Calibration of the Hyper-Kamiokande Detector

Menai Lamers James

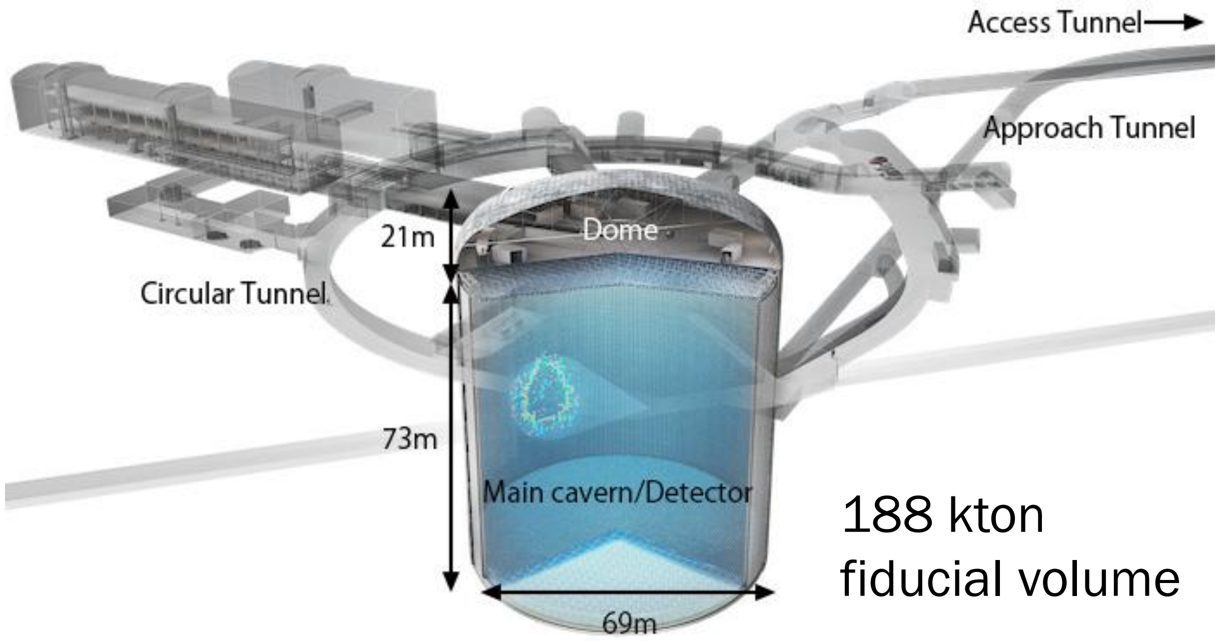
Erice: International School of Nuclear Physics, 47th Course

16 - 22/09/2026

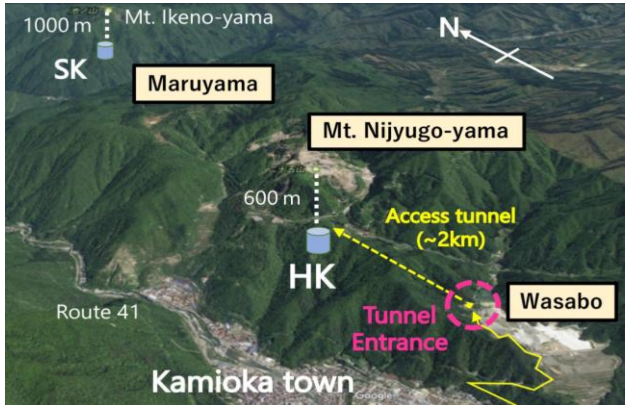
UNIVERSITY OF WARWICK

Hyper-K

The Hyper-Kamiokande Detector



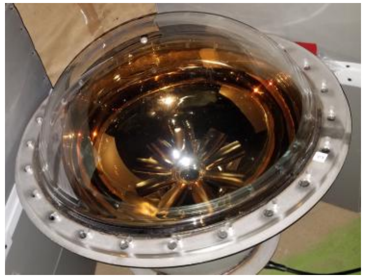
188 kton
fiducial volume

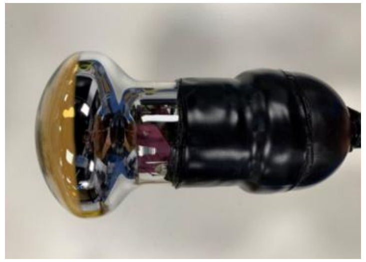


- Large water Cherenkov detector.
  - Similar conceptually to Super-Kamiokande (Super-K) -> tried and tested methods.
- Fiducial volume ~8x Super-K.
  - Larger size = more statistics.
- ~20,000 50 cm PMTs.
- ~800 multi PMTs.

$\Big\}$ Located throughout the Inner Detector.

