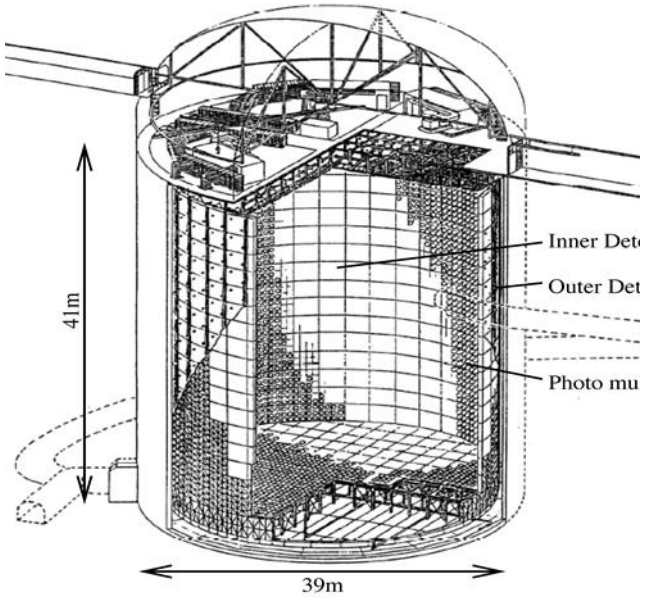
Wagasci/BabyMind: Off-axis



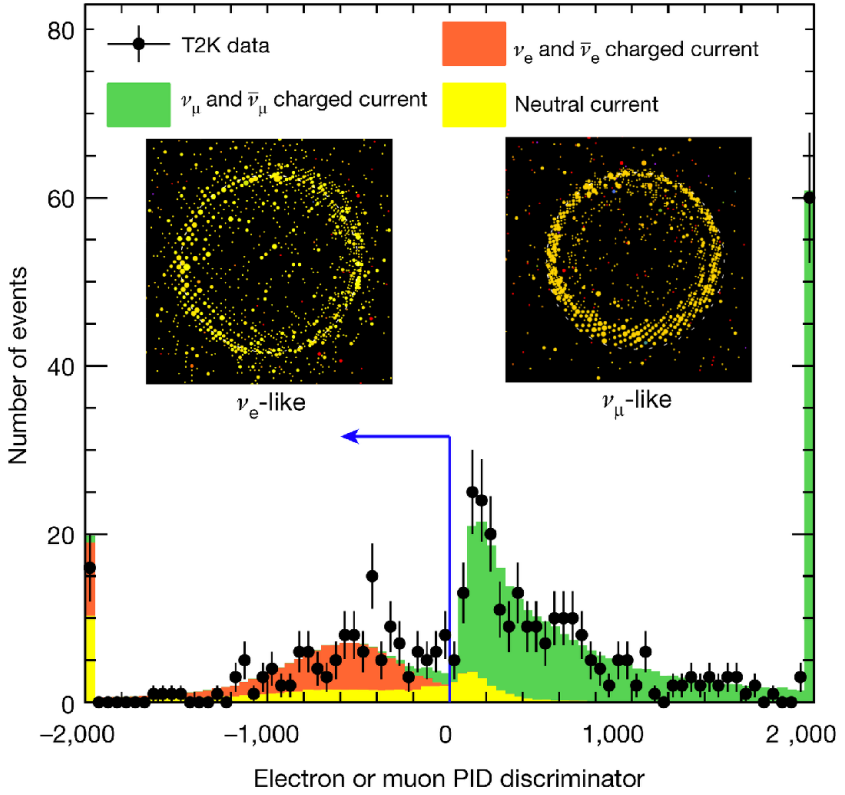
ND280: Off-axis
Constrains cross-section and flux uncertainty model

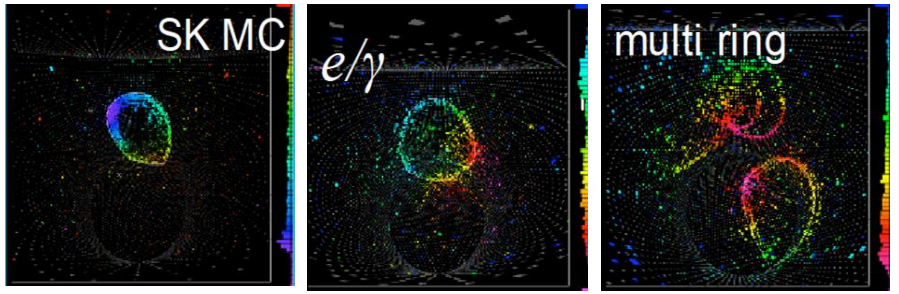
Far detector: Super-Kamiokande





- Particle identification
- Interaction vertex reconstruction
- Particle range
- Electromagnetic energy reconstruction
- Track Multiplicity
- Hadronic interactions



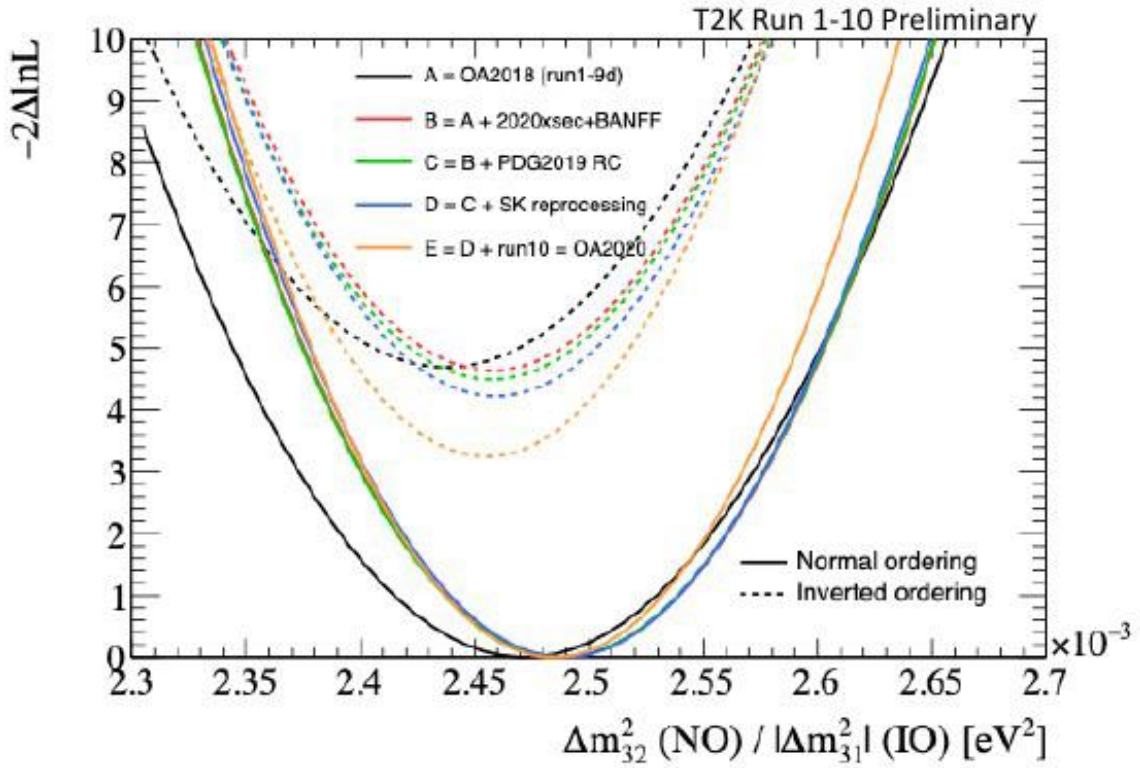


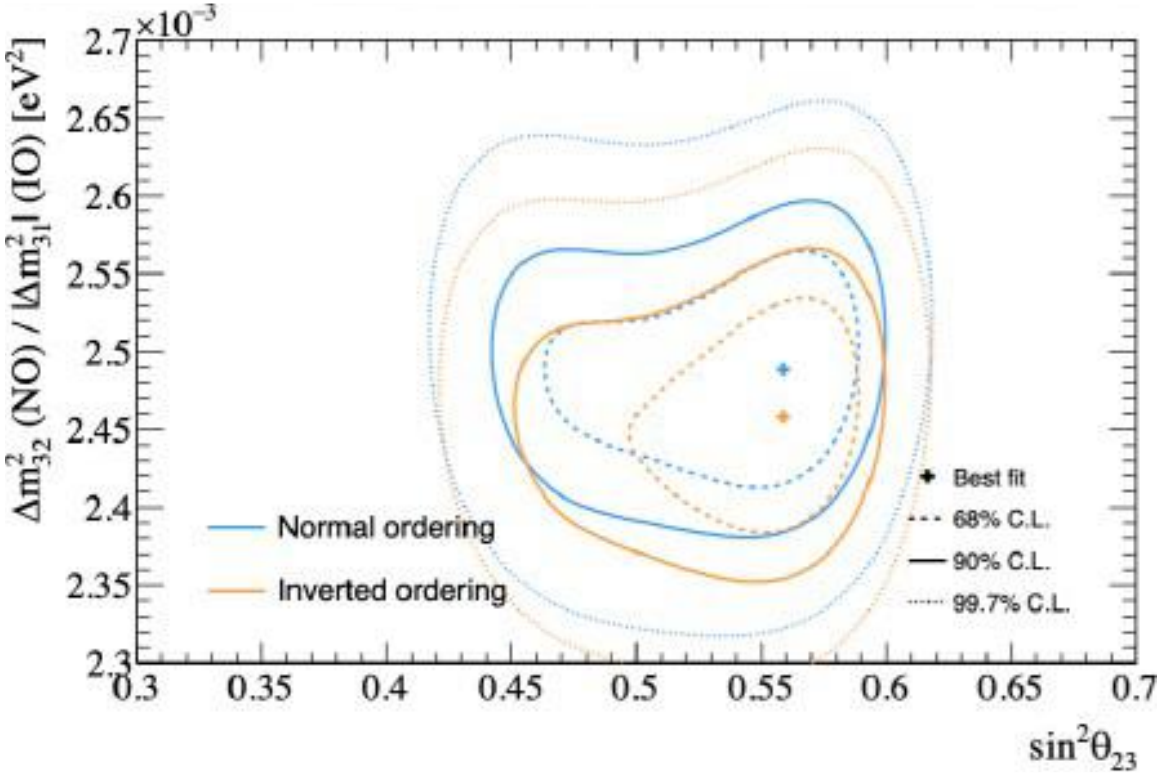
T2K results

ν_μ and $\bar{\nu}_\mu$ disappearance

T2K 2020 Results

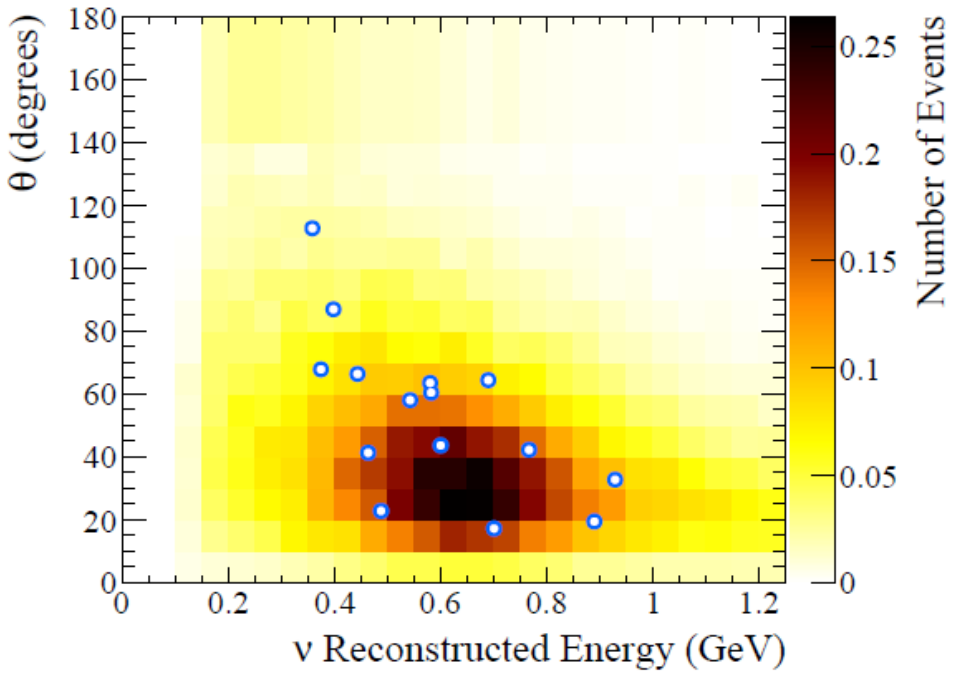
Improvement of Δm^2_{32} measurement
→ Thanks to improved neutrino-interaction model and ND280 constraints





