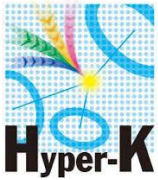


Japanese Neutrino Experiments

Super-K, T2K and Hyper-K

Ellen Sandford, on behalf of the Liverpool group
Liverpool annual HEP meeting
22nd May 2025

Group members

Academics:

- Neil McCauley
- Christos Touramanis
- Kostas Mavrokoridis
- Jon Coleman

Research/technical staff

- Sam Jenkins
- David Payne
- Ellen Sandford
- Balint Bogdan
- Carl Metelko

PhD students:

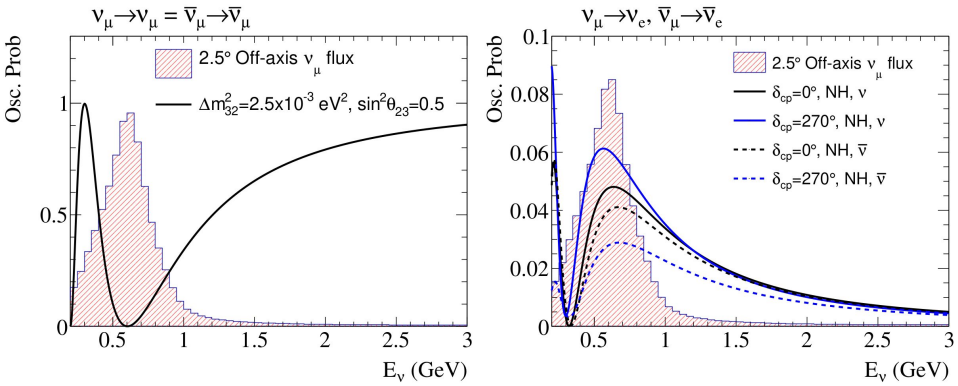
- Patrick Bates
- Unik Limbu
- Naomi Foster

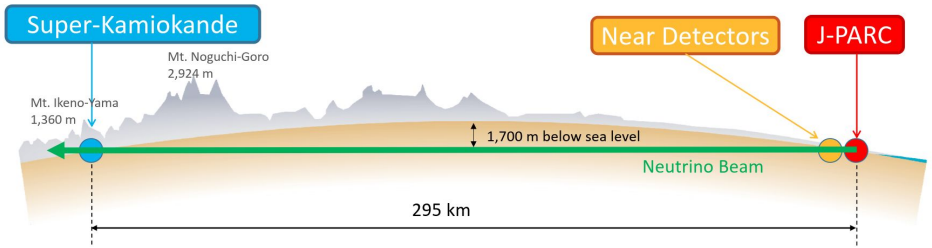
Graduated in the last year:

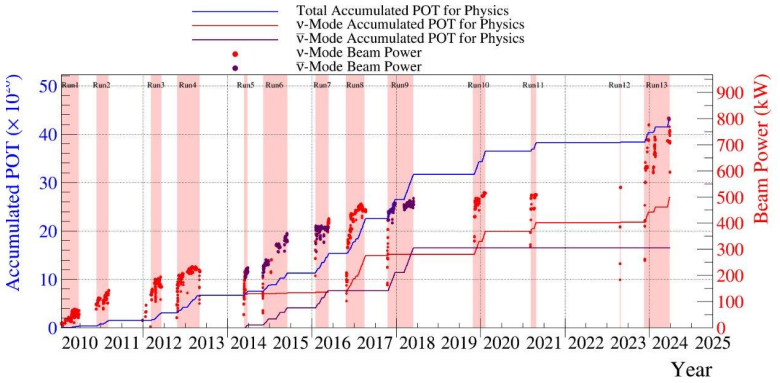
- Jaiden Parlone 
- Adam Tarrant 

T2K overview

- Long baseline neutrino oscillation experiment
- Beam of (anti-)muon neutrinos produced at J-PARC travel 295 km to far detector - Super-Kamiokande in Kamioka mine
- Suite of near detectors sits 280 m from the beam source
- SK and ND280 detectors sit 2.5° off axis
- Neutrino energy peak at ~600 MeV







