Water Cherenkov Detector R&D

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Thanks to many people for inputs
See last slide for references

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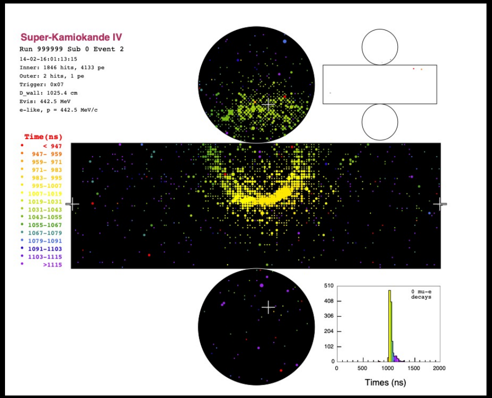
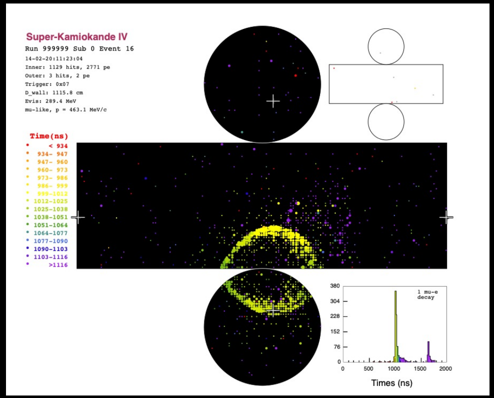
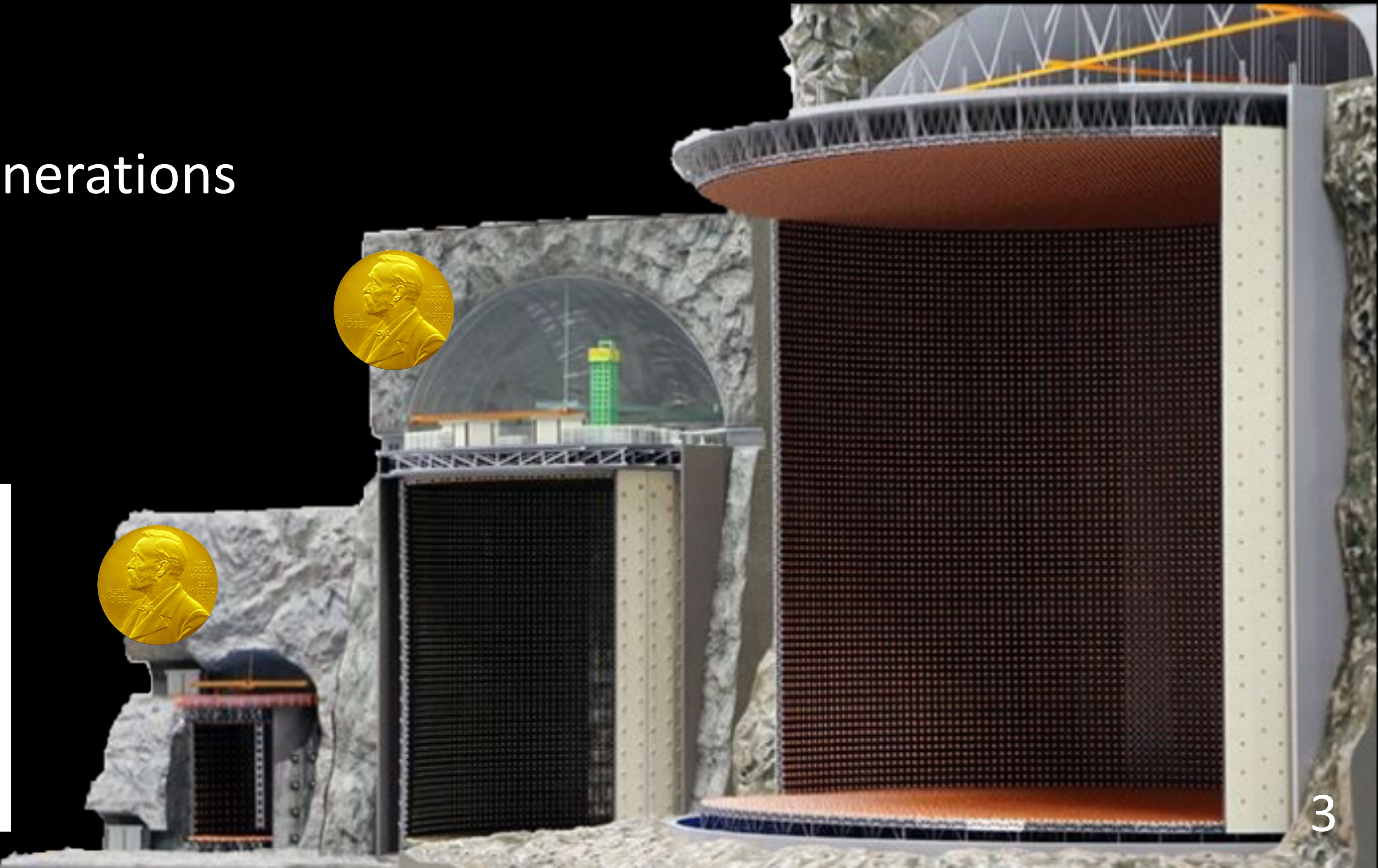
Strong bias towards Japanese program in this talk but R&D applies to:
- ESSnuSB
- THEIA (WbLS)
- WATCHMAN
- ANNIE
- CR air shower arrays eg. SWGO
- (Deep sea arrays: ORCA/ARCA)

Why Water Cherenkov?

