Form No. 24

JINR participation in the Japanese neutrino program: from T2K to Hyper-Kamiokande

Project

T2K

DLNP: Baranov V.Yu., Boikov A.V., Brazhnikov A.O., Budagov J.A., Davydov Yu.I., Demin D.L., Glagolev V.V., Khomutov N.V., Kirichkov N.V., Kiseeva V.I., Kolesnikov A.O., Krasnoperov A.V., Limarev K.K., Malyshev V.L., Popov B.A., Shaikovskiy A.V., Sinitsa A.A., Suslov I.A., Tereschenko V.V., Tereschenko S.V., Vasilyev I.I.,
BLTP: Kozlov G.A.

Joint Institute for Nuclear Research, Dubna, Russia

Khabibullin M.M., Khotjantsev A.N., Kudenko Yu.G., Mineev O.V.

Institute for Nuclear Research of the Russian Academy of Sciences

PROJECT LEADERS V.V. Glagolev, Yu.I. Davydov

SCIENTIFIC PROJECT LEADER Yu.A. Budagov

DATE OF SUBMISSION OF PROPOSAL OF PROJECT TO SOD _____

DATE OF THE LABORATORY STC _____ DOCUMENT NUMBER _____

STARTING DATE OF PROJECT ____2022_____

(FOR EXTENSION OF PROJECT — DATE OF ITS FIRST APPROVAL) _____

Date of the Lab seminars 17.03.2021

T2K(Tokai-to-Kamioka) experiment

Long base-line neutrino oscillation experiment

Super-Kamiokande
(ICRR, Univ. Tokyo)

J-PARC Main Ring
(KEK-JAEA, Tokai)

some of T2K results so far :

- Discovery of ν_e appearance in 2013

  Phys.Rev.Lett. 107, 041801 (2011)
  Phys.Rev.Lett. 112, 061802 (2014)

- Search for CP violation in neutrino oscillation

  Phys.Rev.Lett. 121, 171802 (2018)

Мотивация участия в эксперименте T2K-II

Status and future prospect of T2K experiment with J-PARC neutrino beam and near detectors / The Hyper-Kamiokande project

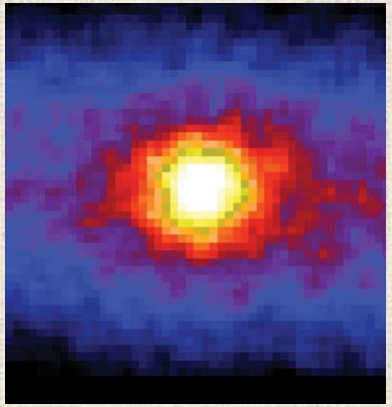
Seminars

Date and Time: *Wednesday, 24 April 2019, at 3:00 PM*

Venue: *Conference Hall, building 3, Dzhelepov Laboratory of Nuclear Problems*

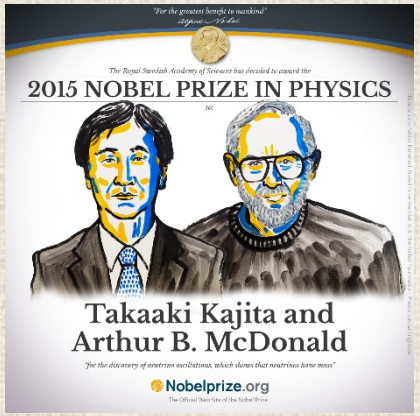
1 ***Seminar topic***: *«Status and future prospect of T2K experiment with J-PARC neutrino beam and near detectors»*

Speakers: *Masashi Yokoyama (University of Tokyo) and Ken Sakashita (KEK and J-PARC)*



The Sun at night. Solar neutrinos as detected by Super-Kamioknade looking through the Earth.

- Основное направление исследований в ЛЯП - нейтринная физика
- Предложение об участии со стороны лидеров коллаборации T2K и ИЯИ РАН.
- T2K – эксперимент наивысшей значимости в нейтринной физике.
- Договор с ИЯИ о совместном создании активной мишени Super FGD детектора ND280 и проектировании платформы и оснастки для ее сборки
- Ресурсы – с эксперимента Mu2e – из за больших проблем с получением US виз, невозможности работы в национальных лаб. США…
  - Следуем рекомендациям ПКК + УС



For the discovery of neutrino oscillations, which shows that neutrinos have mass

September 6, 2019

Academician Viktor Matveev
Director of the JINR
cc: Professor Vadim Bednyakov
Director of JINR-DLNP
cc: Professor Vladimir Glagolev
Deputy Director of JINR-DLNP

Dear Academician Matveev,

This letter is to express our interest in collaborating with the Joint Institute for Nuclear Research (JINR) within the framework of the T2K experiment at J-PARC (Japan Proton Accelerator Research Complex), Tokai, Japan. J-PARC is the best facility in the world for low and intermediate-energy nuclear/hadron and particle physics experiments.

As you know, the T2K experiment is a long baseline neutrino oscillation experiment and takes a leading position in the world in the study of neutrino physics.

The experiment uses an intense proton beam generated by the J-PARC Main Ring synchrotron, and is composed of a neutrino beamline, a near detector complex (ND280), and a far detector (Super-Kamiokande) located 295 km away from J-PARC.

We welcome the participation of JINR scientists from Dzhelepov Laboratory of Nuclear Problems (DLNP) in the T2K experiment. We are sure that JINR participation in the T2K experiment will be useful for JINR as well as for KEK/J-PARC and will make the cooperation between the two leading world physics scientific centers closer.

Taking into account the great and wide experience and high qualifications of physicists, engineers and technicians from DLNP JINR, we hope that in the case of JINR's participation in T2K, the JINR-T2K group can efficiently become active in the different detector systems, including their construction.

I would be grateful if you could discuss whether or not full participation of JINR's scientists, and financial support for them, in the T2K international collaboration would fit into the research strategy of your institute.

Should you have any questions regarding terms of collaboration, we would be happy to discuss it with you and your experts in the near future.

Your sincerely,

Atsuko K. Ichikawa
Spokesperson of the T2K Collaboration

Federico Sanchez Nieto
International Co-spokesperson of the T2K collaboration

October 20, 2020

Prof. Victor A. Matveev
Director of JINR
6 Joliot-Curie St.
141980 Dubna, Moscow Region
Russia

Dear Professor Victor Matveev,

We would like to inform you with a great pleasure about the positive decision of the T2K Institutional Board regarding the application of the JINR group led by Dr Vladimir Glagolev to join the T2K collaboration. This group is already made a valuable contribution to the construction of the Super Fine-Grained Detector in the framework of the upgrade program of the near neutrino detector ND280 and now has become a full member of the T2K Collaboration. We are confident in further active work of the JINR group in the T2K experiment and expect that this group will play a significant role in conducting the experiment and in the analysis of the experimental data.

We also take this opportunity to express our deep gratitude to you for your continued support of the participation of Russian scientists in the T2K experiment.

Sincerely Yours,

Prof Atsuto Ichkawa
T2K Spokesperson

Prof Federico Sanchez
T2K International Co-Spokesperson

JAPAN PROTON ACCELERATOR RESEARCH COMPLEX
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March 2021

Prof. Grigory V. Trubnikov
Director of JINR
6 Joliot-Curie St.
141980 Dubna, Moscow Region
Russia

Dear Prof. Grigory Trubnikov,

I am writing to express our deep respects for the achievements of the group from JINR, led by Dr. V. Glagolev and Dr. Yu. Davydov, in the upgrade of the near detector ND280 of the T2K experiment. We acknowlege the members of the group have great experience in renowned experiments such as CDF, ATLAS. Thanks to their efforts, together with colleagues from INR (Moscow), the creation of a unique SuperFGD target of a new type becomes a reality. The JINR colleagues make a significant contribution to the development of engineering tools and procedures for target assembly, calibration and testing of properties of target elements.

We hope that you and JINR PAC will strongly support the further participation of the JINR group in T2K-II and in the approved Japanese and worldwide leadership Hyper-Kamiokande experiment. We expect that JINR scientists will make a great contribution to data analysis, electronics, DAQ and the construction of the Hyper-Kamiokande detector.

We are looking forward to fruitful scientific results and strengthening scientific cooperation between J-PARC and JINR.

Sincerely Yours,
Director of J-PARC Center
Naohito SAITO

CC:
Dr. Viktor Matveev
Dr. Vadim Bednyakov
Dr. Vladimir Glagolev

Обширная нейтринная физическая программа T2K-II + SK(HK)

- Precision measurements of ν_μ and $\overline{\nu_\mu}$ disappearance -> θ_{23} and Δm^2_{32}
- Precision measurements of ν_e and $\overline{\nu_e}$ appearance -> determine θ_{13} and δ_{cp}
- Search for heavy neutrinos with the T2K near detector ND280
- Gadolinium doping to separate anti-neutrino interaction by neutron capture
- HK program
  - CP violation measurement
  - Determining the Ordering of the Neutrino Masses
  - Cosmic Neutrino Observation (Solar, Supernova, Relic), Dark Matter Search
  - Proton decay Searches

Flavour mixing

ν_e

ν_μ

ν_τ

weak eigenstates

$$\nu_{\alpha L} = \sum_{k=1}^{n} U_{\alpha k} \nu_{kL}$$

(arbitrary sizes)

ν_1

ν_2

ν_3

Δm^2_{12}

Δm^2_{23}

$\Delta m^2_{ij} = m^2_i - m^2_j$

mass eigenstates

θ_{23} θ_{13}, δ_{CP} θ_{12} α_1, α_2

PMNS mixing matrix

Pontecorvo–Maki–Nakagawa–Sakata

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric and accelerator
$\theta_{23} \sim 50°$
$|\Delta m_{32}^2| \sim 2.5\times10^{-3}$ eV^2

Reactor and accelerator
$\theta_{13} \sim 8°$
Accelerator only $\delta_{CP} = ??$

Solar and reactor
$\theta_{12} \sim 34°$
$\Delta m_{12}^2 \sim 7.5\times10^{-5}$ eV^2

Majorana

Dirac

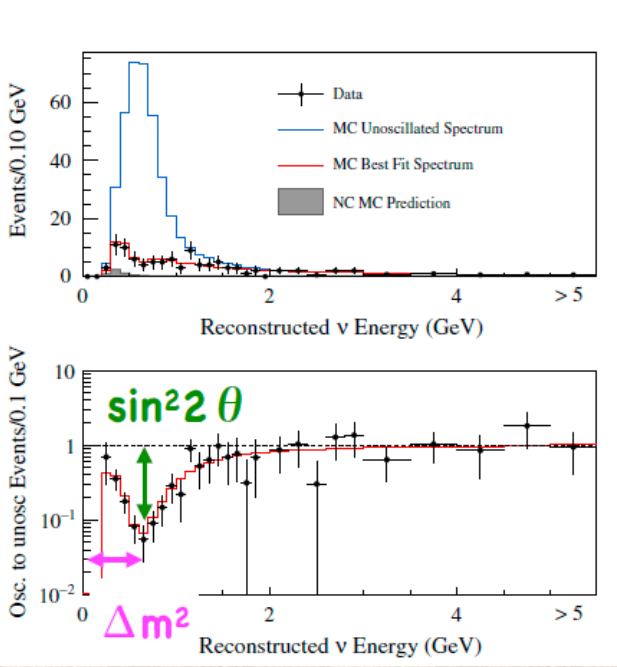
Main T2K physics goals:

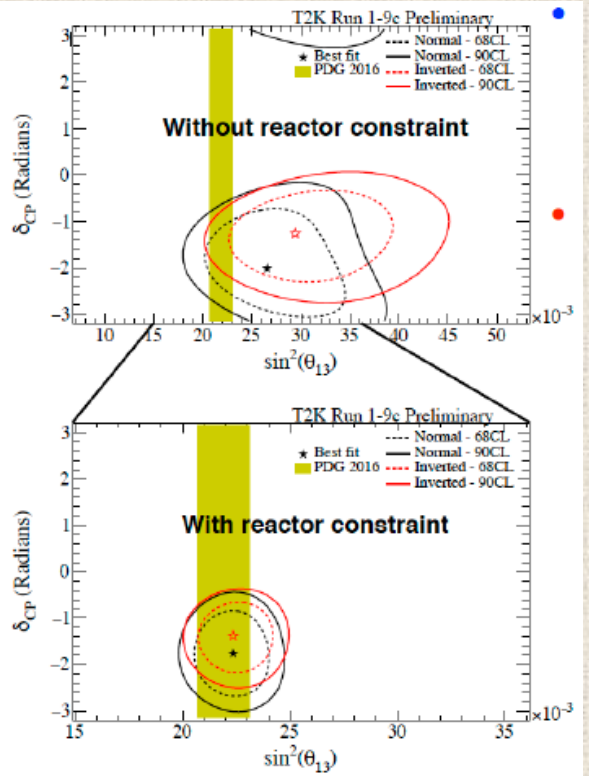
Observation of ν_e and $\overline{\nu_e}$ appearance -> determine θ_{13} and δ_{cp}

Precise measurement of ν_μ and $\overline{\nu_\mu}$ disappearance -> θ_{23} and Δm^2_{32}

probability for muon neutrinos and antineutrinos to maintain their initial flavour

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





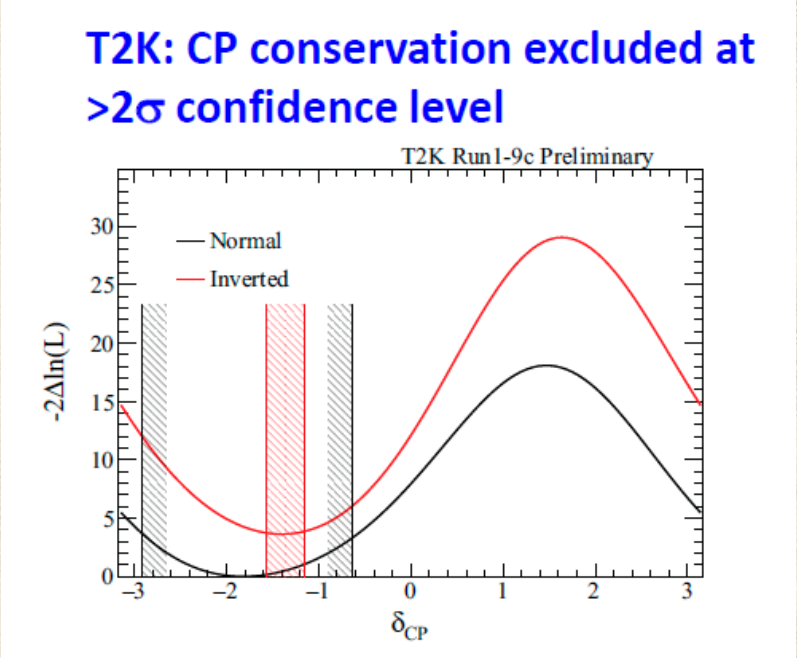
Probability for muon neutrinos (antineutrinos) to oscillate to electron neutrinos (antineutrinos) neglecting effects from propagation through matter

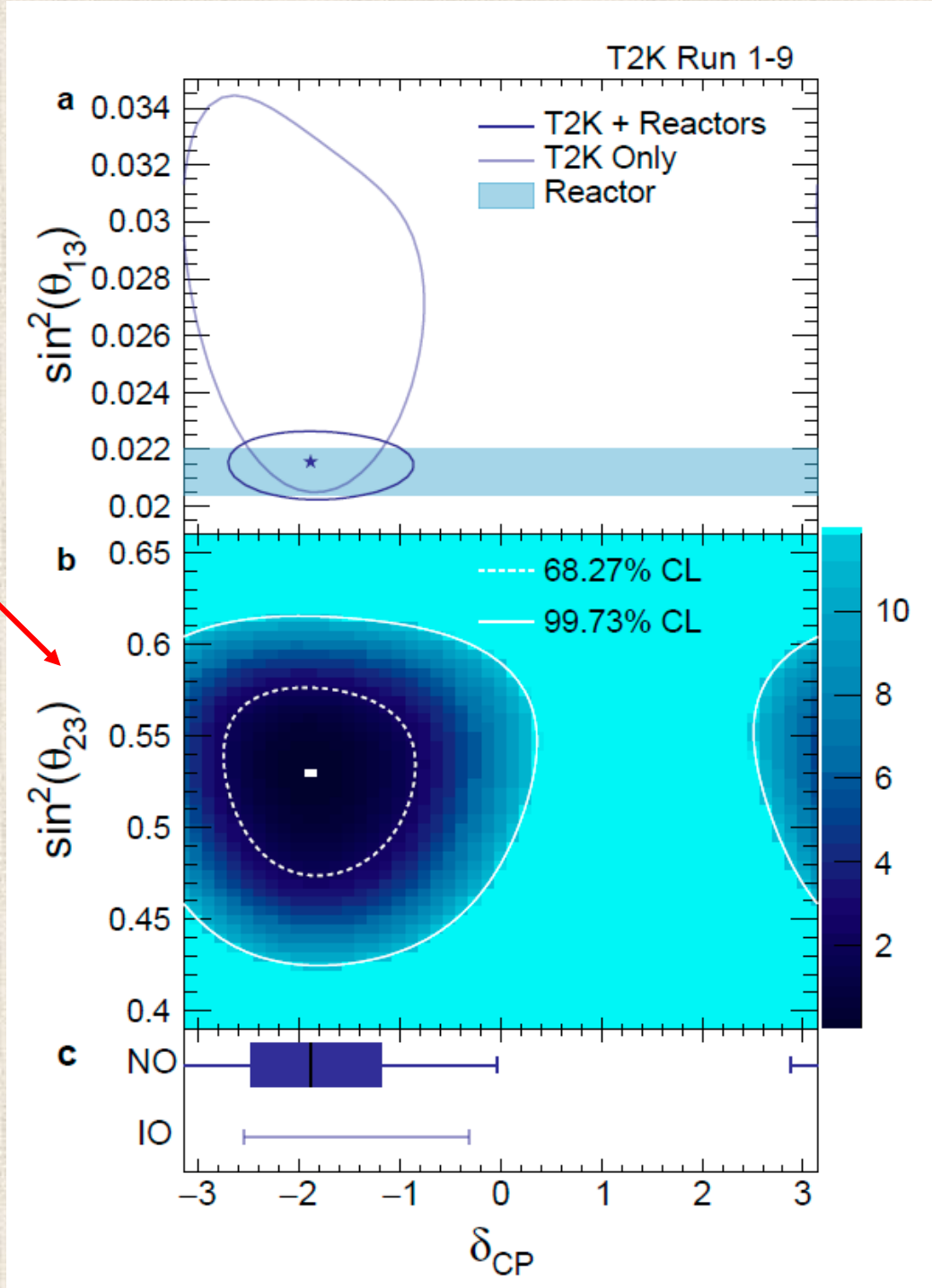
$$A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)} \cong \frac{\Delta m^2_{12} L}{4E_\nu} \times \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \times \sin \delta$$

Constraints on PMNS oscillation parameters
arXiv:1910.03887v3 [hep-ex] 25.01.2021

Two-dimensional confidence intervals at the 68.27% and 99.73% confidence level for δ_{CP} versus $\sin^2\theta_{23}$ from the T2K + reactors fit in the normal ordering, with the color scale representing the value of negative two times the logarithm of the likelihood for each parameter value.

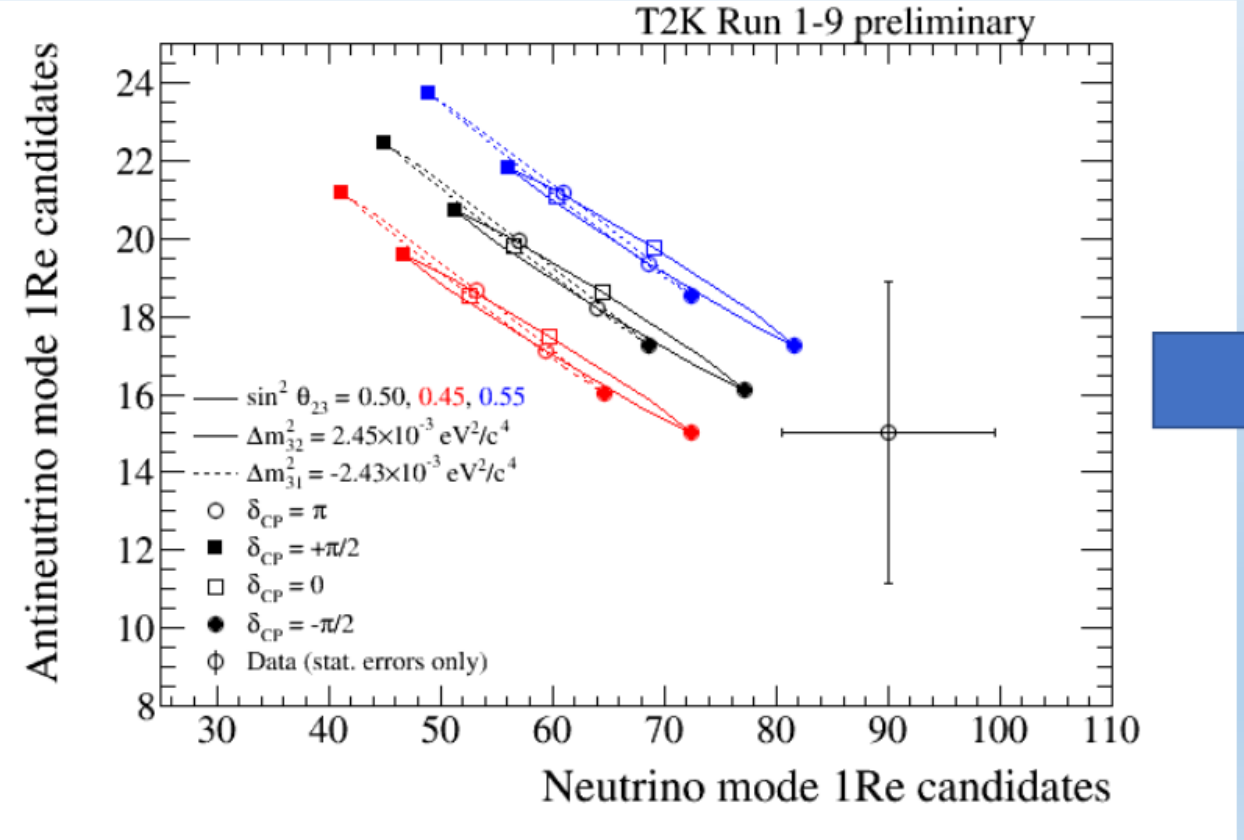
99.73% (3σ) confidence and credible intervals on δ_{CP}. In the favored normal ordering the confidence interval contains [−3.41, −0.03] (excluding 46% of the parameter space)

