

FJPPN 2025: Neutrino cross-section measurements with the current and upgraded T2K near detectors

Andrés Muñoz on behalf of the NU_10 program
14/05/2025

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NU_10 program overview

1. Assembly, commissioning, and installation of upgrade ND280 detectors
2. Data analysis with the new upgrade detectors
3. Neutrino cross-section analyses with current/upgrade detectors
 - a. ND280
 - b. INGRID
 - c. WAGASCI-BabyMIND
4. Members:
 - a. 25(FR)
 - b. 23(JP)
 - c. PIs: Guillaume EURIN, Tsunayuki MATSUBARA
5. Goal:
 - a. Reduce the systematics related to the *neutrino-nucleus interaction* at the near detector in order to maximize the sensitivity of T2K (and eventually Hyper-Kamiokande)

Neutrino oscillations

- Flavor states are a linear superposition of the mass states via the PMNS matrix

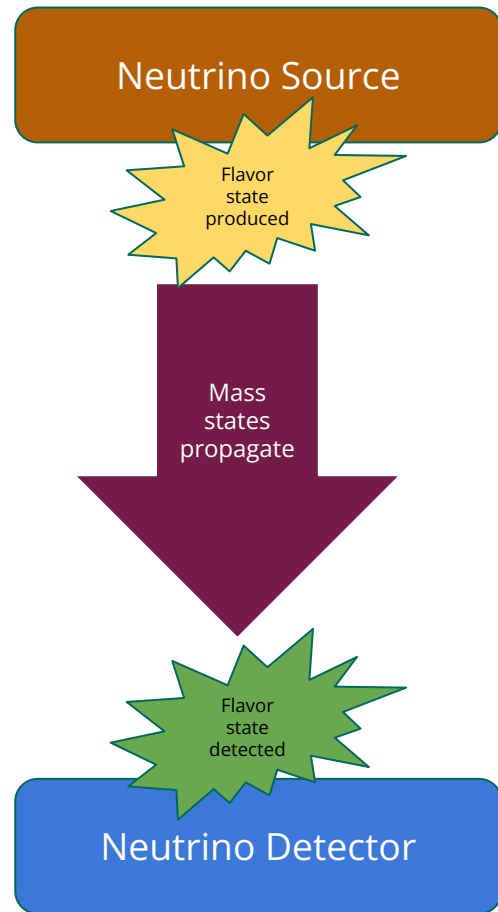
$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle$$

- Flavor states* produced and detected and *mass states* propagate
- For T2K muon neutrino oscillations take place:

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

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{13}) \sin^2(\theta_{23}) \sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right) \mp O(\sin \delta_{CP})$$

- if $\delta_{CP} \neq 0$ and $\delta_{CP} \neq \pi$, neutrino and antineutrino oscillate differently, implications on matter/anti-matter *asymmetry* in the Observable Universe



Neutrino oscillations

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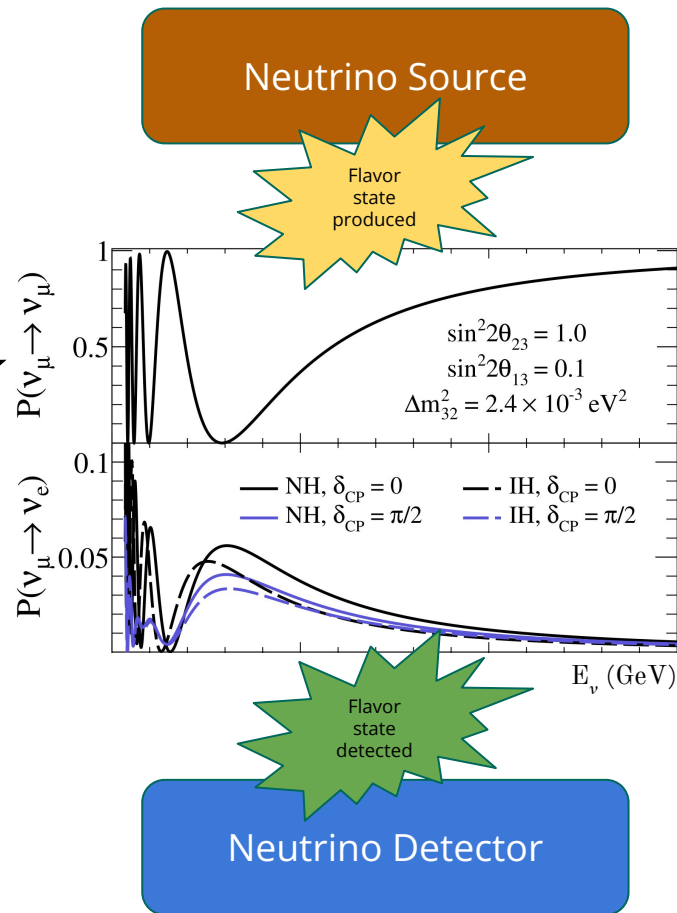
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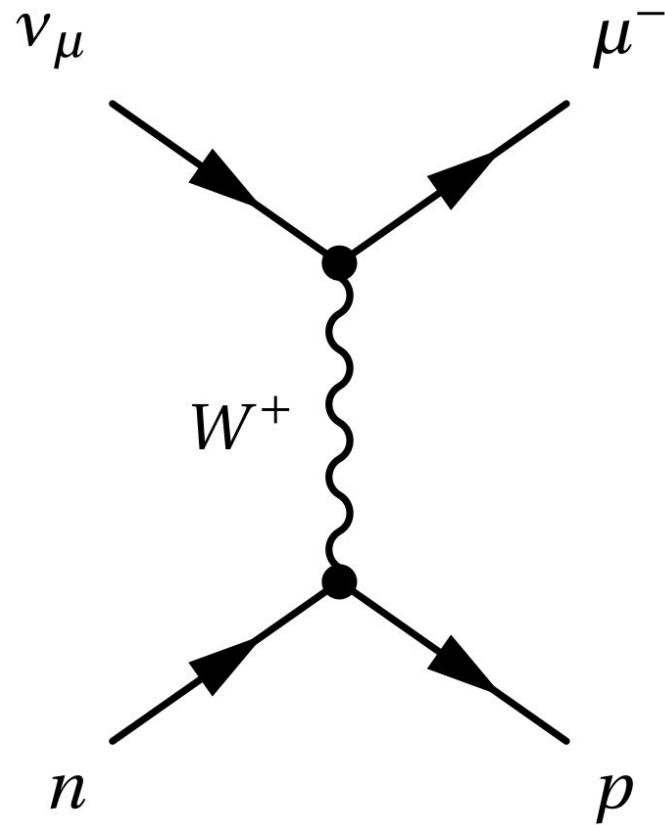
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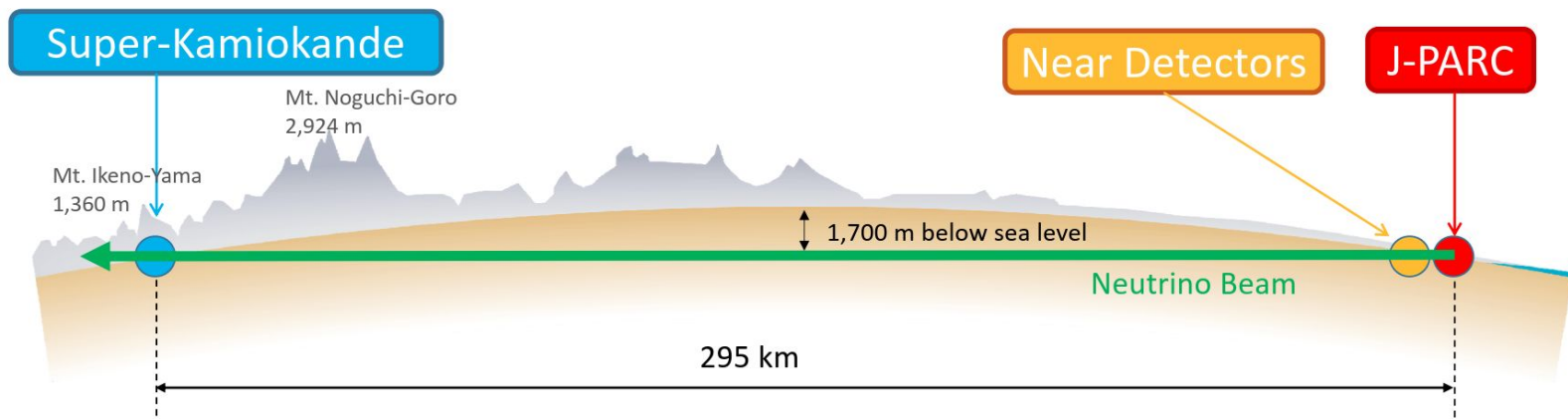
Neutrino interaction

- Charged current interactions
- Neutrino interactions identified by *outgoing lepton* (muon/electron)
- Reliance on muons, missing hadronic part → **Near detector upgrade** will help with this limitation



