Introduction to Water Cherenkov Test Experiment

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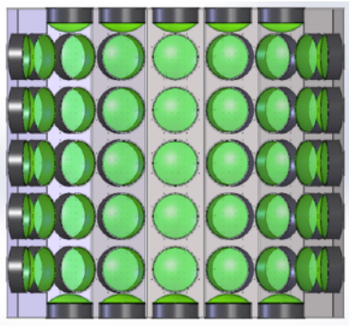
TRIUMF & Kavli IPMU

Motivation

- Next-generation neutrino experiments will use near and far Water Cherenkov Detectors
- Precision measurements require detector responses to be understood at the 1% level
- Event reconstruction performance is critical to achieve the necessary experimental resolution
- We propose a program the builds up from a test-beam experiment to full detectors in neutrino experiments
- Interest from Hyper-K, ESSnuSB, water-based liquid scintillator community

Water Cherenkov Test Experiment

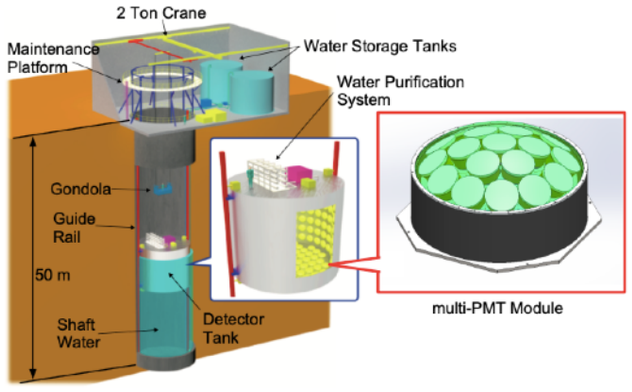


4 m tall x 4 m diameter

In charged particle test beam

130 photosensor units

Intermediate Water Cherenkov Detector (IWCD)

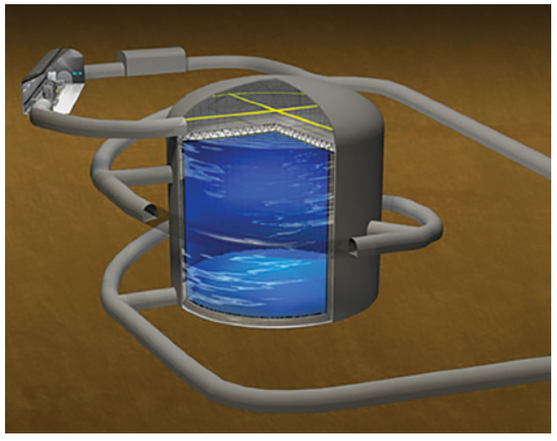


8 m tall x 10 m diameter

In J-PARC neutrino beam

480 photosensor units

Hyper-K



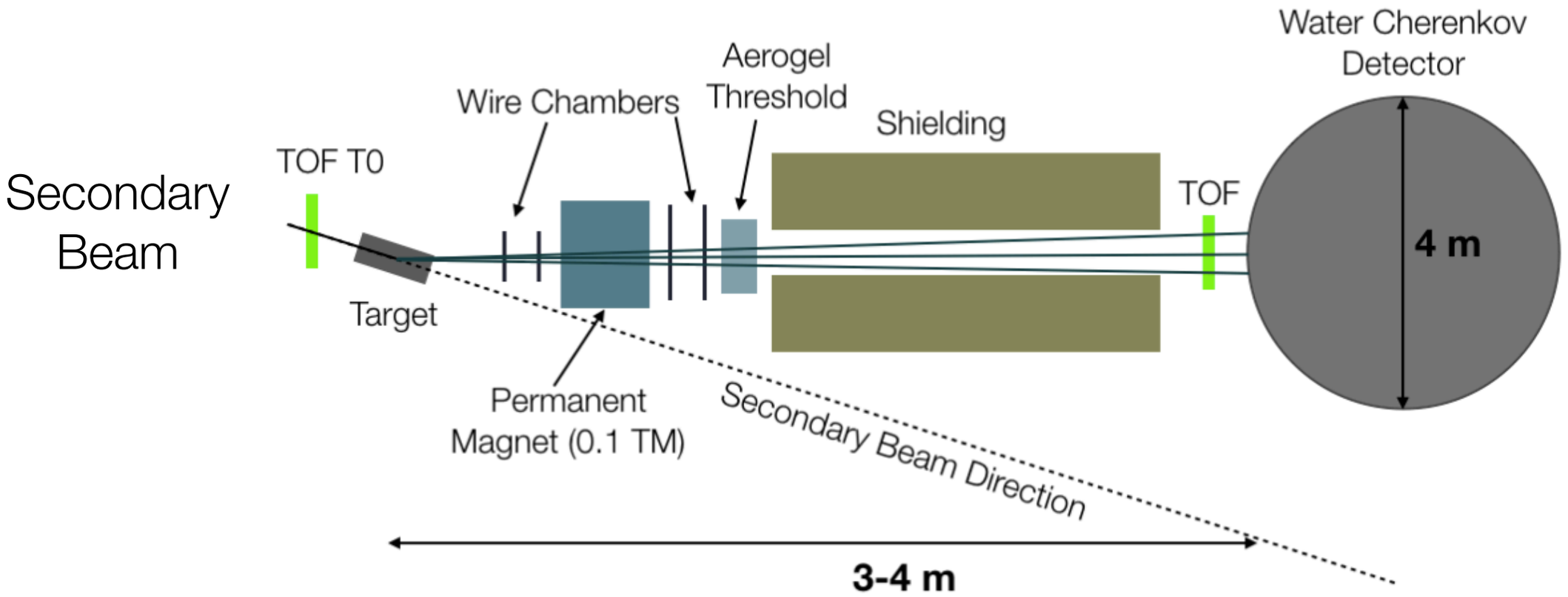
71 m tall x 68 m diameter

295 km from J-PARC neutrino source

>20,000 photosensor units

Proposed Experiment

- Our goal is to study the detector systems and response with pions, muons, electrons and protons in the 200 MeV/c-1200 MeV/c range
- For low momentum hadron production, we consider a tertiary production target and spectrometer a few meters upstream of the detector:

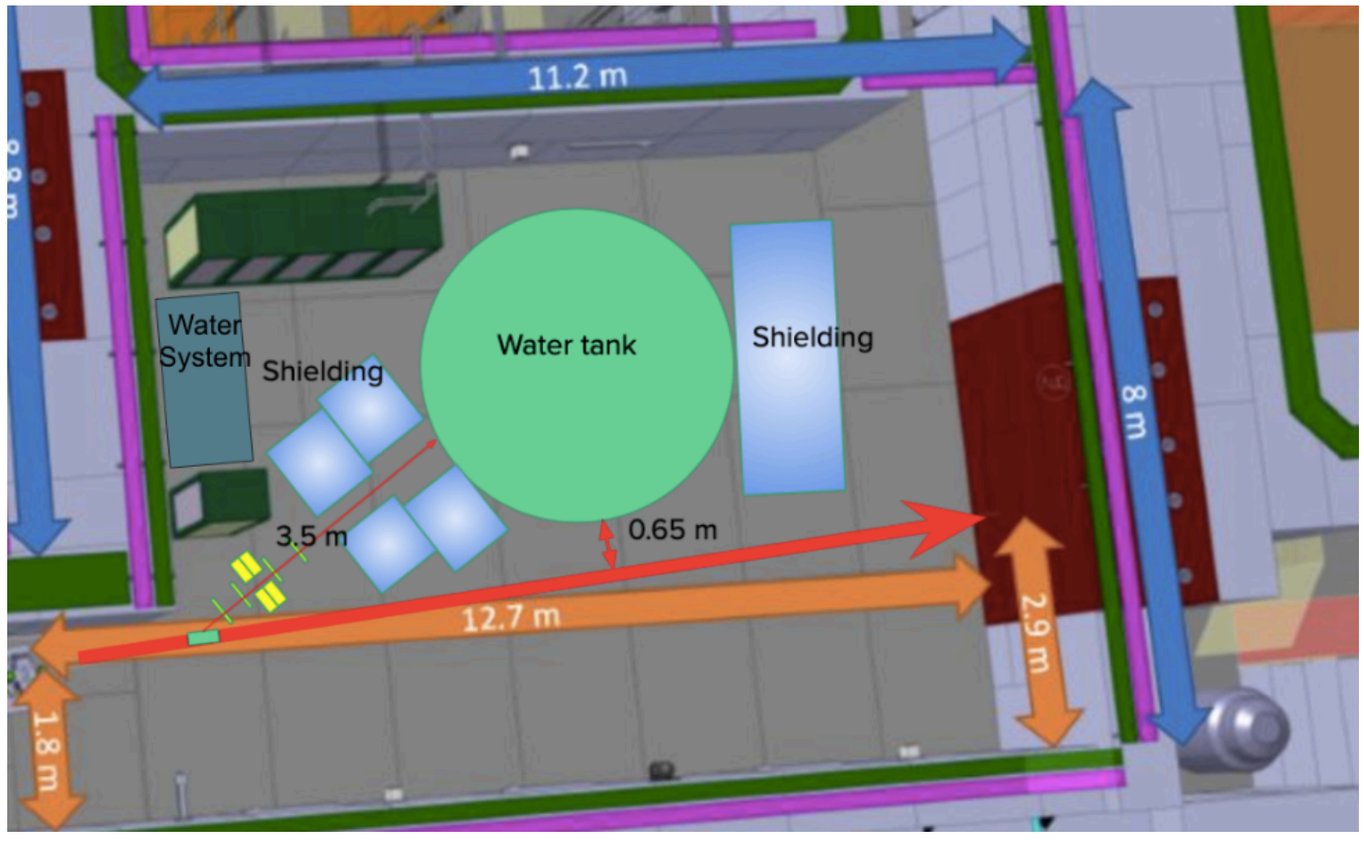


- For low momentum electrons and muons, we propose to use particle fluxes directly from the T9 beam line in low momentum operation

Proposal submitted to CERN SPSC: CERN-SPSC-2020-005 ; SPSC-P-365

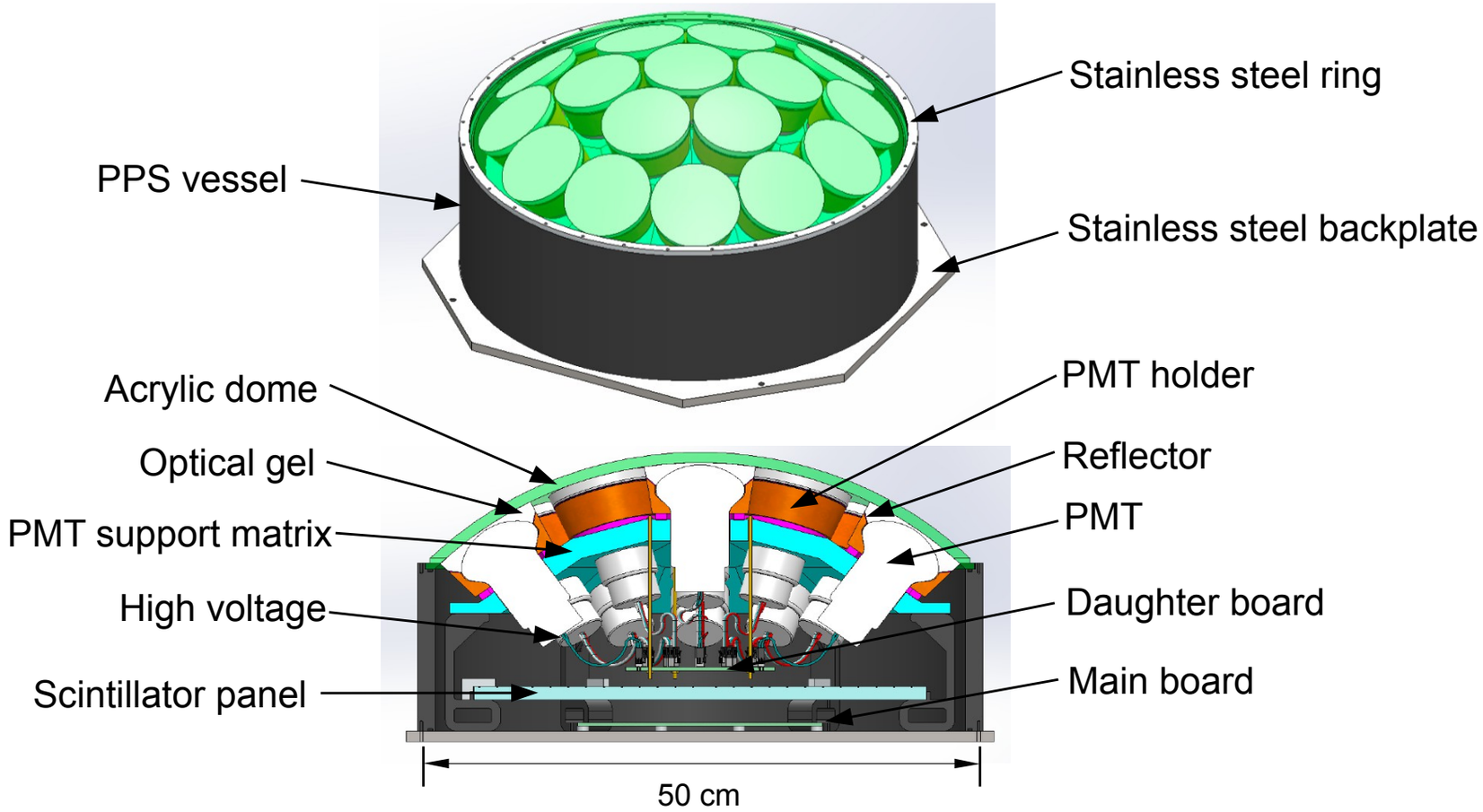
Experimental Area

- We propose to use the T9 beam line in the East Area
- ~40 m secondary beam allows for low momentum muon+electron fluxes
- Enough space for tank and tertiary production apparatus
- **Is there a nearby counting room. If so, how far away is it? What cabling and crates are installed?**



- For low momentum electrons and muons, we propose to use particle fluxes directly from the T9 beam line in low momentum operation
- At least 12 weeks of operation
- Plan for operation in early 2022 (subject to COVID-19 related schedule changes)

Detector Features: mPMT



- We will use a newly developed photosensor module under development for the IWCD and Hyper-K
- 19 3-inch diameter PMTs inside a single unit
- Front end electronics are also integrated in the unit
- ~130 installed in the WCTE

Detector Features: Water System

- Water circulation and purification system will keep ultra-pure water in tank
- We plan to use 2 ton/hr flow rate
- Water system with footprint of 1.55 m × 0.7 m and maximum power consumption of 3.1 kW
  - 2 ton/hr flow rate
  - Ion exchange resin, UV lamp, microfilters
- **If there is a source of de-ionized water that can be used for initial filling (50 tons), that would allow for simplification of the water system**

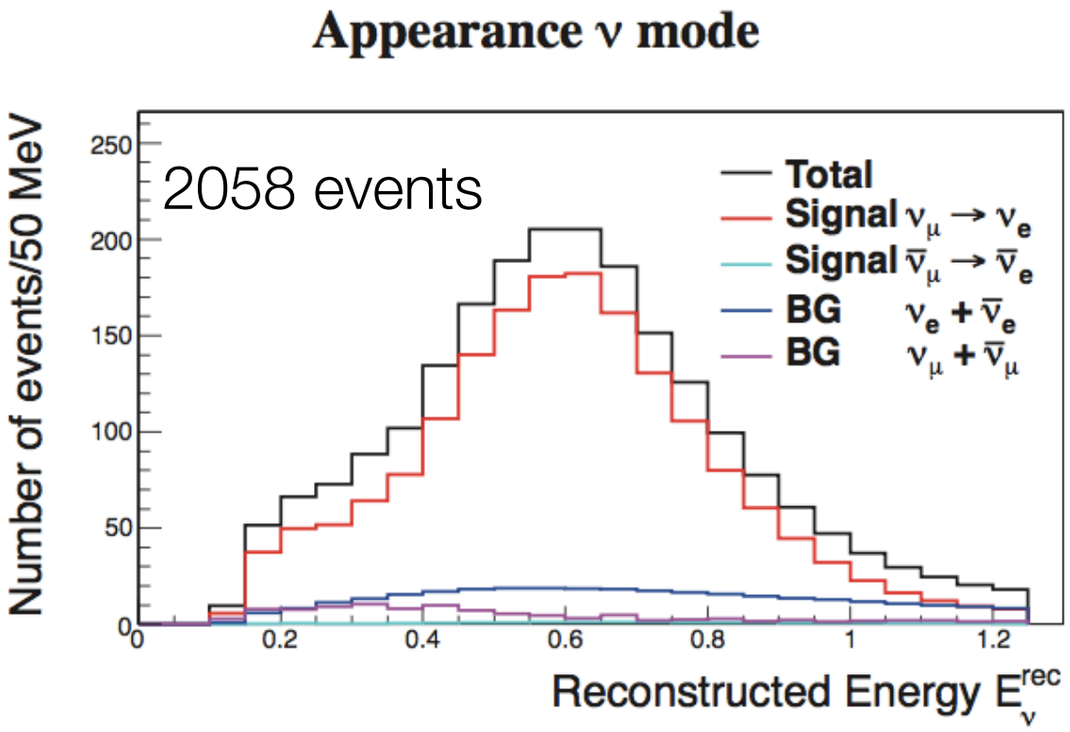
- We plan a second operation phase with 0.2% $Gd_2(SO_4)_3$ loading in the water
  - For neutron detection
  - $Gd_2(SO_4)_3$ can only be loaded once (can't switch back and forth between phases)
  - Requires change to water system to operate with special resins
  - **Are there any safety/environmental considerations?**
- **Is there a drain in the experimental area that we can use to empty the tank. If so, what is the maximum flow rate?**

