Timing properties of T2K ND280Upgrade detector

Gioele Reina (he/him)

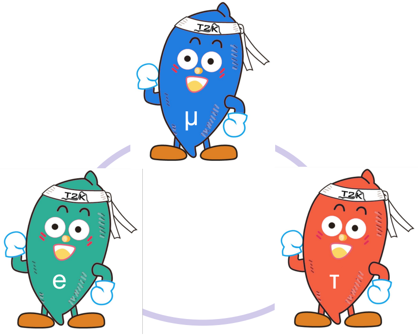
MPA retreat 2024

Overview

- Neutrino oscillations
- T2K experiment and its near detector ND280
- Neutron reconstruction in ND280
- Timing characterization of the detector

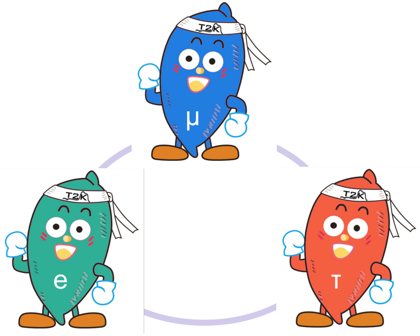
Neutrino Oscillations

Neutrino are produced in a specific **flavour eigenstate** (ν_e, ν_μ, ν_τ) but they travel through the **mass eigenstate** (ν_1, ν_2, ν_3) and so can be detected in a different flavour



Neutrino Oscillations

Neutrino are produced in a specific **flavour eigenstate** (ν_e, ν_μ, ν_τ) but they travel through the **mass eigenstate** (ν_1, ν_2, ν_3) and so can be detected in a different flavour



$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$$s_{ij} = \sin\theta_{ij},\ c_{ij} = \cos\theta_{ij}$$

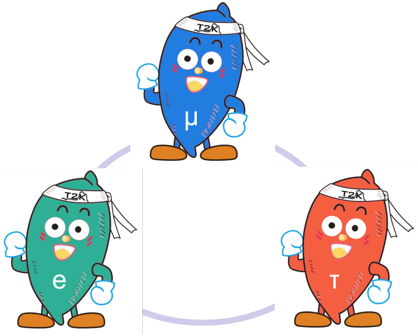
$$P(\nu_\alpha \to \nu_\beta) = sin^2(2\theta)sin^2(1.27\Delta m^2\frac{L(km)}{E(GeV)})$$

Two flavour neutrino oscillation probability where:

- *L* is the distance to the source
- *E* is the neutrino energy
- $\Delta m^2 = m_k^2 - m_l^2$ with *m* neutrino mass eigenstate *k,l = 1,2,3*

Neutrino Oscillations

Neutrino are produced in a specific **flavour eigenstate** (ν_e, ν_μ, ν_τ) but they travel through the **mass eigenstate** (ν_1, ν_2, ν_3) and so can be detected in a different flavour



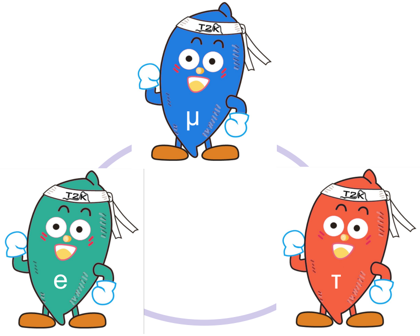
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$$s_{ij} = \sin\theta_{ij},\ c_{ij} = \cos\theta_{ij}$$

Atmospherics and LBL	Reactors and LBL	Solar and Reactors
$\theta_{23} \sim 47.8°$	$\theta_{13} \sim 8.5°$	$\theta_{12} \sim 33.6°$
$\lvert\Delta m^2_{32}\rvert \sim 2.5 \times 10^{-3}$ eV^2	δ_{CP} unknown	$\Delta m^2_{12} \sim 7.5 \times 10^{-5}$ eV^2

Neutrino Oscillations

Neutrino are produced in a specific **flavour eigenstate** (ν_e, ν_μ, ν_τ) but they travel through the **mass eigenstate** (ν_1, ν_2, ν_3) and so can be detected in a different flavour

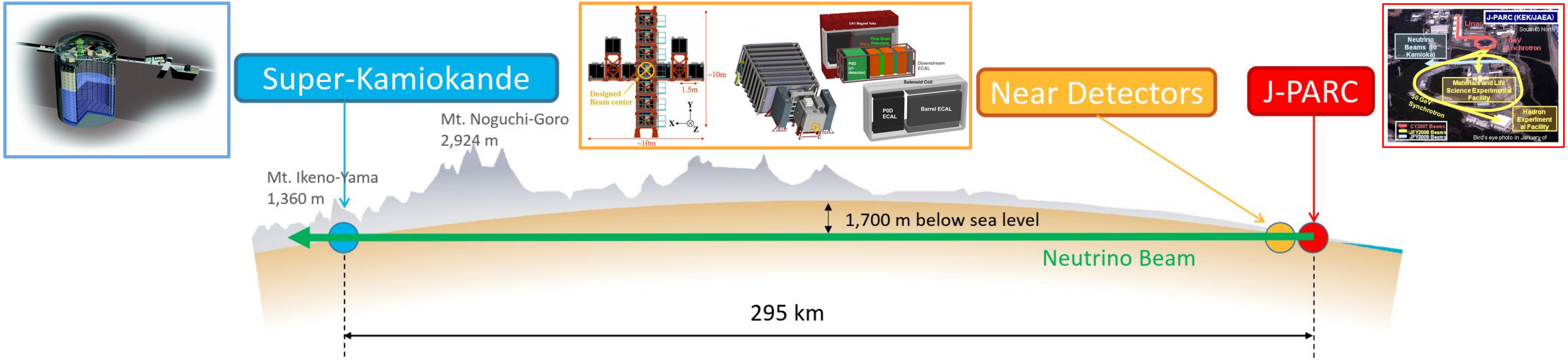


$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

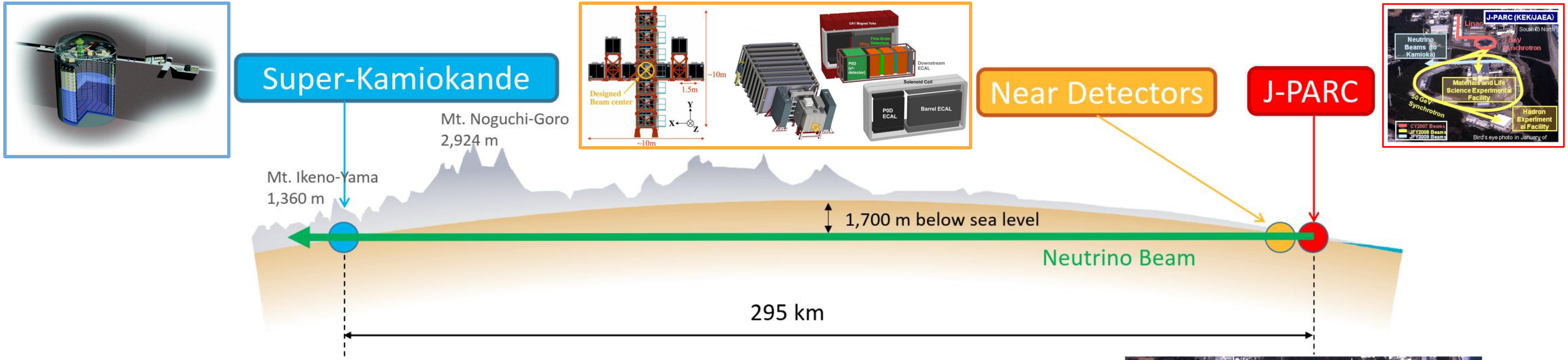
$$s_{ij} = \sin\theta_{ij}, \; c_{ij} = \cos\theta_{ij}$$

Atmospherics and LBL	Reactors and LBL	Solar and Reactors
$\theta_{23} \sim 47.8°$	$\theta_{13} \sim 8.5°$	$\theta_{12} \sim 33.6°$
$\lvert\Delta m^2_{32}\rvert \sim 2.5 \times 10^{-3}$ eV^2	δ_{CP} unknown	$\Delta m^2_{12} \sim 7.5 \times 10^{-5}$ eV^2

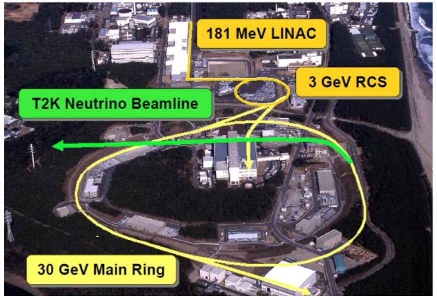
The T2K experiment

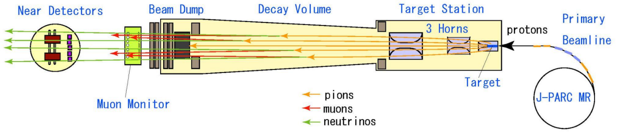


- Long-baseline neutrino experiment
- Neutrino oscillation parameters measurement: δ_{CP}, θ_{23}, Δm^2_{23}, θ_{13}
- Accelerator ν_μ produced at J-PARC
- ν detected in two facilities:
  - Three near detectors (INGRID, WAGASCI-BabyMIND, ND280)
  - Super-Kamiokande far detector (2.5° off-axis)

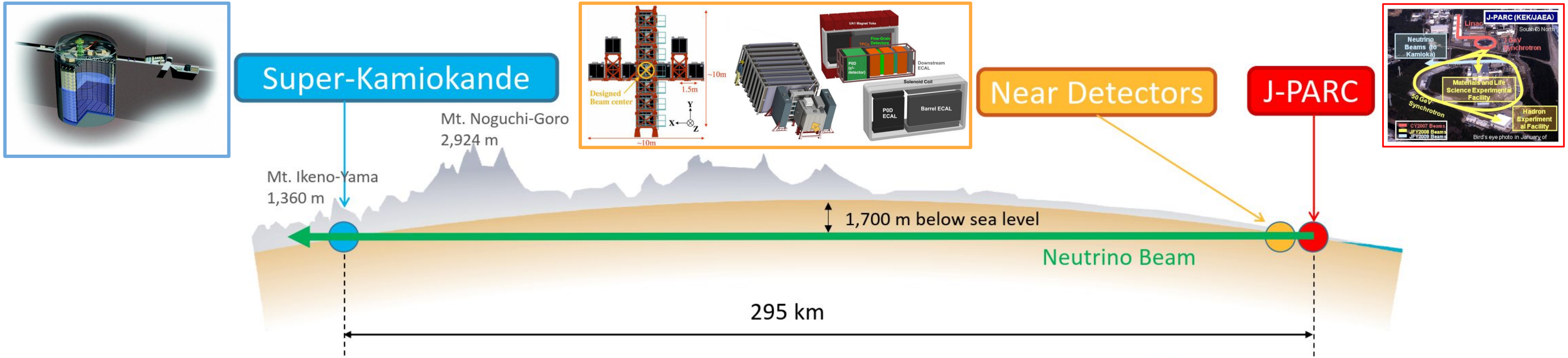


- Long-baseline neutrino experiment
- Neutrino oscillation parameters measurement: δ_{CP}, θ_{23}, Δm^2_{23}, θ_{13}
- Accelerator ν_μ produced at J-PARC
- ν detected in two facilities:
  - Three near detectors (INGRID, WAGASCI-BabyMIND, ND280)
  - Super-Kamiokande far detector (2.5° off-axis)

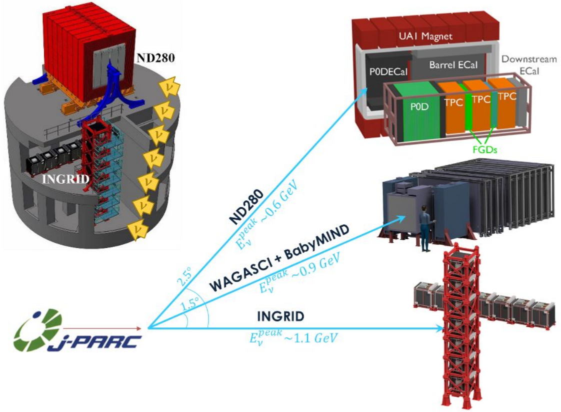




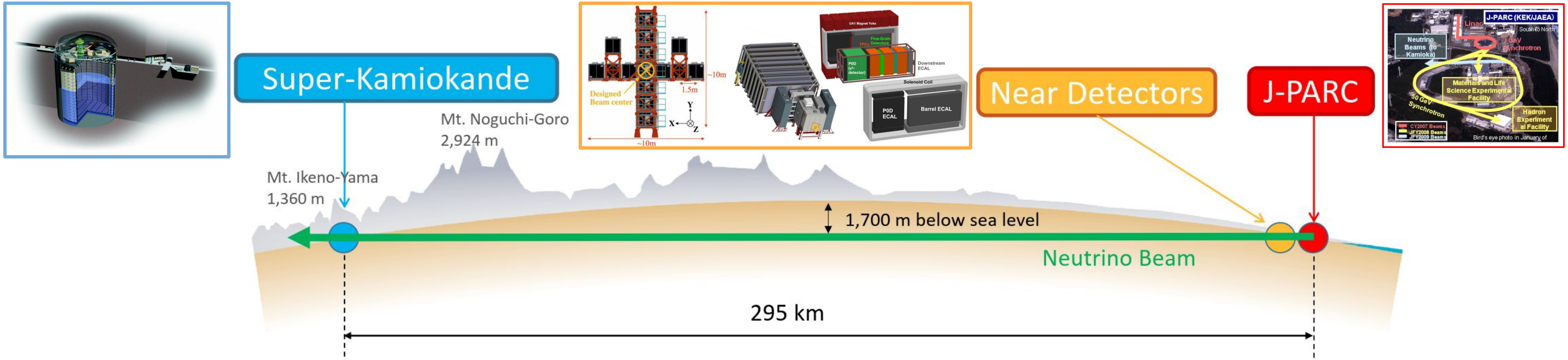
The T2K experiment



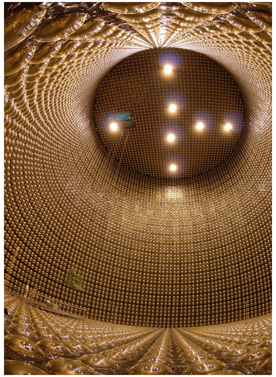
- ❑ Long-baseline neutrino experiment
- ❑ Neutrino oscillation parameters measurement: δ_{CP}, θ_{23}, Δm^2_{23}, θ_{13}
- ❑ Accelerator ν_μ produced at J-PARC
- ❑ ν detected in two facilities:
  - ❑ Three near detectors (INGRID, WAGASCI-BabyMIND, ND280)
  - ❑ Super-Kamiokande far detector (2.5° off-axis)

