22nd International Workshop on Neutrinos from Accelerators

PMT development for Hyper-Kamiokande

C. Bronner for the Hyper-Kamiokande collaboration

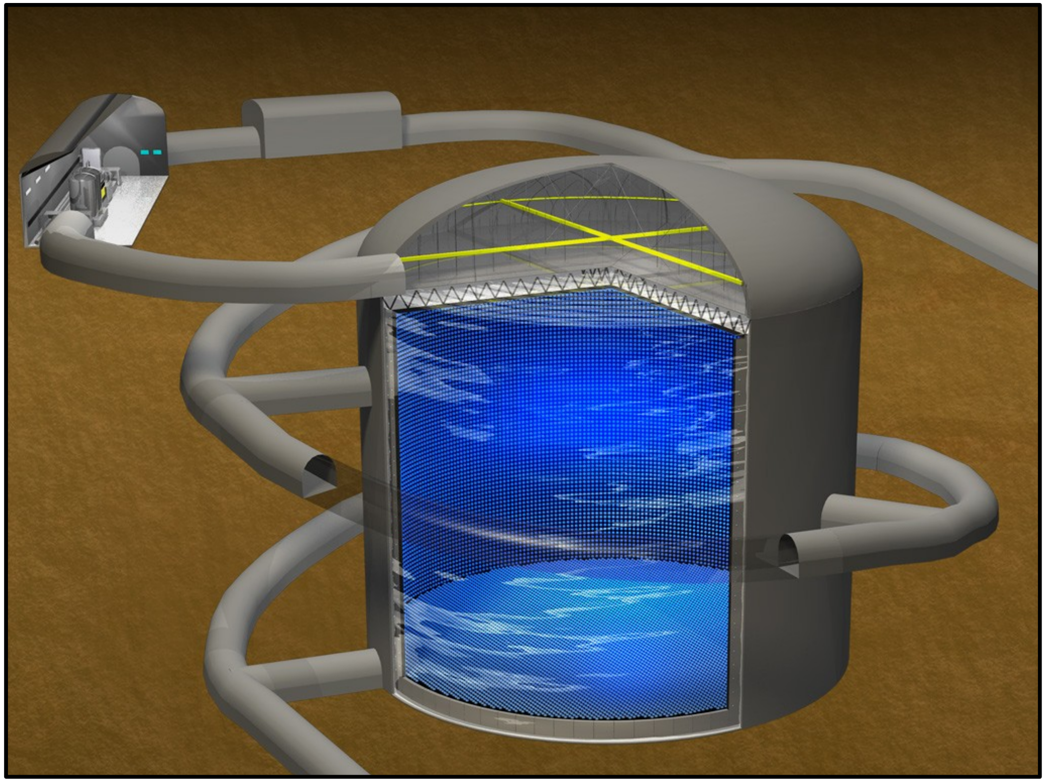
September 7th, 2021

ICRR
Institute for Cosmic Ray Research
University of Tokyo

KAMIOKA OBSERVATORY

The Hyper-Kamiokande experiment

See talk by K. Sakashita for Hyper-K overview



Construction start: 2020
Beginning of data taking: 2027

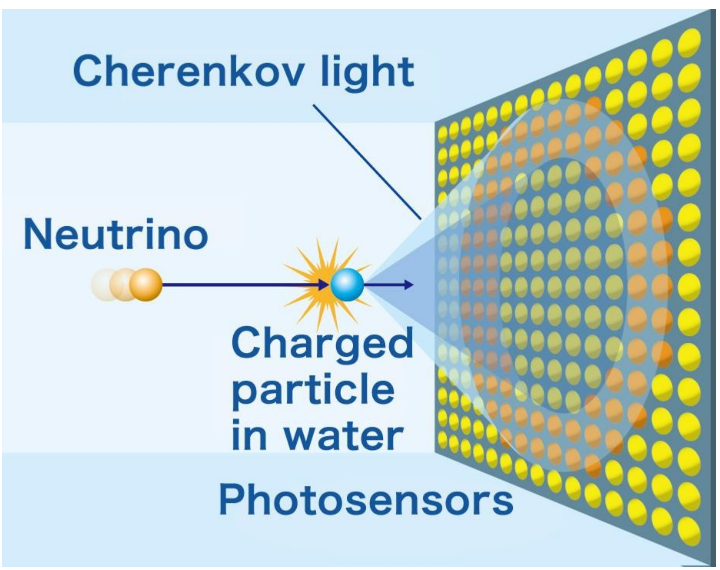
Wide physics program:
- ✓ Atmospheric neutrinos
- ✓ Accelerator neutrinos
  (see talk by L. Munteanu)
- ✓ Solar neutrinos
- ✓ Supernova neutrinos
- ✓ Proton decay
- ✓ Dark matter indirect detection

Builds on the successful strategies used in Super-Kamiokande, K2K and T2K with:

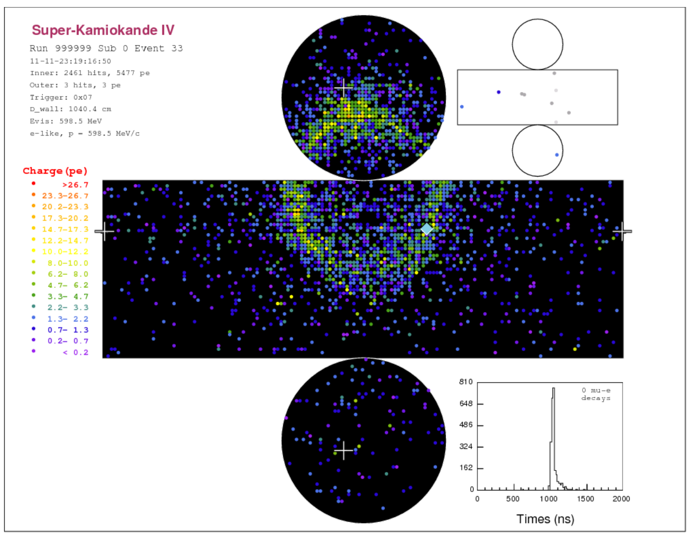
- Larger detector for increased statistics
  72m height x 68m diameter tank, 188.4 kton fiducial volume (SK:22.5 kton)
- **Improved photo-sensors for better efficiency**
- Higher intensity beam and updated/new near detectors for accelerator neutrino part

Events in water Cerenkov detector

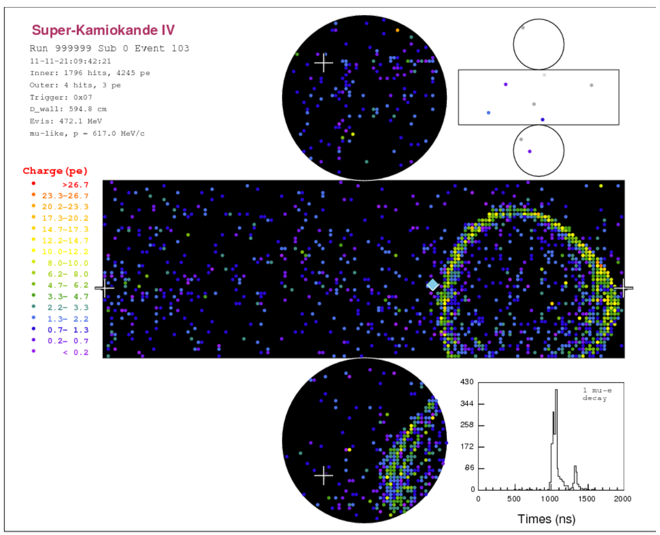
- Charged particles above Cerenkov threshold appear as ring patterns on walls of the inner detector
- PID from sharpness of ring edges, separate between showering ($e^{\pm}$,γ) and non-showering ($\mu^{\pm}$,$\pi^{\pm}$)
- Interaction vertex position by minimizing spread of (photon arrival time)-(time of flight)
- Momentum from charge deposited in a certain region around ring direction
- Reject entering background using outer detector



Showering

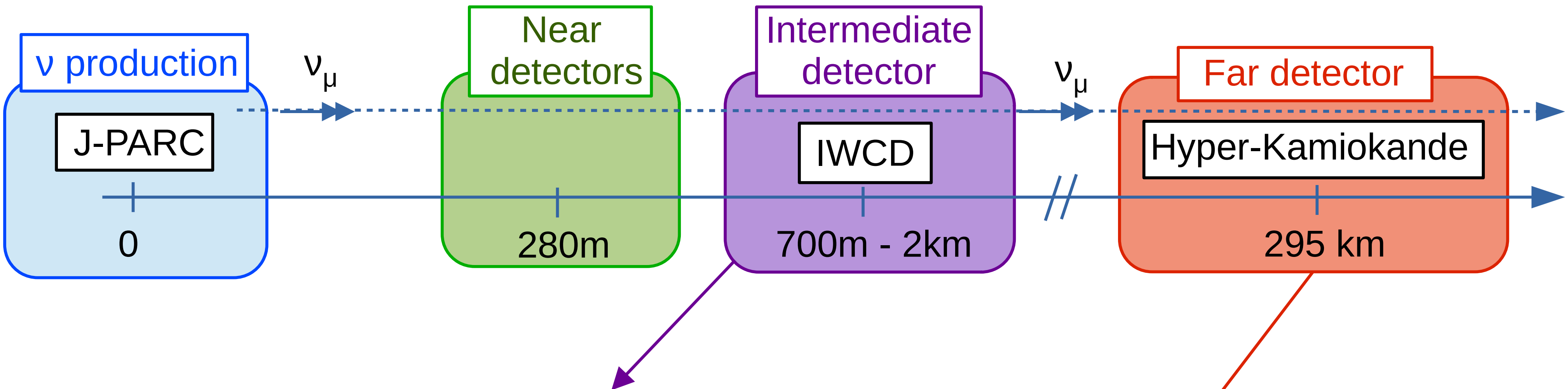


Non-showering

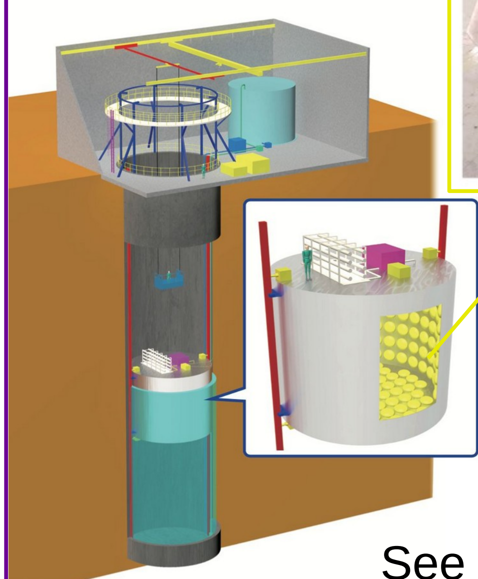


Examples from Super-K simulation

PMTs in Hyper-Kamiokande



Intermediate Water Cerenkov Detector



Multi-PMT modules

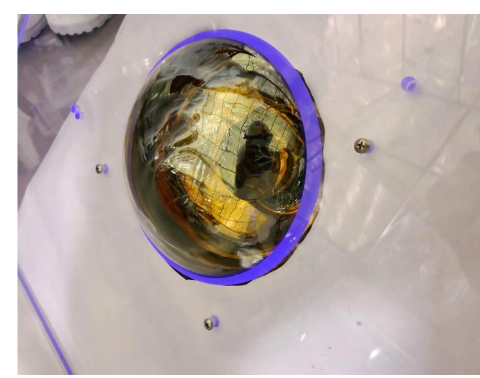
See talk by R. Akutsu

Inner detector

- 40% photocoverage (20% from Japan)
- 20” PMTs
- multi-PMTs

Outer detector

- 10000 3” PMTs
- Mounted on WLS plates + high reflectivity Tyvek



PMTs in the far detector

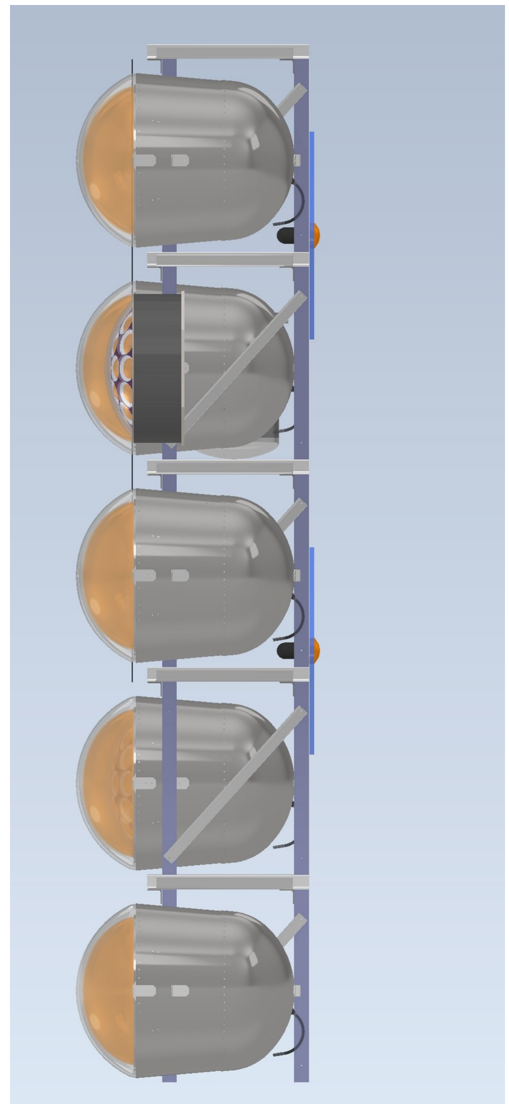
Photo-detection systems have different goals in inner and outer detectors: important characteristics differ

