

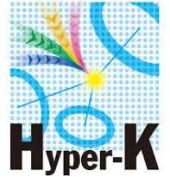


Japan Neutrino Experiments

Super-K, T2K and Hyper-K

Ellen Sandford, on behalf of the Liverpool group
Liverpool annual HEP meeting
23rd May 2024

Group members



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

- Sam Jenkins
- David Payne
- Ellen Sandford

- Balint Bogden
- Carl Metelko

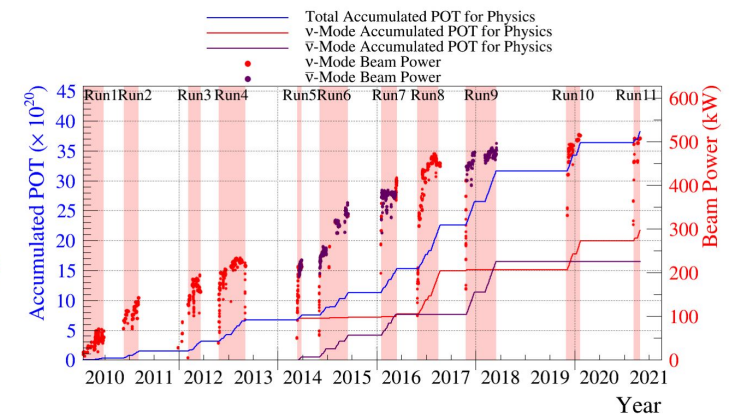
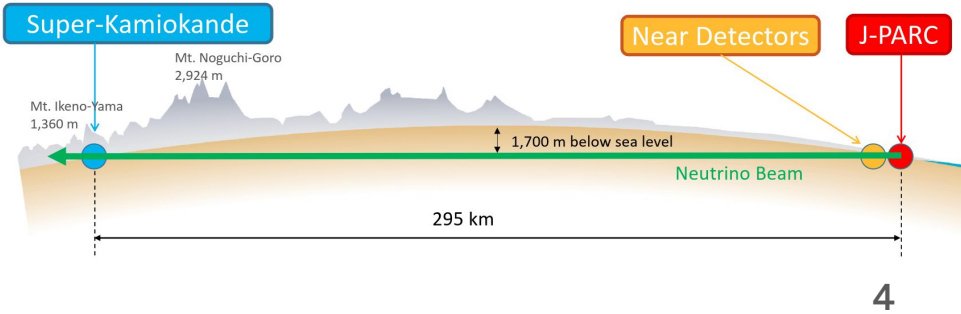
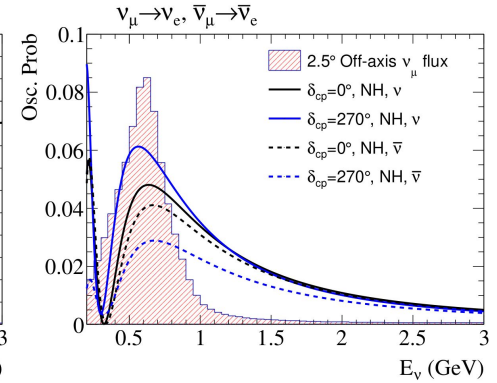
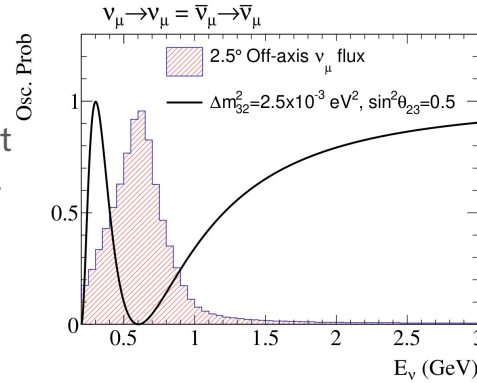
- Jaiden Parlone
- Adam Tarrant
- Patrick Bates
- Unik Limbu

T2K

T2K overview

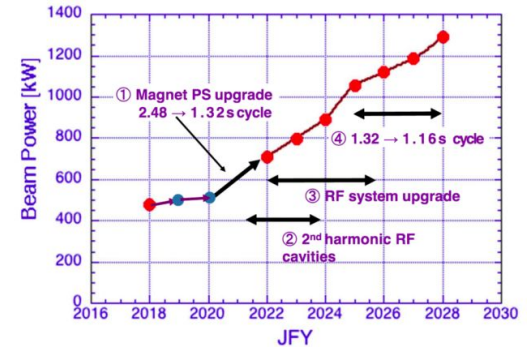
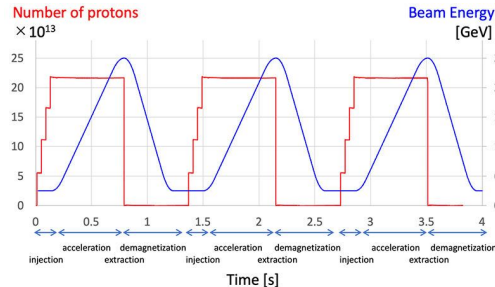
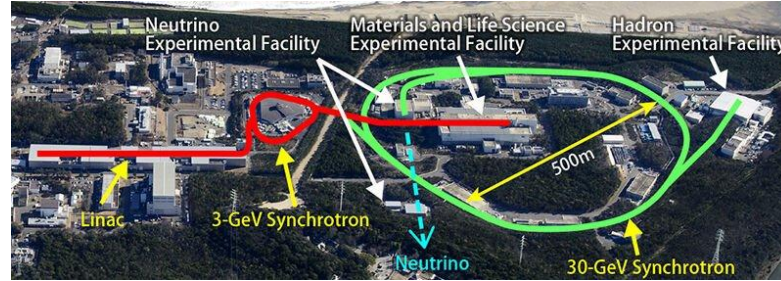