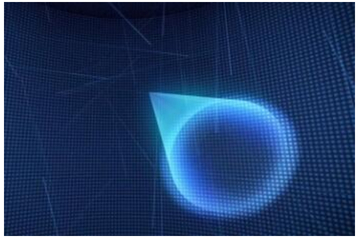


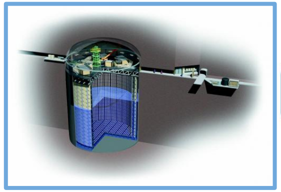
The T2K experiment

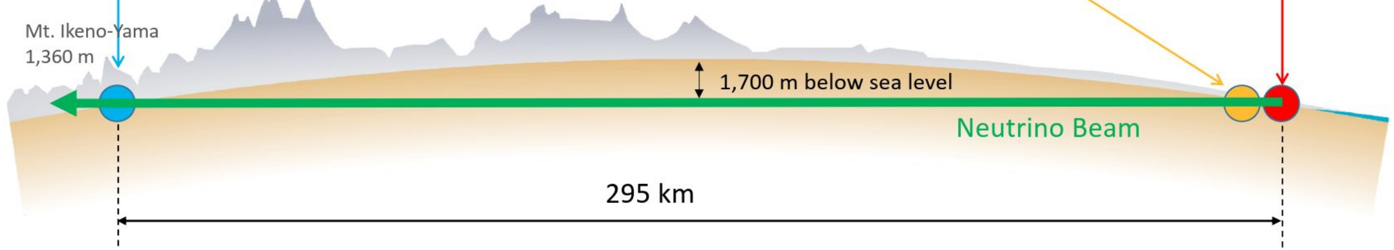


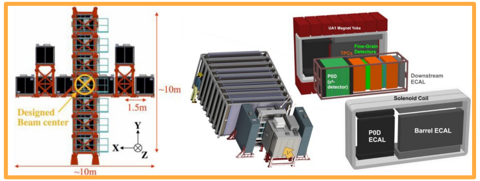
- Long-baseline neutrino experiment
- Neutrino oscillation parameters measurement: δ_{CP}, θ_{23}, Δm^2_{23}, θ_{13}
- Accelerator ν_μ produced at J-PARC
- ν detected in two facilities:
  - Three near detectors (INGRID, WAGASCI-BabyMIND, ND280)
  - Super-Kamiokande far detector (2.5° off-axis)

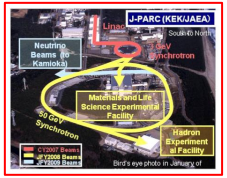










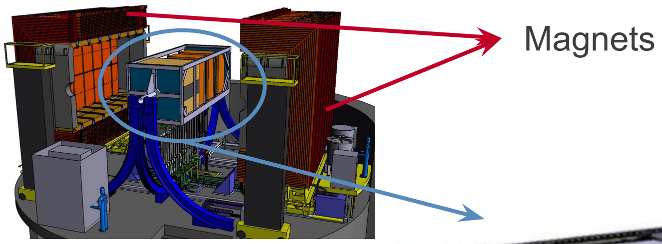


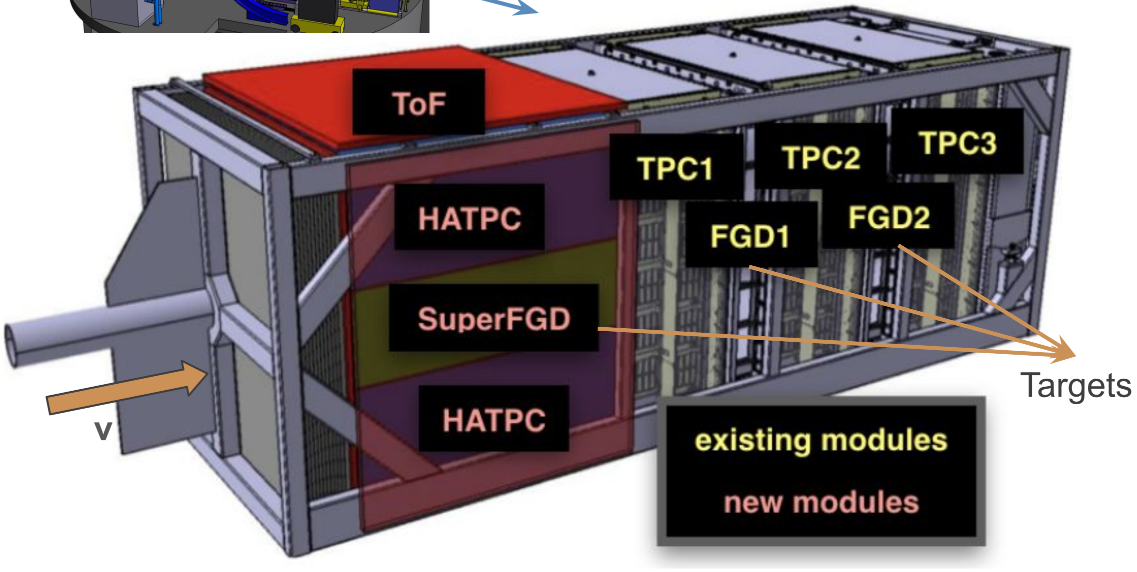
- Long-baseline neutrino experiment
- Neutrino oscillation parameters measurement: δ_{CP}, θ_{23}, Δm^2_{23}, θ_{13}
- Accelerator ν_μ produced at J-PARC
- ν detected in two facilities:
  - Three near detectors (INGRID, WAGASCI-BabyMIND, **ND280**)
  - Super-Kamiokande far detector (2.5° off-axis)

- 2.5° off-axis
- Flux and detector error
- **ND280 Upgrade**

Three new detectors:

- **Time of Flight (ToF)**
  - 150 ps time resolution
- **High-Angle TPC (HATPC)**
  - full angular coverage
- **Super Fine-Grained Detector (FGD)**
  - novel detector concept





SuperFGD Detector

- **> 2M independent 1 cm^3 cubes** of plastic scintillator
- **WLS fibers** crossing the cube along three orthogonal directions
- **Photosensor** at one end of each WLS fibers

High granularity

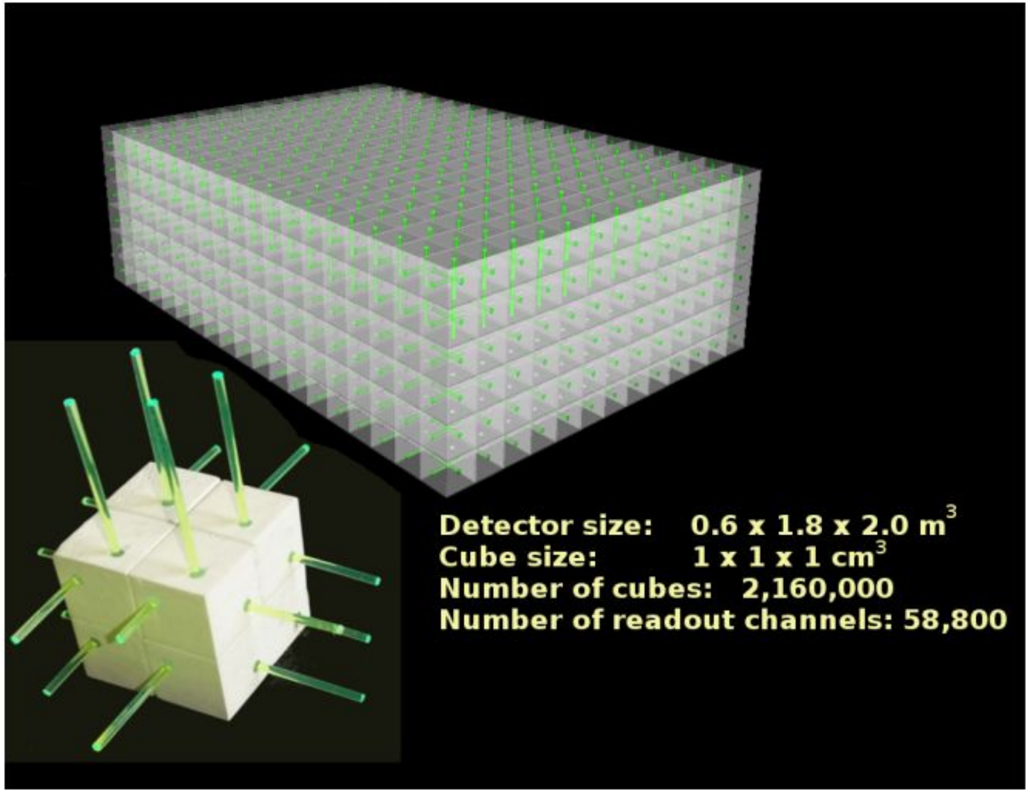
3D reconstruction

↓

PID improvement

Low energy threshold

Neutron reconstruction



SuperFGD Detector

- ❑ **> 2M independent 1 cm^3 cubes** of plastic scintillator
- ❑ **WLS fibers** crossing the cube along three orthogonal directions
- ❑ **Photosensor** at one end of each WLS fibers

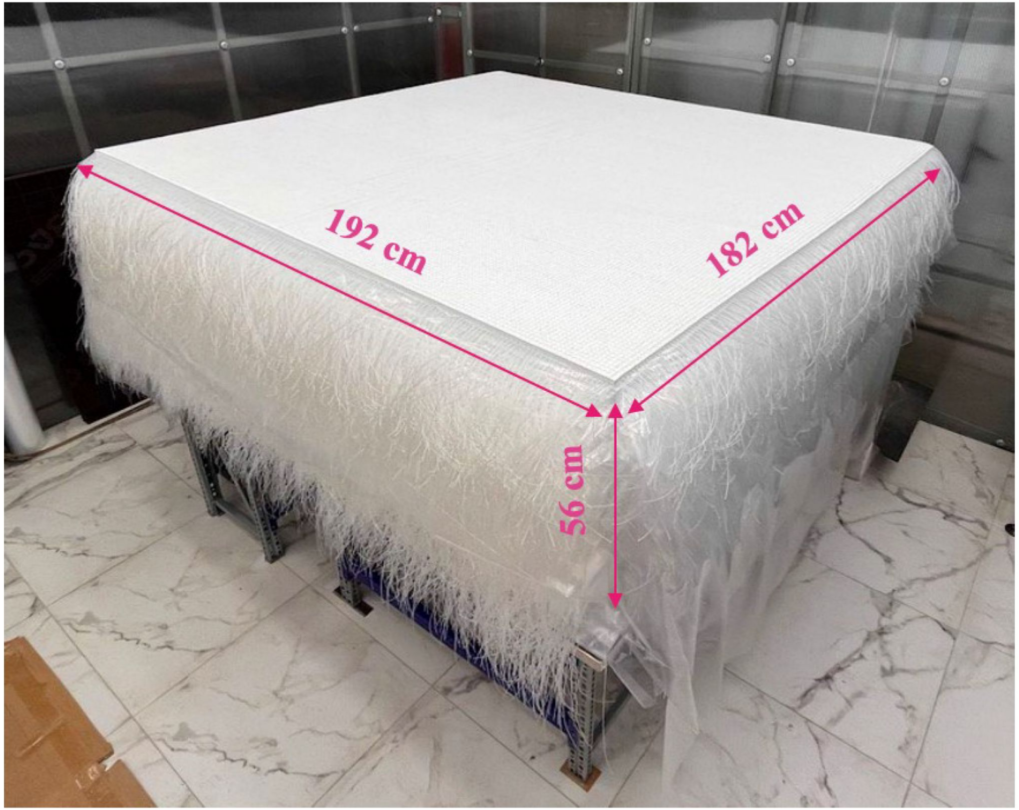
High granularity

3D reconstruction

PID improvement

Low energy threshold

Neutron reconstruction

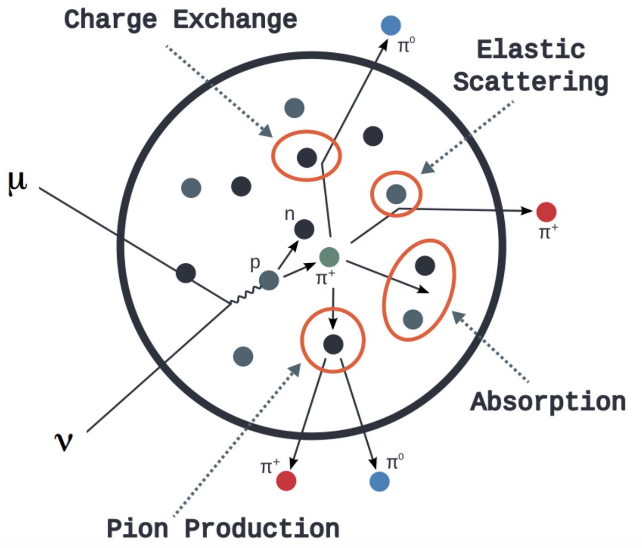


SuperFGD Neutron Importance

Neutrino energy reconstruction from lepton kinematics

Nuclear effects are not considered

→ **Bias in the neutrino energy reconstruction**



- **Final State Interactions** (FSI) make interaction identification challenging
- Topologies identification is the way
- Neutrons come in many of these topologies: (**CC0π1n**, **CC0π0p1n**, **CC0π0pNn**)