Inner detector

Event reconstruction

- Timing resolution for vertex reconstruction
- Charge resolution, coverage and detection efficiency for momentum
- Granularity for PID
- Photo-coverage and detection efficiency for low energy events
- Low dark rate for neutron tagging from hydrogen capture

Optimized high QE 20” PMTs + multi-PMTs



Outer detector

Reject entering background

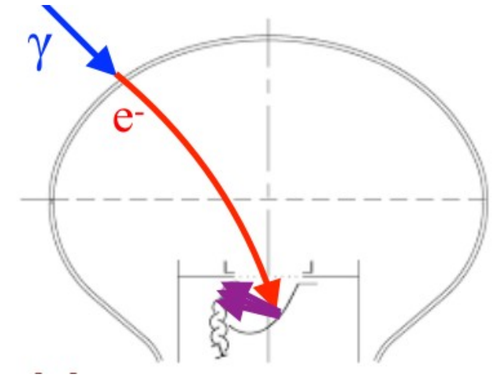
Veto based on cluster of hits above threshold:

- Large number of PMTs to increase information entropy of signal
- Good light collection efficiency
- Low dark rate to be able to use low threshold

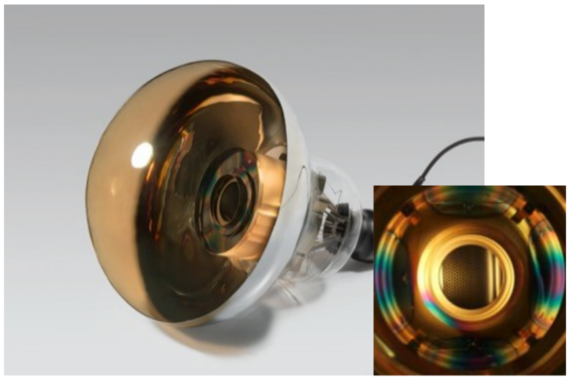
3” PMTs in WLS plates with high reflectivity Tyvek

Candidate 20" PMTs

- 3 models of 20" PMTs have been considered for HK ID
- All have high quantum efficiency, but rely on different amplification methods



Hybrid PMT	Box & Line PMT	MCP PMT
Hamamatsu R12850	Hamamatsu R12860	NNVT GDB-6203



Avalanche diode

- Simple, and excellent resolution
- Challenges for pre-amplifier design and mass-production => abandonned as an option

Box & Line dynode

Micro channel plate

Options considered for selection of 20% ID coverage by Japanese groups in 2020

Hamamatsu R12860

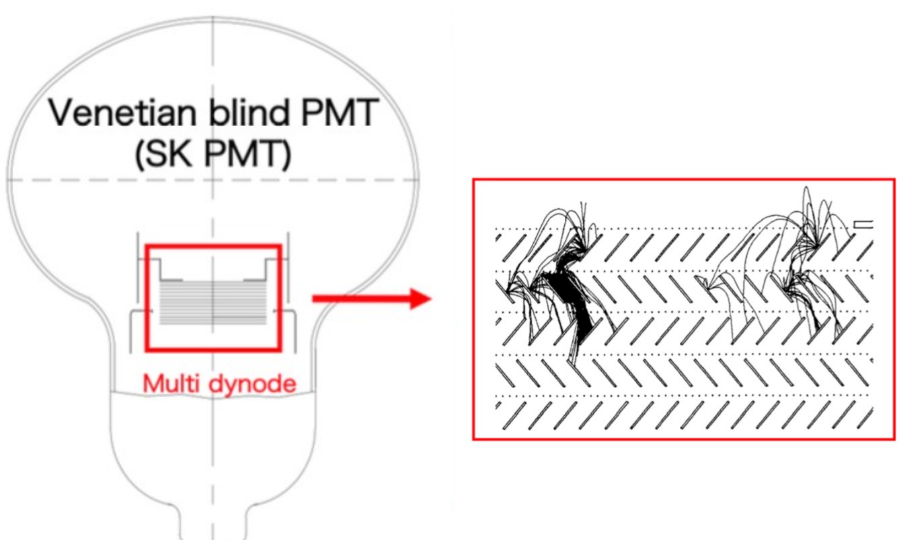
A number of improvement compared to R3600 used in Super-Kamiokande:
- Higher QE and electrons less likely to miss first dynode => higher detection efficiency
- More uniform electron drift path => better timing and charge resolution

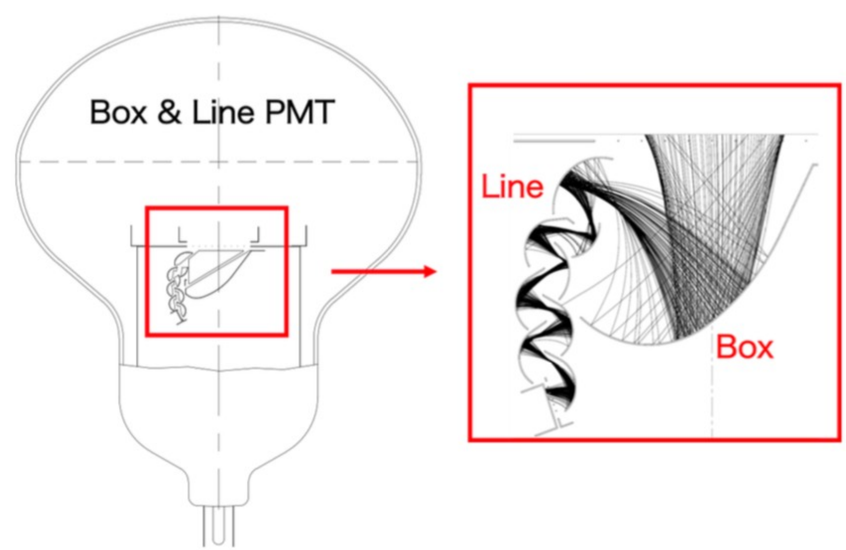
Super-K PMT
Hamamatsu R3600

Venetian blind dynode

Hamamatsu R12860

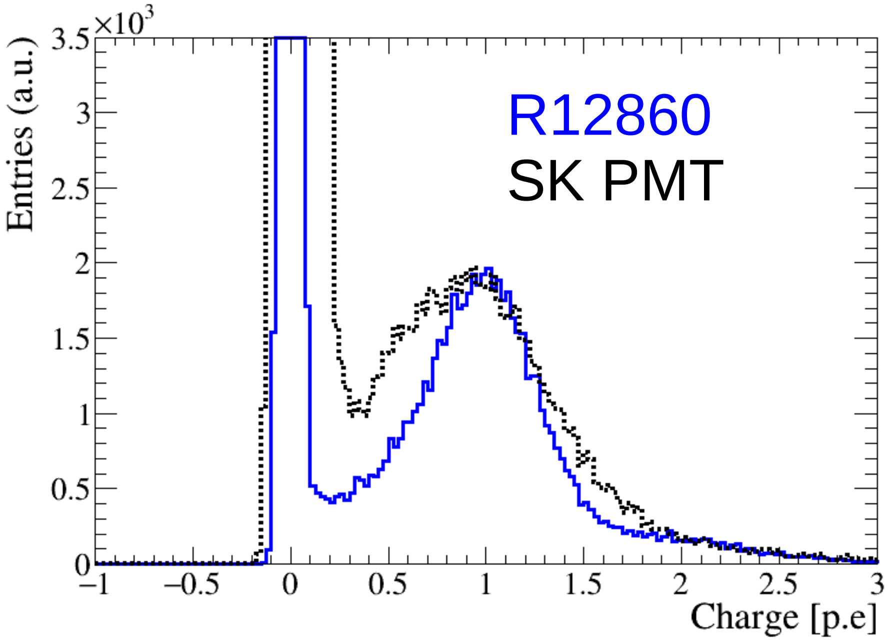
Box and line dynode
+ high QE

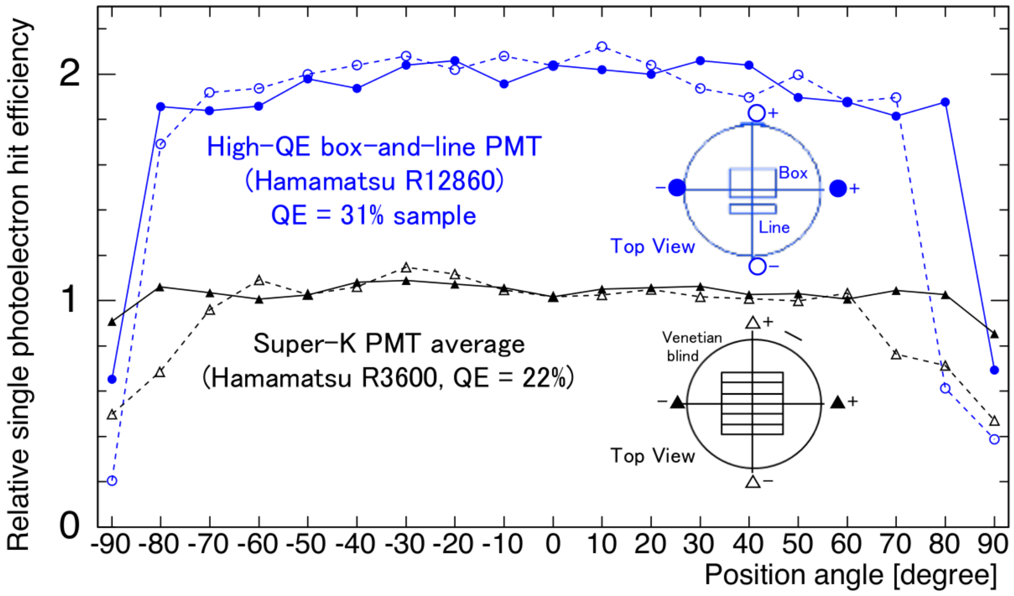


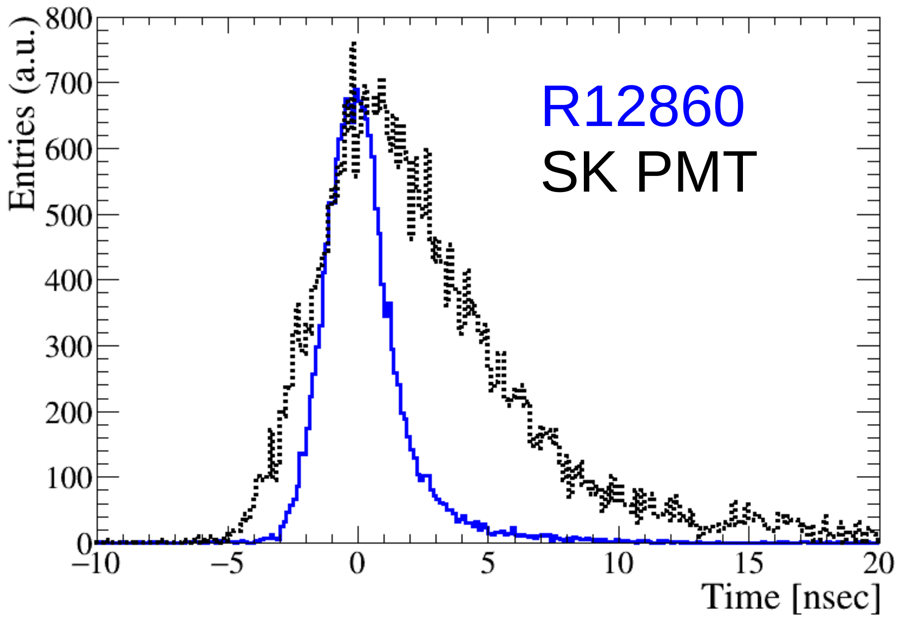


Hamamatsu R12860

Clear improvement seen in tests:
- ~2x photo-detection efficiency
- TTS: 6.73 ns → 2.59 ns (FWHM)
- Charge resolution: 60.1% → 30.8%





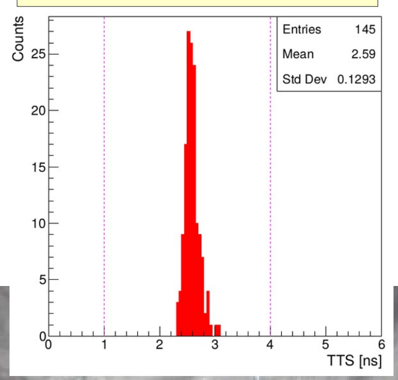


Hamamatsu R12860 Installation in Super-Kamiokande

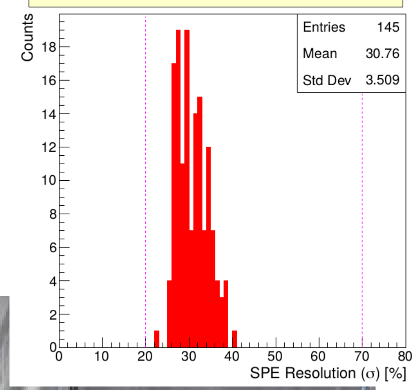
Refurbishment of Super-Kamiokande in the summer of 2018:

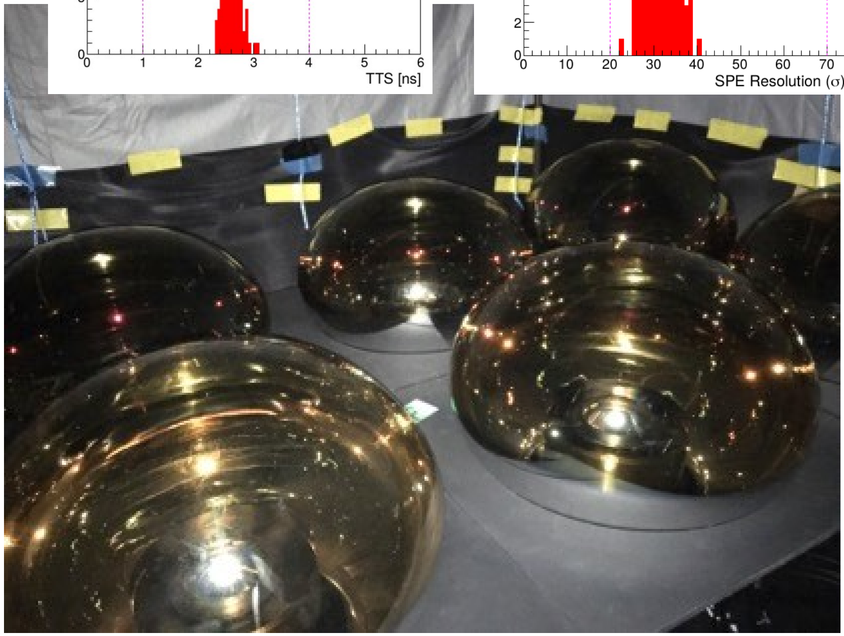
- 140 R12860 PMTs were purchased to replace PMTs from dead channels
- Tested prior to installation: all satisfied criteria to be installed in detector
- 136 new PMTs installed in the detector: high quality new PMTs for Super-K, and provides data on preformance in real detector and long term stability for Hyper-K

Timing resolution



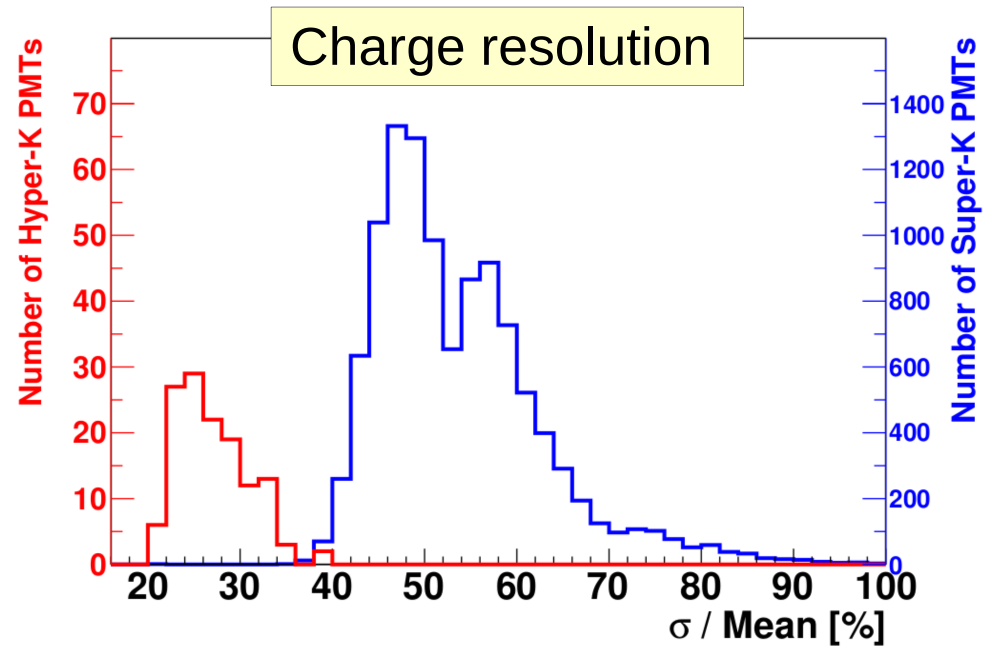
Charge resolution

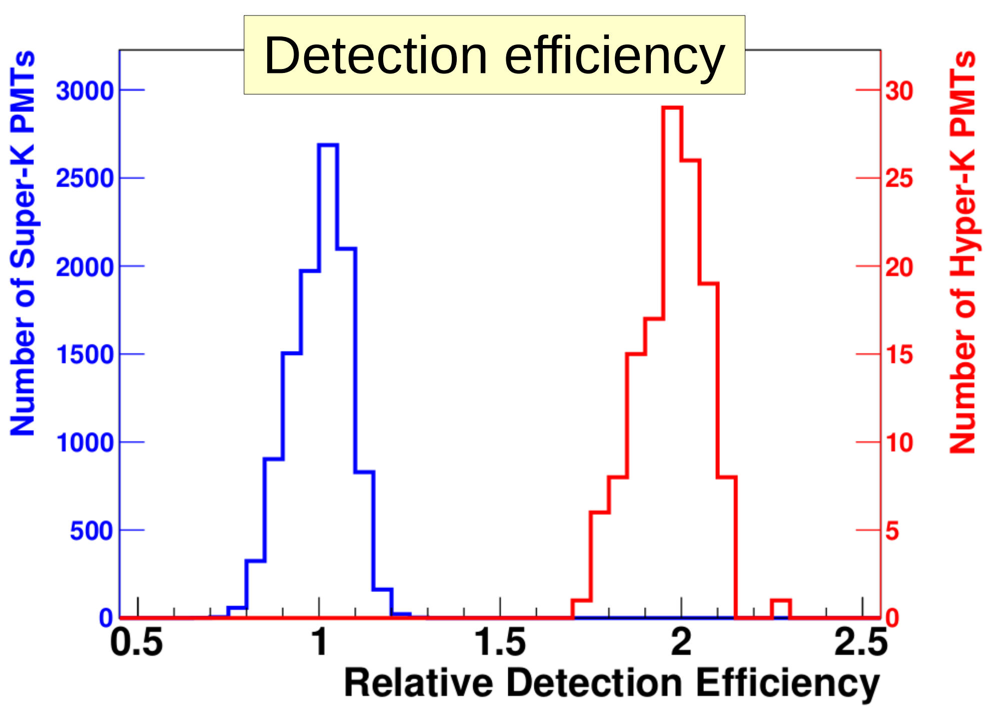


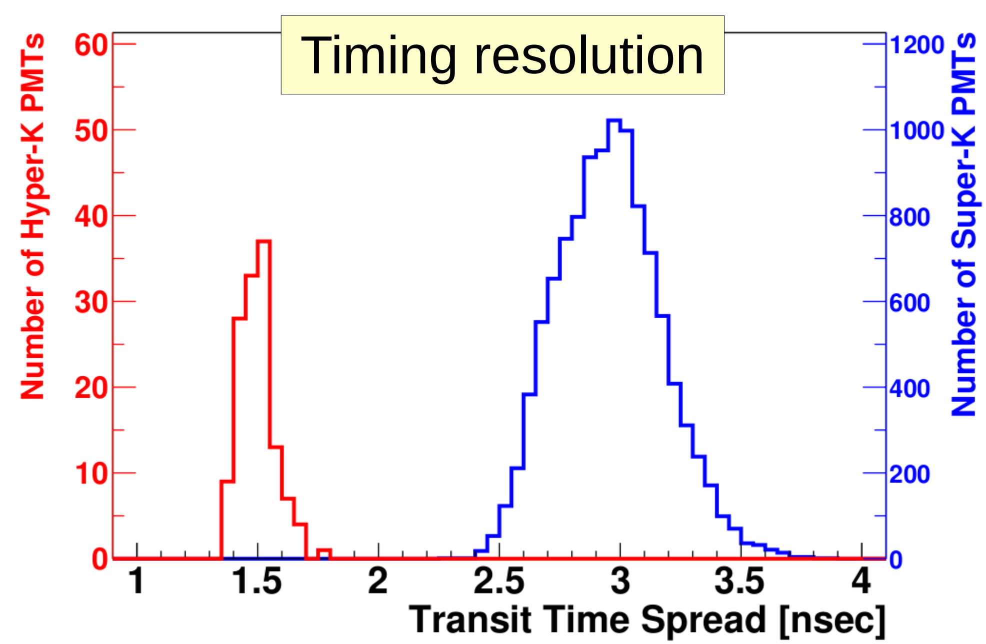


Hamamatsu R12860
Performance in Super-Kamiokande

- Measurement inside Super-K confirmed improved detection efficiency, and charge and timing resolution in real detector conditions
- Measured timing resolution (σ=1.5 ns) worse than pre-installation tests (σ=1.1 ns), believed to be due to unidentified element in Super-K measurement and not change of PMT performance



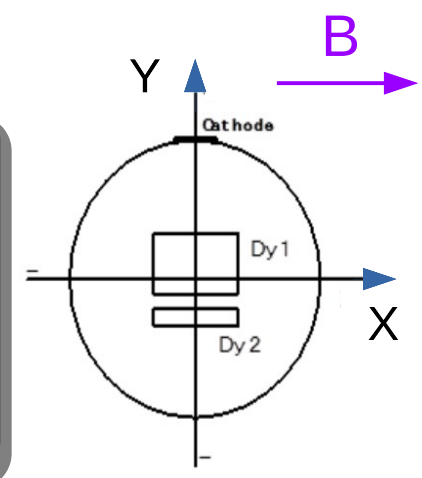




Hamamatsu R12860
Uniformity of performance

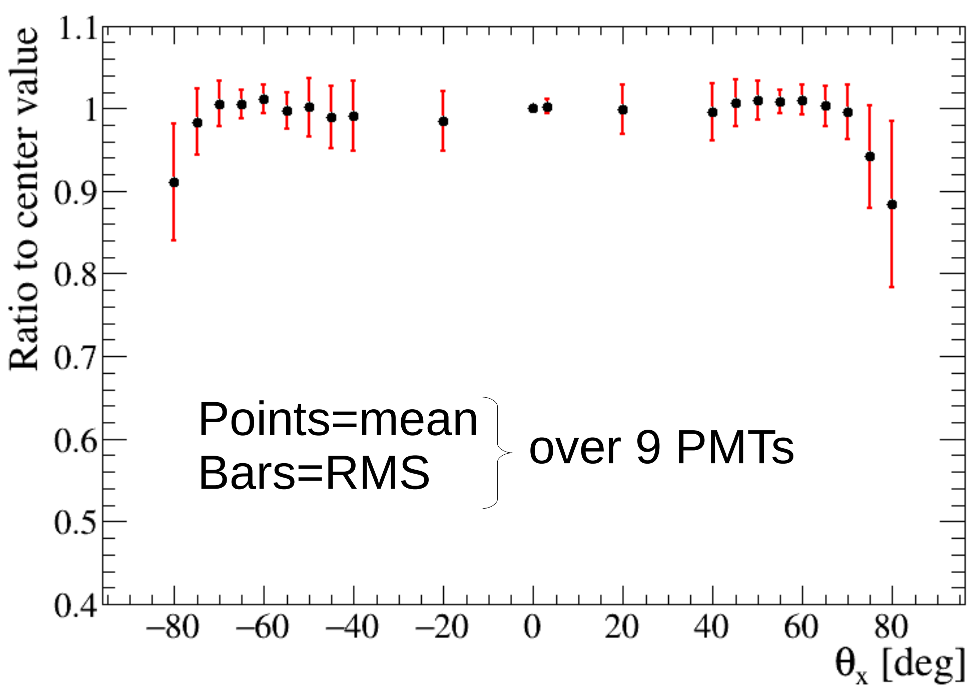
Checked uniformity of PMT performance for 9 PMTs before installation:

- Found to be uniform on a large fraction of the PMT surface,some degradation around the edge and near the “box” dynode
- Magnetic field effect strongly depends on hit position, biggest effect seen near “box” dynode. Other places less than 10% for |B|<100 mG
- Satisfies requirements for Hyper-K

