REDUCING SYSTEMATICS AT HYPER-KAMIOKANDE: CALIBRATION AND DETECTOR STUDIES

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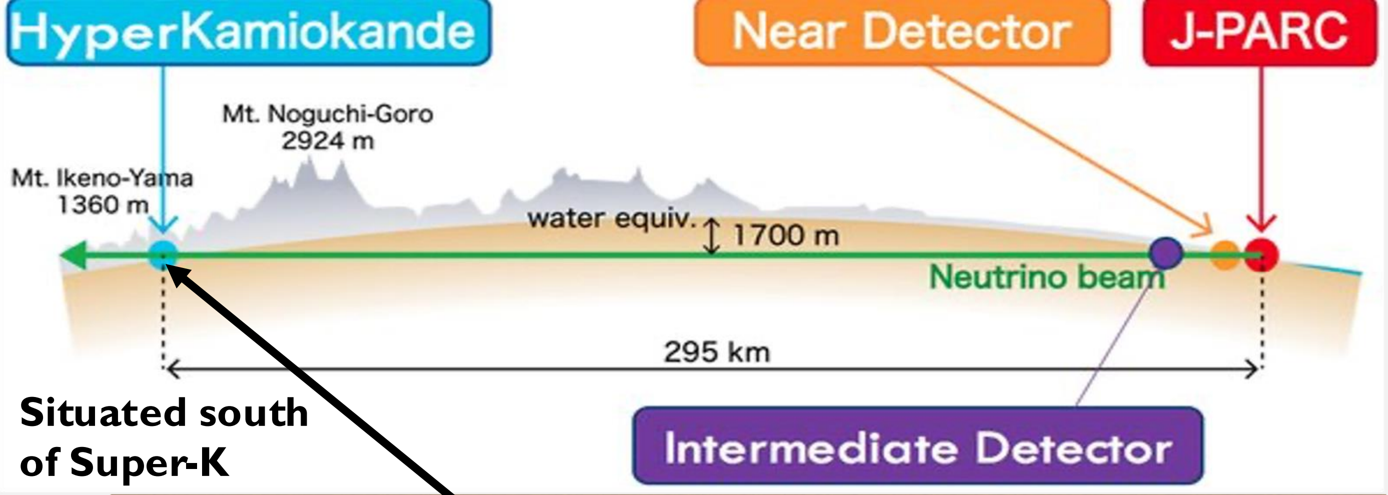
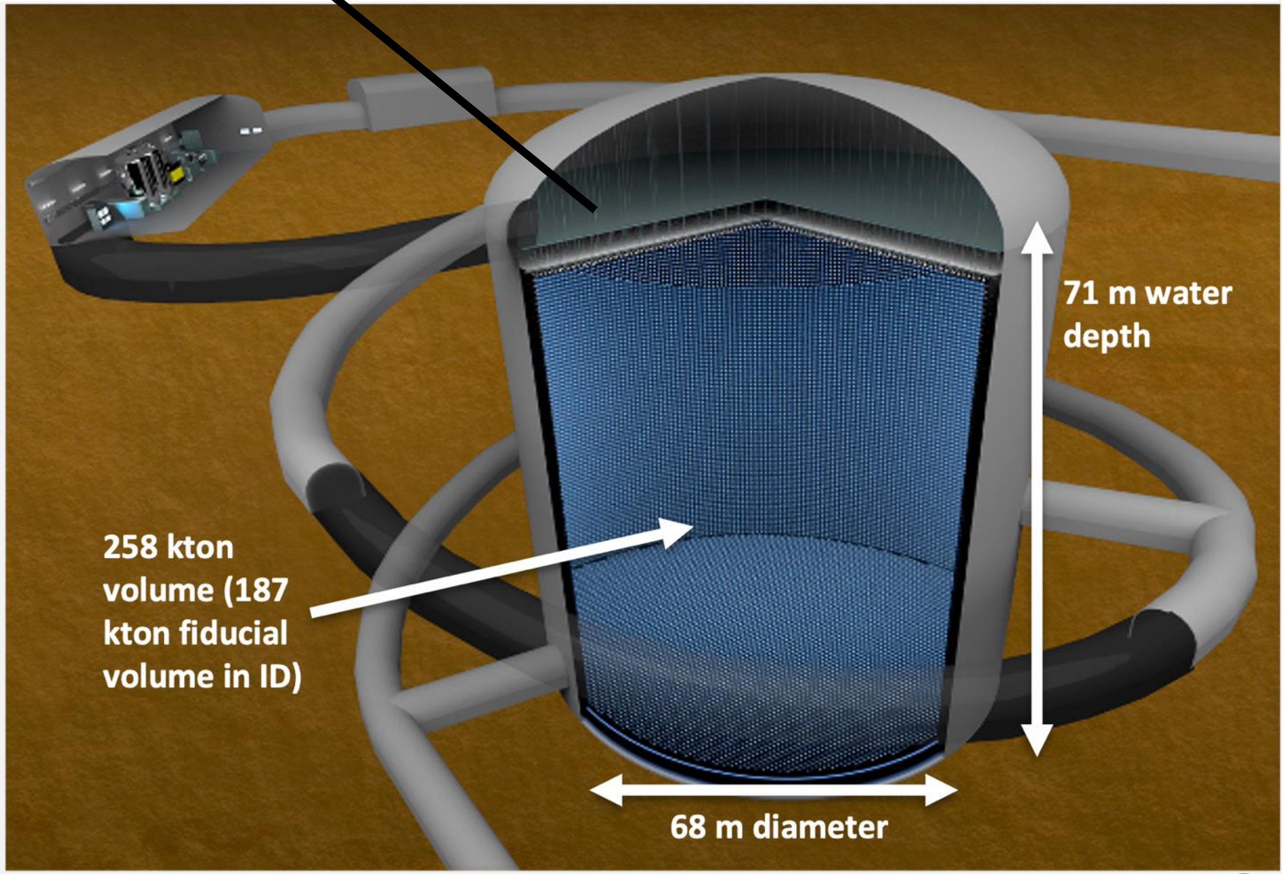
HYPER-KAMIOKANDE

