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

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. 30(FR)
   b. 26(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

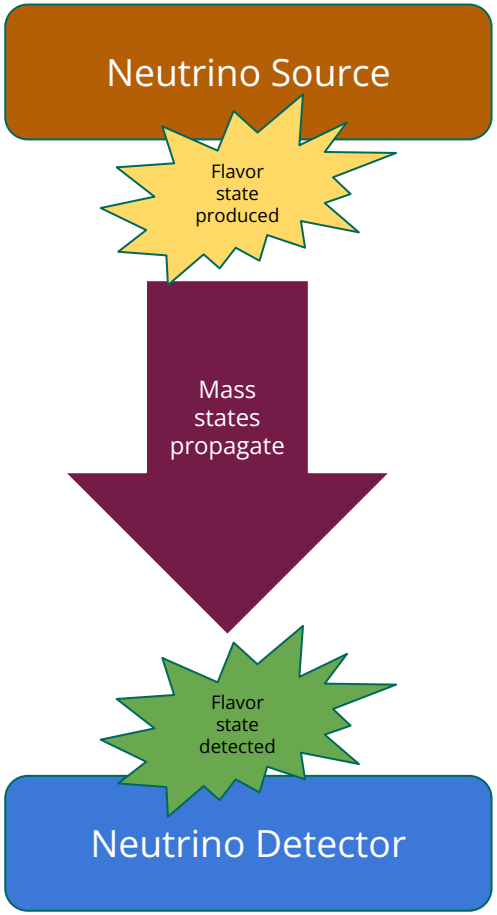
$$|\nu_\alpha >= \sum_i U^*_{\alpha i} |\nu_i >$$

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

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2(\frac{\Delta m^2_{32} L}{4E})$$

$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13}) \sin^2(\theta_{23}) \sin^2(\frac{\Delta m^2_{32} L}{4E}) \mp O(\sin \delta_{CP})$$

- 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



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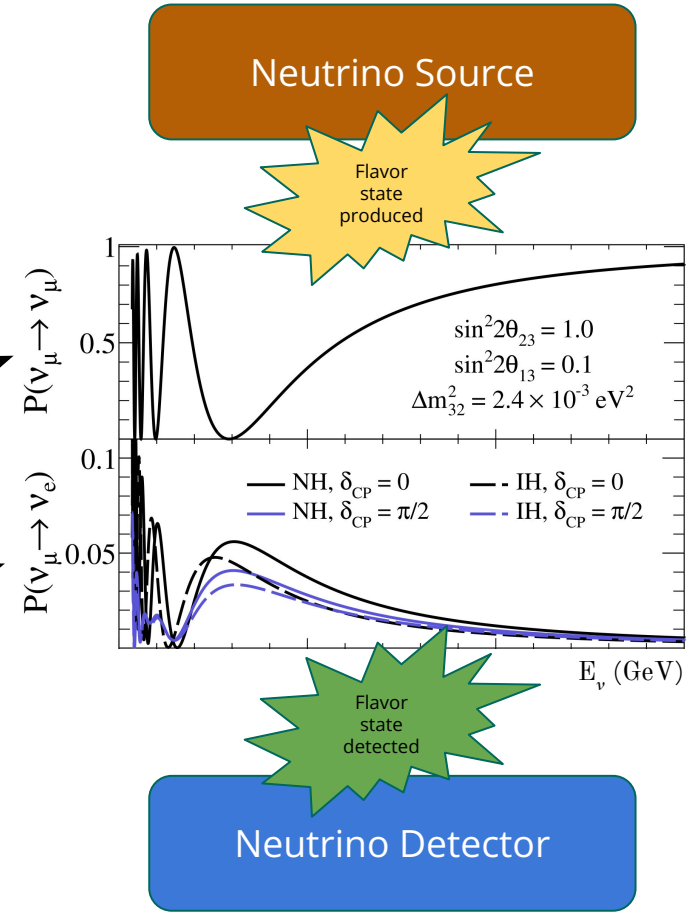
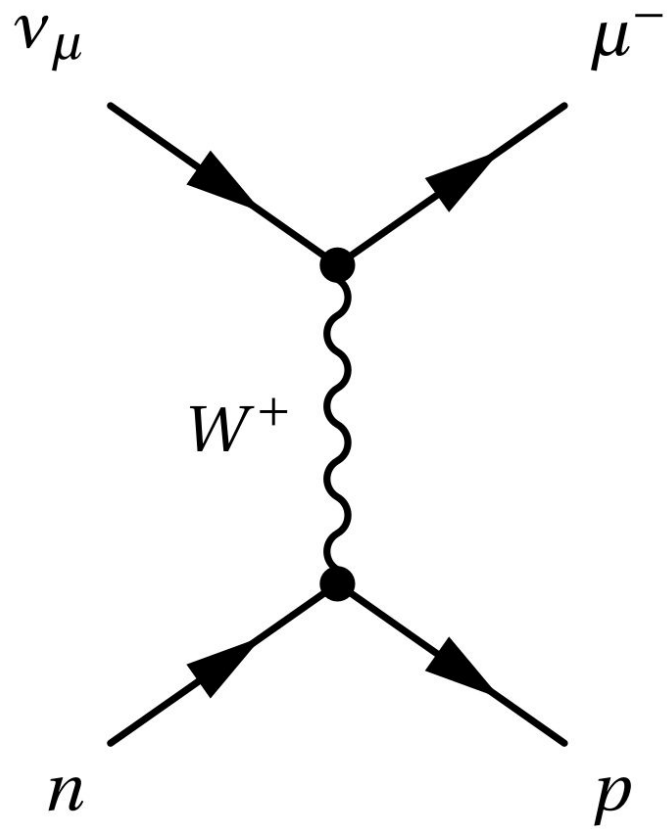