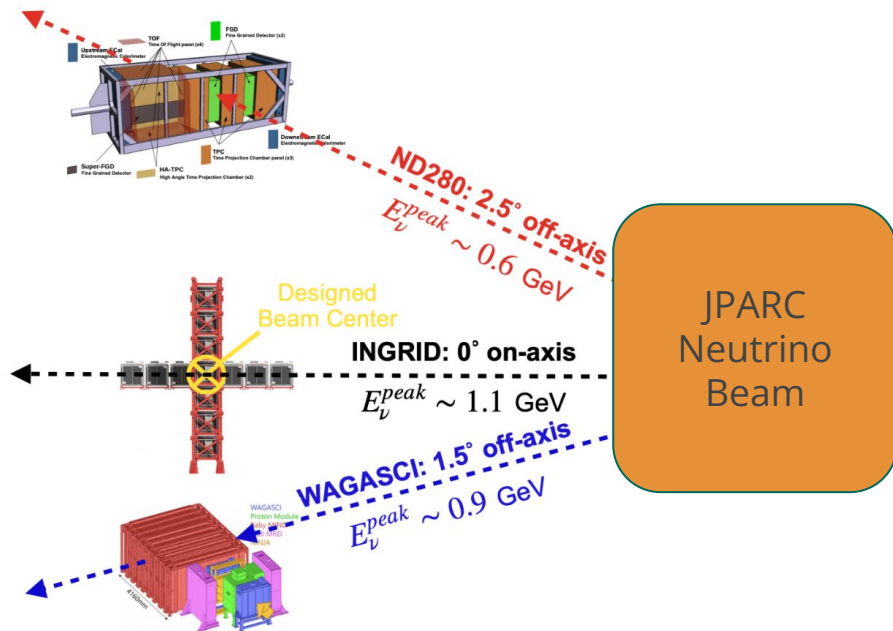
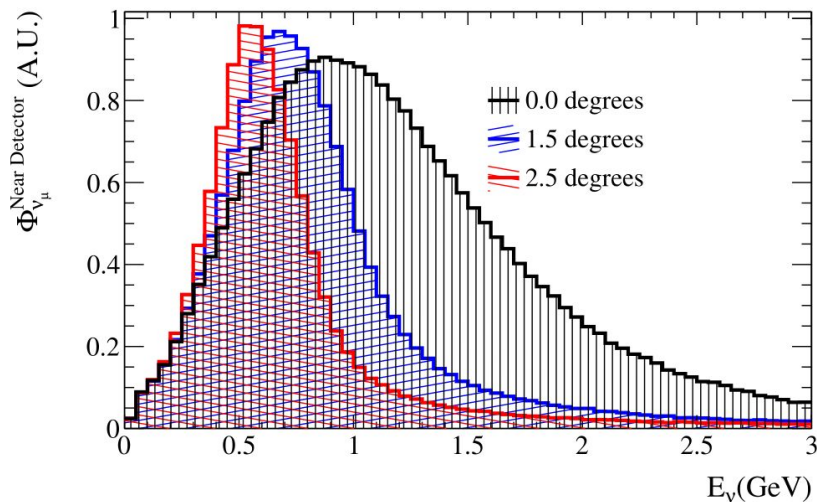
T2K Experiment

- Long baseline neutrino oscillation experiment in **Japan**
- Neutrino ((anti-)numu) beam produced in J-PARC
- First detected at near detector complex (**ND280**) then a second time in the Super-Kamiokande (**SK**) detector 295 km away



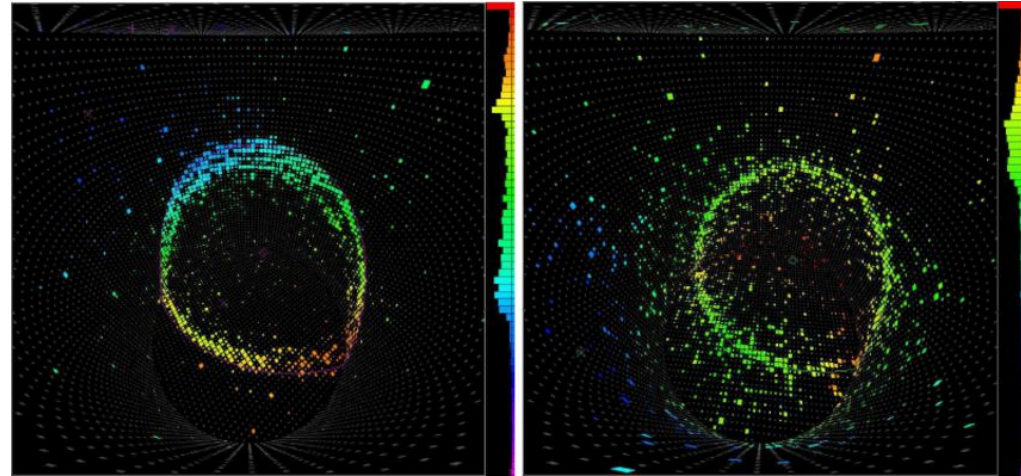
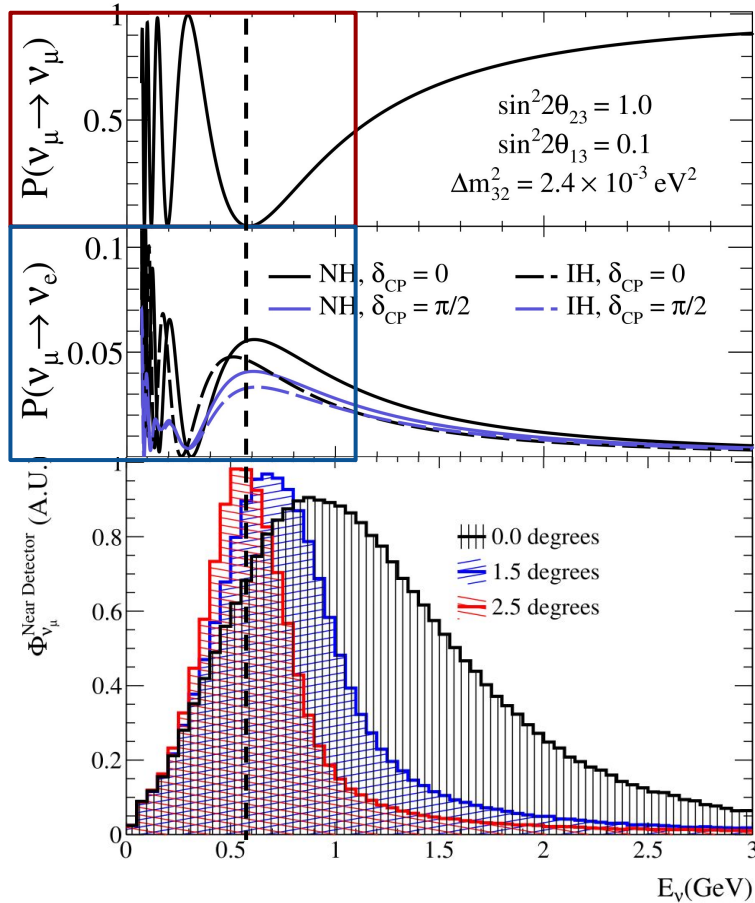
Near detector complex

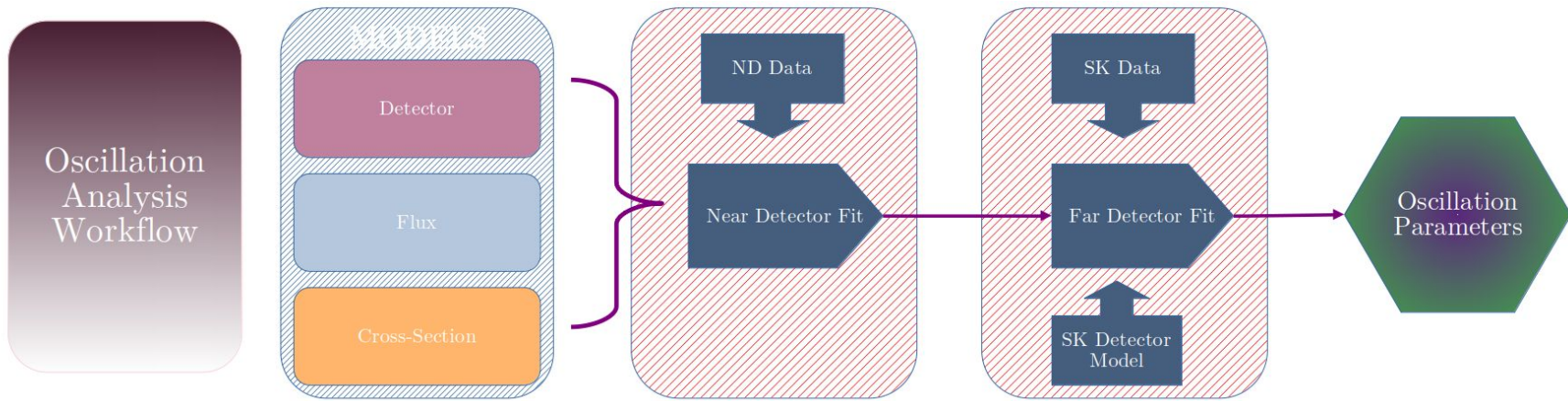
- ★ **ND280**: direction aligned with SK, cross-section measurements
- ★ INGRID: beam monitor
- ★ **WAGASCI-BabyMIND**: Water targets, cross-section measurements