↓

Neutron reconstruction can recover the bias

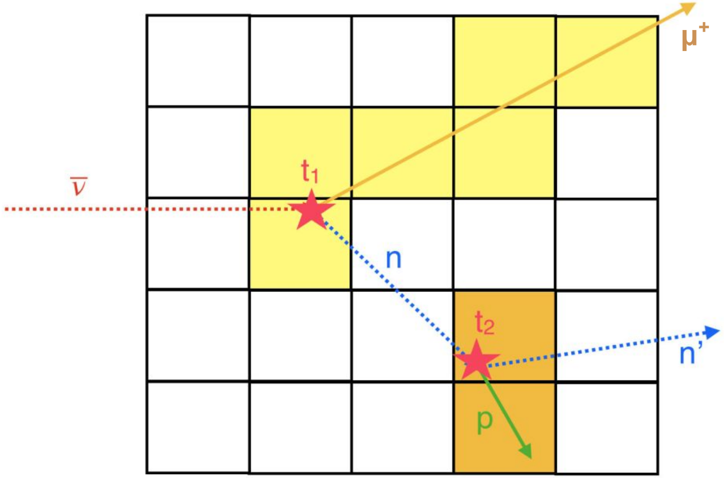
SuperFGD Neutron Reconstruction

Neutrino energy reconstruction from lepton kinematics

Nuclear effects are not considered

→ **Bias in the neutrino energy reconstruction**

$$\overline{\nu}_\mu + p \rightarrow \mu^+ + n$$



→ **Neutron energy reconstruction from time of flight t2 - t1 measurement**

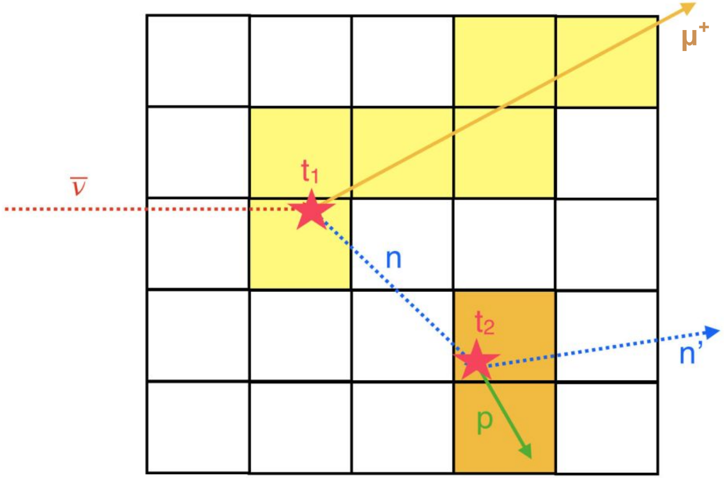
SuperFGD Neutron Reconstruction

Neutrino energy reconstruction from lepton kinematics

Nuclear effects are not considered

Bias in the neutrino energy reconstruction

$$\overline{\nu}_\mu + p \rightarrow \mu^+ + n$$



Neutron energy reconstruction from time of flight t2 - t1 measurement

Timing characterization of the detector is crucial!

Timing Characterization

Time calibration:
time offsets + time walk

Time resolution

Time Calibration Introduction

Goal: evaluate

- ❑ **Channel time offsets** (bias in time ~ns given by electronic units)
- ❑ **Time walk** (effect ~10 ns depending on signal amplitude)

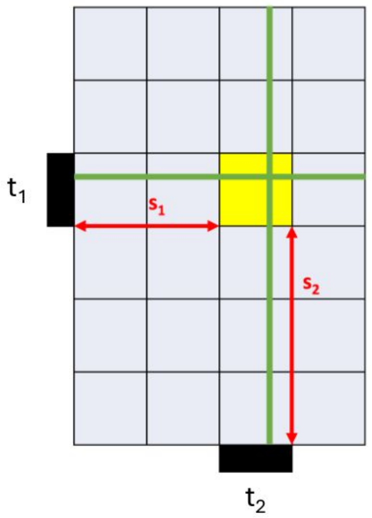
Important for:

- ❑ **Neutron analysis**
- ❑ **Track direction**

Exploit the **granularity** of the detector

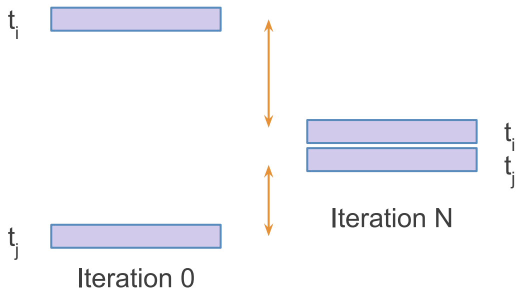
1. Get a set of **matched hits**
2. Apply **iterative process** to evaluate channel offsets

1



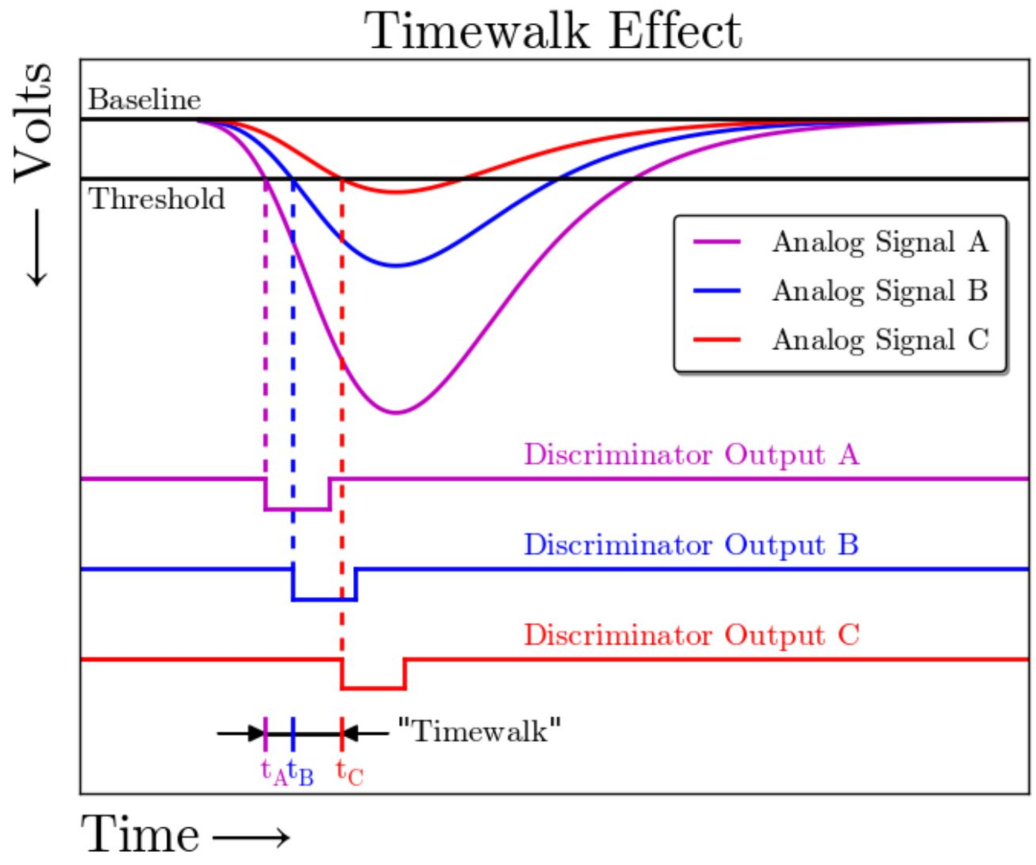
2

Minimize: $\Delta t_{ij} = \frac{(t_i - t_j) - (s_i - s_j)/v}{2}$



Channel time offsets

Time Walk Effect

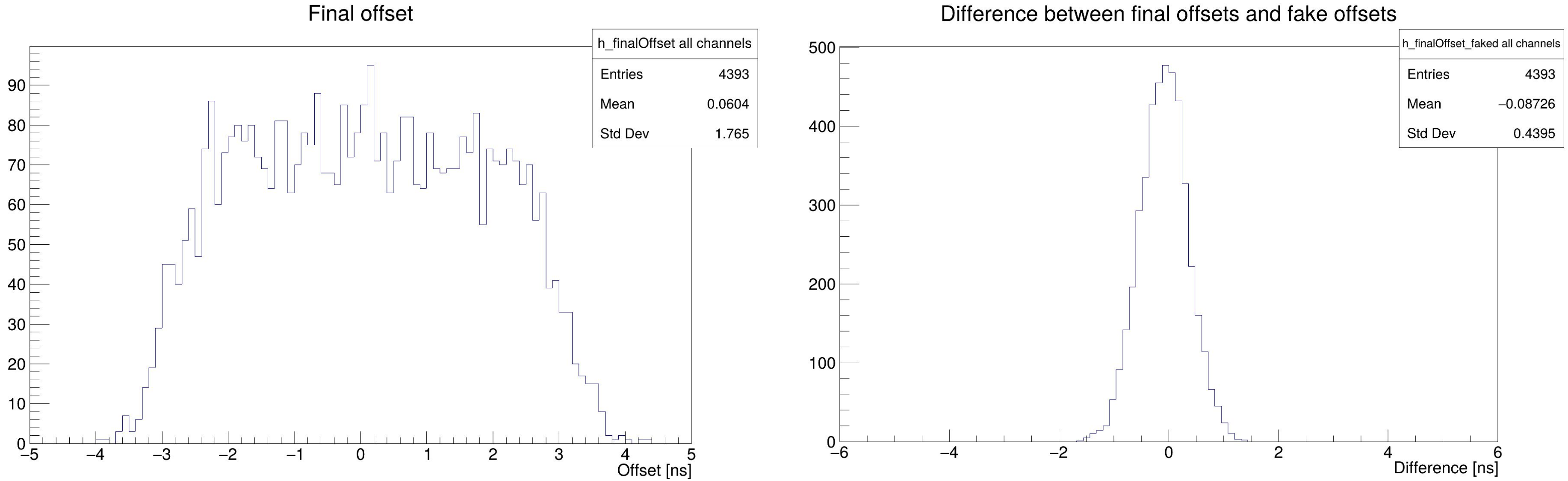


- The threshold is needed to cut the noise out
- Registered time depends on the time when the signal passes the threshold
- Very different amplitude means high time walk contribution
- By comparing similar amplitude the time walk is little