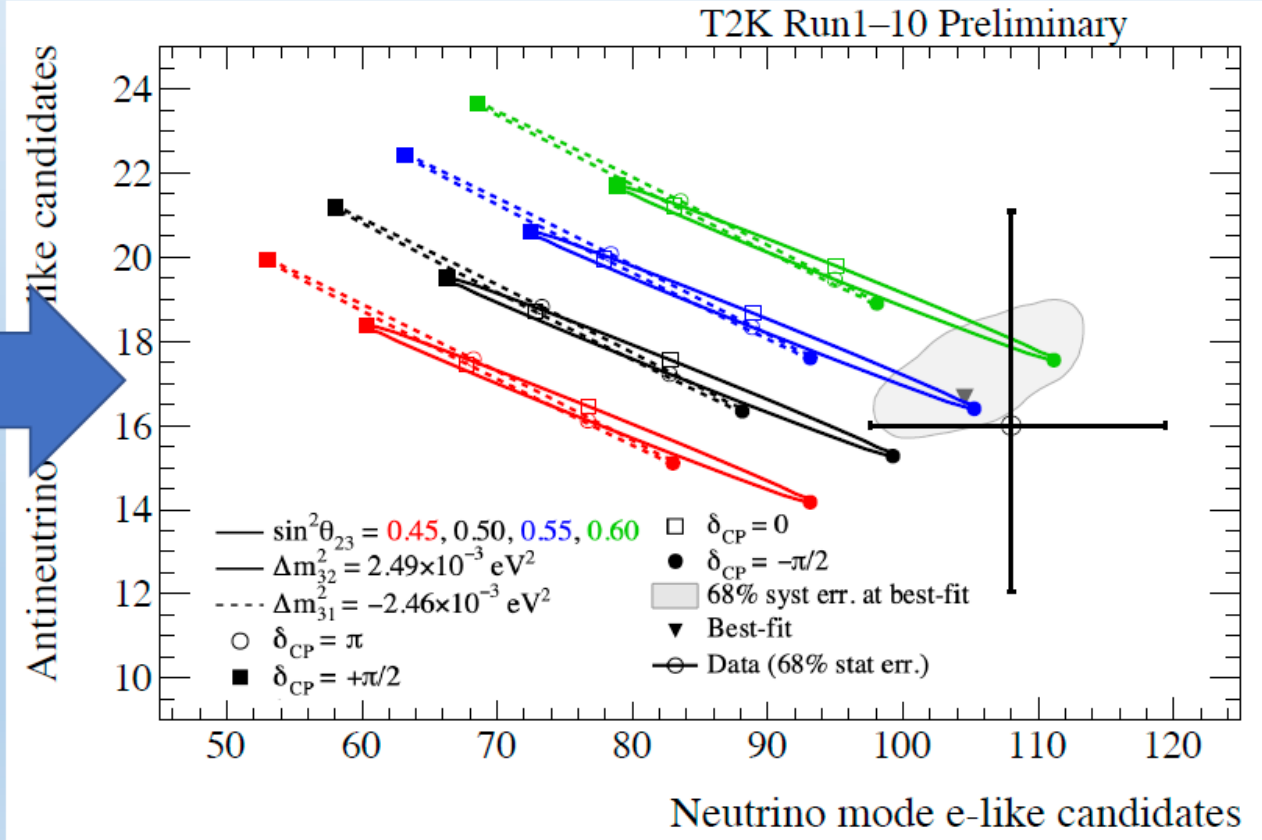




Comparison to previous result

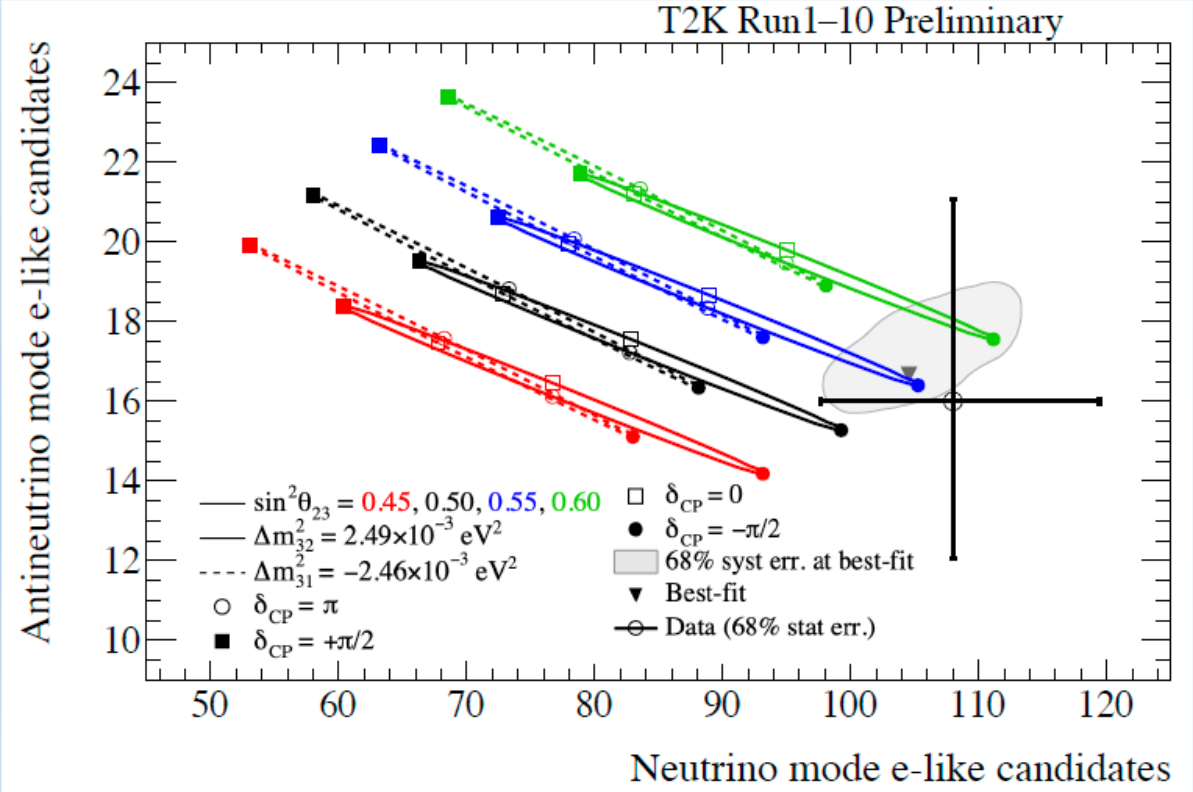
- Data this year closer to PMNS prediction

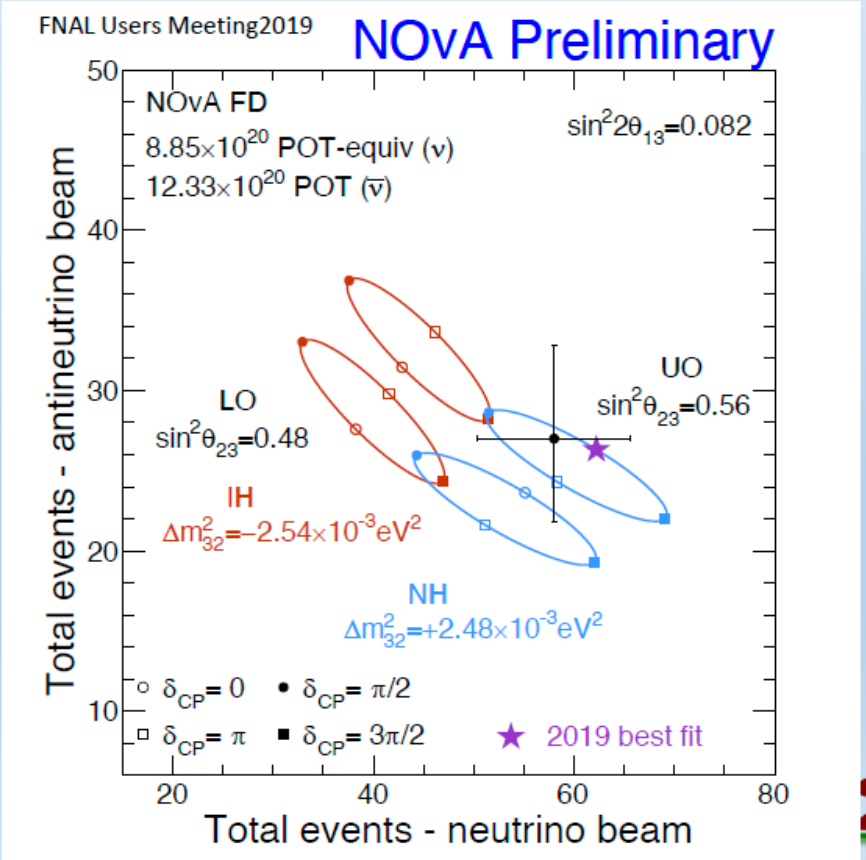




Future joint fits

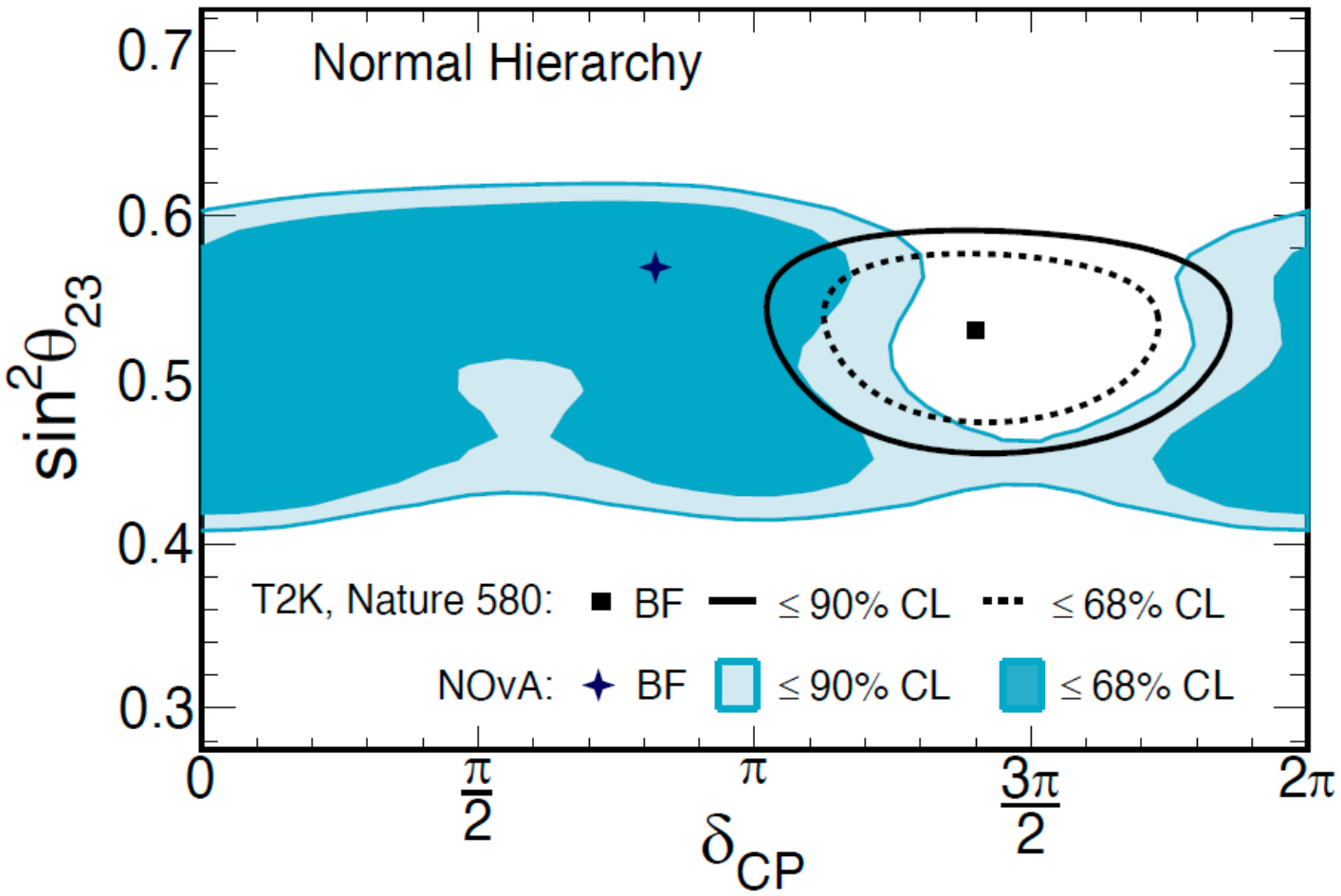
- Experiments with different neutrino energies have different oscillation probabilities and systematic uncertainties
- Combined analysis of data allows degeneracies to be broken and maximises impact of data taken





Comparison to T2K

NOvA Preliminary

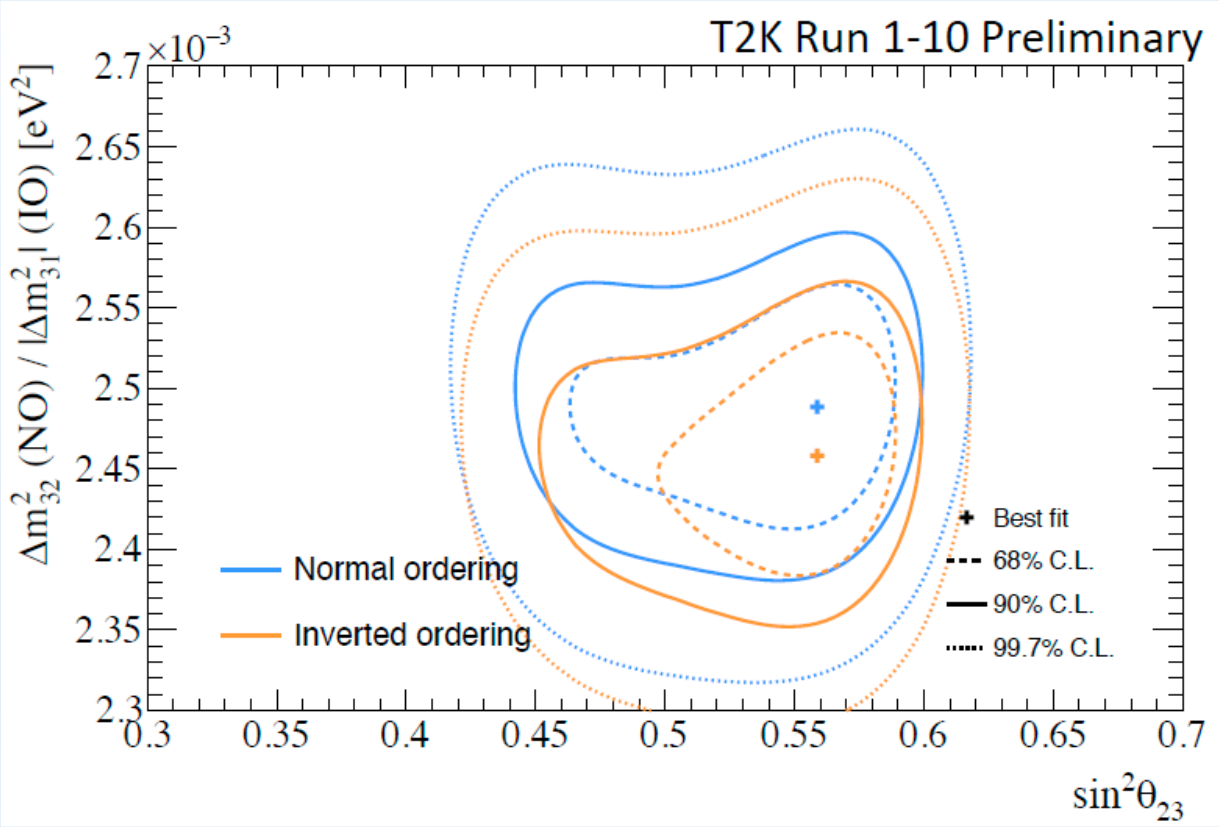


- Clear tension with T2K's preferred region.
- Quantifying consistency requires a joint fit of the data from the two experiments, which is already in the works.
  - Semi-annual workshops, regular joint group meetings, and a signed joint agreement.

Измерить θ_{23} and Δm^2_{32} с точностью of 1.7^0 и 1% или лучше. Сейчас соответственно 2.6^0 для угла (T2K) и 2.9 % (T2K)

Atmospheric sector

- Data shows preference for normal hierarchy and upper octant
- Slight preference for non-maximal $\sin^2\theta_{23}$



Posterior probability

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.195	0.613	0.808
IH ($\Delta m^2_{32} < 0$)	0.034	0.158	0.192
Sum	0.229	0.771	1.000

	$\sin^2\theta_{23}$	$\Delta m^2_{32}(\times 10^{-3})\mathrm{eV}^2$
2D best fit	0.546	2.49
68% C.I. (1σ) range	0.50 – 0.57	2.408 – 2.548
90% C.I. range	0.460 – 0.587	−2.596 – −2.452 & 2.368 – 2.592

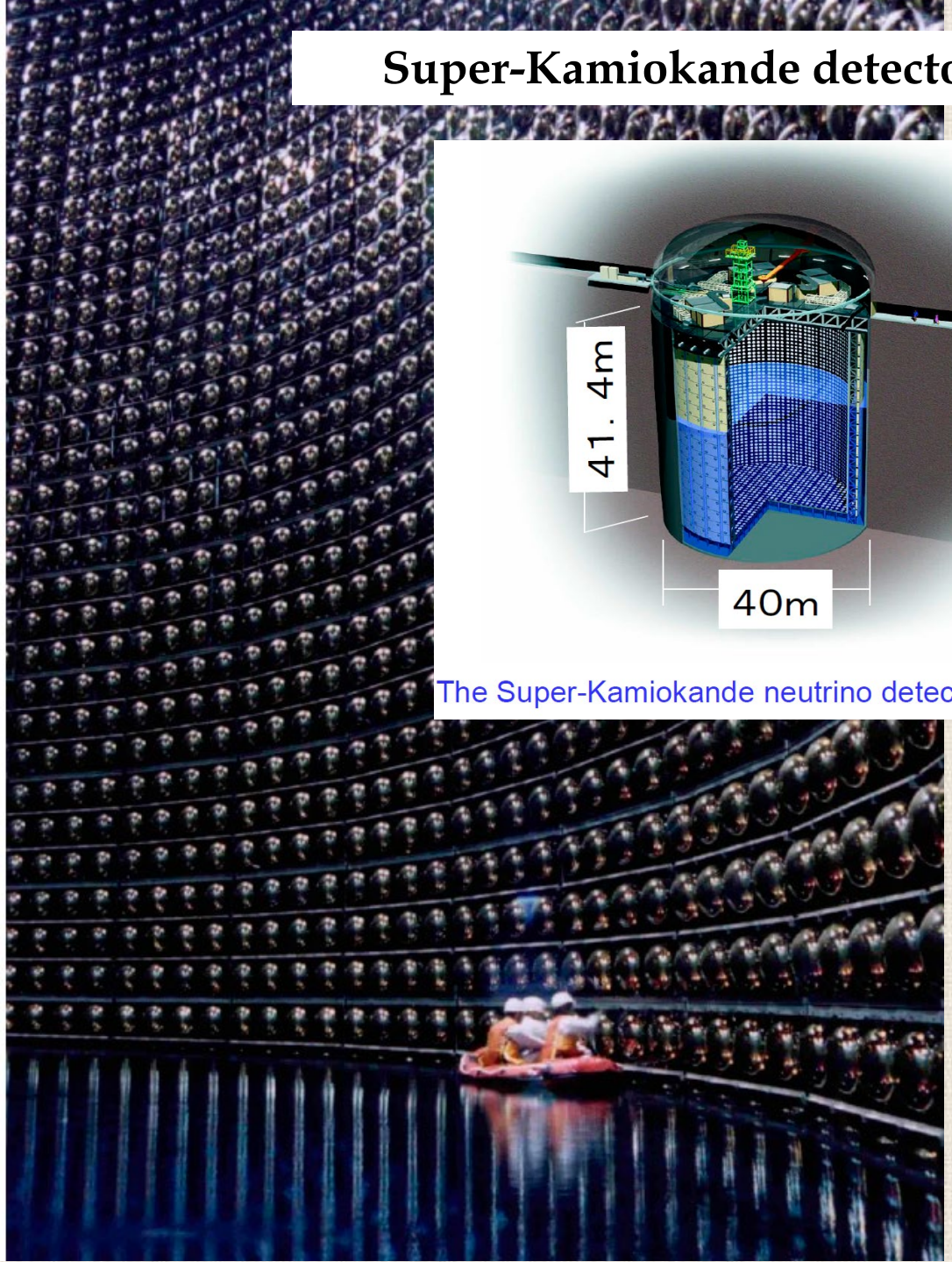
Imperial College London T2K

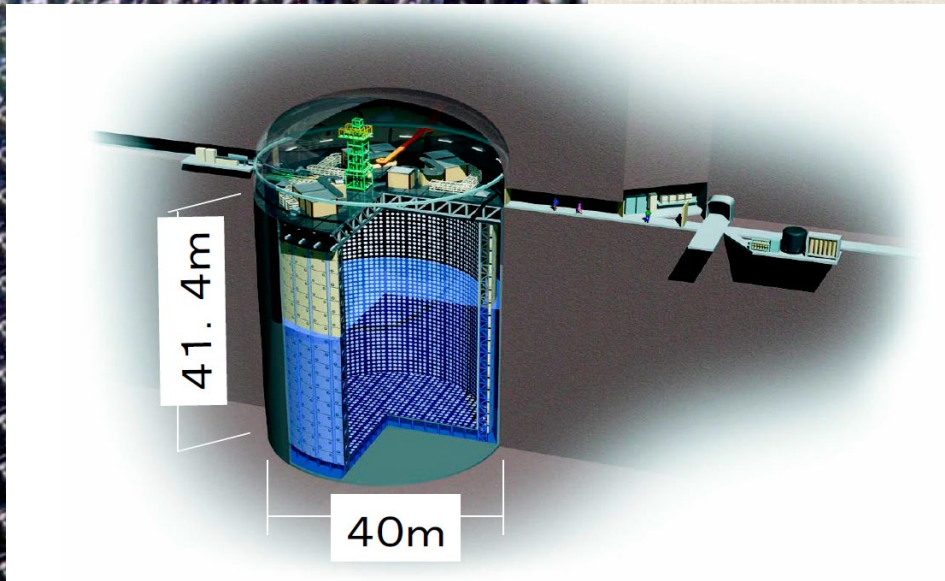
Super-Kamiokande detector

50,000 tons of ultra-pure H_2O

13,000 light detectors

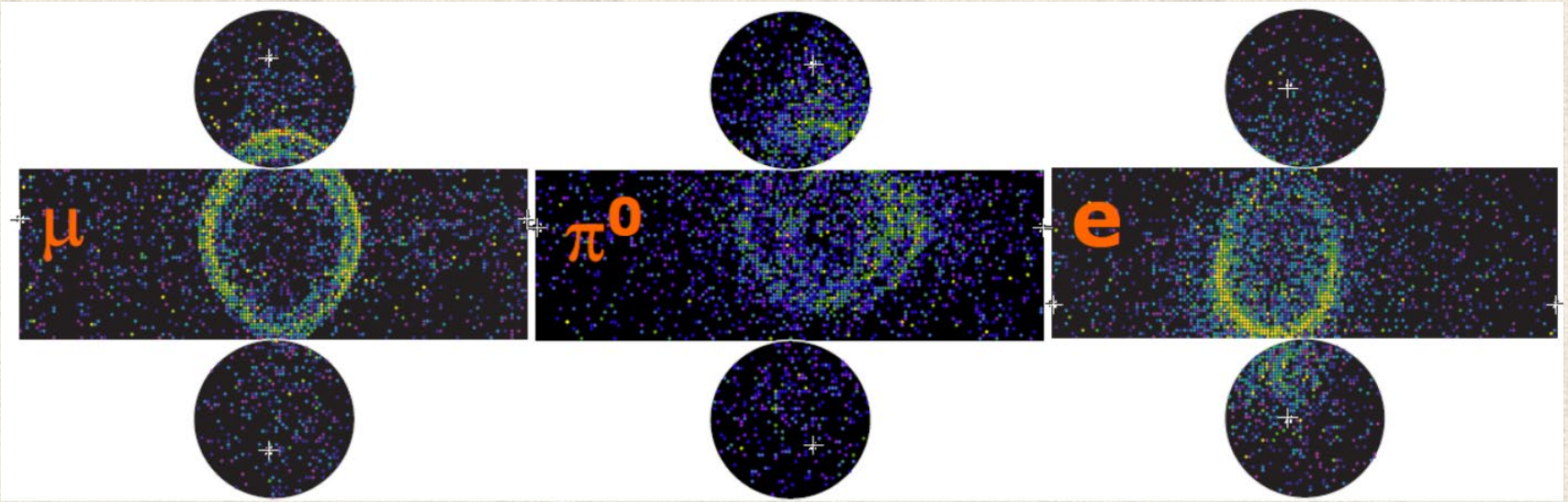
One kilometer underground

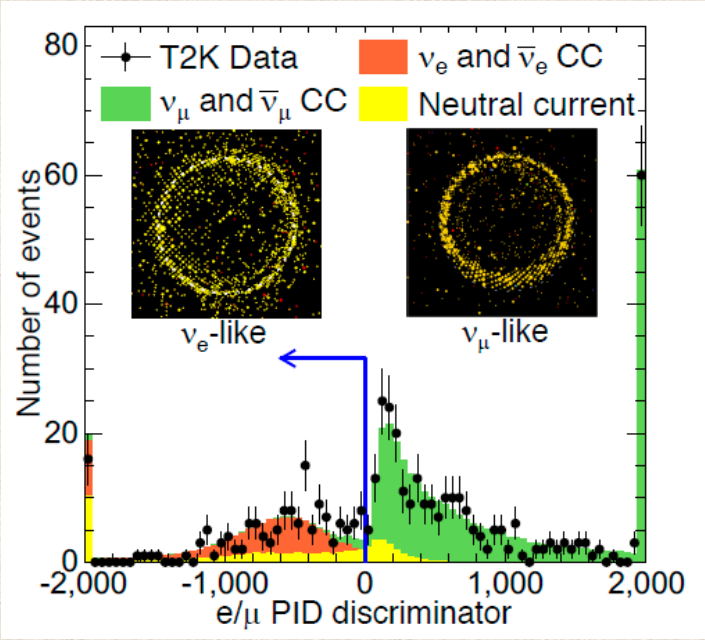




The Super-Kamiokande neutrino detector, in Mozumi, Japan.