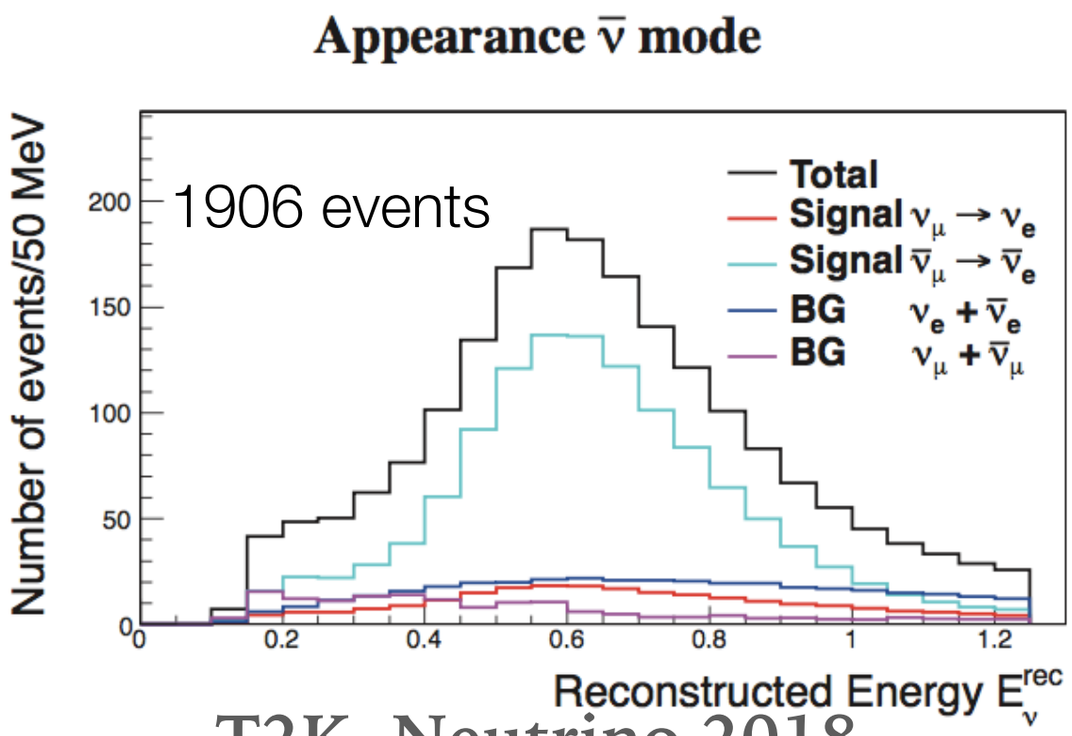
Following Talks

- We would like to present design work on two topics:
  - Tertiary production target/spectrometer/shielding design (M. Pavin)
  - Tank and PMT support structure design (S. Garode)
- We have some more questions to you that will be covered in these talks
- We appreciate any feedback you can give

Thank You

Systematic Uncertainties for Hyper-K





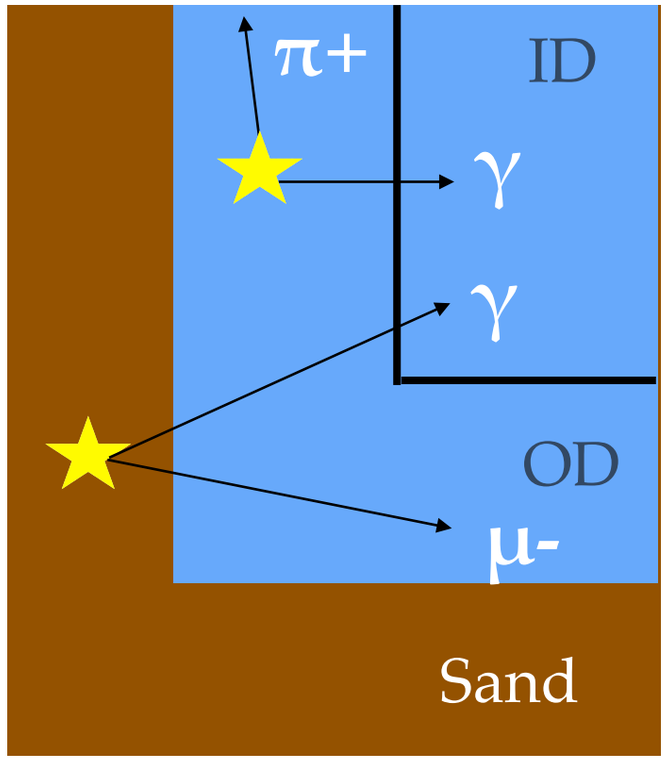
T2K, Neutrino 2018

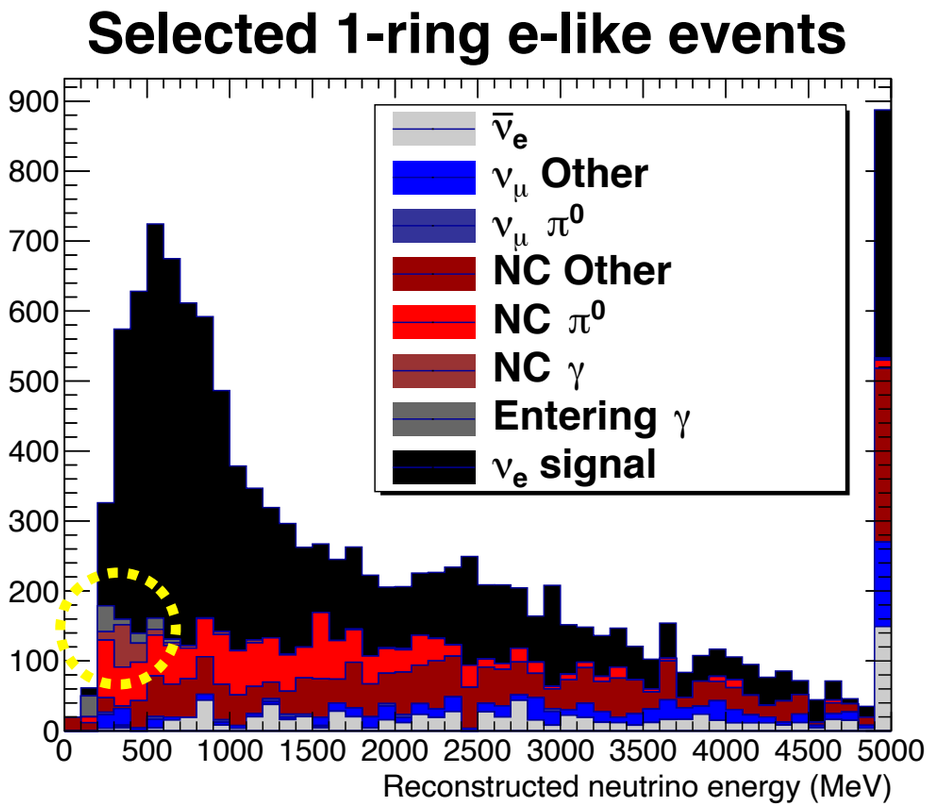
- Statistical errors in Hyper-K CP violation measurement are ~3%
- Systematic errors related to neutrino interaction modeling are ~6%
- One of the dominant errors is the electron (anti)neutrino interaction cross section

Error Source	% Error on neutrino/ antineutrino rate
Pion Interactions	1.58
Neutral Current Background	1.50
Electron (anti)neutrino cross section	3.03
Extrapolation from near detector	2.31
Removal Energy	3.74
Far Detector model	1.47
Total	5.87

