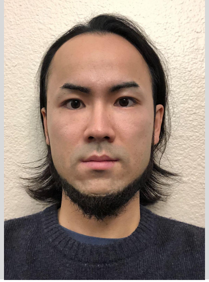
The intermediate water Cherenkov detector for the Hyper-Kamiokande experiment



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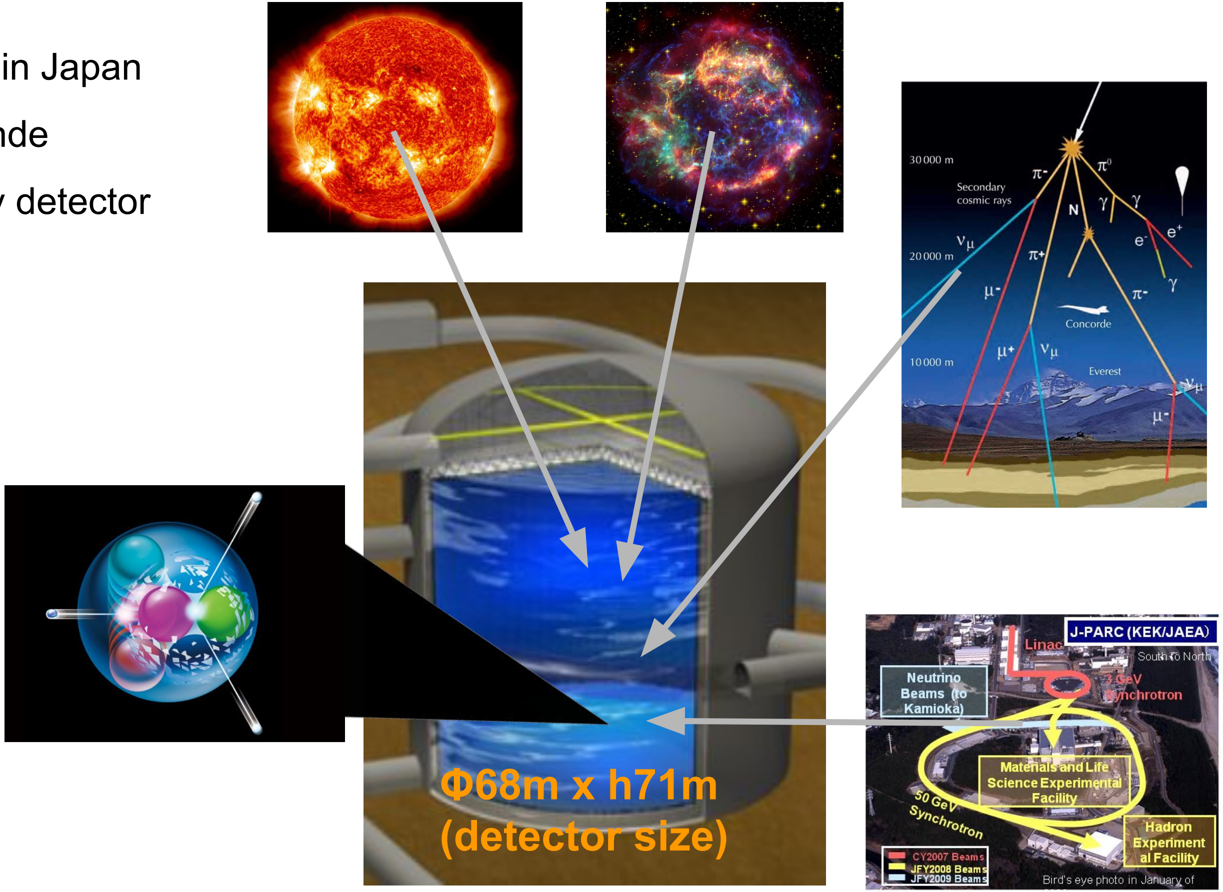
September 9th, 2021/NuFact2021 WG1

TRIUMF

The Hyper-Kamiokande project

- Next generation neutrino experiment in Japan
  - The successor of Super-Kamiokande
  - 260 kiloton scale water Cherenkov detector
  - Overview talk by K.Sakashita
- Rich physics programs
  - Neutrino oscillations
  - Neutrino astronomy
  - Nucleon decay searches
- Construction has began in 2020
  - Plan to start taking physics data in 2027