- Hyper-K is the next generation water Cherenkov neutrino detector
- Located in Japan, part of the long-baseline experiment with the same off-axis angle as T2K
- Much larger and more sensitive than Super-K:
    - **8.4x** the fiducial volume
    - J-PARC beam upgraded to **1.3 MW** for the Hyper-K era

<u>Physics goals:</u>

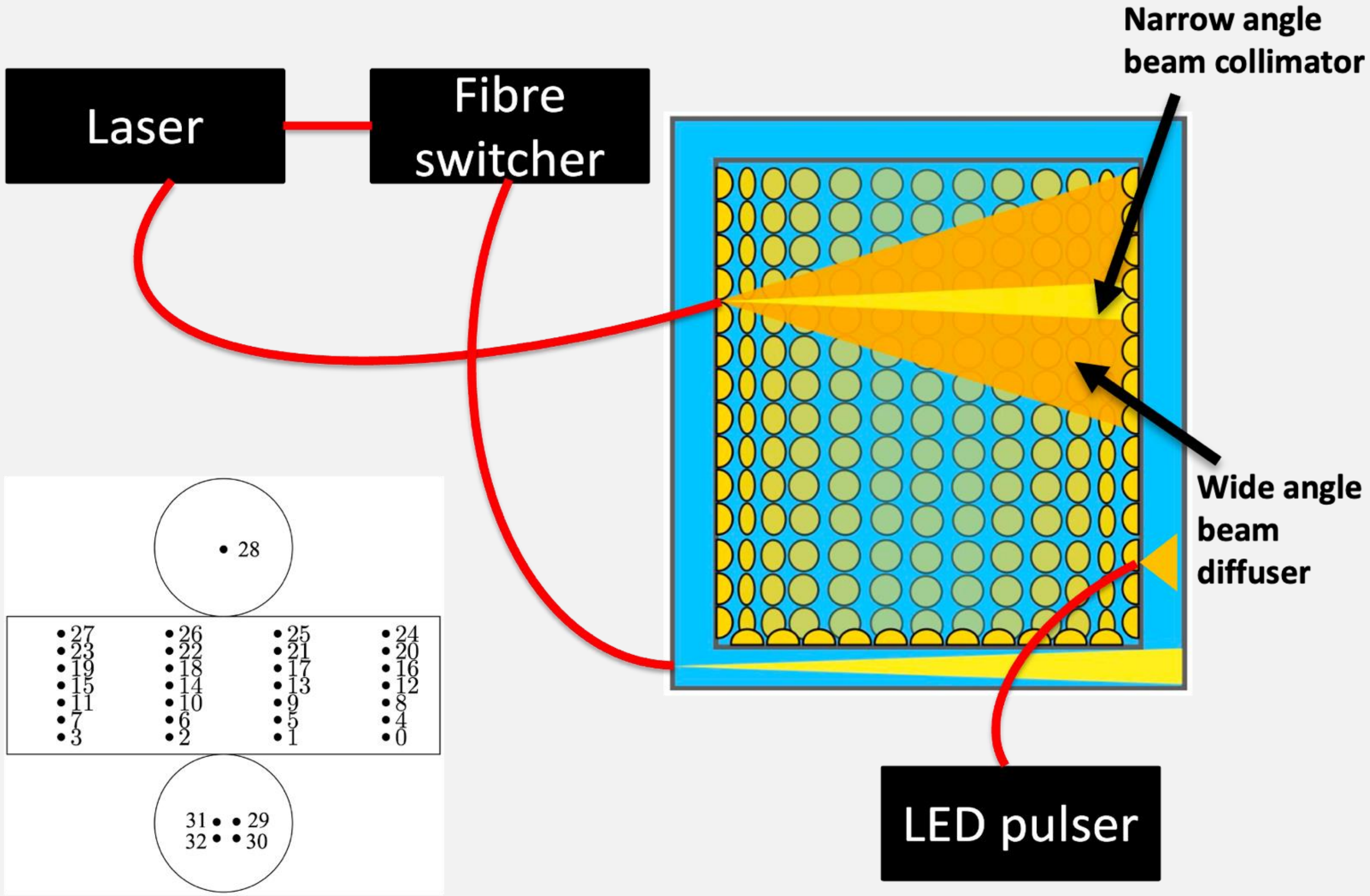
- Precise **neutrino oscillation** measurements
- Search for **CP violation** in **leptonic sector**
- **Proton decay** searches
- Observation of **supernova neutrinos** and the Diffuse Supernova Neutrino Background (**DSNB**)





