The Intermediate Water Cherenkov Detector for the Hyper-Kamiokande experiment

Plans and R&D Progress

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Hyper-Kamiokande

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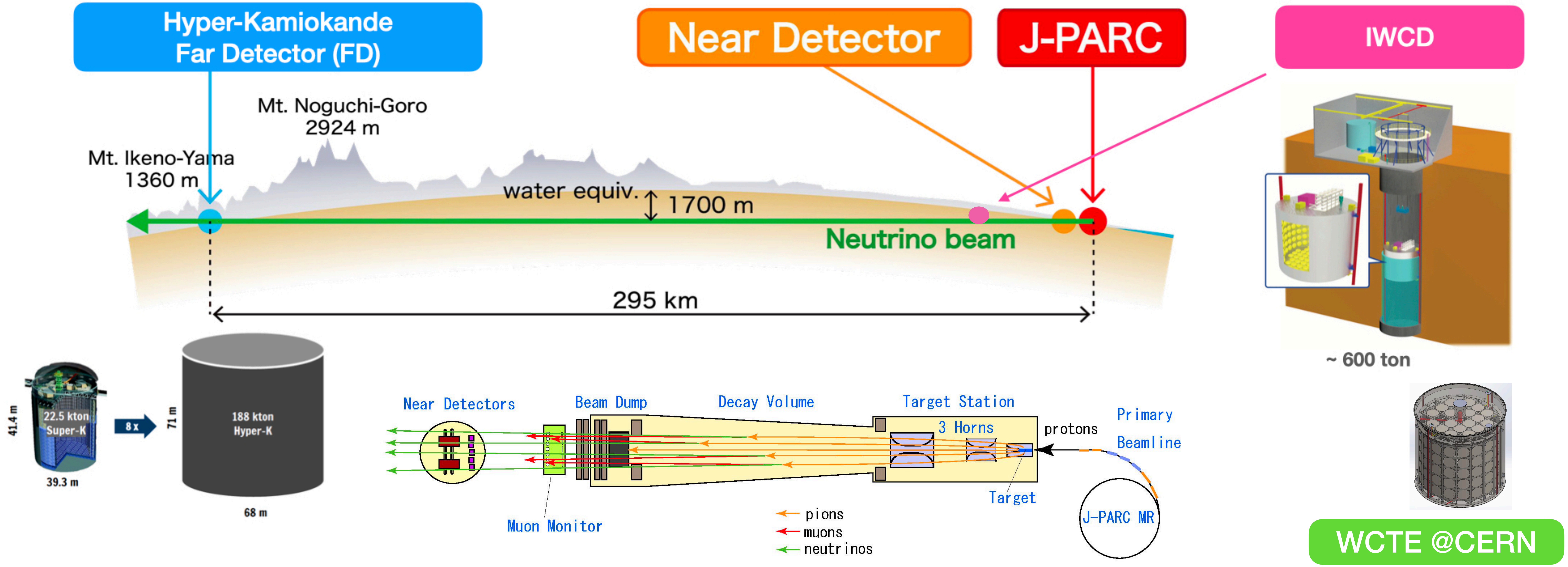
The Hyper-Kamiokande (Hyper-K) experiment

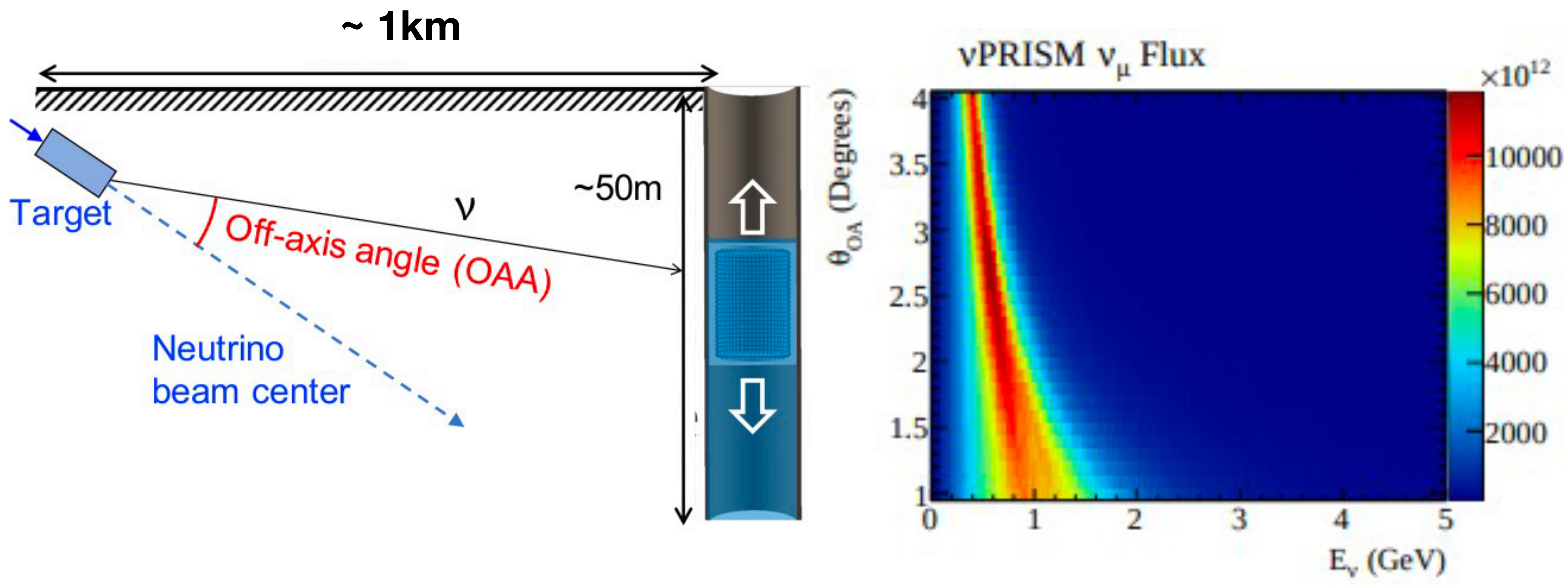


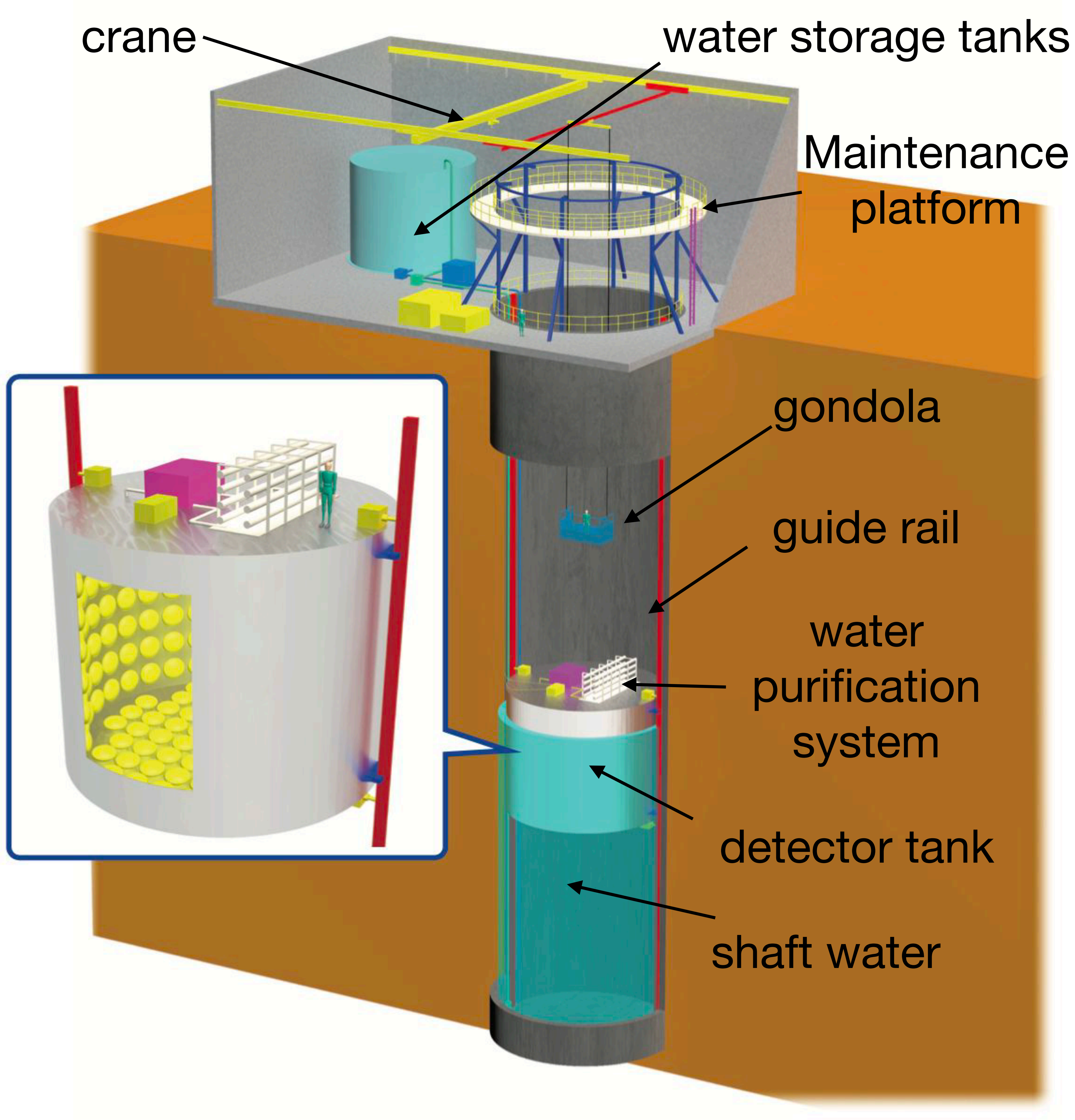
- Hyper-K: The Next generation long-baseline neutrino facility to study oscillations and search for the CP violation in the lepton sector
- Rich physics portfolio, for its **"Physics Program and Current R&D progress" see talk by Sophie King**
- Hyper-K will be statistically powerful, enormous ongoing efforts to mitigate the systematic uncertainties to fully realize the physics potential

The Intermediate Water Cherenkov Detector (IWCD)

- A 600 tonne water Cherenkov detector with diameter ~8 m and height ~6 m, located at ~ 1 km from the neutrino source

- A vertically moving detector, allowing detections at different off-axis angles between 1-4 degrees



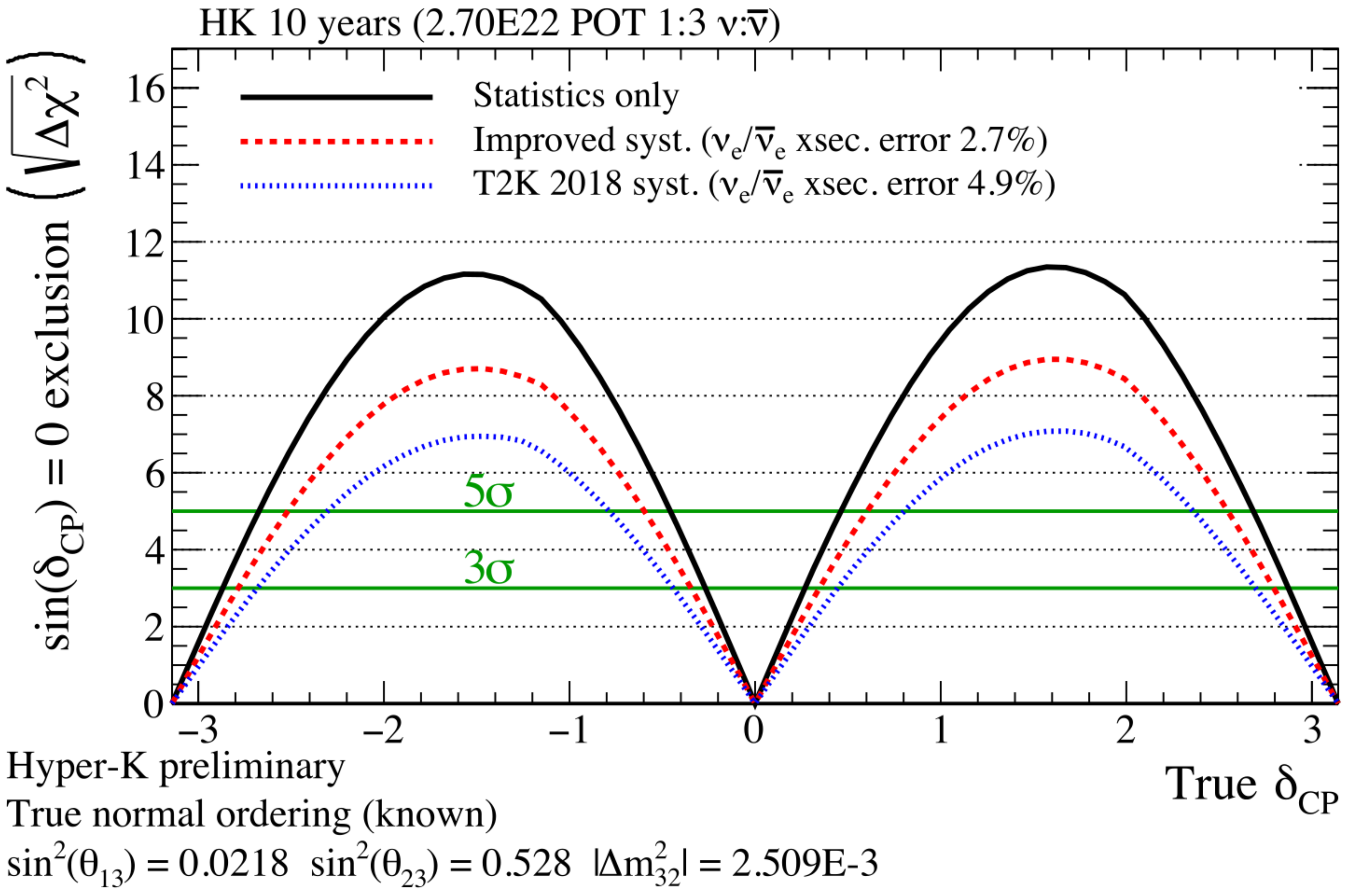


Current systematic uncertainties

T2K: Phys. Rev. D 103, 112008 (2021)