Channel offsets evaluated with matched hits with **0.9<q1/q2<1.11** requirement

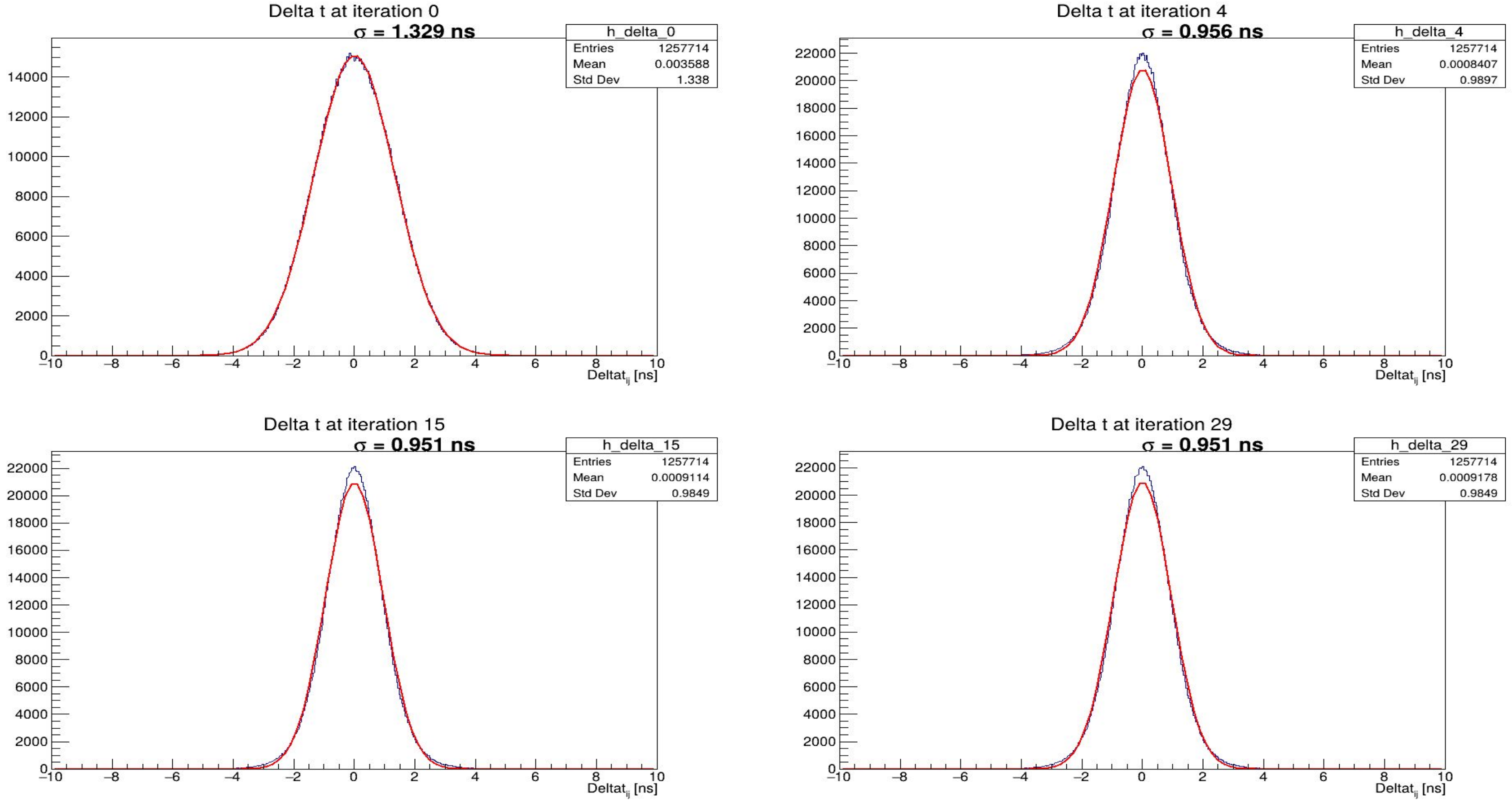
Run on 11k cosmic muons mc

Applied a **fake offset** between -3 and 3 ns

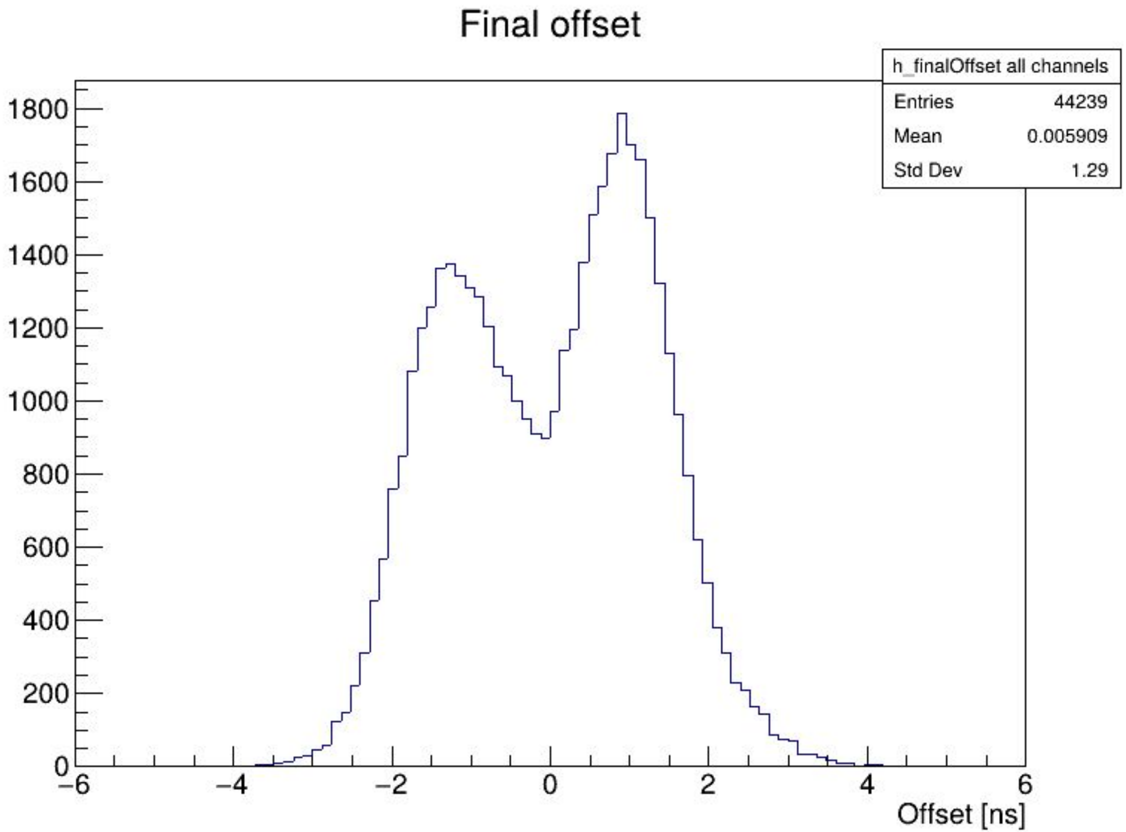


Algorithm works pretty well in MC

Channel offsets: Data

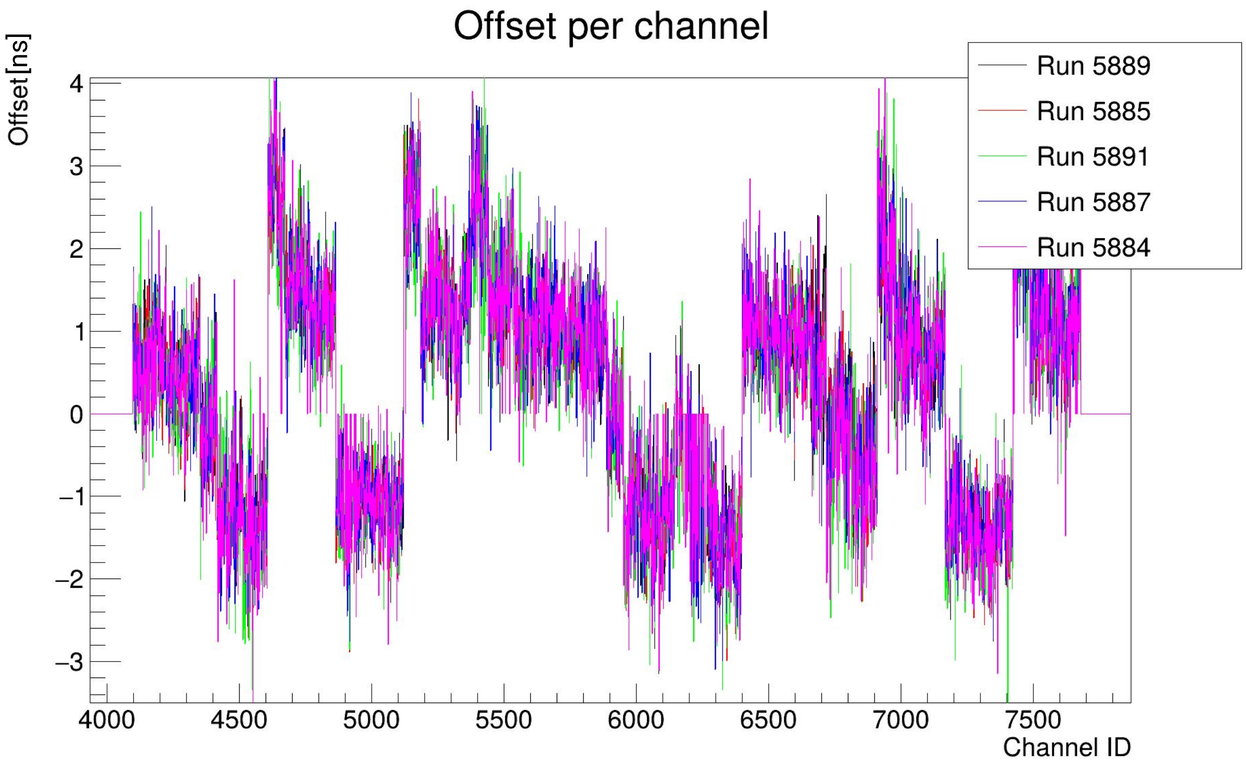


Channel offsets: Data



- Only channels with more than 20 hits are saved
- 44k channels evaluated out of 58k (depend on stats)

Channel offsets: Data run-by-run stability



Good stability in data as well

Time walk correction

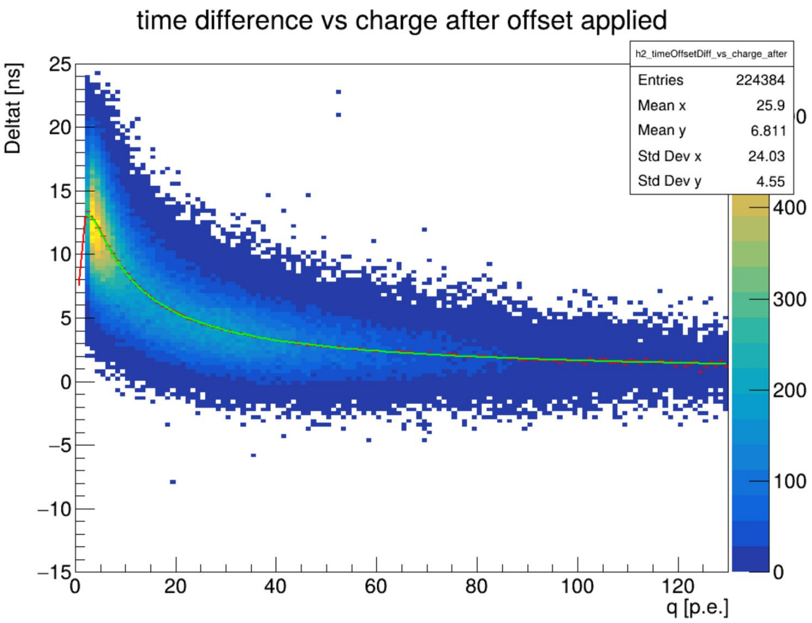
Time walk

- ❑ Apply the offset correction
- ❑ Check the difference between the expected times vs charge

$$\Delta t_{ij} = (t_i - t_j) - (s_i - s_j)/v$$

Fit function: $$\frac{A}{\log(B * q + C)} - \frac{D}{q + E}$$

Fit is not perfect but work in progress



Time resolution

Time resolution

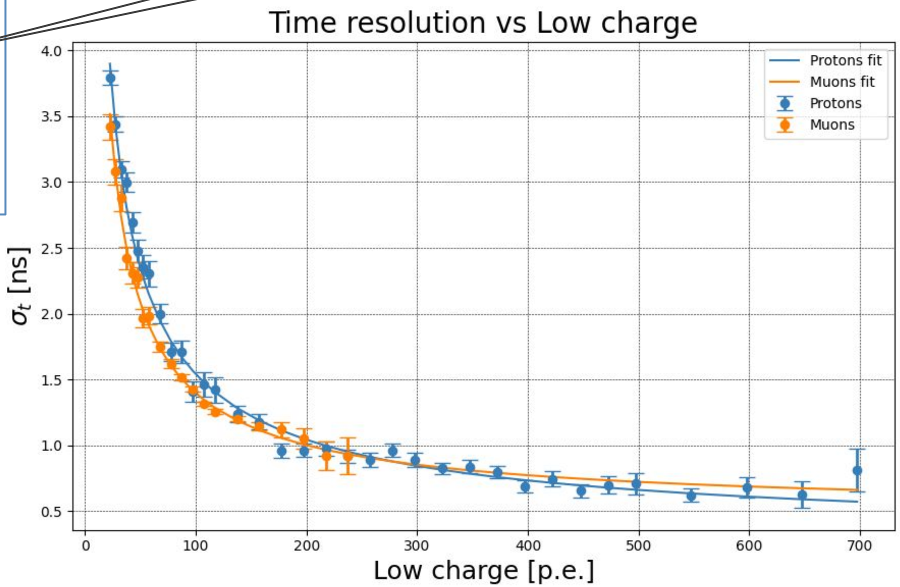
For each pair of neighbouring cubes:

- **Δt_{reco}**: reconstructed cube time difference
- **Δt_{calc}**: calculated cube time difference from position
- Obtain time resolution $\boldsymbol{\sigma_t}$

$t_{i+1} - t_i$

Dist(i+1, i)/speed

$$\sigma_t = \frac{\sigma_{st}\left(\Delta t_{reco} - \Delta t_{calc}\right)}{\sqrt{2}}$$



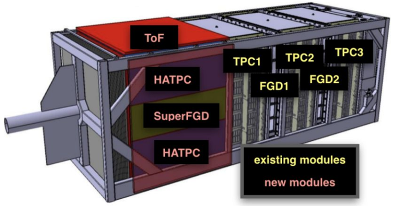
For each pair of neighbouring cubes:

- Build ($\boldsymbol{\Delta t_{reco}}$ - $\boldsymbol{\Delta t_{calc}}$) distribution
- **Low charge** from hit charges q_i and q_{i+1}
- Scan $\boldsymbol{\sigma_t}$ through low charge

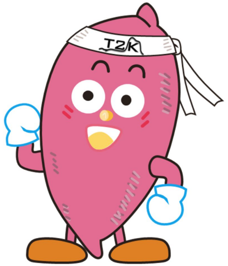
Fit function: $\sigma(A) = p_0/A^{p_1} + p_2$

