Participation of JINR in the T2K-II experiment: status report

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57th meeting of the PAC for Particle Physics

Dubna 23 January 2023

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Introduction

Form No. 24

Project

T2K-II / Hyper-Kamiokande

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The T2K is a world leading long baseline experiment in neutrino oscillation study

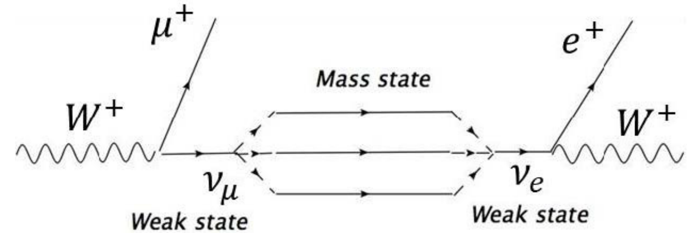
The participation of the JINR group in the T2K-II experiment was approved at the 55th session of the PAC in June 2021 for 2022-2024.

The PAC recommended that a status report be submitted after the first year of participation of the JINR group in the T2K experiment

Seminars at DLNP: 17.03.2021, 30.03.2021, 15.12.2021, 29.06.2022, 22.11.2022

Neutrino oscillations

Mixing between flavor eigenstates (interacting states) and mass eigenstates (propagating states) described by Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix



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

atmospheric — atmospheric and solar — solar

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

$\theta_{23} \sim 45^o$ — $\theta_{13} \approx 8.5^o$ — $\theta_{12} \approx 34^o$

$|\Delta m^2_{32}| \cong |\Delta m^2_{31}| = |\Delta m^2_{atm}| \approx 2.4\times10^{-3}\ eV^2$

$\Delta m^2_{21} = \Delta m^2_{sol} \approx 7.5\times10^{-5}\ eV^2$

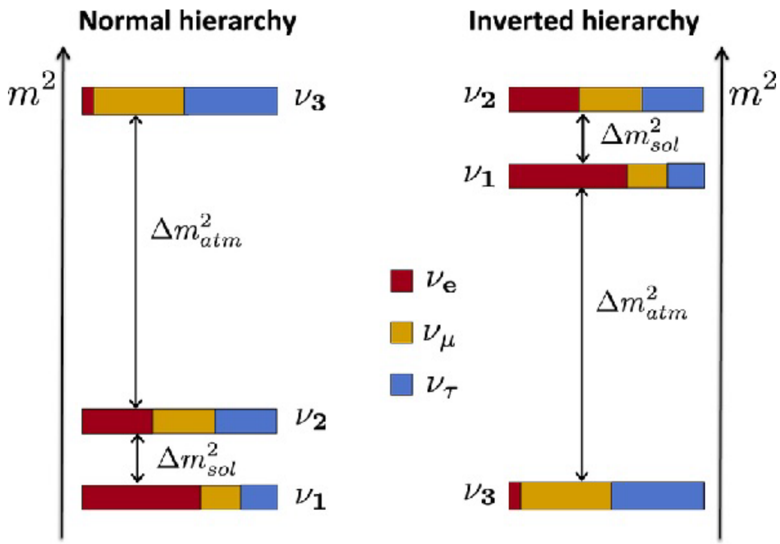
$\Delta m^2_{ij} = m^2_i - m^2_j \qquad \Delta m^2_{12} + \Delta m^2_{23} + \Delta m^2_{31} = 0$

Three mixing angles θ_{12} θ_{13} θ_{23} — Two independent mass square differences $\Delta m^2_{21}, \Delta m^2_{32}$ — CP violating phase δ_{CP}

From reactor experiments (e.g. DayaBay) and from measuring $P(\nu_\mu \rightarrow \nu_e)$

Measuring $P(\nu_\mu \rightarrow \nu_\mu)$

Neutrino oscillations



Oscillation probability depends on:

- The difference in masses of ν_1, ν_2, ν_3
- The PMNS mixing parameters
- The neutrino energy
- The travelled distance (baseline)

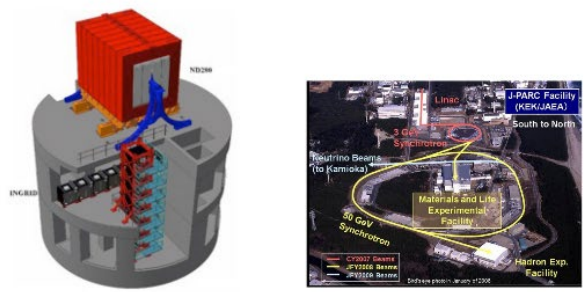
Open questions that T2K can answer :

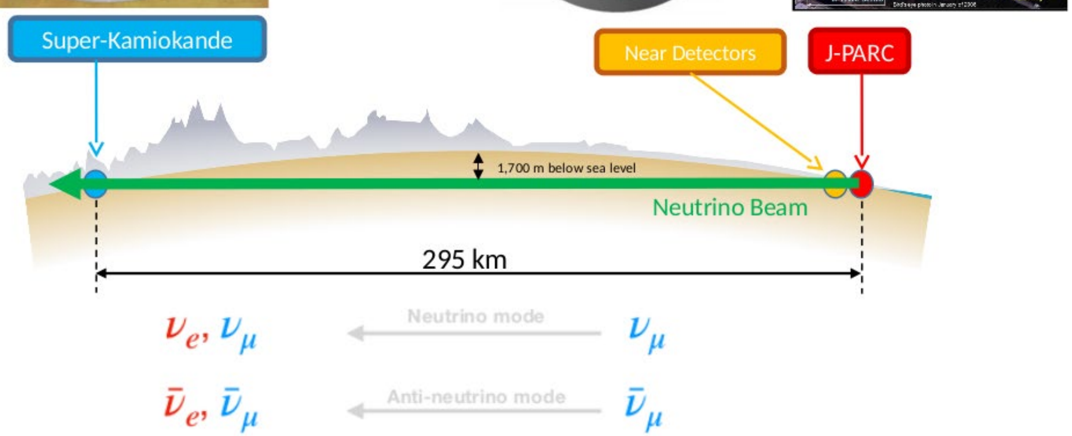
- Neutrino mass ordering – from ν_μ and $\bar{\nu}_\mu$ disappearence
  - Normal ($\Delta m^2_{32} > 0$) or inverted ($\Delta m^2_{32} < 0$)
- Θ_{23} octant – from ν_μ and $\bar{\nu}_\mu$ disappearence
  - Upper ($sin^2\theta_{23} > 0.5$) of lower ($sin^2\theta_{23} < 0.5$) or $\theta_{23} = 45°$
- CP violation in neutrino sector – from ν_e and $\bar{\nu}_e$ appearence
  - $\delta_{CP} \neq 0, \pi$ indicates $P(\nu_\alpha \to \upsilon_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$ in vacuum

T2K experiment

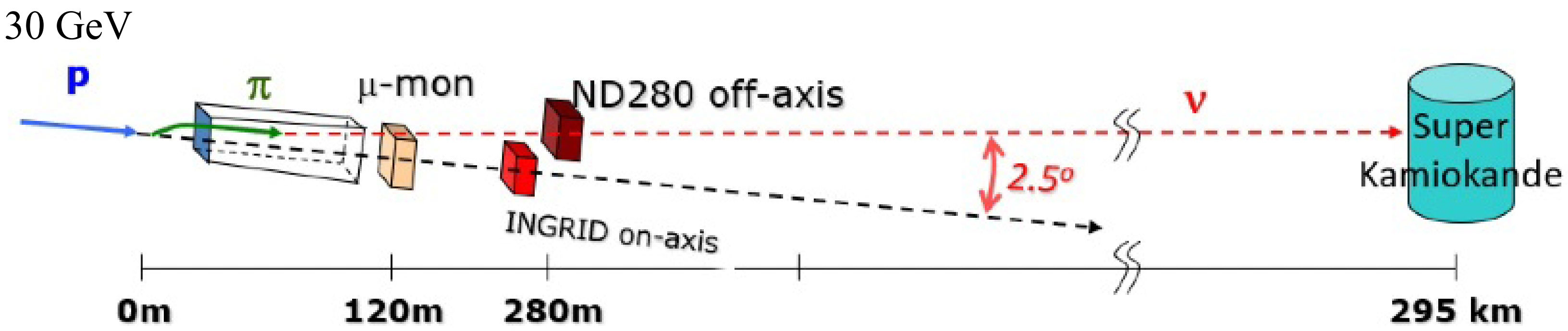
- The T2K (Tokai-to-Kamioka) is a world leading experiment in neutrino oscillation study
- The collaboration consists of about 500 people from ~70 institutions
- The T2K studies the oscillation of the neutrino beam produced at the J-PARC complex and measured by the near detector ND280 and the far detector Super-Kamiokande

T2K is a long baseline experiment studying neutrino oscillations, aiming for precise measurements of θ_{23} and Δm^2_{32} with an accuracy of 1.7° and 1%, respectively, and looking for the neutrino mass ordering and possible CP violation in oscillations





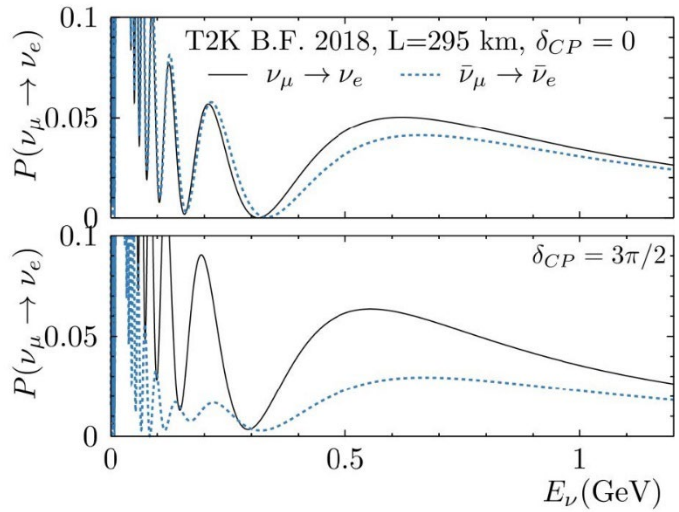
T2K: beam



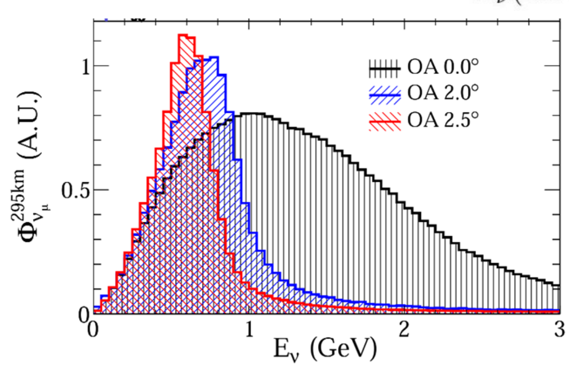
T2K operates in neutrino and antineutrino modes:

$\pi^+ \rightarrow \mu^+ + \nu_\mu$ $\qquad$ $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

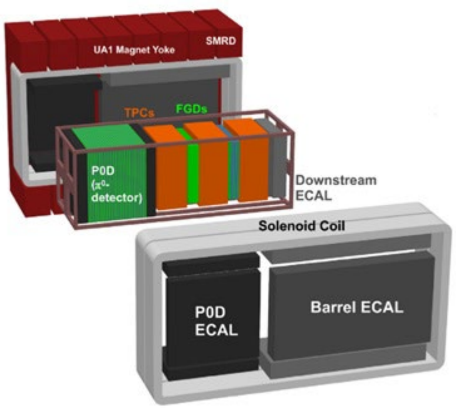
$K^+ \rightarrow \mu^+ + \nu_\mu\ (+\ \pi^0)$ $\qquad$ $K^- \rightarrow \mu^- + \bar{\nu}_\mu\ (+\ \pi^0)$

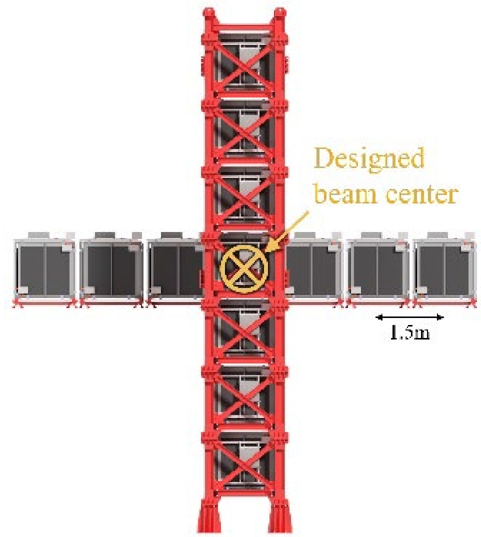


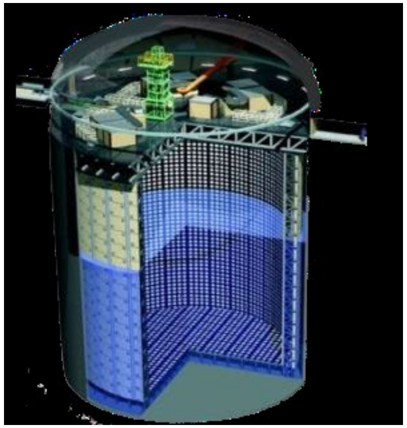
- L=295 km, $\Delta m^2_{23} \approx 2.4\times10^{-3}$ eV^2
  - → Oscillation maximum at $E_\nu \sim 0.6\ GeV$
- Off-axis angle = 2.5º
  - Increase flux at the oscillation maximum
  - Reduce high energy ν backgrounds



T2K: detectors







<u>Near detector ND280 (2.5^o off-axis)</u>

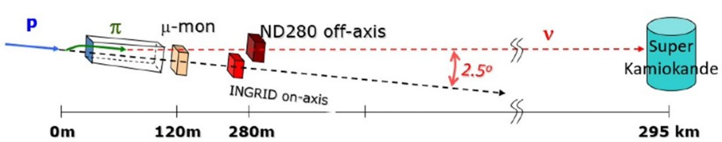
- Error constraints on beam flux and neutrino interactions
- ν cross section measurements
- Magnetized (0.2 T) for charge and momentum measurement with TPCs
- FGDs: Active scintillator + passive water targets

<u>Near detector INGRID (on-axis)</u>

- Beam monitor (direction and intensity)

<u>Super-Kamiokande - the far detector</u>

- 50 kton water Cherenkov detector
- 11000 20-inch PMTs
- Reconstruct neutrino energy from e/μ momentum and angle w.r.t beam
- Good μ/e PID from ring shape

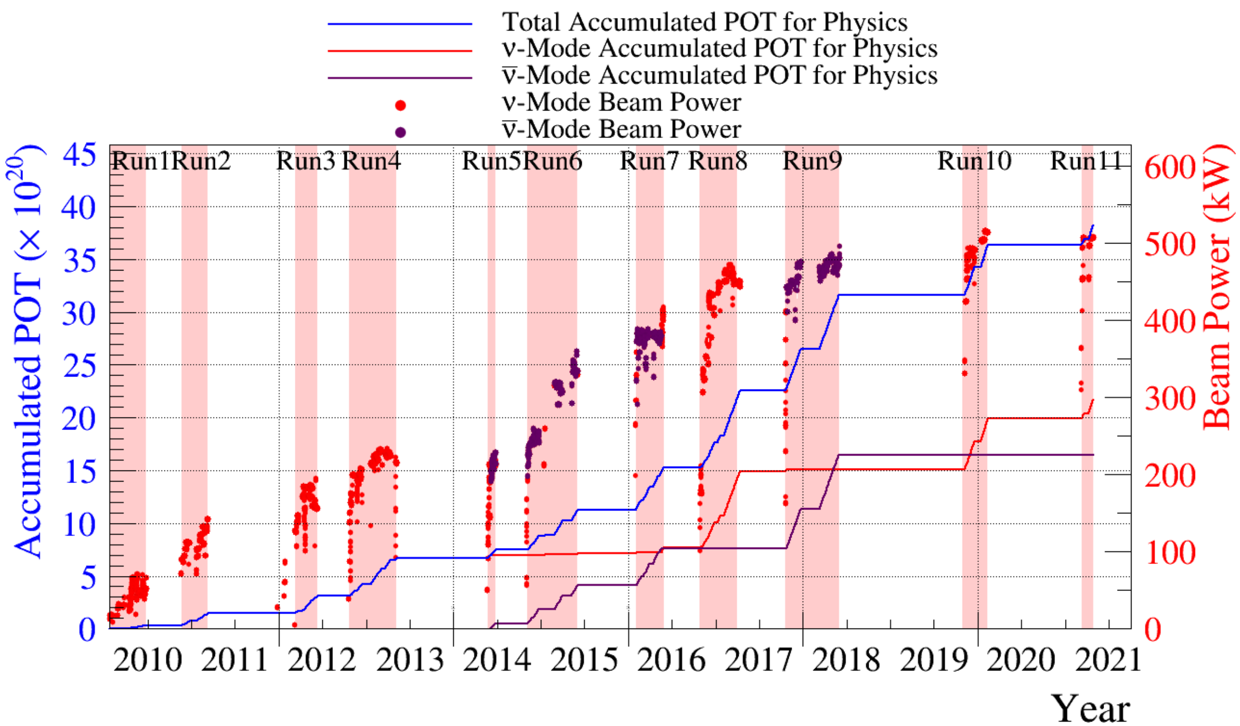


T2K: Dataset

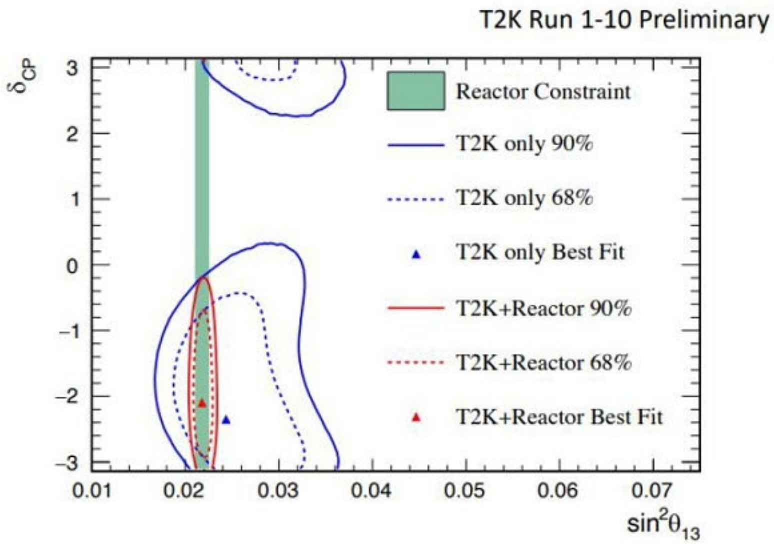
T2K started taking data in 2010
3.6×10^{21} protons on target (POT)

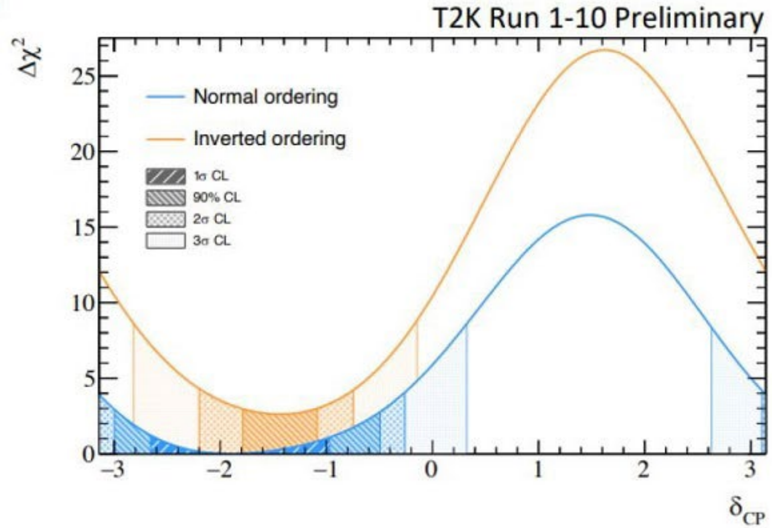
ND280
ν-mode: 1.39×10^{21} POT
$\bar{\nu}$-mode: 0.63×10^{21} POT

Far detector
ν-mode: 1.97×10^{21} POT
$\bar{\nu}$-mode: 1.63×10^{21} POT



T2K: search for CP violation





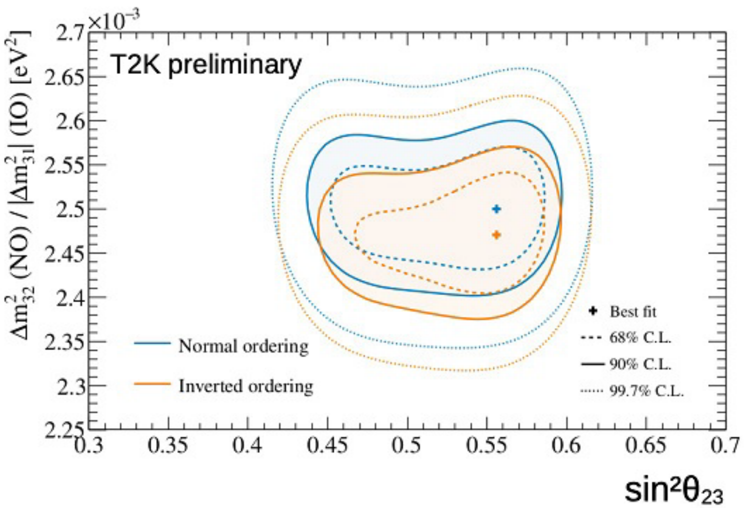
35% of δ_{CP} values excluded at 3σ marginalized over hierarchies
CP conservation ($\delta_{CP} = 0, \pi$) is excluded at 90% CL

