Development of detector simulation and event reconstruction for J-PARC E61 experiment

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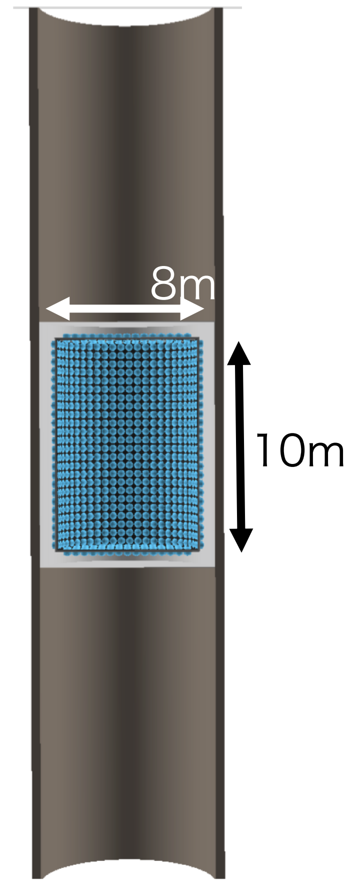
For J-PARC E61 collaboration

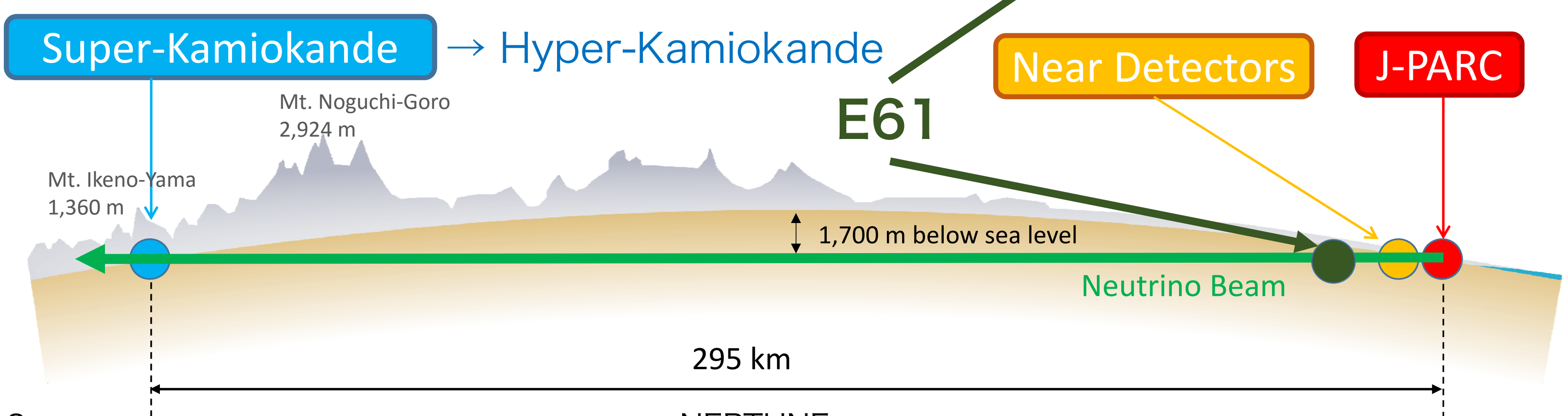
NEPTUNE workshop

J-PARC E61 proposal

An intermediate water Cherenkov detector at 1 – 2 km downstream of J-PARC neutrino beam

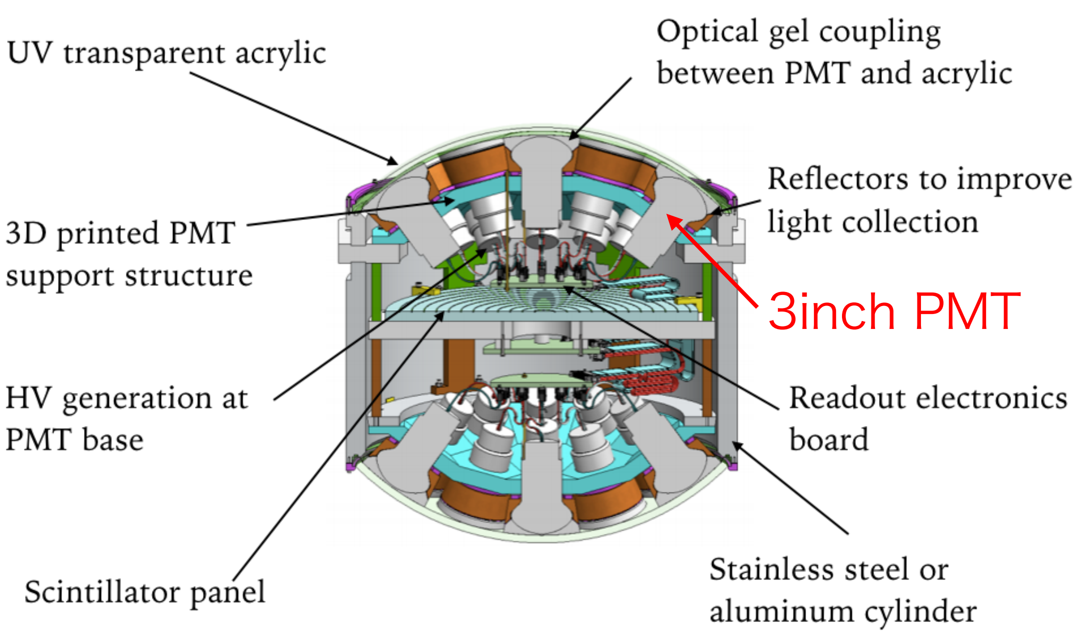
- Constrain systematics in oscillation analysis originating from neutrino interaction uncertainty
- Measure neutrino interaction cross sections as a function of energy