Summary

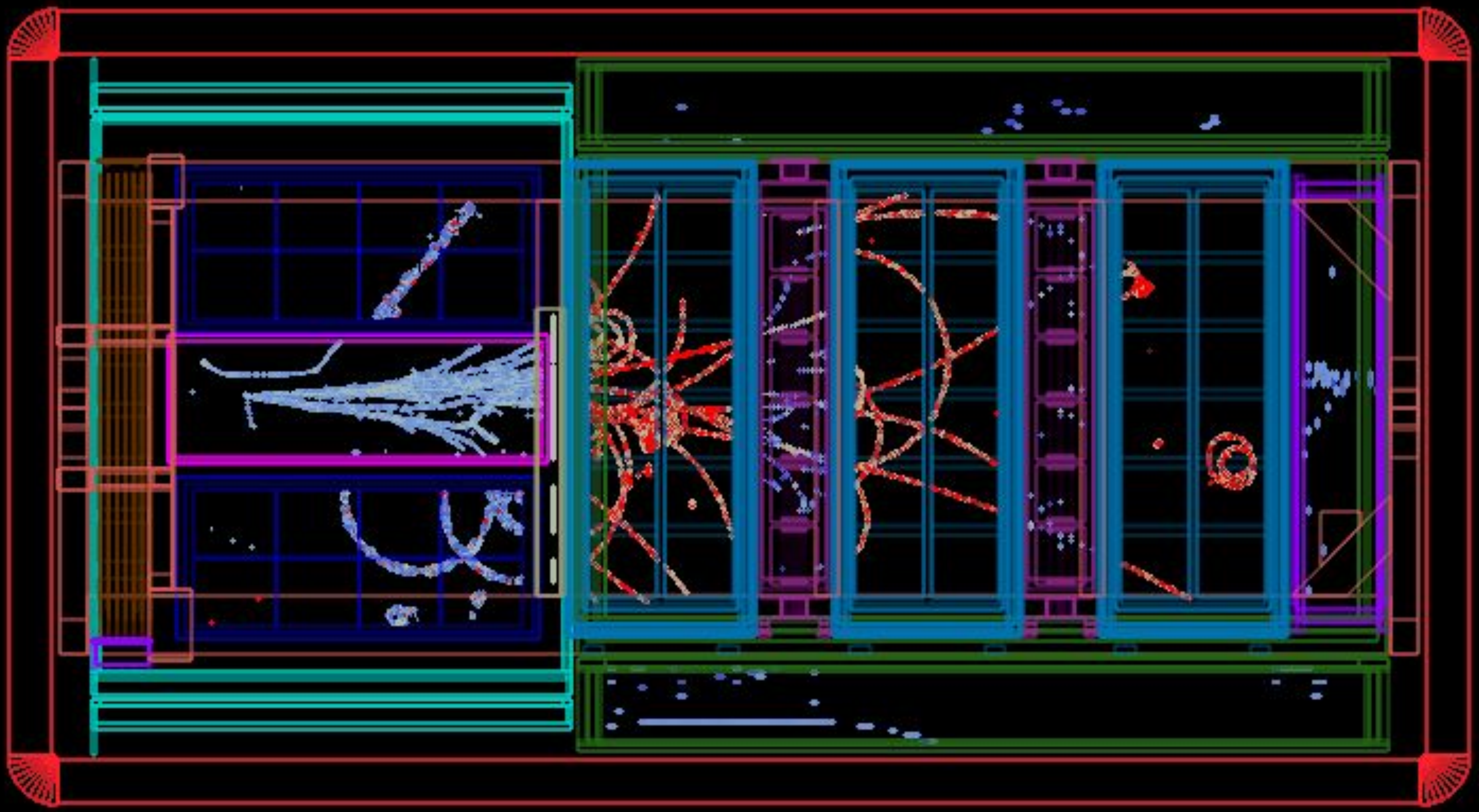
- ❑ **ND280 Upgrade** for systematic errors reduction
- ❑ Neutrons will play a key role in systematic errors
- ❑ Neutron reconstruction relies on time of flight of neutrons



- ❑ **Time calibration** on going
- ❑ **Time resolution** only tested in MC
- ❑ Given a methodology for **time calibration for high granularity detector**



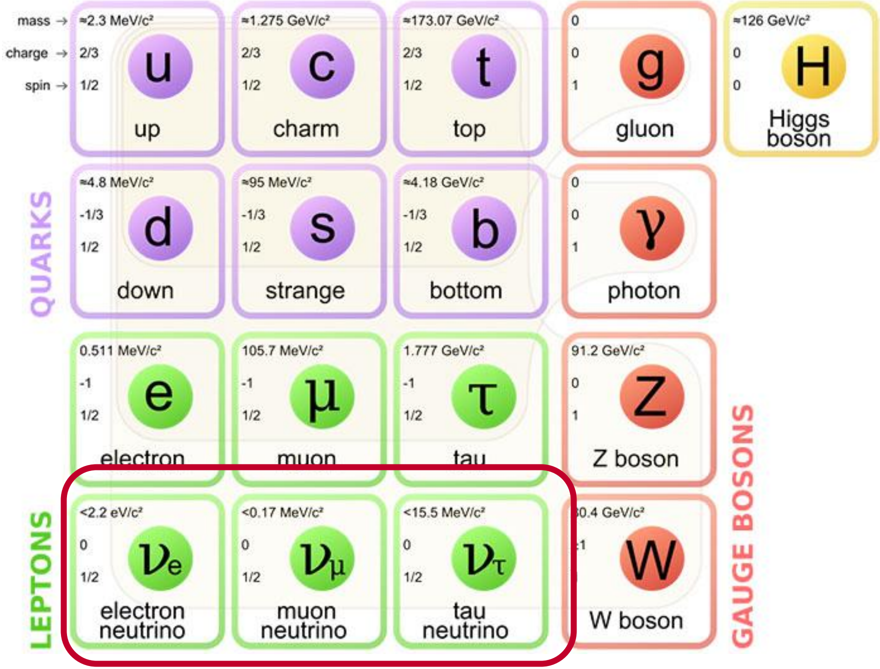
Thanks for your attention!



Backup

- Neutrinos ν belong to the Standard Model of particle physics
- Chargeless leptons
- Treated as **massless particles** (wrongly)

Homestake first (of many) experiment to observe **neutrino oscillations** proves this wrong



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \text{PMNS} \\ \text{matrix} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

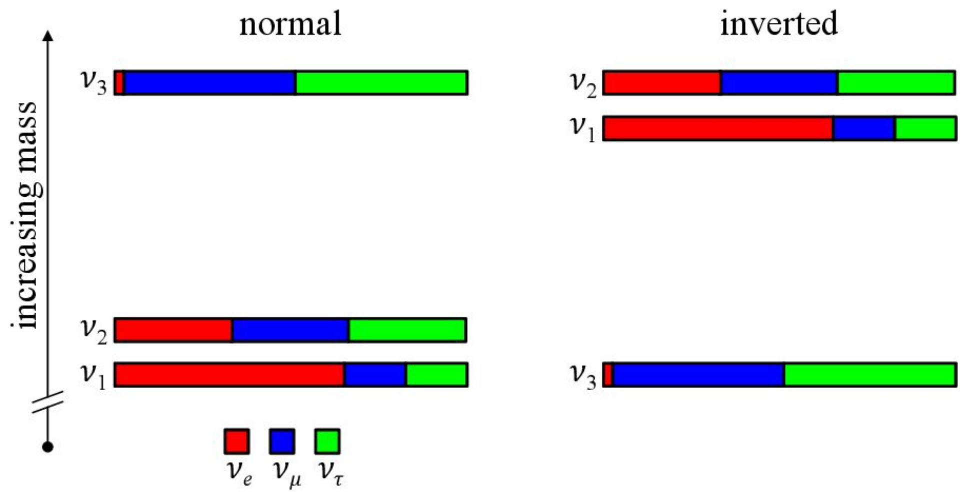
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

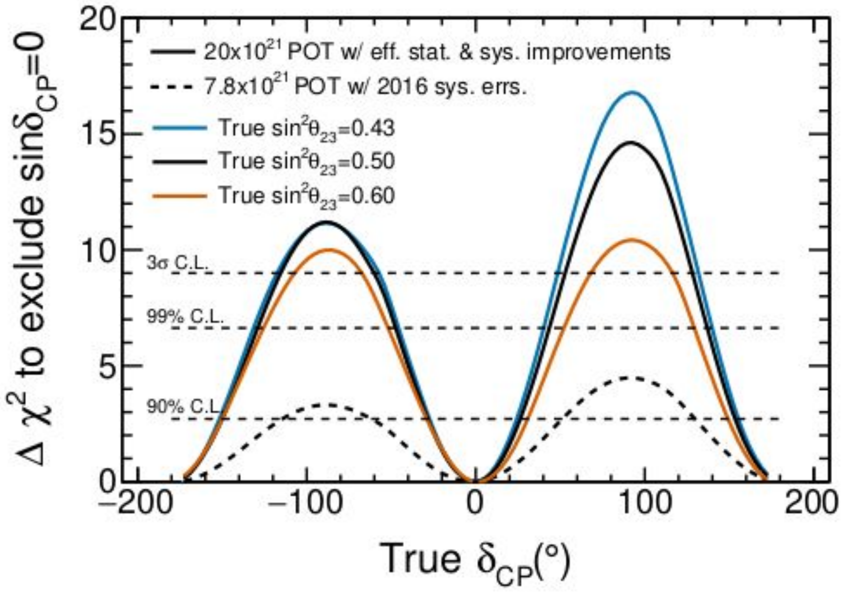
$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(1.27\,\frac{\Delta m^2 L}{E}\,\frac{[\mathrm{eV}^2]\,[\mathrm{km}]}{[\mathrm{GeV}]}\right)$$

