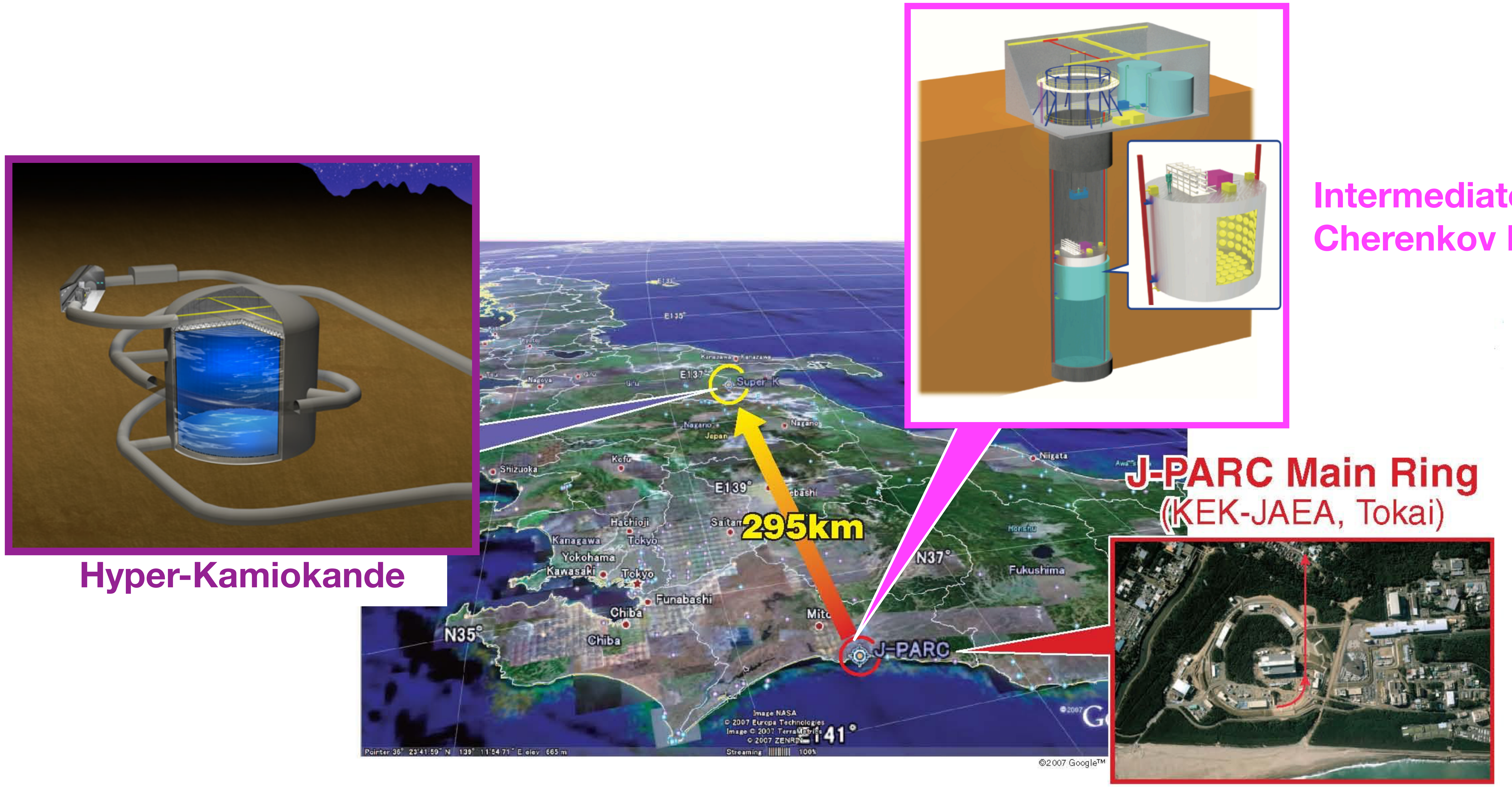
An Intermediate Water Cherenkov Detector for Hyper-Kamiokande Using the NuPRISM Concept

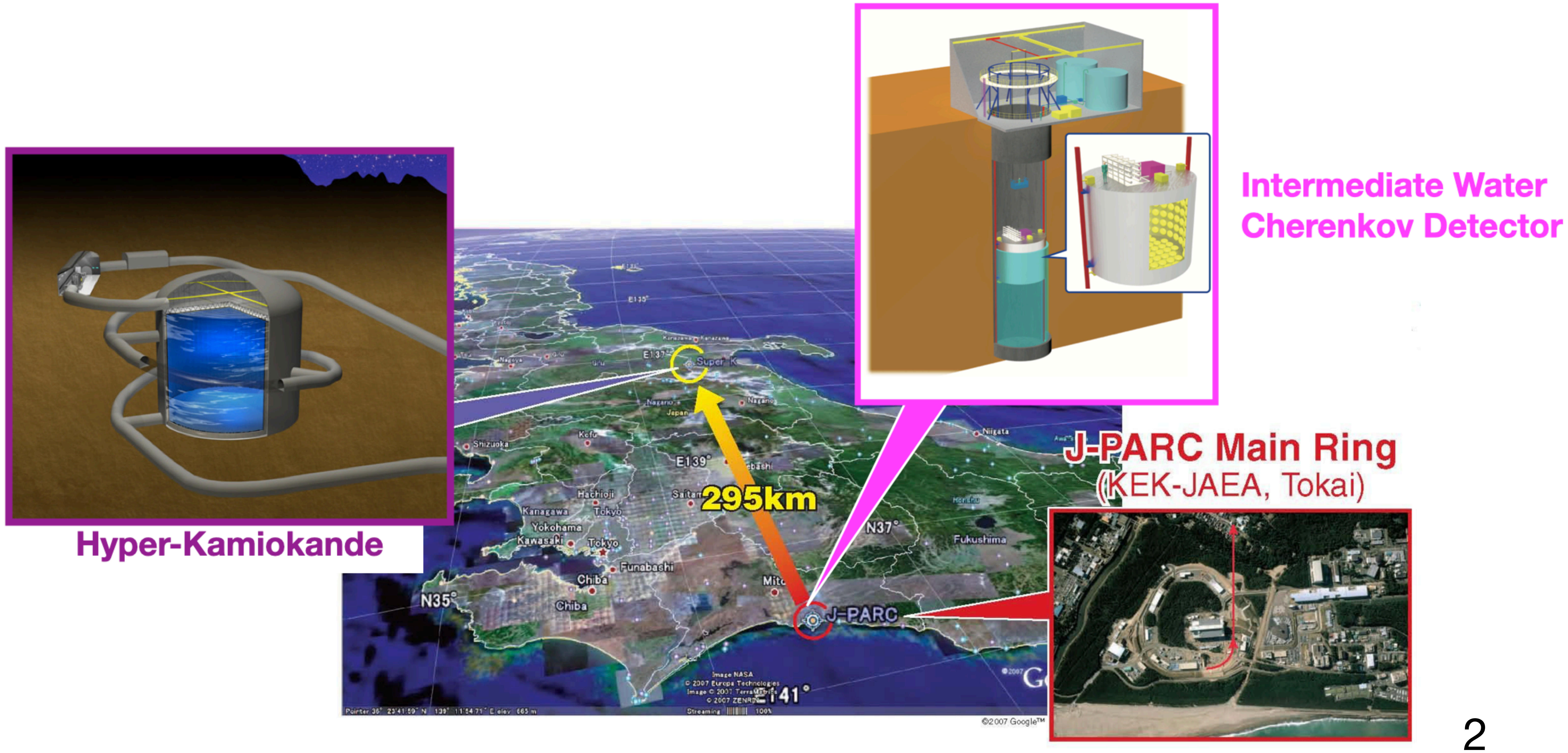


Mark Hartz
TRIUMF & Kavli IPMU, University of Tokyo

TIPP 2021, May 25, 2021

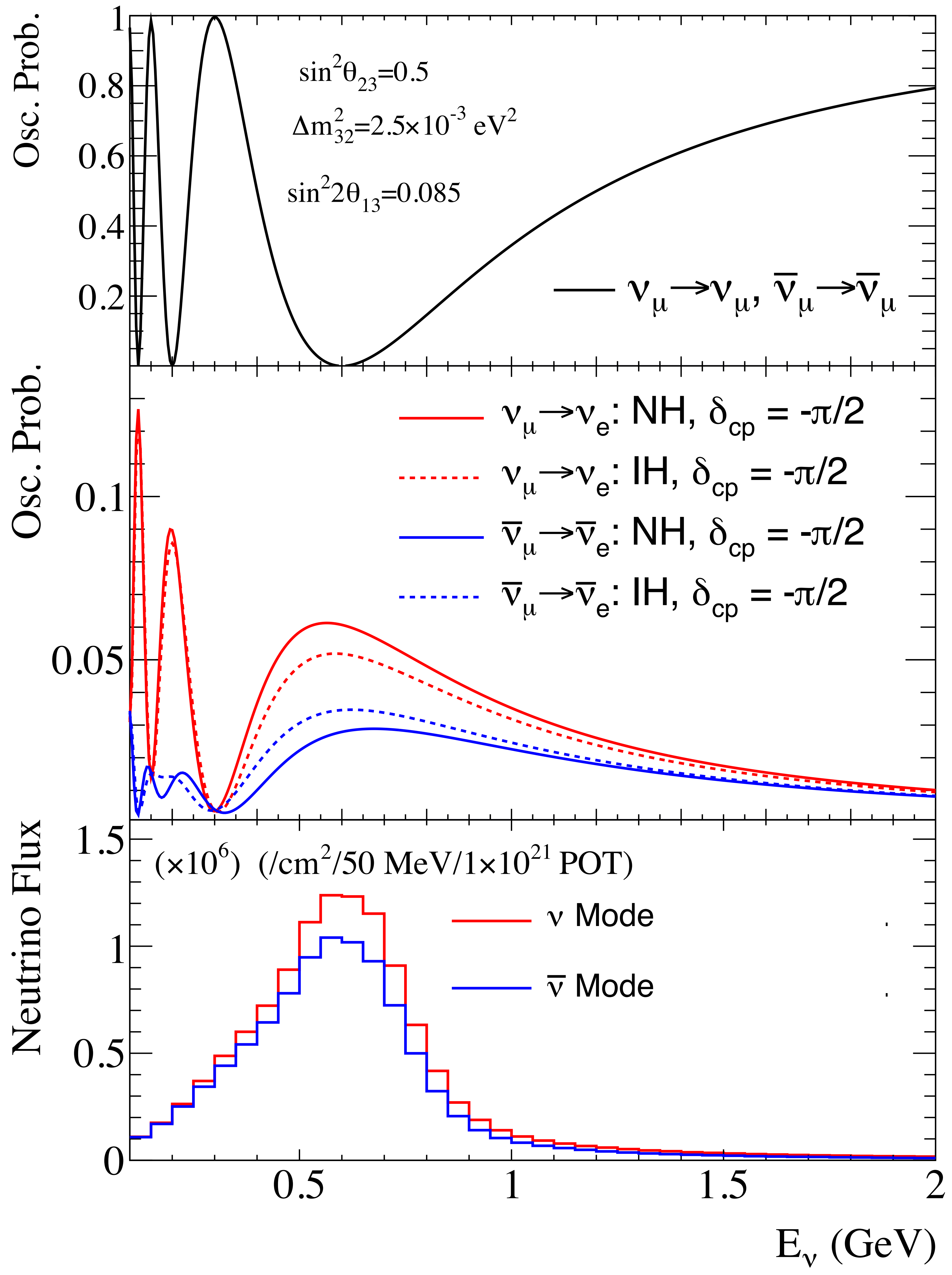
Hyper-K Experiment

- 260 kton detector with fiducial mass is 8x larger than Super-Kamiokande
- Neutrino beam from J-PARC will be 2.5 times more intense (1.3 MW proton beam)
- New photon detectors and near detectors
- 20x the rate of long baseline neutrinos than the T2K experiment
- Broad physics program includes
  - Accelerator neutrinos
  - Proton decay searches
  - Supernova neutrino detection
  - Atmospheric neutrino detection
  - Solar neutrino detection
  - Dark matter searches…