Electron (Anti)Neutrino in IWCD

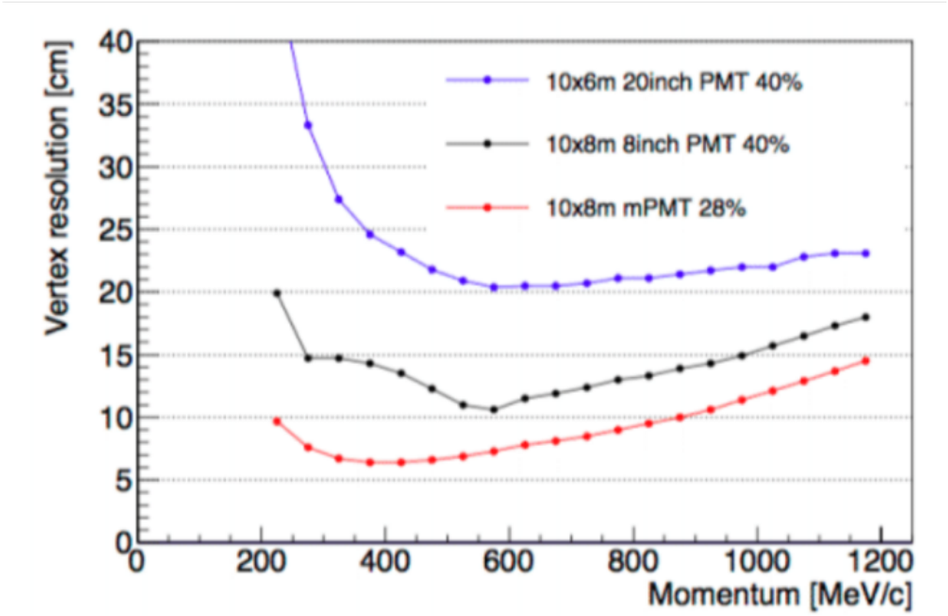
- Use the contamination of electron neutrinos in beam from muon and kaon decays (~1%)
- Water Cherenkov detector is ideal for controlling background from external high energy gammas
- Analysis requires reduction of muon and π^0 backgrounds by multiple orders of magnitude
  - Understanding the detector response to these backgrounds is critical to the analysis



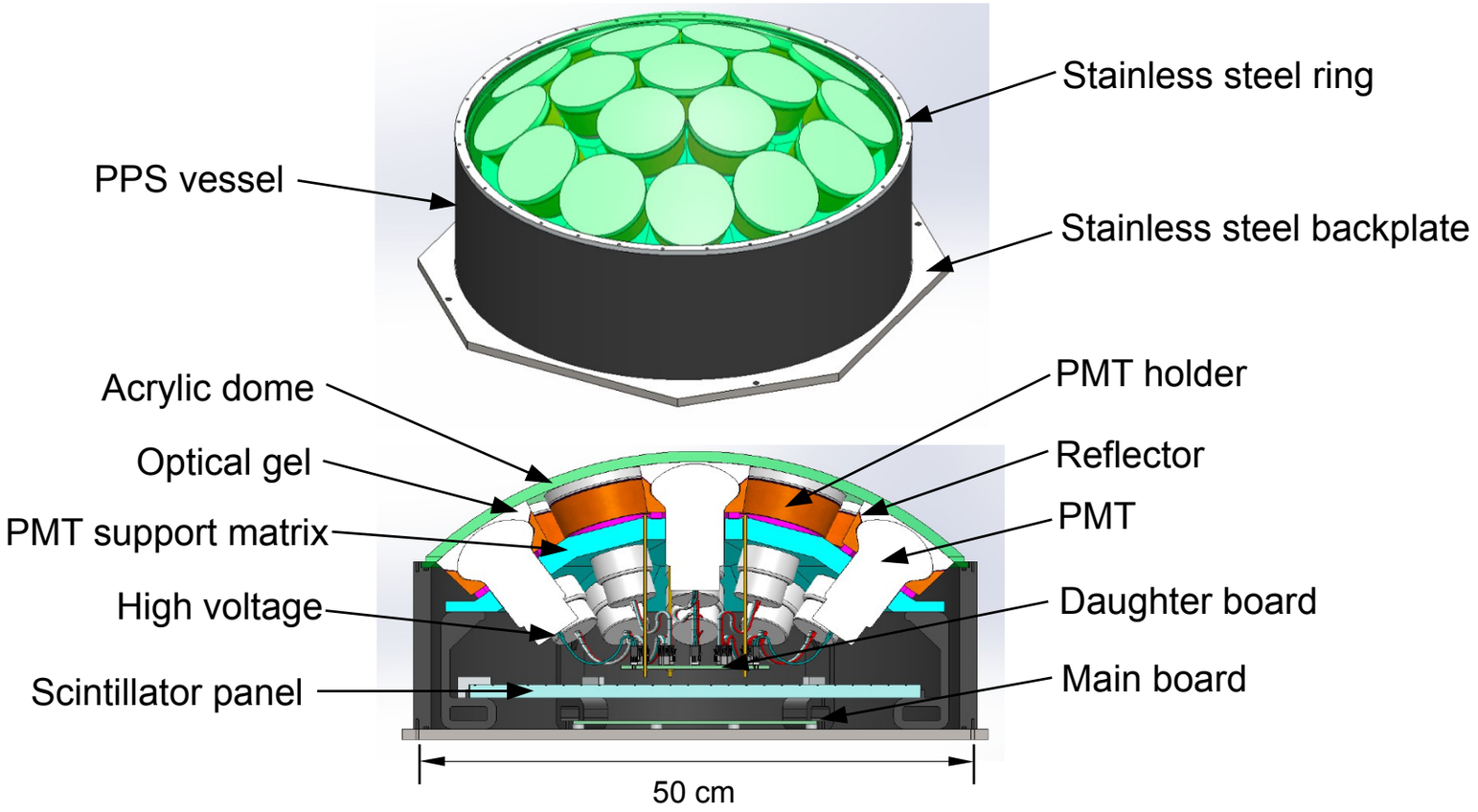


Multi-PMT Photosensors

- IWCD detector size requires small and fast photosensors
- Have developed a multi-PMT photodetector design with many small sensors integrated in modules



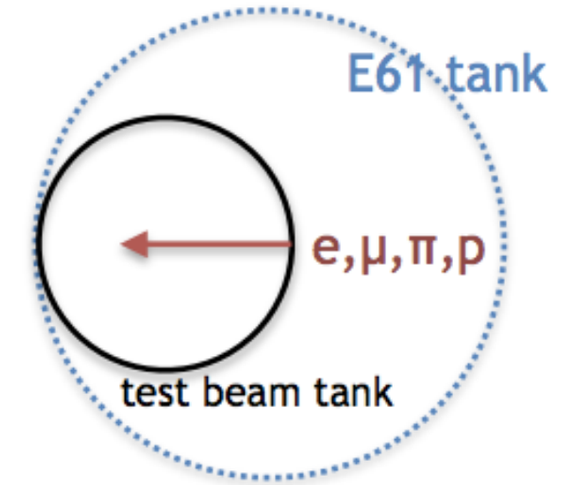
- This is a new technology
- A test experiment can provide a platform for evaluating the operation of the multi-PMTs

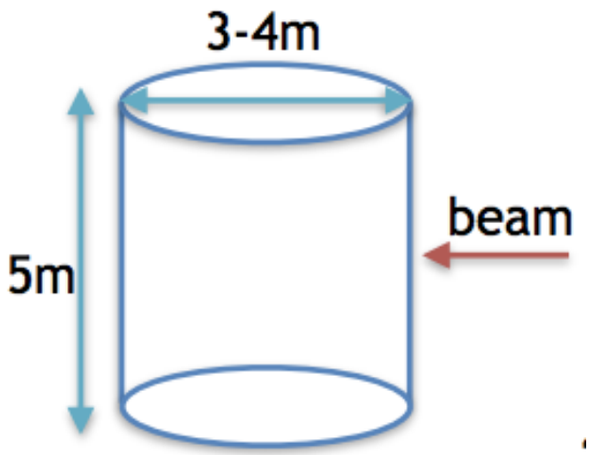


The Test Experiment

- Water Cherenkov detector in a charged particle test beam where particle type and energy are known
- Scale of the experiment is 3-4 m tall and 3-4 diameter
  - This gives a distance to the wall similar interactions at the center of the IWCD

