Timing characterization for T2K ND280Upgrade SuperFGD detector

XXI International Workshop on Neutrino Telescopes

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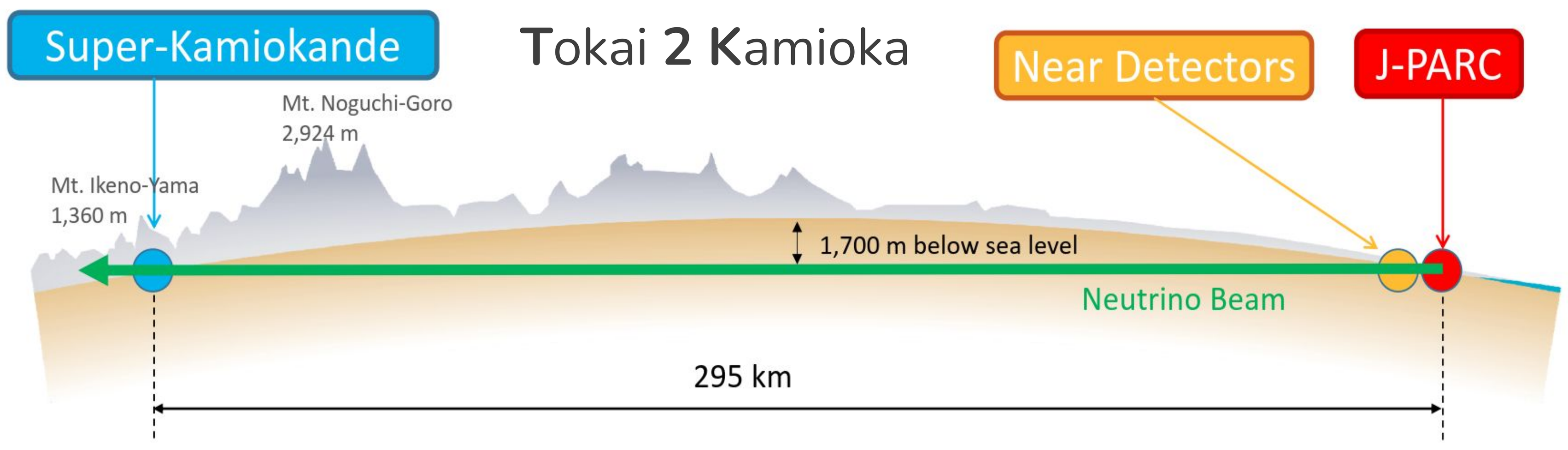
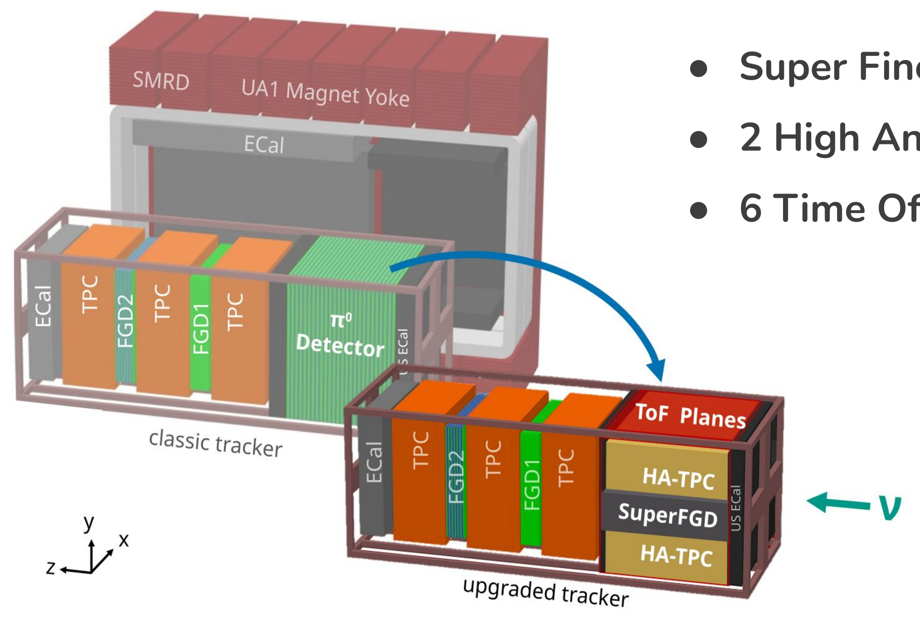
The T2K experiment and its Near Detector Upgrade