Current T2K uncertainty source for CPV search	Error (%)
Flux & cross-section (ND constrained)	2.7
Nucleon removal energy	3.6
ν_e $\bar{\nu}_e$ cross-section ratio	3.0
NC γ + other	1.5
SK detector	1.5
SK FSI+SI+PN	1.6
Total	6.0

IWCD will play an important role in reducing the systematic uncertainties



- The CP violation will be studied by essentially comparing observed ν_e and $\bar{\nu}_e$ event rates
- Reduction of systematic errors has large impact on potential to discover CP violation
- >5σ discovery after 10 years for 60% of δ_{CP} values

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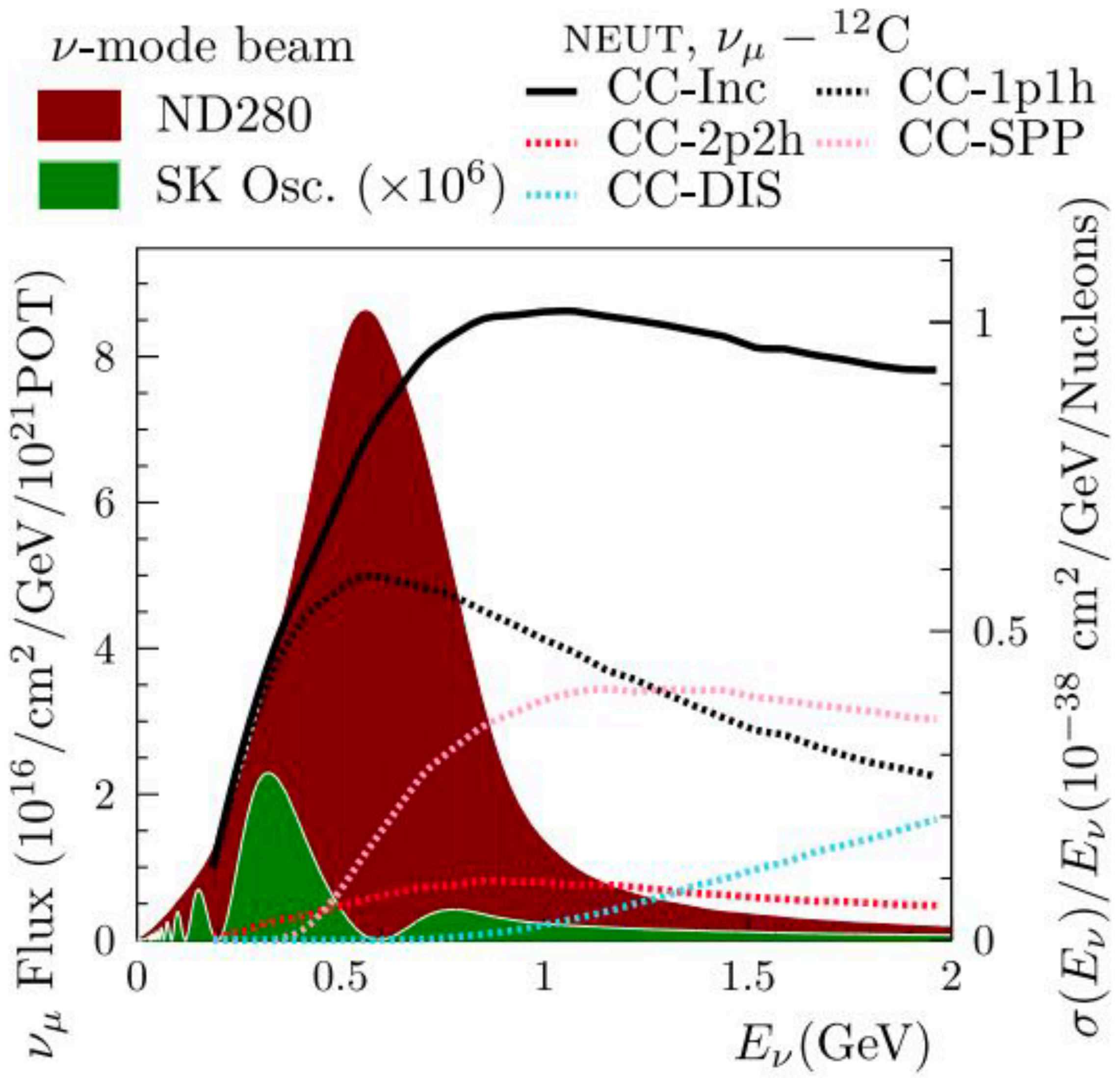
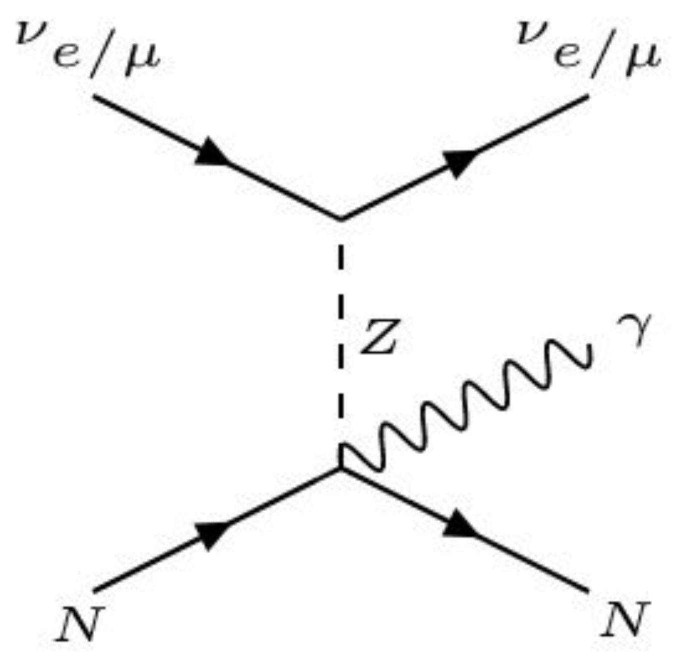
Need to reduce < 3% for the Hyper-K

Imperfect extrapolation of neutrino flux & cross-section from near detector to Super-K



Differing energy spectra between near and far detectors



Neutral current background lacking data driven constraints

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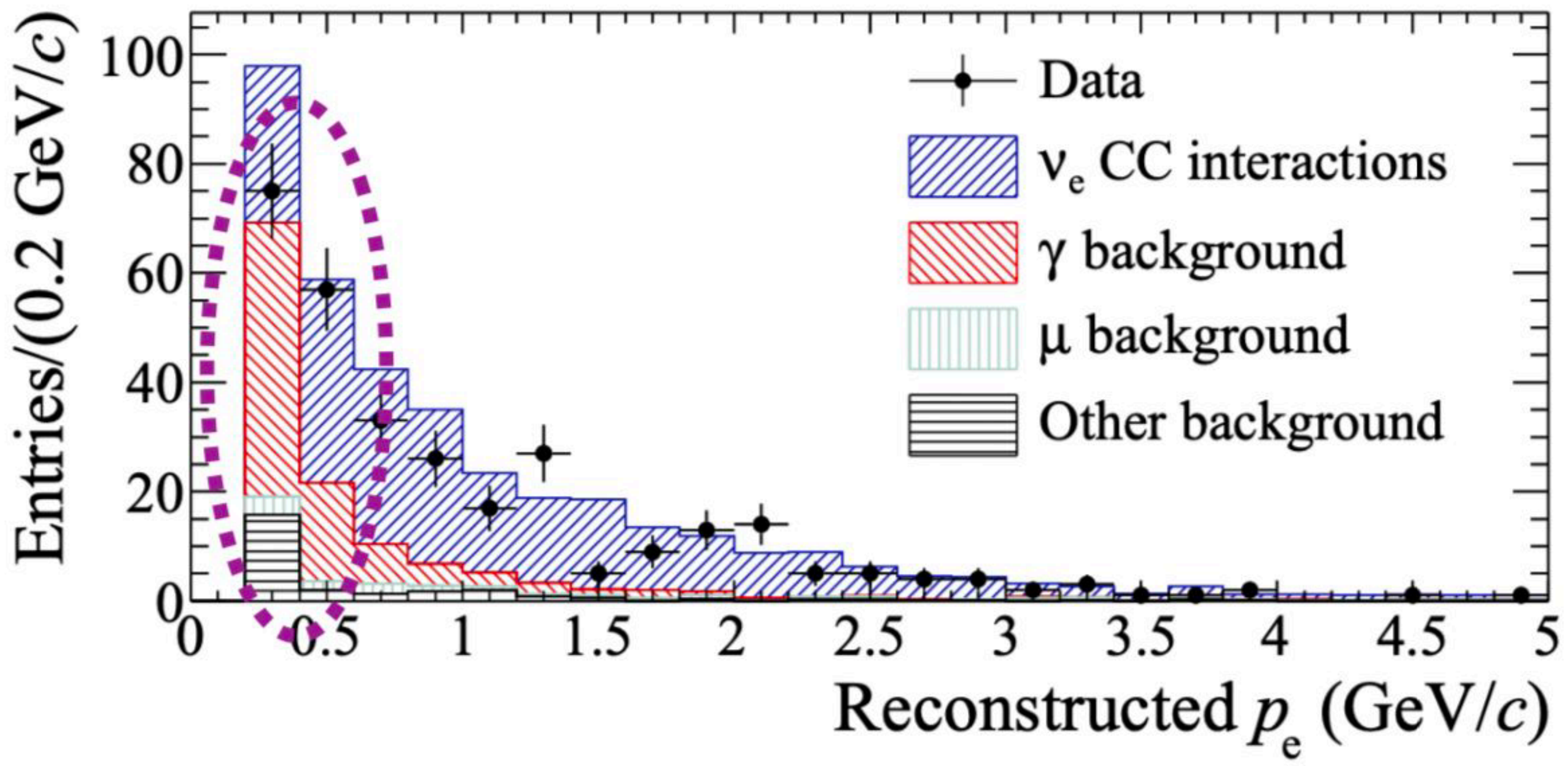
T2K: Phys. Rev. Lett. 113, 241803 (2014)



Difficult ν_e $\bar{\nu}_e$ measurement at near detector mostly ν_μ $\bar{\nu}_\mu$ beam and gamma backgrounds

Other correlated processes between near and far detector such non-QE scattering, pion production, multi-nucleon knockout, etc.

