Optimization of the Hyper-Kamiokande detector to increase sensitivity to low-energy neutrinos

Anastasia Shaykina
INR RAS and MIPT

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HSE Study Center “Voronovo”

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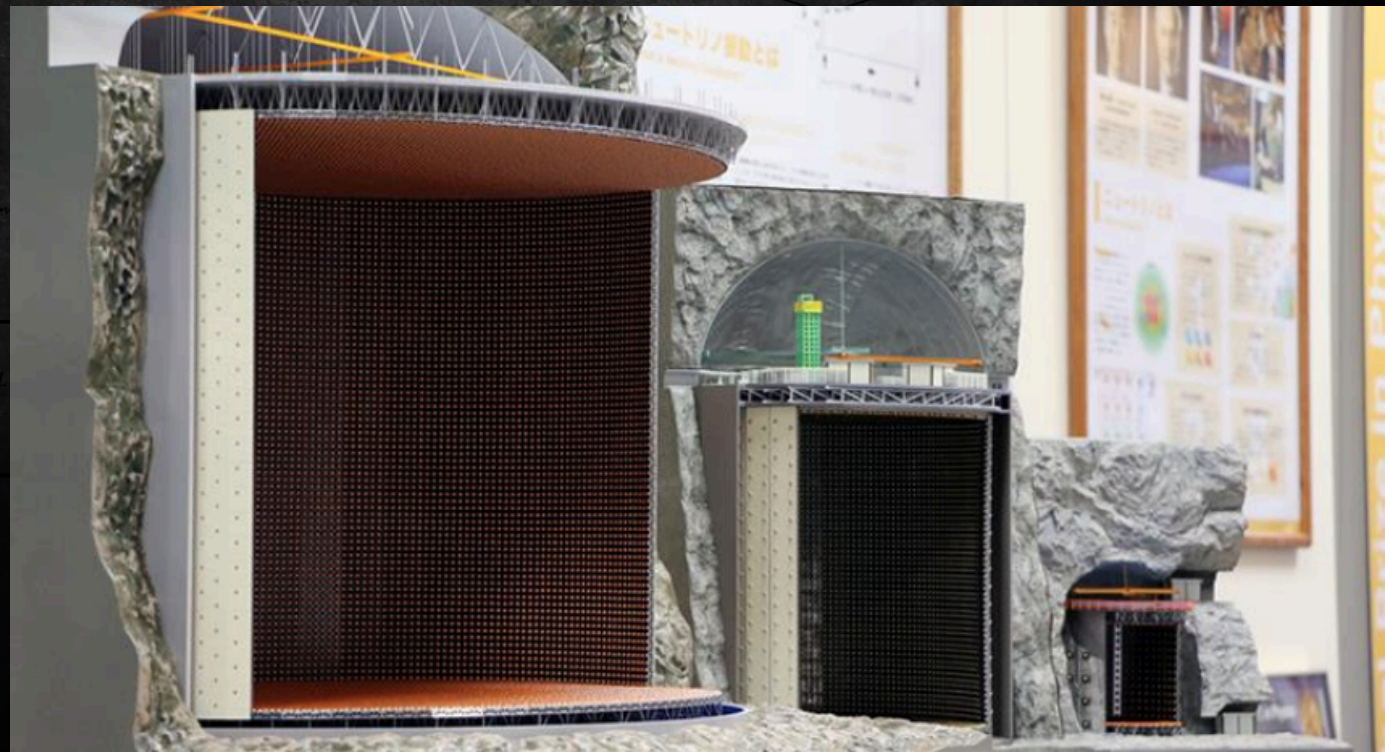
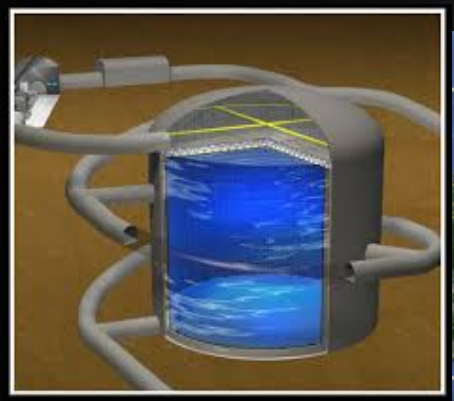
- LC simulation



HYPER-K DETECTOR



Hyper-K

J-PARC Accelerator Complex

Tank:

- 60 m tall × 74 m diameter
- 258 kton ultrapure water
- 187 kton fiducial mass × 8 SK

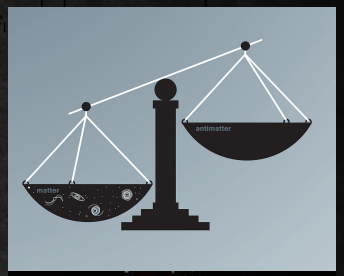
New PMTs:

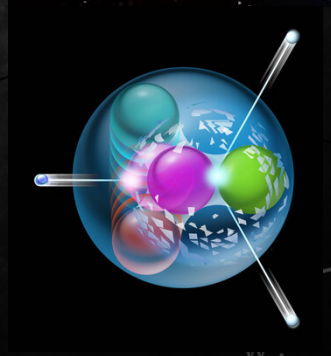
- single photon detection efficiency
- time resolution × 2 SK

approved in January 2020
start data taking in 2027

HYPER-K PHYSICS

- Neutrino oscillations
  - δ_{CP} measurement
  - ν mass ordering
- Neutrino astrophysics
  - Supernova burst ν observation
  - Relic supernova ν measurement
- Solar neutrinos
- Nucleon decay



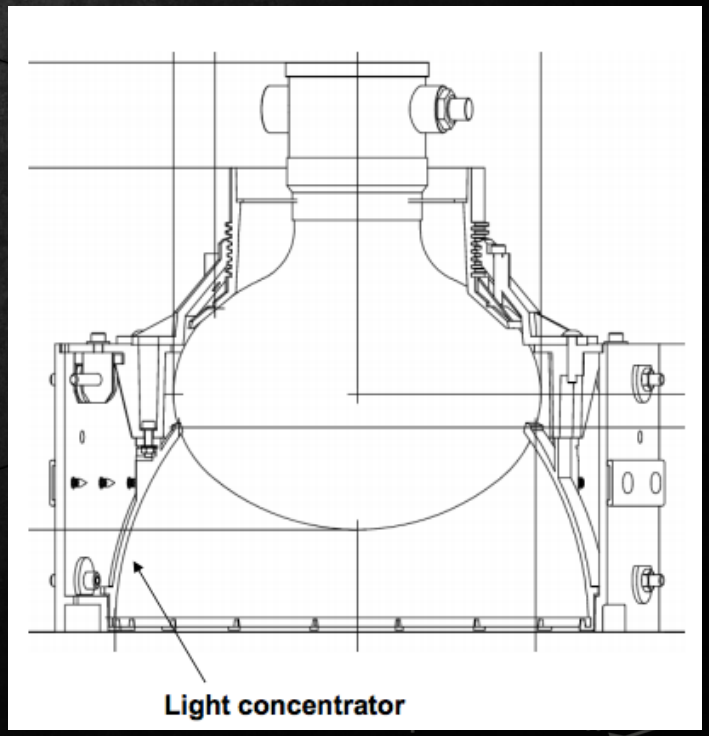


and more …

LIGHT COLLECTORS: MOTIVATION

- More photon detection efficiency at low energy
  - Better vertex resolution, lower analysis threshold
  - Higher efficiency for the neutron tagging
- Much cheaper than PMTs