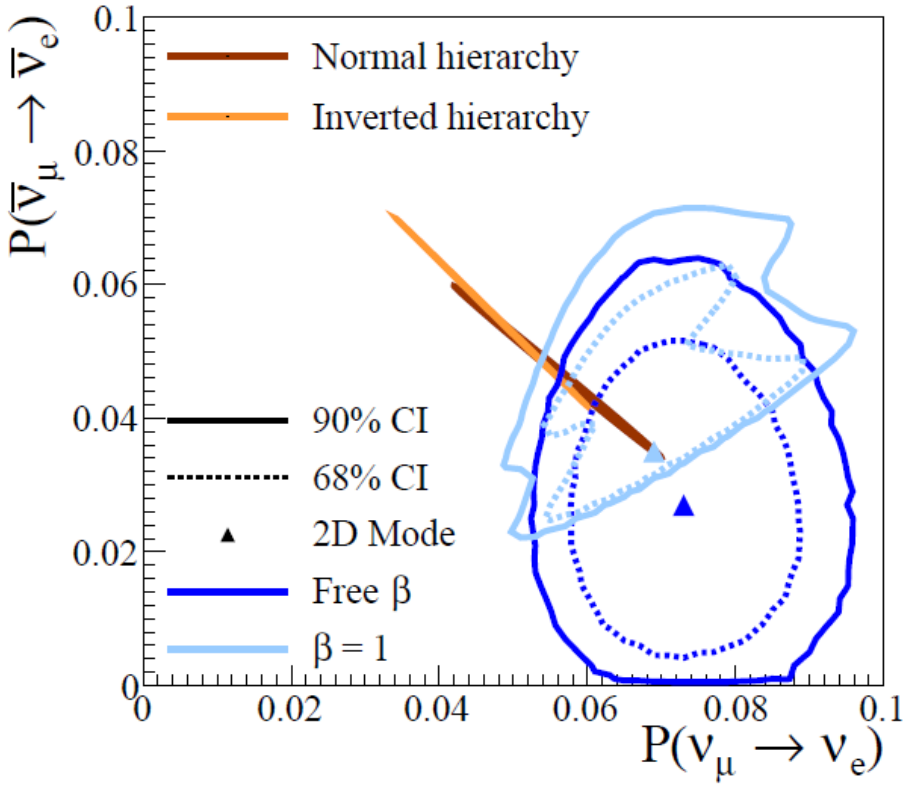
Slight preference for non-maximal mixing with θ_{23} in the second octant

$\bar{\nu}_e$ appearance



15 candidate electron antineutrino events with a background expectation of 9.3 events

High background from ν_e.

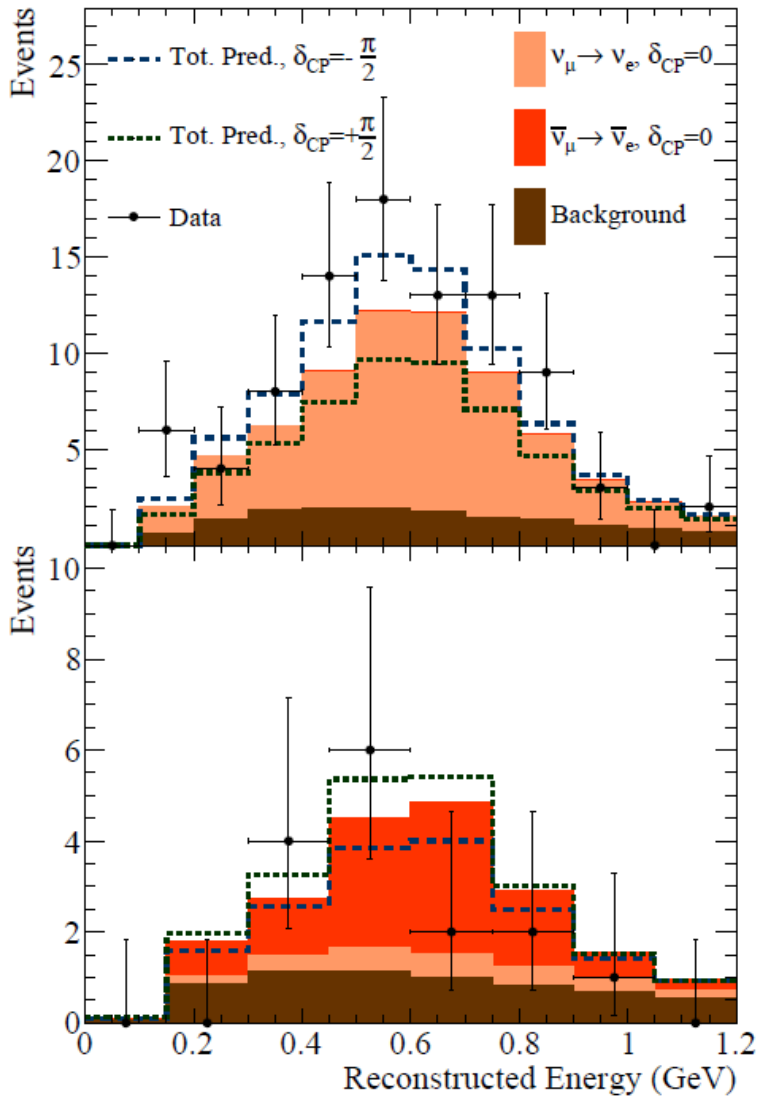


No $\bar{\nu}_e$ appearance disfavoured with a signicance 2.4σ
No discrepancy between data and PMNS predictions is found

$$P(\overline{\nu}_\mu \to \overline{\nu}_e) = \beta \times P_{\mathrm{PMNS}}(\overline{\nu}_\mu \to \overline{\nu}_e)$$

CP violation phase

$\nu_e/\bar{\nu}_e$ Systematic Uncertainty

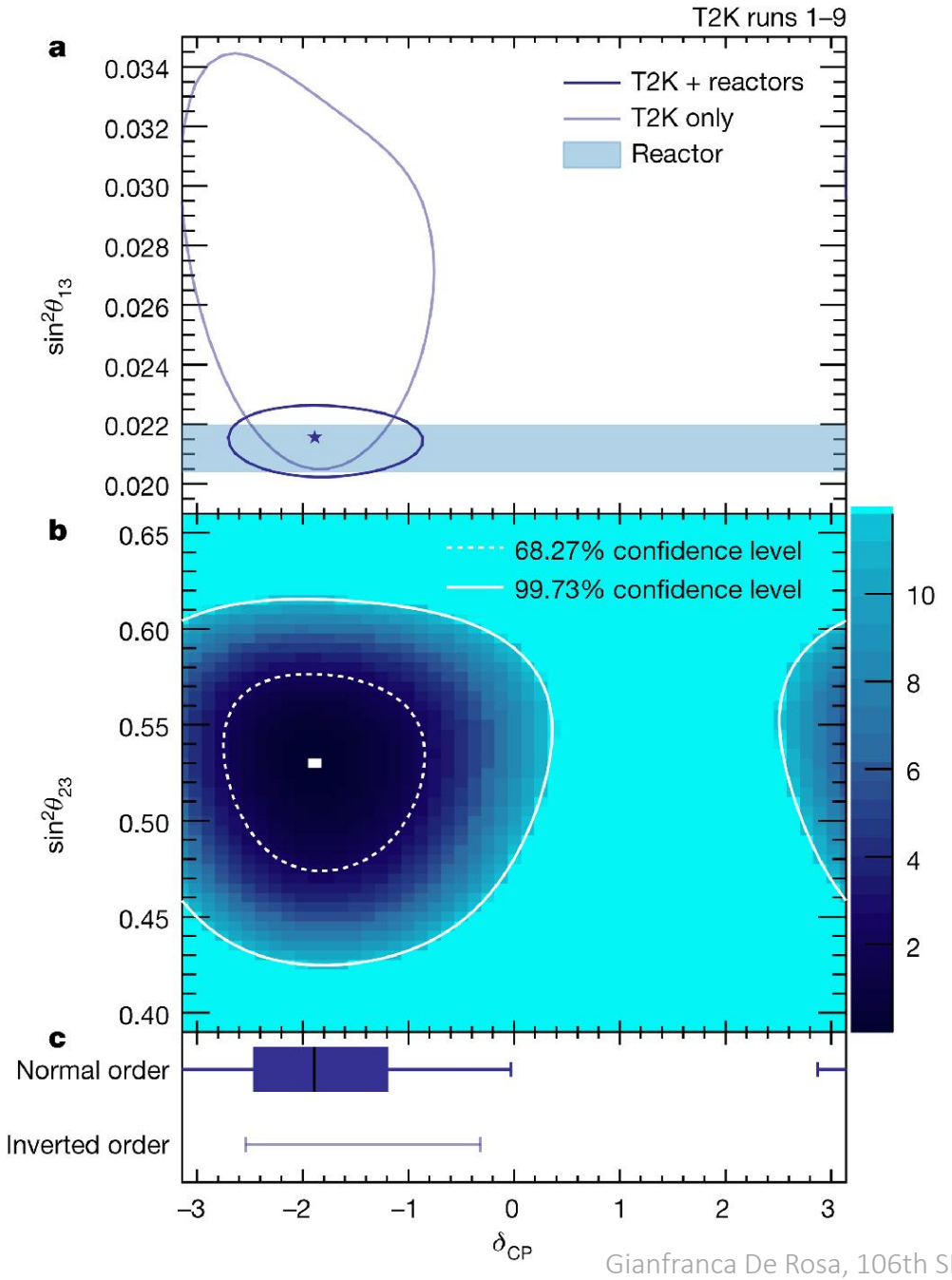


Sample	ν-mode Events	$\bar{\nu}$-mode Events
Single Electron	75 (74.8)	15 (17.2)
Charged Pion	15 (7.0)	N/A

