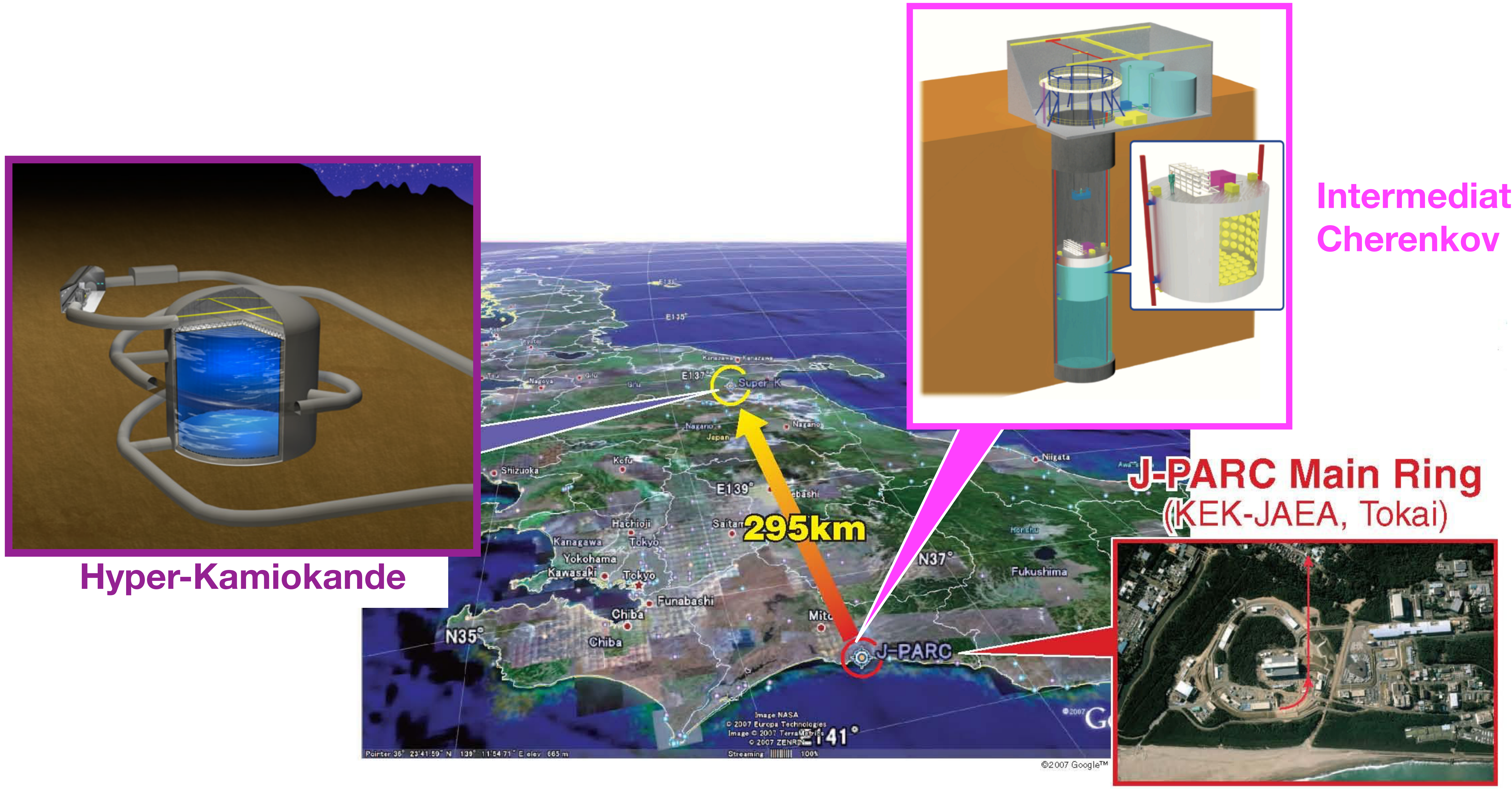
Neutrino Physics and Beyond at T2K and Hyper-Kamiokande



Intermediate Water Cherenkov Detector

J-PARC Main Ring
(KEK-JAEA, Tokai)

Hyper-Kamiokande

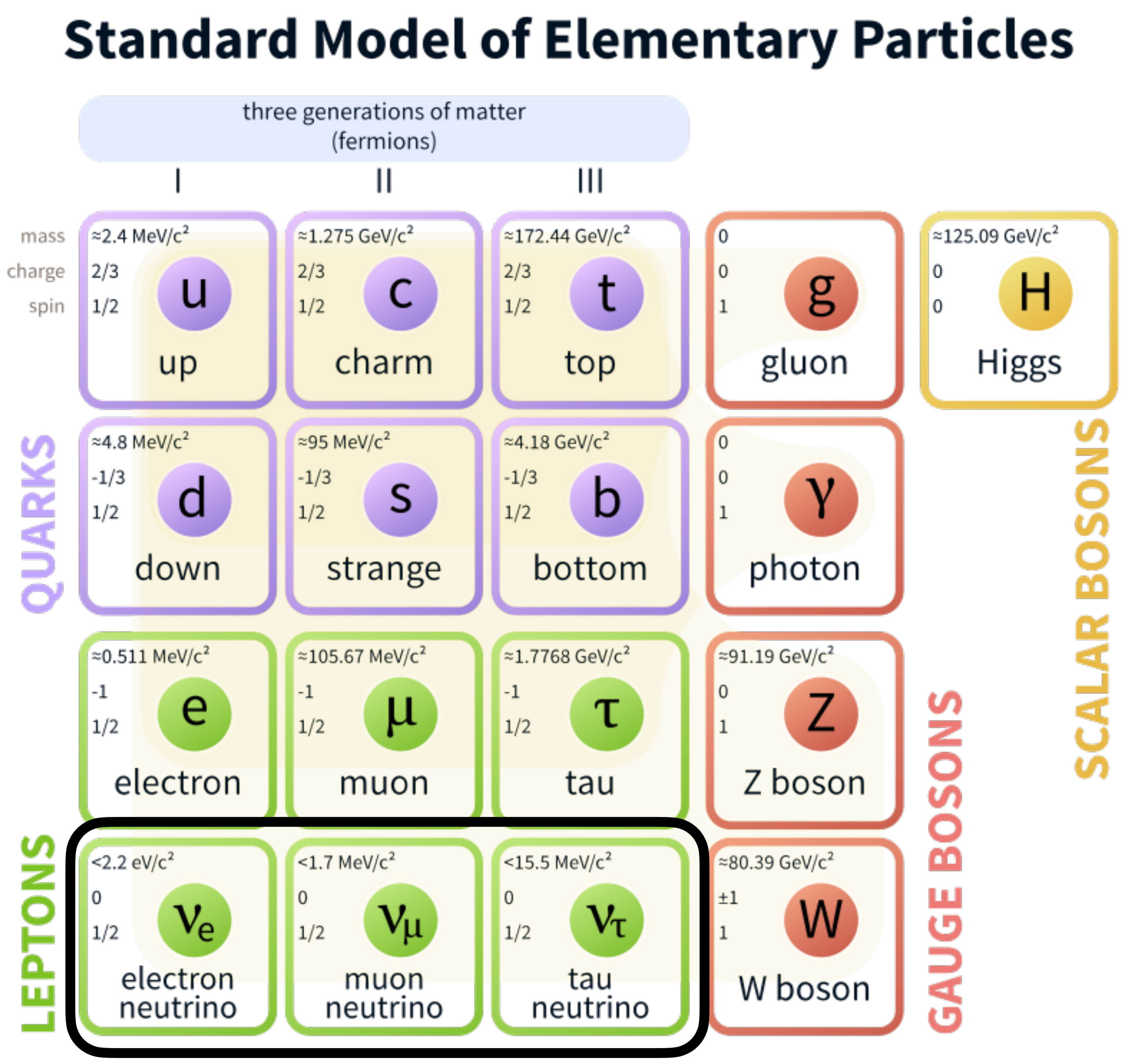
Mark Hartz

For the Hyper-K Canada Collaboration

CAP Congress, PPD Symposium, June 7, 2022

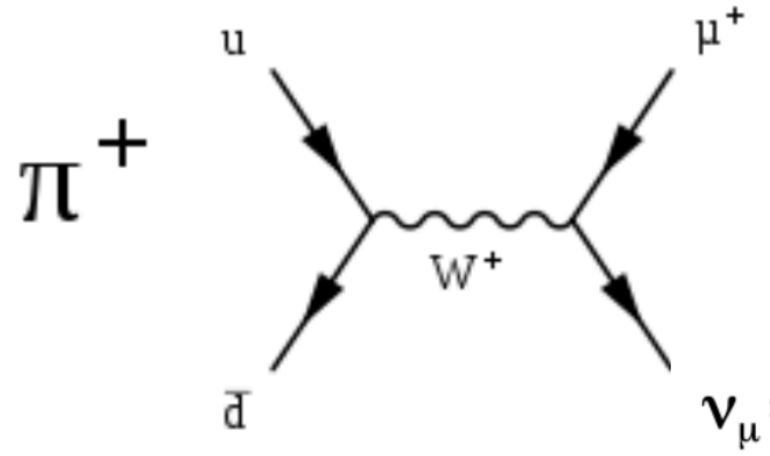
Neutrinos & Their Oscillations

- Neutrinos are neutral and interact via the weak force only
- Flavour and mass states mix, leading to the phenomenon of neutrino oscillations
- From these oscillations, we know that at least two of the neutrinos have non-zero mass



$$|\nu_\alpha\rangle = \sum_{i=1}^{i=3} U^*_{\alpha i} |\nu_i\rangle$$

Flavour state   Mass states

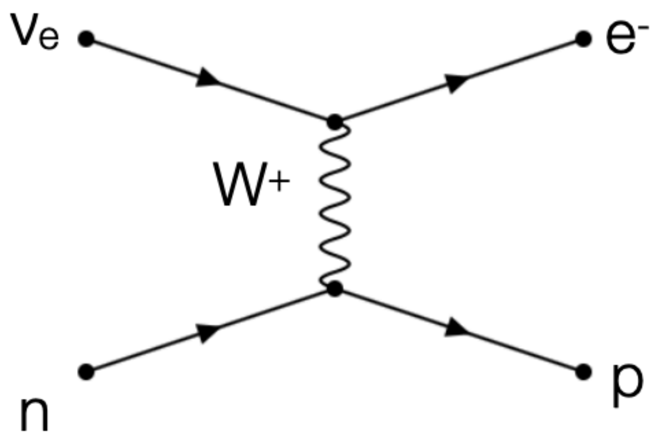


ν_1, ν_2, ν_3

Propagate as mixture of mass states

$$\nu_\mu = U_{\mu,1}\nu_1 + U_{\mu,2}\nu_2 + U_{\mu,3}\nu_3$$

Produce neutrinos as weak eigenstates



Interact as weak eigenstates

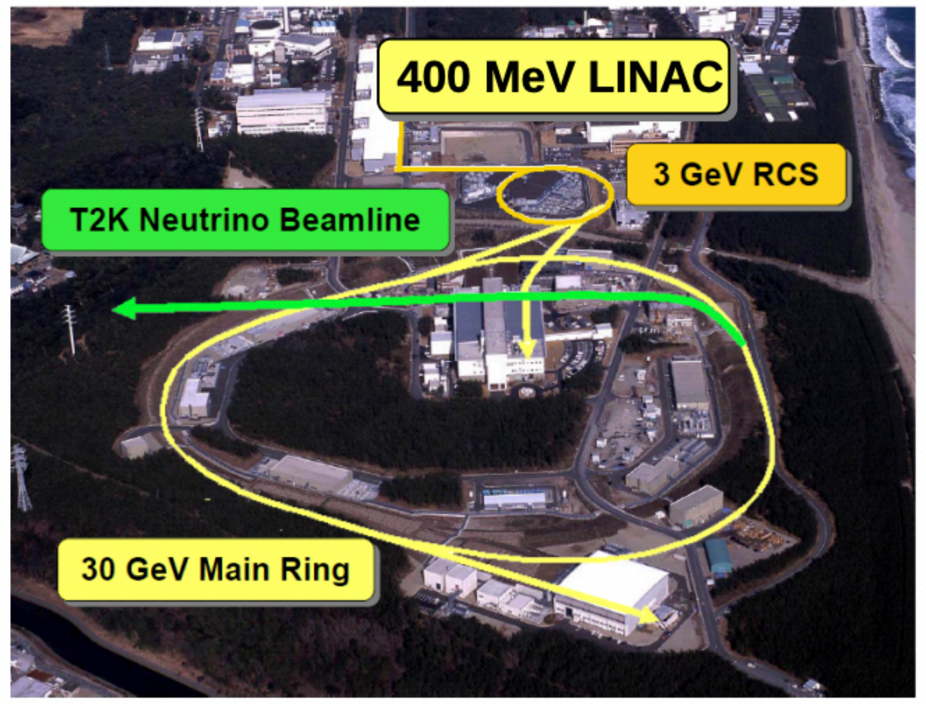
Three mixing angles: $\boldsymbol{\theta_{12}, \theta_{13}, \theta_{23}}$

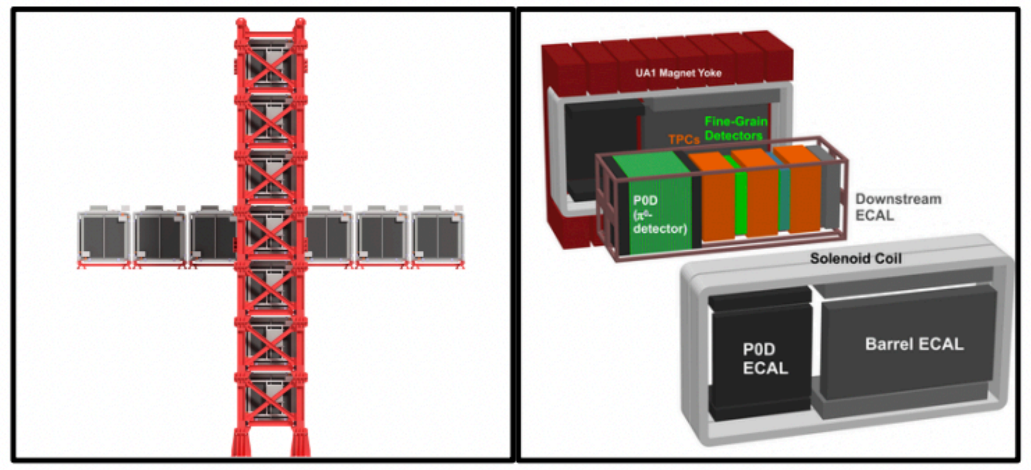
Two mass splittings: $\boldsymbol{\Delta m^2_{32}, \Delta m^2_{21}}$

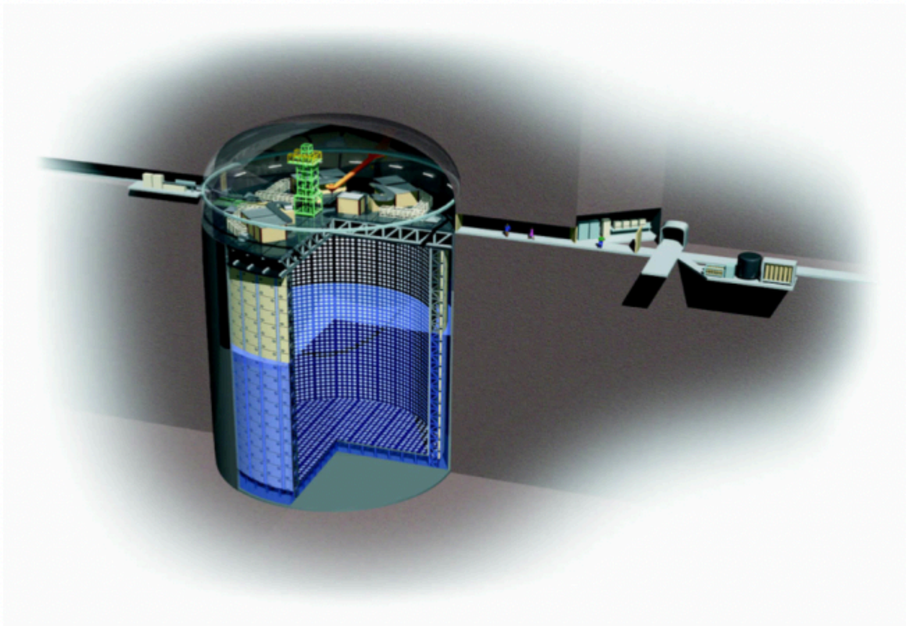
One CP violating phase: δ_{cp}

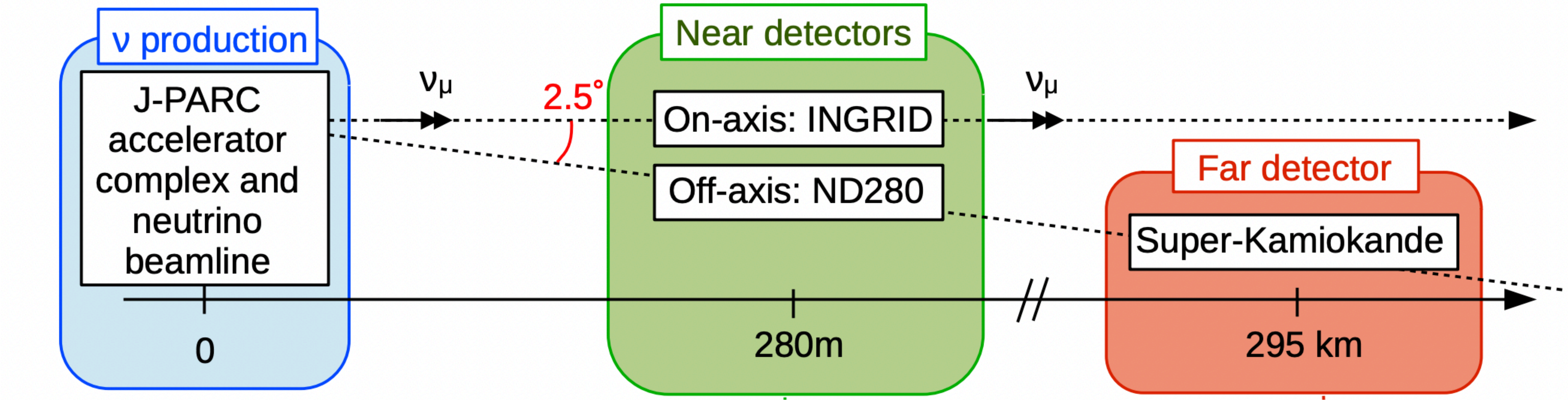
Potential new source of CP violation!

The T2K Experiment









ν production

J-PARC accelerator complex and neutrino beamline

ν_μ

2.5°

Near detectors

On-axis: INGRID

Off-axis: ND280

ν_μ

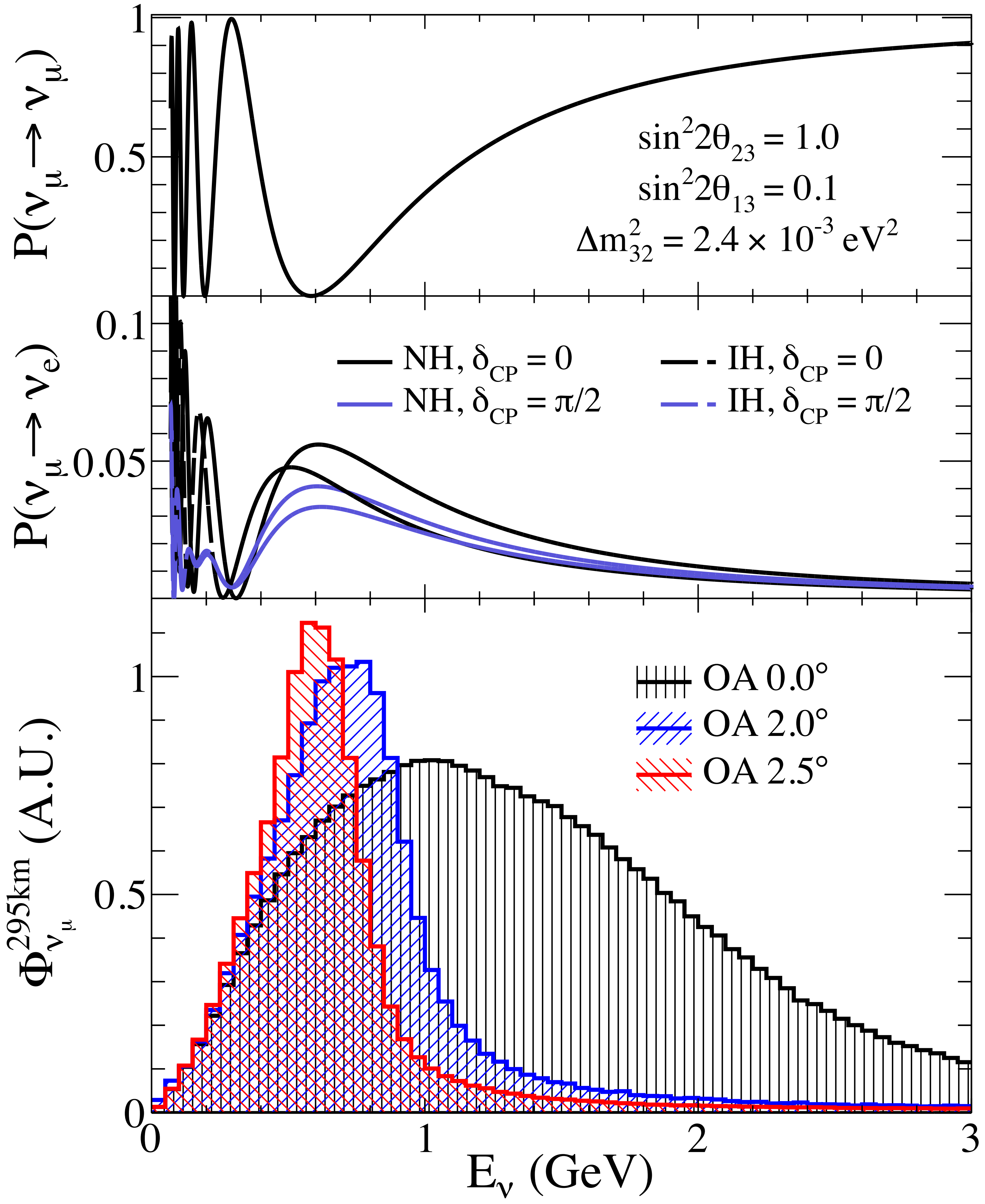
Far detector

Super-Kamiokande

0

280m

295 km

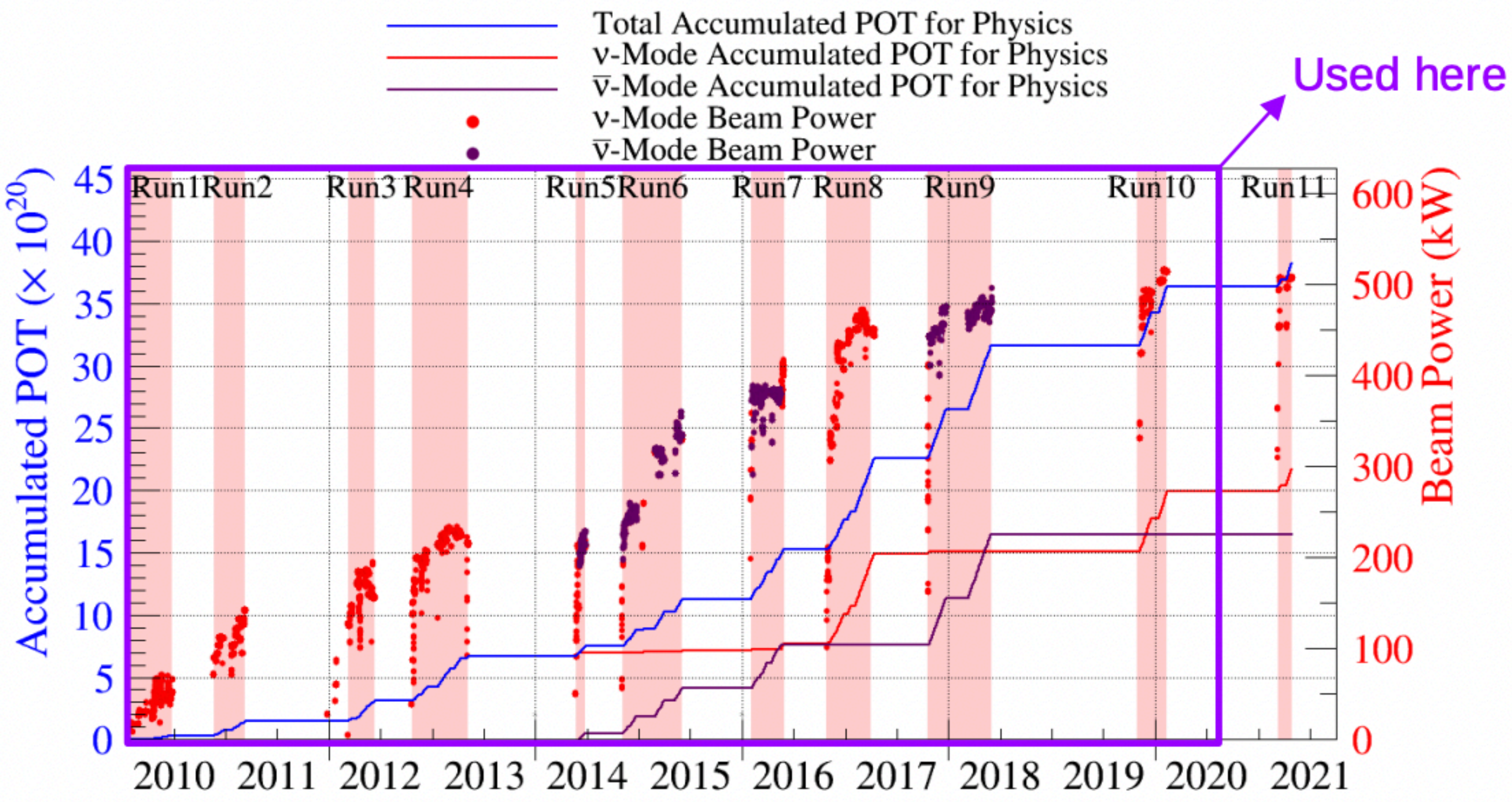


$$P_{\mu\to\mu} = 1 - \left(\boxed{\sin^2 2\theta_{23}} - \sin^2\theta_{23}\cos 2\theta_{23}\sin^2 2\theta_{13}\right)\sin^2\left(\frac{\boxed{\Delta m^2_{32}}\,L}{4E_\nu}\right)+\ldots$$

$$P_{\mu\to e} = \boxed{\sin^2\theta_{23}\sin^2 2\theta_{13}}\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\boxed{\mp}\frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin^2 2\theta_{13}\sin\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\boxed{\sin\delta_{CP}}+\ldots$$

sign flips for antineutrinos

T2K Data



Used here:

Near detectors

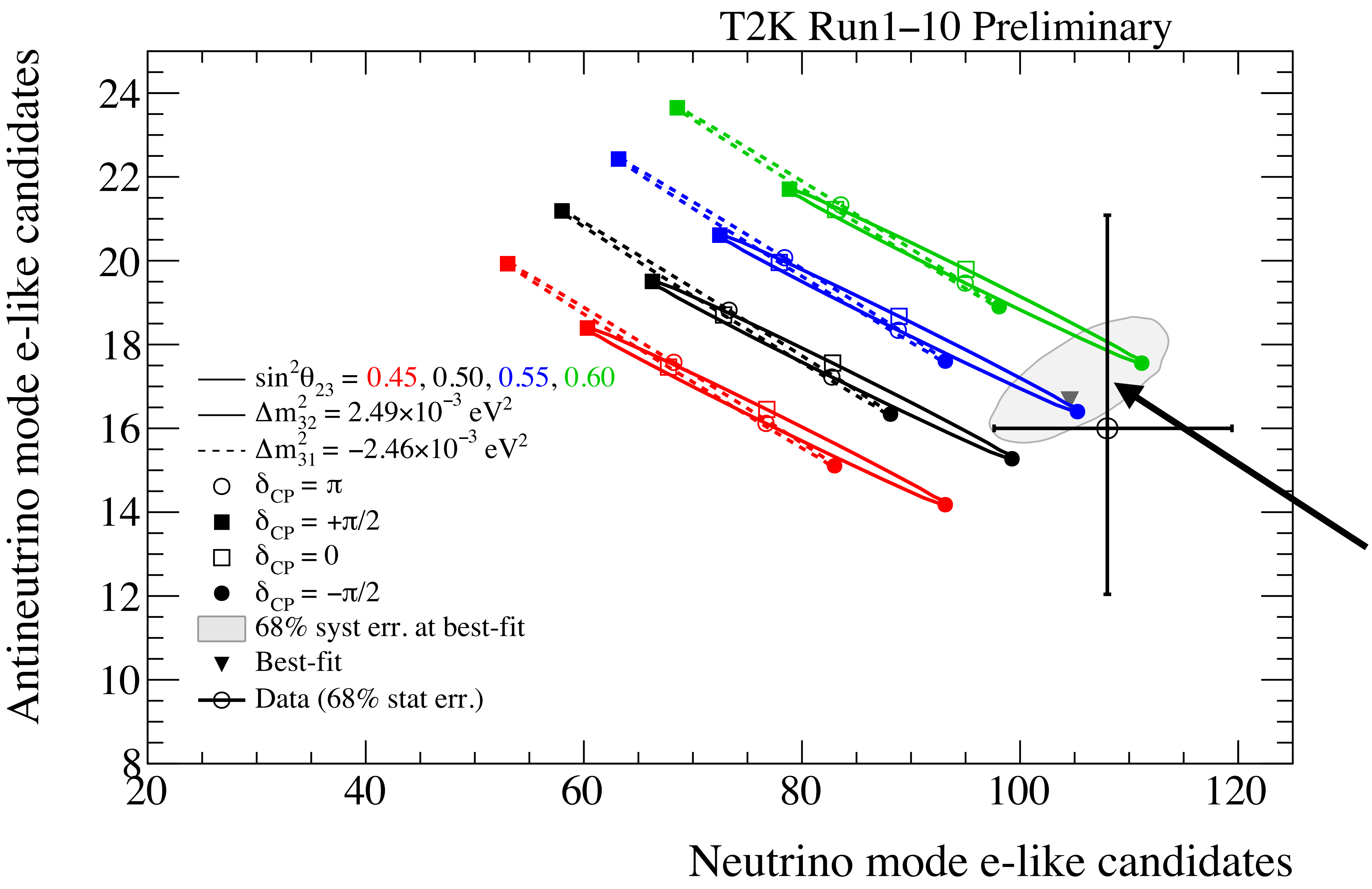
ν-mode: 1.3905 x 10^{21} POT
$\bar{\nu}$-mode: 0.6307 x 10^{21} POT

