Imperial College London

Current Progress and Prospects of the Hyper-Kamiokande Experiment

Vietnam Flavour Physics Conference, 21 August 2025

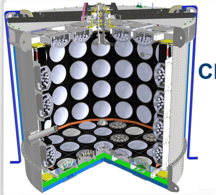
N. Prouse, Imperial College London

Introduction

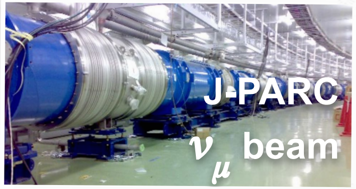
Hyper-Kamiokande (Hyper-K) is a leading neutrino experiment, scheduled to **begin operations in 2028**

Building on the success of **Super-Kamiokande and T2K,** proven **water-Cherenkov detector technology** provides **huge target mass** and **excellent particle reconstruction** to expand physics reach

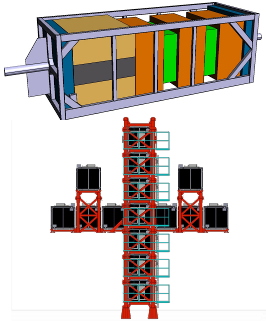
Broad & ambitious physics programme covering many neutrino sources as well as proton decay measurements.



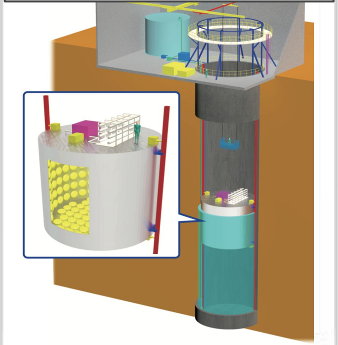
The Water Cherenkov Test Experiment (WCTE) at CERN

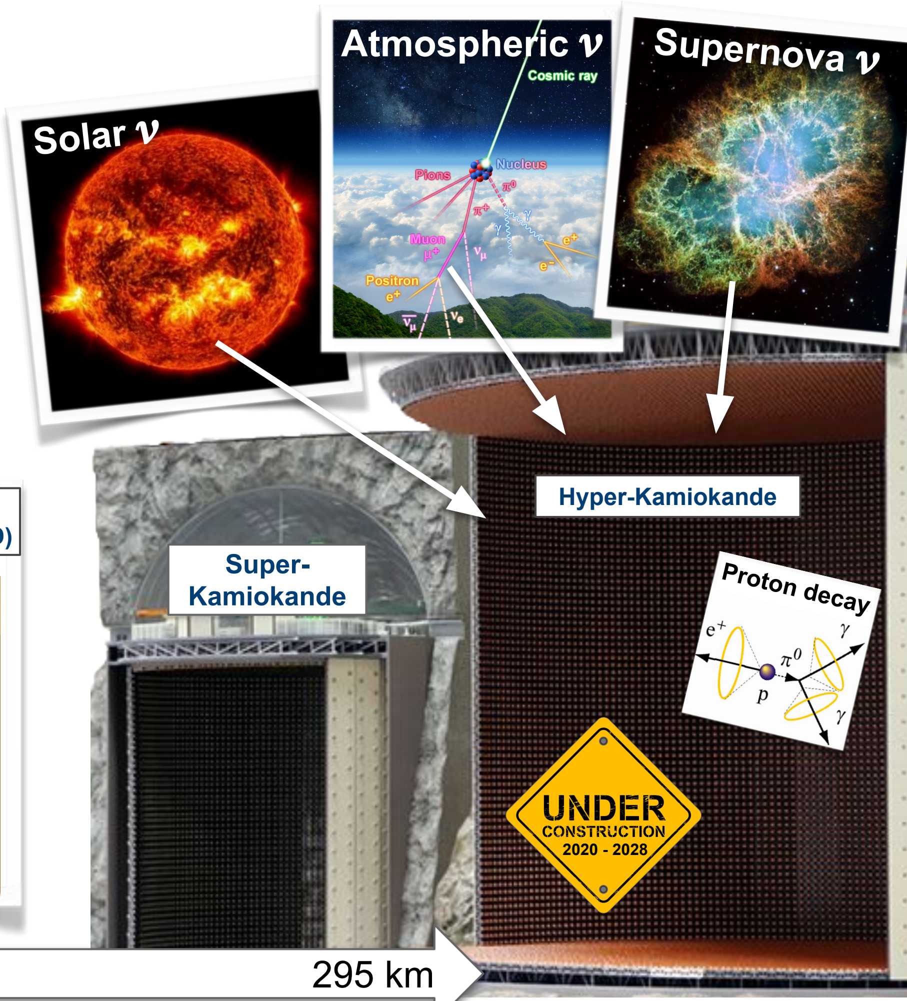


Near detectors



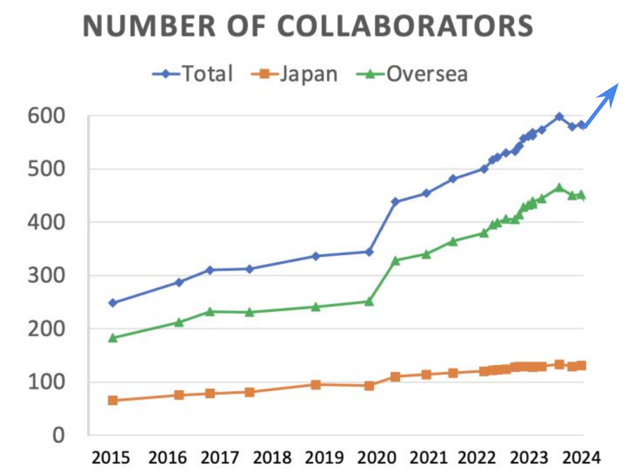
Intermediate Water Cherenkov Detector (IWCD)





280 m → 850 m → 295 km

Hyper-K Collaboration

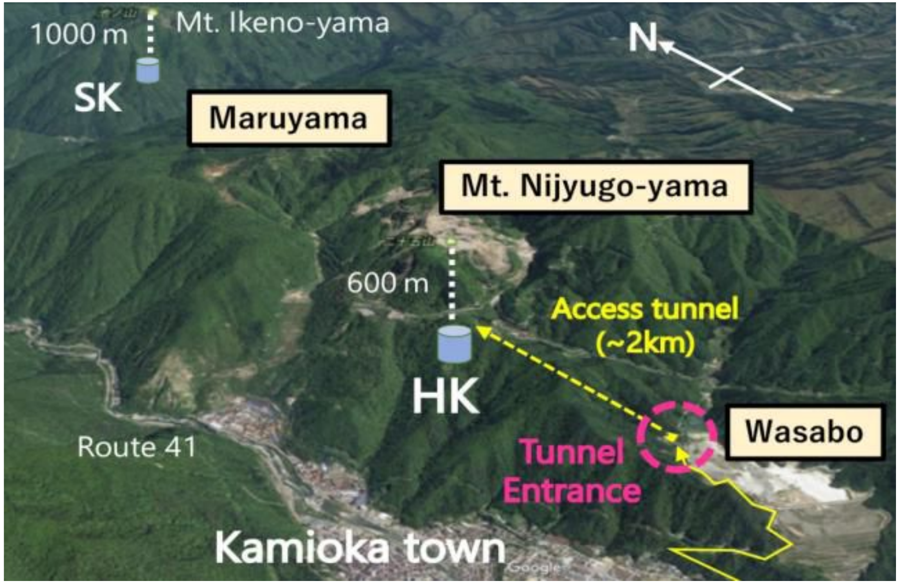


- 22 countries
- 106 institutes
- ~650 members in 2025
- Continuing to grow as construction progresses and operation approaches

Hyper-K Far Detector

New monolithic detector for unprecedented neutrino interaction detection rate

- 600 m below Mt. Nijyugo-yama near Kamioka
- 71 m tall x 68 m diameter tank
- 8 x increase in fiducial mass over Super-K



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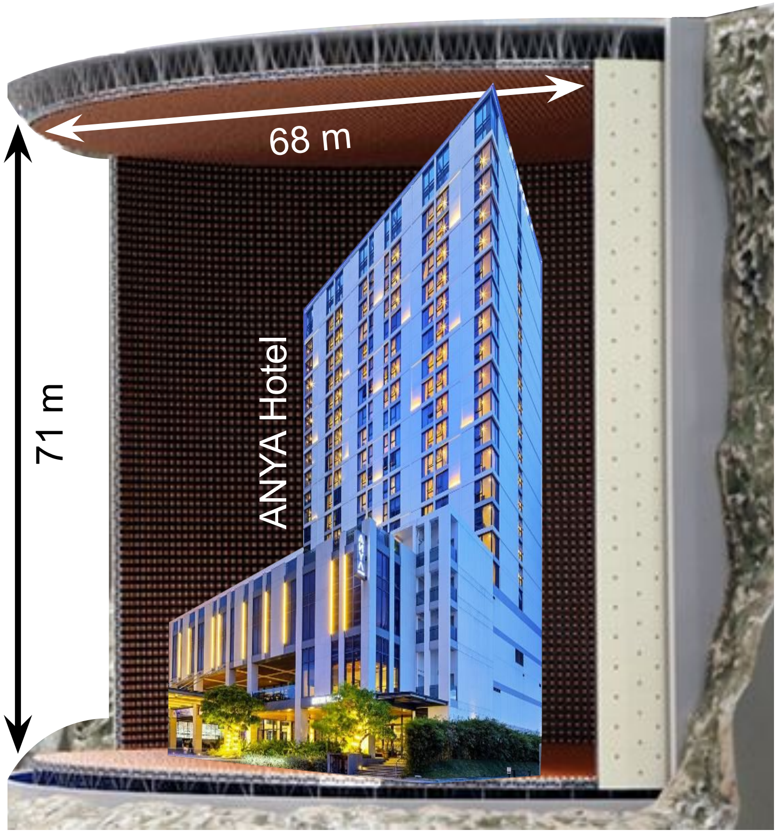

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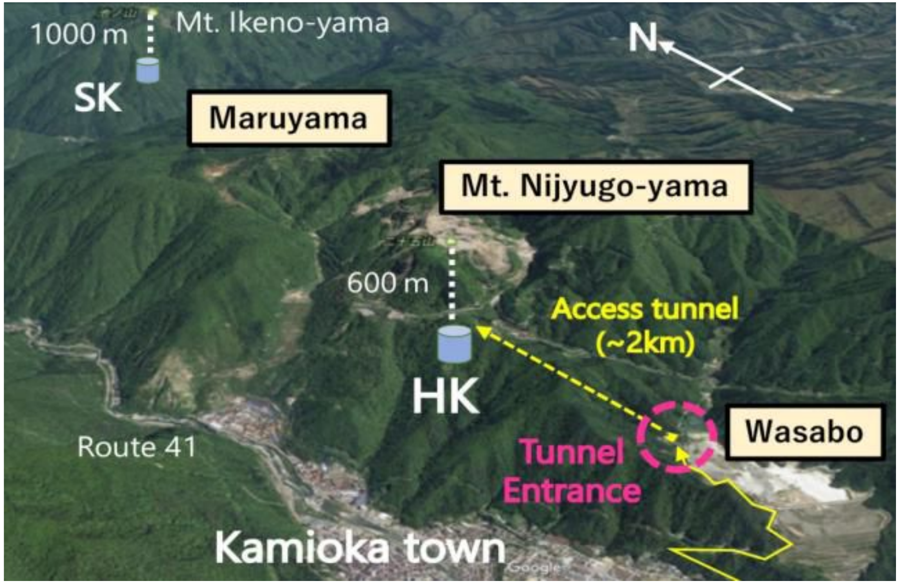

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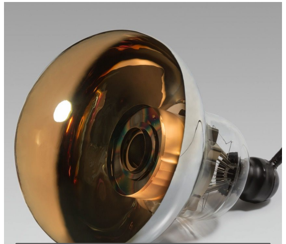
New photo-detector technology for increased sensitivity

- 20,000 50 cm B&L PMTs
  = 20% photo-coverage
  - 1.5 ns timing res. (half SK)
  - 2x efficiency of SK PMTs
- Additional coverage from multi-PMT modules
  - Also for in-situ calibration of 50 cm B&L PMTs

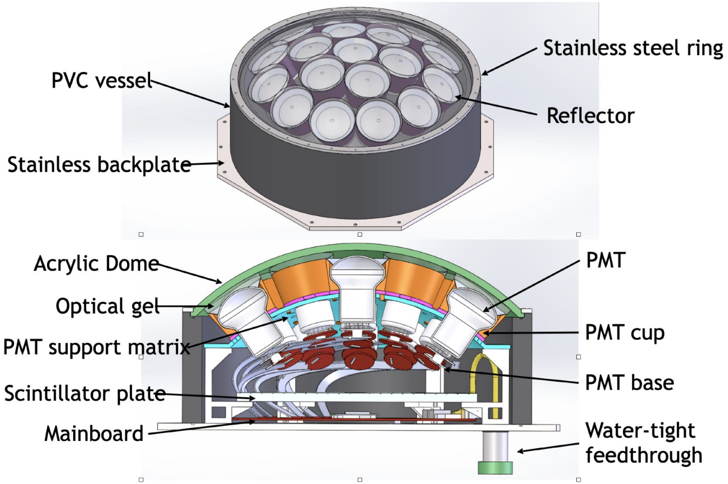


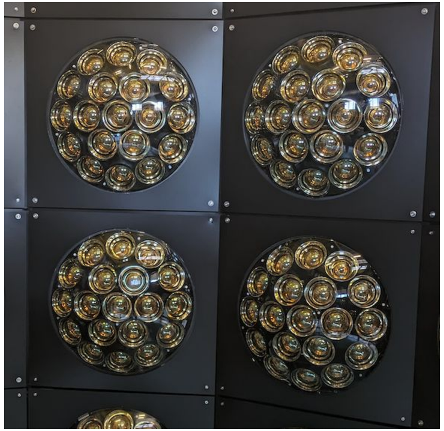
50 cm B&L PMT

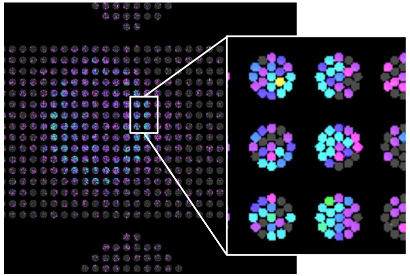
multi-PMT

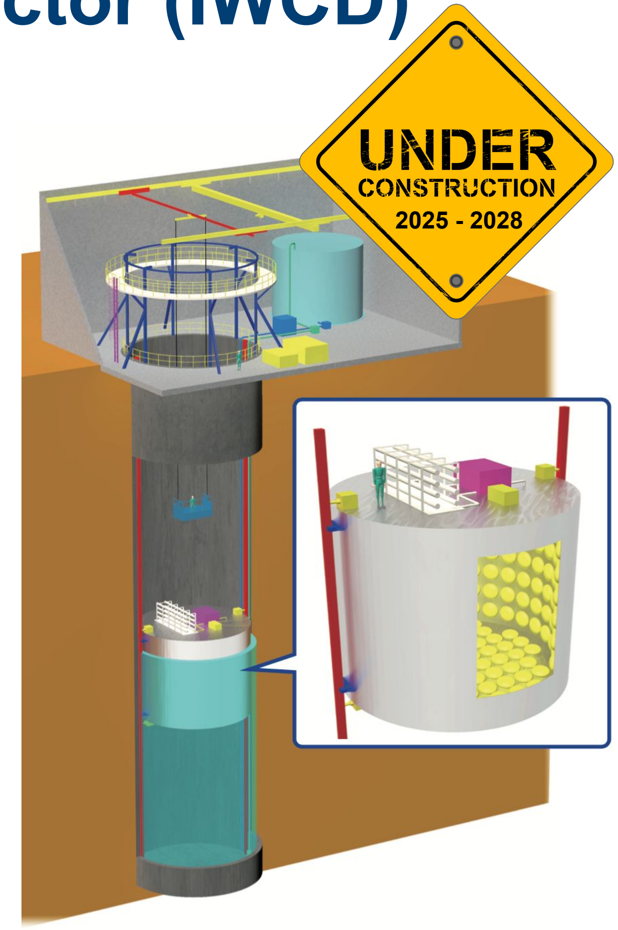
Intermediate Water Cherenkov Detector (IWCD)

- **6 m tall x 8 m diameter** tank
- **Moves vertically in ~50 m tall pit**
  - Spans off-axis angles of ν beam for **different ν energy spectra**
- **~500 multi-PMT modules** (mPMTs)
  - < 1 ns timing resolution
  - Better position resolution









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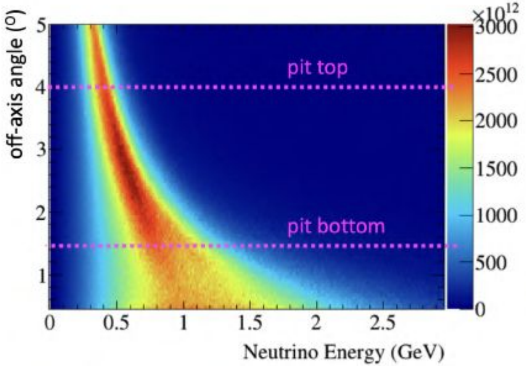
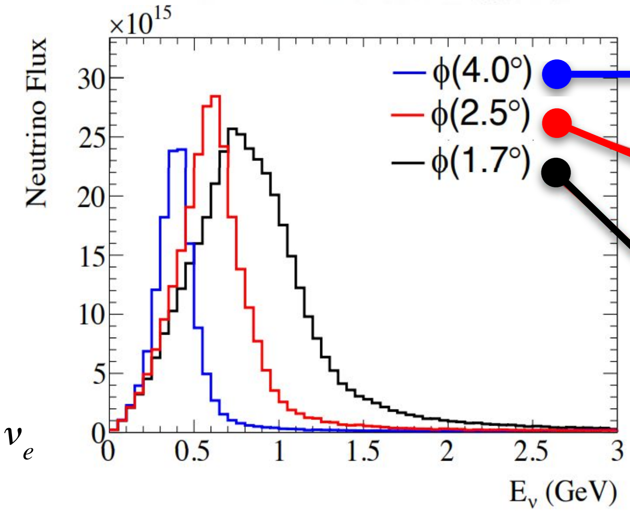
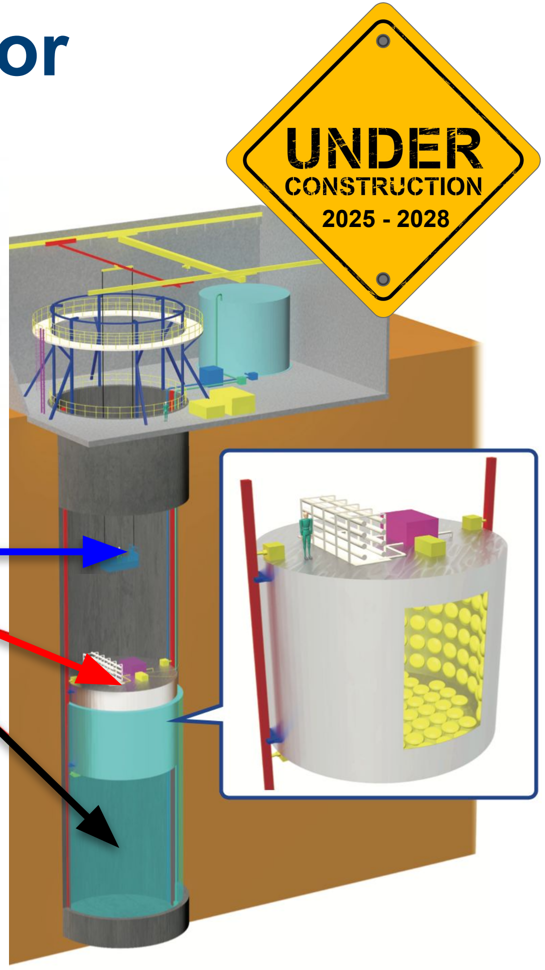
- **6 m tall x 8 m diameter** tank
- **Moves vertically in ~50 m tall pit**
  - Spans off-axis angles of ν beam for **different ν energy spectra**
- **~500 multi-PMT modules** (mPMTs)
  - < 1 ns timing resolution
  - Better position resolution
  - Directionality information
- **Measures ν_e and ν_μ flux and cross-sections** of unoscillated beam ~850 m from source
  - Determine ν_e contamination in ν_μ beam
  - Control ν_e / ν_μ cross-sections
  - Essential for precision on $\nu_\mu \rightarrow \nu_e$



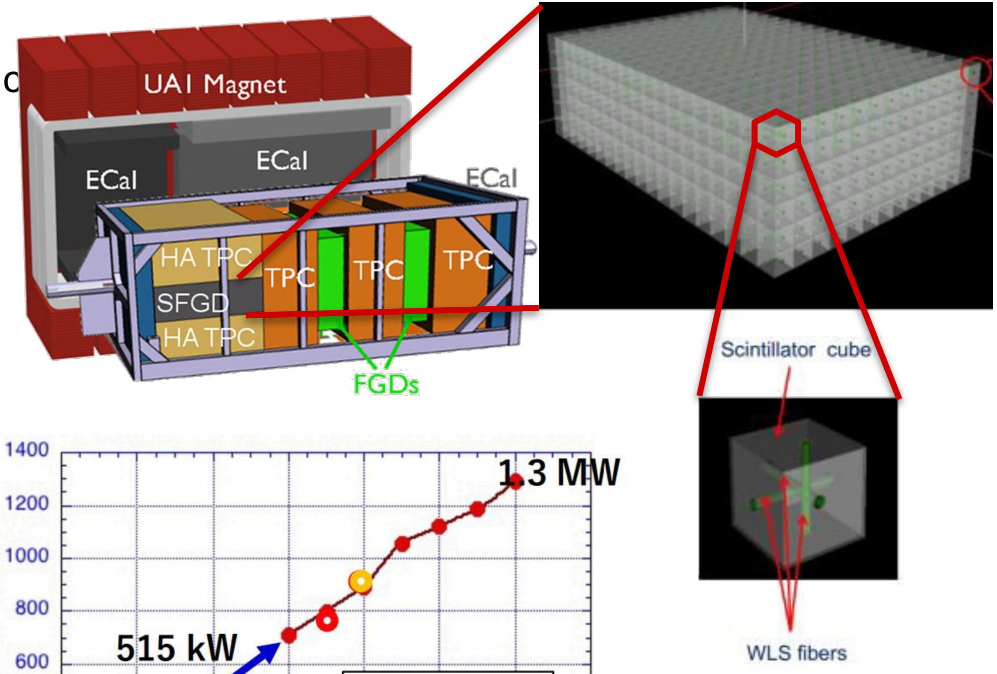




J-PARC Near Detector & Beamline Upgrades

ND280 near detector at 280 m from beam source

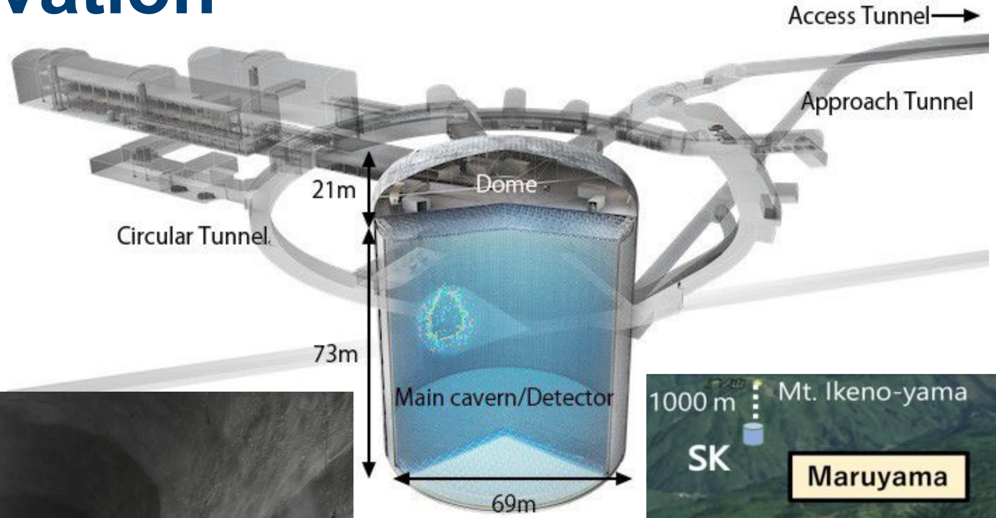
- Provides additional measurements of flux and c
- Magnetised for charge discrimination
- Detector upgrade completed in 2024
  - New Super-FGD fine grained detector, high-angle TPCs and TOF installed
  - Improves angular acceptance to 4π and decreases hadronic energy threshold

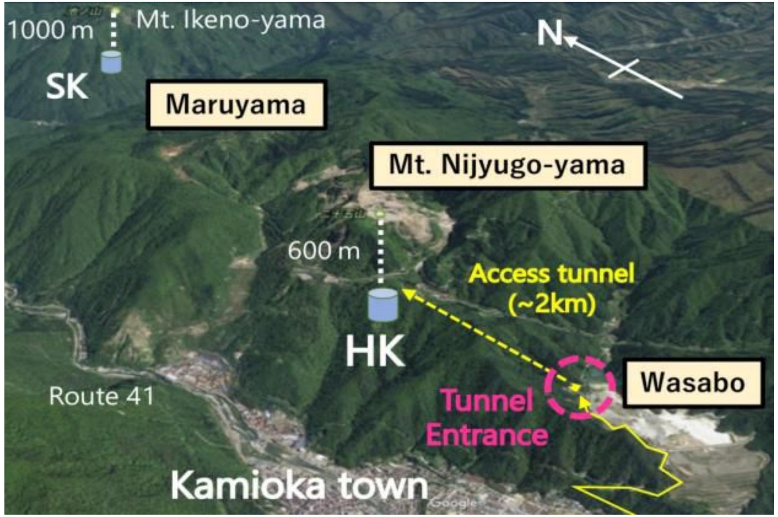


Upgraded neutrino beam

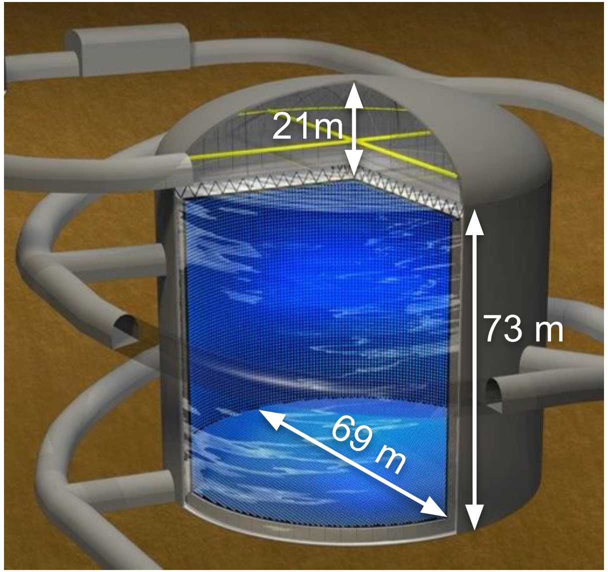
- Continuous beam power at 1.3 MW expected by start of Hyper-K data taking
  - Already exceeded 900 kW
  - T2K running stably at 800 kW in 2024
- Horn current increase from 250 → 320 kA
  - 10% increase in neutrino flux
  - 5 - 10 % reduction in “wrong sign” ν_μ / $\overline{\nu}_\mu$ contamination

Cavern Excavation





Cavern Excavation



Excavation of world's largest man-made cavern completed this summer!