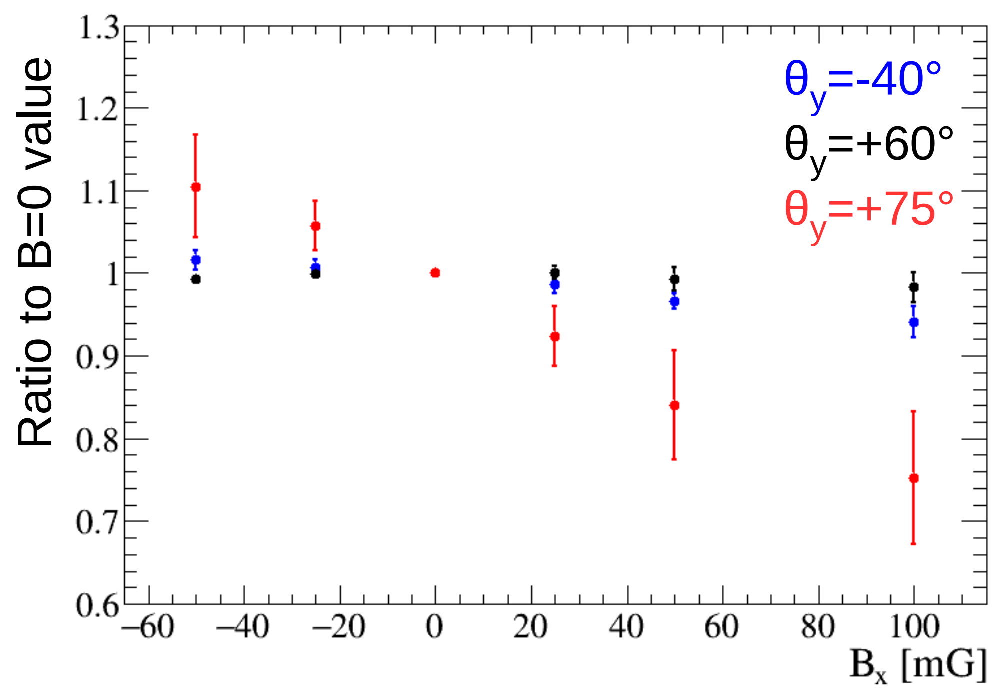


R12860 TOP VIEW

Gain as a function of hit position



Gain as a function of B field



MCP PMT Development

- 20” (and 8”) PMTs using Micro Channel Plates for amplification developed for JUNO
- Good detection efficiency, low after-pulse, pressure tolerance and low RI glass
- Weak point for Hyper-K was timing resolution and high dark rate
- New model using focusing electrodes developed by NNVT to improve timing resolution
- 2270 such PMTs used in the LHASSO experiment

Normal focusing electrode

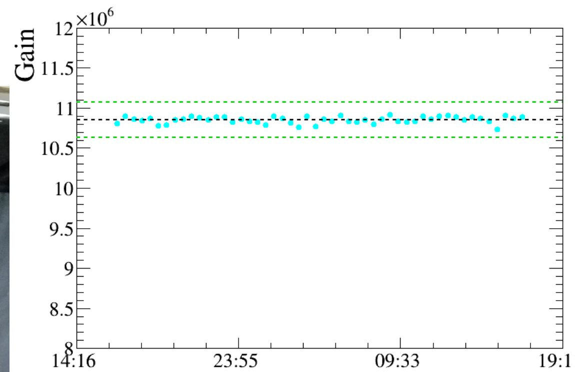
Flower-like focusing electrode

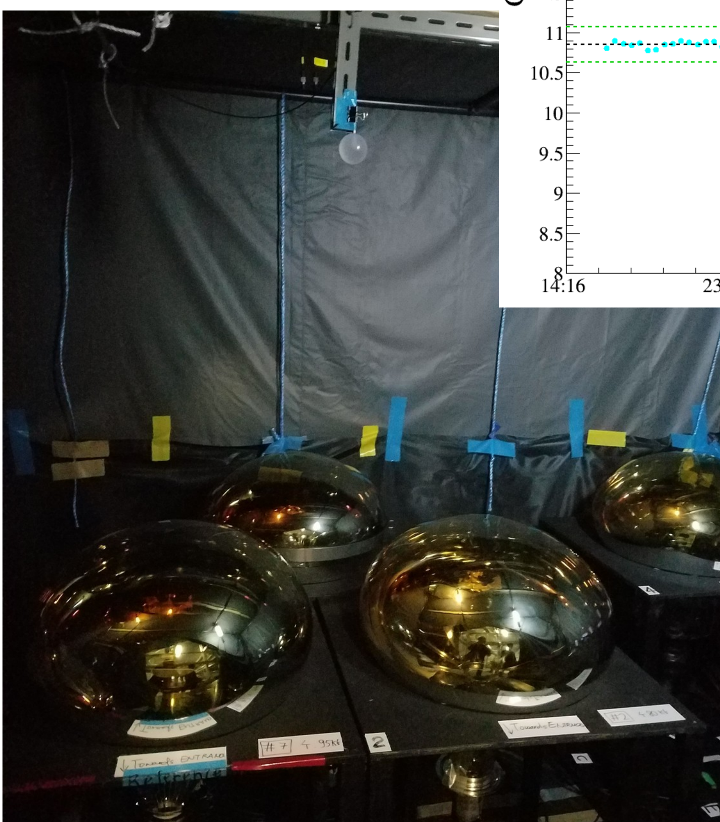
By changing the constructer of the focusing electrode, using the flower-like one, the TTS of the PMTs is improving from 14ns to 5ns, but the CE of the prototype is decreasing to 85%.

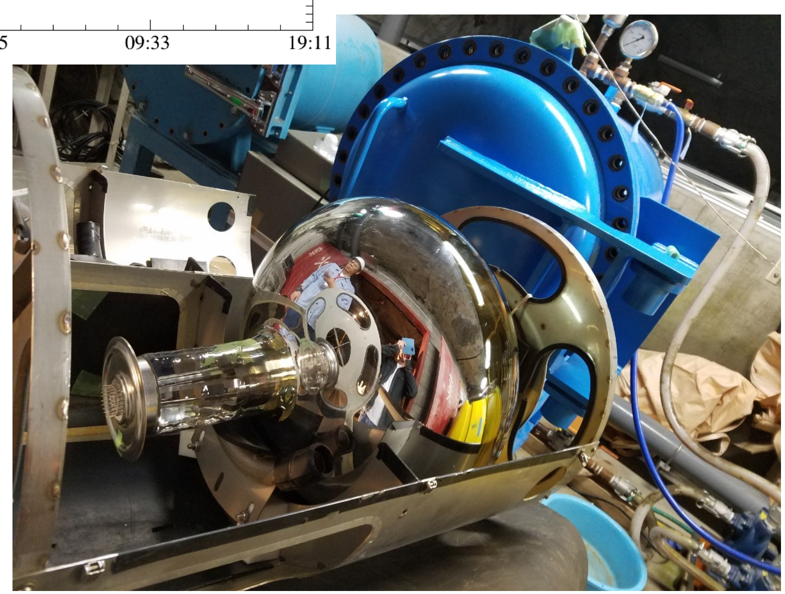
Ling Ren @ PD18 workshop

MCP PMT Test

- This new GDB-6203 MCP PMT was extensively tested as an alternative 20” PMT for Hyper-K
- Various performance were measured and practical aspects tested
- Iteration with NNVT to reduce dark rate
- Satisfied most of the Hyper-K requirements, but dark rate although reduced still higher than 4 kHz target, and concerns about repetition rate to handle nearby supernova
- Decided to use Hamamatsu R12860 for 20% ID photo-coverage from Japan, but MCP PMT open as an option for additional PMTs by other groups







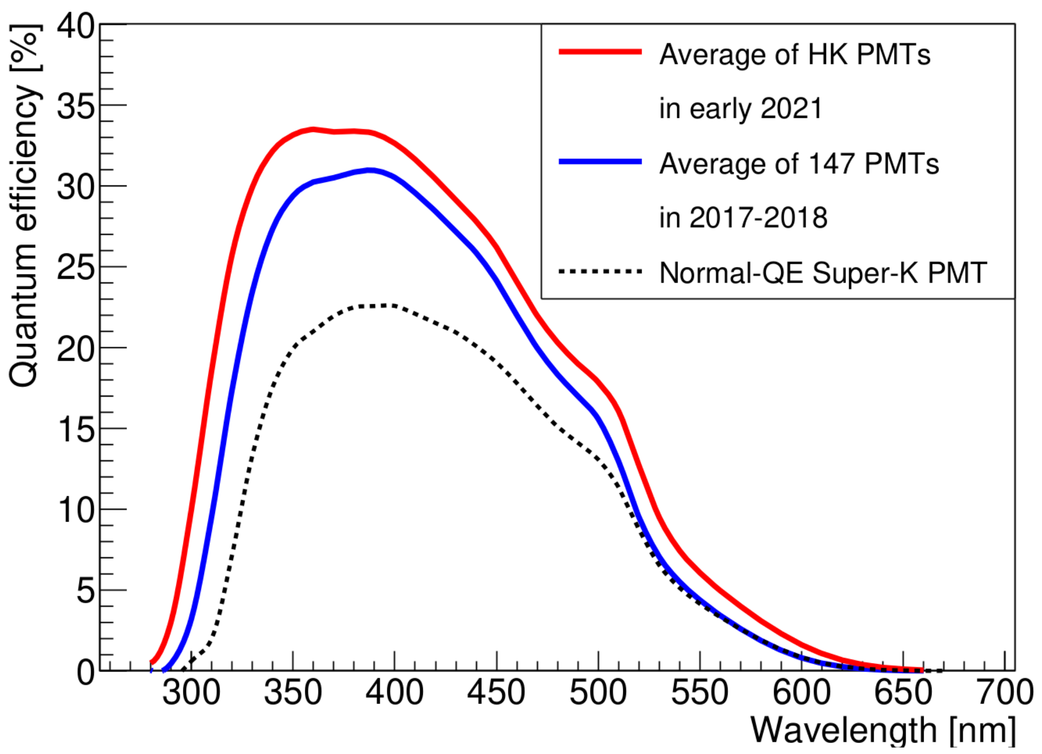
Hamamatsu R12860
Improvement since 2018

A number of additional development on the R12860 since the 140 PMTs were installed in Super-K:

- Glass purity improvement: reduced RI impurities, source of scintillation and improved transparence
- Reduce radon content of cables: 1.4 mBq/m → <0.1 mBq/m
- Further reduction of dark rate by Hamamatsu achieved 4 kHz target

Radio isotopes in glass (Bq/kg)

	Super-K (R3600)	R12860 (before)	R12860 (after)	R12860 (2021)
U	5.5	5.4	2.9	2.5
Th	1.8	1.8	0.95	0.7
^{40}K	18.2	1.6	2.0	1.0

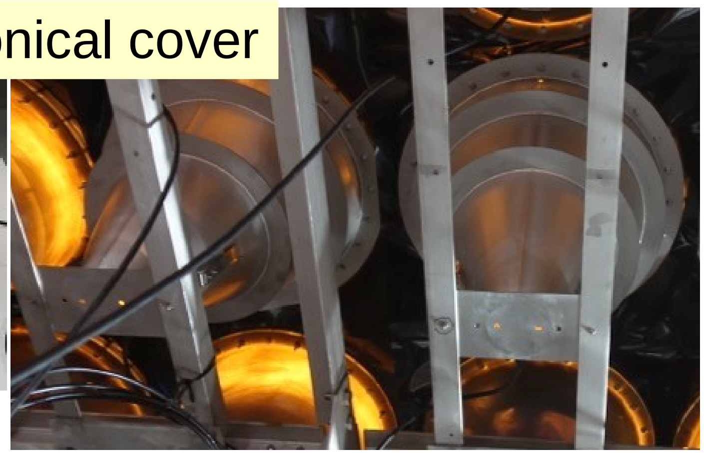


Hamamatsu R12860
Start of mass production

- Mass production of the 20k R12860 PMTs from Japan has started
- First PMTs delivered in Dec. 2020, 300 by the end of JFY2020
- >1500 PMTs delivered to date
- ~800 were checked (visual inspection+signal check): no major problems found, feedback to Hamamatsu led to a number of modifications
- Setup in preparation for more detailed performance checks of a fraction of the delivered PMTs

Anti-implosion covers

- Protective covers to prevent chain implosion
- Developed new covers producing less background than Super-K ones
- 3 different designs considered for Hyper-K
- Validation using underwater implosion tests. Some designs already passed the test
- Final decision after next implosion test at the end of the year