T2K is a long-baseline neutrino oscillation experiment located in Japan[1]. Accelerator ν_μ and anti-ν_μ are produced at the J-PARC proton accelerator facility, and are then detected by a set of **near detectors** and the **Super-Kamiokande** far detector.
It measures **ν_μ disappearance** and **ν_e appearance** to estimate **neutrino oscillation parameters**.

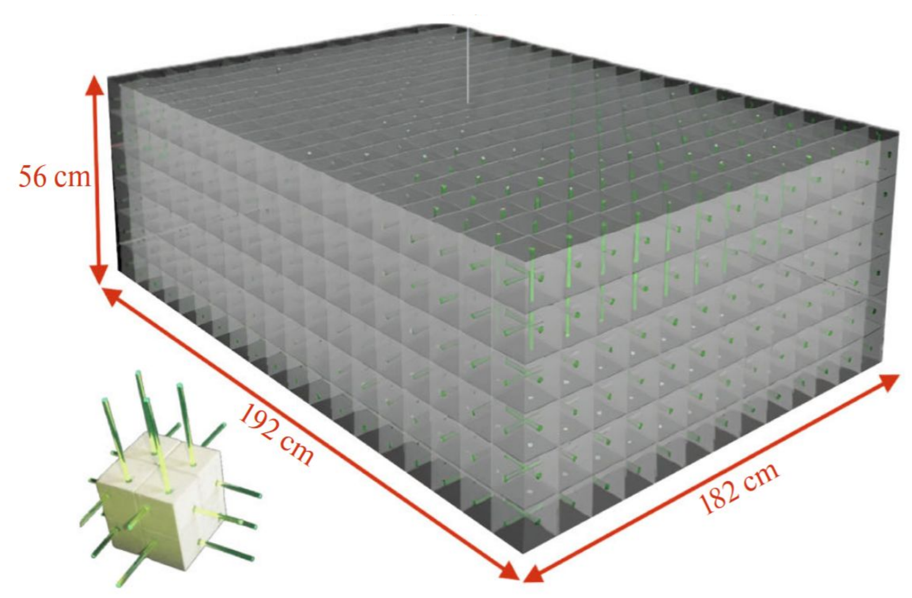
ND280 is one of T2K's near detector. It is located off-axis and is needed to **constrain flux** and **cross section**. For the **upgrade**[2], the upstream section is replaced by three **new sub-detectors**:



- **Super Fine Grained Detector (SuperFGD)**
- **2 High Angle Time Projection Chambers (HA-TPCs)**
- **6 Time Of Flight planes (ToF)**

Upgrade improvements
- **Lower proton detection threshold**
- **Higher detection efficiencies**
- **Higher angular acceptance**
- **Neutron kinematics via time of flight**