LC from SNO experiment

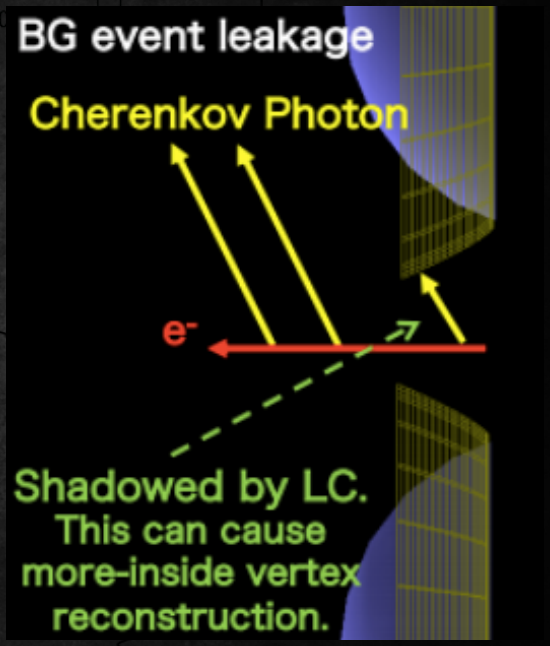


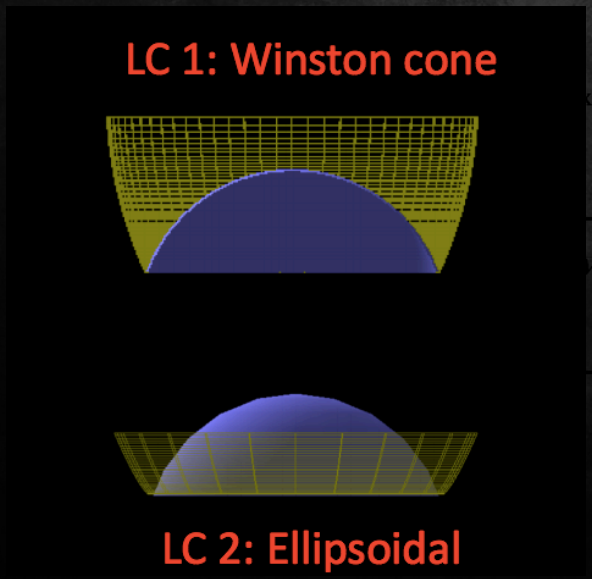
Working topics:

- physics impact (negative)
- material selection
- mirror shape optimization

LIGHT COLLECTORS: PHYSICS IMPACT

- Low-E background event leakage into FV
- Reflection at high-energy events
  - High energy neutrinos, cosmic-ray muons
- Shadowing effect for PID, nearby the wall





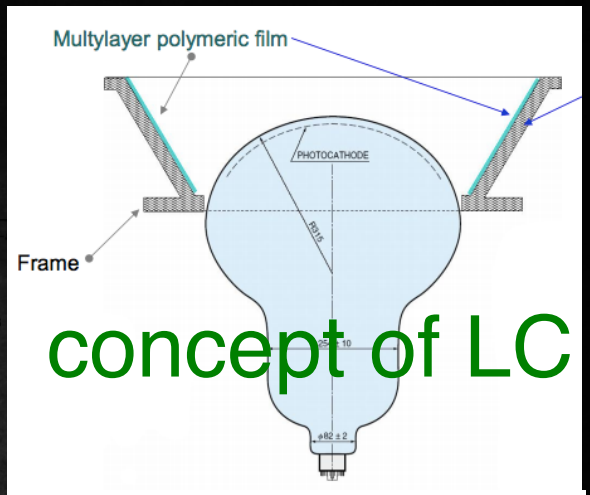
LIGHT COLLECTORS: MATERIAL SELECTION

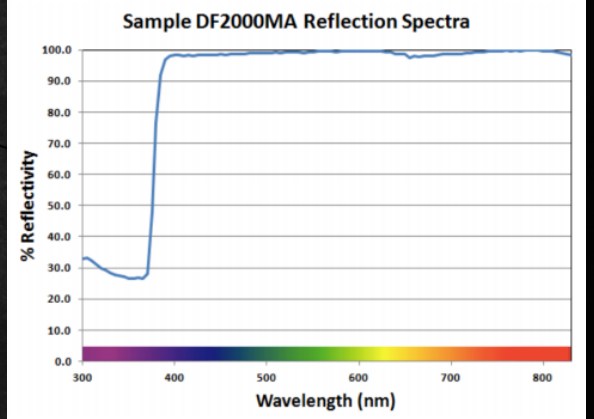
Material requirements:

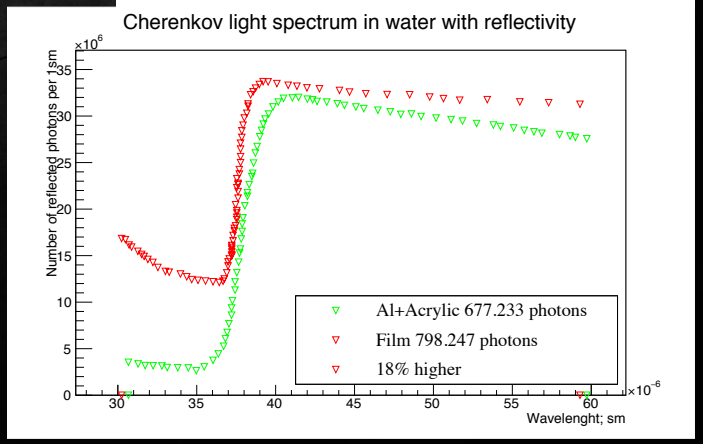
- High reflectivity (>80%) at PMT sensitive wavelength 300~600 nm
- Resistance to (Gd) water w/ reflectivity loss of O(1)% loss after 5 years
  - For stability of detector energy scale
- Mechanical strength for transportation

Film DF2000MA - possible light concentrator for Hyper-K

- High reflectivity, more than 98% for > 390 nm
- Stable in water for about 10 years (tested in GERDA)
- Metal free, non-corroding and non-conducting