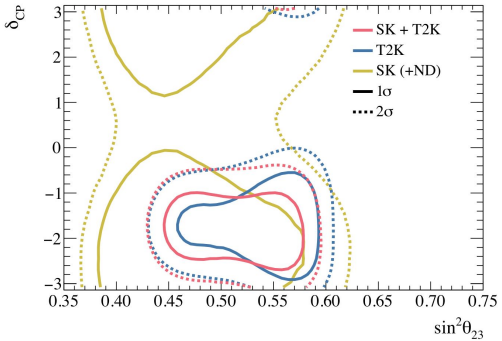
Recent T2K news

- T2K-SK and T2K-NOvA analyses - successful first joint analyses, important for breaking degeneracies
  - T2K-SK paper published: Phys. Rev. Lett. 134, 011801
  - T2K-NOvA being submitted to Nature
- Also upcoming papers on
  - Neutron capture multiplicity measurement of NCQE events in Gd-loaded Super-K
  - Electron Neutrino Charged-Current Pion Production Cross Section on Carbon (arXiv:2505.00516)
  - Differential NC1π+ measurement (arXiv:2503.06849)
  - Cross-section measurement in WAGASCI-BabyMIND
- Upcoming oscillation analysis to include important features
  - Such as addition of run 11 (10% statistics in neutrino mode), first data including SK-Gd
  - New near detector samples
- JPARC beam upgrade: beam power of 810 kW, increased from 500 kW
  - Steady upgrades planned to reach 1.3 MW for Hyper-Kamiokande era
- ND280 near detector upgrade completed
  - Analyses well underway, first results coming very soon

Joint analyses

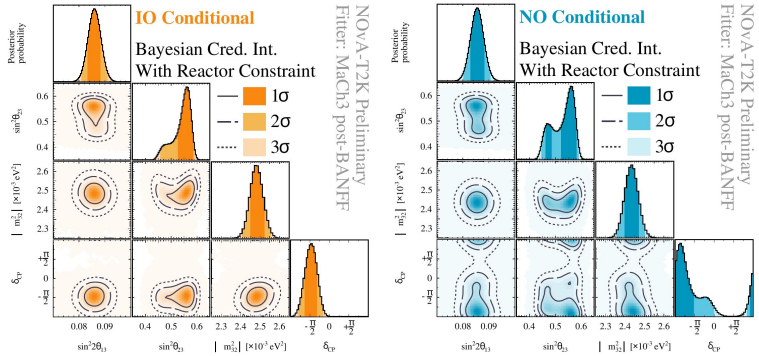
T2K-SK joint analysis

- First joint measurement of oscillation parameters using both atmospheric SK data and T2K beam neutrino data
- Paper published! Phys. Rev. Lett. 134, 011801
- CP conservation excluded between 1.9σ and 2.0σ
- Low preference for normal mass ordering



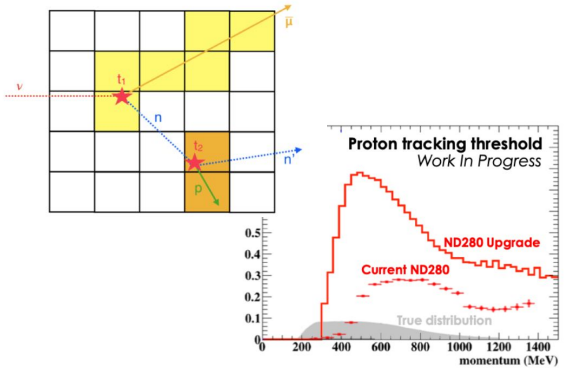
T2K-NOvA joint analysis

- First full combination of two long baseline experiments!
- NOvA: peak neutrino beam 1.2 GeV, baseline 810 km
- T2K stronger sensitivity to δ_{CP}, NOvA stronger sensitivity to mass ordering → possibility to lift degeneracies
- Full study of combined systematic model
- Paper being submitted to Nature

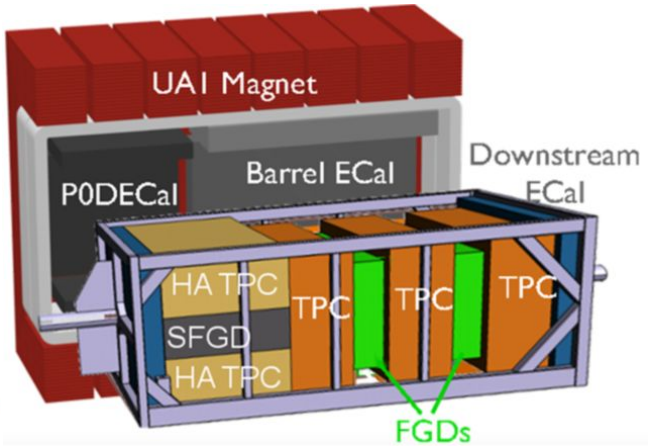


ND280 upgrade

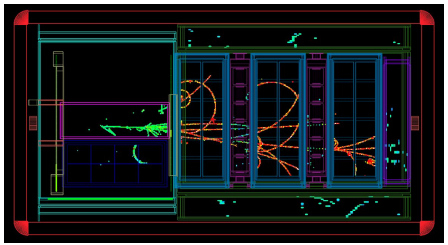
SFGD: segmented 3D detector made of 2 million scintillating cubes provides high granularity, ability to reconstruct shorter tracks and reconstruct neutrons



HATPCs: provide increased angular acceptance (more similar to that of SK)