- Long baseline neutrino oscillation experiment
- Beam of (anti-)muon neutrinos produced at J-PARC travel 295 km to the far detector - Super-K located in Kamioka
- A suite of near detectors sits 280 m from the beam source
- Detectors sit 2.5° off axis
- Neutrino energy peak at ~ 600 MeV



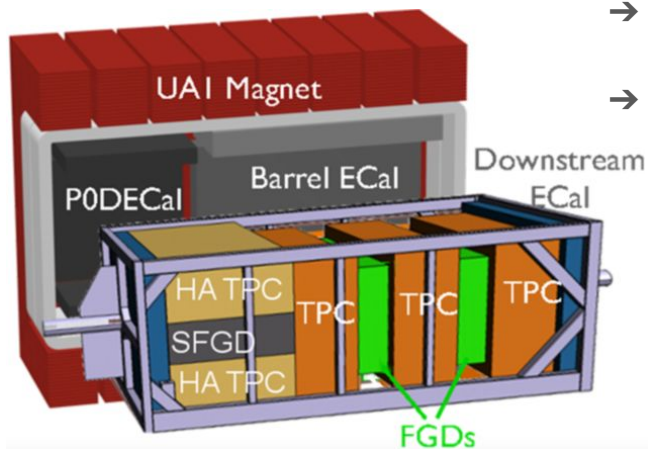
Beam upgrade

- The J-PARC neutrino beam was recently upgraded
- Electromagnetic horns current increased from 250 kA → 320 kA, increasing neutrino flux
- Beam cycle decreased from 2.48s → 1.36s, increasing beam power
- On 25th December 2023 the beam ran stably at **760kW**, increased from ~500kW and surpassing for the first time the original design power of 750kW

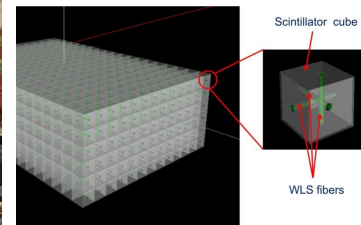
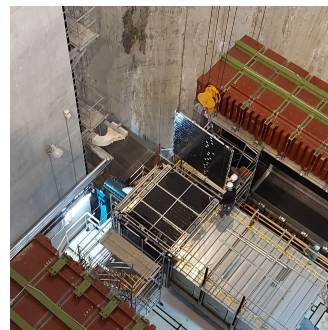


Looking forward to Hyper-K era, the beam is planned to be upgraded further to **1.3 MW**

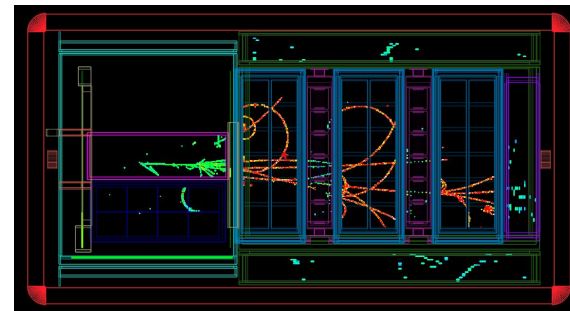
Detector upgrade



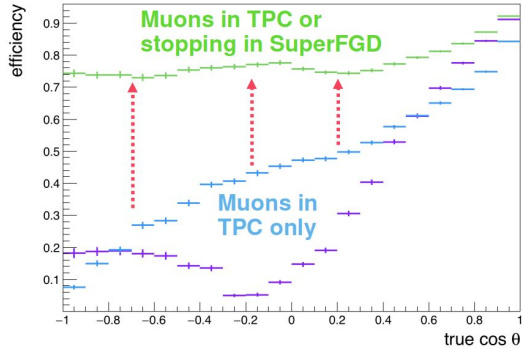
- Near detector constrains interaction uncertainties for SK
- New sub-detectors provide increased angular acceptance
- SFGD: 2 million scintillating cubes with fibres and MPPC readout, for high granularity
- Time of flight detector to reconstruct direction



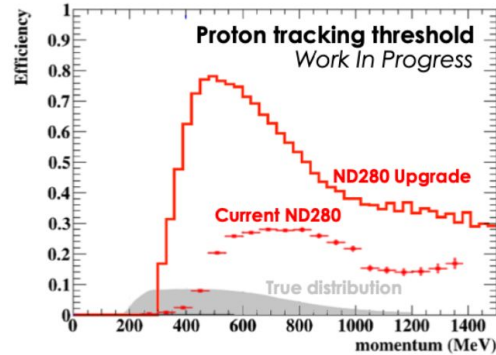
- In July 2023 upgrade installation started with the first TOF panels
- SFGD was installed in ND280 pit in October
- Data taken with SFGD, bottom HAT and first TOF panels
- 14th May 2024 (last week) final two TOF side panels were installed
- **The upgrade of ND280 is now complete and ready for physics data**
- First beam data with complete upgraded ND280 in June