LIGHT COLLECTORS: MIRROR SHAPE

Goal:

To develop the method to evaluate the impact of shape

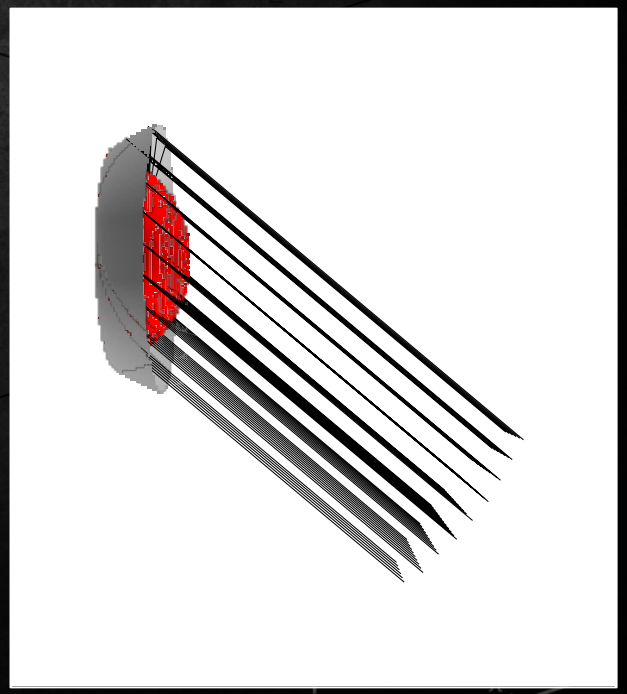
- high collection
- low reflection
- low shadowing of the PMT

R&D method:

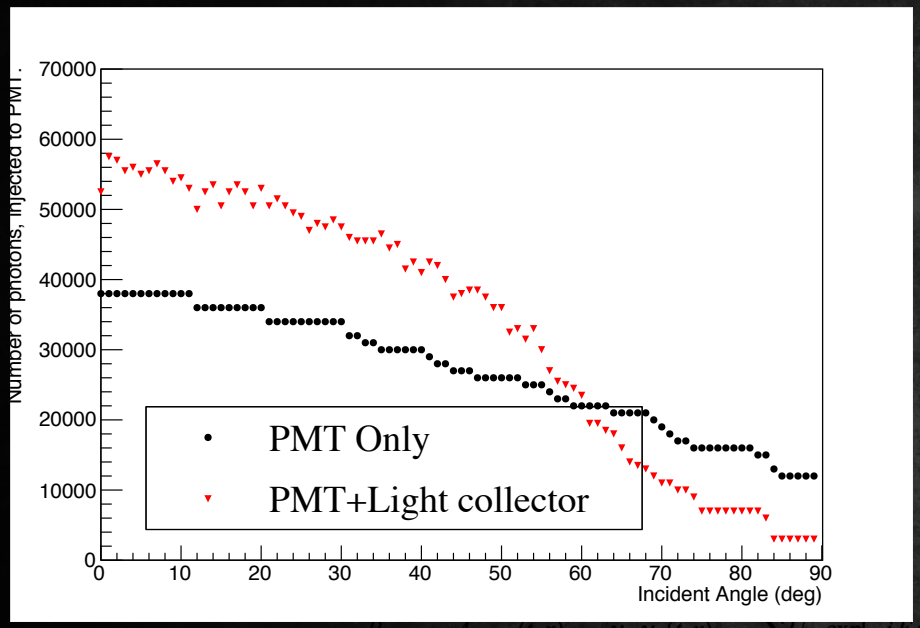
Computer simulation

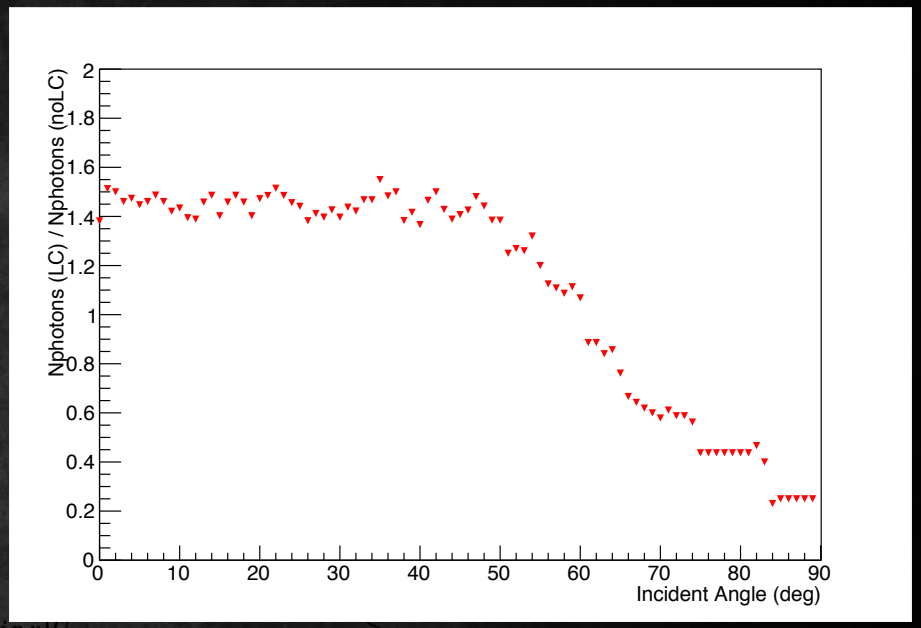
- ROBAST (ROOT-based simulation, for single mirror)
- WCSim (for whole detector)