THE ROLE OF CALIBRATION IN HYPER-KAMIOKANDE

- To **maximise physics sensitivity**, we need:
  - **Precise calibration** of detector systems
  - Accurate **event reconstruction**
- A **systematic understanding** at the **percent level** is crucial:
  - Detector response (PMTs, timing, gain)
  - Water quality
- At Liverpool, we focus on the **Hyper-K light injection (LI) system** for calibration (see Ellen’s talk in the afternoon for more details)



Overview of the Hyper-K LI system (right) and injector location map for inner detector position (left).

BOTTOM-UP CALIBRATION APPROACH

Aim:

Quantify uncertainties on reconstructed quantities, like **energy scale** and **particle identification (PID)** → using calibration-informed uncertainties in the **detector model**

Method:

- Start from known uncertainties in physical detector parameters (e.g. optical properties)
- Propagate these to see their effect on high-level outputs, i.e., energy, PID, etc
- Helps ensure systematics are physically motivated and data-driven

Examples of model parameters:

- **Light absorption** in water (wavelength-dependent)
- **Light scattering** (both **Rayleigh** and **Mie**)
- **Reflections** from PMTs, black sheet, and other internal surfaces

SIMULATION & RECONSTRUCTION TOOLS

Simulation – WCSim:

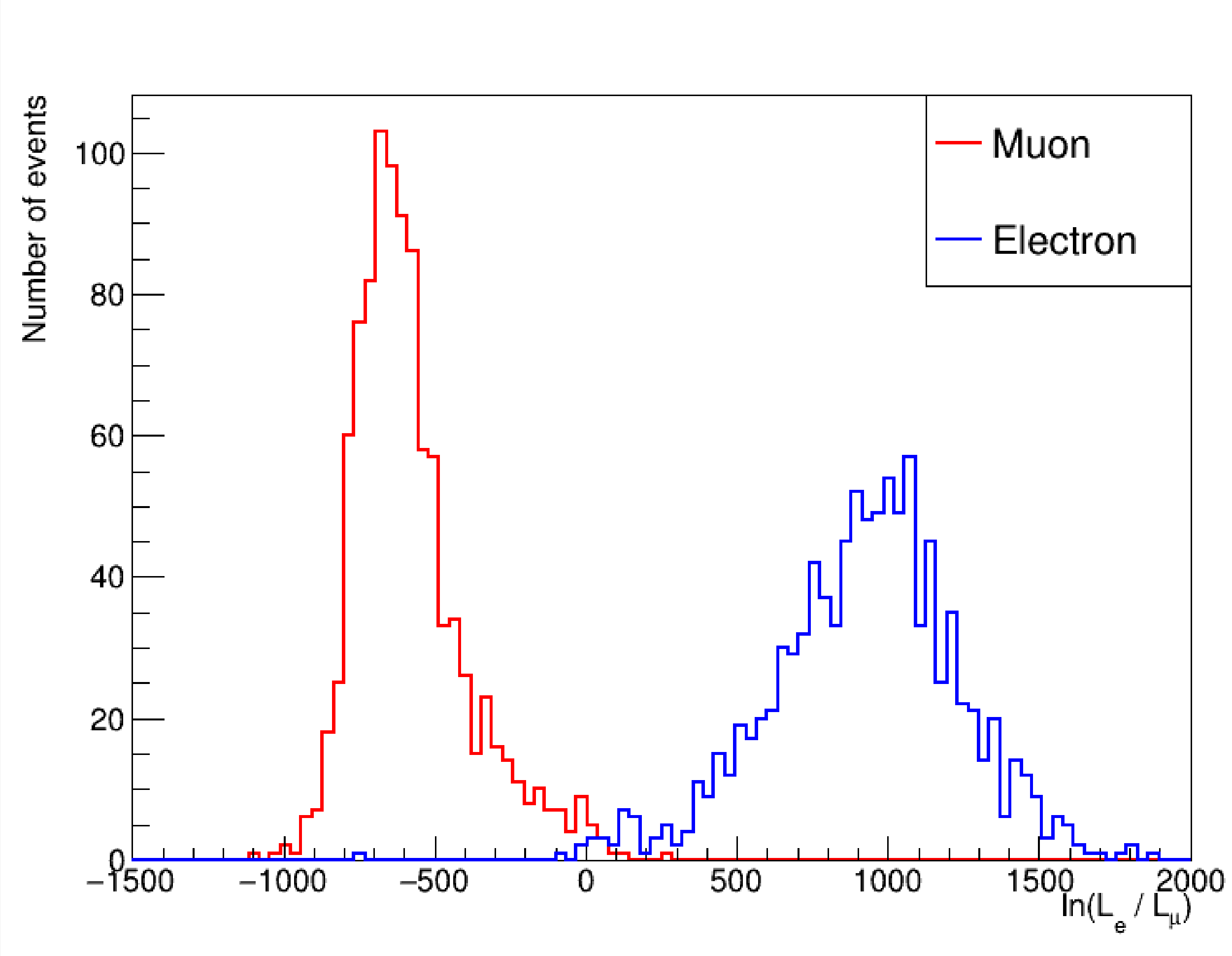
- GEANT4-based simulation for water Cherenkov detectors
- Simulated particle (i.e. electrons and muons) uniformly + isotropically in the detector