The long-baseline program

◆ Will study νμ->νe and ν̅μ->ν̅e oscillations to search for CP violation, following the successful T2K experiment

- 2.5x more intense beam & 8x larger fiducial mass of the far detector

◆ 20x higher interaction rates than the T2K's ones -> measurement will be systematically limited

Current systematic uncertainties

ND: near detectors

FD: far detectors

T2K (PRD 103, 112008, 2021)

Source	Error for CPV search (%)
Φ x σ (ND constrained)	2.7
Φ x σ (ND unconstrained)	1.2
Nucleon removal energy	3.6
FD π re-scattering + PN	1.6
σ(νe) / σ($\bar{\nu}$e)	3.0
NC γ + other	1.5
FD detector	1.5
Total	**6.0**

Imperfect extrapolation from ND to FD (→ Φ x σ (ND constrained))

Estimation based on theory (→ σ(νe) / σ($\bar{\nu}$e))

Detector modeling & calibration (→ FD detector)

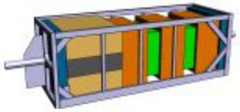
Uncorrelated processes between ND and FD (→ Φ x σ (ND unconstrained), Nucleon removal energy, FD π re-scattering + PN)

No data driven constraint (→ NC γ + other)

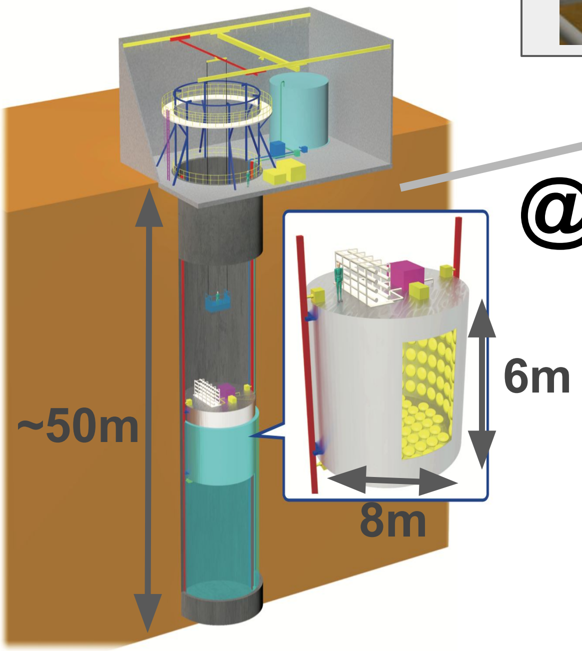
◆ Need to achieve <3 % systematic uncertainties for Hyper-K

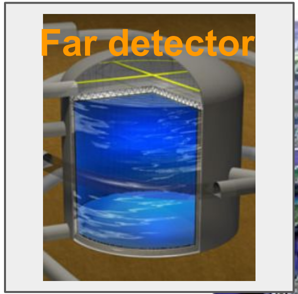
The Intermediate Water Cherenkov Detector

Other near detectors @ 280m
- INGRID
- Upgraded ND280



IWCD





@~1km

- ◆ Sub-kiloton scale water Cherenkov detector
- ◆ **Vertically movable** detector
- ◆ Gadolinium (**Gd**) **loading** option

Why vertically moving detector?

◆ Different energy spectrum between the Hyper-K and near detectors due to neutrino oscillations