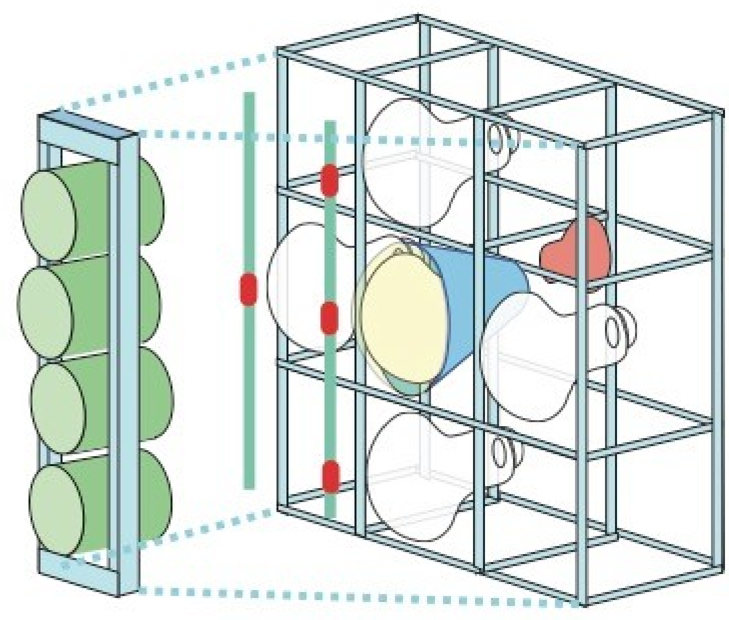



SUS conical cover

Resin cover

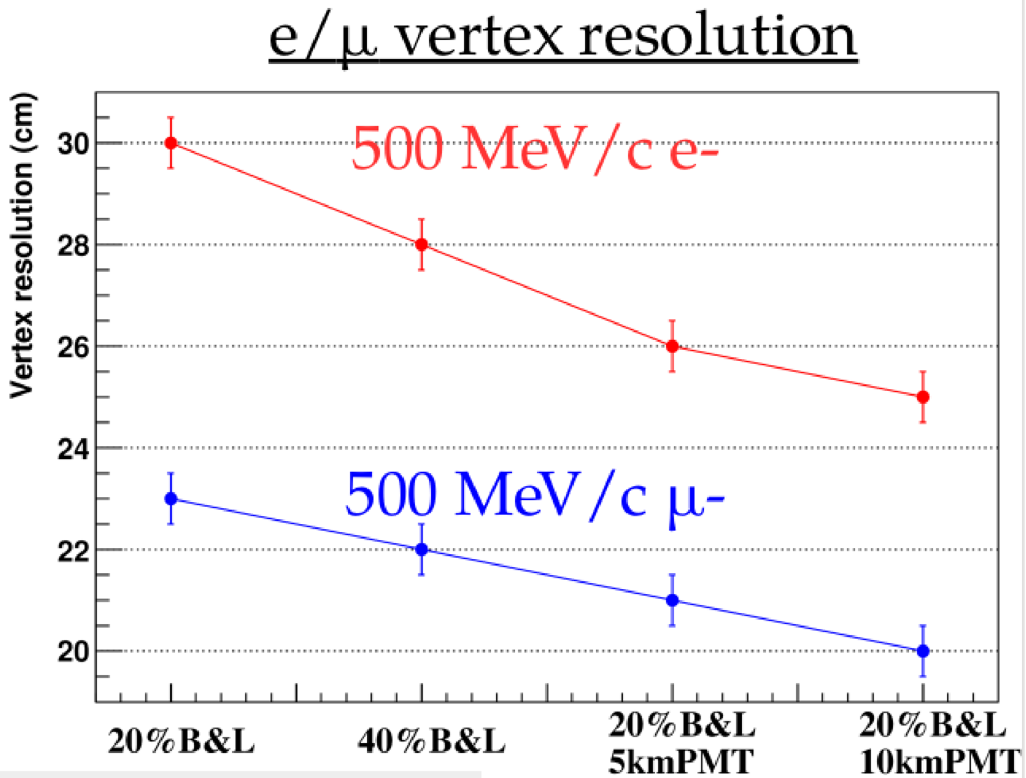
SUS cylindrical cover

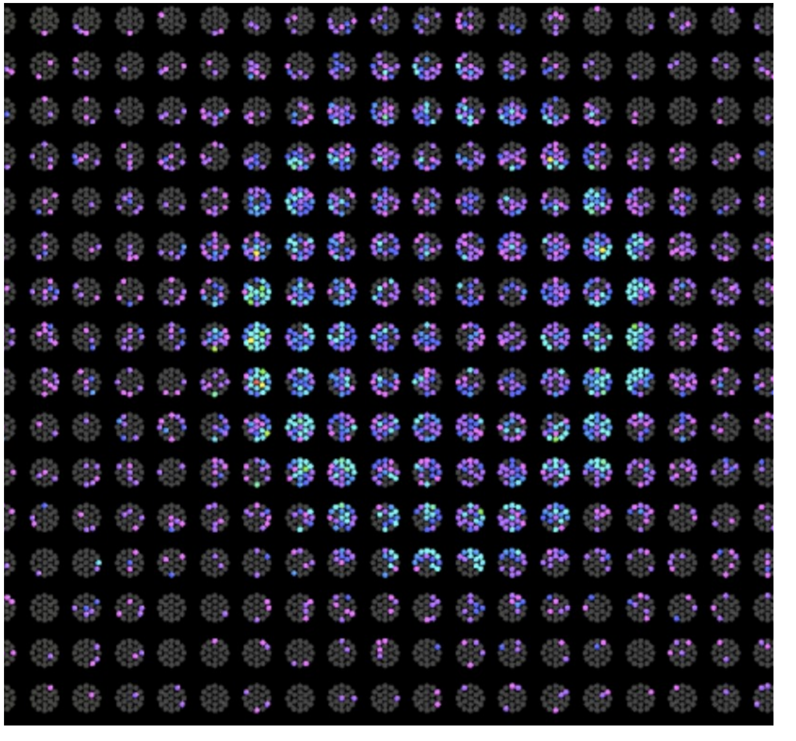
<u>Validation</u>: implosion tests (under water, 80m 3 times)



Multi-PMT
Concept and interest

- 19 3” PMTs in a pressure vessel.
- Will be used in complement of 20” PMTs at far detector, and fully equip IWCD
- High granularity, photon directional information improves reconstruction near the walls and potentially ring separation for multi-ring events
- Better timing resolution than 20” PMTs, improves vertex resolution and PID near the walls
- Improves calibration: reference photo-sensor with good charge/timing characteristics, and LED light sources for photogrammetry and various calibrations

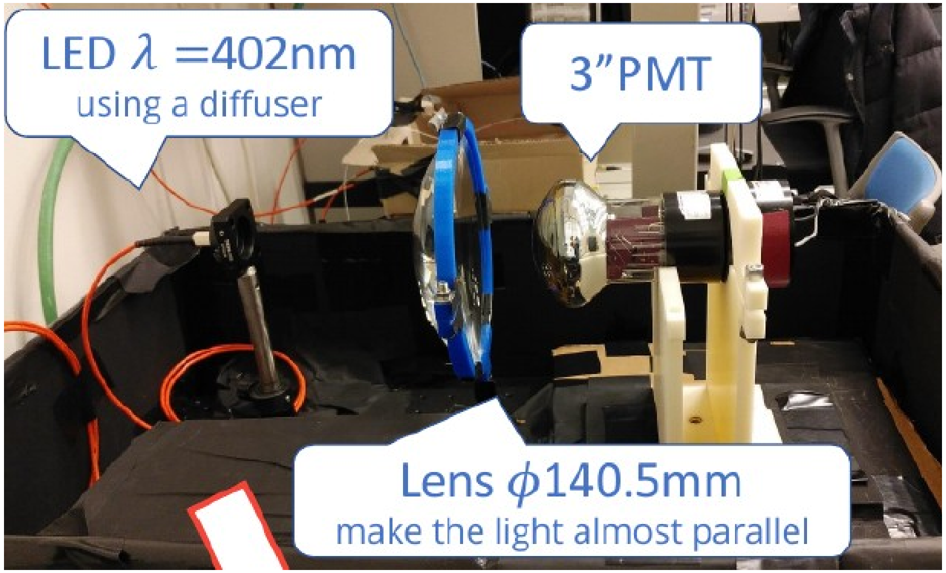


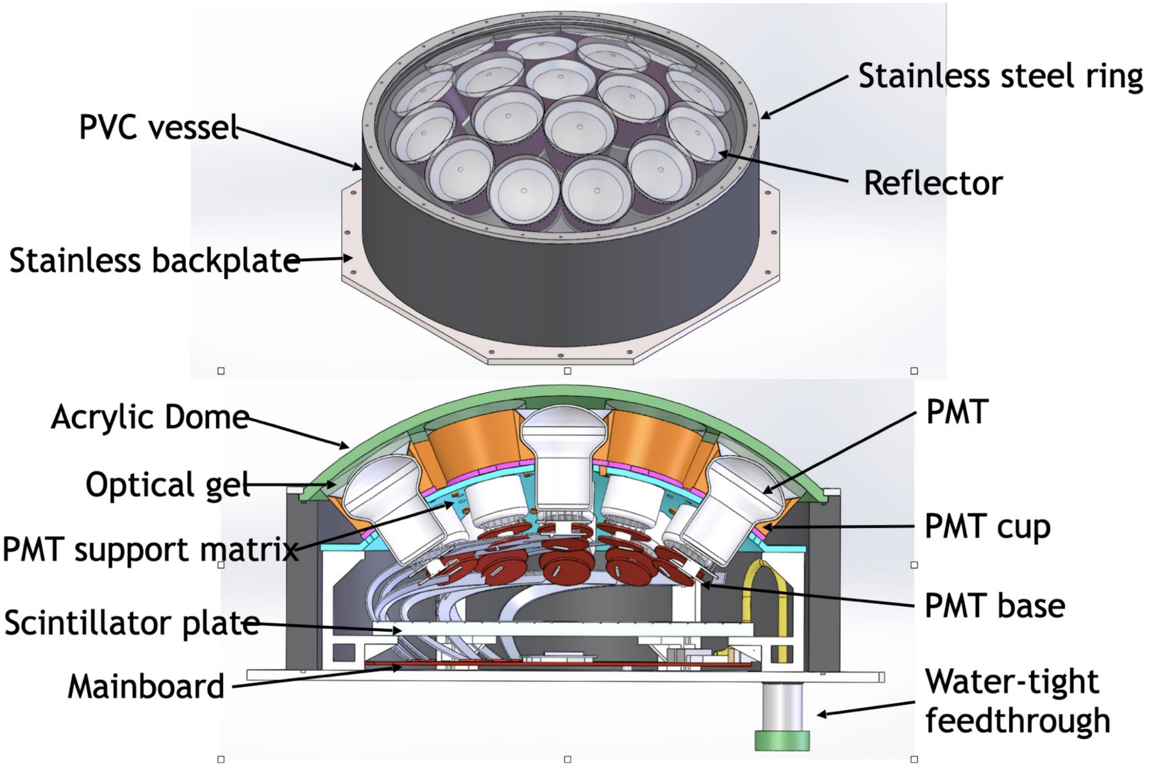


B.Quilain @ TAUP 2019

Multi-PMT Design

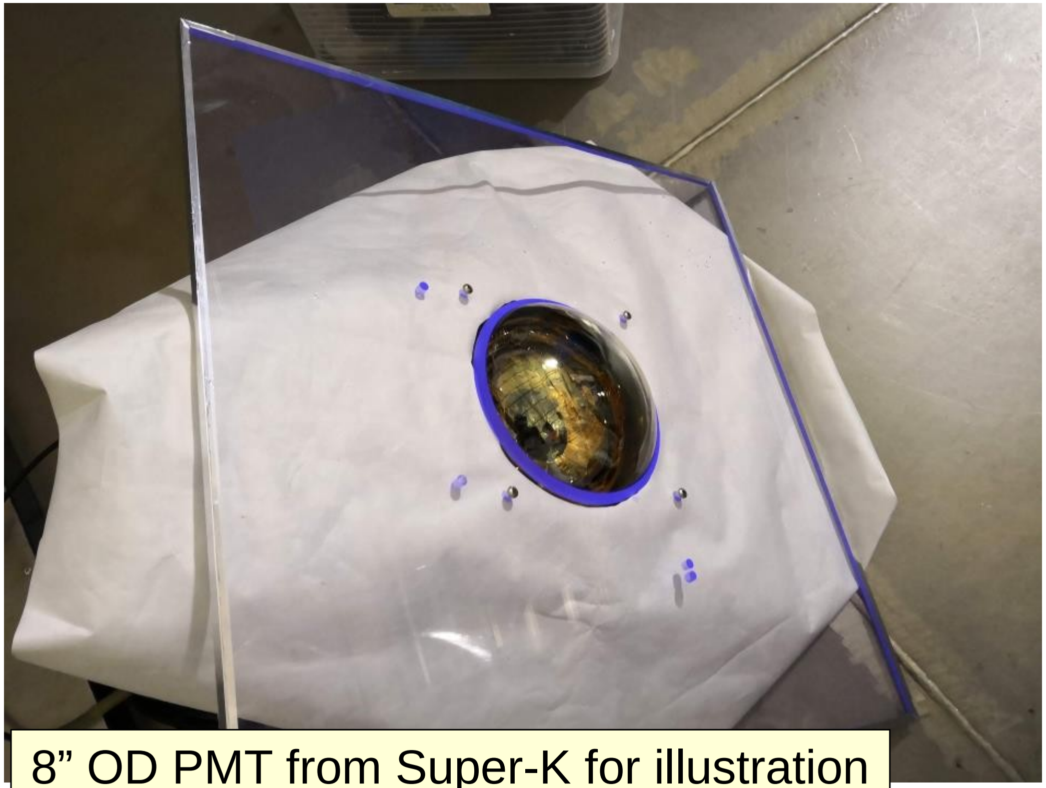
- Module includes PMTs, high voltage and electronics
- Acrylic for the transparent part, PMTs coupled to it using optical gel
- Assembly method being developed, 2 alternative approaches considered
- On-going tests of candidate 3” PMTs in different countries