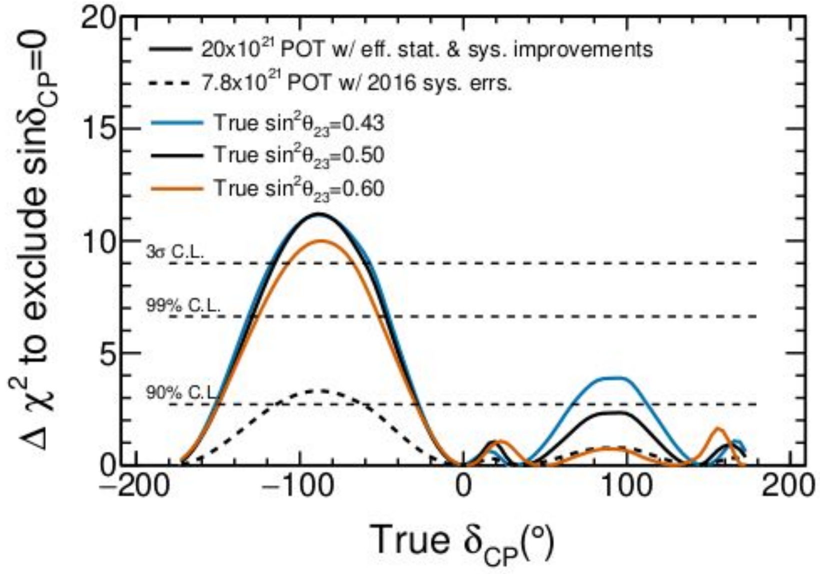
Open questions

- ❑ CP violation phase
- ❑ Neutrino Mass ordering
- ❑ θ_{23} octant

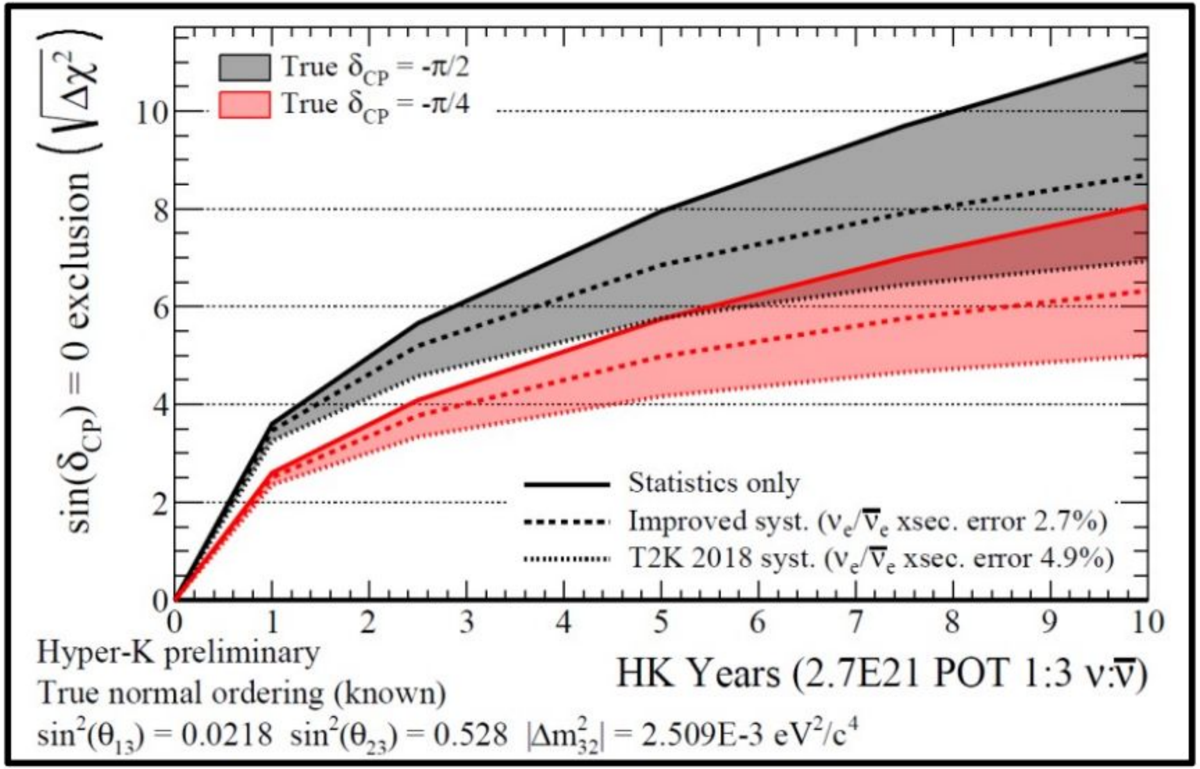


CP violation phase





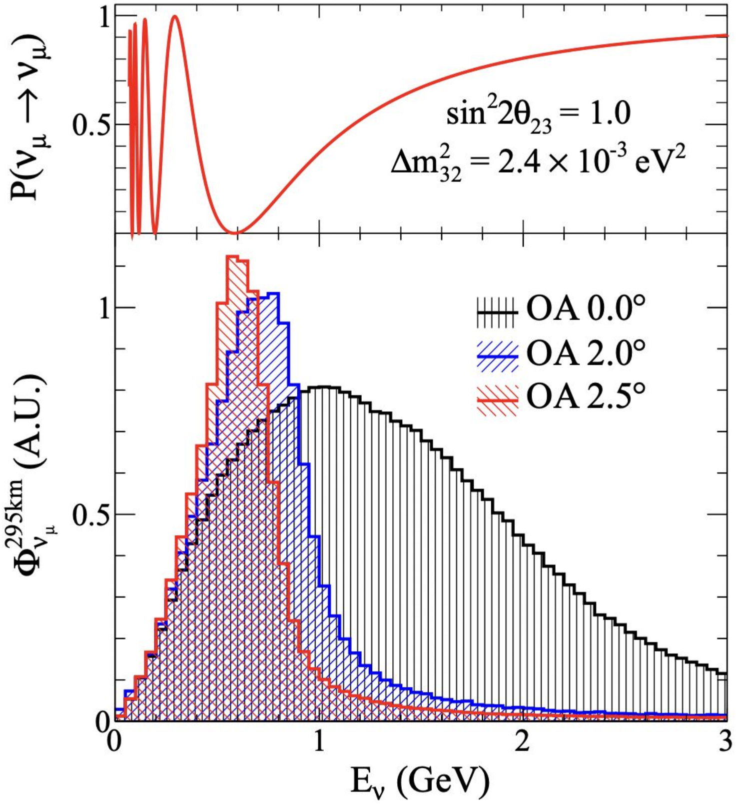
CP violation phase



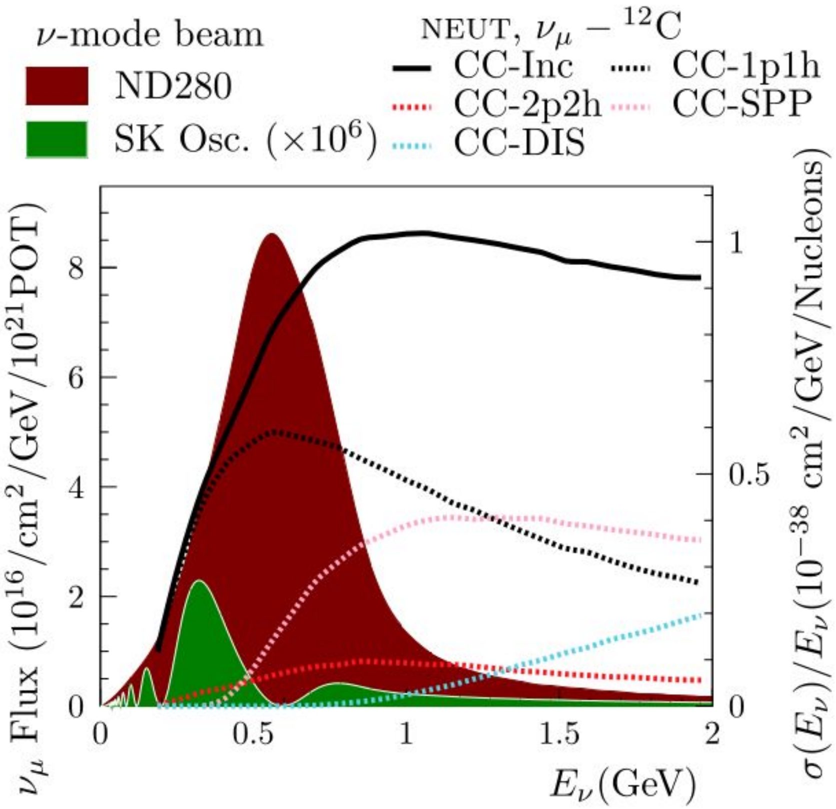
State of art neutrino oscillations

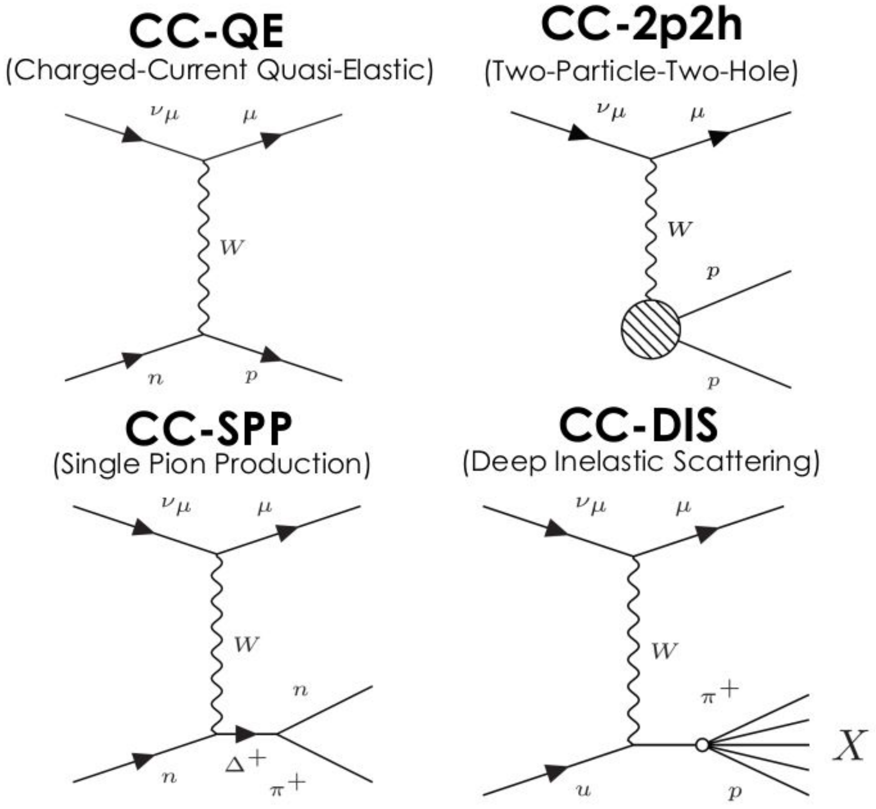
	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
	bfp $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$
$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \to 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \to 0.02428$
$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \to 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.96$
$\delta_{CP}/^\circ$	197^{+27}_{-24}	$120 \to 369$	282^{+26}_{-30}	$193 \to 352$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$

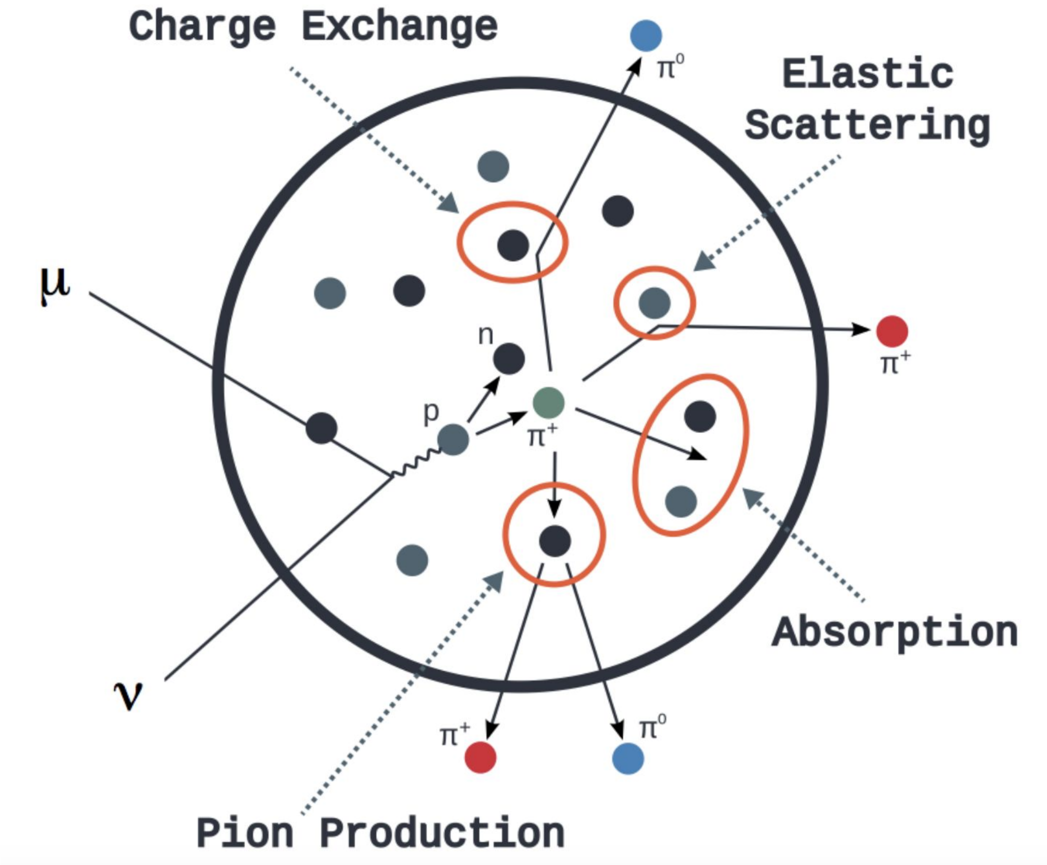
Neutrino flux



Neutrino - nucleus cross section

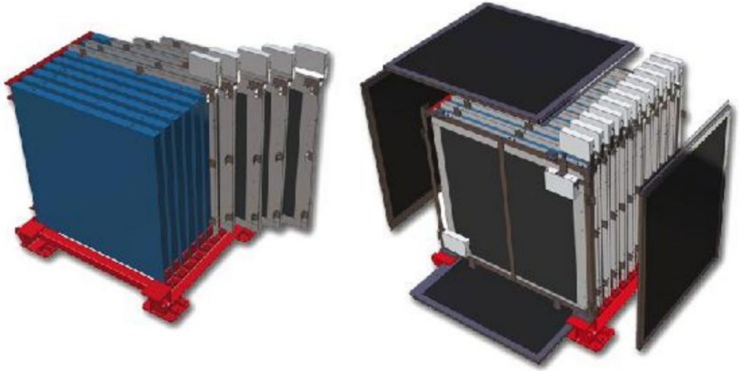


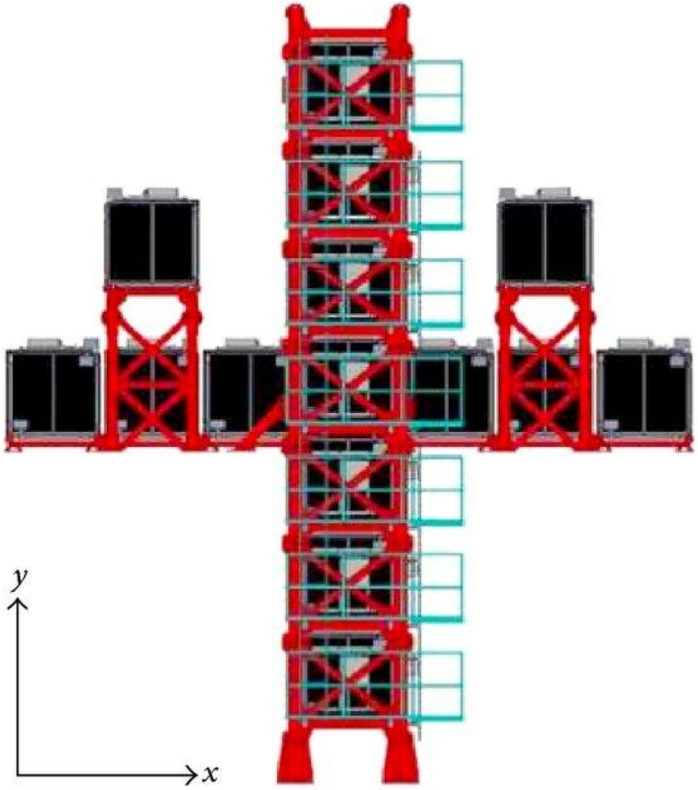



Charge Exchange
Elastic Scattering
Absorption
Pion Production
μ
ν
n
p
π+
π0
π+
π0
π+

INGRID

- On-axis
- 16 modules
- 9 iron target plates + 11 tracking scintillator planes
- Surrounded by scintillator veto planes
- Flux direction monitoring





WAGASCI-BabyMIND

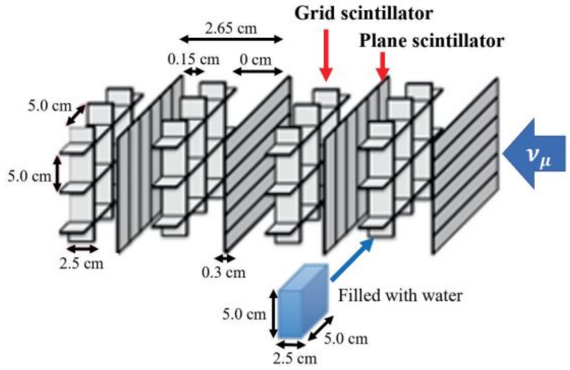
- 1.5° off-axis
- Reduce systematic errors