- The cause of imperfect extrapolation

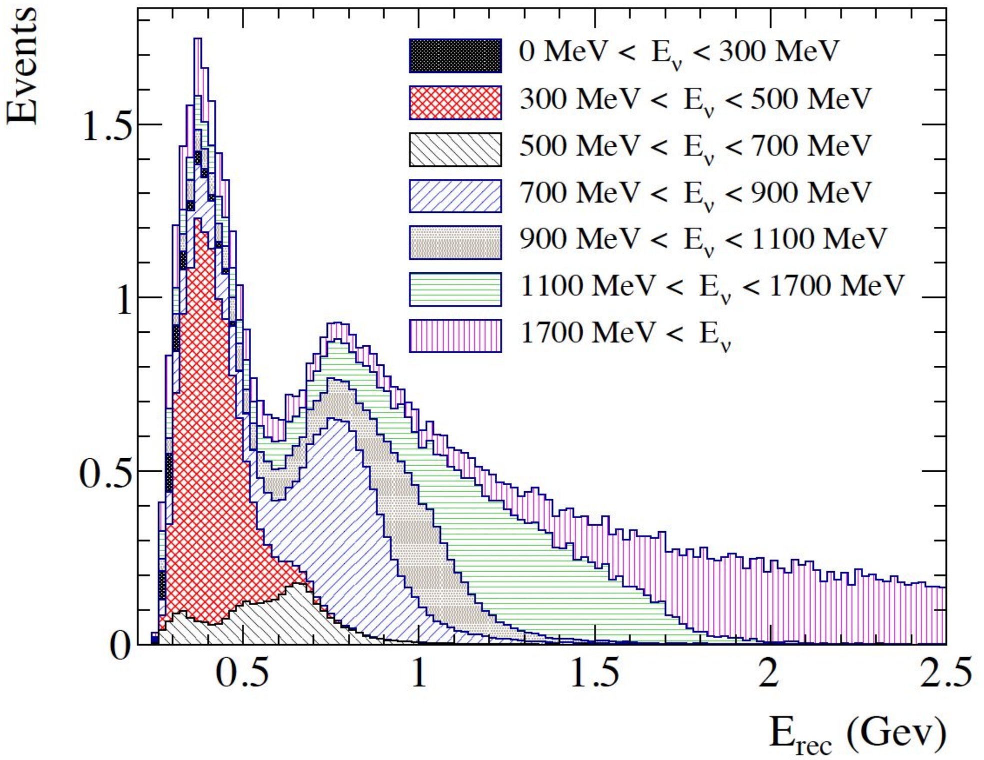
  ⇒ **Need to produce the same flux**

◆ Reconstruct neutrino energy, assuming Charged-current quasi-elastic (CCQE) interaction

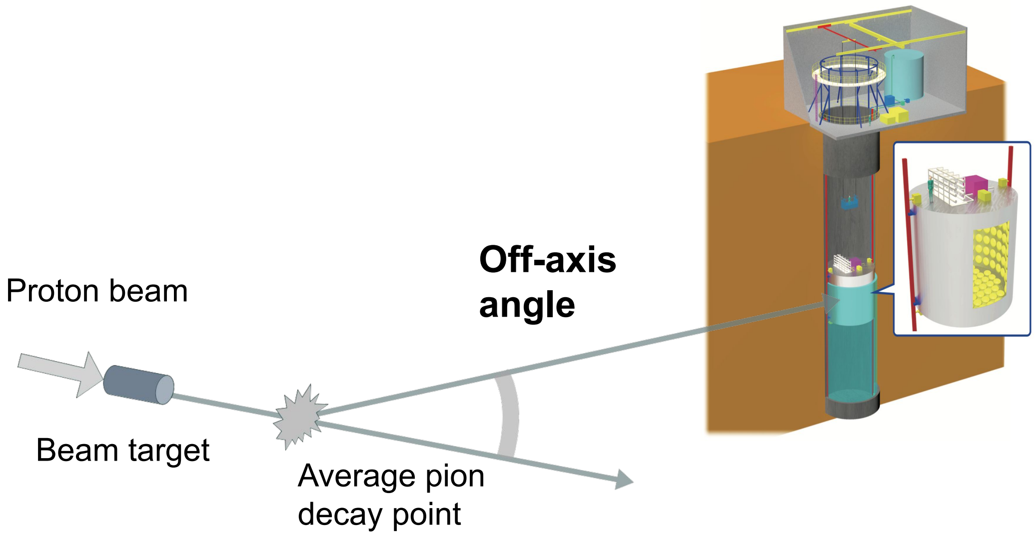
- Mis-reconstruction for non-CCQE interactions with large energy (i.e. feed-down events) affects measurements