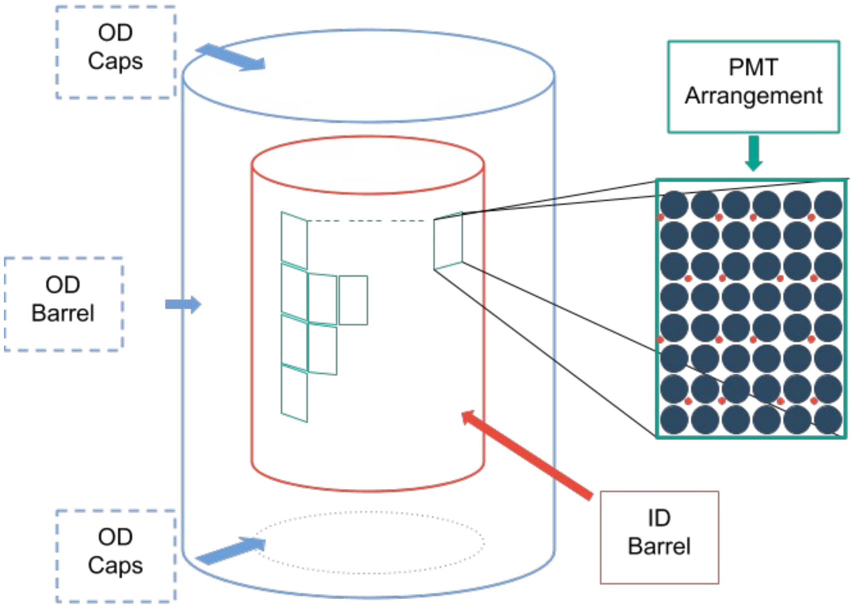


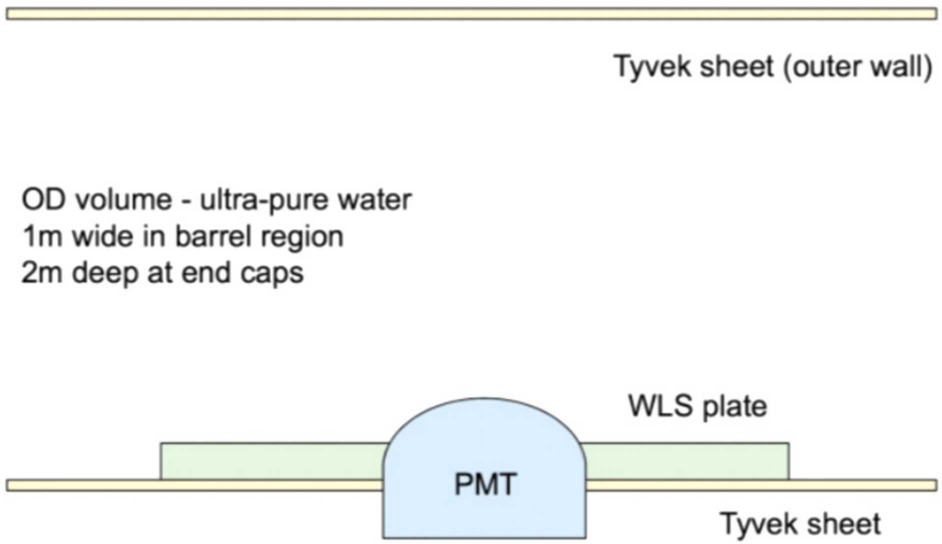
Outer-detector Concept

- Main goal of the OD is to reject entering background
- Instrumented with 10k outward looking 3” PMTs
- WLS and reflective material on the wall to increase light collection



8” OD PMT from Super-K for illustration





Outer-detector Candidate PMTs

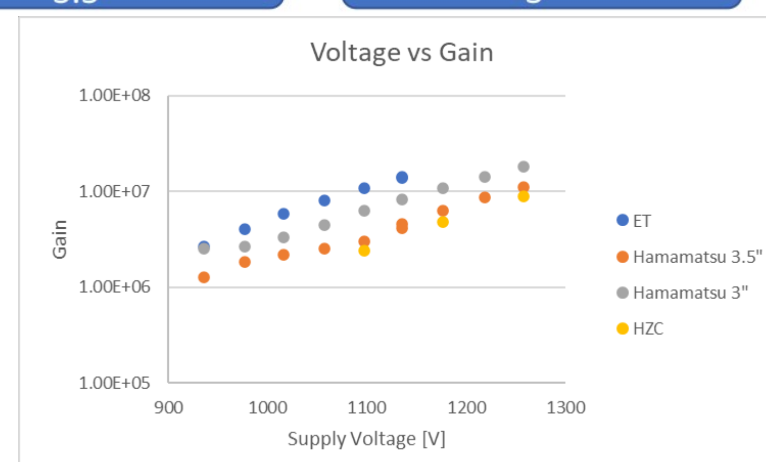
- Several 3” PMT models considered have been tested
- Found to satisfy gain, resolution and dark rate requirements

HZC XP72B2F 3”

ET Enterprises D459/2KFLB 3”

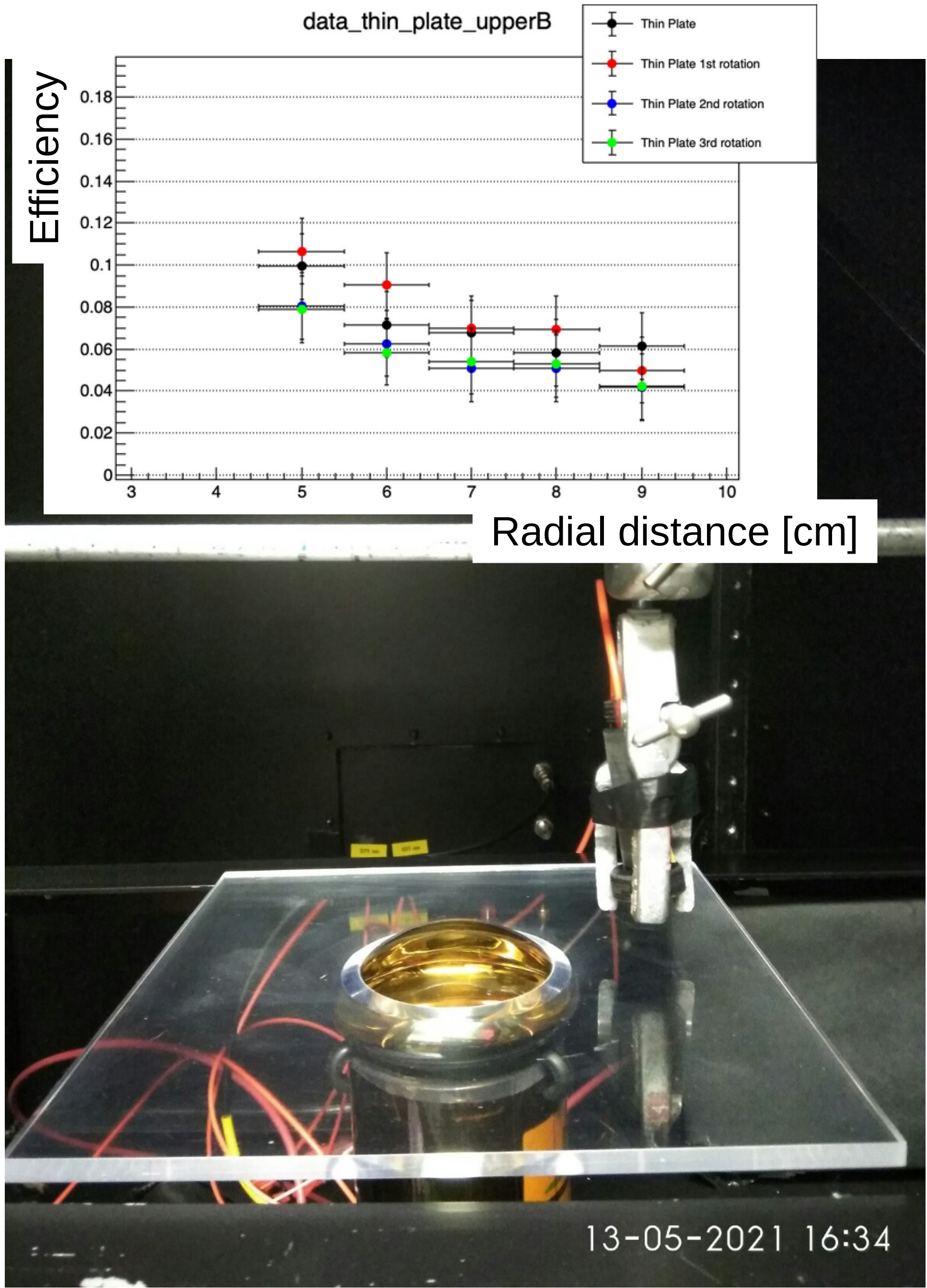
Hamamatsu R14689 3.5”

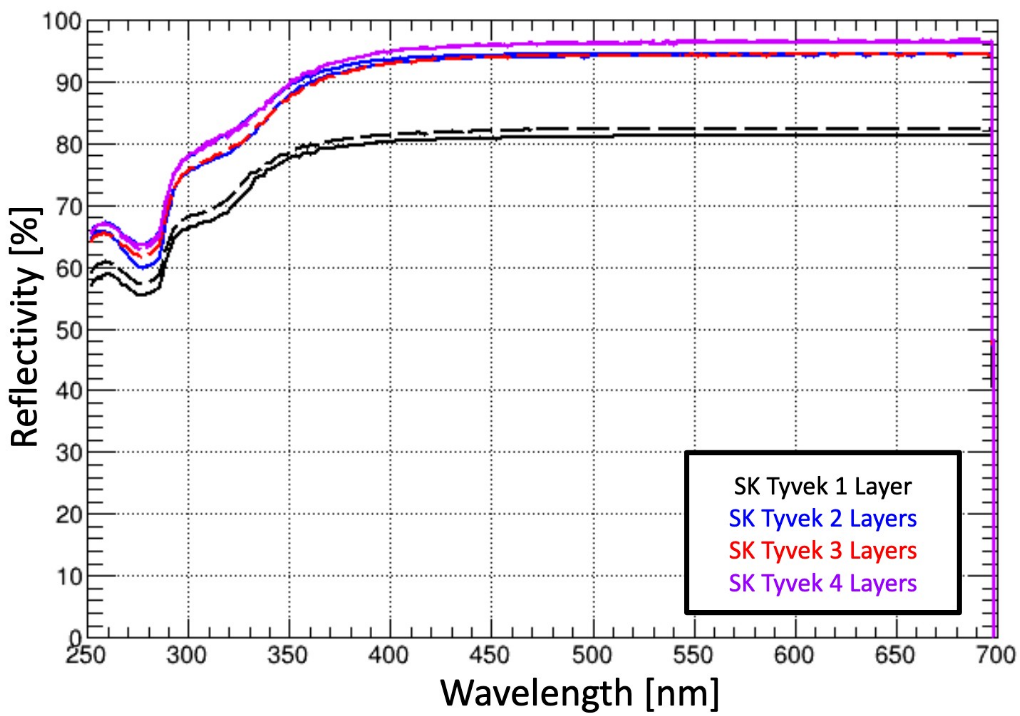
Hamamatsu R14374 3”



Outer detector
Light enhancement

- Different WLS plate were tested, measuring detection efficiency as a function of hit position
- Reflectivity of different Tyveks measured
- Found that reflectivity varied with the different types, but also number of layer used and way they were attached together