94 m total height
69 m diameter

Photosensor Production & Testing

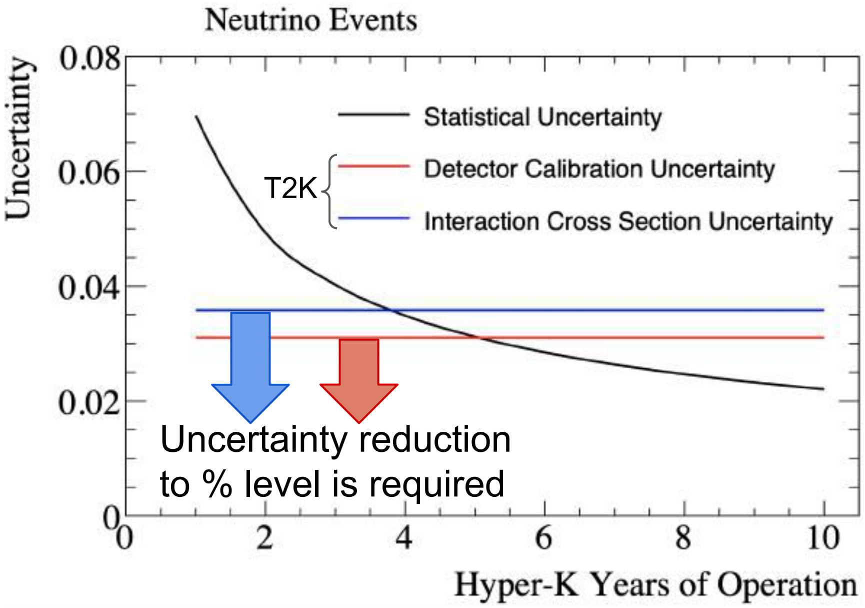
- **Mass production well underway with over 15,000 PMTs delivered**
  - QA, signal check and visual checks completed by collaborator shifts
- **Further tests taking place at dedicated PMT testing facilities**
  - Detailed measurements of PMT response
  - Long term stability tests performed in batches

Two dark rooms in Kamioka for 200 50cm PMTs at a time

IWCD Site Preparation

- Land preparation outside of J-PARC site underway
- Temporary access road completed
- Civil construction started in March
- Pit excavation starting this year
- Completion of construction in 2028

Uncertainties & Challenges



Huge rates of ν observations at Hyper-K will quickly reduce statistical uncertainty below current systematic uncertainty

Total systematic uncertainties should be reduced to below 2%

Neutrino interaction model uncertainties

Critical to CP violation measurement

- **ν & $\bar{\nu}$ production** for ν_μ (or $\bar{\nu}_\mu$) beam and contamination of $\bar{\nu}_\mu$ (or ν_μ) & ν_e
- **ν interaction cross-sections on water** for $\nu_\mu \rightarrow \nu_e$ signal and ν_μ backgrounds

Detector model uncertainties

Precision understanding required of

- **Interactions** of particles propagating in water
- **Cherenkov light production** of charged particles
- **Propagation of light** through water
- **Photosensor response** to light
- **Reconstruction** of complex and challenging event topologies

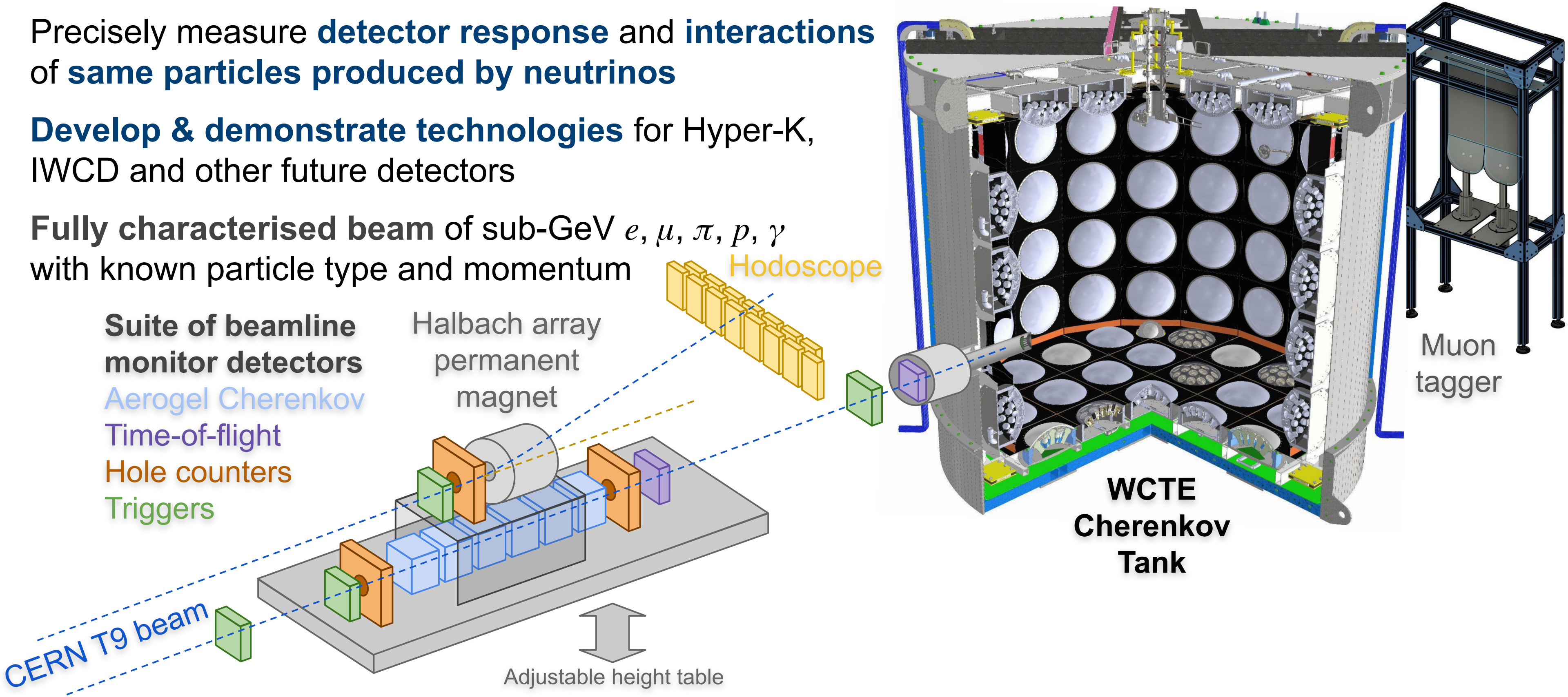
The Water Cherenkov Test Experiment (WCTE)

40-ton detector in CERN **T9 charged particle test beam**

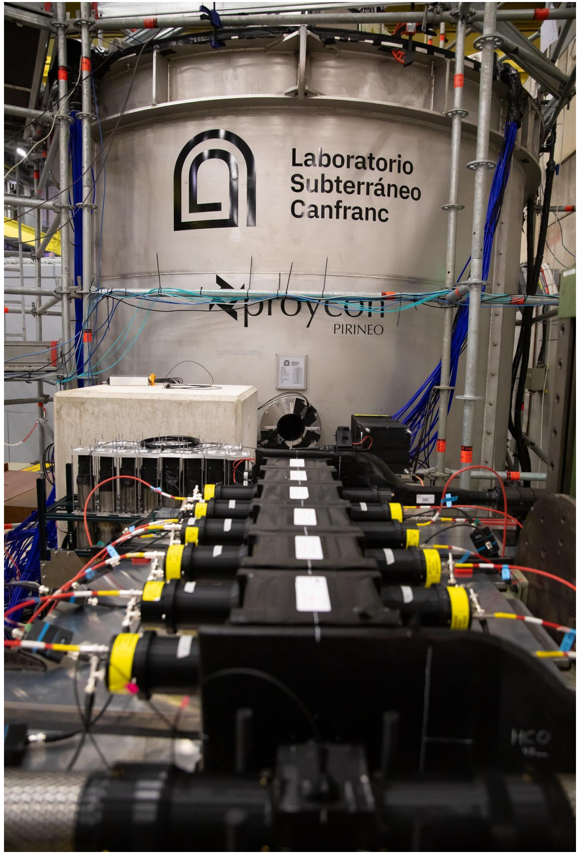
Precisely measure **detector response** and **interactions** of **same particles produced by neutrinos**

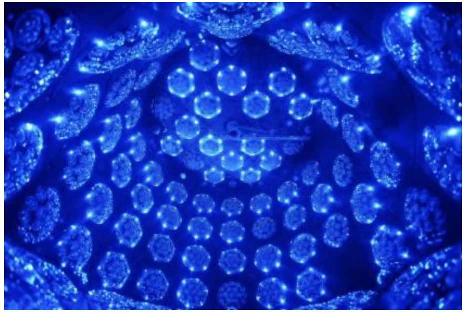
Develop & demonstrate technologies for Hyper-K, IWCD and other future detectors

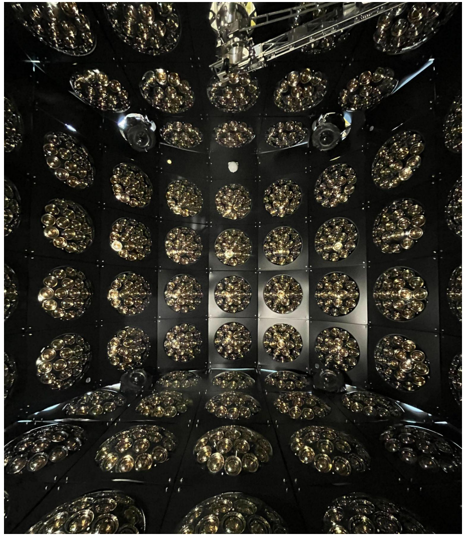
Fully characterised beam of sub-GeV e, μ, π, p, γ with known particle type and momentum



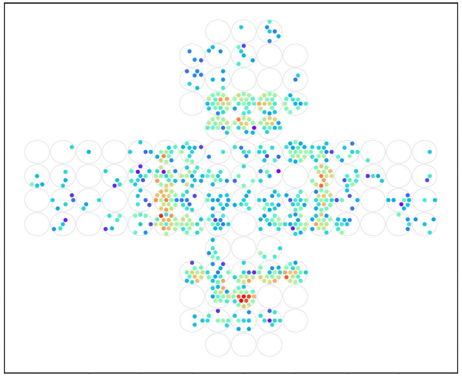
WCTE installation & operation



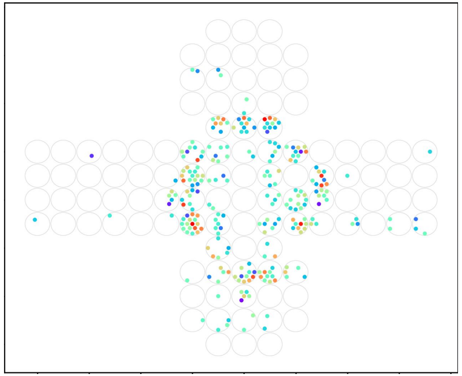




250 MeV electron



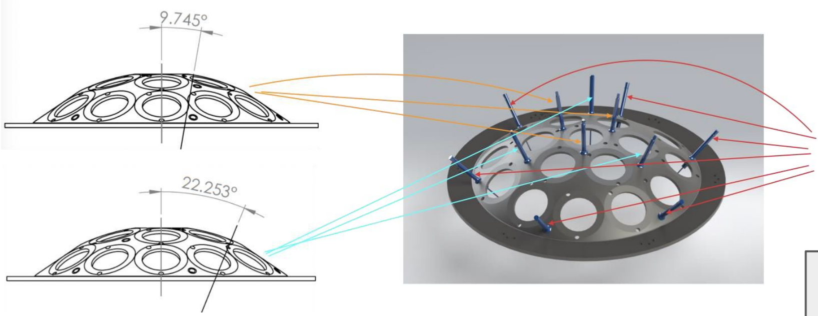
250 MeV muon



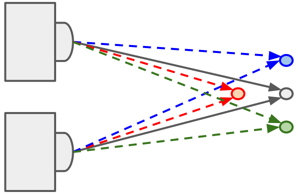
Improved Detector Calibration Techniques

Towards comprehensive calibration of all detector components

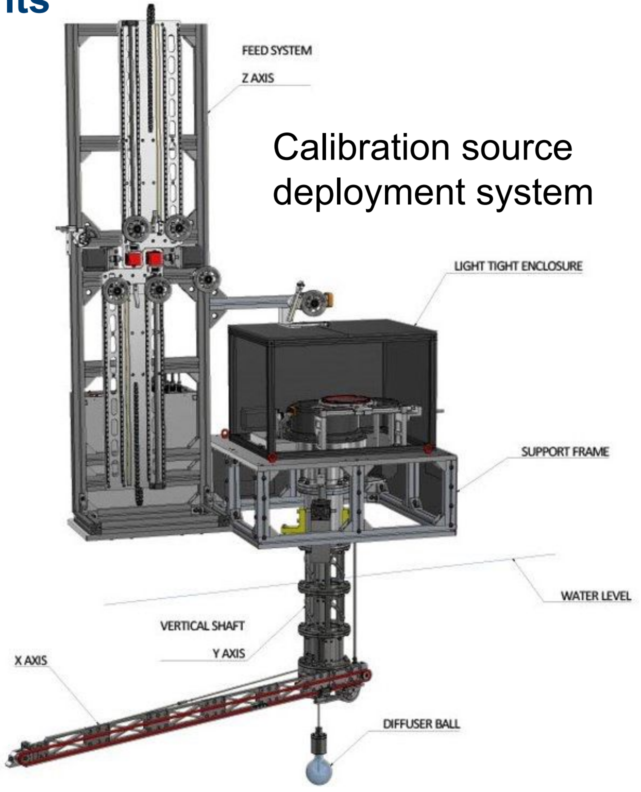
- Existing approach using control samples leaves ~1.9% discrepancy, needs to be <1% for Hyper-K
- Precise and comprehensive calibration of all detector components required to resolve degeneracies
- New calibration hardware developed and used in WCTE
- Modern techniques being developed, inspired by machine learning to handle complex high-dimensional problems



Calibration LEDs installed on mPMTs



Photogrammetry detector geometry calibration



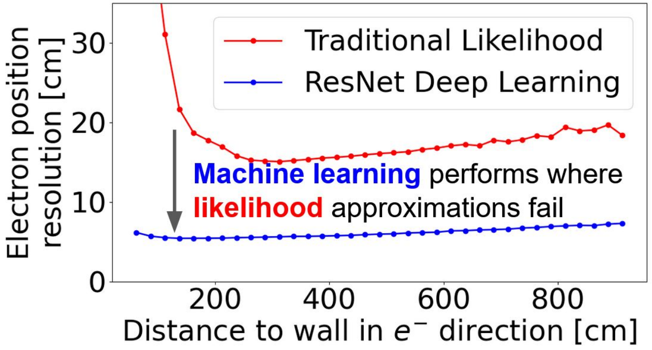
Calibration source deployment system

WCTE provides essential data-driven validation of these new methods for Hyper-K

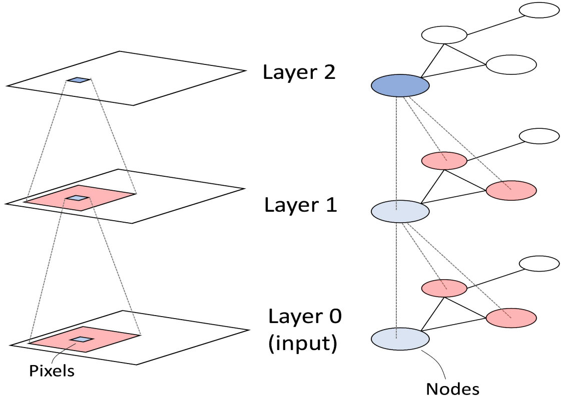
Improved Analysis with Machine Learning

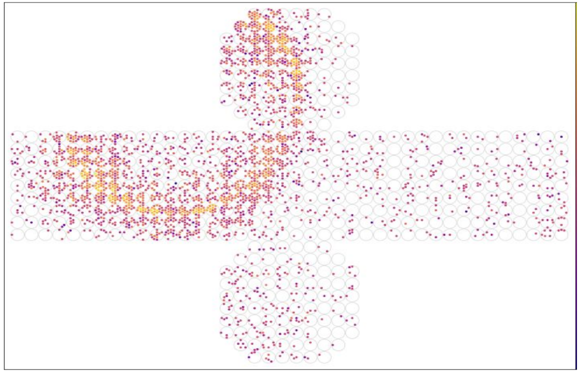
Reaching limit of traditional maximum-likelihood reconstruction methods

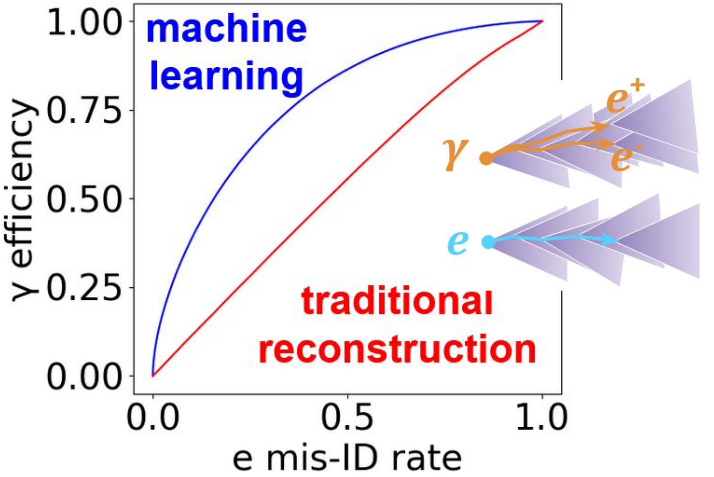
- Computation time is limiting factor:
  1M events with traditional reco. > 10,000 CPU-hours
  Physics approximations in likelihoods limit precision
- Machine Learning can reconstruct in fraction of the time:
  1M events with CNN < 100 CPU-hours or < 1 GPU-hour
  Networks learn from simulations with full physics models



CNN (image) & GNN (graph) networks







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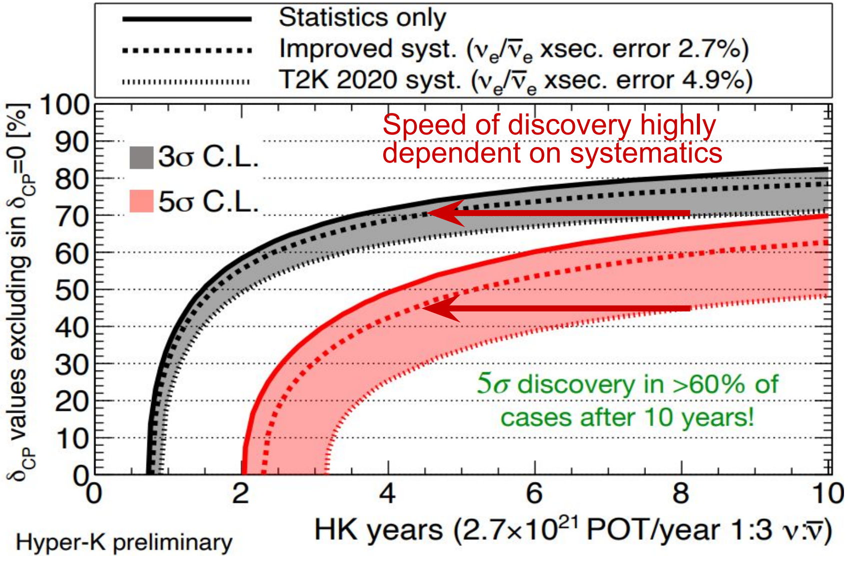
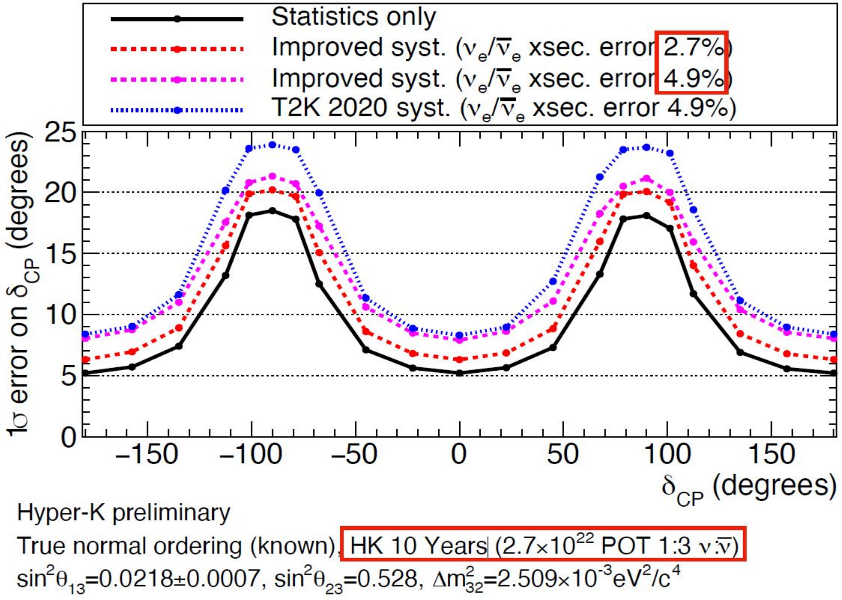
Hyper-K Oscillation Physics - Search for CP Violation





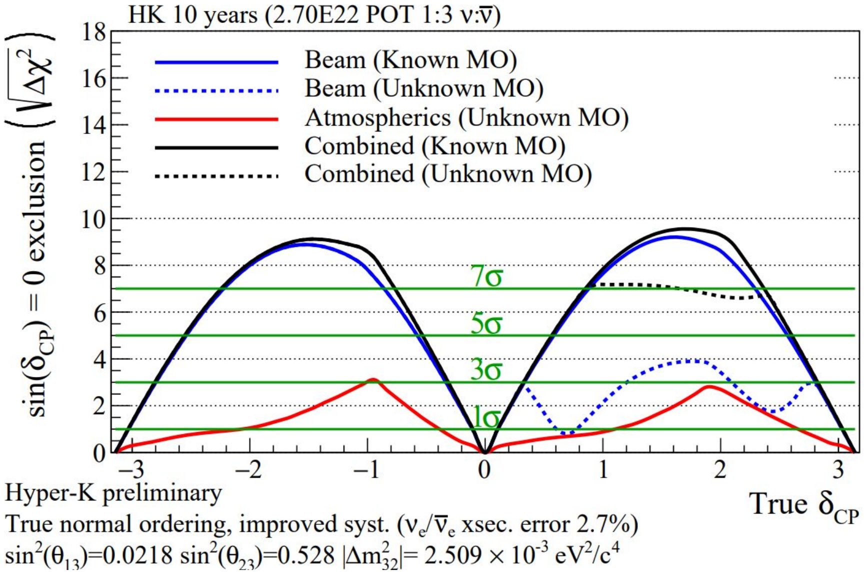
- Reduction of systematic errors has large impact on potential to discover CP violation
- 5σ discovery after 10 years for 60% of δ_{CP} values
- Below $20°$ precision on δ_{CP} across all possible true values

Hyper-K Oscillation Physics - Atmospheric ν + Beam

	$\sin^2\theta_{23}$	Atmospheric ν		Atmospheric + beam ν
Mass ordering	0.40	2.2 σ	→	3.8 σ
	0.60	4.9 σ	→	6.2 σ
θ_{23} octant	0.45	2.2 σ	→	6.2 σ
	0.55	1.6 σ	→	3.6 σ

10 years with 1.3 MW, normal mass ordering is assumed

- Atmospheric neutrinos sensitive to mass ordering through Earth's matter effect
- Beam measurements enhance sensitivity to mass ordering and atmospheric mixing angle

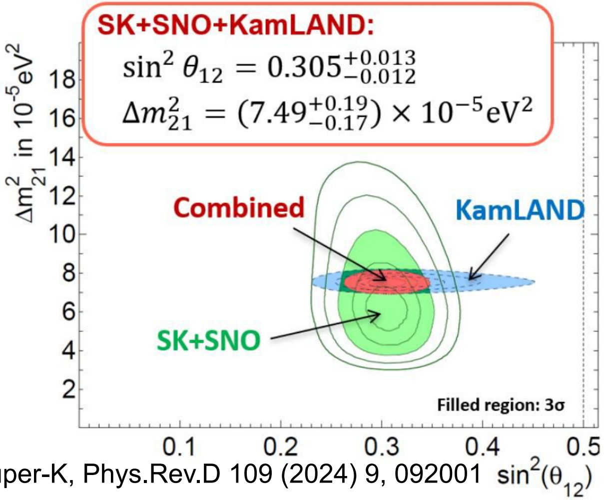


- CP violation and matter effect both create difference between ν and $\bar{\nu}$ oscillations
- Breaking degeneracies also enhances CP violation search

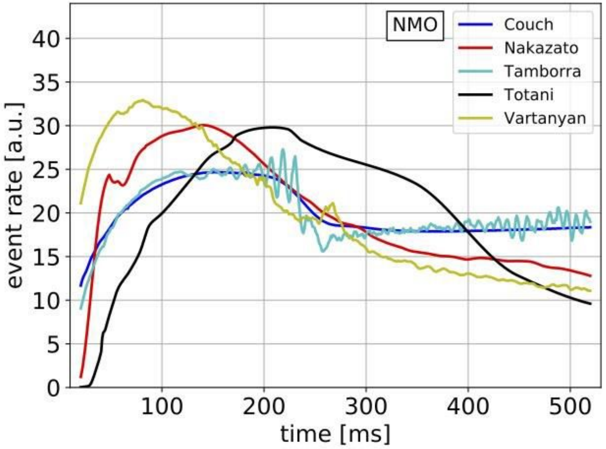
Solar & Supernova Neutrinos

Solar neutrinos

- Measure solar upturn predicted by MSW effect
- Day-night asymmetry (from matter effect through Earth)
  - Study $\sim 2\sigma$ tension in Δm^2_{21} between solar & KamLAND



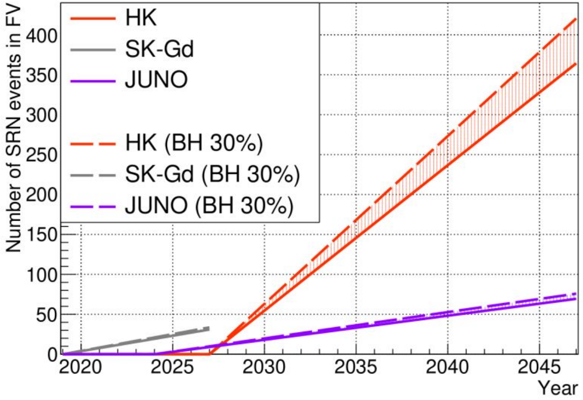
Super-K, Phys.Rev.D 109 (2024) 9, 092001



Hyper-K, ApJ. 916 (2021) 15

Supernova neutrinos

- O(100,000) ν events from a supernova in galactic centre
  - Ability to distinguish supernova models
- O(10) events from supernova in Andromeda galaxy
- Directional information provides pointing for astronomer early warning
- 4.2σ observation of supernova relic neutrinos within 10 years