Upgrade was completed in 2024 and **first physics data** was taken in June

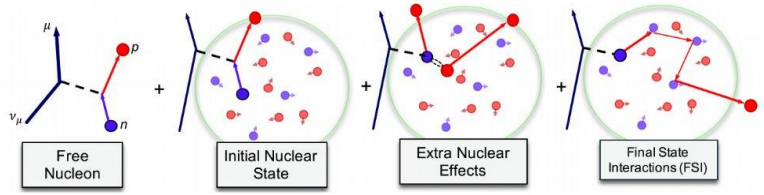


Time of flight detectors: planes surround the SFGD/HA-TPCs to reconstruct direction with precise timing information

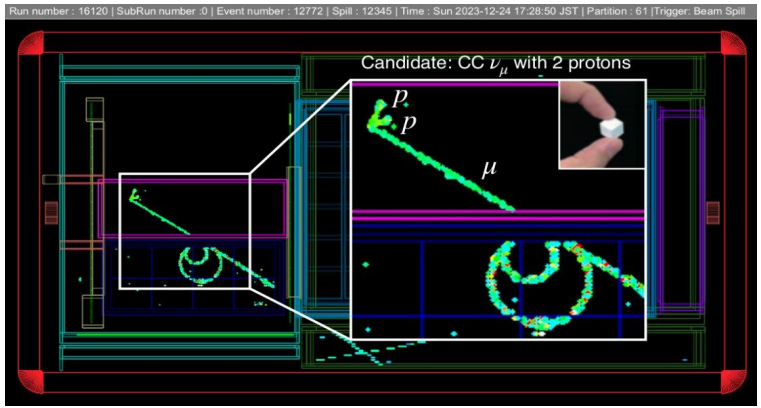
With the ND280 + beam upgrades we can collect the same POT in 4 months as we did in the whole period 2010-2022 !

Analysis with ND280 upgrade data

- Interaction model uncertainties are the largest systematic for the oscillation analysis
- The upgrade can allow us to reconstruct short tracks at the interaction vertex, giving greater sensitivity to nuclear effects such as 2p2h and FSI
- Currently developing a CC0pi2proton selection with plan to look more generally at multi-nucleon events
  - Includes looking at differences between generators such as NEUT and NuWro



Real data taken with ND280 upgrade!



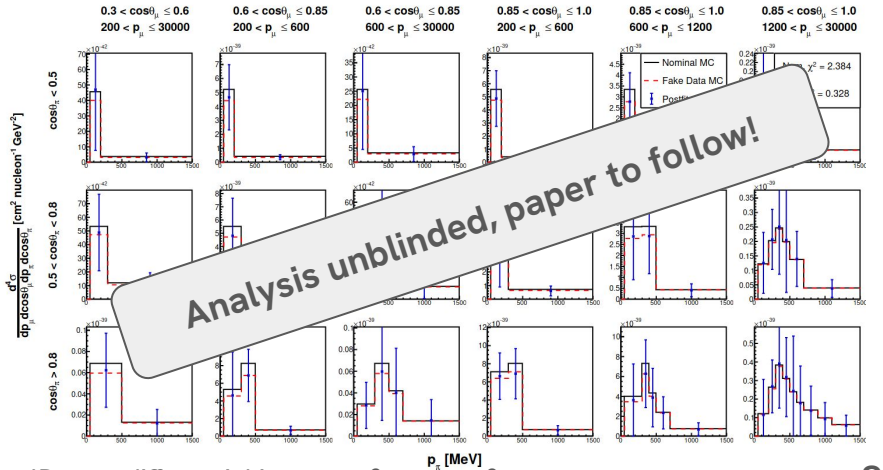
- **Patrick** is also working on a global PID tool for ND280, working within new AI/ML working group within ND280 physics → see more on this in his talk tomorrow morning

Work by Ellen Sandford

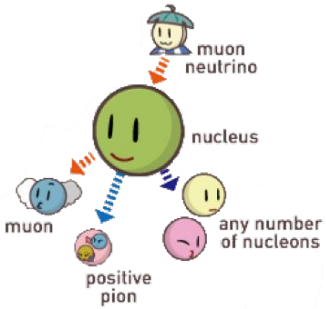
CC1pi+ on CH and H2O

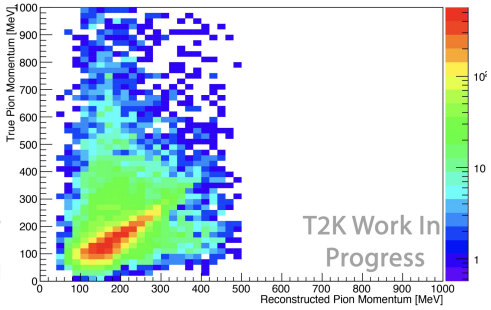
Work by Sam Jenkins

- Measurement of single positive pion production on hydrocarbon and water targets – main background to CCQE dominated OA
- Technique developed to reconstruct short-range pion momentum from range of Michel electrons produced - first use in T2K, several analyses now adopting this