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

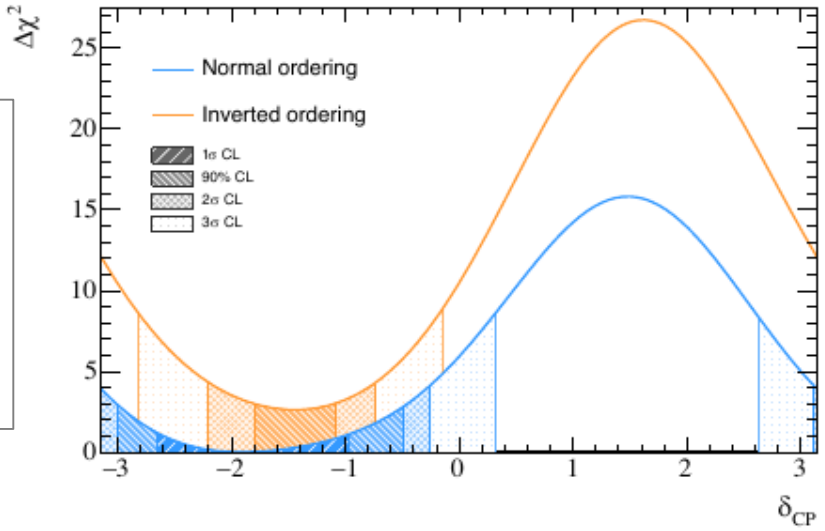
Type of Uncertainty	$\nu_e/\bar{\nu}_e$ Candidate Relative Uncertainty (%)
Super-K Detector Model	1.5
Pion Final State Interaction and Rescattering Model	1.6
Neutrino Production and Interaction Model Constrained by ND280 Data	2.7
Electron Neutrino and Antineutrino Interaction Model	3.0
Nucleon Removal Energy in Interaction Model	3.7
Modeling of Neutral Current Interactions with Single γ Production	1.5
Modeling of Other Neutral Current Interactions	0.2
Total Systematic Uncertainty	6.0

δ_{CP} measurement



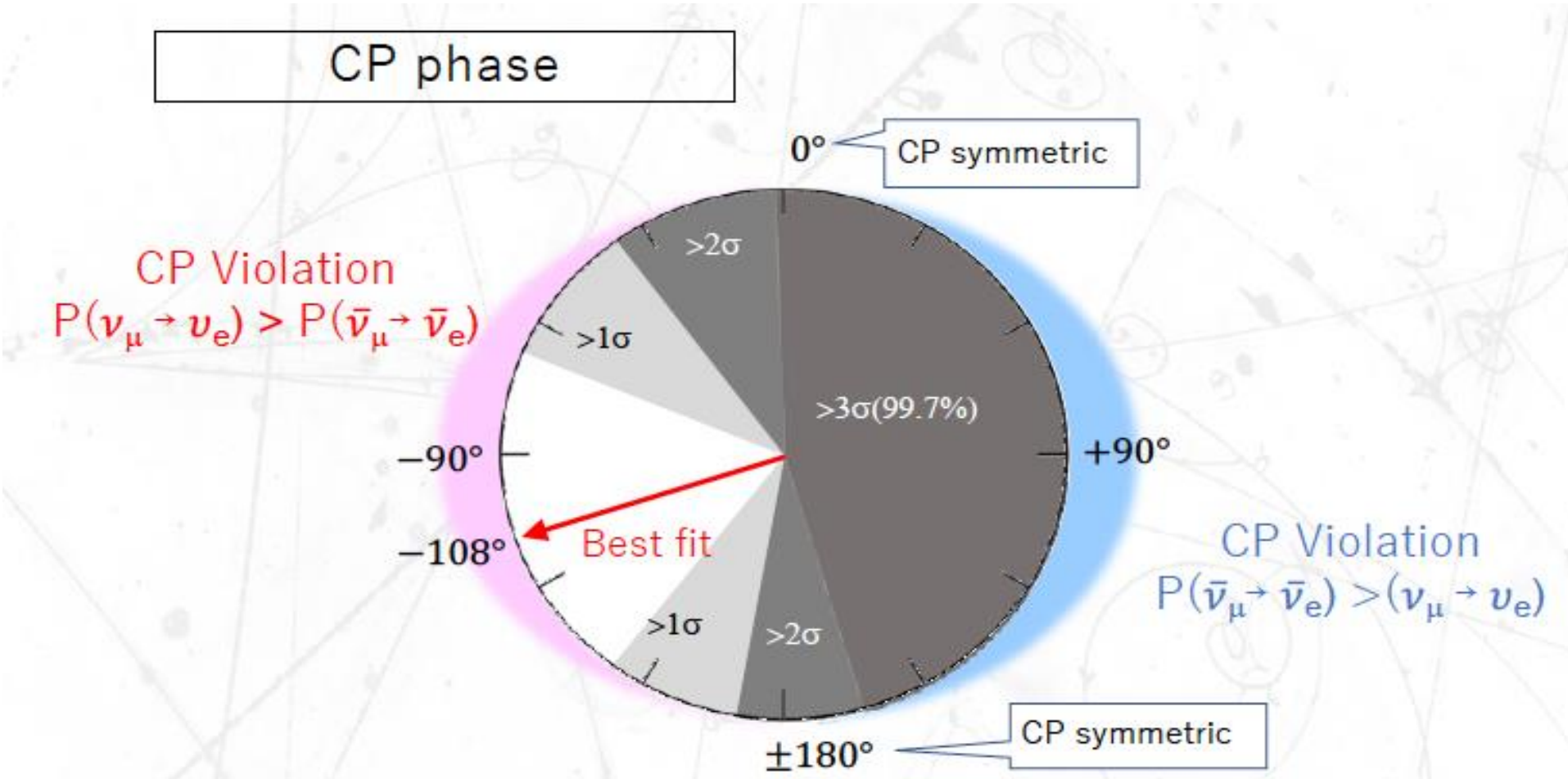
Fit uses the value of θ_{13} from reactor experiments

Data also prefers Normal Hierarchy with a posterior probability of 89%



CP violation phase

T2K result excludes most of the $\delta_{CP}>0$ values @ 99.7% CL

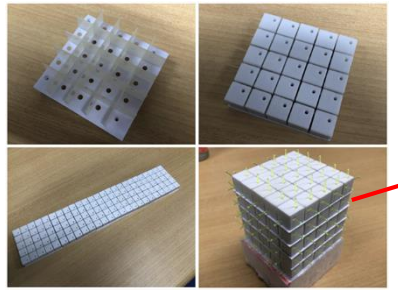


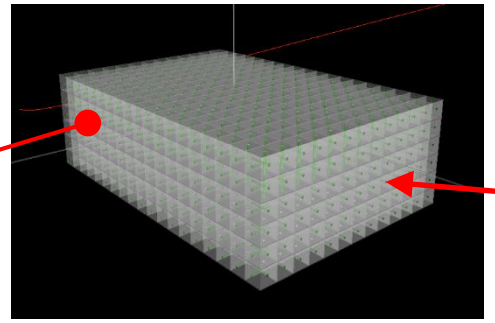
Not a discovery, but the first step in the long path towards the measurement of leptonic CP violation

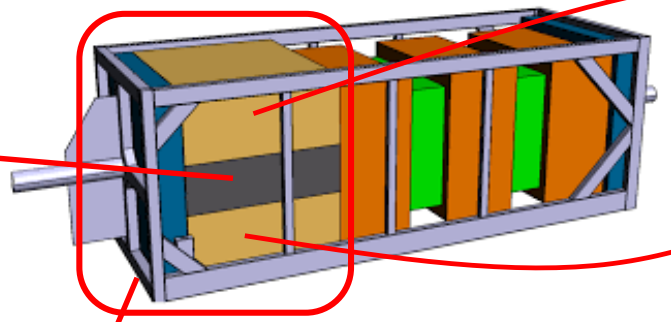
Next steps and beyond

ND280 upgrade plan for T2K

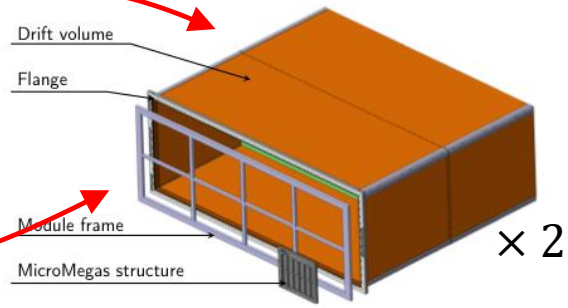
- **Large angle acceptance** to constrain neutrino interaction models
- Measurement of **short tracks** to identify non-QE, NC γ etc.







High Angle TPC



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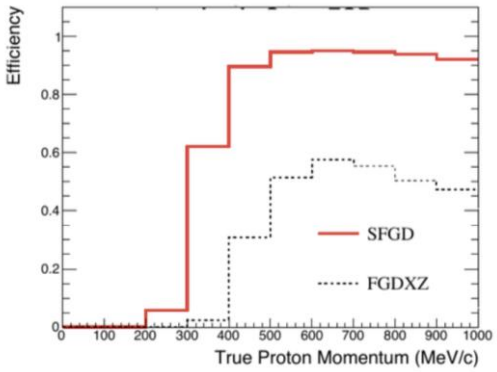
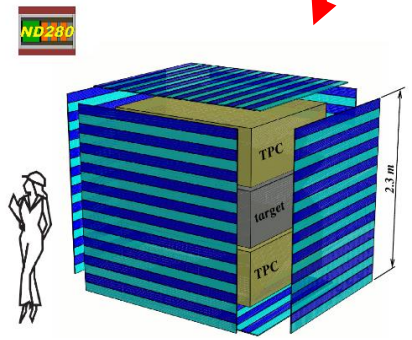
Improve reconstruction of hadron (short) tracks



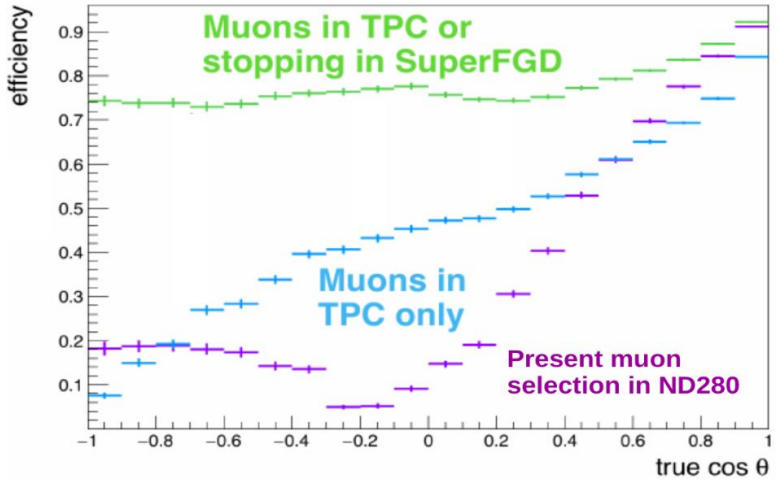
SuperFGD

(scintillator target tracker)