Far detector oscillations

- Maximal muon neutrino *disappearance*
- Maximal electron neutrino *appearance*



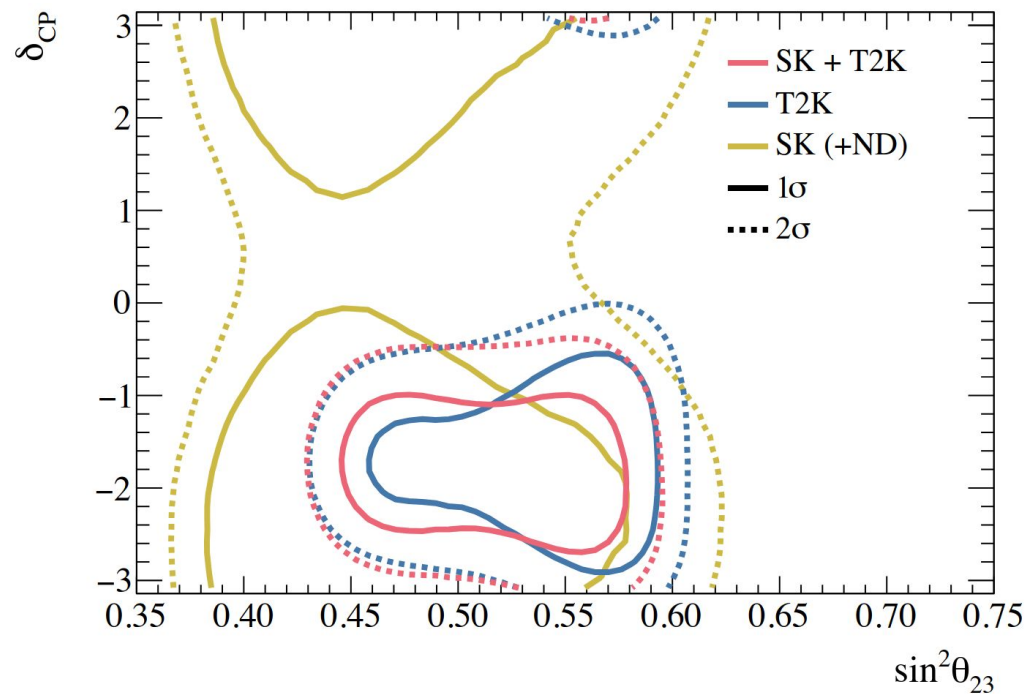


$$\frac{N_{events}^{far}(\vec{x})}{N_{events}^{near}(\vec{x})} = \frac{\sigma(E_\nu, \vec{x}) \otimes \Phi(E_\nu) \otimes D^{far}(\vec{x}) \otimes P_{osc}(E_\nu)}{\sigma(E_\nu, \vec{x}) \otimes \Phi(E_\nu) \otimes D^{near}(\vec{x})}$$

- Near detector fit used to constrain **cross-section**, **flux** and **detector** models by tuning a series of parameters that describe these models
- Tuned flux and detector models used to predict the spectra at Far Detector
- Far detector fit used to extract the oscillation parameters

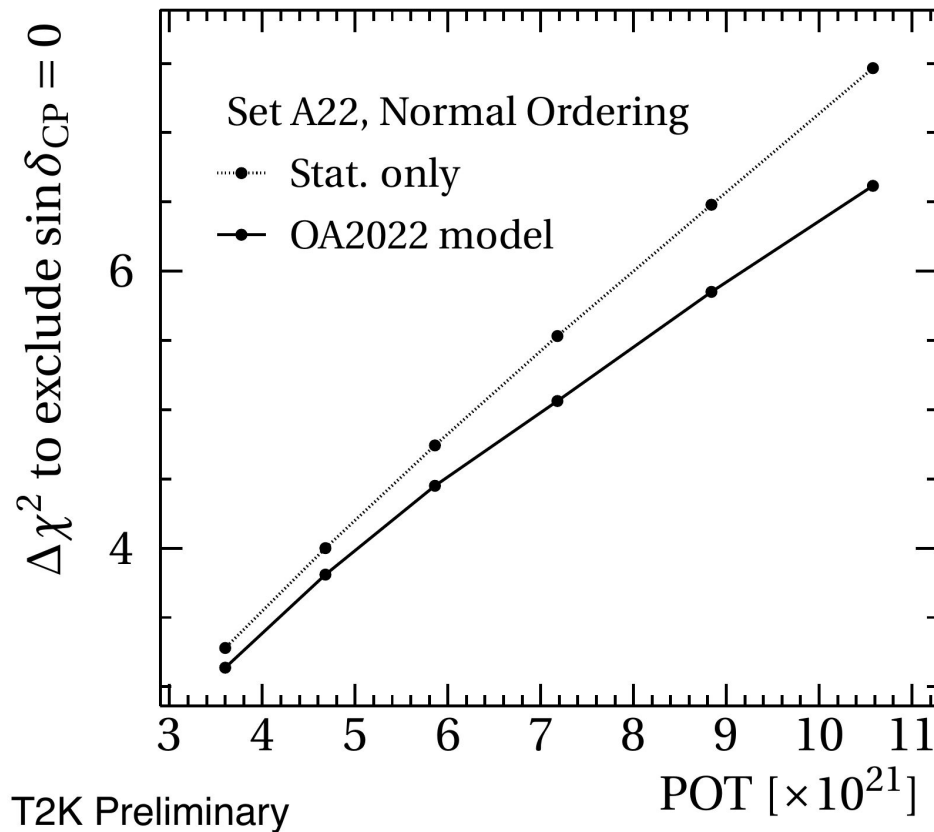
Recent Results: SK + T2K joint oscillation analysis

- Joint measurement of neutrino oscillation parameters from (SK) **atmospheric** and (T2K) **beam** neutrino data with overlapping neutrino energy
- Phys. Rev. Lett. 134, 011801
→ results show an exclusion of the CP-conserving value of the Jarlskog invariant and an exclusion of the inverted mass ordering



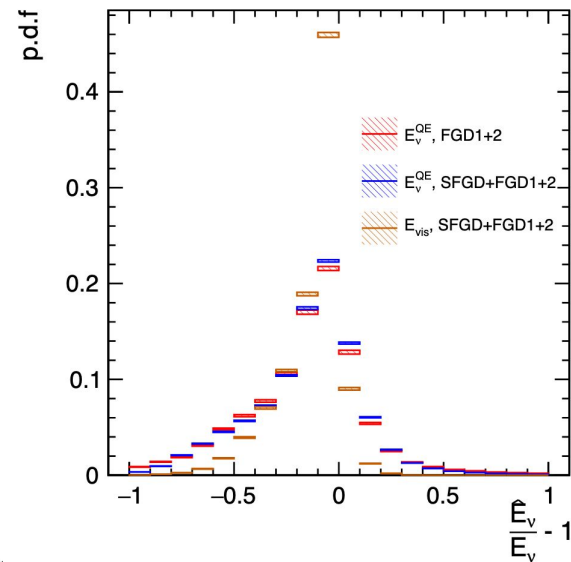
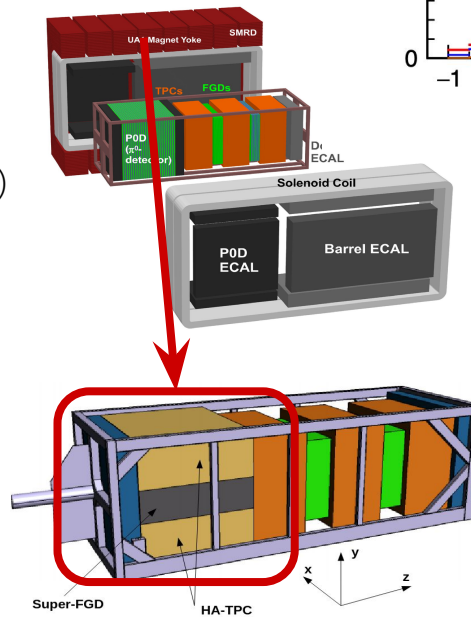
T2K-II : Future sensitivity

- Still very limited by *statistical* uncertainties in oscillation analysis
- T2K will take data with greater beam power $\rightarrow$ increased statistics, but **systematic uncertainties** become more relevant
- To counteract this upgraded near detectors used to constraint **cross-section** and **flux** systematic uncertainties



Near Detector Upgrade

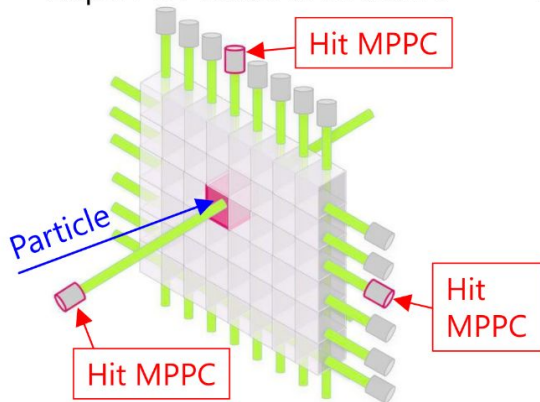
- Upgrade to address certain limitations of the Near Detectors (ND280)
 - Short track reconstruction (low momentum pion/protons/neutrons)
 - Low acceptance for reconstructed particles, mostly forward tracks
- Upstream detector replaced by:
 - **SuperFGD** : interaction target and tracking
 - **2 HA-TPC** : tracking and covering large (4π) acceptance
 - **6 ToF** : PID, veto, cosmic trigger



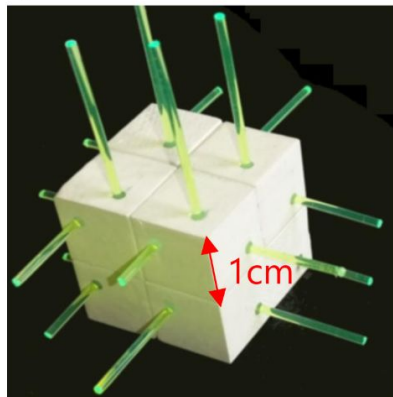
SFGD: Super Fine Grained Detector

- Target detector filled with around **2 million** scintillator cubes (approx. 2 tonnes active volume)
- 4π tracking of protons tracks down to 300 MeV/c
- Probe interactions with nuclear effects