The Super Fine Grained Detector



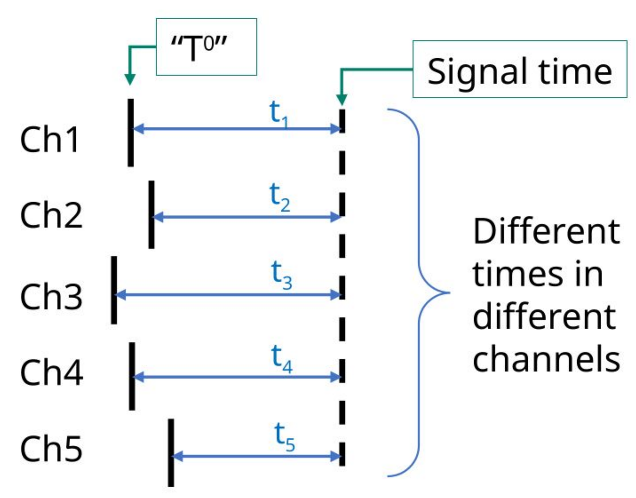
The **SuperFGD** is the new active target:
- ~2 million 1 cm^3 scintillator cubes
- 3 WLS fibres crossing each cube
- SiPMs readout at one end of each fibre
- ~58'000 readout channels

SuperFGD purposes:
- **PID improvement**
- **Low energy threshold**
- **Neutron reconstruction**

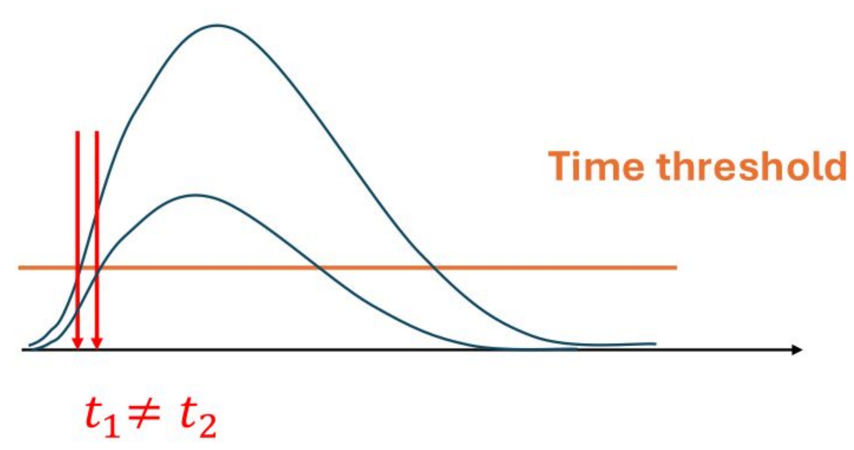
The **SuperFGD** is the first scintillator detector that allows **neutron kinetic energy reconstruction**, by measuring the **time of flight** of a neutron produced in a neutrino interaction inside the detector.
The **time characterization is crucial** for this purpose.

The time measurement is affected mostly by two contributions: **time offsets** and **time walk**.