4D xsec differential in p_μ, $\cos\theta_\mu$, p_π, $\cos\theta_\pi$





- Fit MC to data using binned template likelihood fit, then calculate xsec per kinematic bin as

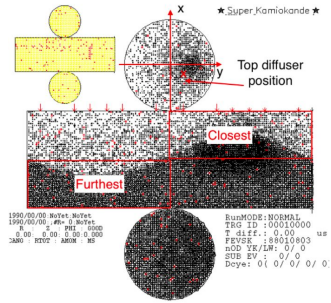
$$\left(\frac{d\sigma}{dx}\right)_i = \frac{N^{sig}_{i,true}}{\epsilon_i \phi T \Delta x_i}$$

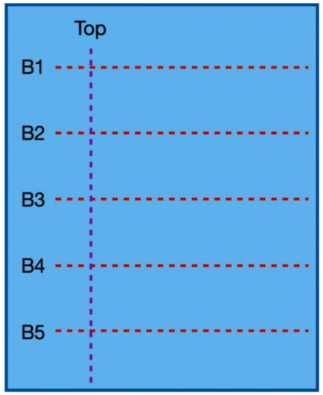
- Current status: Analysis unblinded!
  - Paper to follow
- Sam is also a member of task force investigating CC1pi excess in SK data

Super-K monitoring and calibration system

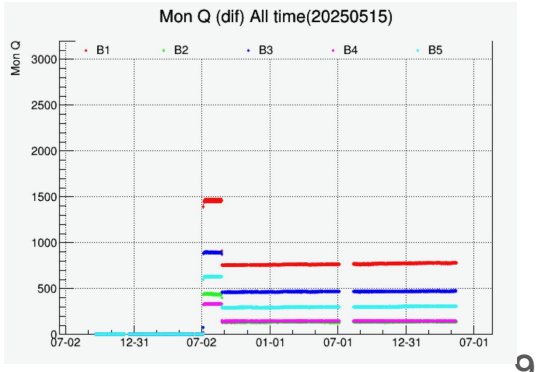
- UKLI system in Super-K for water quality monitoring and PMT response
  - Five horizontal injector positions + top diffuser
- Report weekly in the Super-K steering meeting
- Monitor PMT replaced ~2 years ago, since then stable output

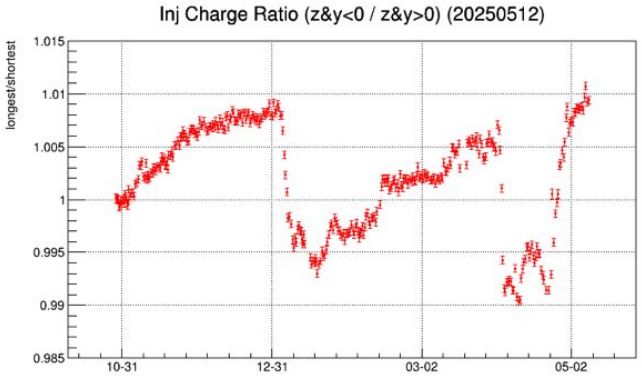
- Charge ratio between furthest and closest region of detector sensitive to changes in water quality
- Can see drop in charge ratio when work being carried out, then period of recovery