- Water is cheap: best technology for scaling detector masses
  - Statistics for long baseline neutrino oscillations
  - Good separation EM from μ
  - Atmospheric and solar oscillations
  - Proton decay
  - Supernova burst
- Proven technology over many generations
  - PMTs up to 50cm diameter
  - Charged particle identification
  - Directionality
  - 4π detector







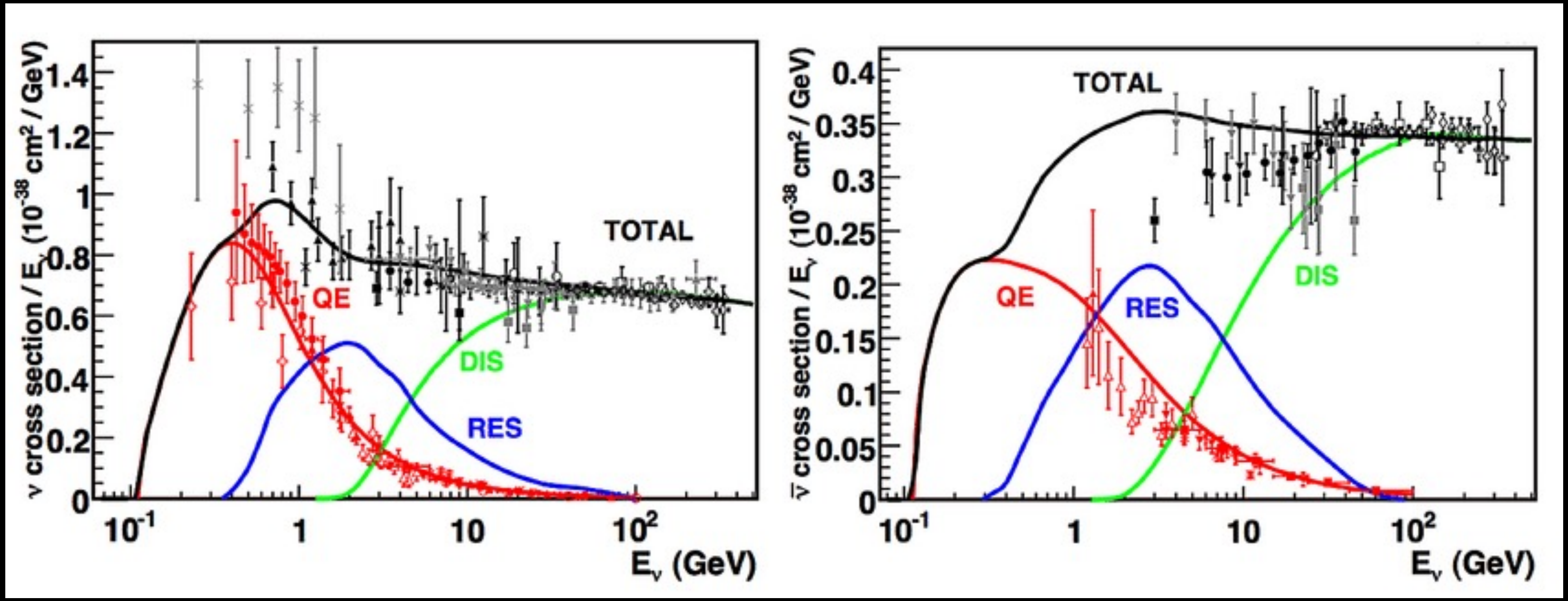
R&D Challenges

- Engineering at a large scale:
  - Hyper-K tank will be 70m deep → PMTs at the bottom must withstand 7bar
    - PMT protective covers to prevent implosion chain reaction
  - Takes months to fill and drain → require high level component reliability
  - Underwater electronics
  - Many thousands of photo-detectors
- Cost effective large area instrumentation
- Low backgrounds required
  - Underground construction of huge cavities and infrastructure
  - Water purification systems – continuous circulation for purity and temperature control (~150t/day and >80Nm^3 radon free air)
- Calibration and detector / interaction modelling for precision oscillation measurements (few % level)

Instrumentation

- More photons detected = better resolution, lower energy threshold
  - Larger PMTs (50cm used in Super-K, Hyper-K)
  - More PMTs
  - High QE PMTs
  - Light concentrators (eg Winston cones)
    - Degradation over time, reflections, angular response calibration
  - Wavelength shifter plates
    - Delayed photons from larger area
- Finer granularity, Better PMT timing = improved position resolution (mPMTs)
- PMT developments
  - Different dynode designs
  - Improve QE and pe collection efficiency
  - Control dark noise (~4kHz for 50cm PMT)
  - Wavelength separation (Dichroicon [6])

Interaction channels [1]