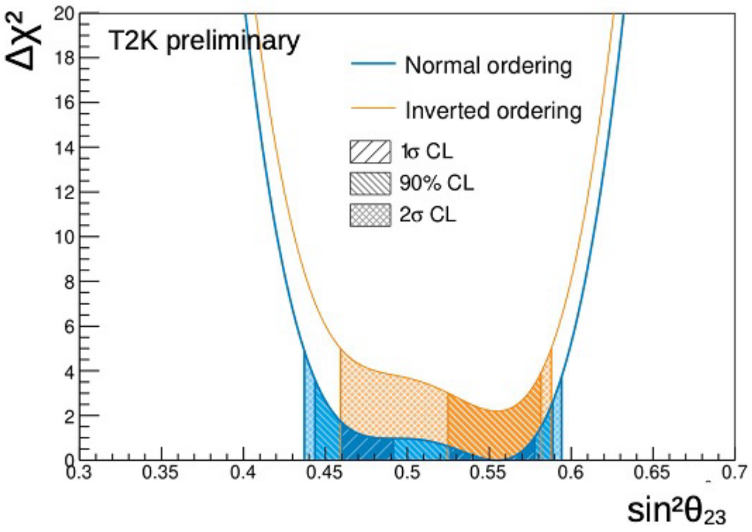
$\boxed{\delta_{CP} \sim -\pi/2}$

Normal hierarchy is preferred at 80% CL

T2K: oscillation analysis

Using θ_{13} constraint from reactor experiments: $sin^2 2\theta_{13} = 0.0861 \pm 0.0027$





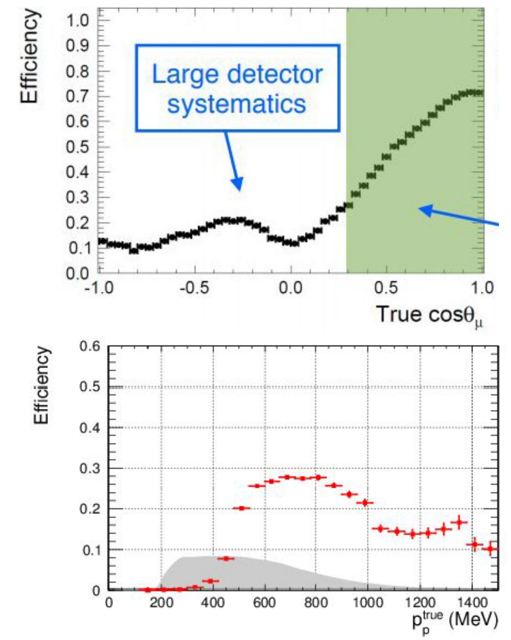
- Weak preference of upper octant θ_{23} and normal mass ordering
- Lower octant still allowed at the 68% CL level

Upgrade of T2K → T2K-II

Systematics at the level of 6-7% limits further improvement in results

Motivation for ND280 upgrade:

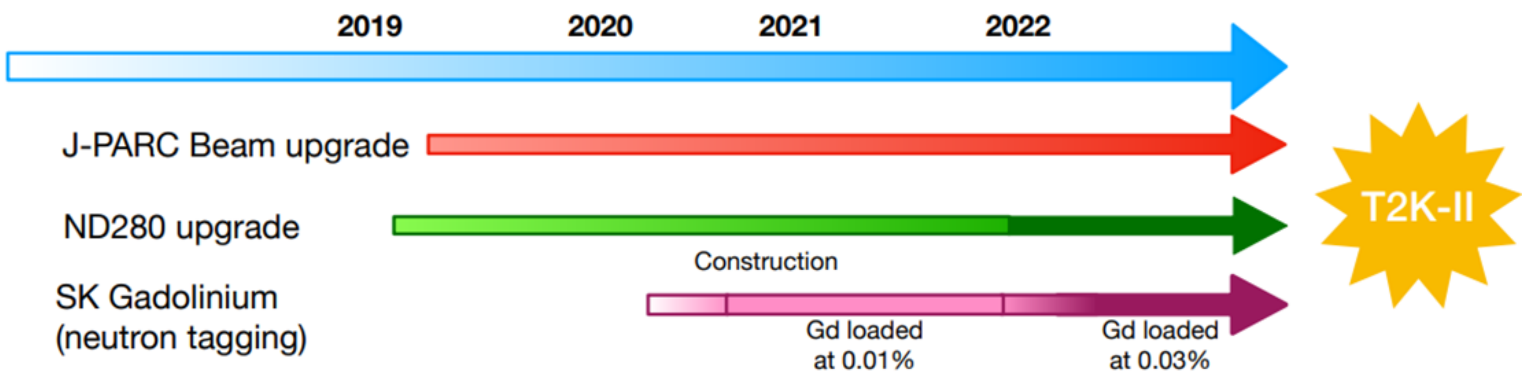
- Important to measure neutrino interactions in all phase space
- Precisely detect particles produced at any angle
- Non-isotropic efficiency (unlike Super-Kamiokande)
- Reduce proton detection threshold (from ~450 MeV/c to ~300 MeV/c)
- Measure neutrons in $\bar{\nu}_{\mu}$ interactions
- Reduce background, obtain better track identification using TOF
- Provide e/γ separation



Low muon (top) and proton (bottom) registration efficiencies

In 2027 50 kt Super-Kamiokande will be replaced by the 260 kt Hyper-Kamiokande, and modernized T2K-II will become part of a single Hyper-Kamiokande project

Upgrade of T2K → T2K-II (2)

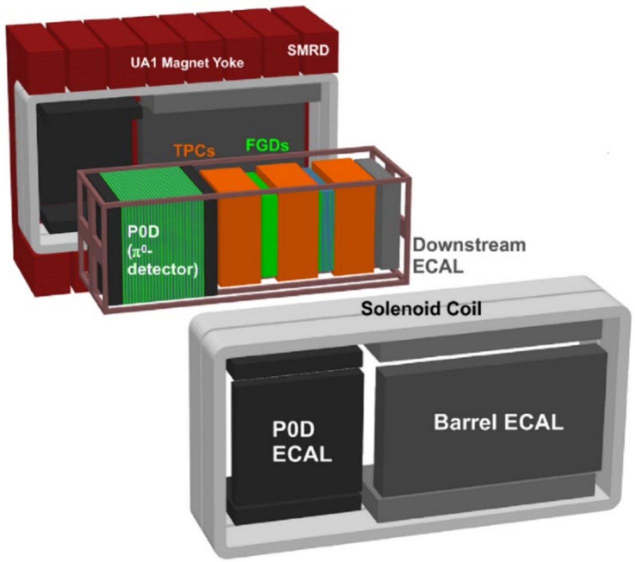


The upgrade includes:

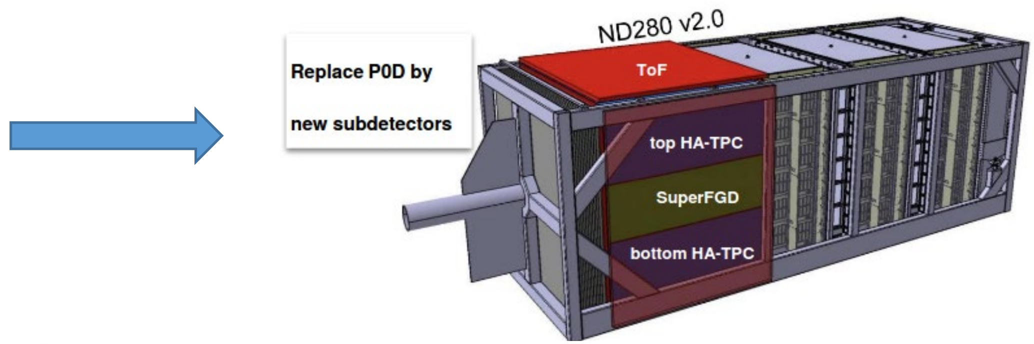
- Beam upgrade: 500 kW → 900 kW (2024) → 1.3 MW (2028)
- SK: dissolution of Gd sulfate in water (up to 0.03%) for neutron detection (eff. up to 90%)
- ND280 upgrade

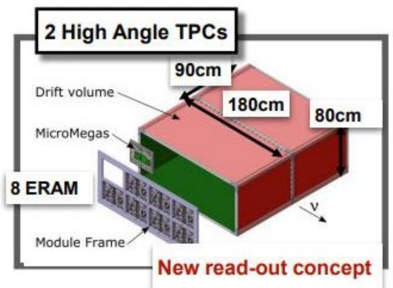
ND280 upgrade

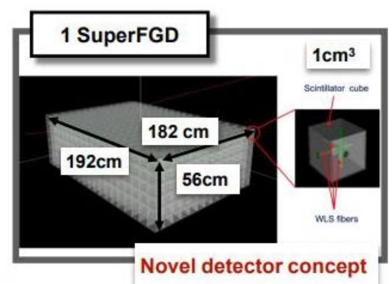
Old ND280

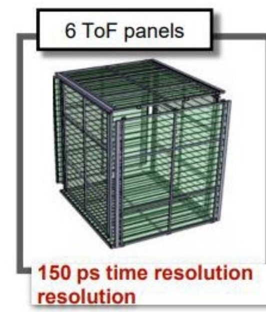


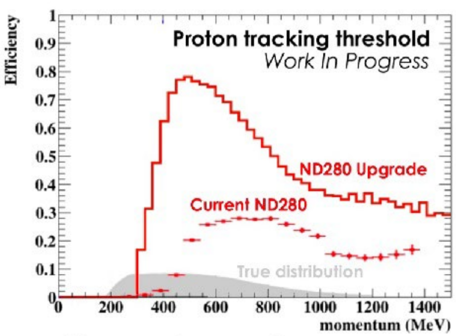
New ND280

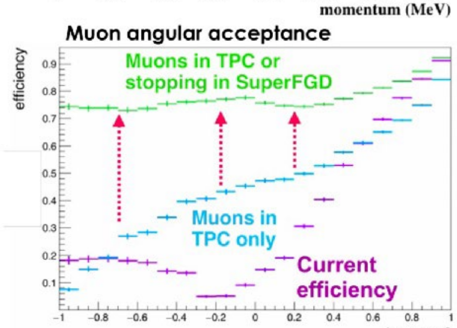












Goal:

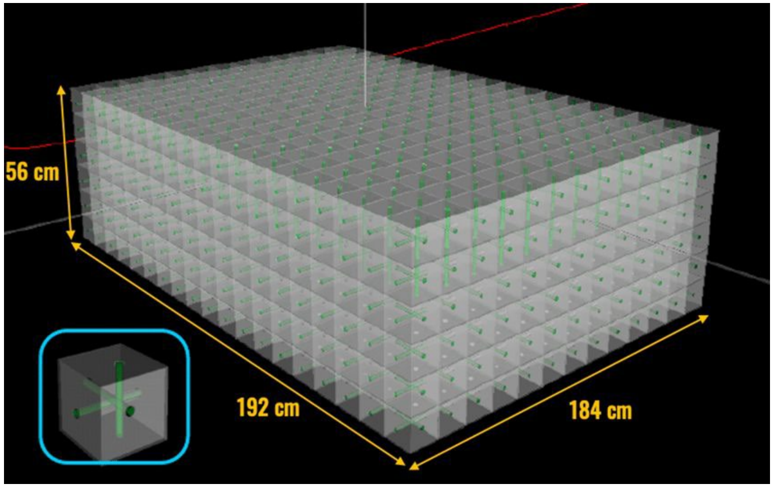
- reduce systematics down to 3-4%;
- 4π-acceptance for leptons from ν-interactions;
- reduce proton detection threshold (to ~300 MeV/c);
- neutron detection (for $\bar{\nu}$ detection).

New sub-systems:

- HA-TPC with new resistive MicroMegas Modules
- Six planes of time-of-flight scintillating detectors
- Active 3D target SuperFGD

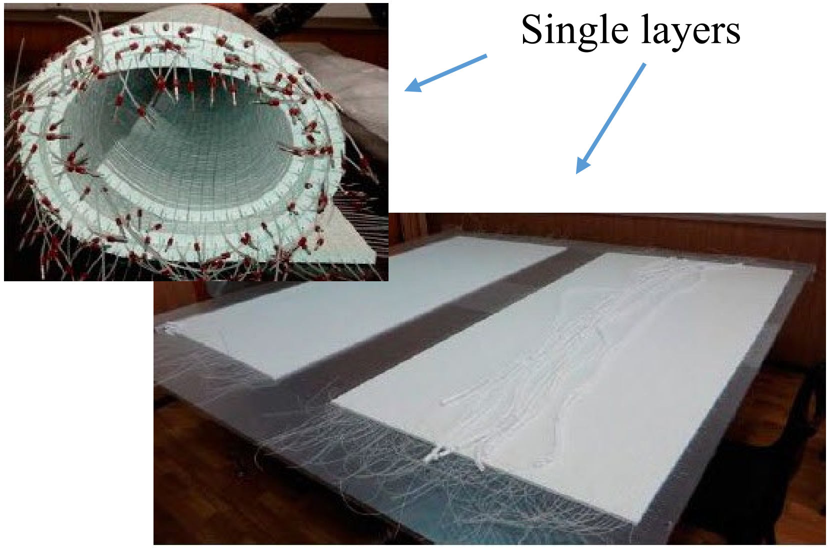
ND280 upgrade: Super Fine Grained Detector

General view of the array



- **Active element**: scintillator **cube** 1 cm3 with 3 orthogonal holes for WLS fibers
- **Full detector**:
  184 (Z) x 192 (X) x 56 (Y) = **1,978,368** cubes
- **Weight** (cubes): **~2,000 kg**
- **WLS Fibers** (3 diff. lengths): **56,384** pcs
- **Light Readout**: **56,384** MPPCs
- **Electronics**: MPPC-PCBs and FEBs based on CITIROC
- **Calibration**: Light-Guide Plate (LGP) + LED
- **Mechanical box**: sandwich of carbon fiber and other materials

Single layers

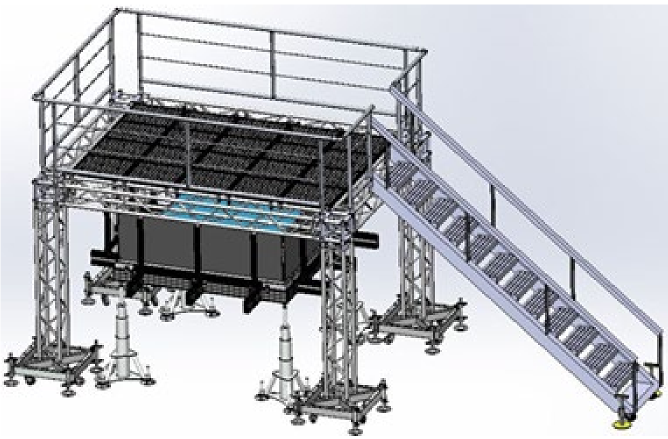


SFGD layers assembled at INR RAS

Contribution of the JINR group in the T2K

- Design and creation of tooling for assembling an SFGD active target, including an assembly platform, an access system from above for mounting a detector; SFGD assembly at J-PARC
- Investigation of the optical properties of the elements of the SFGD active target
- Development and production of the SFGD calibration system
- Participation in the study of yields of secondary particles from a graphite target (T2K replica target at CERN) in the NA 61/SHINE experiment at CERN
- Analysis of data on the search for light dark matter
- Performing studies to assess systematic errors in various kinds of analyzes on ND280 data

Development of tooling for the SFGD target assembly



- Design documentation developed
- Calculations for seismic stability of the system and for static loads were carried out
- Platform assembly and SFGD assembly procedure were developed
- All tooling elements were made and test assembly was carried out in Dubna
- In July 2022 the equipment was delivered to J-PARC (Japan)

Tooling
← in Dubna and at J-PARC →

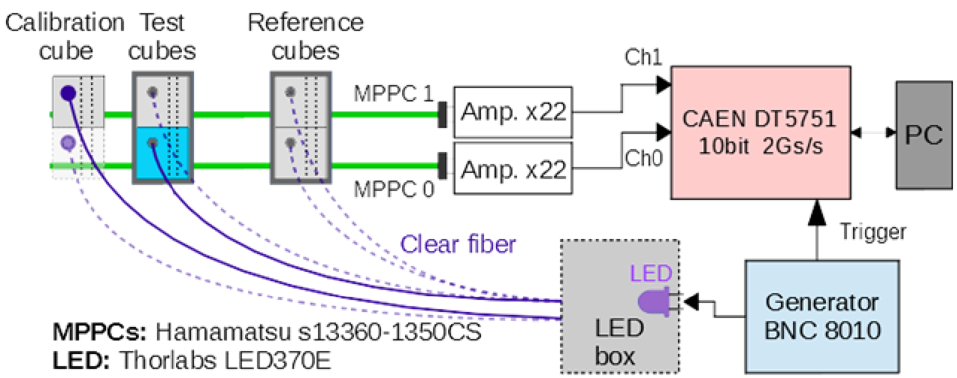
SFGD assembly at J-PARC

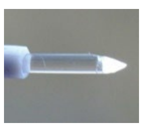

October 18, 2022

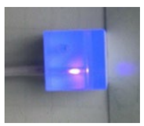
- The assembly of SuperFGD in a box with fishing lines started in mid-October 2022 with the participation of colleagues from JINR, INR RAS, Japan, the USA, Great Britain
- By mid-December, all layers were installed in the box
- All side walls have been installed and on 27 December 2022 box was closed
- Ready for replacement of fishing lines with WLS fibers!

December 27, 2022

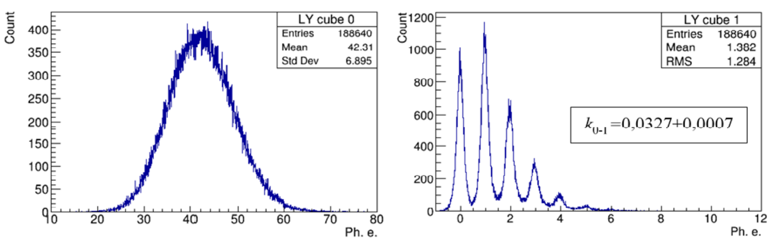
Study of the optical properties of SFGD elements

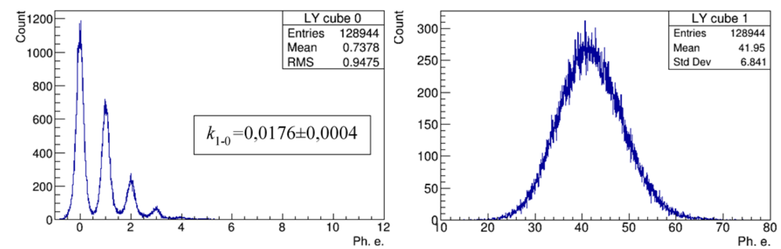


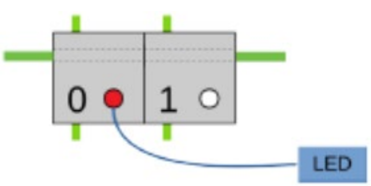


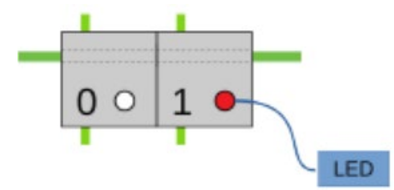


- The study of optical parameters was carried out using an LED
- The amount of light leakage through one face found to be at the level of 2.6%
- The effect of positional sensitivity of light leaks from a distance to the side face is found.