~2m^3, ~2M cubes, ~60k ch

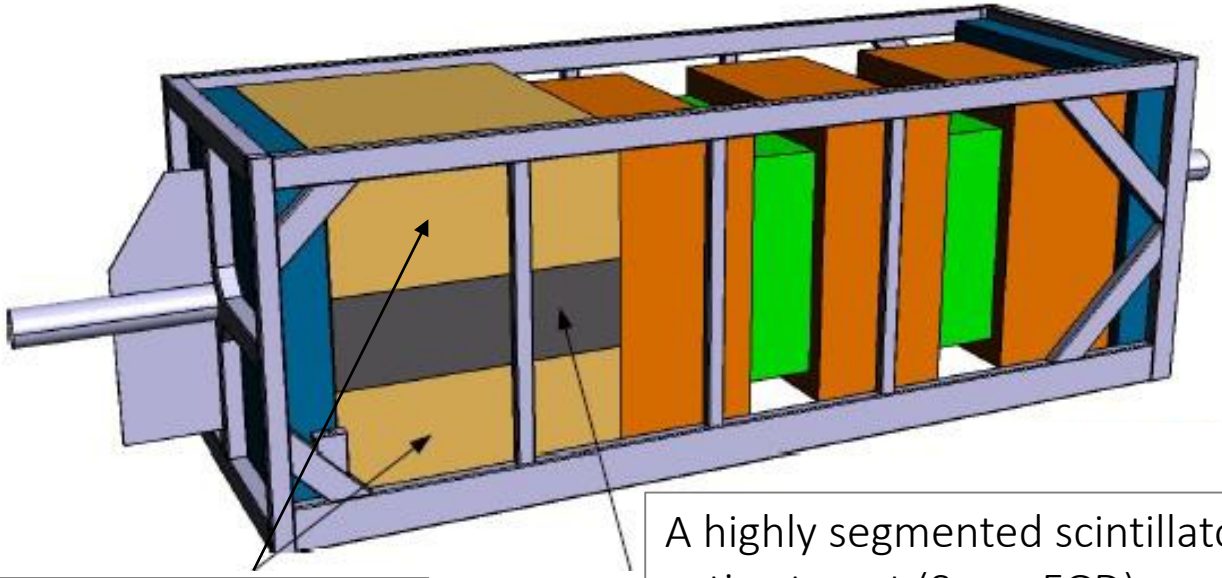


TOF



- Enlarging phase space of CC-Inclusive events will reduce the flux+xsec systematic uncertainties by 30-40%
- ToF detectors precisely determine the track direction and reject the Out-of-Fiducial Volume events (<1%)
- Increase events by 15-20% with detection muons (>90% efficiency, <3% momentum resolution)

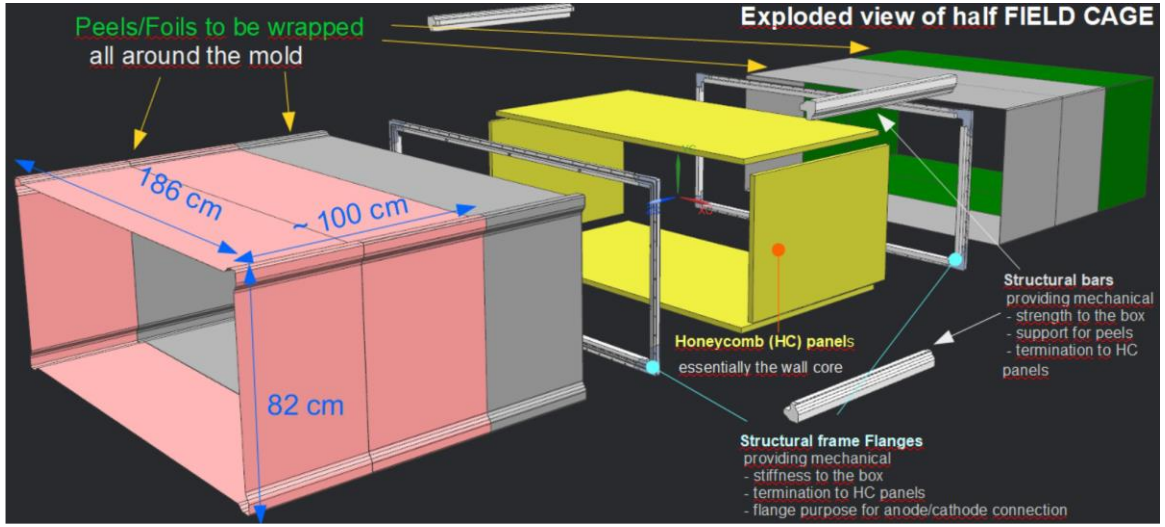
New Horizontal TPCs whit Resistive MM readout

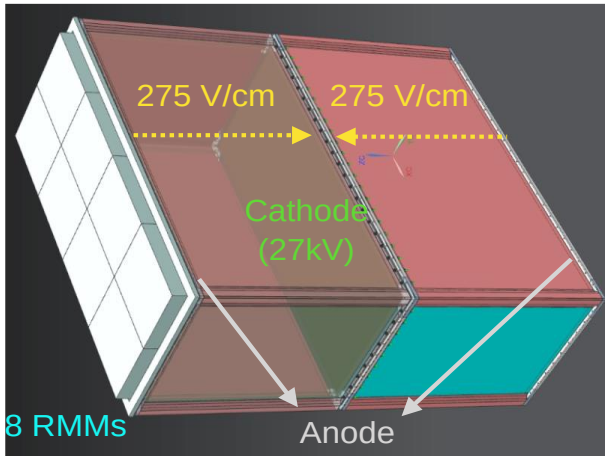


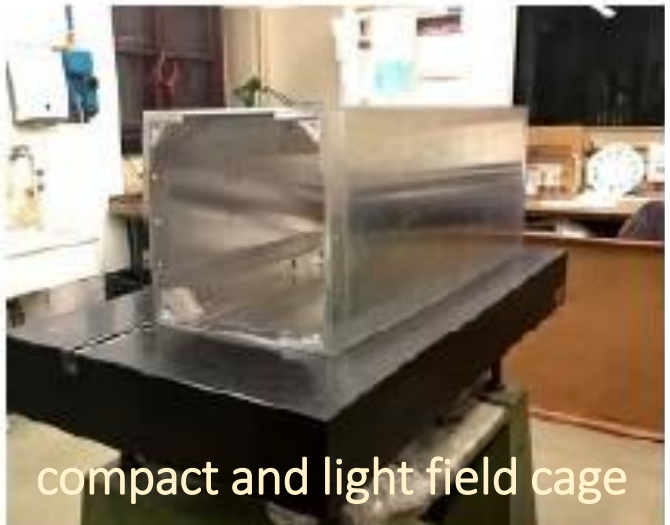
Two new High-Angle TPCs (HA-TPC)

A highly segmented scintillator active target (SuperFGD)

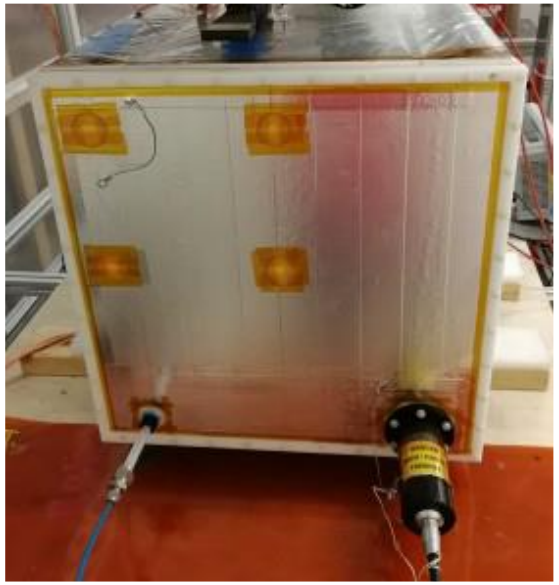
INFN: HATPC Field Cages







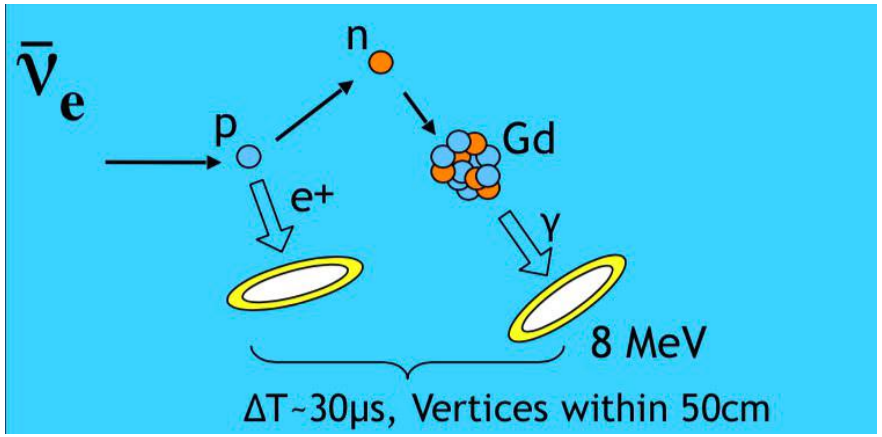
Prototype at CERN
→ T2K lab facility
@ Neutrino Platform Area

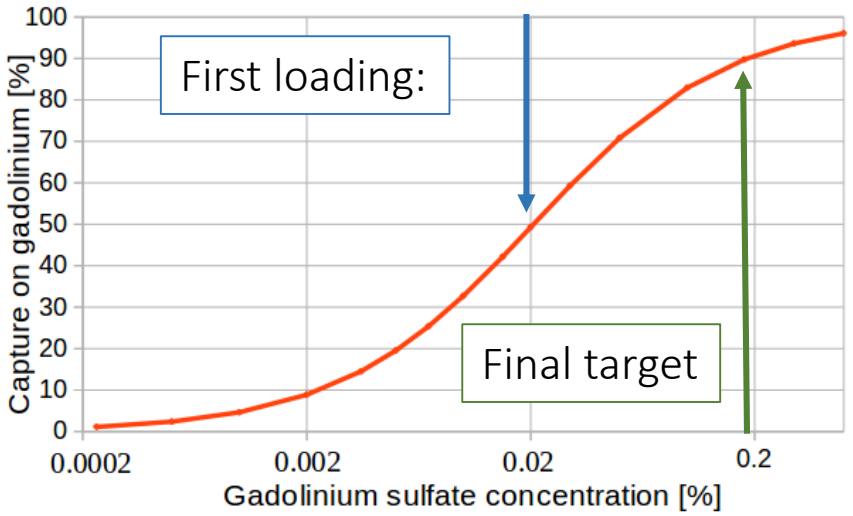


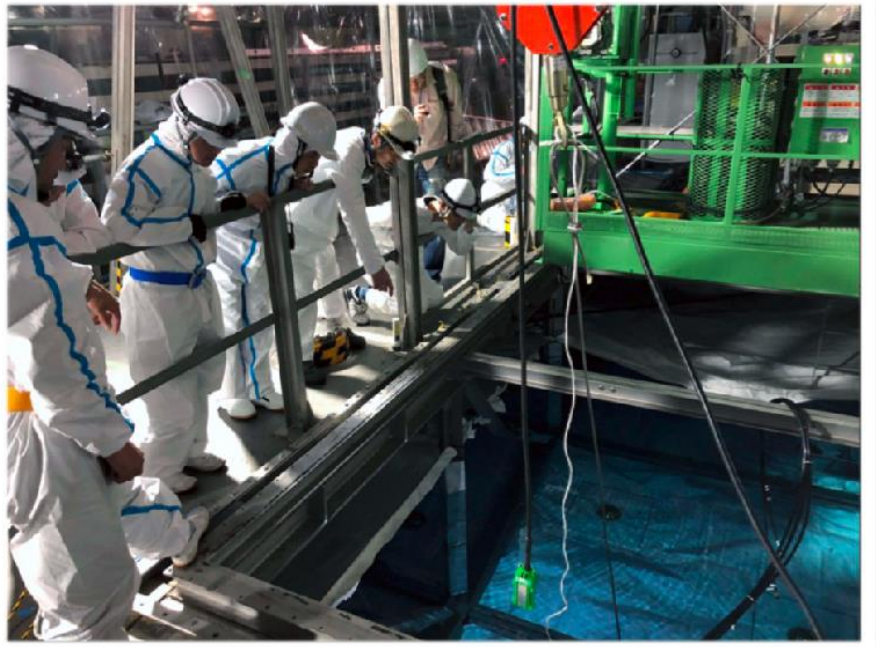
SK Gadolinium

SK Gadolinium project

- enhance neutron detection
- improve low-energy ν_e detection (non-T2K goal)
- may provide wrong-sign background constraint in ν_e
- more data samples
- Leak repairs to SK tank finished in 2019
- Load $Gd_2(SO_4)_3$ in stages up to 0.2%.