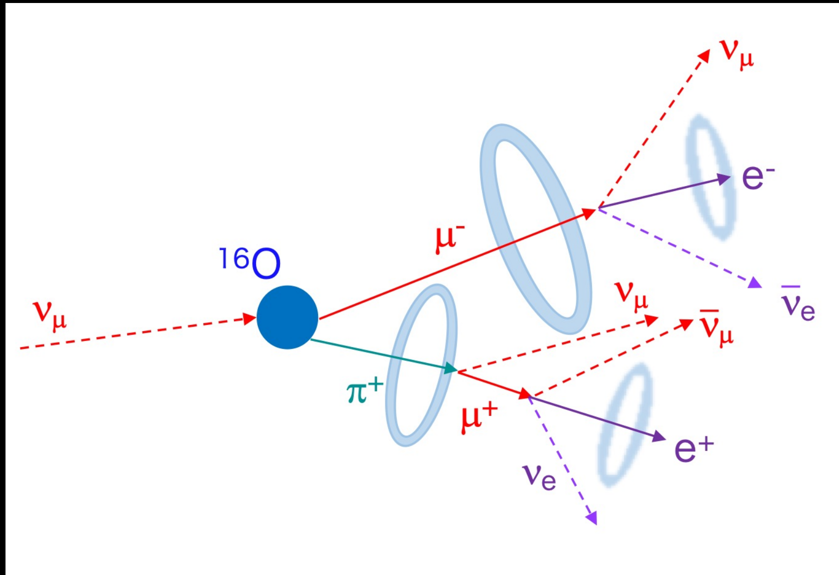
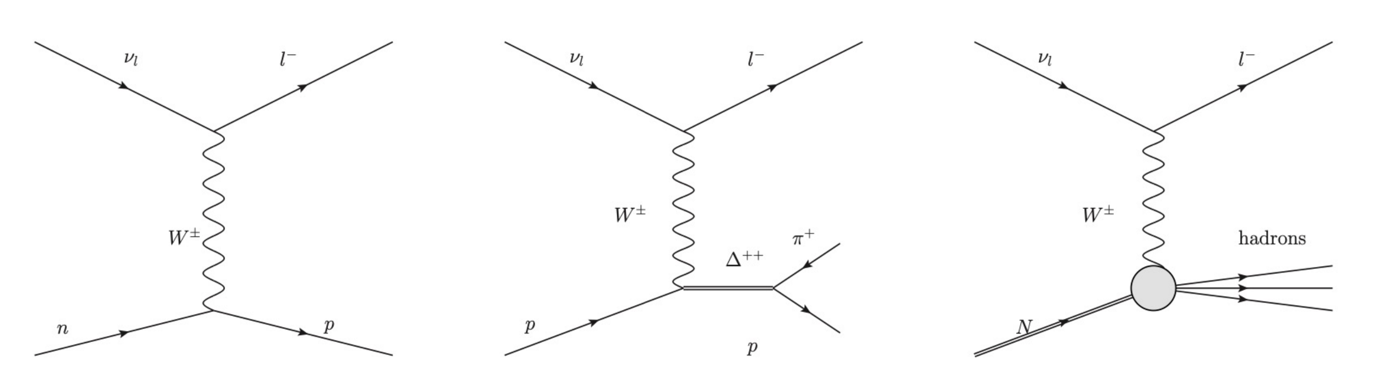
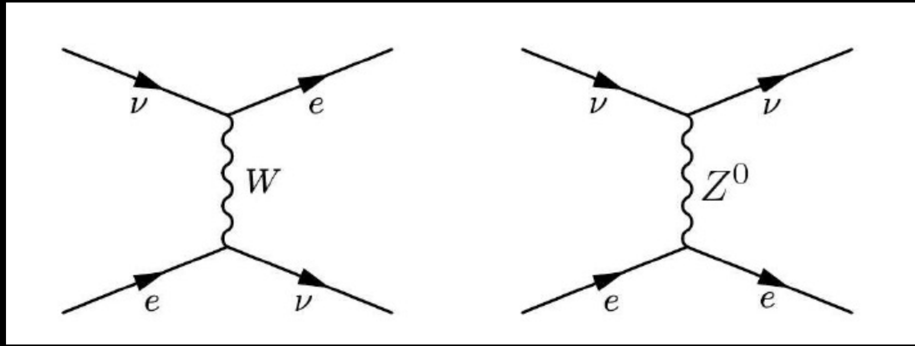


Figure 5.1: Schematic illustration of a ν_μ CC1π^+ event in SK.

Kinematic energy reconstruction



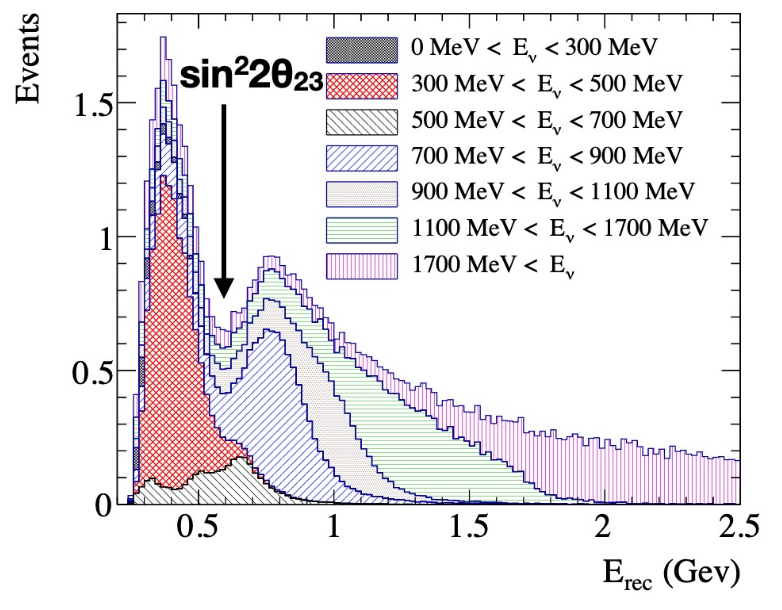
CC Quasi-Elastic | Resonant production | Deep Inelastic Scattering