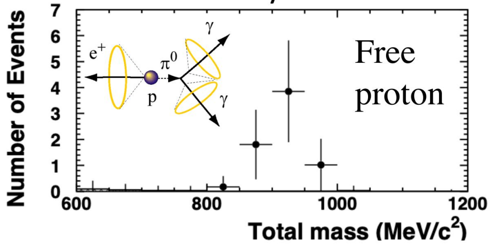


Proton Decay

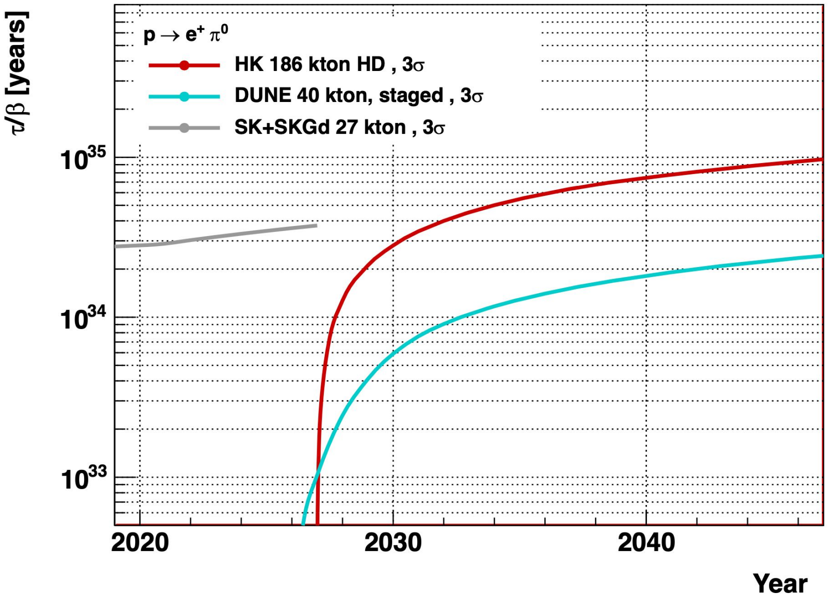
- Proton decay predicted by Grand Unified Theories
- Huge detector volume for searching for proton decays
- Push limits an order of magnitude beyond current limits

10years of HK

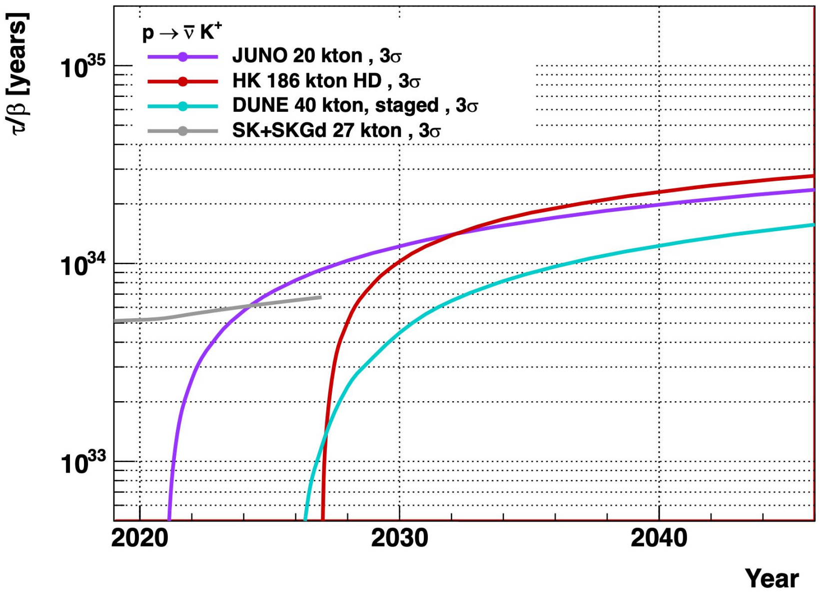
τ = 1.7 x 10^{34} years case



$p \rightarrow e^+ + \pi^0$ 10^{35} years



$p \rightarrow \overline{\nu} + K^+$ 3×10^{34} years



Summary

Hyper-K construction progressing towards operation in 2028

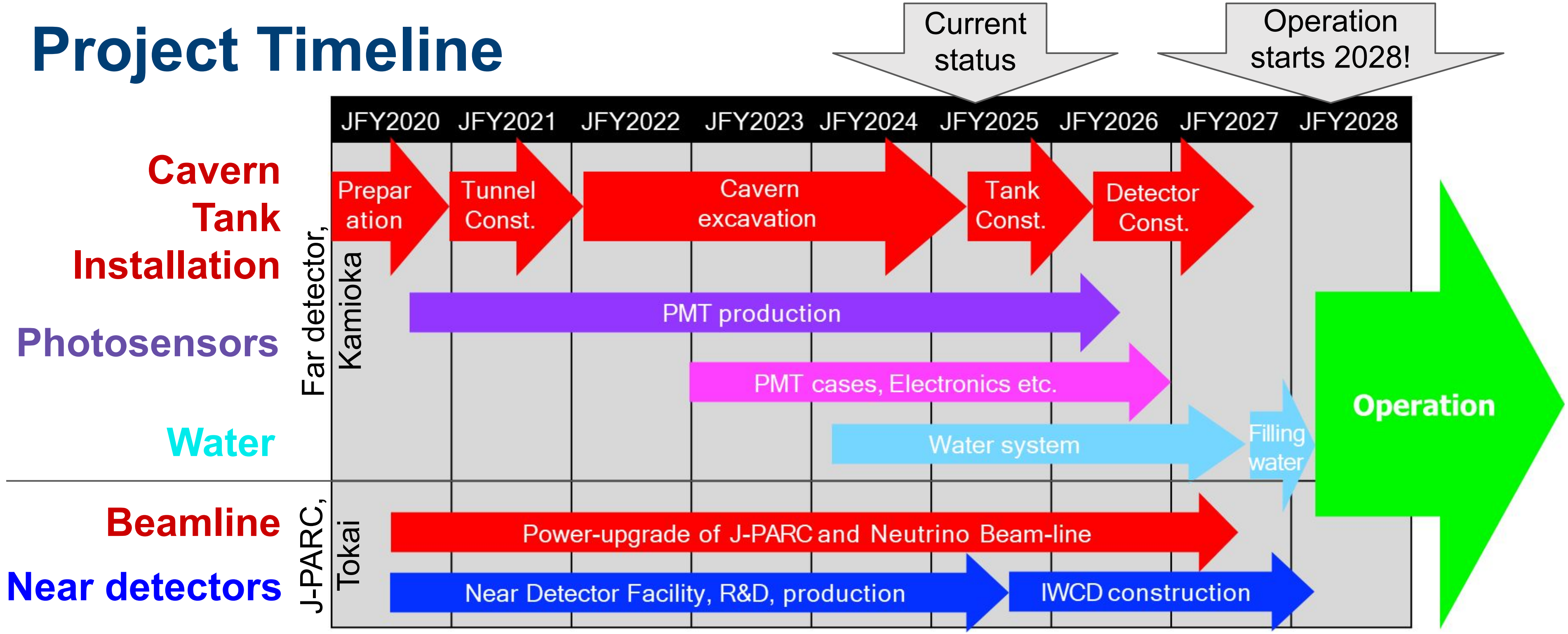
- New far detector provides order of magnitude increase in observation capabilities over Super-K
- New intermediate detector, upgraded near detector, improved calibration and analysis to reduce systematic uncertainties

Wide-ranging potential for physics discovery in the next decade

- First precision measurement in search for CP violation in leptons
- Unprecedented neutrino astrophysics & nucleon decay

Backup

Project Timeline

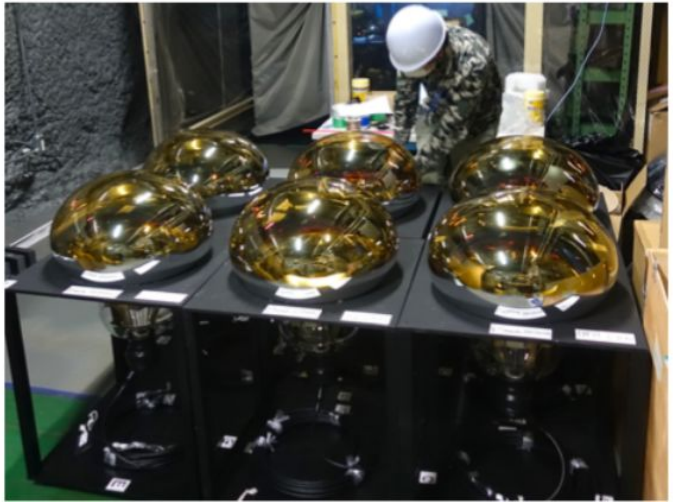


Latest construction timeline including updated far-detector & cavern designs

- Huge engineering feat excavating the main cavern
- Additional support added for safety → extended excavation time by 6 months
- Redesigned tank roof → extended construction by 5 months

✤ Production of the 50cm PMTs has started on time

Visual inspection & Testing signal for all the PMT is on-going

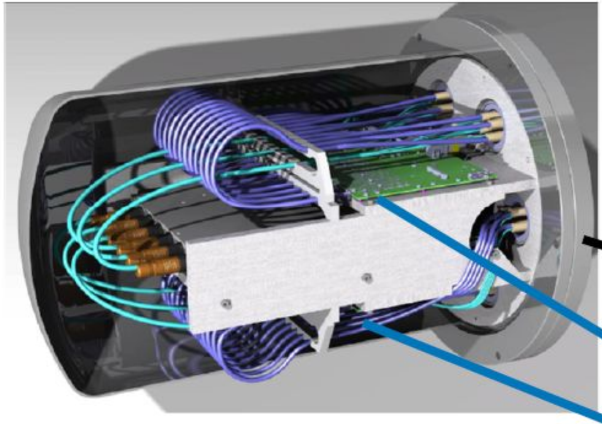


PMTs for the Inner Detector

	Super-K	Hyper-K
Number of PMTs	11,129 50cm PMTs	20,000 50cm PMTs (JPN) (+ additional PDs (Oversea))
Photo-sensitive Coverage	40 %	20 %
Single photon efficiency /PMT	~12%	~24%
Dark Rate /PMT	~4 kHz (Typical)	4 kHz (Average)
Timing resolution of 1 photon	~3 nsec	~1.5 nsec

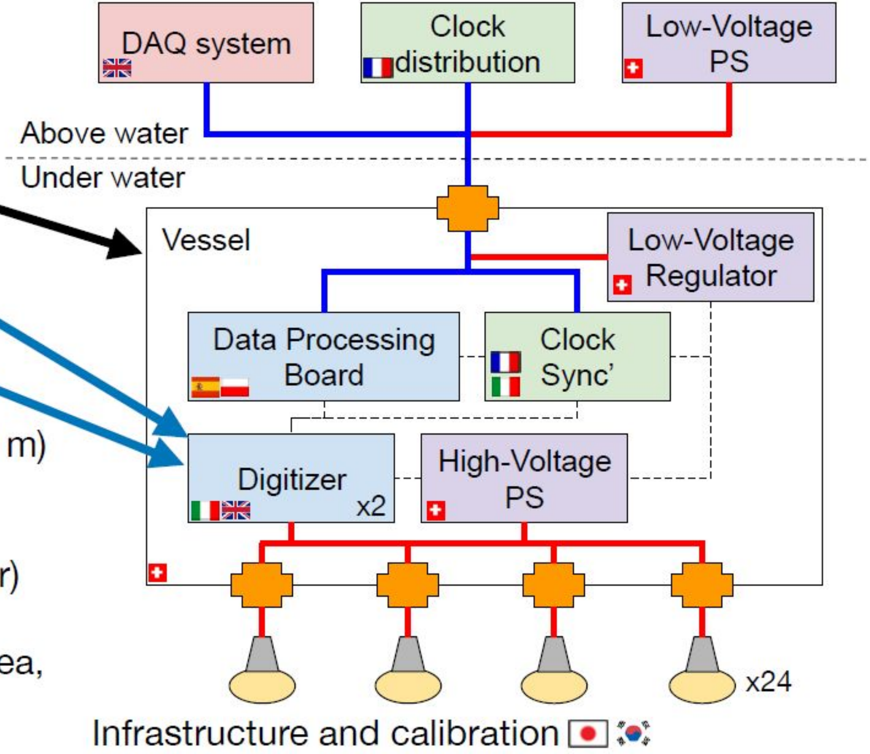
R&D for the 50cm PMT covers is in progress (material test, fabrication method, full validation under water pressure etc.)

Underwater electronics vessel

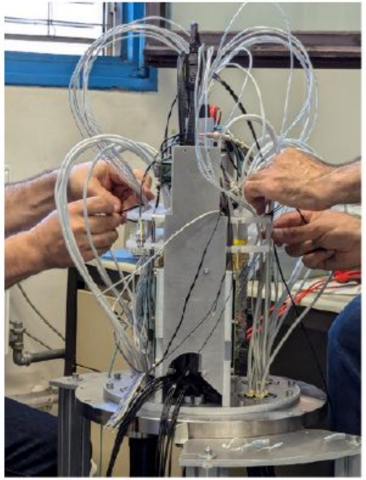


Underwater digitisation electronics
- Short distance between PMT and electronics (<20 m)
- All signals must be brought to vessel
- Data sent back to DAQ (out of water)
- Different from Super-Kamiokande (smaller detector)

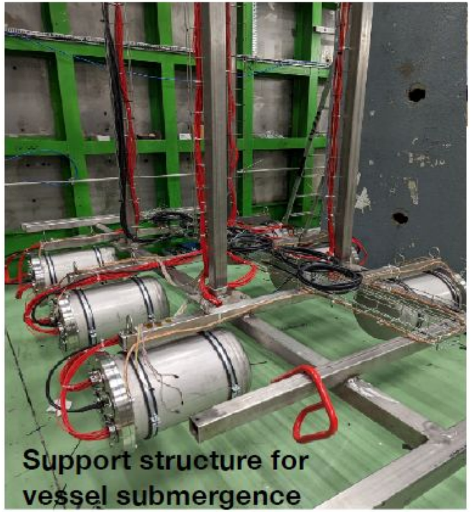
International collaboration: France, Italy, Japan, Korea, Poland, Spain, Switzerland, UK



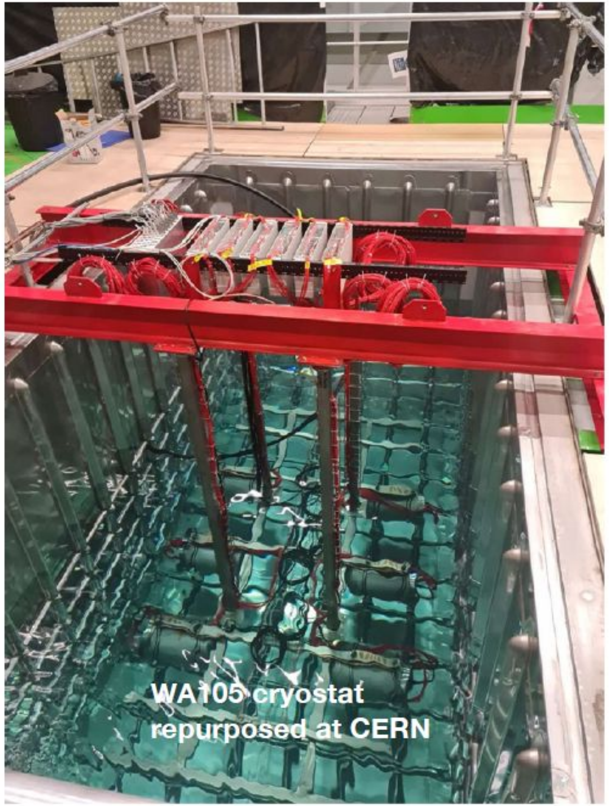
Underwater tests and assembly at CERN



Assembly test-stand



Support structure for vessel submergence



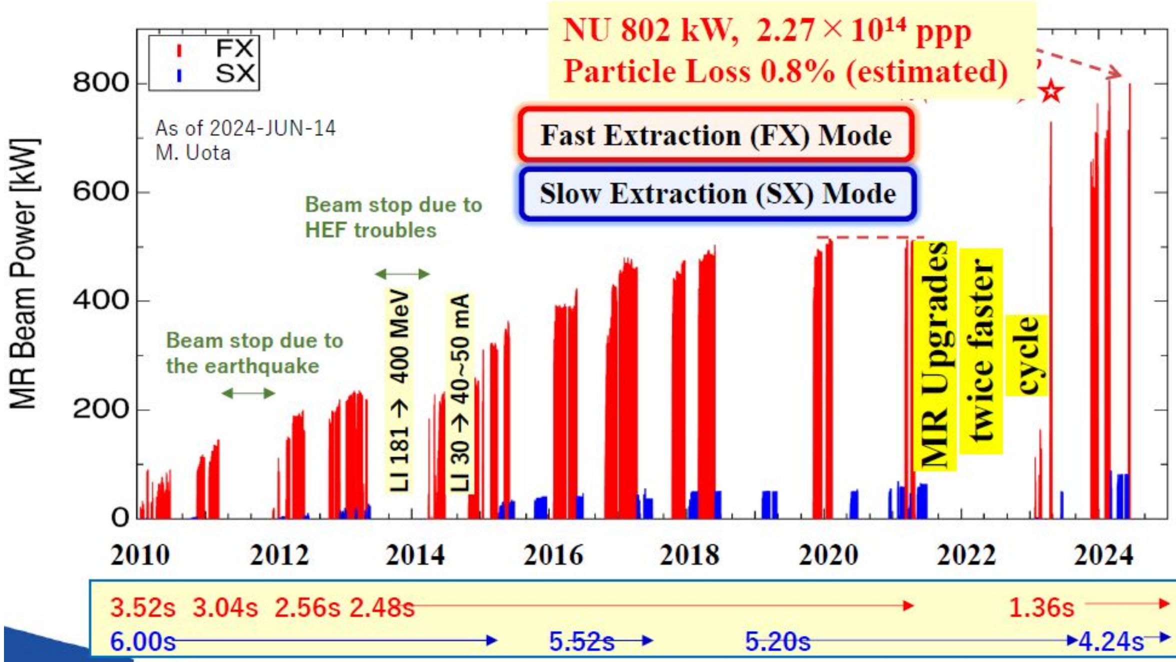
WA105 cryostat repurposed at CERN

Hosted at CERN Neutrino Platform (NP08)
- Vertical test-stand (integration tests of all components)
- Assembly tests on mock-ups
- Assembly and calibration of 1000 vessels
- Storage before shipment to Japan

→ **Vessels assembly and calibration planned for 2nd half of 2026**

J-PARC Accelerator (MR) upgrade status

- Stable continuous **~800kW** (FX) operation for users is established!
  : MR power is being improved almost as planed.



JFY2024 - JFY2028 Plans

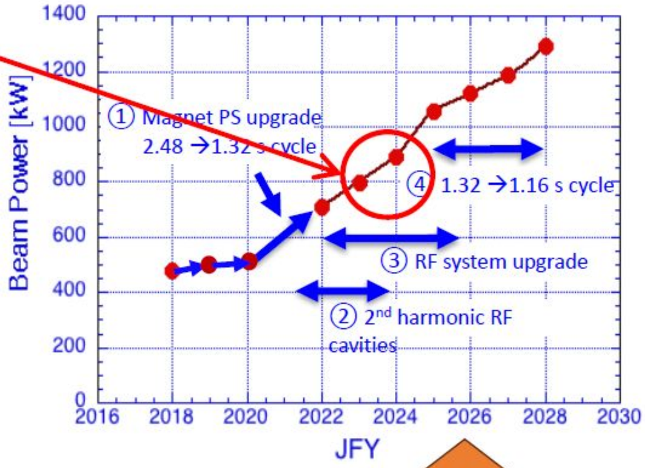
- RF system upgrade (continued)
- More magnet power supplies for beam correction
- Reinforcement of the main magnet PSs
- Upgrade MR-Abort-Dump

By courtesy of Y. Sato (J-PARC Accelerator)

J-PARC KEK Institute of Particle and Nuclear Studies

J-PARC neutrino beam-line upgrade

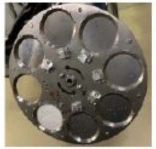
- HW modification for MR 1Hz op. was done in 2021-2022 LS.
  - Horn current reinforcement: +10% yields/protons.
    → acceptable beam power ~900kW
  - Radiation protections in Target Station are reinforced.
    → Government approval for 1.3MW has been obtained.



New Horn PS/trans/ strip-lines for 320kA & 1Hz

New Horn1 & 2 w/ upgraded cooling capability

New OTR



New FVD2 magnet for better maintainability

New MUMON Si (half of sensors)

New water tank for radio-active waste handling improvement

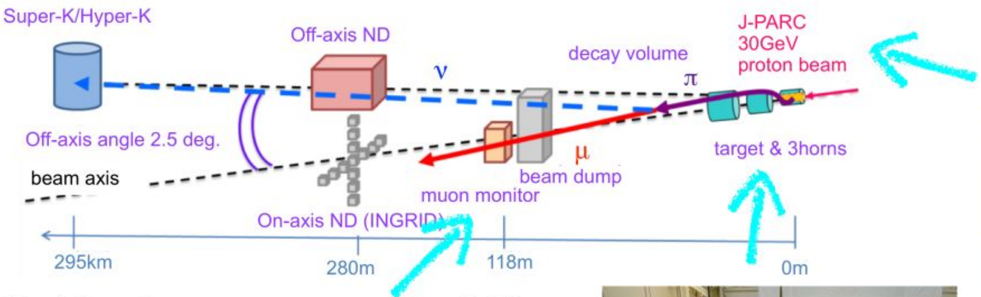
New target cooling system

New target

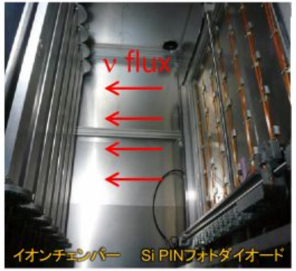
Another beam-line HW upgrade for 1.3MW in JFY2026.

Institute of Particle and Nuclear Studies

J-PARC accelerator & beam line upgrade status



Rad-hard. new muon monitor R&D



- 2種類の独立な検出器
- 7×7のアレイ

PTEP 2018, no.10, 103H01(2018)
https://doi.org/10.1093/ptep/pty104

New Power
Supply for MR main magnets

New 2nd horn magnet

New RF cavities

New target installation test

Beamline upgrade work w/ strong international cooperation is also in progress

Multi-PMT Photosensors

19 x 8 cm diameter PMTs in each mPMT module

- Better position resolution
- < 1 ns timing resolution
- Additional directionality information

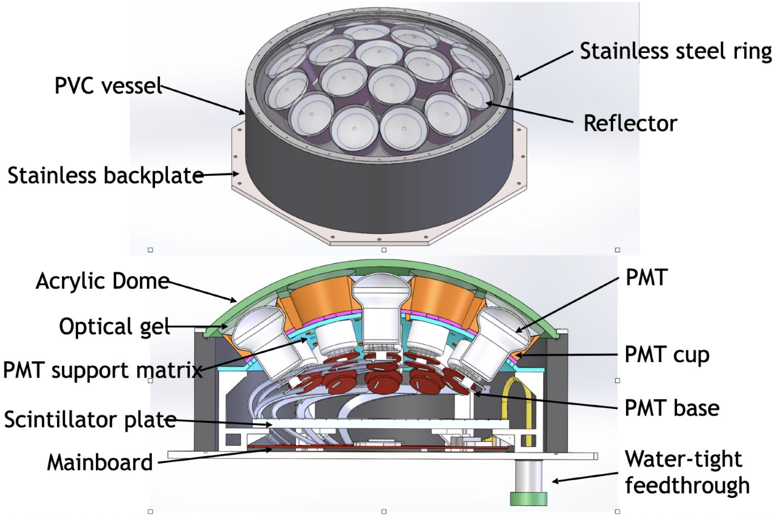
High voltage generated at each PMT base with attached Cockroft-Walton circuit

In-module digitizer mainboard with power and communication over single PoE cable

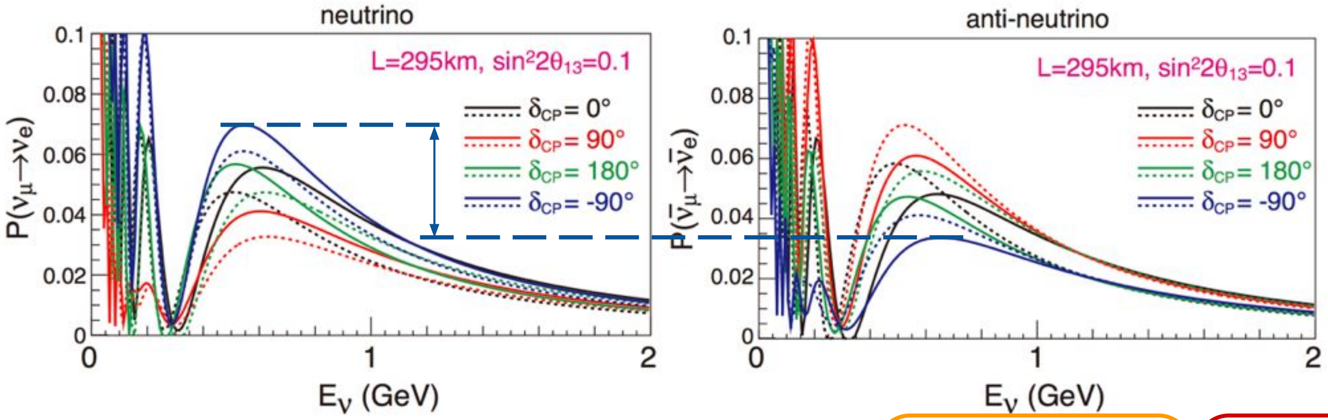
LED light sources used for calibration and as photogrammetry beacons

Pulsed LEDs with sub-ns pulse width used in timing calibration

Necessary for smaller detector size



Measuring CP Violation in ν Oscillations

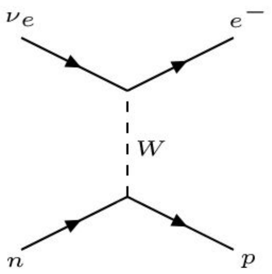


Search for CP violation through difference in oscillation probabilities of $\nu_\mu \rightarrow \nu_e$ vs $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$

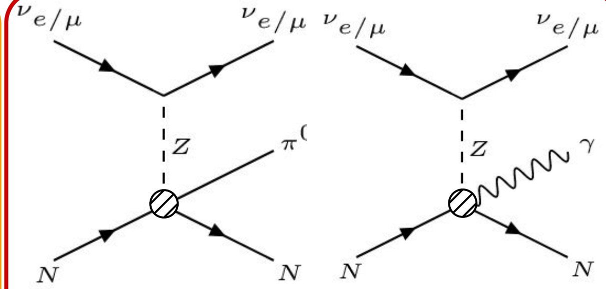
Significant effect of δ_{CP} in P($\nu_\mu \rightarrow \nu_e$) vs P($\overline{\nu}_\mu \rightarrow \overline{\nu}_e$)

At oscillation maximum around 0.6 GeV

- **Charged Current Quasielastic (CCQE)** is dominant signal ν_e interaction
- **Significant background sources:**
  - **Neutral current interactions** (ν_e or ν_μ) producing neutral pions or gammas mimicking ν_e electrons
  - **Misidentified muons** from ν_μ as electrons from ν_e