Neutrino Oscillation Measurements

Hyper-Kamiokande



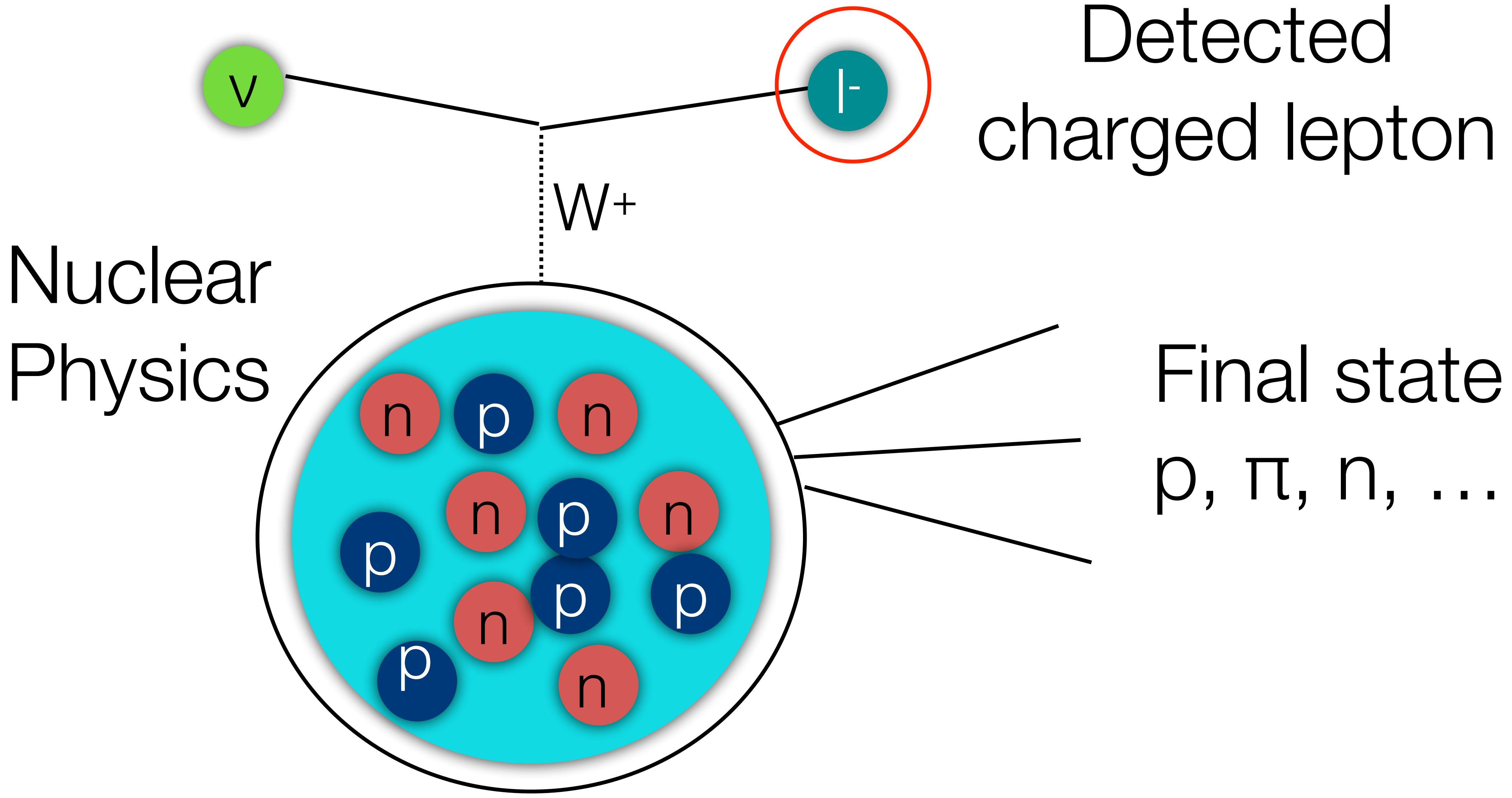
- Over **295 km baseline**, study neutrino oscillations:

$$\nu_\mu \to \nu_\mu,\ \bar{\nu}_\mu \to \bar{\nu}_\mu$$
$$\nu_\mu \to \nu_e,\ \bar{\nu}_\mu \to \bar{\nu}_e$$

- Important measurements include:
  - Determine if there is **CP violation** in neutrino oscillations and measure phase δ_{cp}
  - Measure the mixing angle θ_{23} and determine if it is consistent with **45°**
- Beam aimed **2.5° off-axis** from direction to Hyper-K detector is narrow and peaked at oscillation maximum (in energy)

Neutrino Detection

- Detect **charged current scattering** of (anti)neutrinos on **nuclei**
- **Electron or muon** in final state identifies **flavour of parent (anti)neutrino**
- In water Cherenkov detector, below threshold hadrons are not tracked - **no full energy reconstruction**
- Need accurate modeling of (anti)neutrino interactions but **scattering on nuclei is difficult to model**
- Hyper-K will have a suite of near/intermediate detectors to measure:
  - Properties of the (anti)neutrino beam
  - Properties of the (anti)neutrino scattering on nuclei



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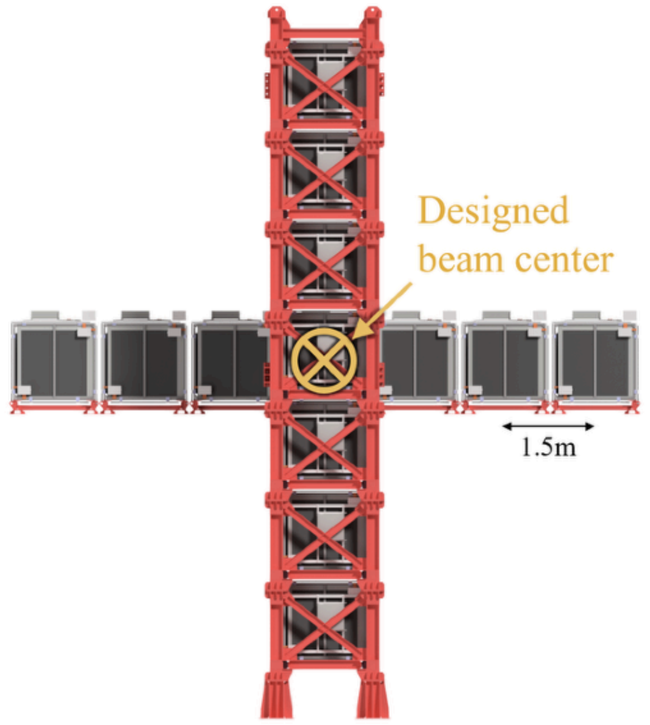
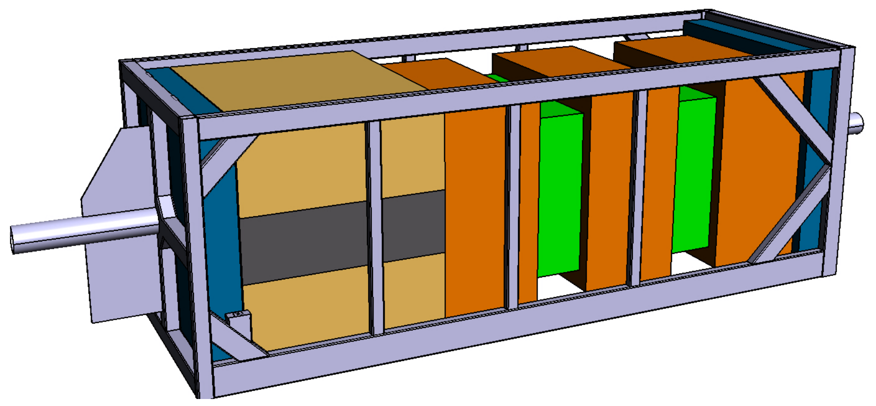
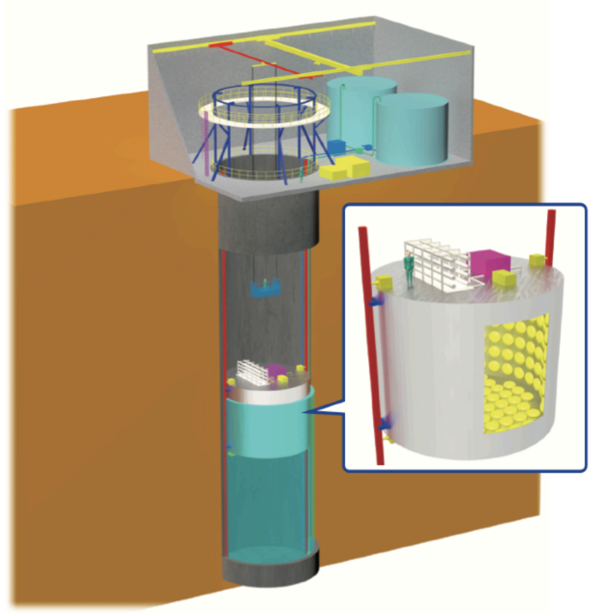


Ugraded ND280





Intermediate Water Cherenkov Detector (IWCD)

Systematic Uncertainties

Uncertainties in T2K measurement
(L. Berns, Moriond 2021)

Error Source	% Error for CP Violation search
Error from near detector constraint	1.7
Modeling of events that aren’t quasi-elastic scattering	2.1
Electron (anti)neutrino cross section error	3.0
Neutral current background error	1.0
Total cross section model error	**4.1**