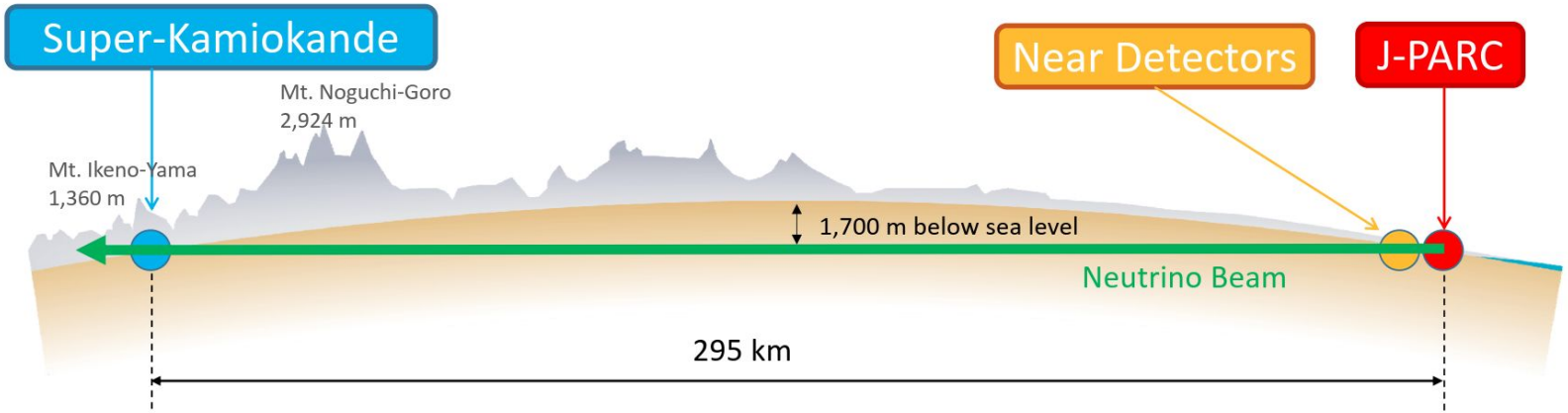
Neutrino interaction

- 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



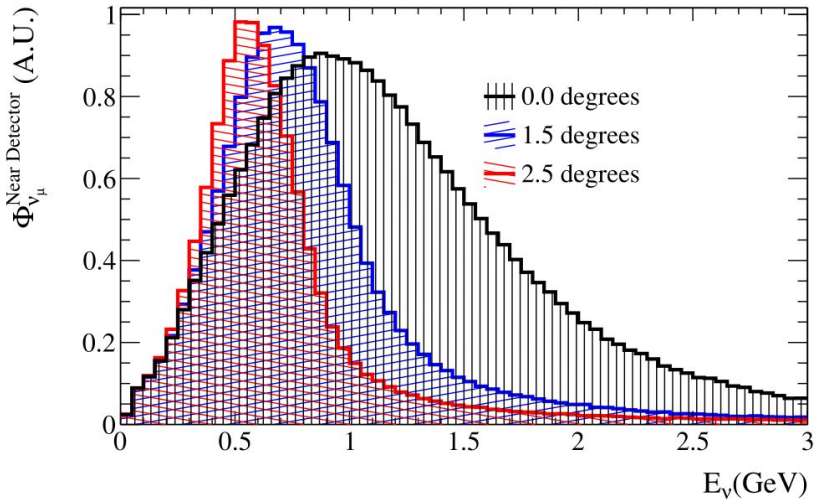
T2K Experiment

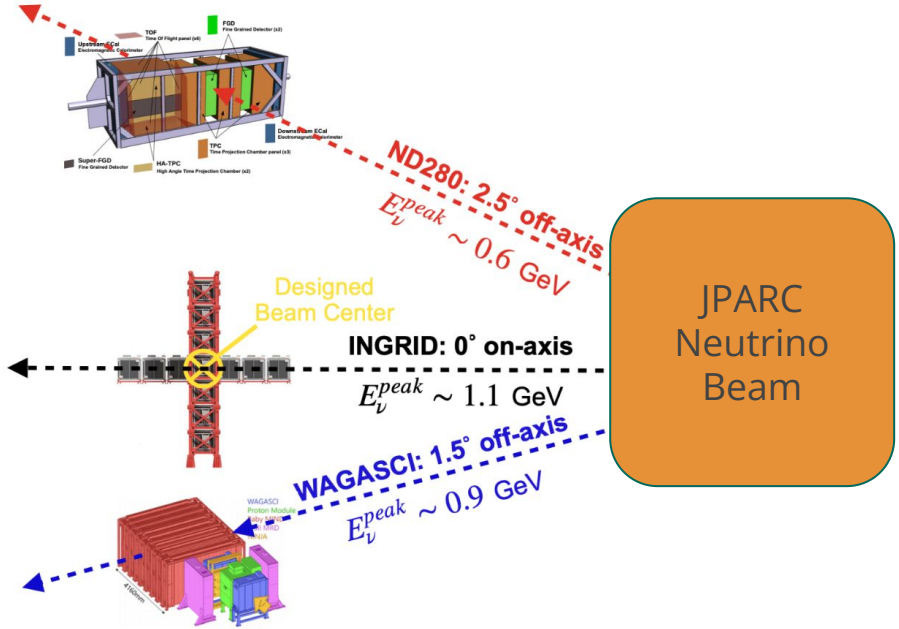
- Long baseline neutrino oscillation experiment in **Japan**
- Neutrino ((anti-)numu) beam produced in J-PARC
- First detected at near detector complex (**ND280**) then a second time in the Super-Kamiokande (**SK**) detector 295 km away



