The T2K Near Detector upgrade

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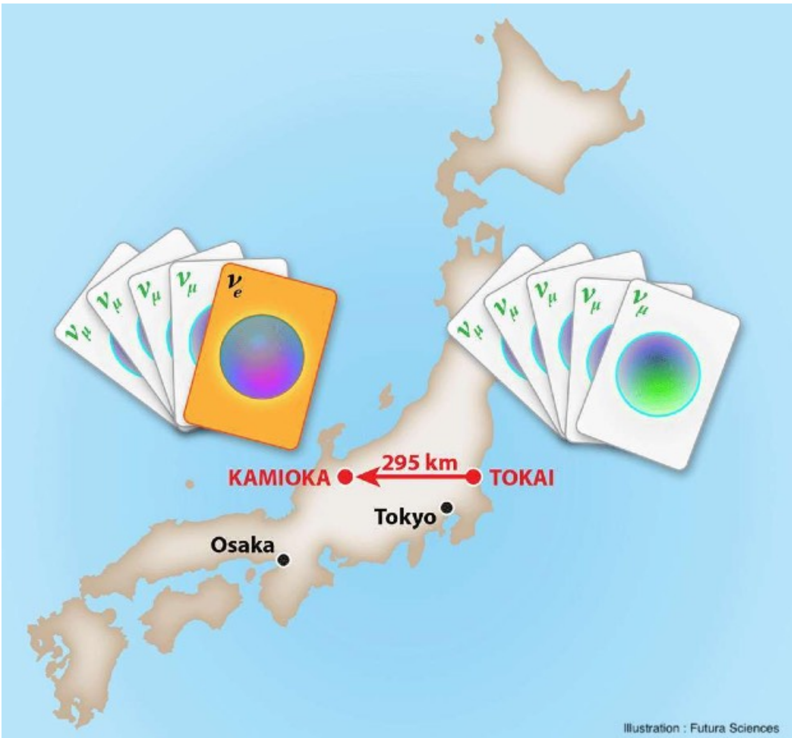
on behalf of T2K collaboration

ICHEP, 6-14 July 2022, Bologna, Italy

Outline

- ➡ Introduction of T2K experiment and motivation for the upgrade
- ➡ ND280 upgrade overview
  - Super-FGD
  - High Angle TPCs
  - TOF planes
- ➡ ND280 upgrade physics studies
- ➡ Conclusions

T2K neutrino experiment

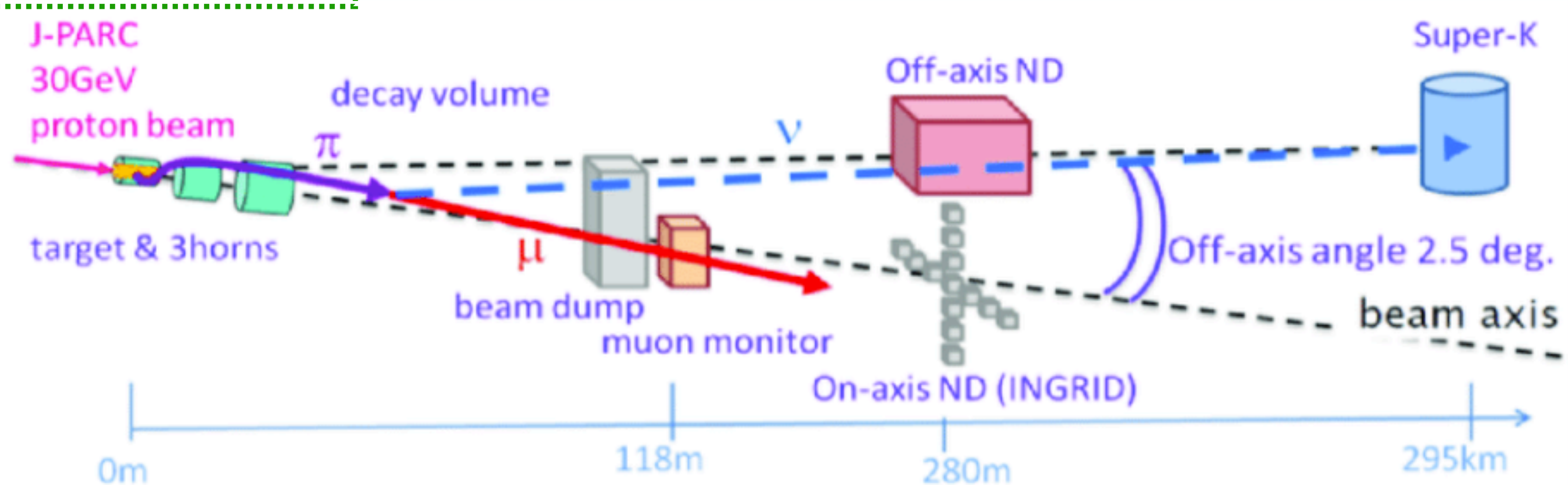


T2K goals:

- Measure θ_{13} and δ_{CP} through ν_e and $\bar{\nu}_e$ appearance
- Estimate the θ_{23} and Δm^2_{32} through ν_μ and $\bar{\nu}_\mu$ appearance

$$\nu_\mu + n \to \mu^- + p$$
$$\bar{\nu}_\mu + p \to \mu^+ + n$$

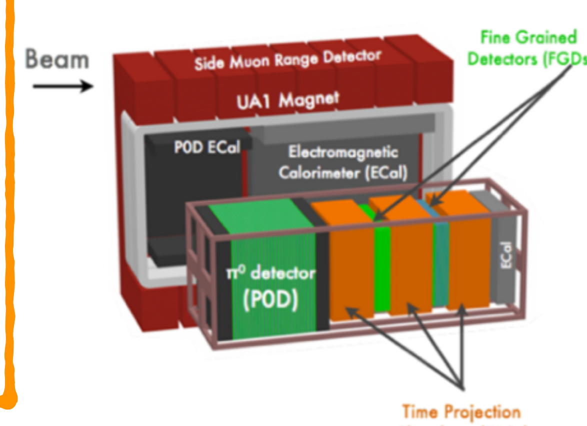
T2K upgrade → 3σ sensitivity on δ_{CP}



T2K Fall 2022 upgrade:

- The beam from 500 kW to > 750 kW (final beam power 1.3 MW)
- take data with ~ 10^{22}POT (Proton On Target)
- ↑ statistics ↣ control systematic uncertainties ↣ **upgrade of ND280**

ND280



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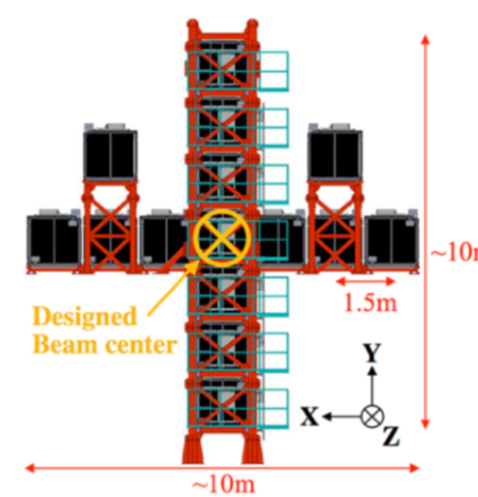
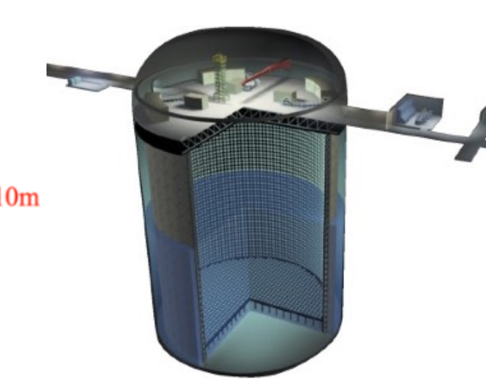


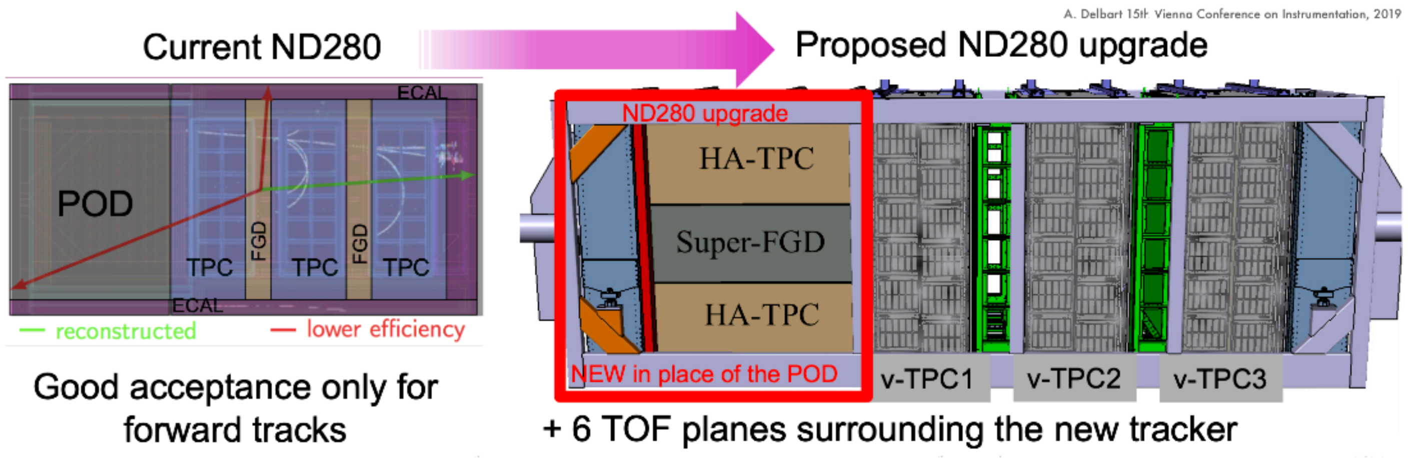
SK



ND280 upgrade

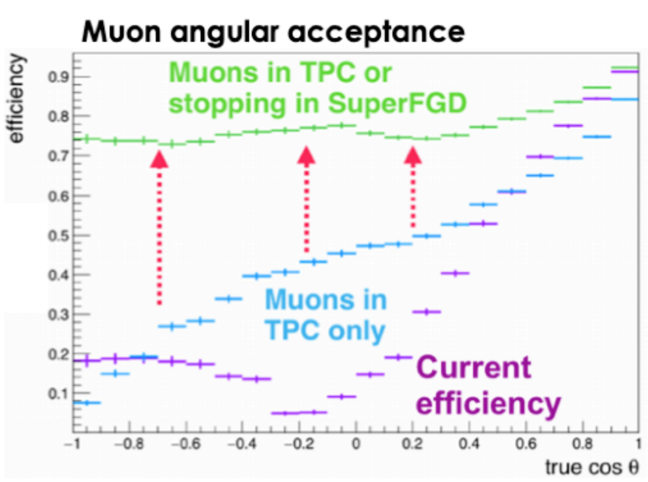
Motivation:

- ➡ ND280 has limited acceptance for tracks with high angle
- ➡ Low efficiency to reconstruct the hadronic part of the interactions, therefore, only muon kinematics are accessed for T2K oscillation analysis

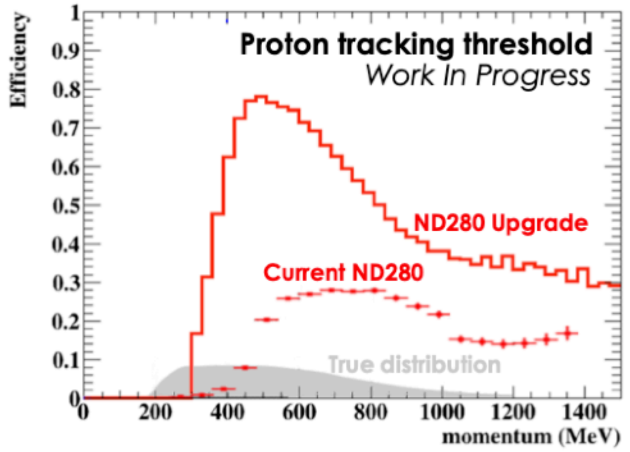


The upgraded configuration of ND280 is expected to reduce the overall systematic uncertainty to 4%

- The highly segmented target for **Super-FGD** ↣ improve the reconstruction of hadronic part and low momentum leptons
- 2 new **HA-TPC** ↣ improve the reconstruction of high angle leptons
- 6 **ToF** planes ↣ reduce background from the outside of SuperFGD



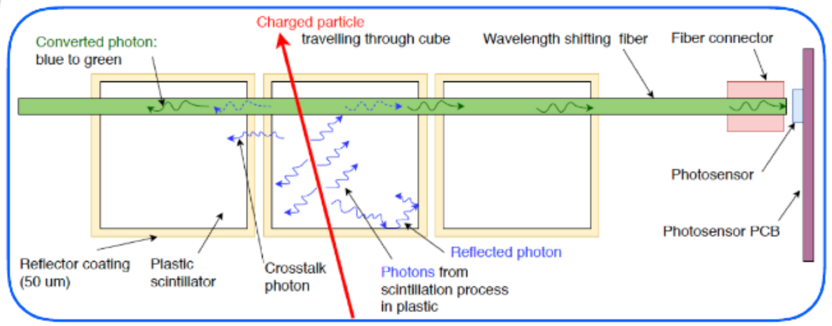
Efficiency to select CC0pi events



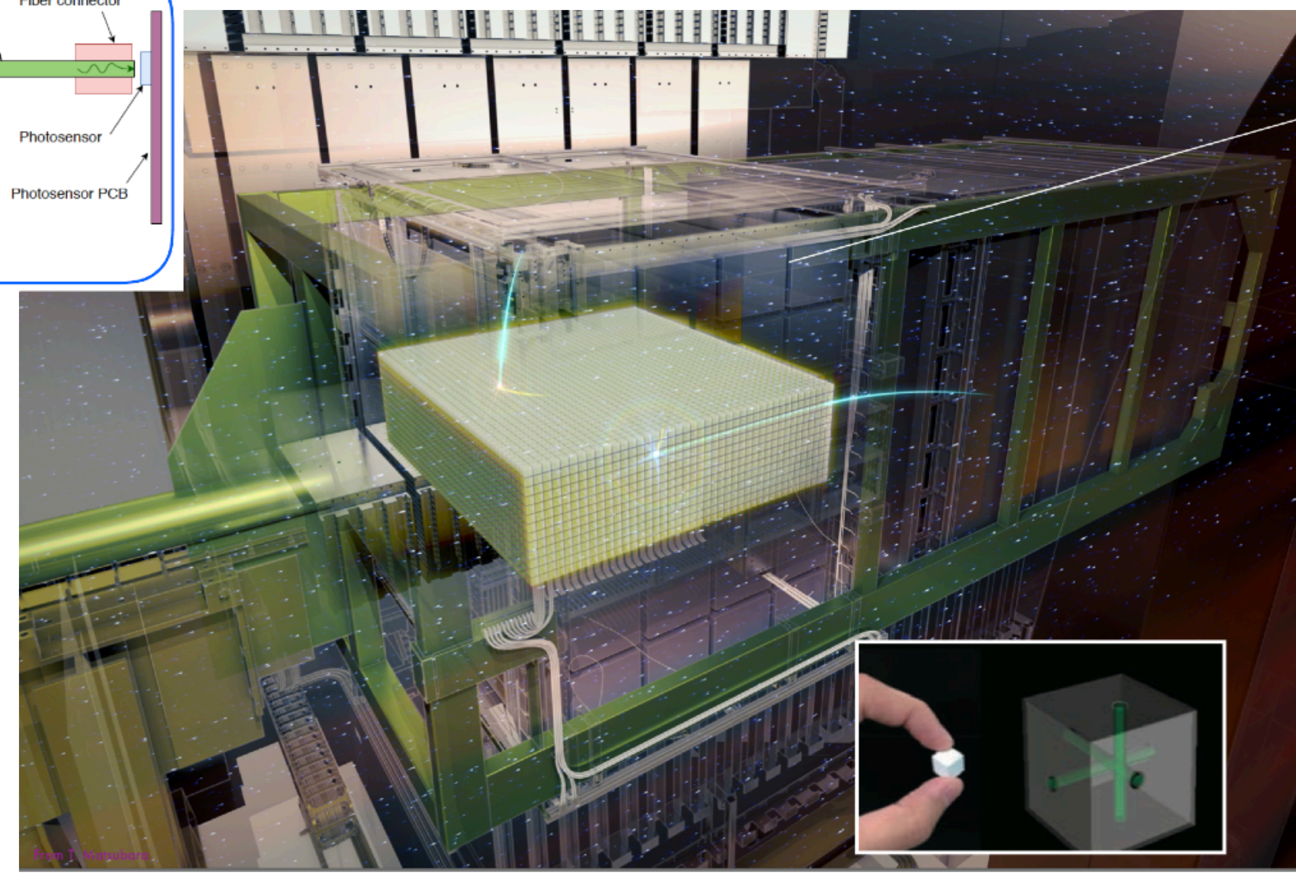
installation of the upgrade is expected in the first half of 2023

Super-FGD

Overview



- Fully active plastic scintillator detector (200×180×60 cm^3)
- 2 million cubes 1×1×1 cm^3
- 2.2 tons target mass
- WLS three orthogonal directions read out ↣ cover full solid angle
- 3D reconstruction
- Low energy threshold, short track detection
- High spatial resolution
- **Neutron detection** PhysRevD.101.092003 (2020)



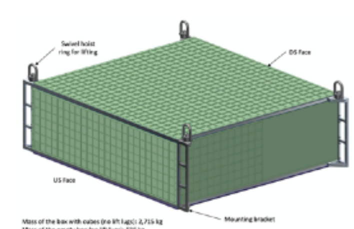
Prototypes tests:

- CERN (2017, 2018) NIMA 936 (2018), JINST 15, 12 (2020) ↣ 125 and 9216 cubes
- Neutron test beam in LANL

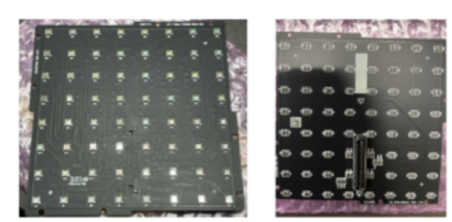
Main components:

Scintillator cubes

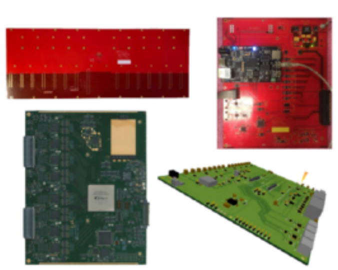
Mechanical box



Optical parts



Electronics

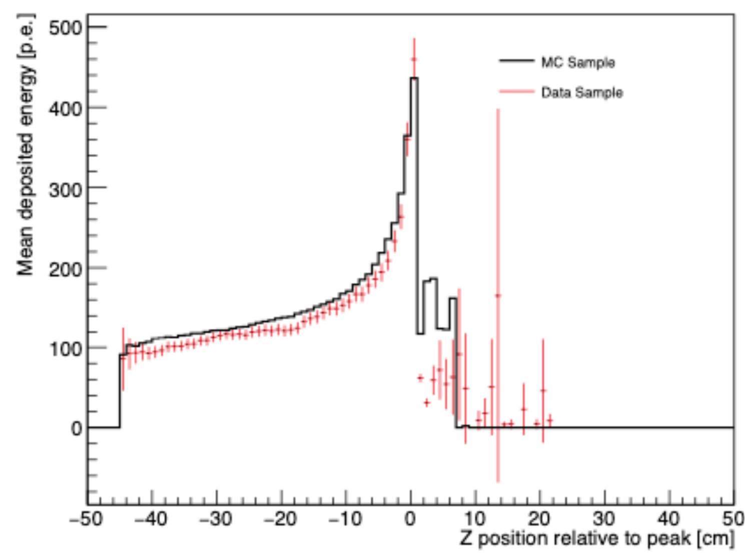


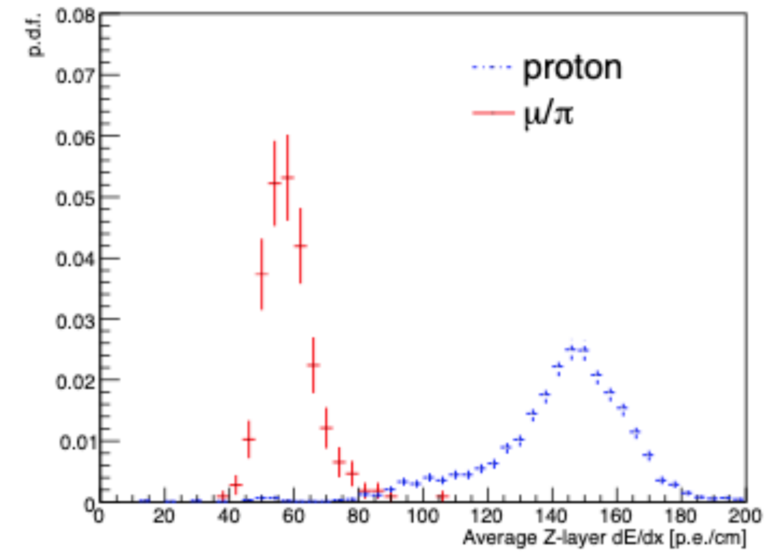
Super-FGD performance

CERN Test Beam (2017, 2018)