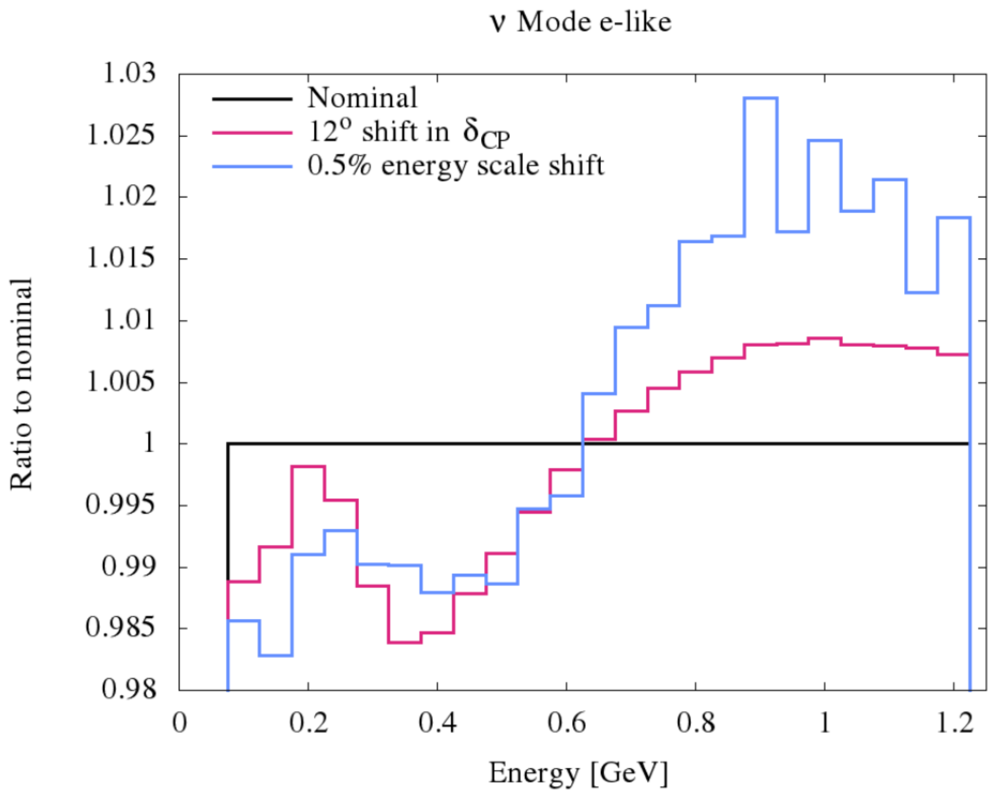
- ~3600 3" PMTs in the Outer Detector.
- Pure water target, cheap relative to other materials.





Calibration Goals

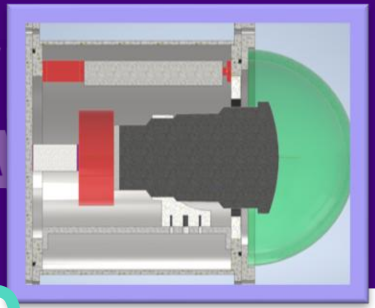
- High precision experiment only possible if we understand our detector response
  -> well calibrated detector vital.
- Goal: 0.5% level precision for systematics constrained by calibration system. Risk mistaking oscillation effects for systematics if poorly constrained.
- Targeted systematics include:
  - Energy scale and resolution.
  - Vertex reconstruction.
  - Angular resolution.
  - Cherenkov ring PID efficiency.
  - Cherenkov ring counting efficiency.



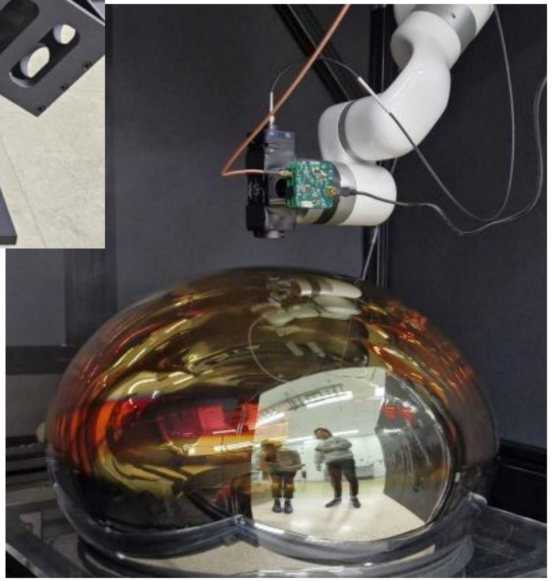
PoS (NuFact2021) 056

Calibration System

- Variety of sources tackling different systematics.
- PMT Pre-calibration
- Light injection
- Radioactive sources
- LINAC
- Photogrammetry