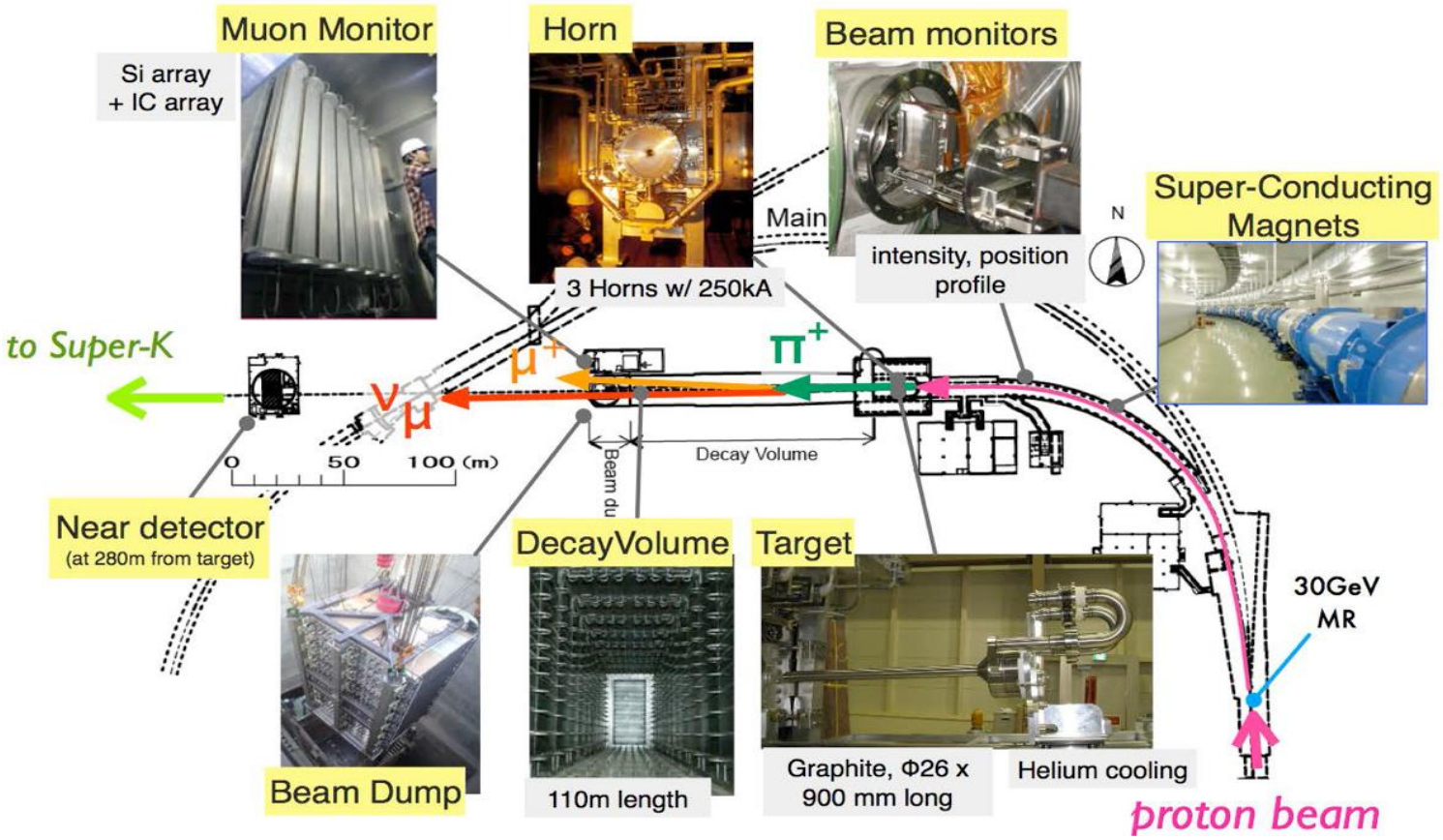


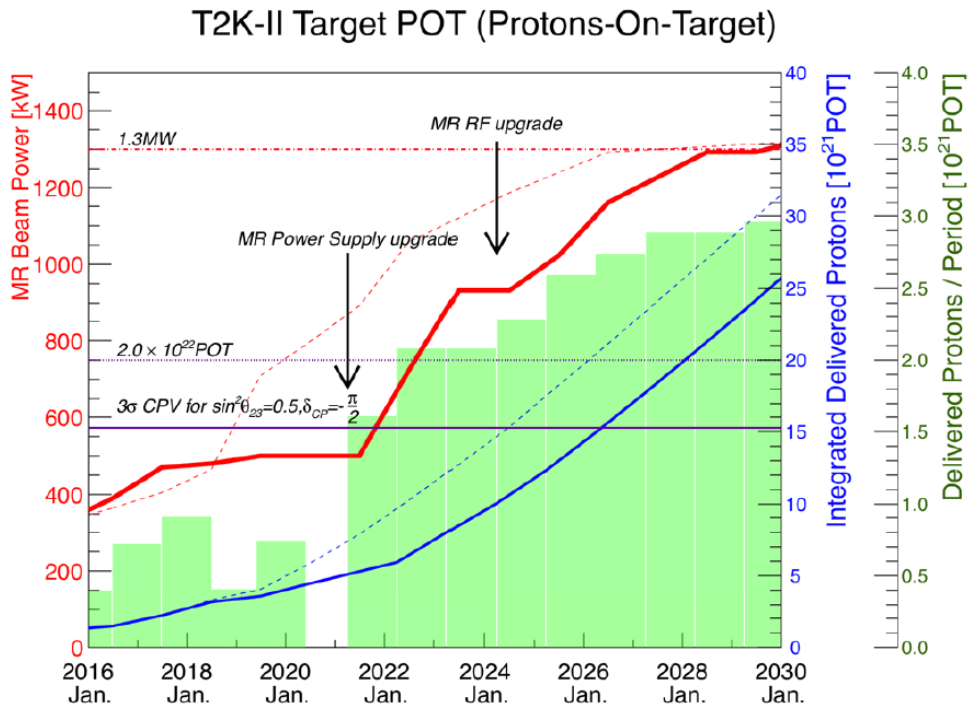




SKGd will be ready for T2K beam by January 2021

Beam upgrade



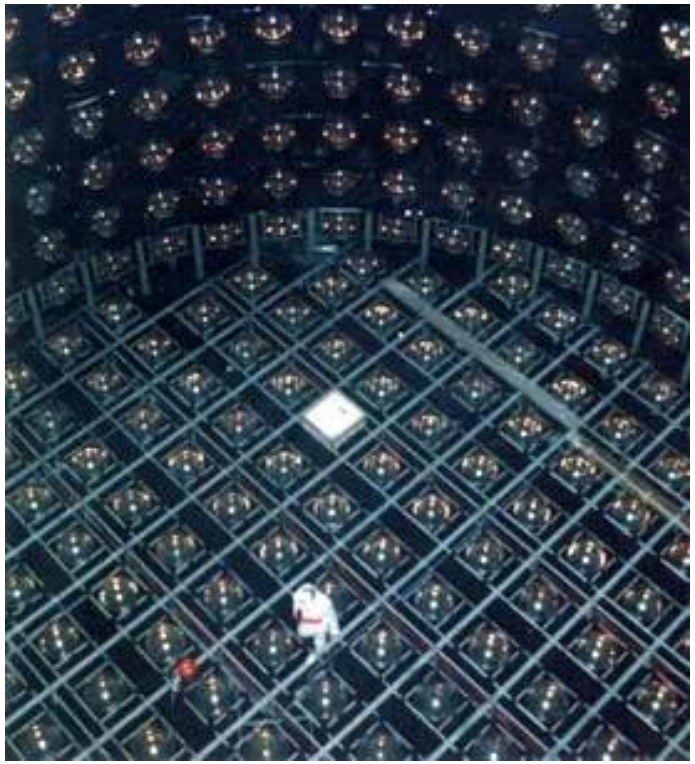


- ✓ Aim 1.3 MW by upgrading the main ring accelerator and neutrino beamline.
- ✓ Further ~7% increase by horn current 250 kA → 320 kA

- ➢ Upgrade of MR main power supply, RF and collimators
- ➢ Upgrade of neutrino beamline
- ➢ New beam monitors
- ➢ Reinforcing cooling capability (target, horn, ….)

By 2022 from 550kW to >750kW with double repetition rate → before 2027: 3σ CPV sensitivity expected (>10x10^{21} POT) in case of maximal CPV

3rd generation underground water Cherenkov detector in Kamioka

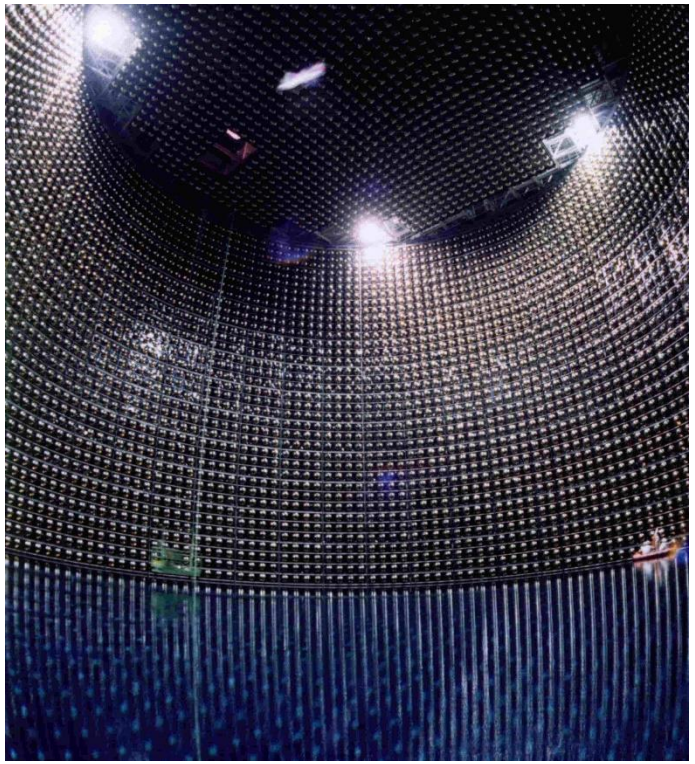


Kamiokande

(1983-1996)

