

The Outer Detector system for the Hyper-Kamiokande experiment

31st July 2020

Detectors for Future Facilities (incl. HL-LHC), R&D, Novel Techniques

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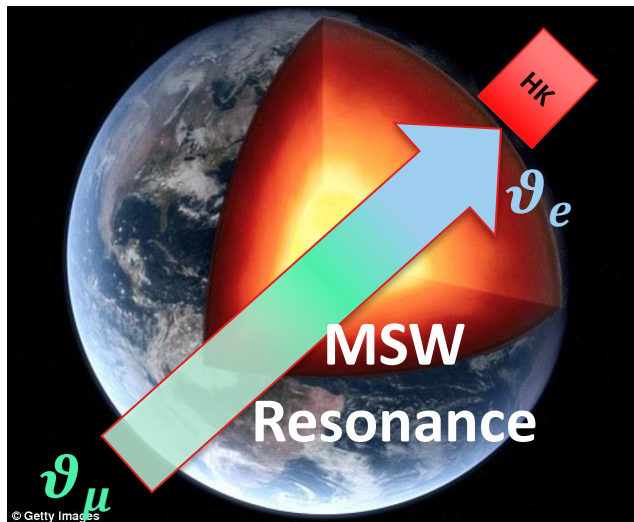
UC Berkeley / King's College of London





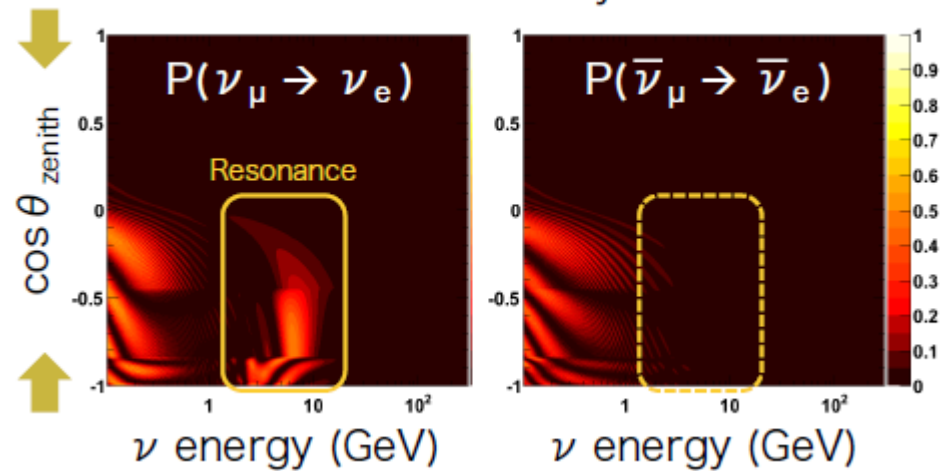
Mass hierarchy for ν_{atm}

- In void, the oscillation probability for ν_{atm} appearance and ν_{atm} disappearance are function of $\sin^2 \Delta m^2 \rightarrow$ **no sign dependency**
- In matter, neutrinos and antineutrinos undergo an enhancement or suppression resonance depending on the sign of Δm_{31}^2 from $\Gamma = aE_\nu / \Delta m_{31}^2$
- Substitute in void equations:
$$\sin^2 2\theta_{13}^M = \frac{\sin^2 2\theta_{13}}{\sin^2 2\theta_{13} + (\Gamma - \cos 2\theta_{13})^2}$$



Use e-/e+ appearance

Normal Hierarchy case



$E_\nu \in [2, 10] \text{ GeV}$

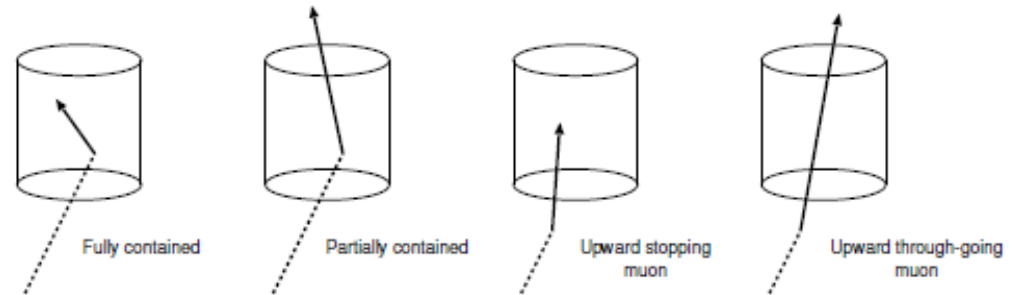


Mass hierarchy sensitivity increase

- By increasing Fiducial Volume (FV): **better event selection**
 - Classify **Fully Contained (FC)**, **Partially Contained (PC)**, and **Upward-going muons (UPMU)**

Use e-/e+ appearance

- Veto to cosmic muons
- Improve purity of FC samples
- Better identification of UPMU



- By improving selection and separation of muon stopping in the ID/OD

$$E_\nu \in [2, 10] \text{ GeV}$$

- Tag PC more effectively
 - Stronger resolution on entry and exit points
 - Increase rejection capability
- Calorimetry