Charged current quasielastic (CCQE) signal

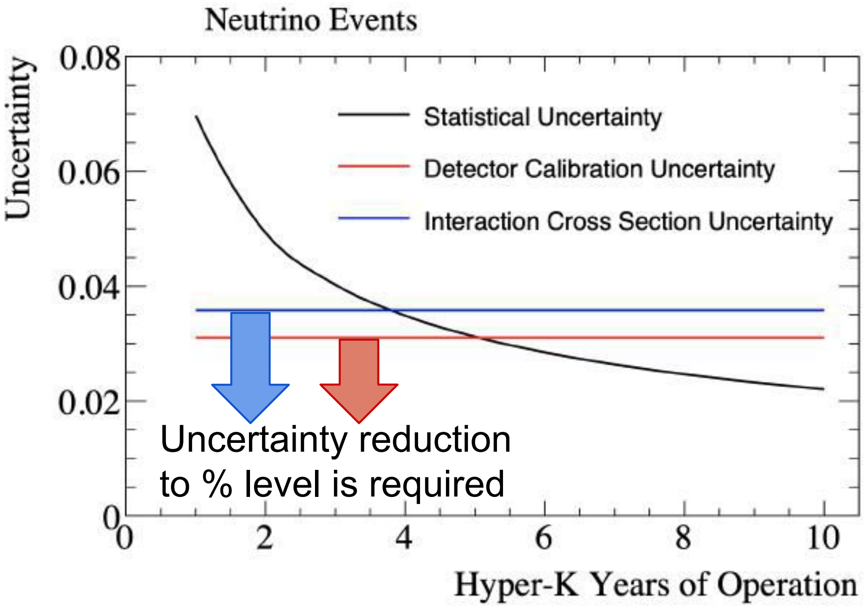


Neutral current $NC\pi^0$

Neutral current $NC\gamma$

Backgrounds

Uncertainties & Challenges



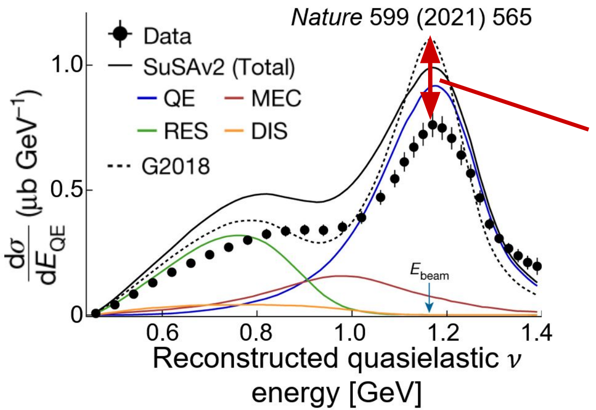
Huge rates of ν observations at Hyper-K will quickly reduce statistical uncertainty below current systematic uncertainty

Total systematic uncertainties should be reduced to below 2%

Interaction model uncertainties

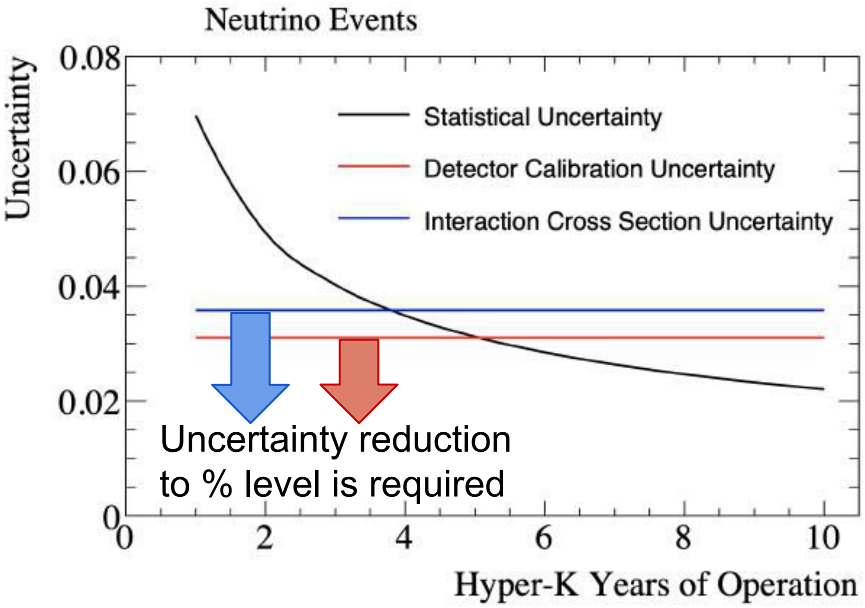
Critical to CP violation measurement

- **ν & $\bar{\nu}$ production** to understand ν_μ beam flux, ν_e contamination and "wrong sign" background
- **ν interaction cross-sections on water** for ν_e CCQE signal, other ν_e CC signal channels and wide array of backgrounds



significant uncertainty in ν measurements from ν interaction cross-sections

Uncertainties & Challenges



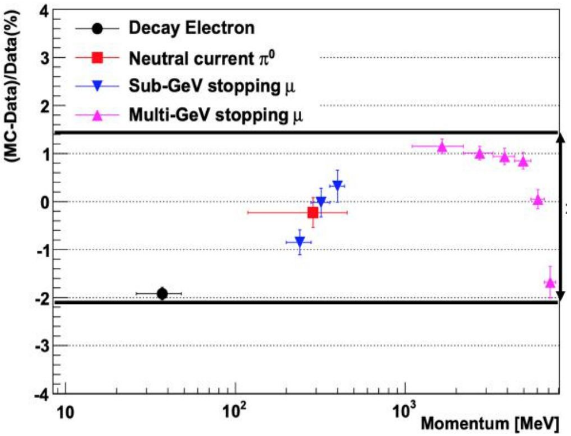
Huge rates of ν observations at Hyper-K will quickly reduce statistical uncertainty below current systematic uncertainty

Total systematic uncertainties should be reduced to below 2%

Detector model uncertainties

Precision understanding required of

- **Interactions** of particles propagating in water
- **Cherenkov light production** of charged particles
- **Propagation of light** through water
- **Photosensor response** to light
- **Reconstruction** of complex and challenging event topologies



1.9% discrepancy in energy scale at Super-K

WCTE Goals

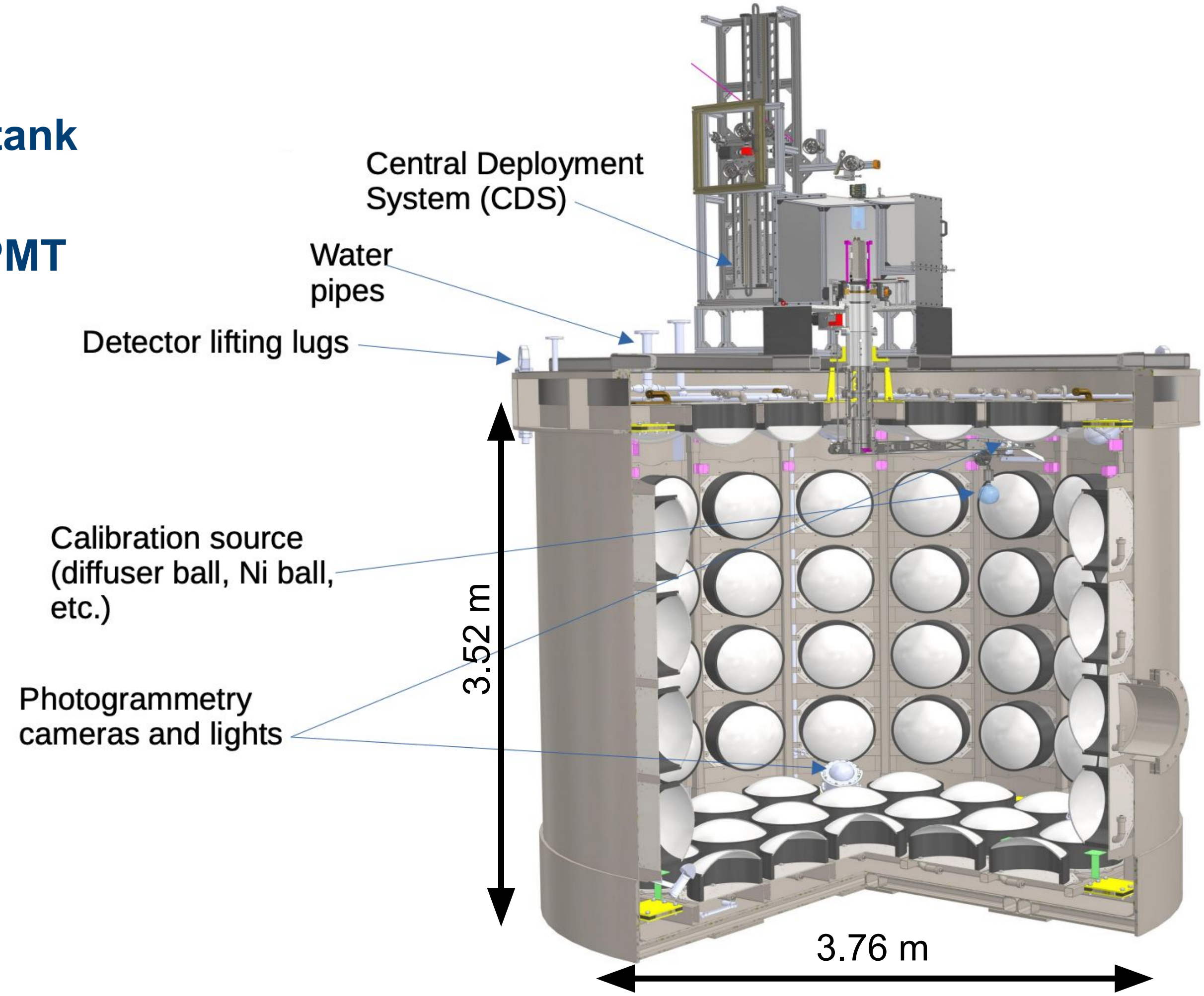
Measurements	Beam Momentum	Water	Beam Mode
Reco. capabilities, pion scattering	200-1200 MeV/c	Pure	Charged Particle
Muon/electron scattering	800 MeV/c	Pure	Charged Particle
Gamma Identification	500-1000 MeV/c	Pure	Tagged Gamma
Neutron Production	200-1200 MeV/c	Gd-doped	Charged Particle
Photonuclear with n tagging	500-1000 MeV/c	Gd-doped	Tagged Gamma

- Array of physics measurements to inform Hyper-K physics
- Directly measures Cherenkov Detector response to charged particles
- Pure control samples of charged particle and photon interactions feed validation and improvement of neutrino interaction models
- Demonstration of new detector calibration technologies and advanced analysis techniques

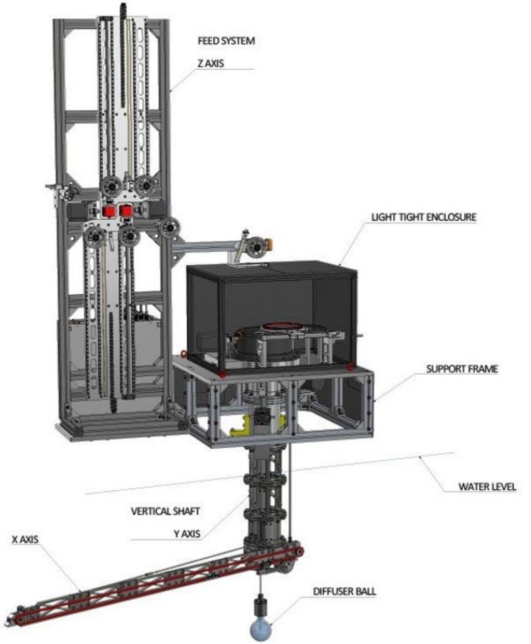
WCTE detector

3.5 m height x 3.76 m diameter tank
filled with 40 tons of pure water

- Instrumented with **96 multi-PMT** (mPMT) photosensors
  - 92 of style planned for IWCD
  - 4 of style planned for Hyper-K far detector
- Instrumented with **built-in calibration** systems
  - Cameras for 3D geometry photogrammetry
  - Light source & radioactive source deployment system



WCTE Calibration Systems

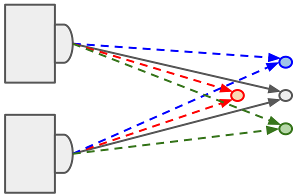


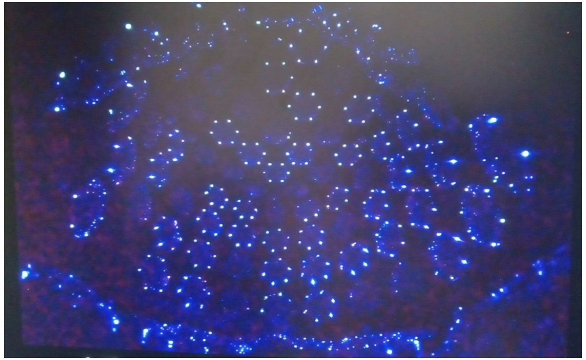
Central Deployment System mounted at top of detector to deploy calibration sources at any location throughout the detector volume

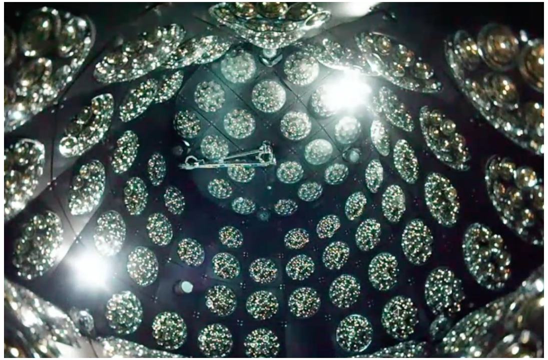
- **Centimetre level position accuracy** of source
- 3 different sources deployed with CDS
  - **Pulsed laser in diffuser ball** for uniform illumination of detector
  - **NiCf source** for calibration with low energy gammas
  - **AmBe + scintillator source** for tagging neutrons

8 Photogrammetry Cameras mounted inside detector

- **3D detector geometry reconstruction** from each mPMT LEDs visible to multiple cameras
- **< 1cm position resolution** expected to observe any deformation of mPMT support structure after filling

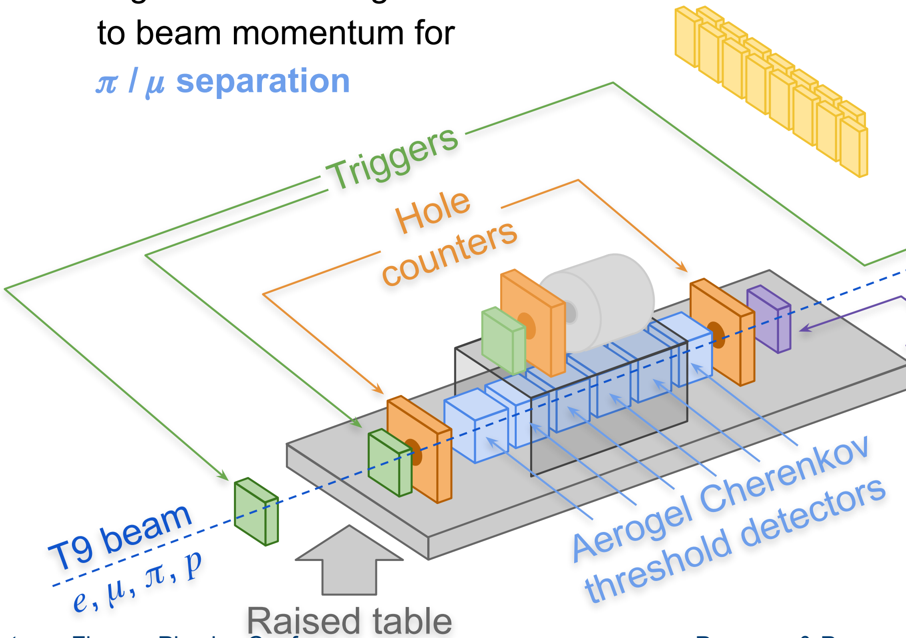


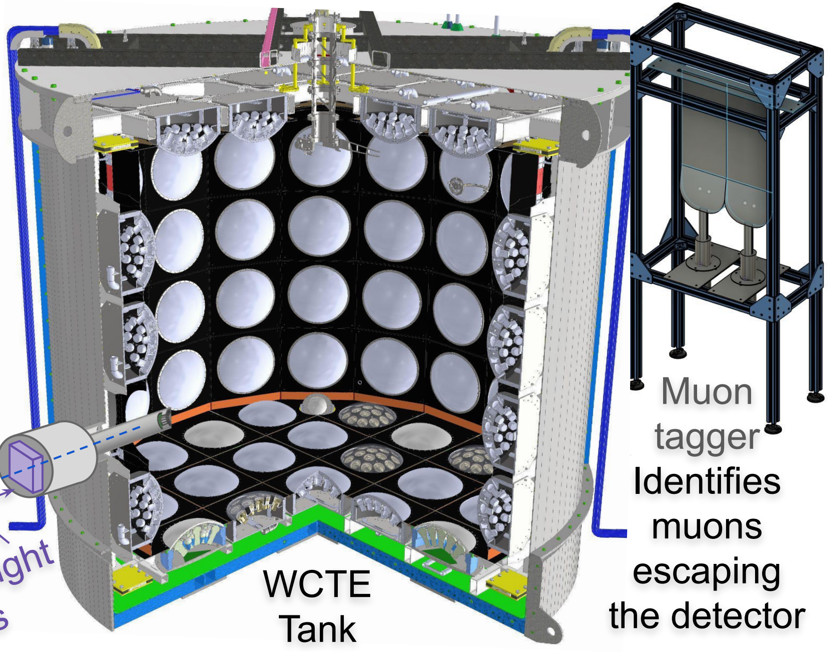




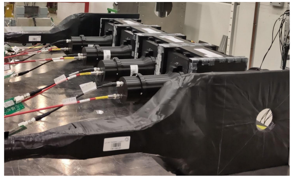
Charged Particle Configuration

- **Triggers** identify particles in beamline while **hole counters** veto particles that shower before reaching WCTE
- **Aerogel Cherenkov Threshold** detectors use aerogel produced at Chiba university with n = 1.006 to 1.15
- Low index aerogel used to **identify e^+ / e^-**
- Higher index aerogels are matched to beam momentum for **π / μ separation**

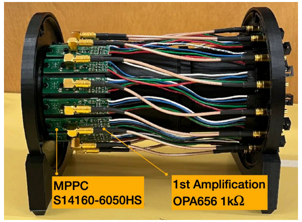




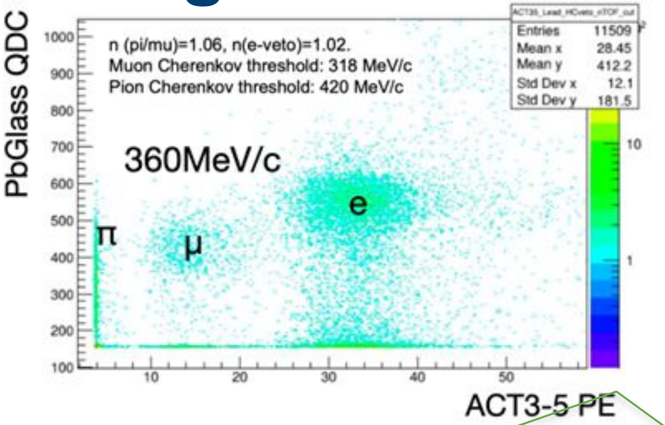
Identifies muons escaping the detector



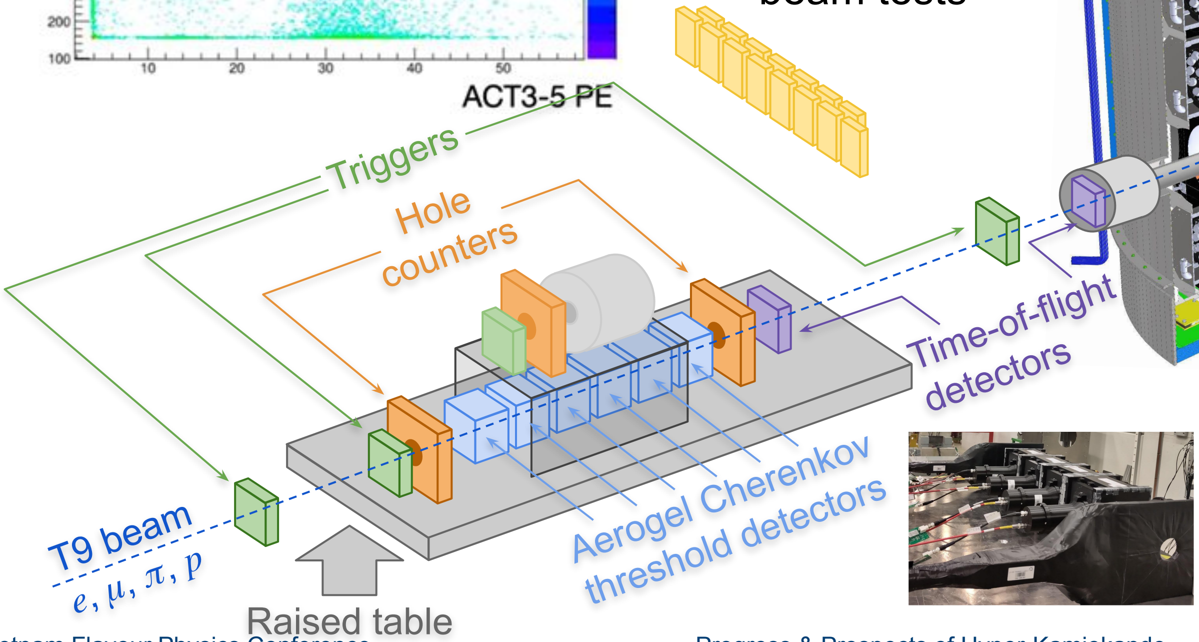
SiPMs allow **Time-of-Flight detectors** to fit into beam pipe to tag heavier entering particles

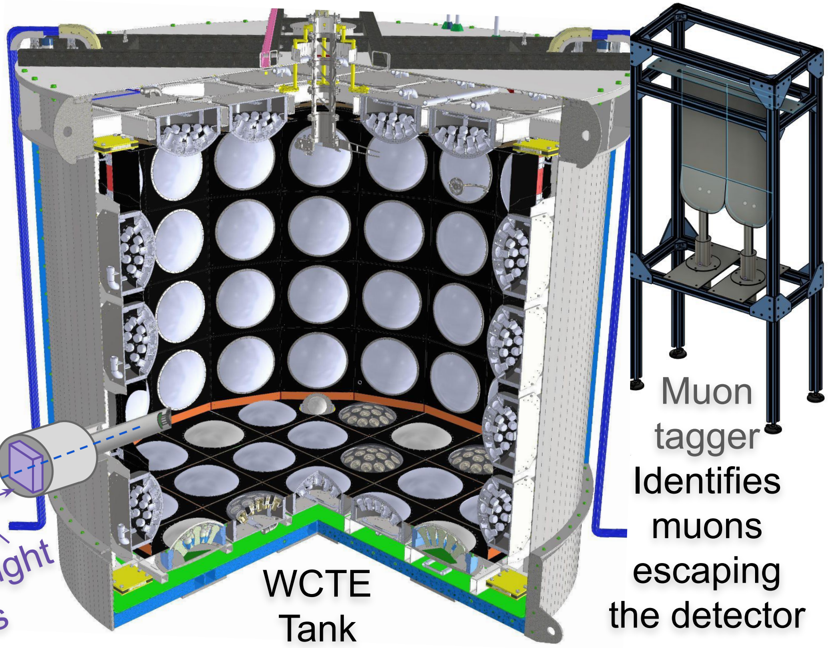


Charged Particle Configuration

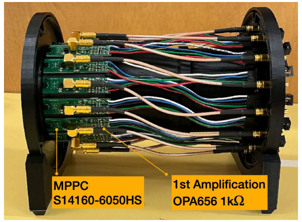


Demonstrated quality particle identification
during 2023 & 2024 beam tests



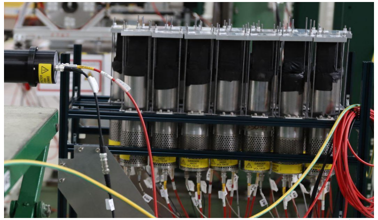


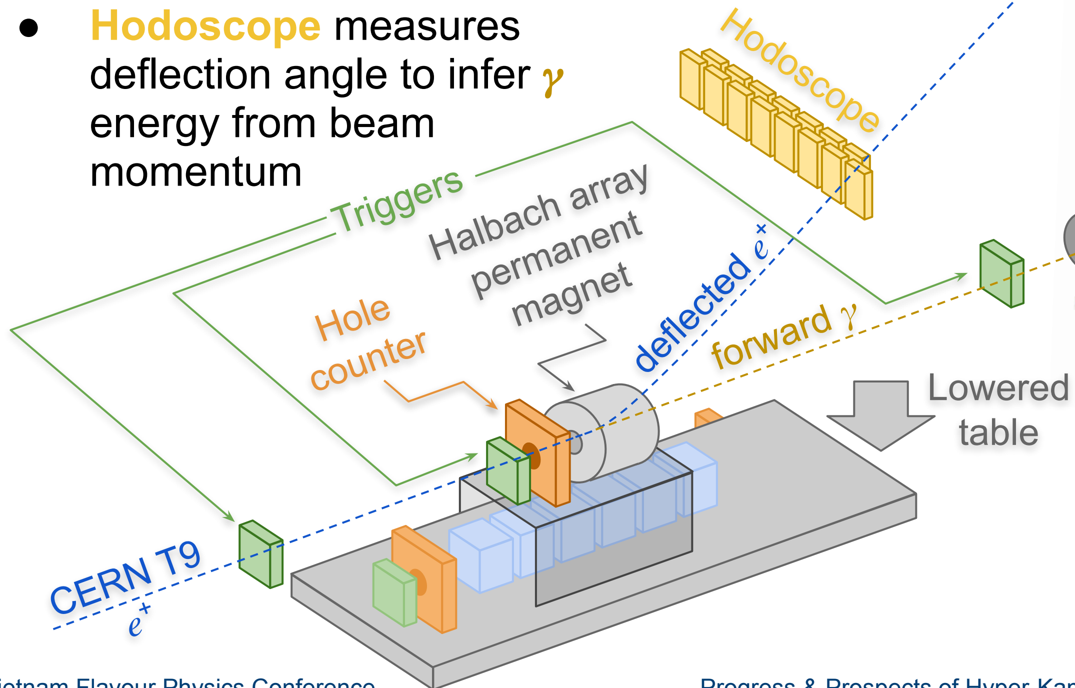
SiPMs allow **Time-of-Flight detectors** to fit into beam pipe to tag heavier entering particles

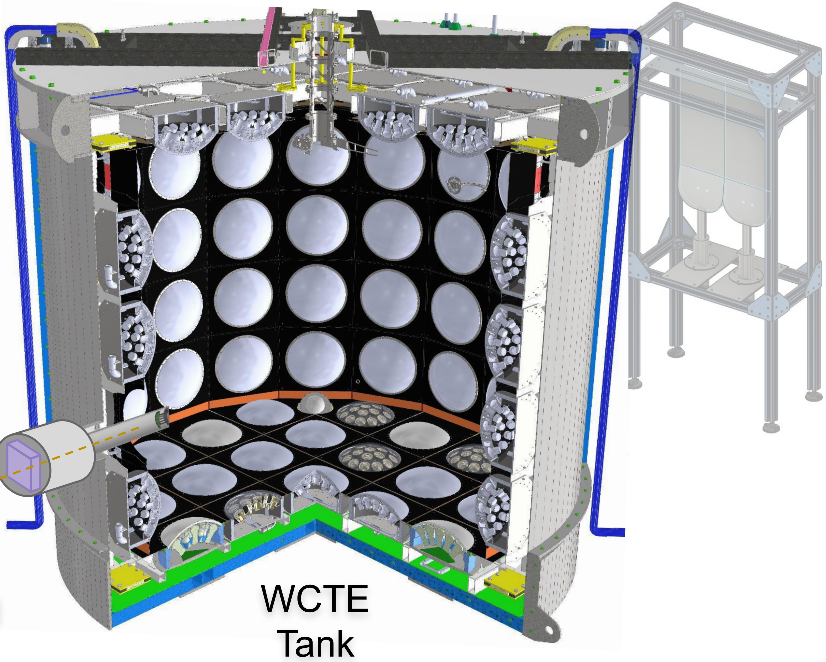


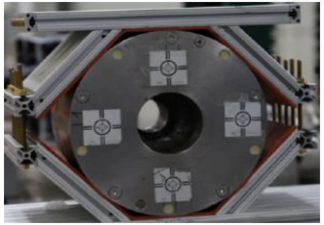
Tagged Photon Configuration

- e^+ produces γ by bremsstrahlung
- **Permanent magnet deflects $e^\pm$**
- **Hodoscope** measures deflection angle to infer γ energy from beam momentum