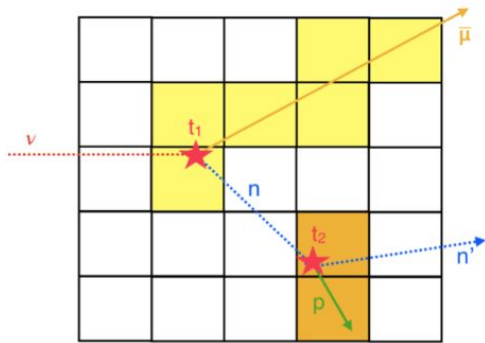
Analysis with upgraded ND280



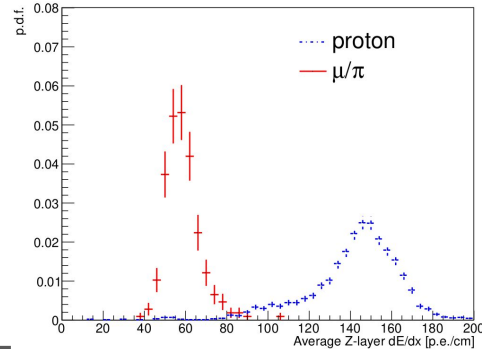
Upgraded near detector provides acceptance for full angular range.



Lower threshold for observing protons - decreased to approx. 300 MeV.



SFGD will allow near detector to be able to reconstruct **neutrons** for the first time.



Better **PID**: Will be better able to differentiate photon/electron and proton/muon.

Multi-nucleon study

Work by Ellen Sandford



- Large uncertainties related to our knowledge of neutrino-nucleus interactions
- 2p2h is the largest cross-section systematic for oscillation analysis
- Near detector can make important measurements to understand these and reduce systematics

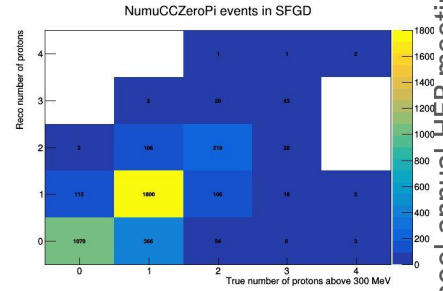
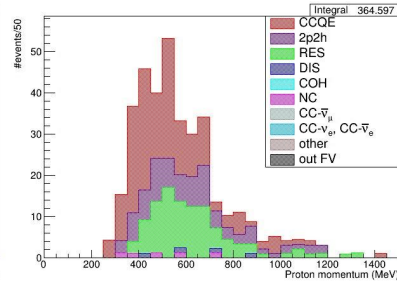
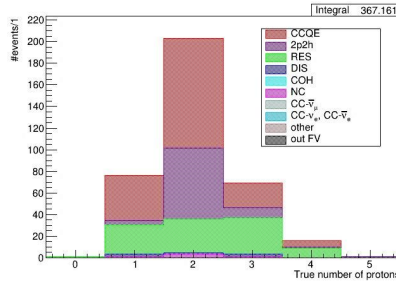
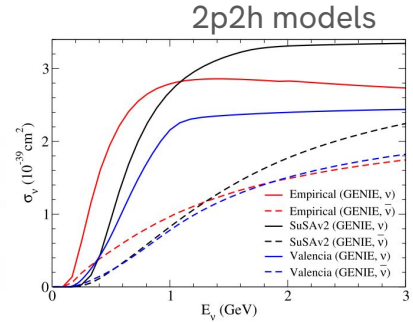
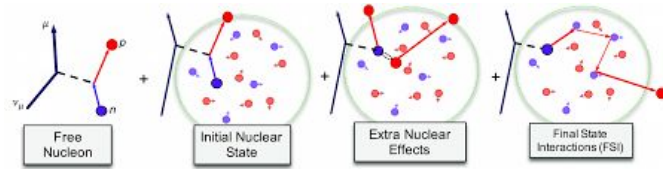
- Working on CC0 π 2prot selection with an enhanced rate of 2p2h

- Approx 22% currently

- Increasing this further by improving reconstruction of these multi-nucleon events

- Back to back proton events
 - Aligned muon-proton tracks

- Plan to include neutrons in future



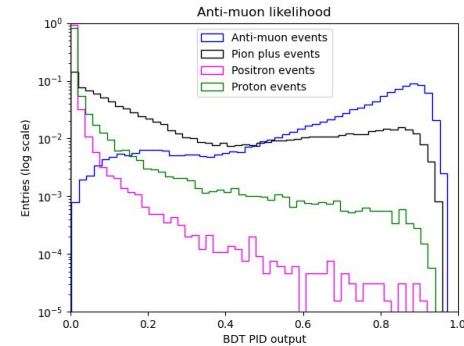
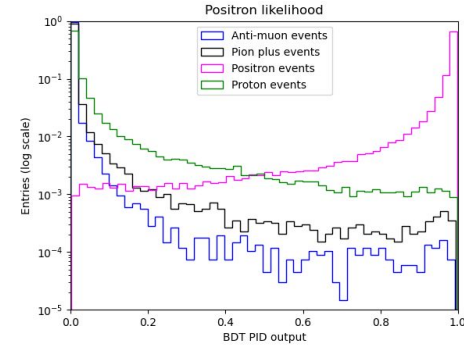
ND280 global PID tool

Work by Patrick Bates



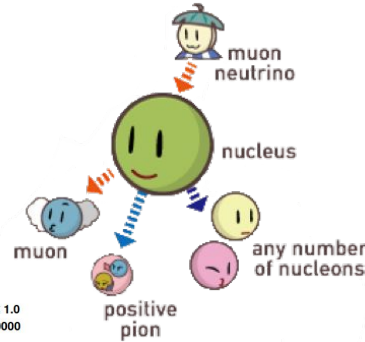
- Developing a boosted decision tree (BDT) analysis
- Global PID tool
 - Replacing tools that carrying out PID in each sub-detector separately
 - Use information from multiple sub-detectors
- Currently updating for the upgraded ND280
 - Optimising new input variables from SFGD, HA-TPC and TOF
- Tool will be used in CC1pi cross-section analysis

See Patrick's talk on Friday morning for more detail.