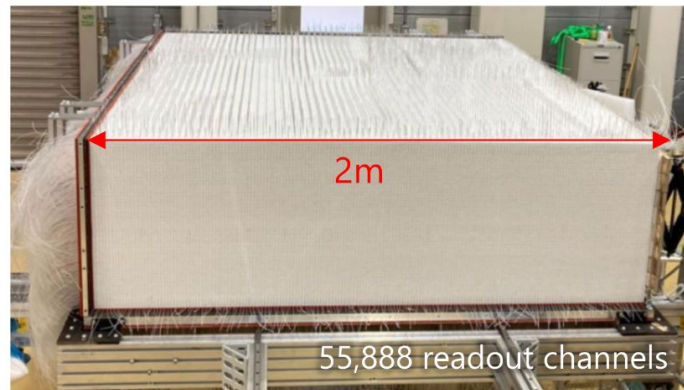
SuperFGD readout structure



SuperFGD scintillator and fiber



SuperFGD scintillator cubes under assembly



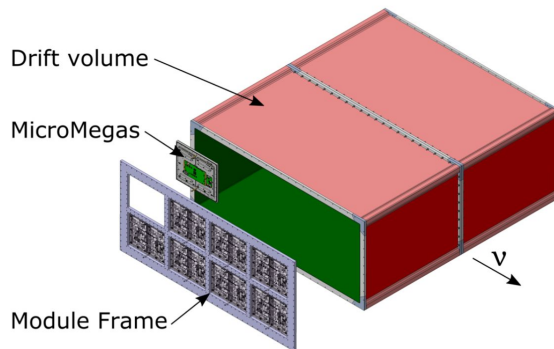
HAT

- SFGD sandwiched between these two modules
- Installation:
 - bottom HAT (spring 2023)
 - Top HAT (spring 2024)
- ERAM (Encapsulated Resistive Anode Microegas)

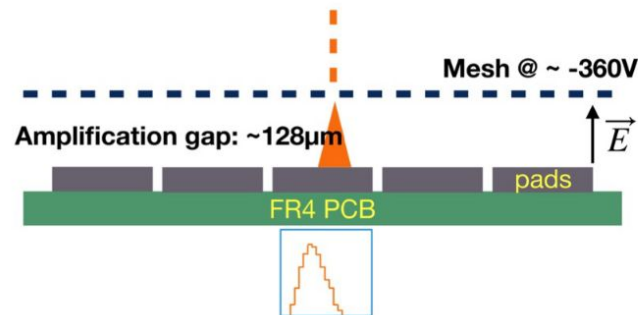
technology allows for improved spatial resolution

- Great amount of contributions from the French group:
 - MicroMegas
 - Front-end/back-end electronics
 - Power supplies

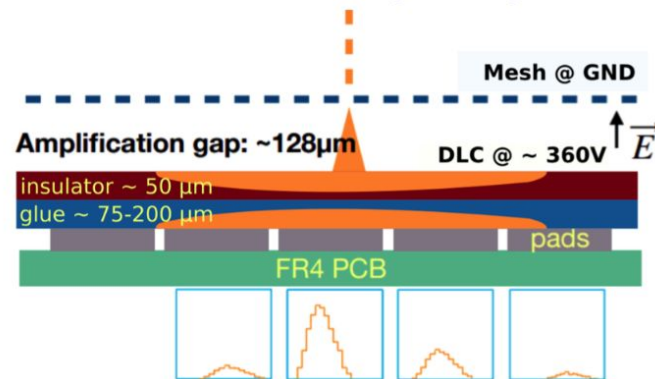
HA-TPC schematic view



Standard bulk-MicroMegas

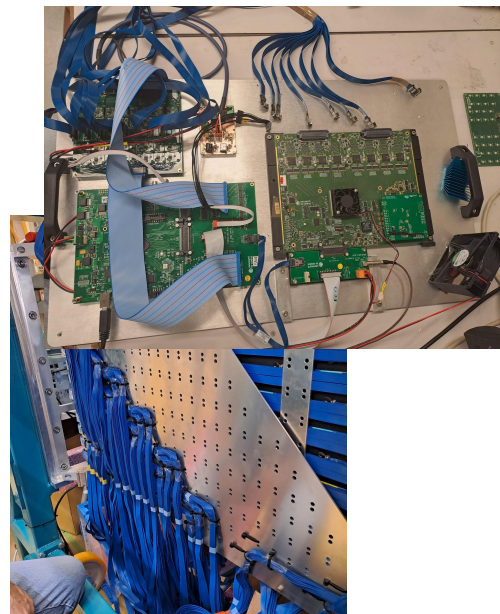


Encapsulated Resistive Anode MicroMegas (ERAM)



(SFGD) assembly and installation

- Front end board (FEB) Production and testing in France
- Testing of the of FEBs joint french and japanese effort!
- Cable management at J-PARC
- Cooling plates for FEBs produced in France (LLR)



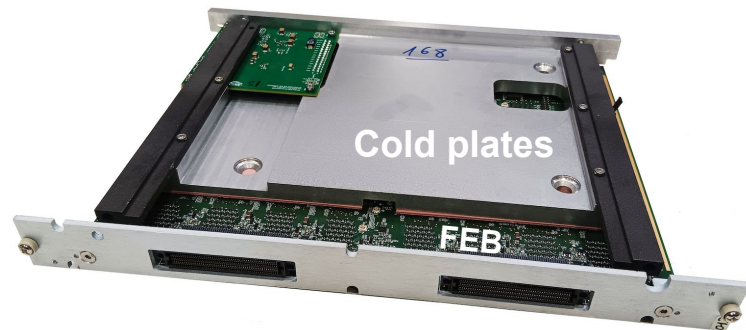
TOF installation
(July 2023)



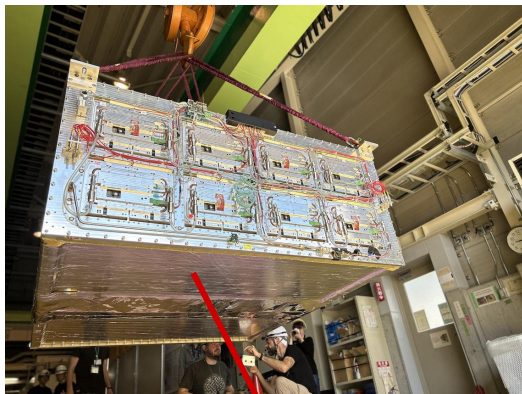
HA-TPC installation
(Sep. 2023)



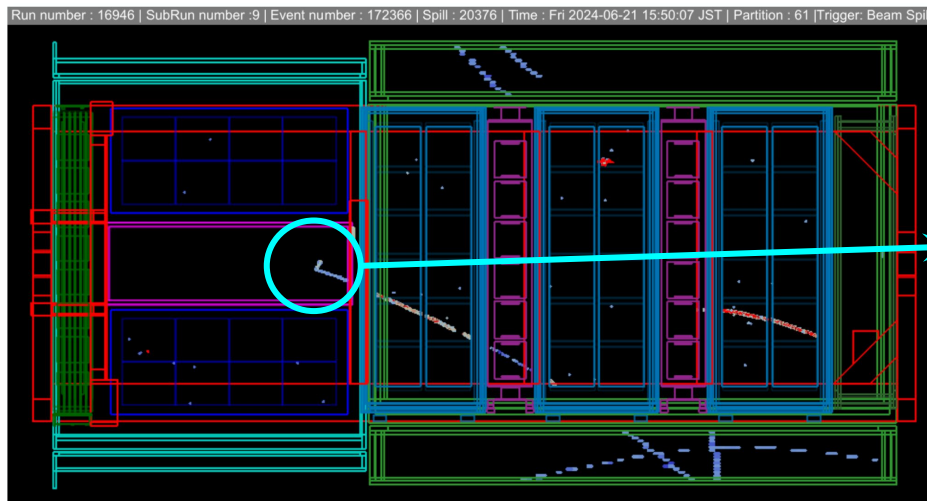
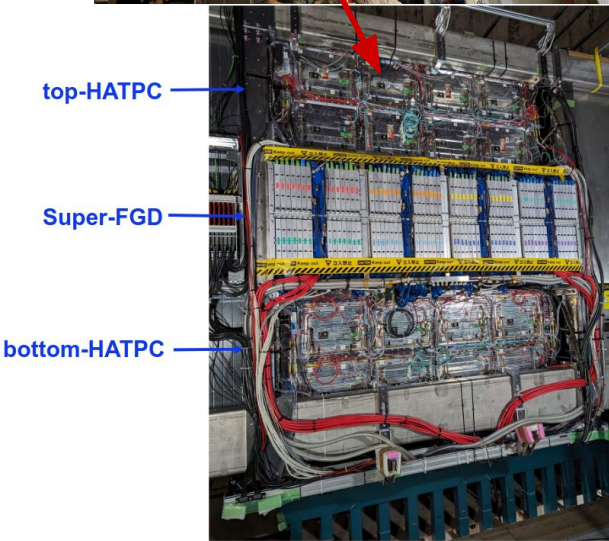
SuperFGD installation
(Oct. 2023)