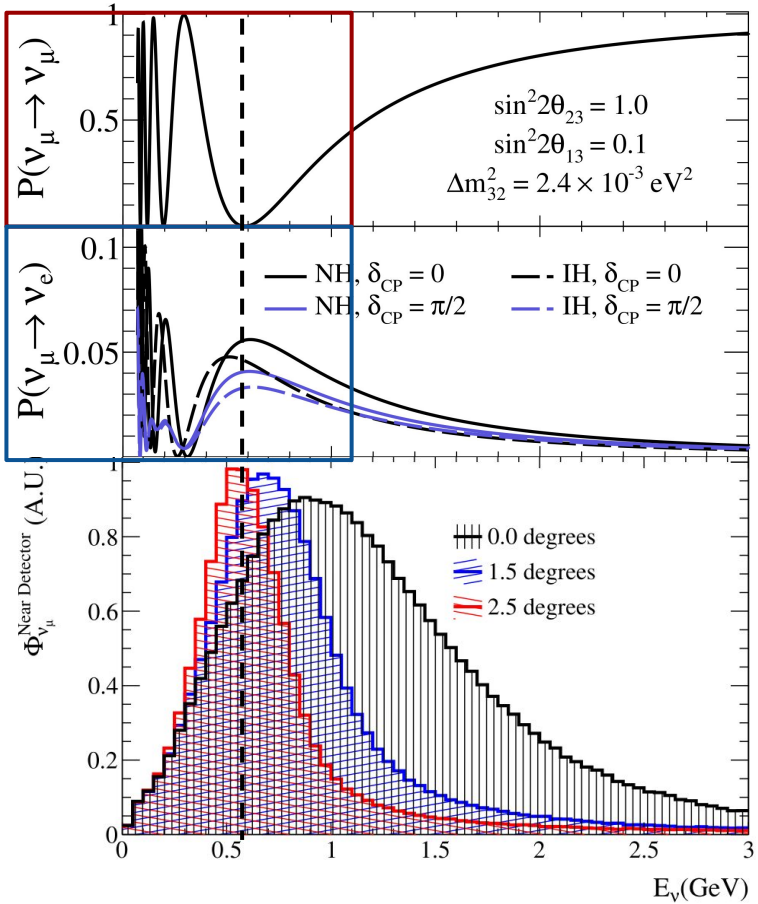
Near detector complex

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

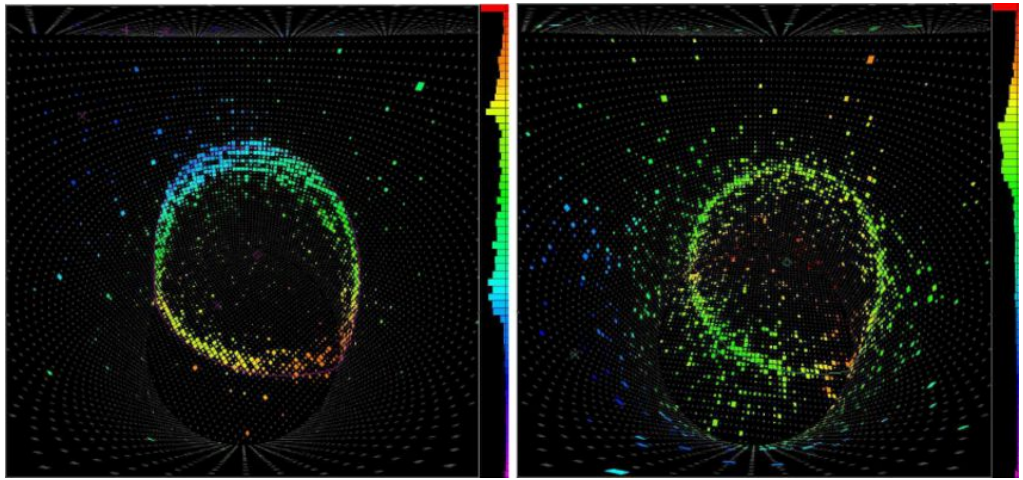


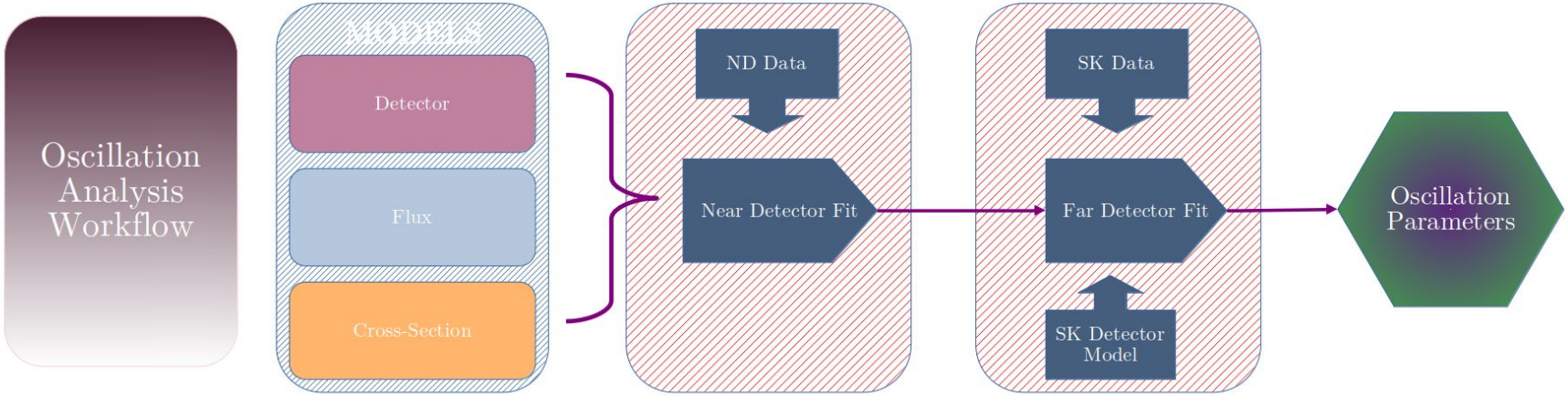


Far detector oscillations



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



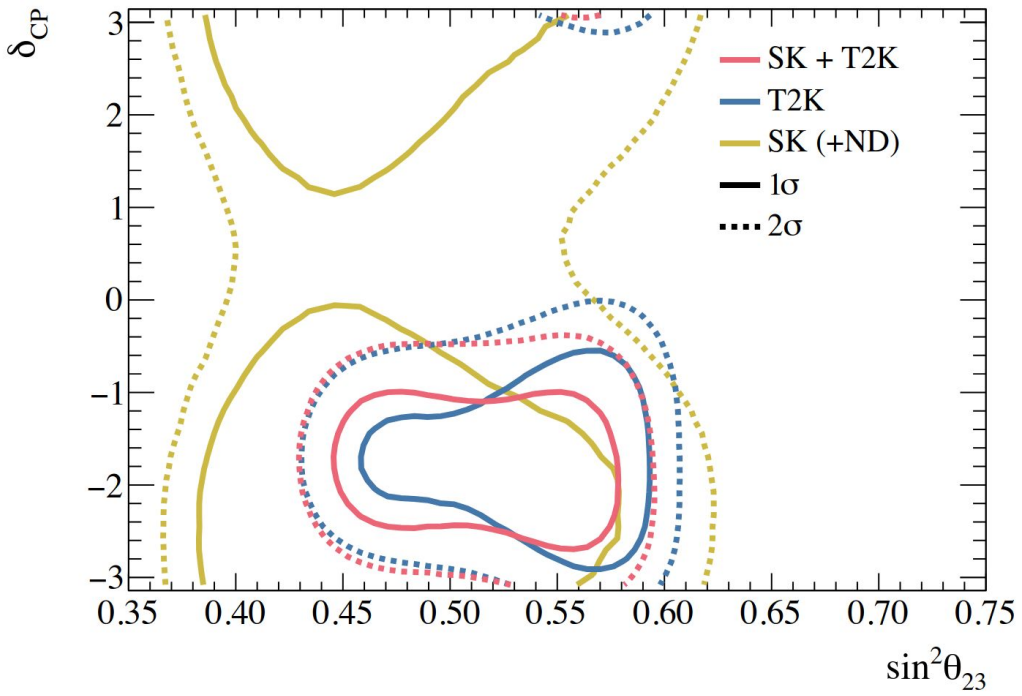


$$\frac{N^{far}_{events}(\vec{x})}{N^{near}_{events}(\vec{x})} = \frac{\sigma(E_\nu,\vec{x}) \otimes \Phi(E_\nu) \otimes D^{far}(\vec{x}) \otimes P_{osc}(E_\nu)}{\sigma(E_\nu,\vec{x}) \otimes \Phi(E_\nu) \otimes D^{near}(\vec{x})}$$

- 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

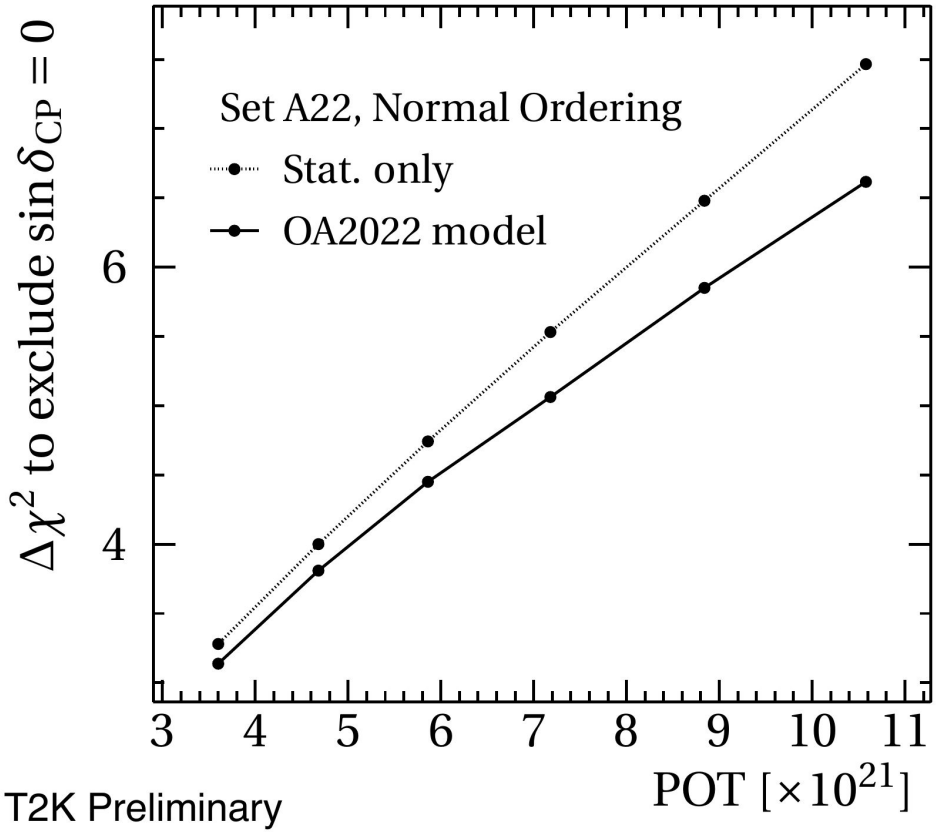
Recent Results: SK + T2K joint oscillation analysis

- 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



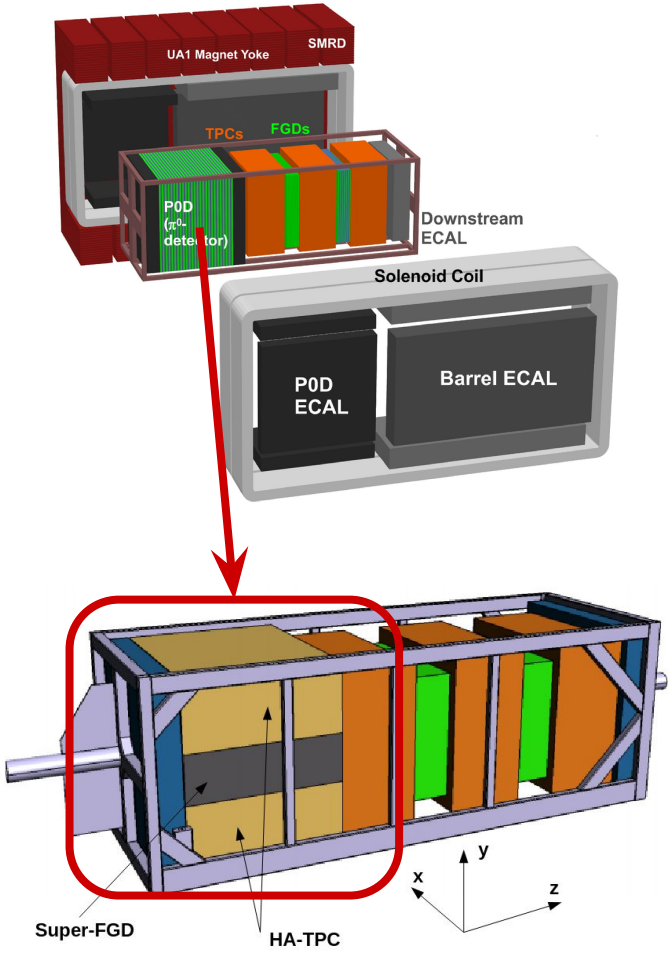
T2K-II : Future sensitivity

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



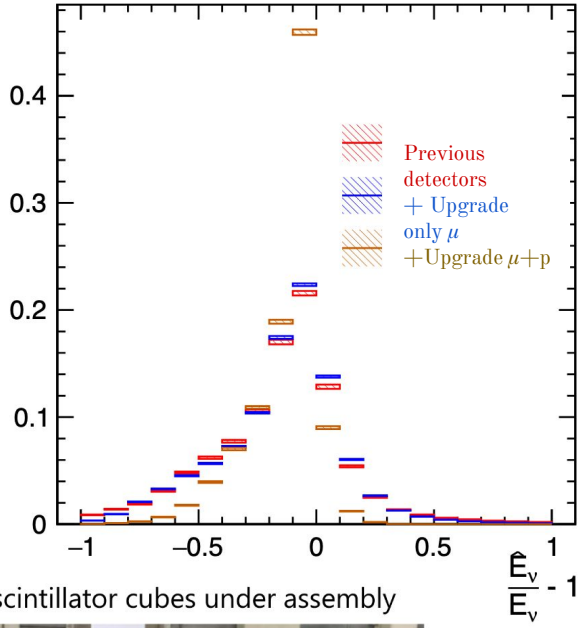
Near Detector Upgrade

- 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 (4pi) acceptance
  - 6 **ToF** : PID, veto, cosmic trigger

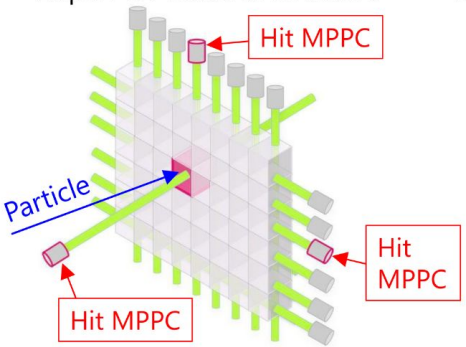


SFGD: Super Fine Grained Detector

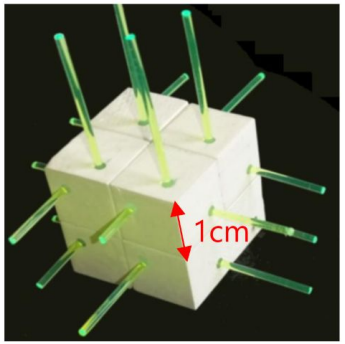
- Target detector filled with around **2 million** scintillator cubes (approx. 2 tonnes active volume)
- 4π tracking of protons tracks down to 300 MeV/c
- Probe interactions with nuclear effects