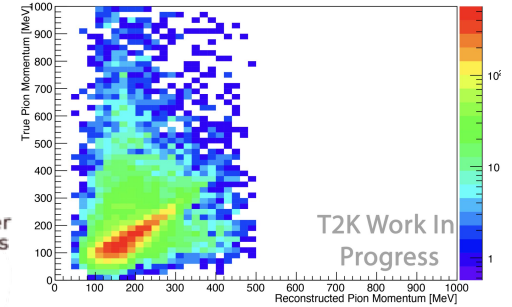


CC1pi+ on CH and H2O

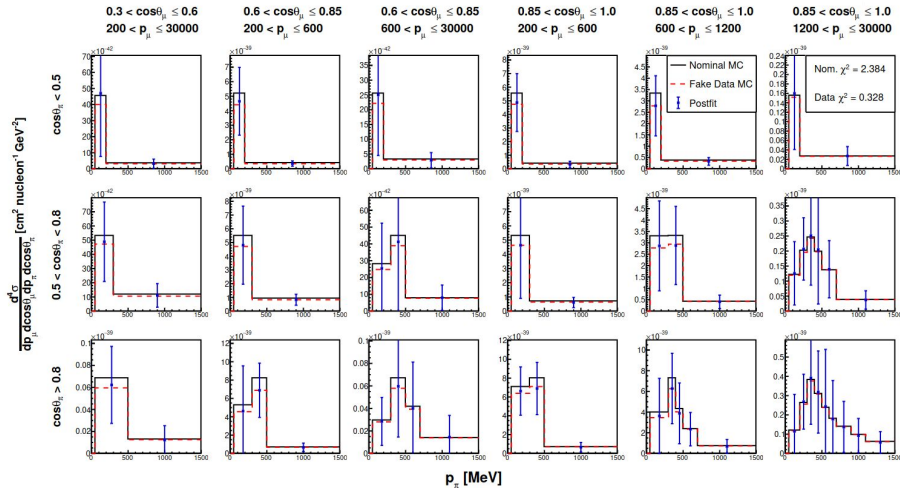
- Measurement of single positive pion production on hydrocarbon and water targets - main background to CCQE dominated OA
- Technique developed to reconstruct short-range pion momentum from range of Michel electrons produced - first use in T2K, several analyses now adopting this



Work by Sam Jenkins



T2K Work In Progress



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

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

- Current status: Wide range of fake data studies completed, currently undergoing review for data unblinding. **Paper to follow this year.**
- Sam is also a member of task force investigating CC1pi excess in SK data and ND280 CC1pi convenor.

Oscillation analysis

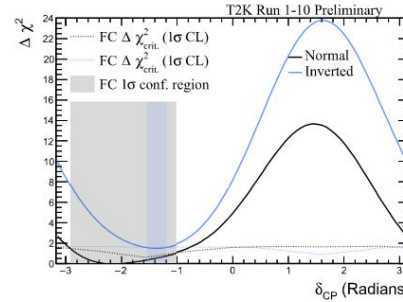
Work by Jaiden Parlone



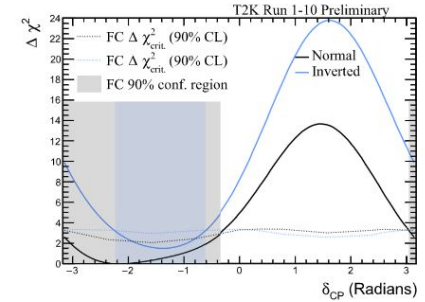
- Jaiden's work involves using VALOR
 - Performed a model update
 - Included resonance dominated event sample in analysis
- Analysis finished late last year and currently writing thesis

| Confidence Level | Confidence Interval | |
|------------------|----------------------------------|-------------------|
| | Normal Ordering | Inverted Ordering |
| 1σ | $[-2.92; -1.02]$ | $[-1.55; -1.19]$ |
| 90% | $[-\pi, -0.35] \cup [3.04, \pi]$ | $[-2.24; -0.61]$ |
| 2σ | $[-\pi, -0.08] \cup [2.89, \pi]$ | $[-2.47; -0.42]$ |
| 3σ | $[-\pi, 0.51] \cup [2.42, \pi]$ | $[-3.01; 0.06]$ |

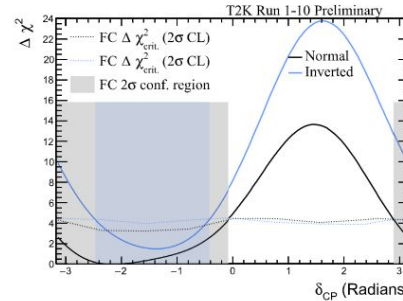
- Analysis places precision constraints on the oscillation parameters
- δ_{CP} confidence intervals, best fit value -2.13
- Neil is chairing review of ND280 inputs to the OA