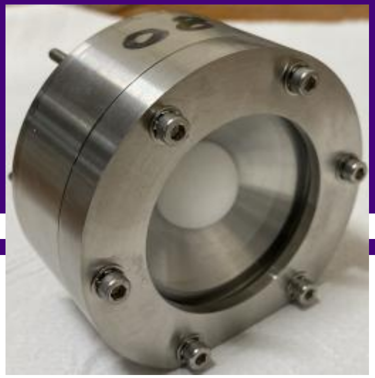


Pre-calibration

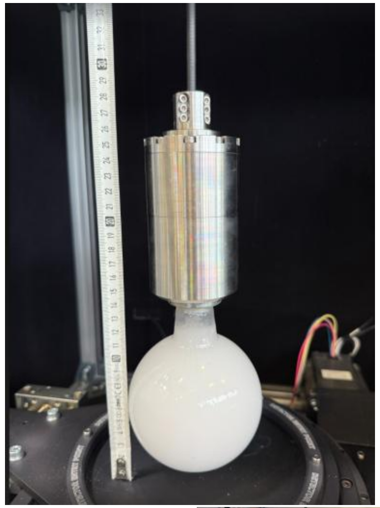


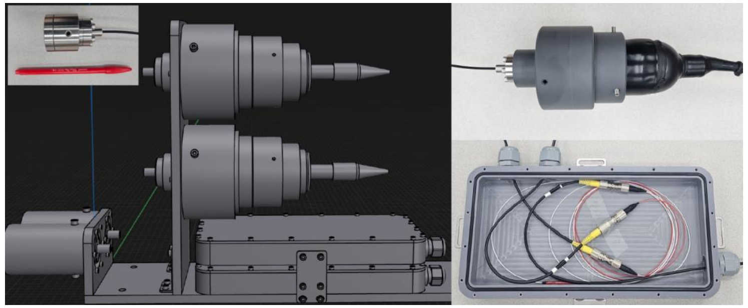
- Pre-calibrate ~2% (~400) of the PMTs and distribute evenly across detector.
- Use well-understood pre-calibrated PMTs in analysis to disentangle degeneracies causing increased systematic uncertainty.
- Two PMT testing systems, one robotic arm, the other PMT rotation.
- Complementary, and cross-checks performed between systems.
- Precision goal of ~1% relative QE, angular response measurement and < 1 ns timing.

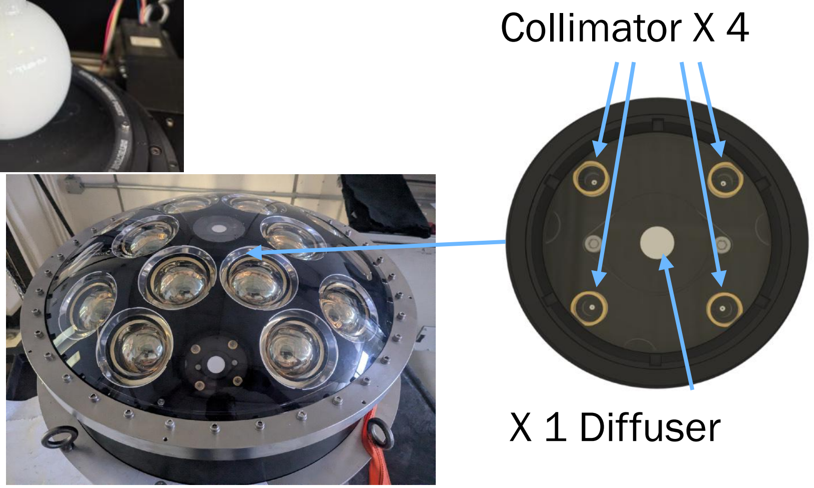
Light Injection



- Multiple light injection sources, each with different strengths.
- Narrow beam sources will generally target water parameter estimation: absorption and scattering.
- Wider beam angle sources also targets water parameter measurement, alongside angular response, timing and gain measurements.
- Analysis combining narrow and wide beam can break degeneracies.