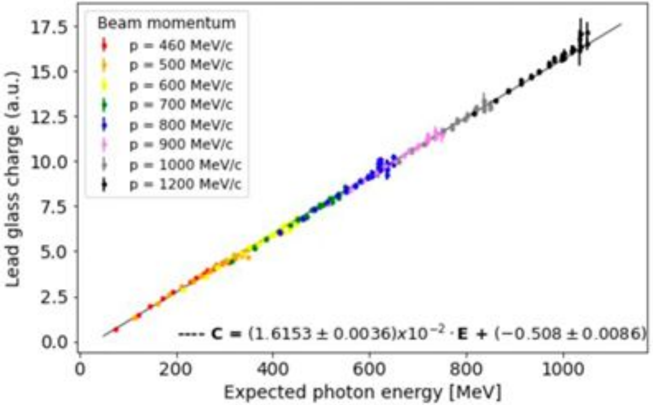




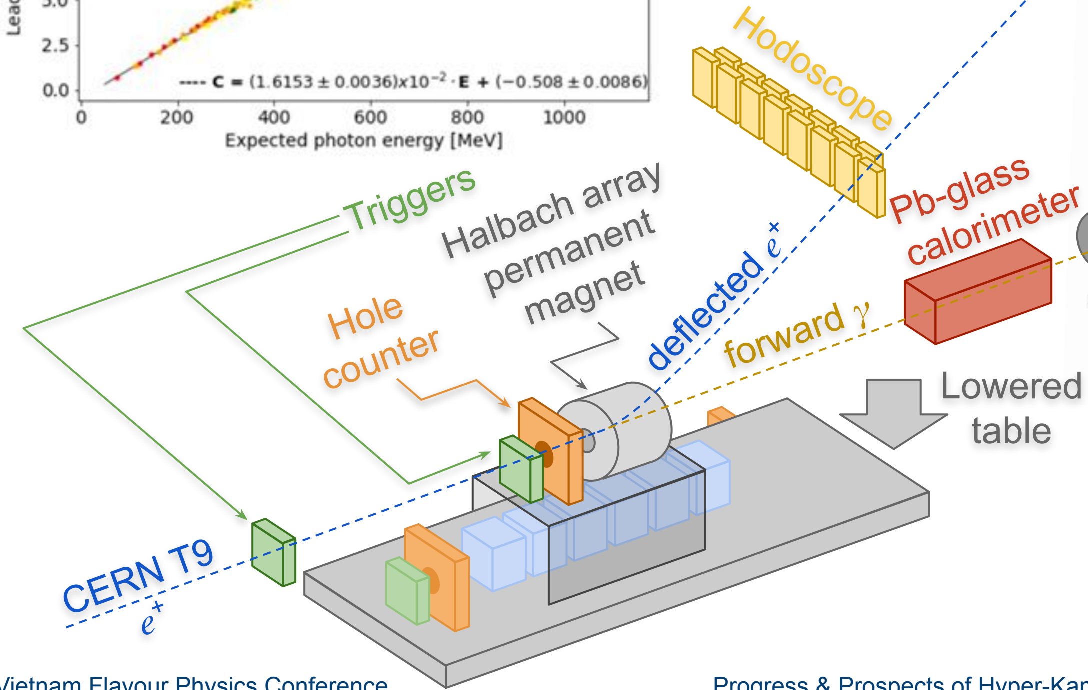


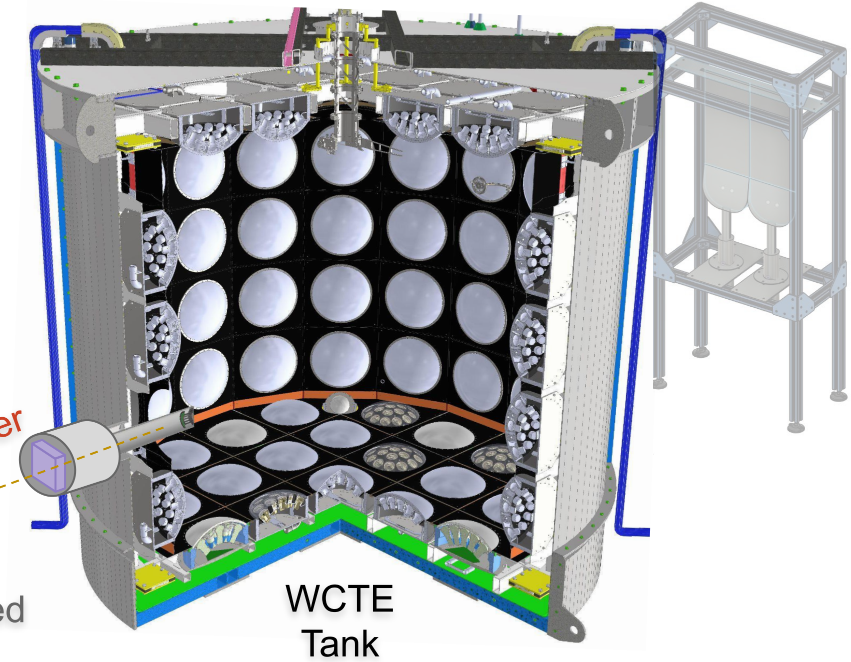
Halbach array permanent magnet with 0.7 T, 0.2 Tm

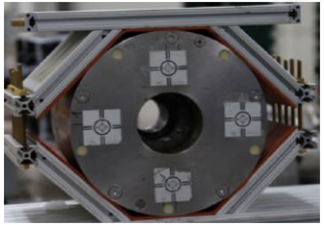
Tagged Photon Configuration



Validated γ energy measurement using **lead glass calorimeter**



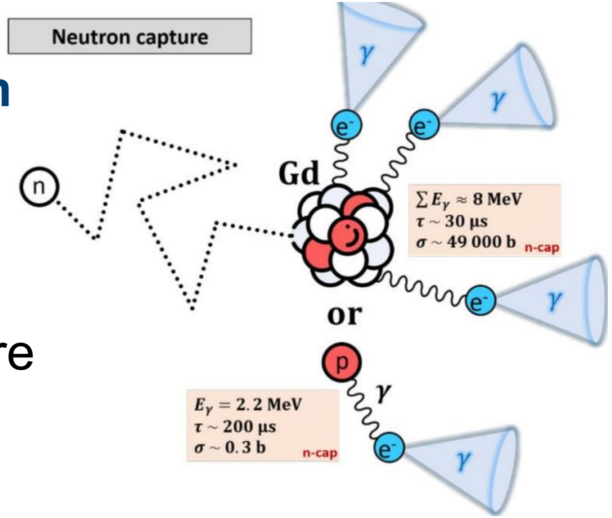




Halbach array permanent magnet with 0.7 T, 0.2 Tm

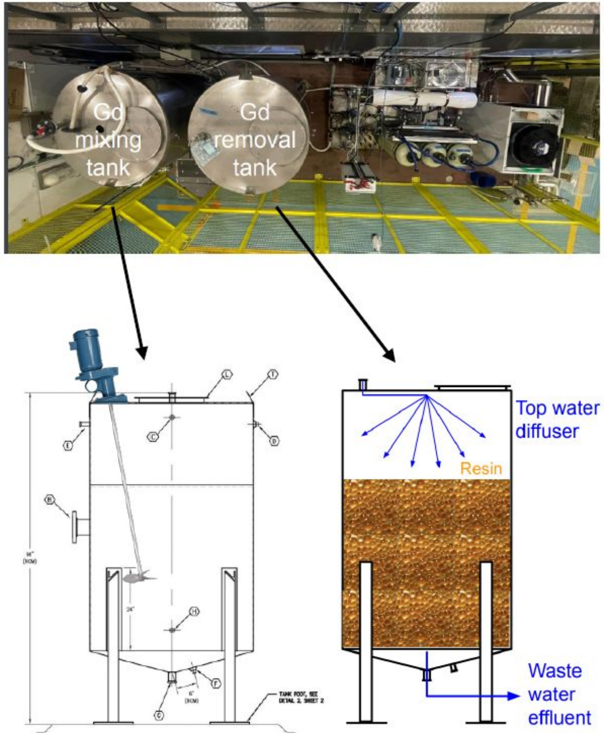
Gadolinium Loading for Neutron Measurements

- Gd has **large neutron capture cross section** and produces delayed energetic gammas totaling ~8 MeV
  - Without Gd, capture on H produces 2.2 MeV γ

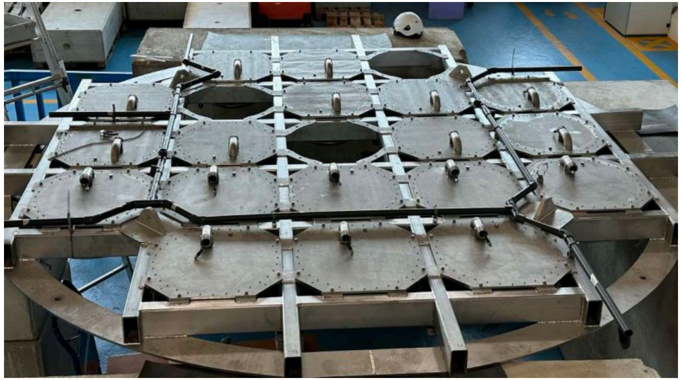


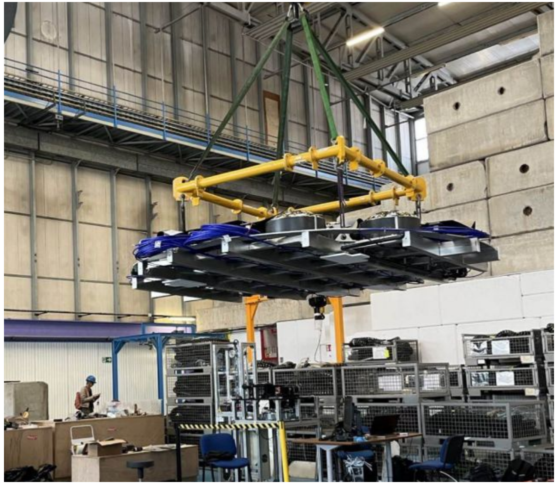
- Loading of with **~0.1% Gd** in detector gives **90% neutron capture efficiency**

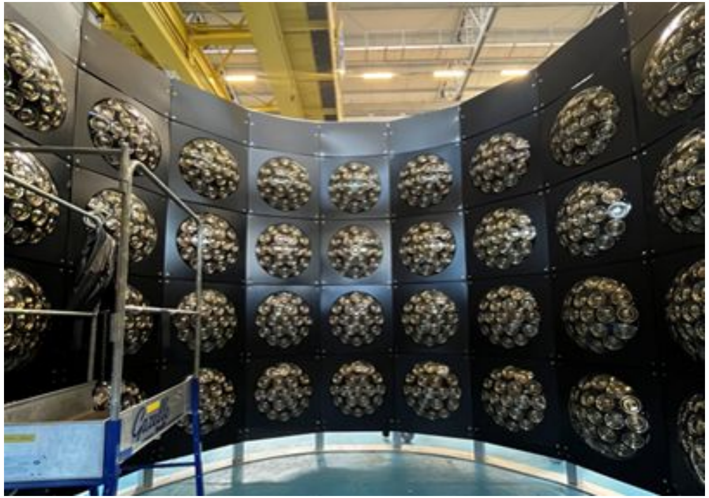
- WCTE water system can accommodate Gd loading and it is being **prepared for the 2025 run**

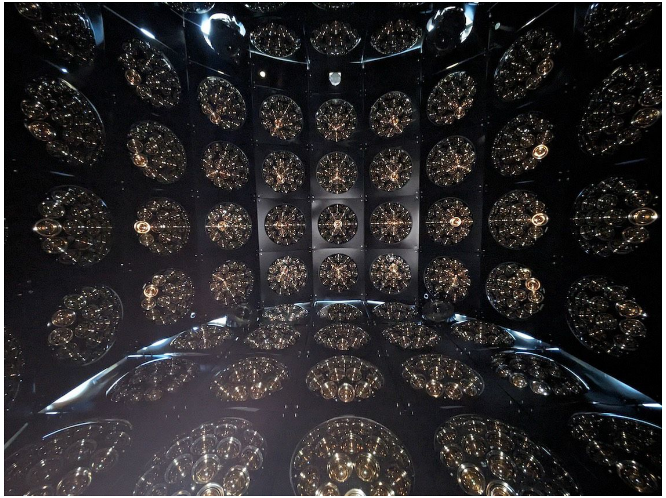


WCTE Assembly & Installation

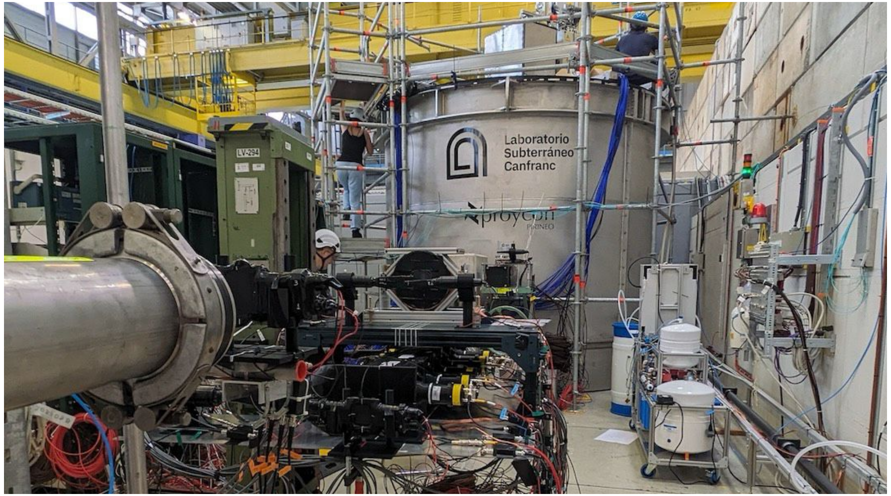








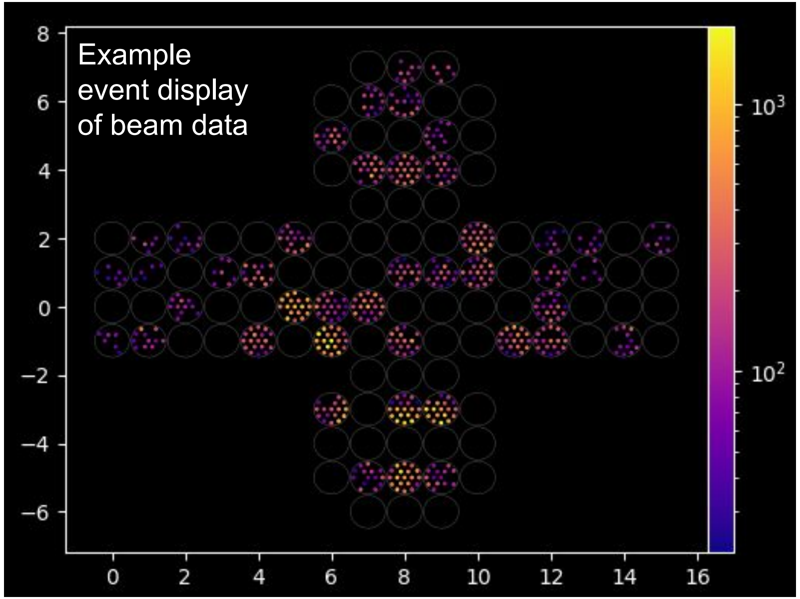
Assembly & Installation



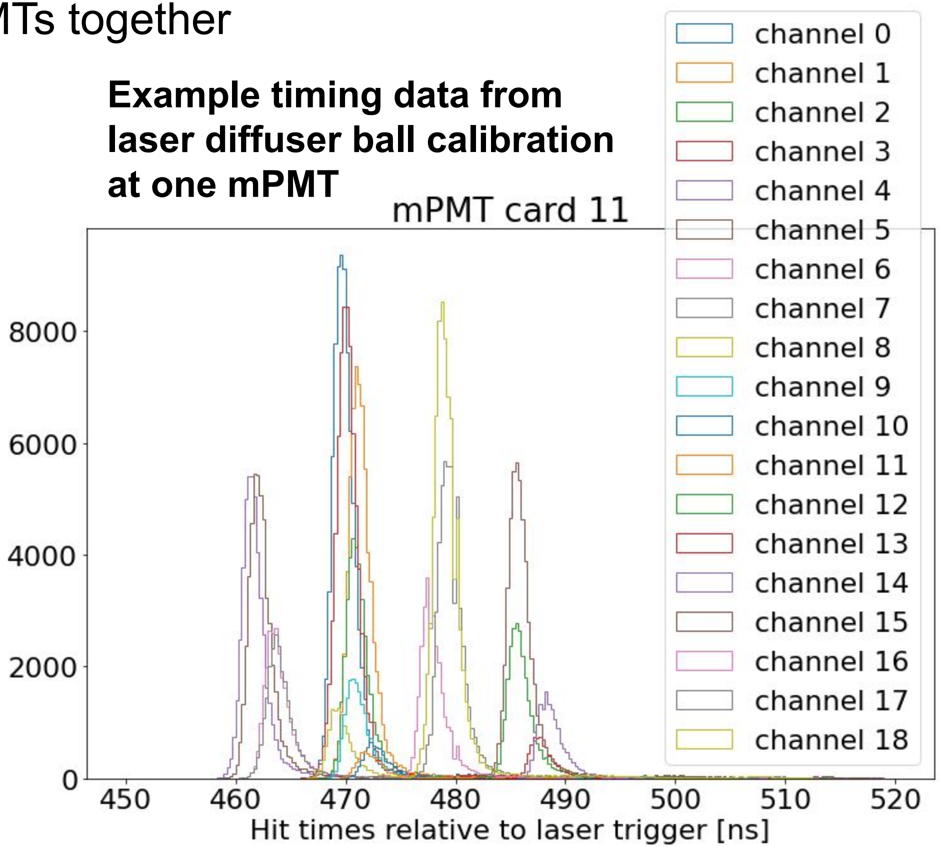
2024 WCTE Operations

Significant effort to overcome challenges to collect quality WCTE data in 2024

- First instance of operating ~100 multi-PMTs together
- Issues in firmware, readout and DAQ
- Achieved **~50% of mPMTs operational**
- Collected **calibration and beam data**



Example timing data from laser diffuser ball calibration at one mPMT



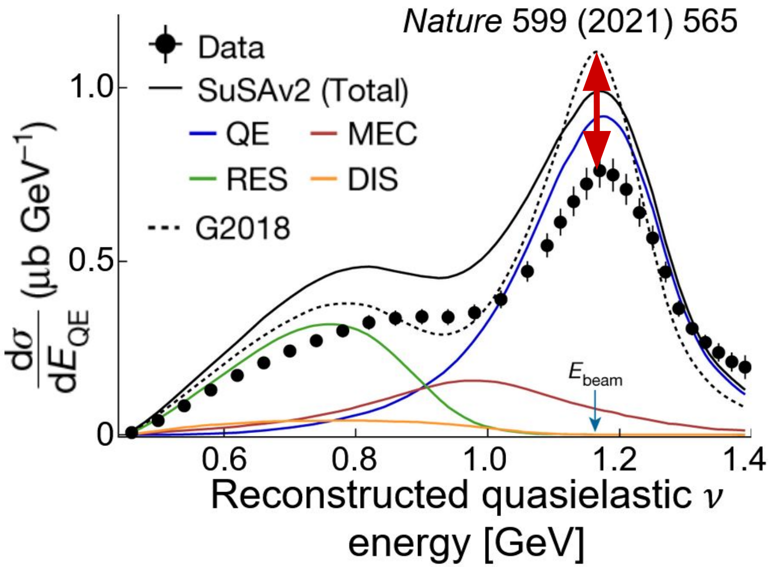
Interactions on Water

Controlling ν **cross-section uncertainties** essential for future ν measurements

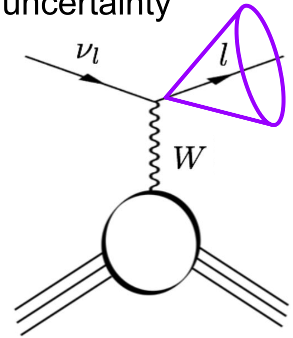
- ν interaction cross-sections contribute **significant uncertainty to neutrino measurements**
- Nuclear interaction of ν products also **complicates ν energy reconstruction**

Pure control samples of WCTE feed improvement and validation of interaction models

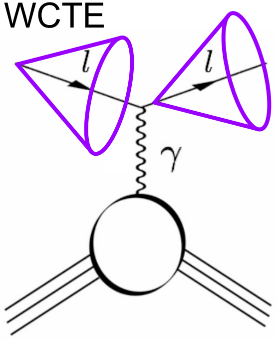
- **Lepton-nuclear interactions** provide information on neutrino-nuclear interaction models through corresponding electroweak cross-sections
- **WCTE can measure lepton scattering in water** by searching for two-ring events
- **Photonuclear scattering** tagged γ mode to control ν_e background when losing one γ of π^0 decay from NCπ^0



ν-water interaction has large model uncertainty



lepton-water scattering control sample measured at WCTE



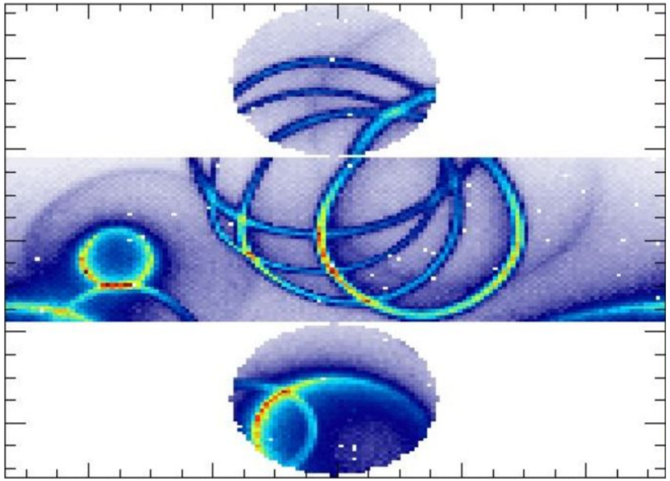
Hadronic Interactions

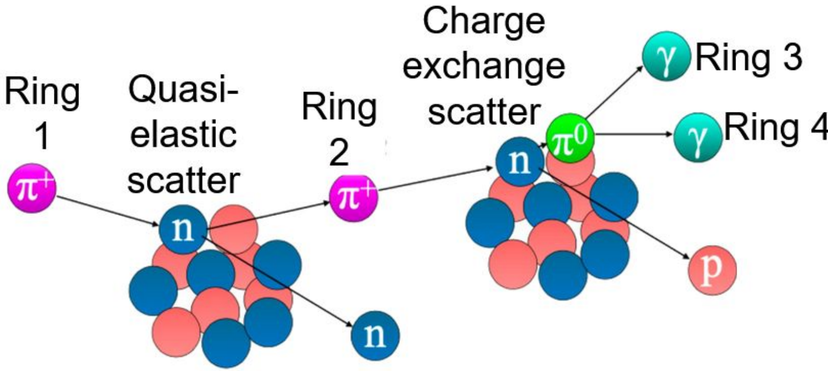
Pion production in ν interactions introduces several challenges for ν measurements

- Complex hadronic interactions of pions **cannot be simulated from first principles** resulting in significant model uncertainties
- **Multi-ring event topologies are difficult to reconstruct** requiring development of new reconstruction methods to handle pion events
- **WCTE directly measures pions, including all their interactions and detector response**

Potential to also measure **pion photo-production** in tagged γ configuration

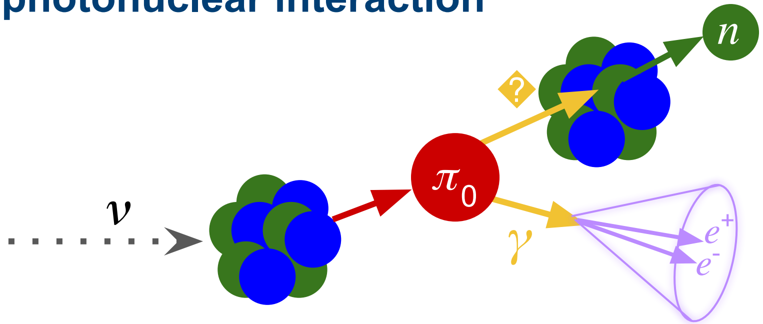
- Control sample for NC$\pi^{\pm}$ ν interactions



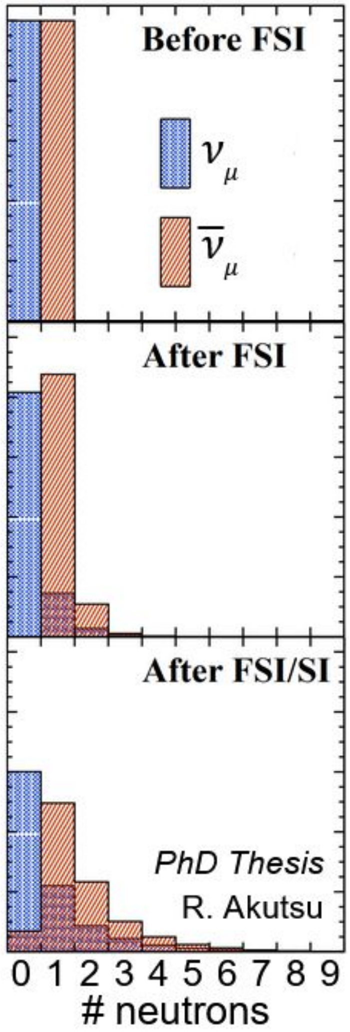


Neutron Multiplicities

- CCQE **neutrino interactions produce 1 proton**, while **antineutrino interactions produce 1 neutron**
- **Tagging neutrons** allows statistical ν / $\overline{\nu}$ separation
- **Large model uncertainties** in final state interactions (FSI) and secondary interactions (SI) that modify observed neutron distribution
- **Gadolinium doped water enables neutron detection** via gammas after n-capture
- WCTE will help understand FSI/SI by measuring **secondary neutron production from protons** in water
- Tagging neutrons in tagged γ mode provides measurement of **photonuclear interaction**