ROBAST simulation



LC SIMULATION





Number of photons, focused on PMT

The gain in photons with LC

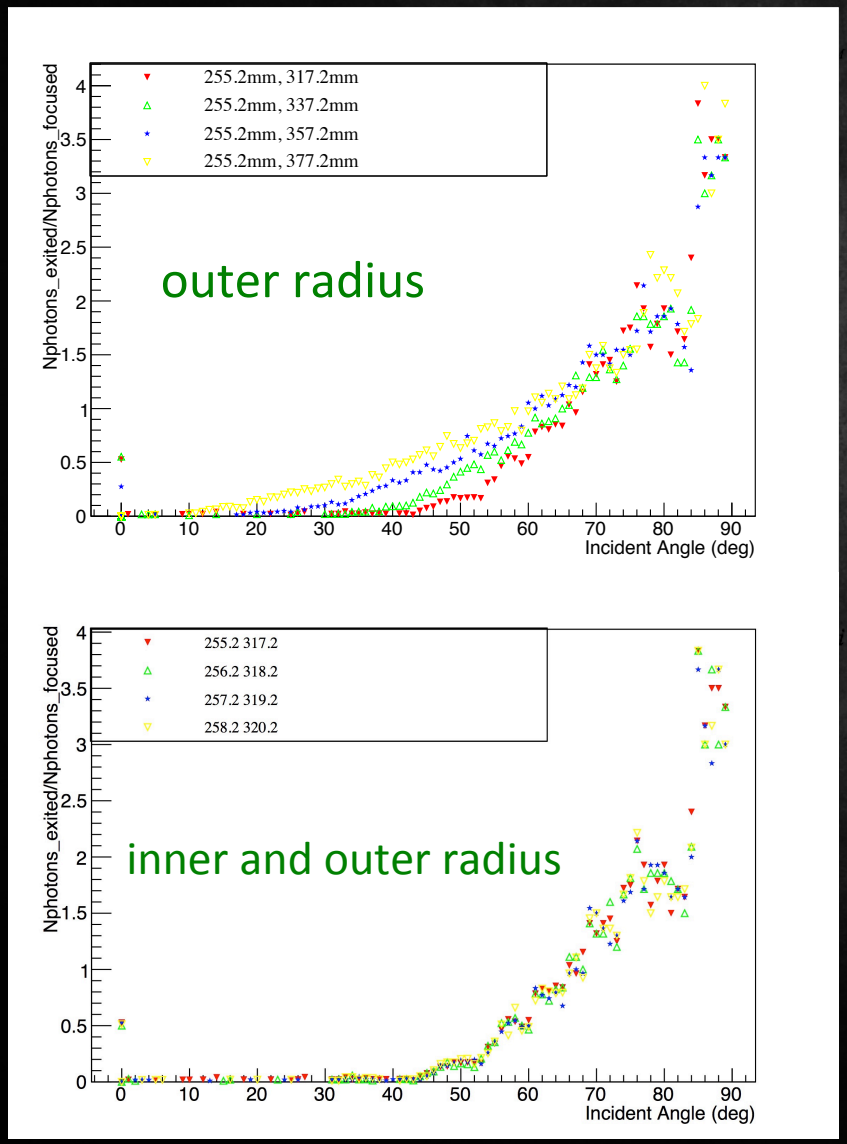
Parameters of LC

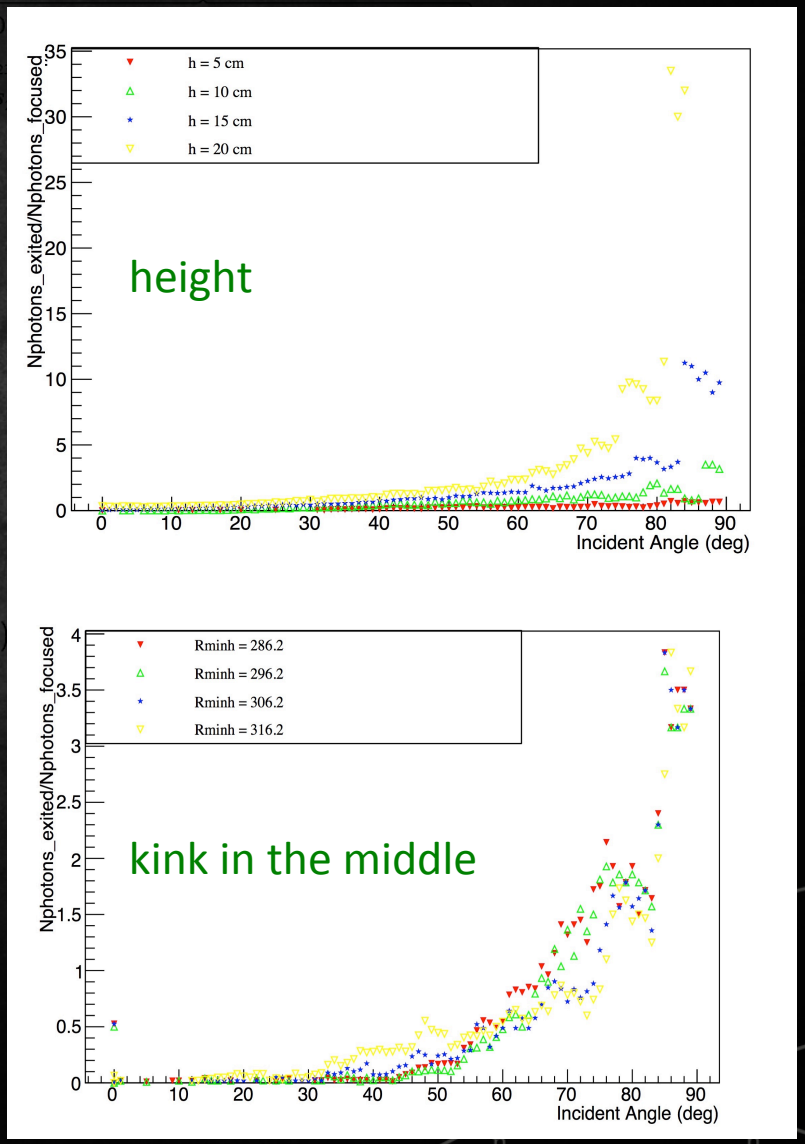
shape – cone
height - 114 mm

inner radius - 255.2 mm
outer radius - 317.2 mm

LC SIMULATION

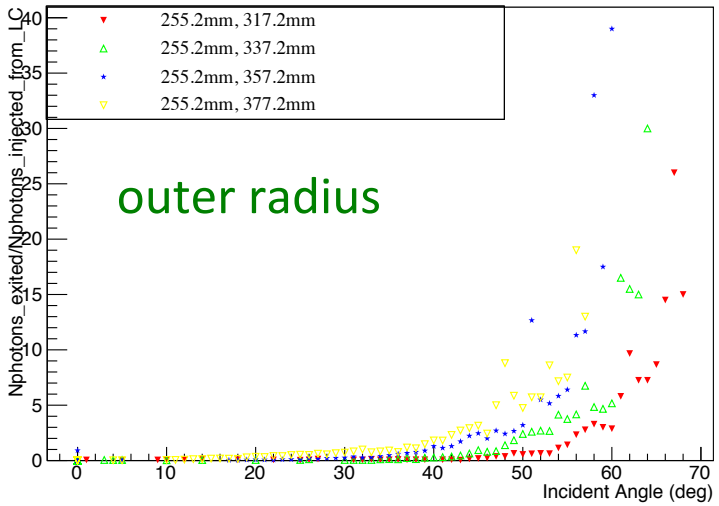
y = Number of photons exited from LC/Number of photons focused on PMT