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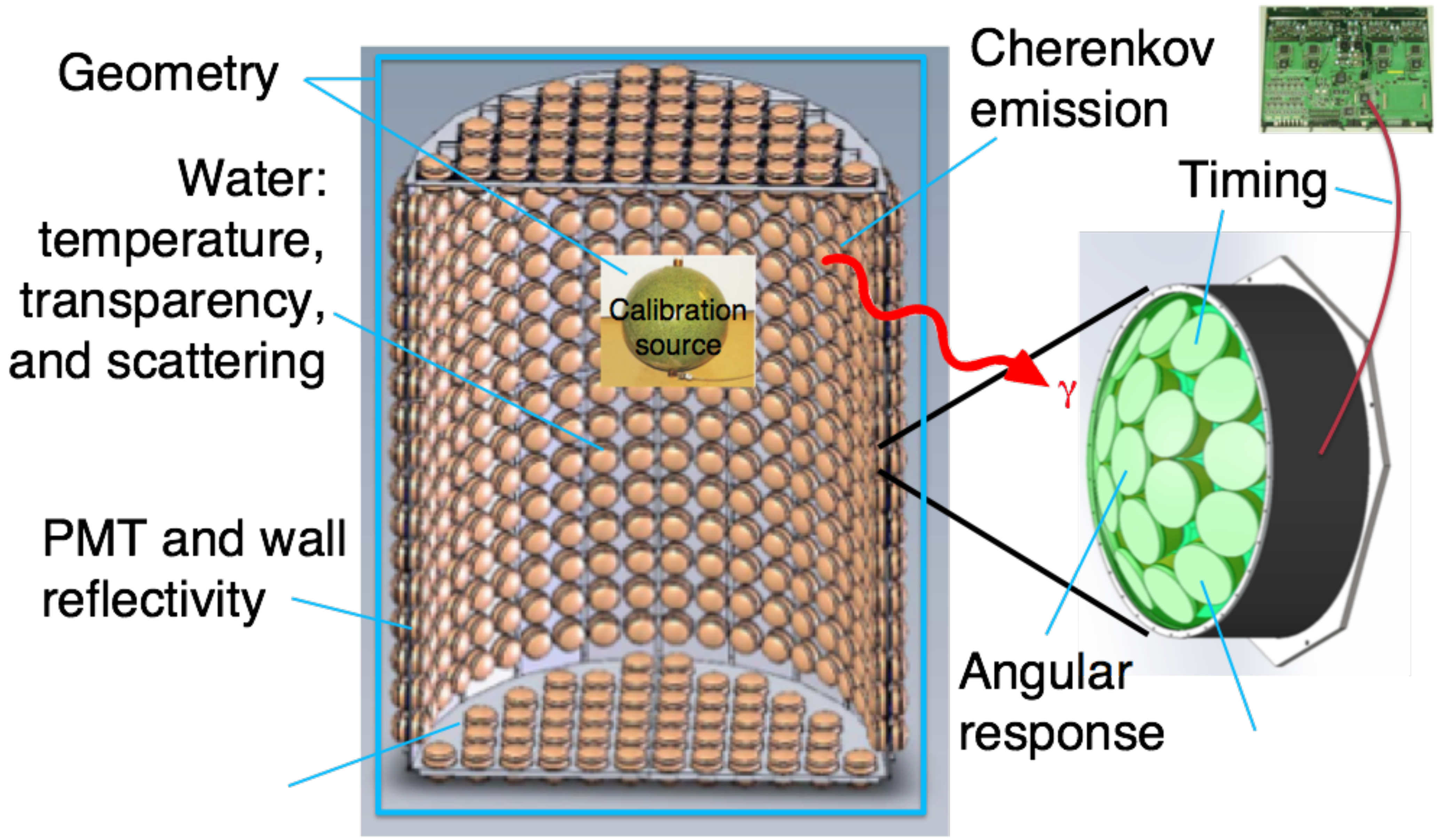
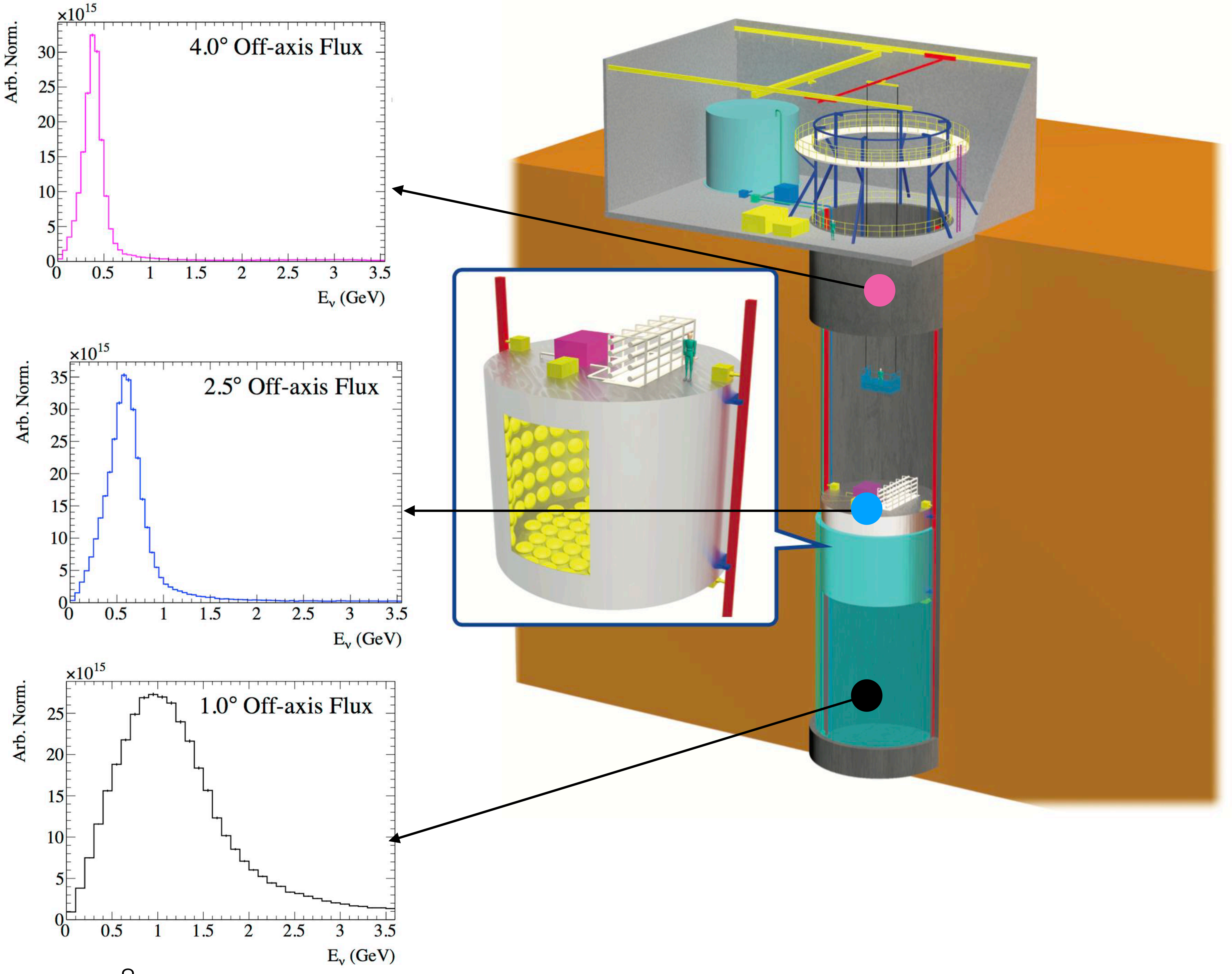


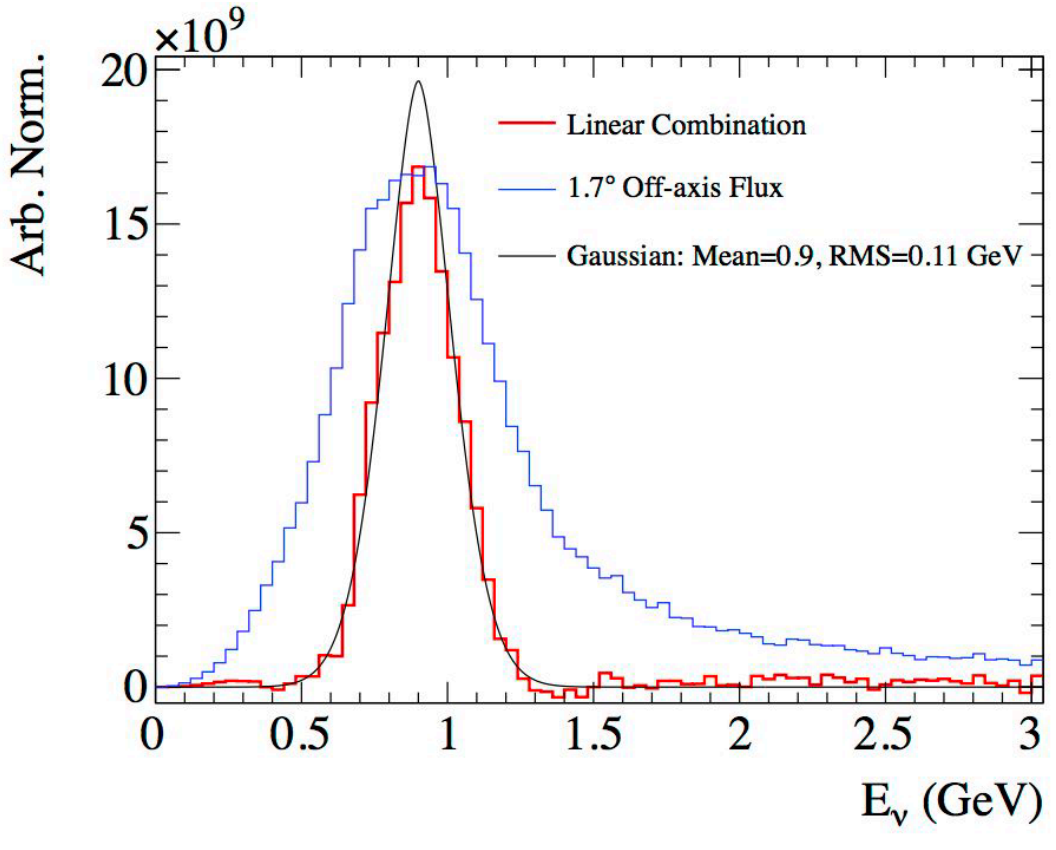
Need for a robust calibration campaign

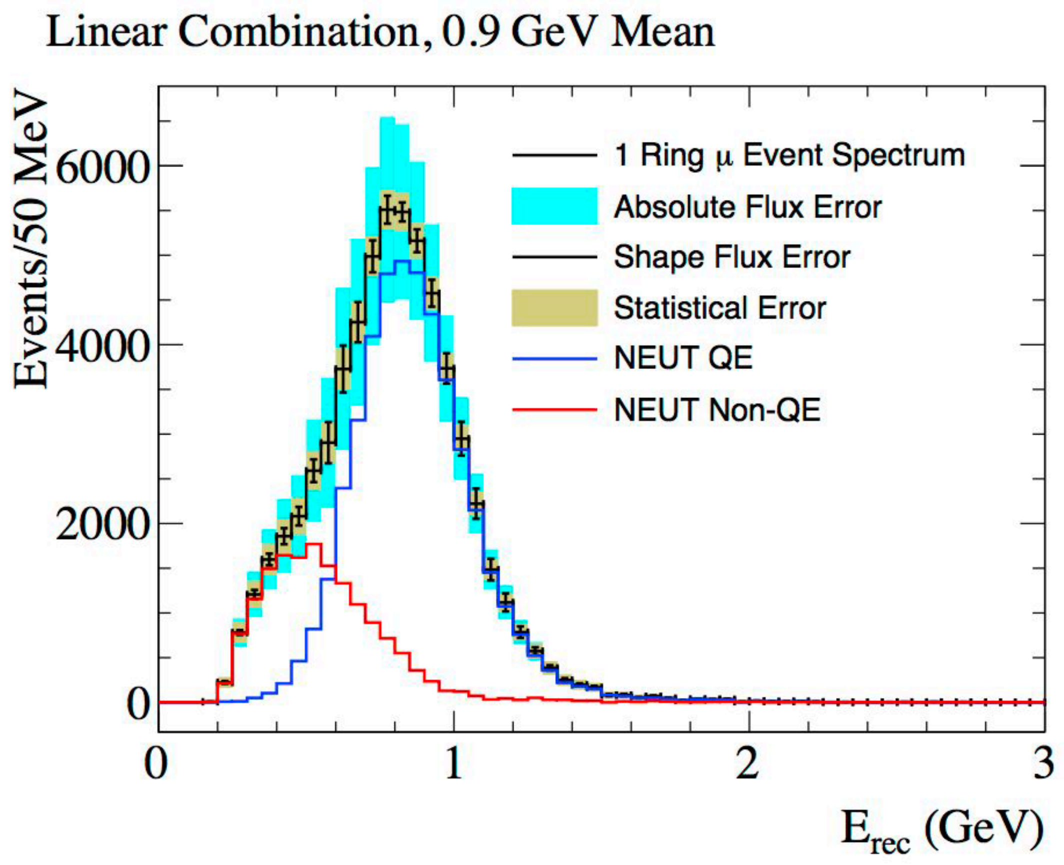
Errors associated with detector modelling and calibration