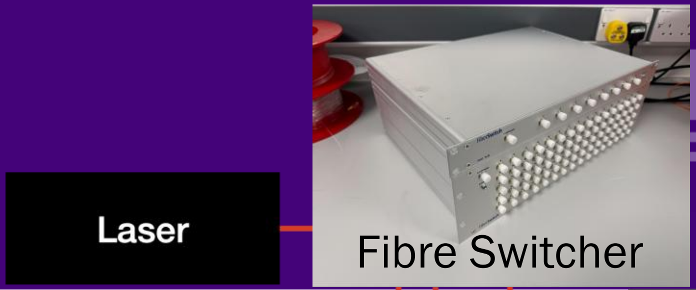


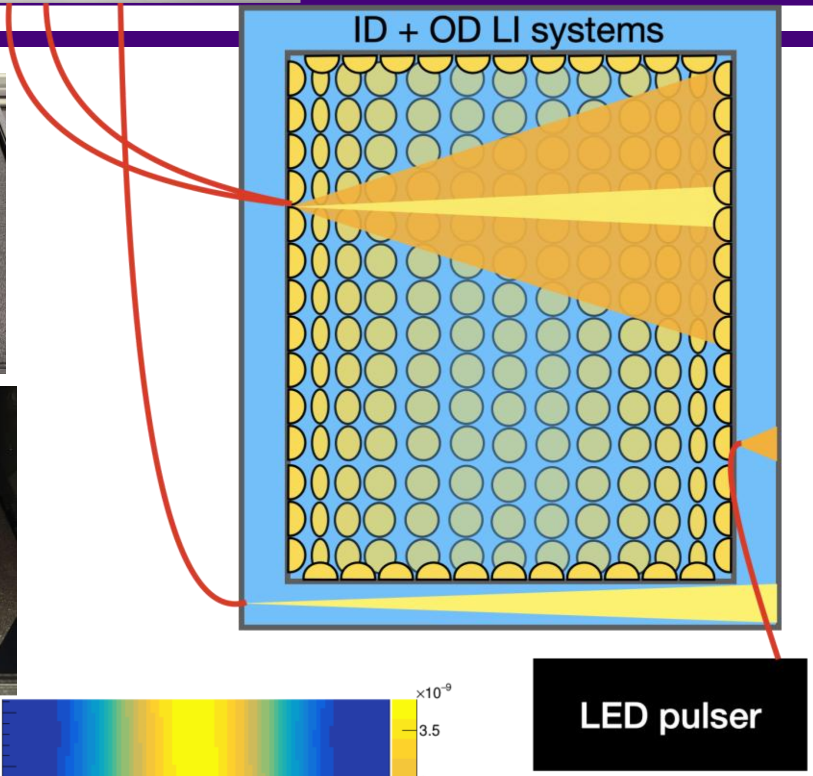




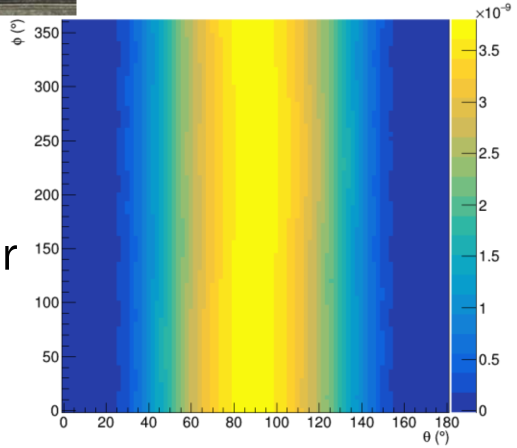
Light Injection

- 33 inner detector injector positions each with collimator and diffuser.
- Laser source across six wavelengths (337 – 500 nm).
- Collimators have an opening half-angle of 3˚ in water, diffusers are 40˚.
- All injectors scanned in water prior to deployment.
- All injectors passed QA and ready in Japan.



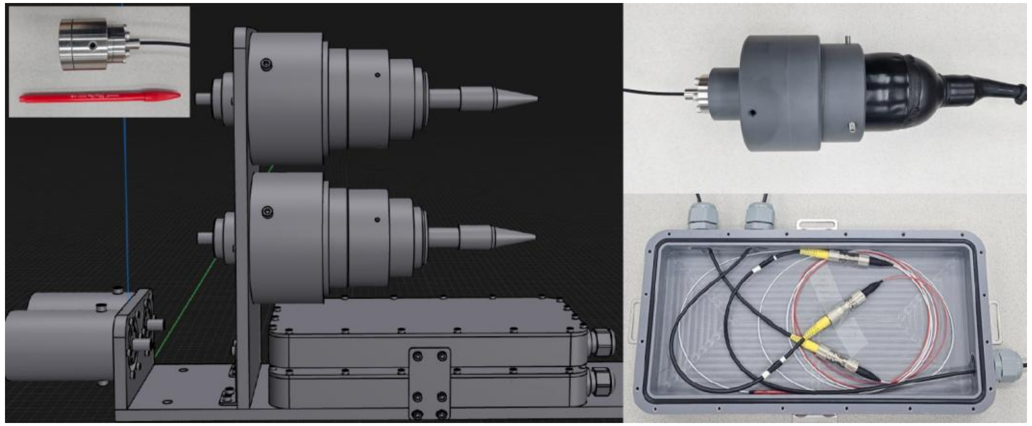


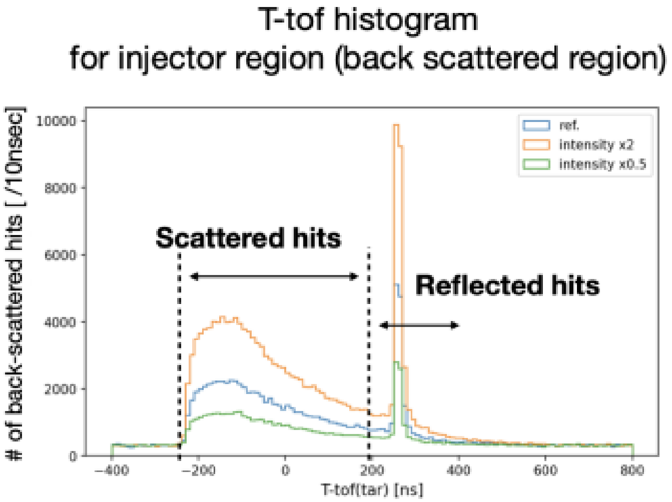
Diffuser water scan

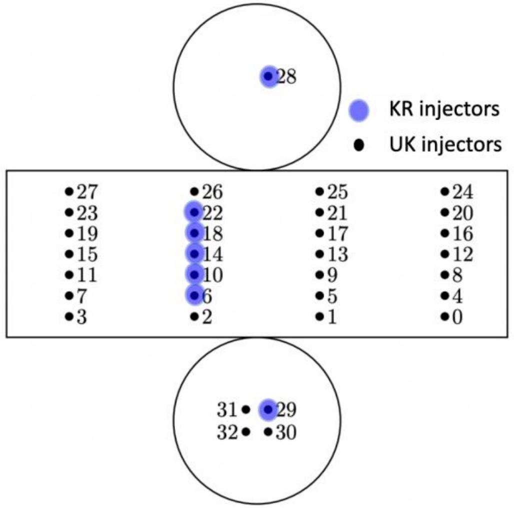


Light Injection – Korean System

- Seven injector sites, adjacent to other light injection system.
- Two injectors and two monitor PMTs at each site. Identical to SK system.
- Independent laser system at five wavelengths (337- 473 nm).
- Bare fibre with opening half-angle of 5˚. Larger than UK system.
- Monitor PMT at the end of the fibre relative to UK system.