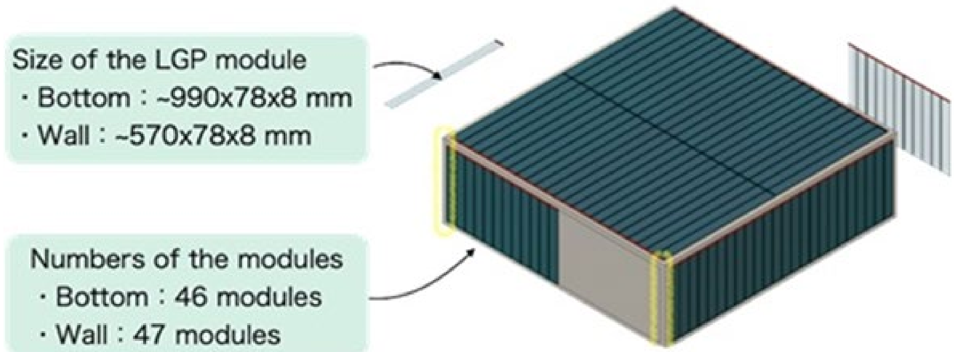




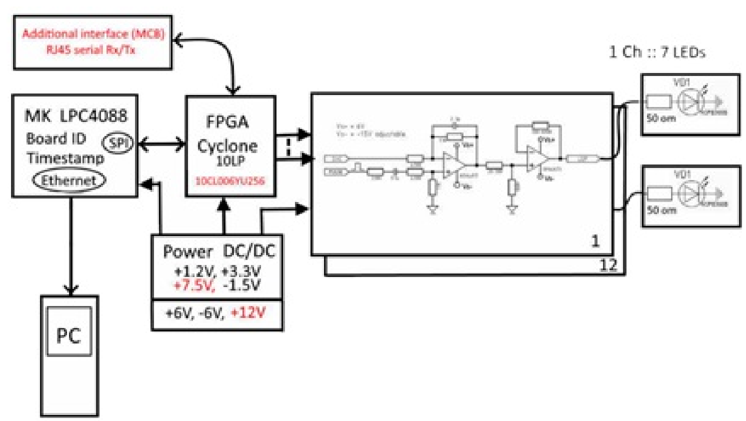


Artikov, A., Baranov, V., Boikov, A. et al. ***Investigation of Light Collection in Scintillation Cubes of the SFGD Detector***. Phys. Part. Nuclei Lett. 19, 784–791 (2022)

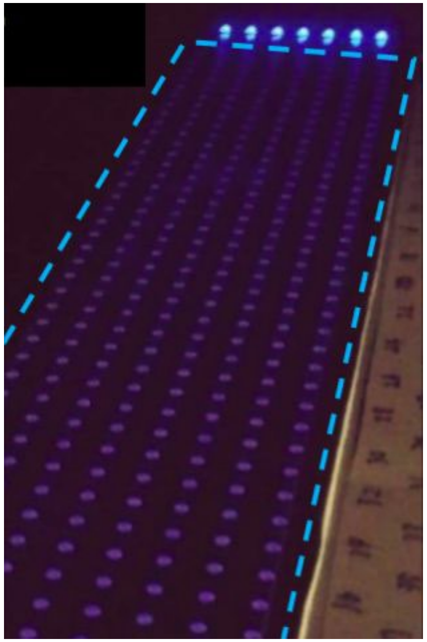
Development of the SFGD calibration system



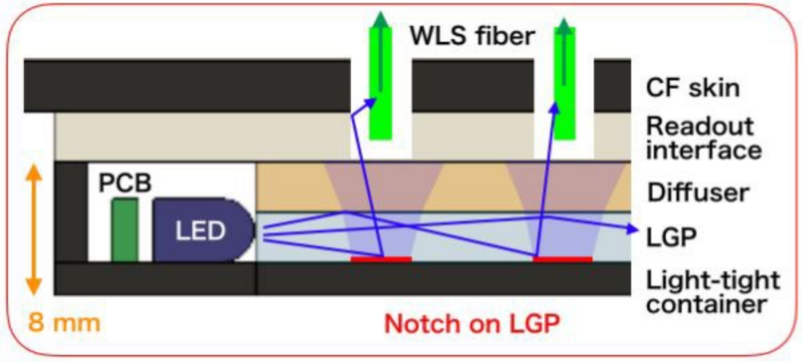
- LED based calibration system of the SuperFGD has been developed and tested
- The system comprises 93 Light Guide Plate (LGP) modules – 46 modules on the bottom and 47 modules on the side walls (the box on the left is shown upside down)
- DLNP developed electronics for the calibration system
- A few versions of LED driver were developed and tested

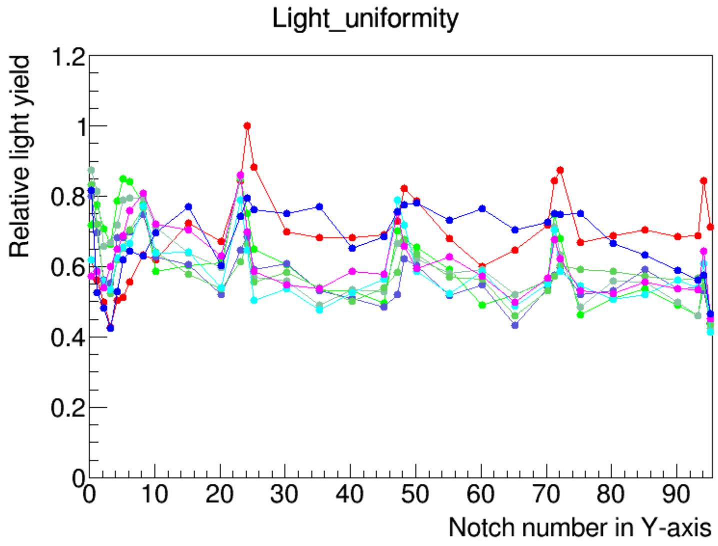


Development of the SFGD calibration system (2)



- The design of the Light Guide Plates has been optimized
- The system is designed with the module thickness of 8 mm
- Good light uniformity along the LGP achieved



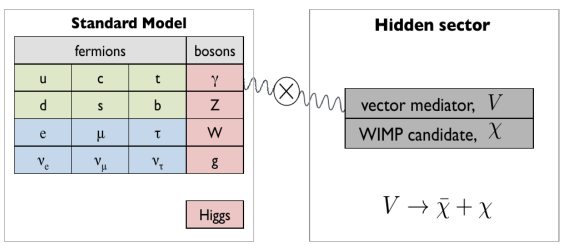


T Arihara, A Boikov, Yu I Davydov, O Drapier, H Kakuno, T Matsubara, S Tereshchenko and V Tereshchenko. ***Development of the in-situ Calibration System using LEDs and Light Guide Plates for the SuperFGD****, Journal of Physics:Conference Series, 2374(2022), 012118.*

Light dark matter search with ND280

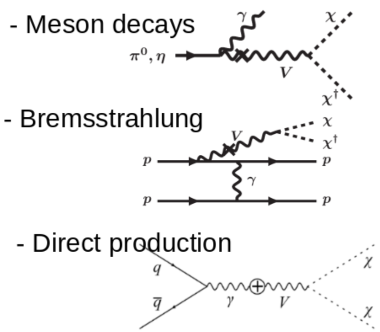
- Finding out the nature of dark matter is an important task for cosmology, astrophysics and particle physics
- Traditional search strategies are less sensitive to light dark matter (LDM) candidates with masses less than one GeV, and therefore it is important to consider alternative experimental approaches to detecting dark matter in this mass range.
- Experiments with a fixed target can provide significant sensitivity to LDM interacting with matter through a "dark photon" mediator
- LDM production: meson decays, bremsstrahlung, direct production
- Advantage: high luminosity allows to create intense streams of dark matter through the detector
- Difficulties: high background from neutrino interactions with matter

A mediator that decays to low mass WIMPs

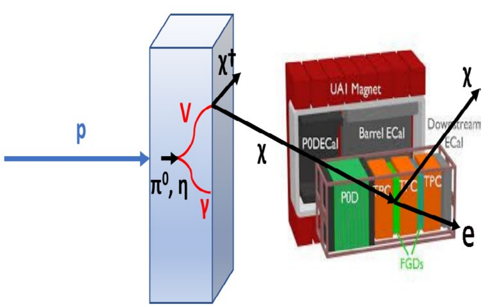


Kinetic mixing between Standard Model γ and vector mediator V is one possibility

LDM production channels

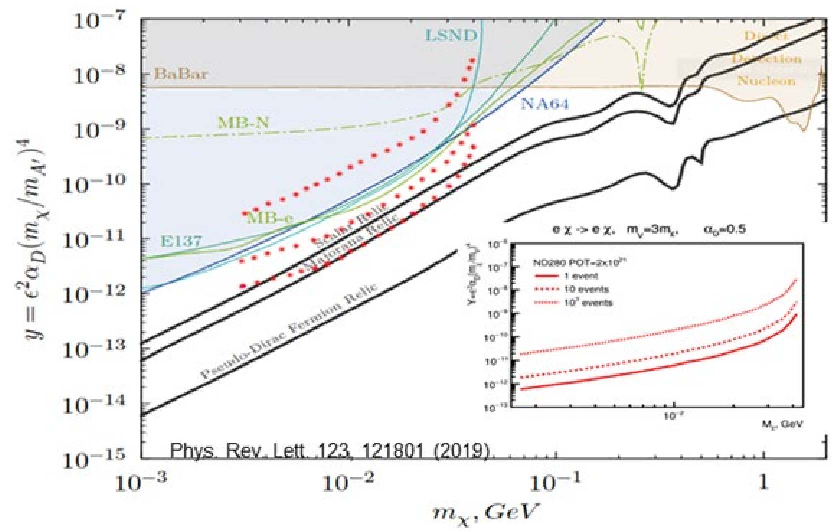


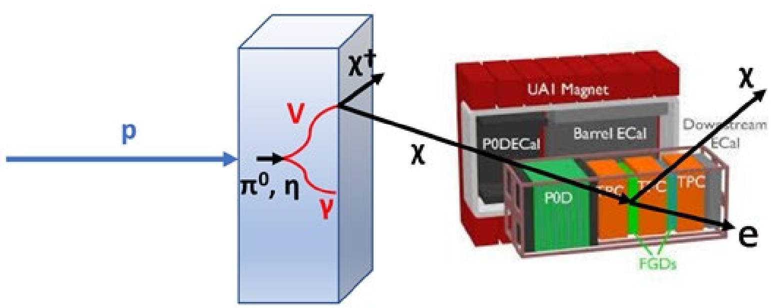
- A stream of dark matter particles could be created as a result of collisions of protons with a carbon target, followed by the detection of dark matter by scattering it in the ND280 detector
- The processes of elastic scattering of LDM on nucleons and electrons, quasi-elastic single pion production provide nucleon, **electron** and pion channels for detecting LDM



LDM search in electron channel

- A study has been started to search for LDM candidates in the electron channel in the ND280 detector
- We select events with a negatively charged track that would start in one of the FGD, track must have the PID of the electron. We require that the electron scattering occurs forward. This condition makes it possible to reduce the neutrino background.
- Advantage: small background from neutrino interactions with matter
- Our studies show that ND280 using data already obtained has the potential to improve the limits presented by MiniBooNE in the mass region of $5\times10^{-3}<m_\chi<3\times10^{-2}$ GeV
- T2K-II has even more prospects, as we expect the statistics to grow several times