Work by Sam Jenkins

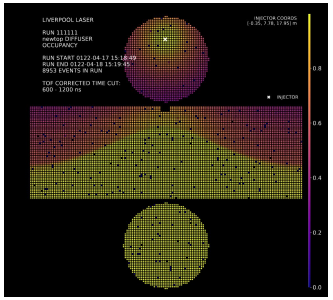


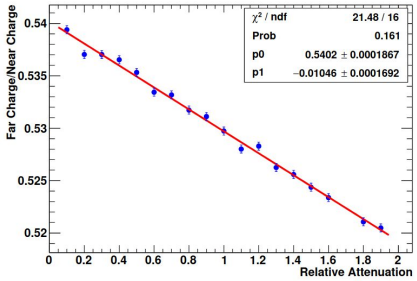


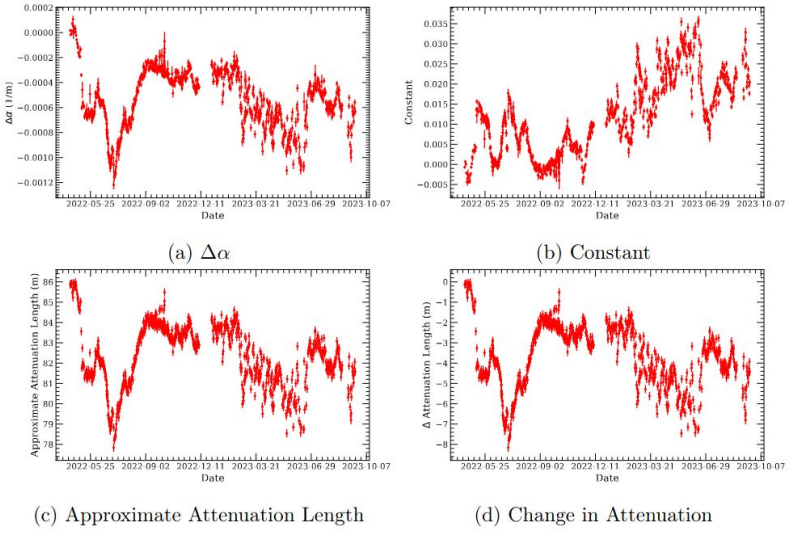
Super-K monitoring - top diffuser analysis

Work by Sam Jenkins and Adam Tarrant

- ➔ Demonstrate with simulations that charge ratios can be sensitive to attenuation and scattering
- ➔ Adam carried out analysis using the top diffuser in order to measure the relative attenuation of light over time
- ➔ In order to get **absolute change in attenuation** the mean charge is calculated in slices of injector-PMT distance and fitted with an exponential







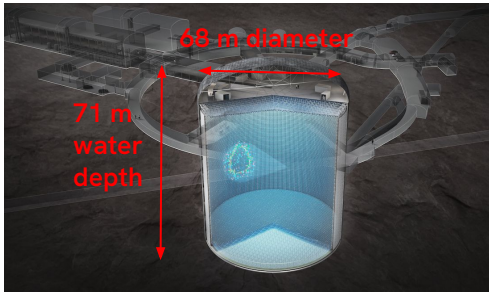
(a) $\Delta\alpha$ (b) Constant

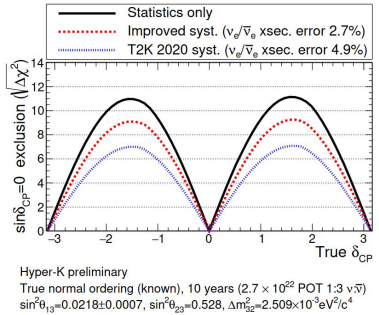
(c) Approximate Attenuation Length (d) Change in Attenuation

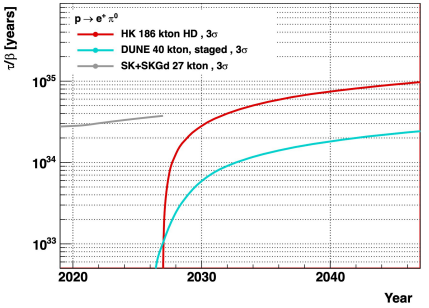
➔ **Unik** will be taking over this work analysing SK calib data

Hyper-Kamiokande

- ➔ The HK detector is currently under construction
- ➔ 258 kton volume overall
  - 187 kton fiducial volume in ID, approximately 8 times larger than SK
  - 1m thick outer veto
- ➔ HK will be instrumented with PMTs, as well as mPMTs for improved timing and spatial resolution







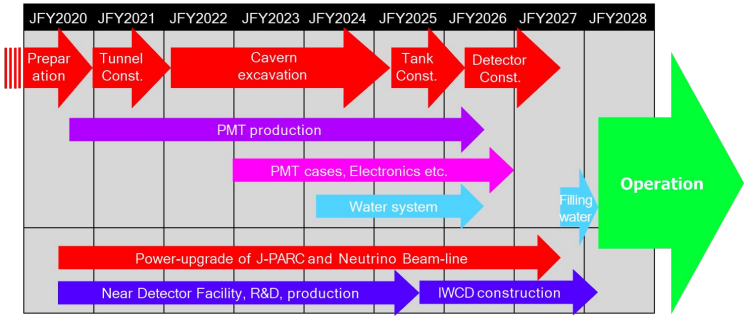
Hyper-K has a vast physics program:

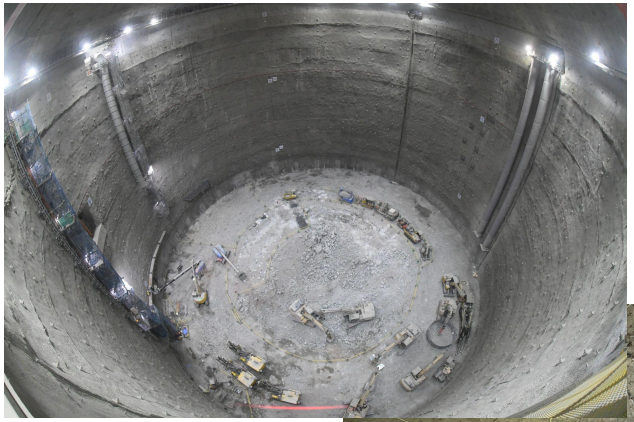
- ➔ Neutrino oscillation measurements
  - CP violation, mass hierarchy, precise θ_{23} measurement
- ➔ Solar neutrino measurements
- ➔ Proton decay
- ➔ Supernova burst neutrinos and relic neutrinos
- ➔ Exotics