T2K signals


μ
π0
e


T2K Data
νe and ν̄e CC
νμ and ν̄μ CC
Neutral current
νe-like
νμ-like
Number of events
80
60
40
20
0
-2,000
-1,000
0
1,000
2,000
e/μ PID discriminator

T2K oscillation analysis method

$$N_{FD}(E_{rec}) = \sum_{E_t} \Phi(E_t) P_{osc}(E_t) \sigma(E_t) \epsilon(E_t, E_{rec})$$

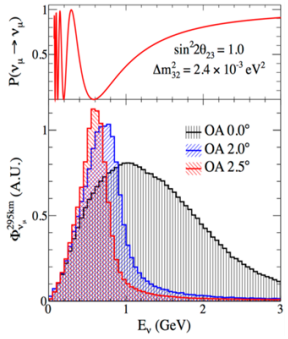
E_t:true ν energy, ε:efficiency

extracting oscillation parameters
by comparing observation and prediction at FD.
But, uncertainties from ν flux and ν-N cross section

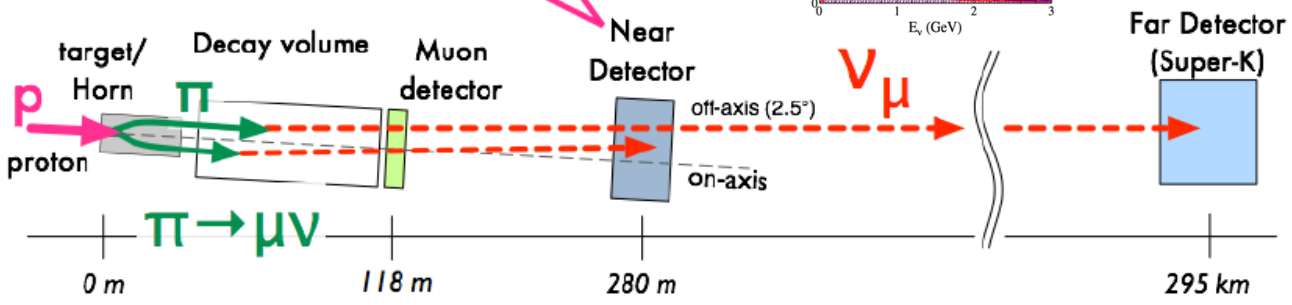
$$N_{ND}(E_{rec}) = \sum_{E_t} \Phi(E_t) \sigma(E_t) \epsilon(E_t, E_{rec})$$

Modeling ν flux and ν-N cross section and constraint those models by ND data

Target N. : C,O
Acceptance : Forward dir.



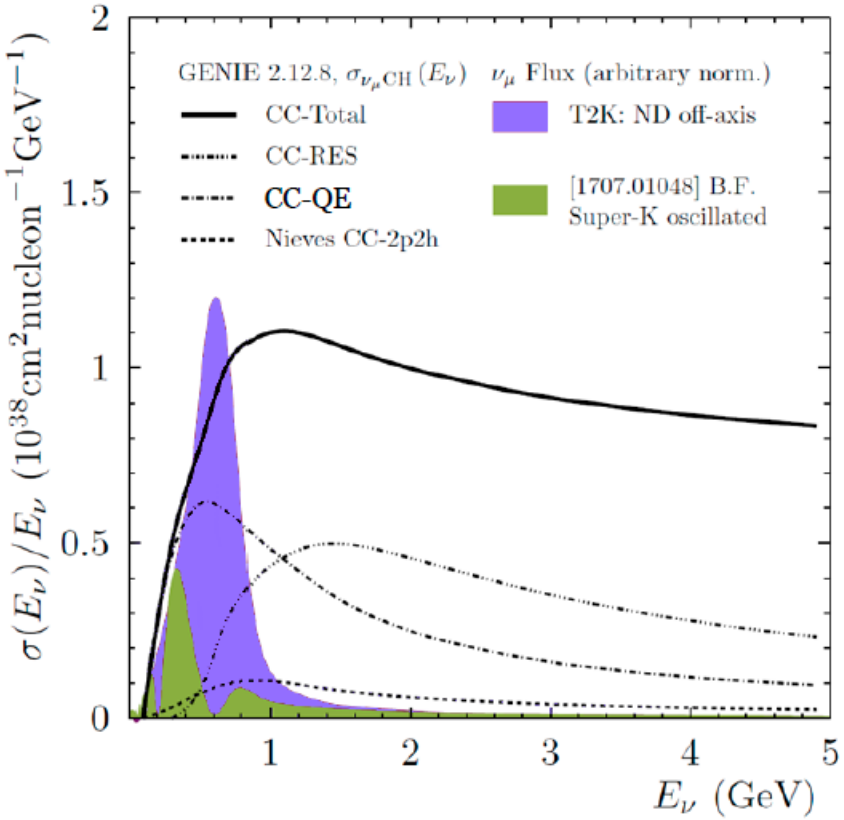
Target N. : O
Acceptance : 4π



taking into account difference of target nucleus and acceptance btw ND and FD

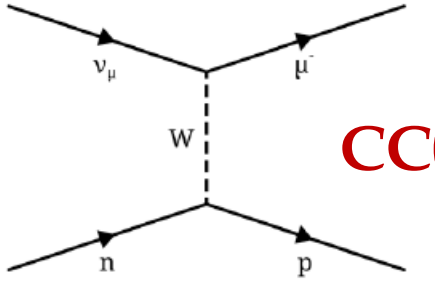
12

Neutrino Interactions at T2K



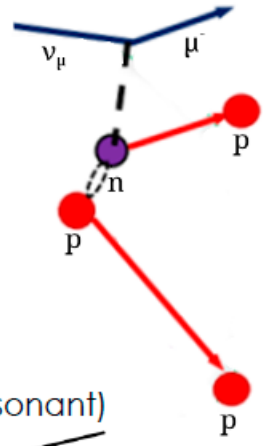
$$N_\mu(E_\nu) = P(\nu_\mu \to \nu_\mu)\sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

CCQE (1p1h)
(Charged-Current Quasi-Elastic)

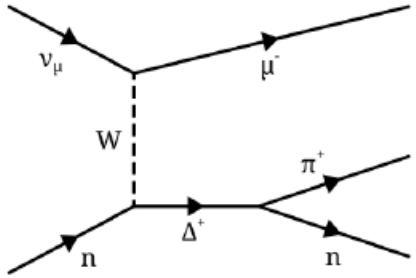


CC0π

2p2h
(2 particle, 2 hole)



CCRES
(Charged-Current Resonant)

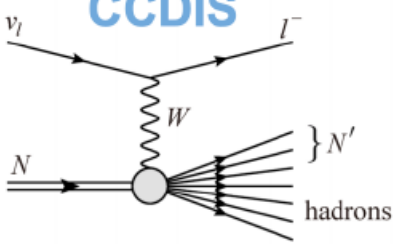


CC1π

ND280 samples

CC deep inelastic scattering

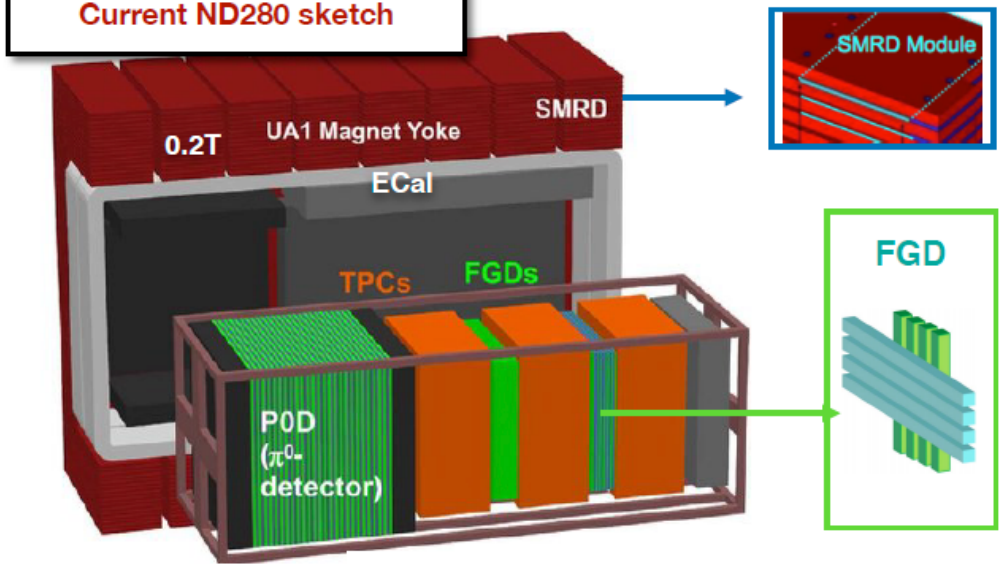
CCDIS



CCOther

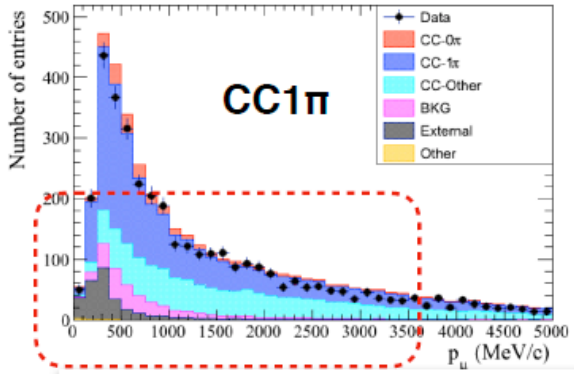
The current ND280 detector

Current ND280 sketch



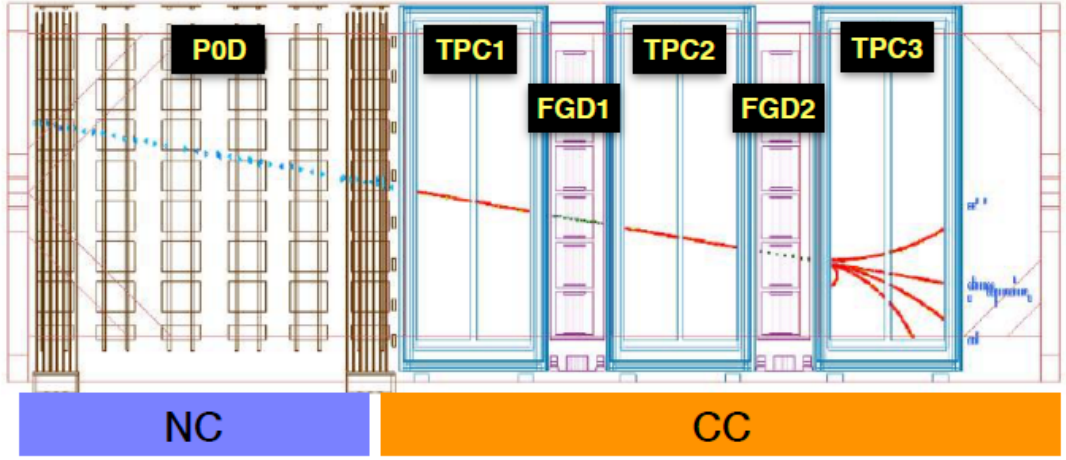
Current limitations

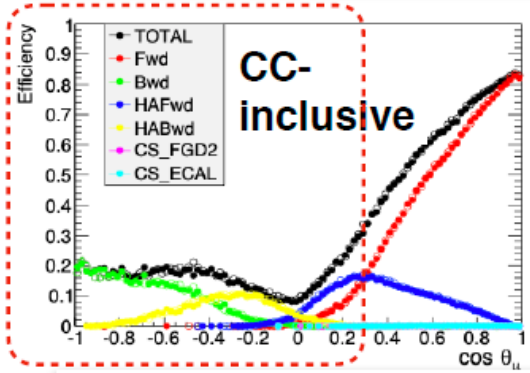
- Tracks w/o TPCs (high angle).
- Tracks w/o TPCs (low momentum).
- Limited timing information.
- No 3D.
- No neutrons info.



Sub-optimal purity in some samples

Event display of basket elements



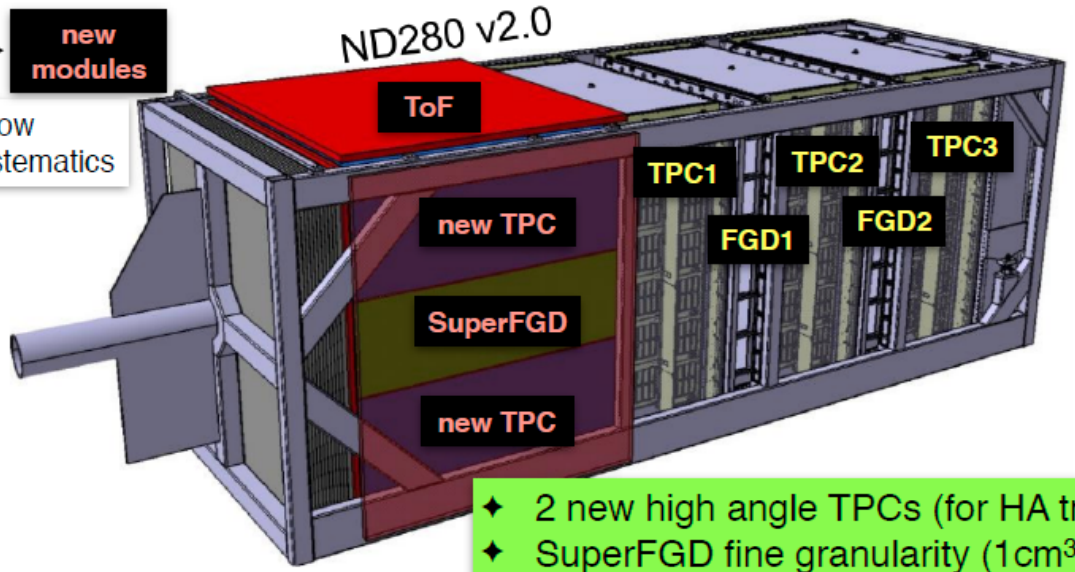


Efficiency is mainly forward

The upgraded ND280 detector

P0D → new modules

The P0D is now limited by systematics



Milestones

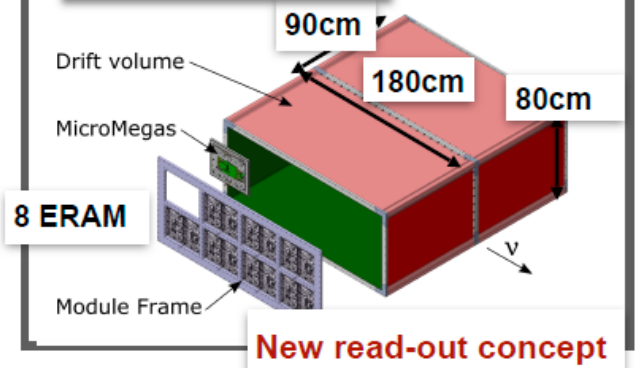
- 2018 → TDR
- 2021/22 final modules
- 2022 installation
- late 2022 data taking!

Solutions of the upgraded ND280

- 2 new high angle TPCs (for HA tracks!)
- SuperFGD fine granularity (1cm^3 ~isotropic) (3D, neutron detection and lower momentum threshold)
- 6 ToF panels (150ps) + new SuperFGD electronics (better timing!).

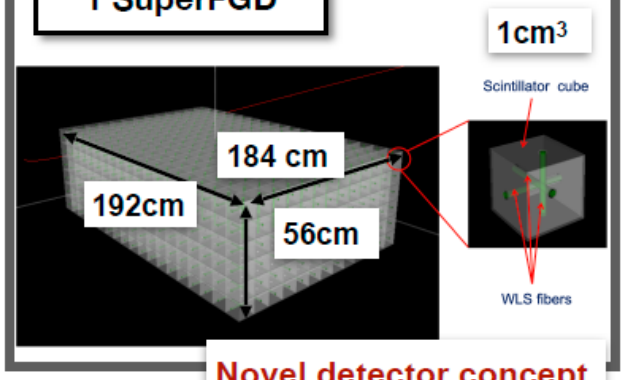
A lot of R&D going on!

2 High Angle TPCs



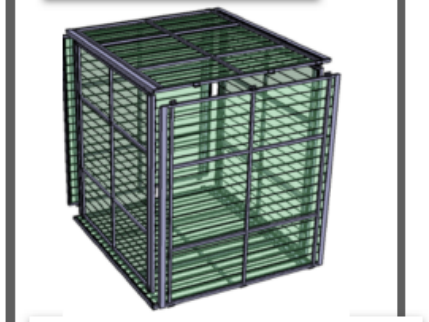
New read-out concept

1 SuperFGD



Novel detector concept

6 ToF panels



150 ps time resolution

Physics motivation

Present ND280

ND280 provides mainly acceptance for tracks in forward direction, while Super-Kamiokande has 4π acceptance

Neutrino nucleus interactions are not well known → model dependence

The near-to-far prediction in oscillation analysis relies on a cross-section model

Upgrade

- Important to measure neutrino interactions in all phase space
- Precisely detect particles produced at any angle
- Reduce detection threshold, measure protons with low threshold
- Measure neutrons in anti-ν_μ interactions
- Reduce background, obtain better track identification using TOF
- Provide electron/gamma separation

Systematics improvements

Number of ν_μ CC events

		# of events ($/10^{21}$ POT)
current	FGD 1	50507
	FGD 2	50125
upgrade	FGD 1	52655
	FGD 2	51460
	SuperFGD	95490

Sensitivity to flux and cross section parameters for 8×10^{21} POT

arxiv:1901.03750

Parameter	Current ND280 (%)	Upgrade ND280 (%)
SK flux normalisation ($0.6 < E_\nu < 0.7$ GeV)	3.1	2.4
MA_{QE} (GeV/c^2)	2.6	1.8
ν_μ 2p2h normalisation	9.5	5.9
2p2h shape on Carbon	15.6	9.4
MA_{RES} (GeV/c^2)	1.8	1.2
Final State Interaction (π absorption)	6.5	3.4

Projected systematic uncertainties for T2K oscillation analysis for 8×10^{21} POT

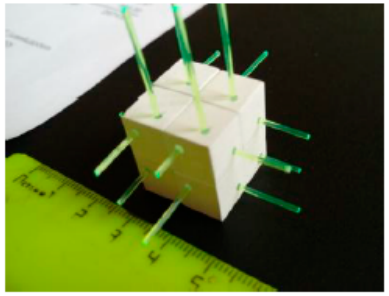
Source of uncertainty	ν_e CCQE-like $\delta N/N$	ν_μ $\delta N/N$
ND280 unconstrained cross-section	3%	1%
Flux + cross-section (constrained by ND280 upgrade)	1.8%	1.9%
SuperKamiokande detector systematics	1%	1%
Hadronic re-interactions	1%	1%
Total	3.8	2.6

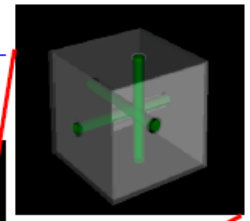
SuperFGD

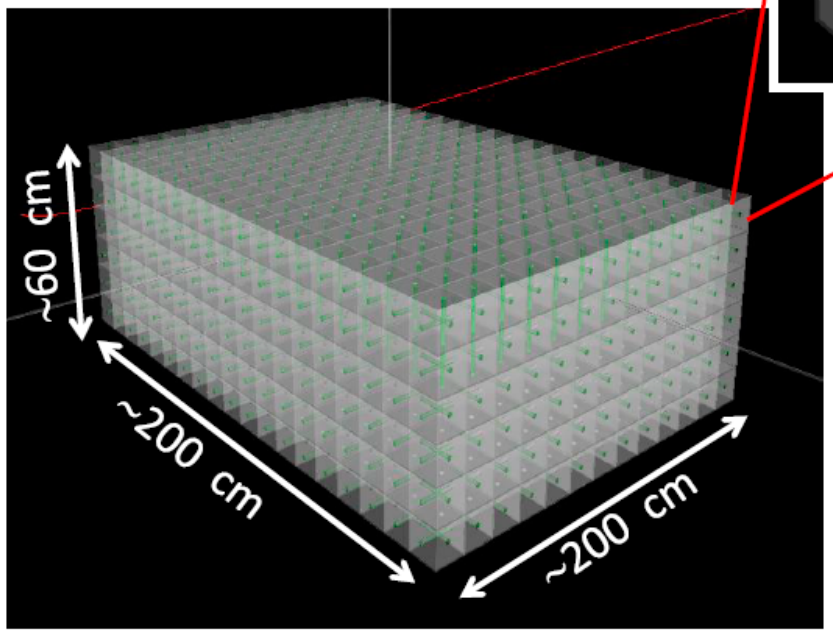
JINST 13 (2018) 02006

- Volume ~200 x 200 x 60 cm^3
- **~2 x 10^6** scintillator cubes , each 1 x 1 x 1 cm^3
- Each cube has orthogonal 3 holes, diameter 1.5 mm
- 3D (x,y,z) WLS readout
- About **60000** readout WLS/MPPC channels
- Total active weight about **2 t**

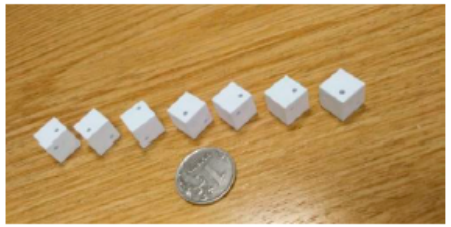
Fully active, highly granular, 4π scintillator neutrino detector with 3D WLS/MPPC readout

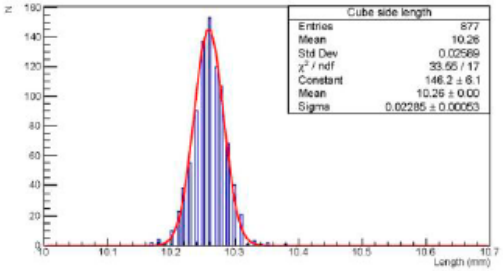






Cubes produced by injection molding
Covered by chemical reflector
Tolerance (each side) about 30 microns