Final installation



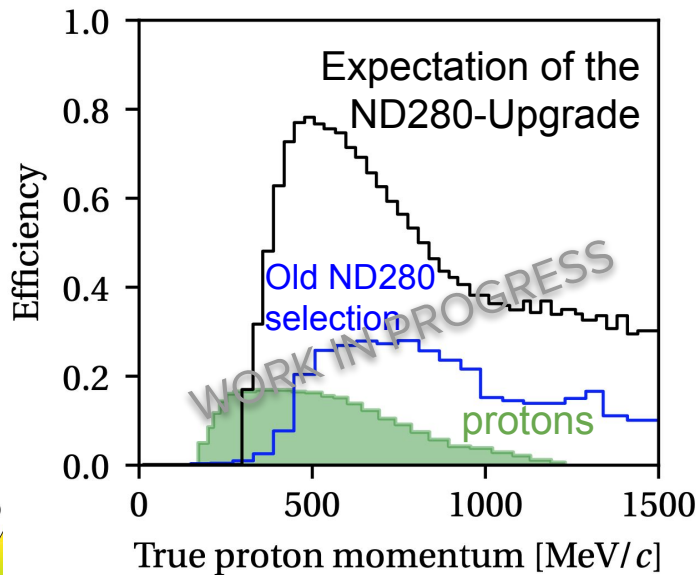
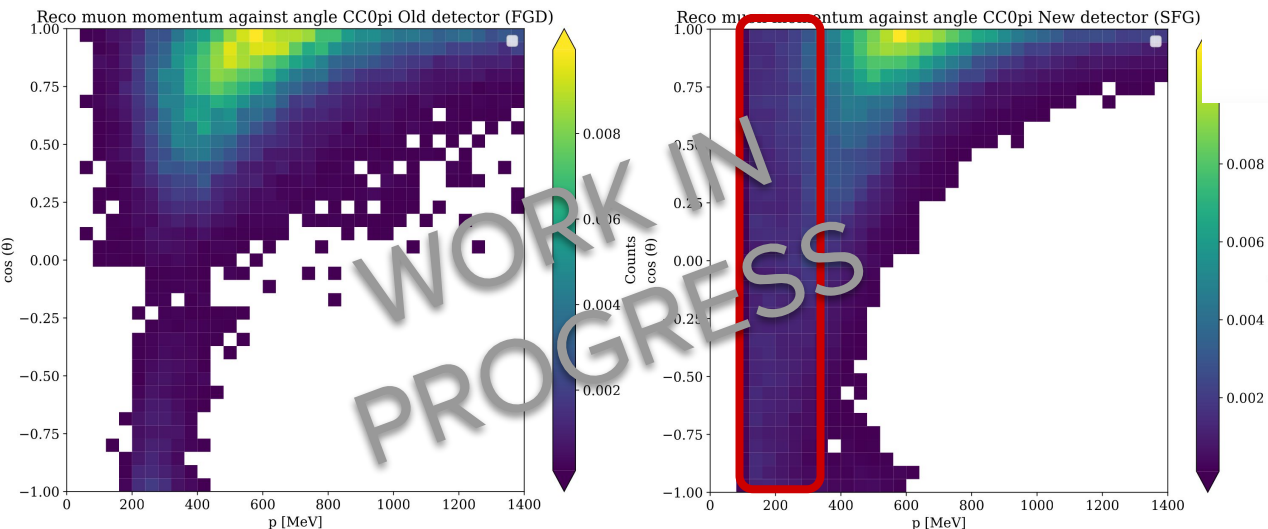
- Finalized installation of upgrade detectors in May 2024 with the installation of the top HAT
- New physics data taking started with ND upgrade!
 - From May 2024 to July 2024
 - From Nov 2024 to Dec 2024
 - In Feb 2025



Proton???

Upgrade selection

- New selections currently being made for new upgraded detectors $\rightarrow$ joint japanese + french effort
- Exploiting proton reconstruction efficiency:
 - SFGD, out of 102904 selected events 54407 are with protons, proportion is: **52.87%**
 - FGD, out of 52743 selected events 16715 are with protons, proportion is: **31.69%**

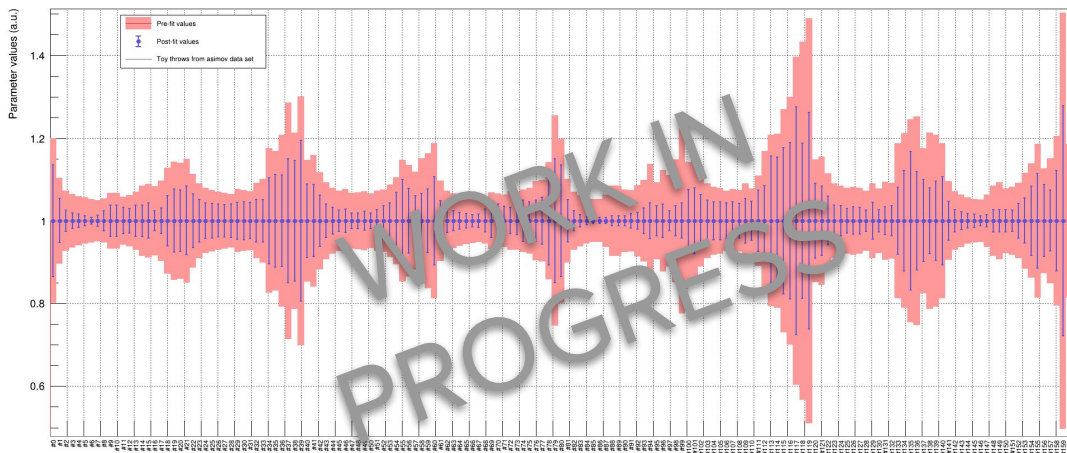


- Access to more backward tracks, more phase space!

GUNDAM: Fitter for Upgrade Analyses

- GUNDAM developed in the context of physics sensitivity studies meant to quantify the improvement in the constraint of *systematic uncertainties* with the Near Detector Upgrade
- Provide user friendly workflow to accommodate a variety of complex analyses with the use of configuration files that can be easily defined and modified

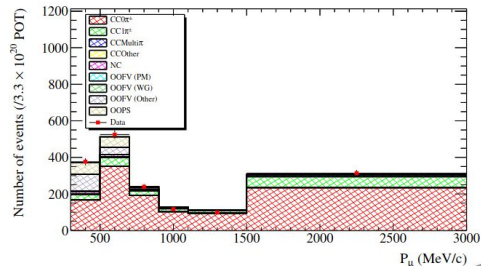
Pre-fit/Post-fit comparison for Flux Systematics



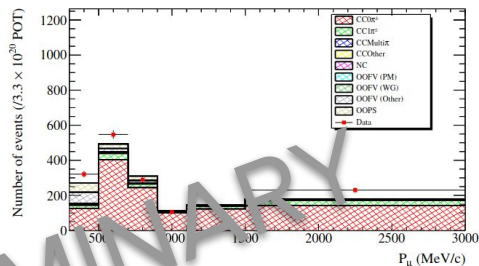
- Addresses challenges that may come with future analyses such as:
 - Increasing number of samples
 - Additional complex systematic parameters
 - Among other things!
- Already used for *ND upgrade* and *WAGSCI-BabyMIND* sensitivity studies and will be used for many more analyses!

WAGASCI-BabyMIND cross-section analysis (Results public, awaiting publication)

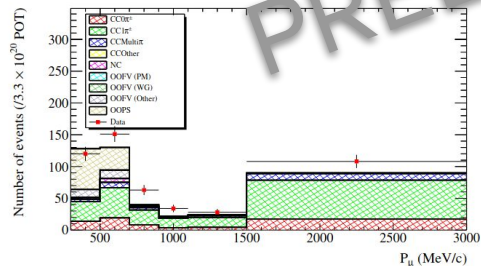
- First full analysis with current detector setup
- Same **target** and **acceptance** as SK
- Different off-axis, different energy spectrum