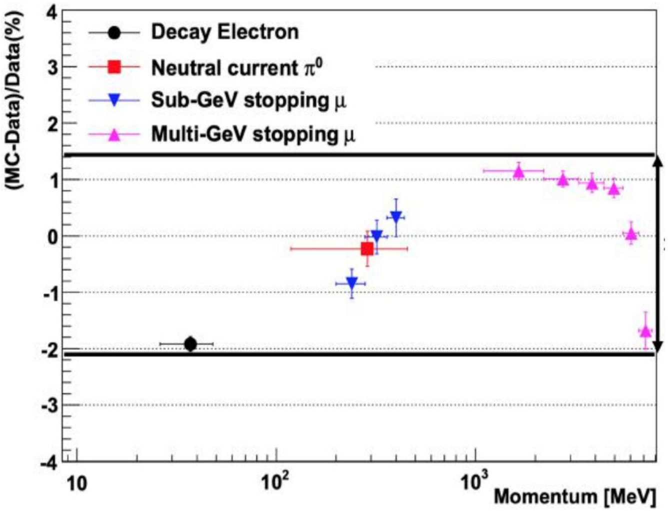


Common NCπ_0 background looks exactly like ν_e signal when one γ interacts with water before producing light



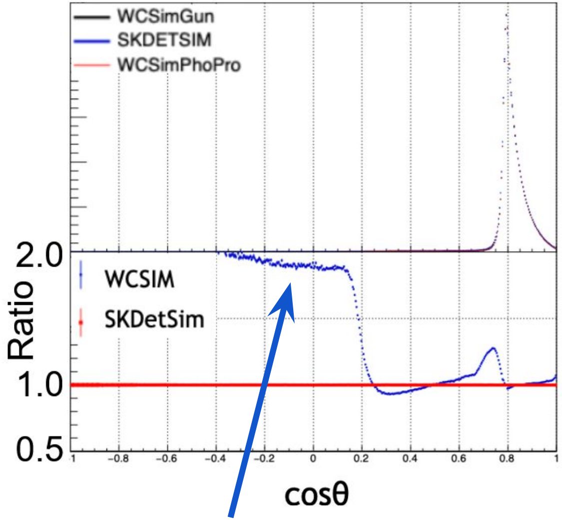
Cherenkov Detector Response to Charged Particles

- **WCTE directly measures detector response** to reduce detector uncertainties
- **Reduction to < 1% uncertainty** is necessary for ν measurements at Hyper-Kamiokande
- **WCTE measures e / μ observed PMT charge ratio** at fixed beam momenta



1.9% discrepancy in energy scale at Super-K

< 1% needed for Hyper-K

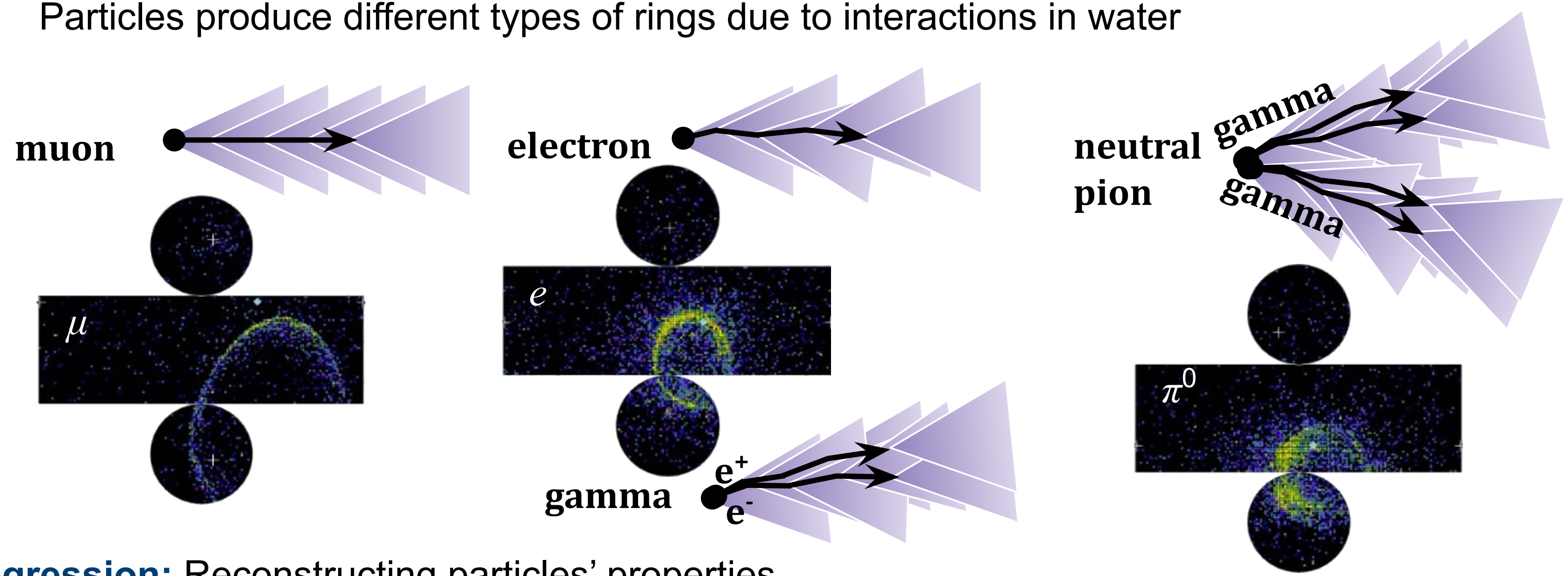


- **Discrepancies in Cherenkov production models** limit ability to use backward-going Cherenkov light to enhance reconstruction
- **WCTE measures emission profile** from e and μ of known momenta

Reconstruction in Water Cherenkov Detectors

Classification: Particle type identification (PID)

- Particles produce different types of rings due to interactions in water



Regression: Reconstructing particles’ properties

- Location and time of PMT hits allow triangulating particle’s position and direction
- Amount of charge observed at PMTs gives estimate of particle’s energy

Machine Learning Reconstruction for WC

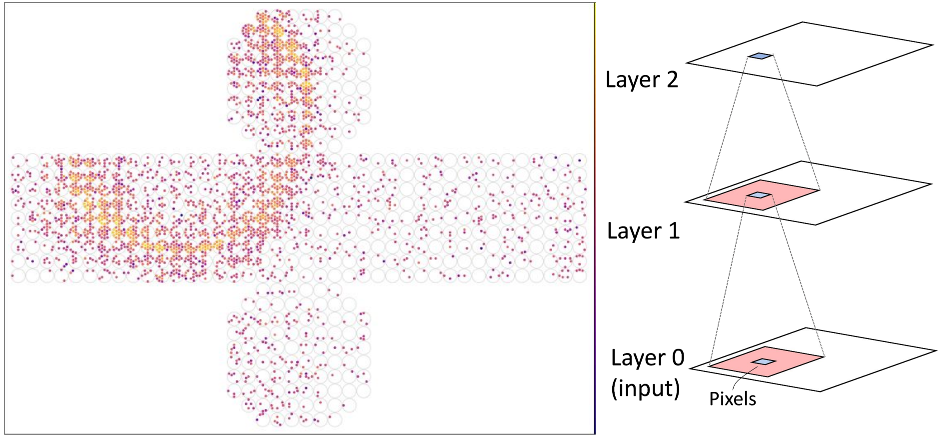
Reaching limit of traditional maximum-likelihood reconstruction methods (**fiTQun**)

- Improved resolutions require more complex algorithms with fewer approximations
- Computation time is limiting factor: **1M events in fiTQun = 10,000s CPU-hours**

Machine Learning (ML) and deep neural networks have potential to push reconstruction further

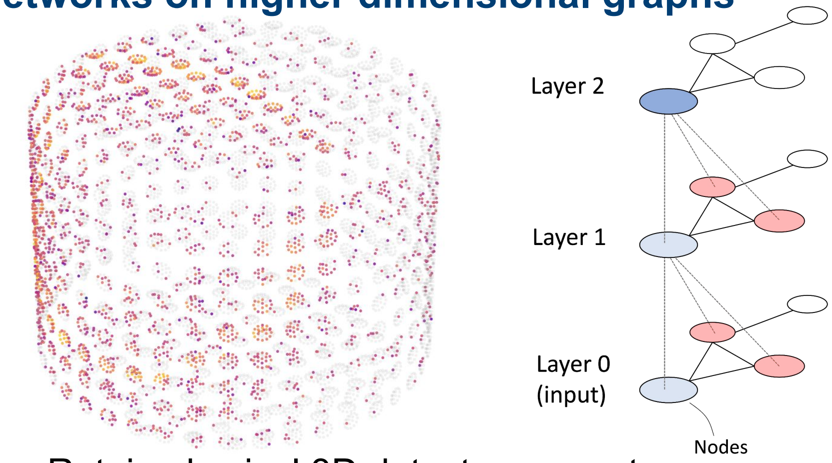
- Potential to use all information based on full detector simulation's physics model
- Very fast once network is trained: **1M events with CNN < 100 CPU-hours or < 1 GPU-hour**

Networks on 2D image-like data



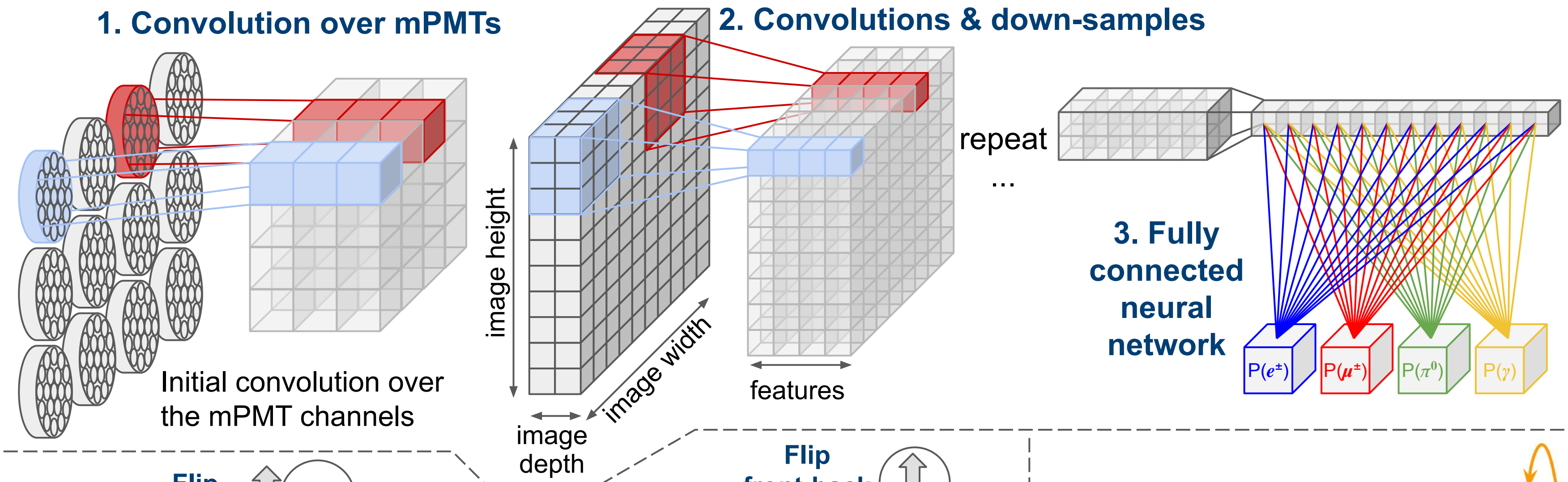
- Fast and well understood CNN-based networks
- Leverage extensive progress in computer vision

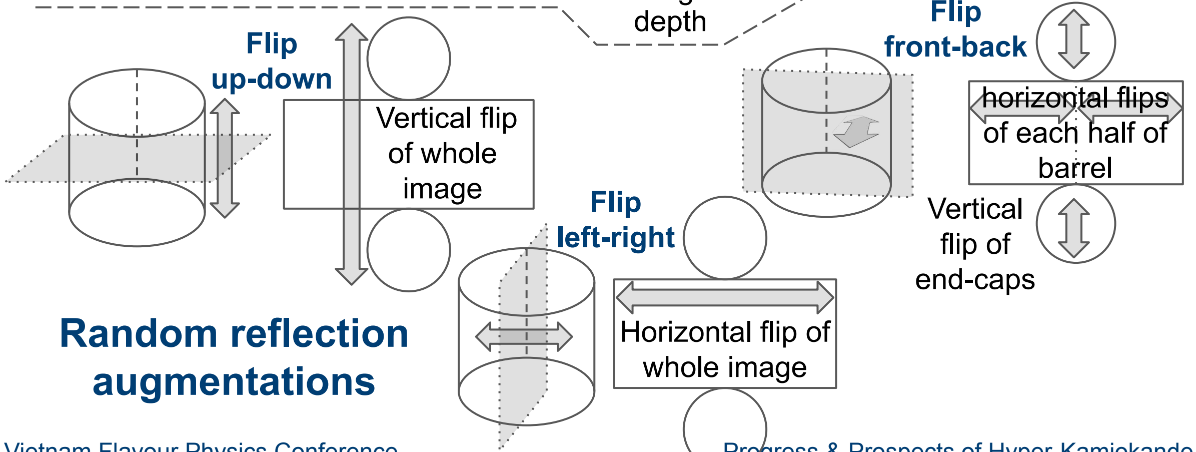
Networks on higher dimensional graphs

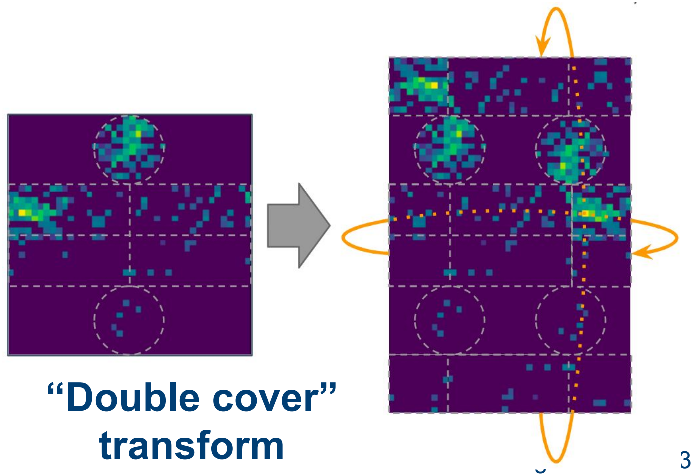


- Retain physical 3D detector geometry
- More complex and challenging to explore

ResNet-50 CNN for IWCD







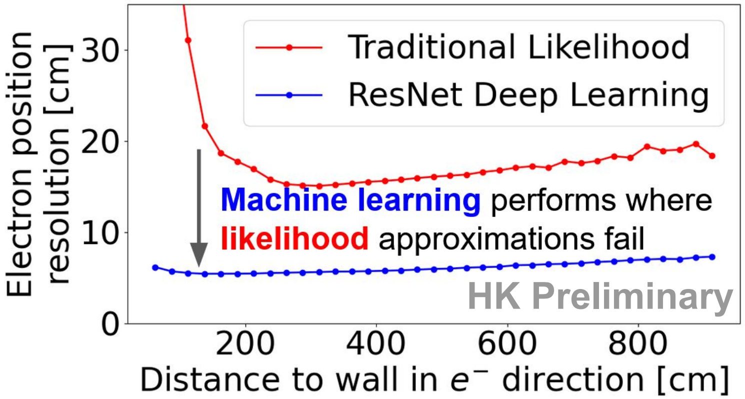
Machine Learning at WCTE

WCTE leading development of new calibration & reconstruction

- Essential data-driven validation of **machine-learning based methods**

Neutral current ν interactions producing single γ contribute **significant background to ν_e**

- This cross-section has not been measured and has **large theoretical uncertainty**
- **γ conversion to e^+ + e^-** produces overlapping electron rings
- **Single e** events look identical to **existing event reconstruction**
- Promising **70% separation accuracy** from novel **machine learning reconstruction**
- **WCTE measurements of electrons and tagged photons enable development and validation on pure samples of e & γ data**



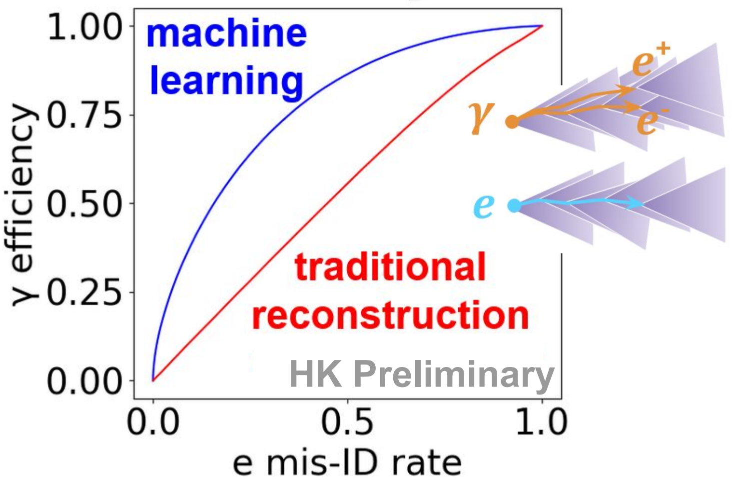
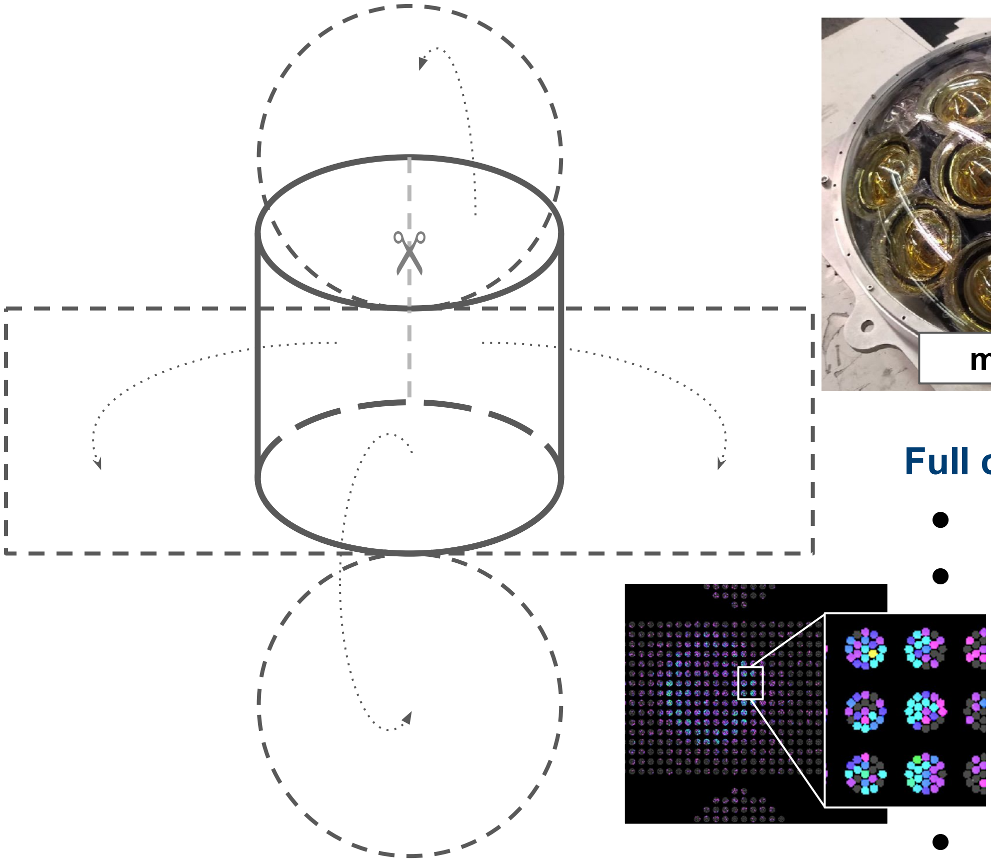
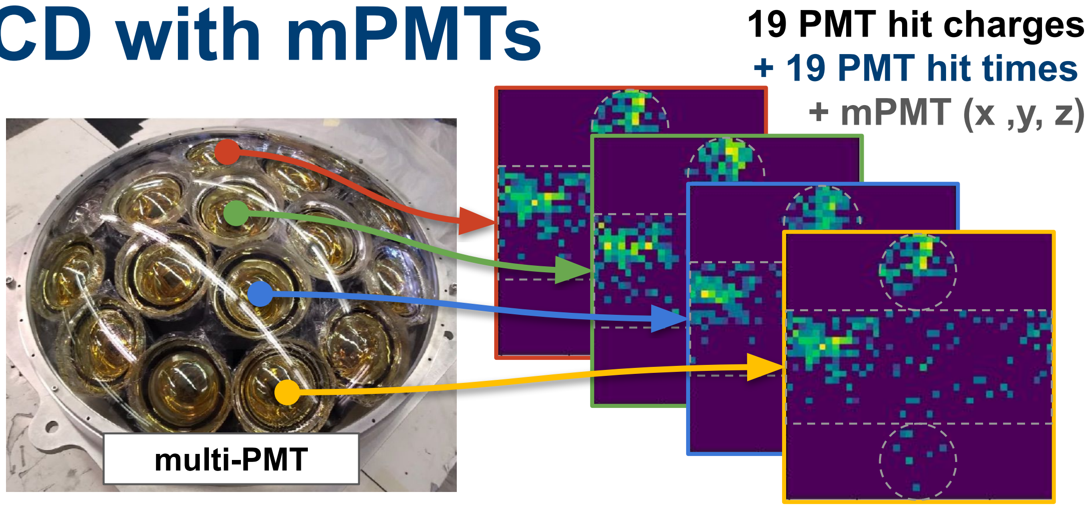


Image-like data for IWCD with mPMTs

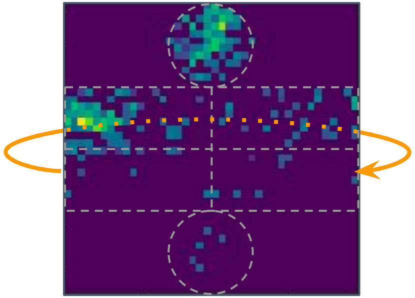


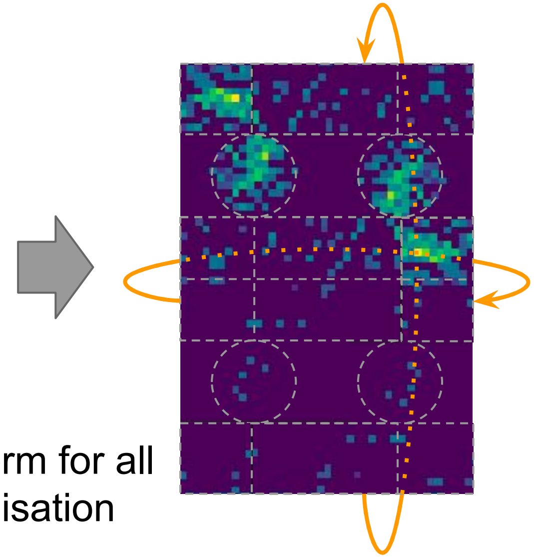


Full cylinder is unwrapped onto flat image

- One pixel per multi-PMT
- 41 channels per pixel:
  - 19 charge (at each of the 19 PMTs per mPMT)
  - 19 time (first hit time of each PMT is digitized)
  - (x, y, z) positional encoding of mPMT location helps network learn geometric information
- Tried other topological mappings with less success

Data Transformations and Augmentation





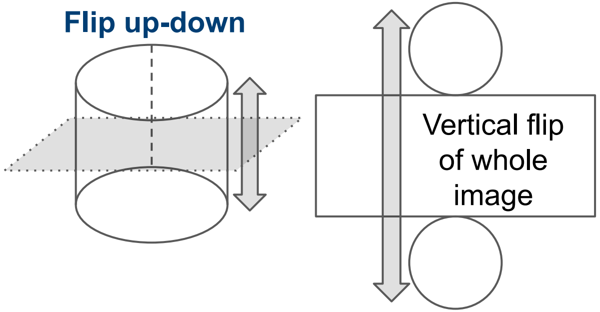
Double cover transform for all events helps generalisation

Rearranging and duplicating the geometrical surface has several advantages

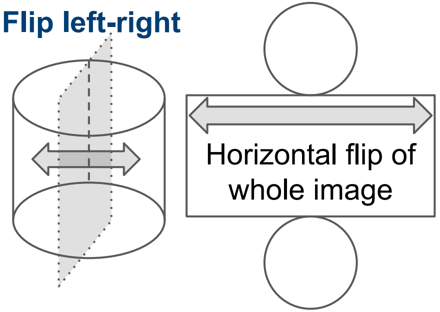
- Less dependence on choice of slice along barrel to unwrap cylinder
- All segments appear exactly twice, with minimal blank space
- Circular boundary conditions in both directions

Applying random transformations using detector symmetry effectively increases dataset

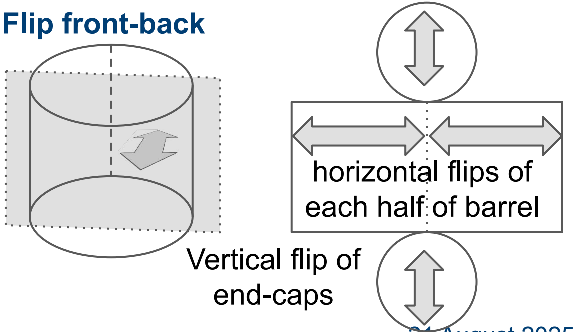
Flip up-down



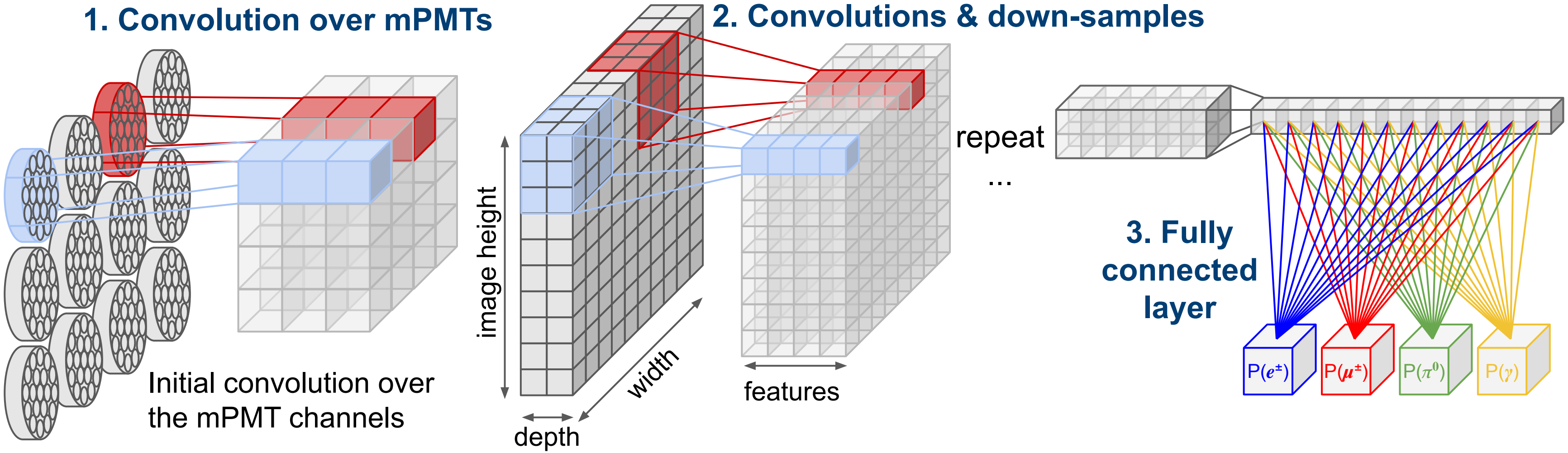
Flip left-right



Flip front-back



ResNet event reconstruction for IWCD with mPMTs



Convolutional Neural Network based on ResNet-50

- Initial 7x7 convolution with downsampling replaced by convolution over mPMT features
- Circular padding applied on each convolution to exploit cyclic boundary conditions