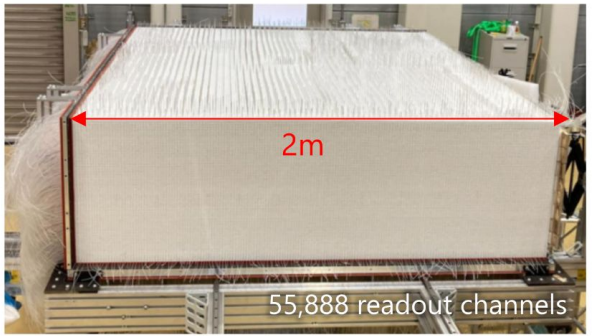
SuperFGD readout structure



SuperFGD scintillator and fiber



SuperFGD scintillator cubes under assembly



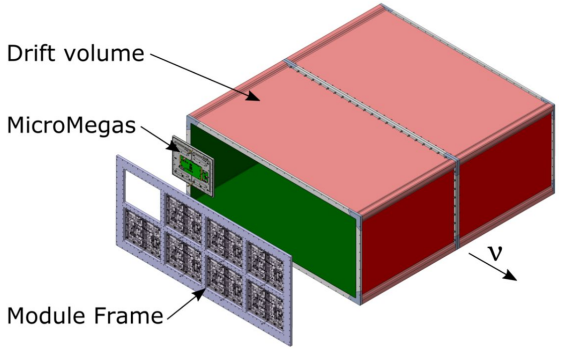
HAT

- SFGD sandwiched between these two modules
- Installation:
  - bottom HAT (spring 2023)
  - Top HAT (spring 2024)
- ERAM (**E**ncapsulated **R**esistive **A**node **M**icromegas)

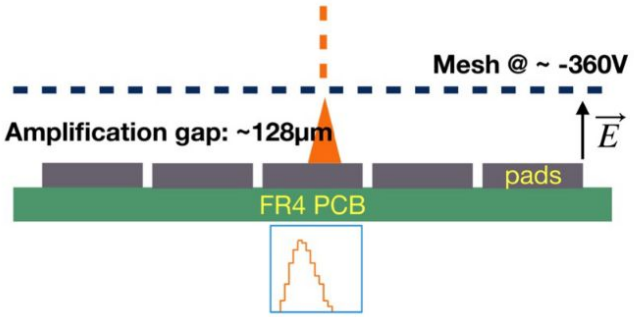
  technology allows for improved spatial resolution

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

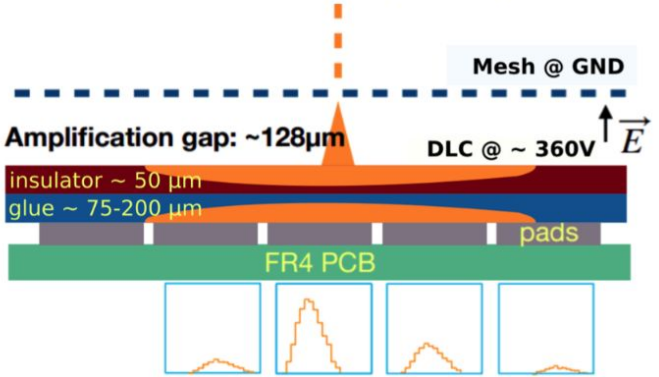
HA-TPC schematic view



Standard bulk-MicroMegas

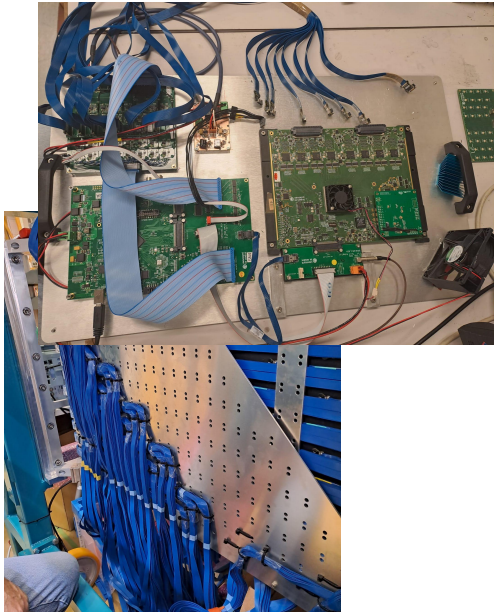


Encapsulated Resistive Anode MicroMegas (ERAM)



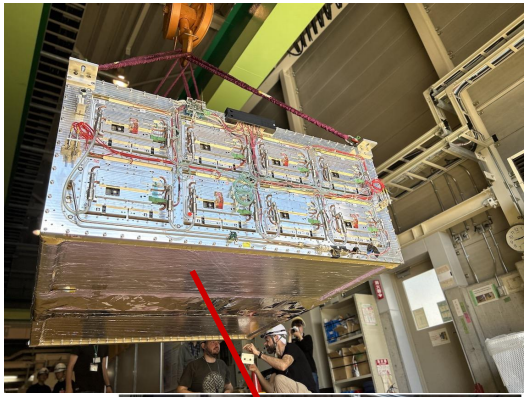
(SFGD) assembly and installation

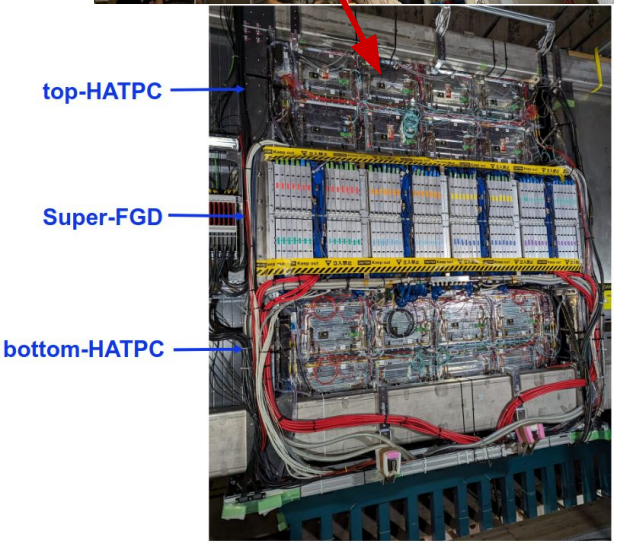
- Front end board (FEB) Production and testing in France
- Testing of the of FEBs joint french and japanese effort!
- Cable management at J-PARC
- Cooling plates for FEBs produced in France (LLR)



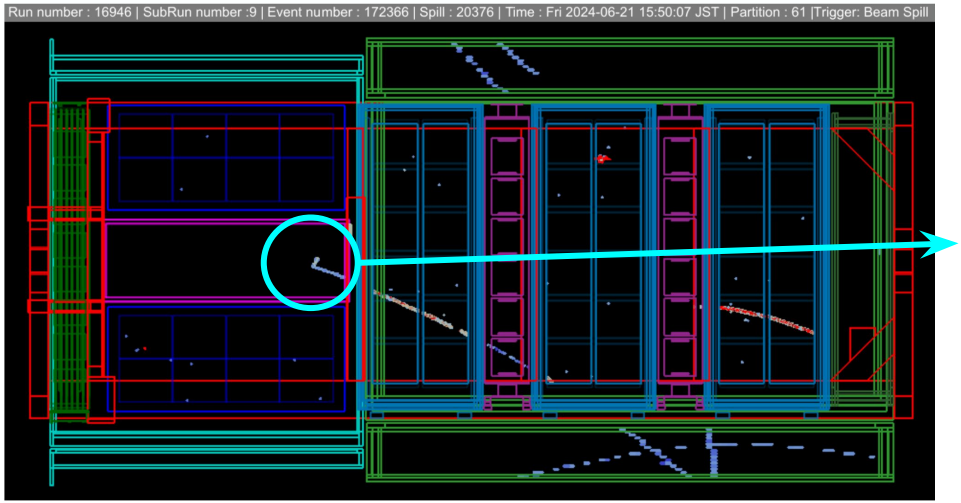
TOF installation (July 2023) | HA-TPC installation (Sep. 2023) | SuperFGD installation (Oct. 2023)