Lower energies: elastic scattering
Weak energy correlation, good direction

Interaction Uncertainties (I)

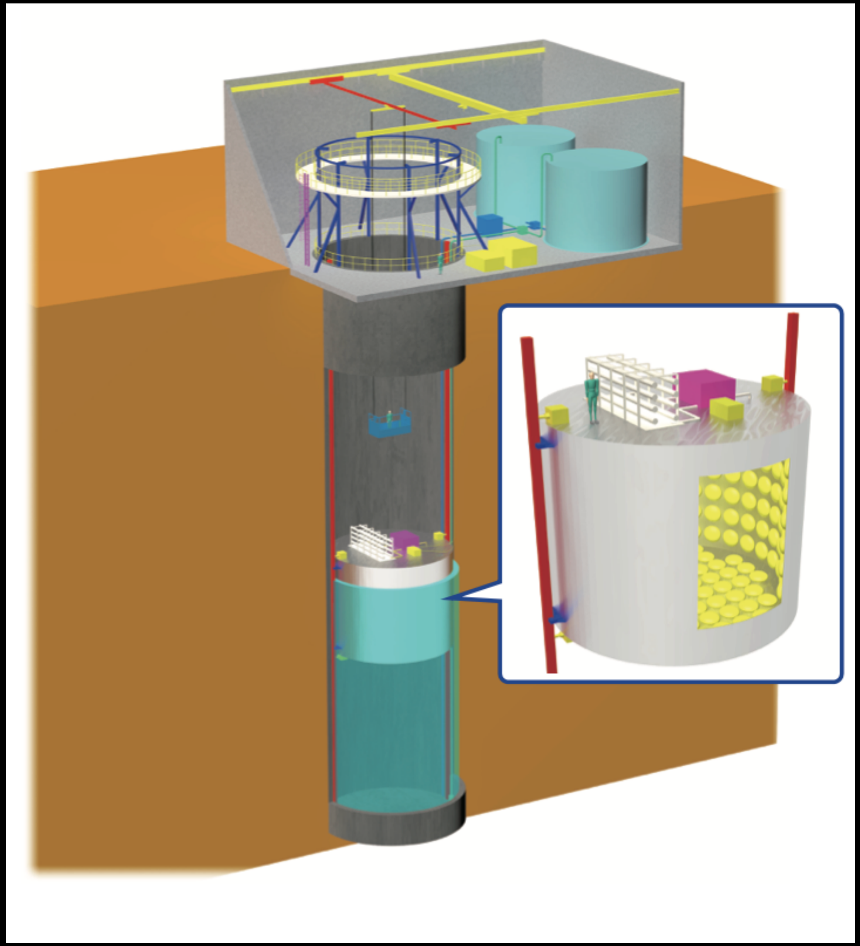
- Difference between $\sigma(\nu)$ and $\sigma(\bar{\nu})$ → CP violation
- Difference between $\sigma(\nu_e)$ and $\sigma(\nu_\mu)$ → Octant, mass hierarchy, atmospheric oscillations
  - Differences stem from subtleties in nuclear physics
  - Different models predict quite different cross-section ratios
- Measure $\nu_\mu/\overline{\nu_\mu}$ at ND but need to know about $\nu_e/\overline{\nu_e}$ to measure δ_{CP}
- Need <3% relative error on these cross-sections



- Feed-down of non-CCQE interactions (above 0.7GeV) into θ_{23} oscillation dip
- Measure these σ (as function of energy) on water to 5% precision

Interaction Uncertainties (II)

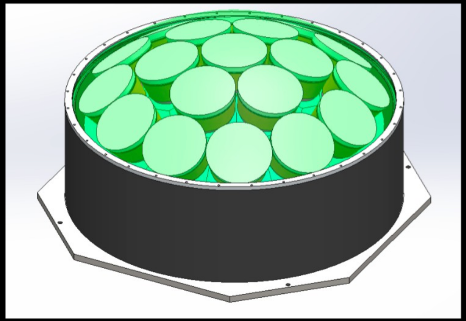
- Beams are mostly ν_μ
- Most cross-sections measured in 'tracking detectors' (not on water)
- Near WC detector for statistics (and to range out muons) but not so 'near' that pileup is a problem
  →0.5-2km
- Axis scanning technique allows to probe relationship between neutrino energy and observed final states in water Cherenkov detector
- Need to control uncertainties in kton sized detector to ~1% level