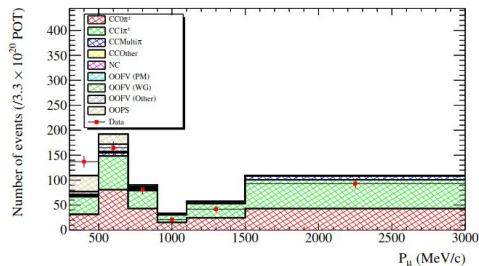
(a) CC0 $\pi^\pm$, CH target



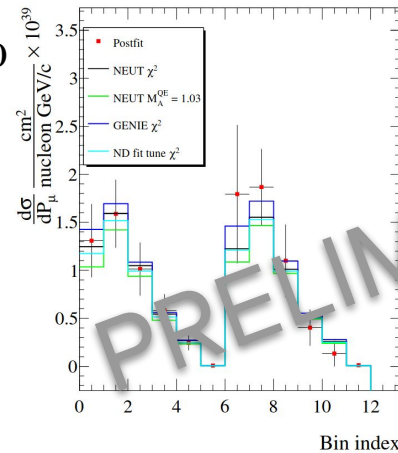
(b) CC0 $\pi^\pm$, H₂O target



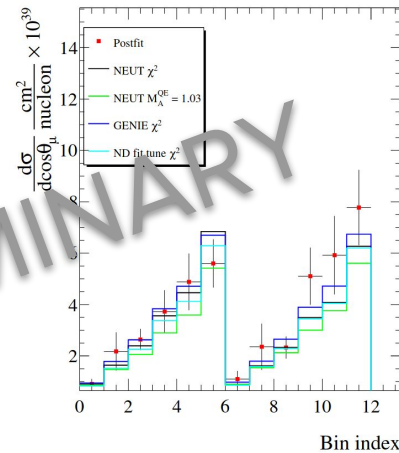
(c) CC1 $\pi^\pm$, CH target



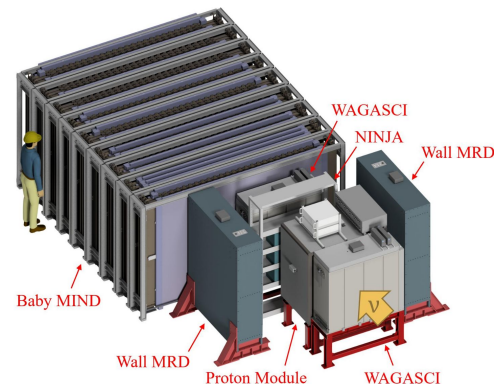
(d) CC1 $\pi^\pm$, H₂O target



(a) As a function of P_μ

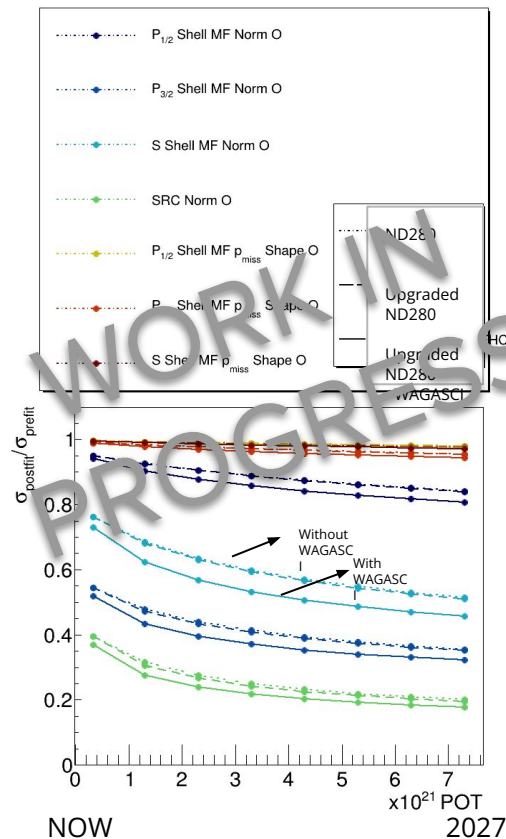
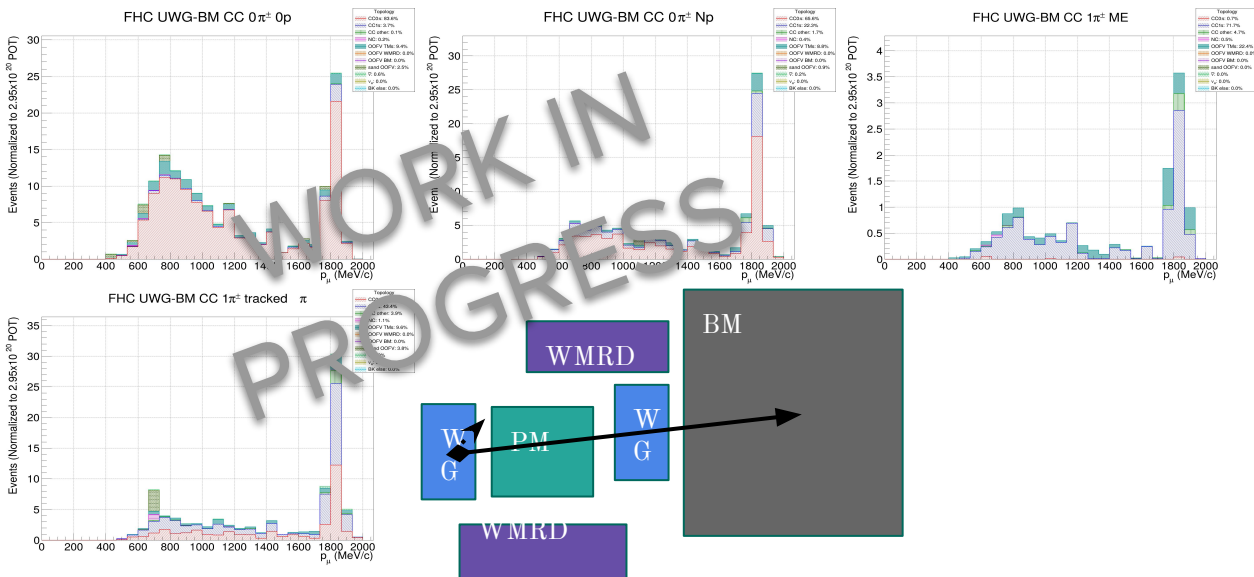


(b) As a function of $\cos \theta_\mu$



WAGASCI-BabyMIND for joint analyses

- Integration of software into common **analysis framework**, facilitate future analyses
- *Sensitivity studies* realized to see potential effect of the addition of WAGASCI-BabyMIND detectors
- Validation of said integration with previous mentioned cross-section analysis and creation of new analysis samples



Conclusion

- Huge achievement → completion of near detector upgrade with a significant participation on the French + Japanese side along with other members of the T2K collaboration
- Recent analyses:
 - [Eur.PHys.J.C, 2023, 83, \(782\)](#) , [Phys. Rev. Lett. 134, 011801, 10.1103/PhysRevD.108.112009](#)
 - And soon many more!
- With the recent runs an additional $\frac{1}{4}$ of current statistics, more beam power!
- Now that upgrade detectors installed and running, many analyses are in the works which will lead to many new publications
- Expect **major** updates for ***Neutrino 2026*** and ***FJPPN 2026!***

Thank you for
your attention!

BACKUP

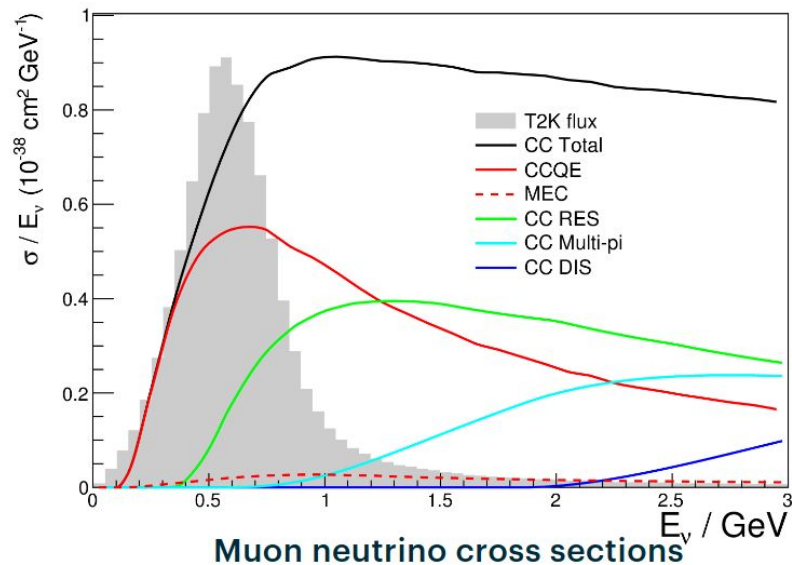
Neutrino Interaction

➤ Neutrinos rarely interact via weak interaction

- **Charged Current(CC)**
- **Neutral Current(NC)**

➤ Interaction in range of T2K beam flux

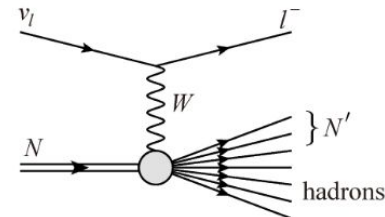
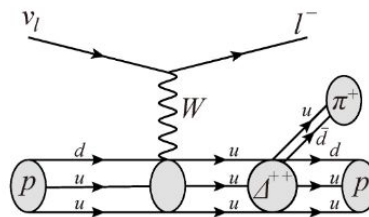
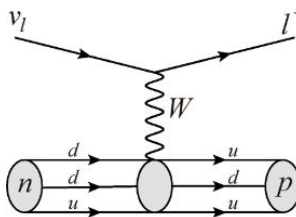
- **CC Quasi-elastic (QE)**
→ lepton, proton(anti-neutrino:neutron)
- **CC Resonance scattering (RES)**
→ lepton, proton(neutron)+ π , η , K , γ
- **CC Deep inelastic scattering (DIS)**
→ lepton+multiple hadrons
- **CC coherent pion production (coh)**
→ lepton+charged pion



Quasi-elastic

Resonance scattering

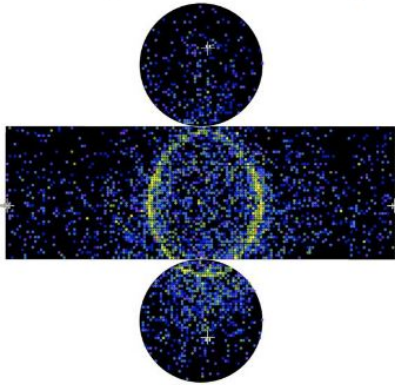
Deep inelastic scattering



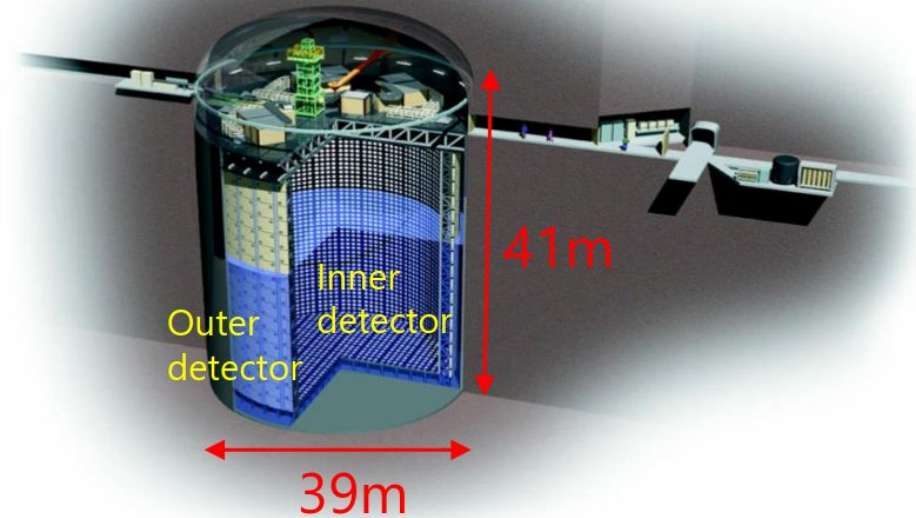
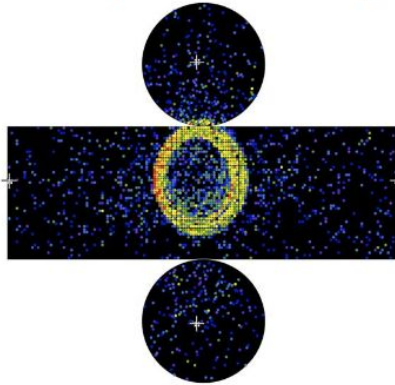
SK

- 50kt water Cherenkov detector having $\sim 11,000$ 20-inch PMTs.
- Good separation of electrons and muons. $\rightarrow$ Separate ν_e and ν_μ CC interactions.
- Gd loaded for enhanced neutron detection in 2020.