Final installation



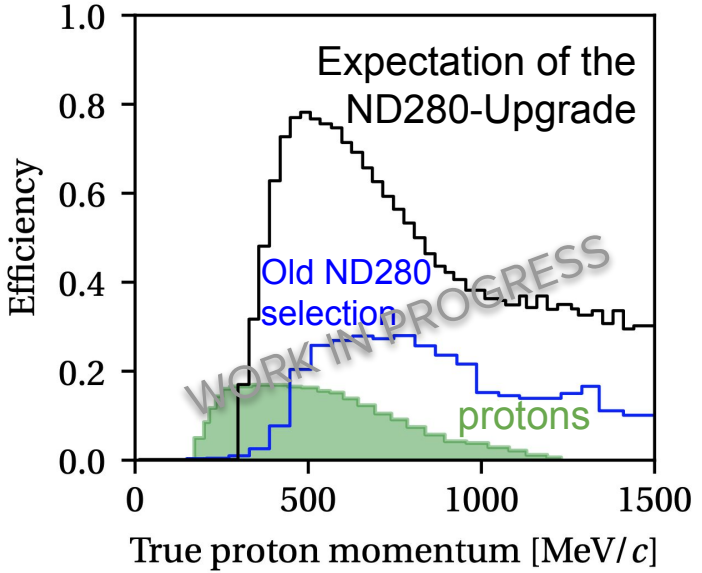


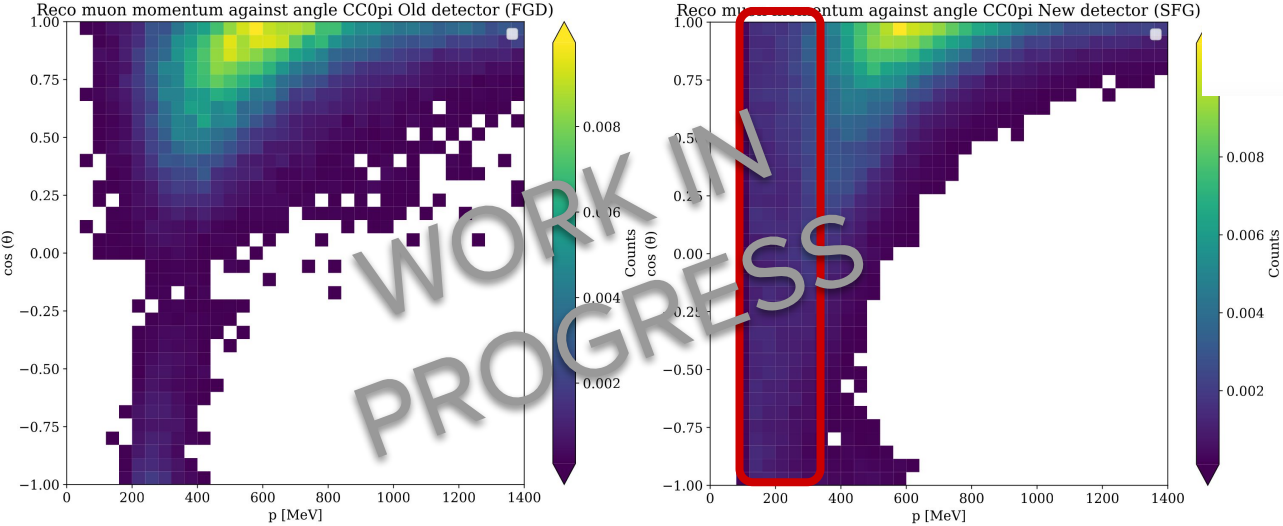
- Finalized installation of upgrade detectors in May 2024 with the installation of the top HAT
- New physics data taking started with ND upgrade!
  - From May 2024 to July 2024
  - From Nov 2024 to Dec 2024
  - In Feb 2025



Upgrade selection

- New selections currently being made for new upgraded detectors → 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%

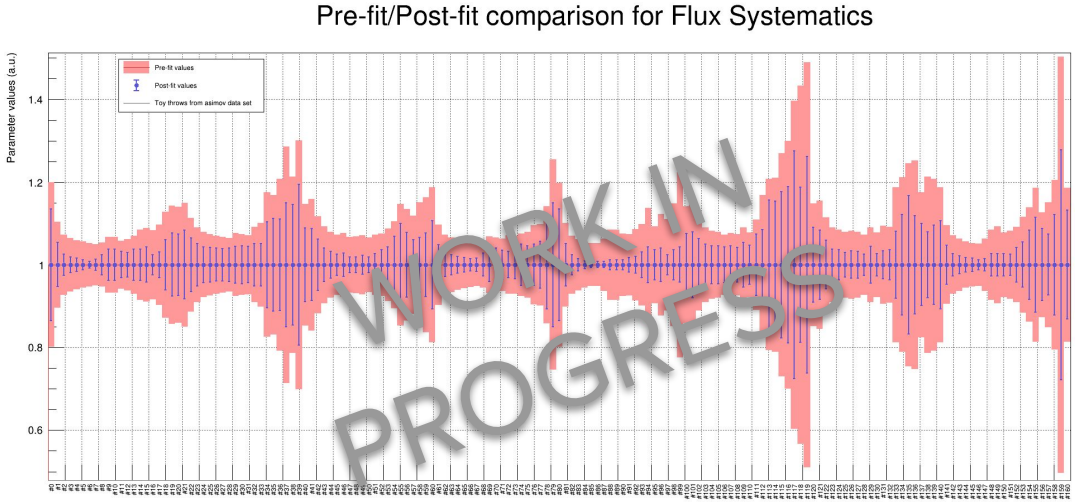




- Access to more backward tracks, more phase space!

GUNDAM: Fitter for Upgrade Analyses

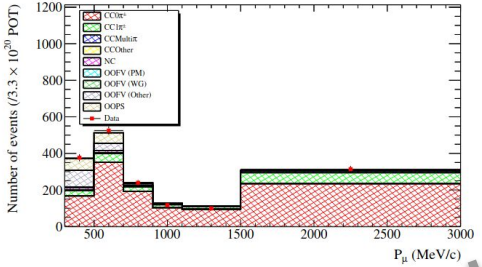
- GUNDAM developed in the context of physics sensitivity studies meant to quantify the improvement in the constraint of *systematic uncertainties* with the Near Detector Upgrade
- Provide user friendly workflow to accommodate a variety of complex analyses



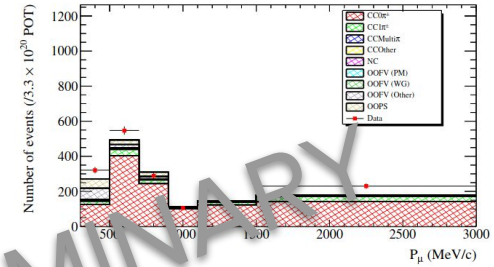
- Addresses challenges that may come with future analyses such as:
  - Increasing number of samples
  - Additional complex systematic parameters
  - Among other things!
- Already used for *ND upgrade* and *WAGASCI-BabyMIND* sensitivity studies and will be used for many more analyses!

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

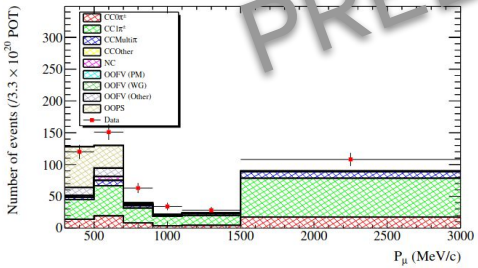
- First full analysis with current detector setup
- Same **target** and **acceptance** as SK
- Different off-axis, different energy spectrum