The NuPRISM Concept

- Neutrino energy spectrum depends on off-axis angle to the neutrino beam source.
- Moving IWCD vertical ⟶ varying off-axis angle ⟶ measurements with different energy spectra.
- Linear combinations of measurements at off-axis angles can mimic a monochromatic beam, or the far-detector spectrum







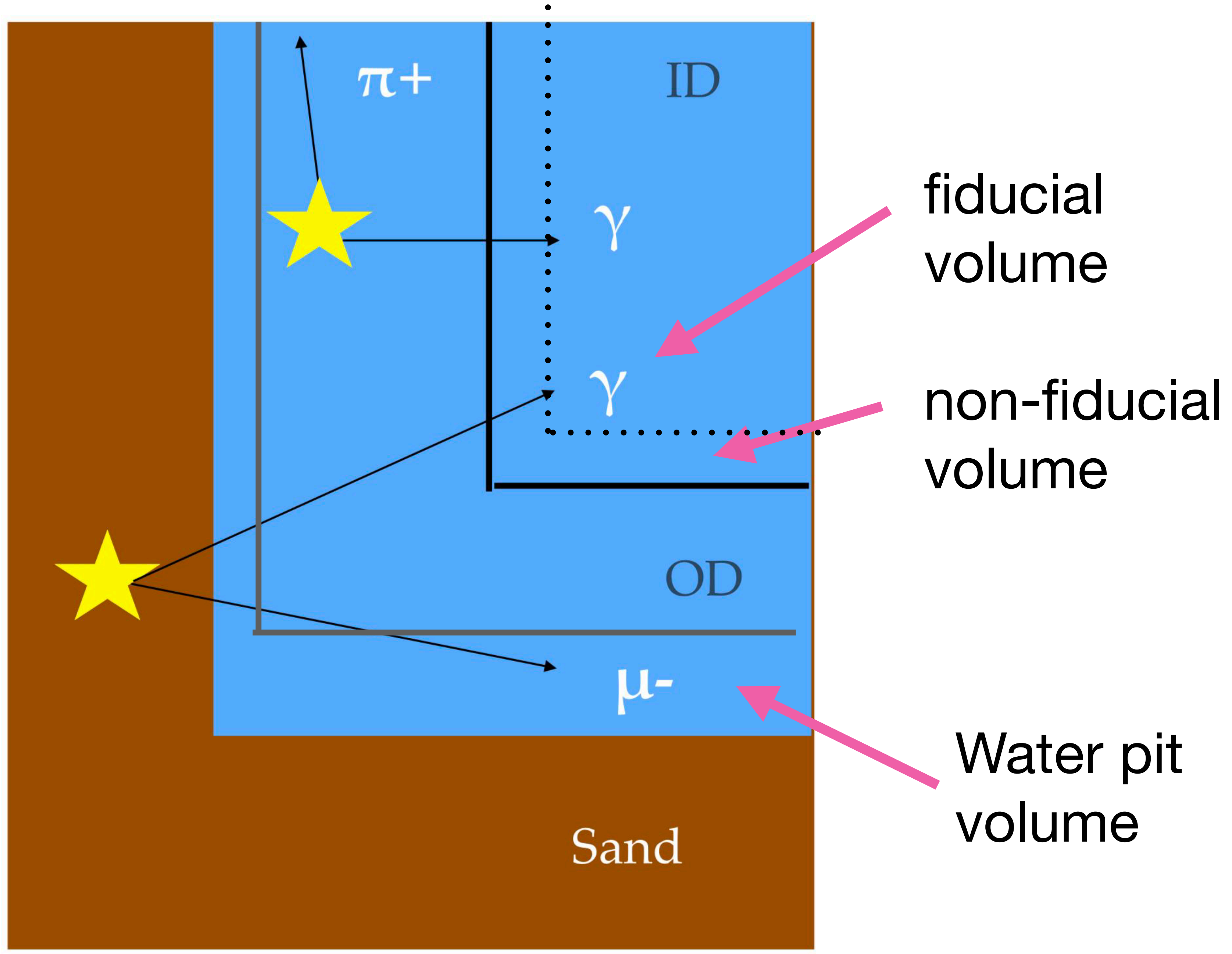
IWCD ν_e $\bar{\nu}_e$ cross-section measurement

Constrain using 1% ν_e $\bar{\nu}_e$ contamination in the beam

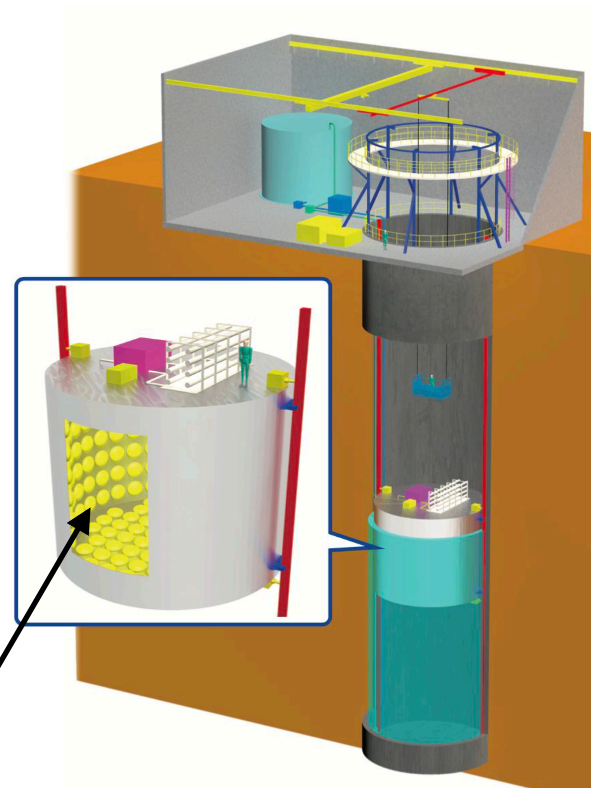
Measure the double-ratio for the CP violation search

$$\frac{\sigma(\nu_e)/\sigma(\nu_\mu)}{\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)}$$

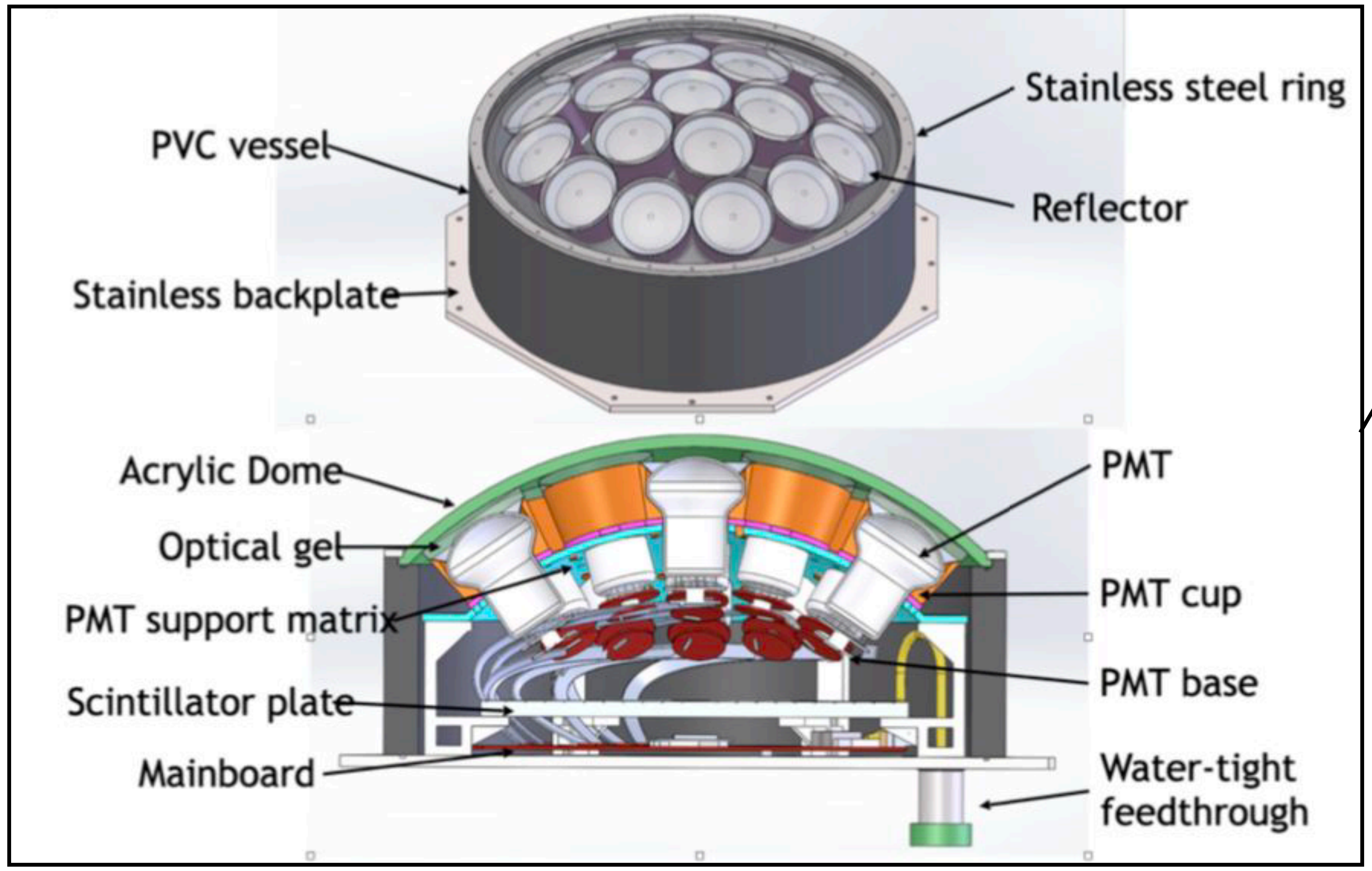
γ background mostly mitigated by water Cherenkov active shielding

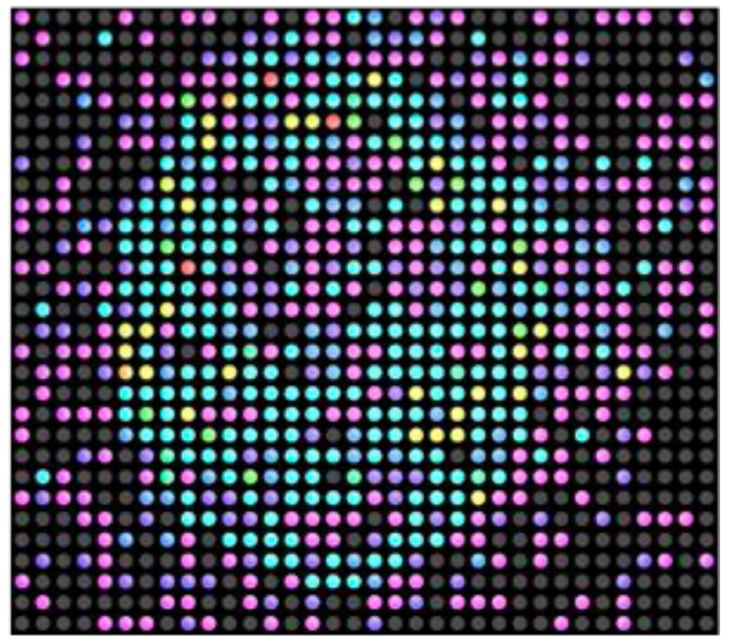


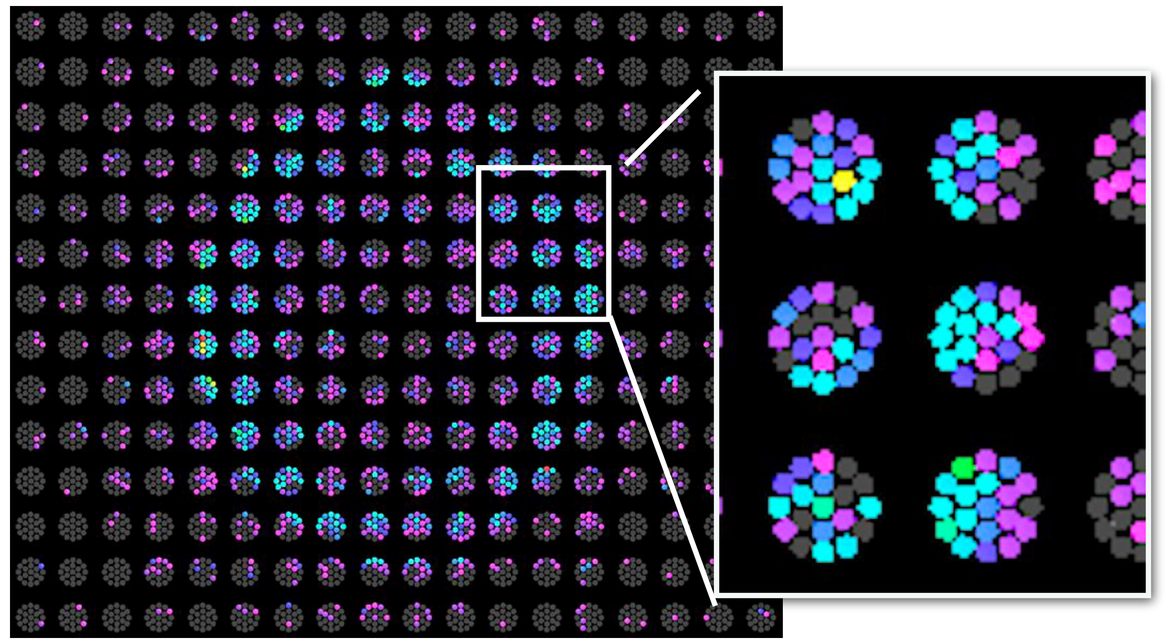
multi-PMT photosensor module



- New photo-detector technology for increased sensitivity
- 19 x 3” diameter PMTs in a water tight vessel with high voltage and readout electronics