ν_e candidate event
(fuzzy Cherenkov ring)

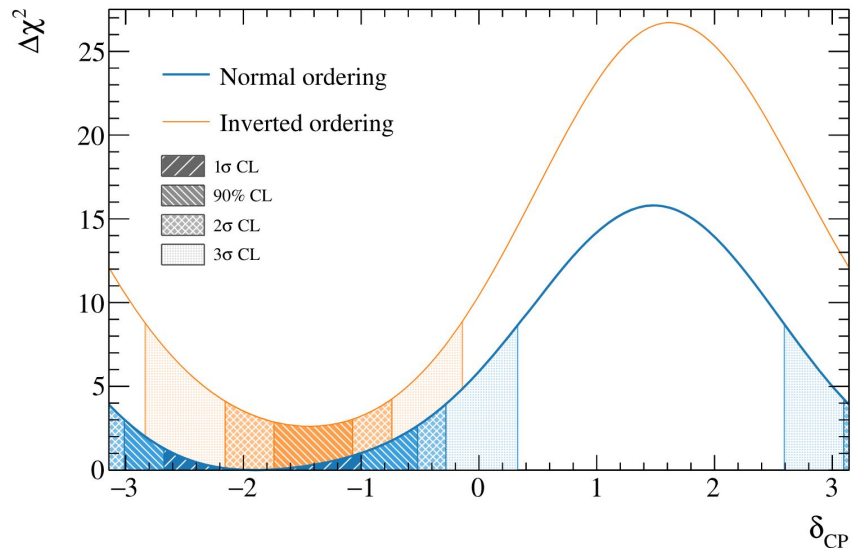


ν_μ candidate event
(sharp Cherenkov ring)



Recent Results: T2K oscillation analysis (was shown last year)

- Measure: $\delta_{CP}, \theta_{ij}, \Delta m_{ij}^2$
- Eur.PHys.J.C, 2023, 83, (782) → Exclude CP-conserving values of $\square_{CP}$

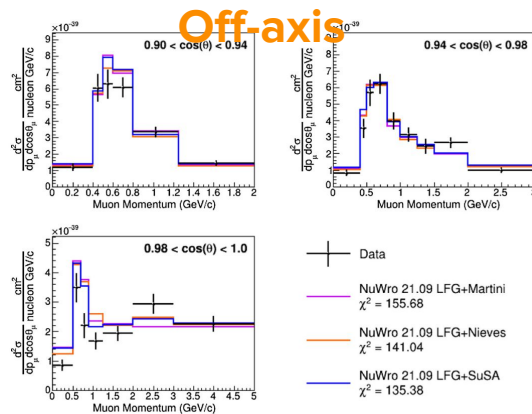
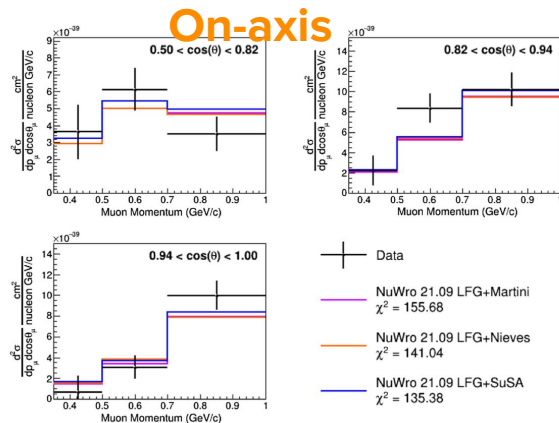


Parameter	With reactor constraint	
	Normal ordering	Inverted ordering
δ_{CP} (rad.)	$-1.97^{+0.97}_{-0.62}$	$-1.44^{+0.56}_{-0.59}$
$\sin^2 \theta_{13}/10^{-3}$	—	—
$\sin^2 \theta_{23}$	$0.561^{+0.019}_{-0.038}$	$0.563^{+0.017}_{-0.032}$
$\Delta m_{32}^2/10^{-3}$ (eV ²)	$2.494^{+0.041}_{-0.058}$	—
$ \Delta m_{31}^2 /10^{-3}$ (eV ²)	—	$2.463^{+0.042}_{-0.056}$

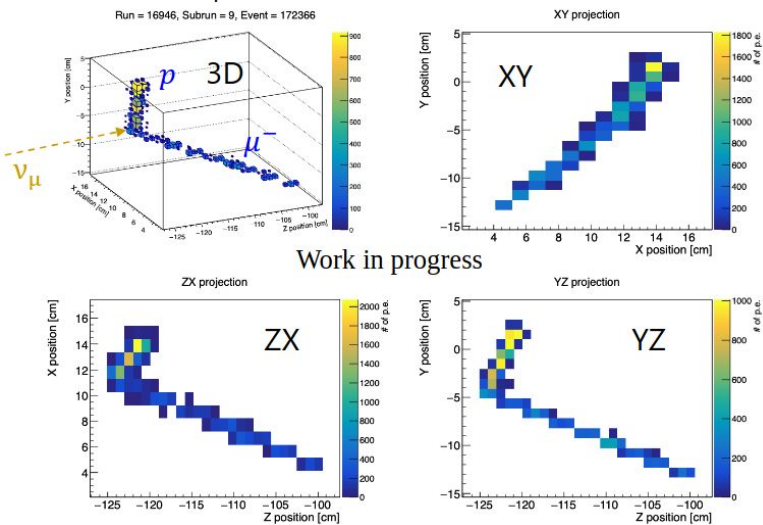
Joint INGRID + ND280 cross-section analysis

(10.1103/PhysRevD.108.112009)

- Correlated neutrino flux spectra reduce flux uncertainty



Upgrade reconstruction (remove?)



Neutrino oscillations

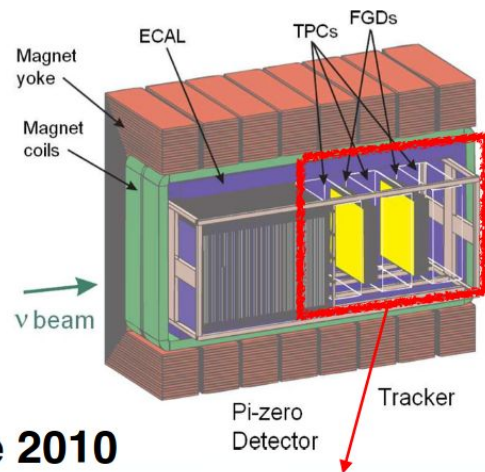
$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{pmatrix}$$

Commissioning

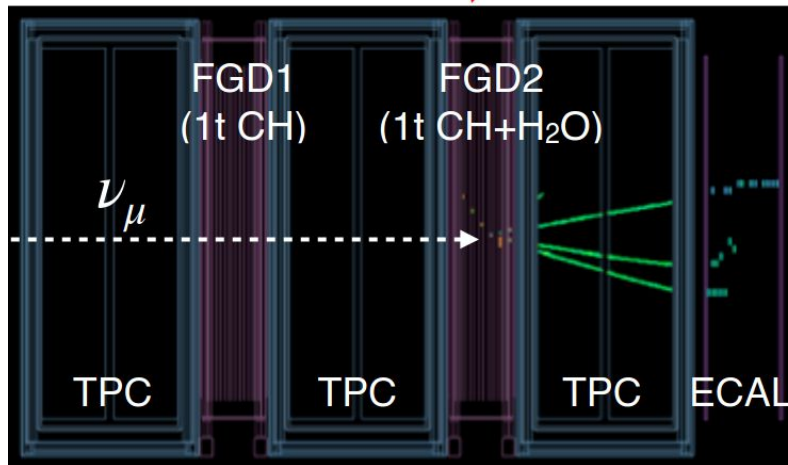
Probably move to back up, or put few plots

Joint fit atmos detailed

Old detectors



Since 2010



- Plastic scintillator (FGD1 and 2)
✓ ν target ($\sim 2t$)
✓ Forward tracking, PID
- UA1 magnet (0.2T) instrumented with scintillator detectors (SMRD)
✓ Charged ID $\rightarrow \nu$ vs $\bar{\nu}$
- Time Projection Chambers (TPC)
- EM Calorimeter (ECAL)
- π^0 detector (scintillator + water)