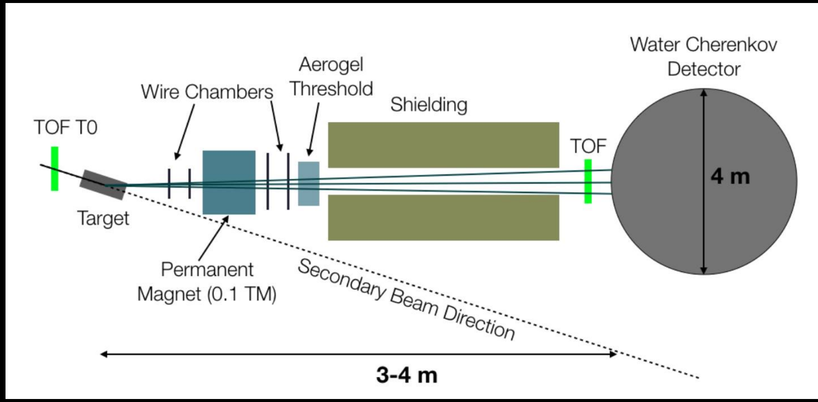


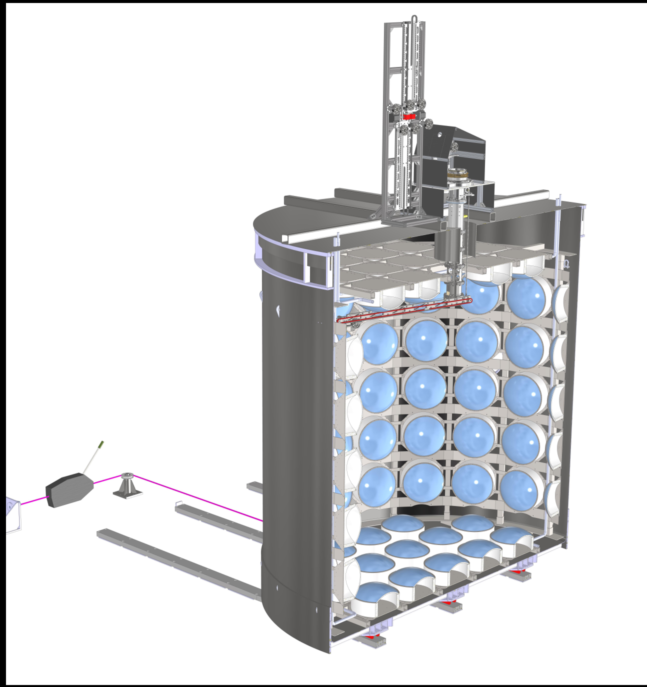
IWCD for the T2K / Hyper-K projects

A Water Cherenkov Test Experiment (WCTE) @ CERN [2],[5]

- 4 m diameter x 4 m tall water Cherenkov detector with multi-PMT photodetectors
- Build over next 2 years, operation in 2023. Infrastructure support from CERN
- Secondary or tertiary beam particles to study the response and precision calibration of WC detectors to electrons, muons, pions and protons in the 300 to 1000 MeV/c momentum range.
- Expected outputs:
  - 1%-level calibration of water Cherenkov detectors with known particle fluxes
  - Measurement of the propagation, scattering and signature of charged pions in water Cherenkov detectors.
  - Measurements of secondary neutron production by hadrons (see Gd)
  - Precise of measurements of Cherenkov light production to constrain simulation software.





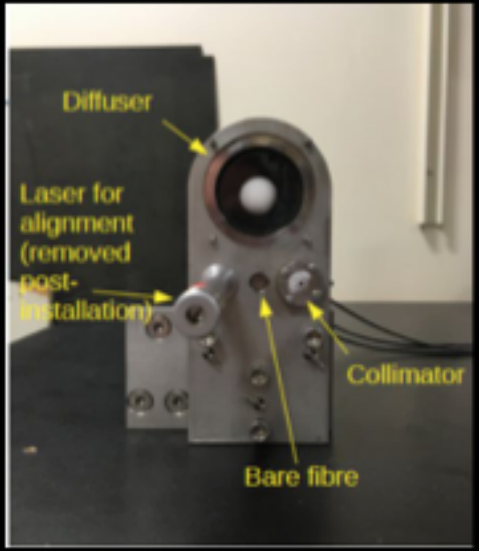


Calibration [4]

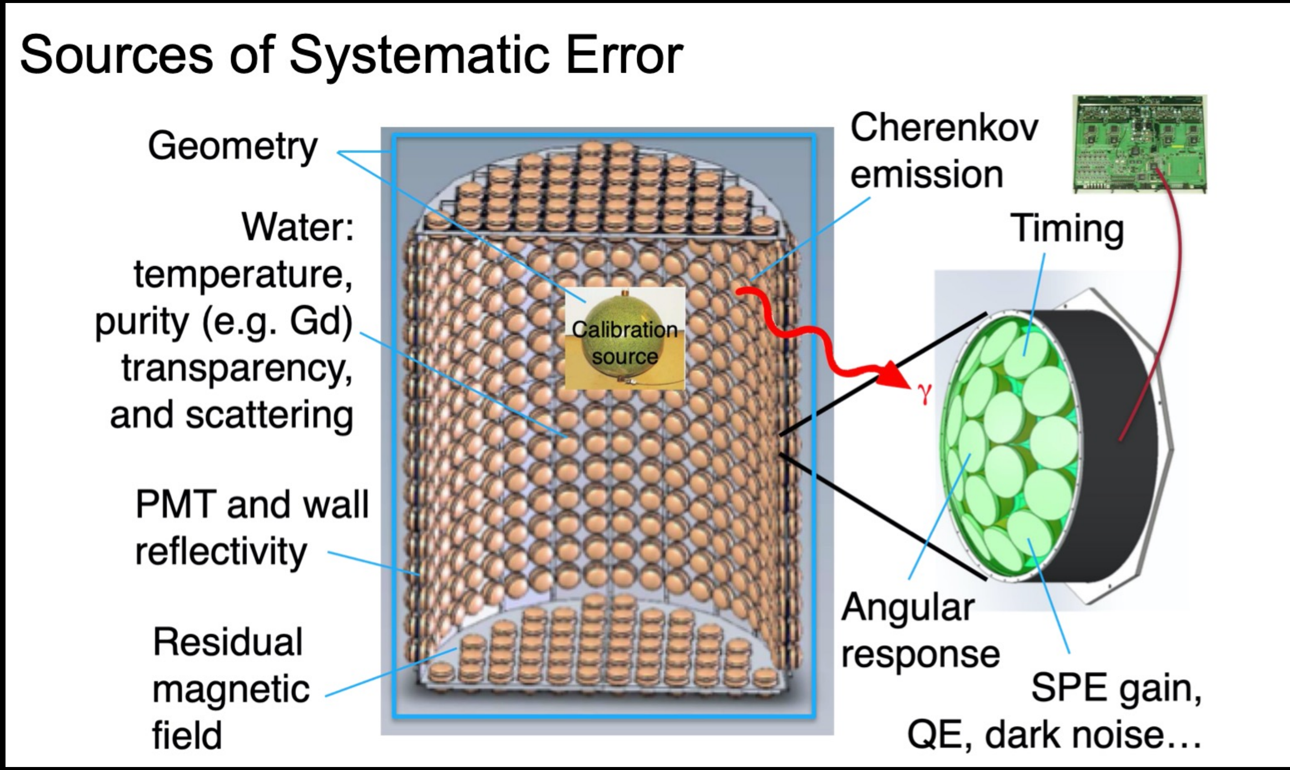
- Need to calibrate the detectors and understand their responses with ~ 1% accuracy.
- Including unbiased modelling of the energy scale, detection efficiency, particle identification and fiducial region in the event reconstruction