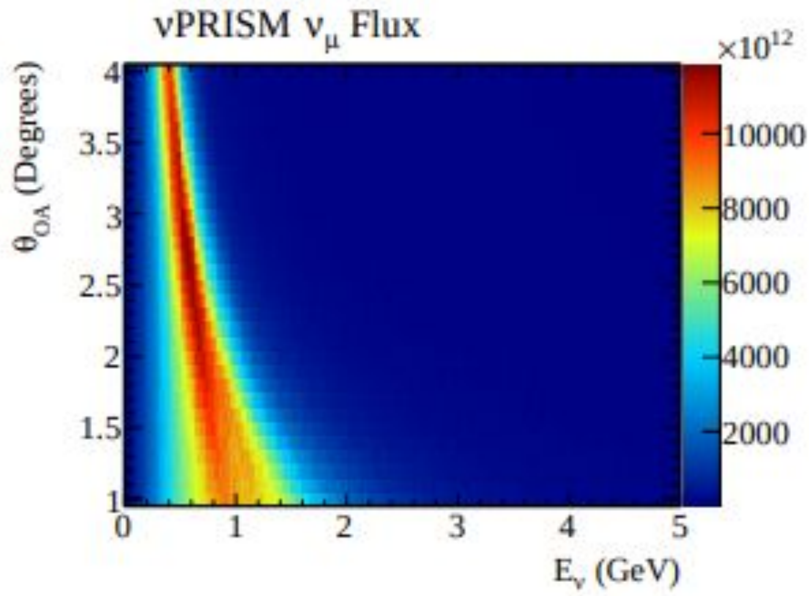
  ⇒ **Need to measure relationship between true and reconstructed energies**