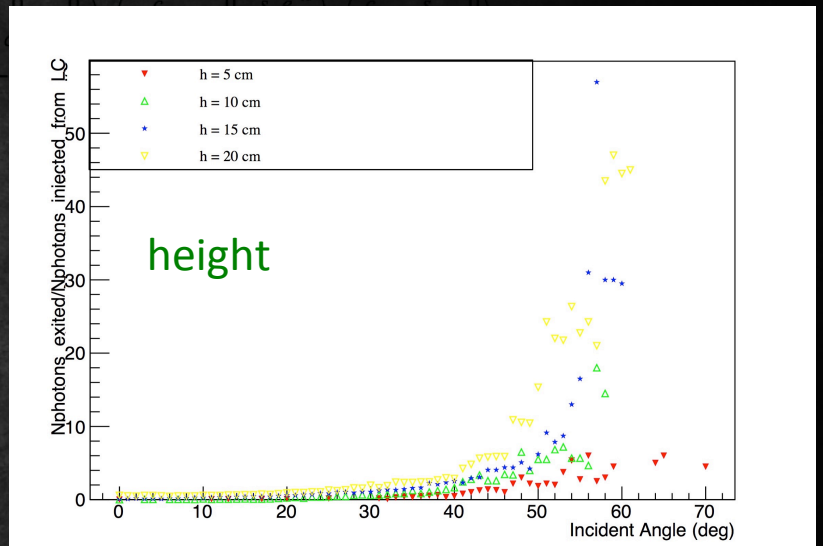


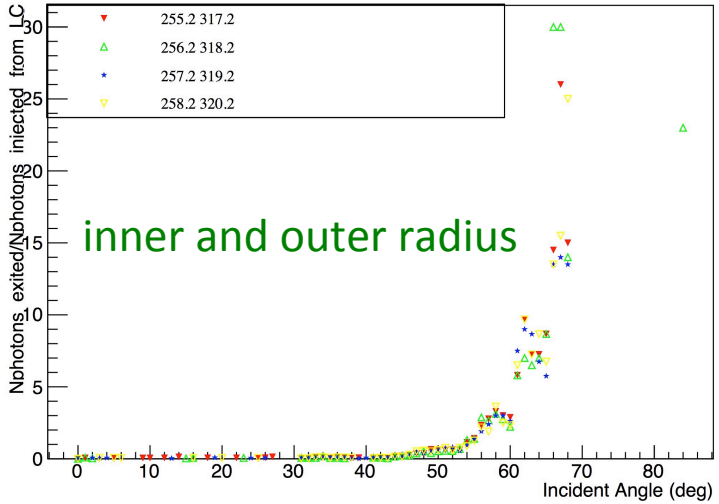


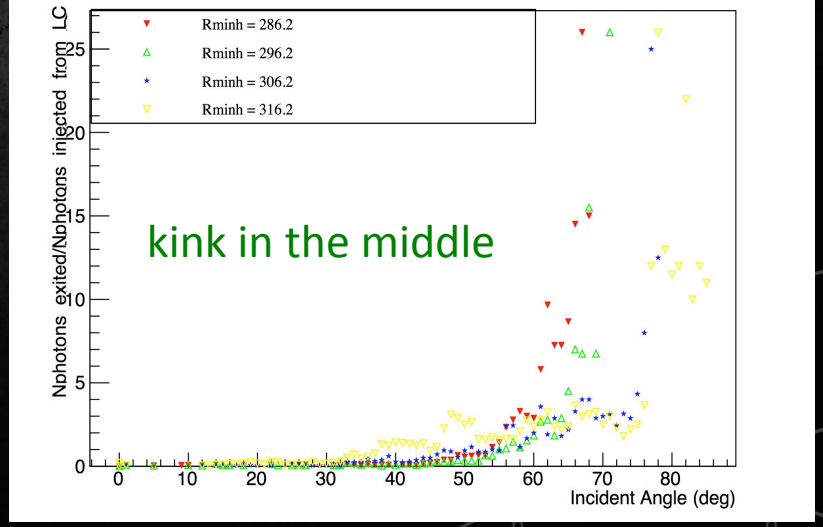
LC SIMULATION

y = Number of photons exited from LC/Number of photons focused on PMT *from LC*



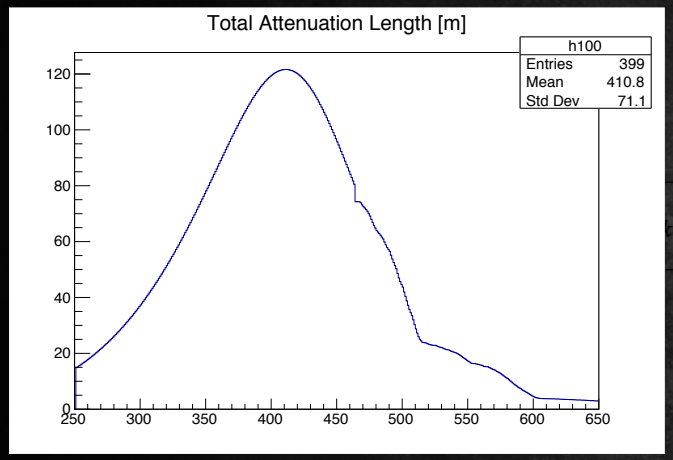


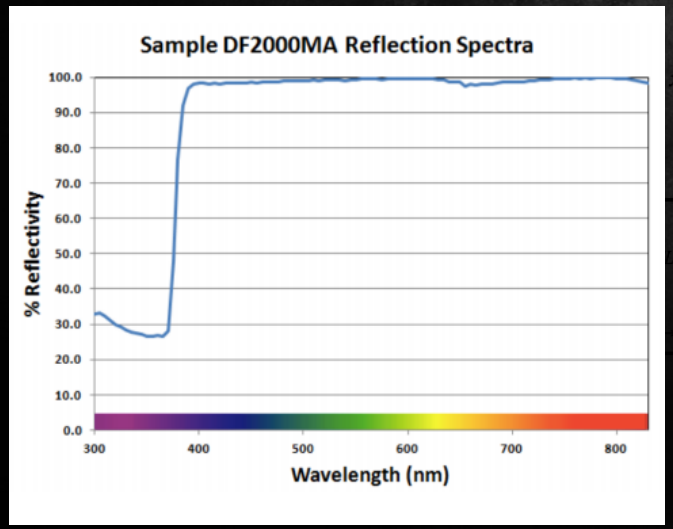


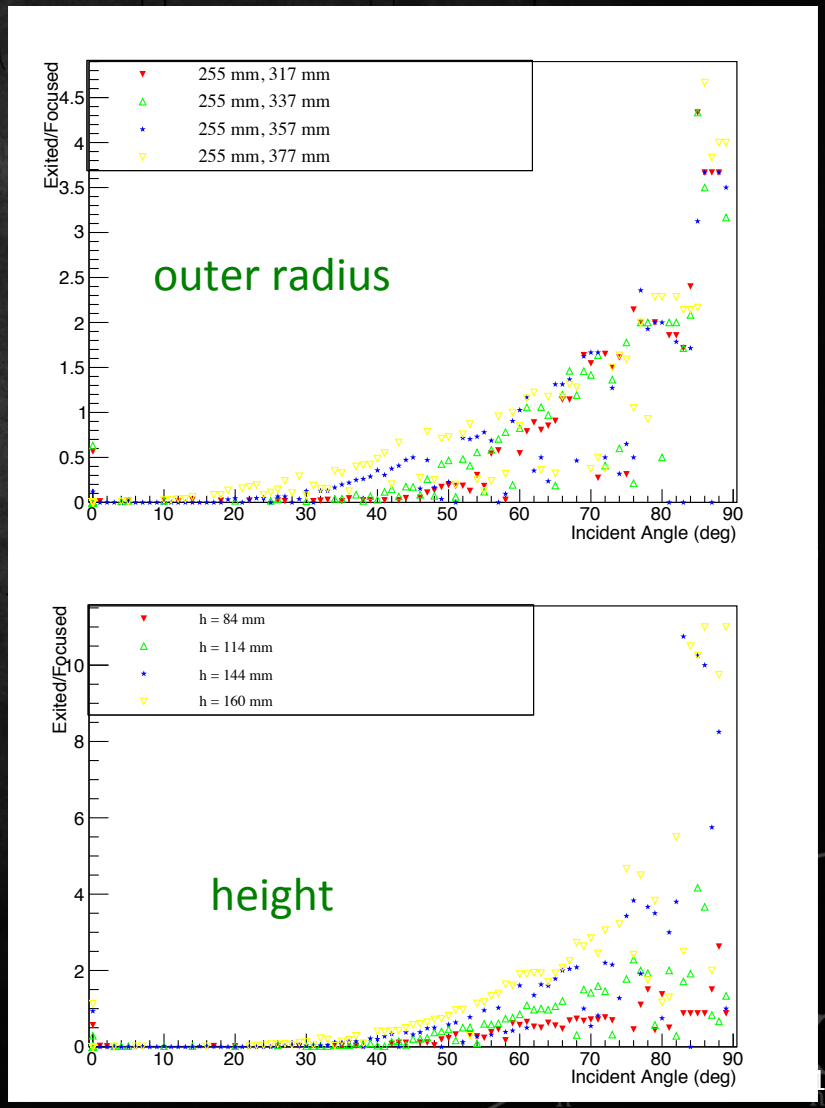


LC SIMULATION: REAL SPECTRUM

y = Number of photons exited from LC/Number of photons focused on PMT







SUMMARY

- It is proposed to use Light Collectors (LC) to increase the sensitivity for neutrino detection in the Hyper-K.
- The simulation for the single LC was done.