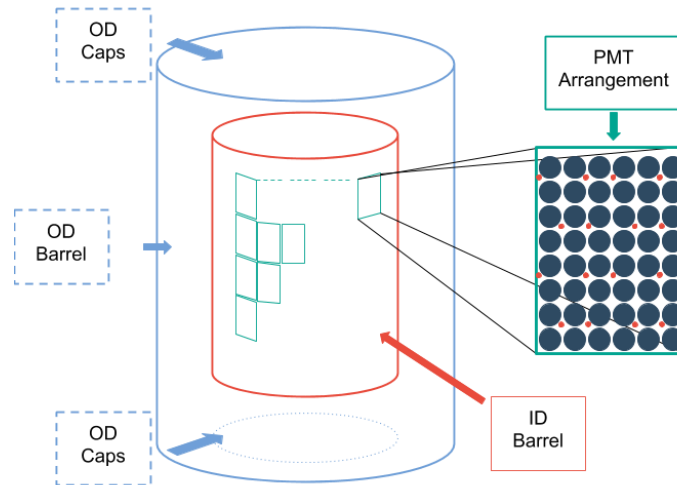
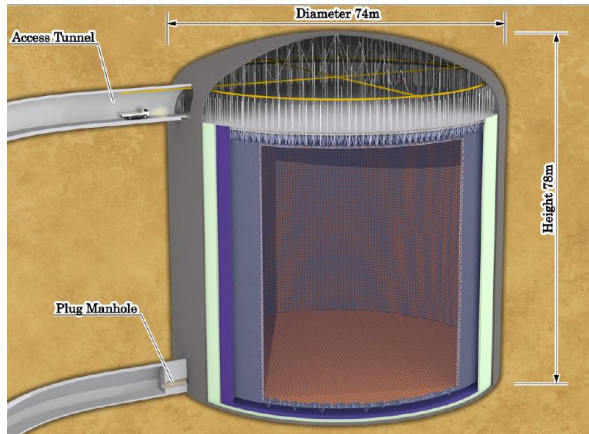
Measuring E_μ for stopping muons thanks to track length

Hyper-Kamiokande Outer-Detector

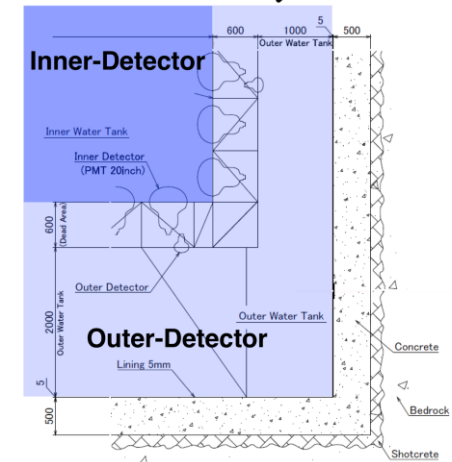
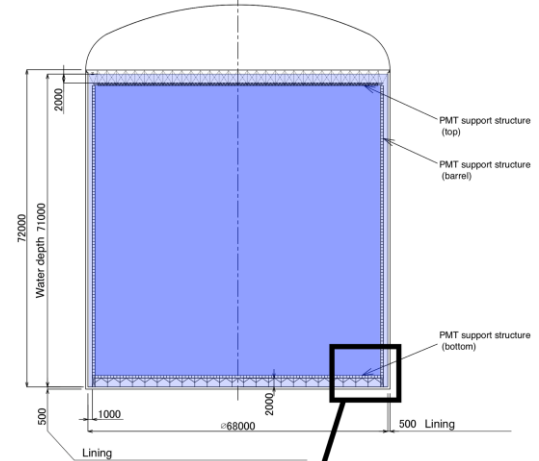


Design for improved performance

- ~ 13.3k 3" PMTs facing outward
→ ~ 0.3% coverage
- OD Water thickness : 1m barrel / 2m top and bottom



Cross section of Hyper-Kamiokande detector



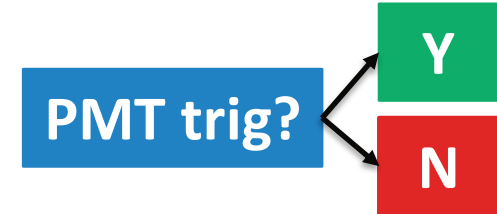
Original design based on Super-K OD

- ~ 6.7k 8" PMTs facing outward
→ 1% coverage
- OD Water thickness : 1m barrel / 2m top and bottom

Requirements and improvements



- The outer-detector is a **veto** for background particles, based on **PMT triggers hits clusters above threshold**
- Therefore, the information extracted from the OD is both
 - Number of PE collected (\rightarrow E loss in OD)
 - Number of PMTs hits (\rightarrow E loss and spatial)
- Using Super-K experience, we can understand the minimum performance required to classify events, which is directly related to the #PMTs
 - Increasing number of PMTs linearly increase the amount of information



Increase # of PMTs

- In order to make the system to work, we need to set a system with efficient trigger