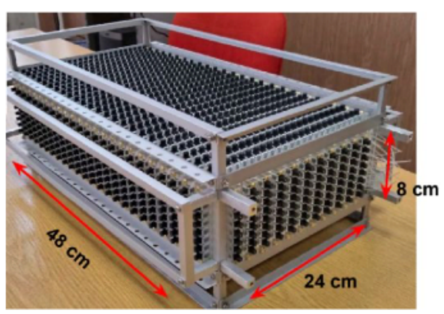
NIMA 936 (2018), JINST 15, 12 (2020)

- CERN-PS T9 beamline provided charged particles of various types in the momentum range ±400 MeV/c to ±8 GeV/c
- Time resolution 1.14 ns for a single channel

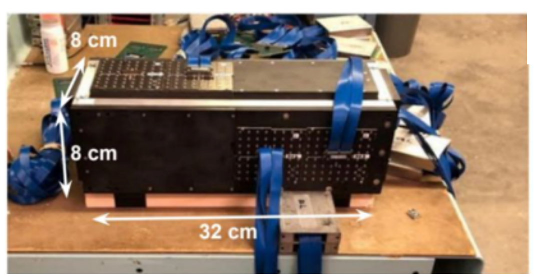




SuperFGD



US-Japan



Access to neutron kinematics is crucial to understanding better anti-neutrino CCQE and 2p2h interactions

Neutron test beam in LANL:

- 2 prototypes (Super-FGD and US-Japan) were tested in 2019 and 2020 in the LANL LANSCE facility.
- Neutron beam energy ranges from 0 to 800 MeV
- Neutron kinetic energy was measured with 2% uncertainty using ToF
- Total cross-section as a function of neutron energy was measured by fitting an exponential function to the event rate depletion
- Sources of uncertainties: time resolution, invisible scattering, detector effect, light yield, geometric acceptance, collimator-induced energy

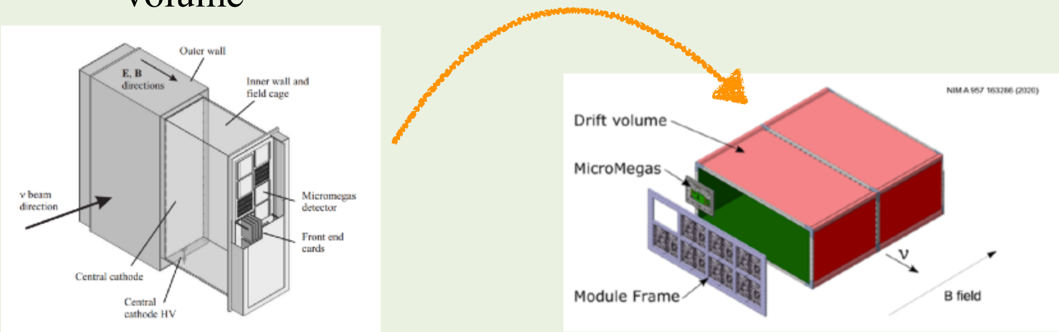
$$N(z) = N_0 e^{-T\sigma_{\text{tot.}} z}$$

High-Angle TPCs

What is new:

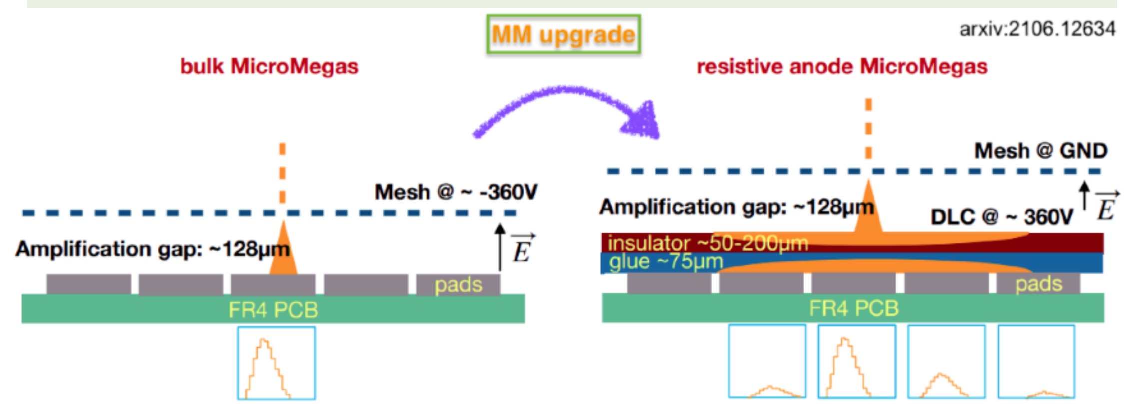
➡ **New field cage**

- ✦ Minimize the dead space and maximize the tracking volume

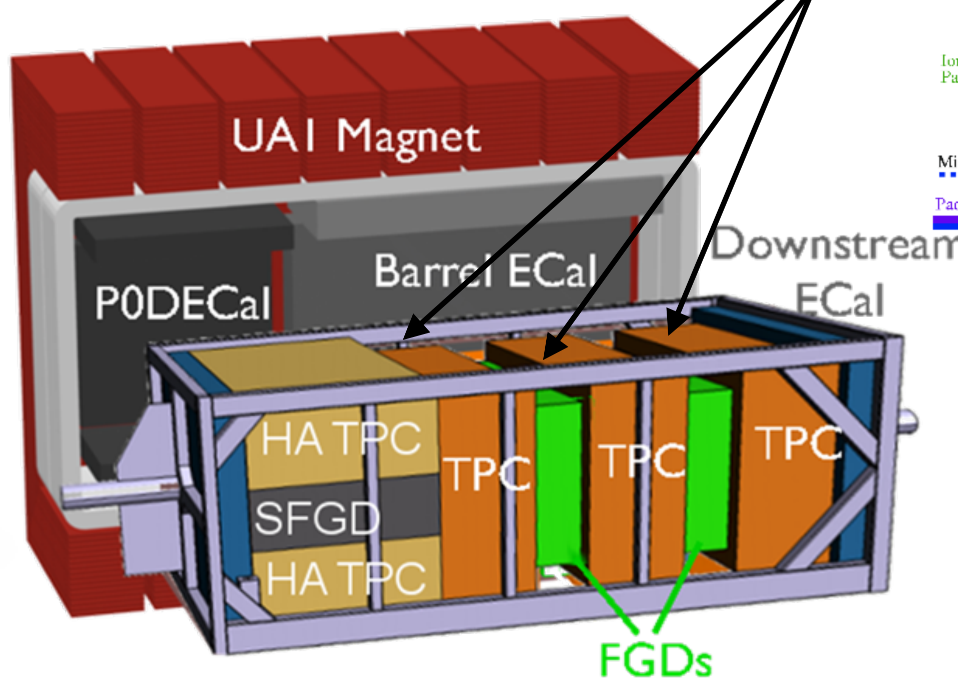


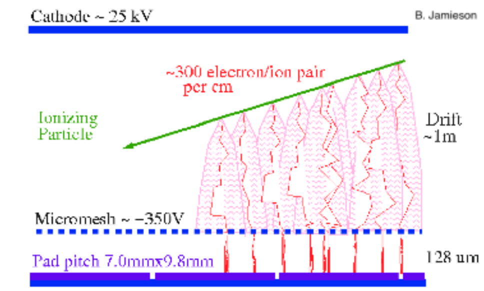
➡ **New resistive Micromegas module:**

- ✦ Bulk Micromegas readout module replaced by new resistive Migcromegas Modules (ERAM) ↣ spread the charge over multiple pads ↣ improving the spatial resolution and reducing the number of readout pads, no need in sparks protection



➡ Inherit the design of the existing TPCs





Main goal:

- High-resolution tracking (3D reconstruction) of charged particles
- Particle identification (charge and momentum measurements)

HA-TPC requirements:

➡ To distinguish between muons and electrons at 3σ level ↣ energy resolution < 10%.