Reconstruction – fiTQun:

- A **maximum likelihood** reconstruction algorithm
- Uses **PMT hit time** and **charge information** to estimate particle properties

$$L(\mathbf{x}) = \prod_{j}^{\text{unhit}} P_j(\text{unhit}|\mu_j) \prod_{i}^{\text{hit}} \{1 - P_i(\text{unhit}|\mu_j)\} f_q(q_i|\mu_i) f_t(t_i|\mathbf{x})$$

- Likelihood function includes:
  - Probability of PMT being hit or unhit
  - Expected **charge** and **time** distributions for each hit
- Enables strong electron/muon separation

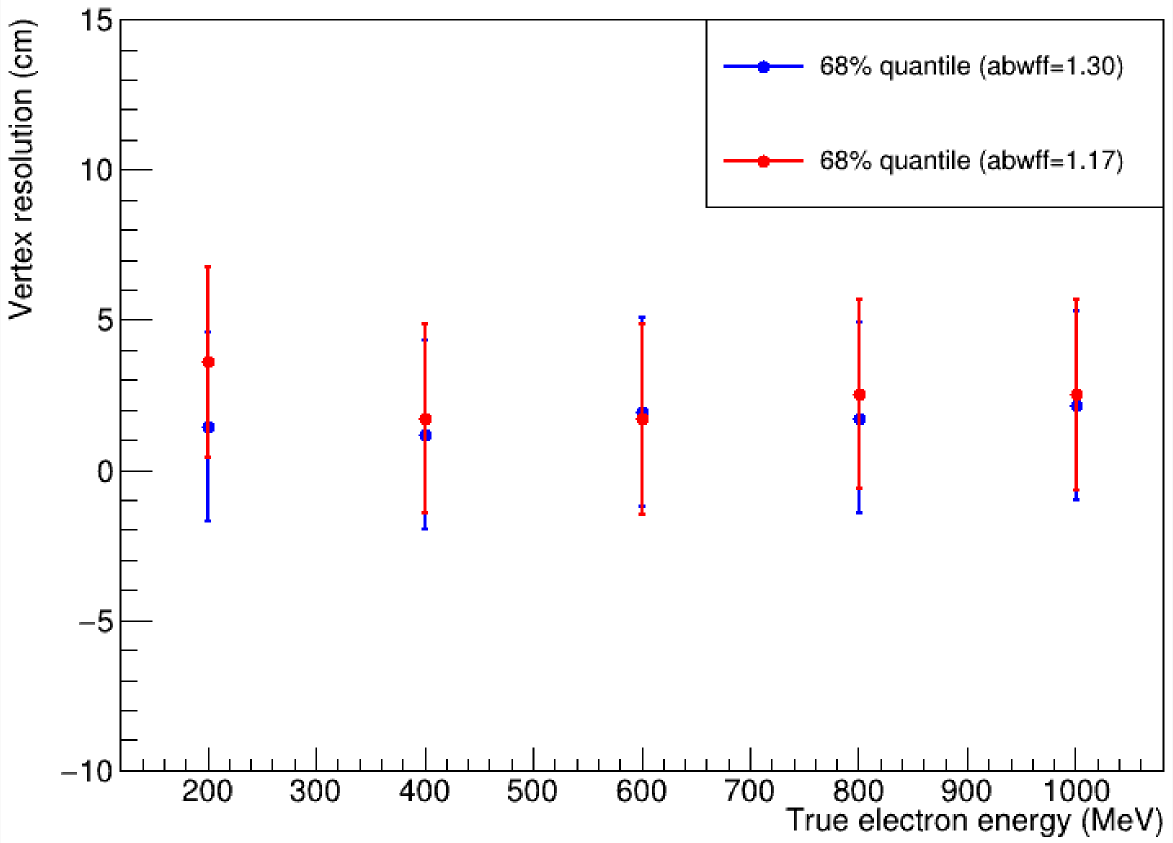


Example of electron-muon PID separation for 600 MeV.

IMPACT OF ABSORPTION ON RECONSTRUCTION PERFORMANCE

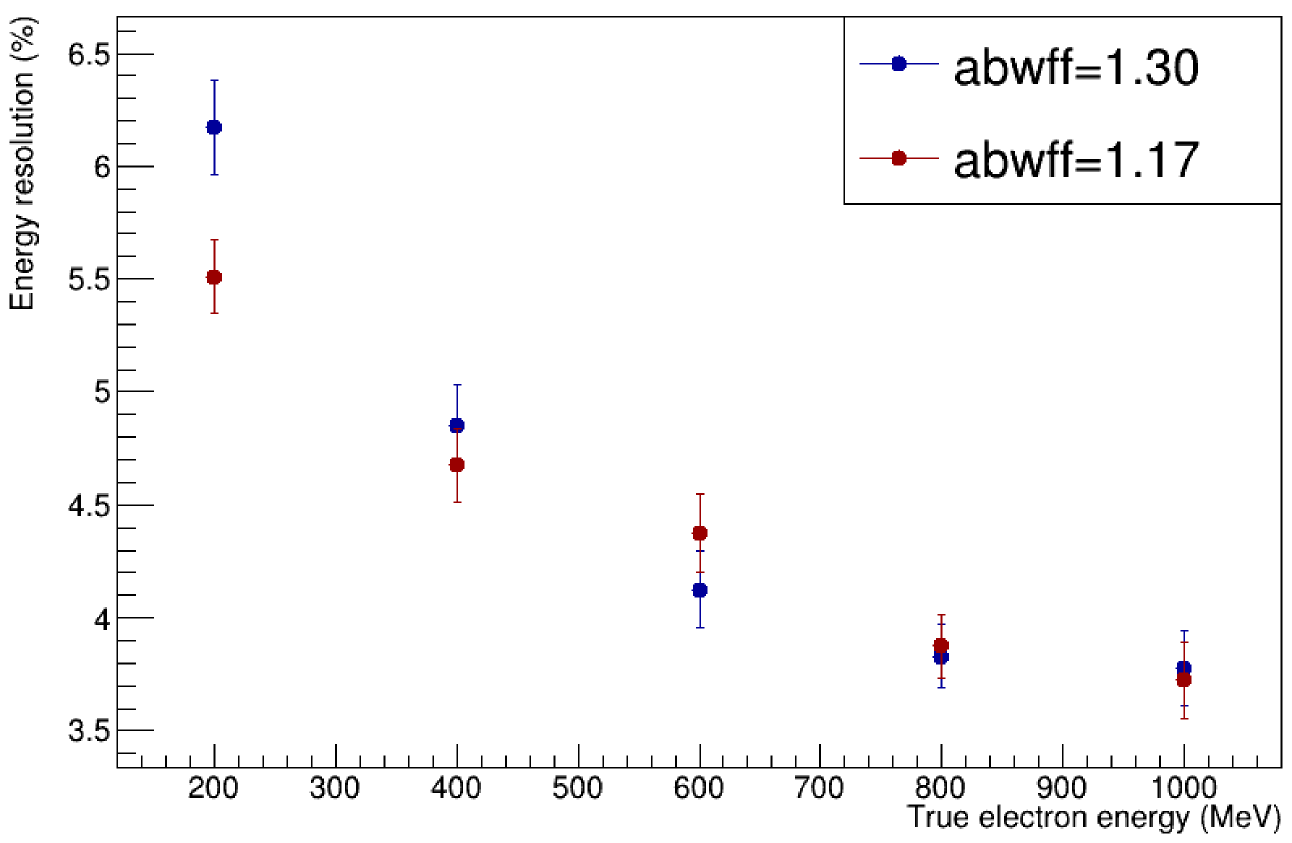
<u>Vertex Resolution:</u>

- Little difference between absorption coefficient, abwff = 1.30 and abwff = 1.17
- Vertex reconstruction appears relatively stable against absorption changes