Good light collection

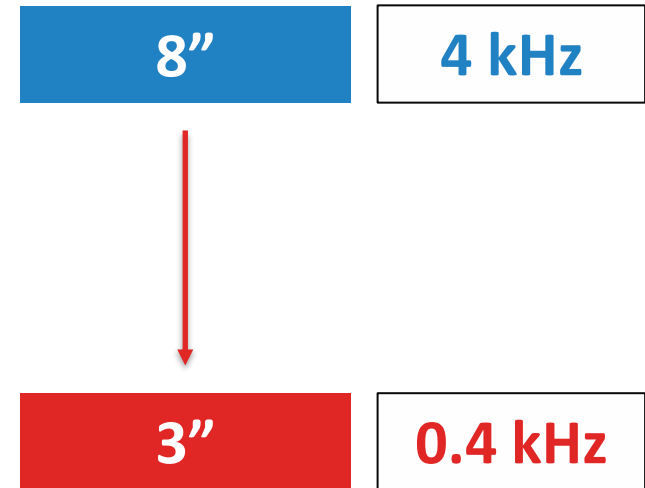
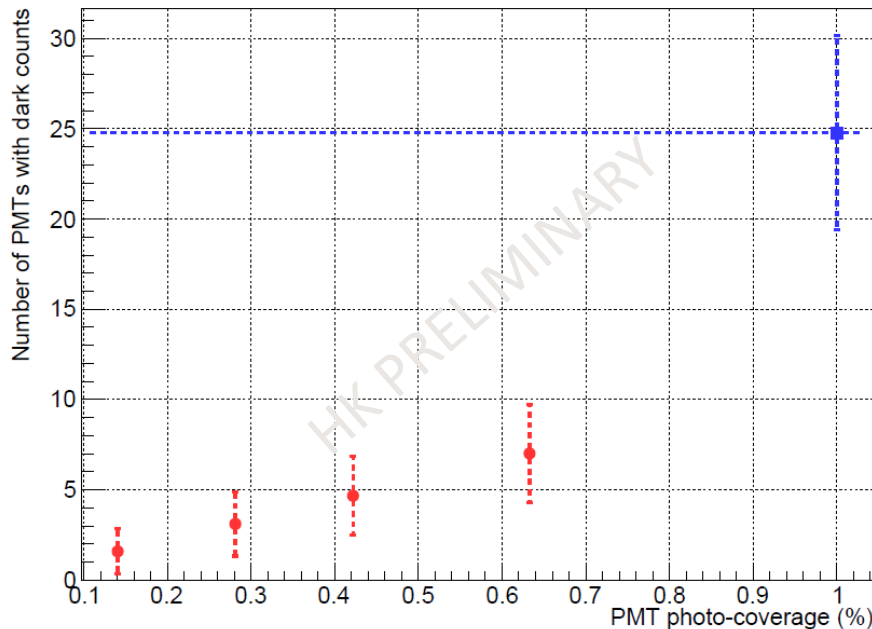
Low dark rates for low PE threshold



Small PMTs design and dark counts

- A simple reduction cut for PC classification: 50hits in the OD (from **Super-K**)
- Comparing the dark rates per events
 - Use binomial distribution to estimate dark counts in a window of 800ns (typical value for selection in atmospheric neutrino analysis)

Dark counts per trigger vs photo-coverage



Low dark rates for low PE threshold

PMTs candidates for the OD



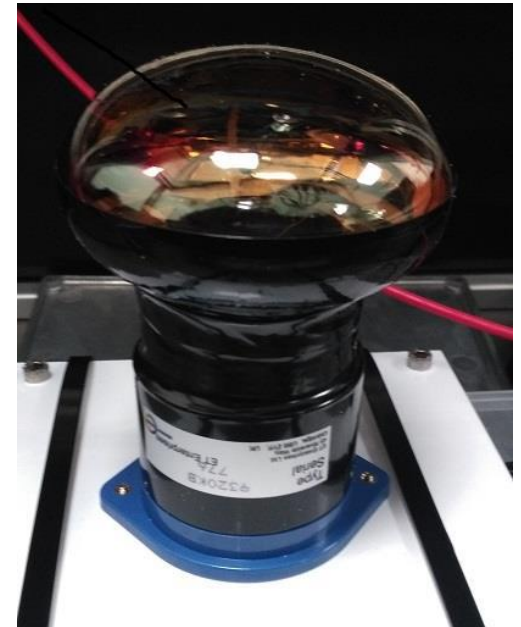
Hamamatsu
R14374



HZC XP82B20



EDEL 9302KFL



Setup, PMTs dark rates measurements **results** : [10.1088/1742-6596/1468/1/012240](https://doi.org/10.1088/1742-6596/1468/1/012240)