Far detector

ν-mode: 1.9664 x 10^{21} POT
$\bar{\nu}$-mode: 1.6346 x 10^{21} POT

- T2K has been collecting data since 2010 in both neutrino and antineutrino beam modes
- Results shown here correspond to most of the data collected

CP Asymmetry Measurement at T2K



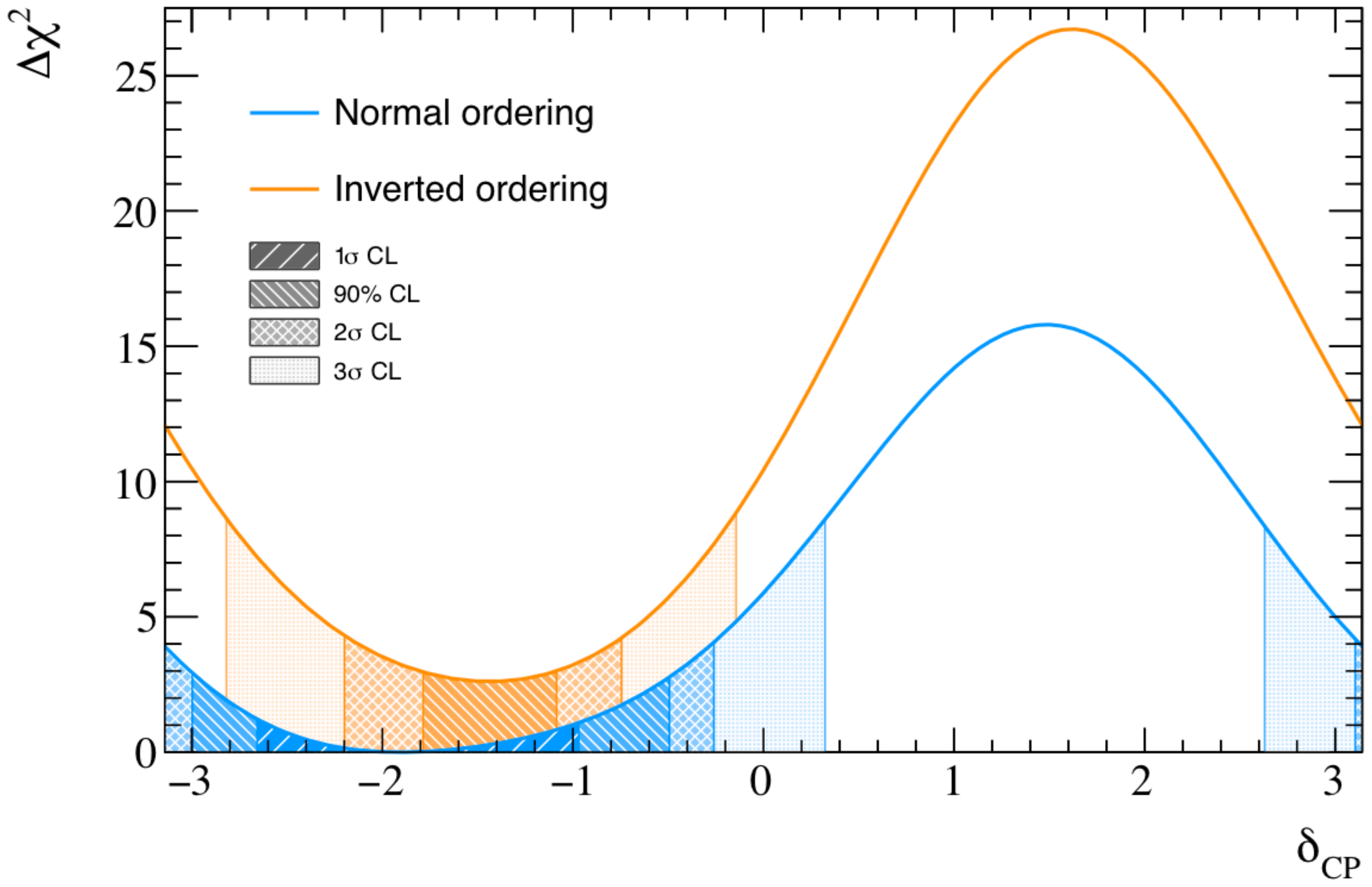
Much lower antineutrino rate is due to experiment being made of matter (to first order)!

Statistical errors still dominate, need more data!

Systematic errors will be become more important with more data

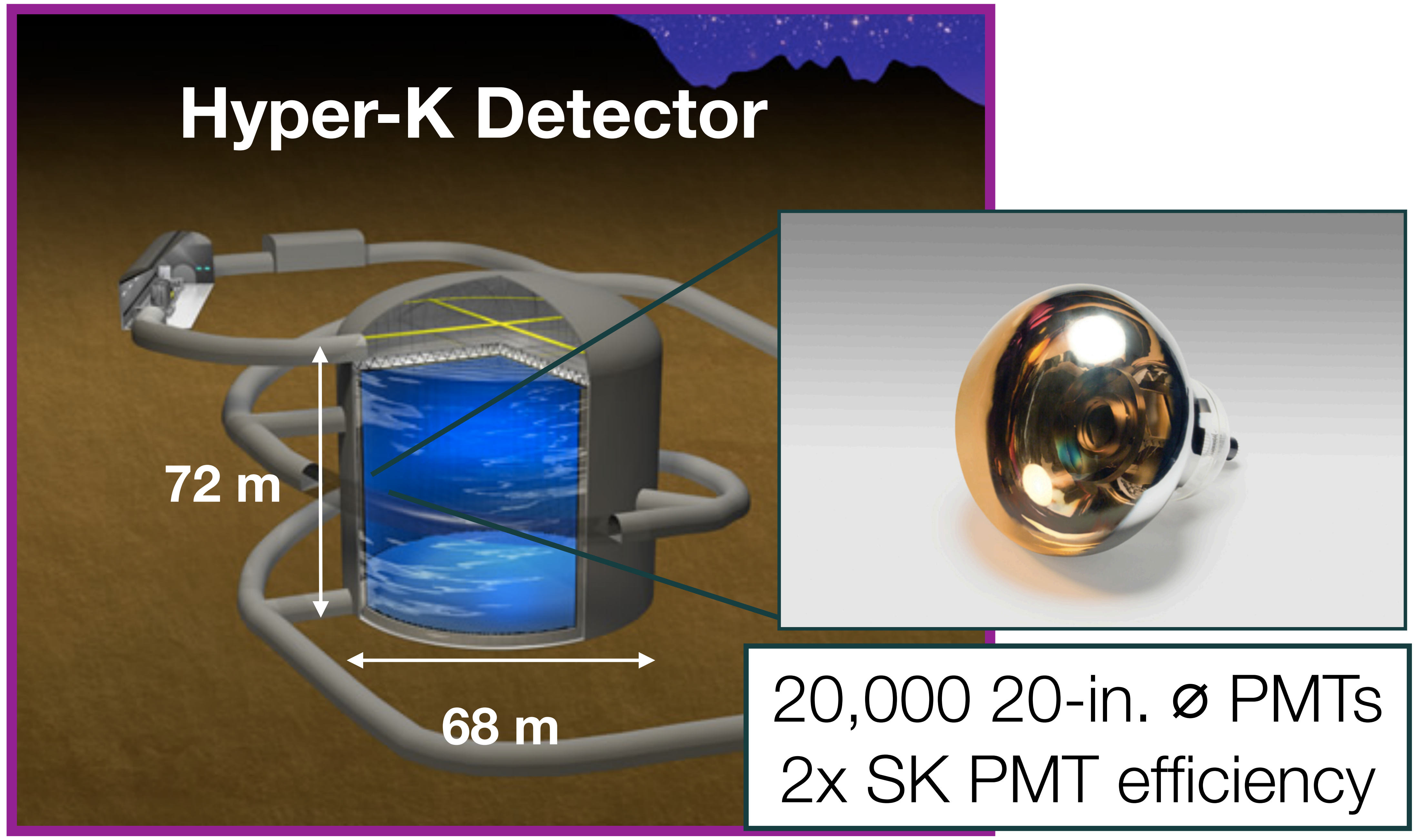
T2K will continue to operate with upgrades to the near detector and beam power

How do we get orders of magnitude more data?



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 (anit)neutrino rate compared to T2K experiment
- Broad physics program includes
  - Accelerator neutrinos
  - Proton decay searches
  - Supernova neutrino detection
  - Atmospheric neutrino detection
  - Solar neutrino detection
  - Dark matter searches…
- Approved in 2020, planned start of operation in 2027



20,000 20-in. ⌀ PMTs
2x SK PMT efficiency

J-PARC upgrade to 1.3 MW beam power

Hyper-K Collaboration

20 countries, 99 institutes, ~500 people as of Jan 2022, and growing

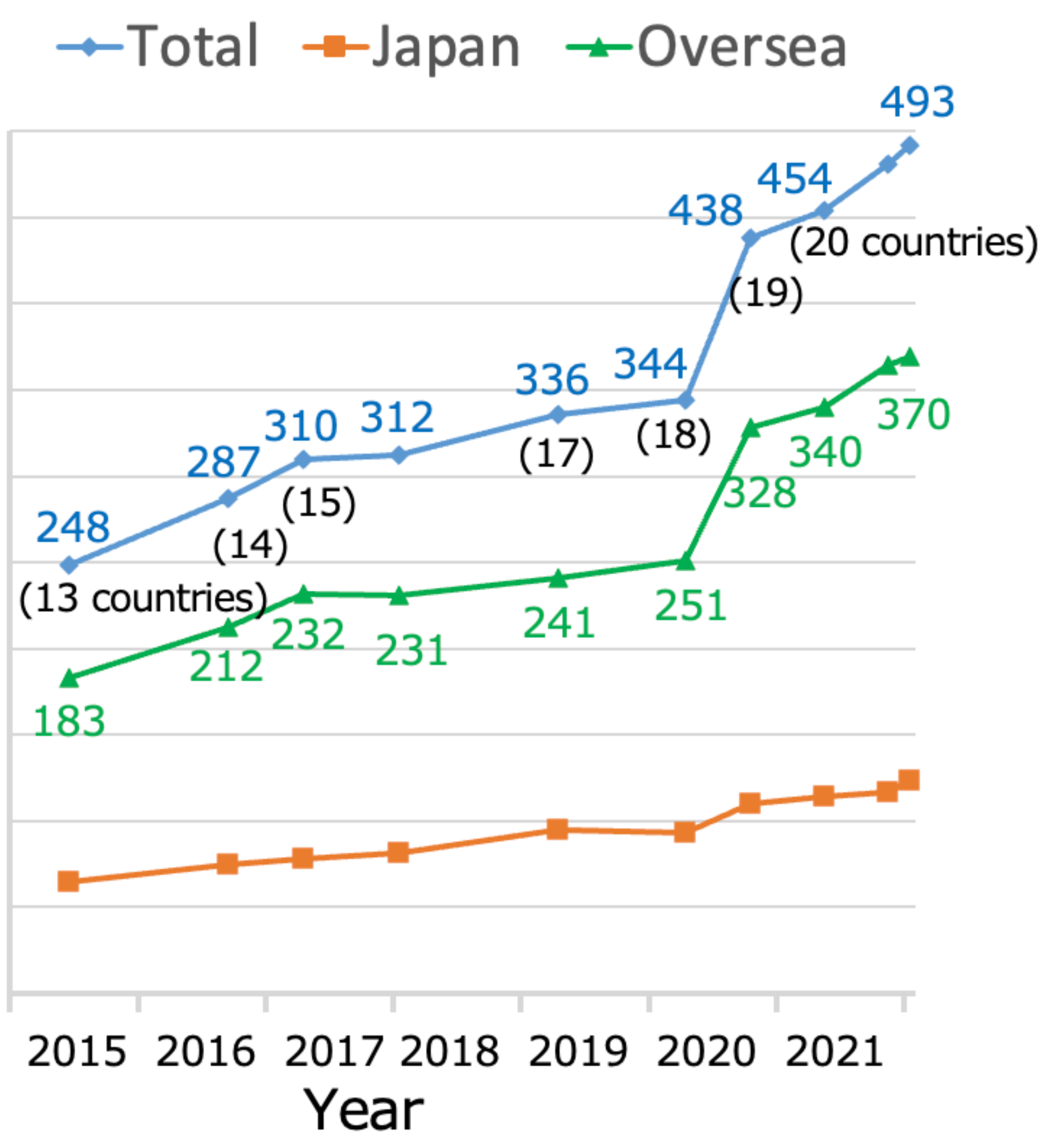
Europe	281 members
Armenia	3
Czech	4
France	27
Germany	1
Italy	55
Poland	38
Russia	22
Spain	35
Sweden	5
Switzerland	13
Ukraine	4
UK	74

Asia	149 members
India	8
Korea	18
Japan	123

Americas	52 members
Brazil	3
Canada	32
Mexico	8
USA	9

Africa	11 members
Morocco	11

Number of Collaborators



Hyper-K Canada Collaborating Institutes

TRIUMF

University of Toronto

York Université
University

The University of Winnipeg

Carleton University

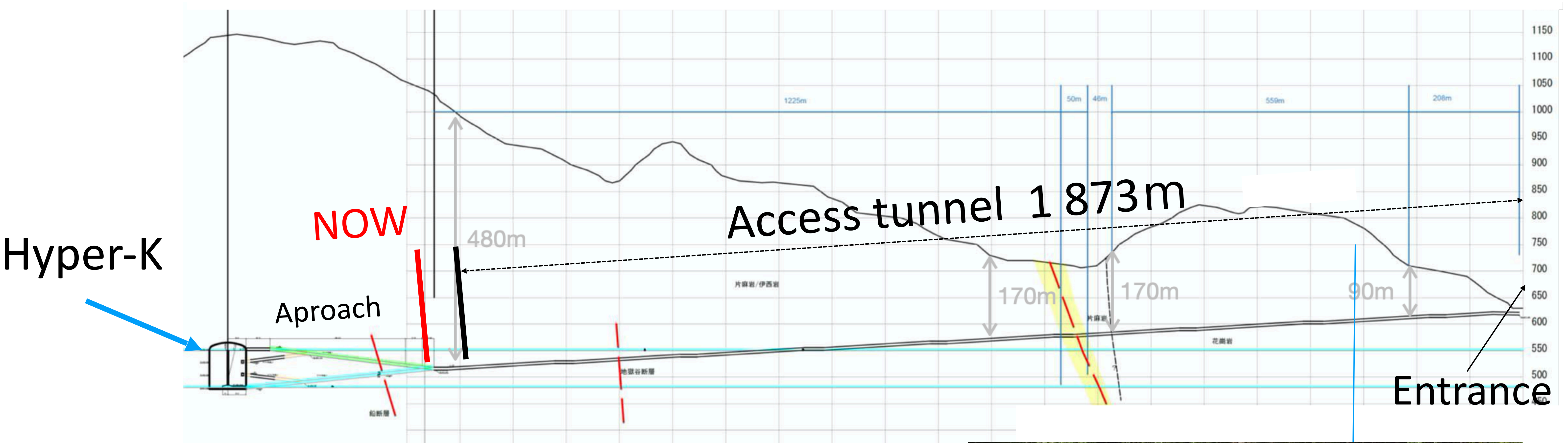
University of Regina

University of Victoria

BCIT
British Columbia Institute of Technology

- Hyper-K is a large international and growing collaboration
- The Hyper-K Canada group was formed in 2018 and is supported by funding from NSERC and CFI
- Hyper-K Canada is open to new collaborators!

Construction Progress in Japan




2022.2 Completion of the Access tunnel (1 873m)

2021.5
Ground-breaking
Ceremony at the
Entrance


Blasting

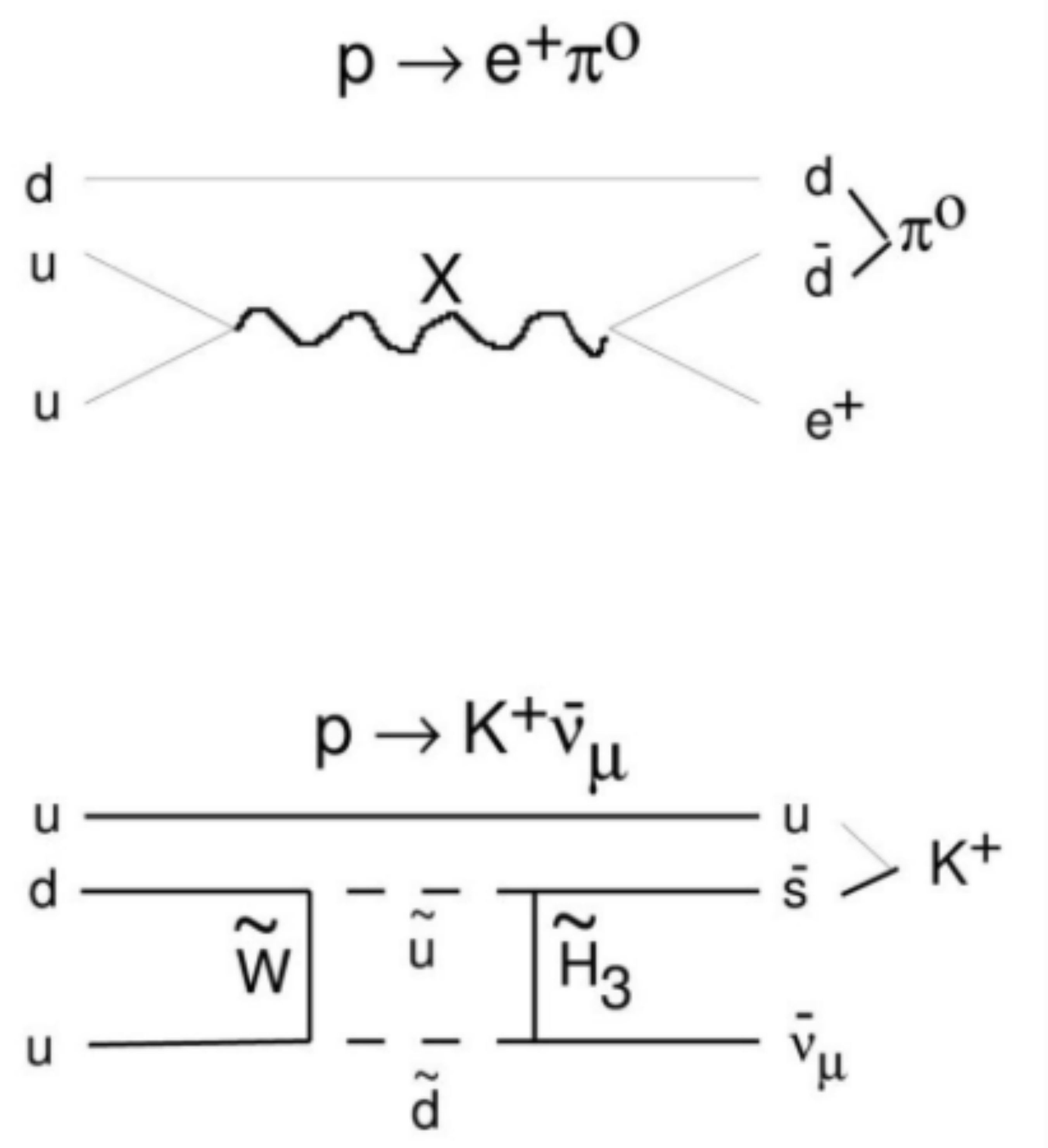

Waste rock disposal

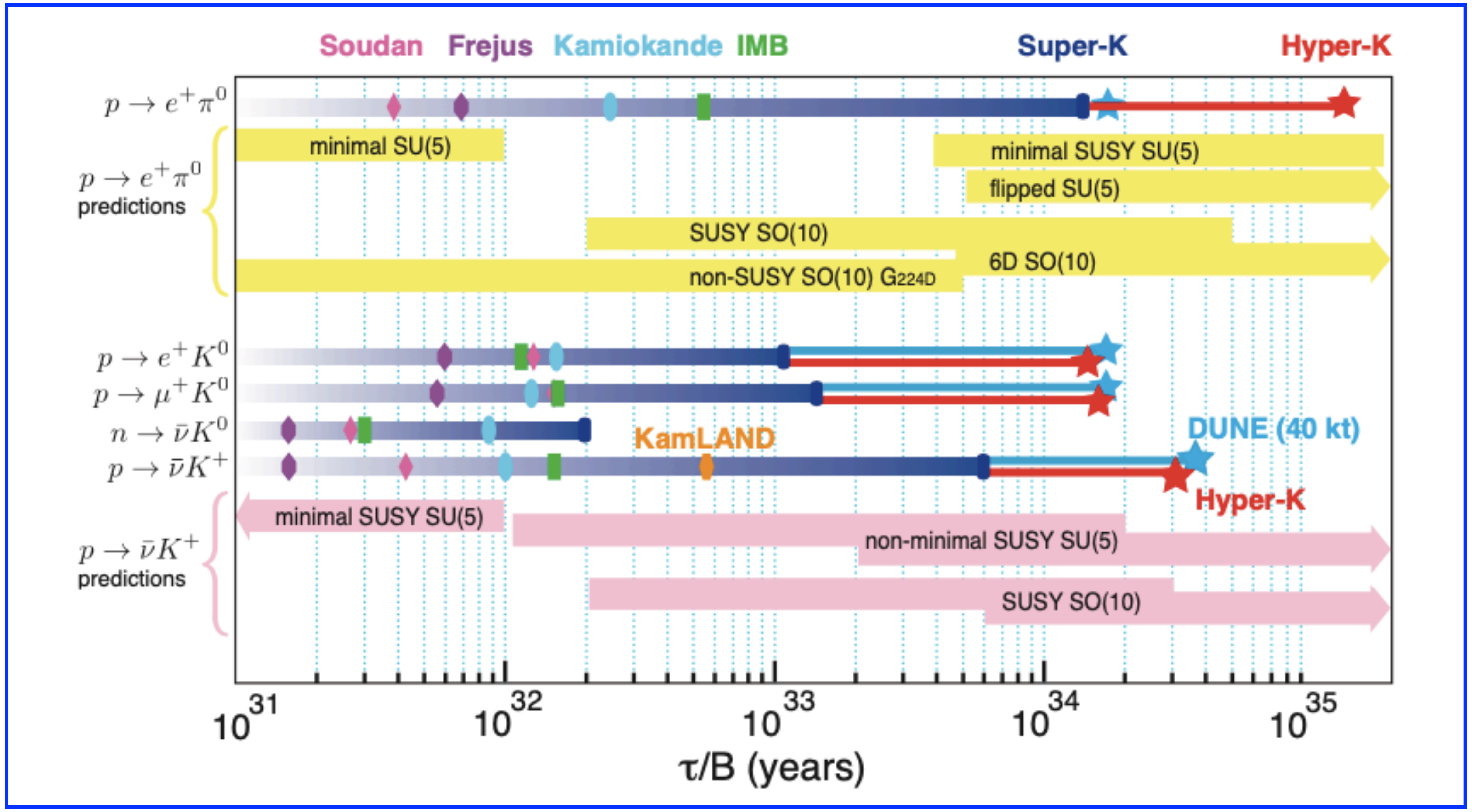
Excavation of the detector cavity, one of the world's largest underground cavities, will begin in October of this year.

Proton Decay at Hyper-K

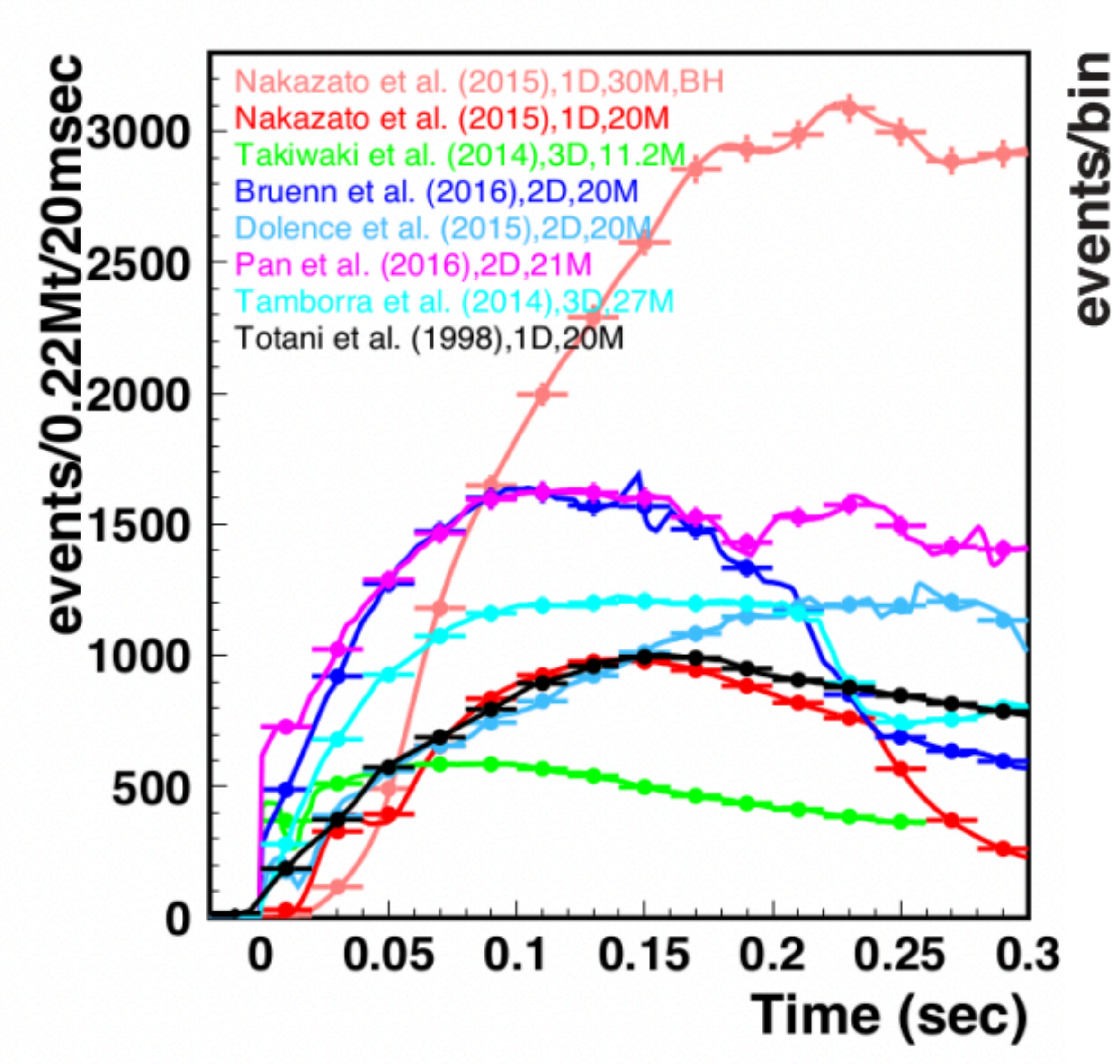
Baryon number violation is generic prediction of GUTs

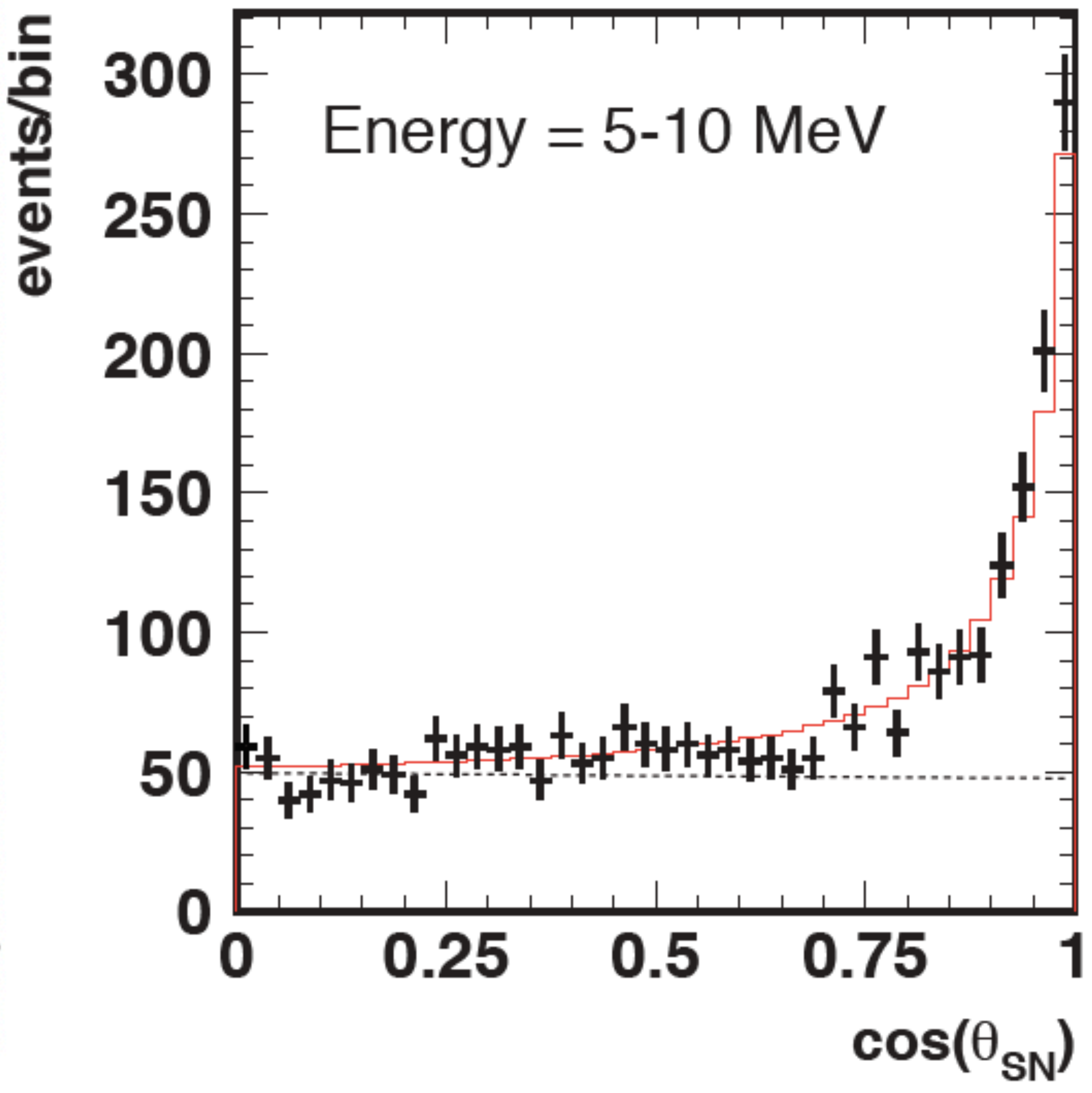
With its 187 kton fiducial mass, Hyper-K will have the largest mass with sensitivity to most channels