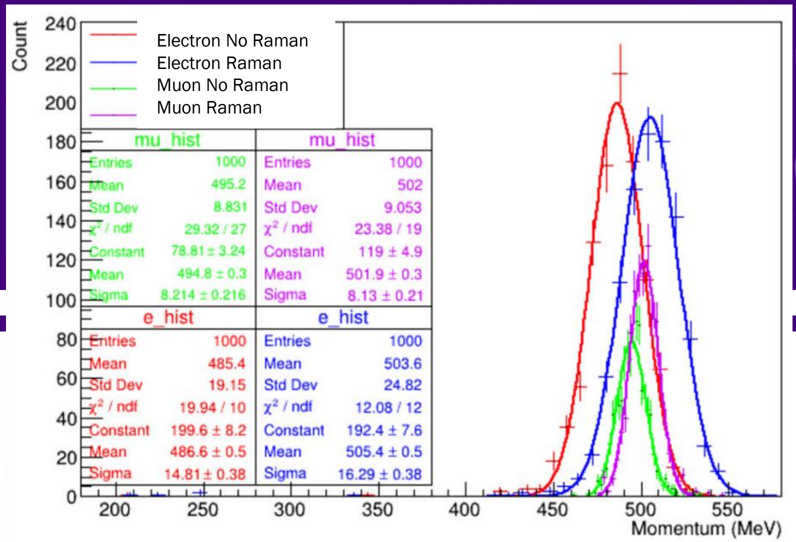






mPMT LEDs

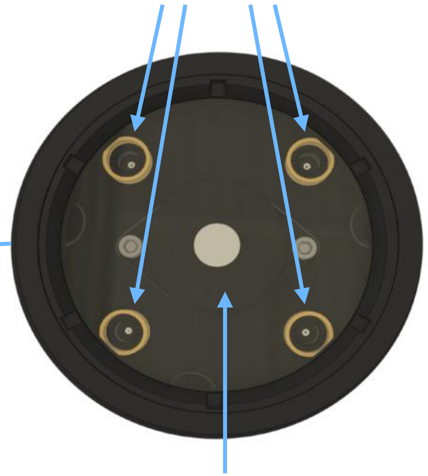
- For 200 of the mPMTs, will replace 5 of the 19 PMTs with LED units.
- Provide fast pulses at multiple wavelengths, including 290 nm for measuring Raman scattering.
- Both wide and narrow angle beams provided.
- Benefit that multiple light sources hit the same PMT for cross-check.