Light collection enhancement system

- Use wavelength shifting (WLS) plates to trap and reemit the light

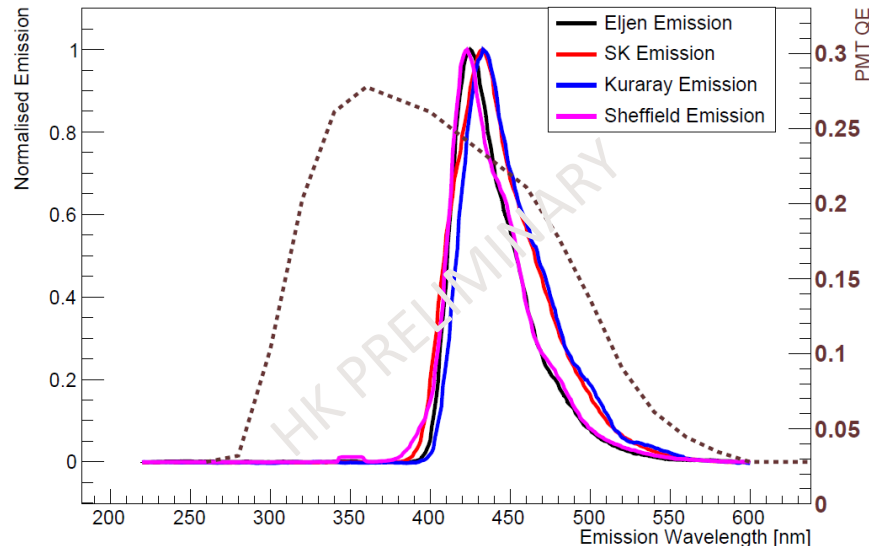
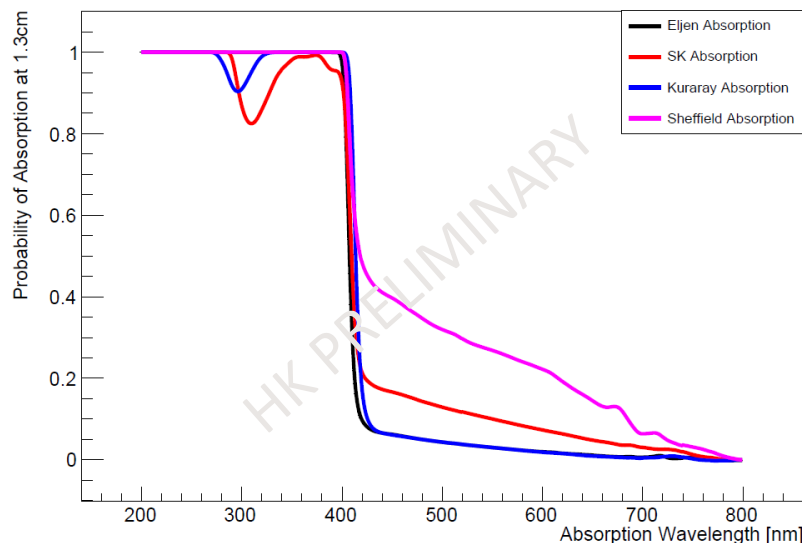


- Compute critical angle when light is trapped
 - ❑ $\theta_{crit} = \sin^{-1}(n_{water}/n_{WLS}) = 57^\circ \cong 1\text{rad}$
 - ❑ $N_{index} = 1.57$ (PVT)
- Then compute the “collection probability” by ratio of solid angle
 - ❑ $P_{CE} = 1 - \frac{2\pi(1 - \cos \theta_{crit})}{2\pi} = \cos \theta_{crit}$
- P_{CE} corresponds to the amount of light trapped inside the plate, i.e. the light reemitted after absorption → **54% in water**



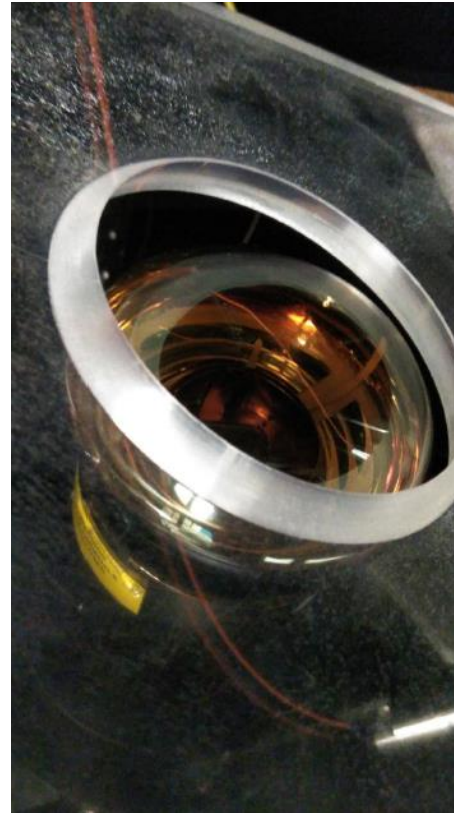
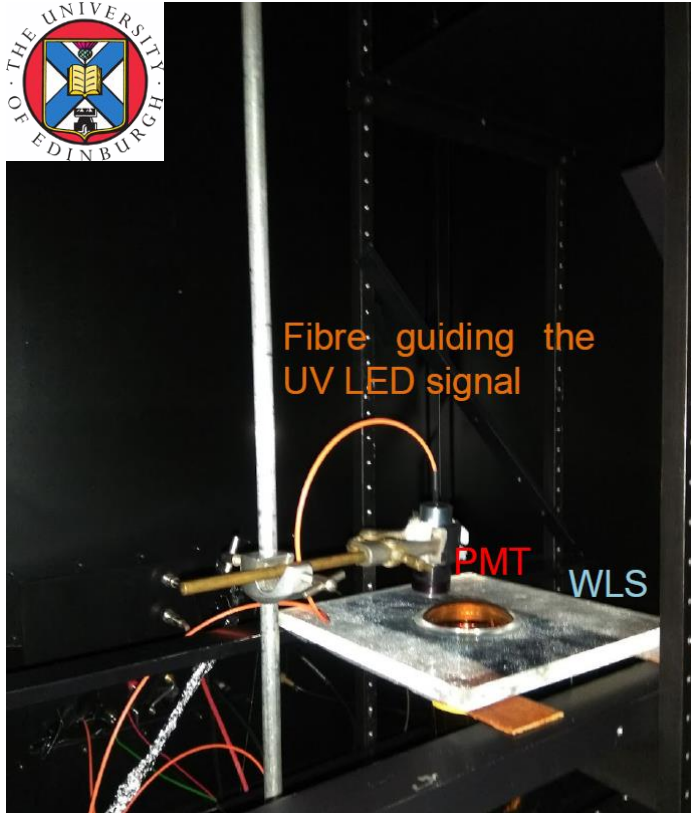
Candidates WLS plates