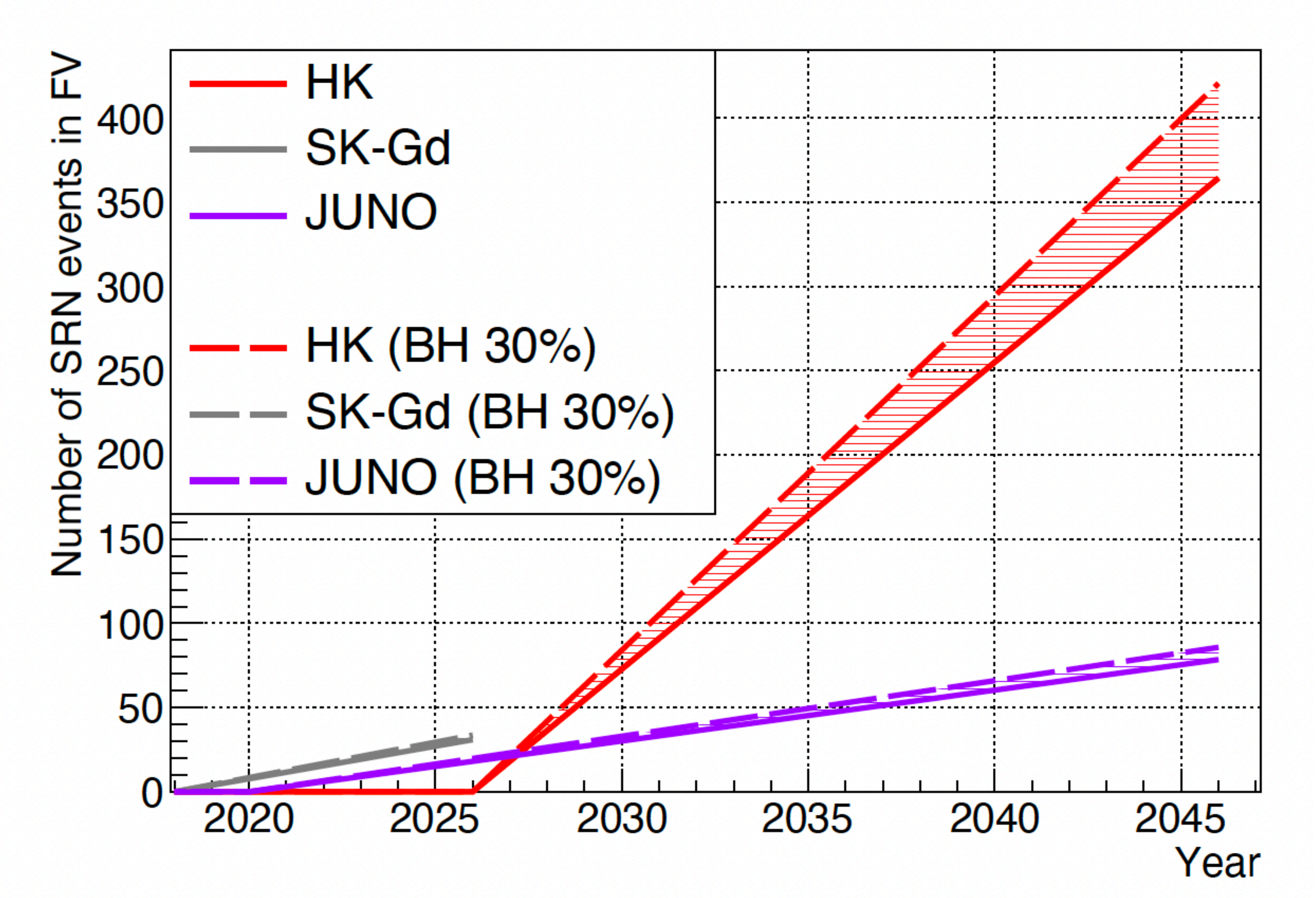


Supernova Neutrinos at Hyper-K



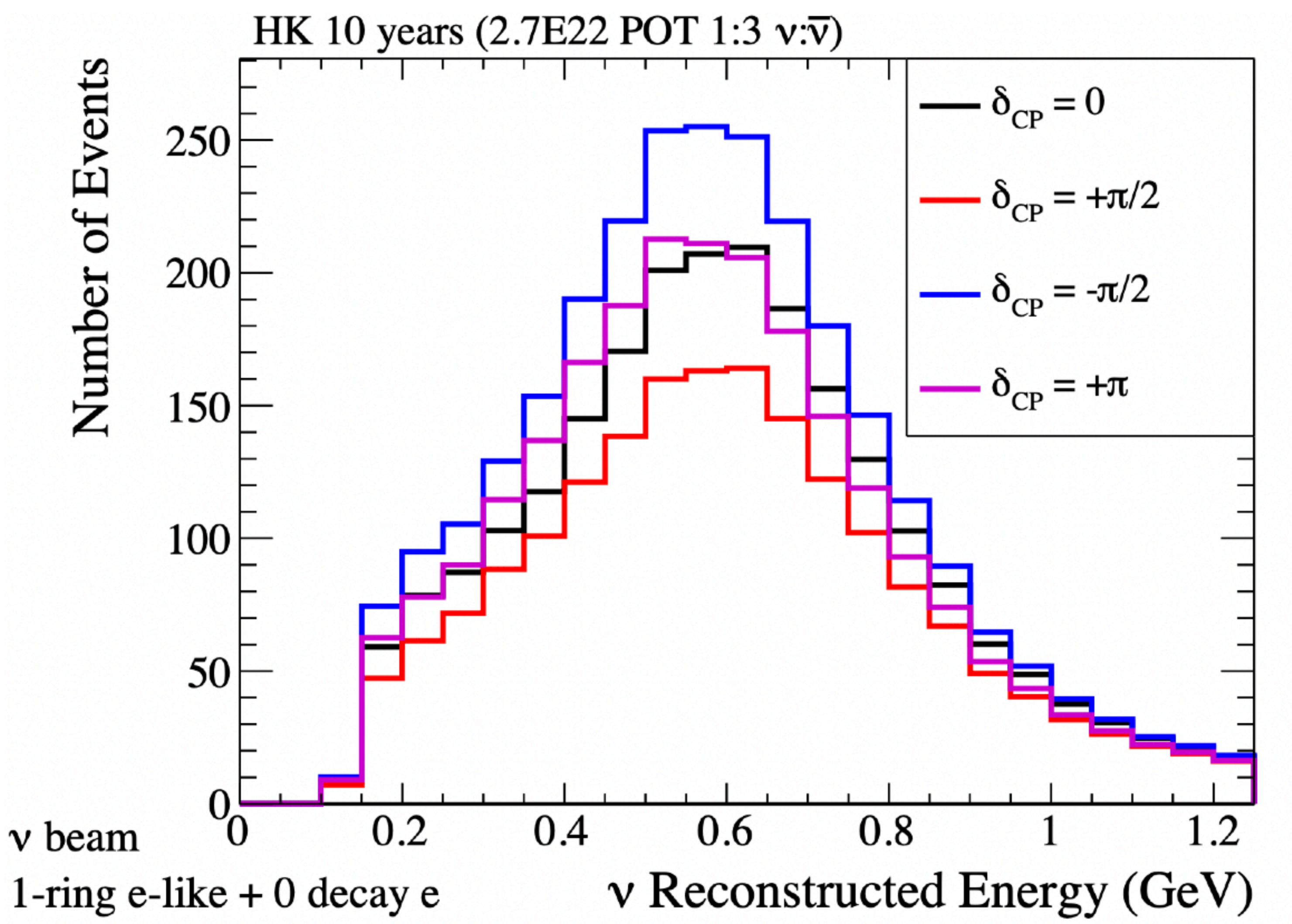


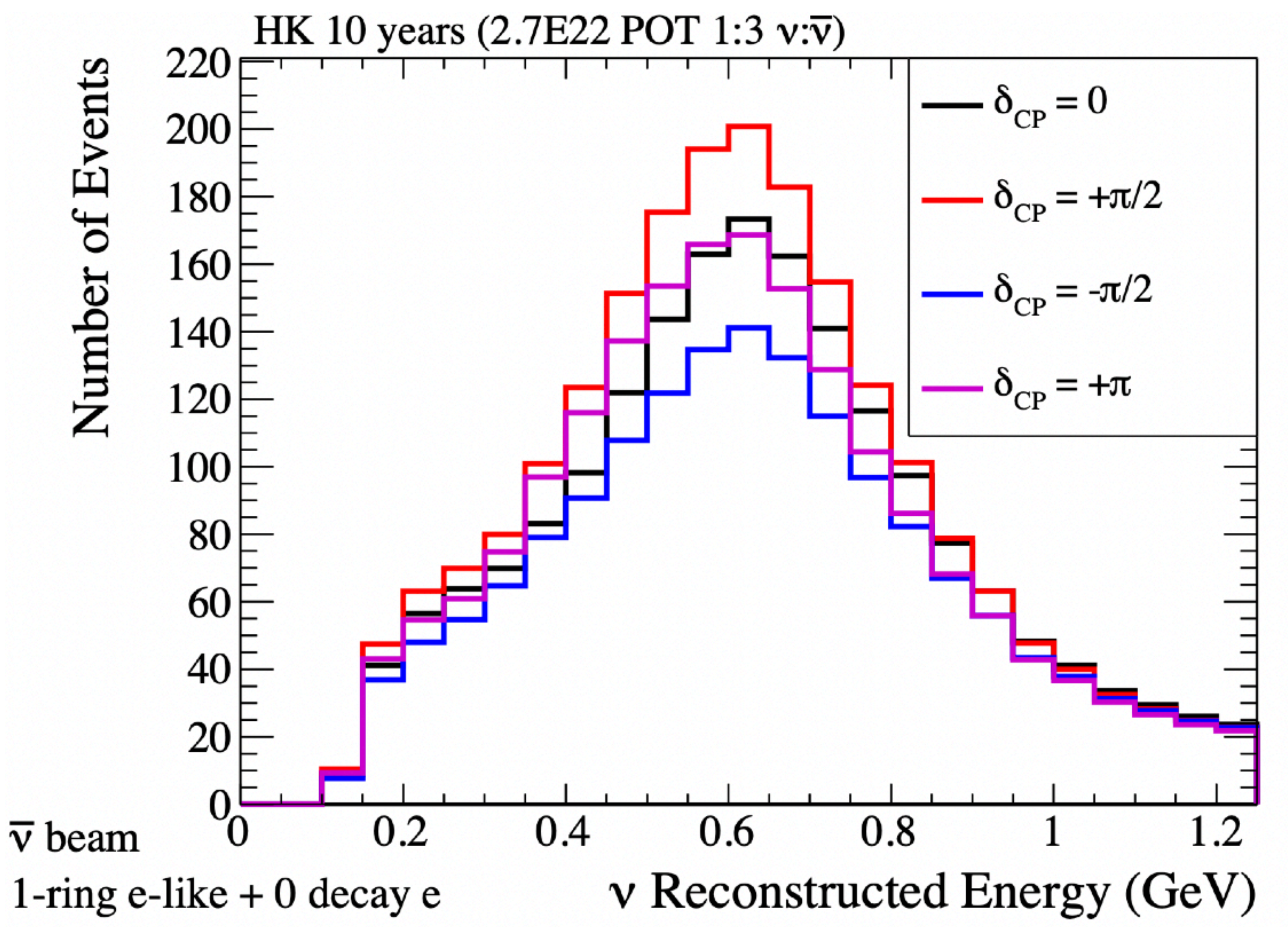
- **54k-90k events for 10 kpc distant supernova**
- ~10 neutrino events for supernova in Andromeda
- Neutrino-electron scattering introduces pointing capability
- **1.0-1.3 degree accuracy for 10 kpc distant supernova**

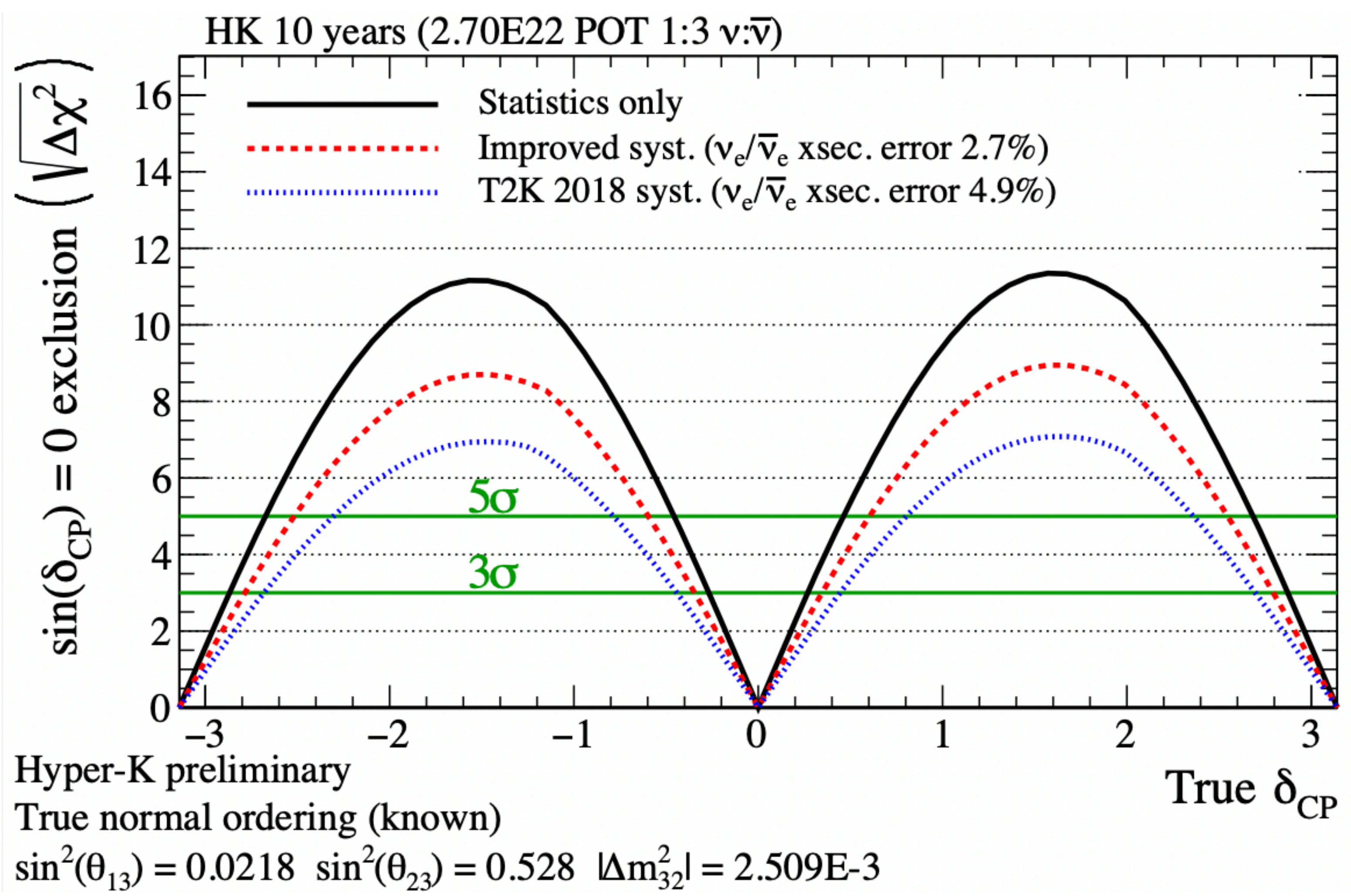


- There is a background of supernova neutrinos from all past supernovas
- Probes history of heavy element synthesis in stars
- Due to its large mass, Hyper-K will improve on sensitivity of SK-Gd

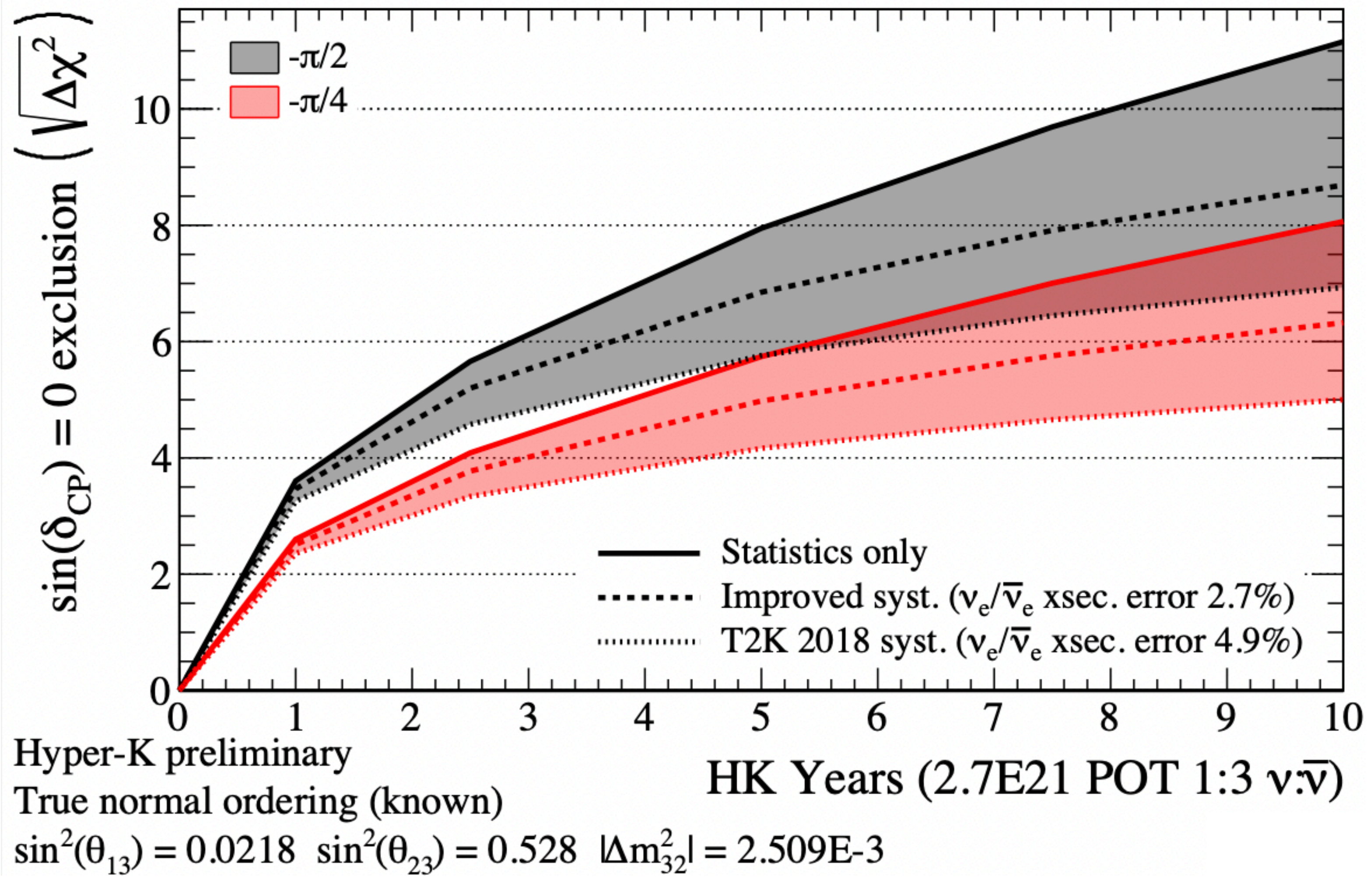
CP Violation at Hyper-K





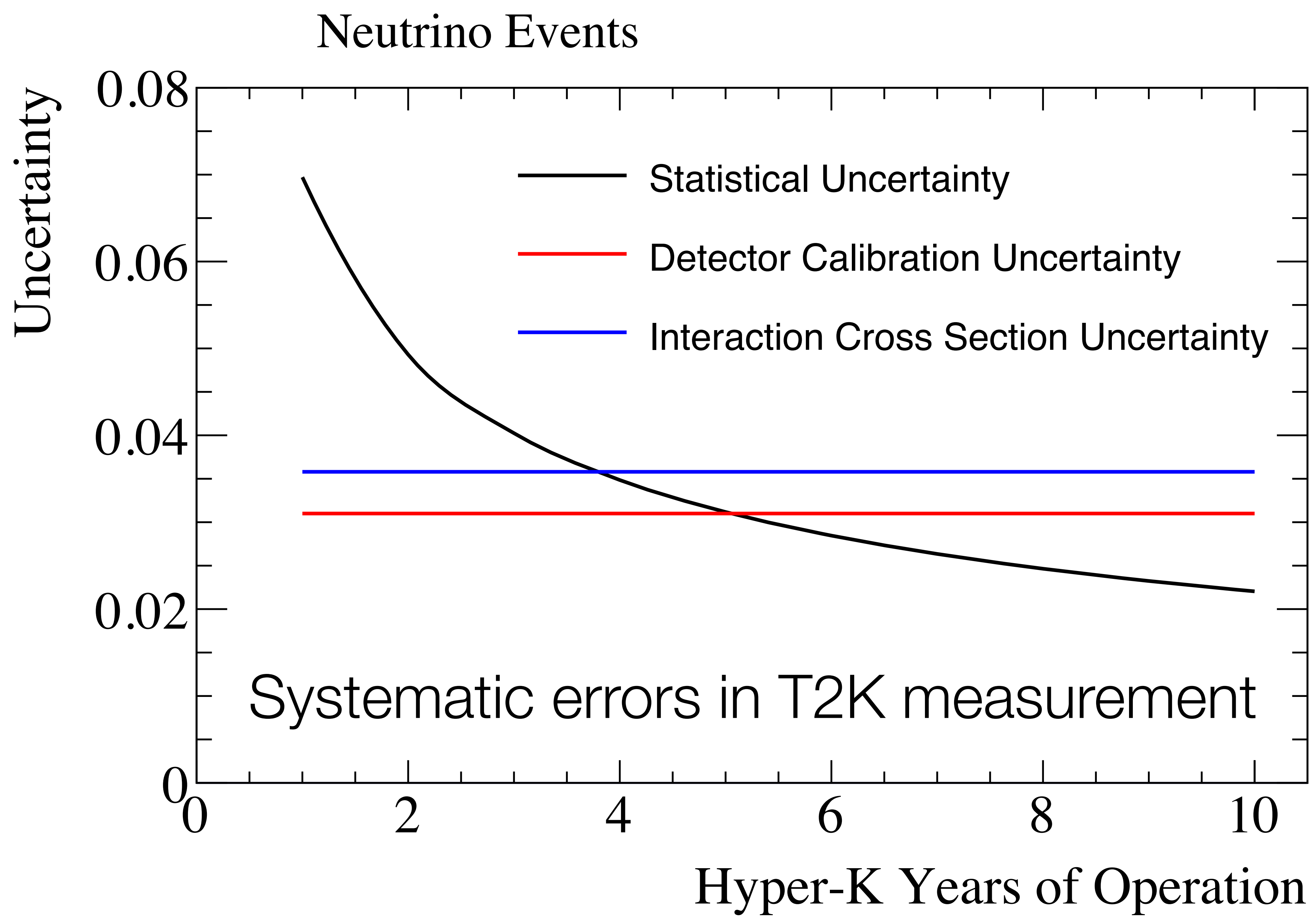


- Hyper-K will observe ~2000 electron neutrino and electron antineutrino candidates each
  - 3% statistical error on the CP violation measurement is achieved
  - **Controlling systematic errors is critical**

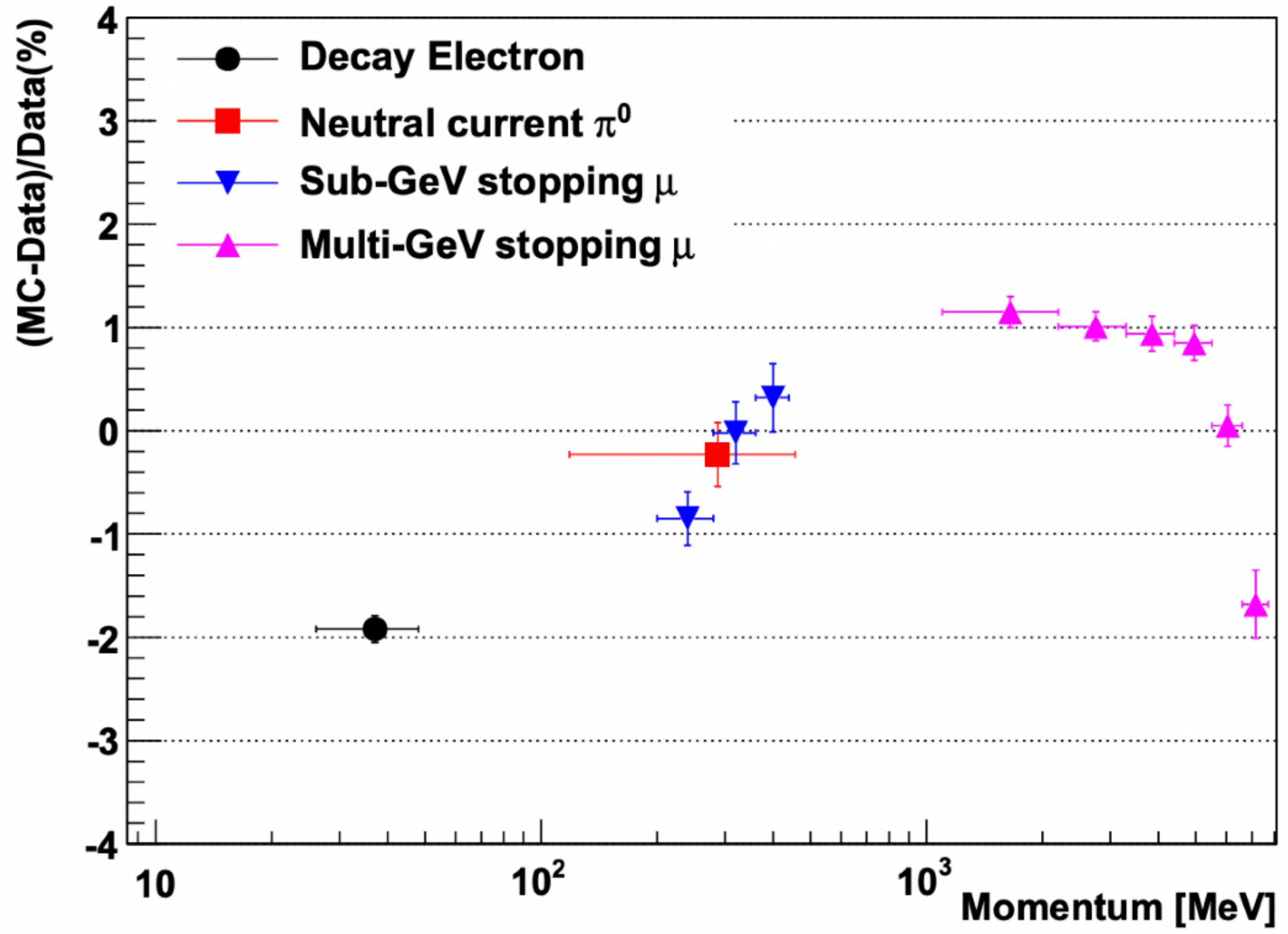


Systematic Uncertainties

- CP violation measurement becomes systematic error dominated
- **Uncertainty on neutrino interaction modeling to be addressed with Intermediate Water Cherenkov Detector (IWCD)**
- **Uncertainty on detector modeling to be addressed with new calibration systems and techniques**