Reconstructed energy assuming CCQE



The NuPRSIM concept

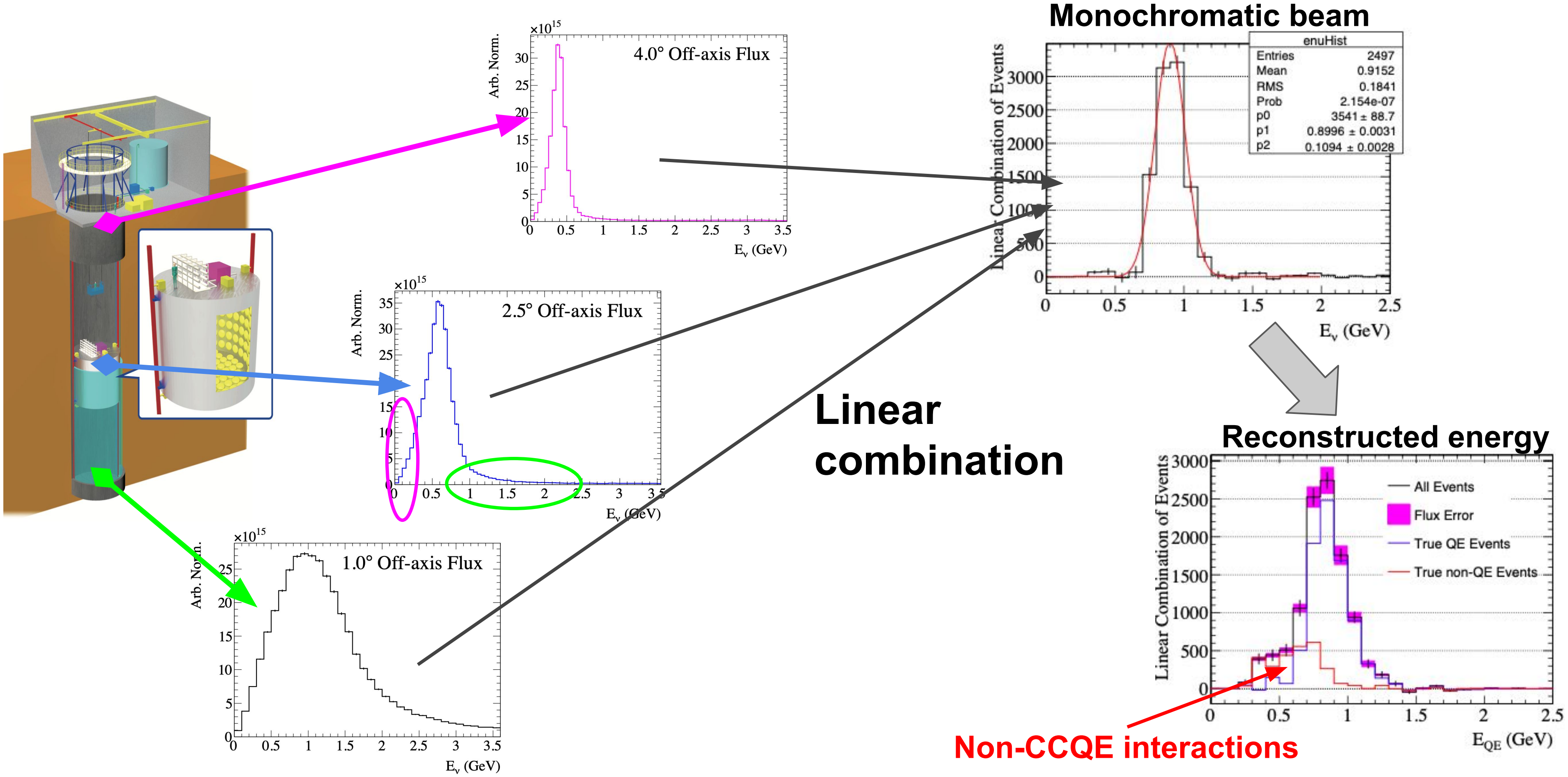




- ◆ Neutrino energy spectrum depend on the **off-axis angle**

- ◆Taking data at various vertical positions enables **mimicking** energy spectrum of interest
  - The spectrum at the Hyper-K detector
  - A monochromatic beam

Linear combination



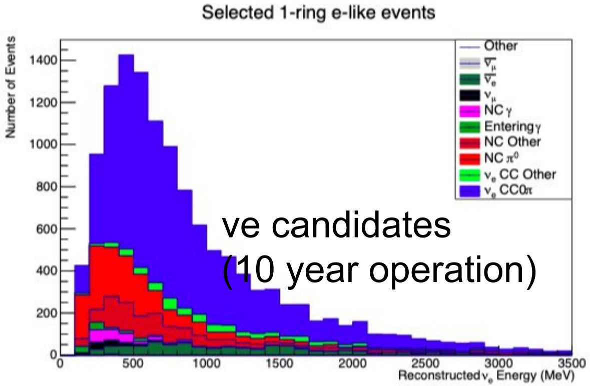
Nue/Nuebar cross section measurement

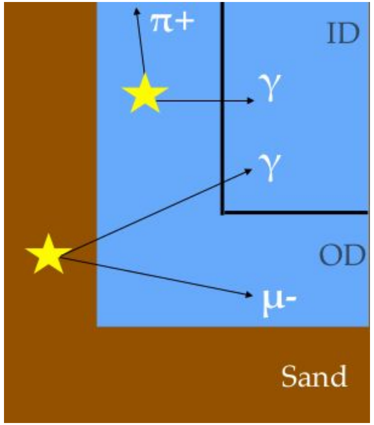
◆ Can identify ~1% of ve/v̄e components in the beam

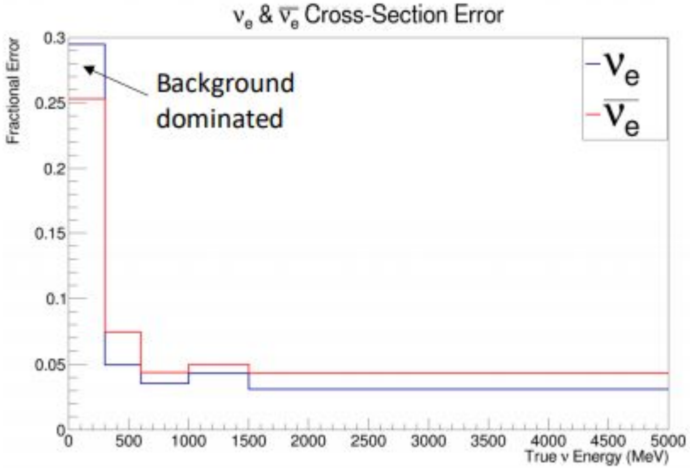
◆ Use the water volume of outer detector as an active shield against entering γ background