- Eljen EJ-286 (existing model from catalogue)
- Kuraray tailored prototypes (delivered to the Hyper-K OD group)
- LabLogic company (Sheffield, UK), not tailored prototypes



- Max absorption in UV (Cerenkov photons)
- Max emission at **430 nm**
 - Matches well quoted PMTs QE
- Material **reflectivity** defines critical angle
 - Eljen uses PVT ($n=1.57$)
 - Kuraray uses PMMA ($n=1.49$), LabLogic similar n

WLS plates performance characterization



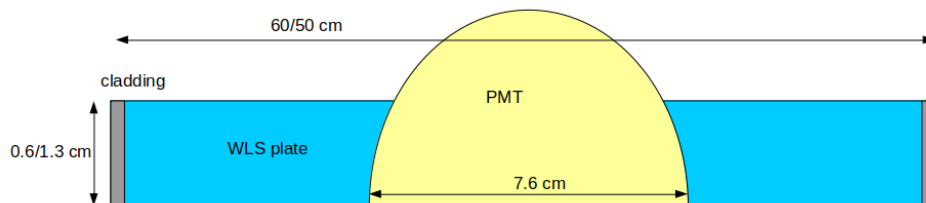
- 3" PMT (9320KFLB)
- WLS square (EJ286)
- UV LED @ 375 nm
- Neutral d filter @ 2.0
- Light injection @ 10kHz
- Optical fiber position w.r.t center of the PMT

WLS plate efficiency study

- Light collected by the PMT w and w/o WLS plate
 - REF: No WLS Plate / LED centered above PMT
 - Insert WLS plate and them move LED from PMT center

$$\text{eff} = \frac{WLS_X - Bckg}{PMT_0 - Bckg}$$

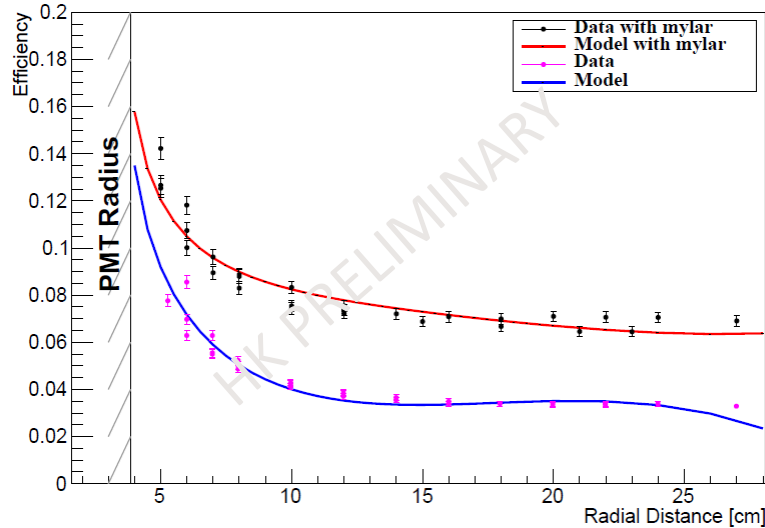
- Simulation model of the expected WLS plate size in Geant4



WLS plates performance characterization

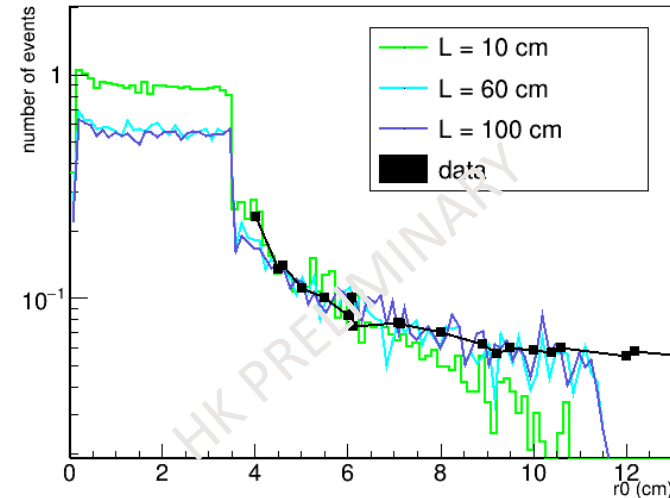


- Model with light attenuation and reflection inside the plate



Data, model, simulation in agreement

$$\text{eff} = \frac{WLS_X - Bckg}{PMT_0 - Bckg}$$



- Mylar cladding covering the edges improves light collection by a **x2 factor**
- Integration on full WLS plates area:
 - 3" PMT, Square WLS Eljen EJ-286, 50cm²x0.73cm

→ **x2.6 light increase**

Summary



The Hyper-K OD will be designed with a large area of small PMTs, in order to **improve light collection, spatial resolution**, to veto and select more efficiently FC / PC / stopping muon events.