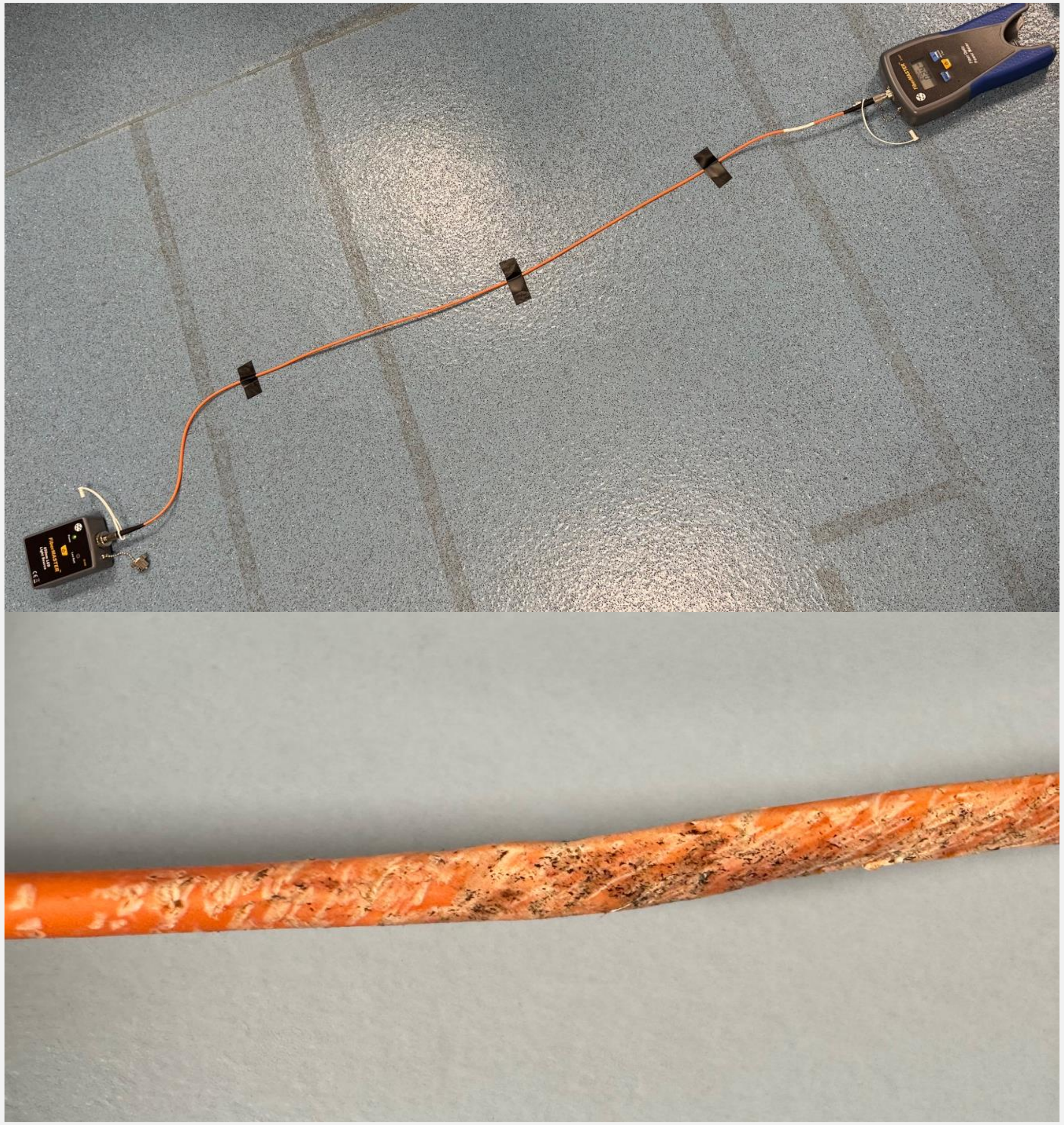
<u>Energy Resolution:</u>

- Noticeable differences between abwff = 1.30 and abwff = 1.17, particularly at lower energies
- Differences reduces at higher energies



HARDWARE WORK

- Tested candidate fibres (i.e. FP400URT and FG105UCA) in the lab for Hyper-K LI system
- Conducted a destructive test project to measure fibre breakage limits and handling tolerances, i.e. how the power output and pulse width measurements are affected
- Preparing for fibre installation and testing work in Japan during my upcoming Long-Term Attachment (LTA)



Setup for trolley test with the light source and power meter (top) and picture of FG105UCA after flattening it with a car (bottom).

SUMMARY AND NEXT STEPS

- Investigated absorption impact on vertex and energy resolution
- Tested fibres and conducted a fibre breakage study

Next steps:

- Extend analyses studies to include scattering, reflections, and optical effects (with more number of events)
- Prepare for LTA in Japan (from September, 1 year):
  - PMT pre-calibration and reception testing
  - Taking over Super-K LI system work (Adam’s PhD)
- Continue contributing to hardware and calibration development

THANK YOU FOR LISTENING!