Components:

- Deployed sources
- Deployment system
- Fibre injection
- Photogrammetry
- PMT Pre-calibration



UK light injectors to monitor optical properties and PMT response over time



Photogrammetry [4][7]

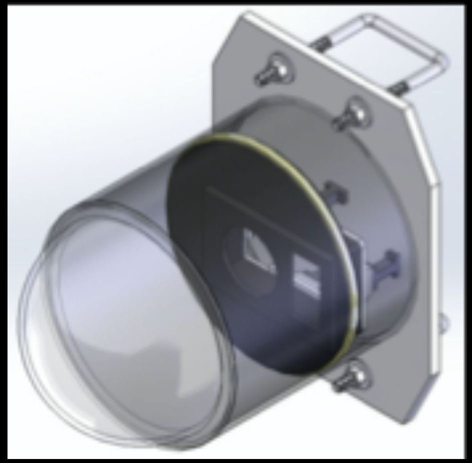
Detector geometry and source position measurements using stereoscopic reconstruction with photographs

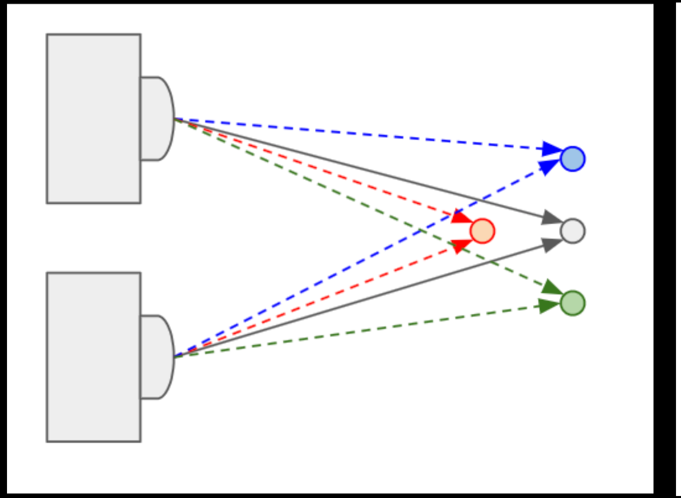
- Mitigate uncertainties due to:
  - Construction tolerances / imperfections
  - Stretching / twisting of support structure due to PMT buoyancy
  - Source deployment positioning
- Minimisation to match model to images