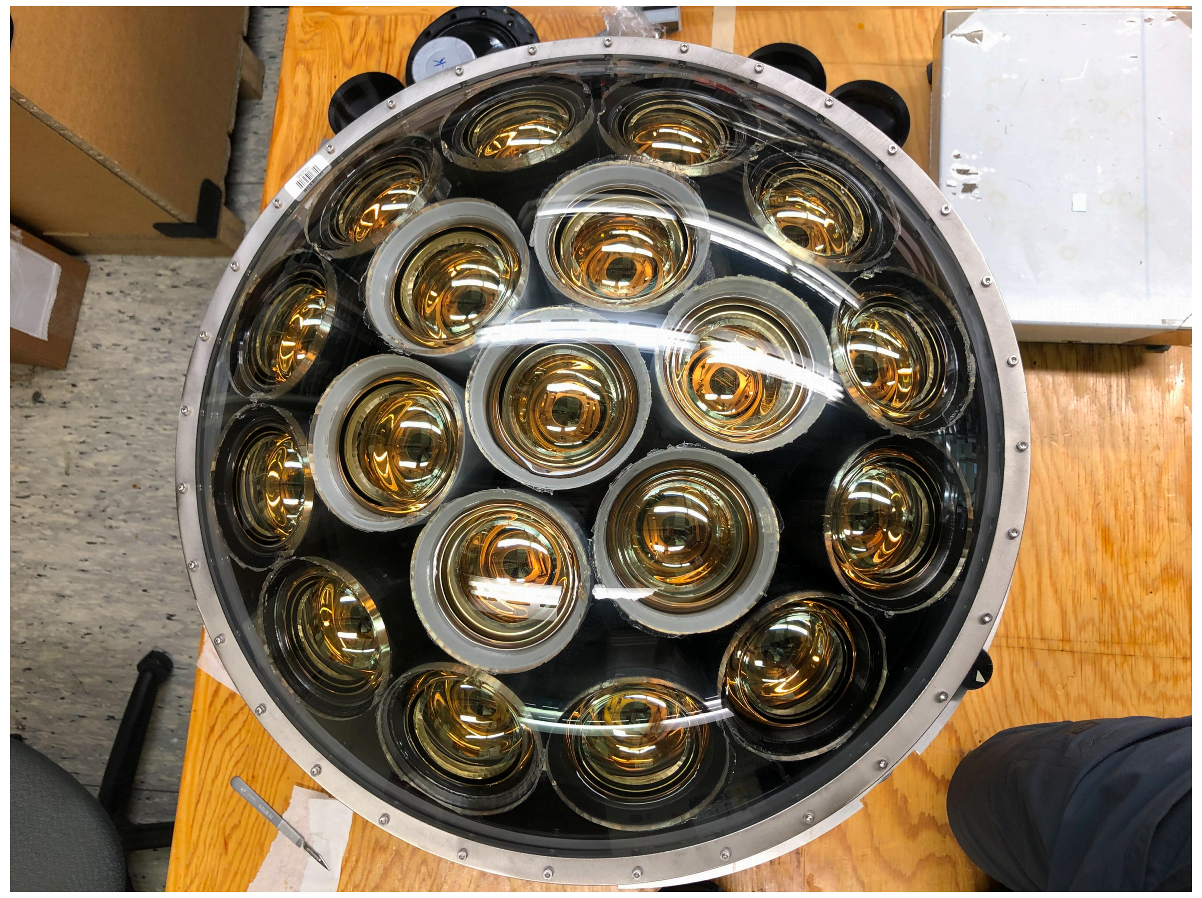




8” PMT

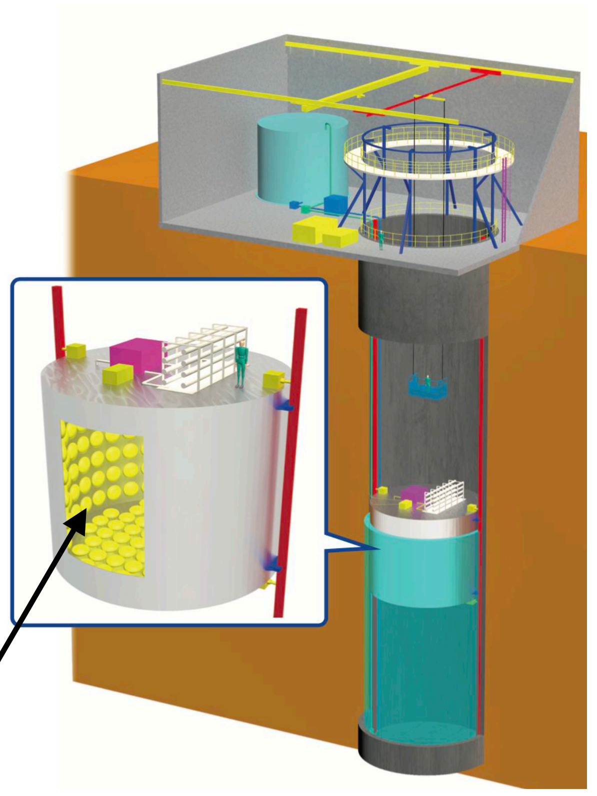
mPMT

- 3” PMTs compared to far detector’s 50cm PMTs
  - Better position resolution
  - 1.6 ns (FWHM) timing resolution
  - Additional directionality information

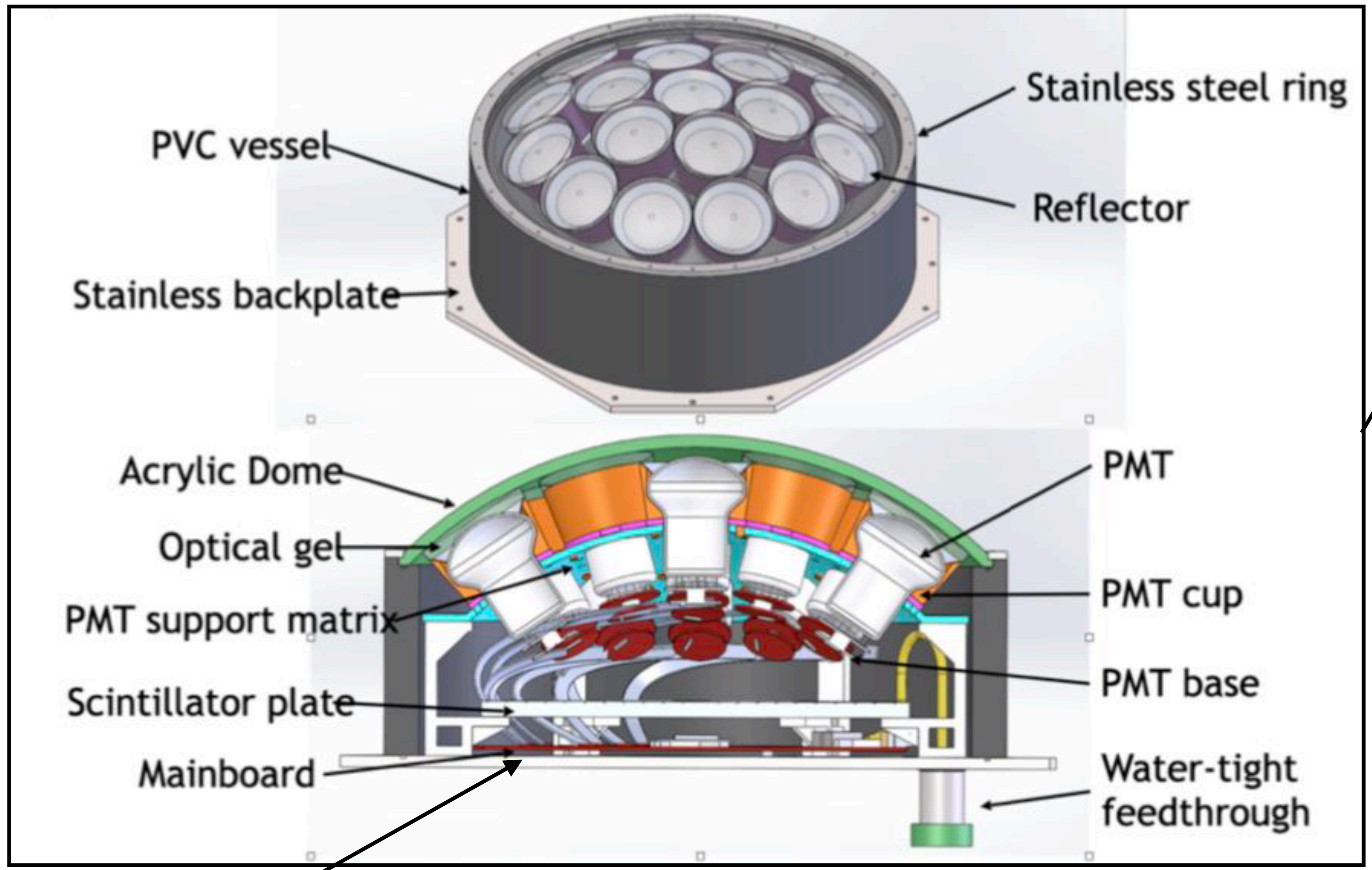


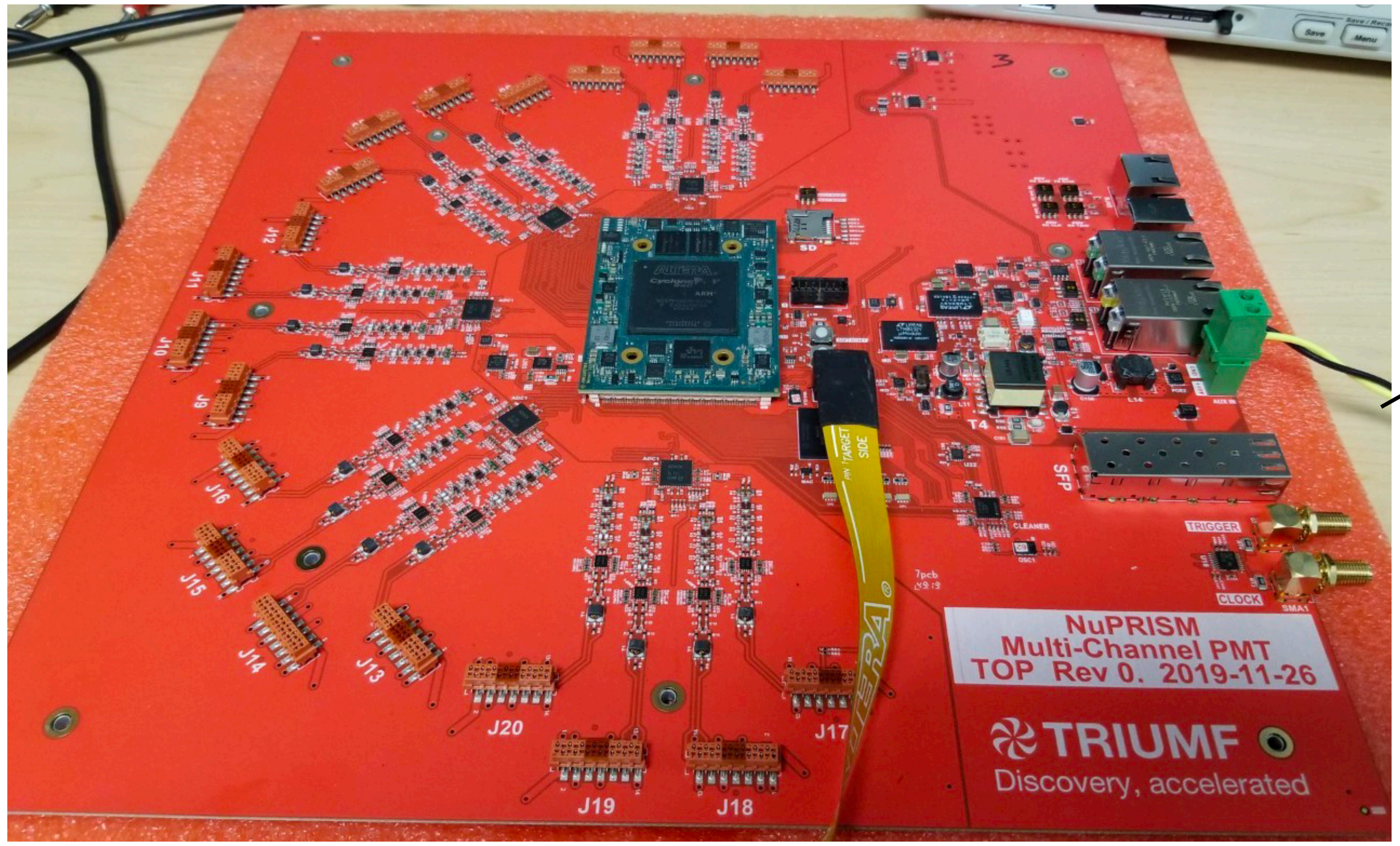
Improved photosensor resolutions and increased granularity are essential for reducing vertex reconstruction uncertainties