Super-K Energy Scale
PTEP, vol. 2019, no. 5, p. 053F01, 2019

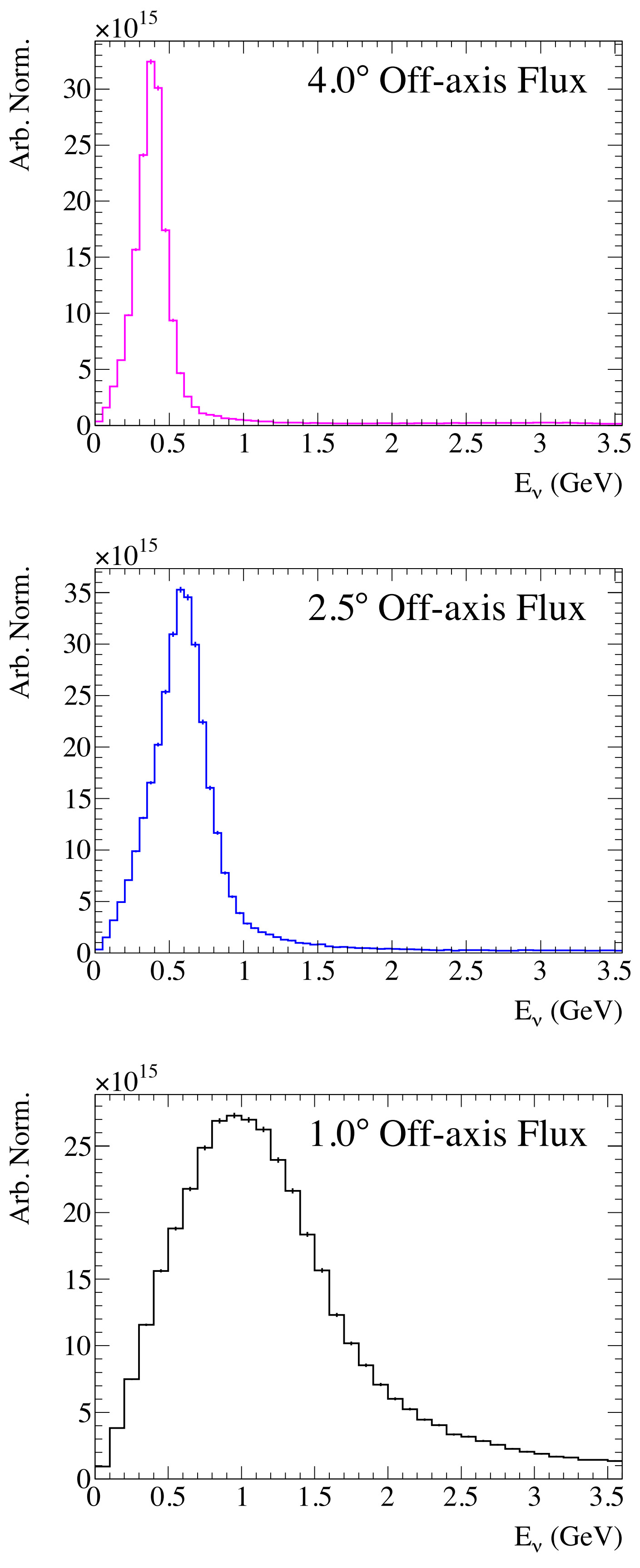


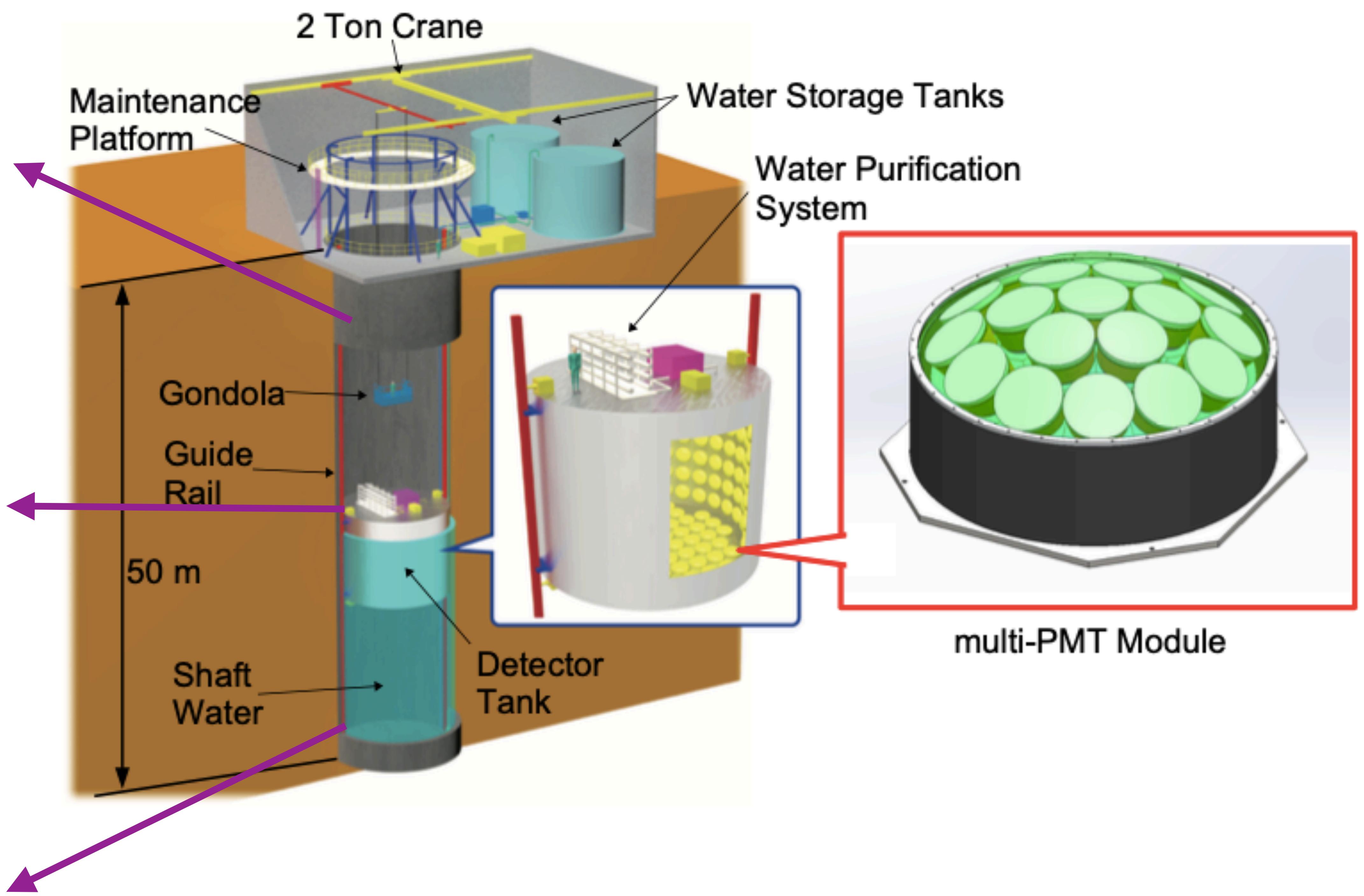
- To make precision parameter measurements, also need to know energy scale to 0.5% level
- Current error in Super-K is ~2%

The Intermediate Water Cherenkov Detector

- Intermediate detector for Hyper-K
- Located ~1 km from neutrino source
  - Land acquisition is primary focus of host lab at this time
- 600 ton water Cherenkov detector
- Position can be moved to different off-axis angles
- Using new high resolution multi-PMT photon detectors
- Primary physics:
  - Electron (anti)neutrino interactions (with 1% of beam)
  - Measuring (anti)neutrino energy reconstruction

Canadian led project





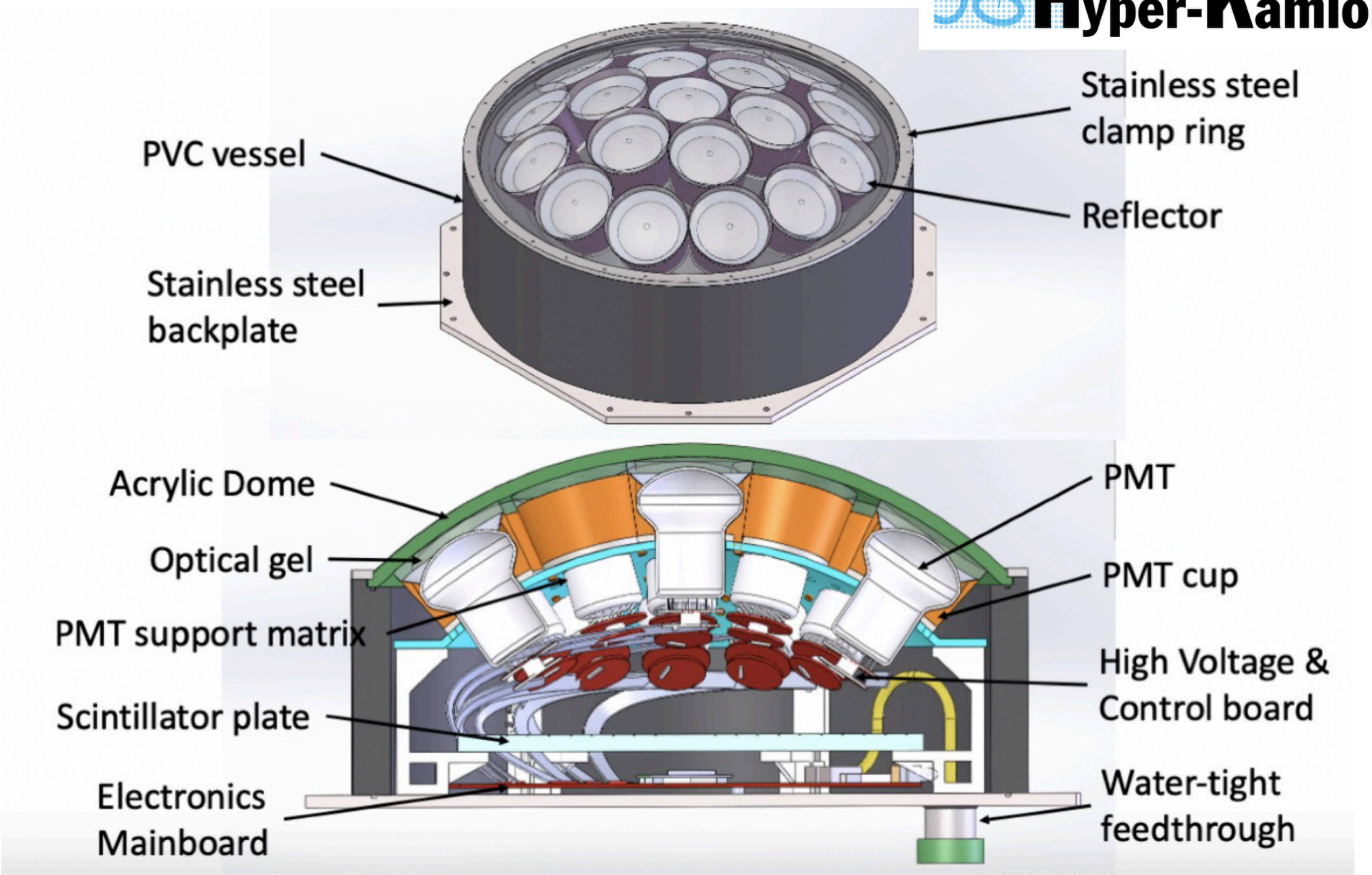
Approved Hyper-K project includes IWCD

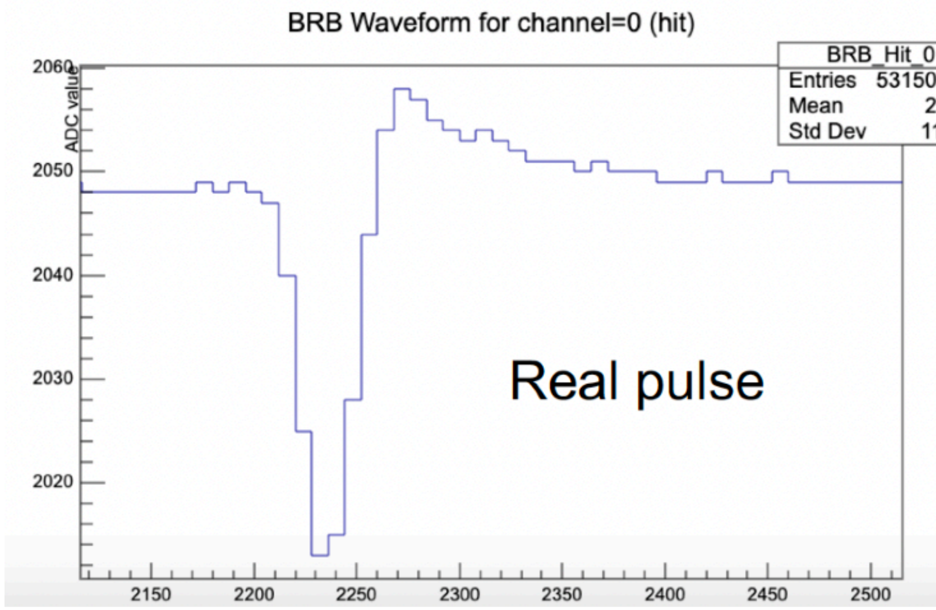
See talk by R. Akutsu at W1-1 Neutrino Experiments (PPD)

Multi-PMT (mPMT) Photosensor

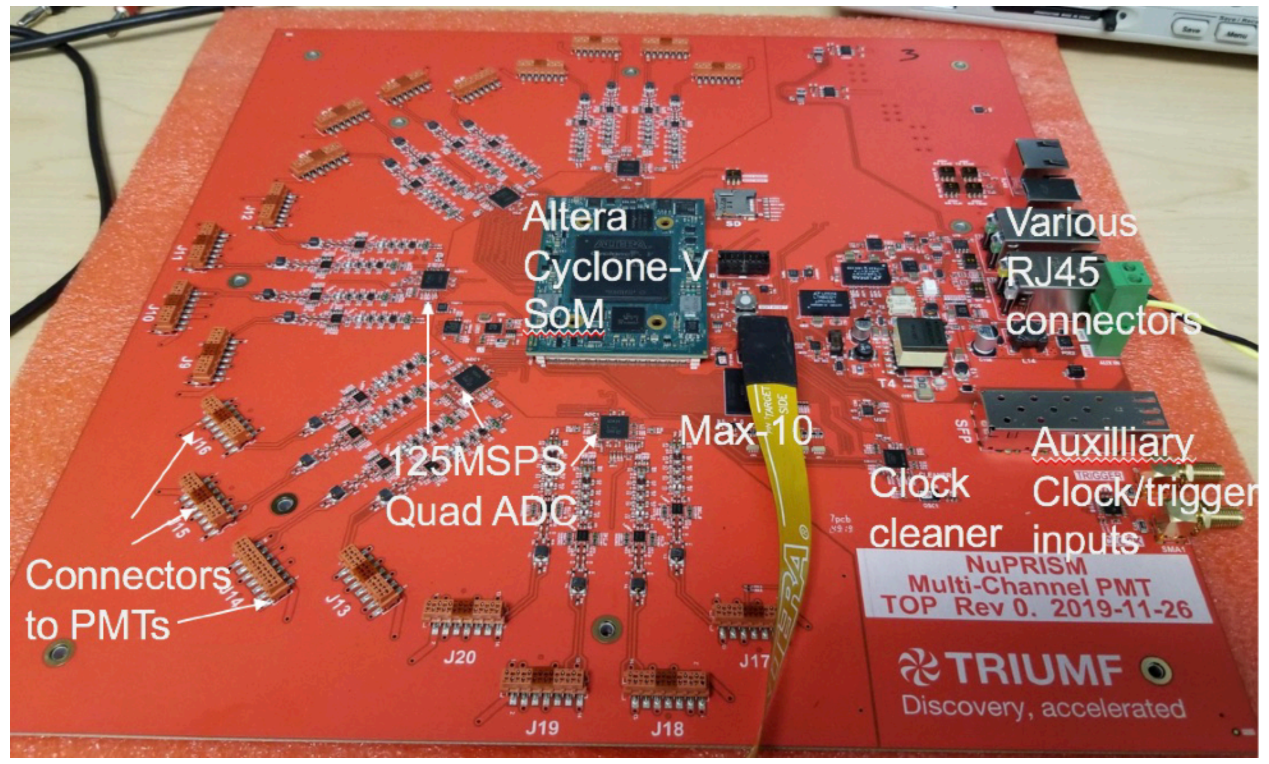
Hyper-Kamiokande

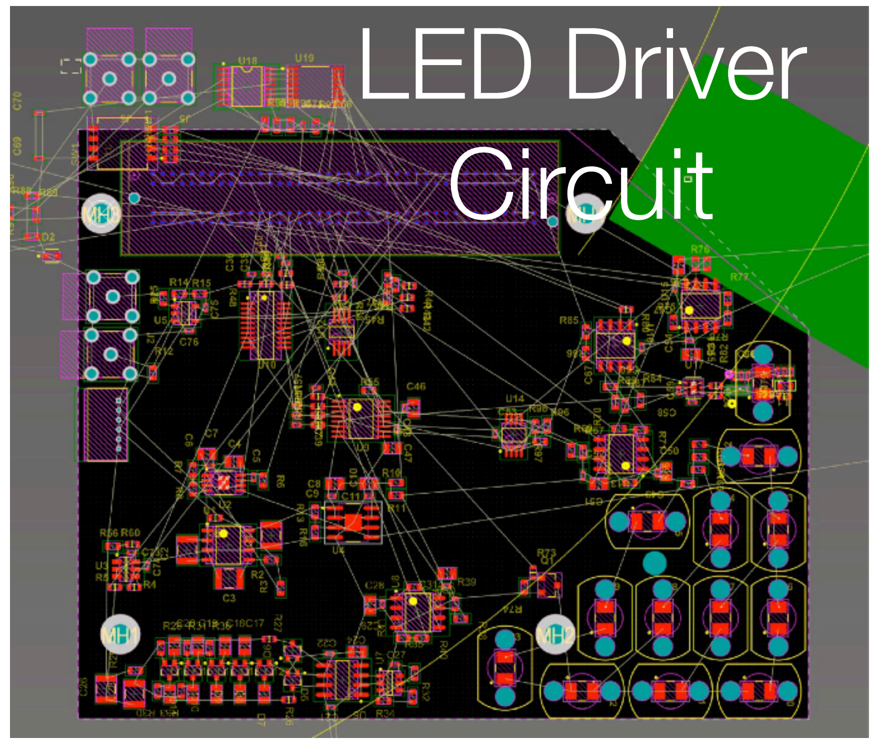
- 19 fast 3-inch diameter PMTs in a single module with readout electronics and HV integrated in the module
- LED light injection will allow mPMTs to be used as light sources in detector calibration
- Electronics development on 125 MSPS 20-channel FADC is well advanced
    - Working firmware for Xilinx FPGA
    - One more prototype revision planned with final decision on shaping circuit
    - Development of mezzanine care for driving of LED light injectors





Electronics main board





Carleton UNIVERSITY

University of Victoria

TRIUMF

THE UNIVERSITY OF WINNIPEG

YORK UNIVERSITÉ UNIVERSITY

Multi-PMT (mPMT) Photosensor Assembly

Hyper-Kamiokande

- Two methods for assembly being explored:
  - Apply gel to PMTs before assembly of module
    - Challenge - achieving good optical contact with limited tolerance to variation in parts dimensions.
  - Assemble PMTs, dome, support matrix and cylinder first, before applying gel
    - Challenge - procedure has to work ~100% of the time since it is a one-time application for each module

Prototype for ex-situ gelling at TRIUMF

Prototype for in-situ gelling at Carleton

See Talk by N. Booth in W2-6 Neutrino Experiment and Related Calibrations II (PPD)

See Poster by L. Koerich (G*) (POS-37) Toward a Veto Mechanism to Reduce Background for the Hyper-Kamiokande's Intermediate Water Cherenkov Detector

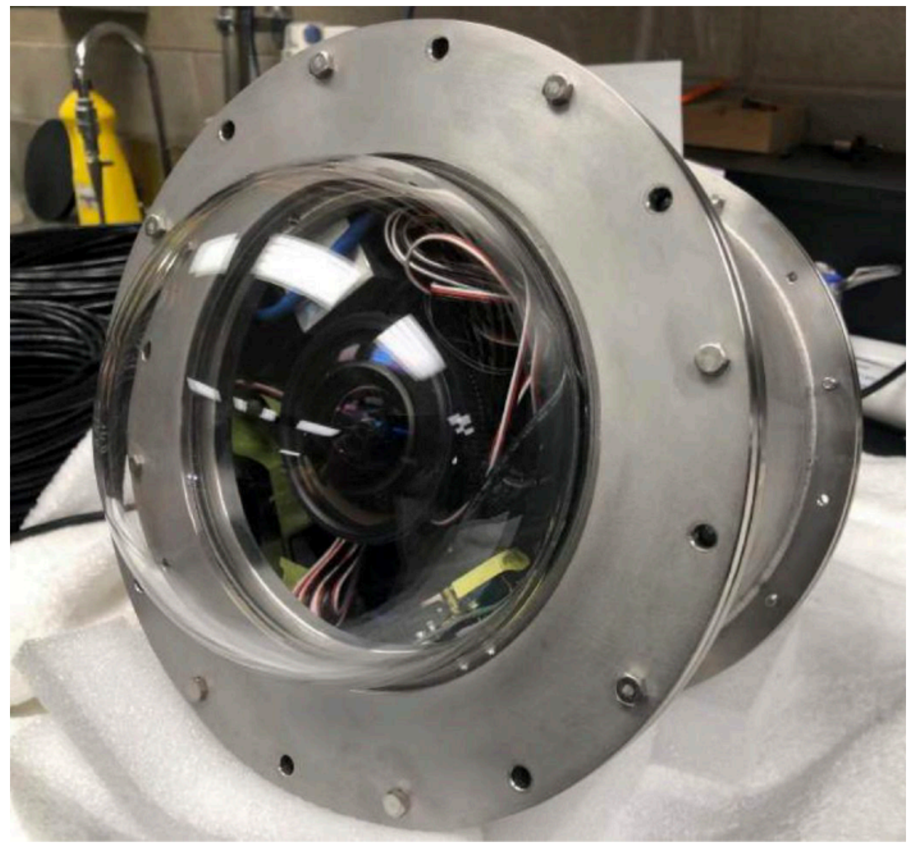
Carleton University · University of Victoria · TRIUMF · The University of Winnipeg · York University

Photogrammetry Calibration

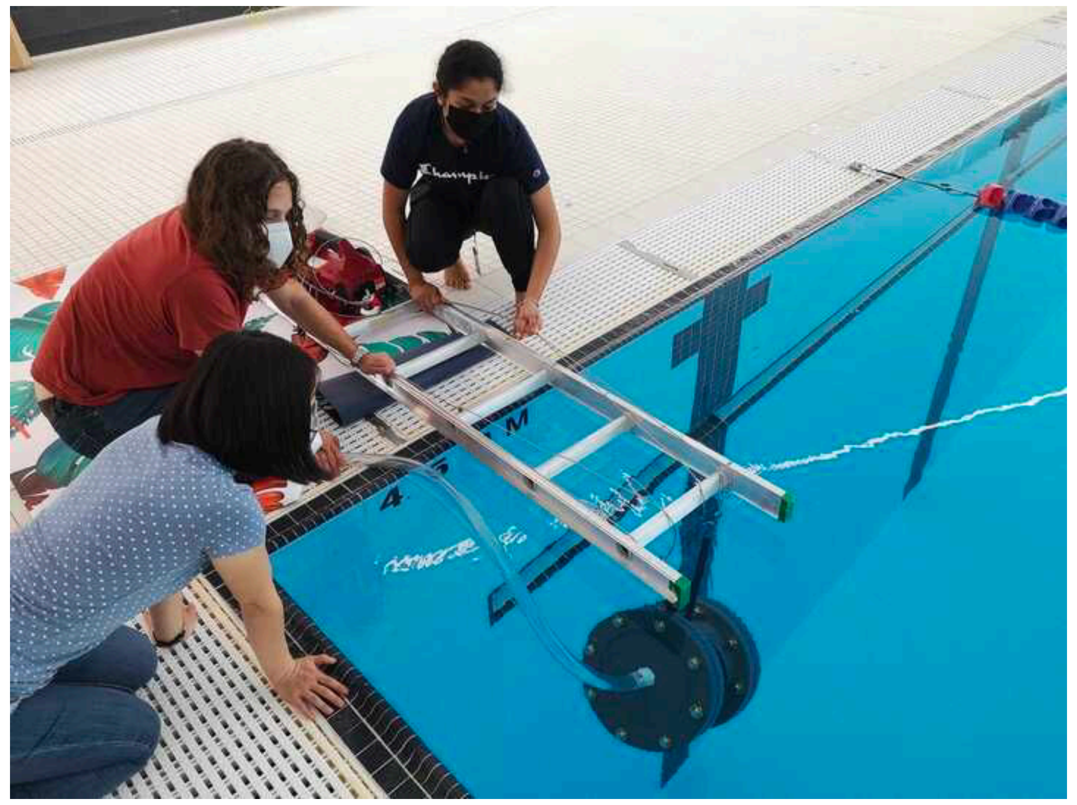
- Imaging of detector to measure calibration source and photosensor positions
- Standard cameras and lenses with custom-built underwater vessels for fixed cameras
- Ongoing tests at the UBC pool to characterize the optics under water
- Prototype readout system has been developed and being tested at U. Winnipeg
- Photogrammetry simulation of detectors under development - choose the best location of cameras in detectors

See talk by R. Gaur at T4-3 New Directions in Accelerator-Based Experiments: Future Experiments - From Collider to neutrinos (PPD)

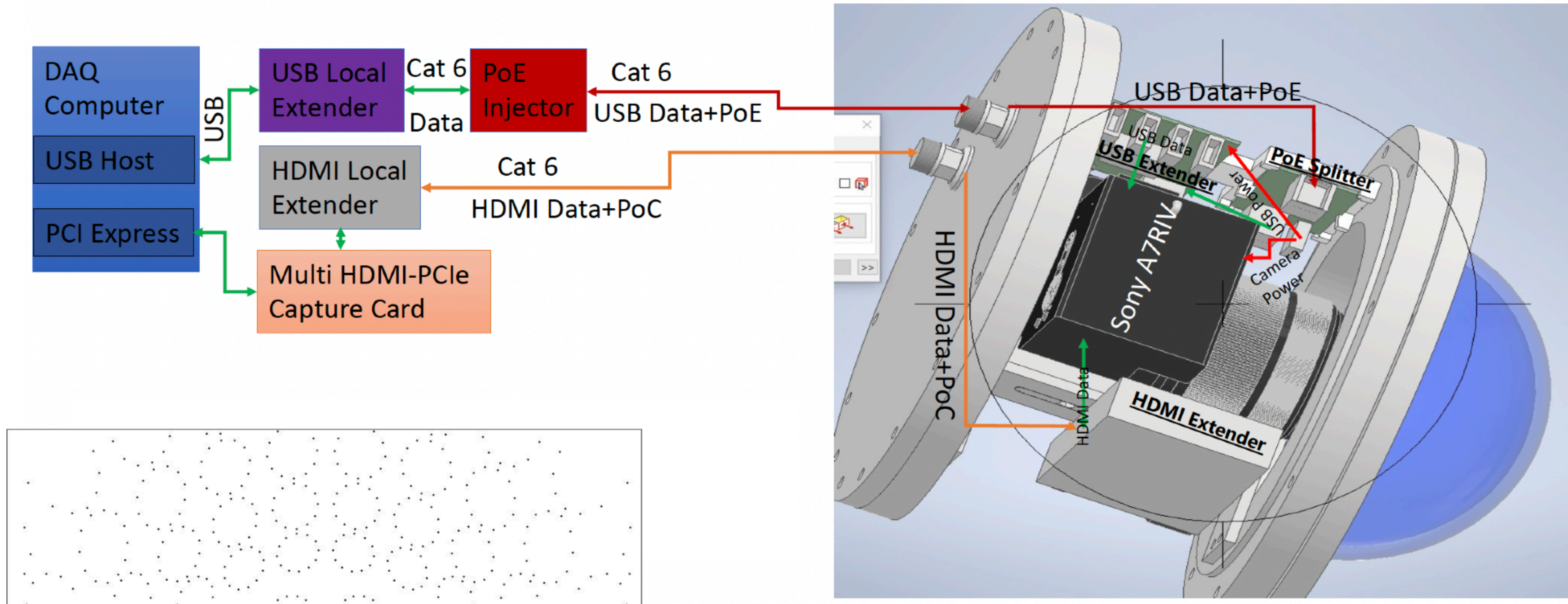
Prototype camera housing

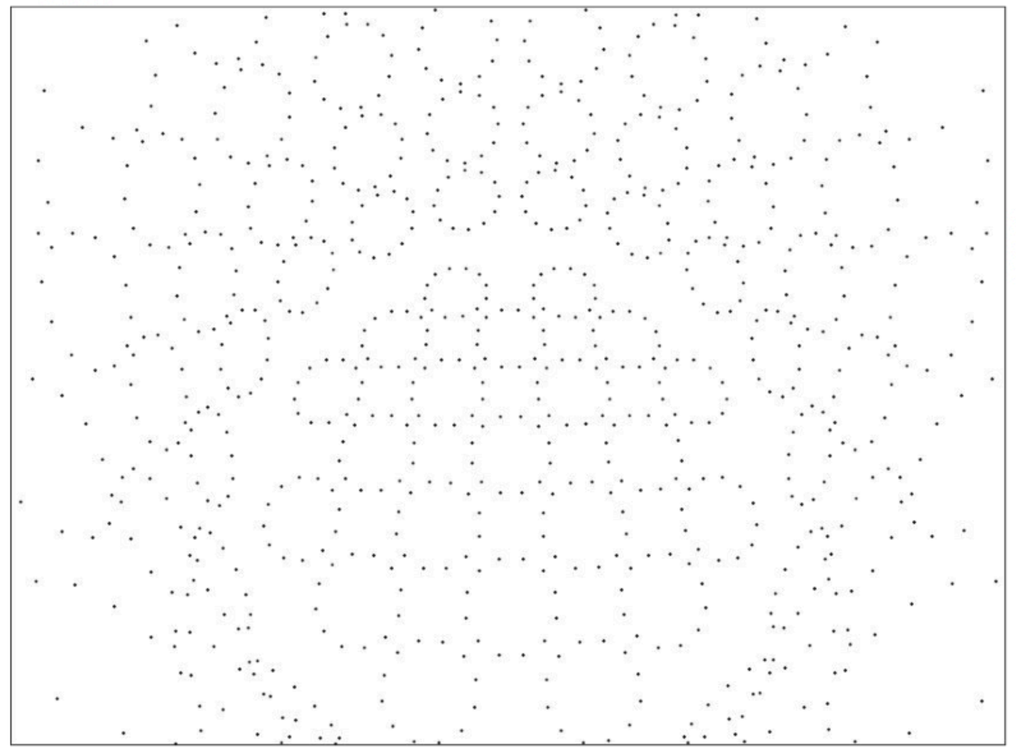


Measurements at UBC Pool



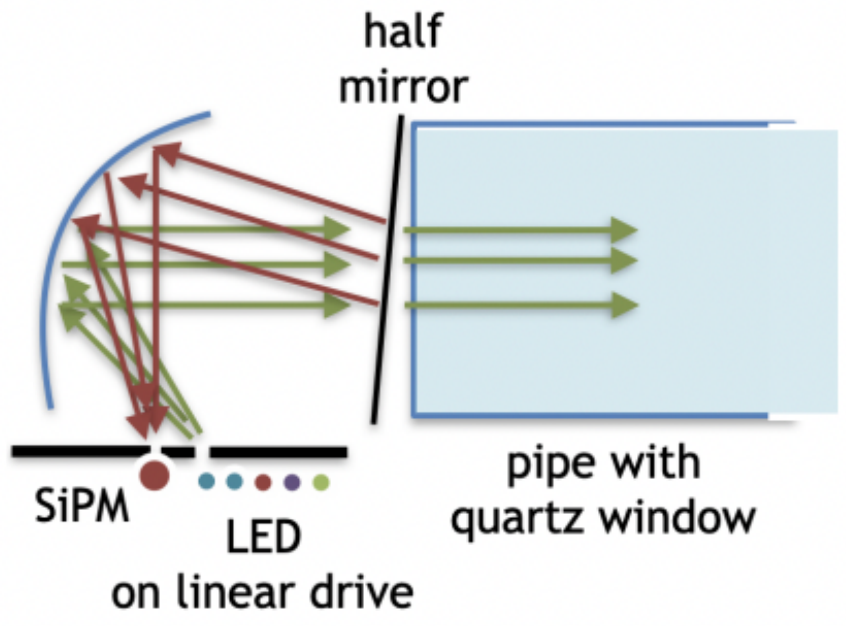
Camera readout (under development)