- LC shape and size optimization is in progress.

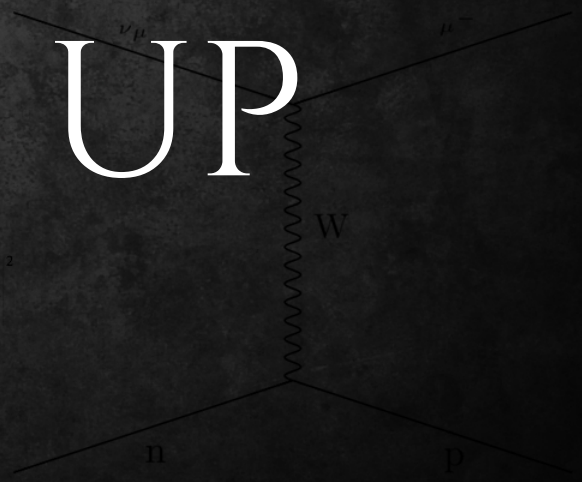
$$U^M = \overbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}^{U^{CP}}$$

$$\times \underbrace{\begin{pmatrix} e^{-i\phi_1} & 0 & 0 \\ 0 & e^{-i\phi_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{P^M}$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

$$\nu_\alpha = \sum_k U^*_{\alpha k} \nu_k$$

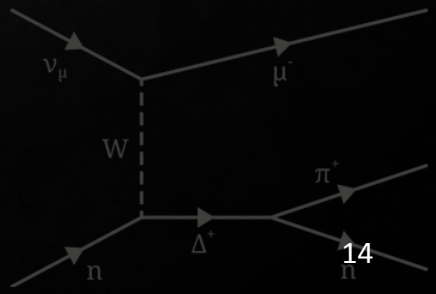
BACK UP



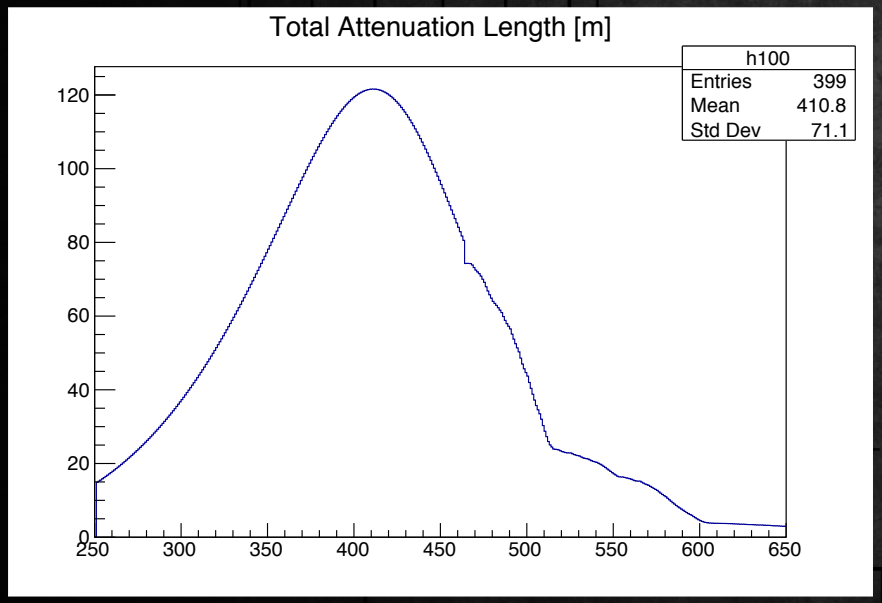
$$P_{\nu_\alpha \to \nu_\beta} = A_{\nu_\alpha \to \nu_\beta}(t,x)^2 = \nu_\beta \nu_\alpha(t,x)^2 = \sum_i U^*_{\alpha i} \exp(-iE_i t + ip_i x) U_{\beta i}^2$$