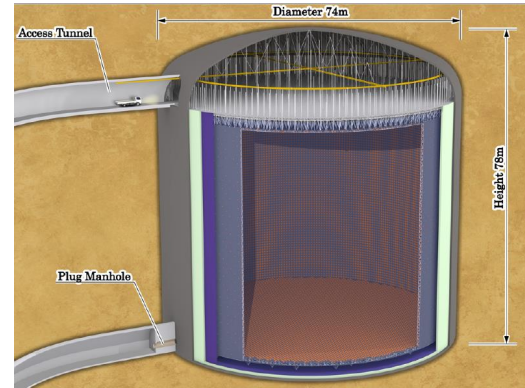
- We can increase the covered area by using WLS plate
 - 0.3% total area covered by 13.3k 3" PMTs → 1% total area covered by 6.7k 8"
- Using more PMTs allow better redundancy for failures
- Large set of PMTs and WLS plate candidates are on the test:
 - 3" and 3.5" from Hamamatsu, ETEL, HZC
 - WLS plate from Eljen, Kuraray, LabLogic
- Developed a two-staged approach to implement results in simulation
 - Full Hyper-K OD geometry included into official Hyper-K simulation, **WCSim**
 - Direct light collection + ad-hoc indirect light collection efficiency by the WLS plates

BACKUP

The Hyper-Kamiokande experiment



- Water-Cherenkov cylinder tank
 - $\varnothing = 68\text{m}$, $H = 71\text{m}$ each
 - Location : Kamioka, Gifu Prefecture, Japan
- Fiducial volume of a tank : 186 kton
 - x8 Super-Kamiokande !
- Proto-Collaboration formed in **2015**
- **Full Collaboration since 2020**
 - 400 people from 19 countries
- White paper for 2nd tank in **Korea** (Hyper-KK)

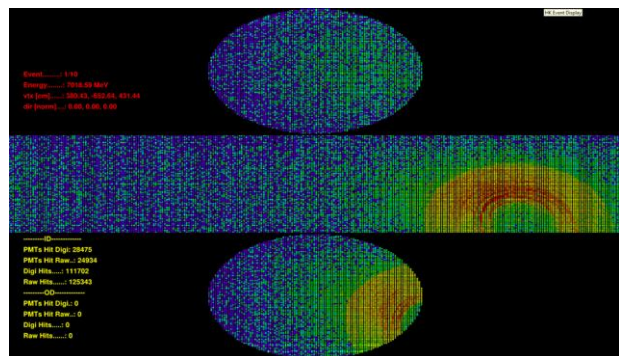


Hyper-K **began**
construction in **April 2020**

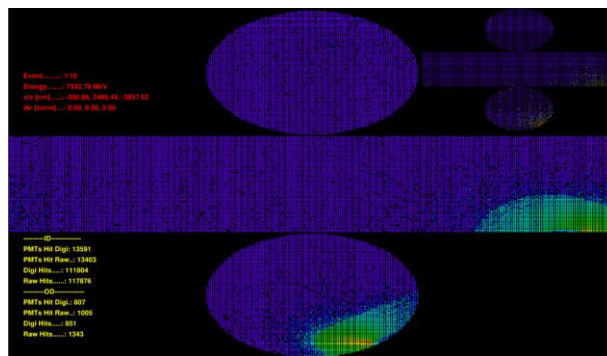


The WCSim GEANT4 application

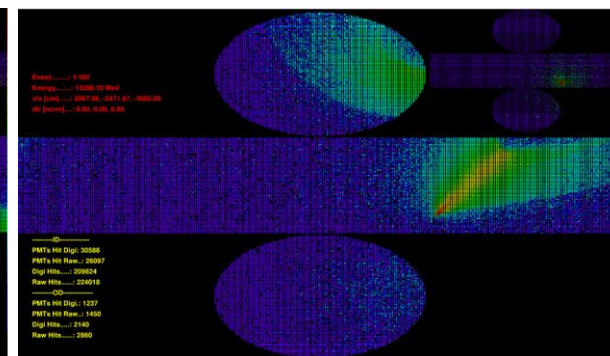
- WCSim is a very flexible GEANT4 based program for developing and simulating large water Cherenkov detectors: <https://github.com/WCSim/WCSim>
- Free and open source
- Contains full implementation of the OD, from light collection on the PMTs to the electronics
- Custom particle generators for cosmic muons and gamma background and signal events
- Study different geometry for comparison
 - 3" PMTs 13.3k covering 0.28% of the area
 - 3" PMTs 18k covering 0.42% of the area
 - 8" PMTs 6.7k covering 1% of the area
- Event display to study topologies