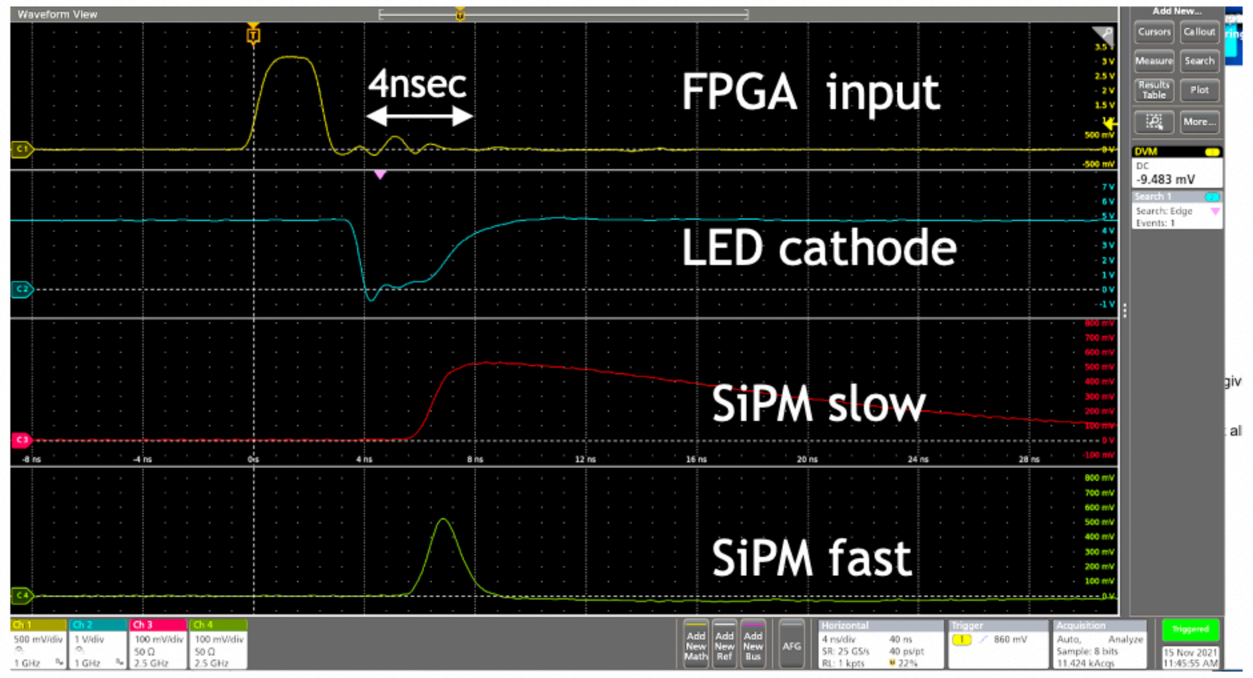




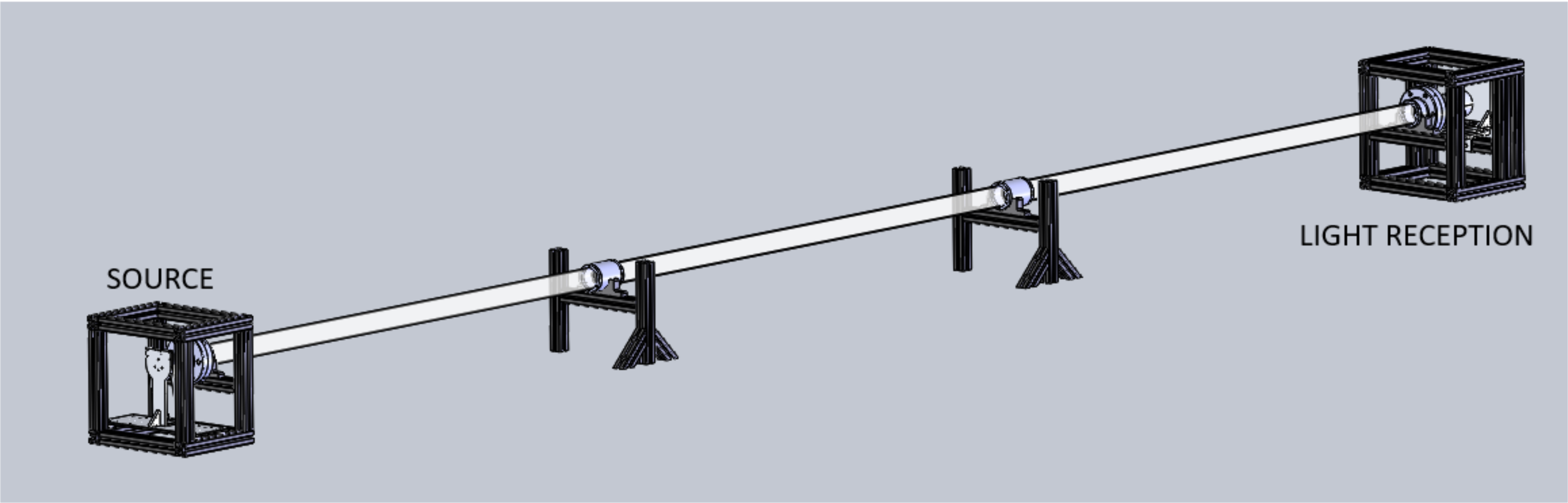
LED beacons from simulation

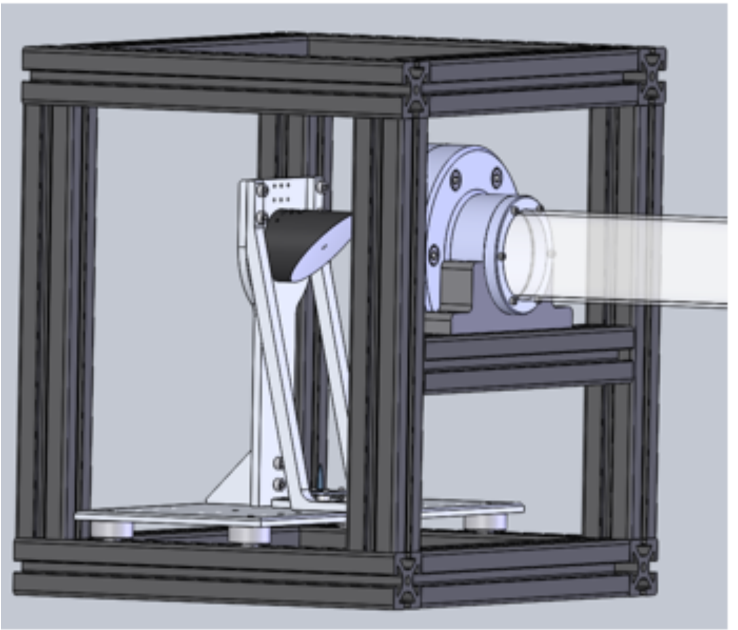
Water Quality Monitoring



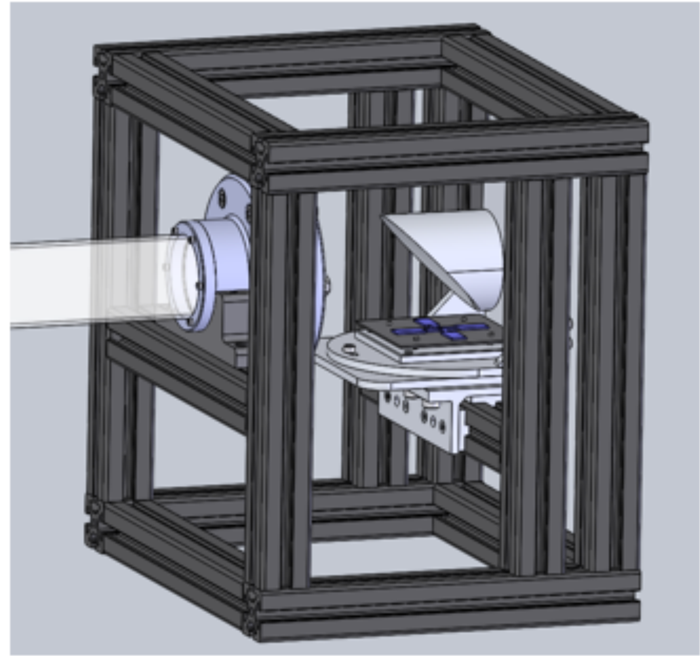


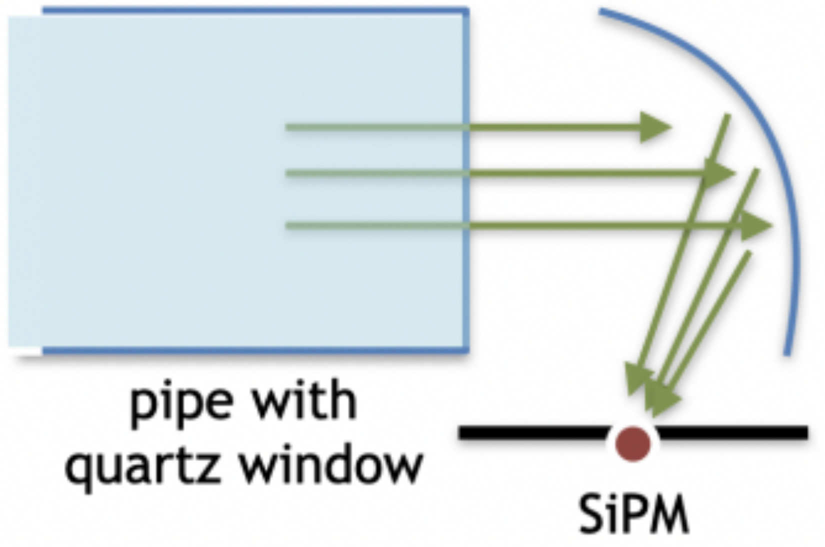
Fast LED

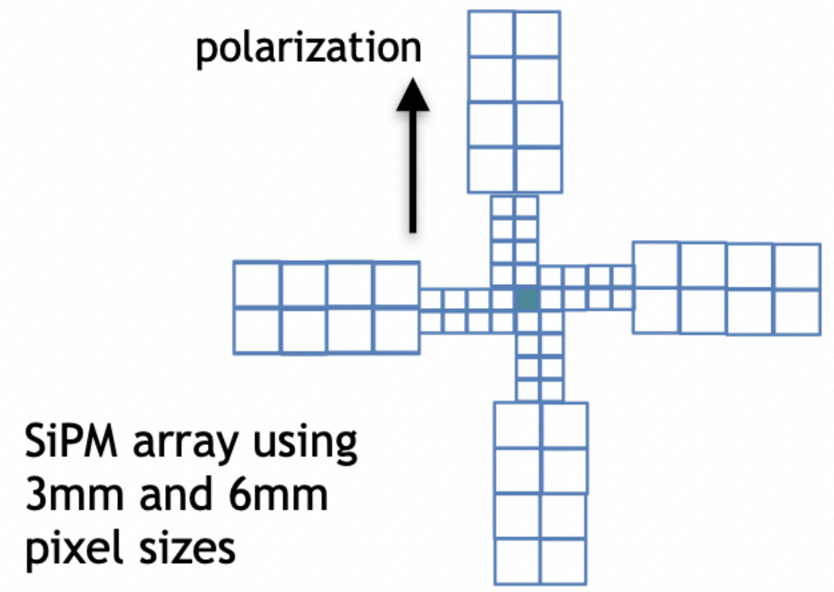




Shorter pipe for scattering measurement







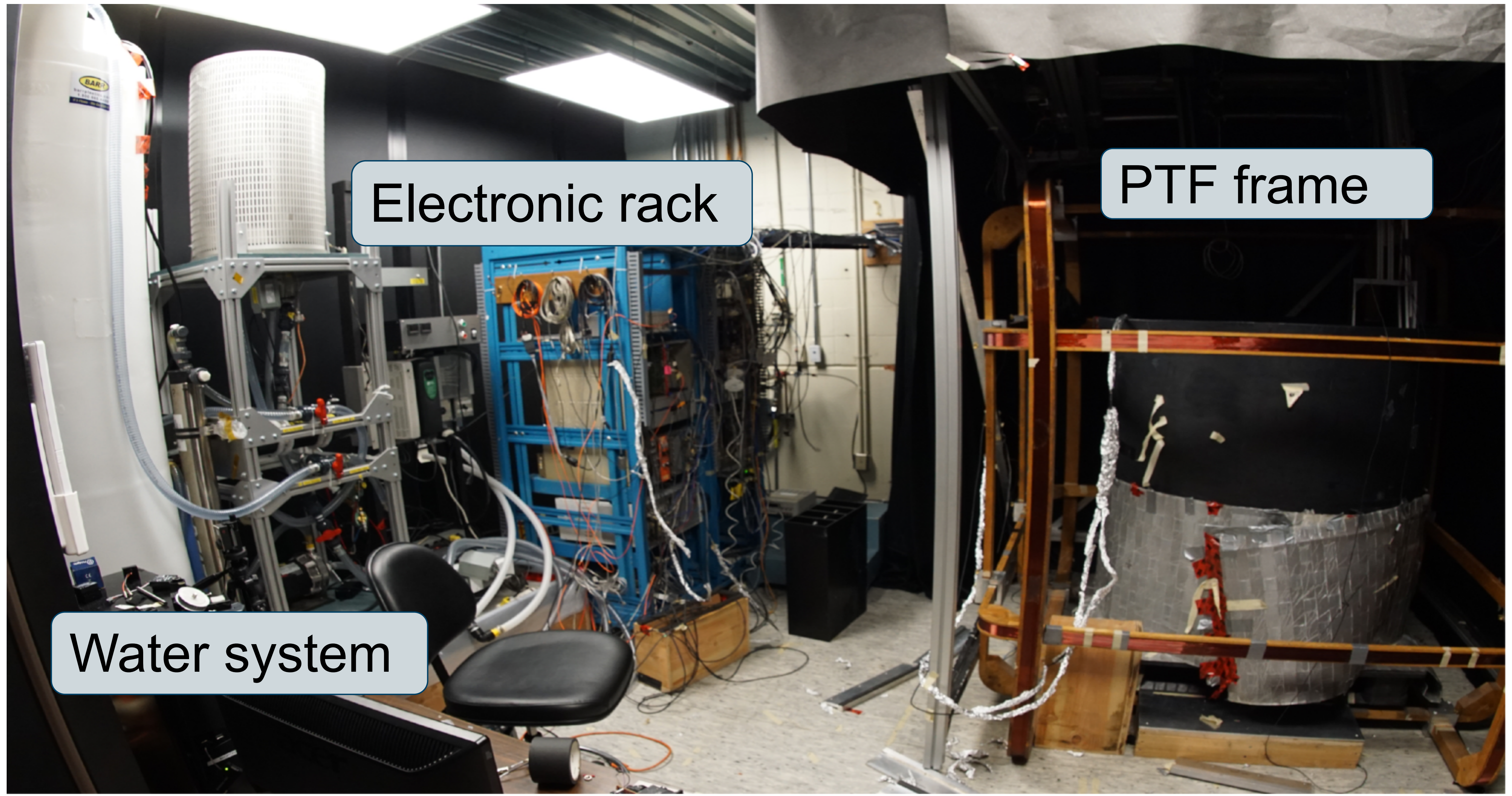
Larger SiPM array for scattering measurement

- Measure light attenuation and scattering in water samples
- Use low-cost sub-ns LED driver being developed at University of Victoria
  - LEDs down to ~270 nm allow for study of Raman Scattering
- Applications for environmental monitoring - NSERC alliance grant working with First Nations University of Canada (FNUniv), Cowessess First Nation, Ahtahkakoop Cree Nation, Weyburn Water Treatment Facility, water treatment engineering faculty at U.Regina

Photosensor Calibration

- Ex-situ measurements of photosensor responses using facility at TRIUMF
- Light source can be scanned along PMT photocathode
- Measurements in air and water
- Magnetic field direction and magnitude can be varied
- Measurements of Super-K 20-inch PMTs show where improvements can be made to PMT model

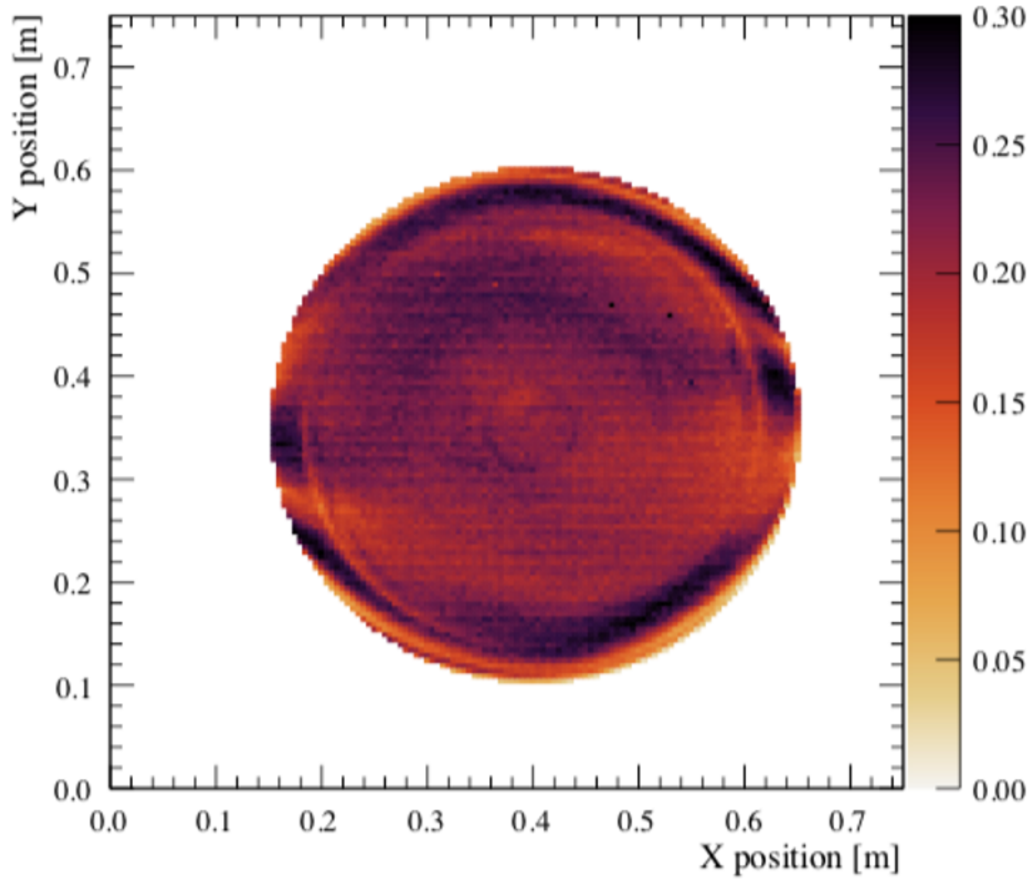
See talk by V. Gousy-Leblanc at W2-6 Neutrino Experiment and Related Calibrations II (PPD)


Electronic rack

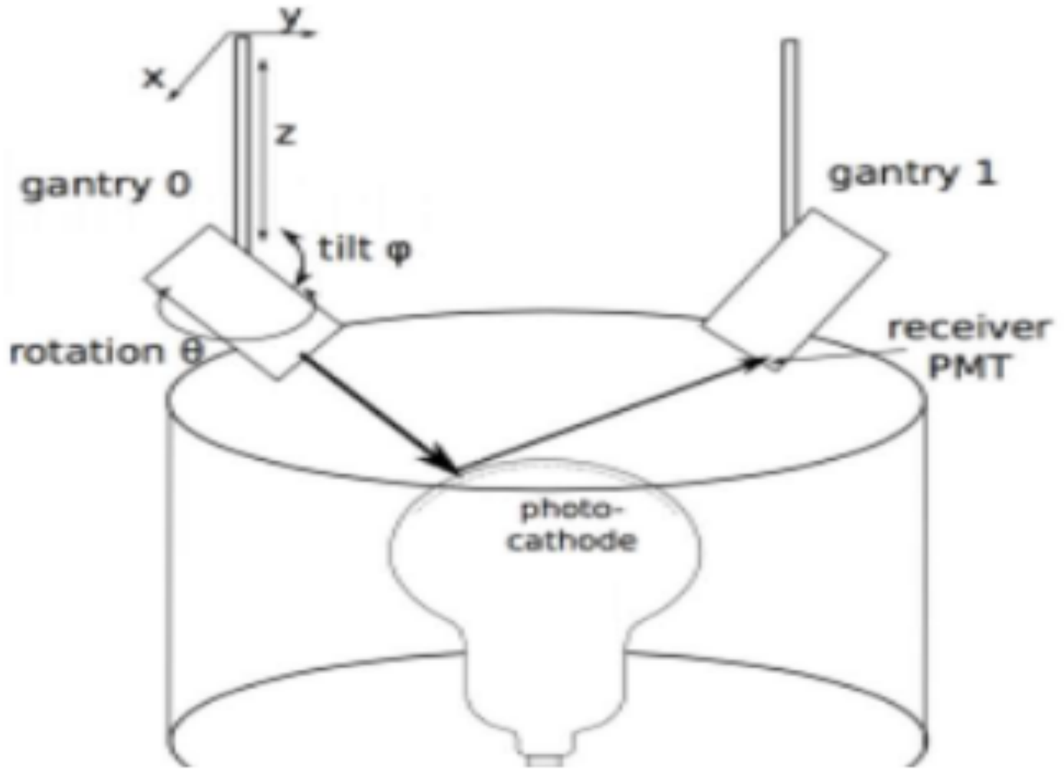
PTF frame

Water system

PTF measurements



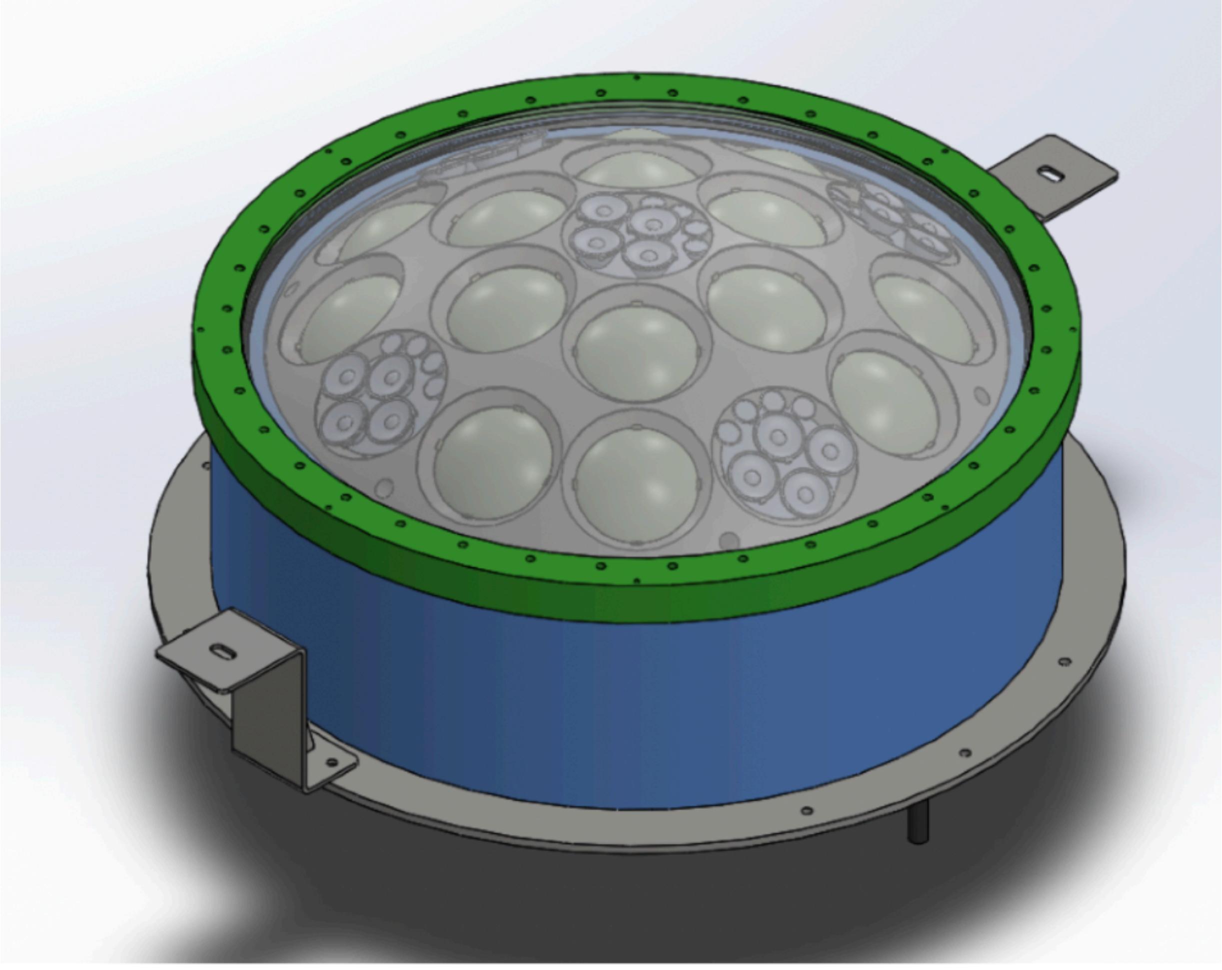
PTF Geometry



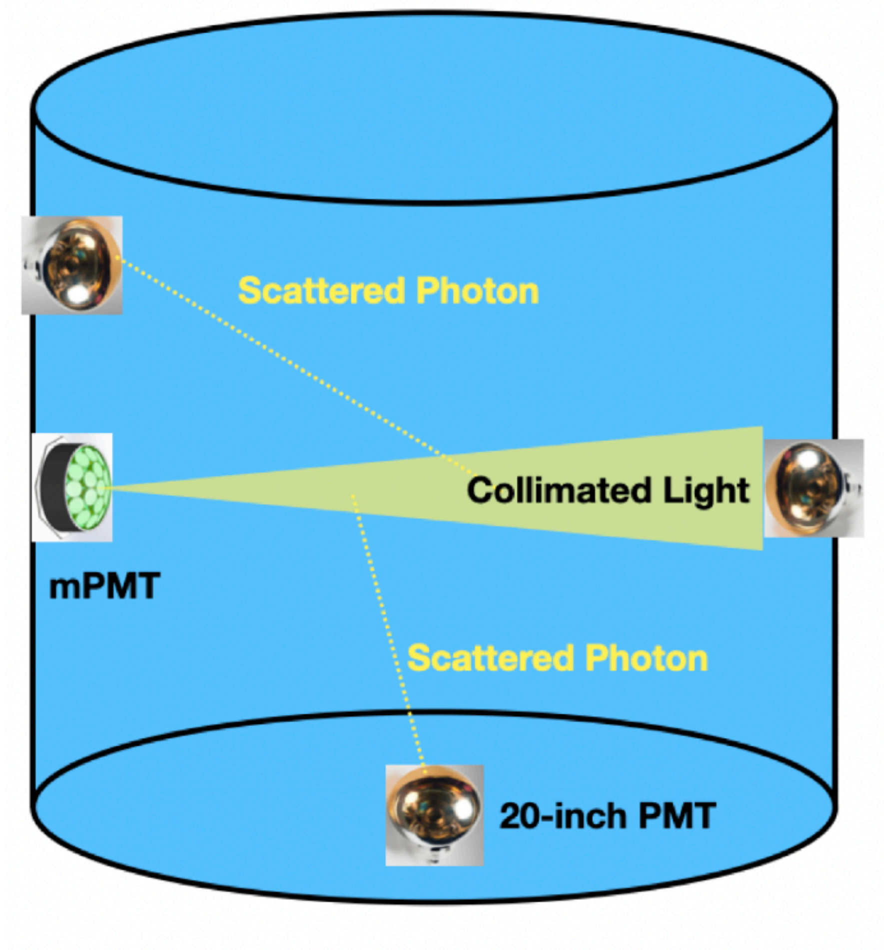
Multi-PMT for Hyper-K Detector

- Replace 5 PMTs with LED light injector boards
- Collimated light with varying wavelengths, including UV to study Raman scattering
  - 278nm - Raman scattering
  - 365nm - Peak Cherenkov intensity
  - 415nm - Peak quantum efficiency
  - 470nm - Tail of light distribution
- Sub-ns LED driver+sub-ns PMT resolution+collimated light = reconstruction of scattering position
- Diffuse light used to characterize in-situ angular response of 20-inch PMTs
  - Large 20-inch PMTs are sensitive to residual magnetic field
  - Nearby multi-PMTs provide relative normalization