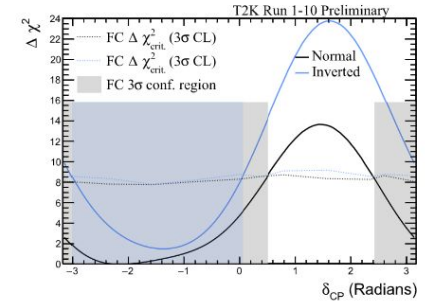
(a) 1σ Confidence Region



(b) 90% Confidence Region



(c) 2σ Confidence Region



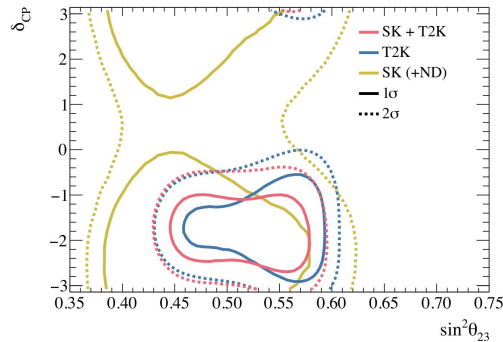
(d) 3σ Confidence Region

Joint analyses



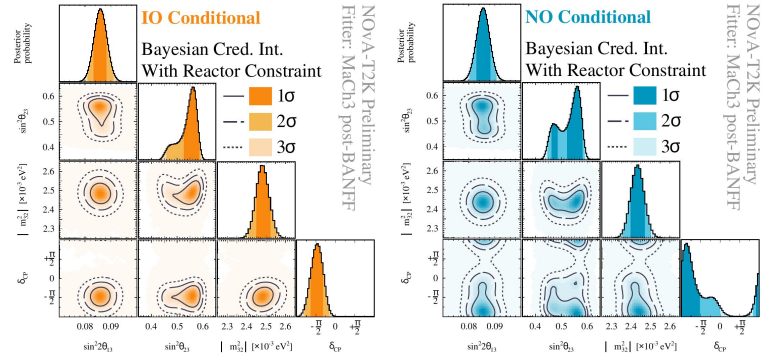
T2K-SK joint analysis

- First joint measurement of oscillation parameters using both atmospheric SK data and T2K beam neutrino data
- Results public, paper available at [arXiv:2405.12488](https://arxiv.org/abs/2405.12488)
- CP conservation excluded between 1.9σ and 2.0σ
- Low preference for normal mass ordering



T2K-NOvA joint analysis

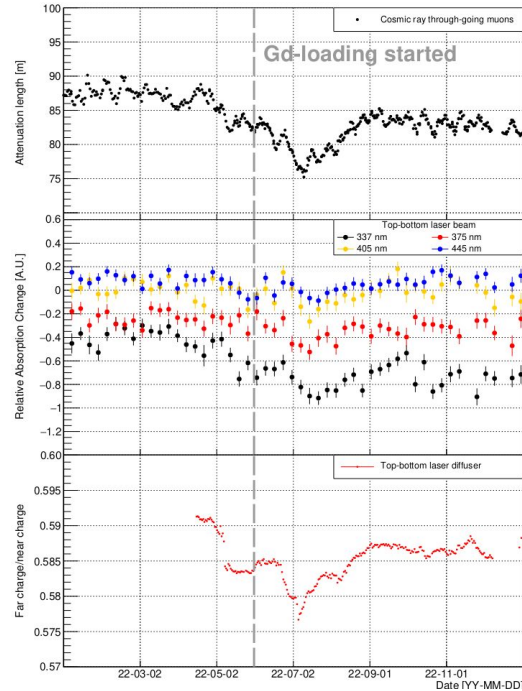
- First full combination of two long baseline experiments
- NOvA: peak neutrino beam 1.2 GeV, baseline 810 km
- T2K stronger sensitivity to δ_{CP} , NOvA stronger sensitivity to mass ordering → possibility to lift degeneracies
- Full study of combined systematic model
- Paper under review



Super-K monitoring and calibration system



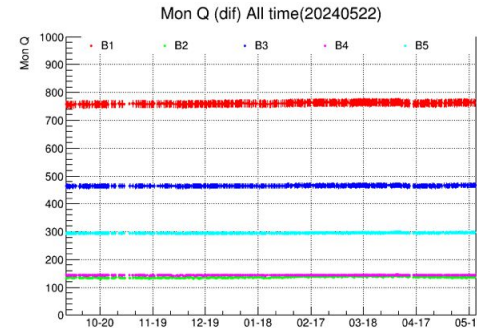
- UKLI system an essential part of SK water quality monitoring
- Top diffuser relative attenuation length (bottom plot) is highly sensitive to changes
- Liverpool give a weekly update at the SK steering meeting
- Featured in new paper on "Second gadolinium loading to Super-Kamiokande" ([arXiv:2403.07796v2](https://arxiv.org/abs/2403.07796v2))



Work by Sam Jenkins and Balint Bodgen



In summer 2023 the group travelled to SK to replace the monitor PMT for the UKLI system