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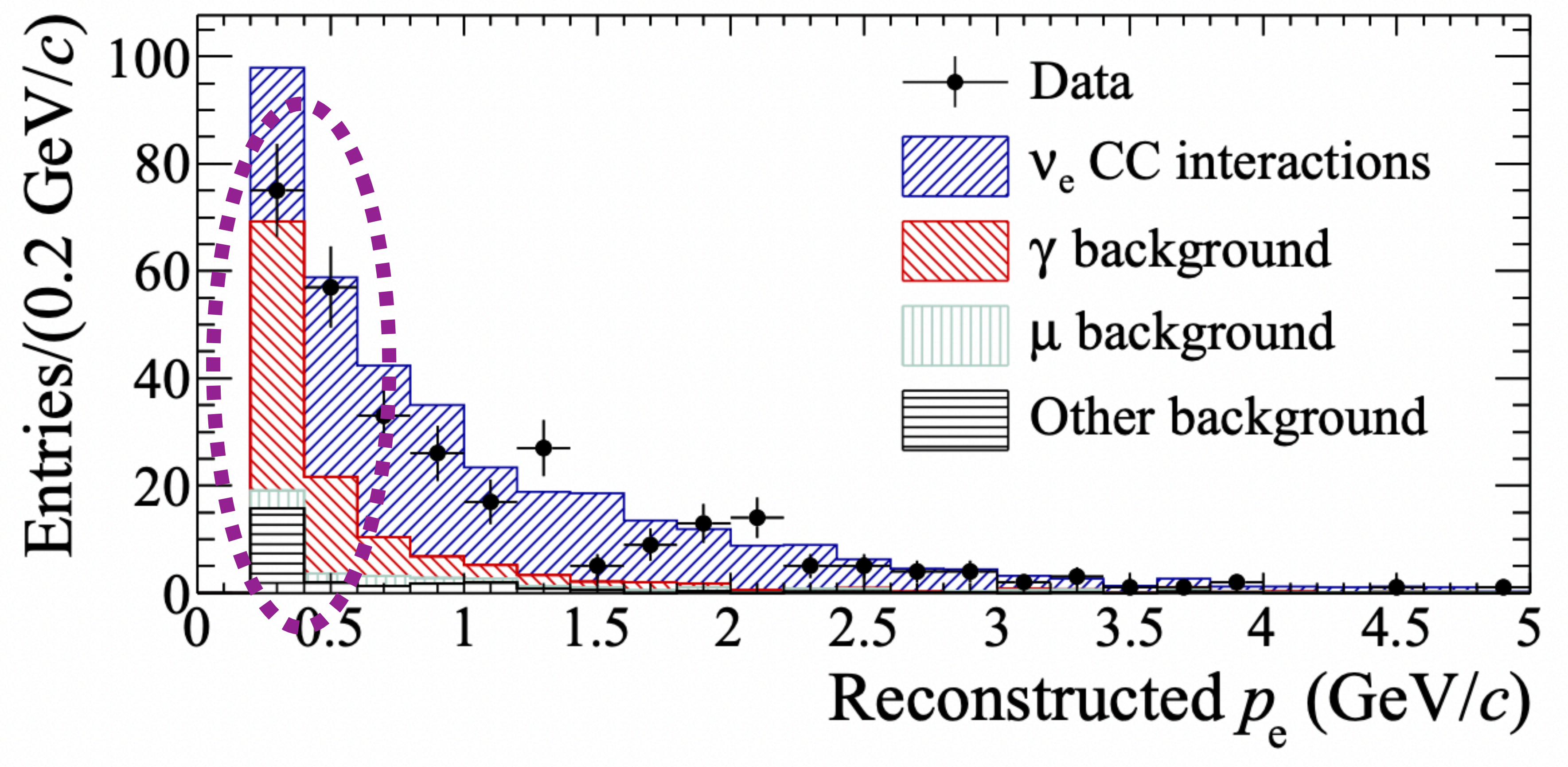
Aim to reduce total error to **<3% for Hyper-K**

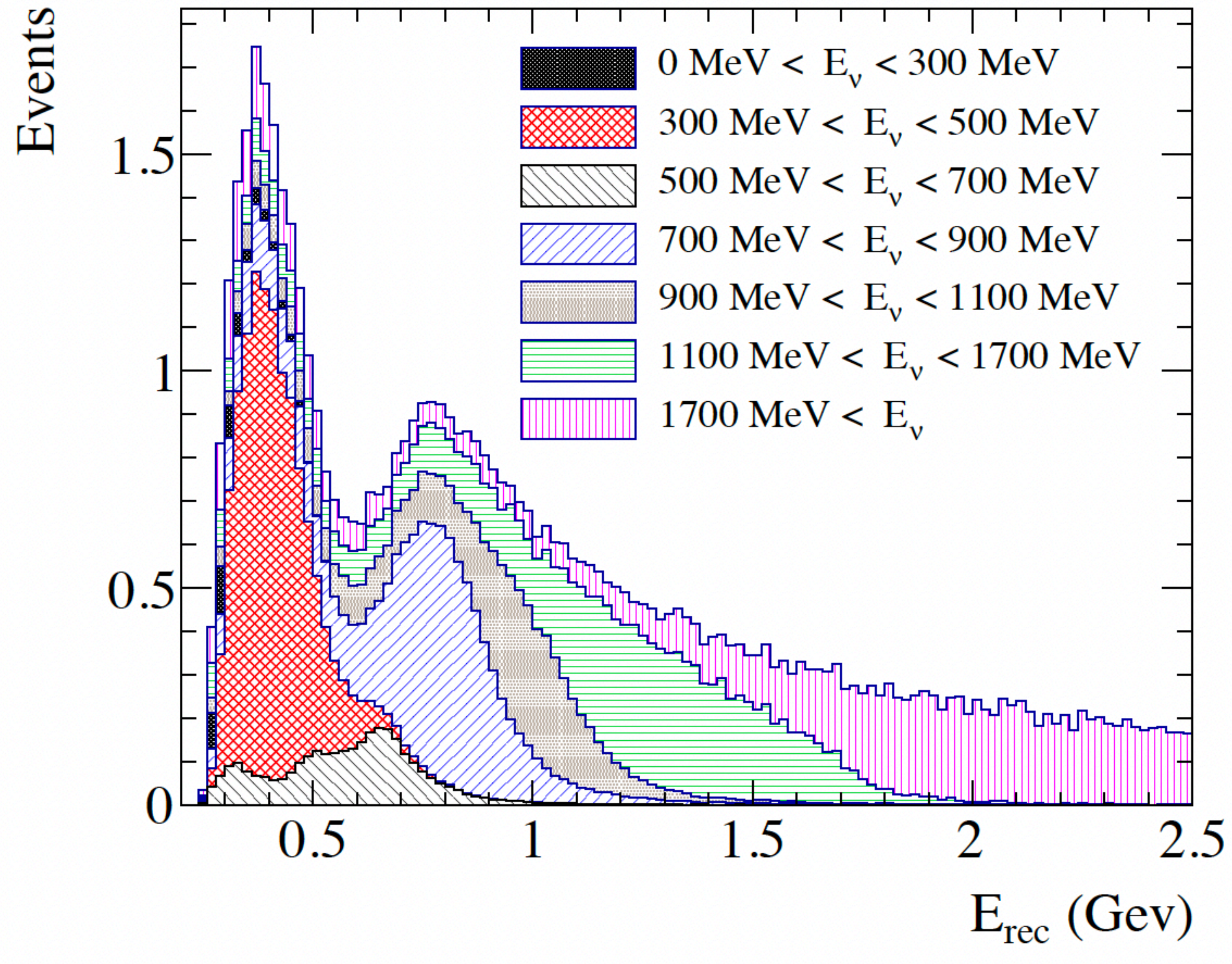
Challenges to Overcome

- Can measure electron (anti)neutrino cross section with 1% contamination in beam
  - Challenge: large background from beam induced external high energy gamma conversions (see T2K results to right)
  - Need to reduce this background

T2K: Phys. Rev. Lett. 113, 241803 (2014)



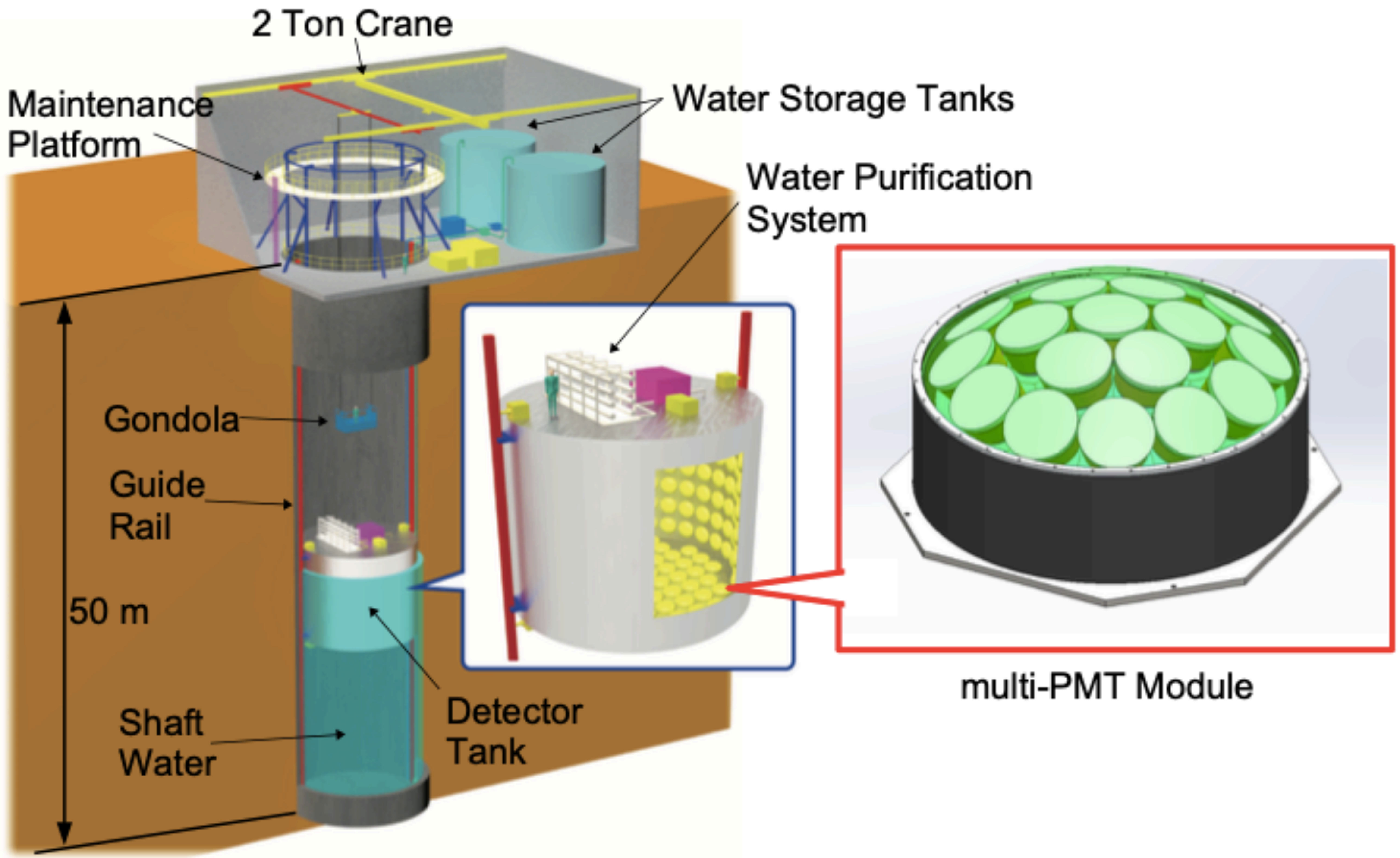
- Energy spectrum at near detector is different than far detector due to oscillations
  - Can't extrapolate near detector measurements perfectly
  - Nuclear effects -> large energy reconstruction error
  - Events with large energy mis-reconstruction can dominate some measurements (right)
  - Need direct measurements