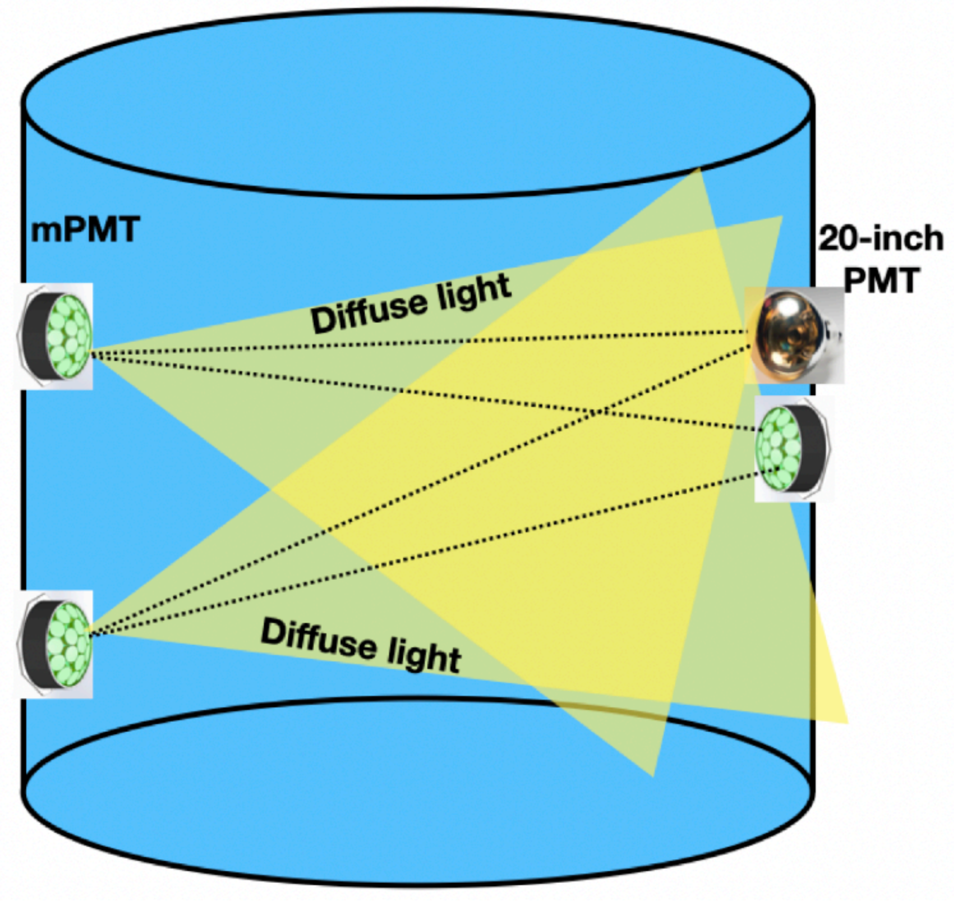
Hyper-K mPMT Design



Collimated light



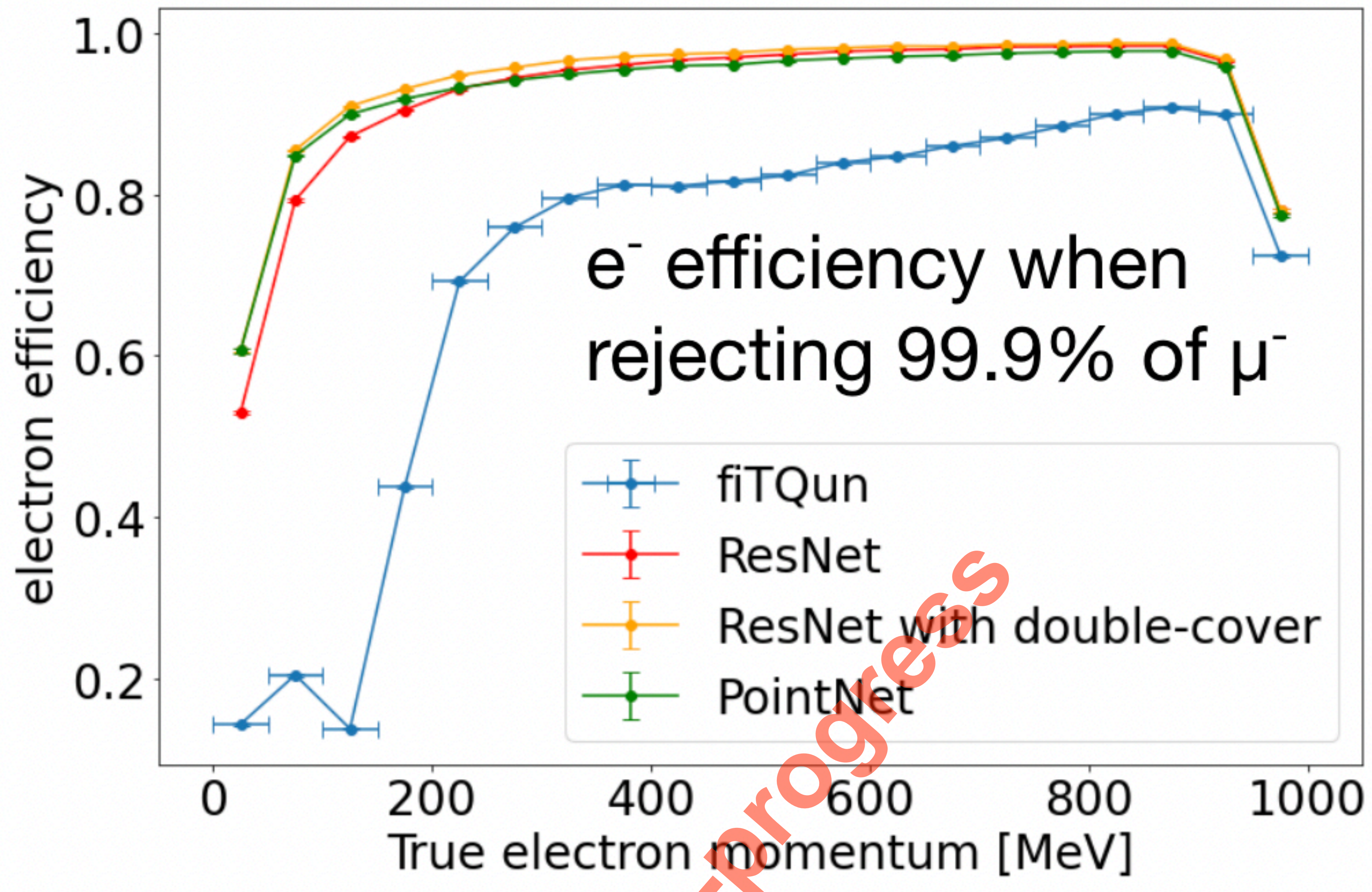
Diffuse light

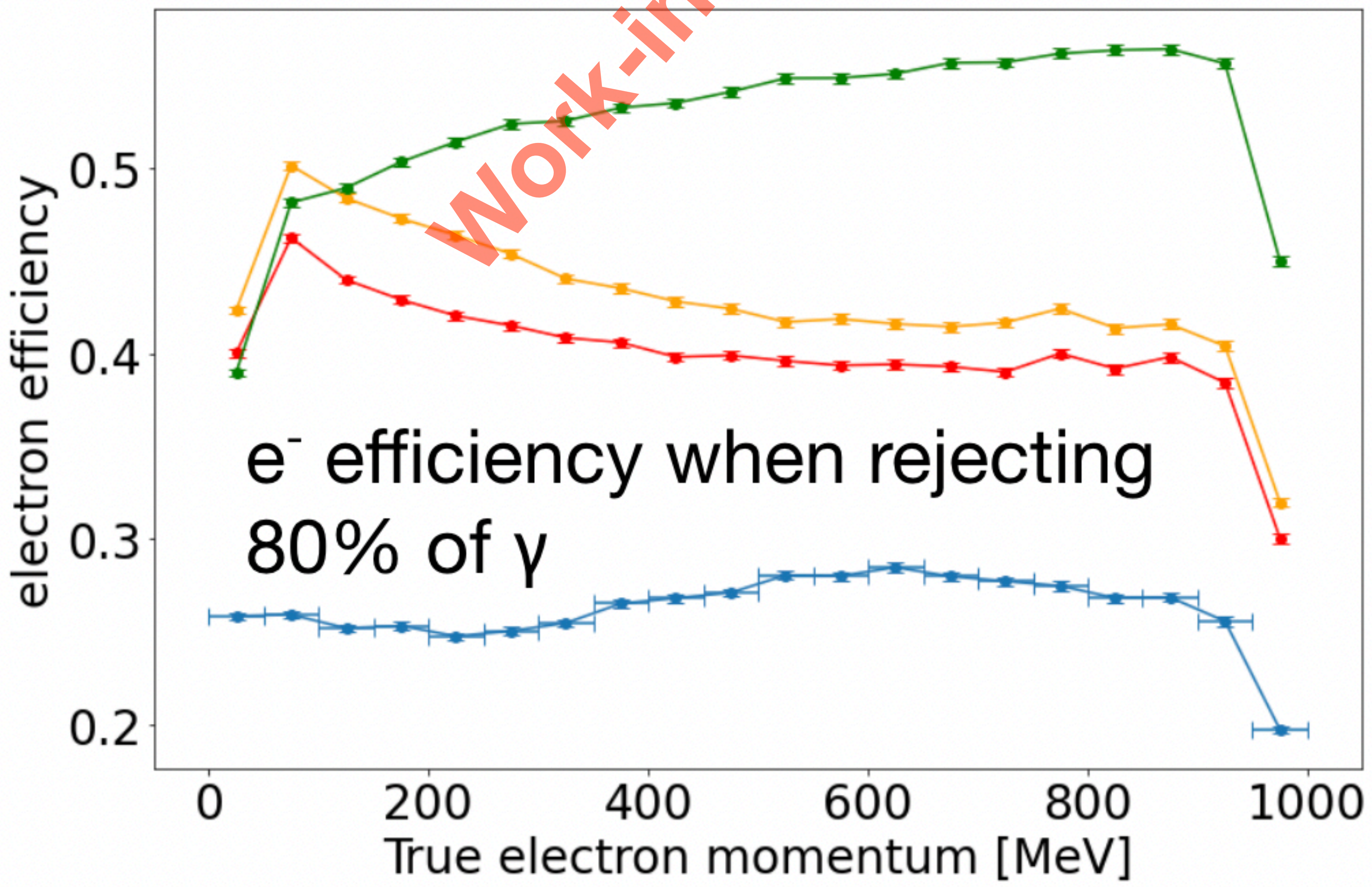


Machine Learning Event Reconstruction

- Machine learning plays a key role in analysis strategy:
  - Use all of the information provided by fine resolution measurements of mPMTs in IWCD
  - Very fast event reconstruction allows for quick study of systematic parameter variation in detector calibration
- WatchMal group started by Hyper-K Canada leads studies of machine learning applications for water Cherenkov detectors across the globe
- Generally seeing significant improvements in areas such as classification compared to the likelihood-based fiTQun reconstruction

See talk by N. Prouse at W2-1 Machine Learning in HEP and Novel Reconstruction Tools (PPD)

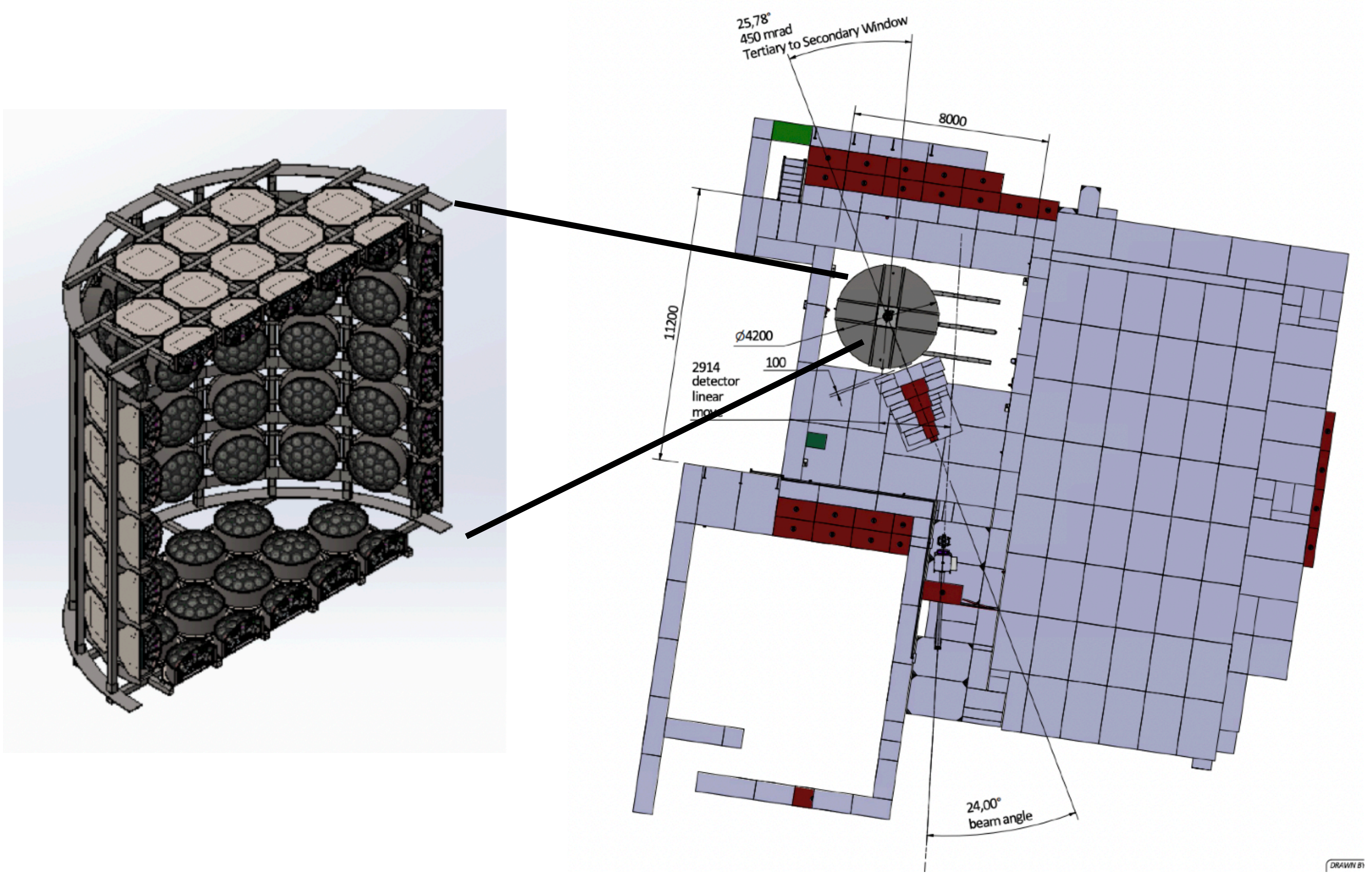

e^- efficiency when rejecting 99.9% of μ^-


e^- efficiency when rejecting 80% of γ

Test Experiment at CERN

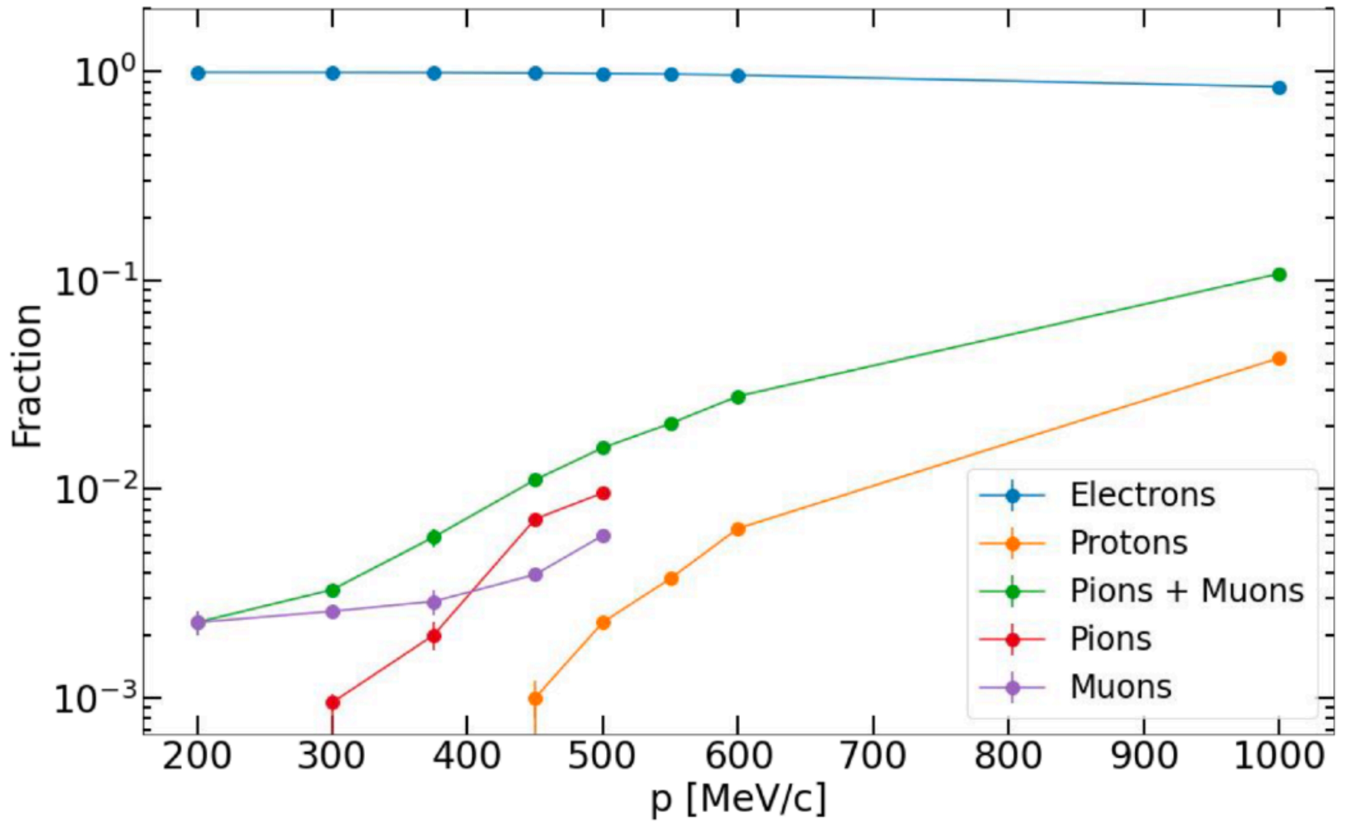
- Operation of IWCD prototype called WCTE in CERN test beam (T9) in 2024
- Study detector calibration and response with known particle fluxes of 0.2-1.1 GeV/c π, p, e, μ
- Beam test data in 2022 to determine if secondary particle fluxes at low momenta are sufficient
  - Test muon/pion separation with Aerogel Cherenkov Threshold detector (ACT)
  - More data collection in low momentum beam configuration in July
- Have received recommendation from the CERN SPSC and Research Board Approval

CERN-SPSC-2020-005; SPSC-P-365: http://cds.cern.ch/record/2712416?ln=en



ACT Detector

Initial Beam Composition Measurement



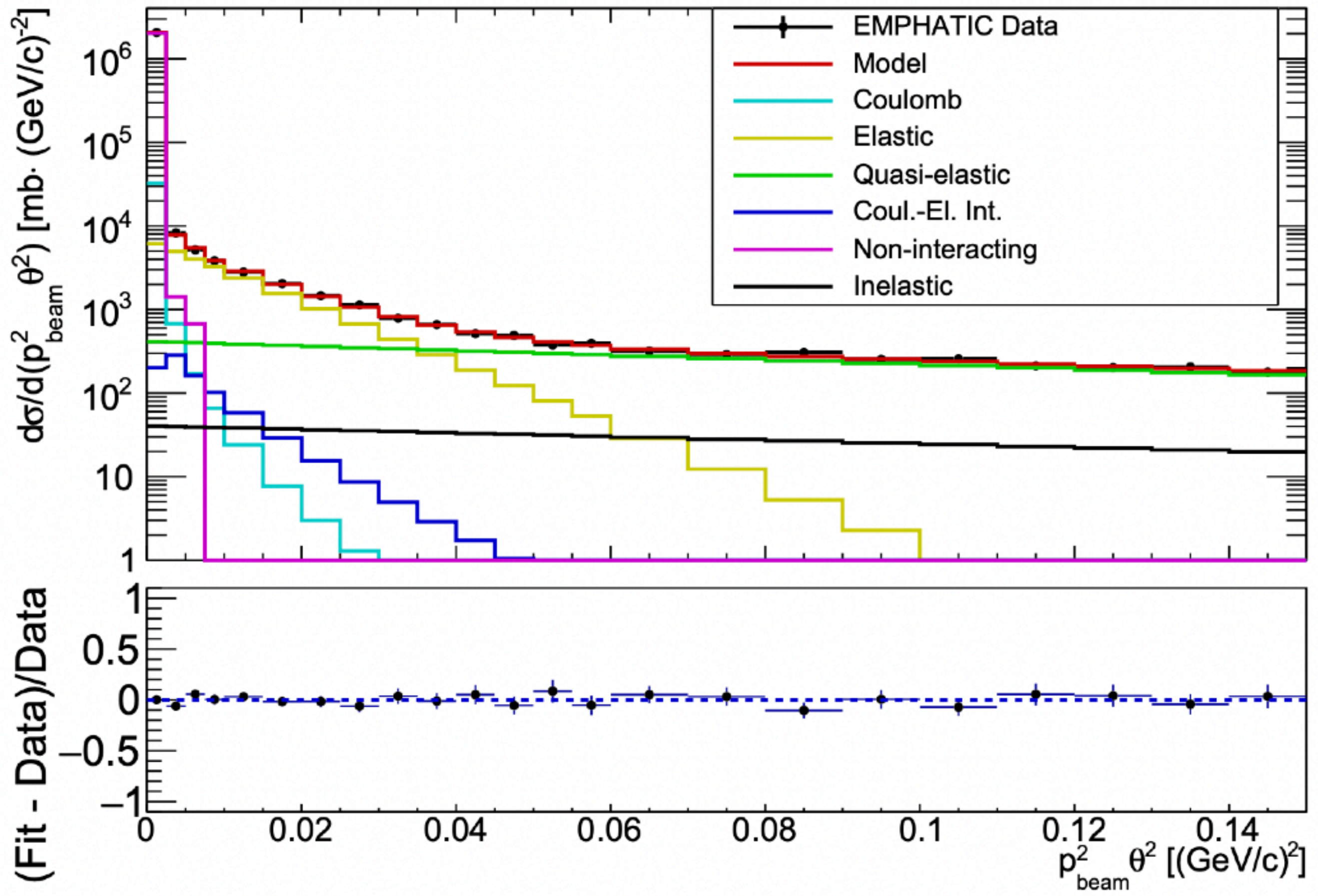
EMPHATIC

- Collaboration on EMPHATIC hadron production experiment at Fermilab
- Pilot run in 2018 to measure p+C forward scattering
    - Analysis led by postdoc M. Pavin, submitted to PRC (arXiv:2106.15723)
- Initial Phase-1 operation in January, but Canada could not participate due to COVID situation
- Second Phase-1 run in June with Canadian Aerogel Ring Imaging Cherenkov (ARICH) detector for PID

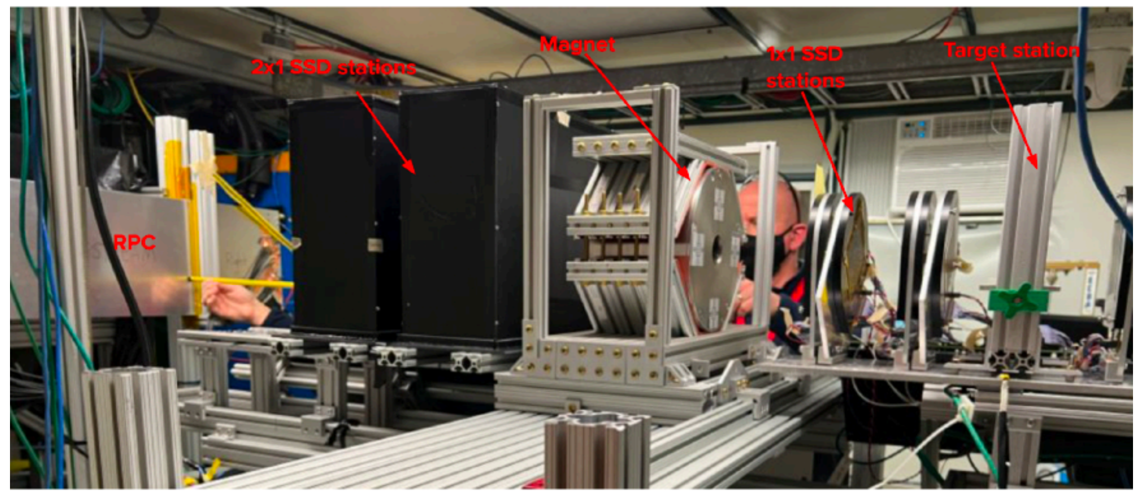
See Poster by B. Ferrazzi (G*) (POS-32) A mirror study in an ARICH detector for a hadron production experiment

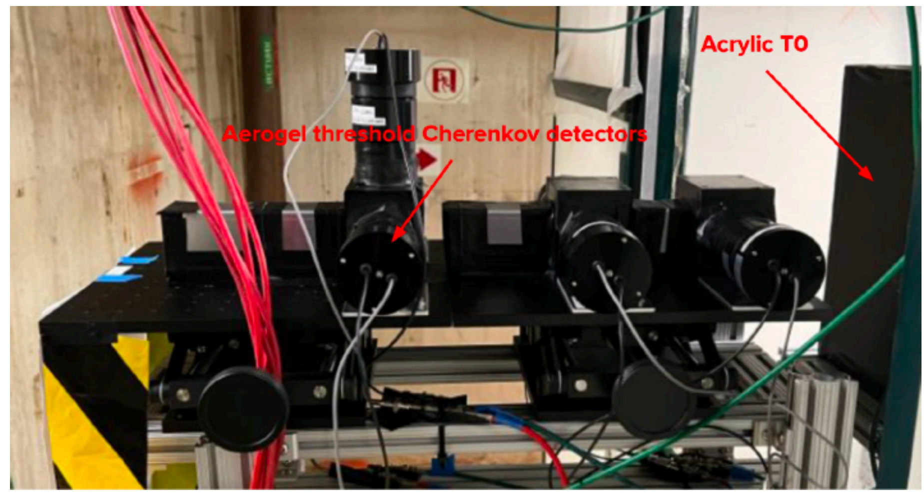
TRIUMF University of Regina THE UNIVERSITY OF WINNIPEG YORK UNIVERSITÉ UNIVERSITY

Model fit to forward scattering data

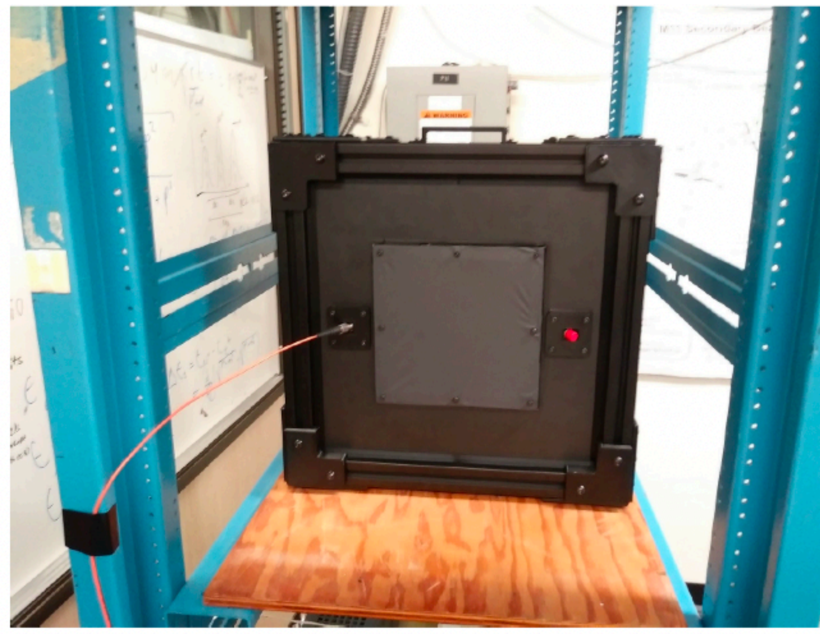


Phase-1 Experimental Configuration





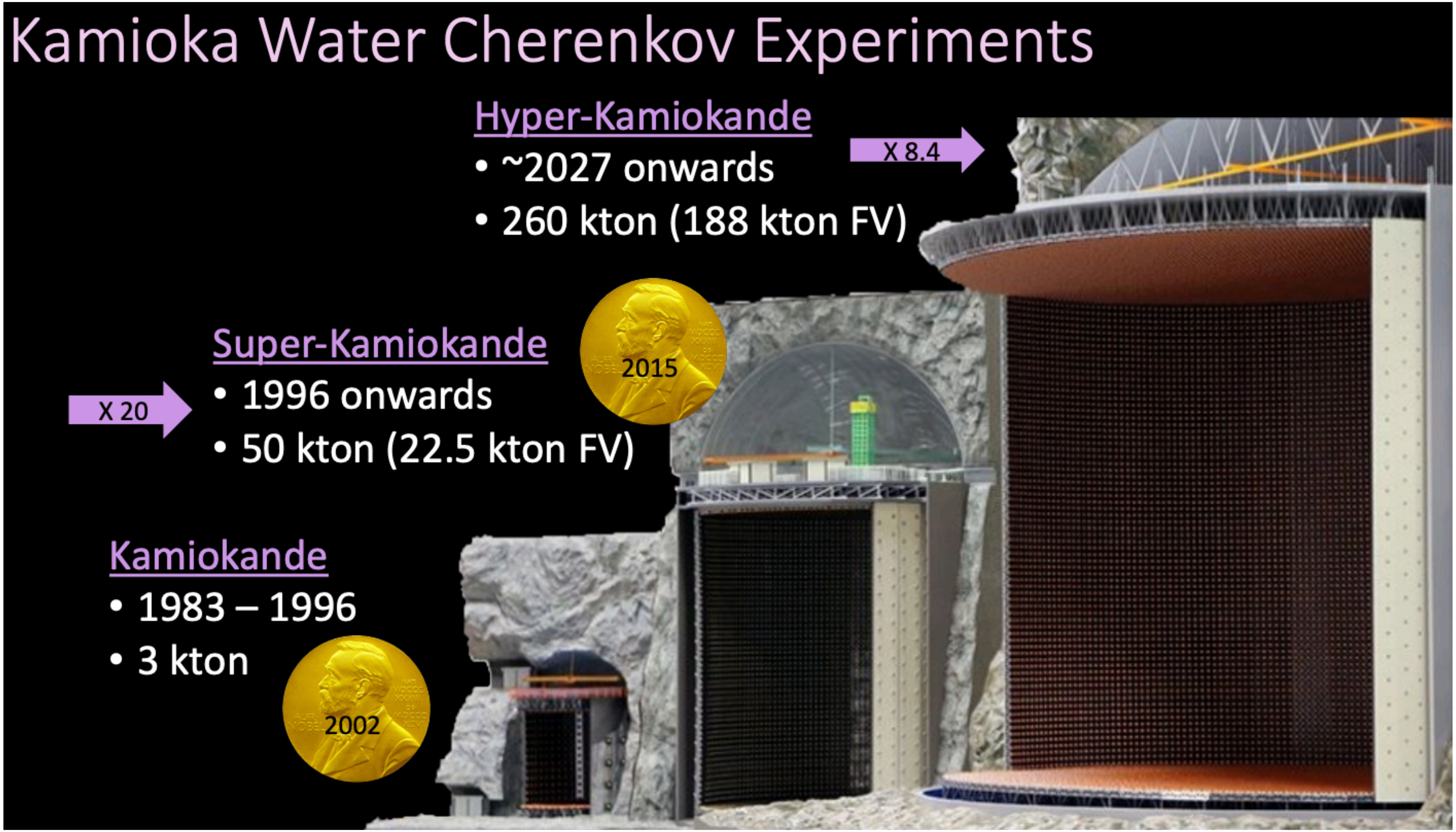
ARICH detector



Summary

- T2K has produced world-leading neutrino oscillation measurements
- The Hyper-Kamiokande experiment will allow us to probe neutrino properties with unprecedented precision amongst a broad physics program
- Construction of the experiment is proceeding on schedule in Japan. Start of detector cavity excavation soon!
- Canada is focussed on contributions to Hyper-K in order to meet the requirements for systematic uncertainty reduction
- Many areas of development in Canada to realize multi-PMT, photogrammetry calibration, water quality monitoring systems
- Exciting time for the Hyper-K project in Canada and overall. We are always looking for opportunities to grow the effort in Canada.