Time offsets
Mis-synchronization and cable length

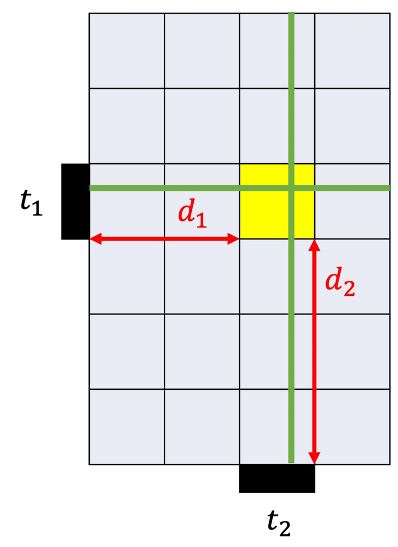


Time walk
Smaller amplitudes appear to be later



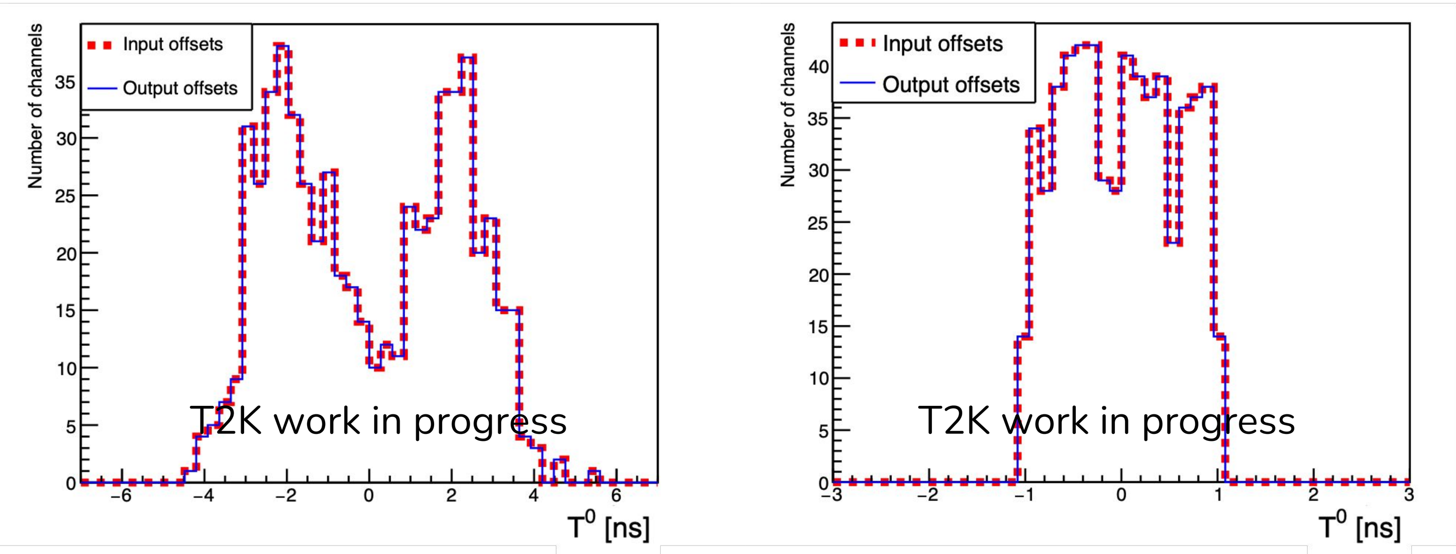
Time Calibration Algorithm

Times t_i of the signals produced in the same cube are highly correlated - **Matching hit pairs**[3].
With a granular detector it is possible to know the distances d_i between the channels.
Each matching hit pair will have two channels (**α, β**), two times (t_1, t_2) and two distances (d_1, d_2).
Measured difference: **$\Delta t = t_1 - t_2$**
Expected difference: **$\Delta d = (d_1 - d_2)/v$**, with **v** speed of light in the fibre
Goal: minimize **$\Delta = \Delta t - \Delta d$** with an **iterative procedure**