The Intermediate Water Cherenkov Detector

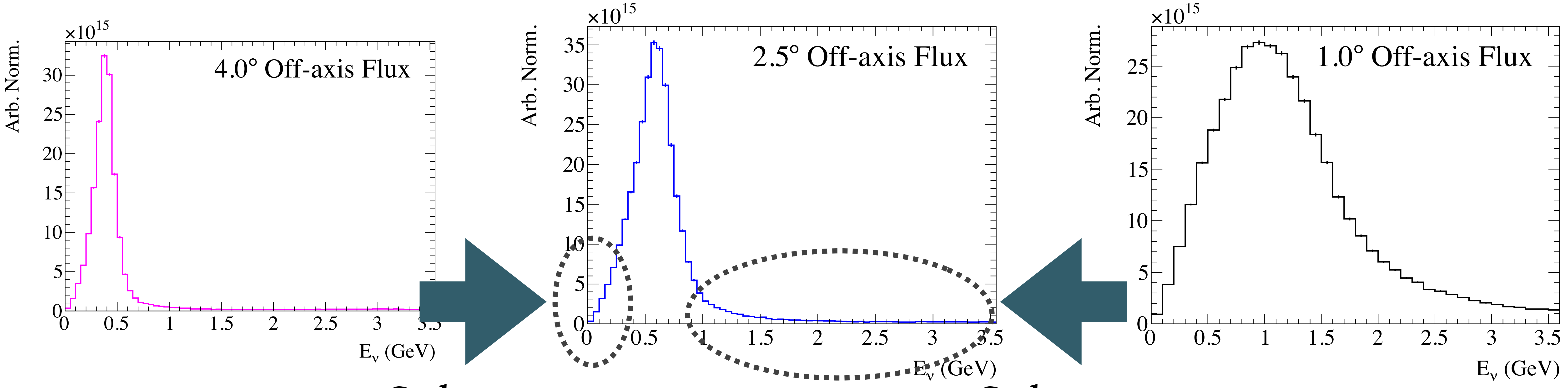
Hyper-Kamiokande

- Intermediate detector for Hyper-K
- Located about 1 km from neutrino source
- 600 ton water Cherenkov detector
- Position can be moved to different off-axis angles
- Loading with Gd to enhance neutron detection
- Using new high resolution multi-PMT photon detectors