Simulated for IWCD 3M each of e, μ, π^0, γ (with γ to e^+/e^- pair conversion at initial position)

- Uniform random position, isotropic directions, uniform energy 0 to 1 GeV above Cherenkov threshold
- 1.5M of each particle for training, 0.3M for validation, 1.2M for final evaluation

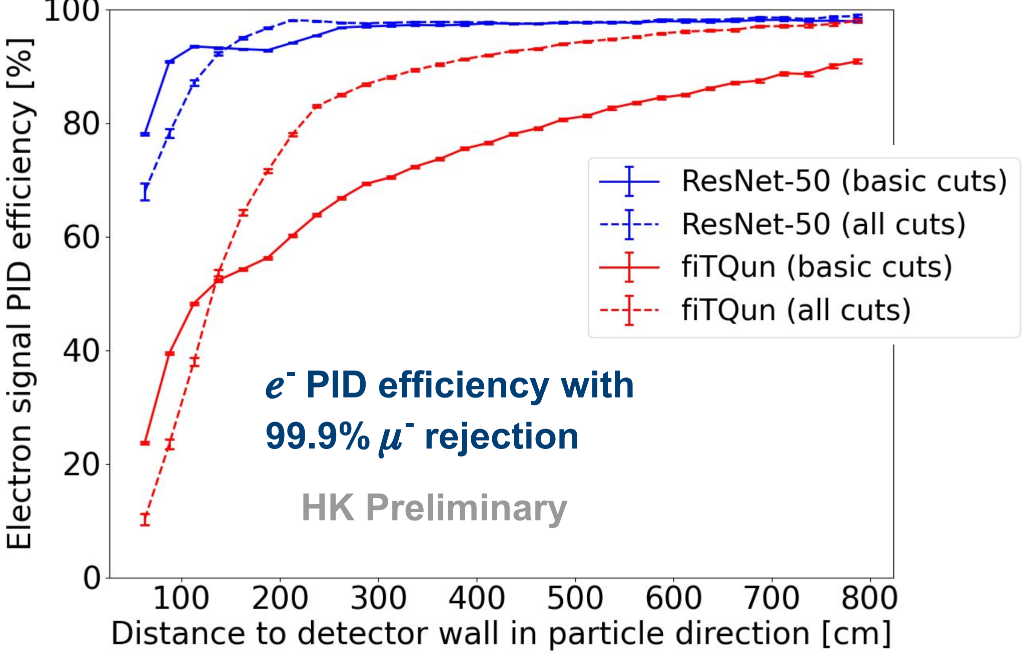
Trained separate models for each task for ~ 12 hours on 4 x A100 GPUs

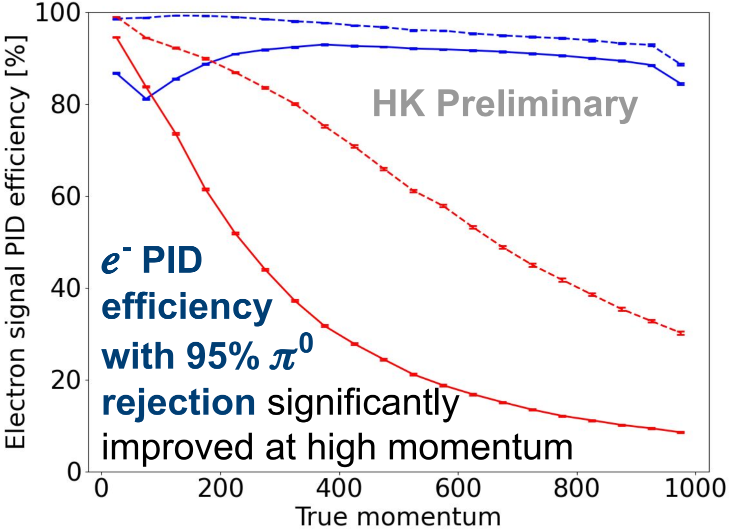
- Single 4-class network for PID classification of e, μ, π^0, γ
- Six networks for position, direction and energy of e and μ

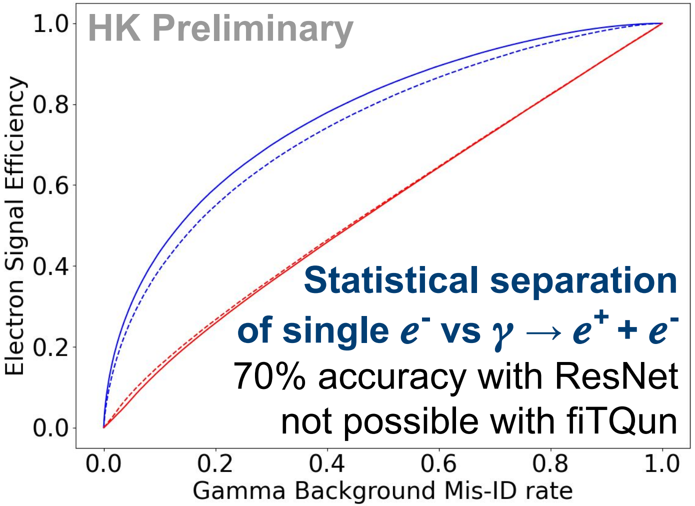
PID results

Basic cuts: > 25 hits
& fully contained event

All cuts: basic cuts
& fiTQun fit converges
& true position > 50cm from tank wall





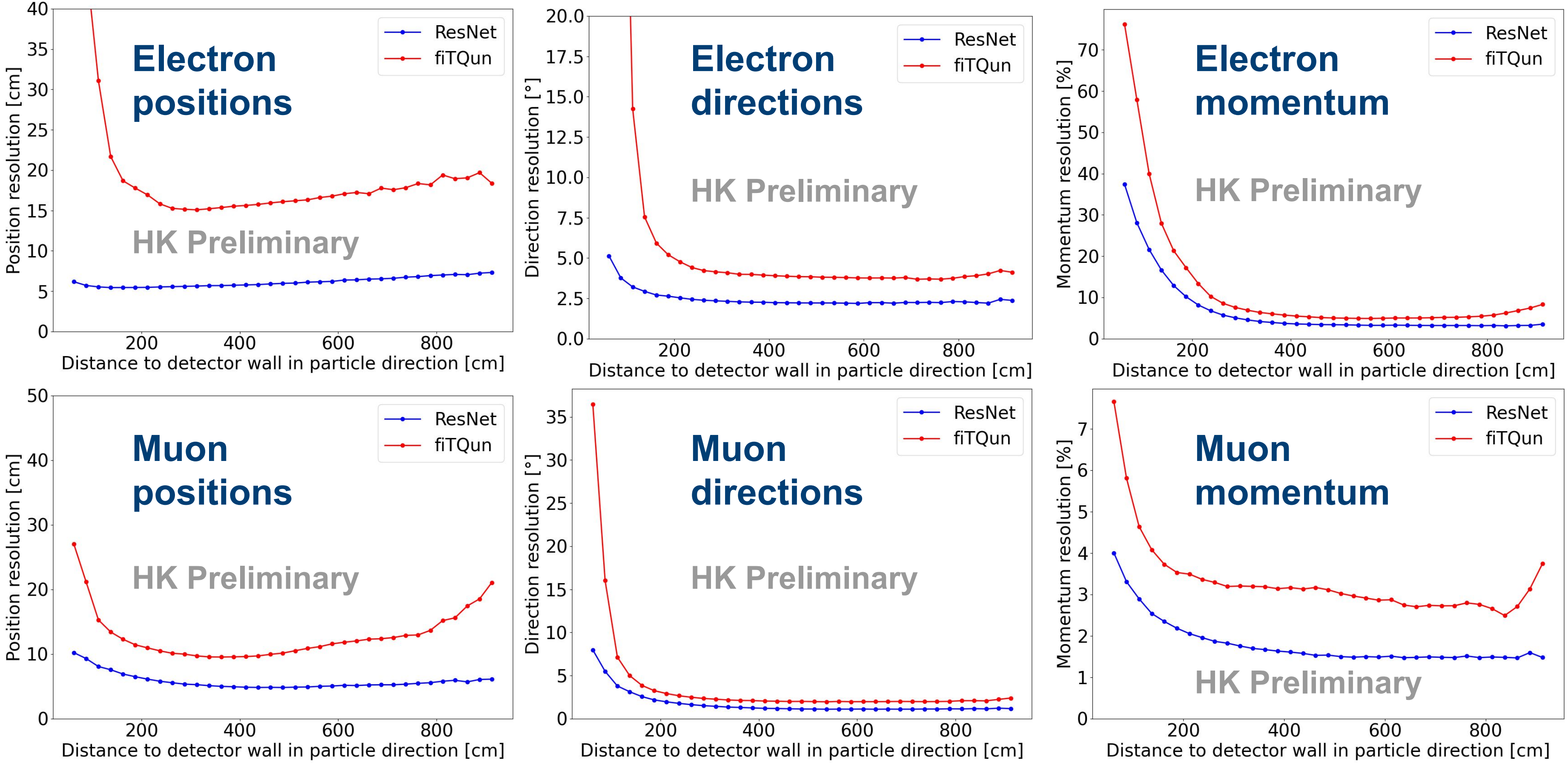


ResNet performing better, particularly where fiTQun's likelihood model approximations fail close to detector wall

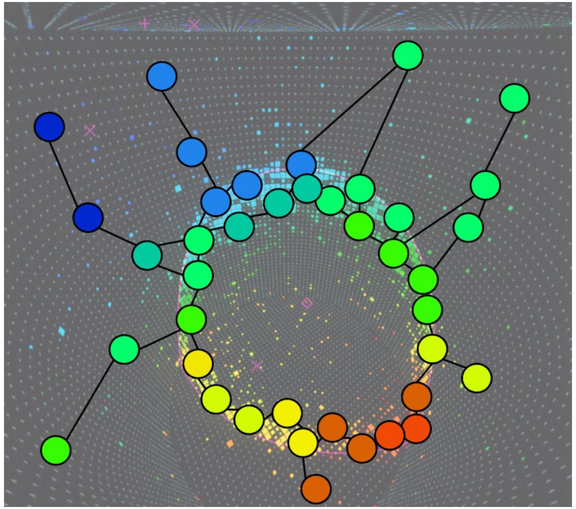
Regression results

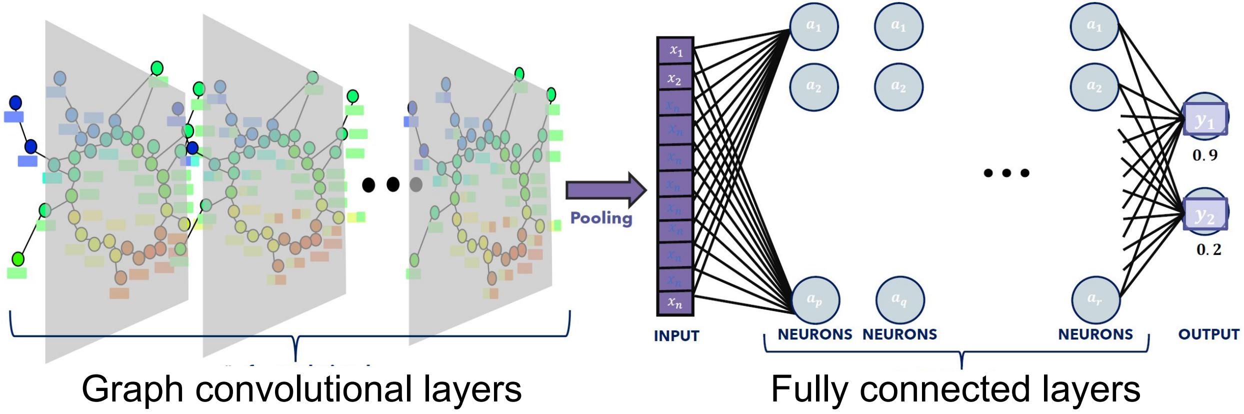
Basic cuts: > 25 hits & fully contained event

Reconstruction resolutions all reduced by 40 - 70%



GRANT: Graph Network for Hyper-K Far Detector





Features at each node (hit PMT)

- PMT hit charge
- PMT hit time
- PMT location

Nearest neighbour graph

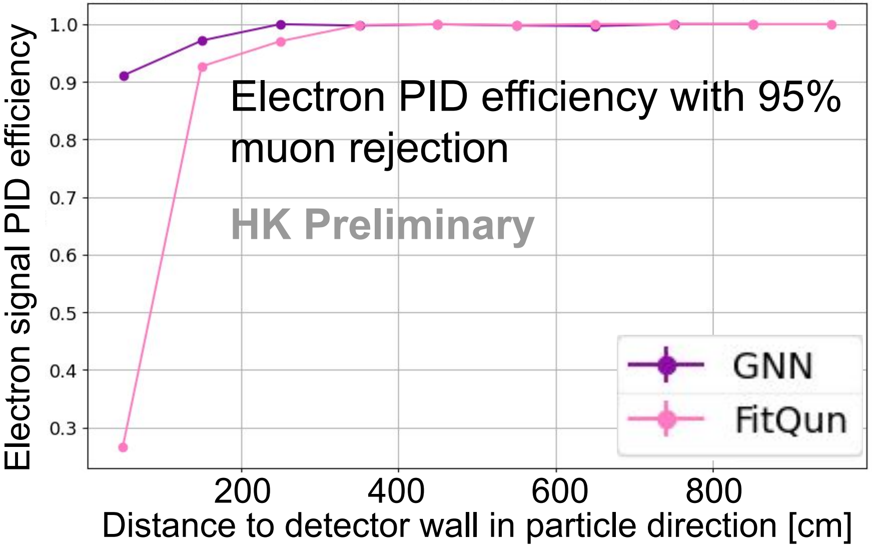
- Physical proximity of PMTs
- or charge, time proximity
- or both

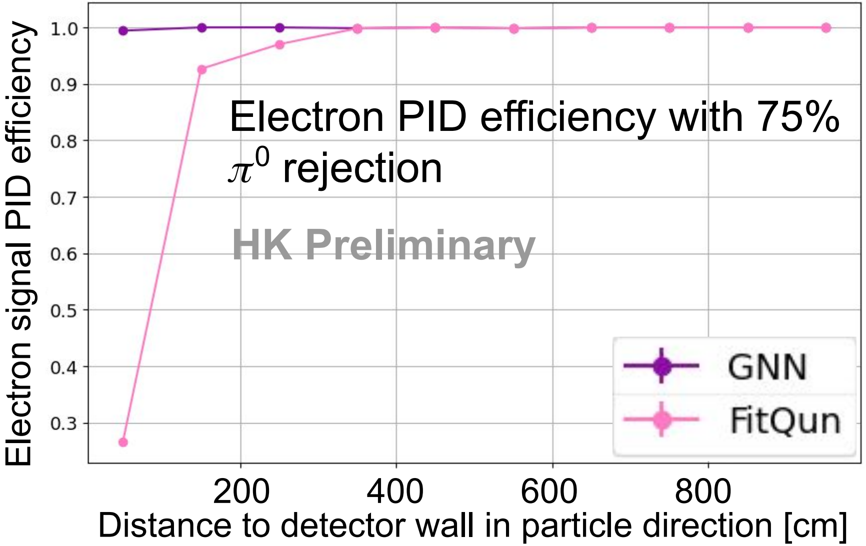
ResGatedGraphConv

- Graph convolution: aggregates information from neighbouring nodes
- Gate mechanism: adaptively controls amount of information passed between nodes
- Residual connection: Adds original node information to updated information for enhanced gradient propagation

Pooling layer followed by fully connected network provides 1D array of output features (PID variables, reconstructed quantities)

GRANT GNN Results





Energy reconstruction	500 MeV electrons	500 MeV muons
GRANT GNN	5.5% resolution, 1.5% bias	2.5% resolution, 0.5% bias
fiTQun	7.0% resolution, 0% bias	6.0% resolution, 0% bias

Traditional method (fiTQun) tuned to MC to avoid / correct for bias, need to investigate bias source in GRANT

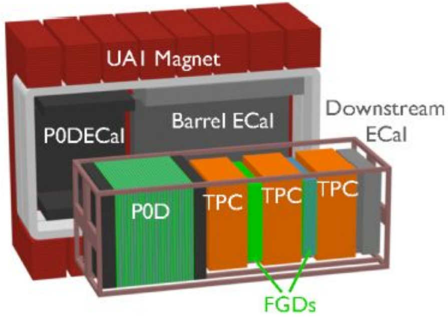
Vertex position reconstruction is not performing well in GRANT, under further investigation

Plan to reduce systematics

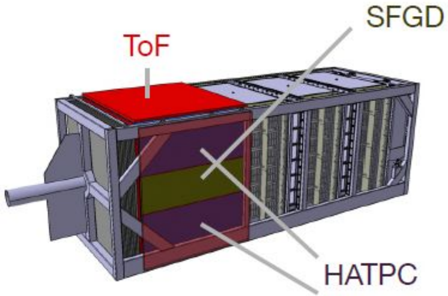
ND280 upgrade(s)

For T2K-II, ND280 upgrade finished in 2024*. **P0D** (π^0 detector) replaced by:

- A **Super-Fine-Grained Detector** (2.1 million 1cm^3 scintillating cubes): higher reconstruction efficiency at high scattering angles
- Two **High Angle TPCS** (below and above SFGD)
- 6 **Time of Flight** panels: to measure direction of particles



Pre-upgrade ND280



ND280 upgrade:
Fiducial mass multiplied by 2
+ better angular coverage

R&D is ongoing for the upgrade of the second half of ND280 during HK lifetime

→ **ND280 upgrade ++**

Goal: further increase mass + improve detecting capabilities

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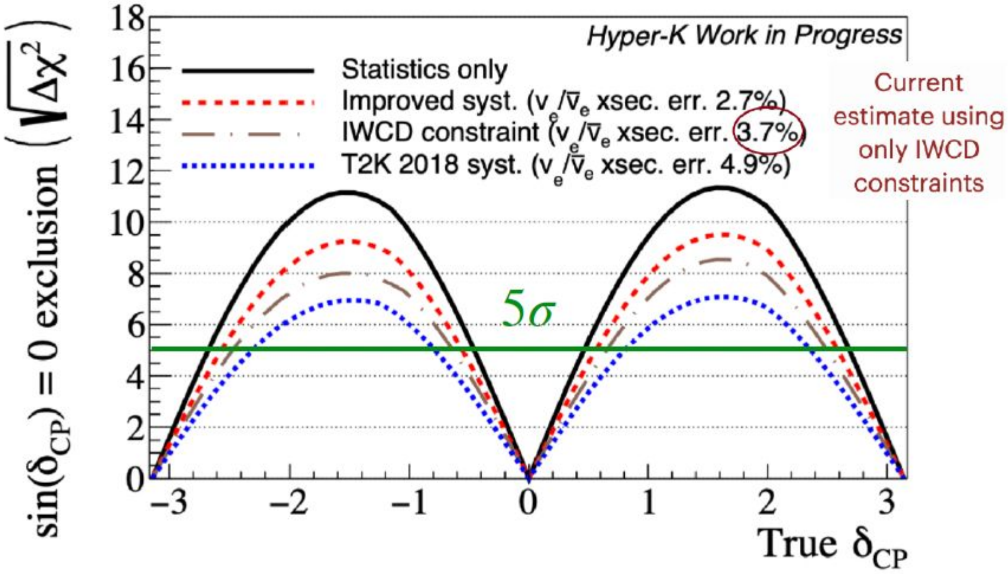
Plan to reduce systematics

Example: $\nu_e/\bar{\nu}_e$ cross-section ratio uncertainty

With **only IWCD**, could reach a **~3.7%** uncertainty

With **ND280 upgrade (++) and IWCD**, can go **below 3%** uncertainty after 10 years of HK-LBL



Significance to exclude CP symmetry after 10 years

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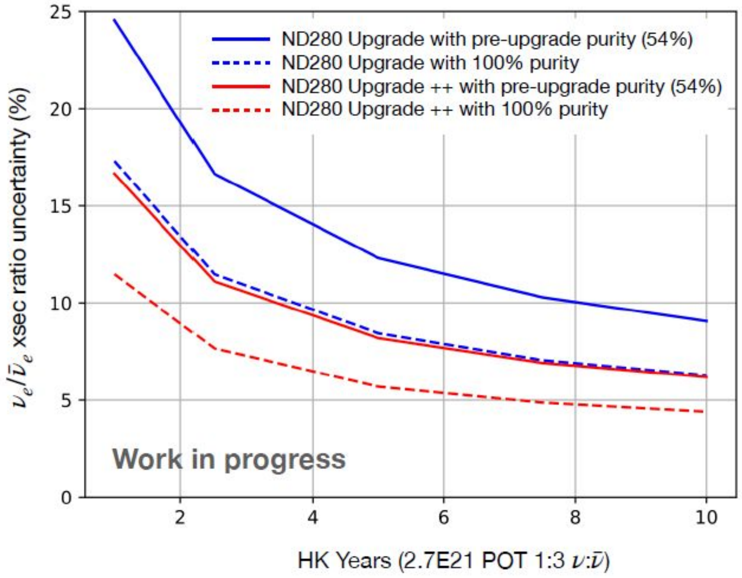
Plan to reduce systematics

Example: $\nu_e/\bar{\nu}_e$ cross-section ratio uncertainty

Estimation of ND280 constraint on $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$ with upgrade or upgrade ++ mass, pre-upgrade efficiency and pre-upgrade or 100% purity.



With **only ND280 upgrade**, could reach a **~7.5%** uncertainty or below with the upgrade ++

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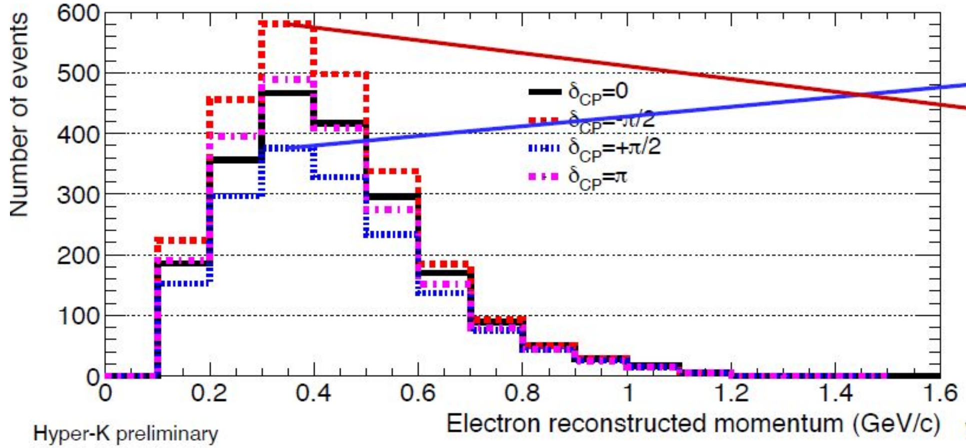
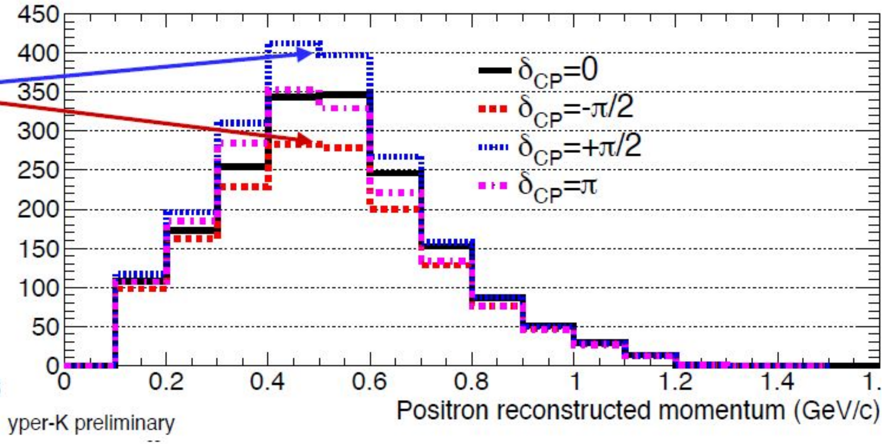
Sensitivity to CP violation

Expected event rates in **e-like** samples after **10 years**: impact of δ_{CP}

Run plan: $\nu : \bar{\nu} = 1 : 3$



neutrino beam



anti-neutrino beam

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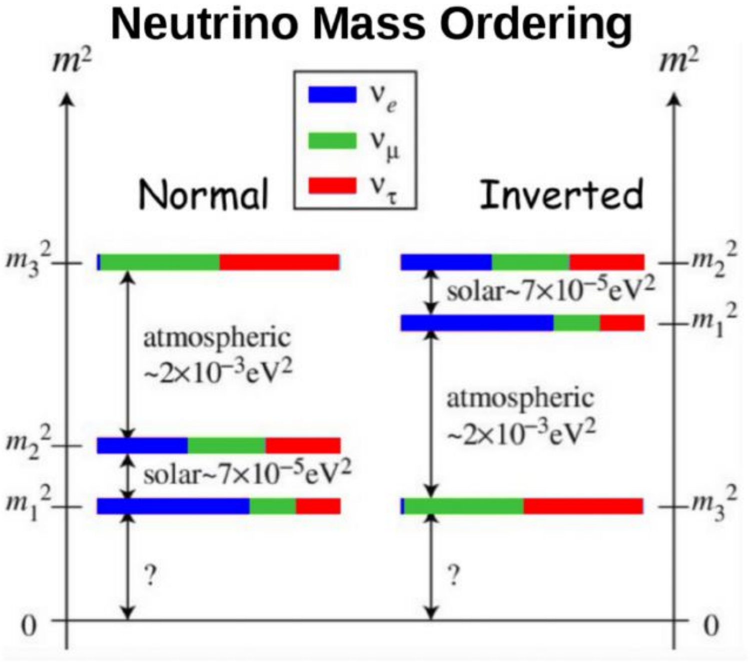
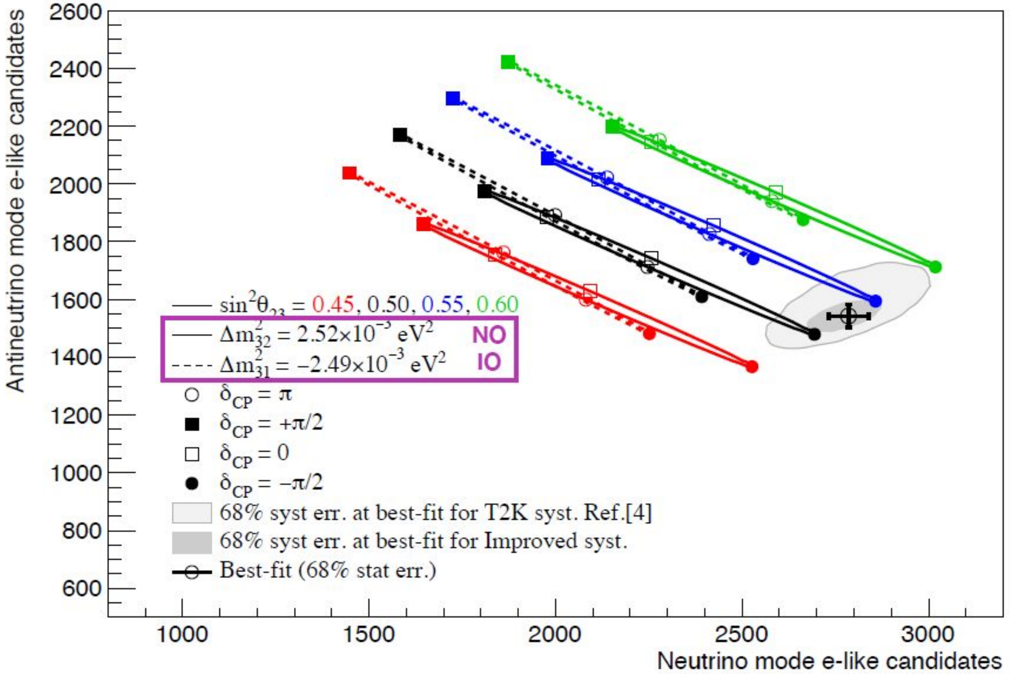
Degeneracy with MO