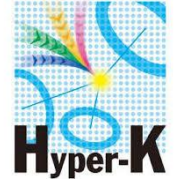
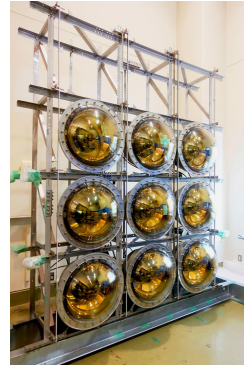
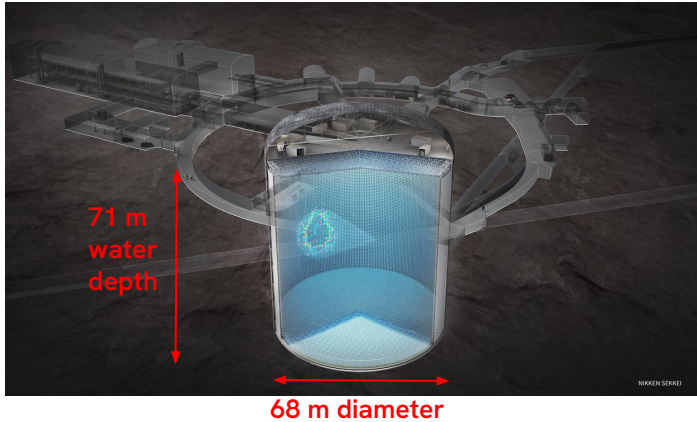


Stable monitor PMT data

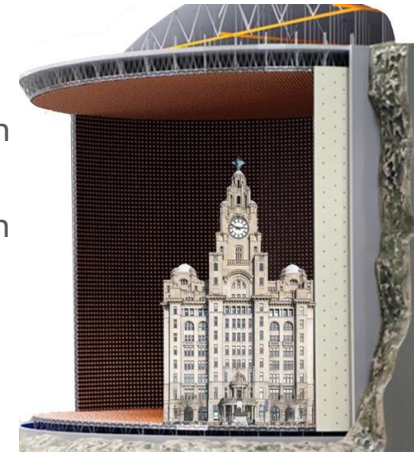
Hyper-Kamiokande

Hyper-Kamiokande

- The Hyper-K detector is currently under construction, located in the Tochibora mine near Kamioka
- 258 kton volume overall
 - 187 kton fiducial volume in ID, approximately 8 times larger than SK
 - Surrounding ID is a 1m thick outer veto



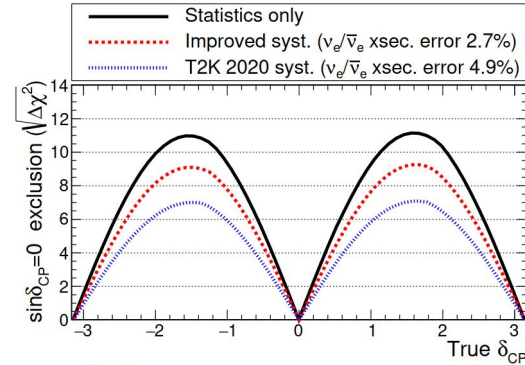
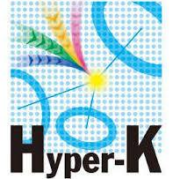
- HK will be instrumented with PMTs in the ID and OD, as well as mPMTs for better timing and spatial resolution
- Cavern excavation: dome complete and barrel section underway
- Right: Hyper-K to scale with the Liver building



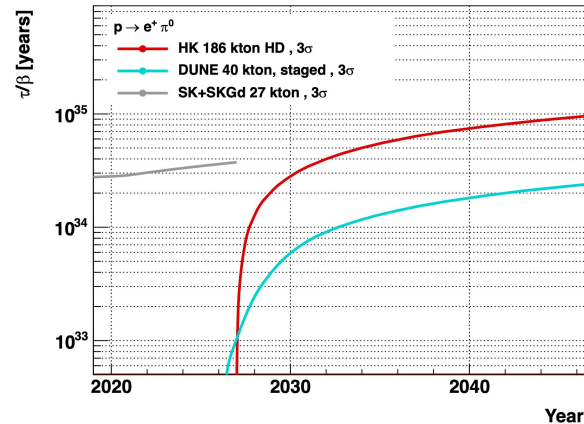
Physics goals

HyperK will start taking physics data in 2027

- Neutrino oscillation measurements
 - CP violation
 - Mass hierarchy
 - Precise θ_{23} measurement
- Solar neutrino measurements
- Proton decay
- Supernova burst neutrinos
 - Part of a supernova alarm system
- Supernova relic neutrinos
- Exotics
 - Sterile neutrinos



Hyper-K preliminary
 True normal ordering (known), 10 years (2.7×10^{22} POT 1:3 $\nu\bar{\nu}$)
 $\sin^2\theta_{13}=0.0218 \pm 0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m_{32}^2=2.509 \times 10^{-3} \text{eV}^2/c^4$