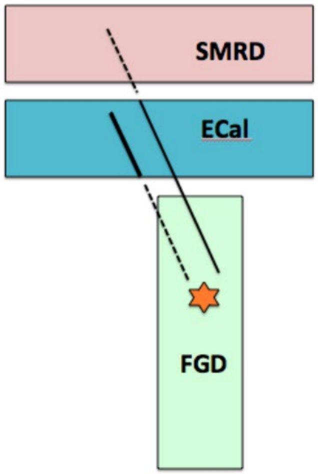




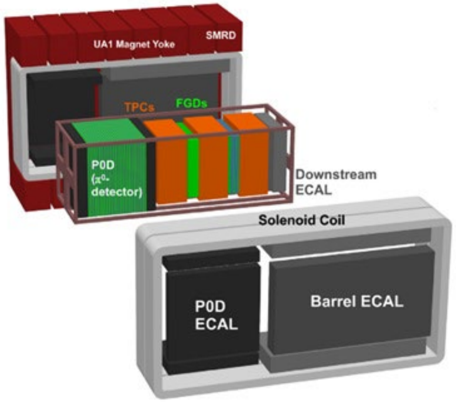
Current activity: preparation of MC samples; event selection; evaluation of the efficiency of registration of LDM candidates at different values of their masses; evaluation of background; study of systematic uncertainties; data fit

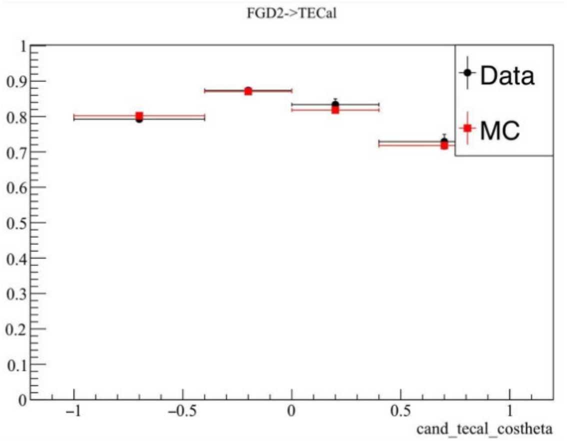
Matching efficiency for objects reconstructed in FGD, ECal and SMRD

- The track reconstruction algorithm determines the track segments in each FGD, ECal and SMRD detector separately and then links them together. There is an efficiency of such "matching".
- The efficiency values may differ between data and MC, which is a source of systematic uncertainty.
- To measure the efficiency, high-angle tracks were used that do not fall into the TPC, which actually stop in the FGD volume. We required the presence of the Michel electron in FGD to identify such tracks.
- The results of this study with new data sets were presented at the T2K workshops and a technical note is being prepared with the results of the study.



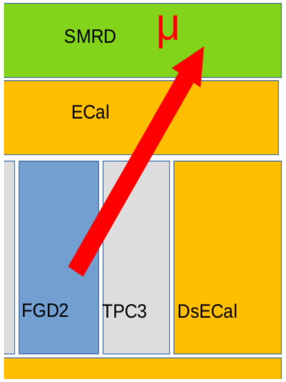
Selection topologies





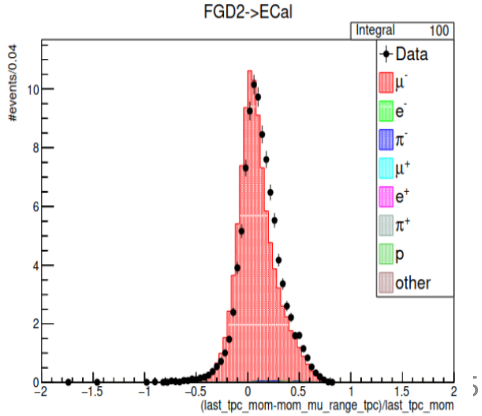
Systematics for momentum estimation from particle range for ND280 tracker analyses

- Estimates of systematic uncertainties related to the calculation of the muon momentum by range in various ND280 sub-detectors were carried out.
- The momentum by range is computed under certain particle hypothesis and using the length of a track and the energy loss. In our studies we compare momentum by range with one determined from track curvature in the TPC and check consistency of experimental data and MC simulation.
- To estimate possible data/MC discrepancies related with momentum reconstructed by range we build the distributions of the relative difference between momentum provided by the TPC and the momentum by range and then compare them in data and MC.
- The characteristics of distributions, such as mean, RMS, and fit parameters were determined. These values used to calculate the corresponding systematic uncertainties.
- The results obtained are intended to determine the systematics in analysis that exploit momentum by range for tracks without reliable TPC information
- The results of the study were presented at meetings and published in the technical note.



Event selection

- Track in one of the TPC and absence of other tracks in the detector
- Track ended in FV of FGD/ECAL/SMRD
- Tracks with a negative charge required the muon PID while tracks with a positive charge required the proton PID.



Publications and seminars

List of publications

1. I. Alekseev, T. Arihara, V. Baranov et al. ***SuperFGD prototype time resolution studies.*** *JINST 18 (2023) P01012.*
2. Artikov, A., Baranov, V., Boikov, A. et al. ***Investigation of Light Collection in Scintillation Cubes of the SFGD Detector***. *Phys. Part. Nuclei Lett. 19, #6, p.784–791 (2022).*
3. T Arihara, A Boikov, Yu I Davydov, O Drapier, H Kakuno, T Matsubara, S Tereshchenko and V Tereshchenko. ***Development of the in-situ Calibration System using LEDs and Light Guide Plates for the SuperFGD***. *Journal of Physics:Conference Series, 2374(2022), 012118.*
4. T2K Collaboration, K.Abe et al. ***Scintillator ageing of the T2K near detectors from 2010 to 2021.*** *JINST* 17 (2022) 10, P10028.

Seminars at DLNP

1. V.Glagolev. *JINR participation in the Japanese neutrino program: from T2K to Hyper-Kamiokande*. Project T2K. 17.03.2021
2. Y.G.Kudenko. *Experiments T2K and HyperKamiokande with the upgraded near neutrino detector ND280*. 30.03.2021
3. I.Vasilyev. *Study of light collection in scintillation cubes of the SFGD detector.* 15.12.2021
4. V.Glagolev, A.Boikov, I.Suslov. *Participation of JINR in the T2K experiment*. 29.06.2022
5. Yu.Davydov, I.Suslov. *Participation of JINR in the T2K-II experiment*. 22.11.2023

Plans of the JINR group in T2K for 2023

- Participation in final SFGD box assembly (replacement of fishing lines with WLS fibers)
- Production, tests and installation of the LED calibration system
- Participation in the installation and commissioning of the SFGD
- Participation in the development MIDAS based DAQ for SFGD/ND280
- Participation in the data taking (including remote shifts) and maintenance of the SFGD
- Analysis of new T2K-II data
- Continuation of the search for light dark matter candidates based on the ND280 and Super-Kamiokande data

Plans of the JINR group in T2K for 2024-2026 and estimated costs

2024	2025	2026
T2K-II data analysis 10 k$	T2K-II data analysis 10 k$	T2K-II data analysis 10 k$
Development ND280 DAQ 10 k$		
R&D for detector subsystems Materials and equipment 10k$	R&D for detector subsystems Materials and equipment 20 k$	R&D for detector subsystems Materials and equipment 20 k$
T2K-II data taking shifts, SuperFGD/ND280 maintenance, meetings, conferences 70 k$	T2K-II data taking shifts, SuperFGD/ND280 maintenance, meetings, conferences 70 k$	T2K-II data taking shifts, SuperFGD/ND280 maintenance, meetings, conferences 70 k$
Operation fee 25k$	Operation fee 35k$	Operation fee 35k$
Total: 125 k$	Total: 135 k$	Total: 135 k$

Total expenses in 2024-2026 are planned in the amount of 395 k$

Estimation of human resources

Name	FTE	Position	Work (apart common duties like shifts)
Artikov A.	0.5	Head of sector	SFGD tests and assembly
Atanova O.	0.6	Engineer	Monte Carlo, Data analysis
Baranov V.	1.0	Junior scientist	SFGD tests and assembly
Boikov A.	0.6	Junior scientist	SFGD calibration system
Brazhnikov A.	0.3	Engineer	tooling for SFGD assembly
Davydov Yu.	0.7	Head of department	SFGD tests and assembly, CollManag
Glagolev V.	0.5	DLNP deputy director	SFGD tests and assembly, CollManag, IB repr.
Khomutov N.	0.5	Scientist	DAQ and Software support
Kirichkov N.	0.3	Head of the design department	tooling for SFGD assembly
Kiseeva V.	1.0	Junior scientist	Monte Carlo, Data analysis
Kolesnikov A.	0.8	Junior scientist	SFGD tests and assembly
Krasnoperov A.	0.3	Senior scientist	DAQ and software support
Krylov V.	0.4	Scientists	Vizualization, software support
Popov B.	1.0	Senior scientist	Data analysis
Shaikovskiy A.	0.3	Engineer	tooling for SFGD and assembly
Suslov I.	1.0	Senior scientist	Monte Carlo, Data analysis
Tereschenko V.	0.8	Head of group	SFGD calibration system
Tereschenko S.	0.6	Engineer	SFGD calibration system
Vasilyev I.	0.7	Junior scientist	SFGD tests and assembly
Zimin I.	0.7	Junior scientist	Monte Carlo, Data analysis
Total FTE	**12.6**		

The names of young colleagues are highlighted in blue

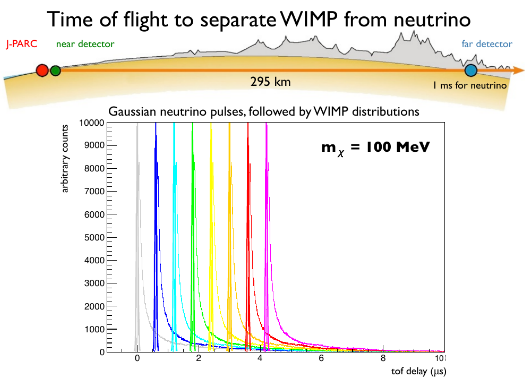
Conclusion

- The JINR group actively participates in the work of the T2K collaboration and has already made a visible contribution to the modernization of the near detector ND280, including the study of the parameters of the SFGD elements, the development of a calibration system, and the assembly of the detector
- Progress has been made in the search for light dark matter candidates on data from the near detector ND280
- Research has been done to improve the systematics in the data. Results were presented at collaboration workshops and in technical notes.
- Participation in the world leading experiment investigating neutrino oscillations is prestigious both for the group and for JINR as a whole. **T2K-II continue to be a separate experiment through 2026.** After that it will become part of the Hyper-Kamiokande experiment. We hope to receive support from the PAC and the Directorate of the Institute to continue our participation in the T2K-II experiment in 2024-2026 at relatively low financial costs.