Approved Hyper-K project includes IWCD

NuPRISM Concept



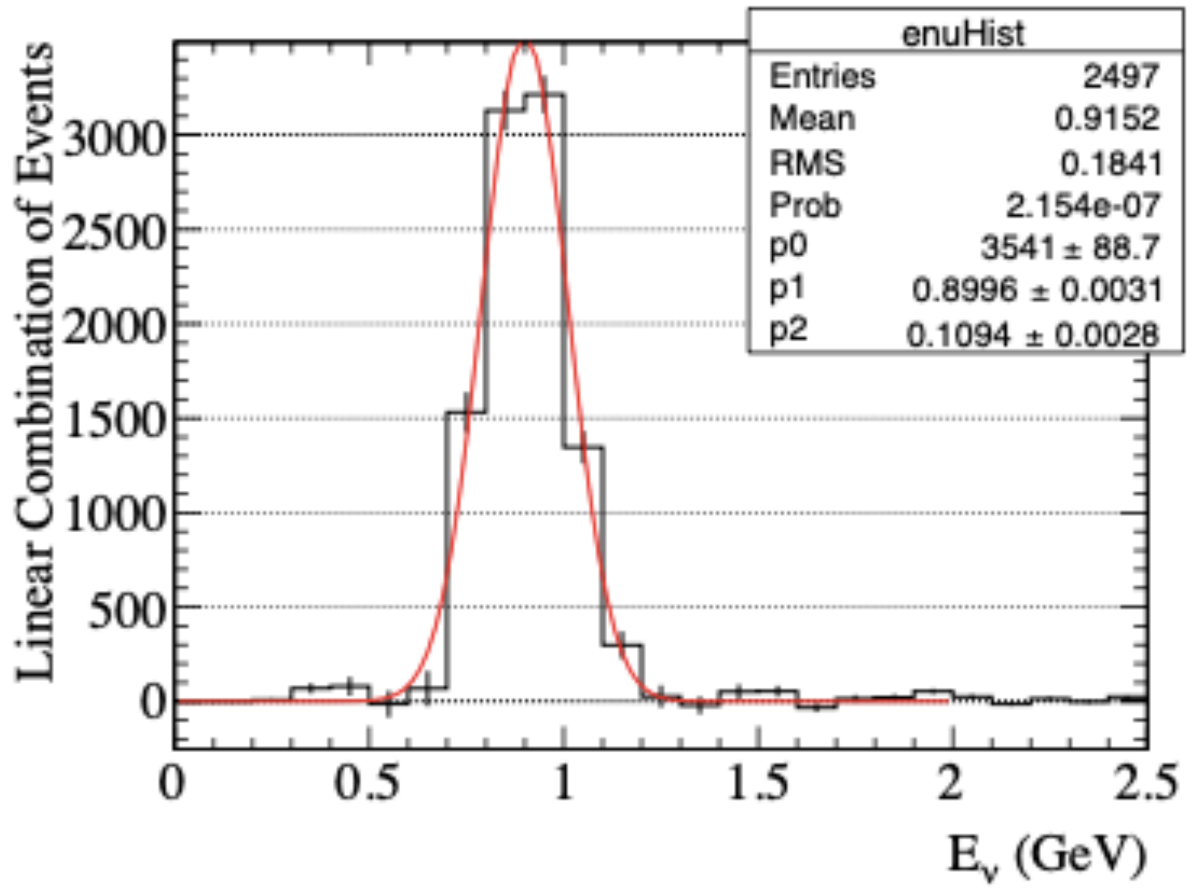
Subtract

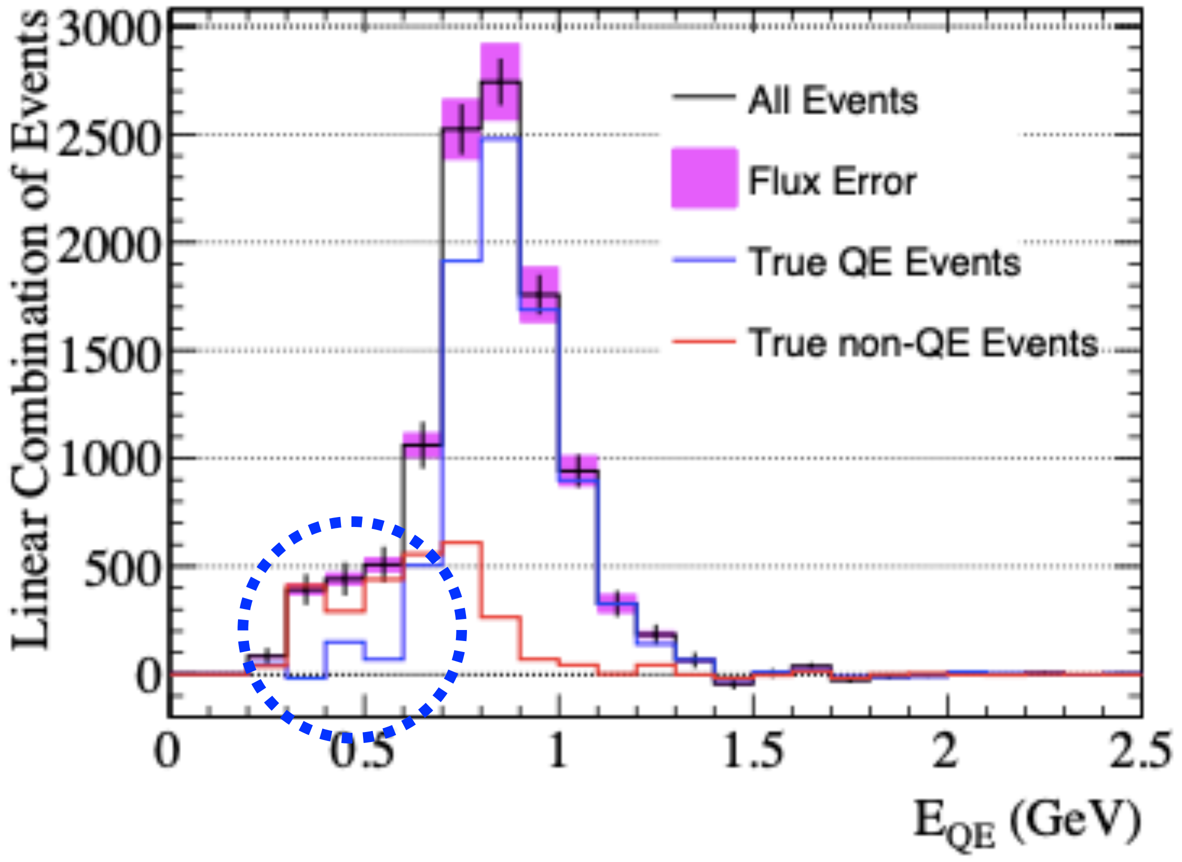
Subtract

Due to pion decay properties, neutrino spectrum varies with off-axis angle

Measurements at different off-axis angle can subtract high and low energy tails

Obtain very narrow spectrum

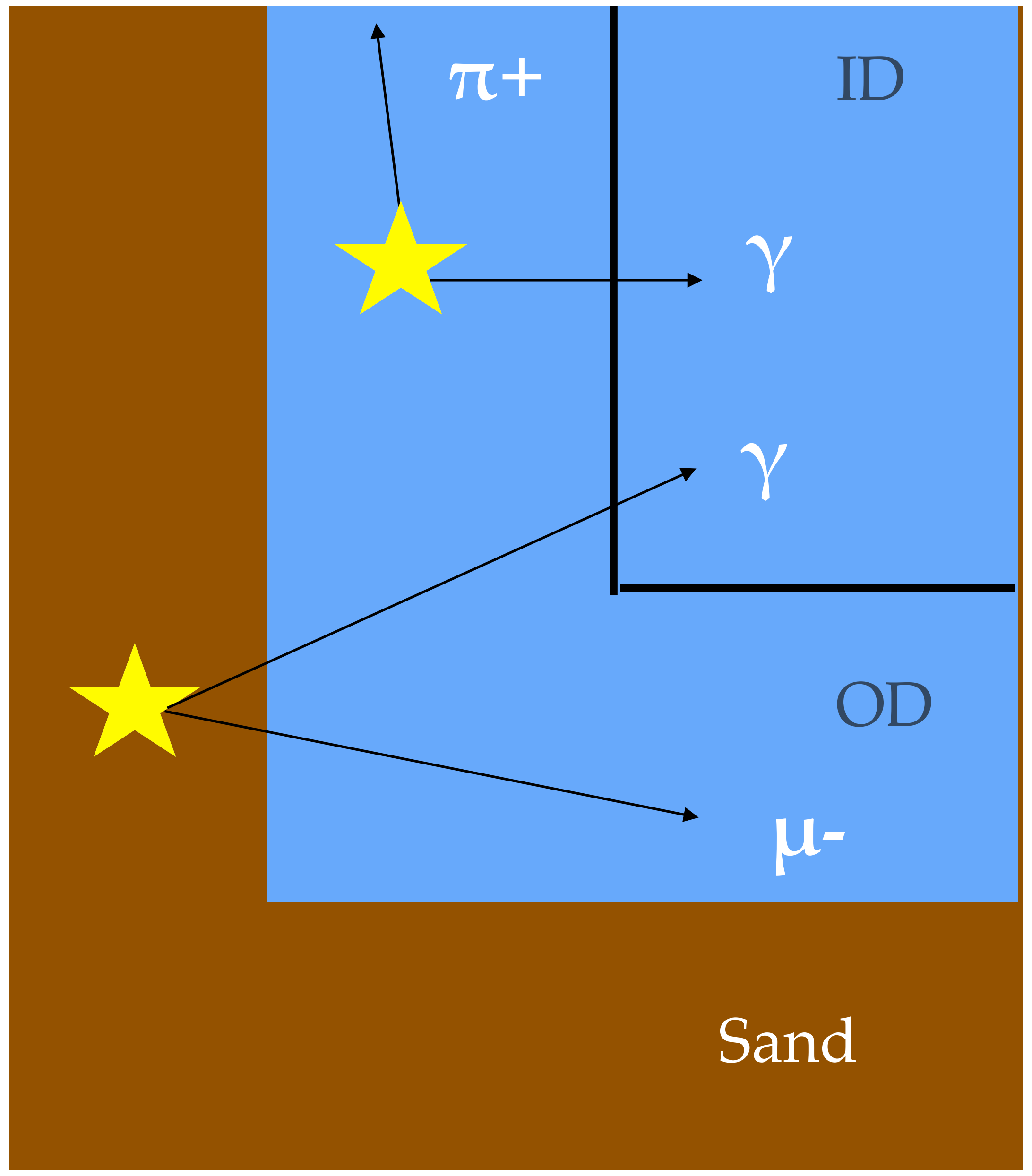




Measure reconstructed energy of events

5% measurement precision on events with large mis-reconstruction

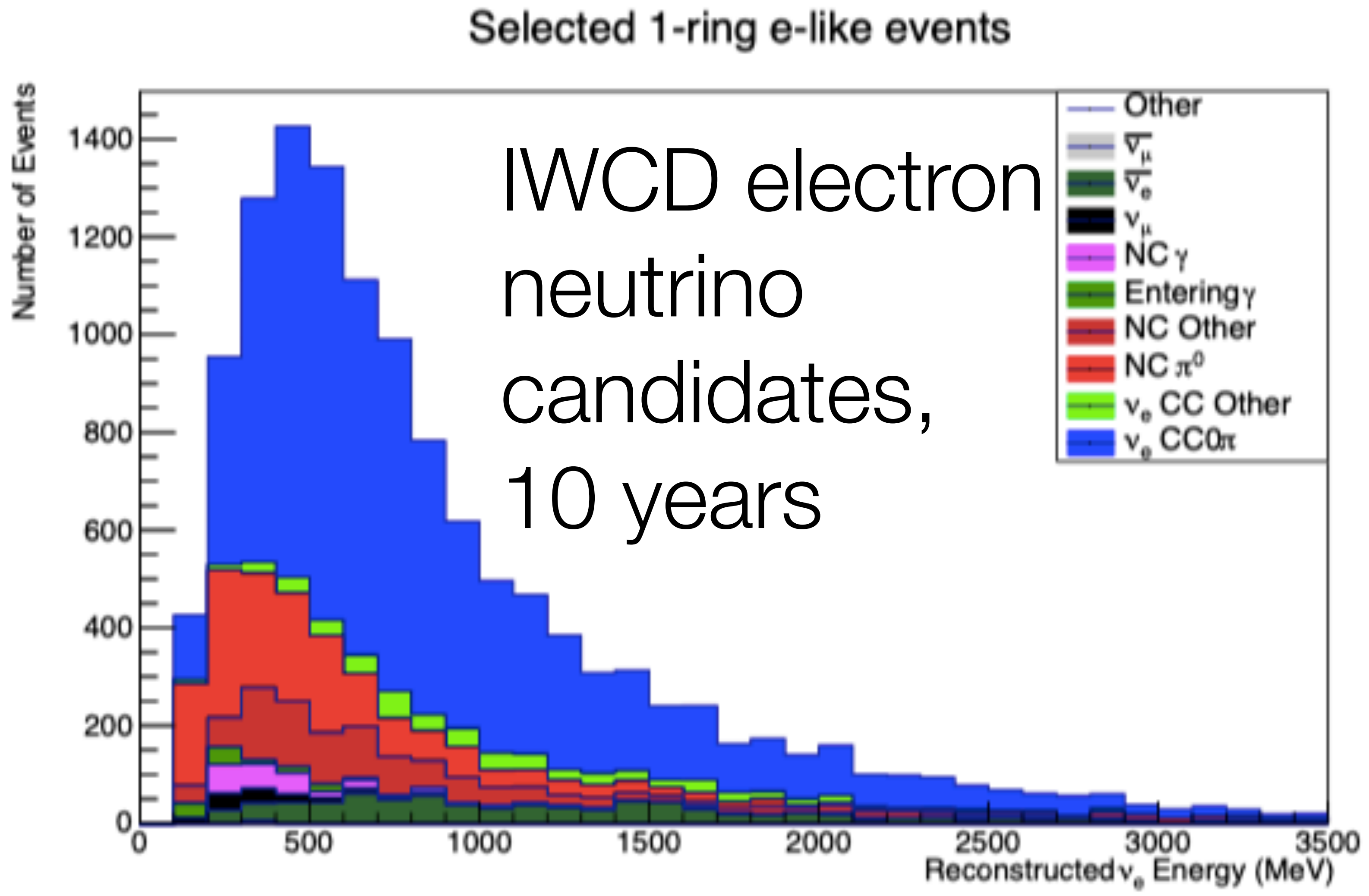
Electron (anti)Neutrinos



- Using 1% contamination in beam, we measure: $$\frac{\sigma(\nu_e)/\sigma(\nu_\mu)}{\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)}$$

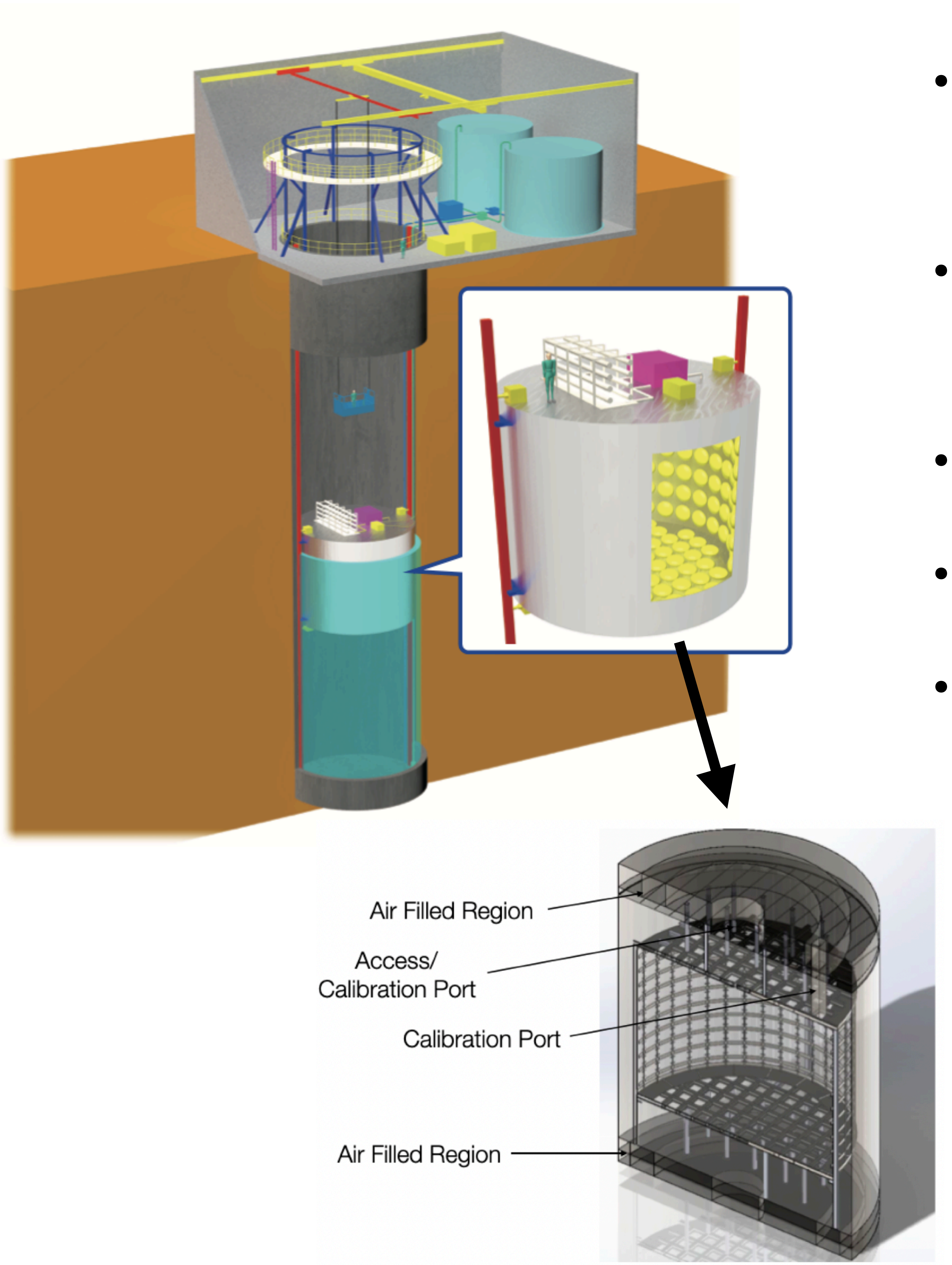
- More off-axis position has **larger fraction of electron (anti)neutrinos**

- Water Cherenkov detector has large active shielding agains **gamma background - almost completely removed**