Paper *"Sensitivity of the Hyper-Kamiokande experiment to neutrino oscillation parameters using accelerator neutrinos"* submitted to EPJC and is available on arxiv - arXiv:2505.15019

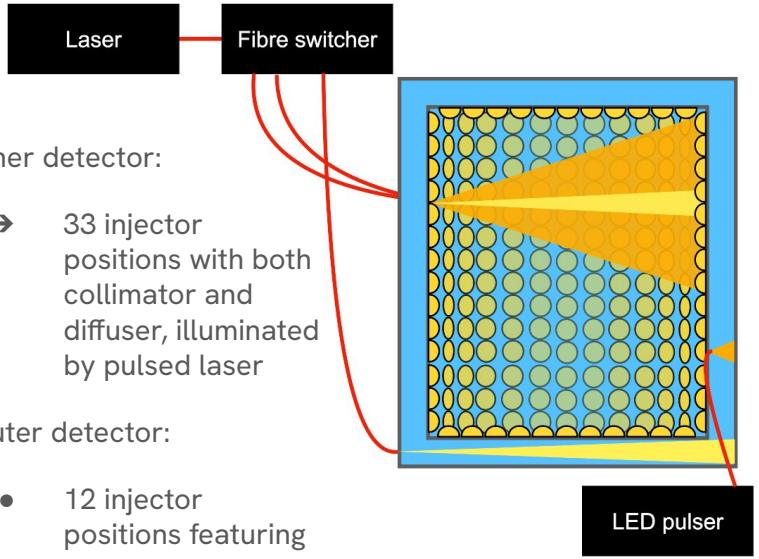
Construction status

- ➔ Excavation of HyperK cavern ongoing
  - ◆ 16 out of 19 barrel sections complete (61m out of 73m)
  - ◆ Cavern excavation will be completed in a couple of months
- ➔ More than 14,500 PMTs delivered so far as scheduled
- ➔ Detector construction completion and water filling on track for 2027





Hyper-K light injection system



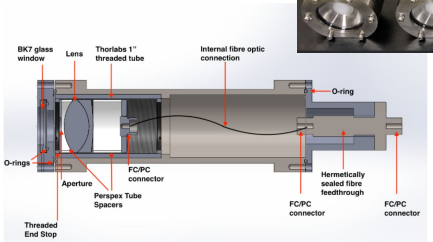
Inner detector:

- ➔ 33 injector positions with both collimator and diffuser, illuminated by pulsed laser

Outer detector:

- 12 injector positions featuring a collimator, illuminated by laser, plus 122 diffusers using pulsed LED source

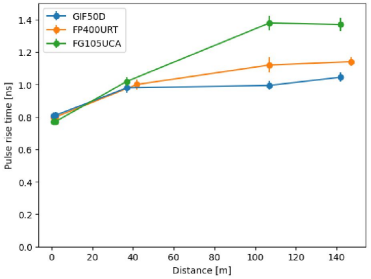
- ➔ UK group is developing light injection calibration system for Hyper-K
- ➔ Recent news: Diffuser construction and QA is completed at Warwick and Sheffield
- ➔ Liverpool group is responsible for **light source and optical fiber specification and testing**

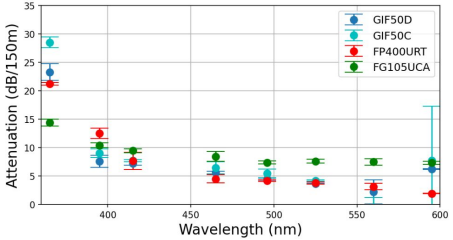


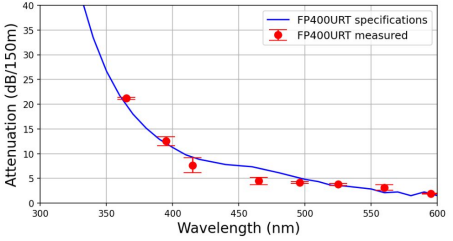
Work by Sam Jenkins, Balint Bogdan, Naomi Foster and Unik Limbu