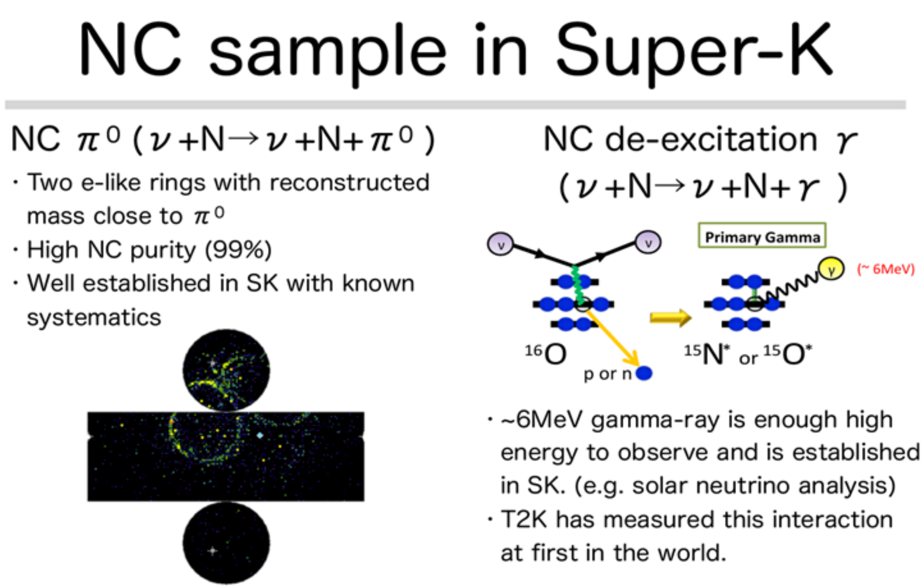
We hope to receive support from you in the near future for full participation in the Hyper-Kamiokande experiment

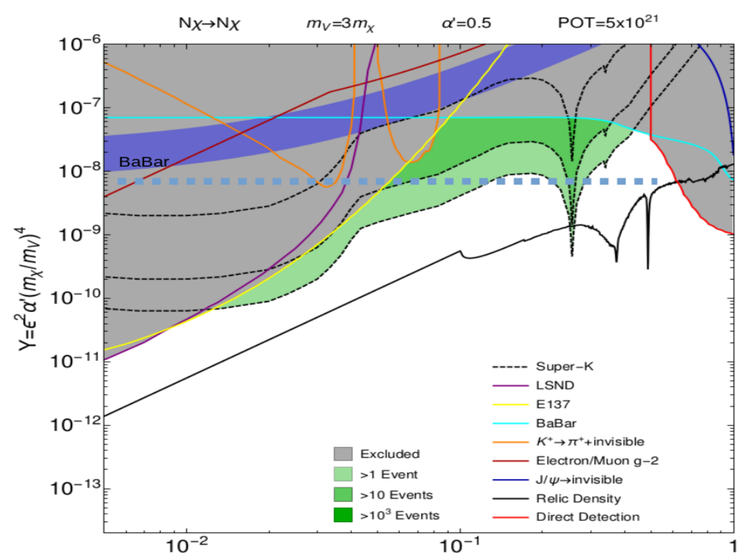
Back up slides

LDM candidate search at Super-Kamiokande



- Plan to evaluate the potential of T2K-II in the search for LDM candidates with the participation of Super-Kamiokande
- Nucleon and pion channels of LDM detection in SK
- SK has fewer events compared to ND280
- For Super-K the longer flight time of the LDM candidate compared to neutrinos allows the separation of the signal caused by dark matter and the background from neutrinos
- Neutrino interactions with a similar signature are well studied on SK

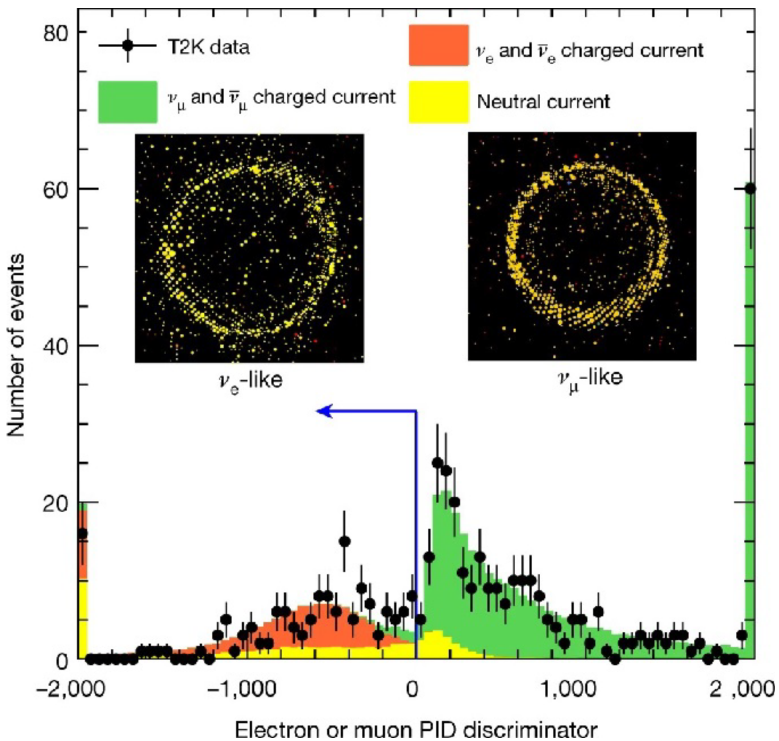




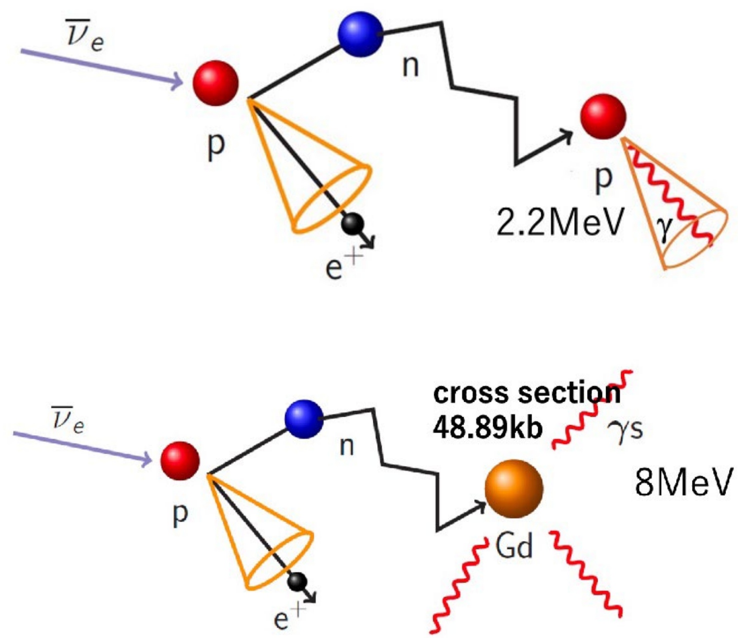
Phys. Rev. D 95, 035006 (2017)