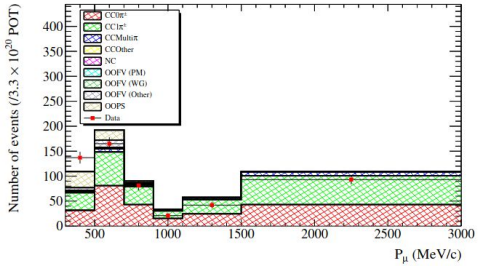
(a) CC0$\pi^{\pm}$, CH target



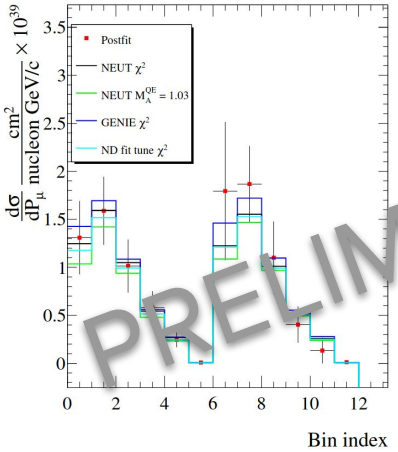
(b) CC0$\pi^{\pm}$, H_2O target



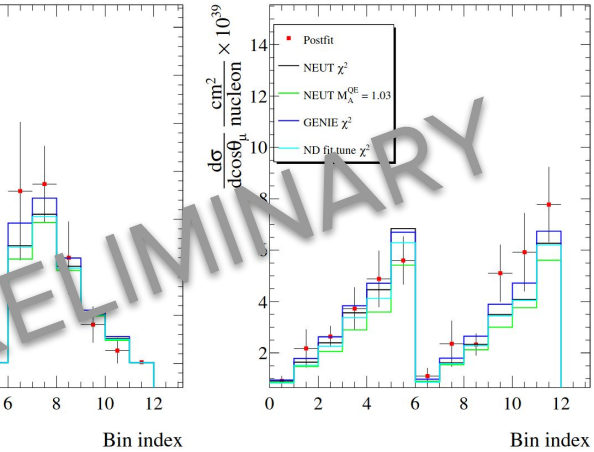
(c) CC1$\pi^{\pm}$, CH target



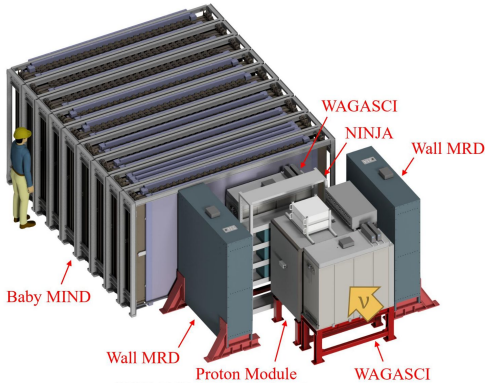
(d) CC1$\pi^{\pm}$, H_2O target



(a) As a function of P_μ

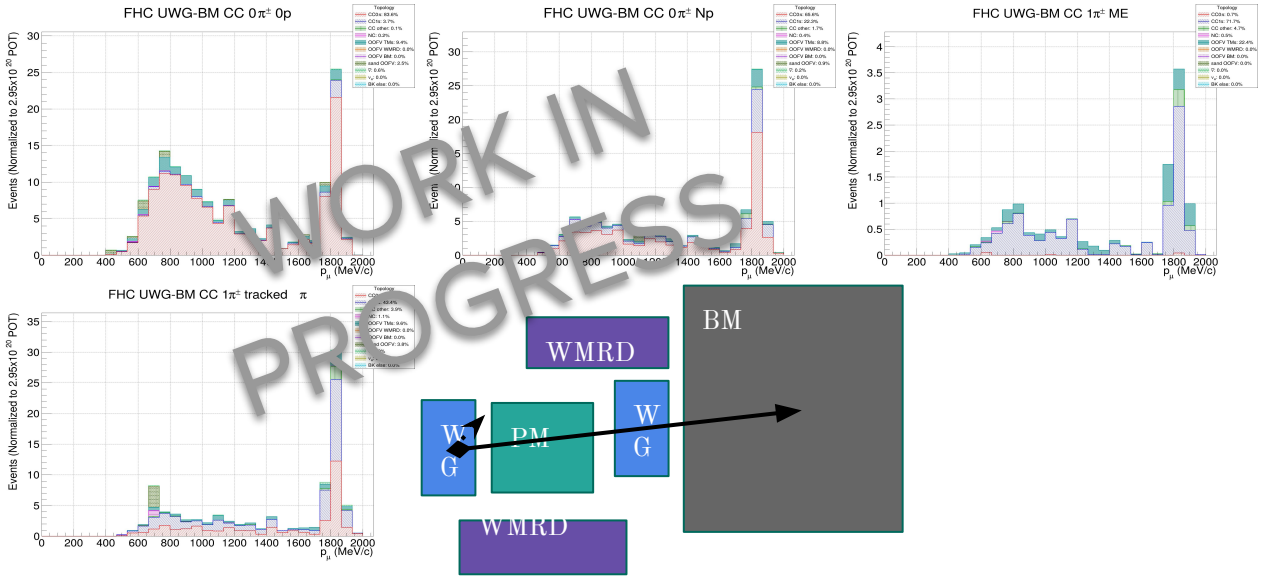


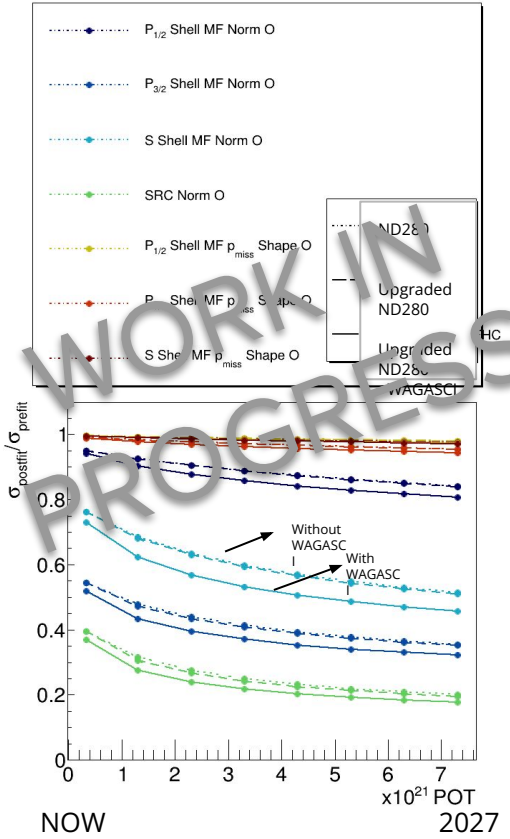
(b) As a function of $\cos\theta_\mu$



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

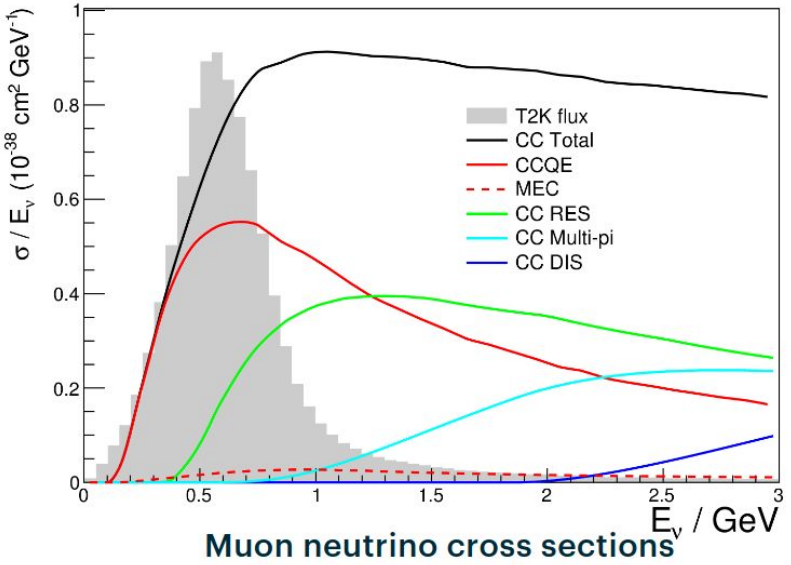
- Huge achievement → completion of near detector upgrade with a significant participation on the French + Japanese side along with other members of the T2K collaboration
- Recent analyses:
  - Eur.PHys.J.C, 2023, 83, (782) , Phys. Rev. Lett. 134, 011801, 10.1103/PhysRevD.108.112009
  - And soon many more!
- With the recent runs an additional ¼ 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

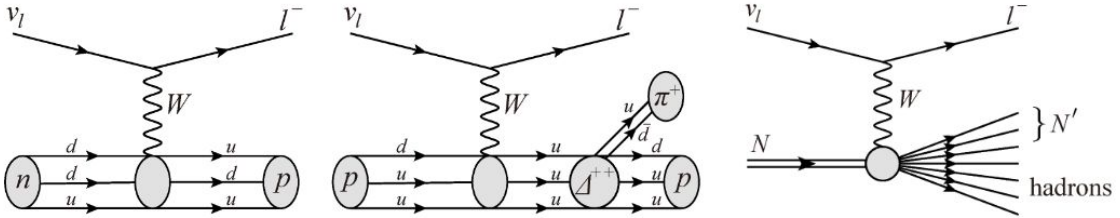
Neutrino Interaction

- **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



Muon neutrino cross sections

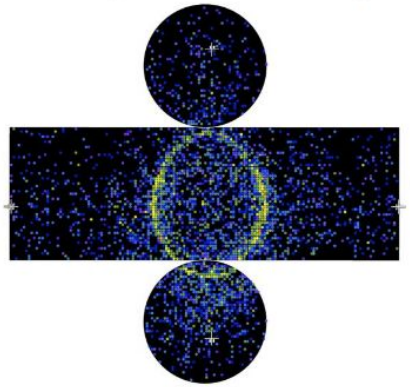
Quasi-elastic Resonance scattering Deep inelastic scattering