ANY QUESTION?

BACKUP

PHYSICS IN HYPER-KAMIOKANDE

Hyper-K is a **multi-purpose detector** with the capabilities:

- Real time measurement of vertex, direction, energy and particles types
- Large fiducial mass with low radioactive background
- Wide dynamic range to observe neutrinos from MeV to TeV energy scale, i.e., from solar, supernova, accelerator, proton decay and even dark matter search

WHY BOTTOM-UP APPROACH?

Top-Down Approach (used in Super-K/T2K):

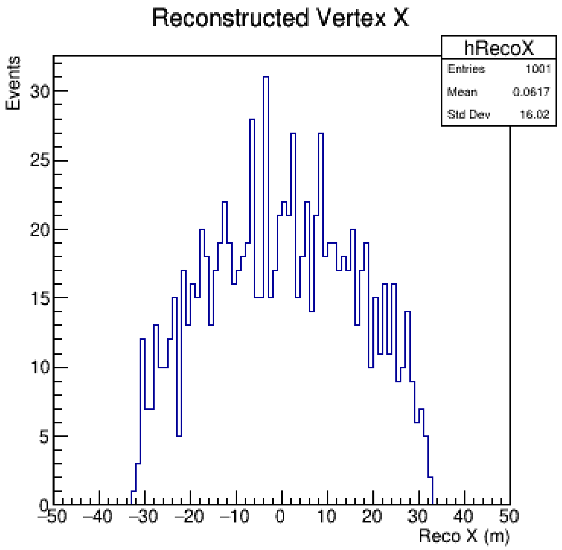
- Uses control samples (e.g. Michel electrons, π^0 mass peak, stopping muons) with known energy depositions
- Effective, but limited when **control samples don't fully cover the analysis range**
- **Assumes biases between data and MC** are covered by assigned uncertainties — without identifying underlying causes

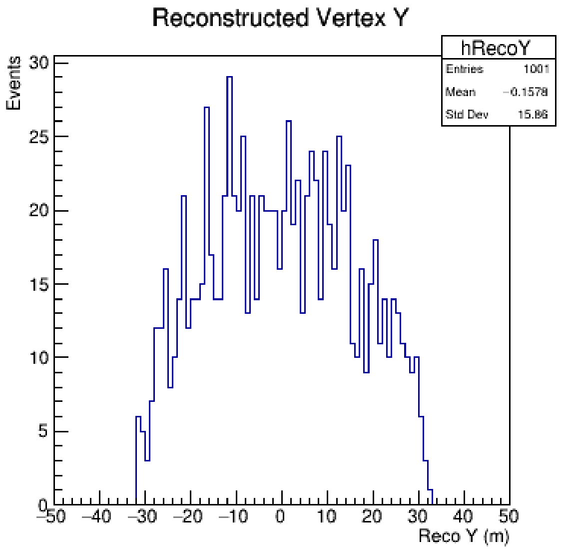
Limitations for Hyper-K:

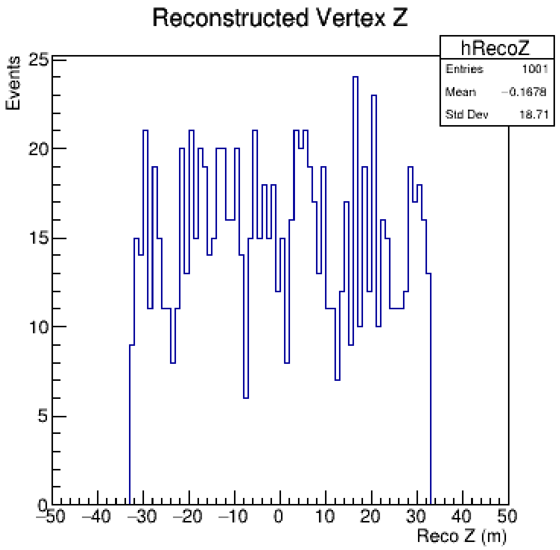
- **Longer photon path lengths increase sensitivity** to water absorption, scattering, and inhomogeneities
- Control samples may be **insufficient** for all analysis ranges
- Greater detector complexity demands more precise modelling of underlying effects