➡ Momentum resolution < 10% at 1 GeV/c ↣ spatial resolution< 0.8 mm

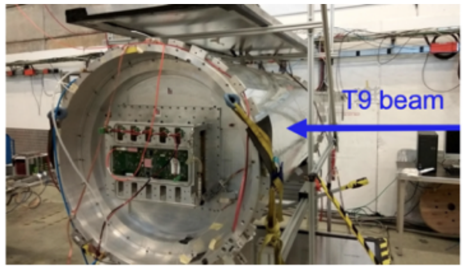
HA-TPCs performance

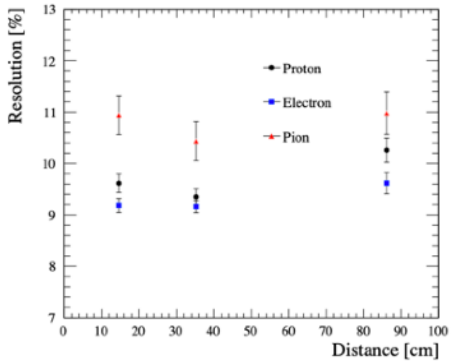
HA-TPCs test beam:

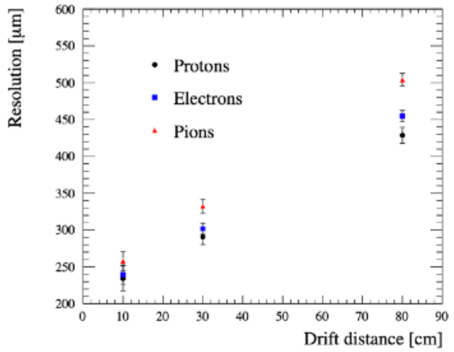
➡ CERN 2018 (10.1016/j.nima.2019.163286) →

✶1.5m drift distance; π, e, p trigger; 2018 MM0-DLC1

dE/dx resolution **Spatial resolution**

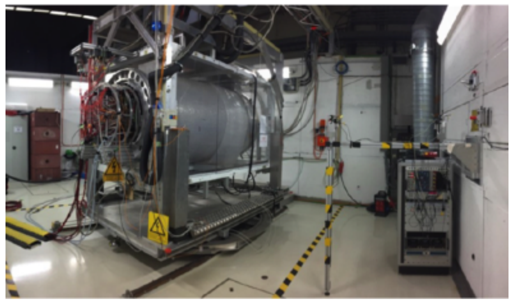


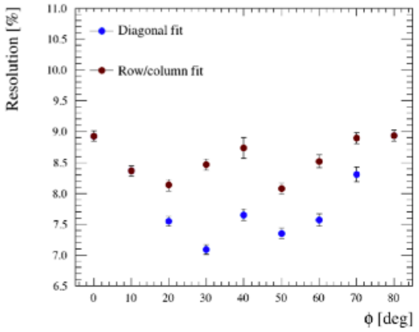


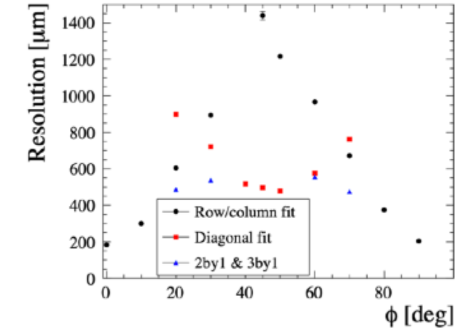


➡ DESY 2019 (arXiv:2106.12634) →

✶4 GeV e- 0.15m drift distance; 2019 MM1-DLC1 (larger pads)







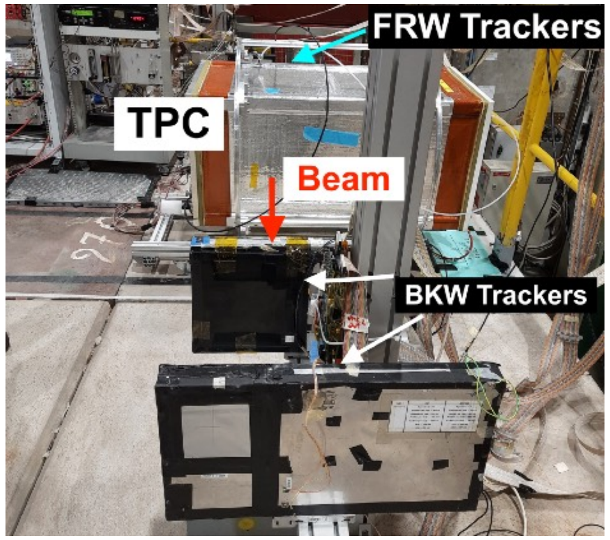
➡ DESY 2021 (ongoing analysis, results are later in the talk)

✶4 GeV e-; 1 m drift distance (**final detector drift distance!**);

✶2020 ERAM#01 (better charge spreading, ↑RC)

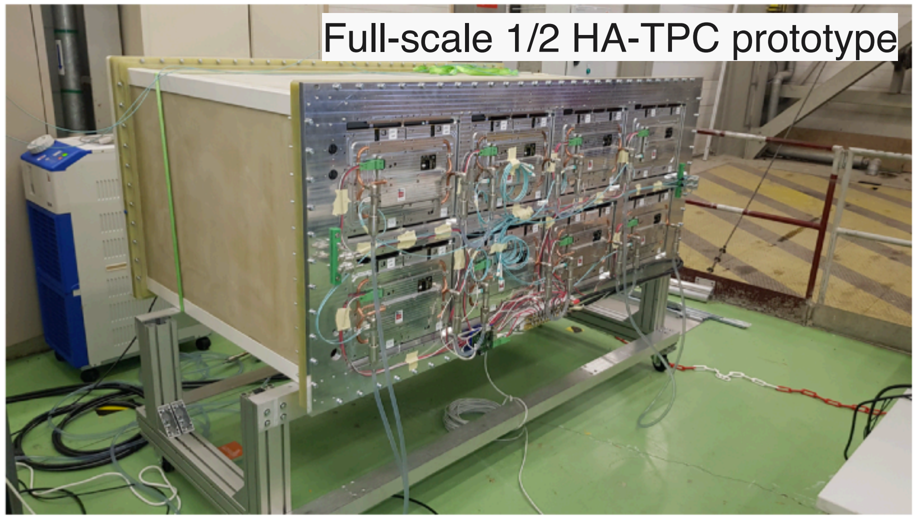
➡ CERN November 2021 →

✶μ beam; the same TPC as for DESY 2021 + TRK; no mag. field.

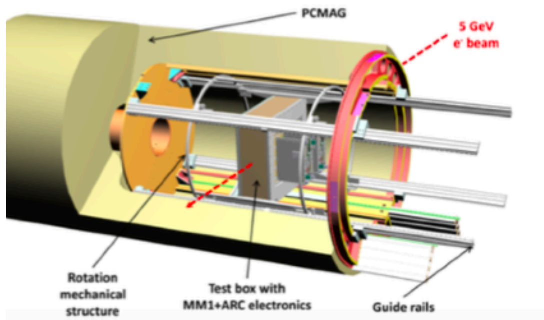


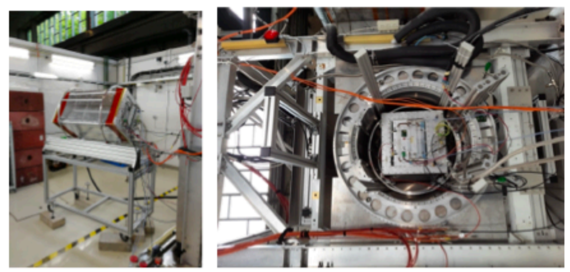
➡ CERN May 2022 (rescheduled)

✶Test of the one-half of HA-TPC (final design)