LED-mPMT

LED-FEB module

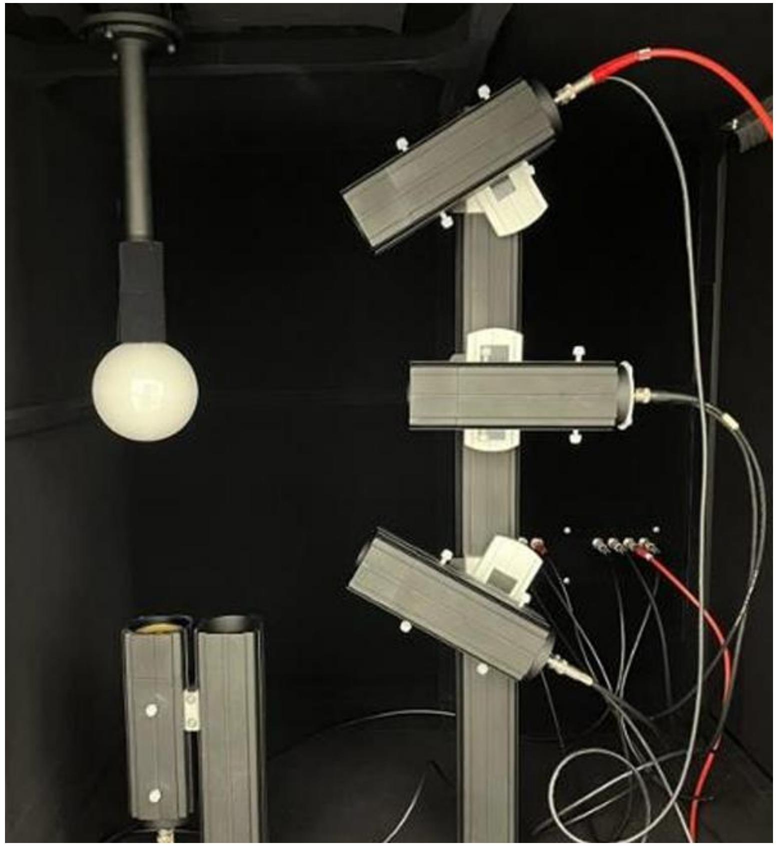
Collimator X 4



1 diffuser

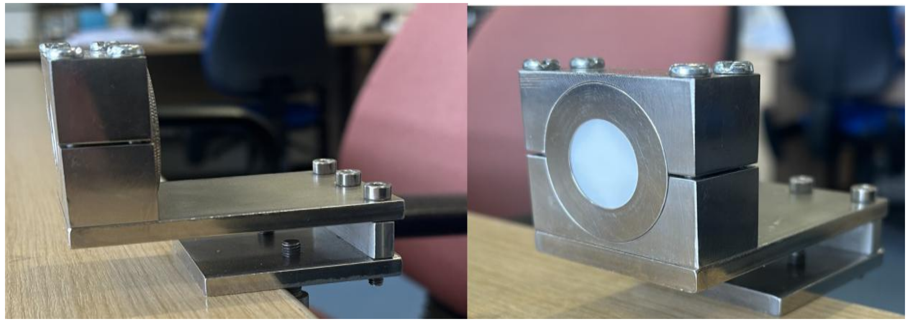
over 3 LEDs

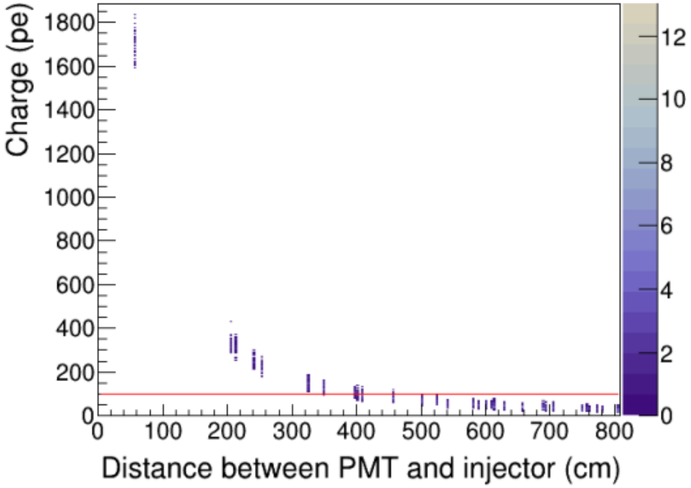
Diffuser Ball



- Deployable diffuser laser ball, may enter the tank via multiple calibration ports, with variation of depth.
- Delivers a well-understood light source with same laser system as light injection system.
- Prototype of the diffuser ball was used in the Water Cherenkov Test Experiment (WCTE) at CERN.
- Useful to have single known light source illuminating PMTs across the detector.

Calibration of the Outer Detector



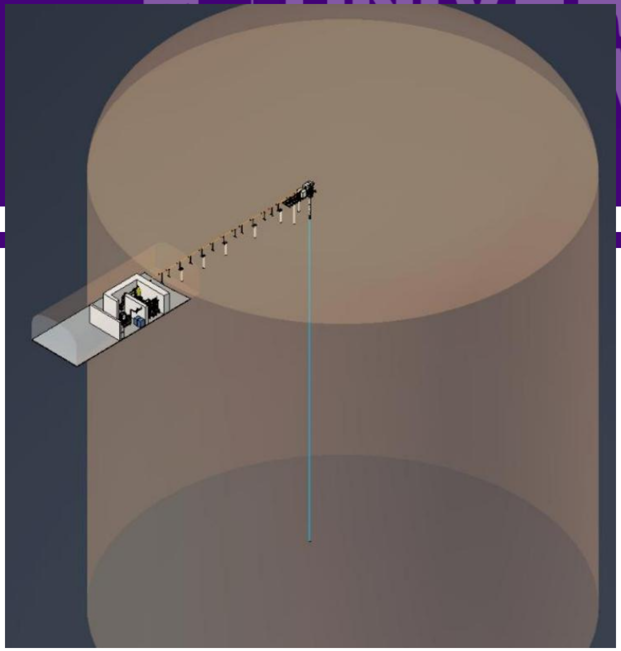


Plot of the saturation distance limit for an OD diffuser, in this case 5 m. Red line shows saturation limit of 100 pe

- Outer detector instrumented with 122 diffusers and 12 collimators, the same as used in the inner detector.
- OD diffusers will have broader opening angle of ~45˚, and higher light yield, to ensure all OD PMTs are illuminated.
- Custom LED pulser system developed for OD diffusers at 365 nm.
- Measuring water parameters and Tyvek reflectivity properties will be needed for vetoing cosmic muons.
- Useful to calibrate the timing between the inner and outer detector.

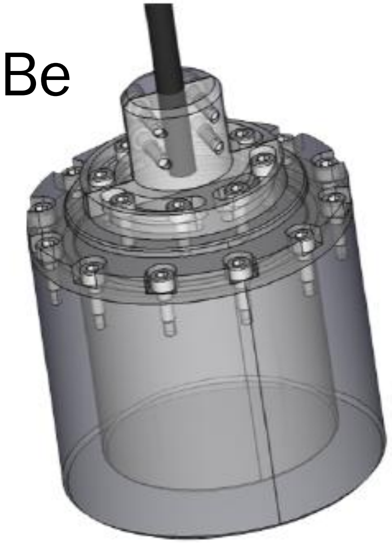
LINAC

- Single 3 - 24 MeV electrons delivered to precise locations in tank.
- 7 calibration ports, 3 depths.
- Beam intensity up to 250 Hz.
- Low energy studies, such as solar neutrino, require uncertainty in energy scale less than 0.5%.
- LINAC energies cover solar neutrino spectrum.
- Can also be used to measure angular resolution.