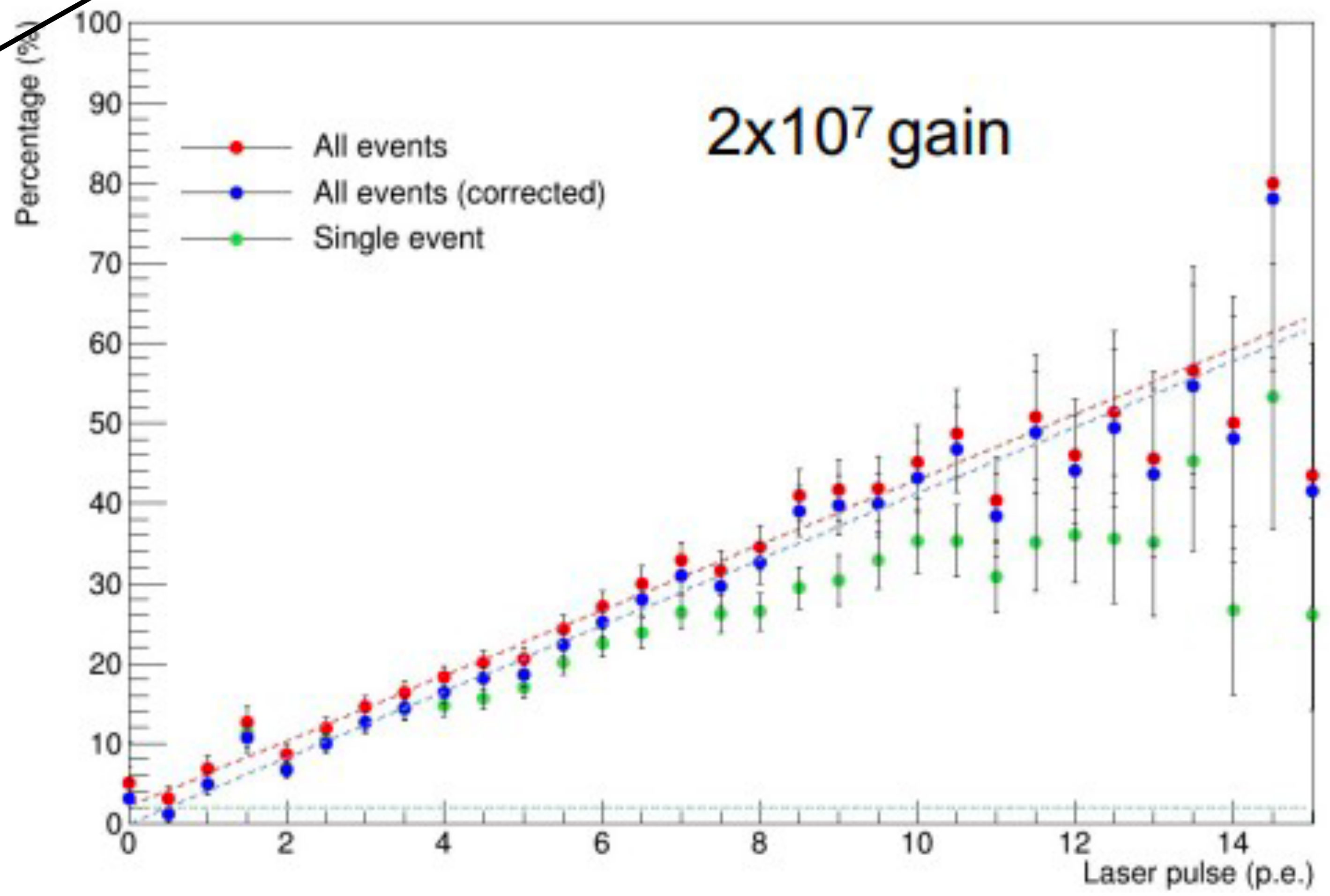
multi-PMT photosensor module



- 20-channel 125 MSPS FADC mainboard developed
- Full waveform can be readout, allowing better pile-up event identification
- LEDs mounted for detector calibration







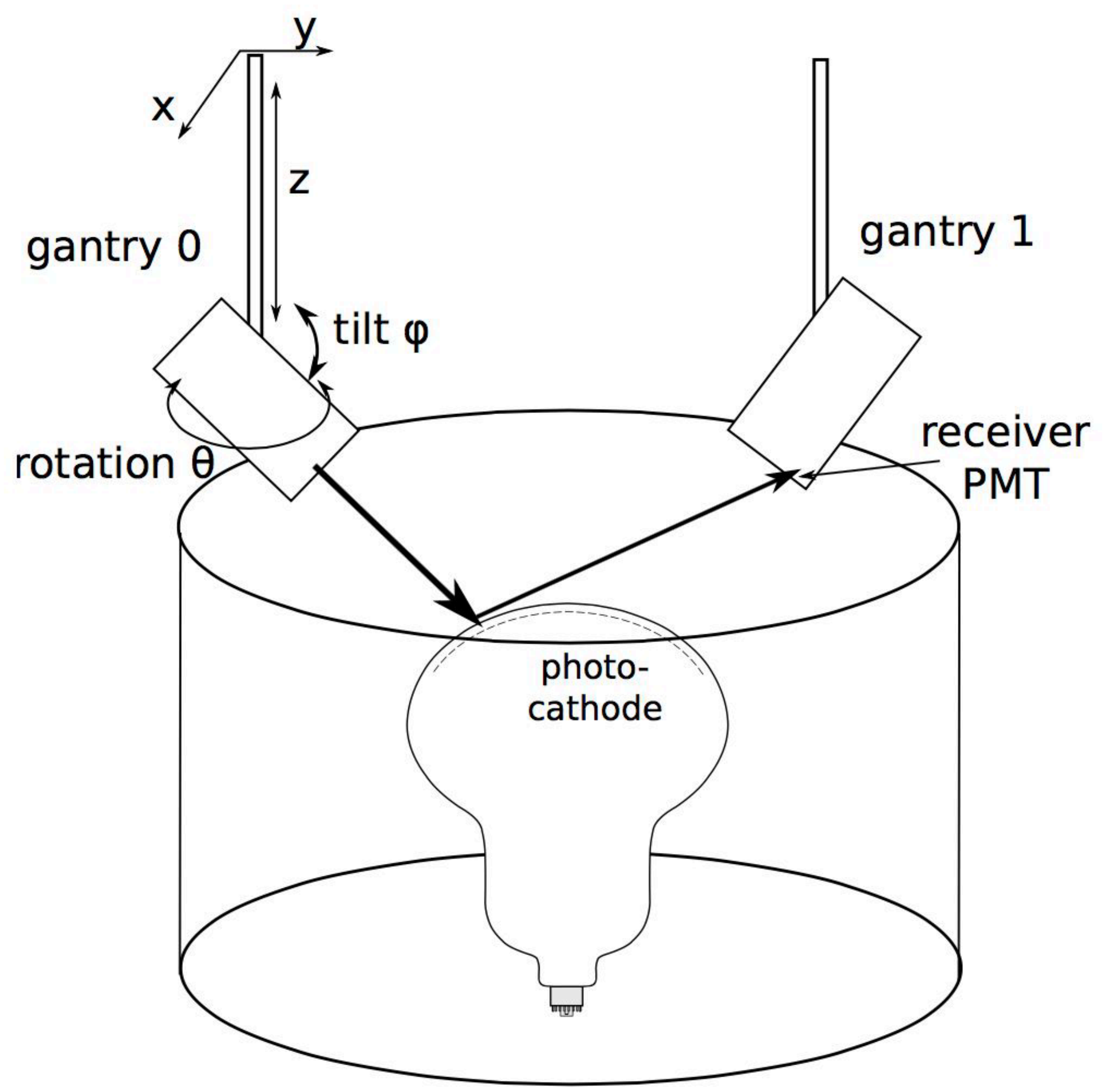
Measured Characteristics of Hamamatsu R14374 3-inch PMT : TTS: ~1.5ns, dark rate: <1kHz, afterpulse rate: <5%/ P.E.

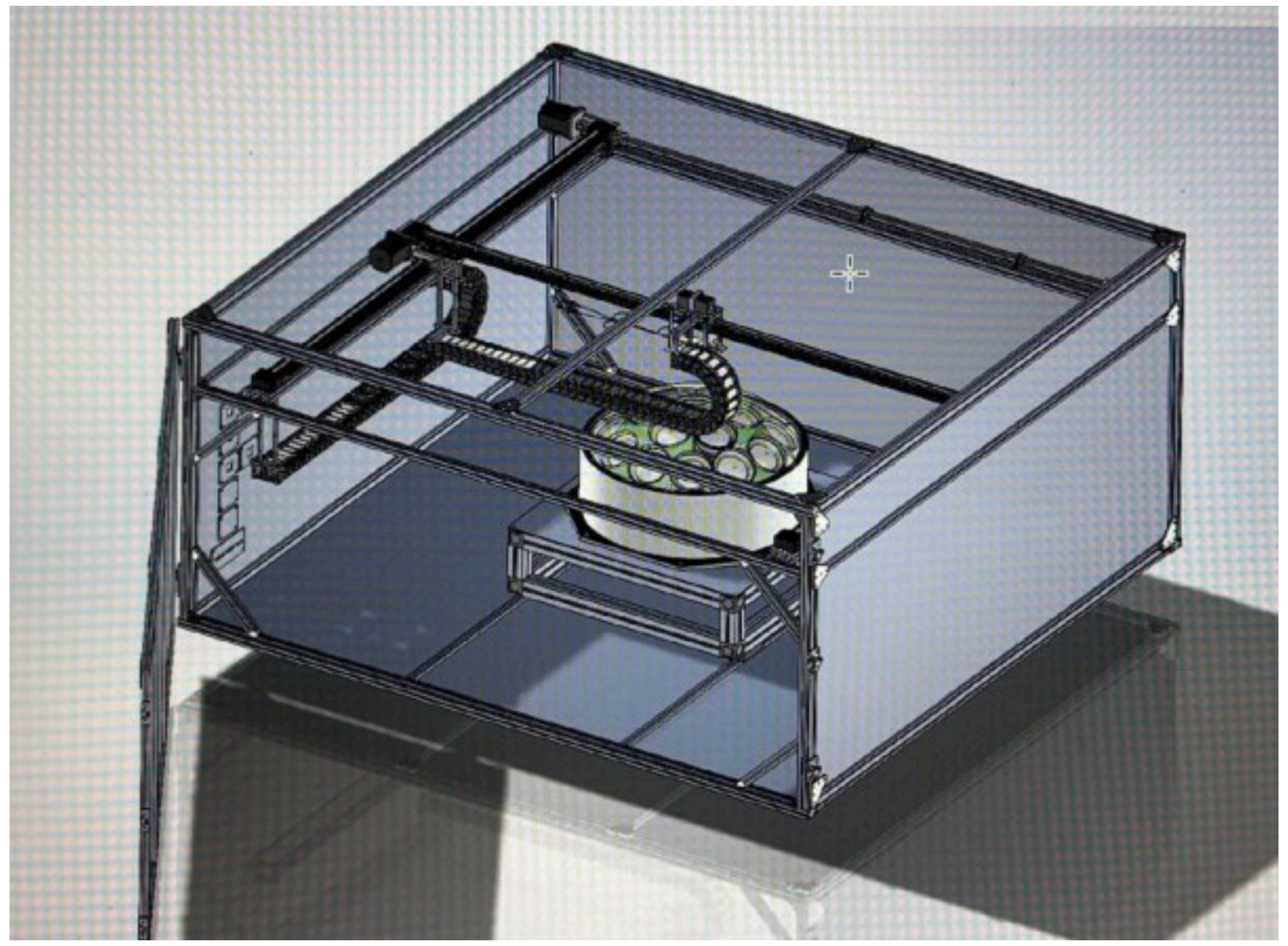
Pre-calibration: Photosensor characterization