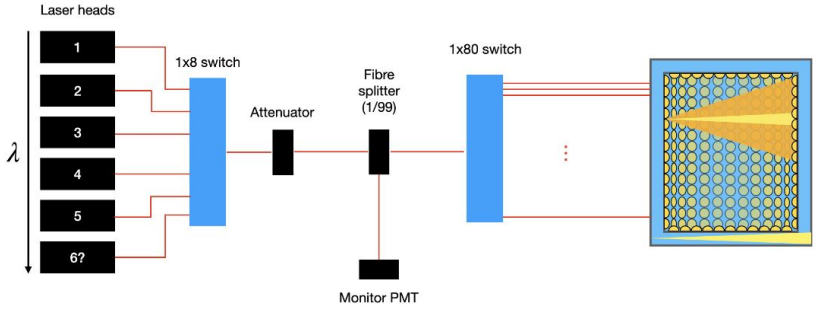
Fiber testing for LI system

- Tech note written summarising the fiber optics and light sources for the LI system, including the tests performed on candidate fibers
- As a result of these measurements a choice was made to move away from graded index fibres, to a narrow core step index fibre for ID
  - Better absorption in UV region
- **Fibers have been selected:**
  - For ID system and OD collimators: Thorlabs FG105UCA
  - For OD diffuser system: Thorlabs FP400URT
- Unik has also been working on destructive testing of the fibers
- 1x4 fibre switching devices tested



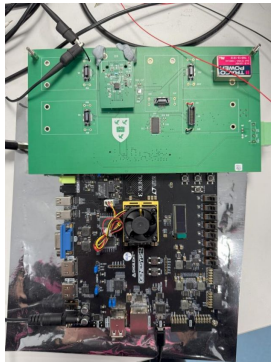


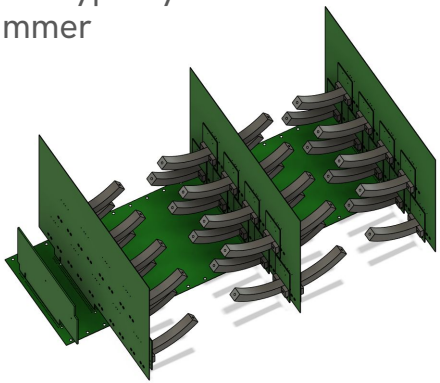




Pulser boards

- ➔ Happy with design and performance of the board
- ➔ Currently writing up a tech note
- ➔ Working on crate electronics
- ➔ Plan to have a full scale system prototype by the end of summer

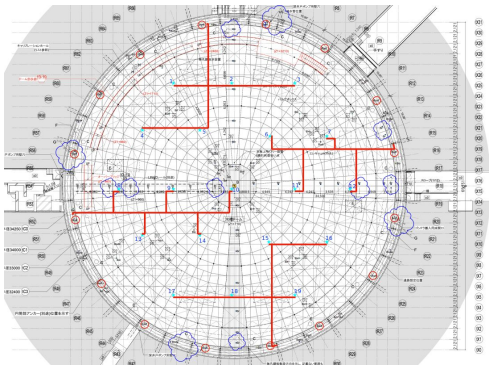




Work by Balint Bogdan, Sam Jenkins

Installation plans

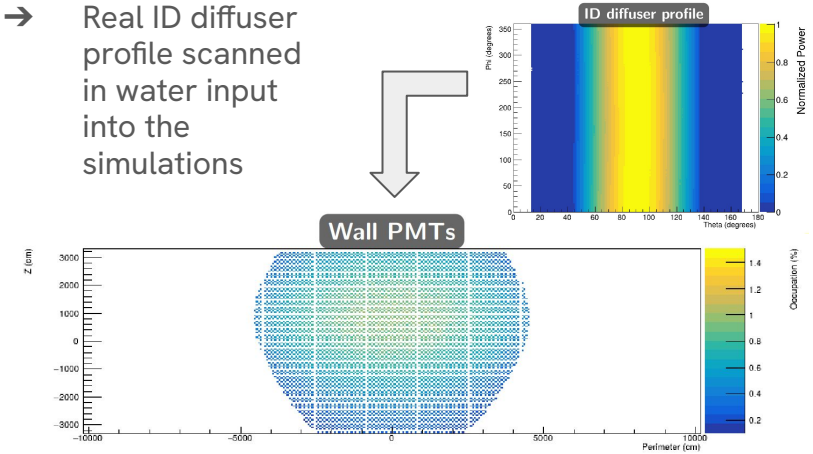
- ➔ Plans being developed for installation of fibers in 1m wide outer detector
- ➔ Plan to practise fiber installation in Oliver Lodge, possibly in the workshop
- ➔ Work ongoing to map exact positions of injectors, plus fiber and cable paths



Gondola mockup

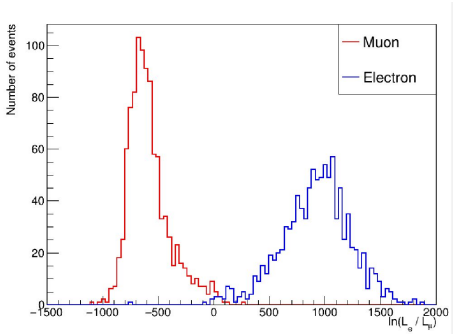
LI system simulations

- The Liverpool group is also involved in analysis of calibration data
- Simulations can be used to understand effect of water parameters on collimator and diffuser data
  - Analysis being developed to fit these parameters in data
  - Also working on fitting for timing offsets for injectors and PMTs
- Real ID diffuser profile scanned in water input into the simulations