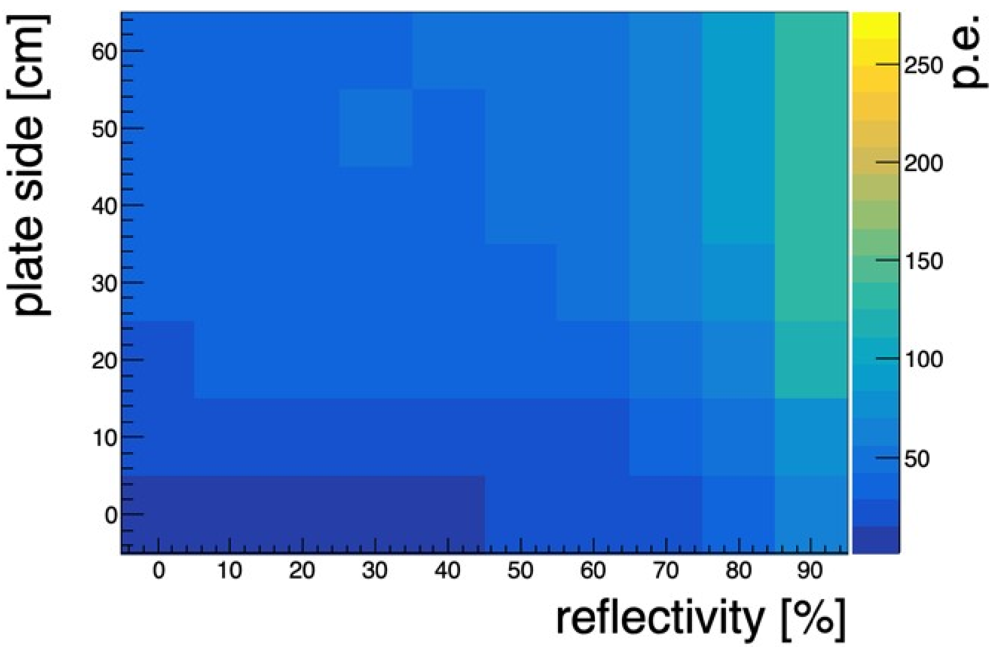




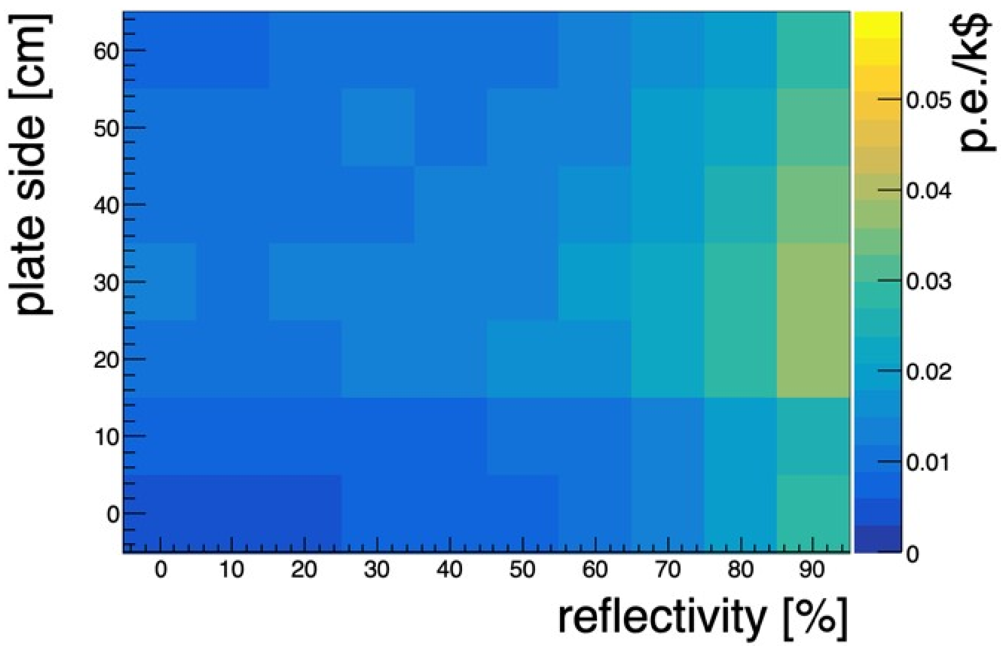
Outer-detector Optimization

- Simulation ran with different sizes of WLS plates and Tyvek reflectivity to optimize design of light collection system
- Found that investing in higher reflectivity Tyvek was a cost-efficient way of increasing light collection
- Baseline design uses 30 cm plates with >90% reflective Tyvek

Photons detected



Photons detected per k$



Summary

- Inner detector of Hyper-Kamiokande will be using improved 20” photo-sensors compared to the currently running Super-Kamiokande

- Hamamatsu R12860 PMTs selected for 20% photo-coverage contribution by Japanese groups has double collection efficiency, twice as good charge resolution and more than twice as good timing resolution

- Mass productions of those PMTs has started and will continue until 2026

- In addition multi-PMTs will provide higher granularity and photon directional information, as well as reference PMTs for calibration

- Outer detector systems relies on 3” PMTs to reject entering background, with WLS plates and high reflective Tyvek on the walls to increase light collection

BACKUP

Test of 140 B&L PMT in Super-K
Pre-selection criteria

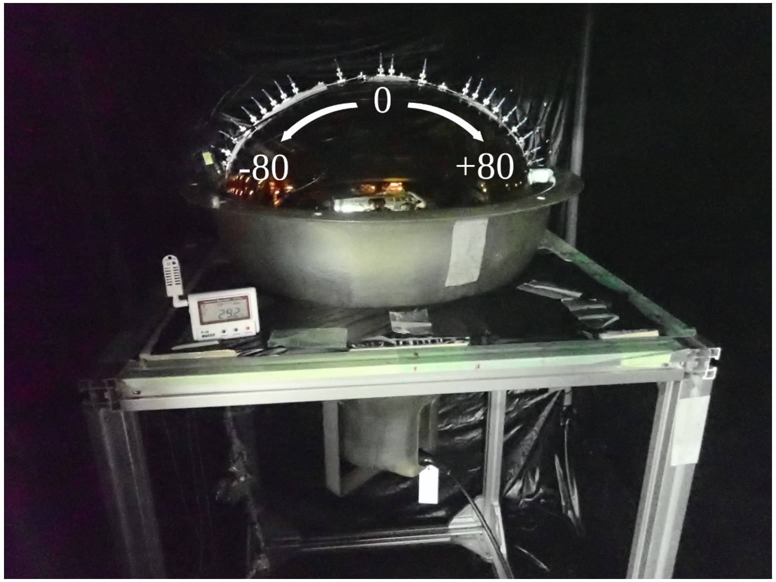
All of the 140 PMTs were tested at Kamioka
- checked PMTs pass requirements to be installed in Super-K
- Measurement with SK gain (1.4e7)

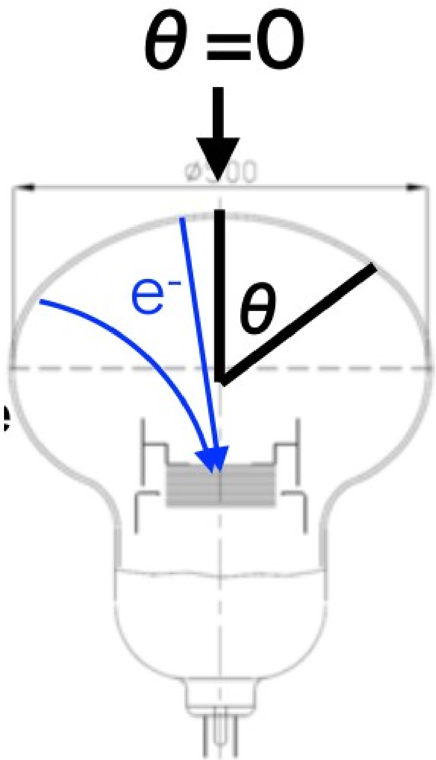
Pre-selection	Min	Max	Unit
Voltage for 1e7 gain	1500	2350	V
Voltage for 1.4e7 gain	1500	2350	V
Dark rate	2	30	kHz
TTS (FWHM)	1	4	nsec
1PE Resolution (sigma)	20	70	%
P/V	2.5	-	
Afterpulse rate (0.5-40us)	0	10	%
Maximum output	3	12	V

Hamamatsu R12860 Uniformity measurement

For 9 PMTs checked uniformity of PMT response and performance:

- As a function of photon hit position for zero magnetic field
- As a function of magnetic field for photons hitting at a given position

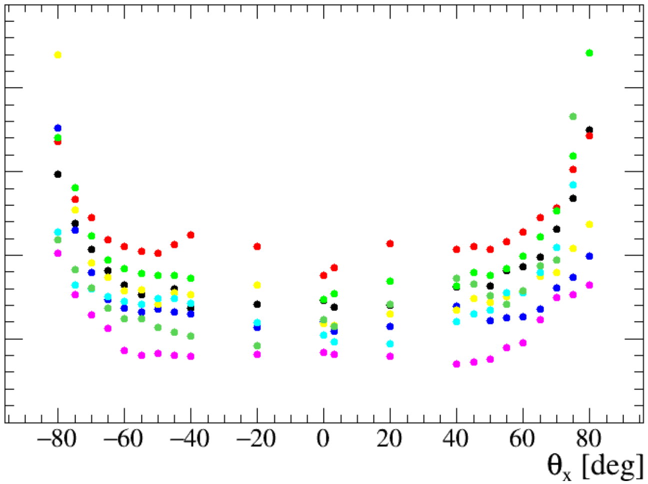




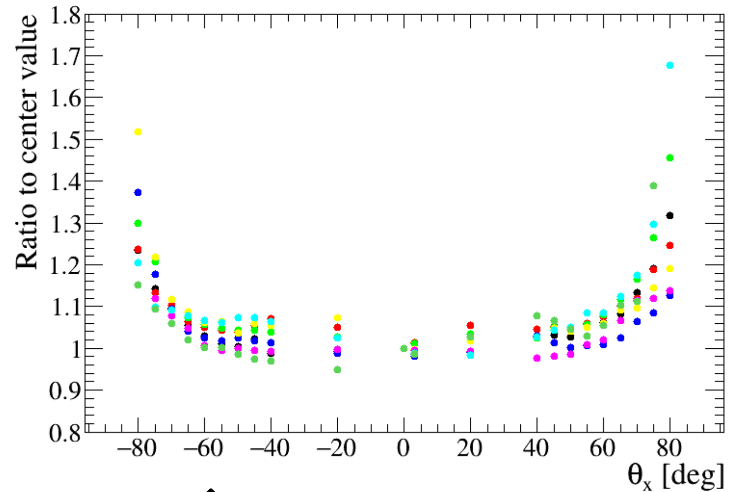
Uniformity measurement: plot construction

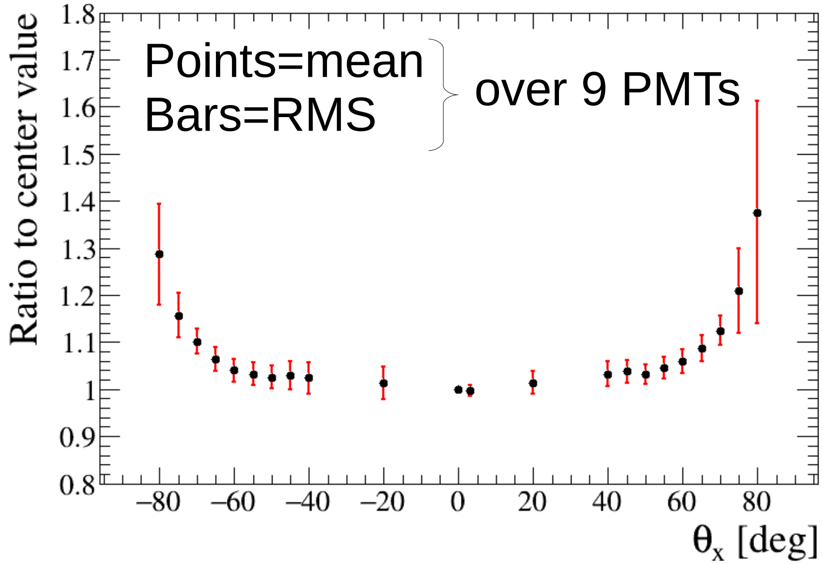
Measurement on 9 different PMTs:
- → differentiate real pattern from problem on one PMT or measurement
- → variation on the size of the effects seen from one PMT to another

1. Measure in each configuration for each PMT



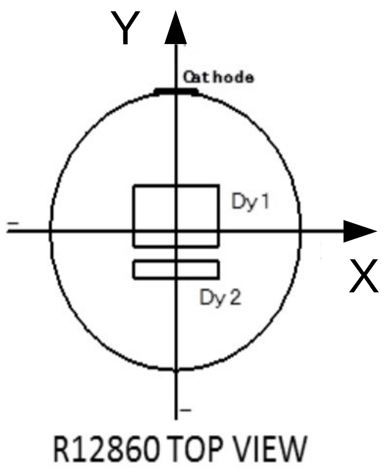
2. Make ratio to reference value (fiber at center or B=0) for each PMT





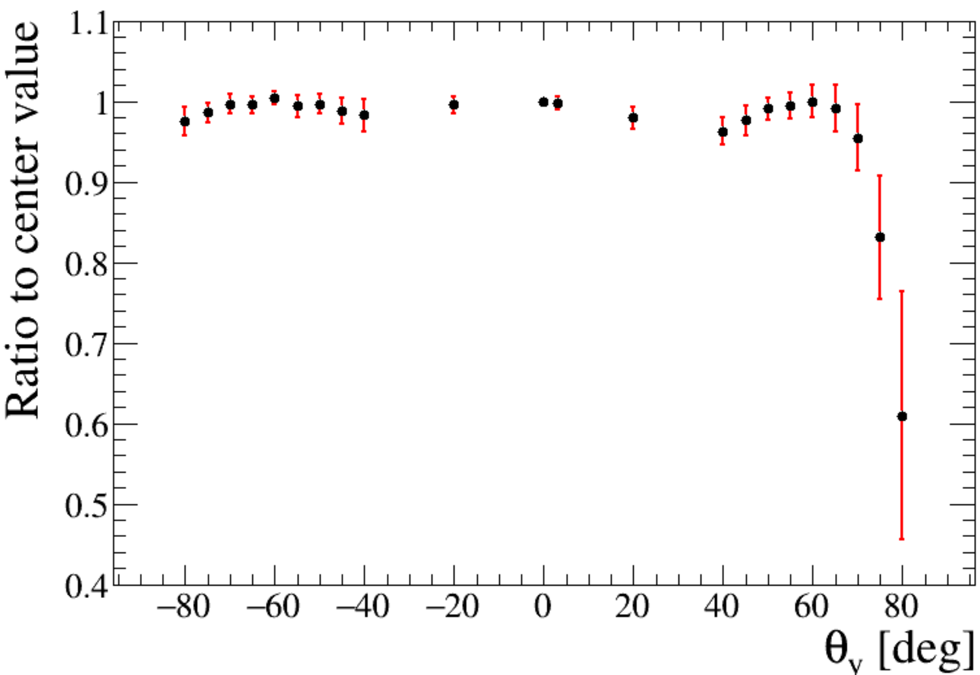
3. Convert to mean and dispersion of the 9 PMTs for each point on the horizontal axis