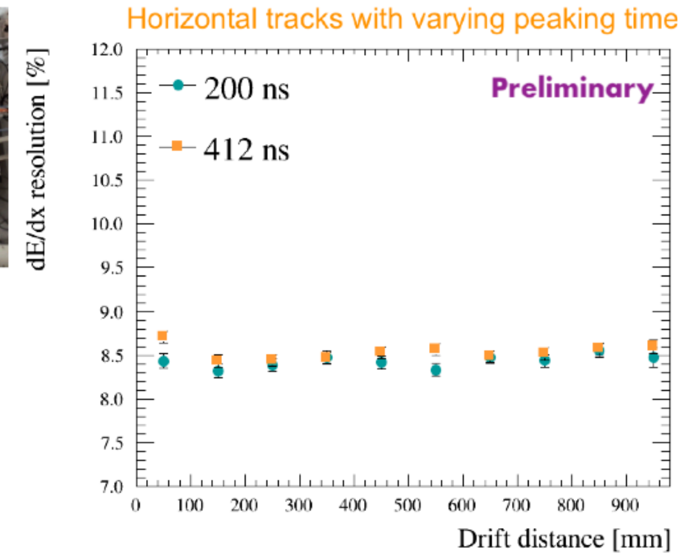
DESY 2021 test beam results

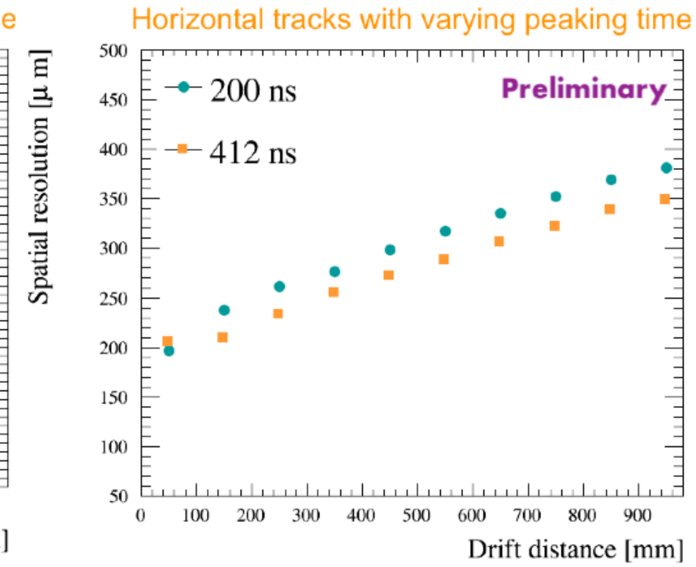


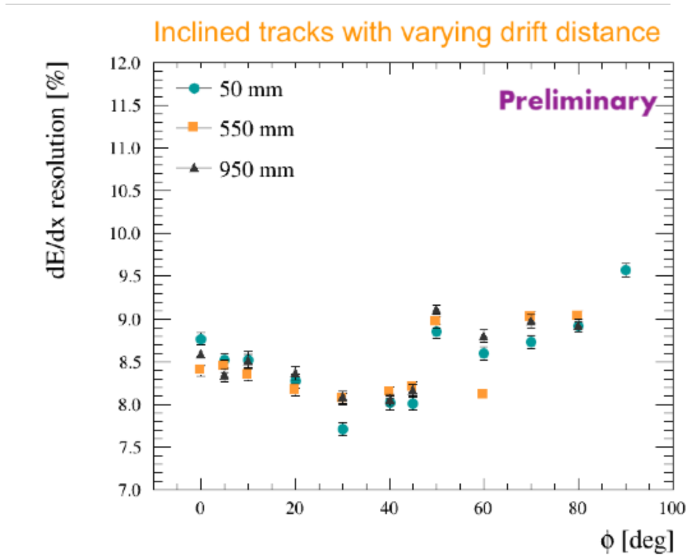


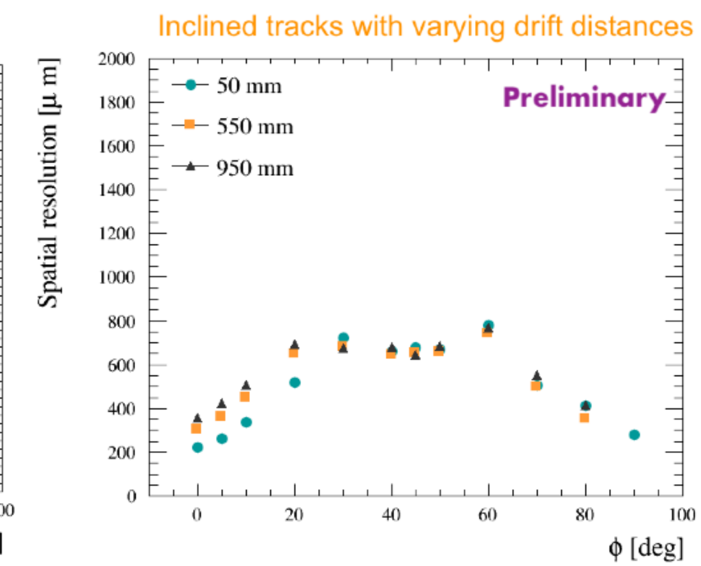
In order to ensure that setup satisfies the ND280 upgrade requirements the test beam intended to:

- test the setup stability
- characterize the charge spreading and study resistive foil uniformity.
- measure spatial and energy resolution;

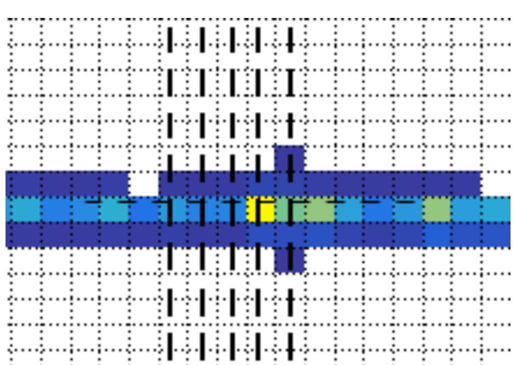




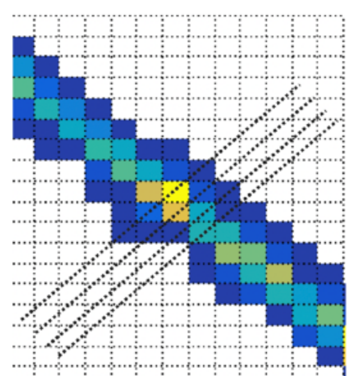




Horizontal track

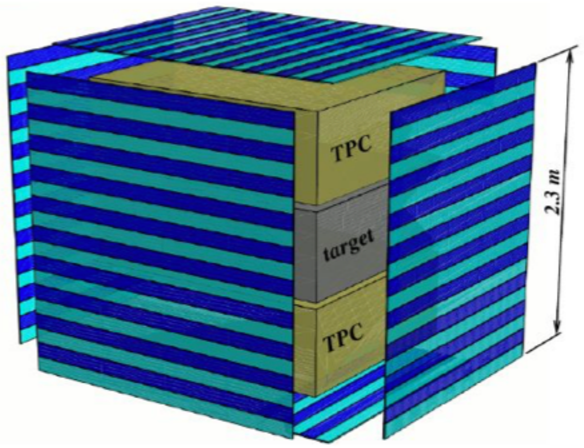


Inclined track



Fullfill the requirements: dE/dx resolution < 10% and spatial resolution < 0.8mm

Time of Flight detectors



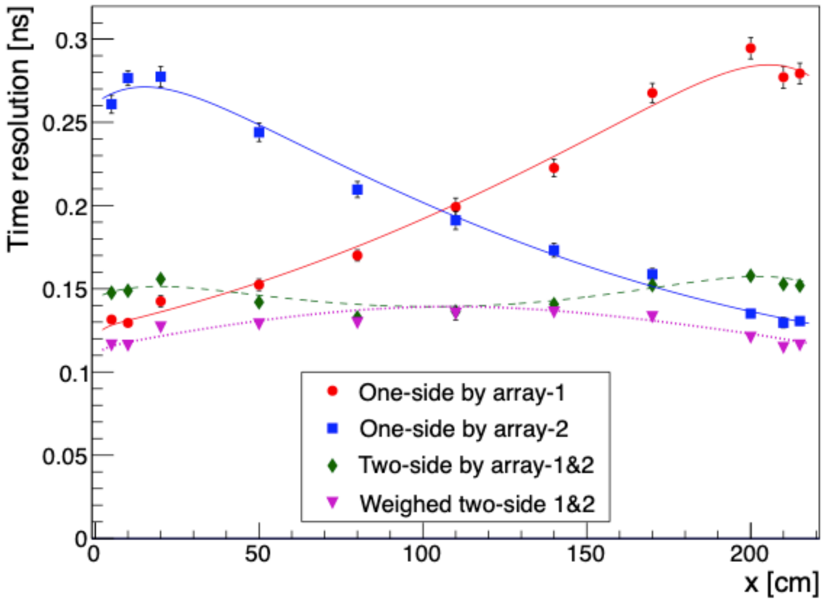
- 6 ToF planes will fully cover 2 HA-TPC and Super-FGD
- Each plane 2.2 x 2.4 mm^2 consists of 20 scintillator bars
- Readout of 16 MPPC at both ends of each bar

Performance:

Single bar test:

➡ Performed for cosmic rays

➡ 140 ns time resolution



arXiv: 2109.03078

Goals:

➡ Provide a time stamp for each track ↣ identify the direction of the tracks ↣ reduce the background

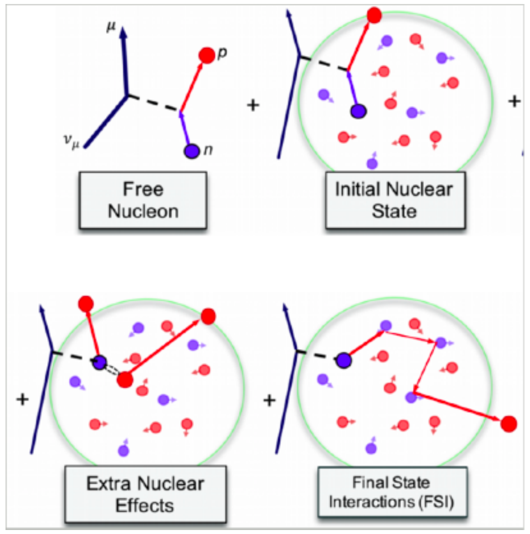
➡ The cosmic trigger for the calibration of Super-FGD and HA-TPCs

ND280 upgrade physics studies

Flux model — Detector model — Neutrino interaction model — Oscillation Probability

$$N^{ND}_{\nu_\alpha}(E_\nu) = \boxed{\Phi^{ND}_{\nu_\alpha}(E_\nu)} \times \boxed{\epsilon^{ND}(E_\nu)} \times \boxed{\sigma^{ND}_{\nu_\alpha}(E_\nu)}$$
$$N^{FD}_{\nu_\beta}(E_\nu) = \boxed{\Phi^{FD}_{\nu_\beta}(E_\nu)} \times \boxed{\epsilon^{FD}(E_\nu)} \times \boxed{\sigma^{FD}_{\nu_\beta}(E_\nu)} \times \boxed{P_{\nu_\alpha \to \nu_\beta}(E_\nu)}$$

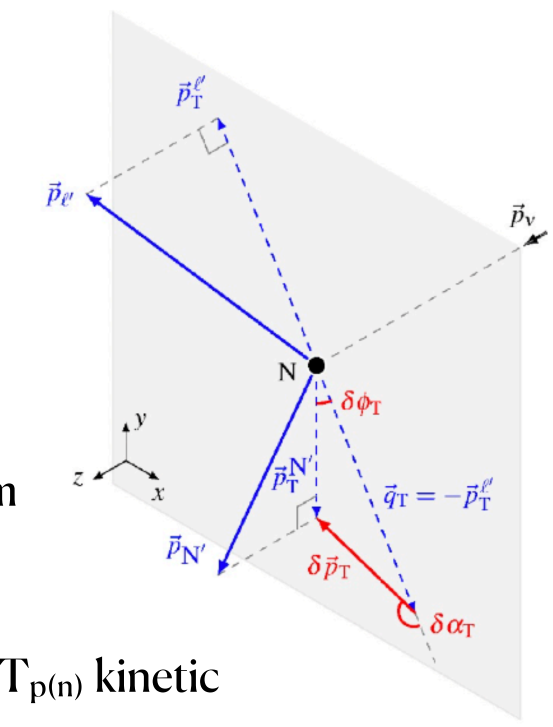
Nuclear effects are the main source of E_ν uncertainty:



- ➡ Fermi motion
- ➡ Removal energy
- ➡ Final State Interactions (FSI)
- ➡ Non quasi-elastic event without pion in the final state (2p2h, pion absorption, undetected pion)