FC



PC



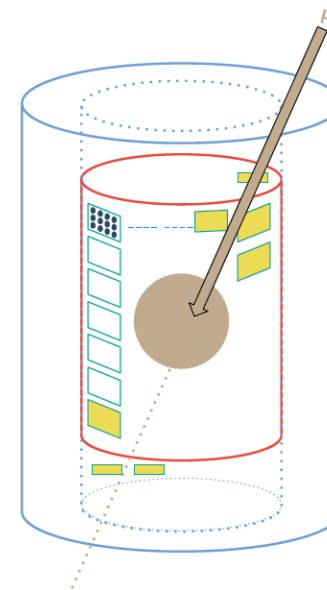
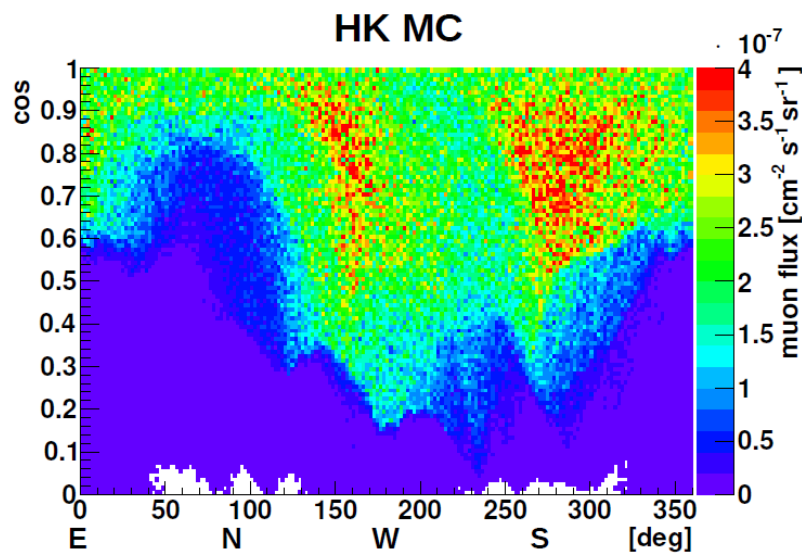
Stopping

Performance evaluation using WCSim



Cosmic muons

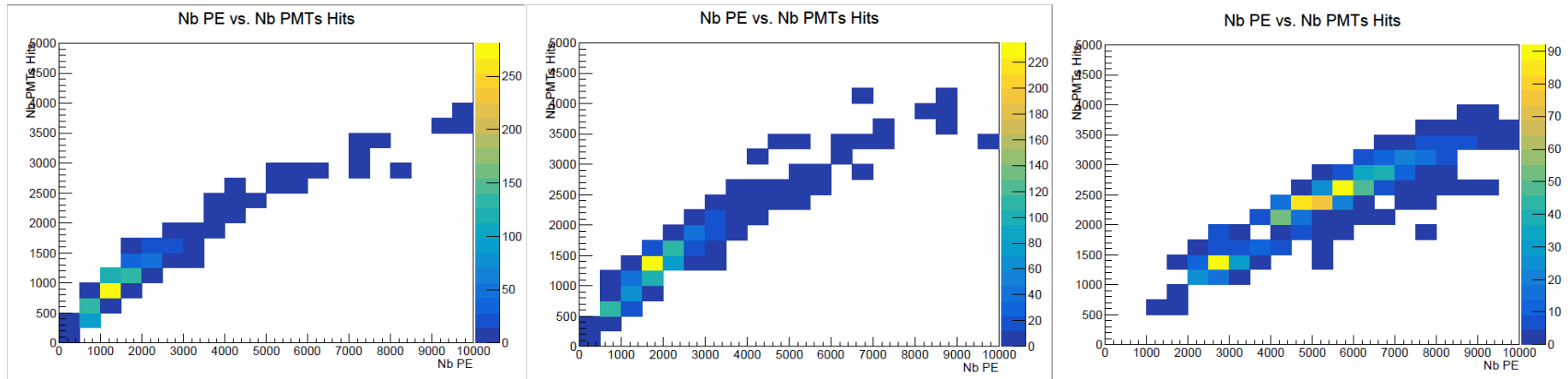
- Cosmic muons generator
 - Muons selected in a 10m sphere around centre of tank
 - Energy and impulsion are randomly generated accorded to Super-K flux extrapolated at Hyper-K
 - Then vertex generated outside Hyper-K
- 1000 events produced
- Results:
 - Total Number of photoelectrons digitized per events collected by all the PMTs
 - Total Number of PMTs with a true hits (**NO DARK RATES**)
 - Efficiency: **request any event produced 50hits with at least 1 detected photoelectron per PMT**



Results



- 2D plot of Nb of photoelectrons collected per event VS Nb of PMTs tube hits



Geometry	Mean PE collected	Mean #PMTs hits	Efficiency
3" 0.28%	1473±933	1033±465	100%
3" 0.42%	2019±1115	1378±548	100%
8" 1%	5102±1699	2294±632	100%