Thank you



Kamioka Water Cherenkov Experiments

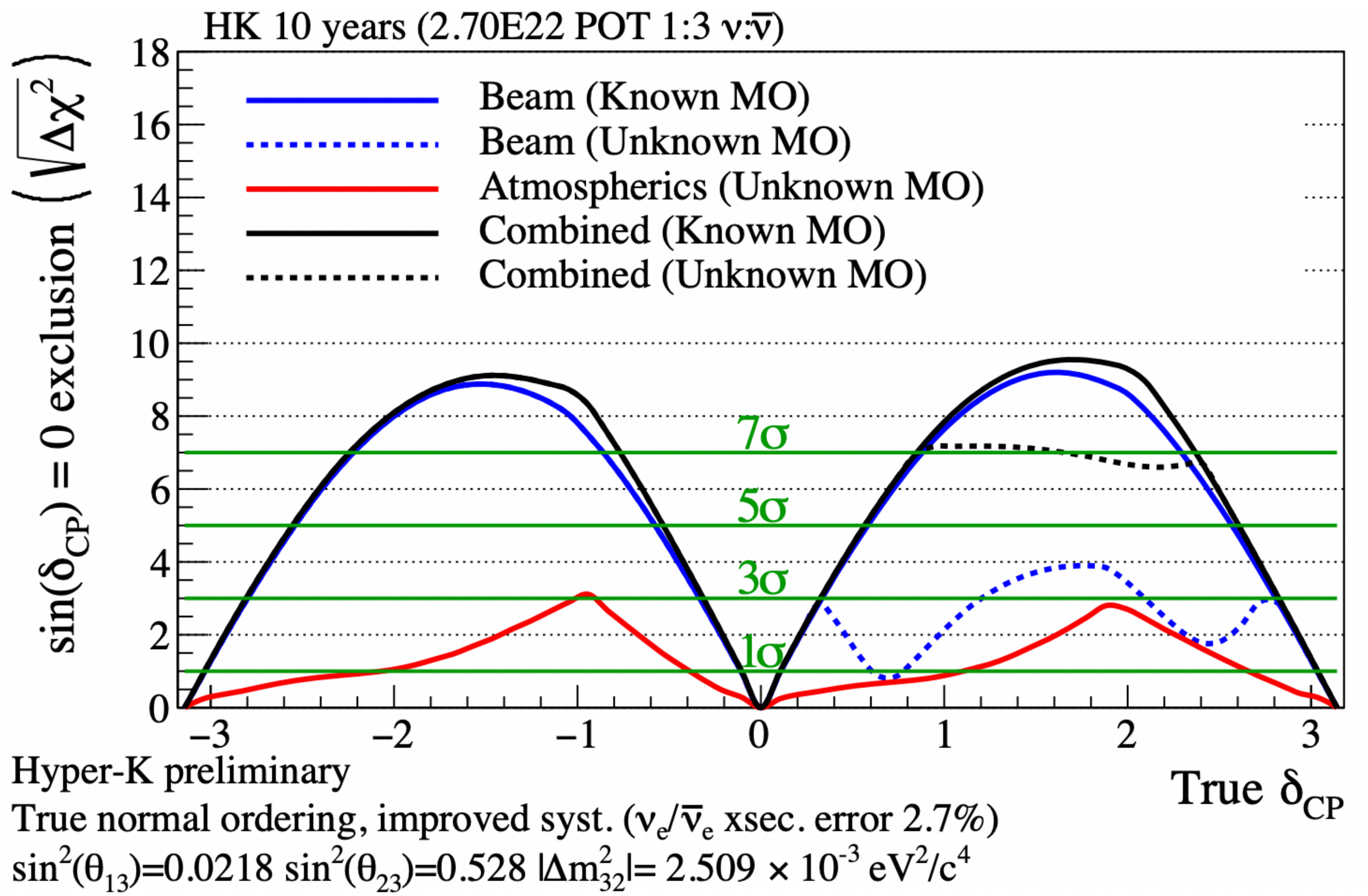
Hyper-Kamiokande
- ~2027 onwards
- 260 kton (188 kton FV)

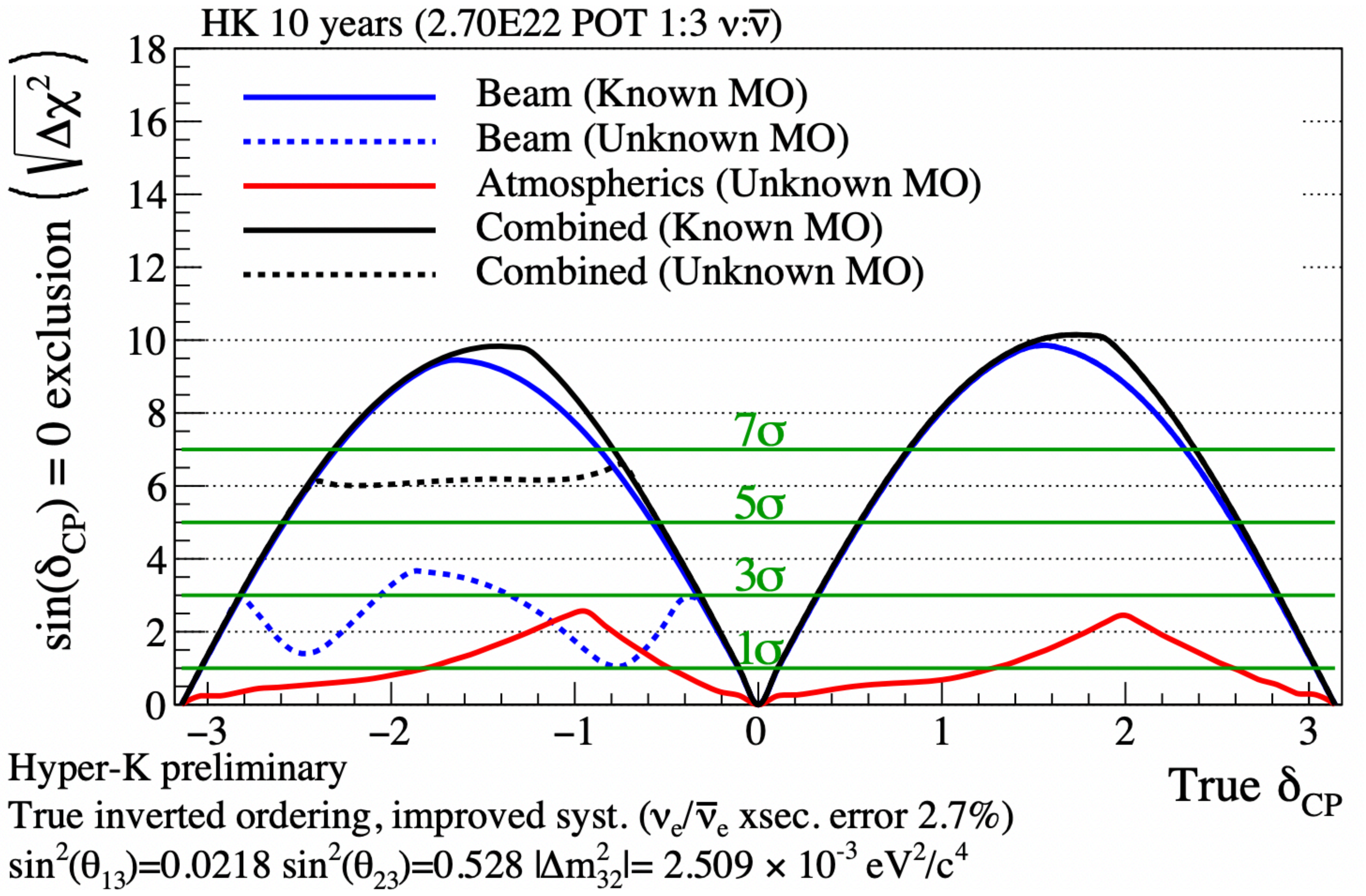
Super-Kamiokande
- 1996 onwards
- 50 kton (22.5 kton FV)

Kamiokande
- 1983 – 1996
- 3 kton

Backup Slides

Atmospheric Neutrinos





- If mass ordering is not determined before HK, HK will have sensitivity by including atmospheric neutrinos in the analysis
- Can maintain 5σ and 3σ sensitivity to CP violation discovery
  - Combination of accelerator and atmospheric gives slightly improved sensitivity, even if MO is unknown

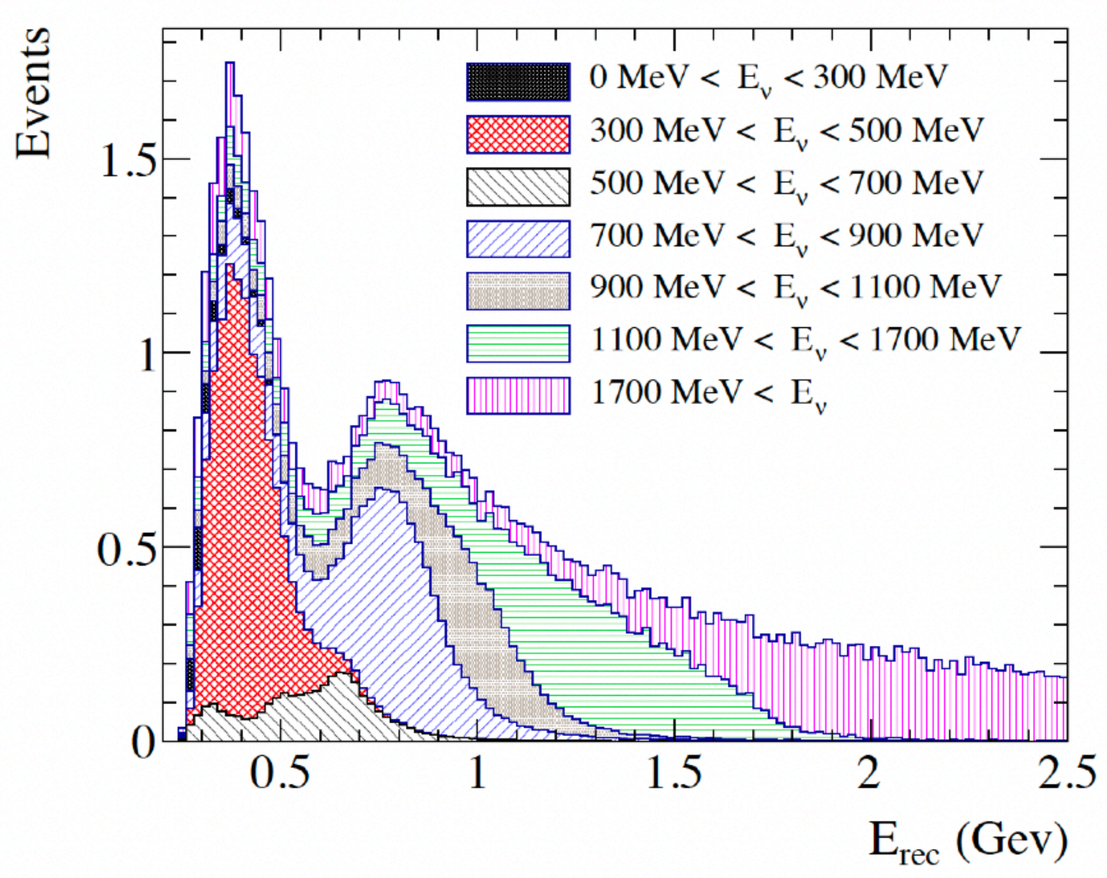
Role of Near(Intermediate) Detectors

- Near detectors measure the neutrino rate/spectrum of neutrino production and properties of neutrino interactions
- Systematic errors don't cancel perfectly in the near-to-far extrapolation due to differences in the neutrino spectrum/flavour
- Important sources of systematic error:

Detect electron (anti)neutrinos at far detector. Uncertainty on the relative interaction cross section must be controlled

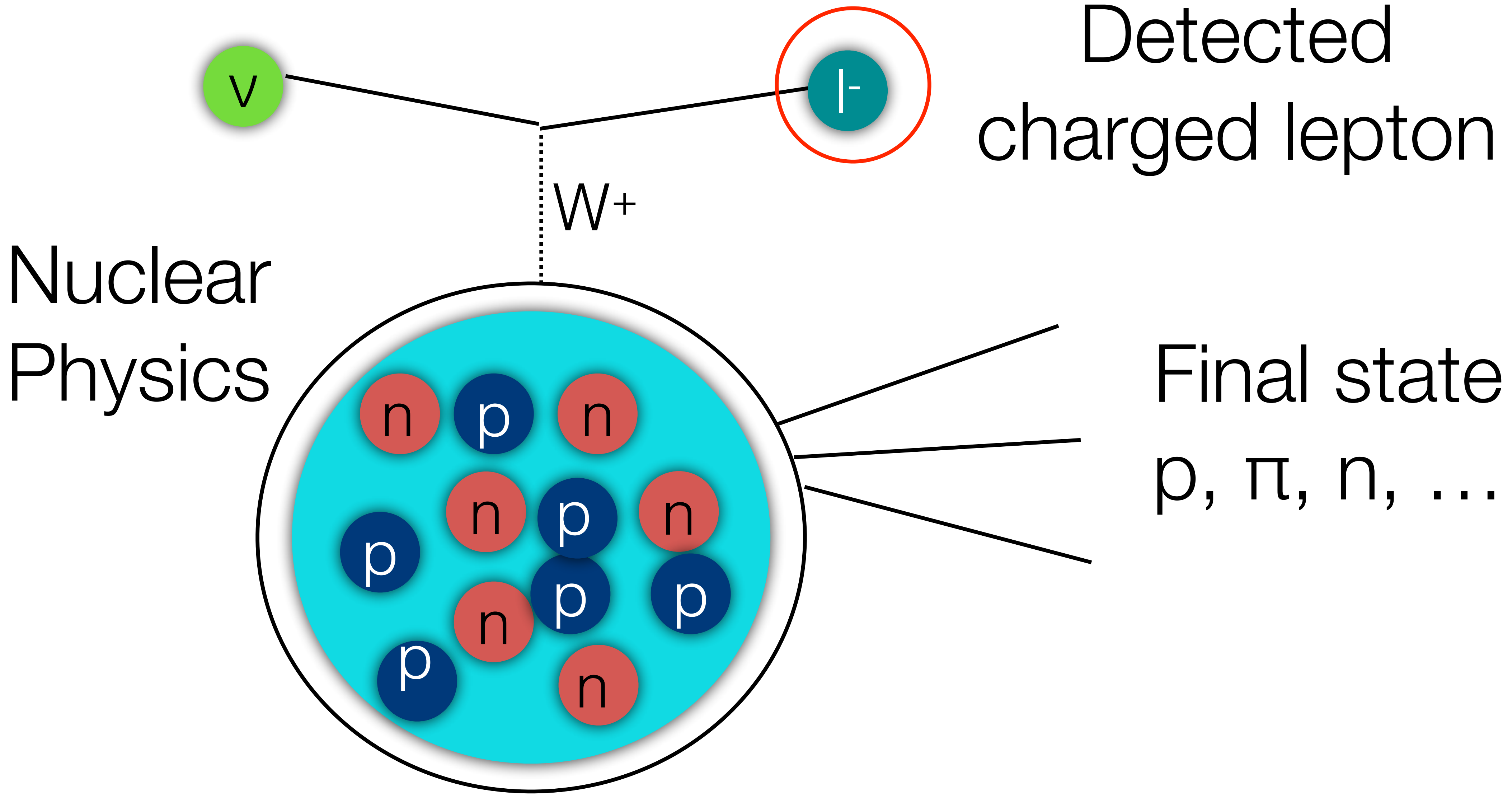
$$\frac{\sigma(\nu_e)/\sigma(\nu_\mu)}{\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)}$$

Must accurately model resolution function for energy reconstruction, including nuclear effects in neutrino-nucleus scattering.



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

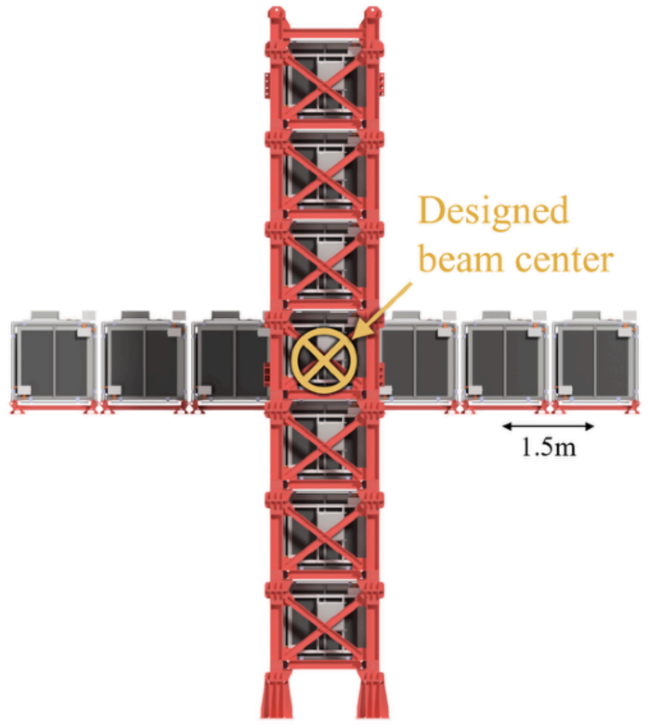


Detected charged lepton

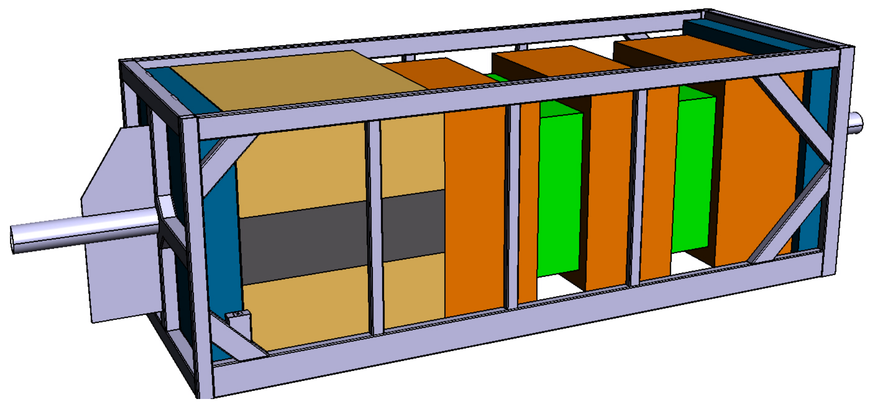
Nuclear Physics

Final state p, π, n, …

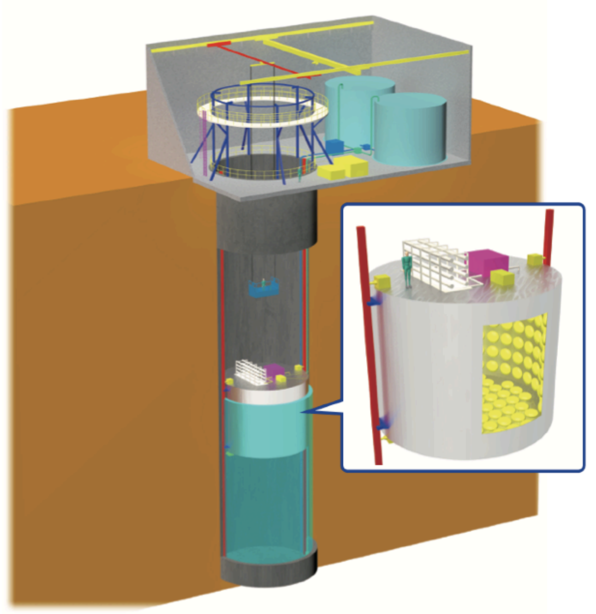
INGRID



Ugraded ND280



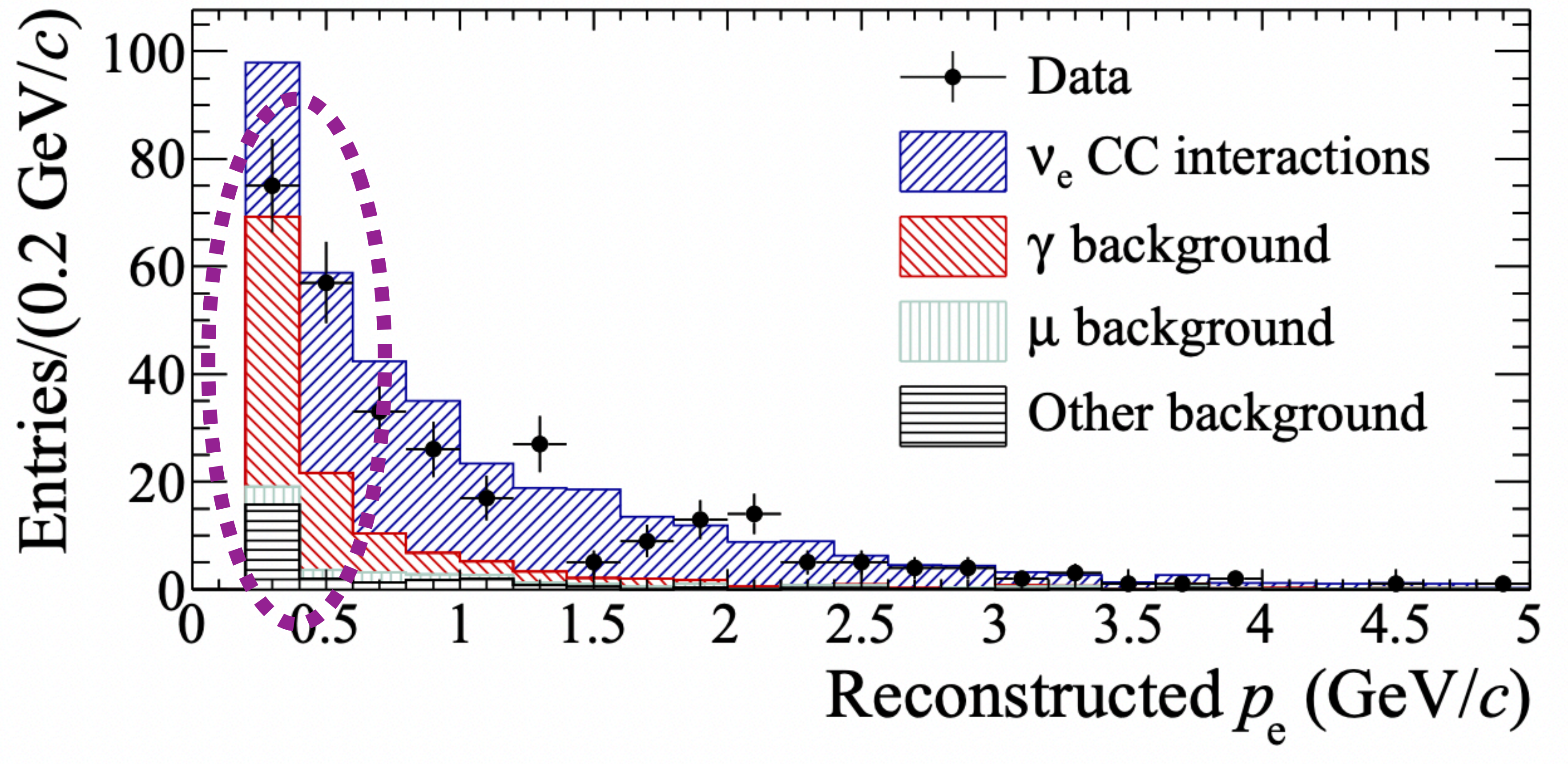
Intermediate Water Cherenkov Detector (IWCD)