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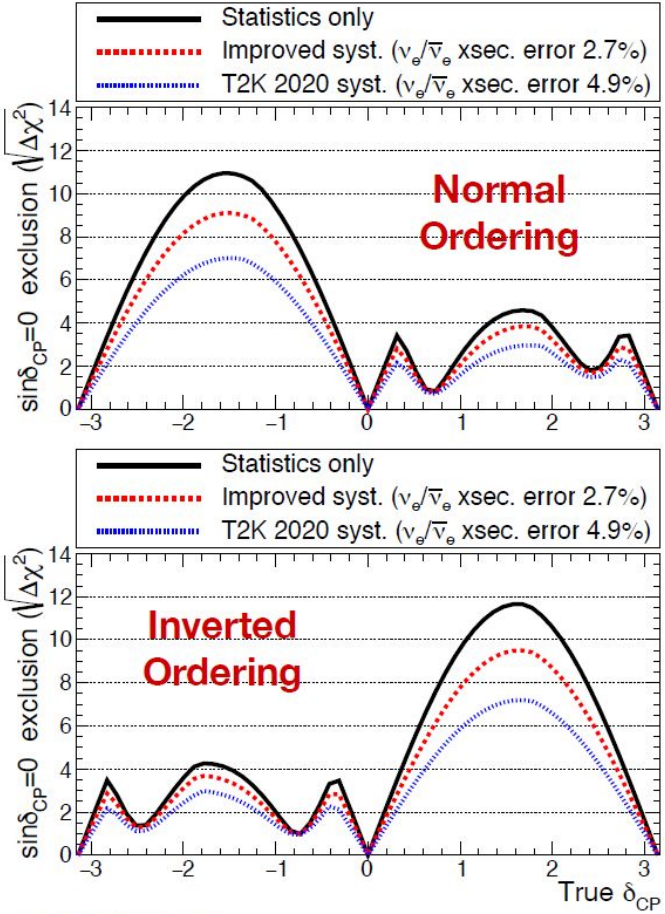
Degeneracy with MO

- In previous slides, considered MO known (True NO)
- **If MO is unknown**, sensitivity to CP violation is degraded in **degenerate** regions
- **Adding atmospheric samples** help lift the degeneracy because flavour oscillation in atmospheric samples measure MO independently



Hyper-K preliminary
True inverted ordering (Unknown), 10 years (2.7×10^{22} POT 1:3 $\nu:\bar{\nu}$)
$\sin^2\theta_{13}=0.0218\pm0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}\,eV^2/c^4$

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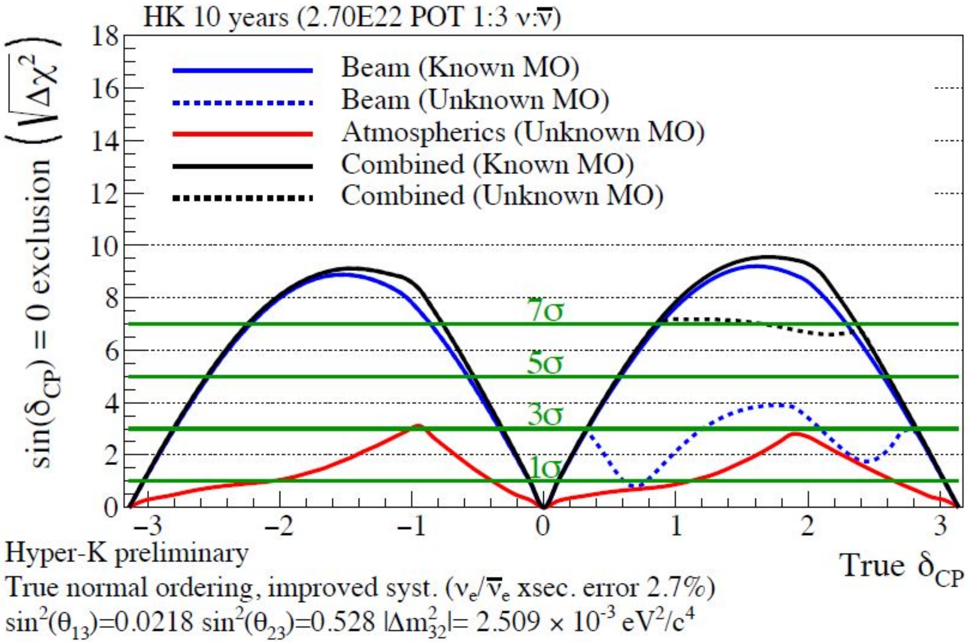
Degeneracy with MO



Previous analysis results: stay tuned for updates!

- In the **degenerate region**, CP symmetry exclusion is **limited by wrong MO exclusion**
- First SK-atm+T2K joint fit results published in 2025: Phys. Rev. Lett. 134, 011801
- **New sensitivity studies** currently being performed for HK atm+LBL joint fit based on T2K+SK framework
- Previous analysis suggested we can get **same 5σ discovery potential in both regions** after 10 years of joint fit.

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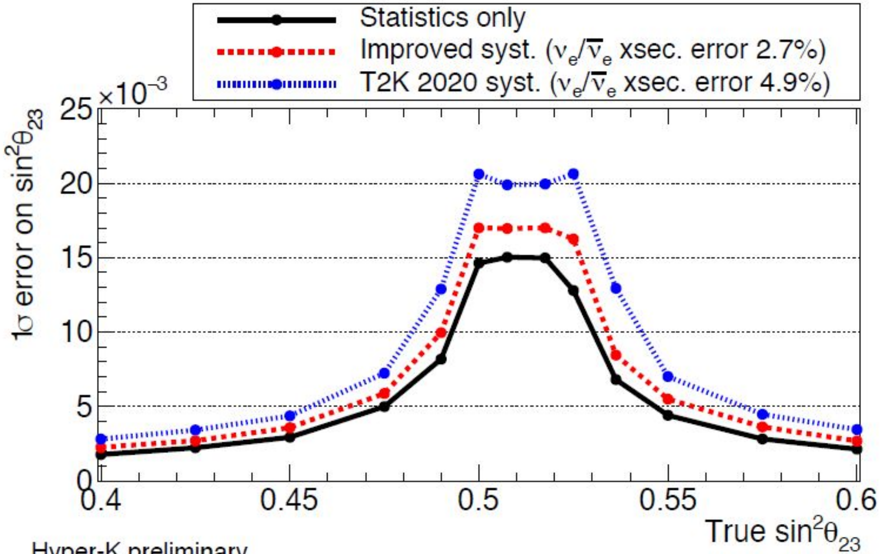
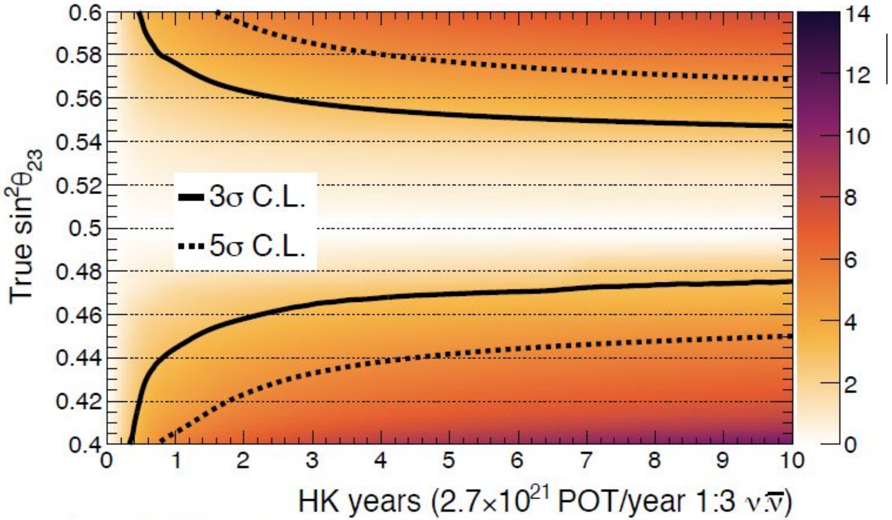
Measurement of θ_{23}



Hyper-K preliminary
True normal ordering (known)
$\sin^2\theta_{13}=0.0218\pm0.0007$, $\Delta m^2_{32}=2.509\times10^{-3}\text{eV}^2/c^4$, $\delta_{CP}=-1.601$



Hyper-K preliminary
True normal ordering (known), Improved systematics
$\sin^2\theta_{13}=0.0218\pm0.0007$, $\delta_{CP}=-1.601$, $\Delta m^2_{32}=2.509\times10^{-3}\text{eV}^2/c^4$

Wrong octant exclusion

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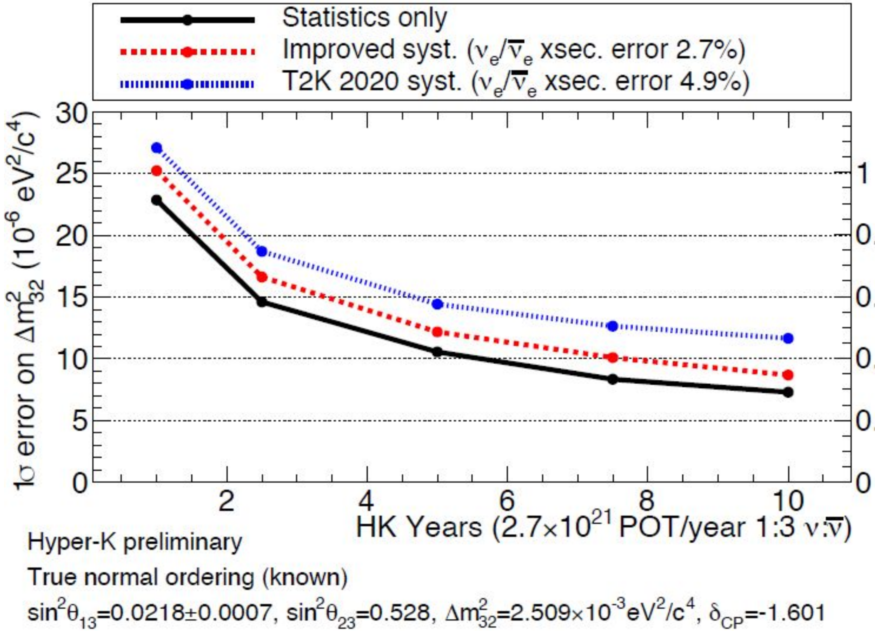
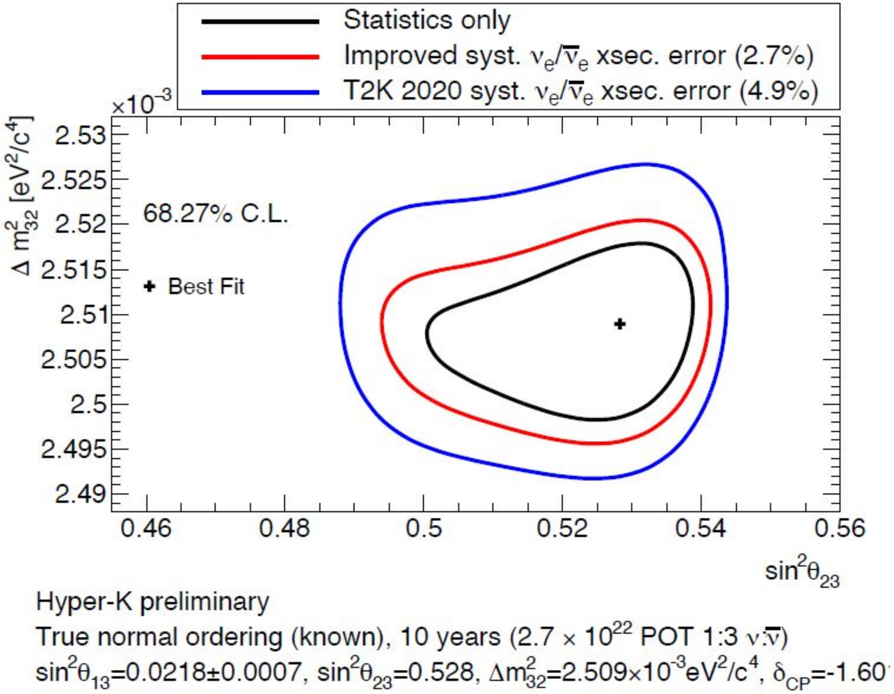
Measurement of $|\Delta m^2_{32}|$





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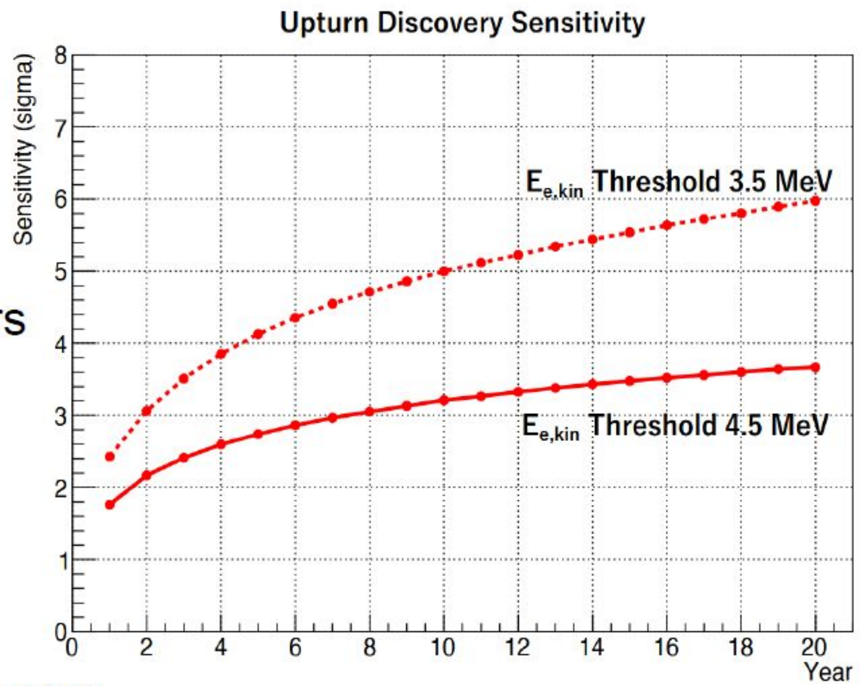
- transition region between the vacuum oscillations and matter-dominated energy regions
- precise measurement of the spectrum shape allows to distinguish the usual neutrino oscillation scenario from exotic models
- 3σ sensitivity to spectrum upturn in 10 years for 4.5 MeV threshold
  (5σ for 3.5 MeV threshold)



- other possible measurements
  - first measurement of *hep* component (2-3σ) providing more information on the Sun core
  - time variation measurement (with rate of 130ν/day) → monitoring of the Sun core temperature

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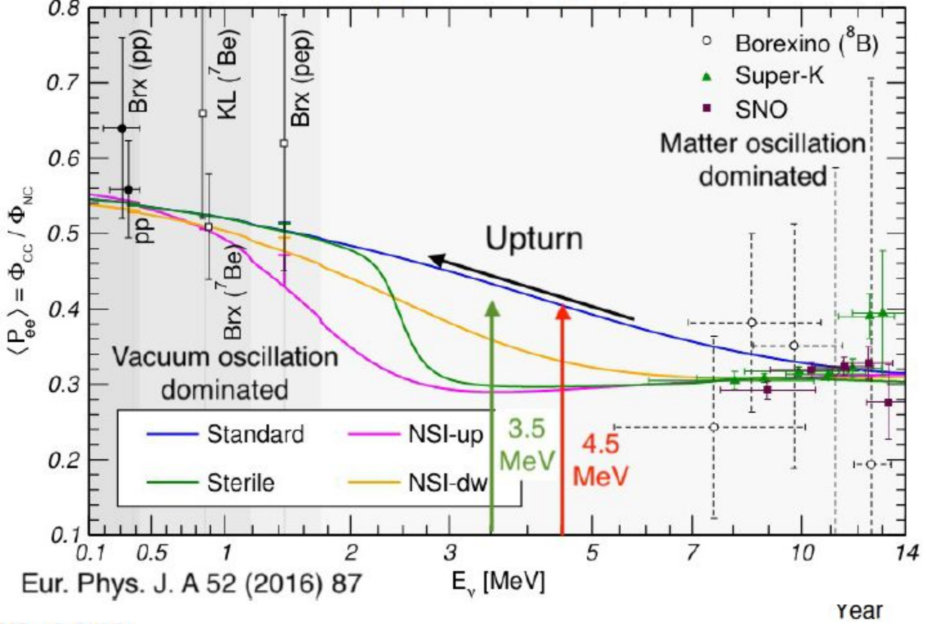
  for 4.5 MeV threshold

  (5σ for 3.5 MeV threshold)

Upturn region



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- other possible measurements
  - first measurement of *hep* component (2-3σ) providing more information on the Sun core
  - time variation measurement (with rate of 130ν/day) → monitoring of the Sun core temperature

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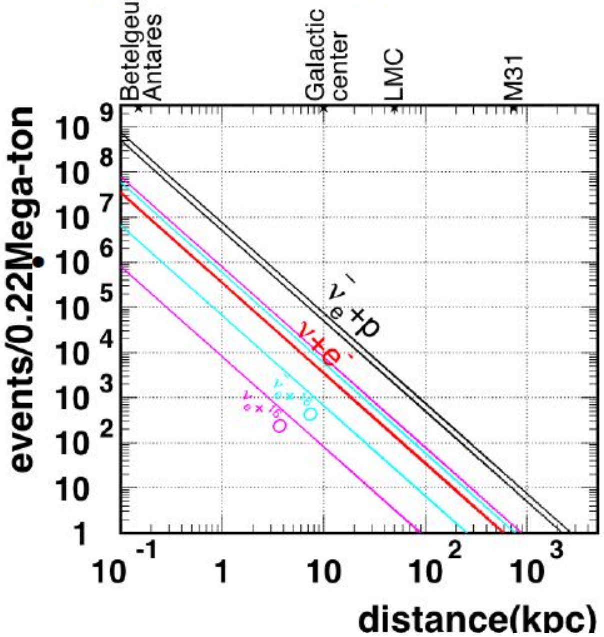
- ν_e from neutronization peak – elastic scattering on electrons (directional information, accuracy 1-1.3° expected for supernova @10kpc)
- $\bar{\nu}_e$ from cooling phase – inverse beta decay

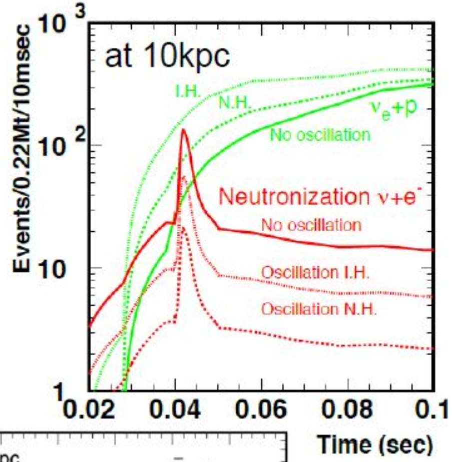


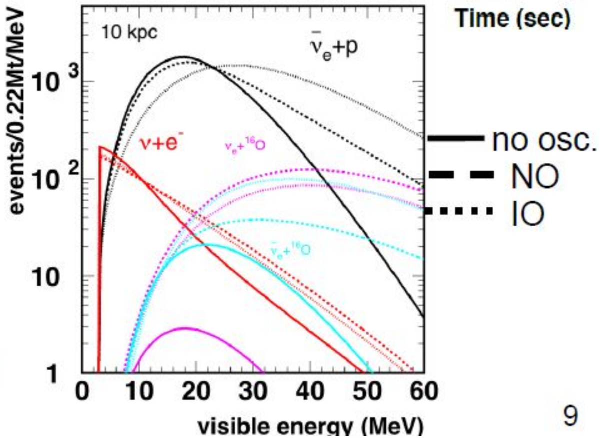
expectations:

~70k events @10kpc
2-3k (SN1987a)

information on
- neutrino oscillations and properties (mass, mass ordering)
- core-collapse supernova models

Early warning for telescopes





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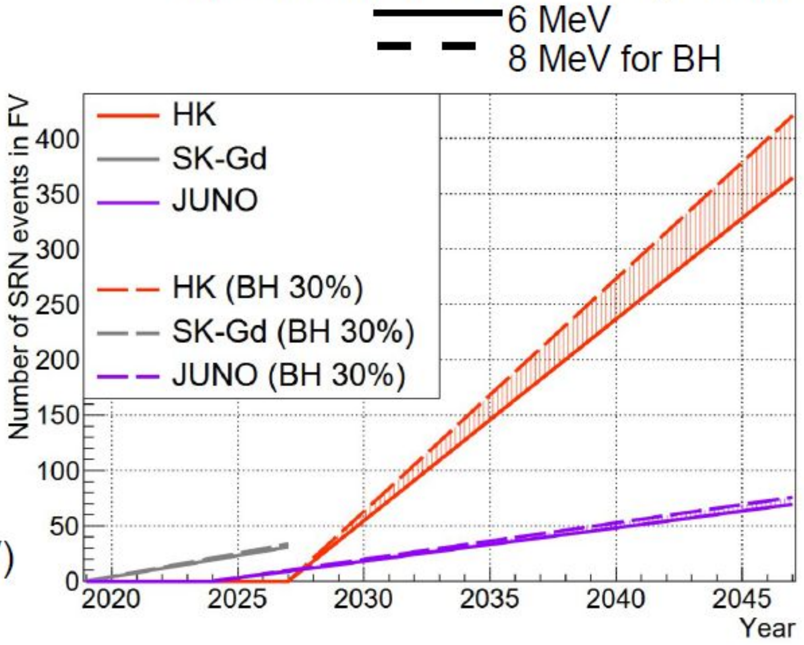
Supernova relic neutrinos

or: diffuse supernova neutrino background

- expected flux few tens/cm^2·s
- search limited by background:
  - spallation for low energies
  - atmospheric neutrinos for high energies
- first measurement may be done by SK-Gd
- Hyper-K may measure the spectrum
- different search window (~16-30 MeV)
  - complementary to SK-Gd searches (10-20 MeV)
  - contribution of extraordinary supernova bursts (like black hole formation, BH): provides information on the star formation history and metallicity

expected inverse beta decay events



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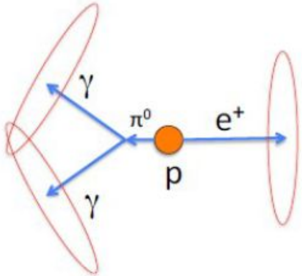
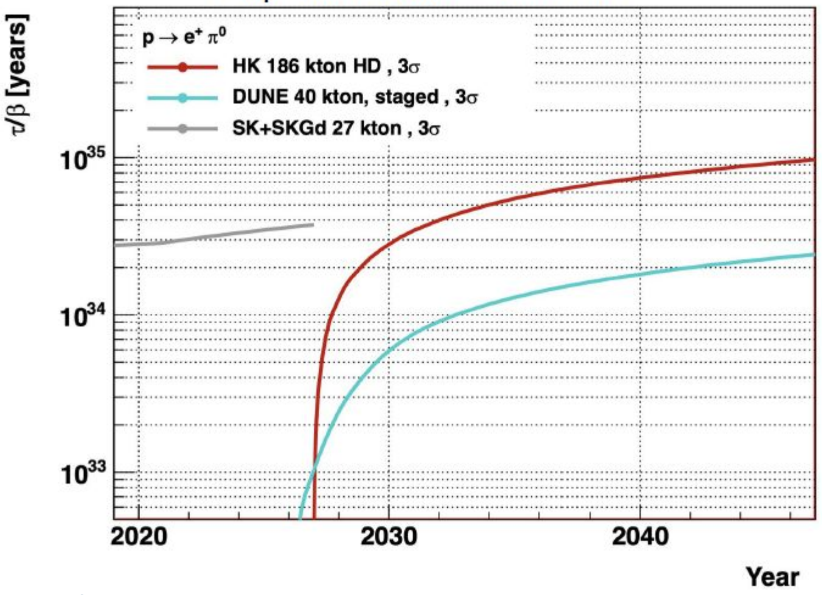
Search for $p \to e^+\pi^0$ decay

- decay mode $p \to e^+\pi^0$ favoured by many GUTs



e^+ and photons detected as e-like rings
→ final state is fully reconstructed
(almost background free)

Expected 90% C.L. limits



- analysis similar as in SK
  - neutron capture in water: n(p,d)γ (2.2 MeV)
  - efficient tagging of prompt γ from residual nuclei deexcitation
  - → ~50% reduction of atmospheric background

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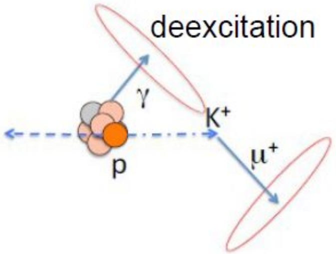
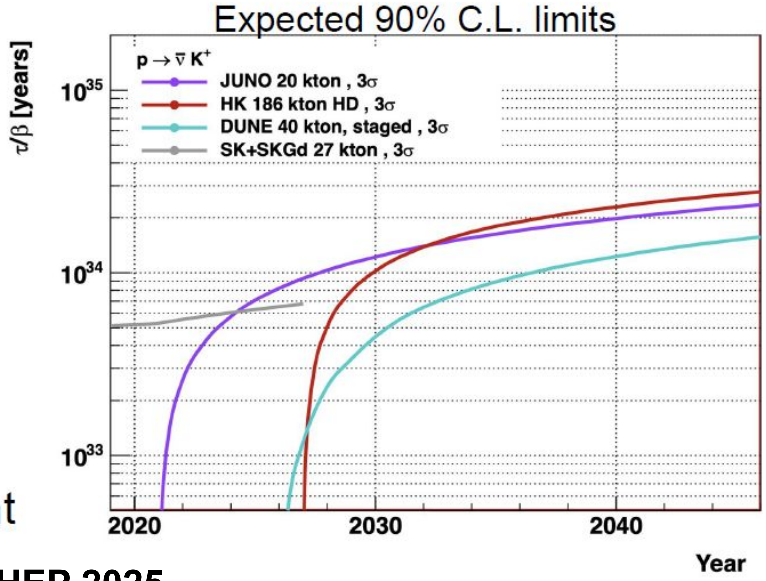
Search for $p \to \bar{\nu} K^+$ decay

- favoured by SUSY GUTs
- kaon not visible in Water Cherenkov detector: reconstructed from decay products
  - monochromatic muon (236 MeV) +prompt deex. photon (6.3 MeV) } $K^+ \to \mu^+ \nu$, BR 64%
  - excess in muon spectrum
  - or search for $K^+ \to \pi^0 \pi^+$ decay (BR 21%, $p_{\pi+}$ = 205 MeV/c, slightly above the threshold)



Partial lifetimes limits
(90% C.L., 10 y exposure)

- $6 \cdot 10^{34}$ years for $p \to e^+ \pi^0$
- $2 \cdot 10^{34}$ years for $p \to \bar{\nu} K^+$
- basically one order of magnitude improvement for many other modes



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