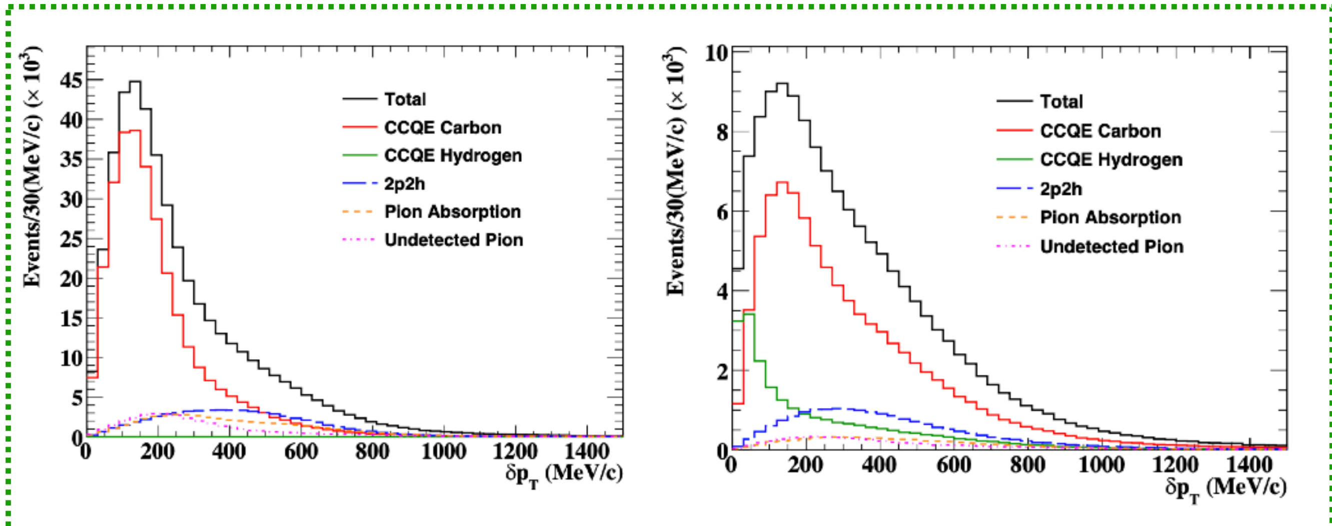
arXiv:2108.11779

Upgrade gives access to hadronic part of the final state ↣ new, more powerful variables: δp_T, $\delta\alpha$, E_{vis}



- $\delta p_T = |p_T{}^{\mu} - p_T{}^{p(n)}|$ missing momentum
- Transverse boosting angle $\delta\alpha$
- Visible energy $E_{vis} = E_\mu + T_{p(n)}$, where $T_{p(n)}$ kinetic energy

Future OA for ND280 upgrade ↣ multidimensional fit μ +hadron kinematics

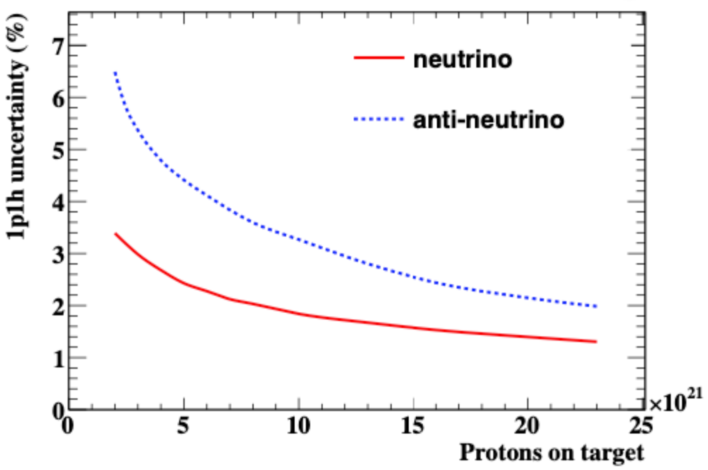


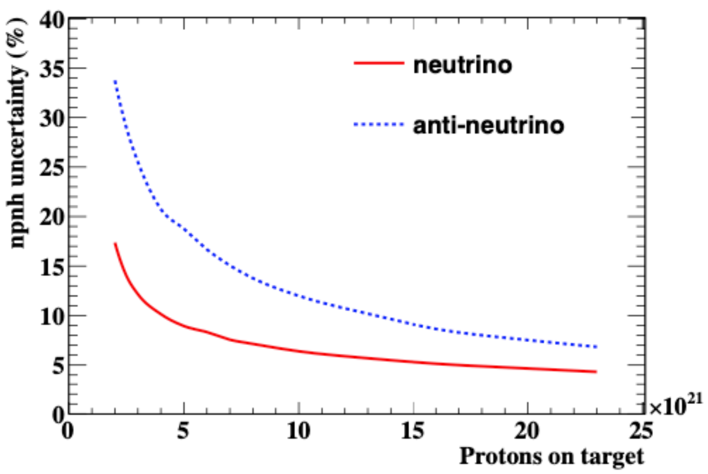
- ✳ δp_T sensitive to Fermi motion and 2p2h, separate CCQE and non-CCQE
- ✳ $\delta\alpha$ shape sensitive to FSI
- ✳ E_{vis} sensitive to nuclear removal energy

ND280 upgrade physics studies

Constraints on parameters using new transverse kinematics: δp_T, $\delta\alpha$, E_{vis}

arXiv:2108.11779





- $CC0\pi$ data binned in δp_T and E_{vis}:
  - 1p1h (CCQE) ↣ contrain uncertainty ~1.5% (~2%) for ν ($\bar{\nu}$)
  - npnh (CCQE+SRCs) ↣ < 5% (10%) for ν ($\bar{\nu}$)

Simple fitter study
shows much better model constrain needed for future LBL analyses

GUNDAM
Generic fitter for Upgraded Near Detector Analysis Methods

- Developed for cross-section and sensitivity studies for ND280 upgrade
- Fast and user-friendly
- intended to find the best parameters values of ND280 model, introduced by flux, detector, and cross-section parameters sets and propagate the uncertainties of the parameters, compare to data

Current and future studies:

- ✓ Constrain ND280 model using transverse kinematic parameters
- ✓ Use of Super-FGD samples
- ✓ Study the ND280 upgrade performance on ν_e selection and ν_e cross-section measurements.
- ✓ Improve the neutrino interaction model
- ✓ Study nucleon FSI (arXiv:2202.10402)

Conclusions

- ➡ T2K upgrade goal is 3σ significance to CP violation
- ➡ Beam power is expected to increase from 0.5 W to 1.3 W
- ➡ ND280 upgrade intended to reduce total systematics
- ➡ ND280 upgrade is in the preparation stage, and an installation is expected in the first half of 2023
- ➡ The tested performance of Super-FGD, HA-TPC and ToF planes fully meets the requirements of the ND280 upgrade.
- ➡ ND280 upgrade program shows the impressive ability to constrain key systematic uncertainties.

THANK YOU!

T2K collaboration meeting, 9-13th May, 2022

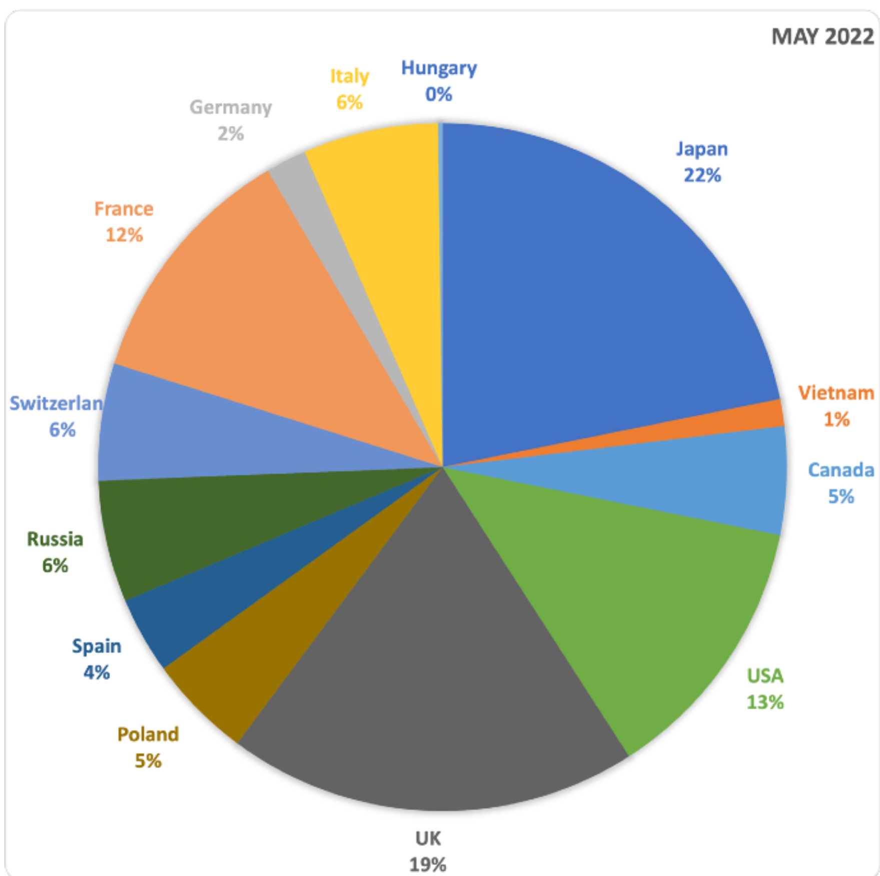
The T2K Collaboration (2022)