◆ Measure the double-ratio for the CP violation search

$$\frac{\sigma(\nu_e)/\sigma(\nu_\mu)}{\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)}$$







Neutrons associated with neutrino interactions

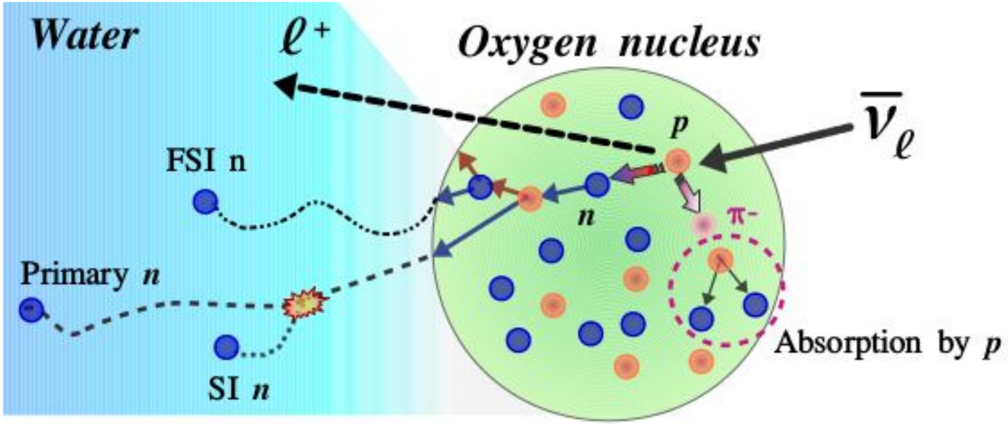
◆ One neutrino interaction in water tends to produce multiple neutrons

◆ Information about those neutrons can benefit the Hyper-K's physics analyses

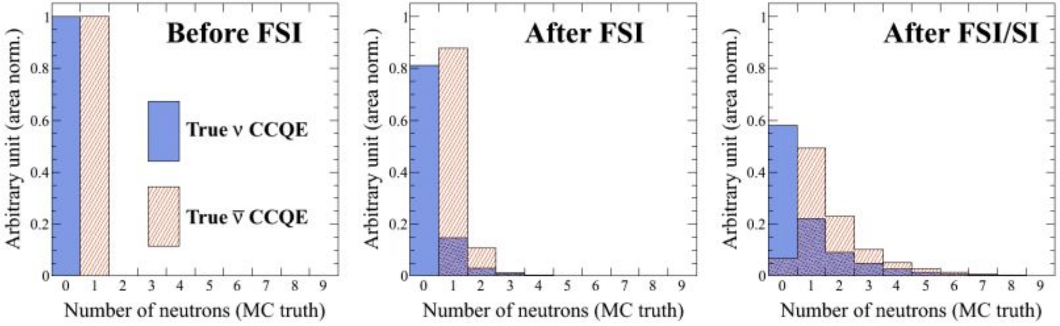
- Large uncertainty due to complicated production processes

◆ Need direct measurement

⇒ **Gd loading option**



FSI: hadronic interactions inside oxygen nucleus



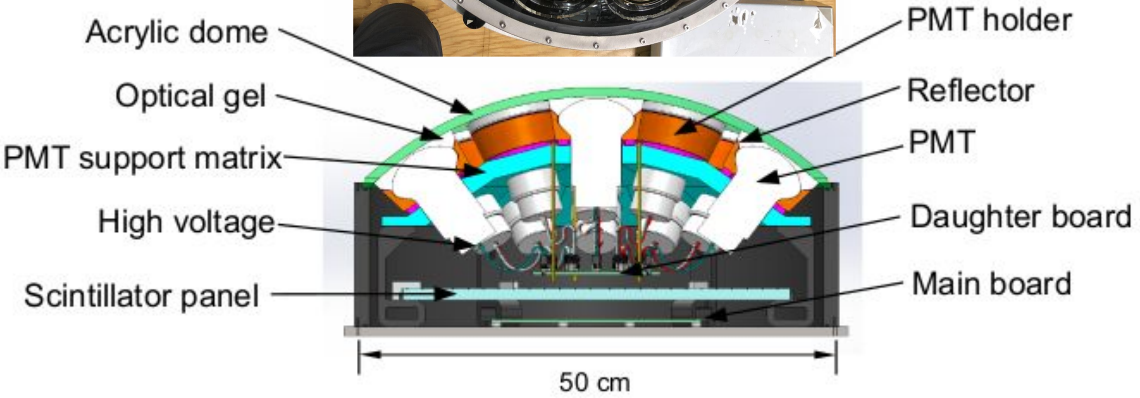
SI: hadronic interactions with detector medium