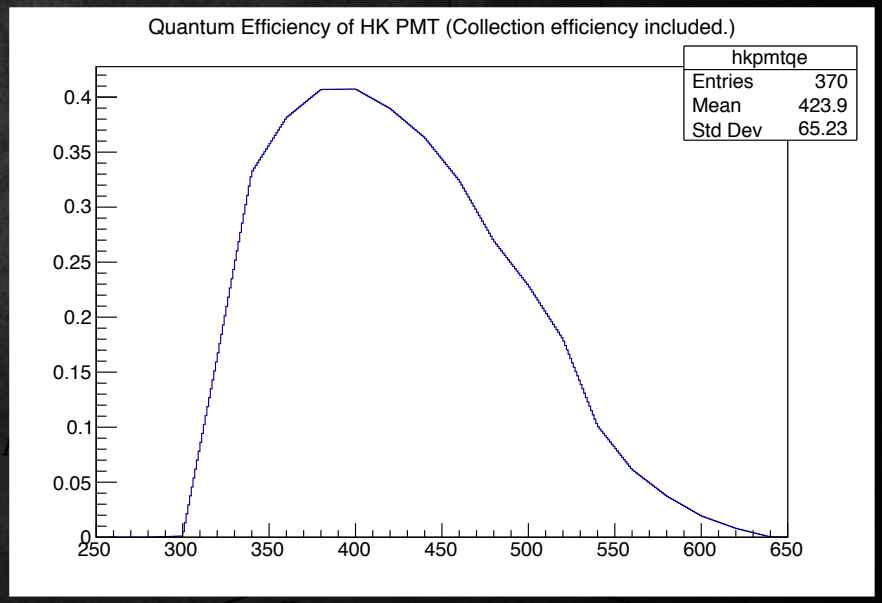
$$\nu_{\alpha L} \to \nu_{\beta L} \overset{C}{\Rightarrow} \nu_{\alpha L} \to \nu_{\beta L} \overset{P}{\Rightarrow} \nu_{\alpha R} \to \nu_{\beta R}$$

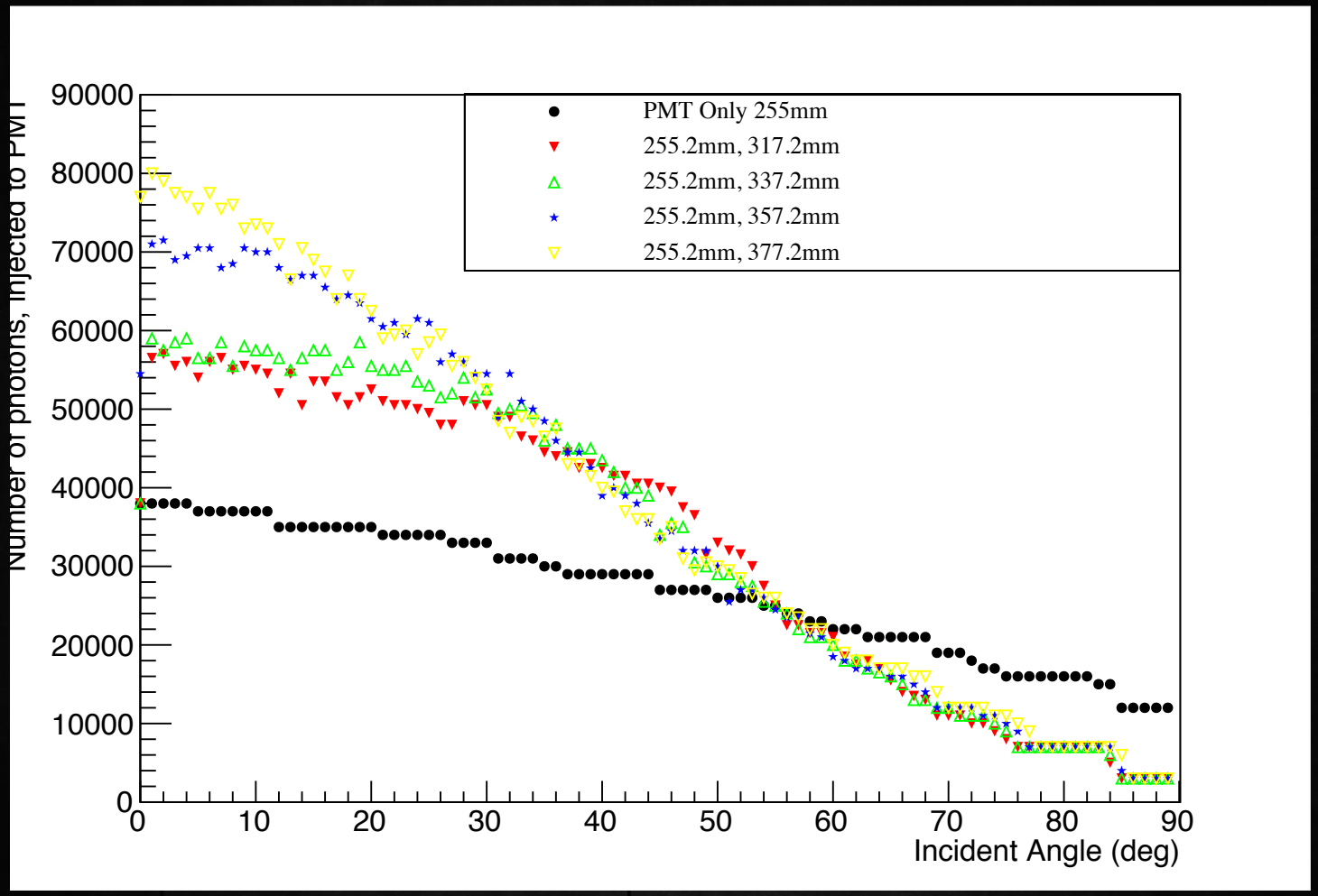
$$P_{\nu_\alpha \to \nu_\beta} \overset{CP}{\Rightarrow} P_{\nu_\alpha \to \nu_\beta}$$