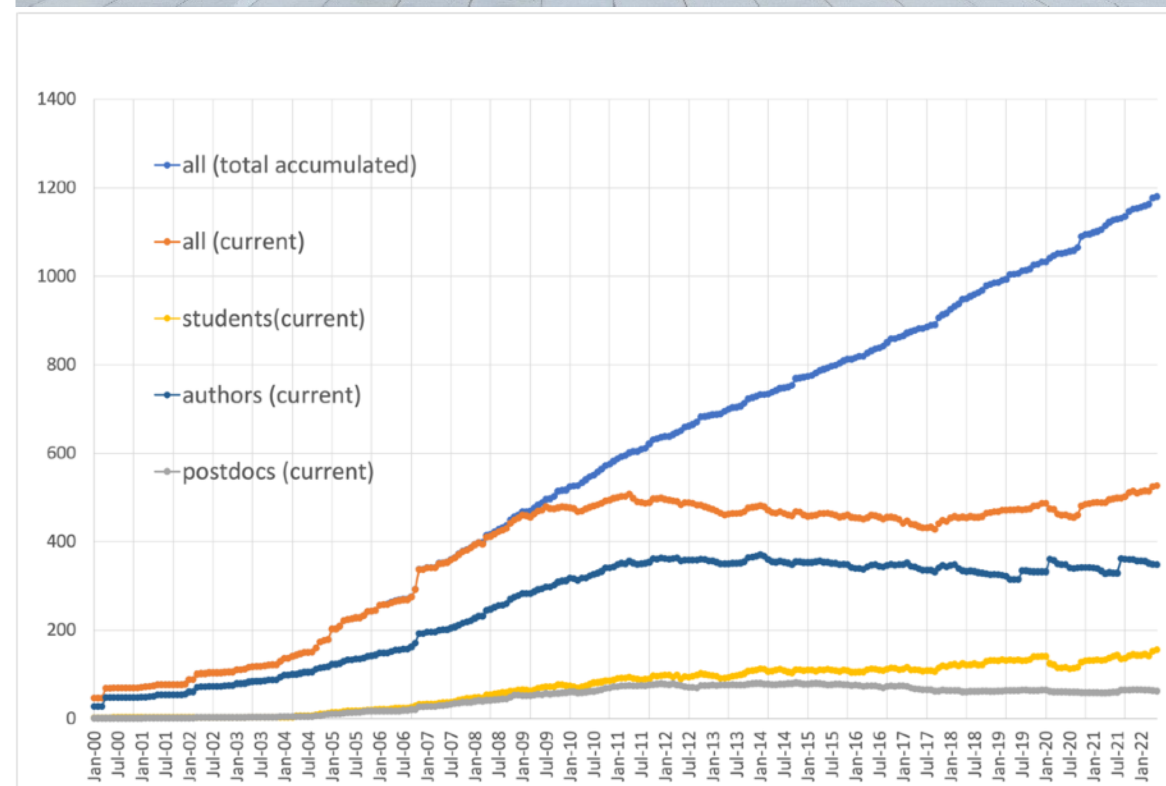
~528 members, 76 Institutes, 14 countries

Asia	109
Japan	103
Vietnam	6

Americas	84
Canada	24
USA	60

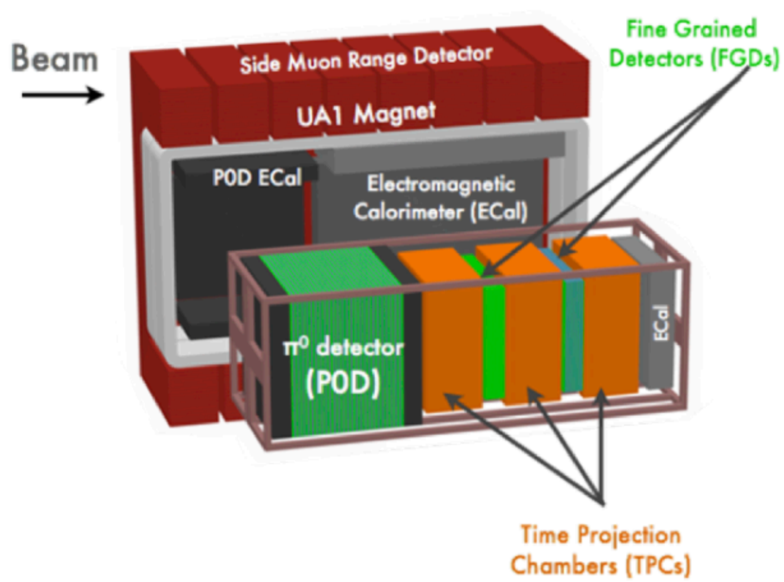
Europe	279
France	55
Germany	9
Hungary	1
Italy	30
Poland	23
Russia	27
Spain	17
Switzerland	26
UK	91





T2K detectors

ND280



- Magnetized detector off-axis detector
- CH (FGD1) and CH/Water(FGD2) targets
- Mesure ν rate before oscillations (p_{μ} and θ_{μ})
- Constraining neutrino flux and cross-section θ

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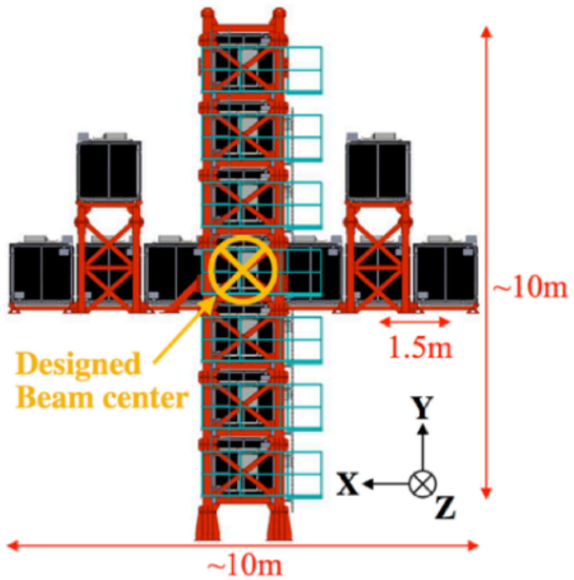
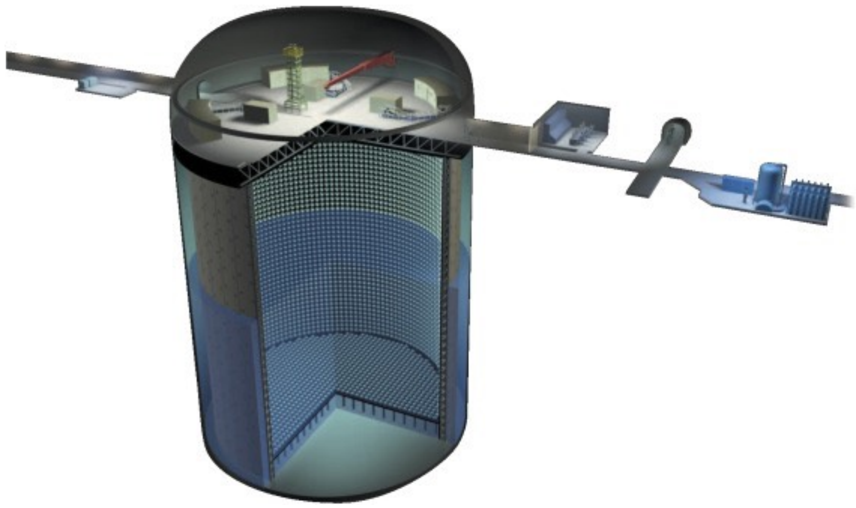


- On-axis scintillating detector
- To monitor the beam position and stability

SK



- Cherenkov detector
- 50 kton of pure water and 22.5 kton fiducial volume
- Equipped with PMTs to detect Cherenkov light
- Reconstruct muon and electrons based on Cherenkov ring patterns

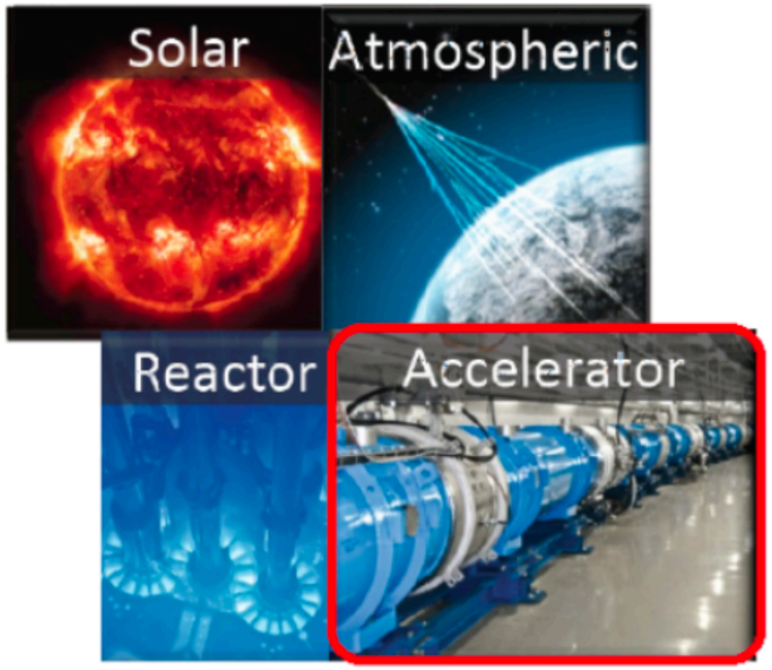
Neutrino oscillation parameters

$$U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

where $c_{jk} = \cos\theta_{jk}$, $s_{jk} = \sin\theta_{jk}$, θ_{jk} - mixing angles, δ – CP-violation phase