Multi-PMT module (mPMT)

- ◆ Much smaller size of the IWCD detector compared to the Hyper-K detector

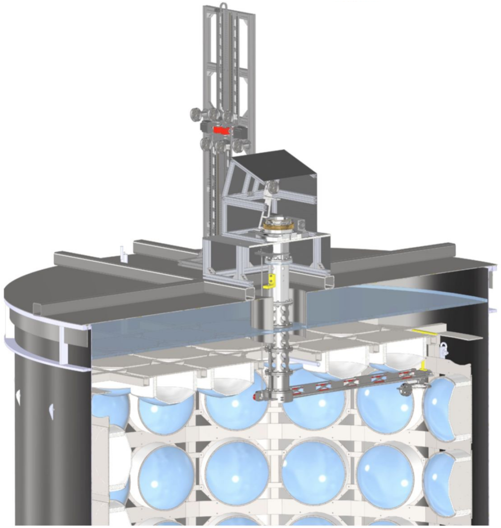
- ◆ Need higher granularity and better timing resolution for good enough spatial resolution
  - 1.6 ns timing resolution (FHWM)

- ◆ 19x 3” diameter PMTs integrated into a water-tight module
  - High voltage and readout electronics
  - Good optical contact between acrylic dome and PMTs thanks to optical gel



Detector calibration

◆ The IWCD detector needs to be calibrated precisely at each vertical position

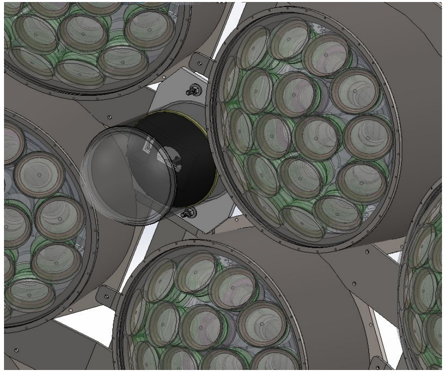


◆ Calibration of position dependence on detector response

- Need to deploy various calibration sources (laser & radioactive sources) across the detector volume
- Arm system for source deployment

◆ PMT position calibration

- Potential deviation from ideal PMT position due to buoyancy and moving detector
- Photogrammetry to reconstruct 3D positions from 2D images



Machine Learning

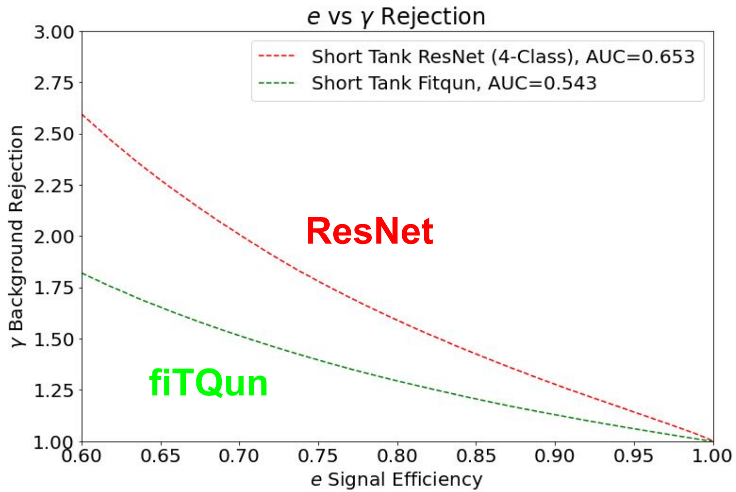
WatChMaL.org

- fiTQun as the current reconstruction
  - Maximum likelihood based algorithm

WatChMaL: an international working group to develop machine learning for water Cherenkov detectors