WAGASCI

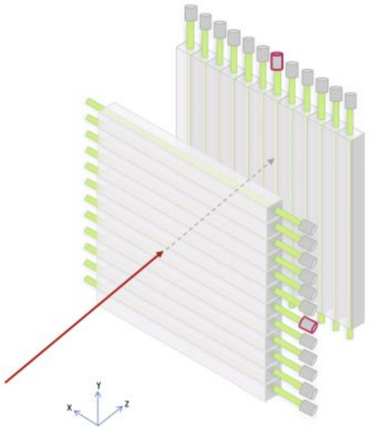
- Main target: pure water
- Cross section ratio scintillator-water

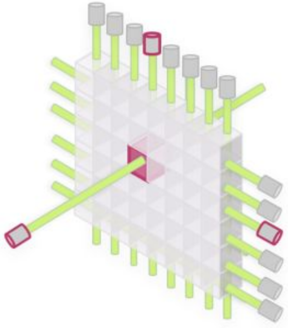
Baby MIND

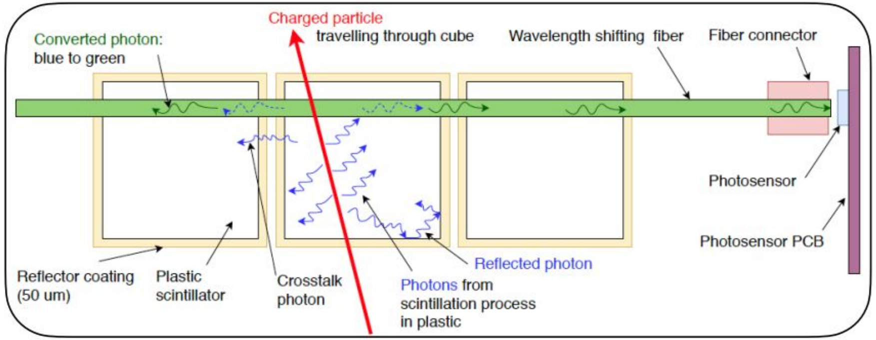
- Magnetized iron neutrino detector
- Charge and momentum of outgoing muon



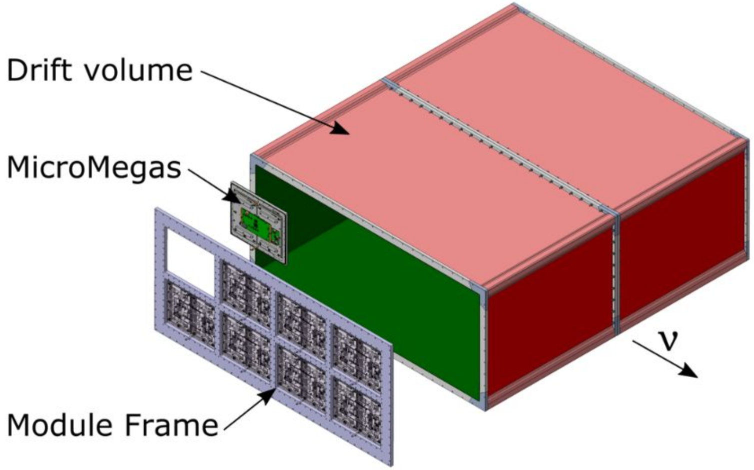
- Polystyrene doped with 1.5% of paraterphenyl (PTP) and 0.01% of POPOP
- Hamamatsu MPPC S13081-050C
- L.Y. around 40 p.e. for MIP

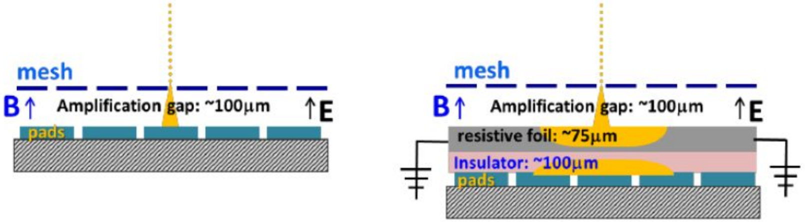






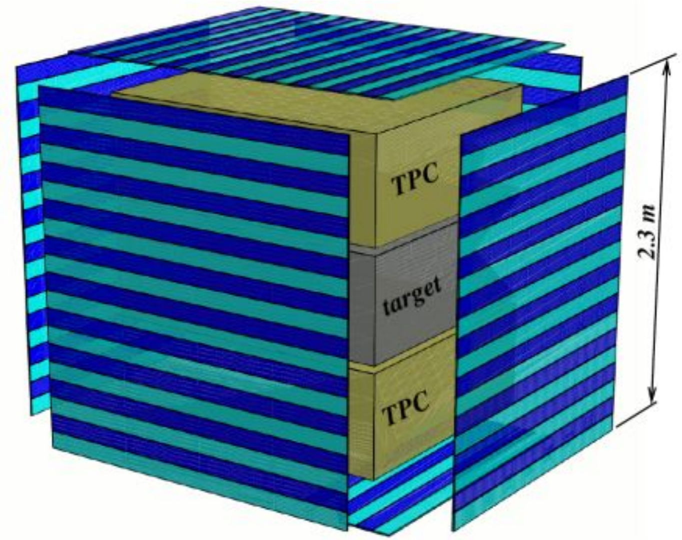
- Similar to old TPCs
- Resistive MicroMegas
- Thin field cage
- Better spatial resolution
- Reduced risk of sparks





Time Of Flight

- ❑ 6 modules of plastic scintillator layers
- ❑ 150 ps time resolution
- ❑ Background discrimination
- ❑ Ingoing and outgoing particle identification



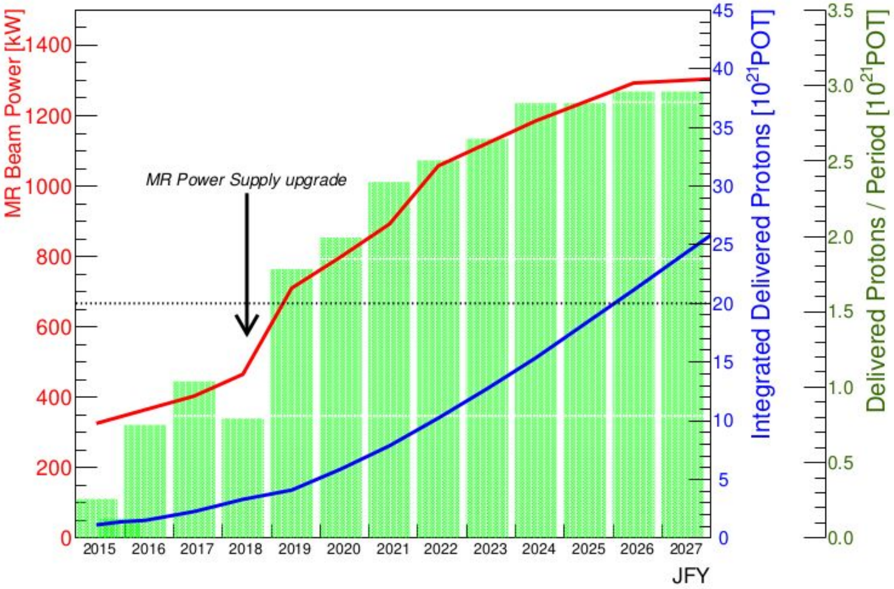
Aim: CP violation with > 3σ significance exclusion

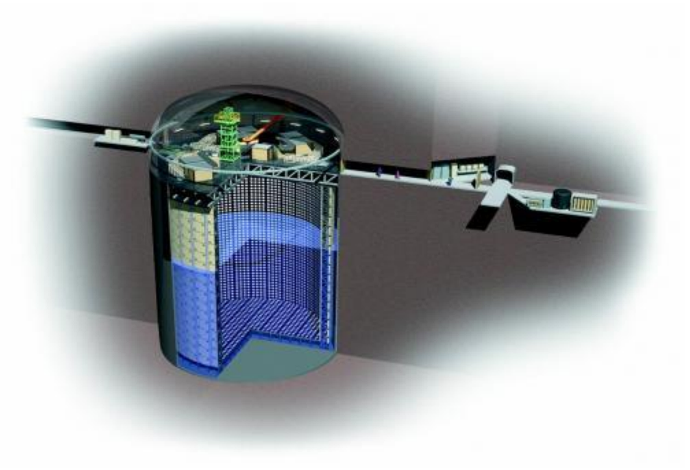
- ❑ Extended T2K running time (Hyper-Kamiokande)
- ❑ Collect **20×10^{21}** Protons-on-Target (PoT)
- ❑ J-PARC **accelerator upgrade reaching 1.3 MW** in few years (485 kW currently achieved)

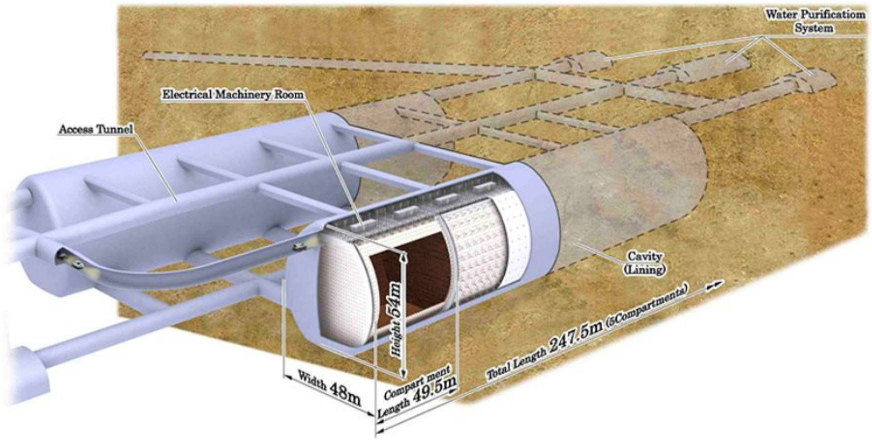
Better understanding of detector uncertainties is crucial!

→ **ND280 UPGRADE**

JPARC - Upgrade







- 41.4 m tall, 39.3 m diameter
- 50k metric tons
- 11’000 PMTs

- 48 x 54 x 250 m^3
- 1 million metric tons
- 99’000 PMTs

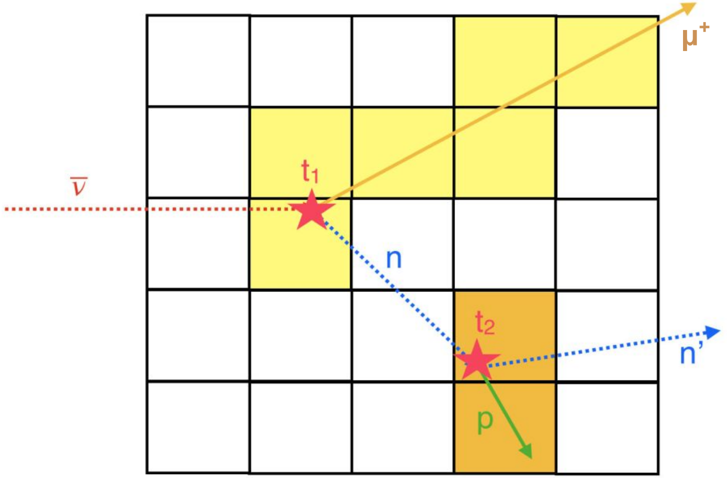
Neutrino energy reconstruction from lepton kinematics

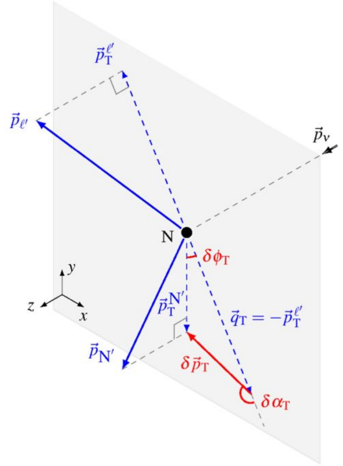
Nuclear effects (FSI) are not considered

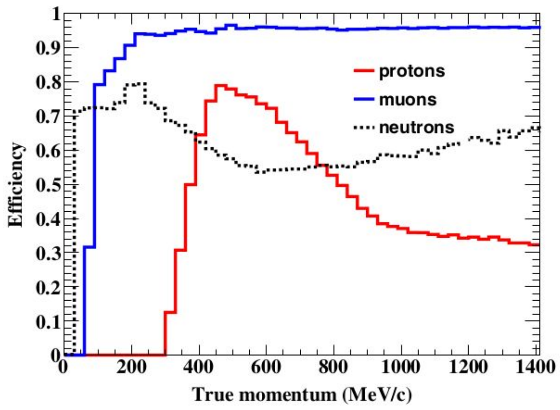
$$E_\nu = \frac{m_n^2 - m_p^2 - m_\mu^2 + 2m_p E_\mu}{2(m_p - E_\mu + p_\mu \cos\theta_\mu)}$$