Hamamatsu R12860
Gain as a function of position

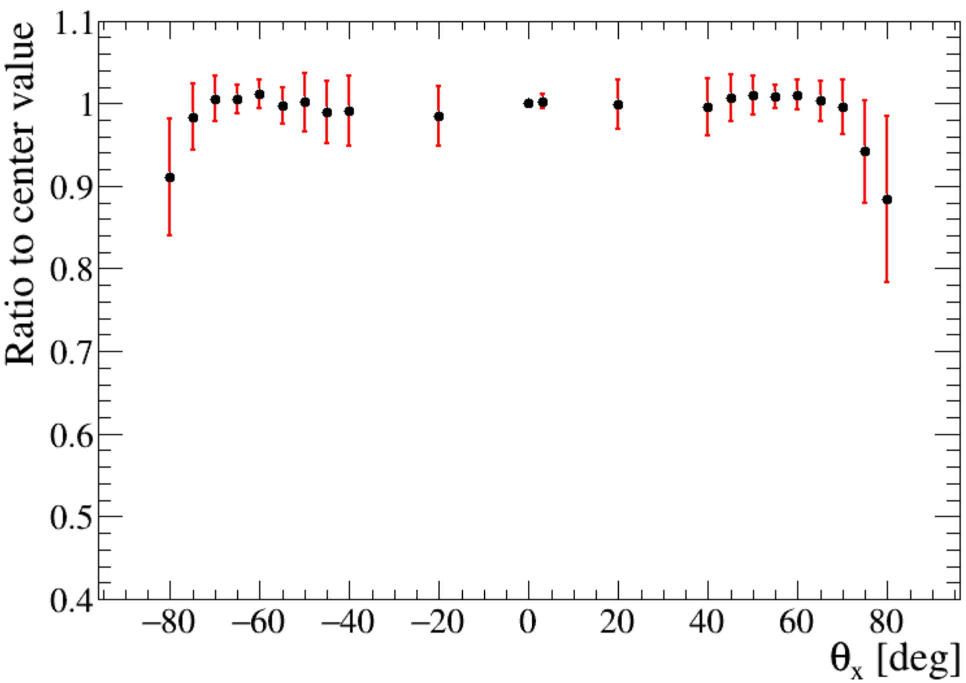


- Gain seen to be stable as a function of the photon hit position, except in the edge regions
- Asymmetry between box and line regions

<u>Line to Box direction</u>
(Y axis)

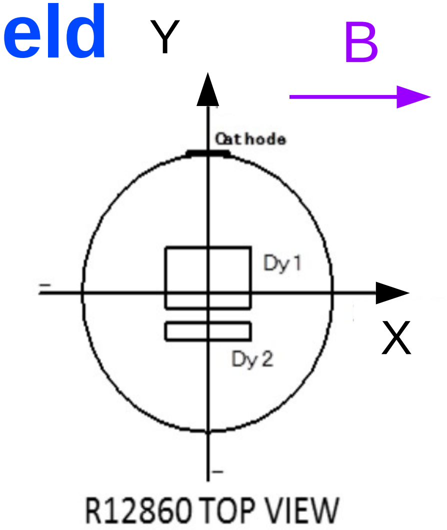


<u>Perpendicular direction</u>
(X axis)



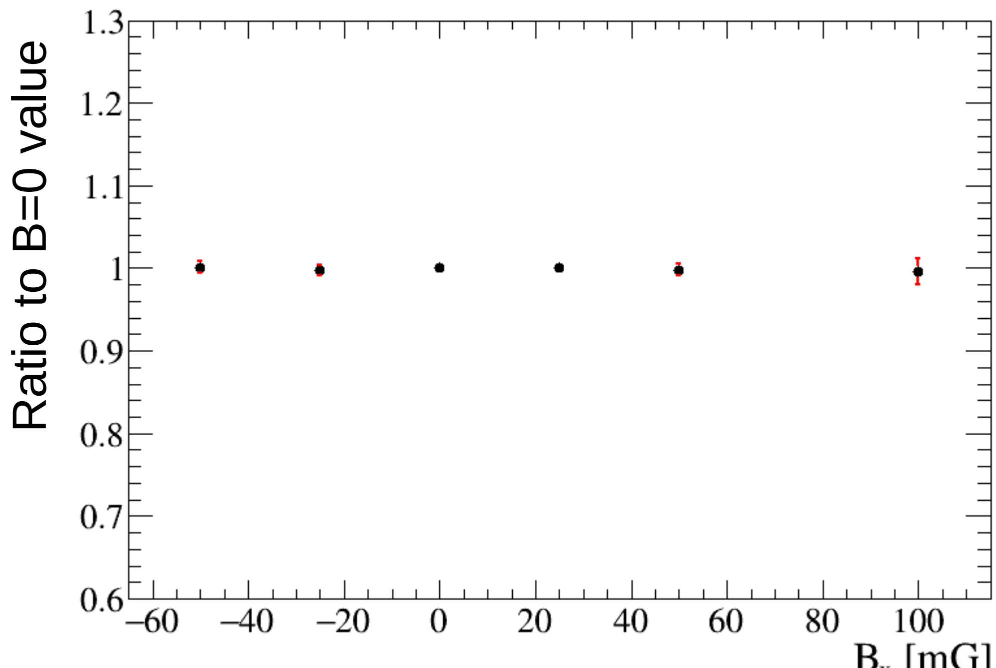
(no magnetic field)

Hamamatsu R12860
Gain as a function of magnetic field

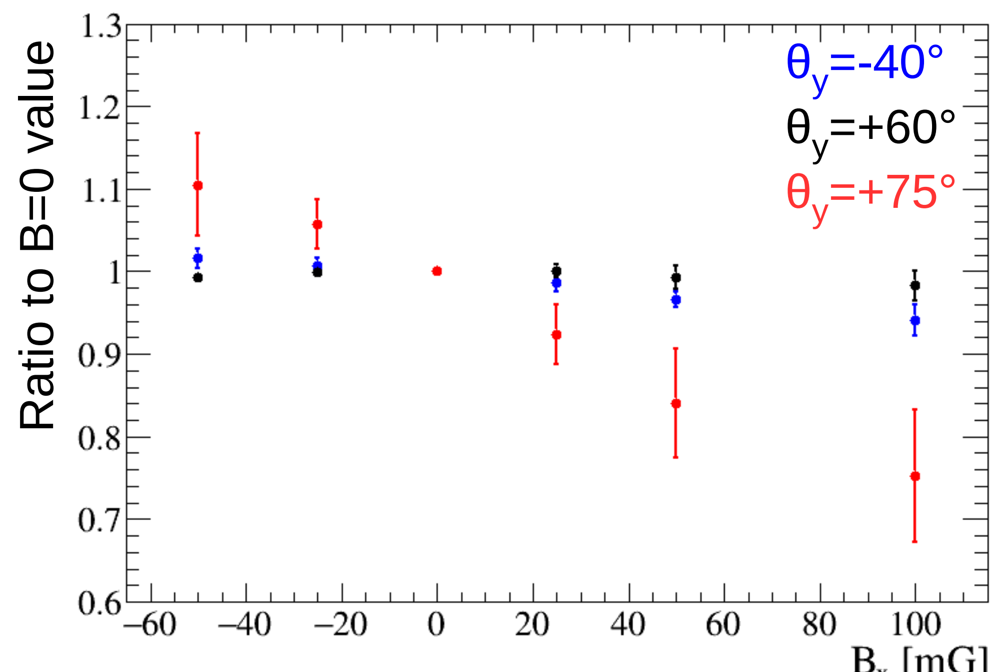


- No effect on gain if photon hits in the central region, or away from center on the axis parallel to the field
- Can see an effect for hits displaced along an axis perpendicular to the field:
  - size of the effect depend strongly on position in that case
  - biggest effect seen on the Y axis behind the box dynode (θ_y>75°)
  - in other places, variations of less than 10% in the expected range of magnetic field in Hyper-K (-100mG to +100mG)

Photon hitting at θ**x**=75°



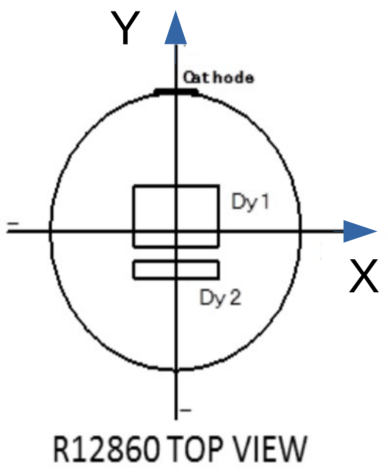
Displacement perpendicular to B field



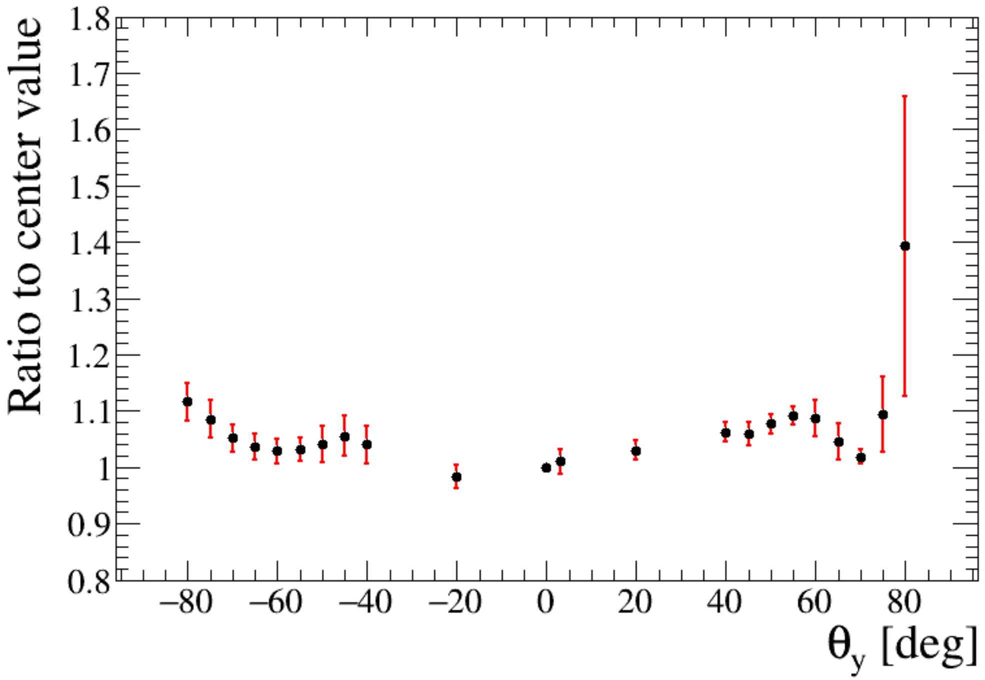
(Magnetic field along the x axis, null along the other axis)

Hamamatsu R12860
TTS as a function of position

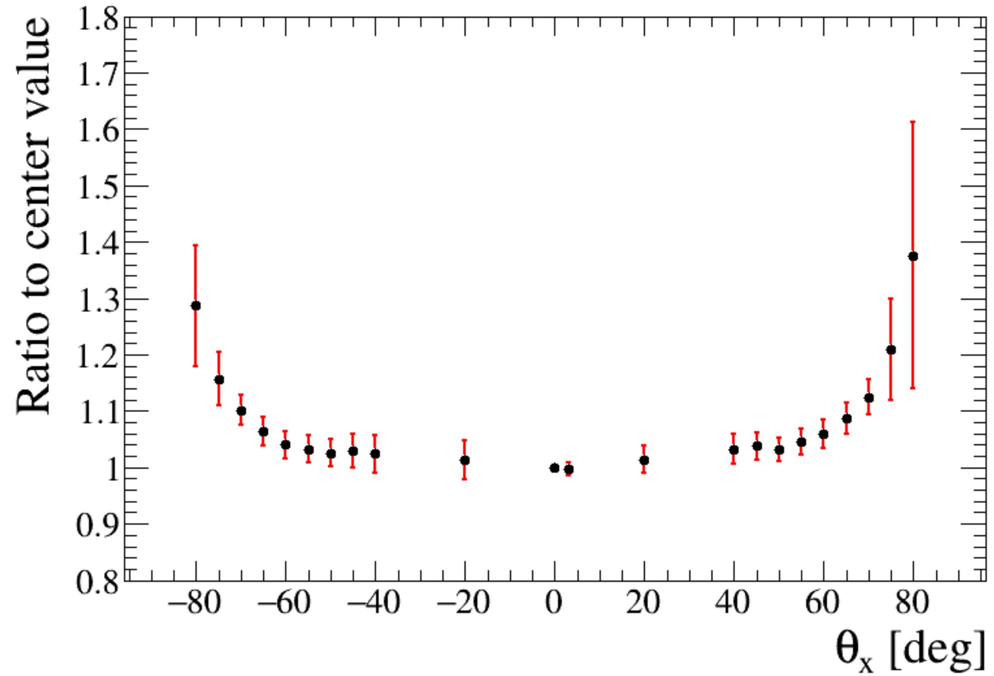
- TTS seen to increase when moving away from the center of the PMT
- Larger effect in the direction perpendicular to the Line to Box axis
- Pattern is a bit more complicated behind the box dynode



Line to Box direction
(Y axis)



Perpendicular direction
(X axis)



(no magnetic field)