Uncertainties in PMT response is a major systematic in water Cherenkov detectors

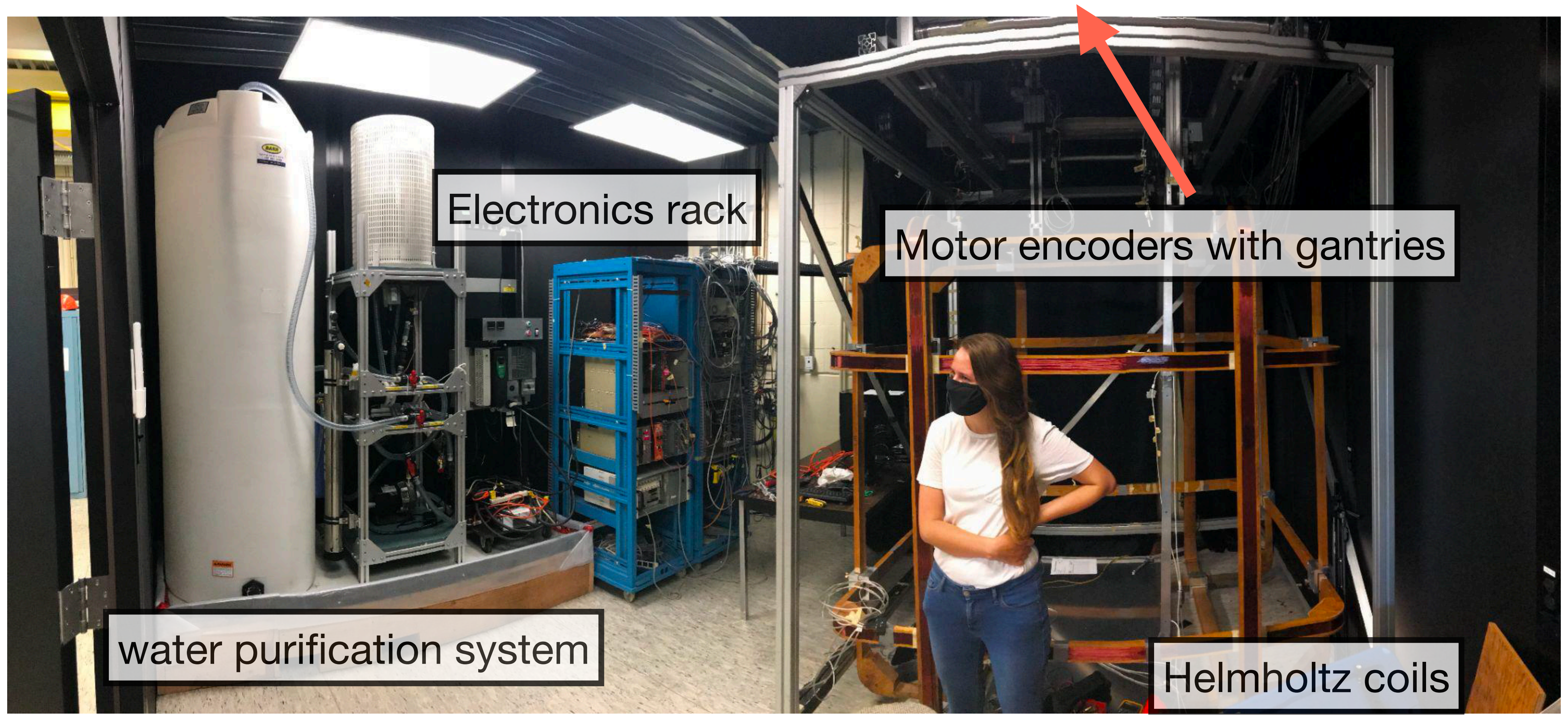
Extensive pre-calibration campaign planned for all mPMTs

Detailed characterization of a few standard mPMTs at a dedicated facility (spatial and angular dependence, wavelength, polarization, magnetic field etc.)





PMT test stand

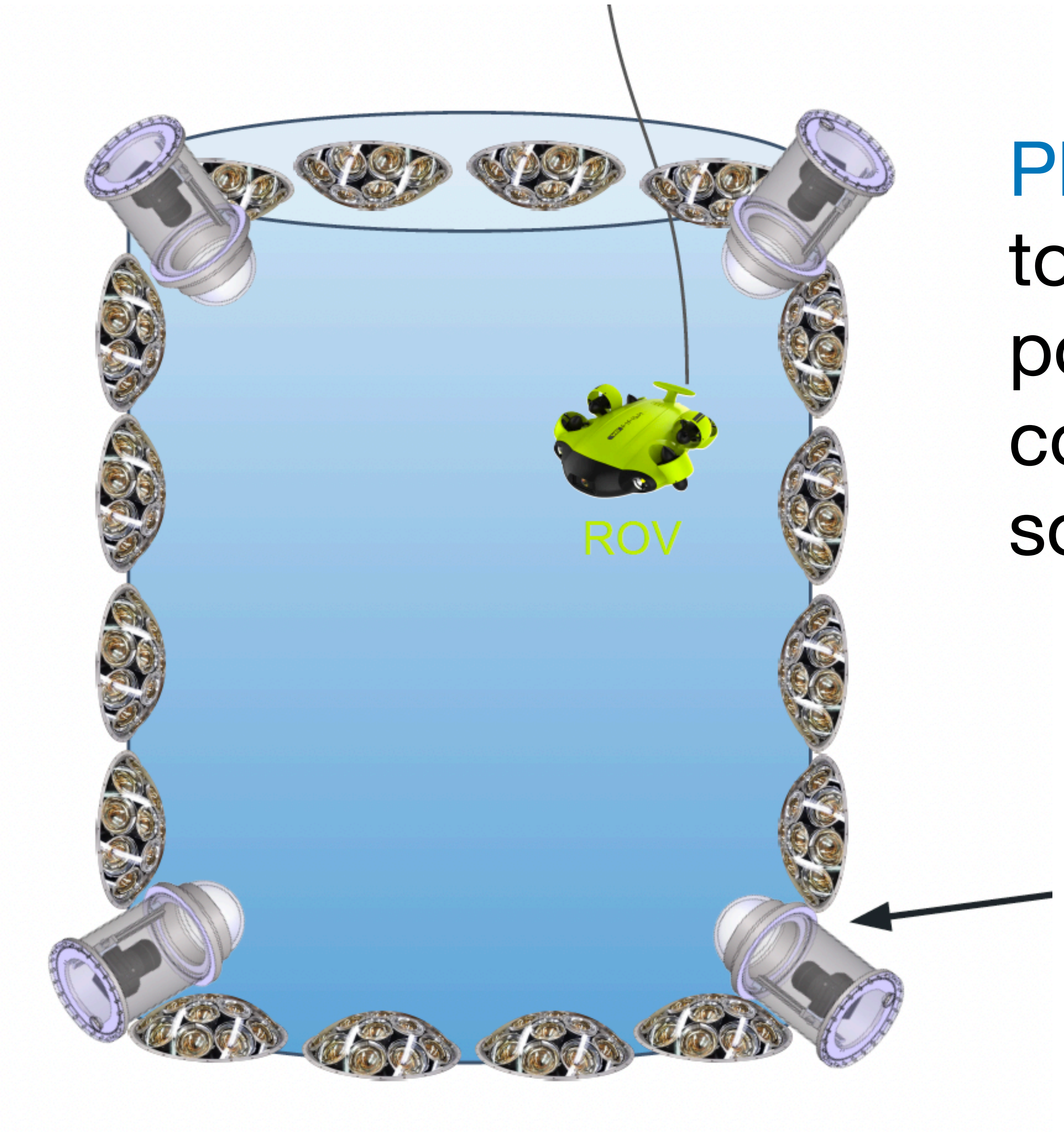


Photosensor Test Facility

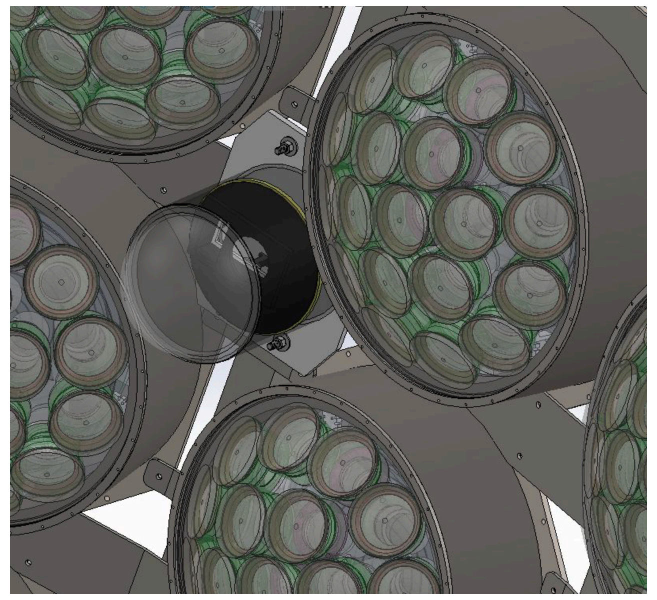
Calibration: Photogrammetry & CDS

The moving detector needs to be precisely calibrated at each vertical position

Potential structural deformation due to PMT buoyancy and detector motion



Photogrammetry is adopted to reconstruct the 3D positions of all detector components and calibration sources from 2D images



Fixed cameras

Regular monitoring of detector response with 3D deployment of laser and radioactive sources (NiCf, AmBe)

Central Deployment System (CDS)

Machine Learning for Water Cherenkov Detectors

WatChMaL.org

WatChMaL: international working group developing water Cherenkov machine learning (ML) to exploit all information from the mPMTs