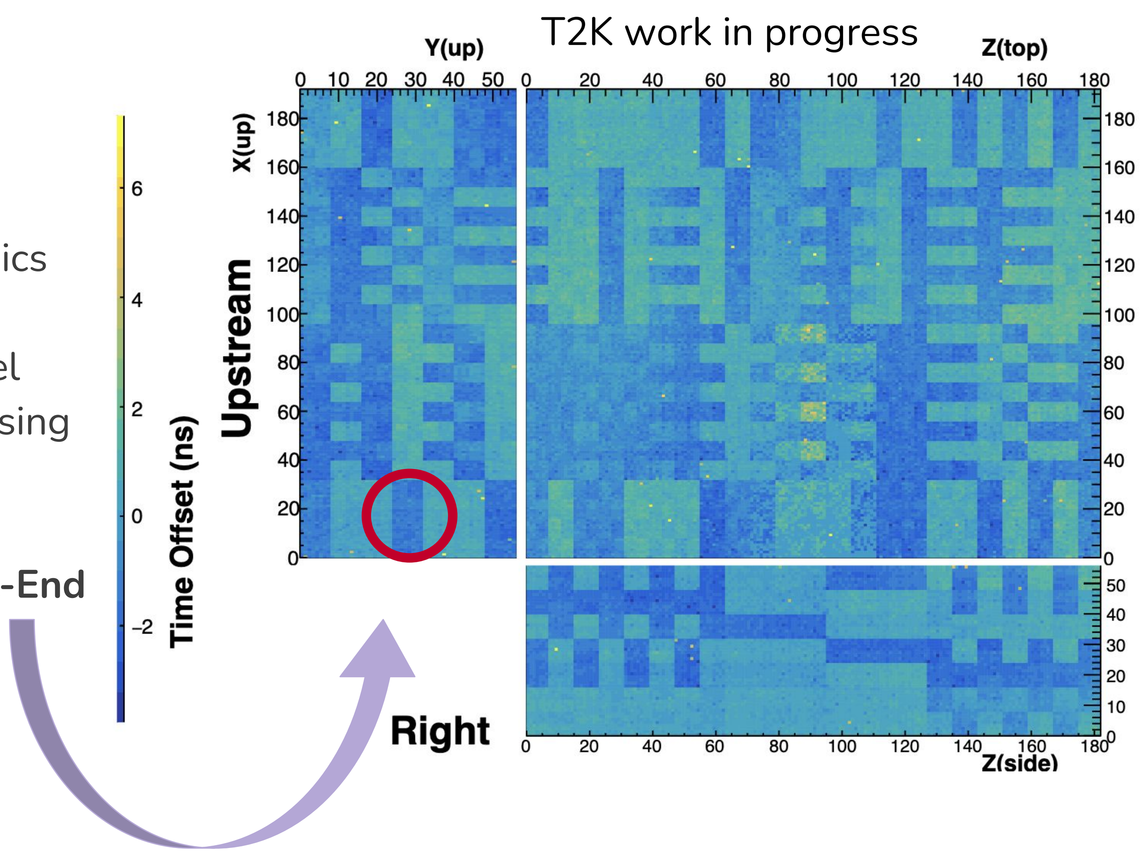
1. For each channel α evaluate average $\Delta_\alpha = \Sigma_\beta \Delta_{\alpha\beta}/N$
2. Δ_α is the **offset correction** for channel α
3. Apply correction at the next iteration $t^{k+1} = t^k + \Delta_\alpha/2$
4. Repeat until **convergence**

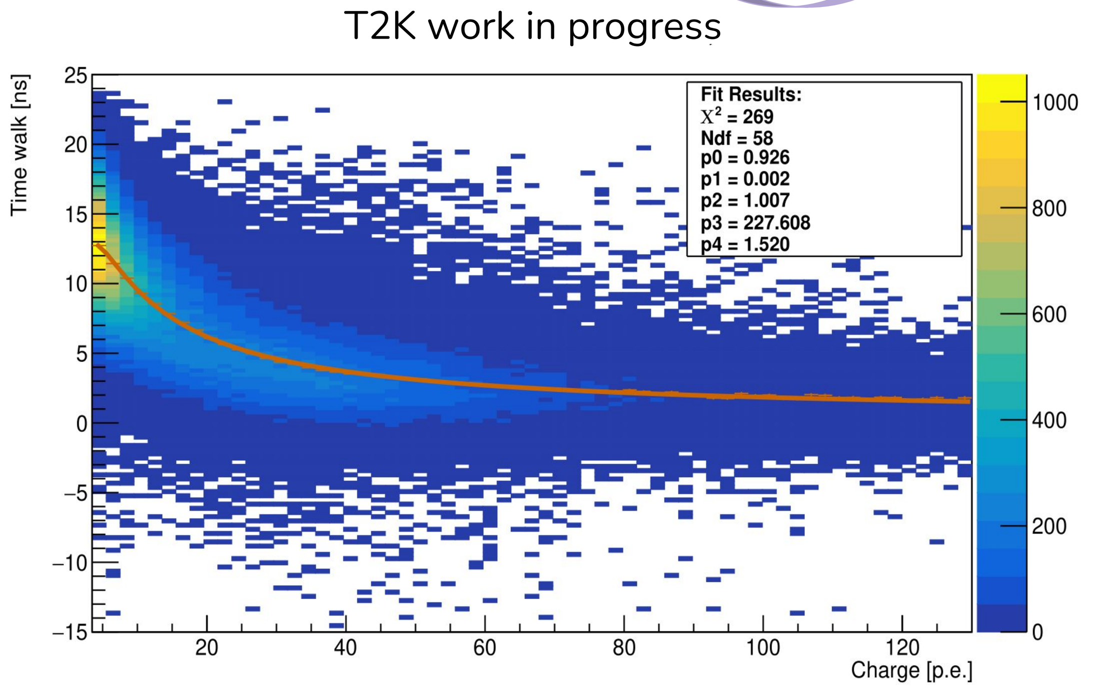
Mathematically equivalent to the convergence of a **row-stochastic matrix (Markov matrix)**[4].
Mathematical convergence dealt with **power method**[5].
Monte-Carlo simulation of random deposits of energy shows the efficiency in extrapolating the **correct offsets T^0** previously applied. Generated offsets with two gaussian distribution centered in -2 and 2 ns (left) and with a uniform distribution between -1 and 1 ns (right).