- Atmospheric and solar neutrino "anomaly"
- Supernova 1987A

Birth of neutrino astrophysics

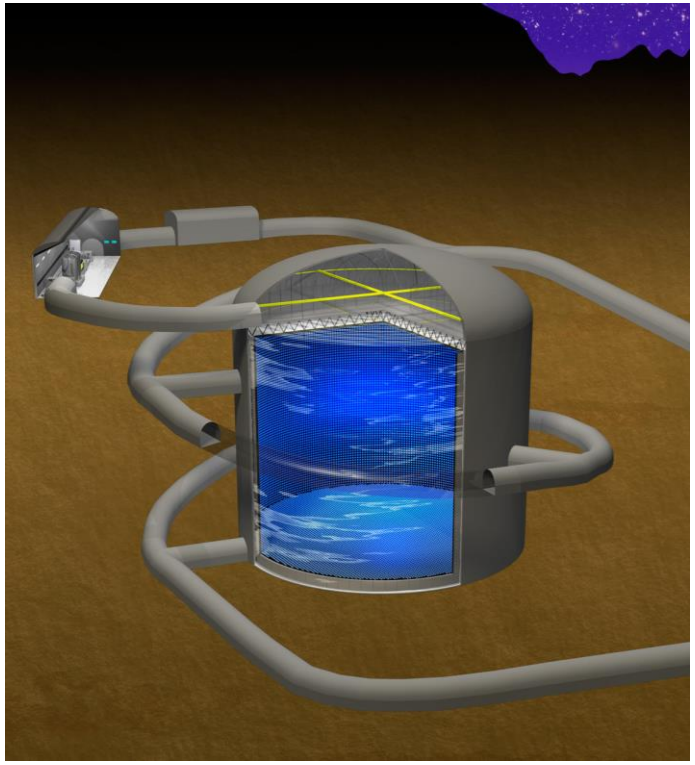


Super-Kamiokande

(1996 - ongoing)

- Proton decay: world best-limit
- Neutrino oscillation (atm/solar/LBL)
  - All mixing angles and $\Delta m^2 s$

Discovery of neutrino oscillations



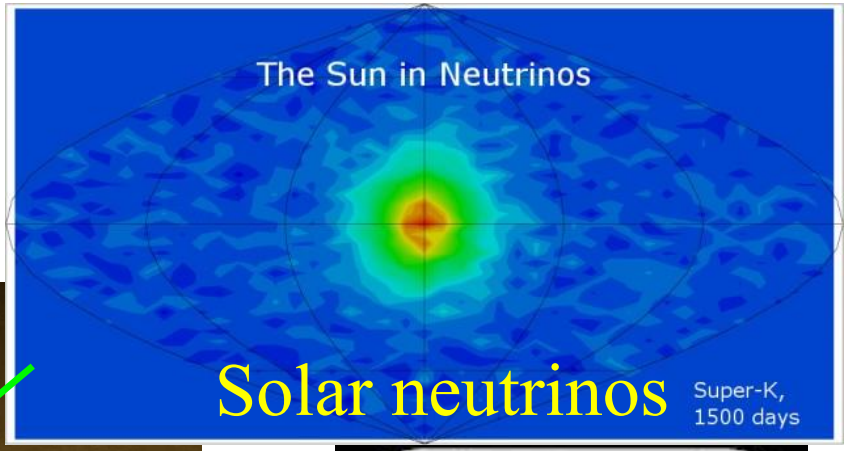
Hyper-Kamiokande

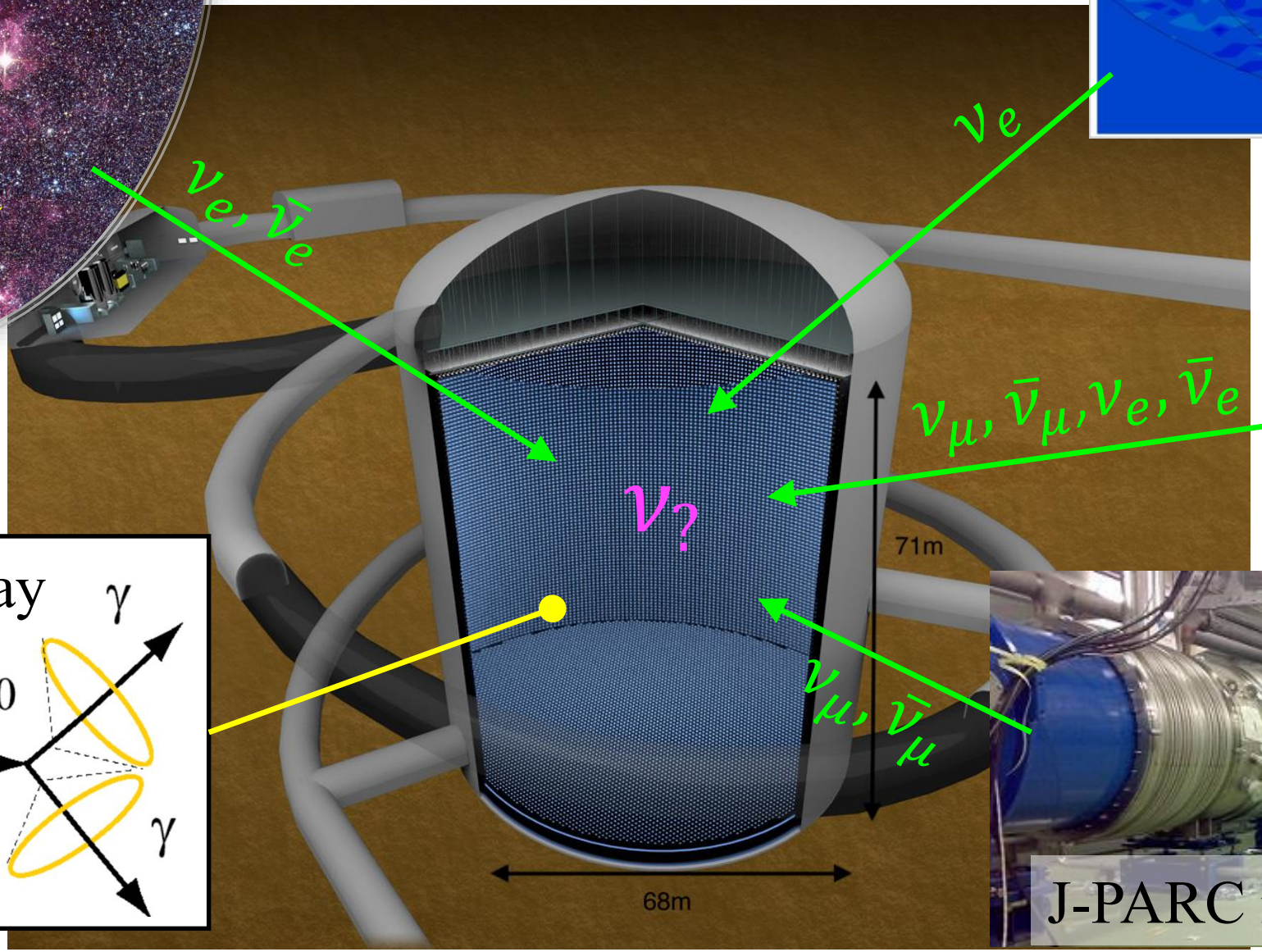
(start operation in 2027)

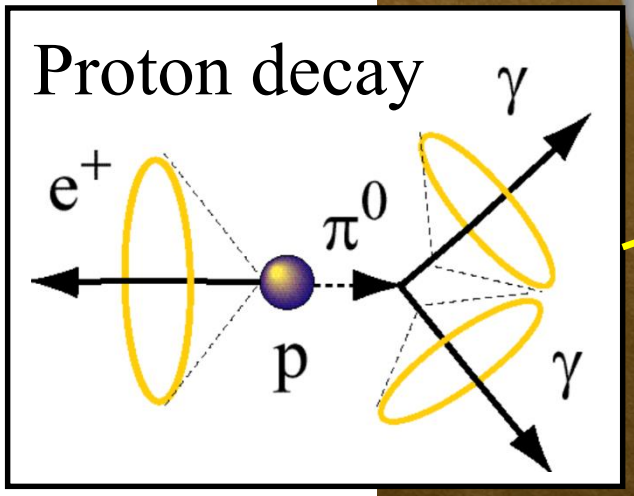
- Extended search for proton decay
- Precision measurement of neutrino oscillation including CPV and MO
- Neutrino astrophysics

Explore new physics

Physics in Hyper-Kamiokande







The Hyper-Kamiokande project is officially approved

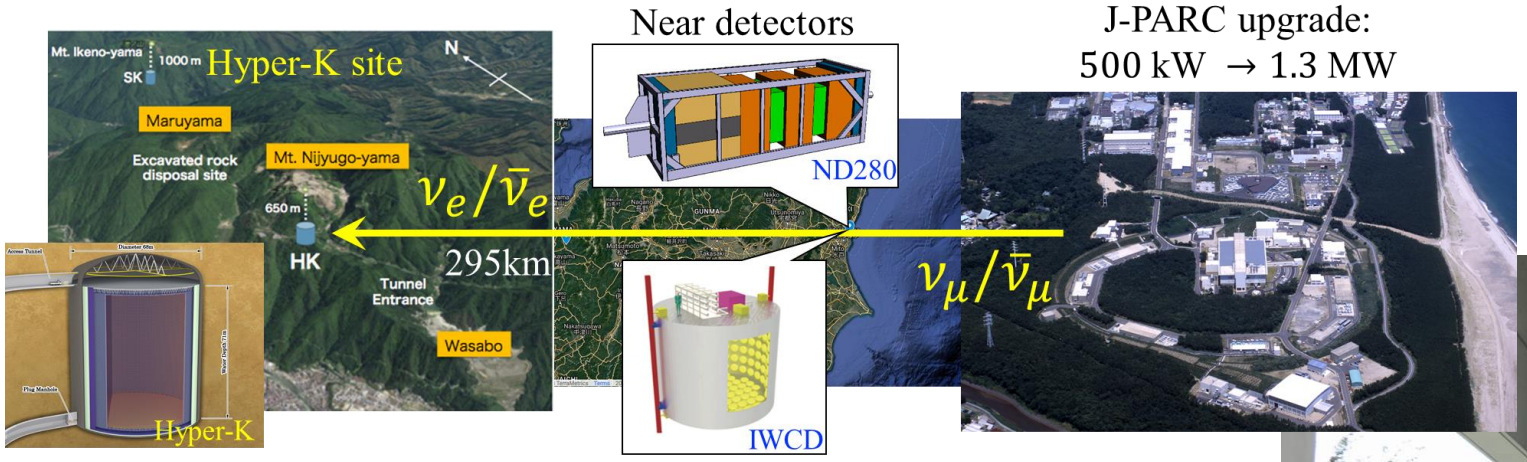
2020 February : First year construction budget approved by Japanese Diet
2020 May: Univ. of Tokyo President and KEK Director General signed MOU

KEK will upgrade and operate the J-PARC accelerator to produce a high-intensity neutrino beam