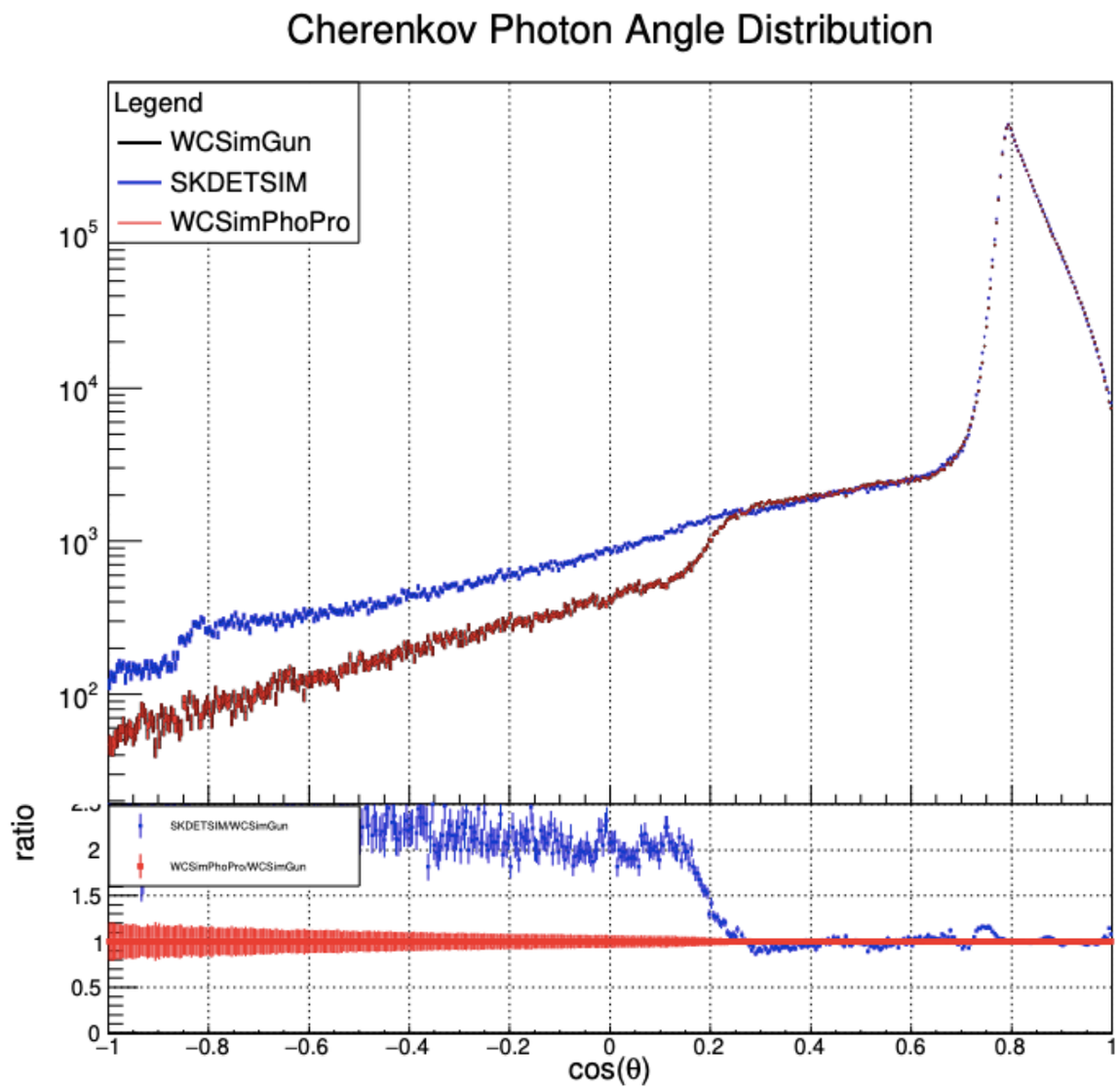
- **Goals:**
  - Test new technologies for water Cherenkov detectors
  - Prove bottom-up calibration of small WC detector at 1% level
  - Measure physics processes, such as Cherenkov light profile and pion scattering
- **Collaboration extending beyond Hyper-K/ IWCD to ESSnuSB and THEIA communities, etc.**





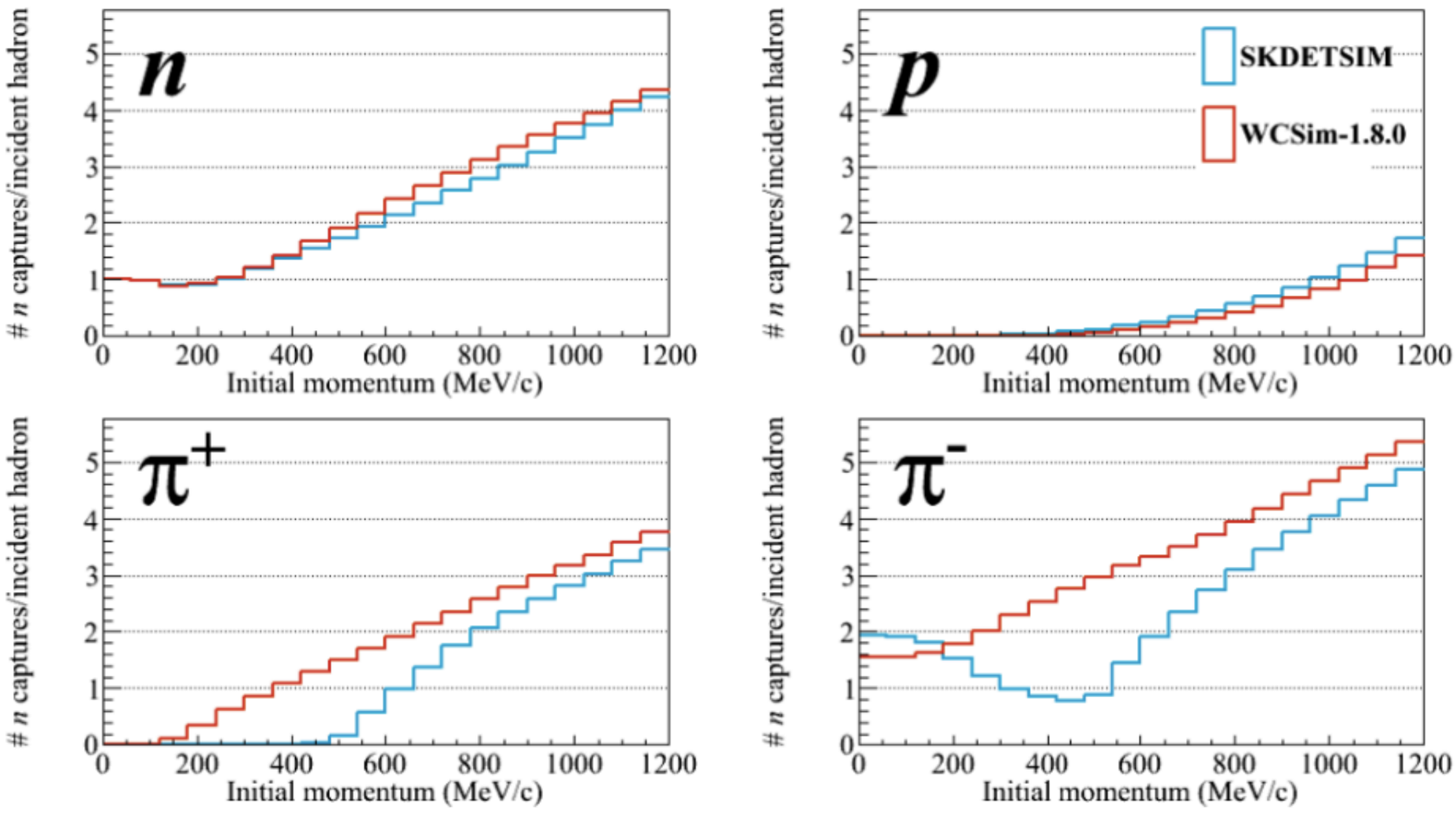
Measurements: Physics Processes

- Properly modeling the detector response is more than modeling Cherenkov photon propagation and detection
- Additional physics processes need to be considered
  - Cherenkov photon production
  - Pion scattering in the detector
  - Secondary neutron production
- These can be measured in a test experiment