SFGD assembly

Installation of soft EPDM foam



Closure of the box



Transfer to new support frame



Fishing lines removal
and WLS fiber insertion



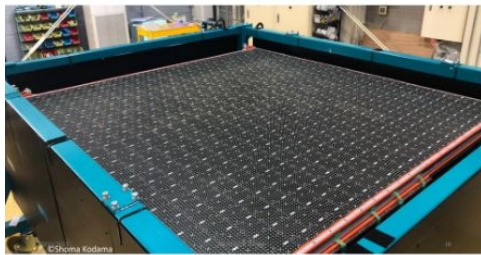
MPPC-PCBs installation



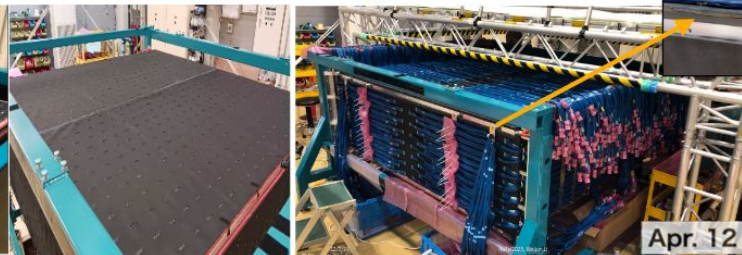
Installation LED calibration



Light barrier installation



Arrangement of MPPC cables



~6 months
since the start
of cube layer
installation

HAT

■ Resistive layer enables charge spreading

- space resolution below $500\text{ }\mu\text{m}$ with cm size pads
- less FEE channels (lower cost)
- improved resolution at small drift distance (where transverse diffusion cannot help)

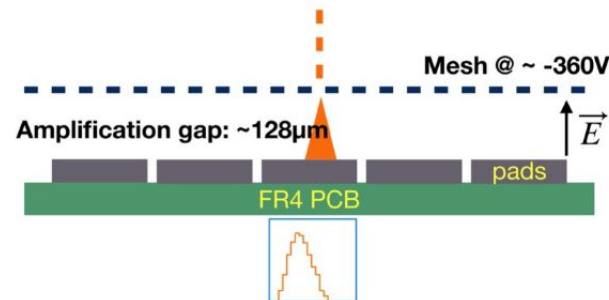
■ Resistive layer prevents sparks

- enables operation at higher gain
- no need for spark protection circuits for ASICs
→ compact FEE → max active volume

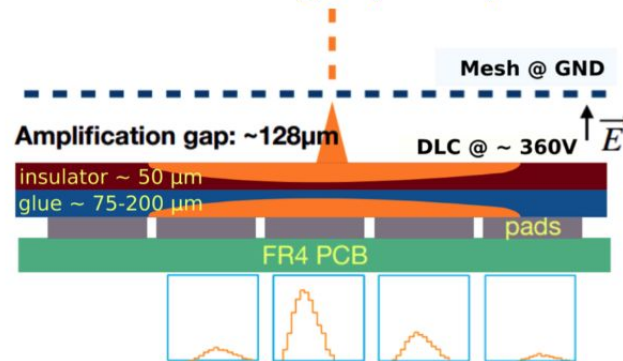
■ Resistive layer encapsulated and properly insulated from Ground

- Mesh at ground and Resistive layer at +HV
- improved field homogeneity → reduced track distortions

Standard bulk-MicroMegas

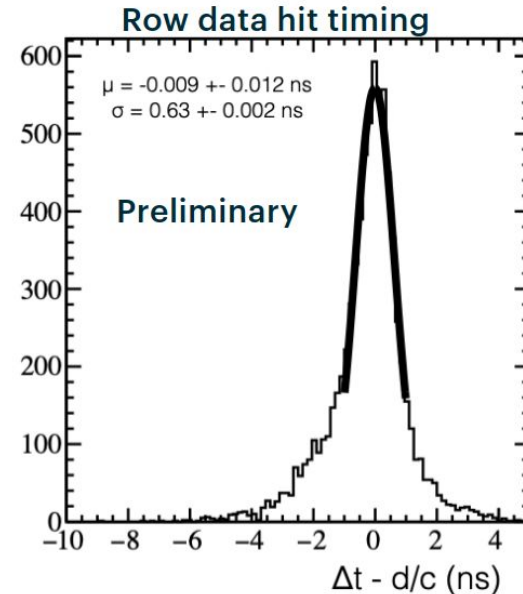
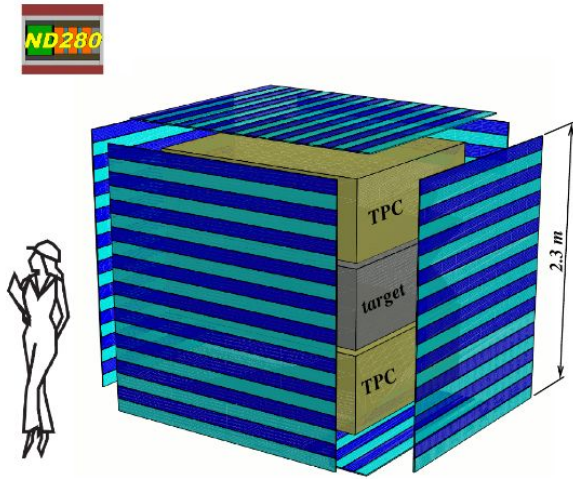


Encapsulated Resistive Anode MicroMegas (ERAM)



ToF

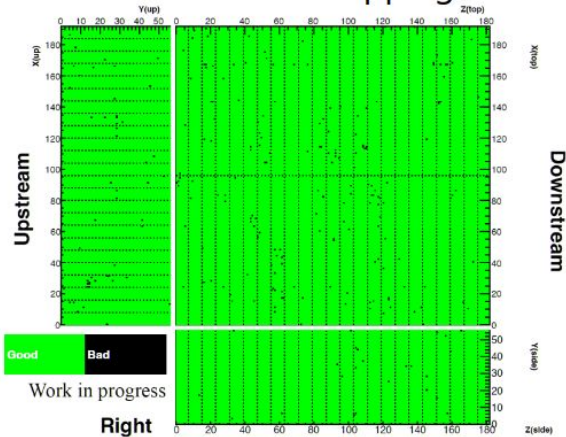
- 6 Time Of Flight(TOF) detectors consist scintillator bars , and surround SuperFGD&HA-TPC
- All TOFs are shipped in summer 2023 after assembly at CERN
- Raw data time resolution of 0.63 ns for twice modules in ND280 pit



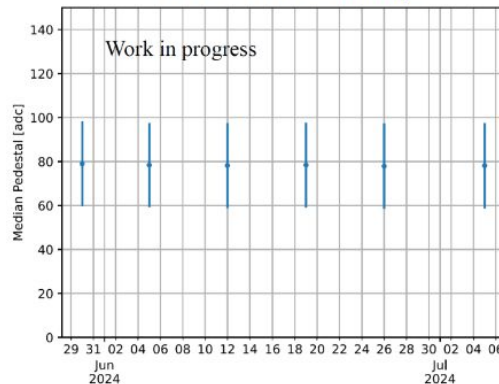
Calibration and stability

- Ratio of bad channels is small.
- Pedestal and gain are stable.
- Inter-calibration of high-gain ADC, low-gain ADC and time over threshold.

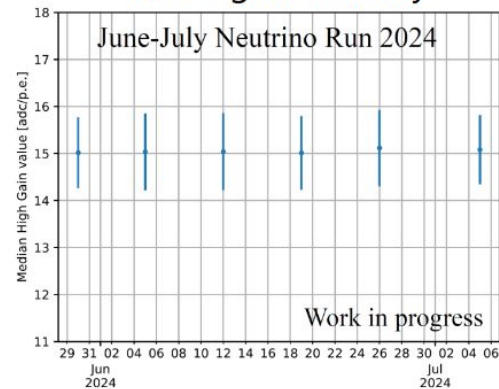
Bad channel mapping



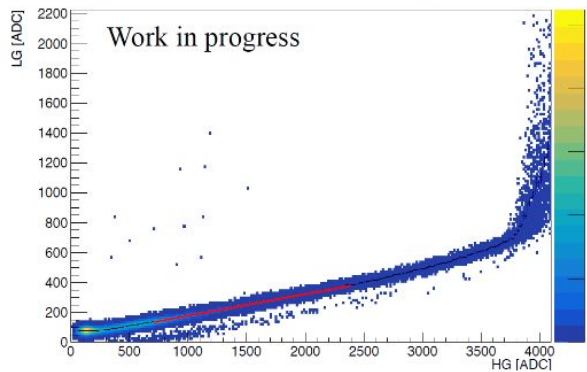
Pedestal stability



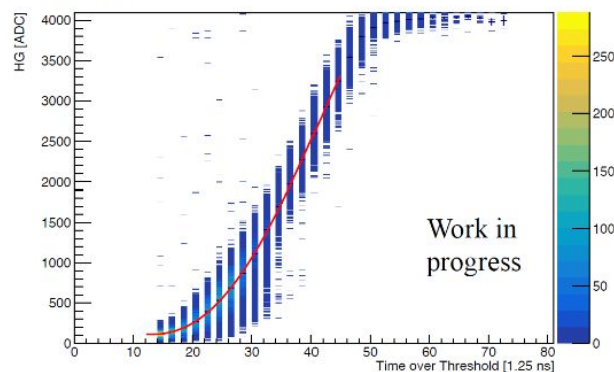
MPPC gain stability



High-gain ADC vs low-gain ADC



High-gain ADC vs time over threshold



Accumulated POT