$\boxed{\text{if } \delta_{CP} \neq 0(\pi) \rightarrowtail \text{CP violation}}$

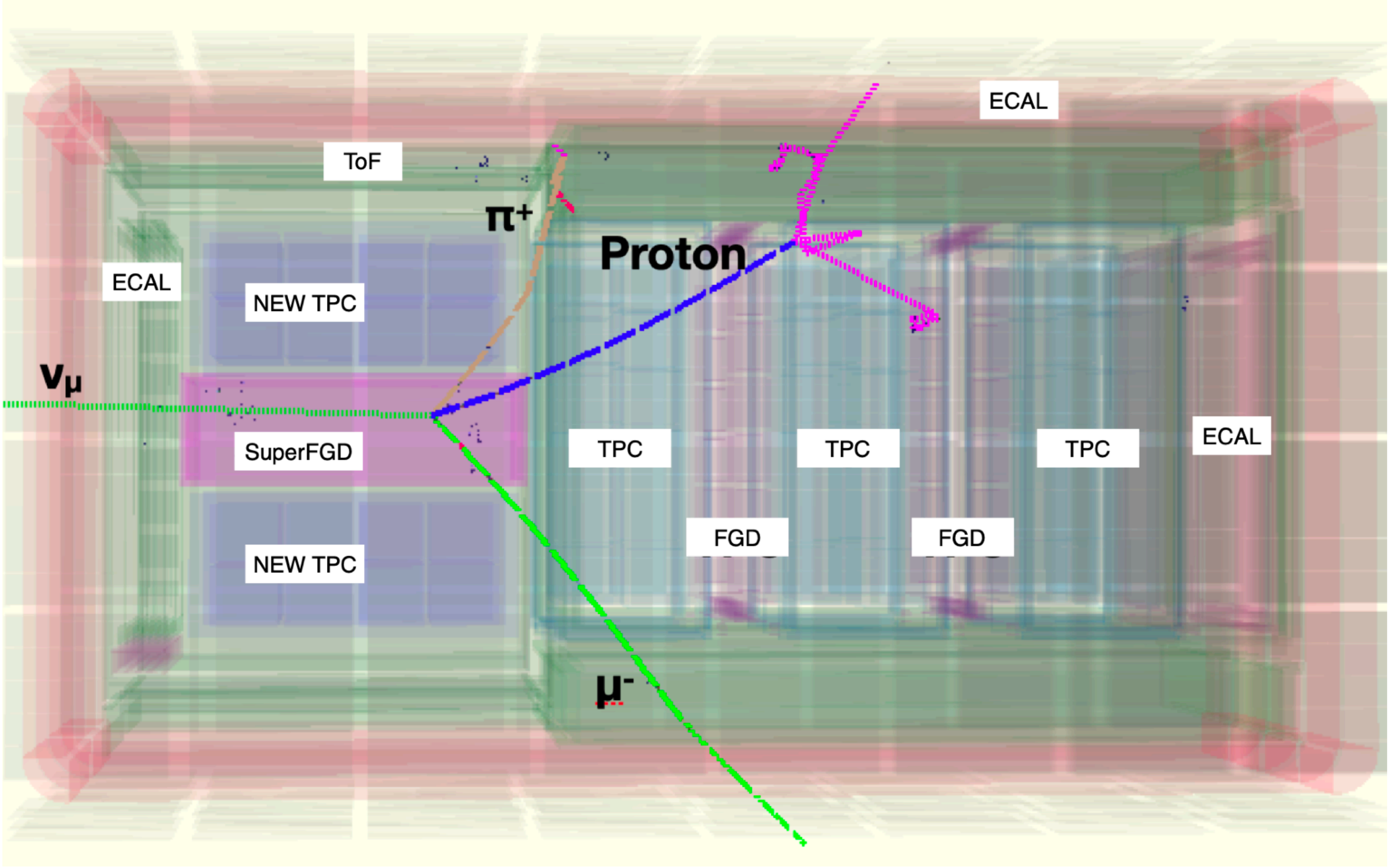
Neutrino sources:



Measured oscillation parameters

- $\Delta m^2_{31} = \Delta m^2_{atm} \simeq (2.56^{+0.03}_{-0.04})\text{x}10^{-3}\text{eV}^2$
  $\Delta m^2_{21} = \Delta m^2_{solar} \simeq (7.50^{+0.22}_{-0.20})\text{x}10^{-5}\text{eV}^2$
- $\sin^2\theta_{23}/10^{-1} \simeq 5.66^{+0.16}_{-0.22}$,
  $\sin^2\theta_{13}/10^{-2} \simeq 0.093 \pm 0.008$,
  $\sin^2\theta_{12}/10^{-1} \simeq 3.18 \pm 0.16$

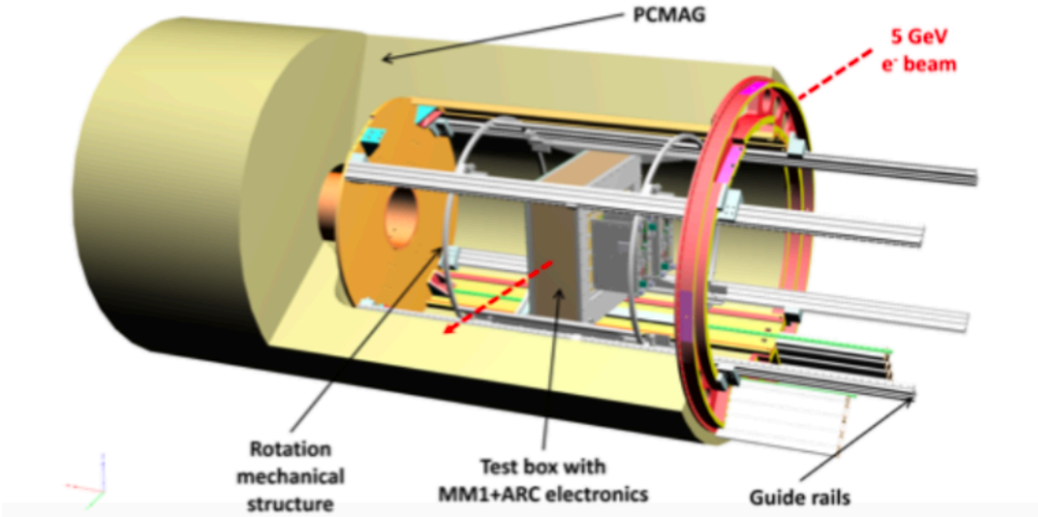
ND280 upgrade

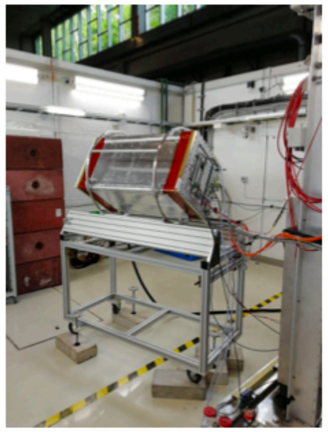


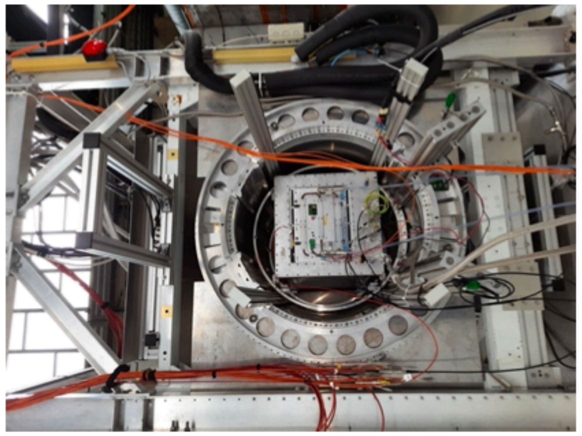
DESY Test Beam area T24/1

ERAM module (design for future HA-TPC) was tested at DESY II test beam facility:

- electron beam from 0.5 to 5 GeV/c in a short chamber of 1 m drift distance
- 0.2 T PCMAG magnet and 360 V
- AFTER chip: sampling time = 40 ns, peaking time of 200 ns and 412 ns, gain of 120 fC
- gas mixture: argon 95 %, 3% (CF_4), 2% (iC_4H_{10})
- oxygen contamination of 30 ppm at gas flow rate of 30 l/h
- the chamber operated under atmospheric pressure



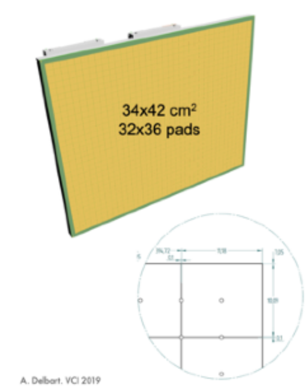


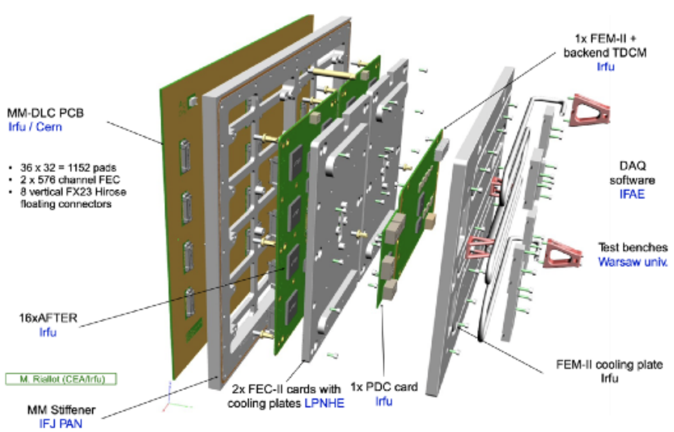


ERAMs performance

Characteristics of the ERAM module:

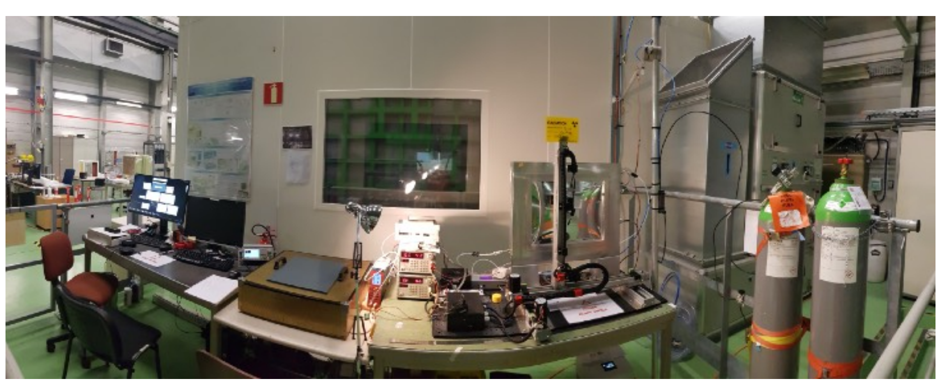
- ➡ Dimensions (z×y): 340×420 (mm)
- ➡ Micromegas gain 1000
- ➡ Pad size (z×y): 10×11 (mm)
- ➡ N pads: 36864 (1152 per module)





Each ERAM module is glued to supporting stiffener and mounted on the module frame. Then various modules such as Front-End cards (FEC), FEC cooling plates, the Front-End Mezzanine (FEM), Power Distribution Cards (PDC) and FEM water cooling plates are connected to complete the design.

In order to characterize and validate the ERAMs production, identify dead pads and check the detector response uniformity
↣ various tests are performed



➡ Cosmic ray test bench

- ✳ Tested DLC voltages (from 330 V to 370 V)
- ✳ Single vertical track per event

➡ X-ray ray test bench

- ✳ Fe^{55} source to scan detector pad by pad, centered at each pad
- ✳ 3 cm drift distance
- ✳ Energy resolution of ~9%

Accepted nonuniformity up to 20%

Gain maps