Measurements: Secondary Neutrons

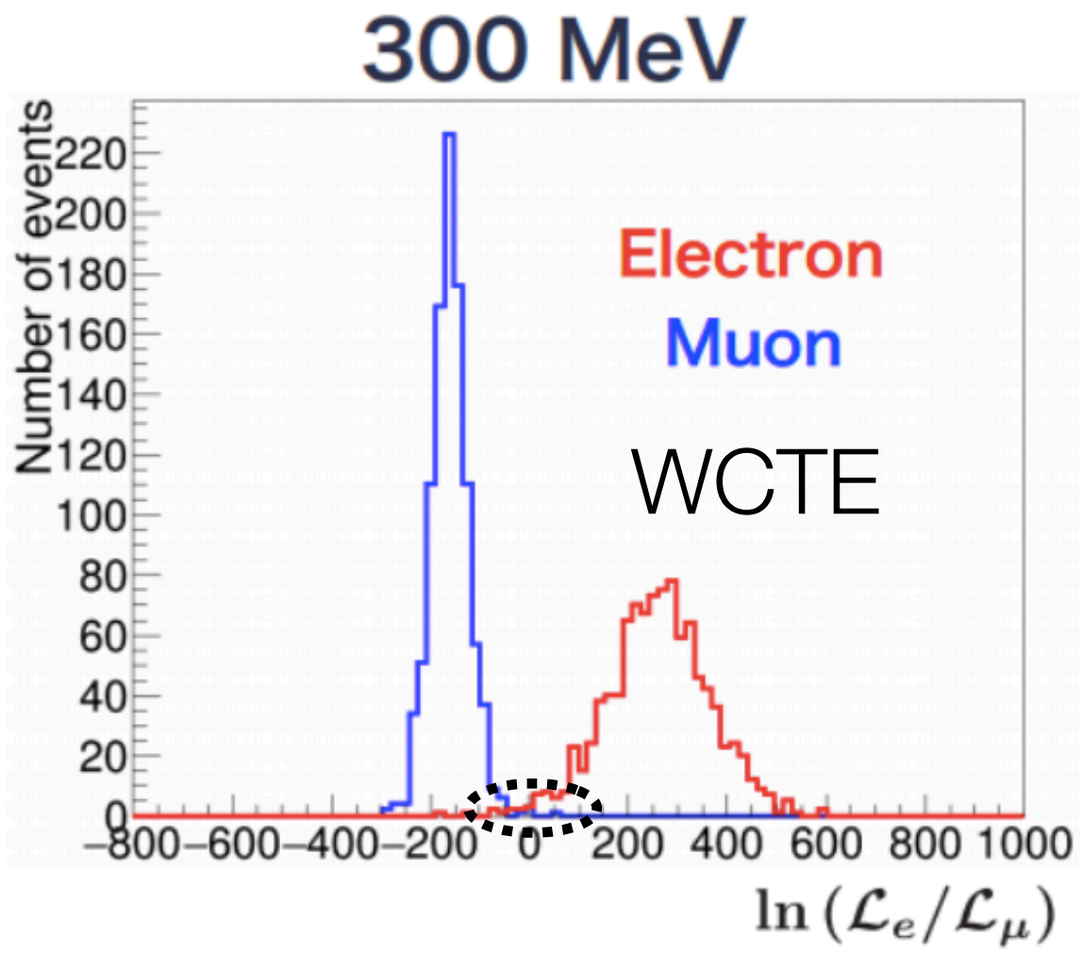
- Can be significant differences in predictions between models

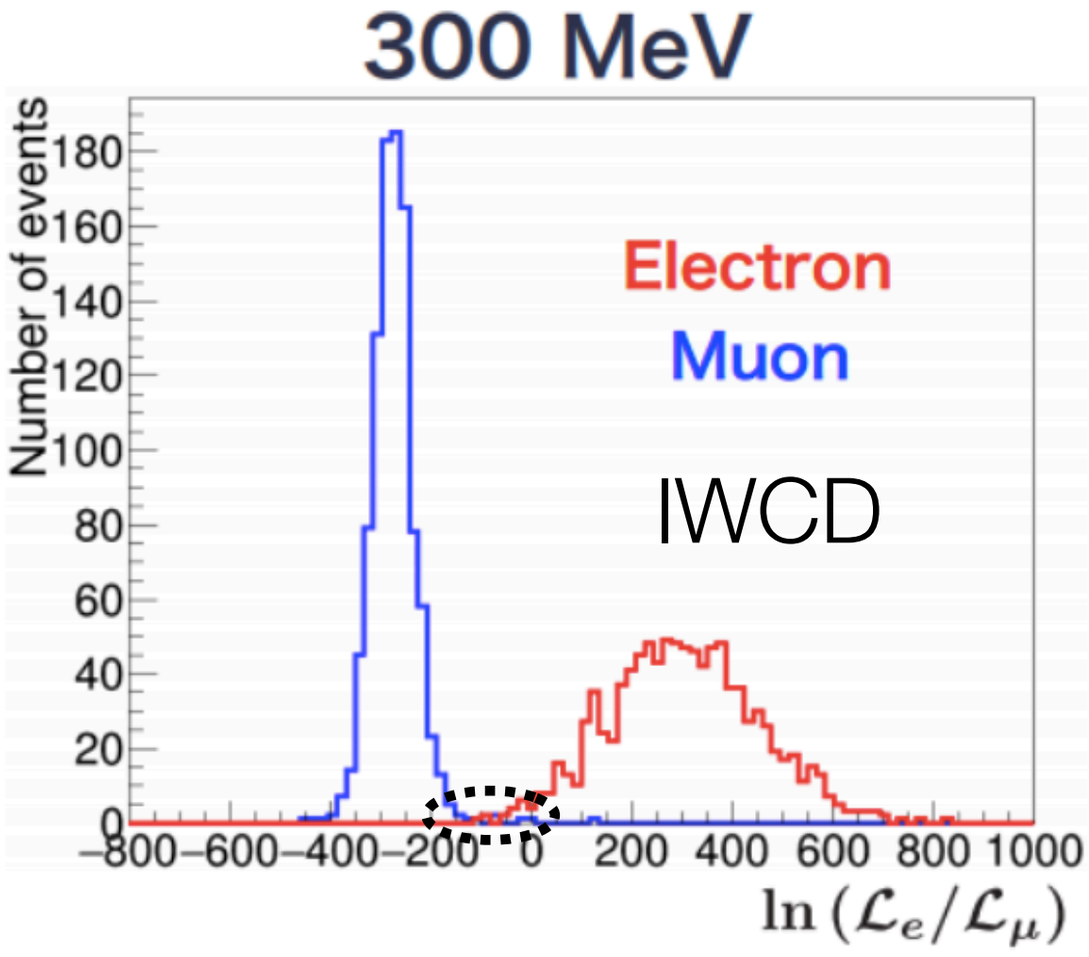


- Can be measured in the test experiment with Gd loading
- Requires a phase of operation with 100 kg of $Gd_2(SO_4)_3$ at
- Dominant cost is removal of $Gd_2(SO_4)_3$, so we can only do the Gd run once

Measurements: Particle Identification

- Particle identification performance can be studied in the WCTE
- IWCD analysis requires ~1e-4 reduction of muon rate to measure electron neutrino cross section