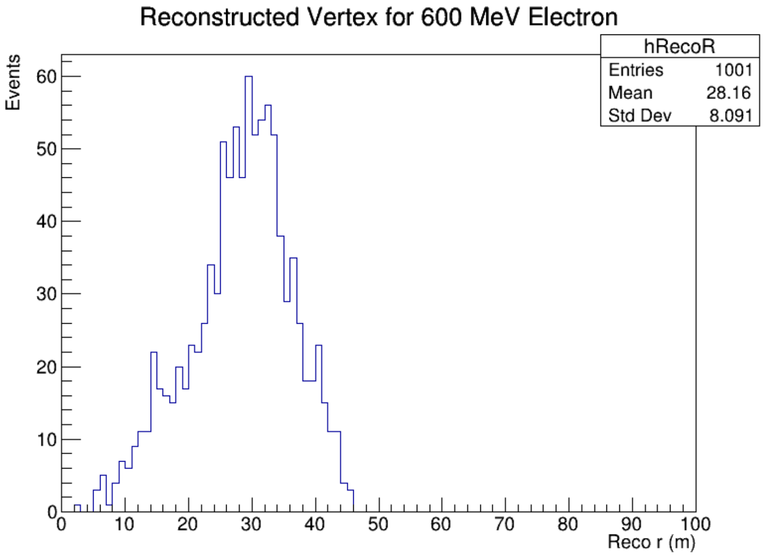
VERTEX RECONSTRUCTION PLOTS

These graphs confirms the geometry that I have used which is the Hyper-K detector’s dimensions.



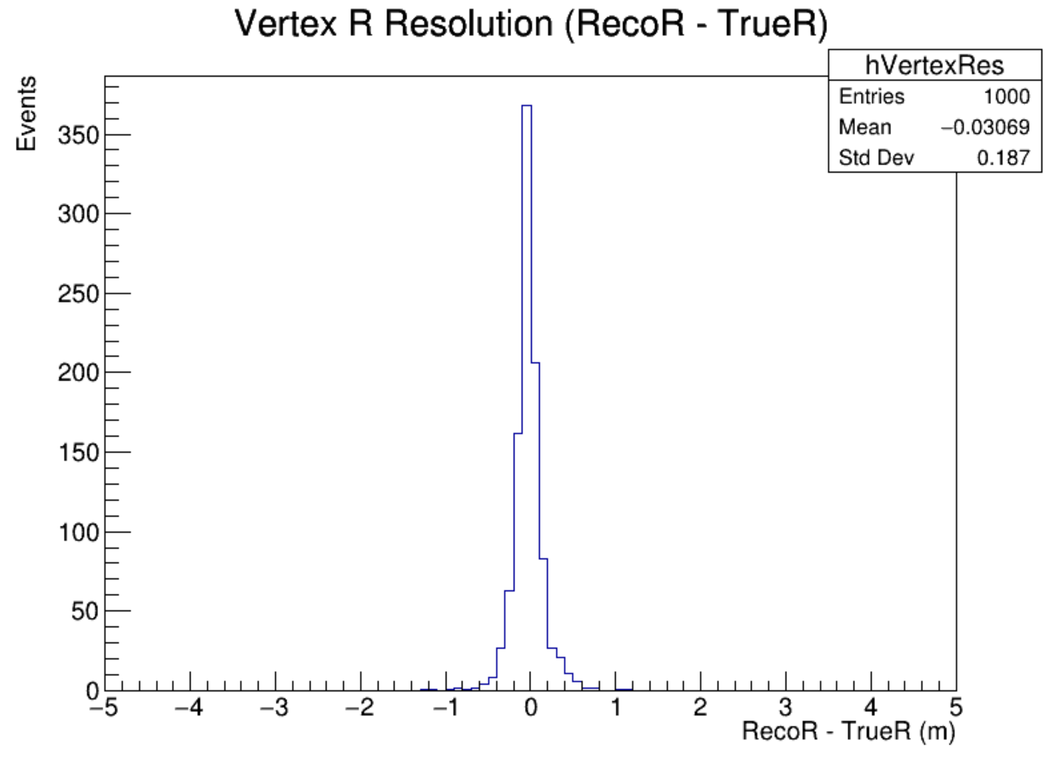






VERTEX RESOLUTION

- Measures accuracy of the **reconstructed interaction point**
- Used **68% quantile** (distance within which 68% of events fall)
- Important for:
  - Event selection within fiducial volume
  - Background rejection (e.g. wall events)
  - Reconstructing event topology in neutrino interactions



ENERGY RESOLUTION

- Measures precision of the **reconstructed energy** relative to true energy
- Defined as:

$$\text{Energy resolution} = \frac{\sigma}{\mathrm{E_{true}}}$$

Where,

- ➢ σ = standard deviation of reconstructed energy distribution
- ➢ $\mathrm{E_{true}}$= true particle energy

- Then the error in resolution:

$$\delta R = \frac{\delta\sigma}{\mathrm{E_{true}}}$$

Where,

- ➢ $\delta\sigma$ = is the uncertainty from the fit for σ

- Important for:
  - ➢ Neutrino oscillation analysis
  - ➢ Separating signal from background
  - ➢ Maximising experiment's physics sensitivity