- Machine learning being developed for IWCD
  - Improved **particle identification** and **kinematic resolution**
  - Application to the IWCD physics samples is ongoing

- Significant benefit in **speed**
  - ResNet (GPU): 100,000 events per minute
  - fiTQun (CPU): ~1 event per minute



Event pile-up

◆ Due to the high intensity of the beam flux, there will be ~7 - 35% of ID interactions will happen with another ID interaction

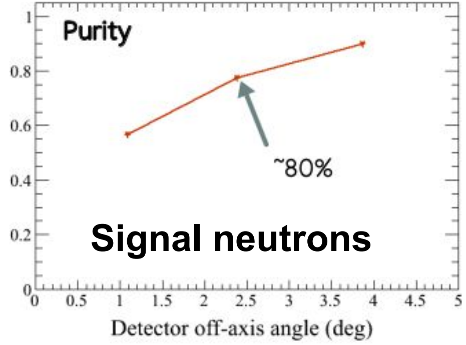
- ID interaction: ν interaction taking place inside the detector

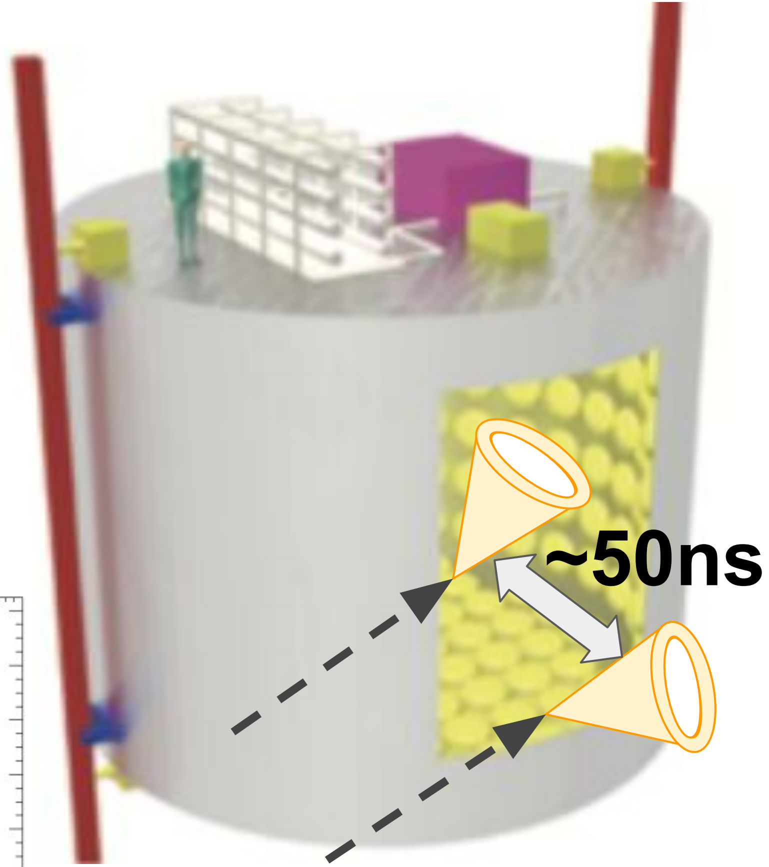
◆ Need to identify pile-up events

- Both classical and machine learning approaches are under development

◆ Beam correlated backgrounds could be an issue for neutron measurement

- Confirmed feasibility with the effect of event pile-up





Summary

◆ The Intermediate Water Cherenkov Detector will play the important role to control systematics uncertainties for the Hyper-Kamiokande project

- Vertically movable detector → Interaction rates
- Gd loading option → Neutron multiplicities

◆ New technologies are being developed to enable IWCD to perform precise measurements

- Hardware → Multi-PMT photo sensor module, photogrammetry, arm-system
- Software → Machine learning

◆ The IWCD group is working toward the compilation of the design