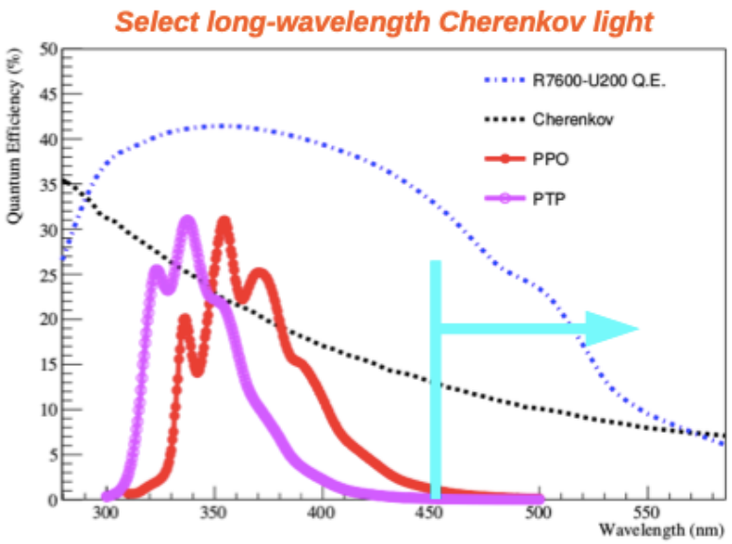


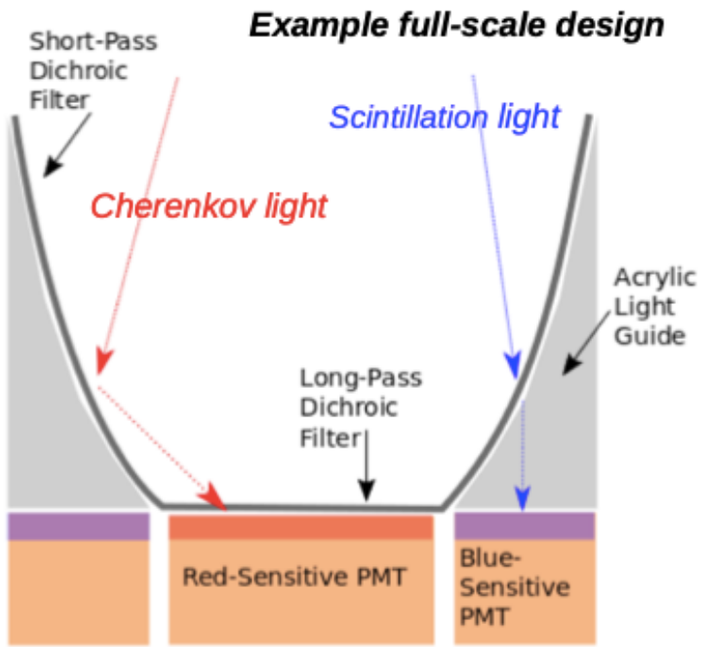


- Need to accumulate ~1e6 muons and electrons for each 100 MeV/c to have statistics to study tails of particle identification distributions

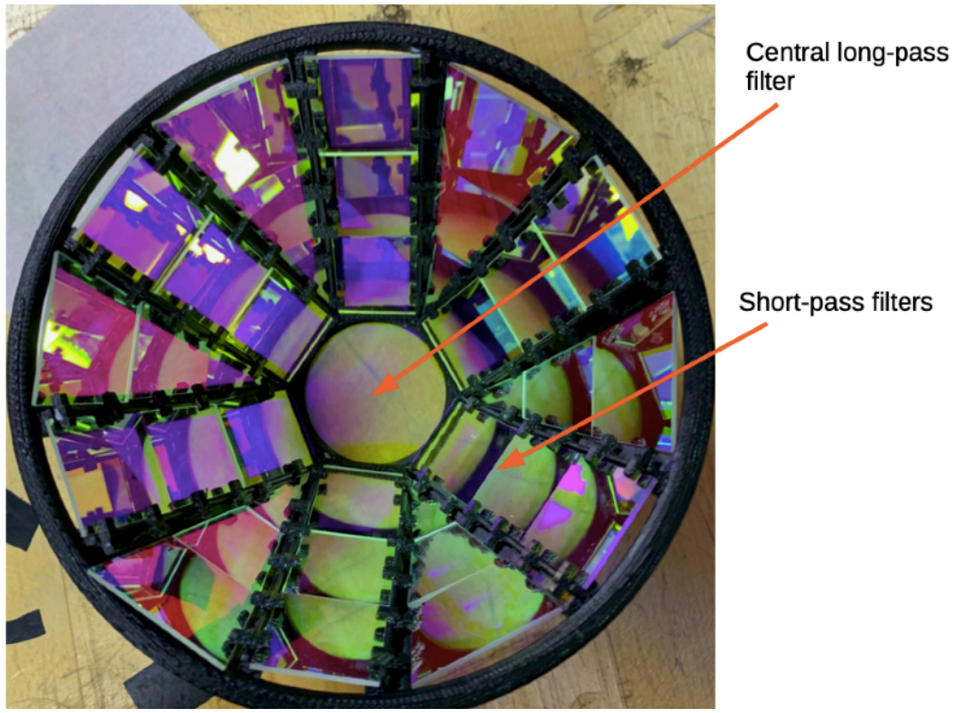
New Technologies

- In addition to the mPMT and other IWCD technologies, there are new water-based detector technologies that can be studied in the test experiment
- Water-based liquid scintillator combines production of Cherenkov and scintillation light in one detector
- New photosensors are being developed to be able to best separate Cherenkov and scintillation light (LAPPDs, dichroicons, etc.)



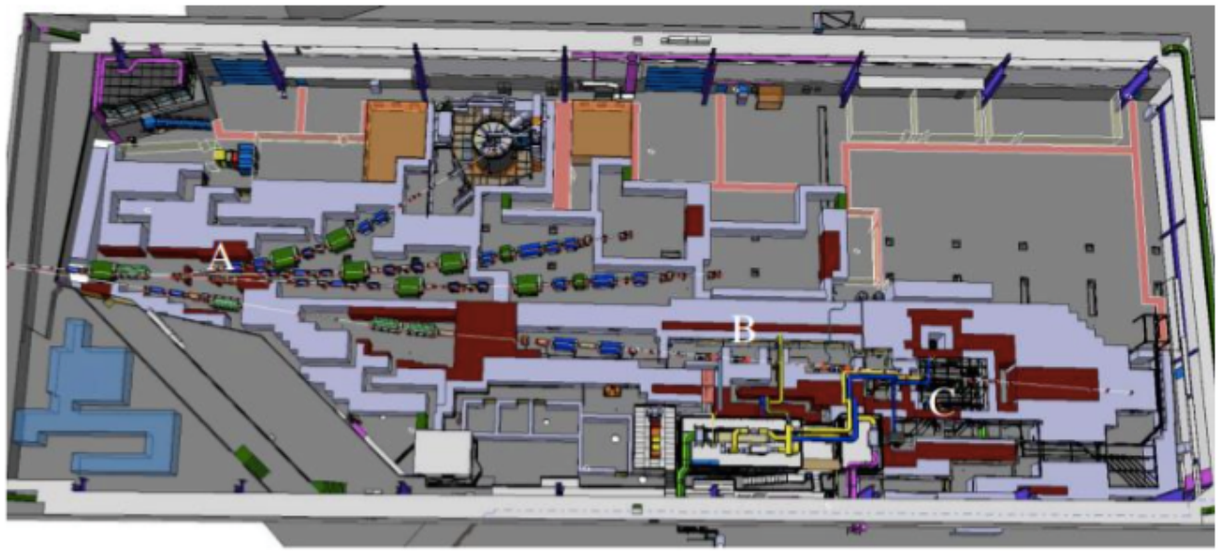


M. Wilking



UPenn

WCTE In The East Area



Parameter	New T9	New T10
Length [m]	50	45
Min/Max Mom [GeV/c]	0.3 - 15	0.3 - 12
Mom. Resolution	0.7%	0.7%
Hor. Acceptance [mrad]	±4	±5
Ver. Acceptance [mrad]	±3.8	±3
Max. Flux per Spill	10^6	10^6

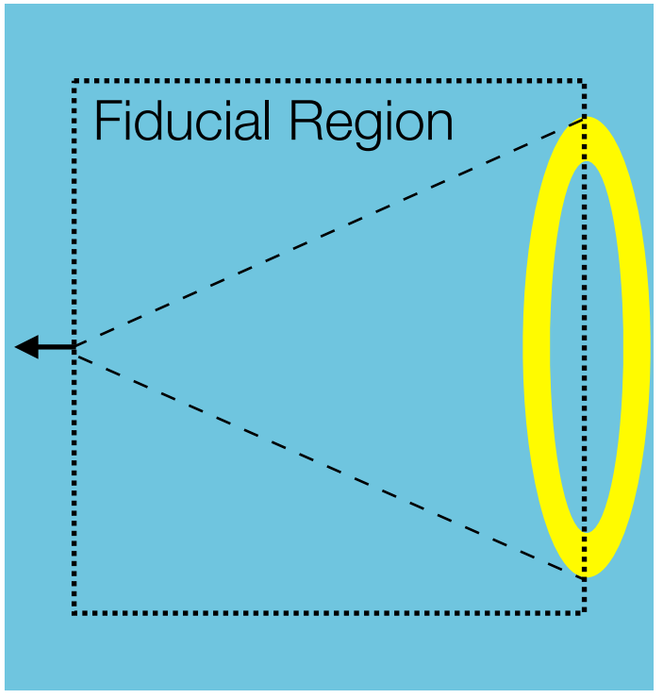
- Possibility for pure hadron/ electrons/muon beams
- Mixed hadron beams (different targets possible, for hadron/electron enrichment)
- 0.4 s flat top

- Available instrumentation:
  - Triggers/profile monitors
  - Cherenkov counters

Area to be operational in 2021 -
For more info, please contact the responsible physicist
J. Bernhard [EN-EA]