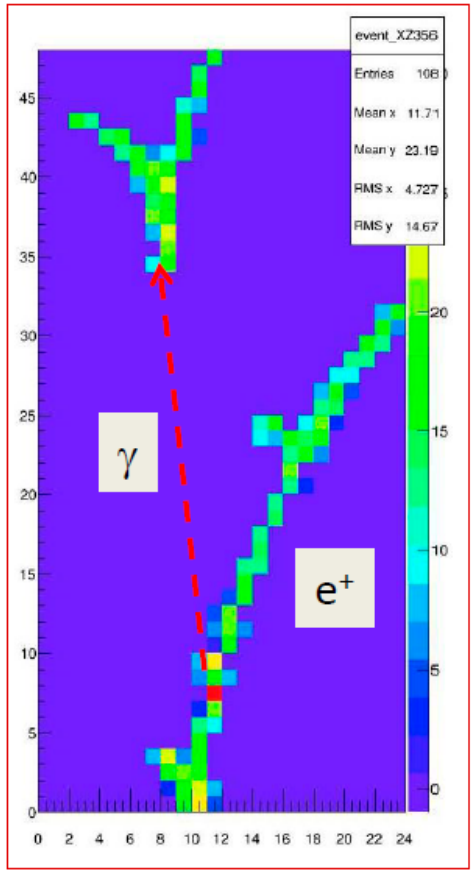


3 holes in each cube drilled
with the tolerance of 50-70 microns

Beam events

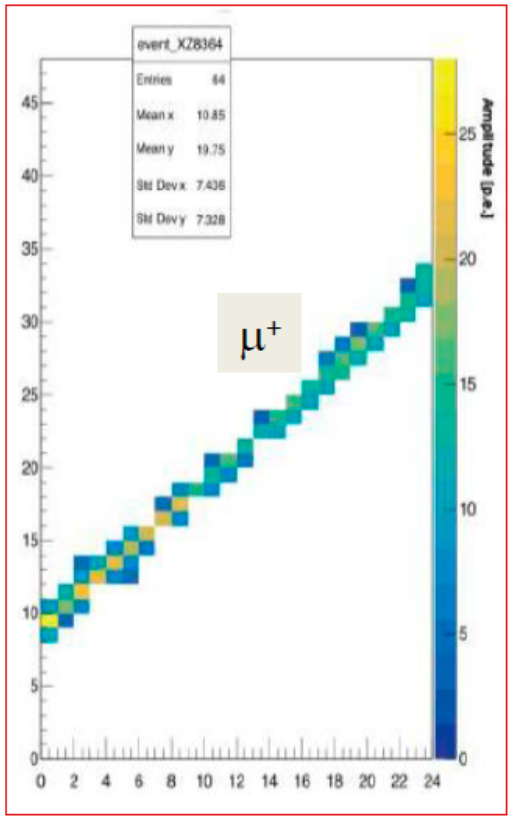
Positron, 1 GeV, B = 0.2 T

Top view



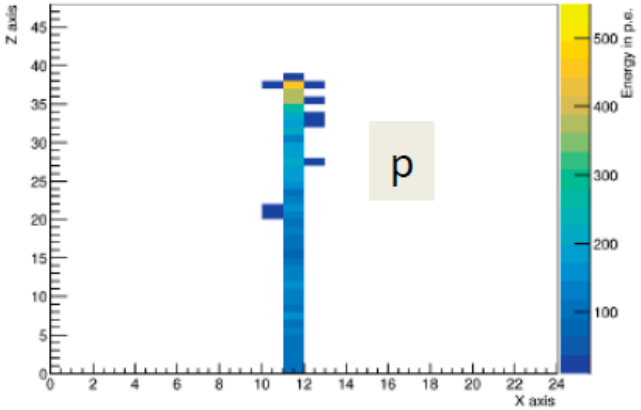
Muon, 5 GeV, 45 deg

Top view

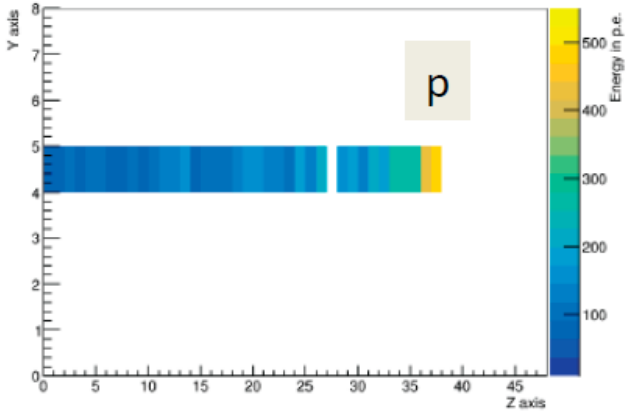


Stopped proton, 0.8 GeV

Top view

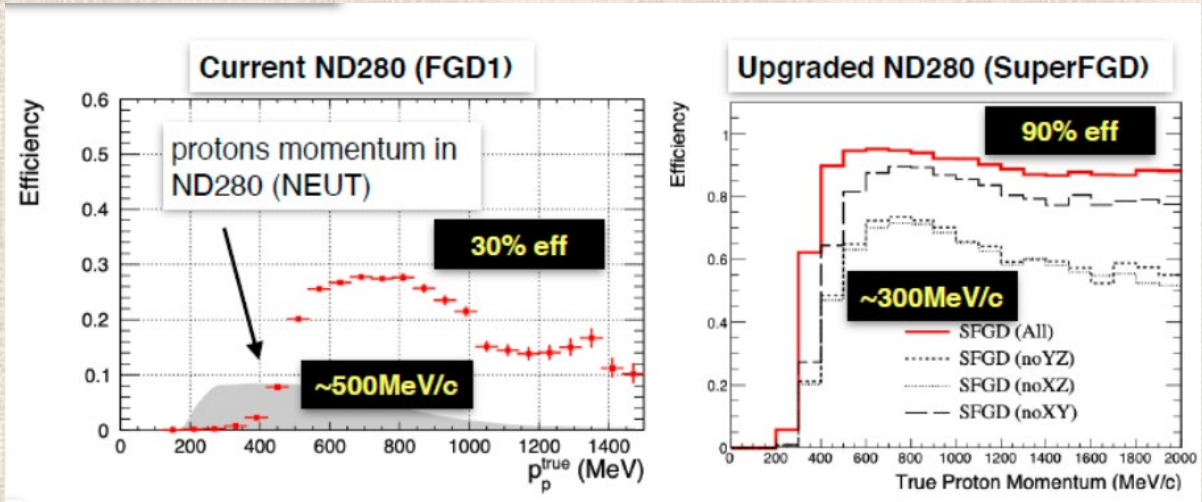


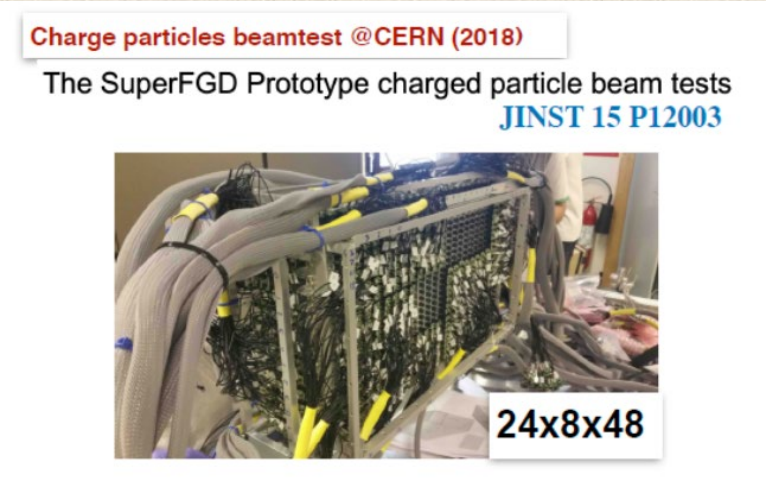
Side view

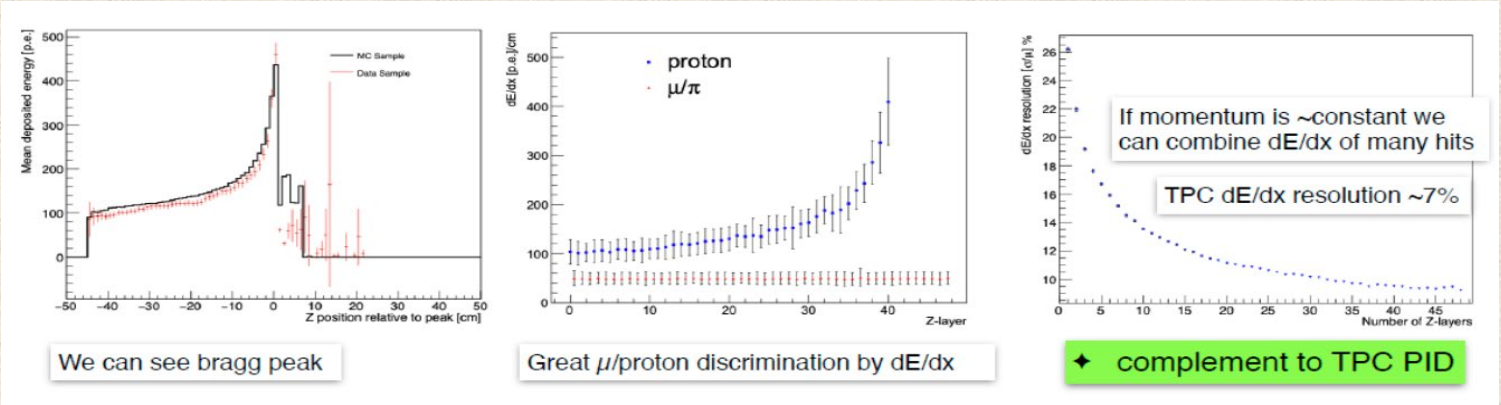


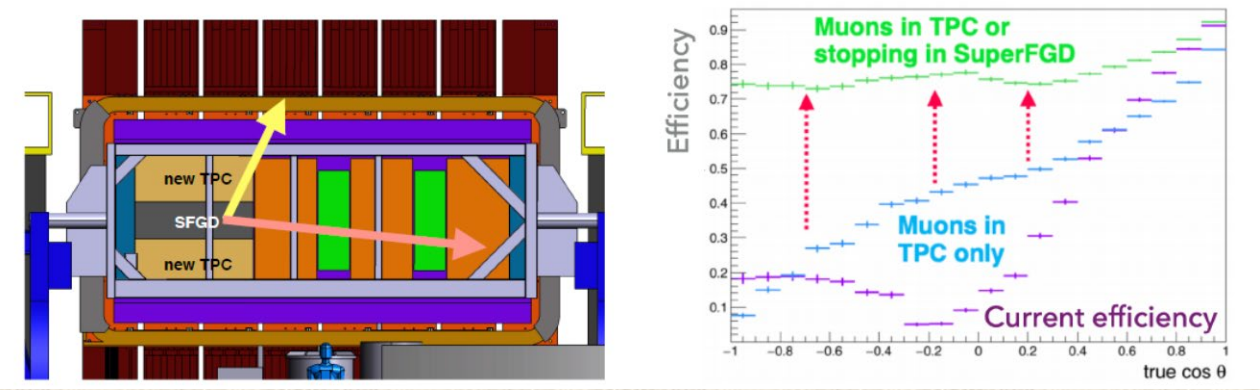
Upgraded ND280

Reduce detection threshold









NEUTRON DETECTION

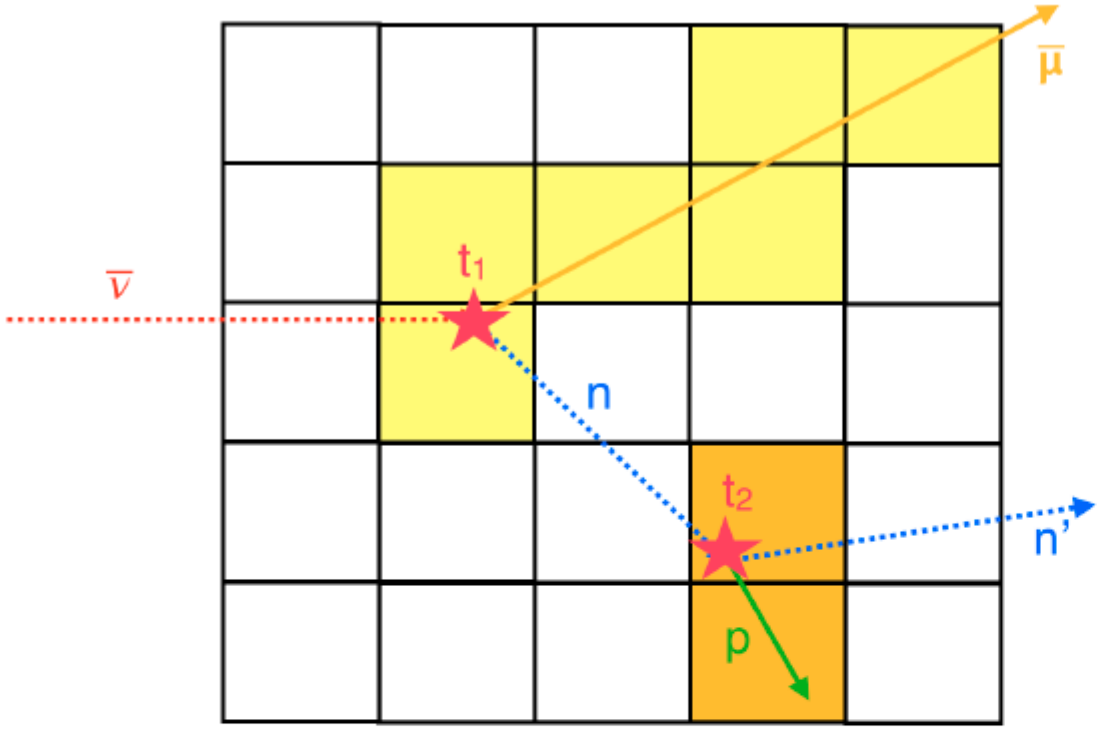


FIG. 3. Representation of an indirect neutron detection through the identification of a proton coming from a secondary neutron interaction. Each cube in the picture represents a detection element (e.g. a single scintillator cube) whilst the lines represent true particle trajectories. An anti-neutrino is shown entering the detector and interacting with a nucleus to produce a muon and a neutron at time t_1. The neutron then interacts at time t_2, ejecting a proton from a nucleus which is detected. The difference between t_1 and t_2 can be used to infer the neutron energy.

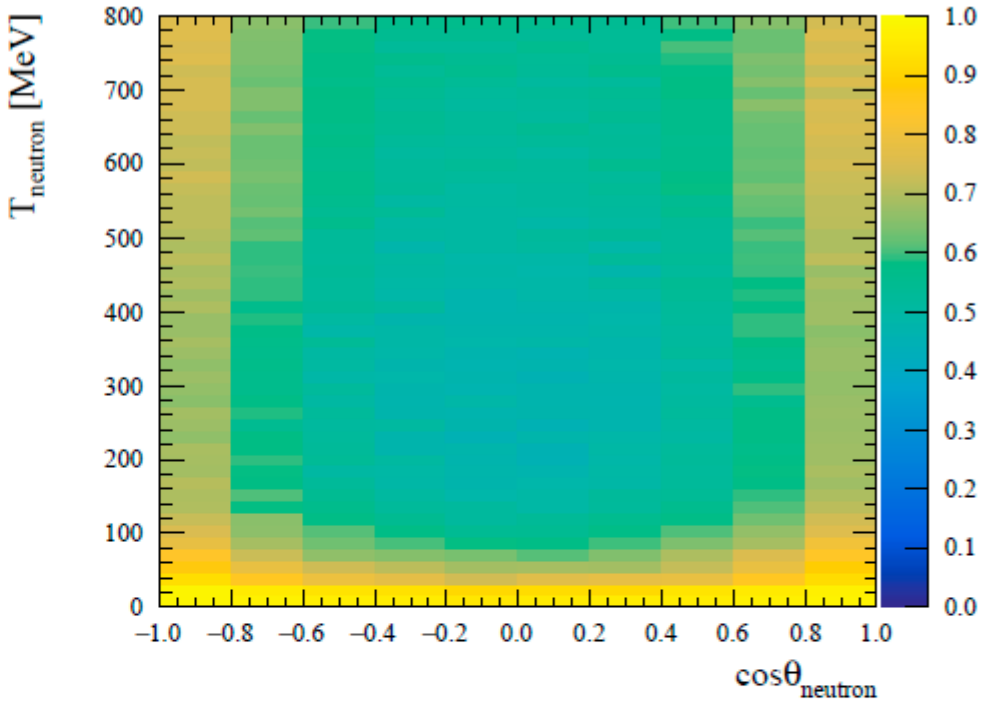
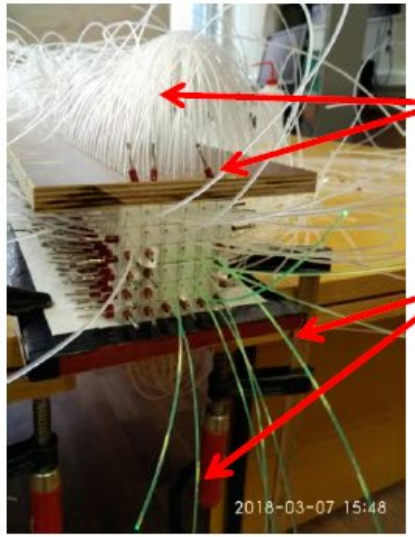


FIG. 4. The neutron detection efficiency for the detector proposed in [14] ($2 \times 0.6 \times 2$ m^3) determined from particle gun simulations.

Assembly procedure

Baseline method: 1- assembly of planes and whole detector using fishing lines
2 - replacement of fishing lines by WLS fibers



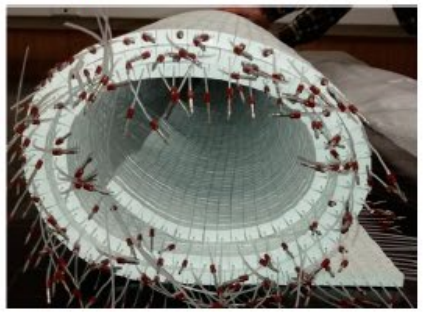
Fishing lines

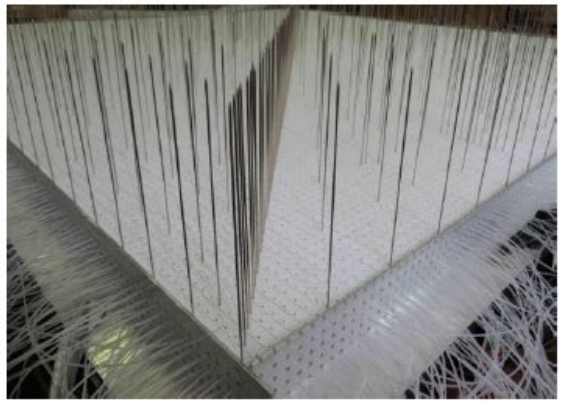
Y11 WLS fibers

Method was tested with small prototypes

Four panes assembled with fishing lines and stainless steel needles

Swiss roll made of a plane of cubes

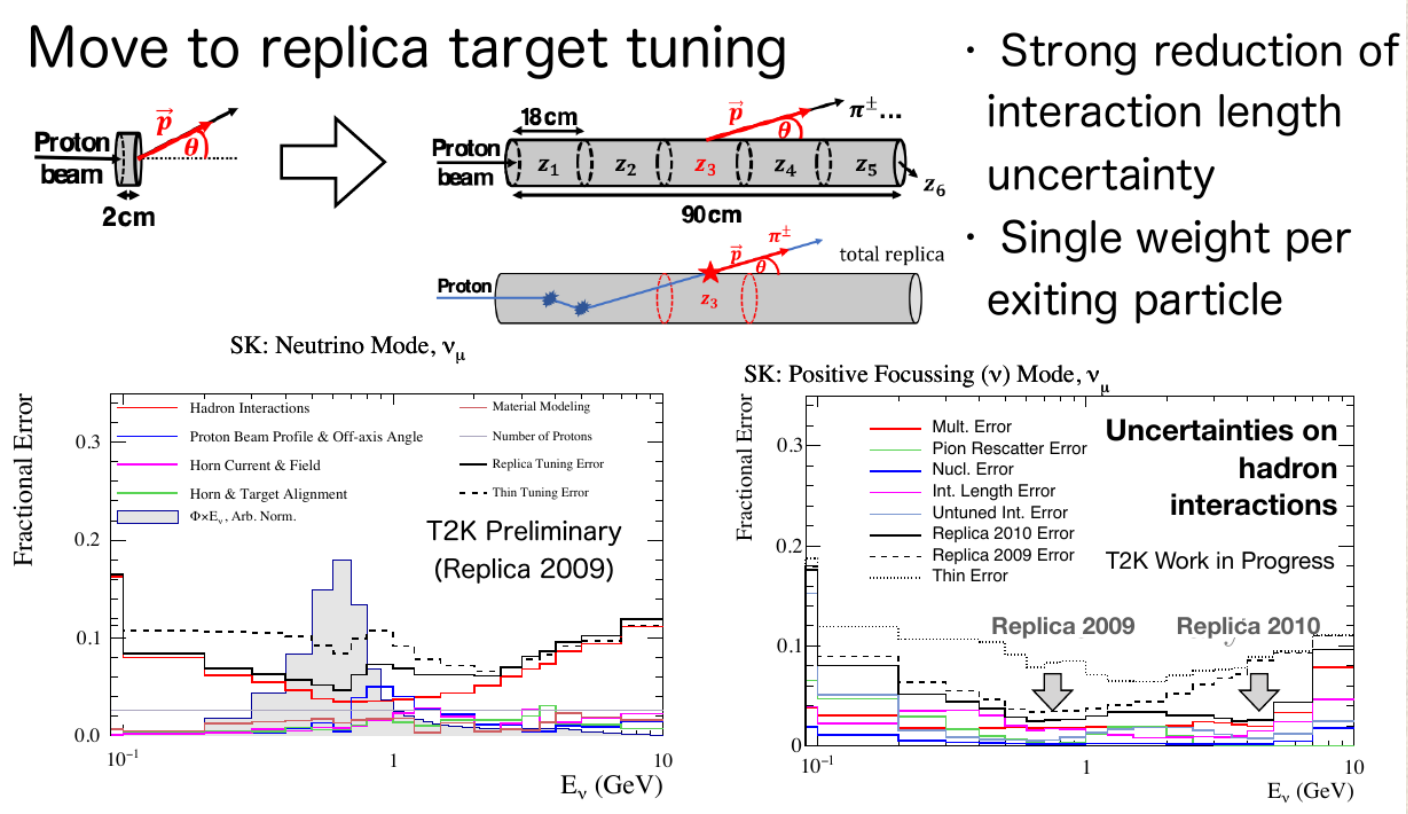




JINR participation in T2K

- Study of the secondary particle yields from graphite target
- Participation in the simulation and data analysis to reduce systematic uncertainties for T2K data
- SFGD box design (alternative variant) Special NOTE
- Design of the SFGD assembly platform and tooling for assembling
- Development of the electronics for LED calibration system
- Study of cubes parameters

NA61/SHINE for T2K-II/HK

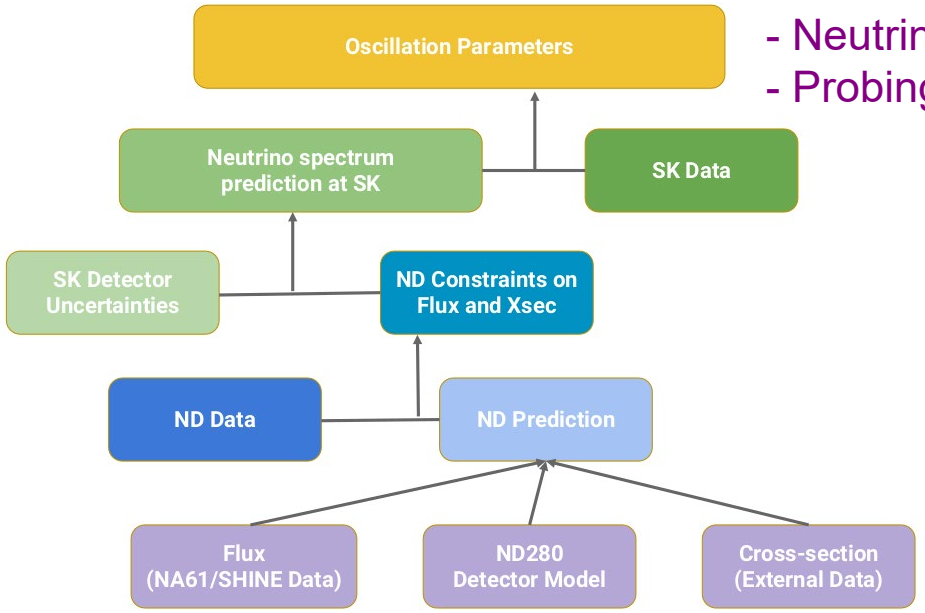


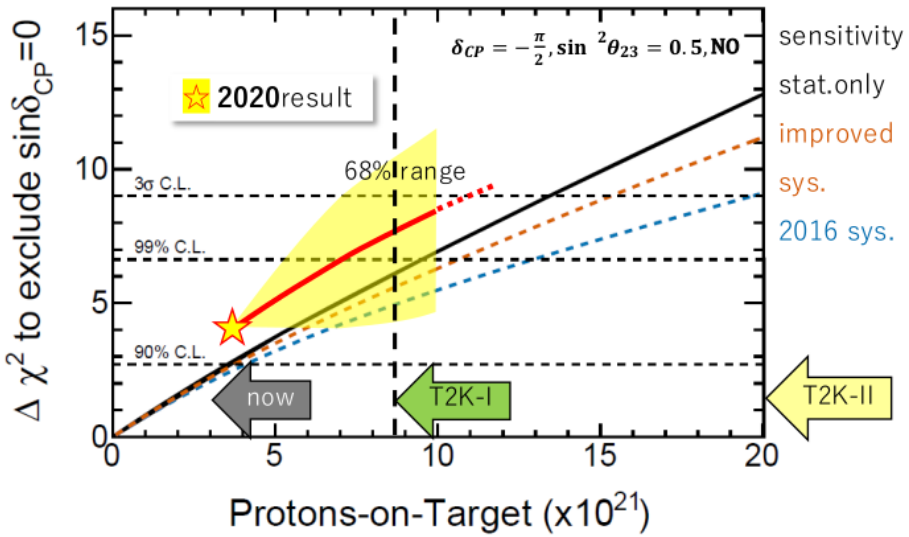
- Strong reduction of interaction length uncertainty
- Single weight per exiting particle

- NA61/SHINE replica-target measurements allow for a significant improvement in T2K (anti-)neutrino flux uncertainty (down to ~5%, unprecedented for accelerator experiments). Even a better knowledge is desired for T2K-II and Hyper-K. New measurements with Carbon target are planned after the CERN LS2 (see CERN-SPSC-2018-008). Additional plans:
  - Improved measurements with T2K replica target, maybe considering alternative target material – Super-Sialon (Si N Al O);
  - Hadron production with lo beam (<12 GeV/c).
  - Improve (anti-)neutrino flux uncertainty down to 3-4%

Oscillation analysis using T2K data

- Parameters of interest: δ_{CP}, $sin^2\theta_{23}$, Δm^2_{32} and $sin^2\theta_{13}$
- Neutrino mass hierarchy
- Probing of the consistency of the PMNS framework





- DLNP group participation in T2K oscillation analysis:
  - analyzing new data obtained with the upgraded ND280 detector;
  - developing event selection methods;
  - performing studies on various types of systematic uncertainties;
  - developing software tools for analysis

- On the first stage (year 2022) we expect to join to the ongoing T2K analyses and focus on adapting and developing their methods with respect of the upgraded ND280 detector.