Reconstruction

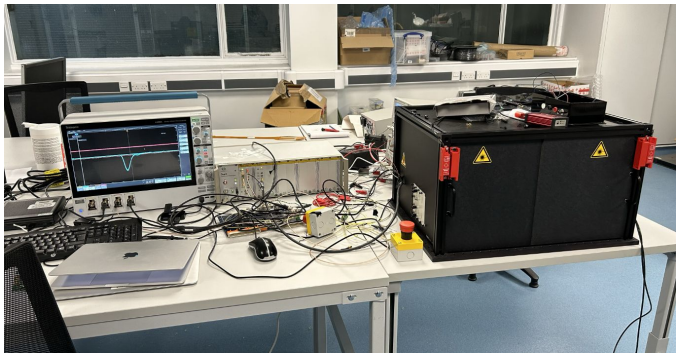
- Also need to understand the effect of water parameters on reconstruction
  - PID, energy scale, resolution
- Plan to use a bottom up approach
- Start from known calibration-informed uncertainties on absorption, symmetric and asymmetric scattering, and investigate degeneracies
- Naomi will be working on machine learning for HK reconstruction



Work by Sam Jenkins, Naomi Foster and Unik Limbu

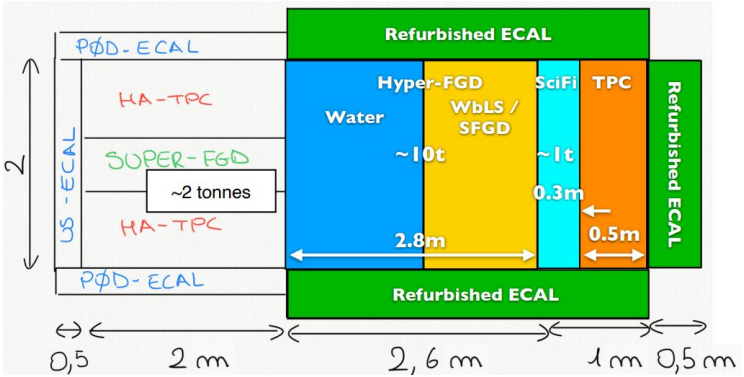
Optical and Electronics Laboratory

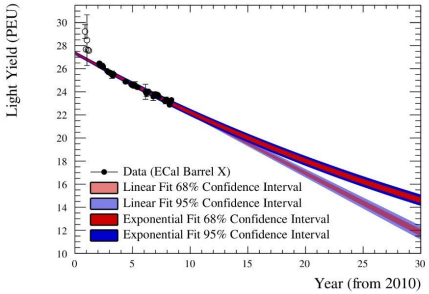
- Much of this HK LI system work goes on in our laboratory in the Chemistry building, managed by Balint Bogdan
- Supporting 3 groups:
  - Hyper-K
  - XLZD/LZ
  - BUTTON
- Activities include PCB design and assembly, fibre characterisation, laser testing, hydraulic system for XLZD, WbLS storage...
- 0 incident and accident since the laboratory opened!
- Aiming for LEAF Gold with sustainability this year

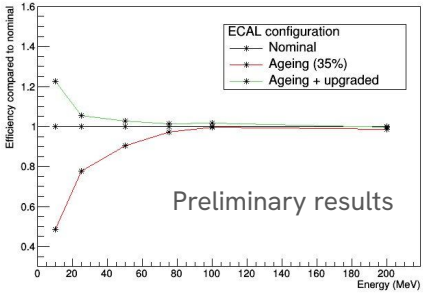


ND280++

- ND280 to become the near detector for HK
- Proposal to carry out upgrades to the “tracker” region of ND280 (the region which was not recently upgraded)
- Goal of high granularity and large mass of hydrogen/water, R&D ongoing to develop new technology
- Barrel ECAl was originally built in Liverpool and Daresbury more than 15 years ago
  - Technology has developed a lot since then
  - Look forward to ensure longevity for ND280 running in 2040 and beyond
- Proposal to refurbish the ECAL
  - Recover light losses from ageing scintillator bars and lower threshold for low energy particles
  - Replace MPPCs, fibers and electronics
- Simulation work ongoing to understand requirements and potential performance improvements







Work by Ellen Sandford

Other news

Sam was recently made T2K neutrino cross-section group convener!

Upcoming meetings/conferences:

- ➔ Hosting all Hyper-K groups in the UK in June for a HKUK meeting
- ➔ Hosting NuFact conference here in Liverpool in September!