Motivation - Calibration and Detector Modeling

- We aim to make measurements with 1% level uncertainty in the IWCD
- Calibration of the detector and understanding of the detector response is critical
- Example systematic error:



- Fiducial region is defined corresponding to a fiducial mass
- A 2 cm bias in the reconstructed vertex position corresponds to a 1-2% bias in the fiducial mass
- Corresponds directly to a bias on measured absolute cross sections

Motivation - Study of Calibration Systems

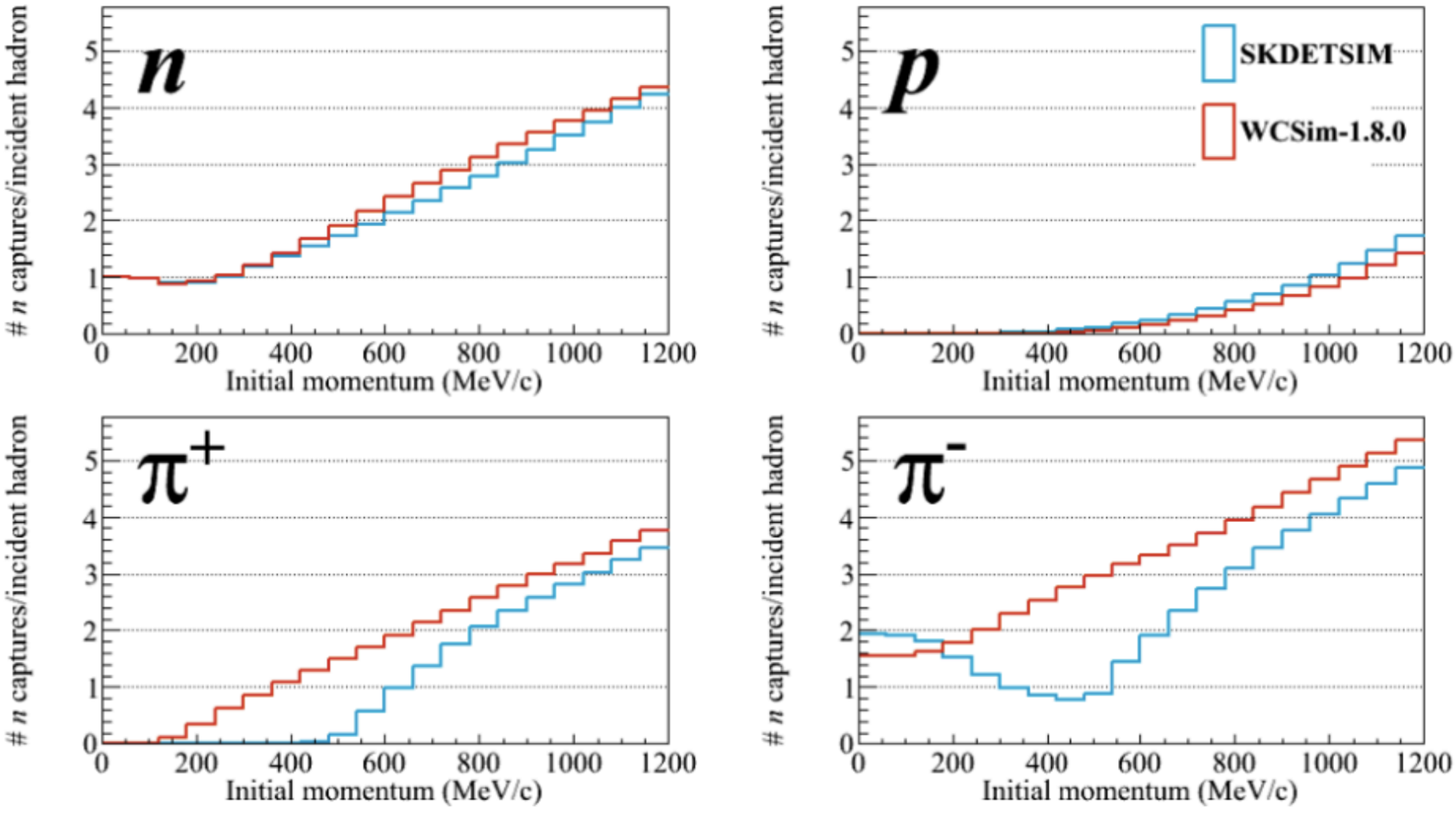
- Consider the systematic effects that must be constrained
- Consider the calibration sources which can constrain the systematic effects

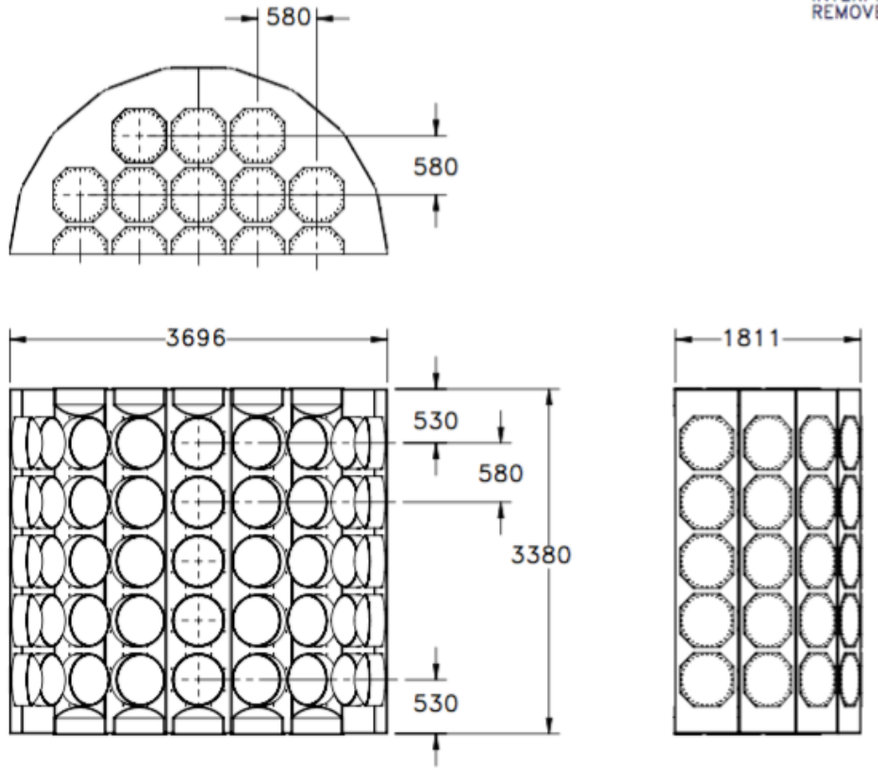
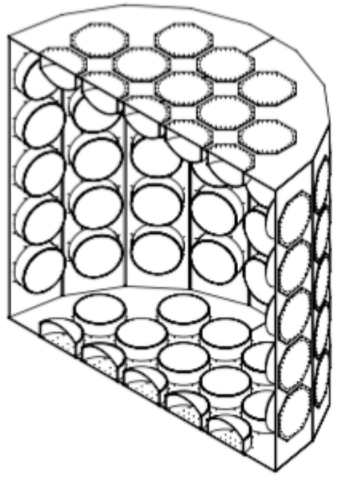
Systematic Parameter	Laser Injectors	Diffuser Ball	NiCf	AmBe	Particle Conduit	Cosmic/ Sand μ	Decay-e	π^0 from ν	LINAC/ CERN	…
Geometry	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Water	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Reflections	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Timing	✓	✓	✓	✓	✓	✓	✓	✓	✓	
PMT ang. response	✓	✓	✓	✓	✓	✓	✓	✓	✓	
PMT SPE/QE	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Cherenkov			✓	✓	✓	✓	✓	✓	✓	

- Need to make sure all systematic effects are addressed by at least one calibration source
- Degeneracies in the calibration that matter for physics events must be broken
- Test experiment is critical for testing calibration sources and strategy to show that 1% level uncertainty can be achieved

Motivation - Secondary Neutrons

- R. Akutsu performed study of secondary neutron production by hadrons
- Can be significant differences in predictions between models
- Can be measured in the test experiment with Gd loading



Detector Design

- PMT structure is 3.67 m diameter, 3.38 m tall
- Houses up to 132 mPMT modules
- Original structure ribbed Al parts
  - Want to move away for Al, need stainless steel design
- Need 4 m diameter x 4 m tall tank to house the structure
  - Tank lid should accommodate deployment of calibration sources, mPMT cabling and water circulation