Application to the Super Fine Grained Detector

Time offsets
- SuperFGD time offsets map obtained with sample of cosmics and neutrino-beam data
- ~200 matched hits per channel
- Time offsets firstly obtained using matching hit pairs having comparable charges
- Evident **dependence on Front-End Board** (FEB) electronic units
- FEB clock phase up to 2.5 ns

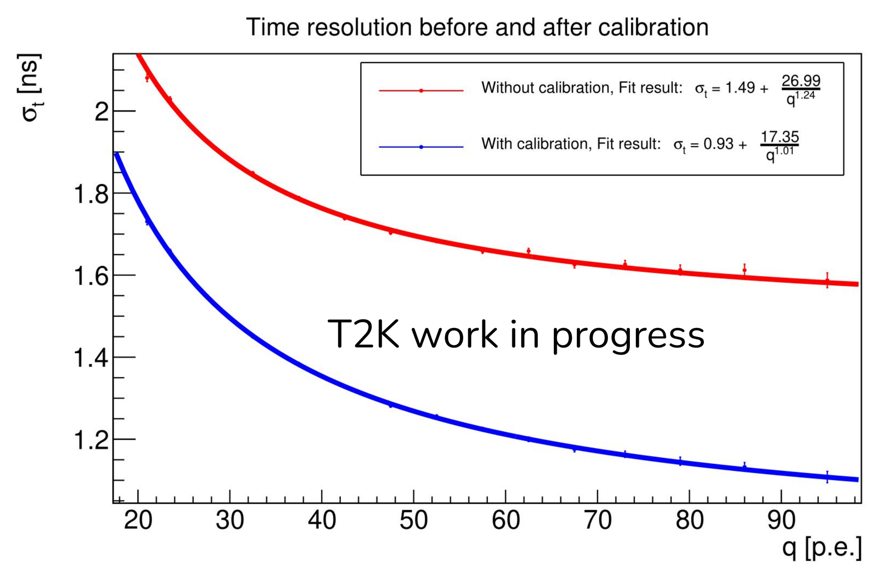




Time walk
- Time walk overall contribution
- After time offset extrapolation
- Obtained using matching hit pairs with charges with large difference
- High charge time walk negligible wrt low charge time walk
- Improvement possible by obtaining time walk for each channel separately