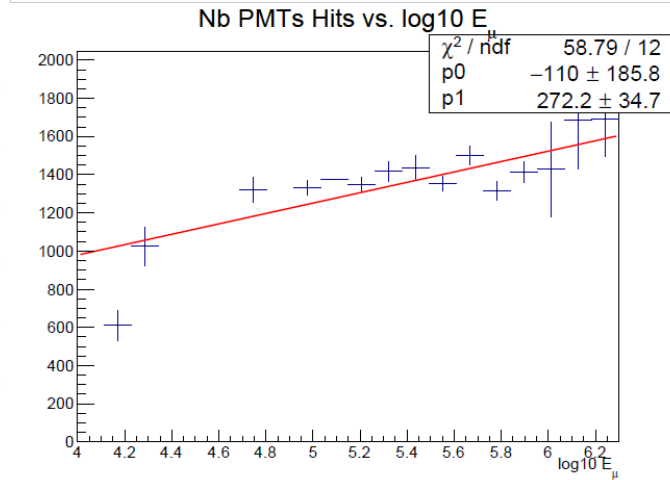
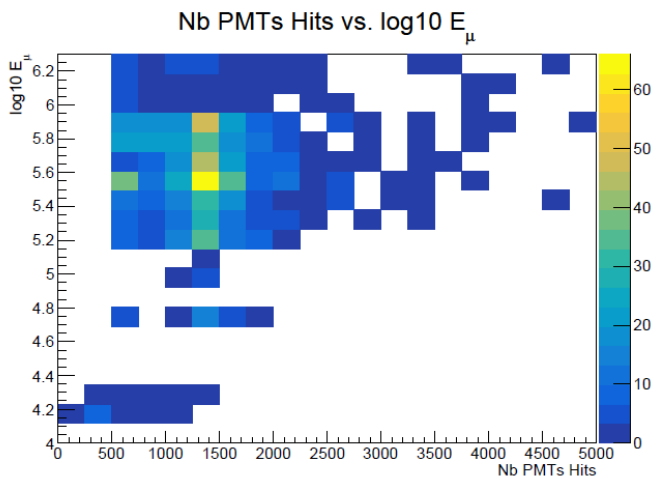
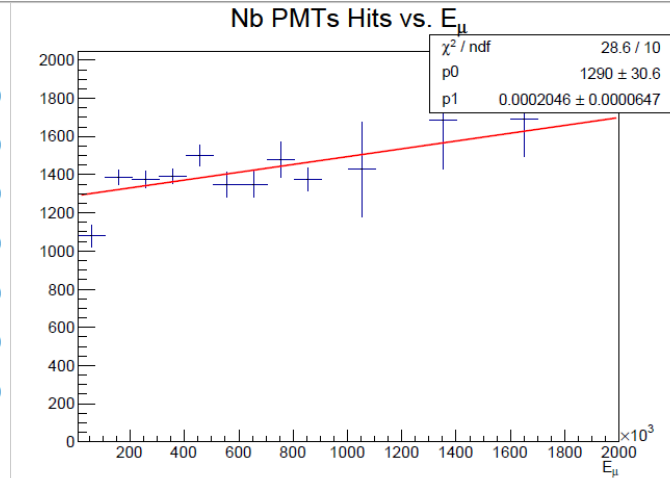
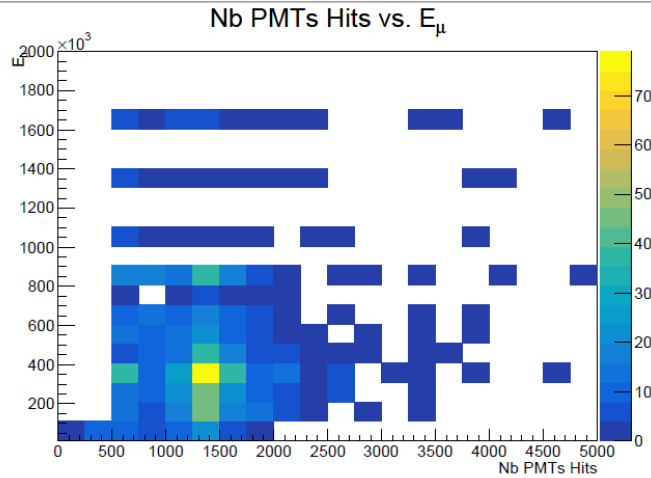
Most common OD rejection cut (50 PMTs hits) is **100%** efficient with **both 3" and 8"** geometries

Cosmic muons physics using the OD



- Look at 2D distribution: Is there any kind of correlation we can do in the OD?
 - Q VS E, Q VS theta, Q VS phi
 - #PMTs hits VS E, #PMTs hits VS theta, #PMTs hits VS phi

3" 0.42%



Cosmic muons physics using the OD



- Look at 2D distribution: Is there any kind of correlation between hits and cosmic muons?
 - **Maybe!**
- Using small 3” PMTs compared improved the χ^2 of linear fits:

Geom	$\chi^2/n.d.f$	Slope
8” 1%	49.79/10	8.0e-5
3” 0.28%	55.91/10	1.5e-4
3” 0.42%	28.6/10	2.0e-4

- Higher the slope, higher the separation between bins \rightarrow “Resolution”

- Looking at $\cos(\theta_\mu)$ cosmic muon we get the opposite behaviour:
 - Better linear fit with 8” 1% PMTs than small 3”