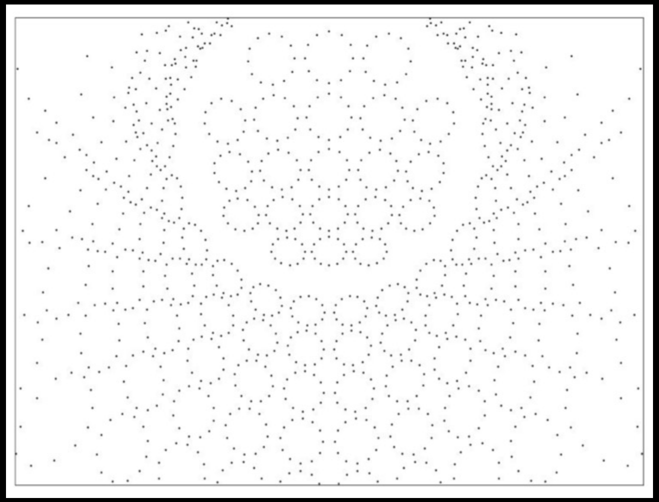
Pulsed LED for timing calibration

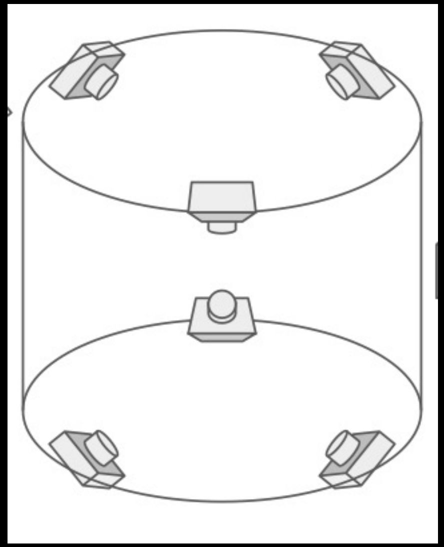
Continuous LEDs for photogrammetry

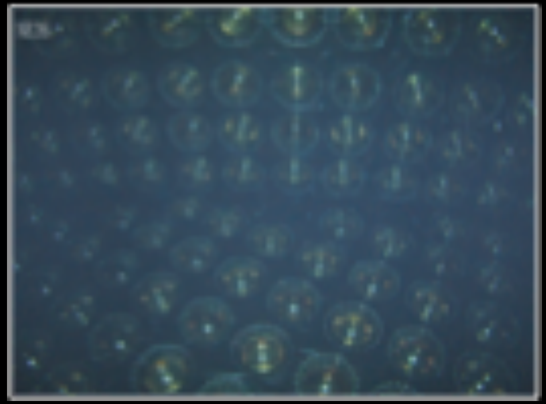
Camera unit







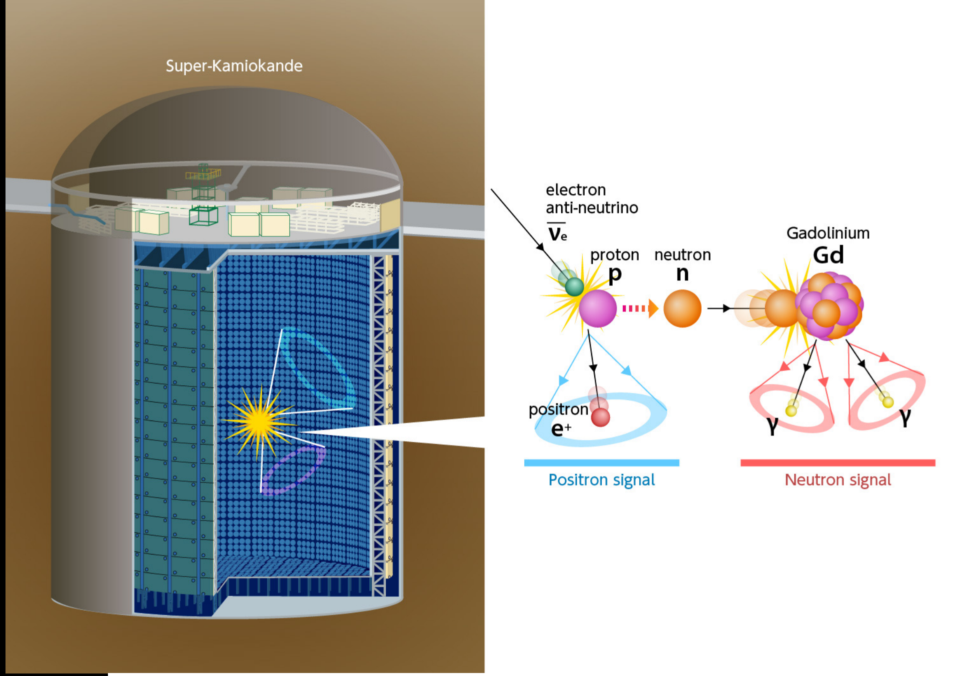


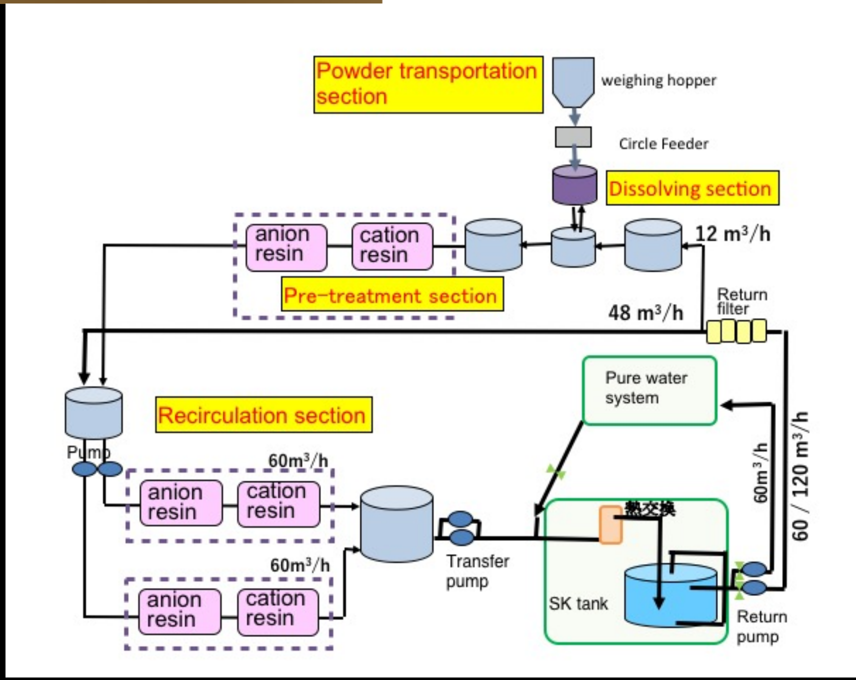


Gadolinium Doping

- n capture on H in water gives 2.2MeV gamma
- n capture on Gd gives 8.6MeV gammas
- Super-K Gd
  - 0.01% loading = 50% Gd n capture
  - 0.1% = 90% Gd n capture
- EGADS
- ANNIE
- WATCHMAN
- WCTE, IWCD, Hyper-K?