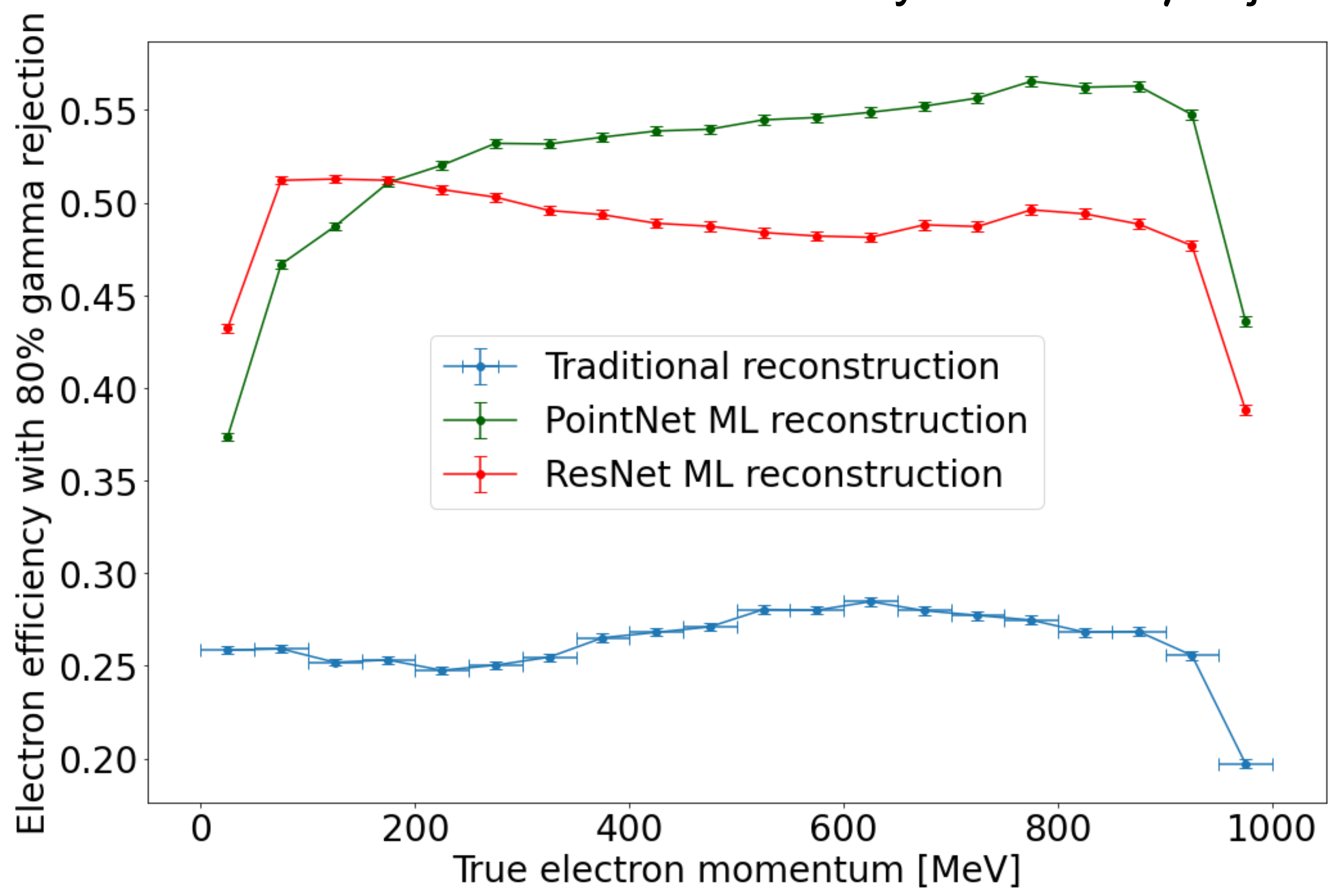
ML-based algorithms have improved particle discrimination and resolution over likelihood-based reconstruction algorithms (fiTQun) in IWCD across several particle types

- Statistical separation of e^- and γ not previously possible
- Better handle on entering γ and NC γ backgrounds
- Identification and reconstruction of multi-vertex and multi-ring events

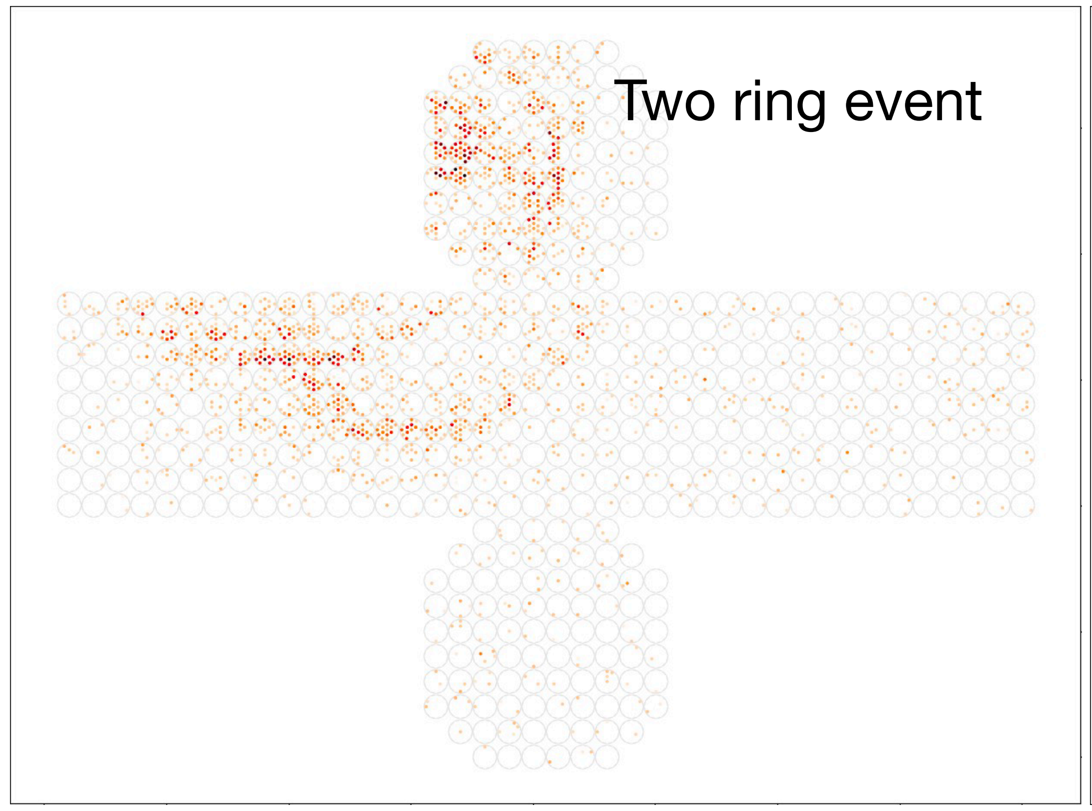
Massive processing speed-up:

- ML-based algorithm (ResNet) on GPU: 10^5 events per minute
- Traditional Algorithm (fiTQun) on CPU : <1 event per minute (likelihood-based event reconstruction)

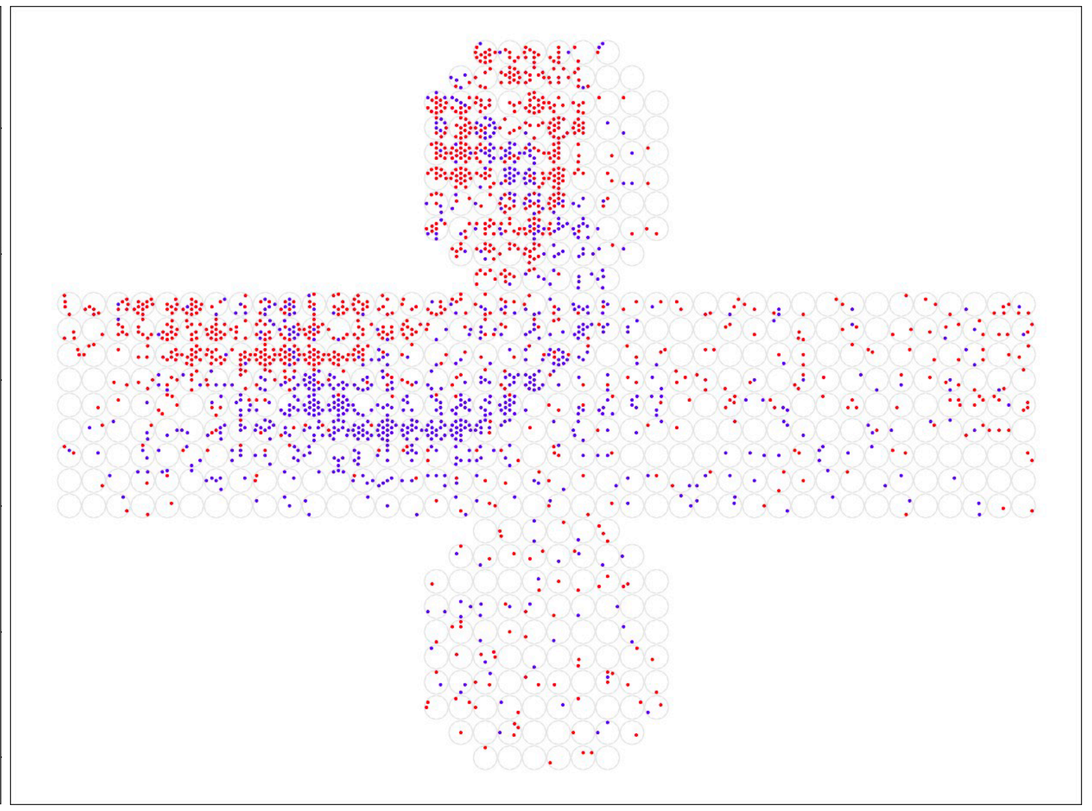
e^- efficiency with 80% γ rejection



Potential for NC γ background reduction and control sample



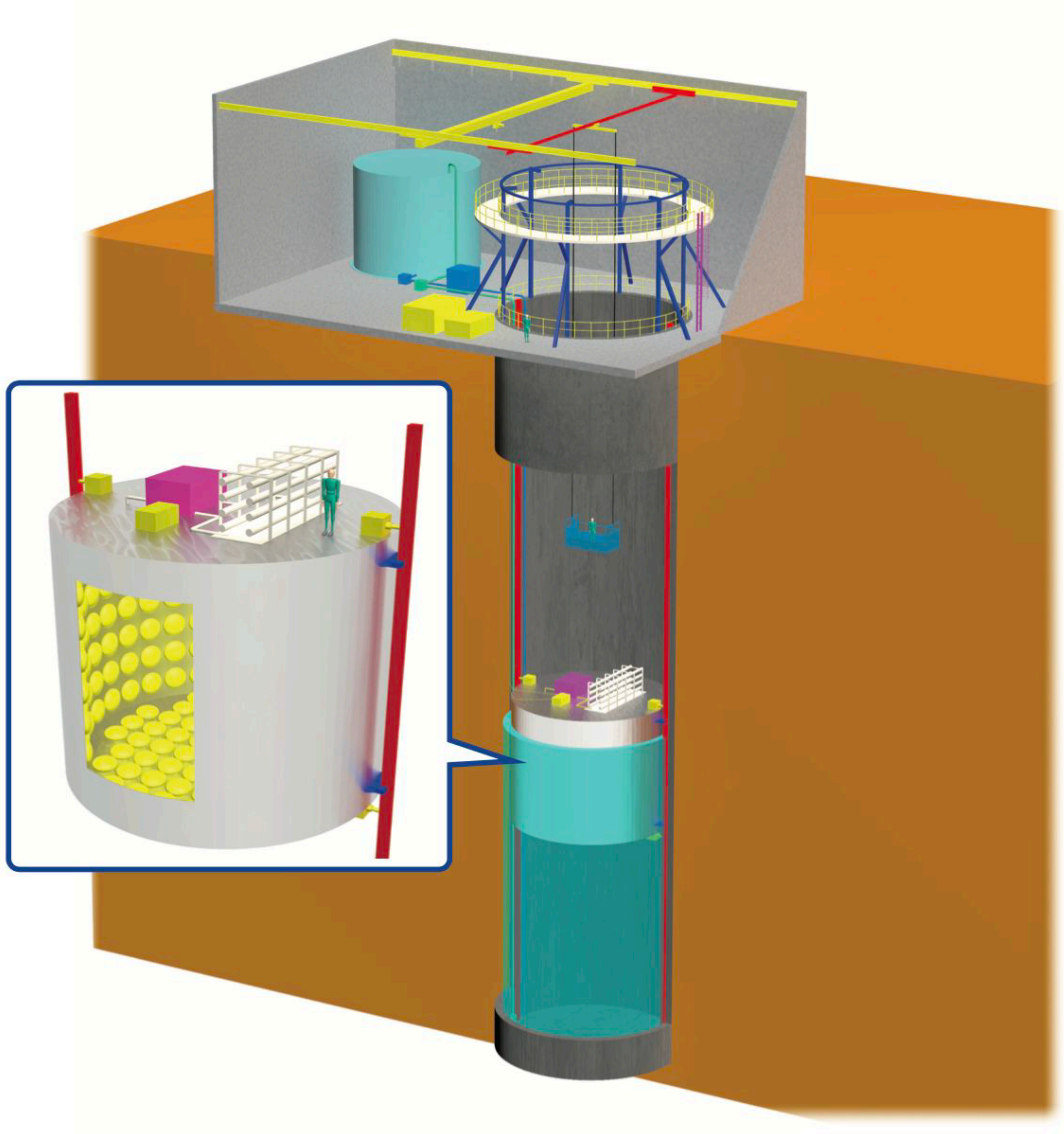
Charge data



Rings separated with ML

Summary

- The Intermediate Water Cherenkov Detector will play an important role in controlling systematic uncertainties in Hyper-K
- An innovative moving detector enables measurement of varying neutrino spectra
- New detector technologies are being developed to enable IWCD to perform precise measurements
- The IWCD group is working towards the compilation of design
- Evaluate and improve systems prior to IWCD and Hyper-K with the Water Cherenkov Test Experiment



Backup slides

Event pile-up

Due to the high intensity of the beam flux, there will be ~7 - 35% of ID interactions will happen with another ID interaction.

Need to identify pile-up events :Both classical and machine learning approaches are under development.

Beam correlated backgrounds could be an issue for neutron measurement - Confirmed feasibility with the effect of event pile-up.