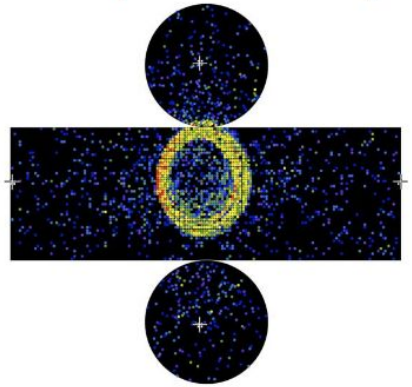
SK

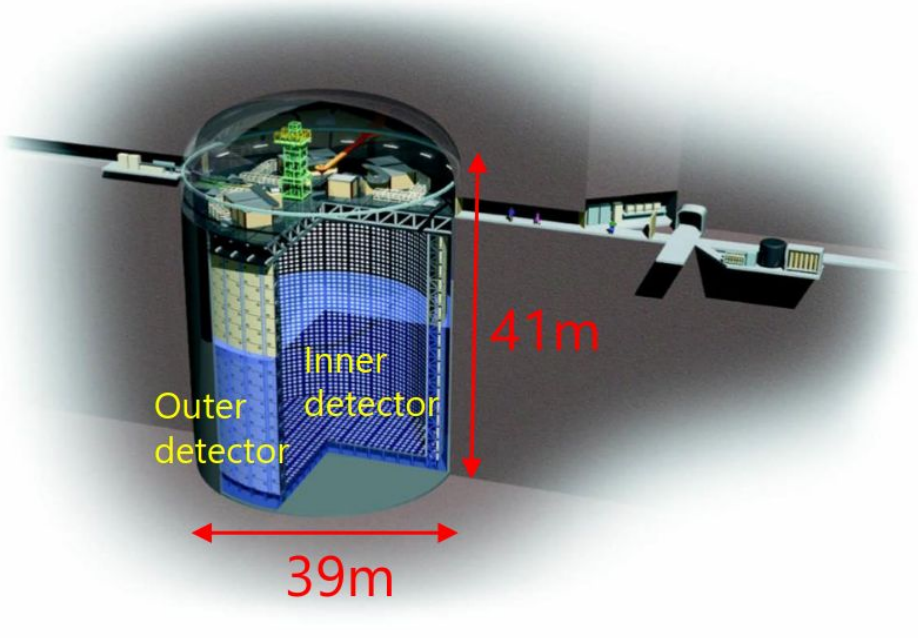
- 50kt water Cherenkov detector having ~11,000 20-inch PMTs.
- Good separation of electrons and muons. → Separate ν_e and ν_μ CC interactions.
- Gd loaded for enhanced neutron detection in 2020.

ν_e candidate event
(fuzzy Cherenkov ring)



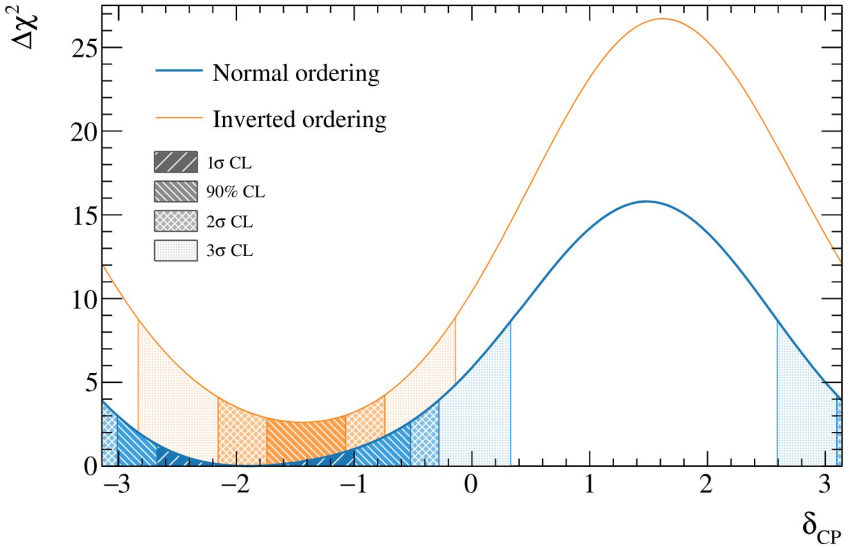
ν_μ candidate event
(sharp Cherenkov ring)





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

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



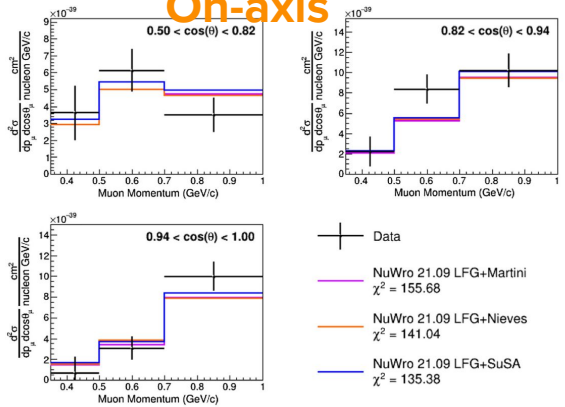
Parameter	With reactor constraint	
	Normal ordering	Inverted ordering
δ_{CP} (rad.)	$-1.97^{+0.97}_{-0.62}$	$-1.44^{+0.56}_{-0.59}$
$\sin^2\theta_{13}/10^{-3}$	–	–
$\sin^2\theta_{23}$	$0.561^{+0.019}_{-0.038}$	$0.563^{+0.017}_{-0.032}$
$\Delta m^2_{32}/10^{-3}$ (eV^2)	$2.494^{+0.041}_{-0.058}$	–
$\lvert\Delta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

Joint INGRID + ND280 cross-section analysis

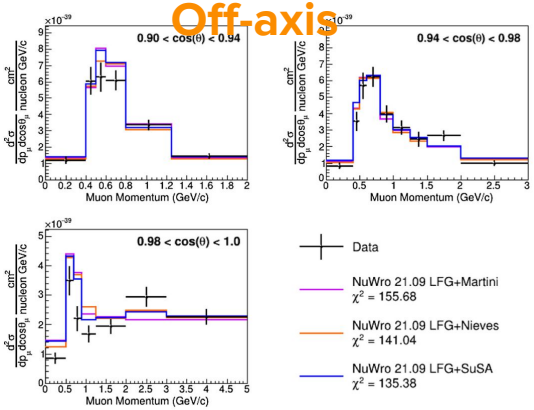
(10.1103/PhysRevD.108.112009)

- Correlated neutrino flux spectra reduce flux uncertainty

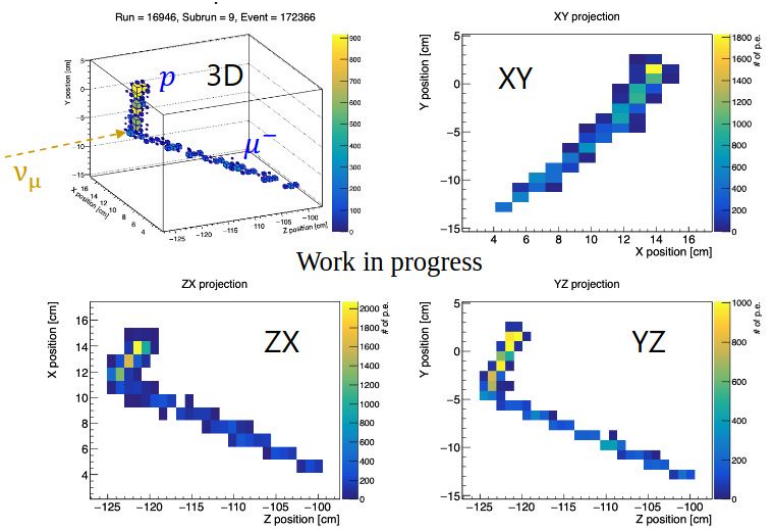
On-axis



Off-axis



Upgrade reconstruction (remove?)



Neutrino oscillations

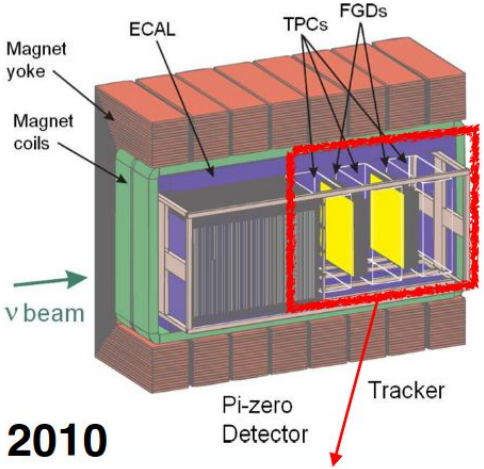
$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}}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

Commissioning

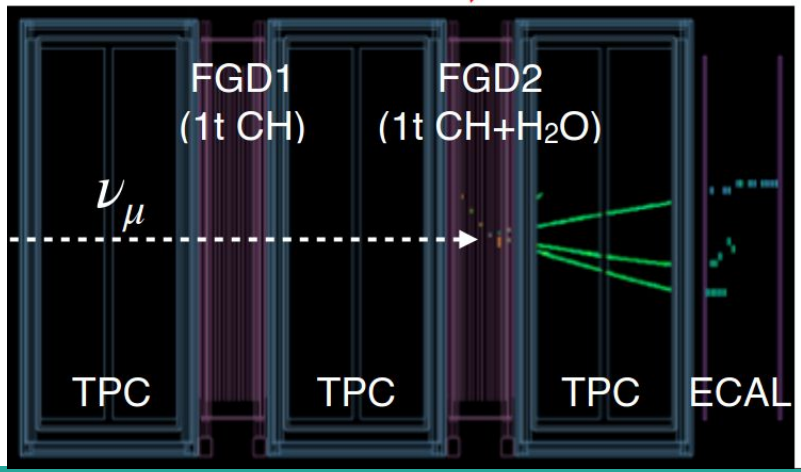
Probably move to back up, or put few plots