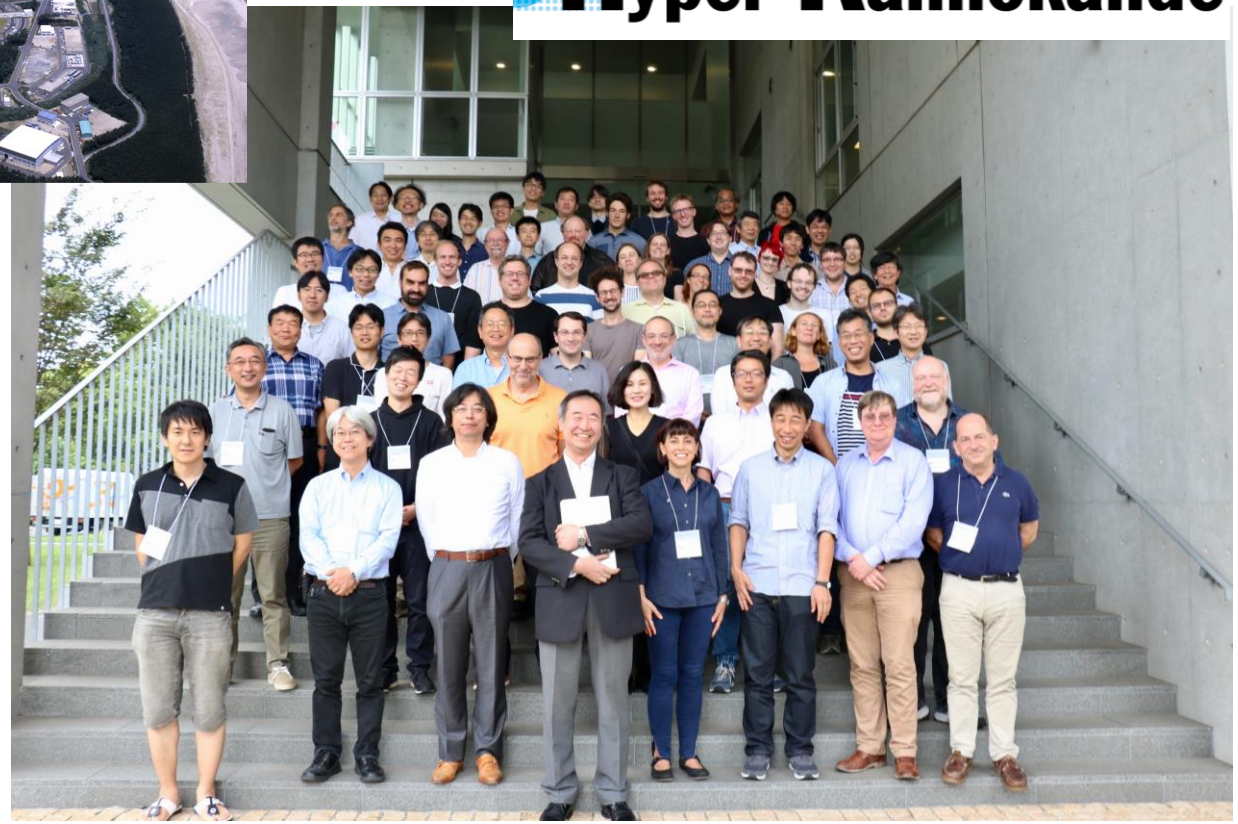
The University of Tokyo will construct and operate the Hyper-Kamiokande detector

Hyper-K is under construction
Operation will begin in 2027

Hyper-Kamiokande



Hyper-Kamiokande



- Hyper-K detector will be built with 8.4 times larger fiducial mass (190 kiloton) than Super-K and will be instrumented with double-sensitivity PMTs.
- J-PARC neutrino beam will be upgraded from 0.5 to 1.3 MW
  - x8 Natural Neutrino Rate and x20 Accelerator Neutrino Rate
  - New and upgraded near detectors to control systematic errors

19 countries, 90 institutes, ~420 people

Photodetectors for Hyper-K

Requirements

Wide dynamic range

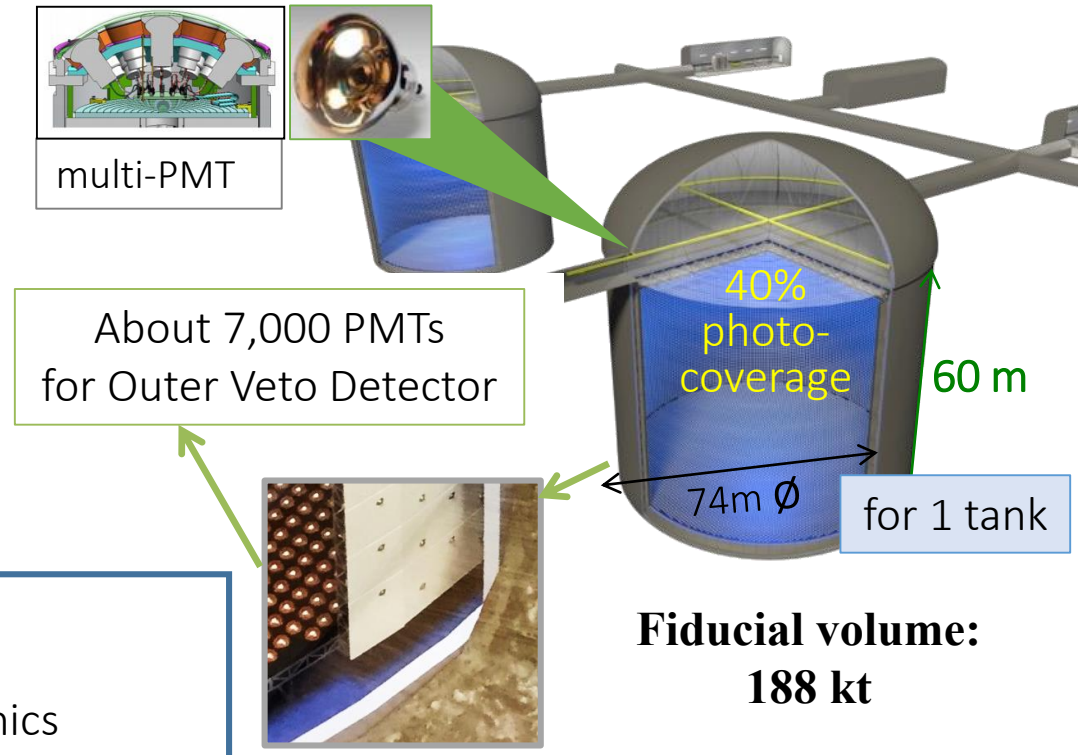
High time&charge resolutions, high detection efficiency, ..

~nsec time resolution

low background

Clear photon counting,

High rate tolerance



Fiducial volume: 188 kt

New high-QE 20'' Box&Line PMT

×2 high pressure bearing for 60 m depth

×2 high detection efficiency and half time&charge resolutions compared to Super-K PMT (up to ~40m depth)

Multi-PMT

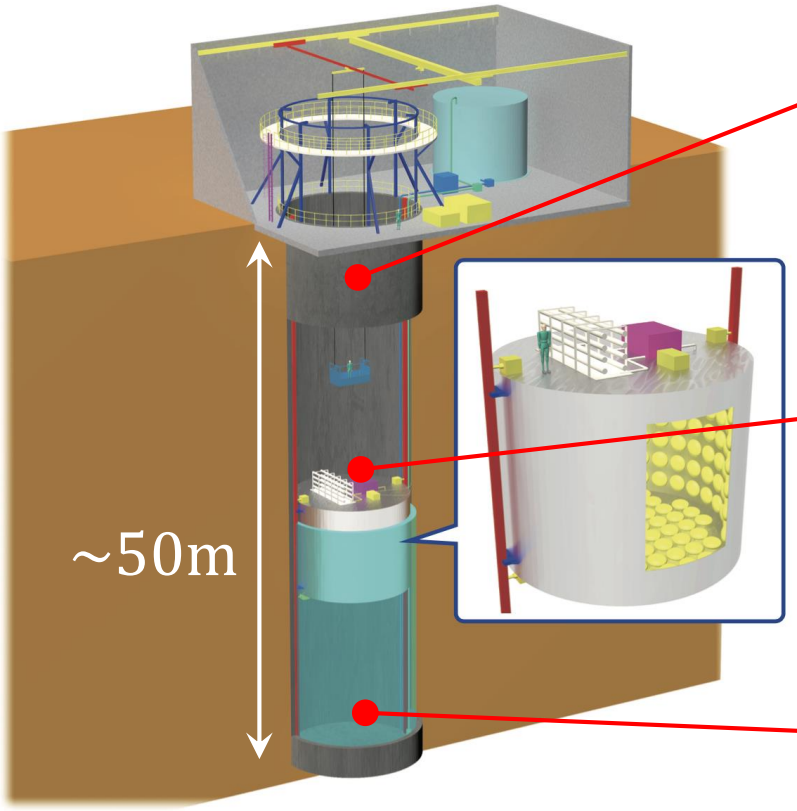
Photodetectors and electronics arranged inside a pressure resistent vessel

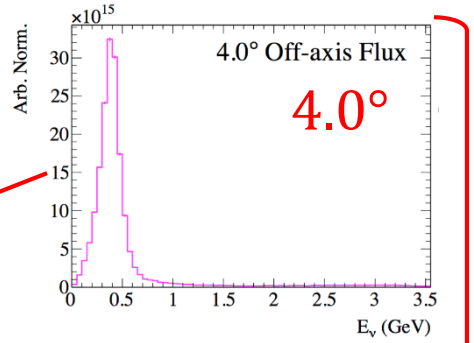
Increased granularity
enhanced event reconstruction, in particular for multi-ring events

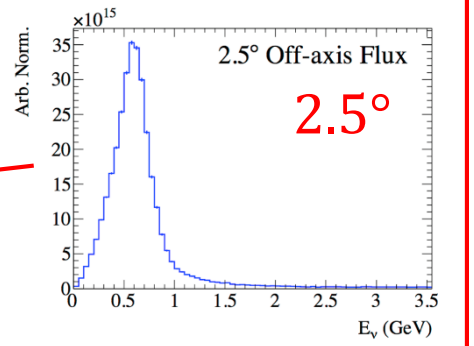
Baseline option
40,000 20'' PMTs
Alternative option:
50% 20'' PMTs and mPMTs

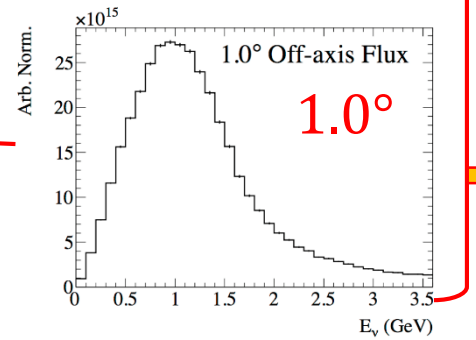
Intermediate water Cherenkov detector (IWCD)

- 1kton scale water Cherenkov detector at ~1km baseline
- Detector can vertically move ⇒ measurement at different off-axis angles





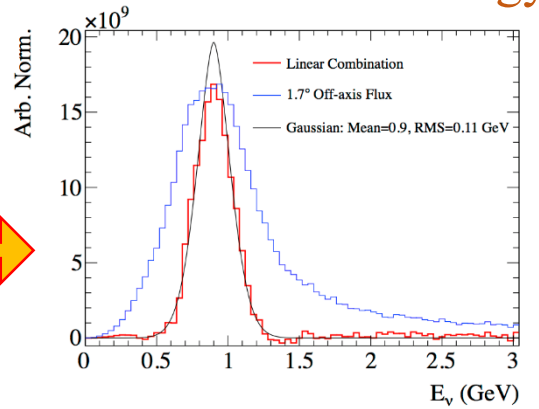




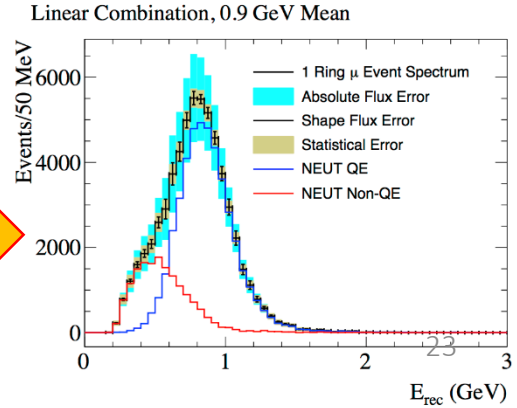
Physics target

- ν-int. measurement by off-axis scanning
- ν_e cross section (3-5% for $\sigma(\nu_e)/\sigma(\nu_\mu)$, $\sigma(\nu_e)/\sigma(\nu_\mu)$)
- NC and intrinsic ν_e BG measurement (3-4%)
- Neutron multiplicity with Gd loading