Super-Kamiokande - the far detector

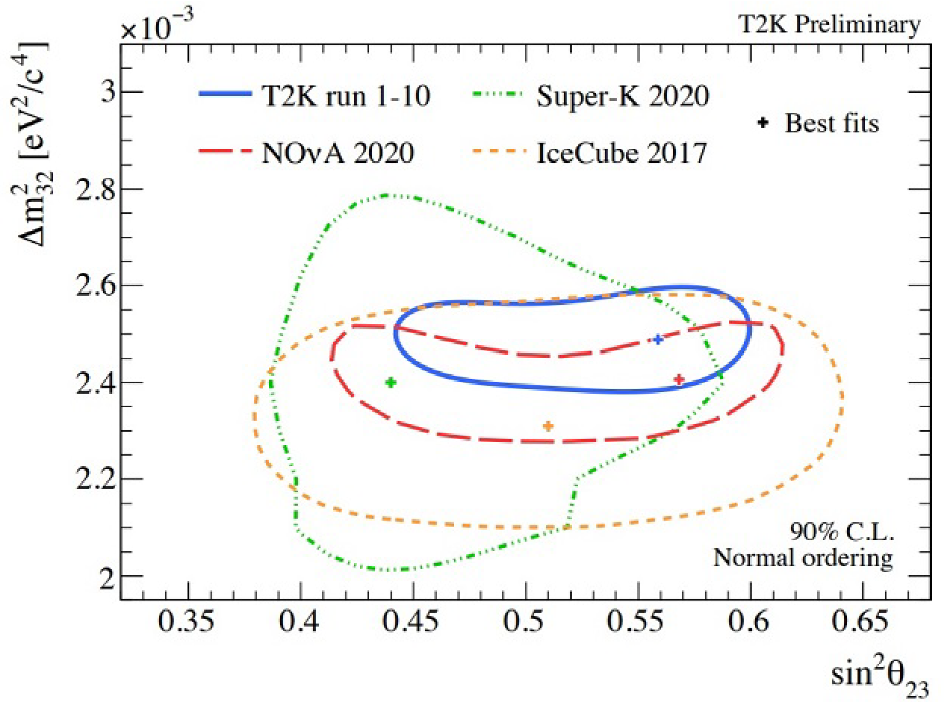
Good μ/e PID from ring shape



Gd loading improved neutron tagging



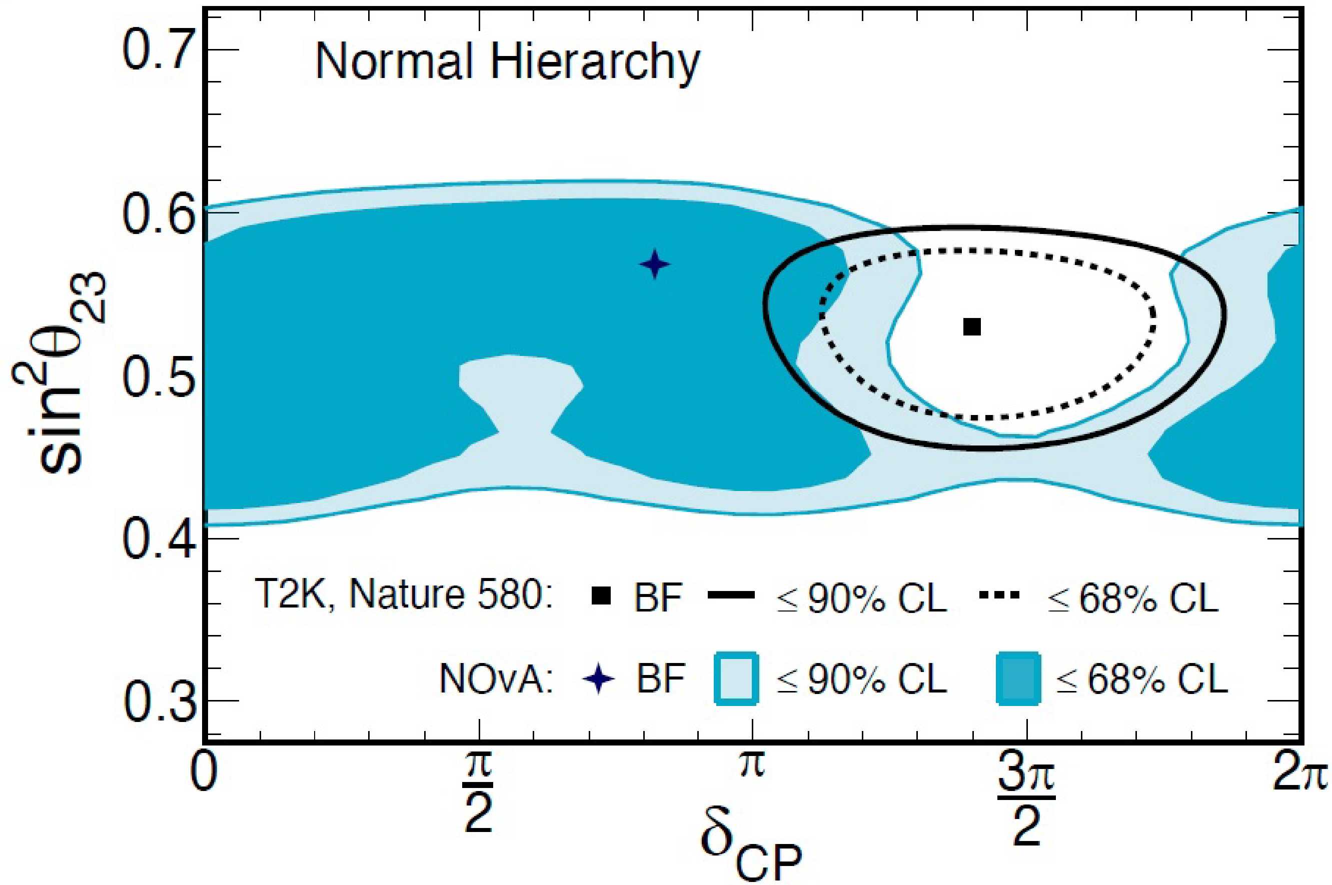
Fit results ($\nu_\mu \rightarrow \nu_\mu$)



- World leading constraint on $\sin^2\theta_{23}$
- Compatible with maximal mixing ($\sin^2\theta_{23}$=0.5)

Standard CP-phase δ_{CP} extracted by the two experiments

NOνA preliminary   Comparison to T2K

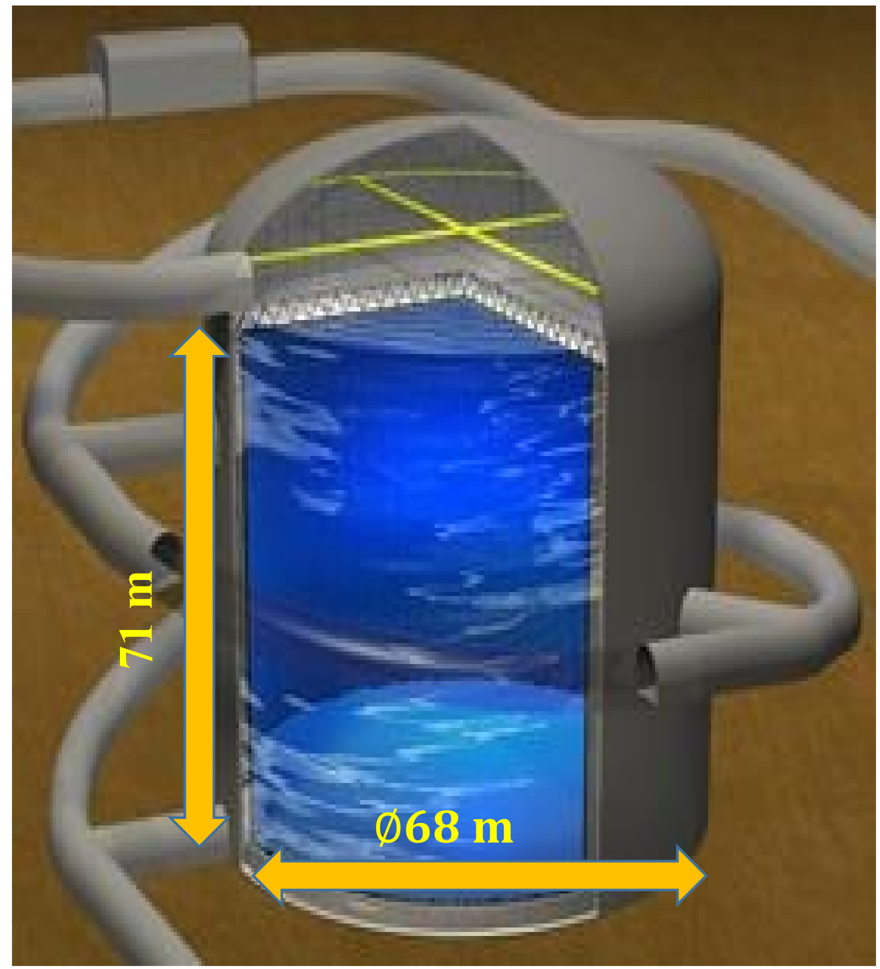


NOνA prefers values close to δ_{CP}~ 0.8π, T2K - δ_{CP}~ 1.4π.

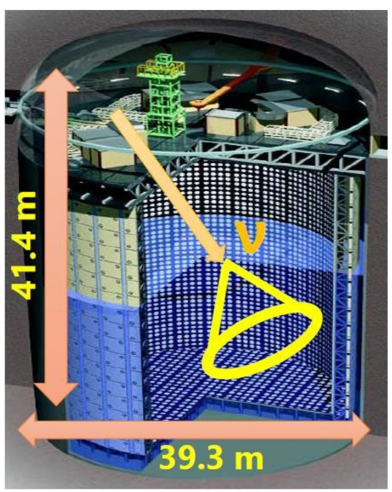
Hyper-Kamiokande

Third generation of water Cherenkov detectors

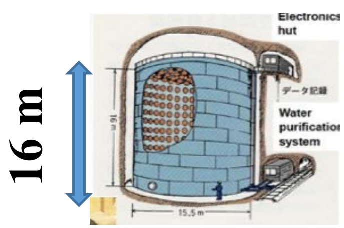
HyperKamiokande
260 kt



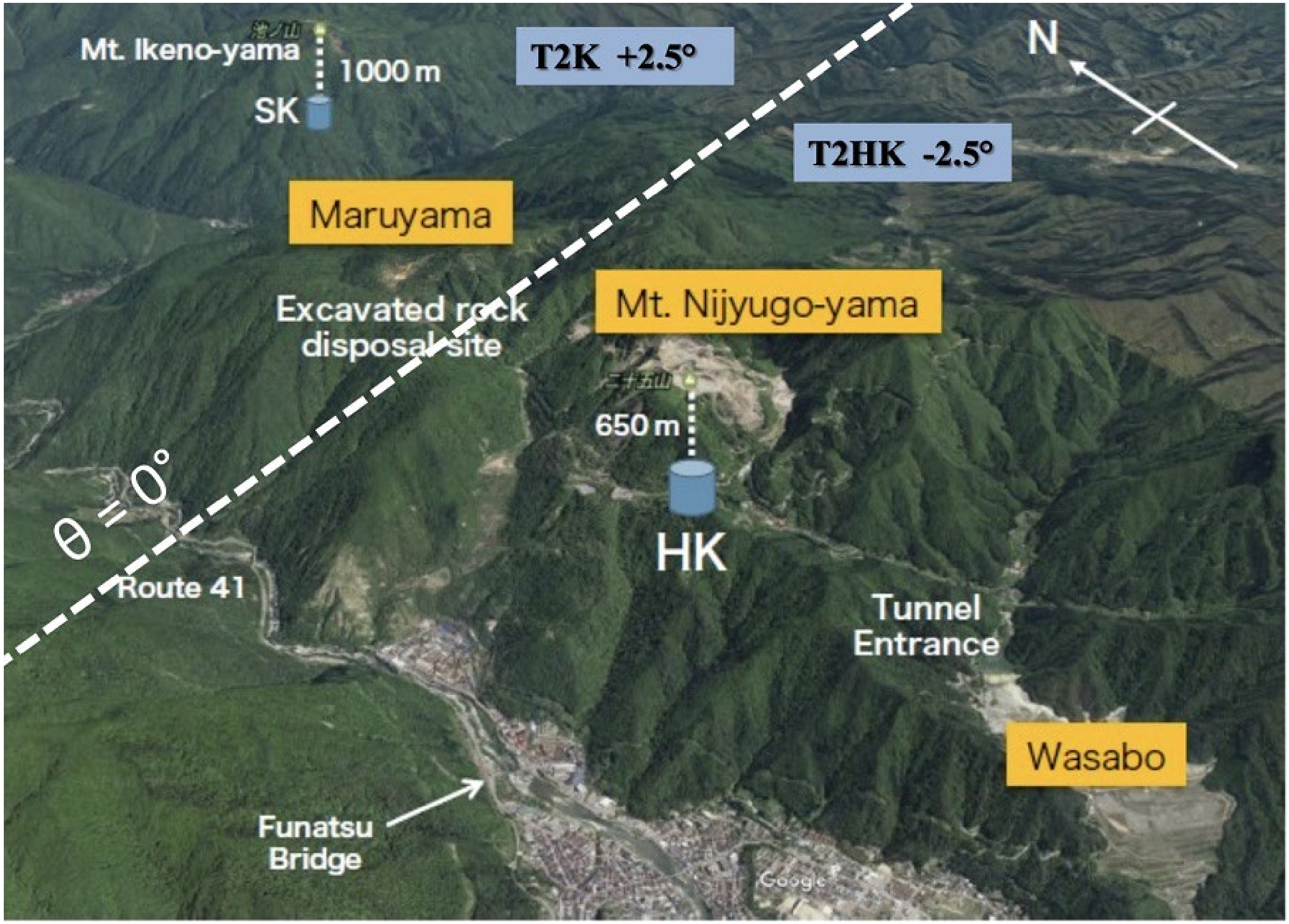
SuperKamiokande
50kt
Taking data since1996
(T2K far detector
since 2010)



Kamiokande
4.5 kt
1983 -1996



Hyper Kamiokande



295 km from J-PARC
2.5 degrees off-axis (as SK)