Transverse momentum imbalance **δp_T**

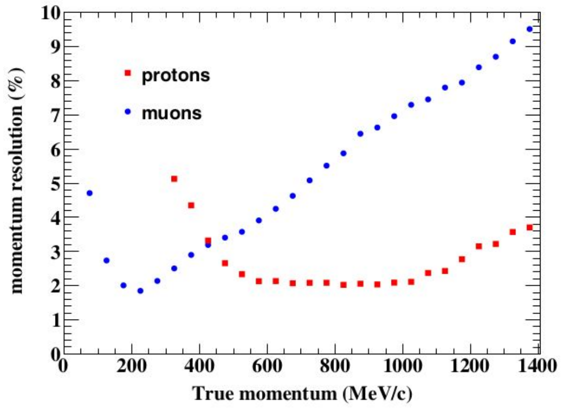
$$\overline{\nu}_\mu + p \rightarrow \mu^+ + n \qquad \delta p_{\mathrm{T}} = |\vec{p}_T^{\,l} + \vec{p}_T^{\,n}|$$







Efficiency
True momentum (MeV/c)
protons
muons
neutrons
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
200
400
600
800
1000
1200
1400



momentum resolution (%)
True momentum (MeV/c)
protons
muons
0
1
2
3
4
5
6
7
8
9
10
200
400
600
800
1000
1200
1400

Time Calibration Introduction

SFGD time calibration doesn't take into account **channel offsets** and **time walk correction**

Offset ~ns given by the electronic components

Effect ~10ns depending on signal amplitude

Goal: time offsets and time walk evaluation

Important for:

- ❑ **Neutron analysis**
- ❑ **Track direction**

Exploit the **granularity** of the detector

- ❑ Get a set of **matched hits**
- ❑ Apply **iterative process** to evaluate channel offsets

We define:

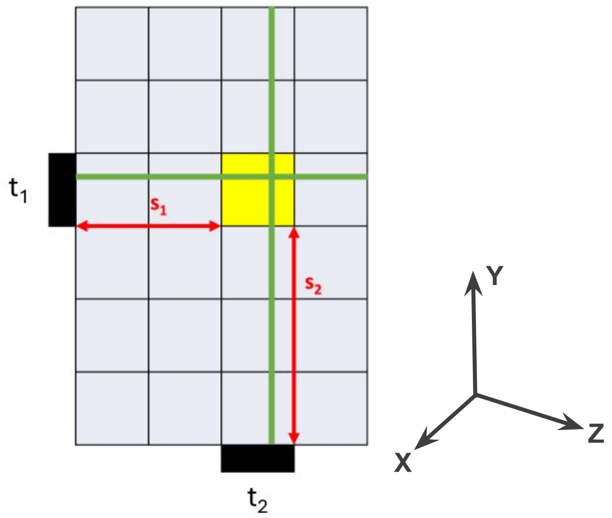
- ❑ **fiber hit**: a THit with time, charge and MPPC position
- ❑ **matchedHit**: a match between 2 fiber hits
- ❑ **t_i**: the time recorded by the i_th channel
- ❑ **s_i**: distance from the MPPC to the reconstructed cube in one of the 2 hits matched
- ❑ **v**: speed of light in the fiber

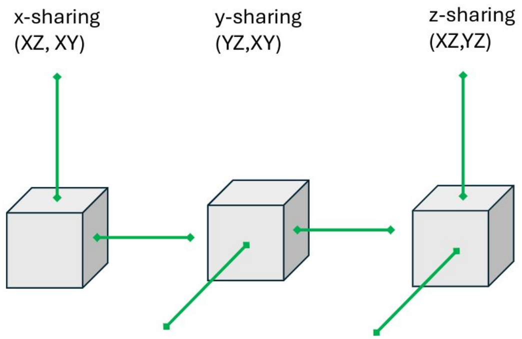
Matching Hit Methodology

Using **cosmics (μ)** in both MonteCarlo and Data:

- ❑ Each event has a single track
- ❑ Each track is reconstructed as a set of **3D cube hits**
- ❑ Each cube hit has **3 fiber hits**, meaning **3 matched hits**
- ❑ **Noise cut**: 10 photoelectrons (p.e.)

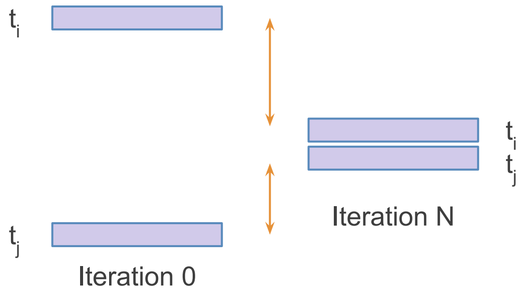
End up with a set of vectors of: $\mathbf{[(t,s,ch,q)_1, (t,s,ch,q)_2]}$



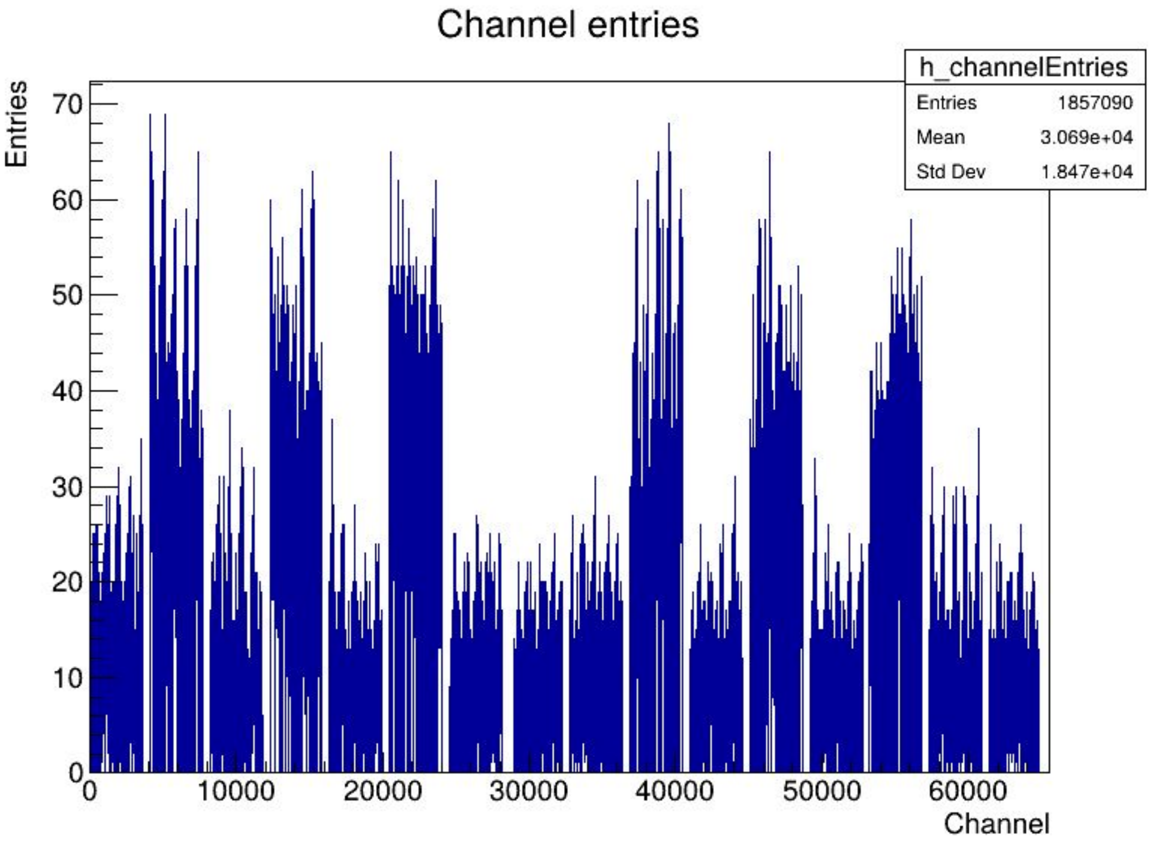


Iteration Methodology

- Loop through matched hits
- For each matched hit:
  - Evaluate: $\Delta t_{ij} = \frac{(t_i - t_j) - (s_i - s_j)/v}{2}$ dividing by 2 necessary to distribute the correction equally to each channel of the matched hit
  - Evaluate: $\Delta t_i = \sum_j \frac{\Delta t_{ij}}{N}$ which is the **correction on the offset**
  - Apply the correction: $t_i^{n+1} = t_i^n \pm \Delta t_i$
- Repeat loop until convergence: maximum number of iteration
- Final channel offset is the sum of all the corrections at each iteration
- In the end the two times should be as close as possible

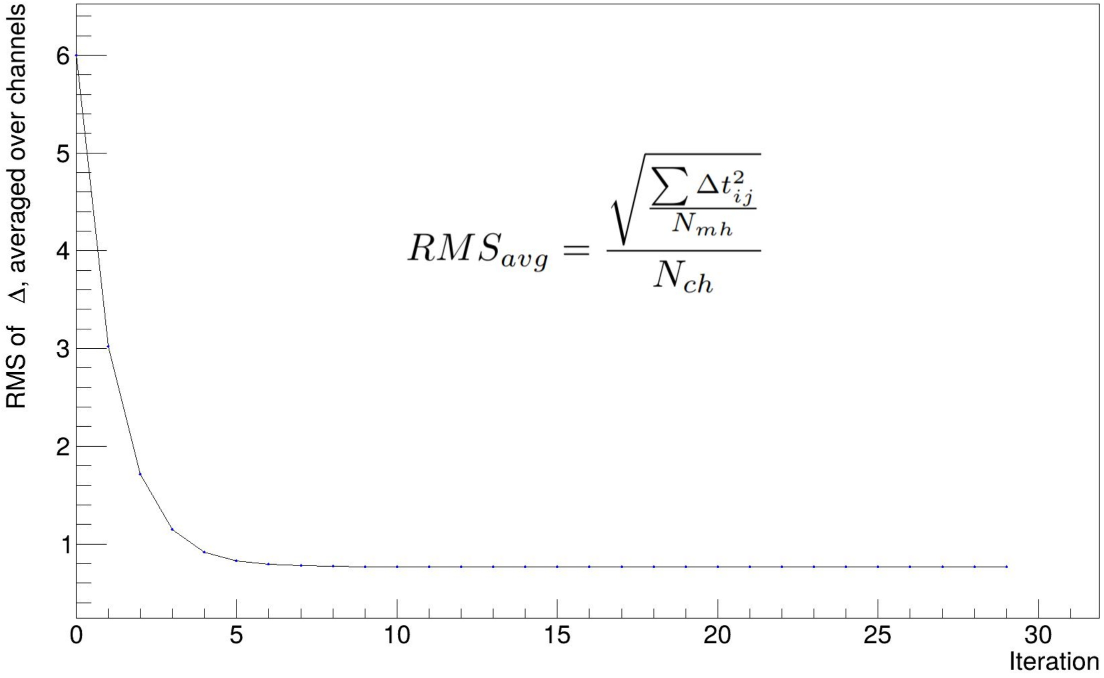


Results: Data run 5889



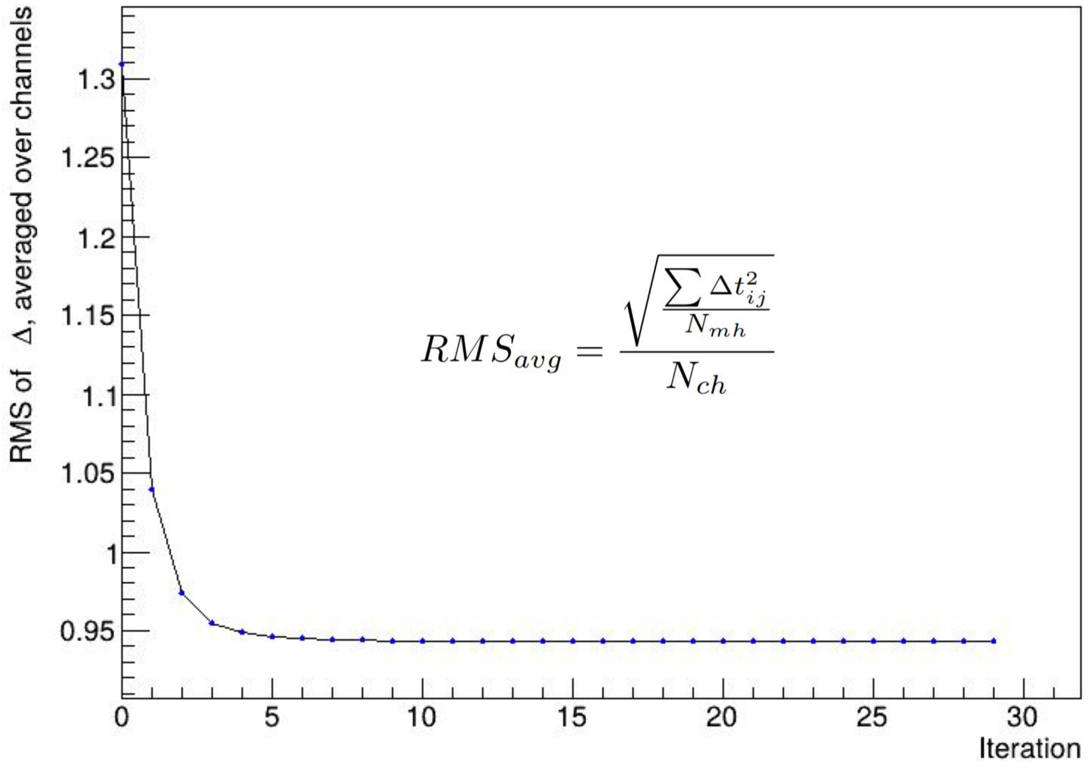
Run on 11k cosmic mc

RMS_{avg} is a metric to the convergence of the algorithm



$$RMS_{avg} = \frac{\sqrt{\frac{\sum \Delta t_{ij}^2}{N_{mh}}}}{N_{ch}}$$

Channel offsets: Data



Unseen channels

For the “unseen” channels we could use the citiroc’s average offset