Radioactive Sources
NiCf, AmBe and DT generator

AmBe



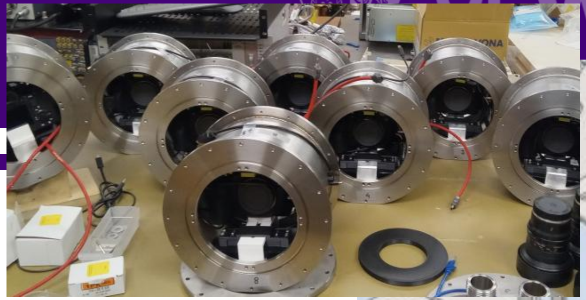
NiCf

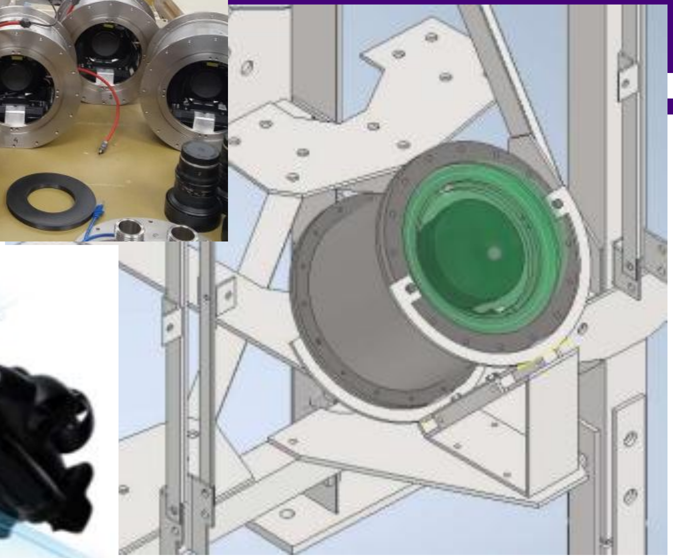
DT generator

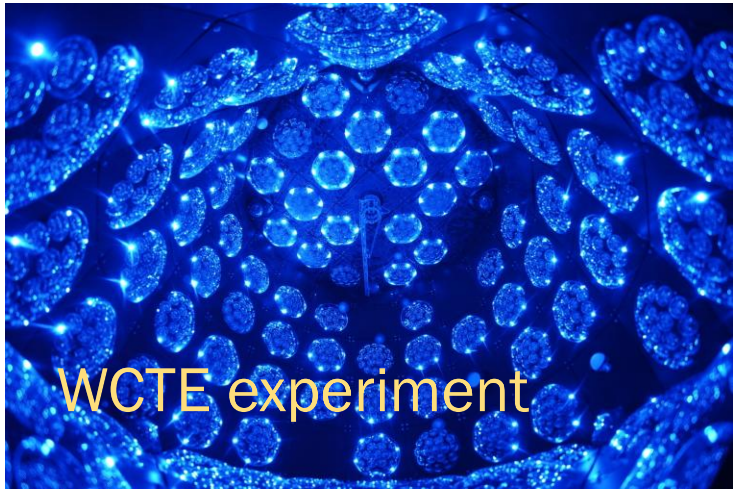
- Neutrons produced by the DT generator interact with oxygen atoms from the water to produce ^{16}N. It undergoes beta decay to produce a known electron spectrum and gammas with energy ~7 MeV.
- Decays are isotropic relative to LINAC (only faces downwards). Understand energy scale as a function of direction.
- NiCf produces isotropic Cherenkov light source. Useful light source for comparing to Chernkov rings from physics signals.
- AmBe surrounded by a BGO crystal, scintillator. Produces bright bursts of light.
- Also useful for measuring relative quantum efficiency and angular acceptance.

Photogrammetry

- Measure the detector geometry via fixed cameras and underwater drones.
- Useful to calibrate the position of the source deployment system.
- Produces cool outreach photos! (Image from use in WCTE)
- Drones allow 3D reconstruction of PMT locations. Can also be used to monitor during water filling period.