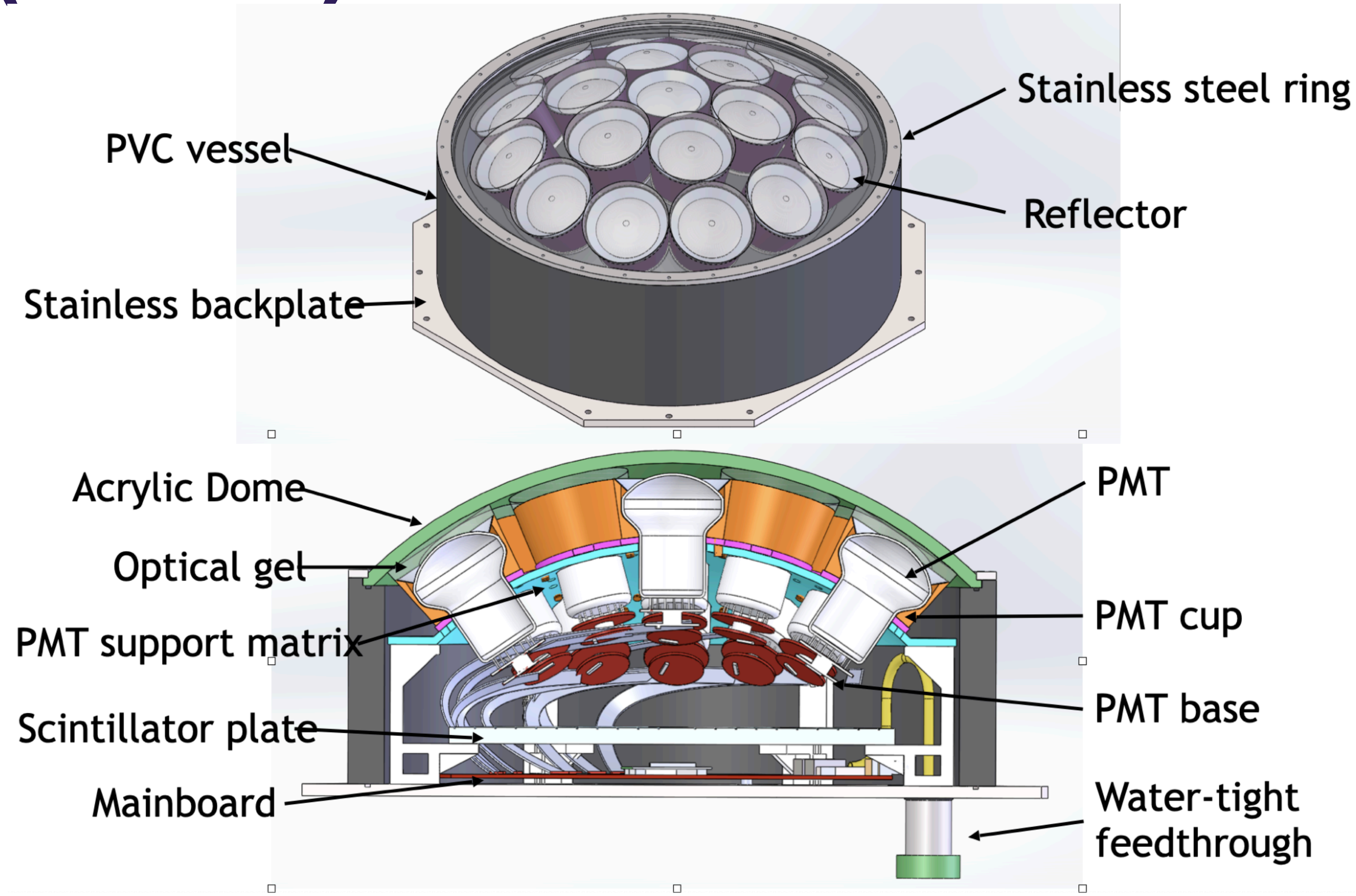
- **2.8% error** on relative event rates for CP violation search
  - Compared to **3.0% error from T2K**
  - Aim to **improve** with application of **machine learning**

Moving Detector



- Moving the detector vertically to different off-axis angle positions is challenge
- **Air-filled regions** in tank make detector **neutrally buoyant**
- **Water level** in pit is kept at the **detector level**
- Rail system to guide detector as it moves
- Parts of the water system, readout electronics and calibration system are **located on top of moving tank**

Multi-PMT (mPMT) Photosensor



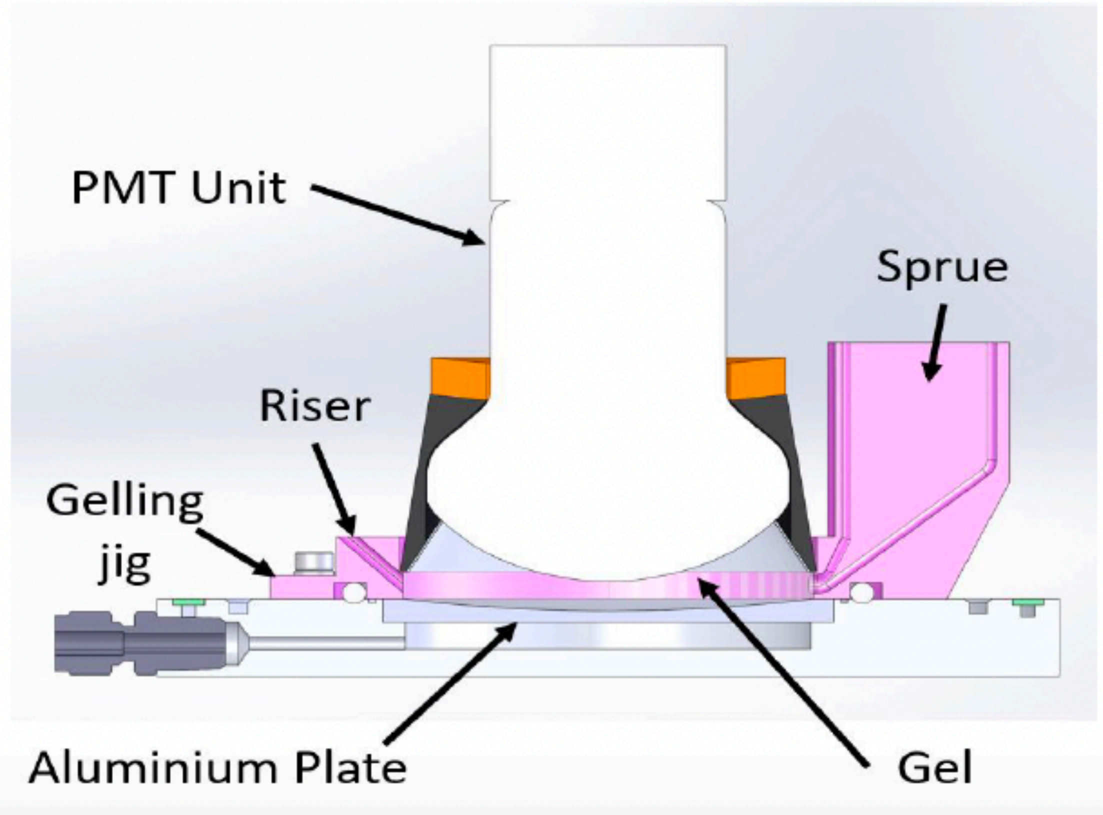
- 19 3-inch diameter PMTs integrated in module with high voltage and readout electronics
- 8-cm diameter PMTs have excellent timing resolution (~1.6 ns FWHM) with good spatial resolution
- High voltage circuits and electronics mainboard are inside the module

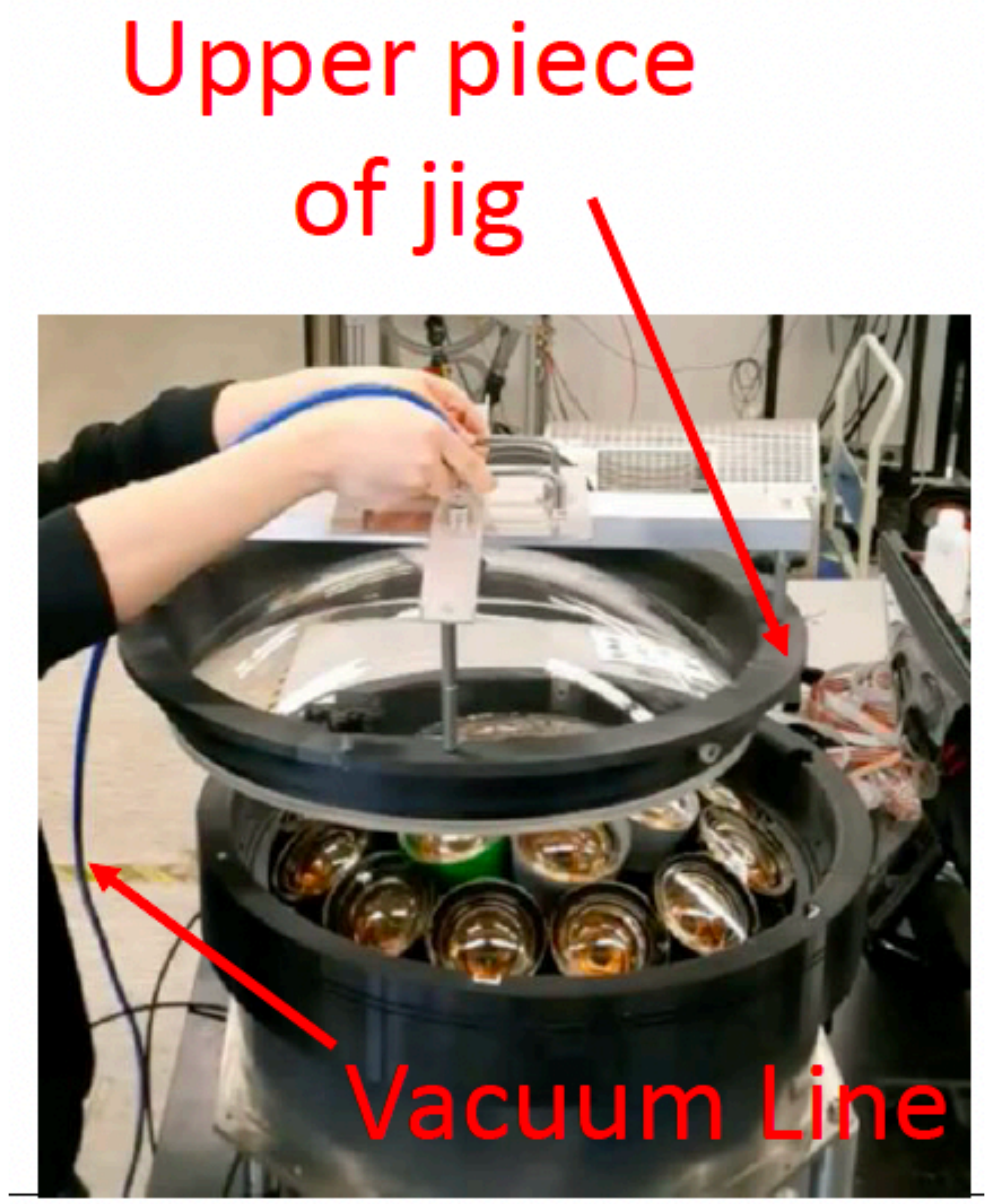
See Talk by M. Ziembicki: Electronics for Multi-PMTs for the IWCD at Hyper-Kamiokande

Multi-PMT Mechanical Design

Hyper-Kamiokande

- Acrylic used for transparent vessel
  - Pressure, transparency and permeability measurements
- Forward looking design with PVC cylinder and stainless steel backplate
- Optical gel couples PMT to acrylic
  - Gel is added to PMT before assembly
- Module assembled from the backplate
  - Last step is to lower dome in place