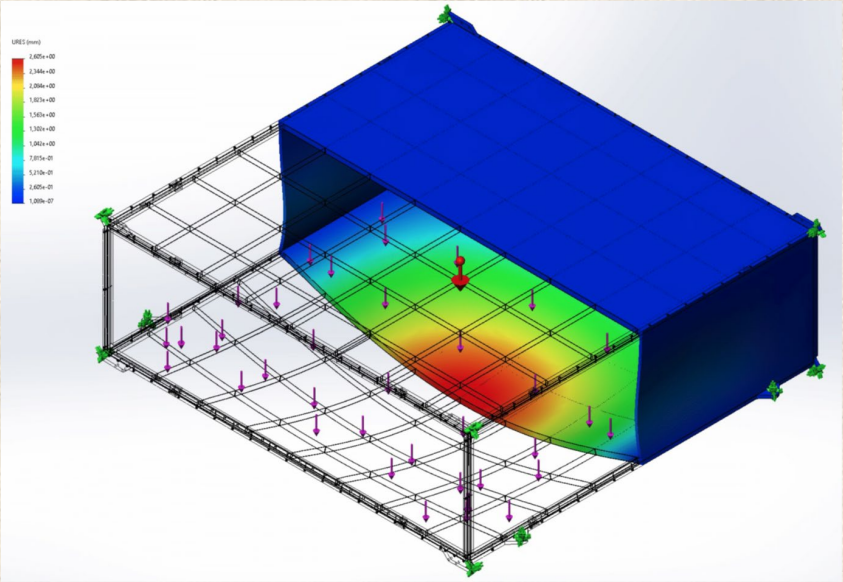
- As soon as the new data from the T2K upgraded arrives and is available (years 2023 and 2024), we are going to participate in analysis of them and in obtaining physical results.

JINR contribution to the SFGD assembly platform

Nikolai Kirichkov, Andrey Shaikovsky, Alexandra Sinitsa, A.O. Brazhnikov

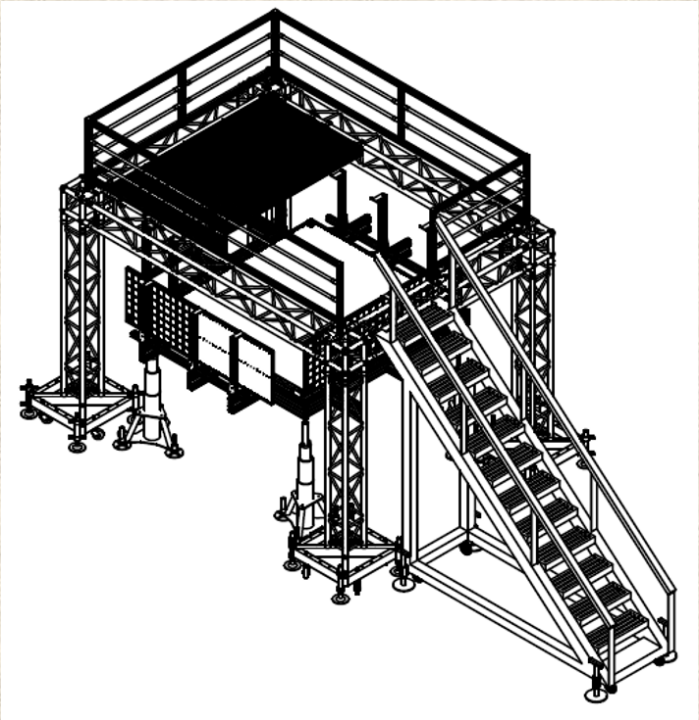
- **Alternative box design with bottom panel reinforcing ribs and suspensions for earthquake compensation**
- **seismic calculation**
- **design of the platform for the SFGD assembly in J-PARC**

A subgroup for SFGD assembly is formed (Yu. Davydov, M. Khabibulin)



Максимальные деформации ящика детектора SFGD при сейсмическом воздействии (2,5 мм)

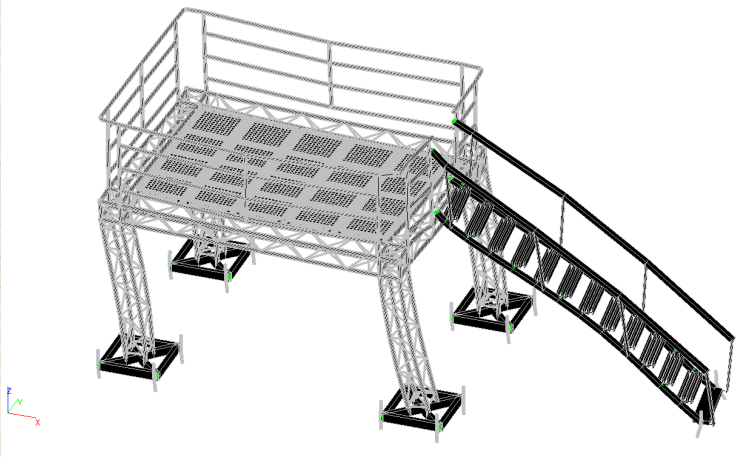
Сборка платформы и опорной системы для первого этапа работ



Seismic calculations

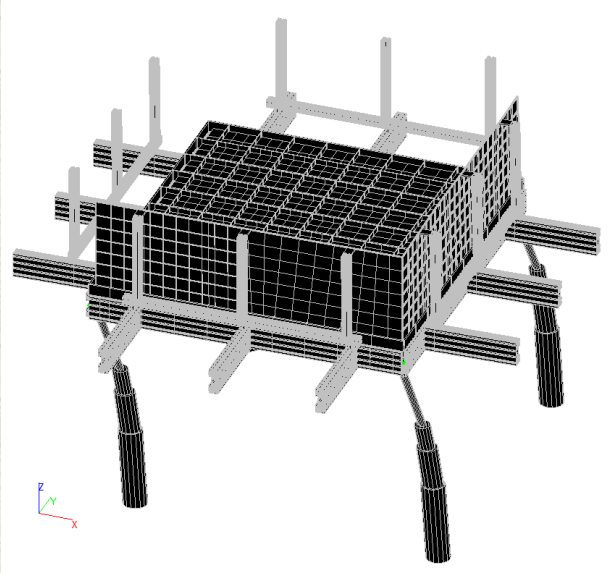
расчет прочности и жесткости по нормам строительства в сейсмических районах Дальнего востока (9 баллов, 0.65 g)

Calculation of strength and stiffness according to construction standards in seismic regions of the Far East (9 points, 0.65 g)



Расчет собственных колебаний системы доступа

Calculation of natural vibrations of the access system



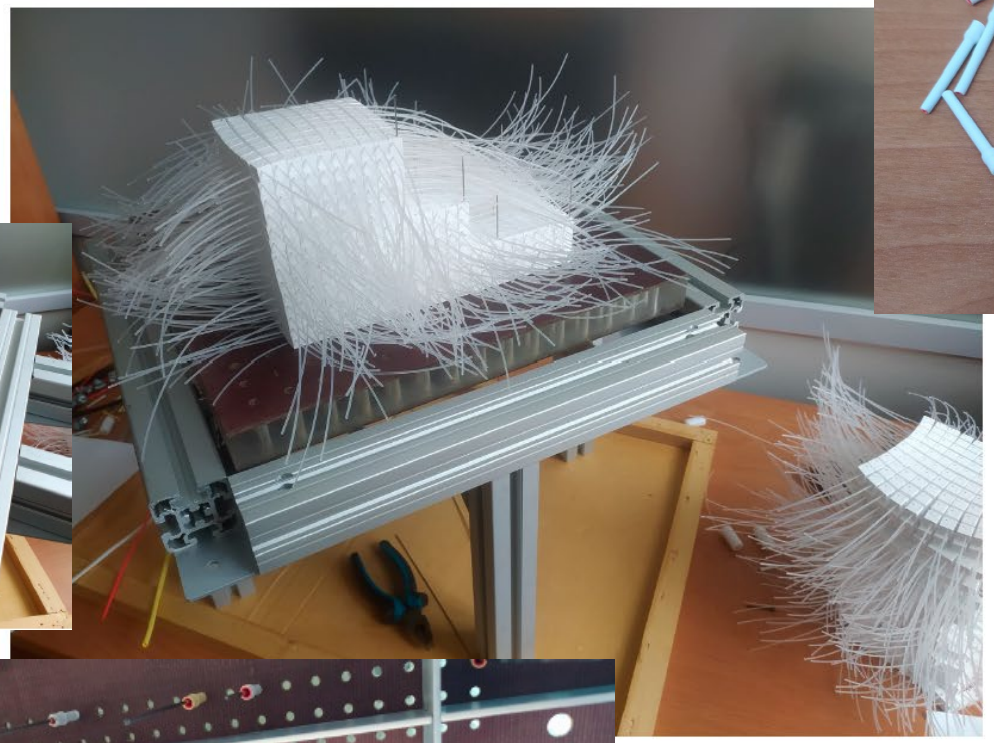
Расчет собственных колебаний опорного стола

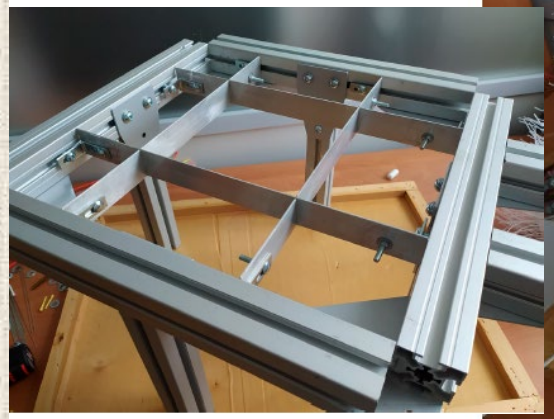
Calculation of natural vibrations of the support table

SFGD detector assembly platform and tooling

Work with a prototypes

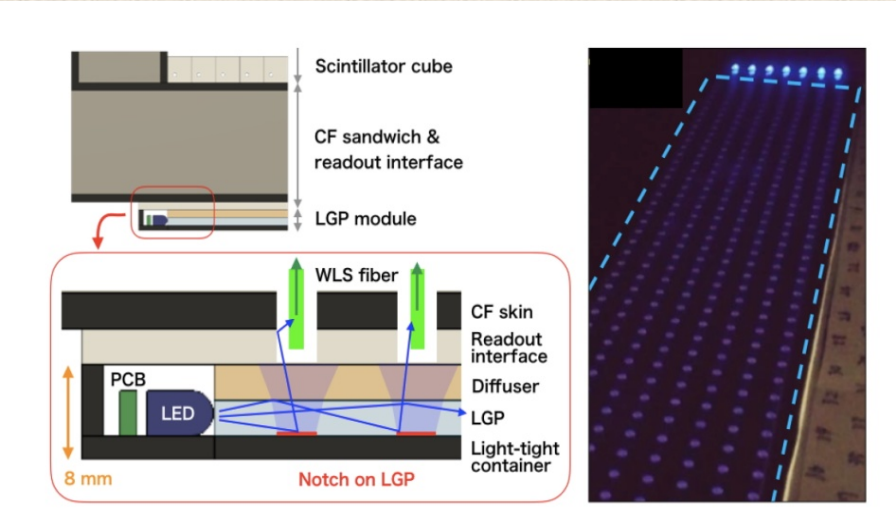
A.Shaikovskiy for JINR Team (Dubna)
15.02.2021

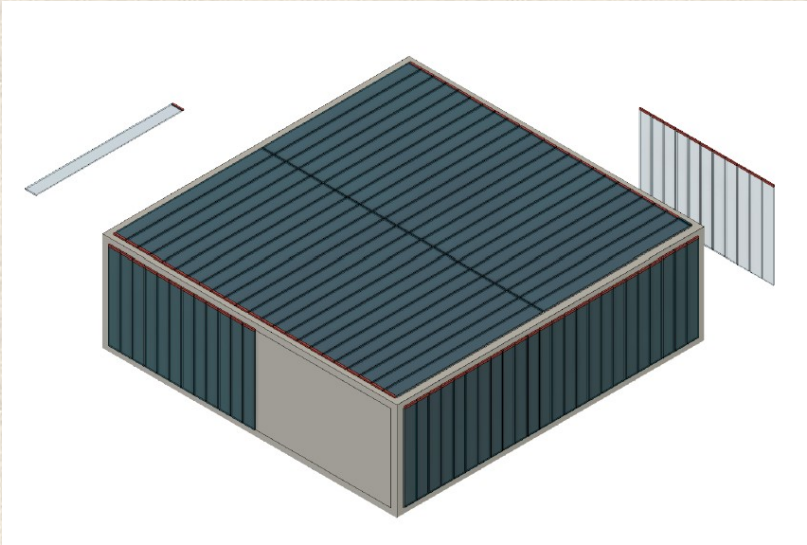


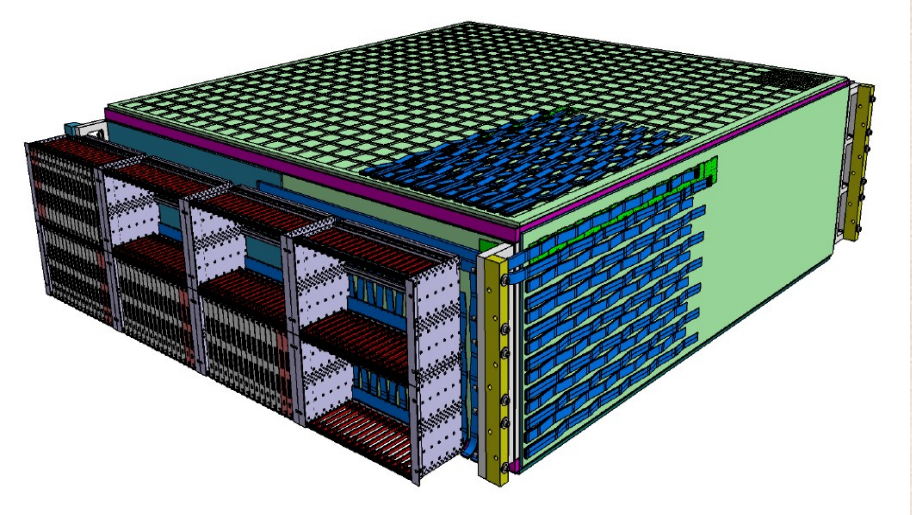


JINR contribution to the calibration system of SFGD

The LNP develops electronics for the SFGD calibration system. The figures show the concept of the calibration system. 93 LGP modules are located around the detector and allow us to calibrate all 56k MPC

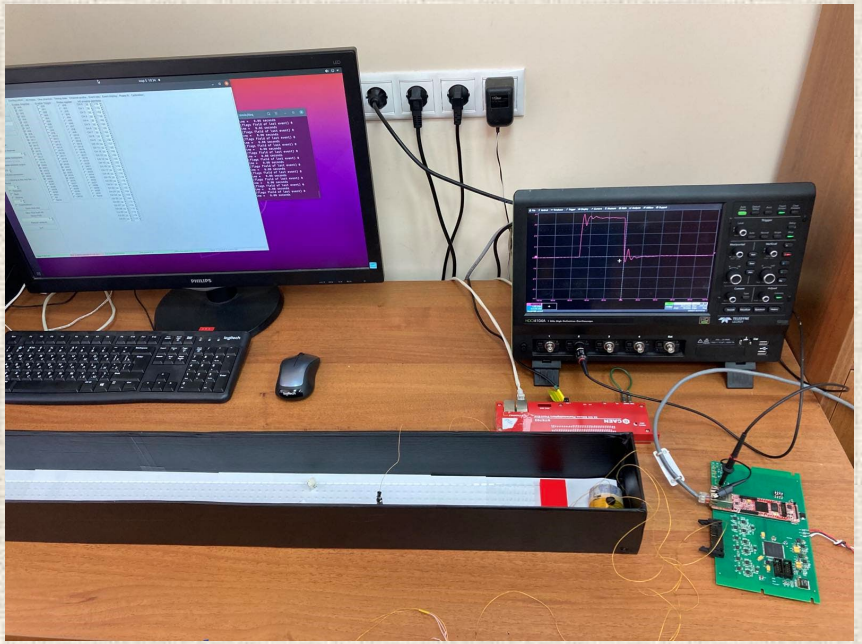


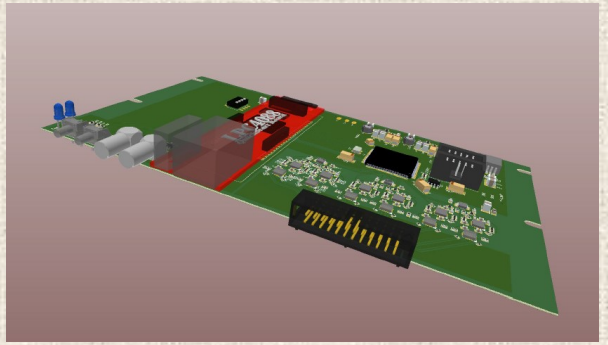


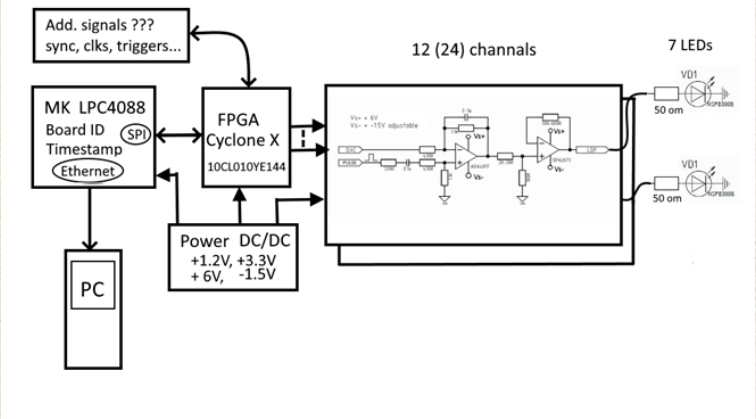


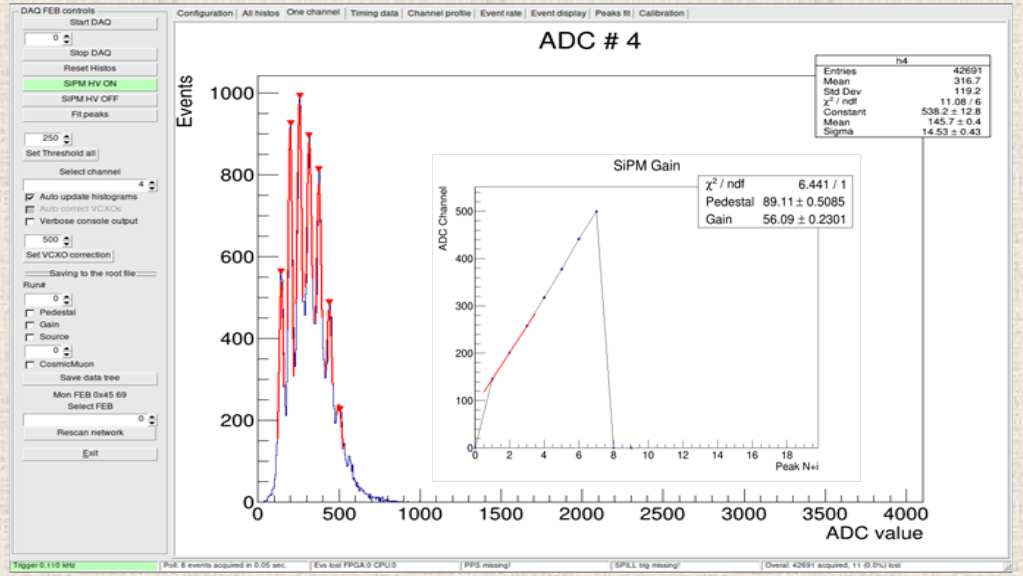
JINR contribution to the calibration system of SFGD

The slide shows the module of the 12-channel SFGD electronics board. The detector will use 8 such modules. The graphs demonstrate the calibration of a single LGP channel by single photons.