- Monitoring of Gd-loading levels in-situ
  - GAD – Gadolinium Absorbance Detector
- External neutron multiplicity measurements
- Accurate modelling

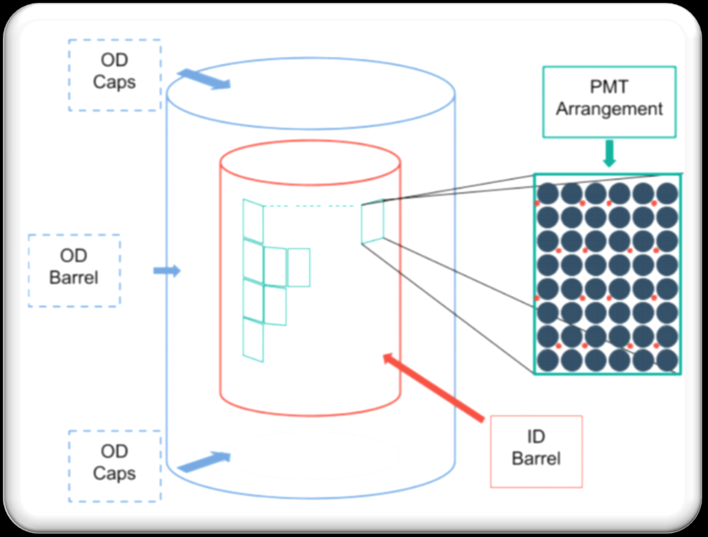


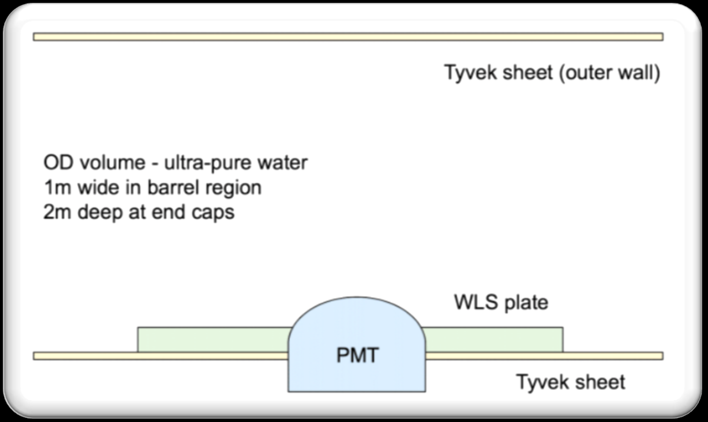


Cost effective veto [8]

- All WC detectors need Outer Detector (OD)
- Acts as both passive shield for low energy backgrounds and active veto for cosmic ray muons.
- For Hyper-K
  - Cosmic ray muon rate ~45Hz
    → Need to veto nearly 4 million muons / day
  - Baseline design: 1m thick (2m at end-caps) volume
    → 41kton water, 20,700m^2 surface area
- Cost optimized light collection with 8cm PMTs, each mounted in ~30cm sided WLS plates and all surfaces covered with high reflectivity (>90%) Tyvek
    - Optimisation of WLS plates and dopants
    - Multilayer bonded Tyvek for improved reflectivity

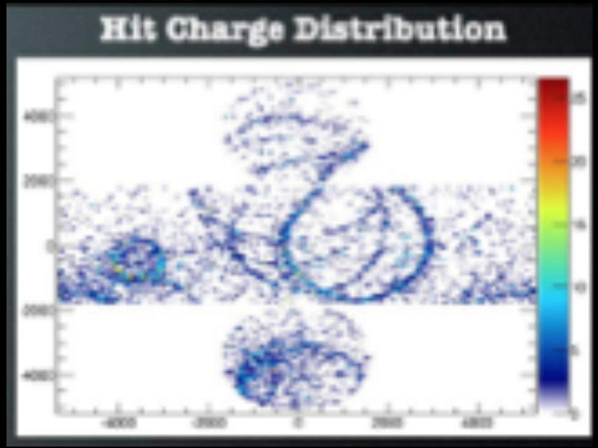
Same technology of interest to air shower array experiments

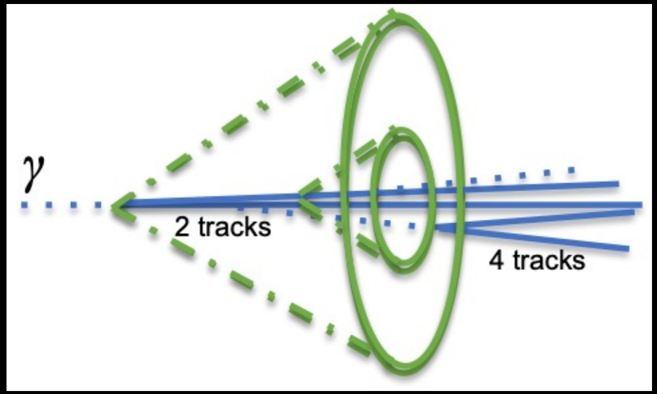




Reconstruction & Software [3]

- WATCHMAL collaboration (**Wat**er **Ch**erenkov **Ma**chine **L**earning)
  https://www.watchmal.org/
- Common challenges:
  - Cylindrical geometry
  - High resolution, sparse data
- Physics goals:
  - Reconstruct complex event topologies
  - Discrimination of e-, γ, π^0
  - Improving detector calibration and systematics
  - Speed





Applications / Impact

- Analysis techniques developed for water Cherenkov detectors may have significant overlap with other areas that use imaging techniques, including medical imaging.
- The use of Gadolinium in water Cherenkov detectors is being developed as a technology for nuclear non-proliferation monitoring.

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