Tour at recent collaboration meeting



PMT production on time and QA ongoing

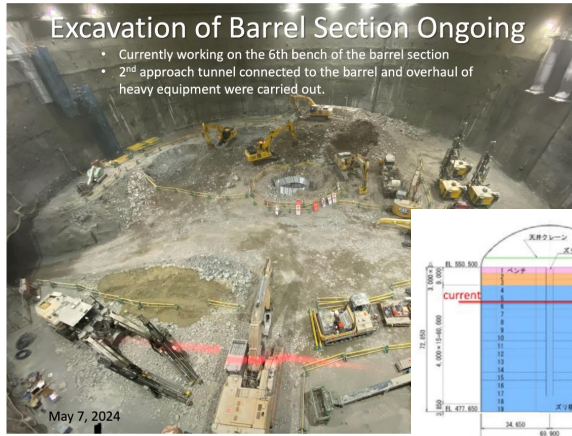


Water purification cavern

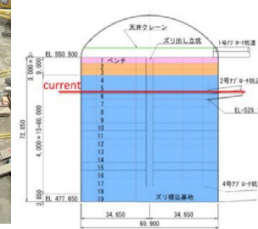


Excavation of Barrel Section Ongoing

- Currently working on the 6th bench of the barrel section
- 2nd approach tunnel connected to the barrel and overhaul of heavy equipment were carried out.

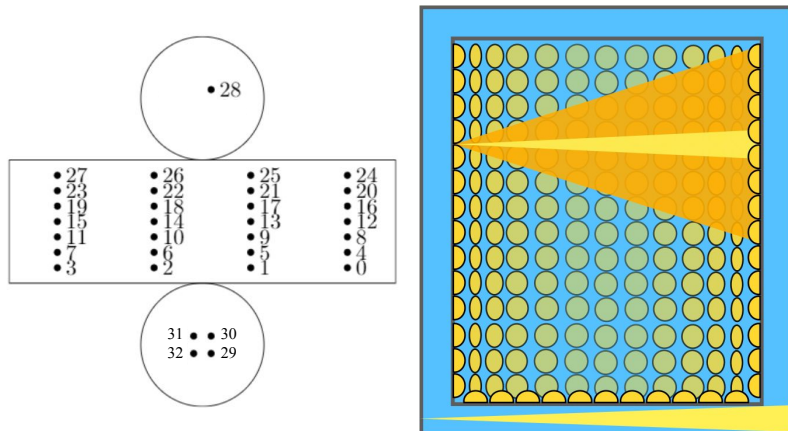


May 7, 2024



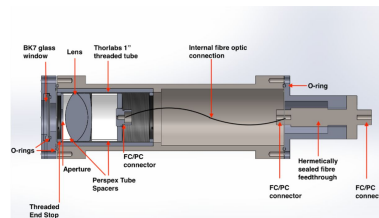
Hyper-K light injection system

- UK group is developing light injection calibration system for Hyper-K
- ID: 33 injector positions with both collimator and diffuser, illuminated by pulsed laser



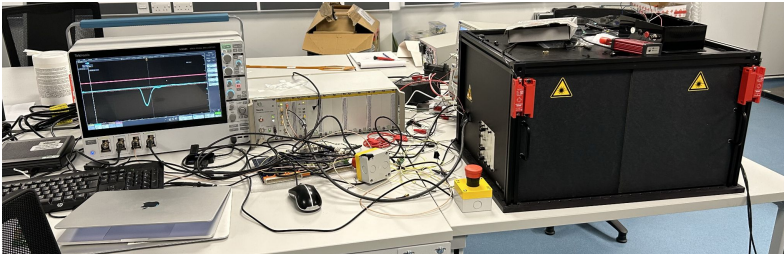
- OD: 12 injector positions featuring a collimator, illuminated by laser, plus 122 diffusers using pulsed LED source

- Plan to use a fibre switching device to allow the same laser signal to be injected into any one of the ID injector positions, plus a monitor
- Narrow beam collimators and 40 degree opening angle diffusers currently being produced and tested at Warwick
- Water based profile measurements will be taken at Sheffield

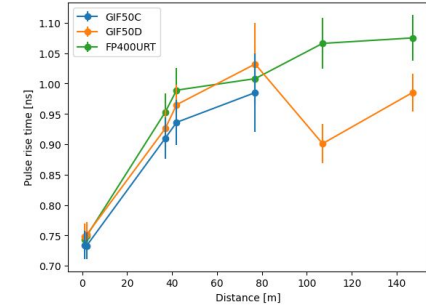
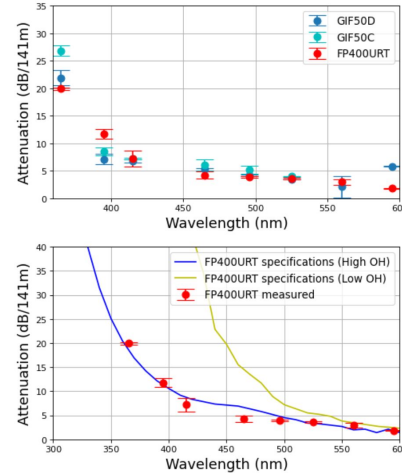
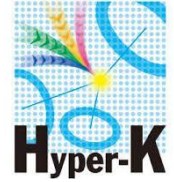


Fibre testing at Liverpool

- Liverpool group in charge of optical fibre specification and testing
- Three main candidate fibres identified and under testing in our Chemistry optics lab
 - Testing both step index and graded index fibres, with various length reels
- Attenuation and dispersion measurements taken using a laser source or LEDs with a range of wavelengths
- Setup housed in a dark box