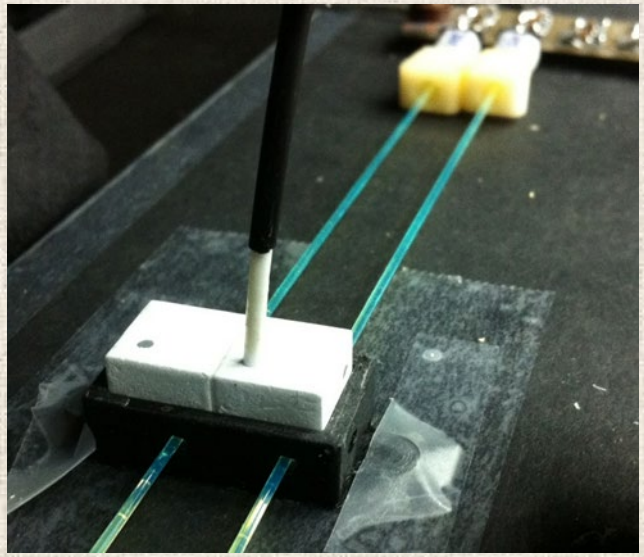


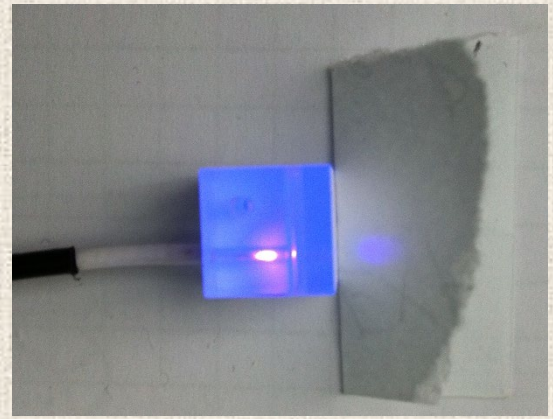




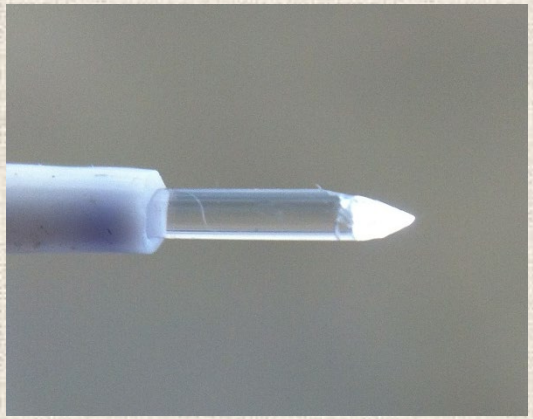


SFGD cubes optical crosstalk study with LED

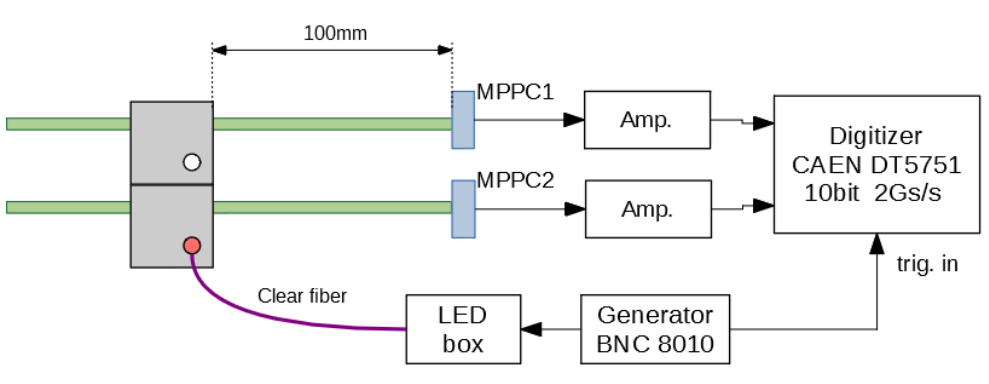




The scintillator cube excited by the LED. Reflective coating has been removed from one side for demonstration.

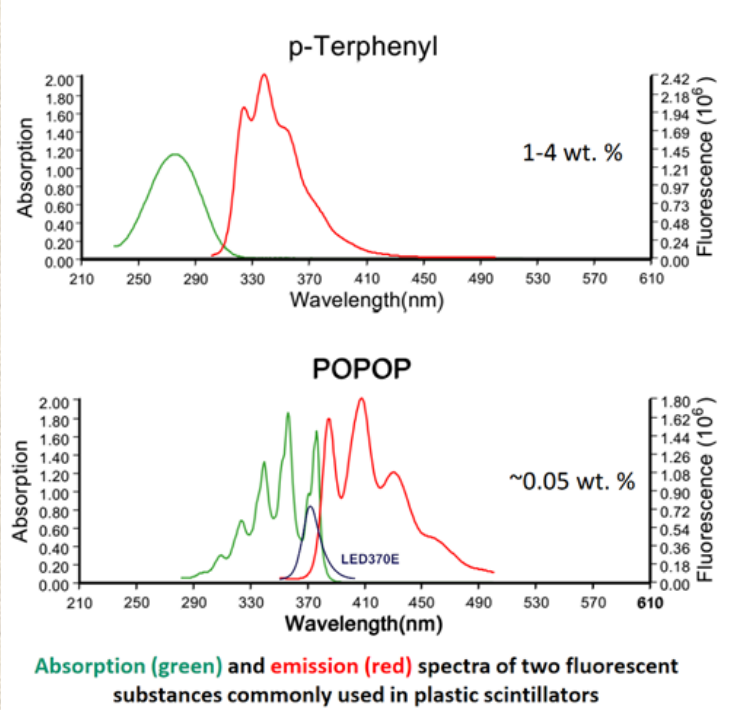


The clear fiber used for light injection has a tapered end.

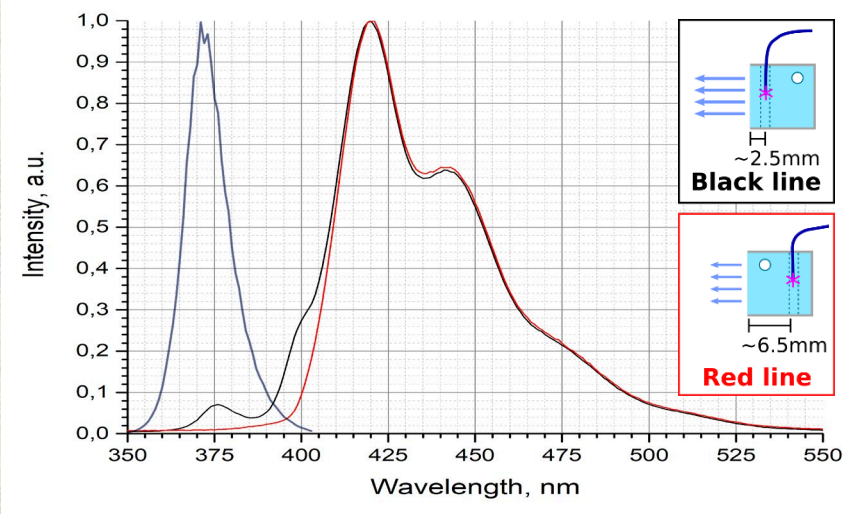


- Fibers: d=1mm, no reflectors/attenuators
- MPPC: Hamamatsu S13360-1350CS 1.3x1.3 mm^2

SFGD cubes optical crosstalk study with LED



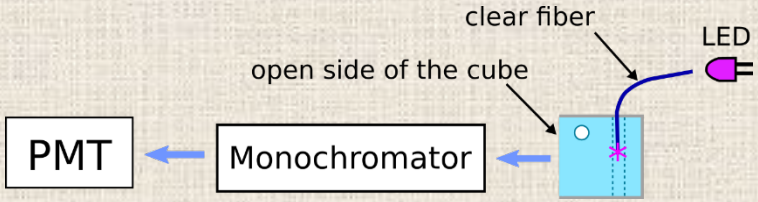
Absorption (green) and emission (red) spectra of two fluorescent substances commonly used in plastic scintillators



SFGD cubes composition:

- polystyrene base,
- (1.5%) paraterphenyl (PTP) ,
- (0.01%) of 1.4-bis benzene (POPOP).

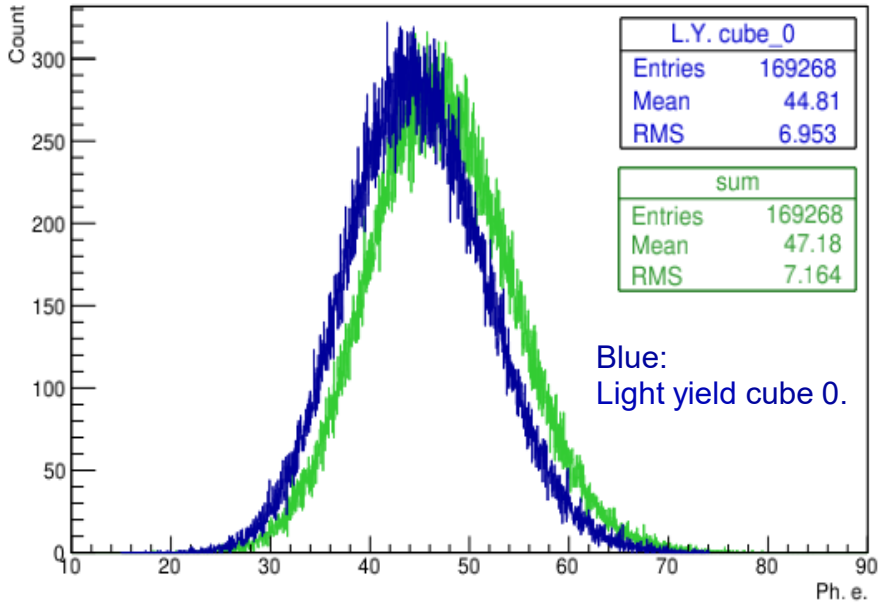
Reflective coating has been removed from the one side of the cube. The light coming out of the cube goes to the entrance slit of the monochromator. High light intensity of the LED.



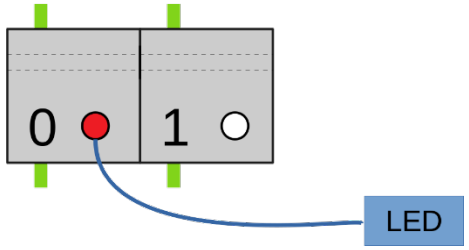
Monochromator (190-1100nm) + PMT Hamamatsu R2059 were used for the measurements. PMT anode current has been measured using Keithley 6487 picoammeter.

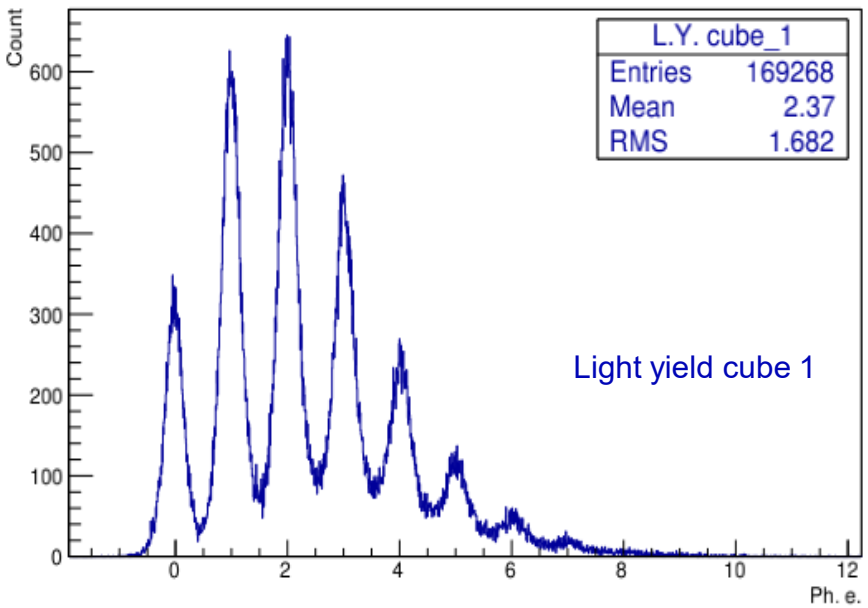
Wavelength of the LED light is in the range of absorption of POPOP.
→ The spectrum of the light which comes out of the cube is mostly the same as one from scintillation.

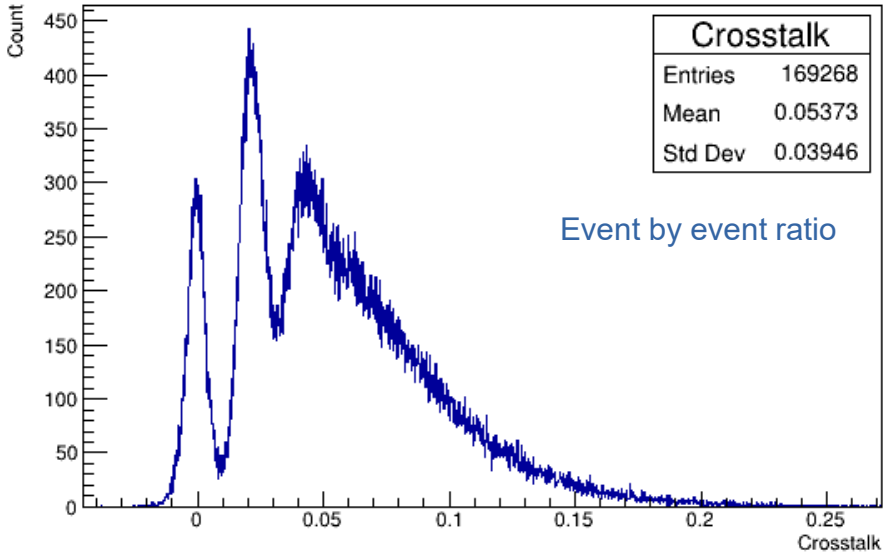
LED light injection into cube 0. (No common fiber, hole is open)



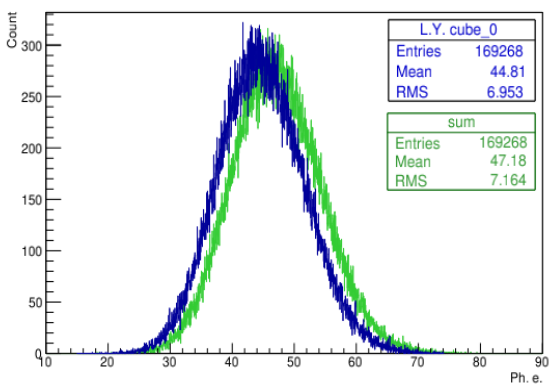
Green: event by event sum:

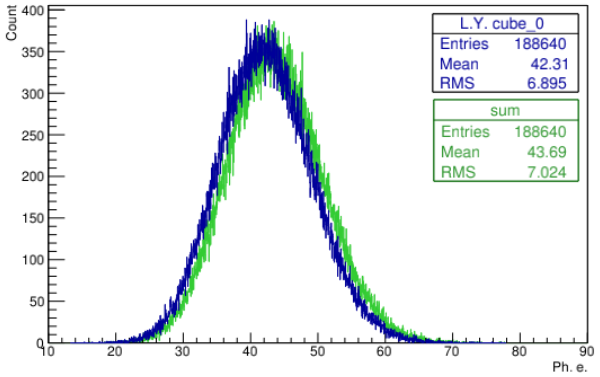


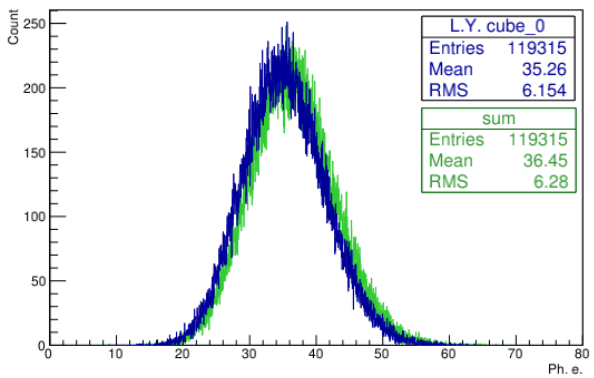




Optical crosstalk for different cases. Led light injection into cube 0

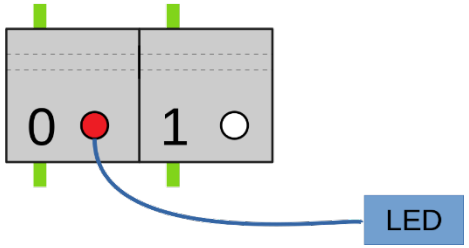


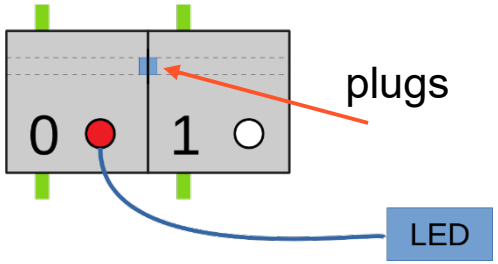


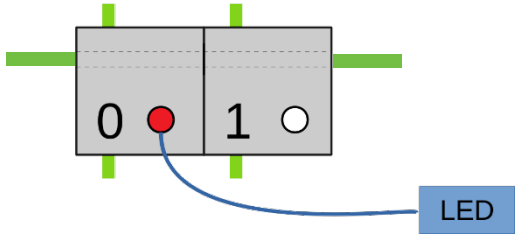


Blue: Light yield cube 0

Green: event by event sum

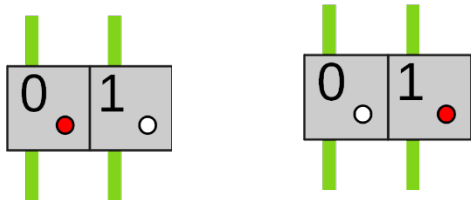






Measured optical crosstalk of the two cubes (%)

The red dot / label indicates the point of light injection.

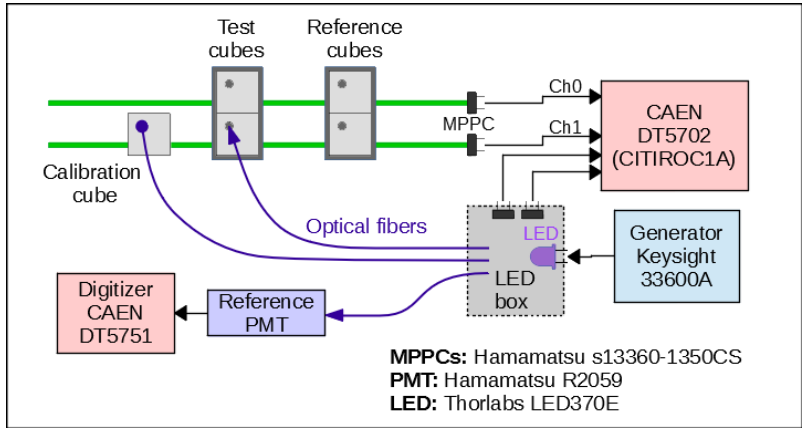


Ratio of the light yield mean values of the cubes

LED light injection into:	0	1
No common fiber, hole is open	5.29±0.34	2.87±0.28
Common fiber hole is closed with plug.	3.27±0.32	1.87±0.26
Common WLS fiber inserted.	3.35±0.29	1.76±0.25

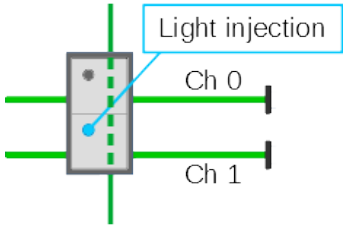
Study of heating influence on the light yield and crosstalk of the cubes

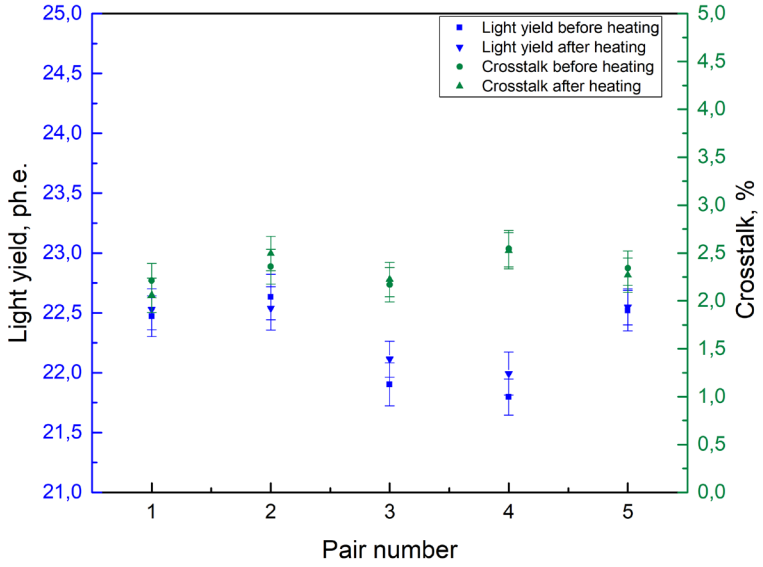
- We want to check how temperature treatment, for example, heating of the transportation container during the transportation of the detector from CERN to J-PARC could affect on the scintillating properties of the cubes and on the reflecting coating and consequently crosstalk.
- Using the UV LED (λ≈375 nm) light injection into the cubes we can measure the light yield and crosstalk of the cubes before and after heating and compare the results.
- Heating of the cubes we are going to do using the industrial thermostabilized chamber.
- We have selected 5 pairs of cubes, measured their light yield and crosstalk before heating and then put it to the thermostabilized chamber and kept under 60 °C for 24 hours, and then allowed them cool to room temperature for 20 hours before measuring.
- Each measurement of the light yield of the cubes was accompanied by measurement of the LED intensity using the PMT Hamamatsu R2059. Using the PMT as a reference will let us to compare the results despite of the LED intensity drift during the measurements. On the plot below one can see the LED intensity drift.



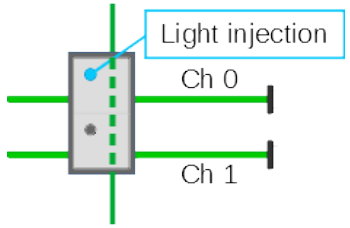
Results

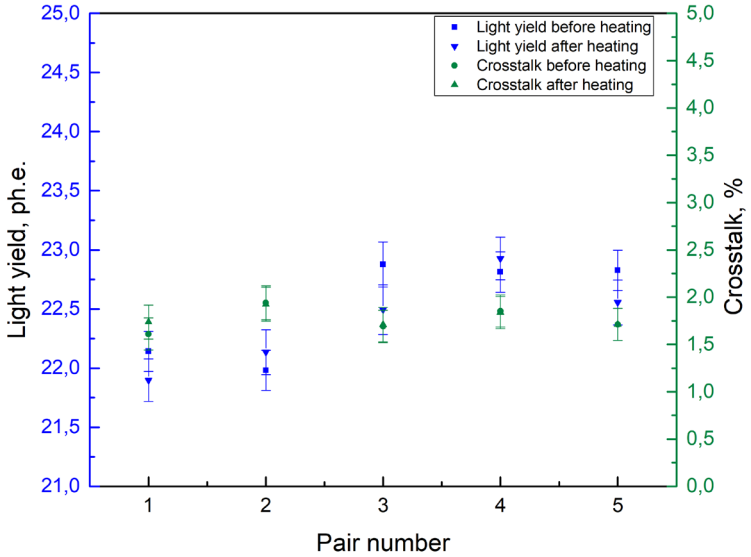
Case 1:





Case 2:





•As one can see, the light yield and crosstalk did not changed significantly after heating.