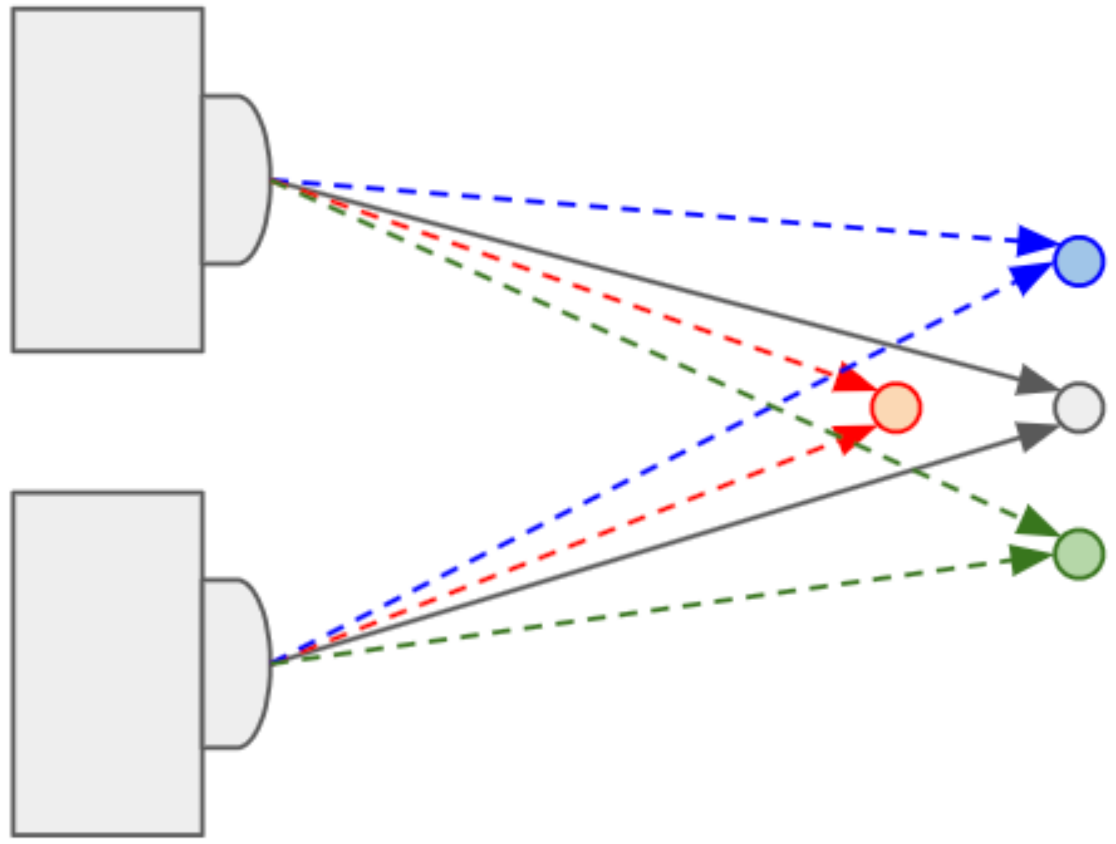


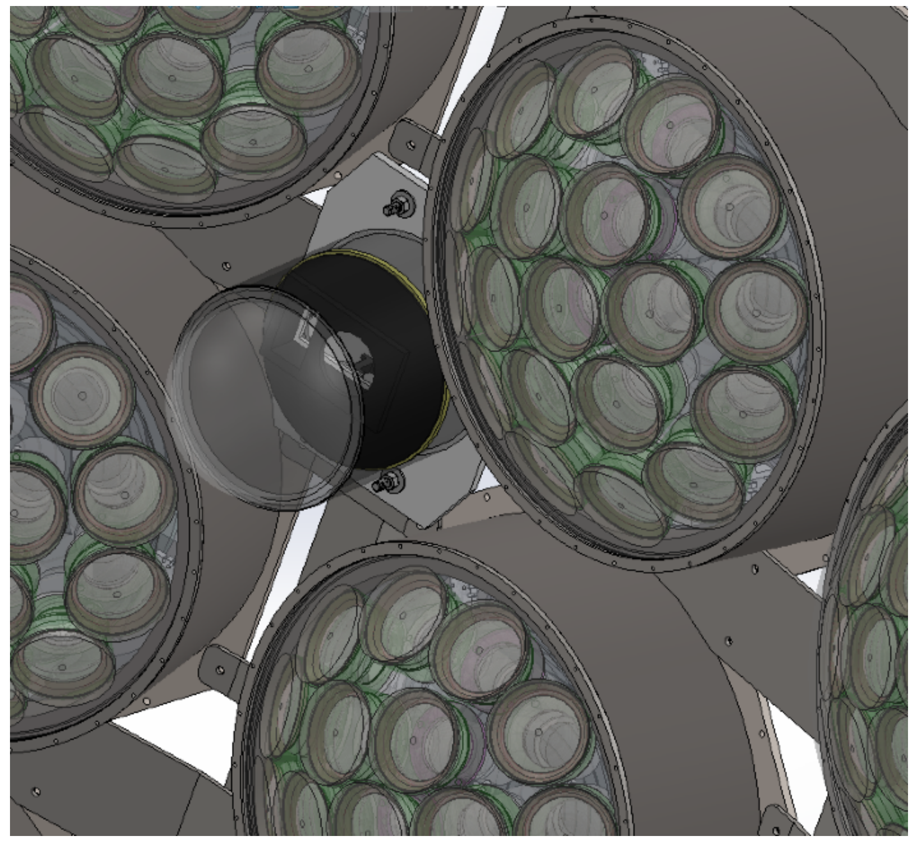
See Poster by N. Deshmuk: Mechanical Design of Multi-PMTs for IWCD

IWCD Calibration

- Calibration of IWCD is critical:
  - Precision measurements require precision calibration
  - Moving detector must be precisely calibrated at each position
- Detector components shift during moving?
- Photogrammetry used to measure the position of all detector components
  - Using cameras inside detector volume
  - Take images to do stereoscopic reconstruction of detector

Photogrammetry imaging concept



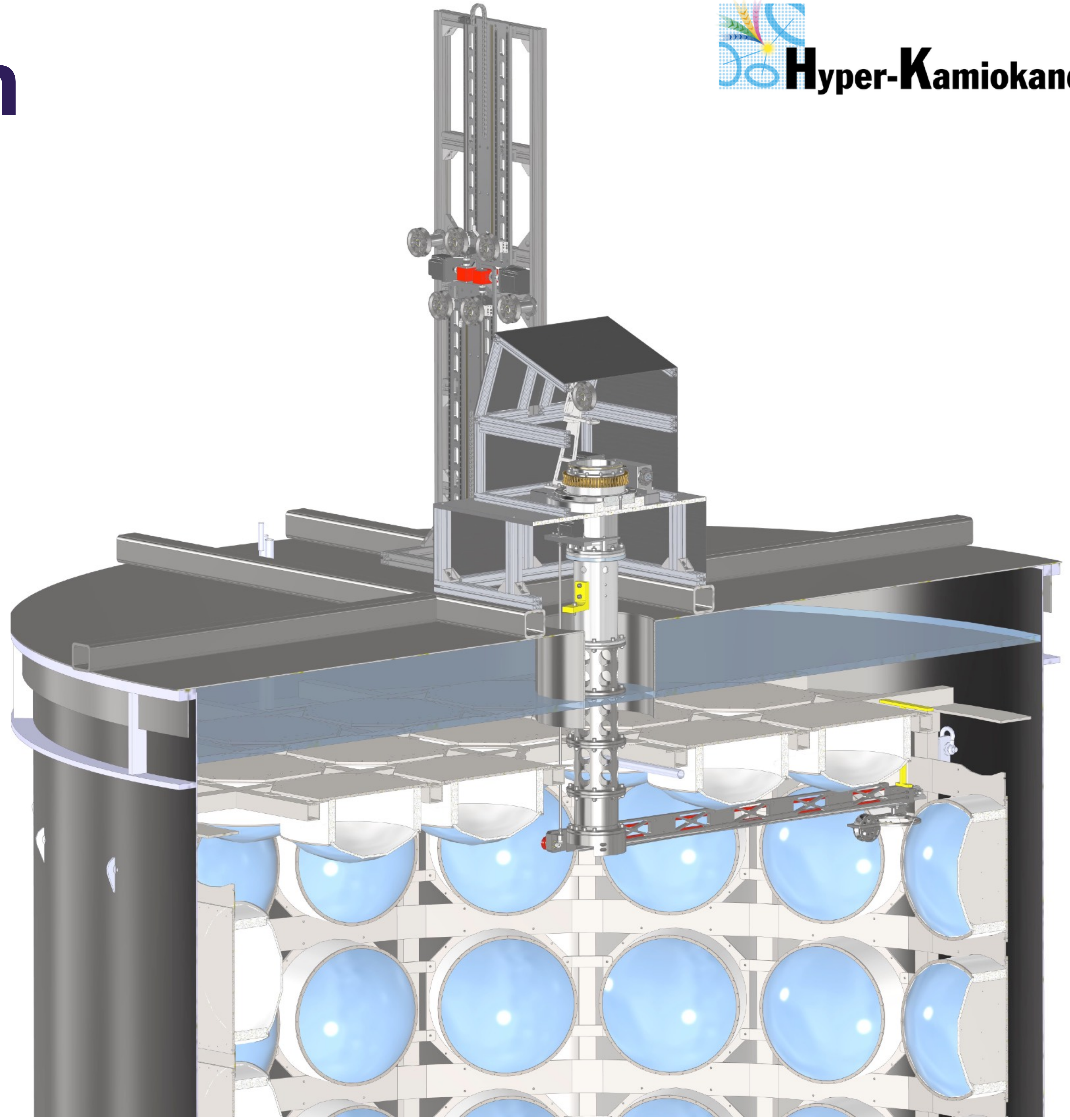


Photogrammetry camera in IWCD

See Talk by N. Prouse: Photogrammetry position calibration for water Cherenkov detectors

Calibration Deployment System

- We need to move various calibration sources throughout the detector volume
- Use arm system with movement in all 3 dimensions
  - Rotation covers azimuthal angle
  - Cart on arm moves radially
  - Source hangs from cable for vertical motion
- This and other calibration systems will have first deployment in Water Cherenkov Test Experiment (WCTE) at CERN