Linear sum to make monochromatic energy

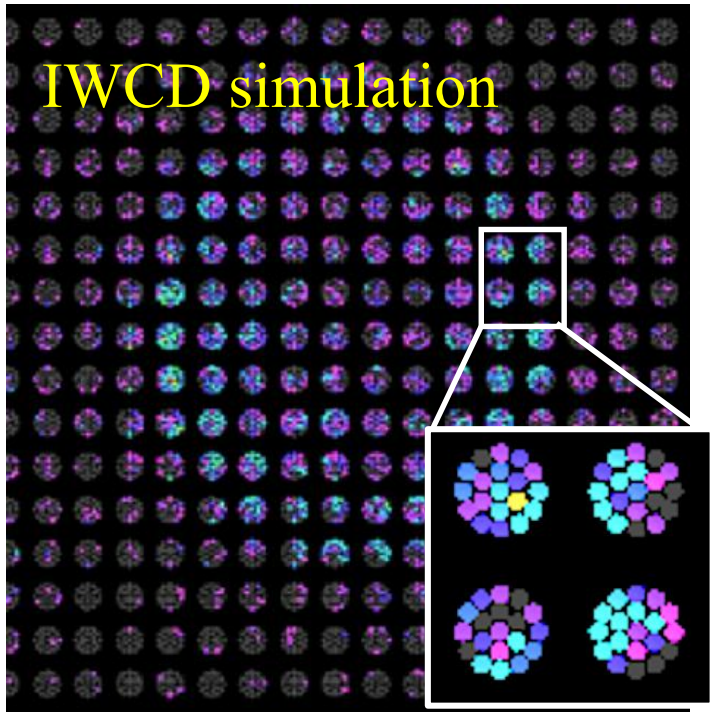


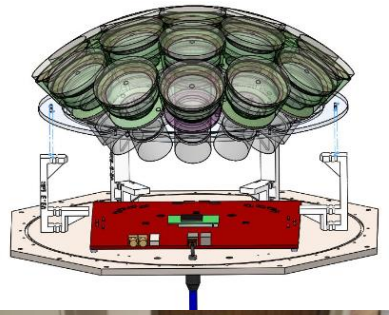
Reconstruction



Detector R&D for Hyper-Kamiokande

Multi-PMT module:
(ref. KM3NeT)
High resolution Cherenkov ring imaging essential for IWCD
Consider to use for part of HK

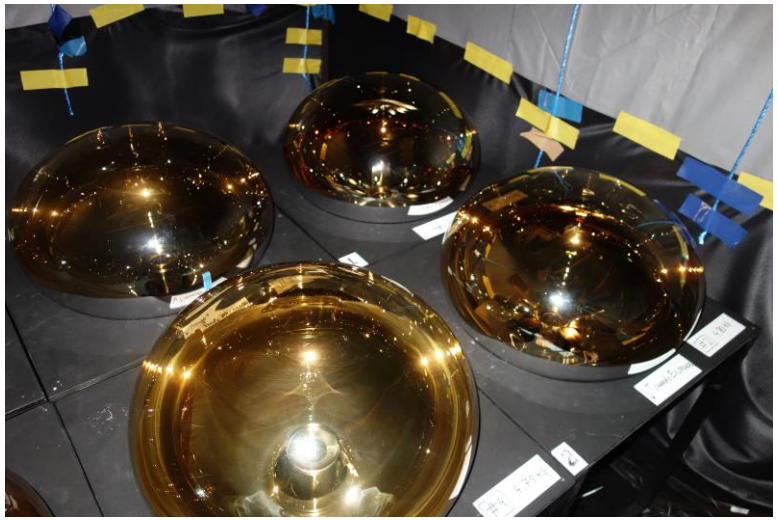




Prototype at TRIUMF

Electronics at INFN

20-inch MCP PMT:
Test in dark room



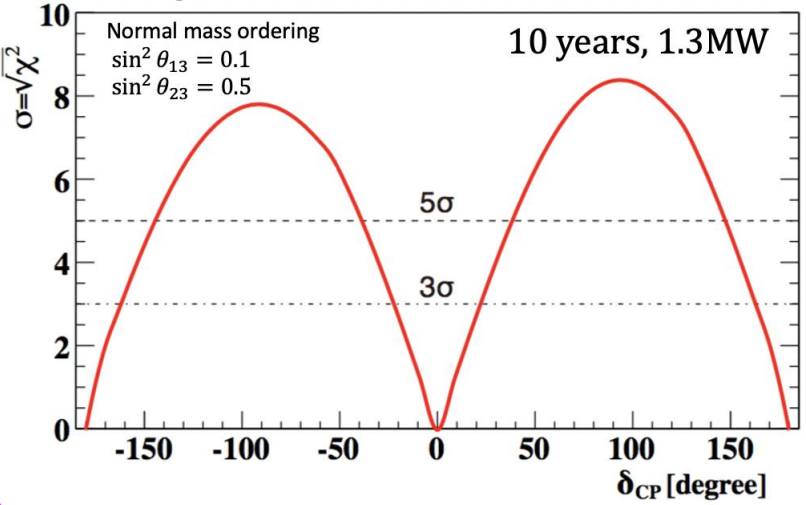
mPMT in Memphyno water tank in France

Box&Line PMT in Super-K

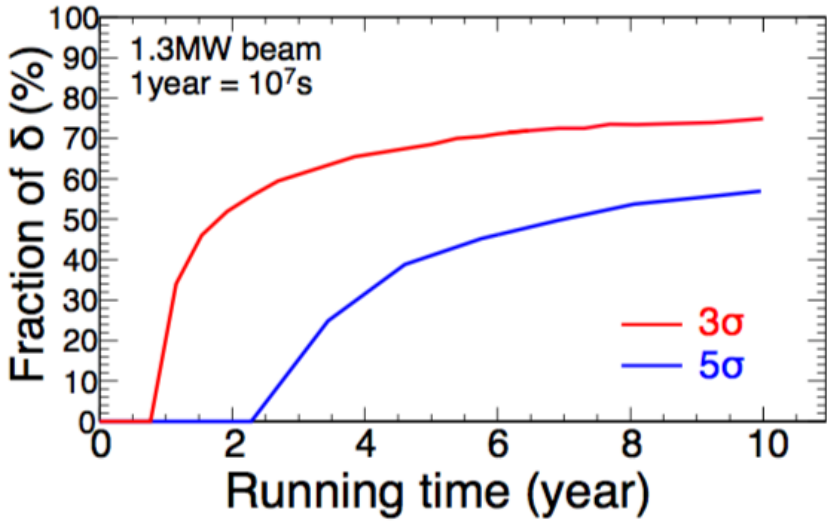
Precision measurement of neutrino oscillations

Syst. errors (T2K 2016 + improvements for Hyper-K) δ_{CP}

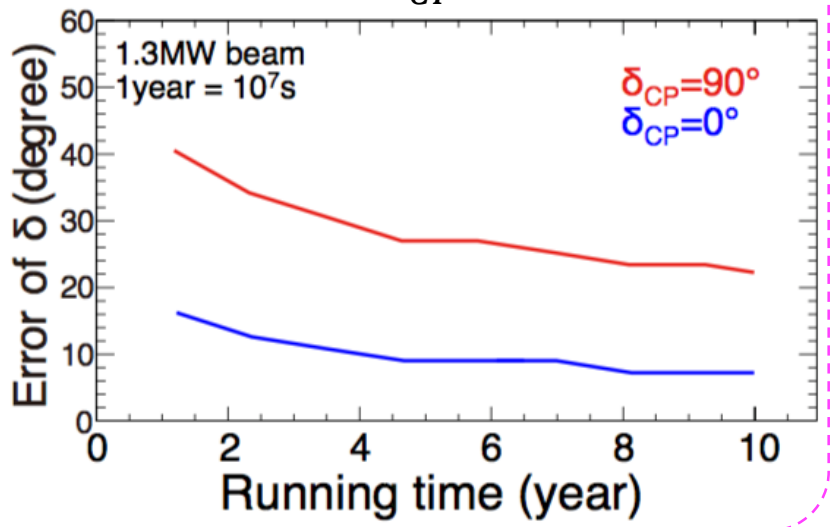
Significance to CP violation



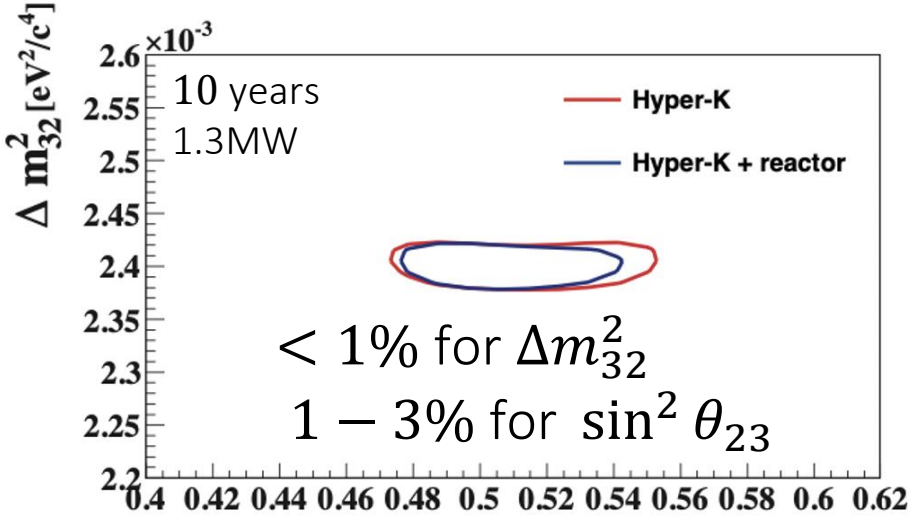
Fraction of δ_{CP} to exclude $\sin\delta_{CP} = 0$



Precision of δ_{CP} measurement



- Exclusion of $\sin\delta_{CP} = 0$
  - $\sim 8\,\sigma$ for $\delta_{CP} = -90°$ (favored by T2K)
  - Good opportunity to make discovery of CP violation in neutrino sector at $> 5\,\sigma$



θ_{23} vs. Δm^2_{32}

Summary

Neutrino oscillations are a powerful laboratory to look for the New Physics hidden behind the neutrino masses
→ What is the New Symmetry hidden behind the mass and flavour mixing?
→ Search of CP violation in the leptonic sector: related with matter/antimatter asymmetry in the Universe

T2K: First 3σ limits on 46% (65%) of the δ_{CP} values in Normal (Inverted) Ordering

- Atmospheric angle close to maximal.
- Rejected $\delta_{CP} > 0$ with 99.7% C.L.
- Mild preference for normal hierarchy

Exciting future plans

- **ND280 Upgrade**
- **SK-Gd**
- **Hyper-Kamiokande**
  - officially approved in Japan
  - under construction; operation in 2027
  - International R&D is actively ongoing to improve the physics potential
  - **New collaborators are welcome to contribute to the detectors and the pioneering physics!**

Thank you!