Plans of the JINR group in T2K

- Finalize design of the SFGD assembly platform (2021)
- Participation in the assembling of the SFGD (2022)
- Participation in the creation of the LED calibration system for SFGD (2021-2022)
- Possible participation in the DAQ of the SFGD (2022)
- Participation in the start-up and maintenance of the SFGD during data taking (2022-2024…)
- Participation in the simulation and data analysis SFGD and T2K in perspective (2022-2024…)
- Participation in the HYPER-KAMIOKANDE in the perspective (HK outer detector, data analysis)

		2022	2023	2024
1	Simulation and data analysis	Improvement of T2K (anti) neutrino flux uncertainty down to 3-4%. Adapting and developing T2K analysis method with respect of upgraded ND280 detector. $ 8 k	T2K data analysis $ 10 k	T2K data analysis $ 10k
2	SuperFGD mechanics. Finalize design of the SuperFGD assembly platform.	Assembling of the SuperFGD	Hyper-Kamiokande Outer detector PMT support system design	Hyper-Kamiokande Outer detector PMT support system design
3	RnD for detector subsystems. SuperFGD properties investigations.	Assembling and start-up of the SuperFGD at near detector facility. Study of the SuperFGD properties. RnD with PMT samples and shifters for Hyper-Kamiokande Outer detector. Materials $ 20 k (scintillators, fibers) Equipment $ 32 k (PMT's, elect. blocks, stand computer)	RnD with PMT samples and shifters for Hyper-Kamiokande Outer detector. Materials $ 20 k (shifters, mech. parts) Equipment $ 30 k (PMT's, elect. blocks)	RnD with PMT samples and shifters for Hyper-Kamiokande Outer detector. Finalize design of the shifters. Materials $ 15 k (shifters, mech. parts) Equipment $ 30 k (PMT's, elect. blocks)
4	Electronic for SuperFGD LED calibration design and DAQ	Creation, assembly and start-up of the calibration system. DAQ support of the SuperFGD. Equipment $ 20 k	Development of electronics and DAQ for further upgrade of the ND280 and Hyper-Kamiokande (Outer detector) Equipment $ 15k	Development of electronics and DAQ for further upgrade of the ND280 and Hyper-Kamiokande Equipment $ 10 k
5	SuperFGD/ND280 maintenance, T2K data taking shifts, meetings, conferences	Participation in the SuperFGD start-up, data taking shifts, meetings $ 85 k	SuperFGD/ND280 maintenance, T2K data taking shifts, meetings, conferences $ 85 k	SuperFGD/ND280 maintenance, T2K data taking shifts, meetings, conferences $ 85 k
6	Operation fee	$ 25 k	$ 35 k	$ 35 k

Estimation of human resources

Name	FTE	Positon	Work (apart common duties like shifts)
V.Yu. Baranov	1.0	Junior researcher	SuperFGD cube tests
A.V. Boikov	1.0	engineer	SuperFGD calibration system
A.O. Brazhnikov	0.3	design engineer	platform and tooling for SFGD assembly
J.A. Budagov	0.2	Chief researcher	SuperFGD
Yu.I. Davydov	0.9	Head of department	SuperFGD assemble group leader
D.L. Demin	0.3	Head of sector	Tests at DLNP Linak-200
V.V. Glagolev	0.6	DLNP Deputy director	SuperFGD
N.V. Khomutov	0.3	scientist	Firmware development
N.V. Kirichkov	0.3	head of the design department	platform and tooling for SFGD assembly
V.I. Kiseeva	1.0	Young researcher	Monte Carlo, data analyses
A.O. Kolesnikov	0.8	Senior engineer	SuperFGD tests
A.V. Krasnoperov	0.3	scientist	Software support
K.K. Limarev	1.0	PhD student	Monte Carlo, data analyses
V.L. Malyshev	0.5	scientist	SuperFGD tests
B.A. Popov	1.0	Senior scientist	Data analyses
A.V. Shaikovskiy	0.7	design engineer category 1	platform and tooling for SFGD assembly
A.A. Sinitsa	0.4	design engineer category 2	platform and tooling for SFGD assembly
I.A. Suslov	1.0	Senior scientist	Monte Carlo, data analyses
V.V. Tereschenko	0.8	Head of group	SuperFGD calibration system
S.V. Tereschenko	0.6	Engineer	SuperFGD calibration system
I.I. Vasilyev	1.0	Junior researcher	SuperFGD cube tests
Total FTE	**14.0**		

Form No. 26

Schedule proposal and resources required for the implementation of the Project

T2K
(Project title)

Expenditures, resources, financing sources			Costs (k$) Resource requirements	Proposals of the Laboratory on the distribution of finances and resources		
				1st year	2nd year	3rd year
Expenditures		Main units of equipment, work towards its upgrade, adjustment etc.	165	60	55	50
		Construction/repair of premises				
		Materials	55	20	20	15
Required resources	Standard hour	Resources of – Laboratory design bureau; – JINR Experimental Workshop; – Laboratory experimental facilities division; – accelerator; – computer. Operating costs.	7000h 600h 420h	3000h 200h 140h	2000h 200h 140h	2000h 200h 140h
Financing sources	Budgetary resources	Budget expenditures including foreign-currency resources.	600 k$	200	205	195
	External resources	Contributions by collaborators. Grants. Contributions by sponsors. Contracts. Other financial resources, etc.	30 10	10 5	10 5	10

PROJECT LEADERS V.V.Glagolev Yu.I.Davydov

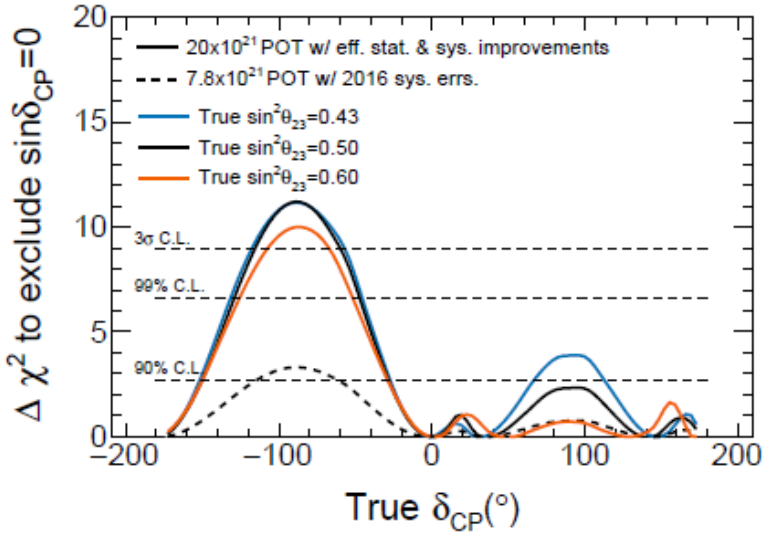
Form No. 29

Estimated expenditures for the Project T2K
(full title of Project)

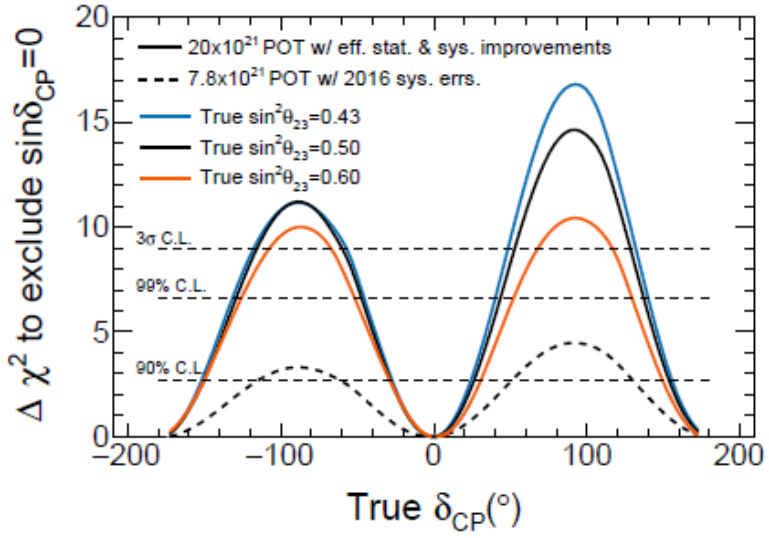
	Expenditure items	Full cost	1st year	2nd year	3rd year…
	Direct expenses for the Project				
1.	Accelerator, reactor	420 h	140	140	140
2.	Computers	h			
3.	Computer connection	k$			
4.	Design bureau	standard 7000 hour	3000	2000	2000
5.	Experimental Workshop	standard 600 hour	200	200	200
6.	Materials	55 k$	20	20	15
7.	Equipment	165 k$	60	55	50
8.	Construction/repair of premises	k$			
9.	Payments for agreement-based research (operation fee)	95 k$	25	35	35
10.	Travel allowance, including:	k$			
	a) non-rouble zone countries	255	85	85	85
	b) rouble zone countries	30	10	10	10
	c) protocol-based				
	Total direct expenses	600	200	205	195

Thank you for attention

T2K-II



(a) Assuming the MH is unknown.



(b) Assuming the MH is known – measured by an outside experiment.

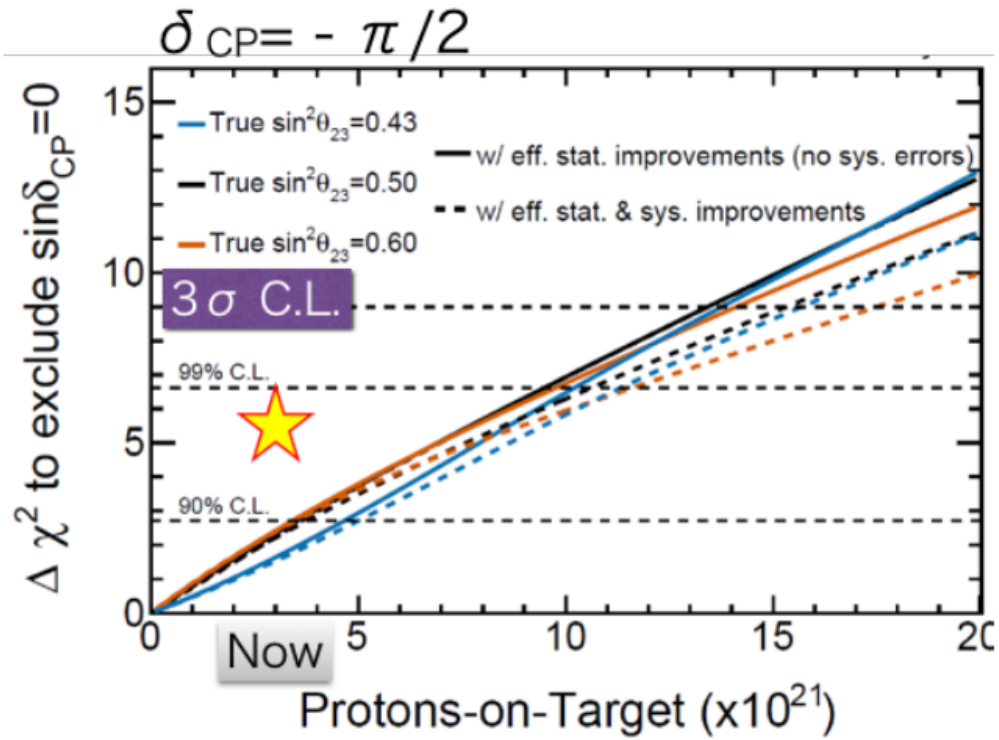
FIG. 2: Sensitivity to CP violation as a function of true δ_{CP} for the full T2K-II exposure of 20×10^{21} POT with a 50% improvement in the effective statistics, a reduction of the systematic uncertainties to 2/3 of their current size, and assuming that the true MH is the normal MH.

arXiv:1607.08004v1 [hep-ex] 27 Jul 2016

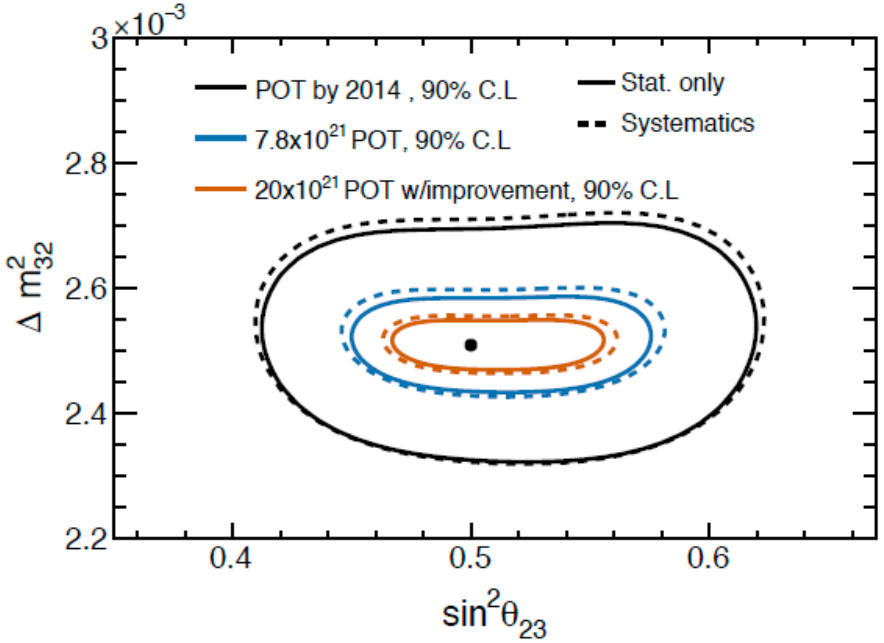
T2K-II Physics Prospects

ND280 upgrade to reduce the total systematic error down to ~ 4%

Sensitivity to exclude $\sin\delta_{CP}=0$



Sensitivity of $\sin^2\theta_{23}$, Δm^2_{32}



>3σ CPV sensitivity

~1% precision of Δm^2,
0.5°-1.7° precision of θ_{23}
(depends on true value)

BACKUP

SWOT Analysis

The **strengths** of the project are undoubtedly its fundamental nature and focus on the missing model parameters of neutrino physics - measuring the neutrino mixing parameter responsible for the cp-parity violation and improved accuracy of neutrino mixing parameters, θ_{23} and Δm^2_{32}.

The T2K-II experiment is based on a well-developed relatively simple technique for reconstructing Cherenkov light in water and the optimal parameters of the distance to the far detector and neutrino energy for a successful and hopefully the world's first δ_{cp} measurement result.

Further goals include the group's participation in the new generation Hyper-Kamiokande project which will follow up the T2K-II experiment. Hyper-K apart from studying neutrinos from an accelerator will provide wide program of neutrino physics in particular the detection of astrophysical neutrinos from sources such as dark matter annihilation, gamma ray burst jets, and pulsar winds could further improve our understanding of some of the most spectacular, and least understood, phenomena in the Universe.

It should be noted that in comparison to US experiments (NOvA, LBNE), there is a huge advantage here in the absence of the enormous problem of obtaining US visas and the prohibition of access to US national Laboratories for JINR employees.

The **weaknesses** of the Project is the possible delay in implementation due to the pandemic.

The longer baseline in the DUNE experiment means their measurement will be more affected by matter effects, which will give them more sensitivity to the mass hierarchy.

It is expected that measurement of the mass hierarchy could be determined not at the T2K alone but combining the future data coming from the ongoing experiments such as NOvA, T2K and reactor experiments.

https://doi.org/10.1038/s41586-020-2177-0

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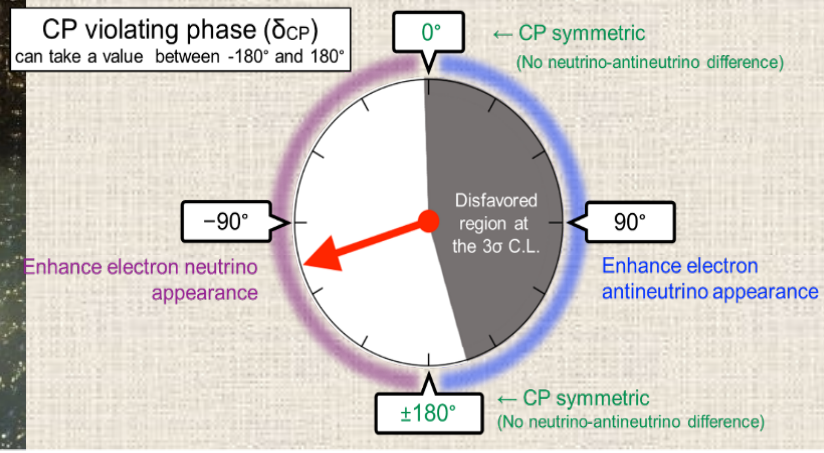
Nature | www.nature.com

Extended Data Table 1 | Systematic uncertainties

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

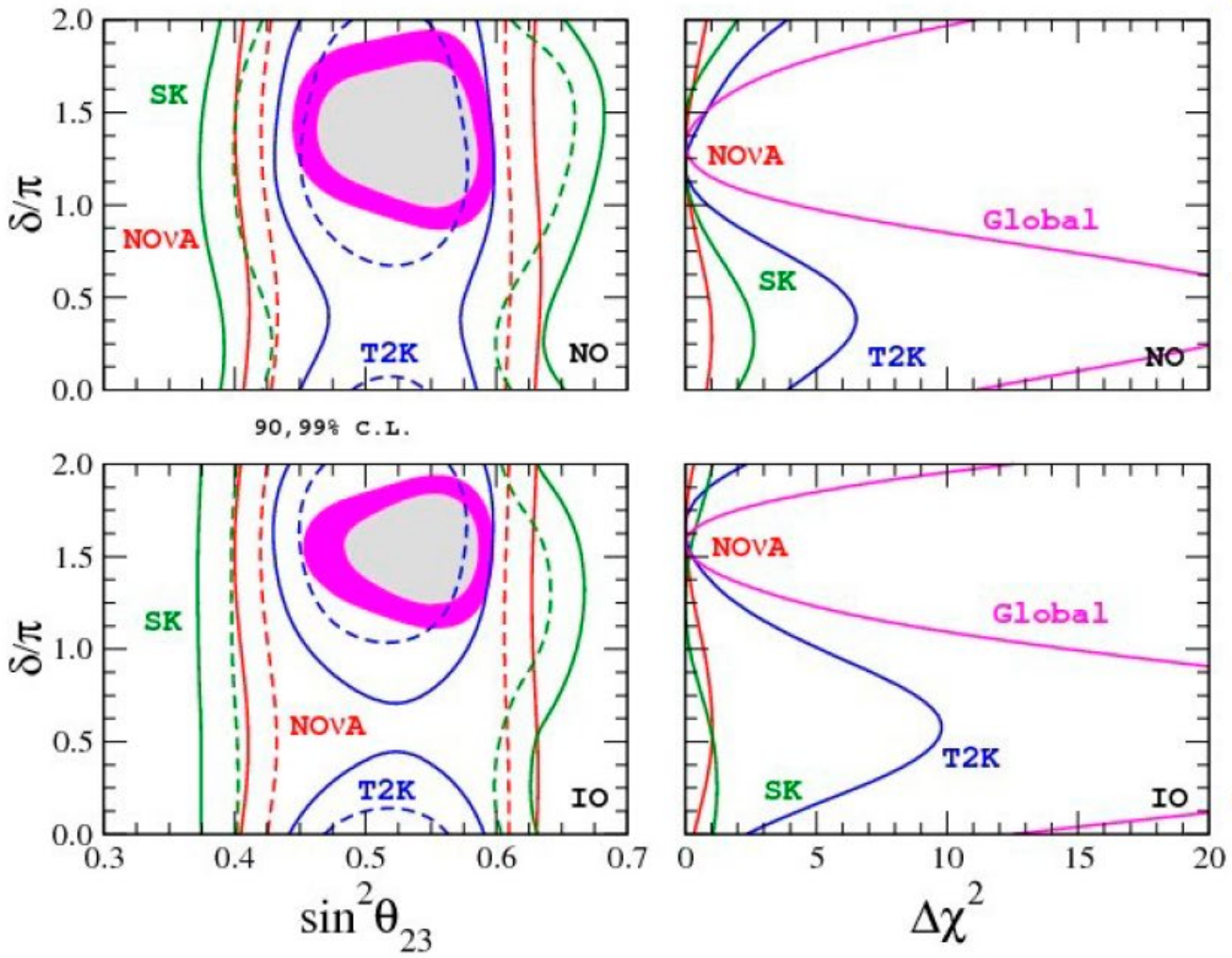
For the first time, T2K has disfavored almost half of the possible values at the 99.7% (3σ) confidence level, and is starting to reveal a basic property of neutrinos that has not been measured until now.



	Observed	Expectation	
		$\delta_{CP} = -90°$	$\delta_{CP} = +90°$
Electron neutrino	90	82	56
Electron antineutrino	15	17	22

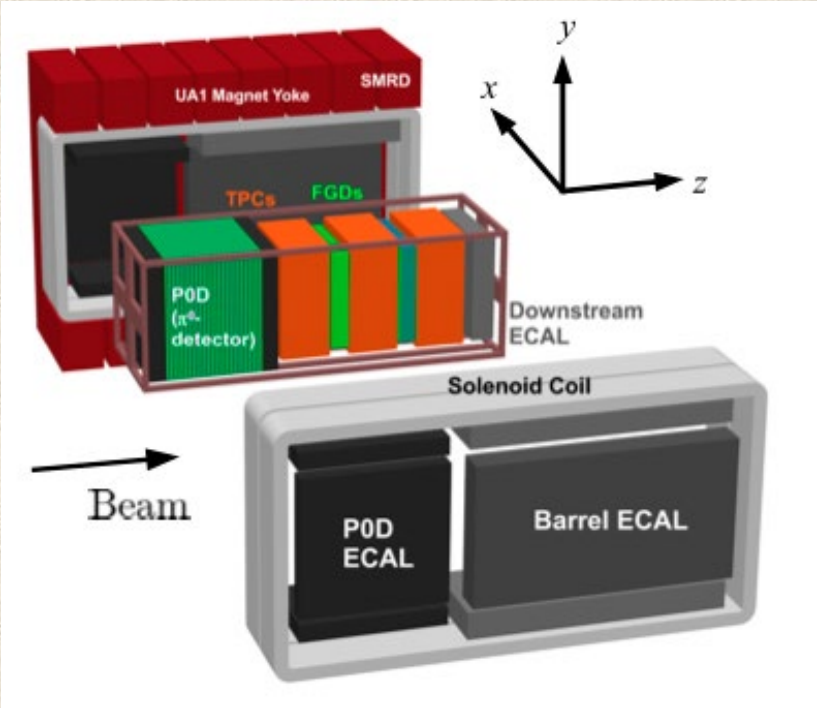
To further improve the experimental sensitivity to a potential CP symmetry violating effect, the T2K Collaboration will upgrade the near detector suite to reduce systematic uncertainties and accumulate more data, and J-PARC will increase the beam intensity by upgrading the accelerator and beamline.

The CP phase

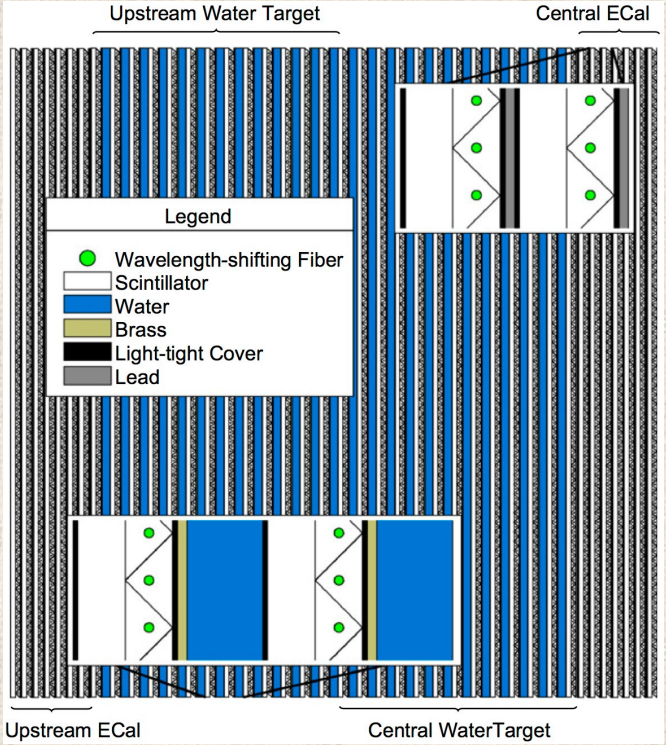


- Best sensitivity to δ comes from T2K
- Constraint on θ_{13} improves sensitivity to δ at all experiments significantly
- This results in exclusion of values around 0.5π at > 4σ

	Super-K	Hyper-K (1st tank)
Site	Mozumi	Tochibora
Number of ID PMTs	11,129	40,000
Photo-coverage	40%	40% (×2 sensitivity)
Mass / Fiducial Mass	50 kton / **22.5 kton**	260 kton / **187 kton**



An exploded cross section of the ND280



A schematic of the PØD, the beam enters from the left side of the figure.