Joint fit atmos detailed

Old detectors



Since 2010



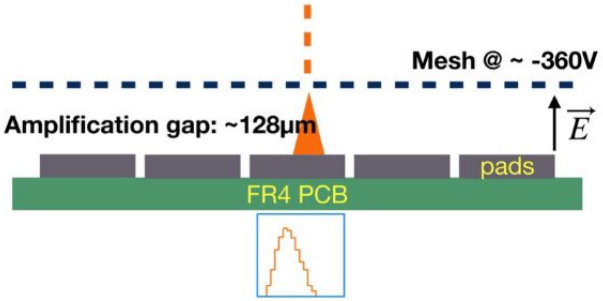
- Plastic scintillator (FGD1 and 2)
  - ✓ν target (~2t)
  - ✓Forward tracking, PID
- UA1 magnet (0.2T) instrumented with scintillator detectors (SMRD)
  - ✓Charged ID → ν vs $\bar{\nu}$
- Time Projection Chambers (TPC)
- EM Calorimeter (ECAL)
- π^0 detector (scintillator + water)

SFGD assembly and commissioning

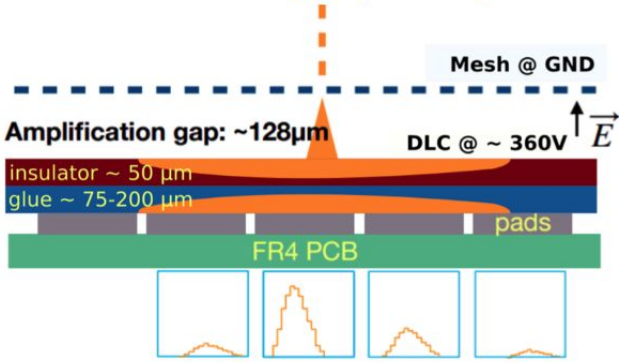
HAT

- **Resistive layer enables charge spreading**
  - space resolution below 500 μm 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



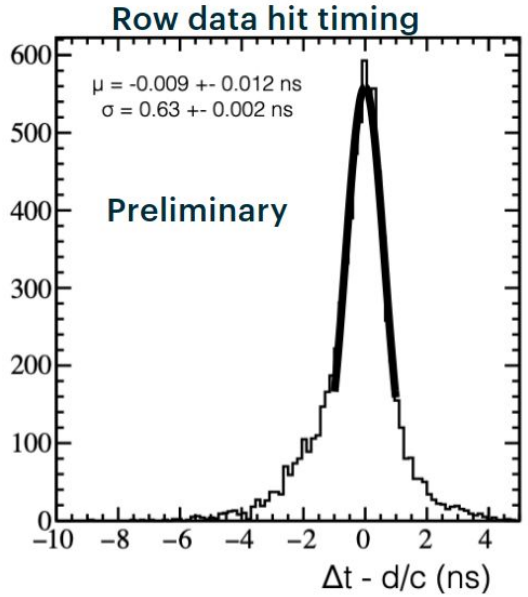
Encapsulated Resistive Anode MicroMegas (ERAM)



8

ToF

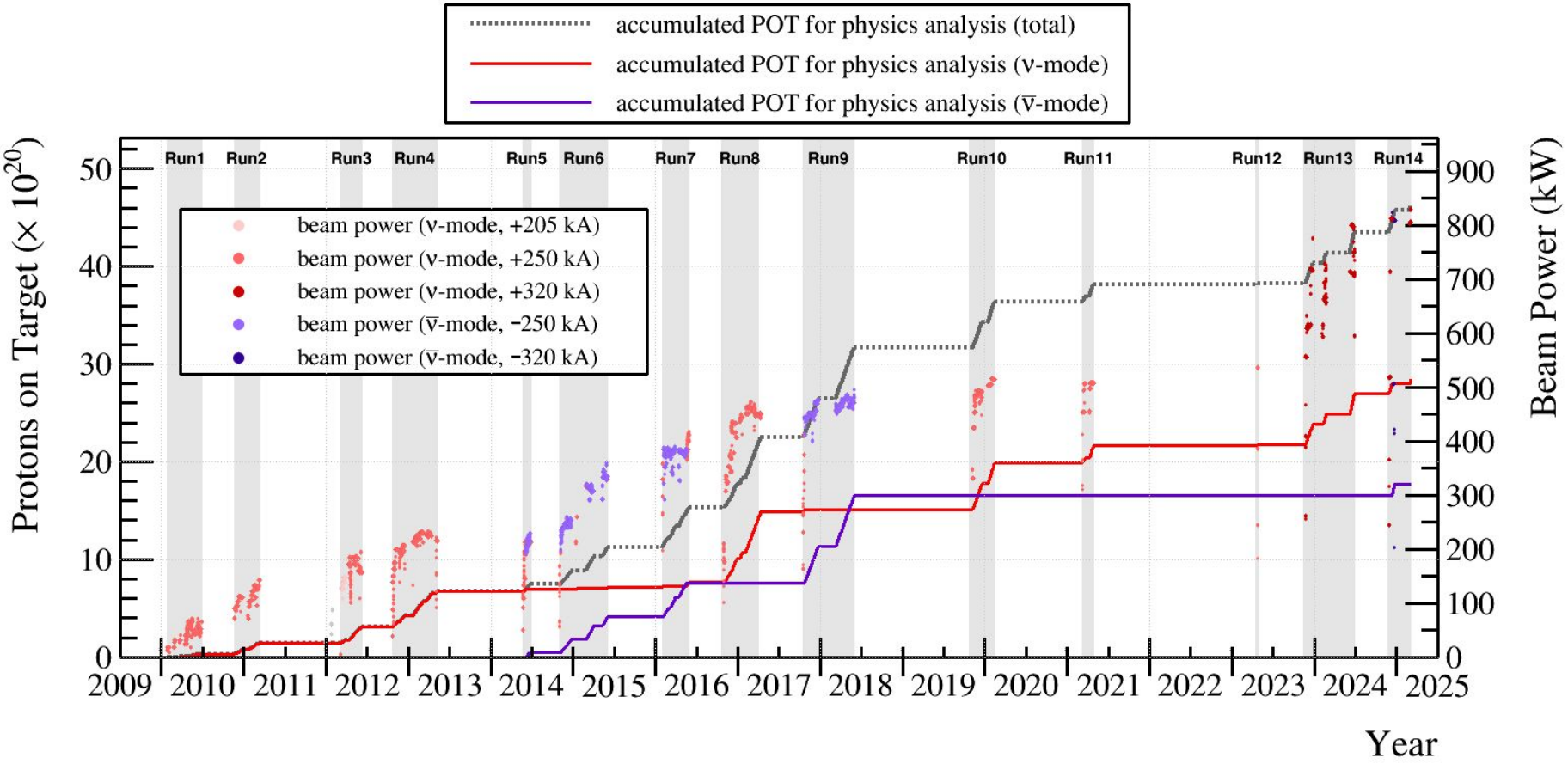
- **6 Time Of Flight(TOF) detectors consist scintillator bars , and surround SuperFGD&HA-TPC**
- **All TOFs are shipped in summer 2023 after assembly at CERN**
- **Raw data time resolution of 0.63 ns for twice modules in ND280 pit**



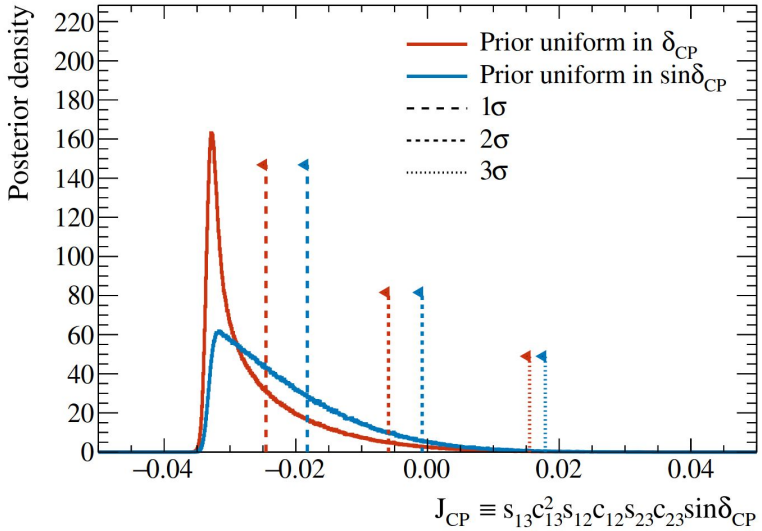
Calibration and stability

Copy slides Kikawa

Accumulated POT



Jarlskog


Posterior density
220
200
180
160
140
120
100
80
60
40
20
0
−0.04
−0.02
0.00
0.02
0.04
Prior uniform in δ_{CP}
Prior uniform in $\sin\delta_{CP}$
1σ
2σ
3σ
$J_{CP} \equiv s_{13}c_{13}^2 s_{12}c_{12}s_{23}c_{23}\sin\delta_{CP}$