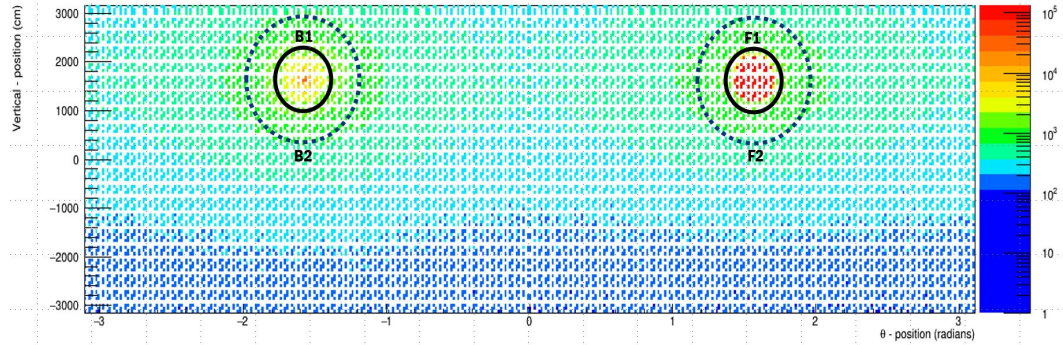
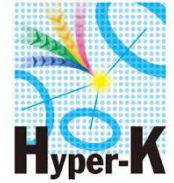
Work by Sam Jenkins, Balint Bogdan and Naomi Foster



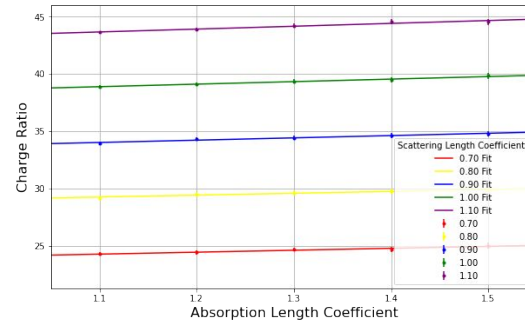
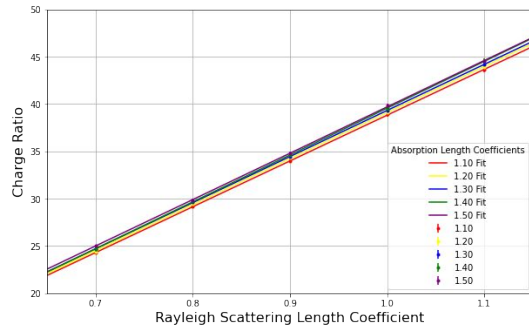
- Fibre switch procured and currently under testing, a second switch is in production
- Plan to finish final tests and tender this summer
- Prototype system for OD LED system is being developed

Optical property simulations and analysis

Work carried out by Naomi Foster, MPhys student who will be joining as a PhD student in September

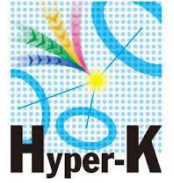


→ Simulations carried out to test sensitivity of diffuser and collimator data to absorption and scattering parameters of the water

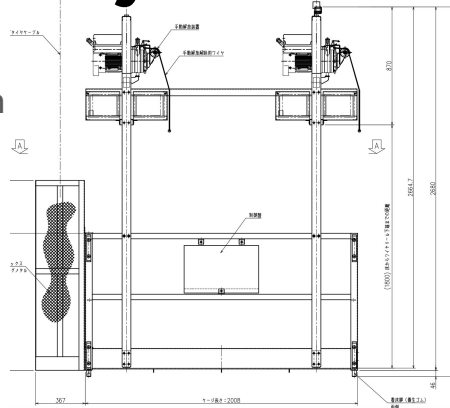


→ Ratio of charge collected within spot compared to around the injector point shows good sensitivity to scattering

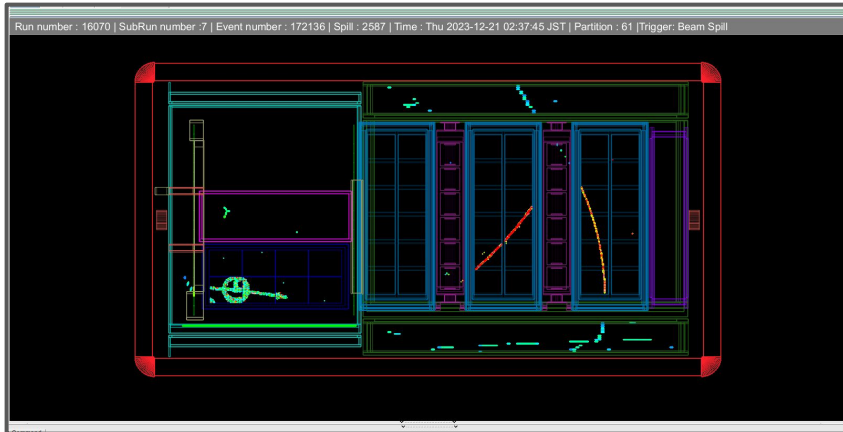
Installation of light injection system



- Work ongoing to develop an installation plan for the light injection system in the 1m wide outer detector of Hyper-K
- Plan to practise fiber installation procedure in the stairwell of Oliver Lodge
- A mock-up gondola has been built in Liverpool using the proposed design
 - Aluminium extrusion bars used
 - Wooden boxes simulate reel boxes and control console
- Providing feedback to the collaboration about the space restrictions in the gondola, particularly the height requirement



Sam not fitting in the gondola mock-up



Liverpool annual HEP meeting 2024, Ellen Sandford