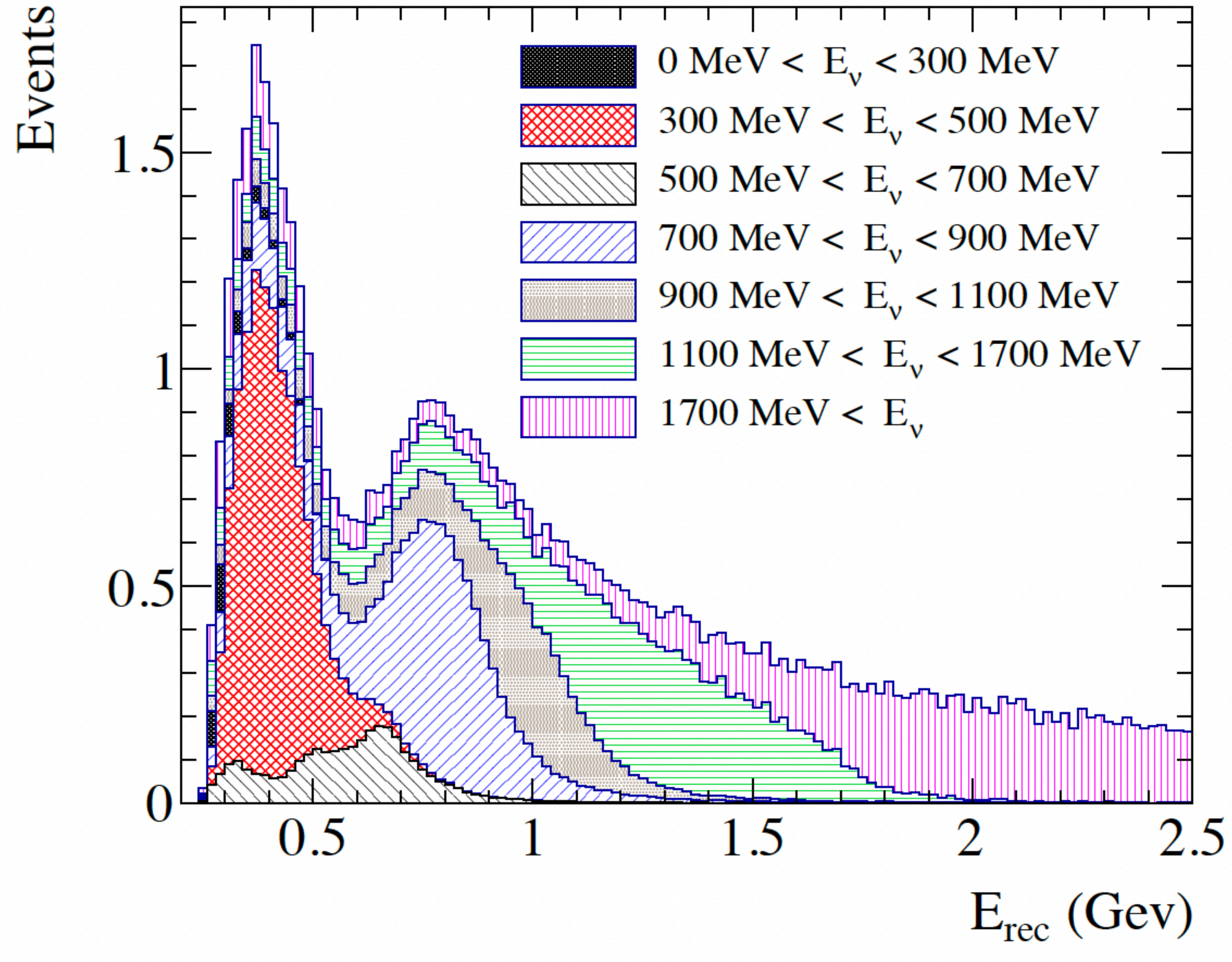
Challenges to Overcome

- 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

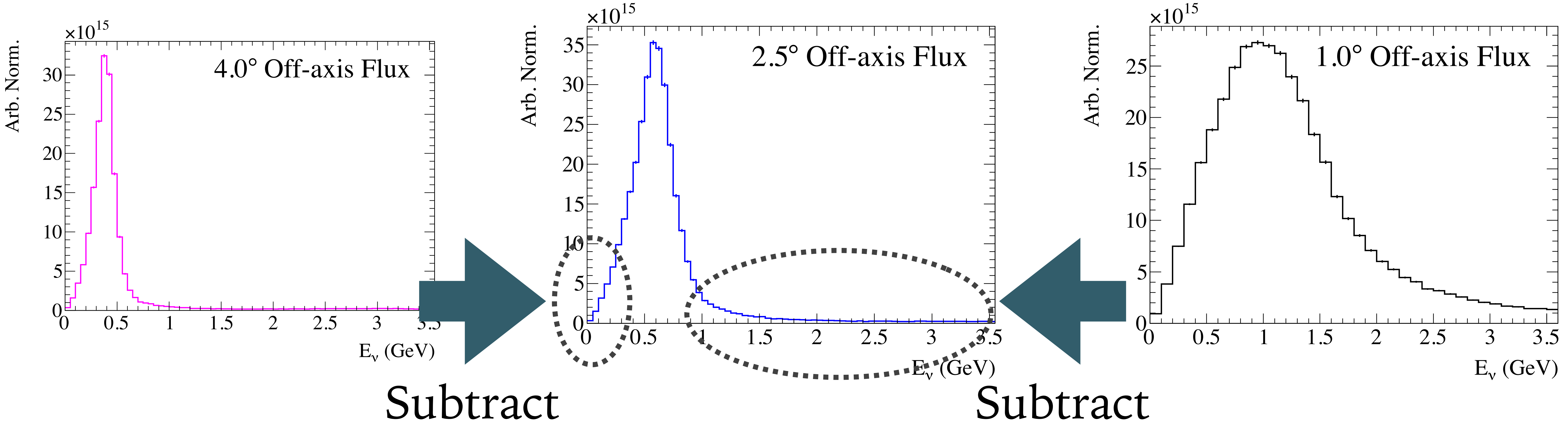
T2K: Phys. Rev. Lett. 113, 241803 (2014)



- **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



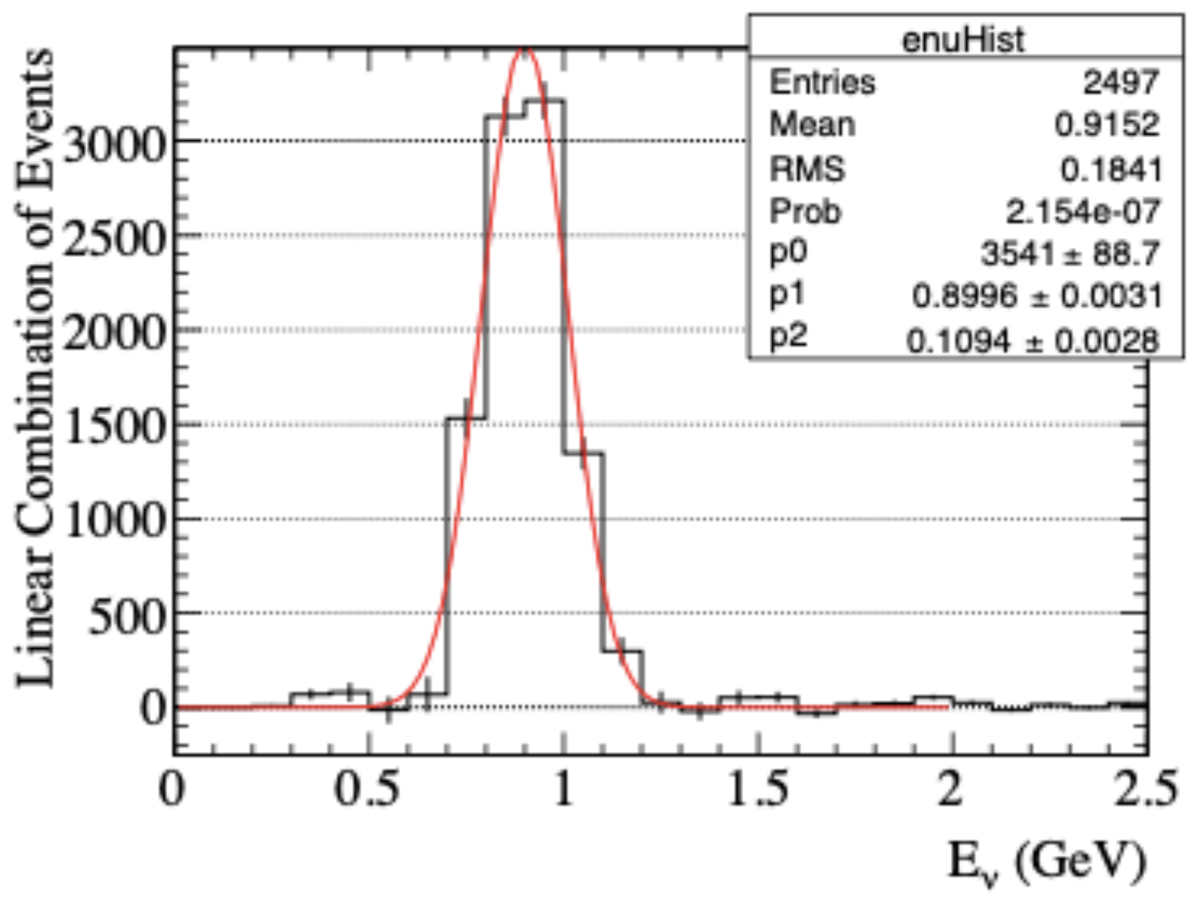
NuPRISM Concept

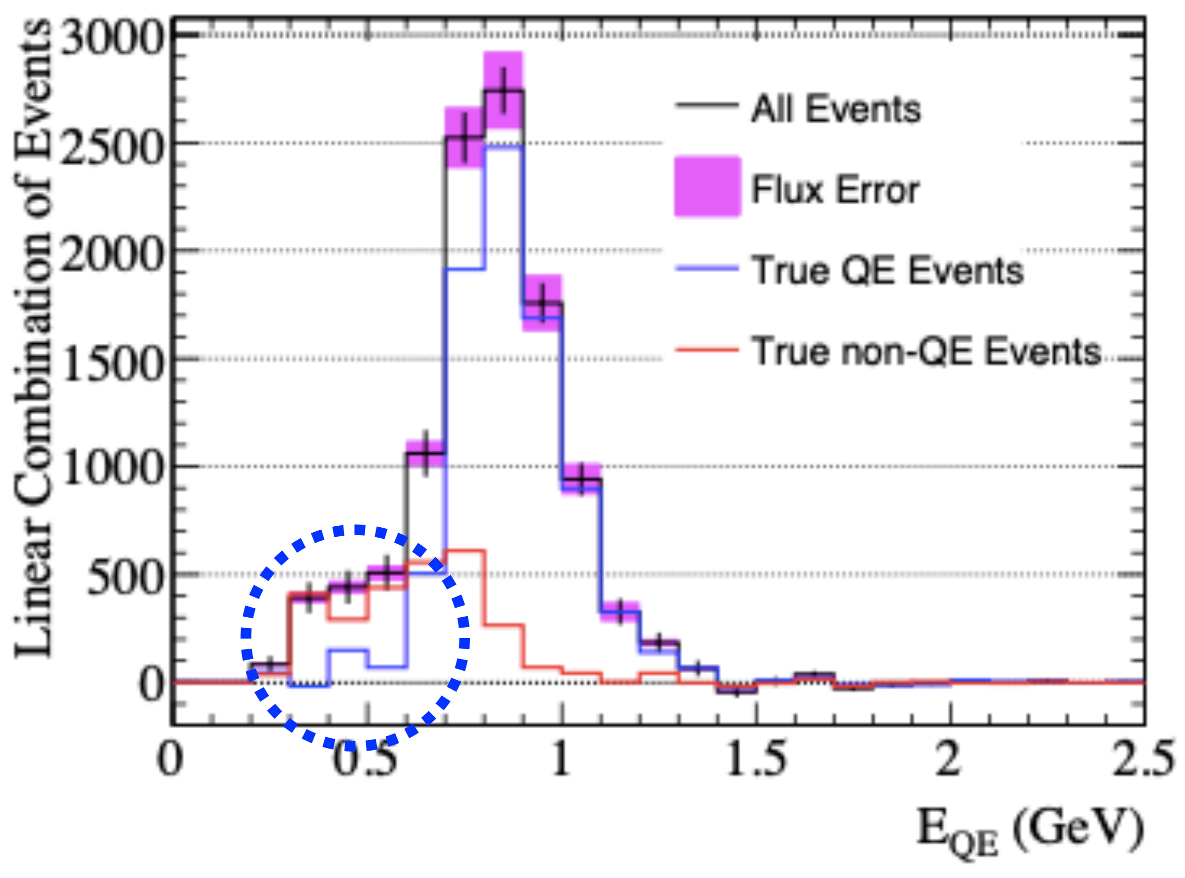


Due to pion decay properties, neutrino spectrum varies with off-axis angle

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

Obtain very narrow spectrum



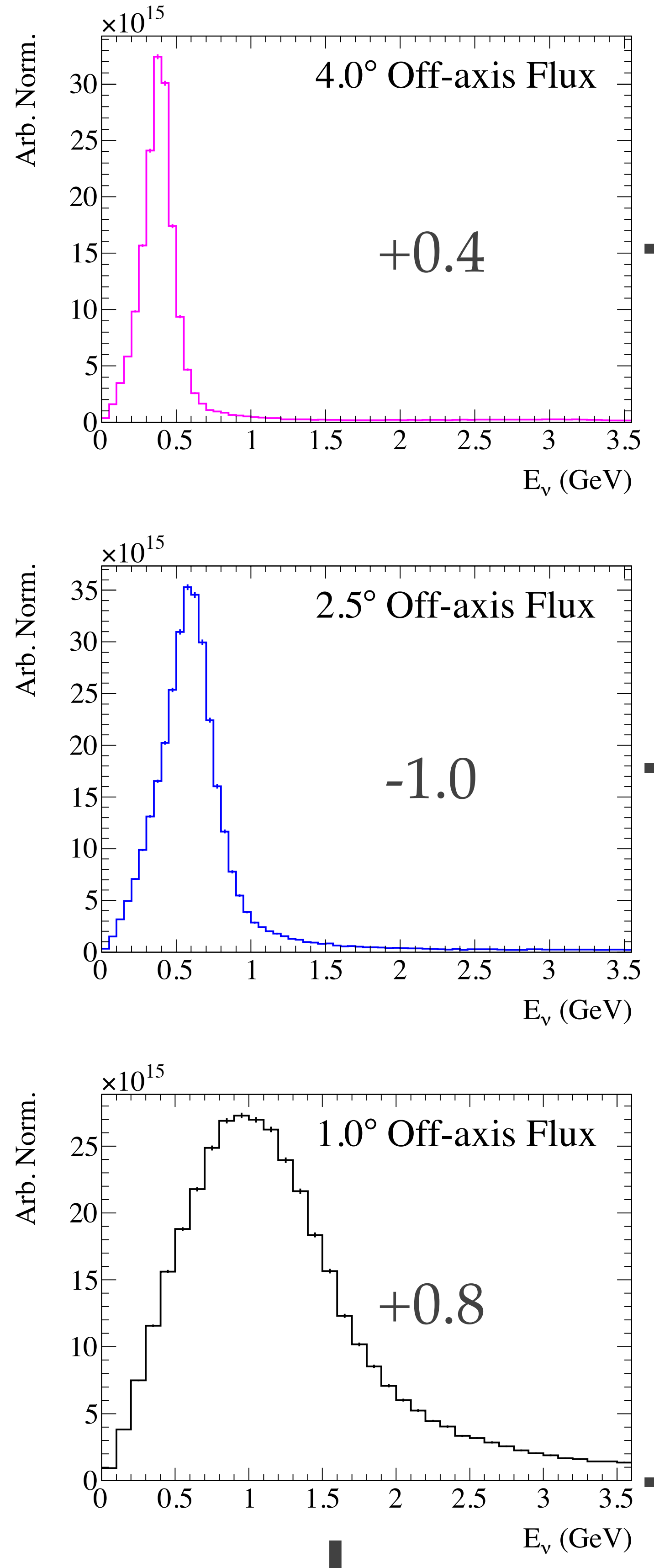


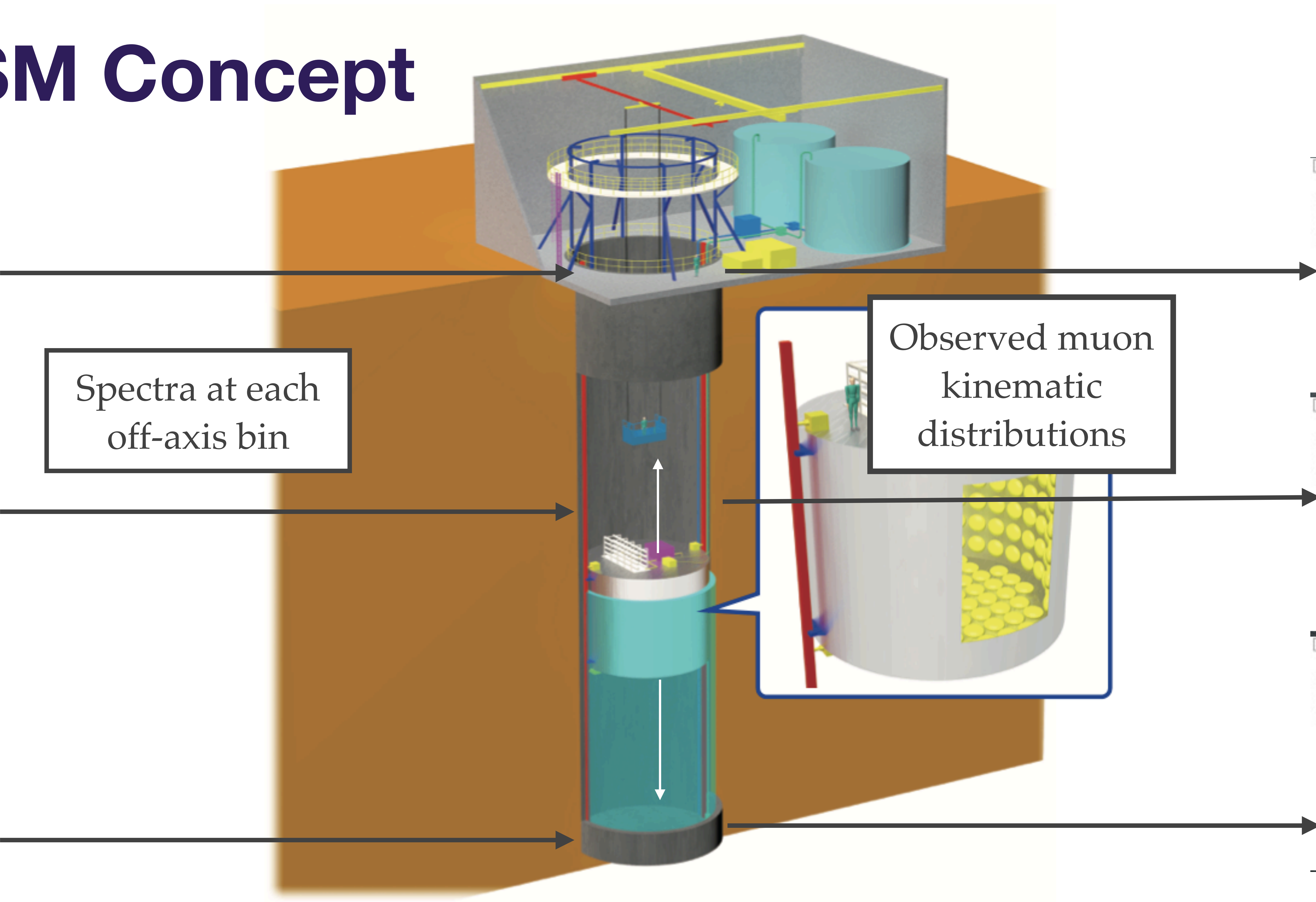
Measure reconstructed energy of events

5% measurement precision on events with large mis-reconstruction

NuPRISM Concept

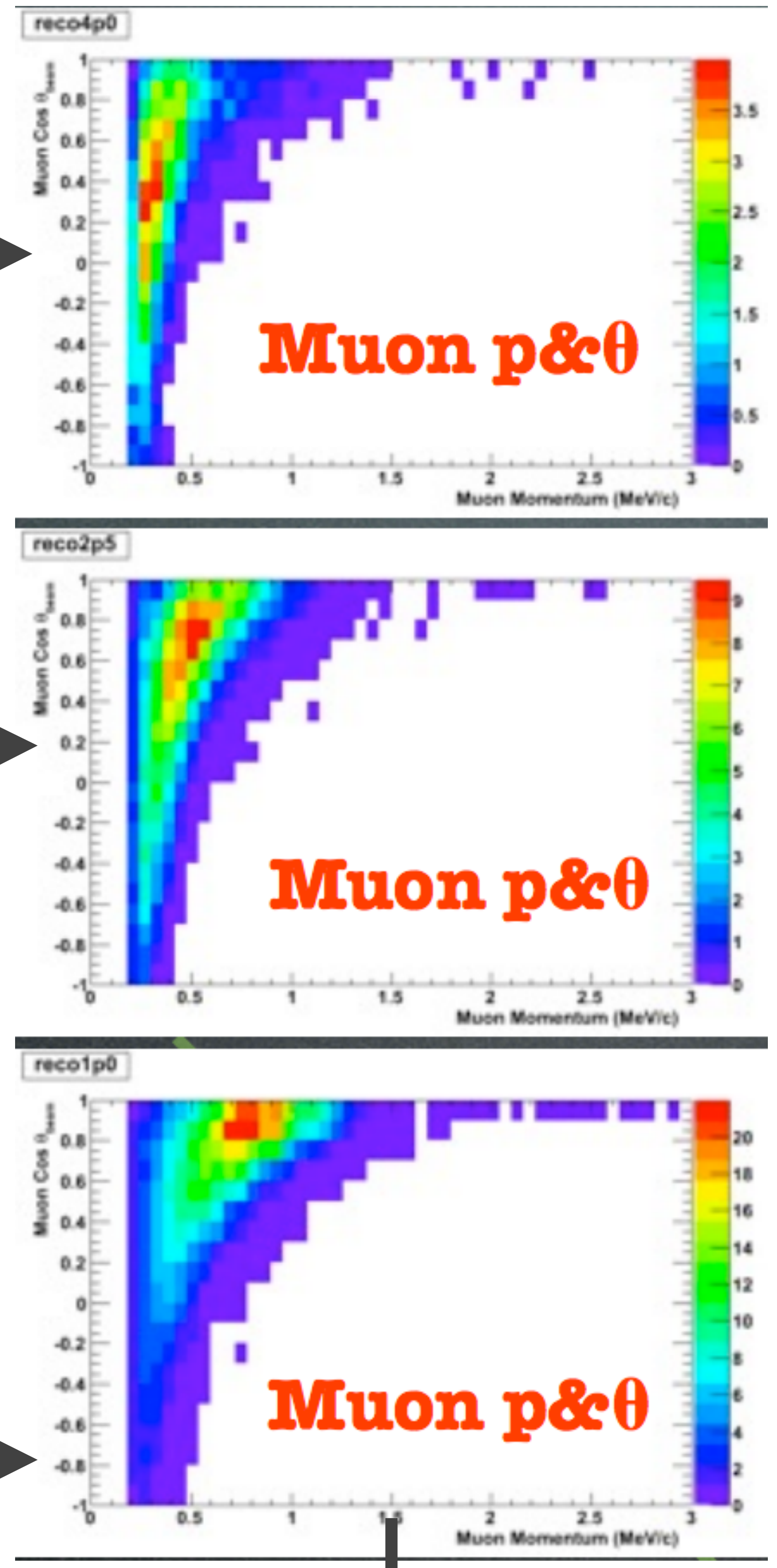
Hyper-Kamiokande

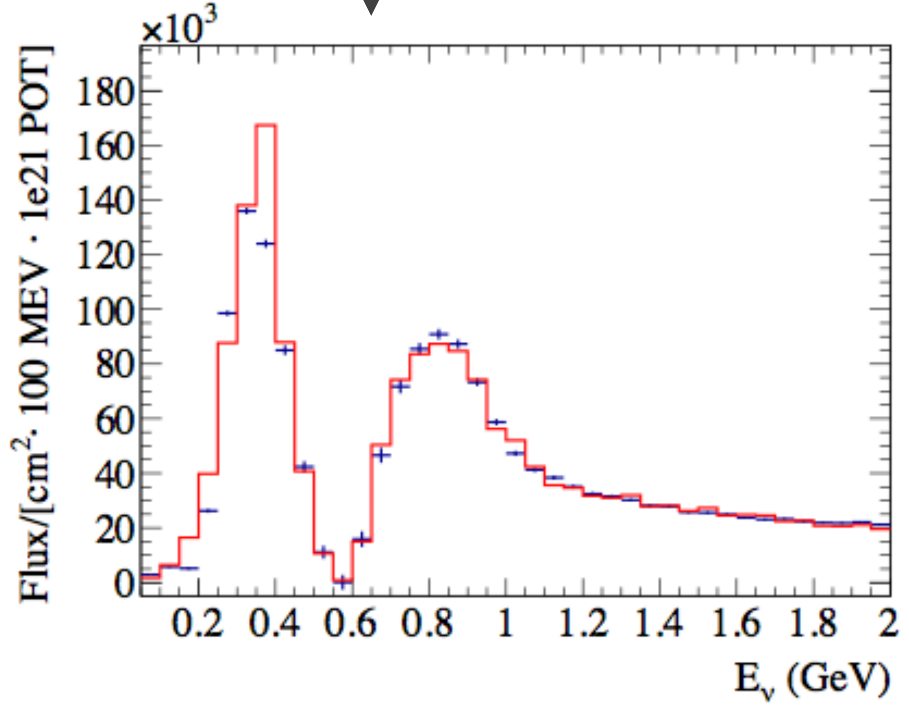




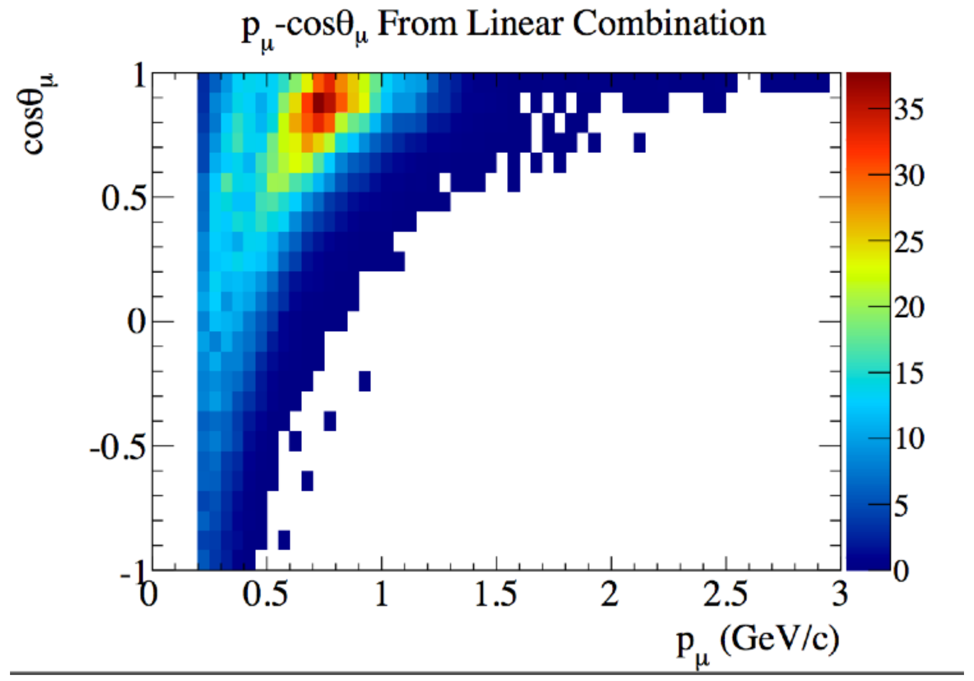
Spectra at each off-axis bin

Observed muon kinematic distributions



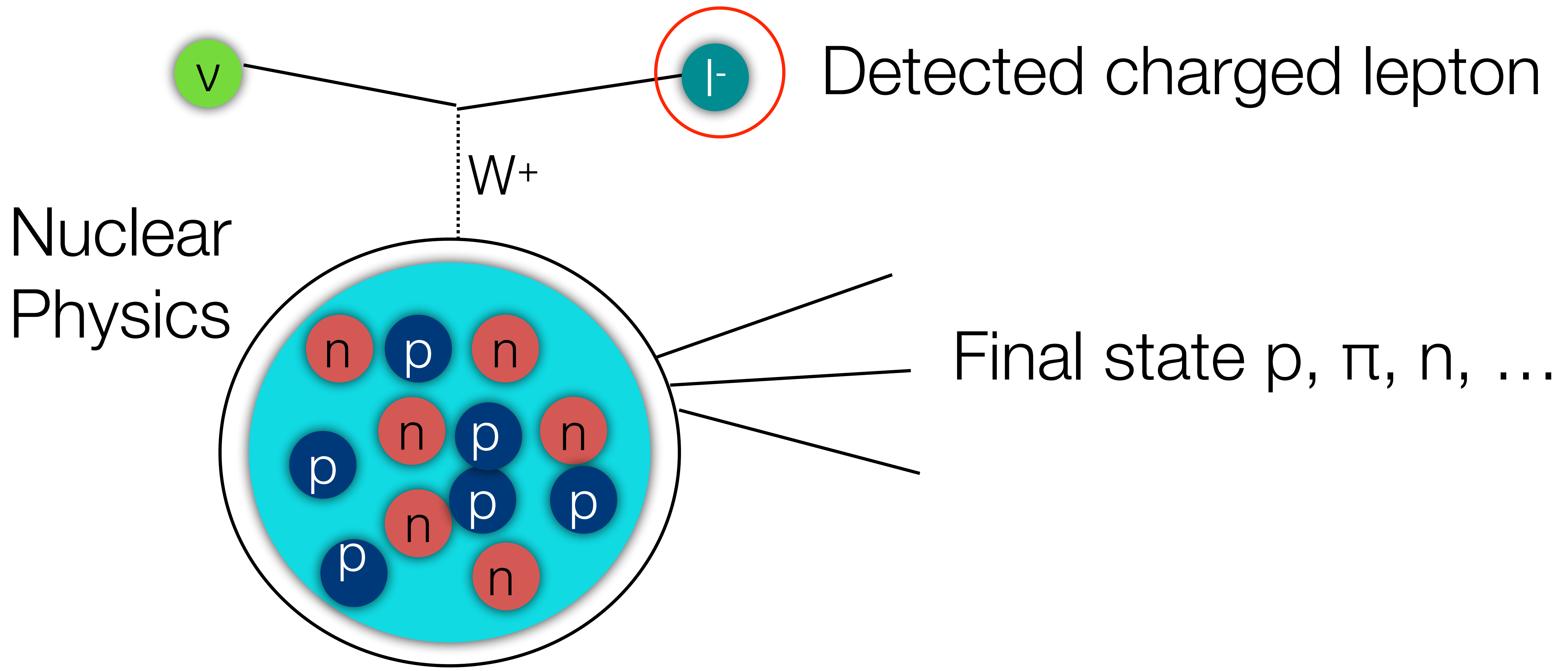


Linear combinations reproduce the oscillated flux, and predict muon kinematic distributions for the oscillated flux



Nuclear Effects in Neutrino Interactions

- We select neutrino interactions in the charged current interaction mode:



- Final state includes hadrons that may not be detected:
  - Water Cherenkov: most protons below Cherenkov threshold
  - Tracking detectors: neutrons may not be detected
- Need neutrino energy to calculate $P(\theta_{23},\Delta m^2_{32},\ldots,E_\nu)$
  - **Since we don't fully reconstruct the event, we rely on models to infer energy**