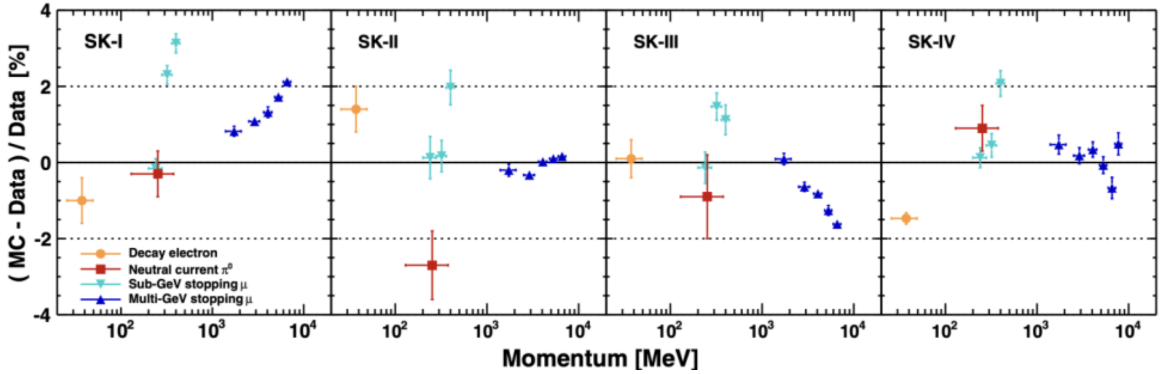




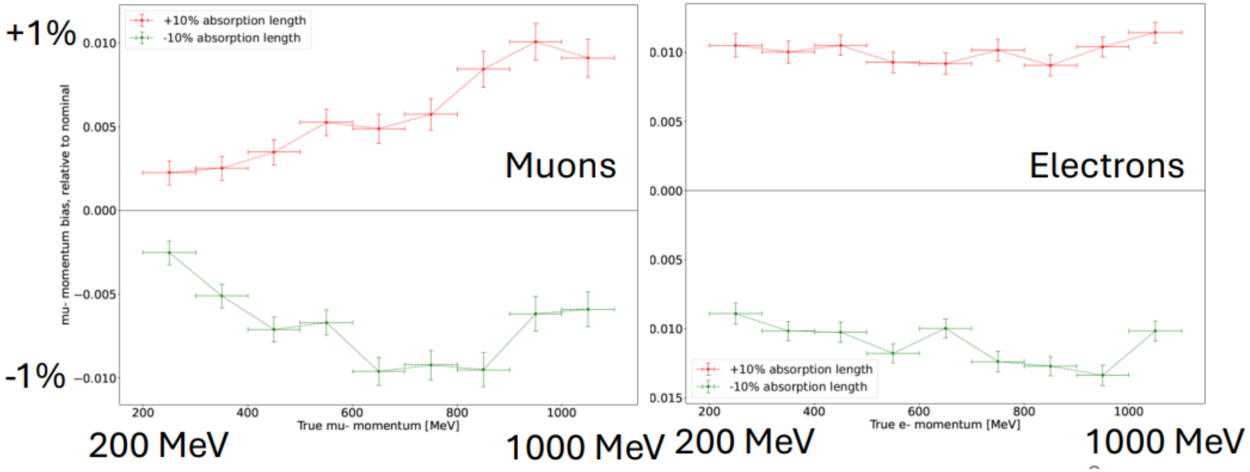
https://indico.ipmu.jp/event/462/contributions/8737/

Calibration Analyses – Bottom-up

- Two ways of doing a calibration analysis, top-down or bottom-up.
- Top-down considers models and uses controls samples to cover the phase space.
- Bottom-up looks at how the detector response varies when underlying systematic parameters are changed.
- Example: shows that varying water absorption causes shape differences between momentum reconstruction for muons than electrons.
- Repeat for a variety of known detector response changes to study impact.

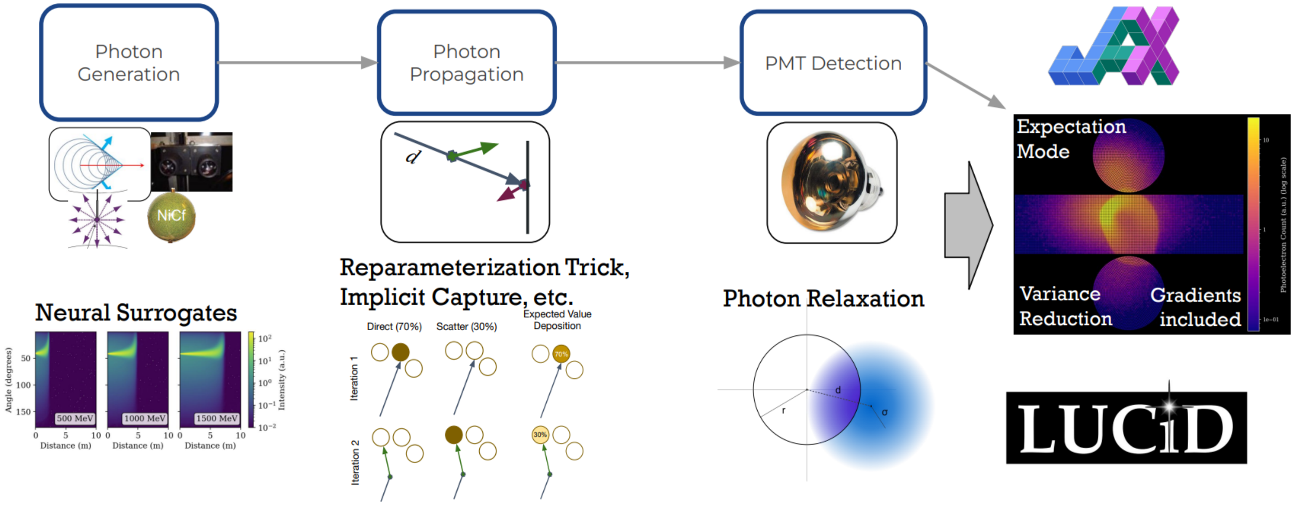


Example of top-down analysis from Super-K, Absolute energy scale measurements for each SK period 10.1103/PhysRevD.97.072001.



Calibration Analyses – Differentiable Simulator

- Differentiable simulator approach– reduces need for regeneration of MC.
- Simulates photon generation, propagation and detection in a differentiable manner.



- Fast response for multiple correlated parameters using ML techniques.
- More details: https://arxiv.org/abs/2602.24129.

Conclusions

- Hyper-Kamiokande will perform a wide range of interesting physics analyses to a high level of precision. This is only possible if the detector response is well understood.
- Broad range of calibration sources are required in the detector to target and study a range of sources of systematic uncertainty.
- Variety of analysis methods in development to ensure robustness of results.