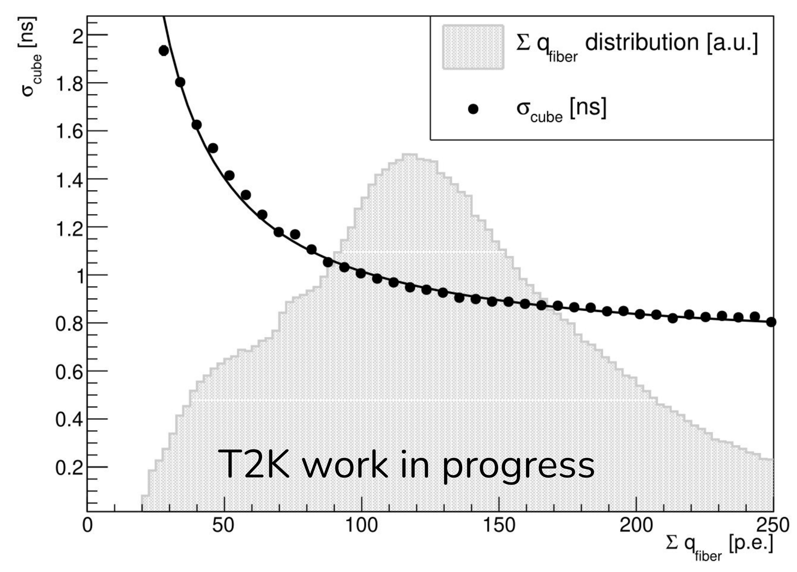
$$\frac{p_0}{\log(p_1 \cdot q + p_2)} - \frac{p_3}{q + p_4}$$

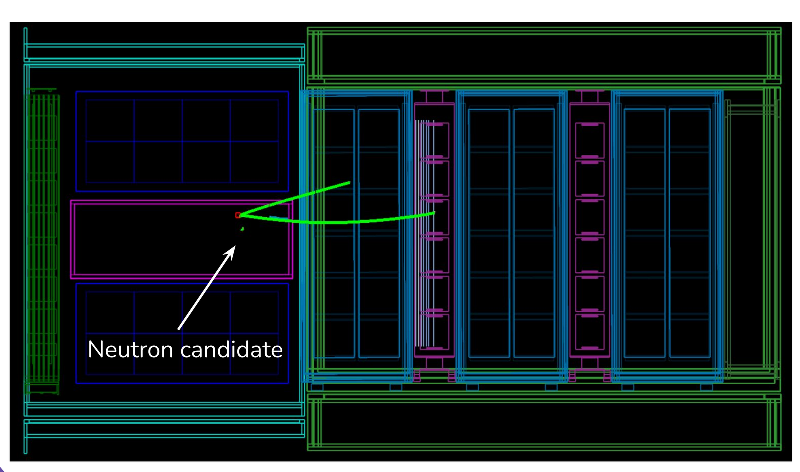
Results and Performances



Fibre time resolution
- Single fibre time resolution after applying calibration
- Similar sample to validate calibration
- $\sigma_t = \sigma(\Delta t - \Delta d)/\sqrt{2}$ for matching hits with similar charges
- Considerable improvement after calibration result
- Time resolution expected behavior as charge increases

Cube time resolution
- Sample of cosmic muon data
- Each cube raw time reconstructed with all the three fibres crossing it
- Similar behavior as a function of cube charge
- Cube time resolution **below 1 ns** at 120 p.e., typical cube charge from a MIP





Neutron candidate event from beam data
- Sub-ns time resolution needed to unlock detection of neutron produced in the detector
- Capability of **tagging and reconstructing neutrons**

References: [1] K. Abe et al., *The T2K experiment*, arXiv:1106.1238; [2] K. Abe et al., *T2K ND280Upgrade: technical design report*, arXiv:1901.03750; [3] S. Abe et al., *Introducing a Markov Chain-Based Time Calibration Procedure for Multi-Channel Particle Detectors: Application to the SuperFGD and ToF Detectors of the T2K Experiment*, arXiv:2508.07846; [4] K.L. Chung, *Markov Chains*, doi:10.1007/978-3-642-62015-7; [5] C.M. Sha and N.V. Dokholyan, *Simple exponential acceleration of the power iteration algorithm*, arXiv:2109.10884

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