To measure beam's flavour composition, energy spectrum, and interaction rates

$$\nu_\mu + N \rightarrow \nu_\mu + N + \pi^0 + X$$

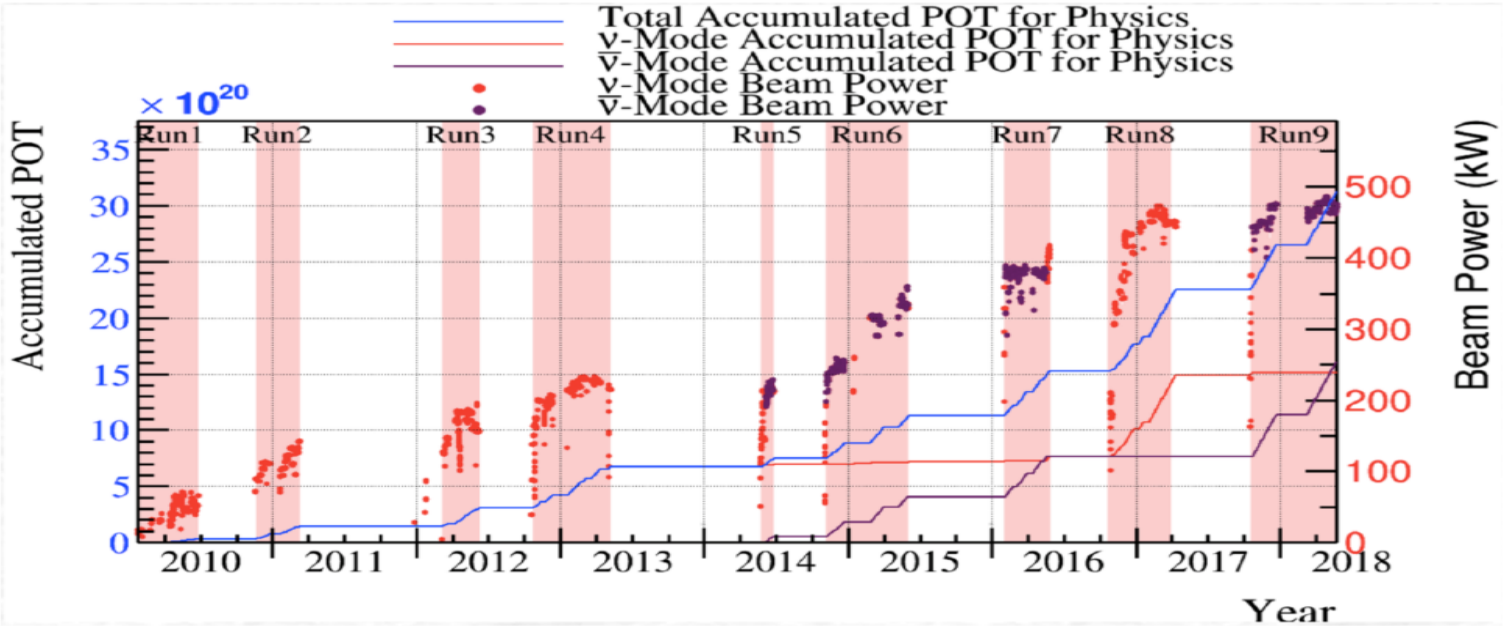
The primary goal is to measure the neutral current process on a water target. These single π^0 form a significant background in the ν_e events at the Super-K

T2K ended its 2019-2020 data-taking 10-th run on February 12, 2020, with a record beam power of 515 kW stably delivered by the J-PARC Main Ring accelerator. T2K has accumulated a total of 3.64×10^21 protons on target (POT) so far.

The protons are produced by the J-PARC Main Ring synchrotron accelerator in Tokai on the east coast of Japan. The 30 GeV protons are directed onto a graphite target, producing charged pions and other secondary particles.

Data taking summary

- Continuous rise in power from ~225 kW (2014) to 500 kW (2018)



3.16×10²¹ POT TOTAL

POT ≡ Protons on Target

1.51×10²¹ POT ν-mode (FHC)
1.65×10²¹ POT ν̄-mode (RHC) → 1.12×10²¹ analysed

Systematic uncertainty for # of FD events

FHC : ν-mode beam, RHC : $\bar{\nu}$-mode beam

(%)

	Single ring μ-like		Single ring e-like			
Error Source	FHC	RHC	FHC	RHC	FHC CC1π	FHC/RHC
SK Detector	2.40	2.01	2.83	3.80	13.15	1.47
Final state, Secondary int.	2.21	1.98	3.00	2.31	11.43	1.57
Flux+Xsec after ND constraint	3.27	2.94	3.24	3.10	4.09	2.67
Binding energy(E_b)	2.38	1.72	7.13	3.66	2.95	3.62
$\sigma(\nu_e)/\sigma(\nu_\mu)$	0.00	0.00	2.63	1.46	2.61	3.03
NC1γ	0.00	0.00	1.09	2.60	0.33	1.50
NC Other	0.25	0.25	0.15	0.33	0.99	0.18
Osc.	0.03	0.03	2.69	2.49	2.63	0.77
Total	**5.12**	**4.45**	**9.19**	**7.57**	**18.51**	**6.03**

- Error on FHC/RHC ratio which contributes to CPV study is ~6%

The uncertainty on the predicted number of selected events at the T2K far detector

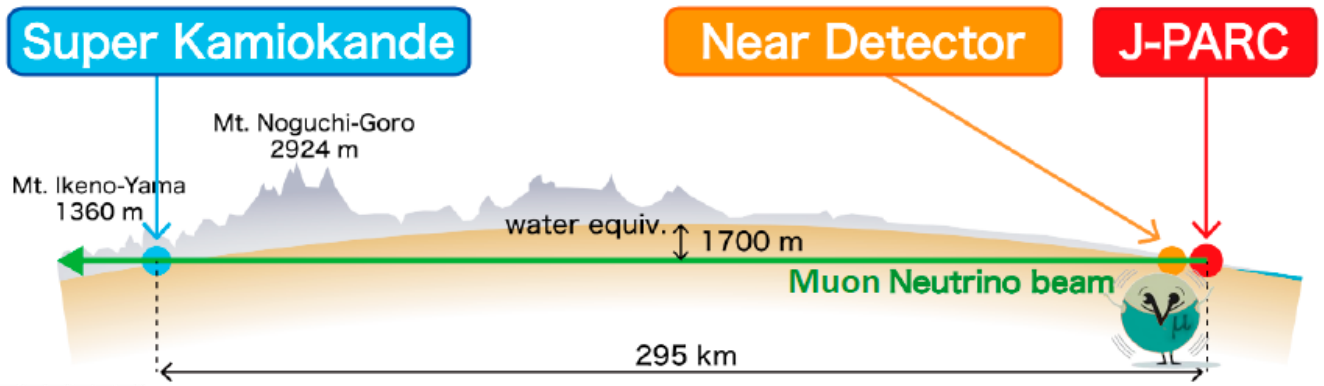
Source of uncertainty		ν_μ sample	ν_e sample
Flux and common cross section	w/o ND measurement	21.7%	26.0%
	w/ ND measurement	2.7%	3.2%
Independent cross sections		5.0%	4.7%
Super-K detector		4.0%	2.7%
Final or Secondary Hadronic Interaction		3.0%	2.5%
Total	w/o ND measurement	23.5%	26.8%
	w/ ND measurement	7.7%	6.8%

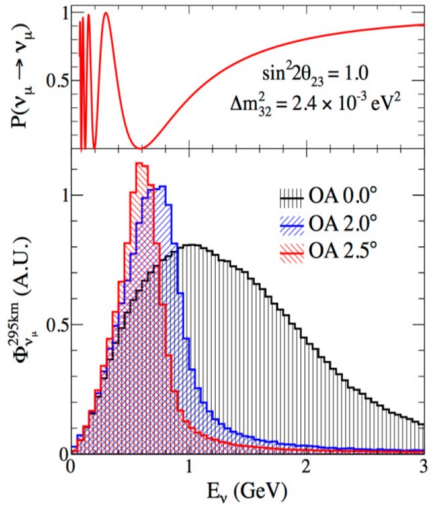
Table I. Table showing the uncertainty on the predicted number of selected events at the T2K far detector.

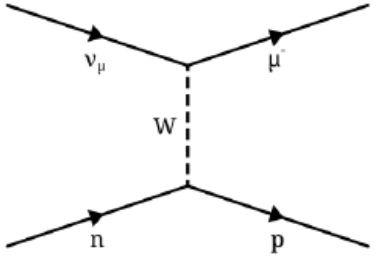
- Different types of experiments are sensitive to different parameters

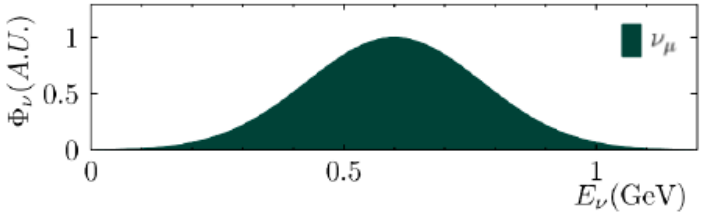
Experiment	Dominant measurement	Sub-dominant measurement
Solar Experiments + LBL reactors	θ_{12}, Δm^2_{21}	θ_{13}
Short baseline Reactors	θ_{13}, Δm^2_{31}	θ_{12}, Δm^2_{21}
Atmospheric experiments	θ_{23}, Δm^2_{31}	θ_{13}, δ
LBL accelerator disappearance	θ_{23}, Δm^2_{31}	θ_{13}
LBL accelerator appearance	θ_{13}, δ	θ_{23}

The T2K Experiment

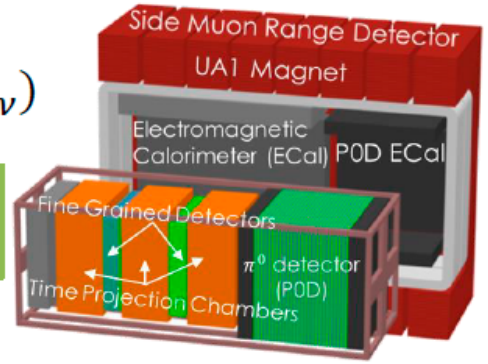








Near Detector
ND280



$$N_\mu(E_\nu) = \sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

Interaction cross section

Neutrino flux

Detector effects

(Mostly Hydrocarbon Scintillator)

pdglive.lbl.gov

(B) Three-neutrino mixing parameters	
$\sin^2(\theta_{12})$	0.307 ± 0.013
Δm^2_{21}	$(7.53 \pm 0.18) \times 10^{-5}$ eV^2
$\sin^2(\theta_{23})$	0.545 ± 0.021 ...
Δm^2_{32}	0.002453 ± 0.000034 eV^2 ...
$\sin^2(\theta_{13})$	0.0218 ± 0.0007

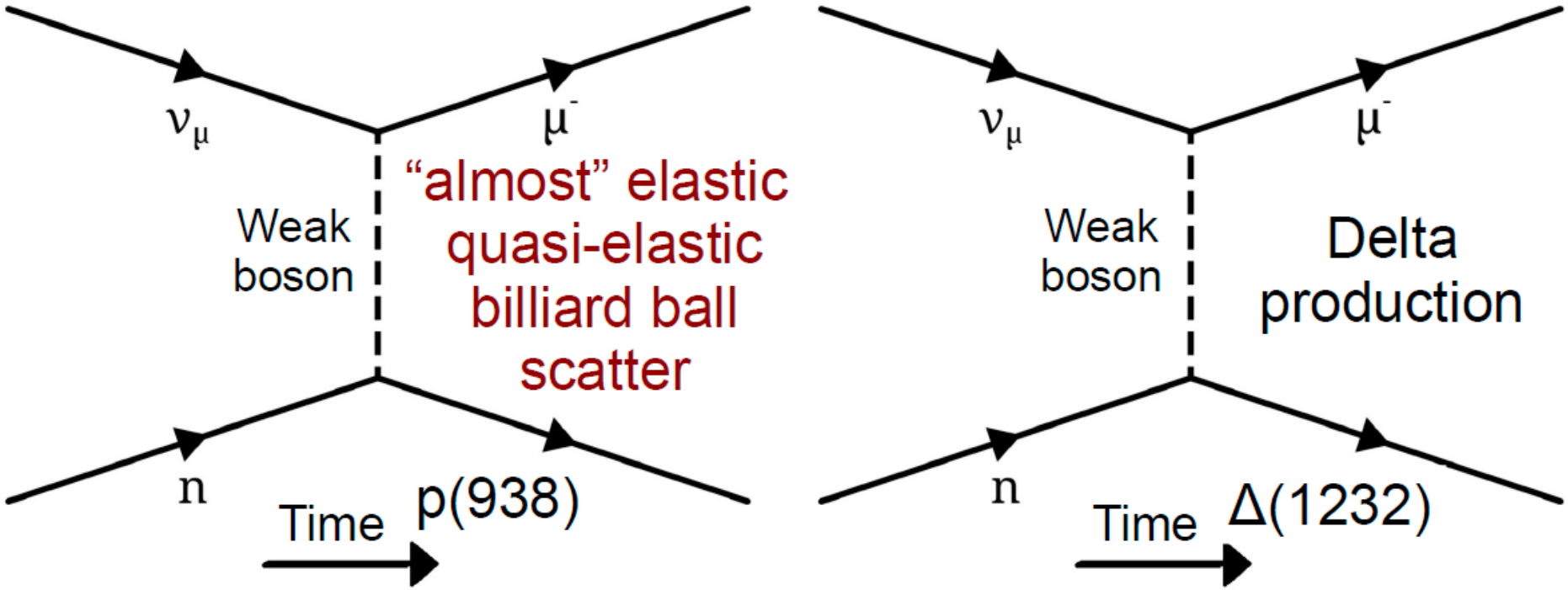
δ, CP violating phase	$1.36 \pm 0.17\ \pi$ rad

{0-2π] range

Summary of the global fit

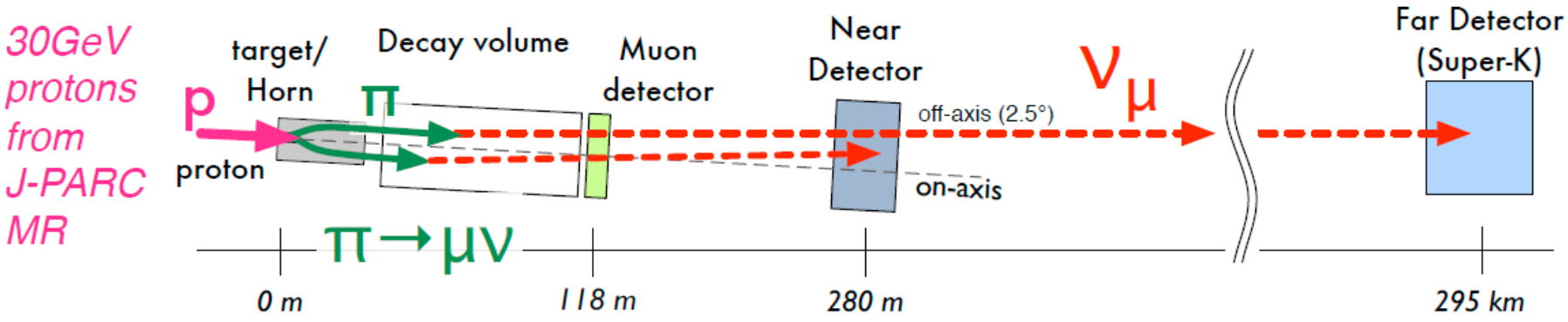
	parameter	best fit $\pm$ 1σ	3σ range
~2.6%	Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.55^{+0.20}_{-0.16}$	7.05–8.14
~1.5%	$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (NO)	2.50 ± 0.03	2.41–2.60
	$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51
~6.3%	$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79
~5.5%	$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99
	$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98
~3.5%	$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41
	$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44
~13.5%	δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94
	δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94

Feynman diagrams for elastic and inelastic reactions

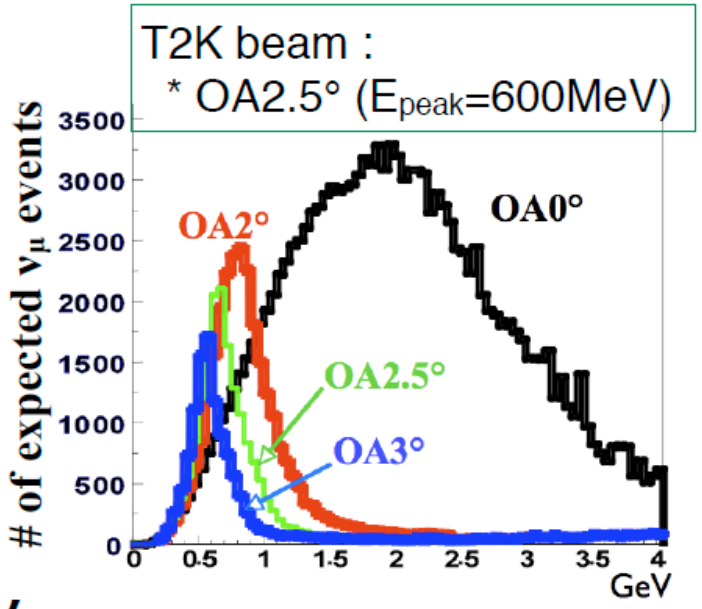


Today's results focus on the kinematics from the quasi-elastic to Delta resonance interactions.
not the only topic, but very important for NOvA, T2K, DUNE.
Will refer to W as the (invariant) mass of the outgoing hadron.
QE has just a proton 0.938 GeV, Δ has 1.232 GeV

T2K neutrino beam



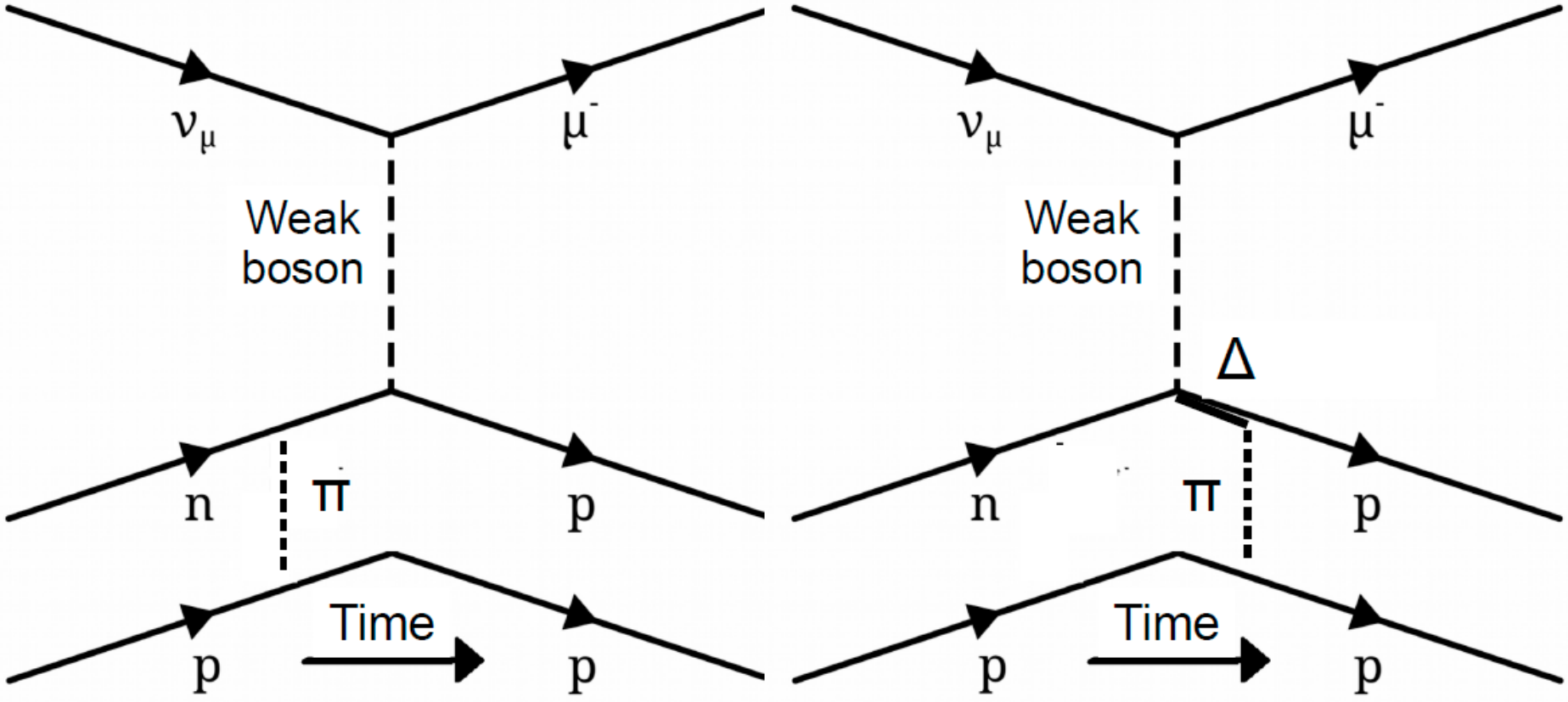
- Accelerator-based ν beam
- ν energy is narrow with off-axis method
  L = 295km → oscillation peak at 0.6GeV
- ν / $\bar{\nu}$ can be switched by flipping horn polarity



- **<1% of intrinsic ν_e at peak energy**
- **~5% of wrong sign component in $\bar{\nu}$ beam mode**

“2p2h” between the QE and the Δ(1232)?

Events where the reaction involved two nucleons



interaction with two particles in the process of pion exchange
both are knocked out, creating two holes in the nucleus (2p2h)
Not a single particle, more degrees of freedom,
can appear to have W between QE (0.938) and Δ (1.232)

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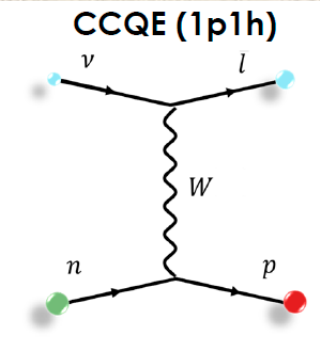
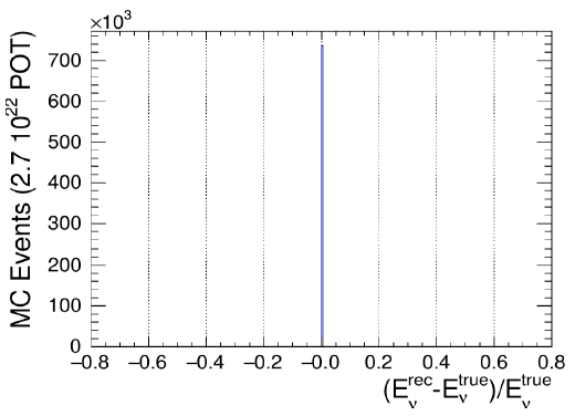
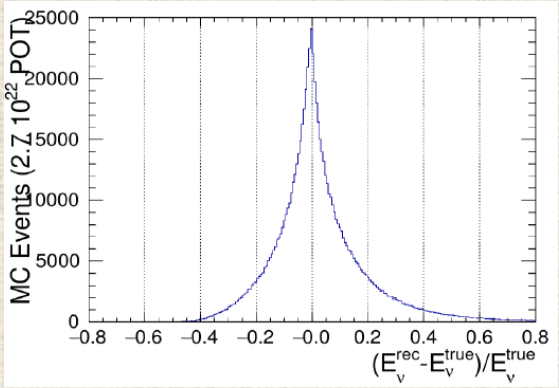
Nuclear effects and E_ν



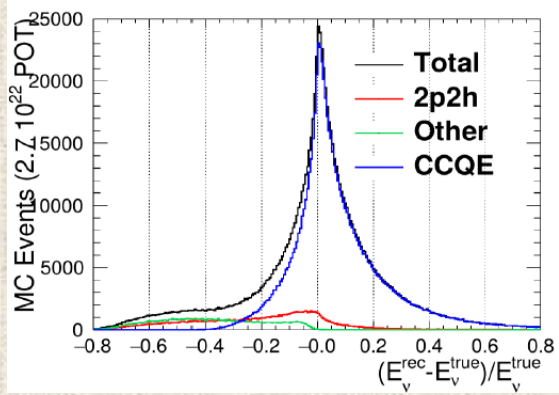


$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu cos\,\theta_\mu)}$$

Proxy for E_ν from lepton kinematics is perfect only for **CCQE elastic scattering** off a **stationary nucleon**



The motion of the nucleons inside the nucleus (*Fermi motion*) causes a **smearing** on E_ν



The energy loss in the nucleus (to extract the struck nucleon from its shell) introduces a **bias**