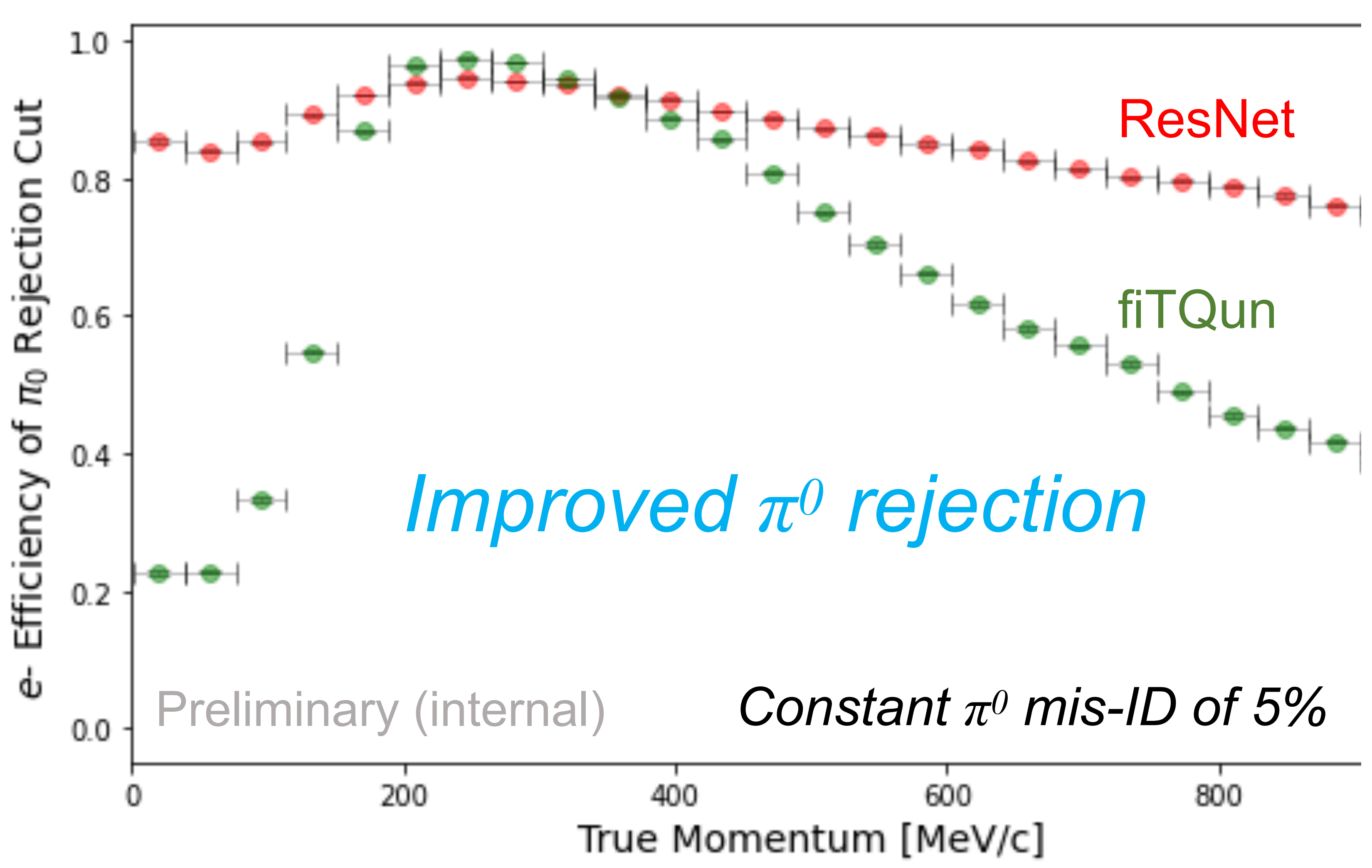


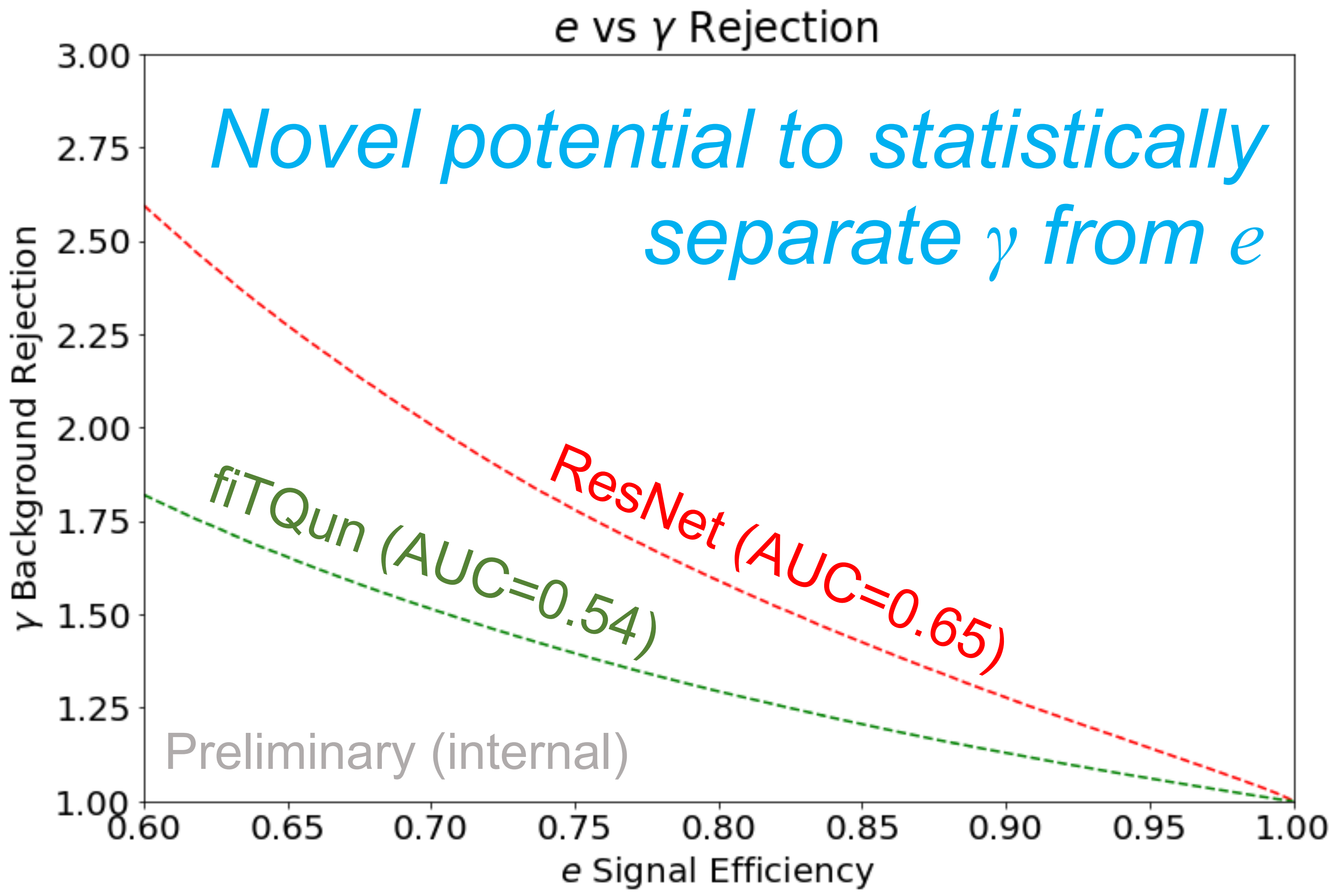
CDS in Water Cherenkov Test Experiment

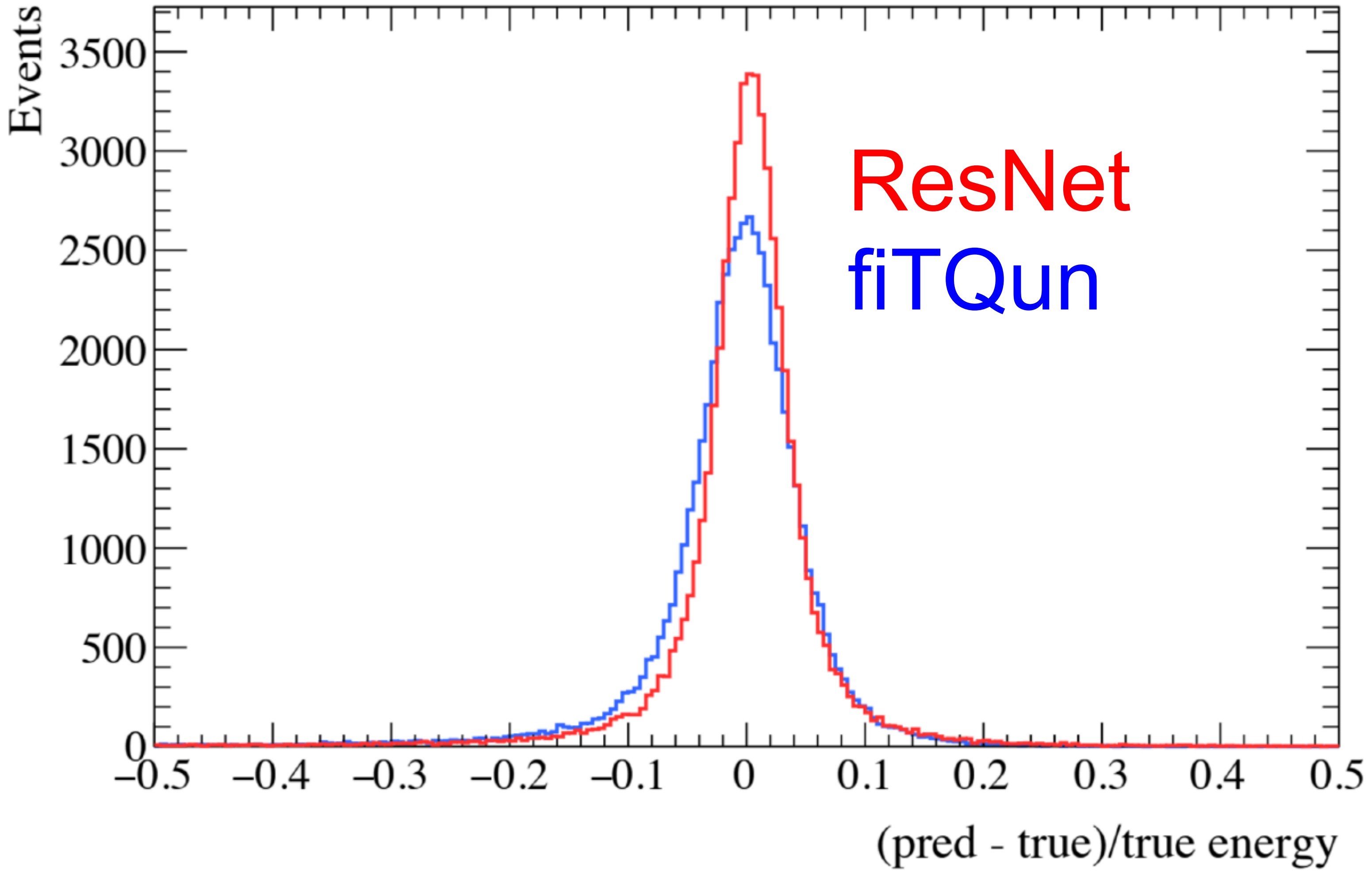
Also See Talk by M. Pavin: Water Cherenkov Test Experiment

Machine Learning

- International working group **WatChMaL** formed for development of machine learning in water Cherenkov detectors
- Improved particle discrimination and resolution in IWCD across several particle types (see below)
- Massive processing speed-up:
  - fiTQun (likelihood based reconstruction) on CPU: <1 event per minute
  - ResNet on GPU: 100,000 events per minute







Summary

- The Intermediate Water Cherenkov Detector is important part of controlling systematic uncertainties for Hyper-K
- Unique properties, including moving detector address measurement challenges in novel manner
- High resolution photon detection and precision calibration are important to IWCD success
- Machine learning will be applied to maximize potential of IWCD
- With approval of Hyper-K, IWCD is now moving towards the design completion and construction phase!

Thank you