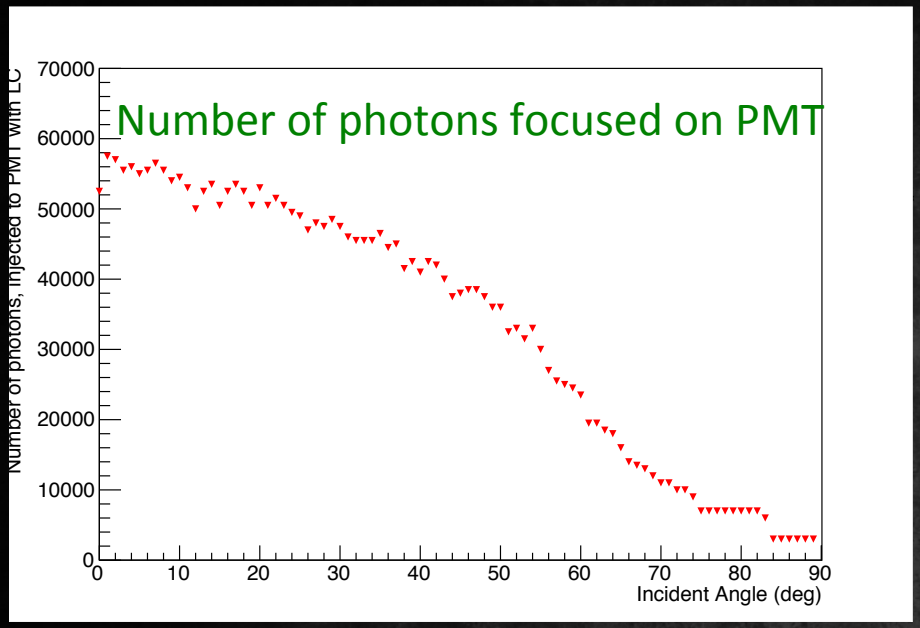
LC SIMULATION: REAL SPECTRUM

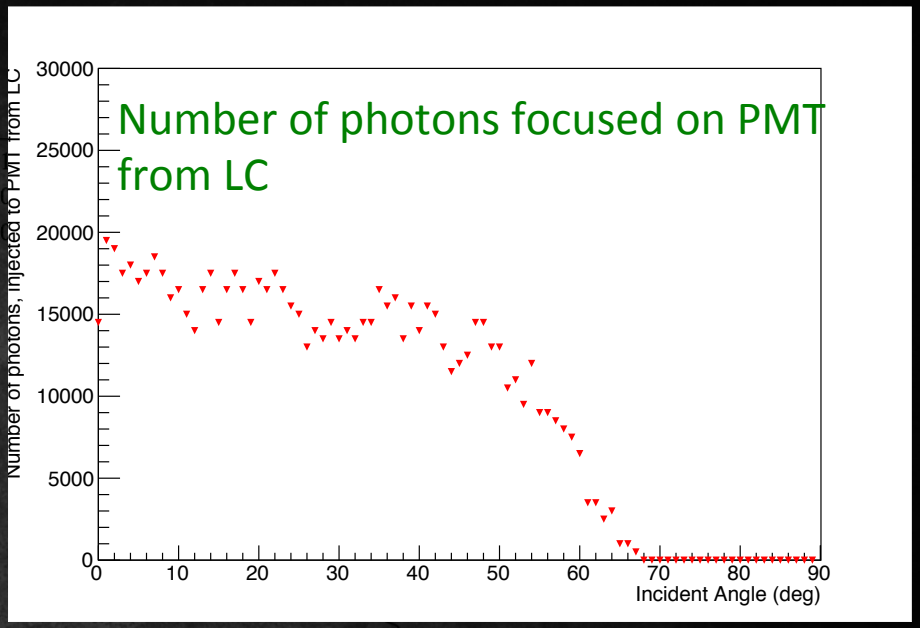


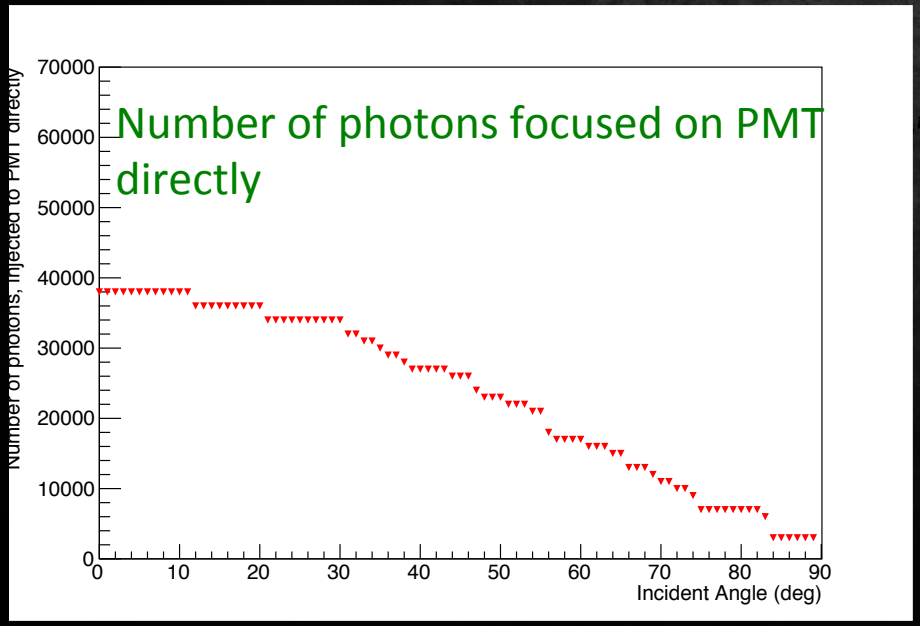


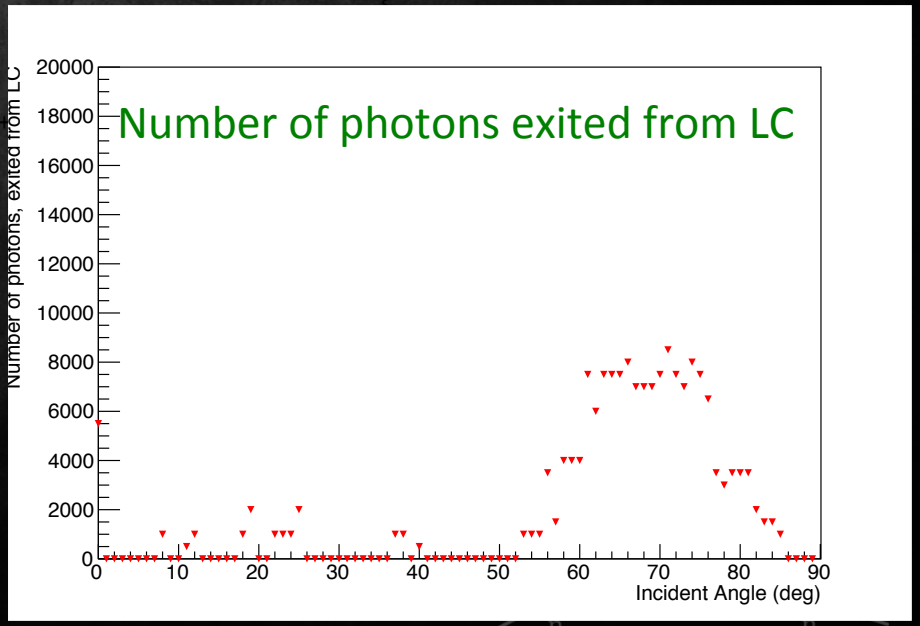


Number of photons focused on PMT


Number of photons focused on PMT
Number of photons, injected to PMT with LC
Incident Angle (deg)


Number of photons focused on PMT from LC
Number of photons, injected to PMT from LC
Incident Angle (deg)


Number of photons focused on PMT directly
Number of photons, injected to PMT directly
Incident Angle (deg)


Number of photons exited from LC
Number of photons, exited from LC
Incident Angle (deg)