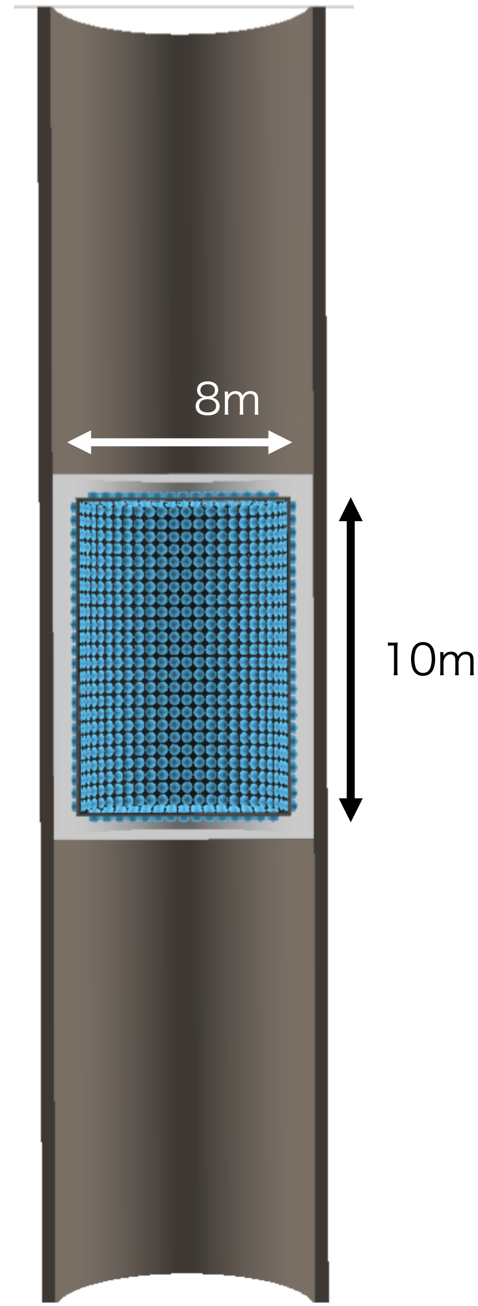




E61 detector

- The detector has optically separated inner and outer detectors.
- Cherenkov photons are detected by 3inch PMTs enveloped in mPMT modules (19 PMTs for ID side).

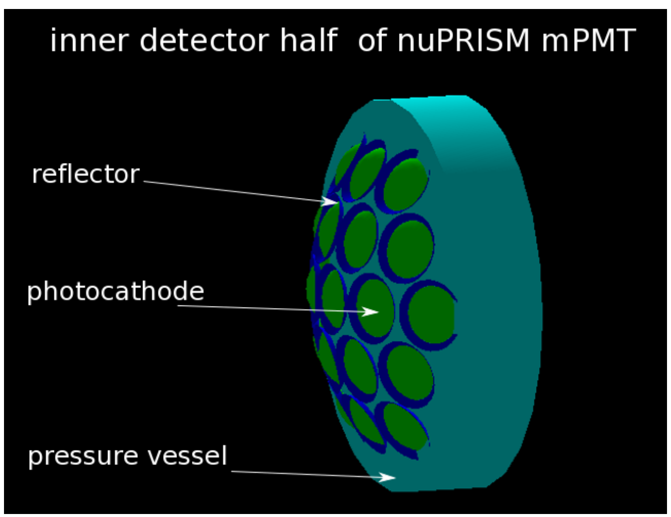


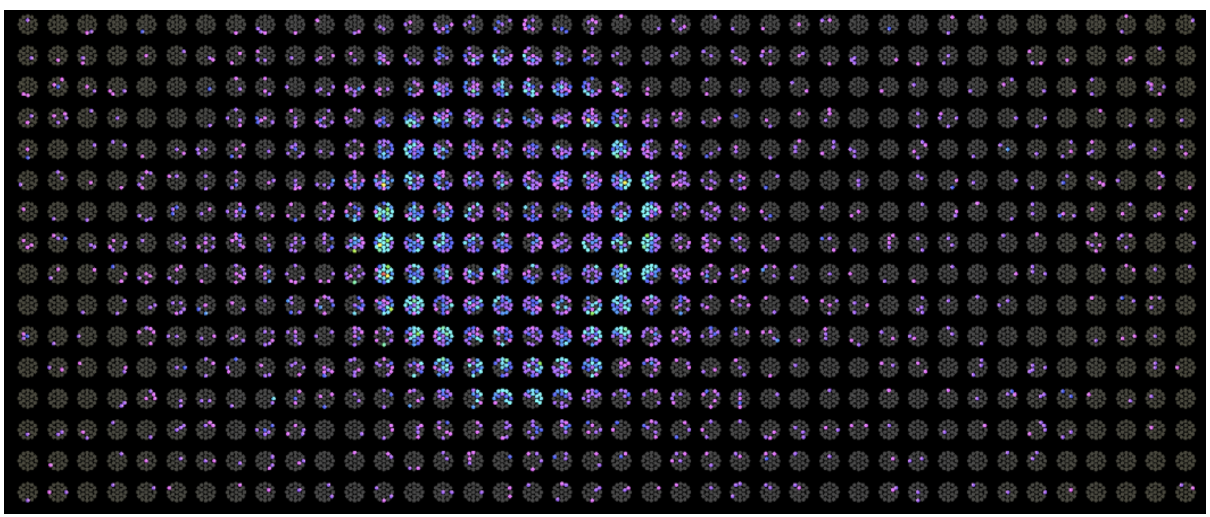


Software development

Full detector simulation and event reconstruction algorithm are developed to study detector optimization and physics sensitivities.

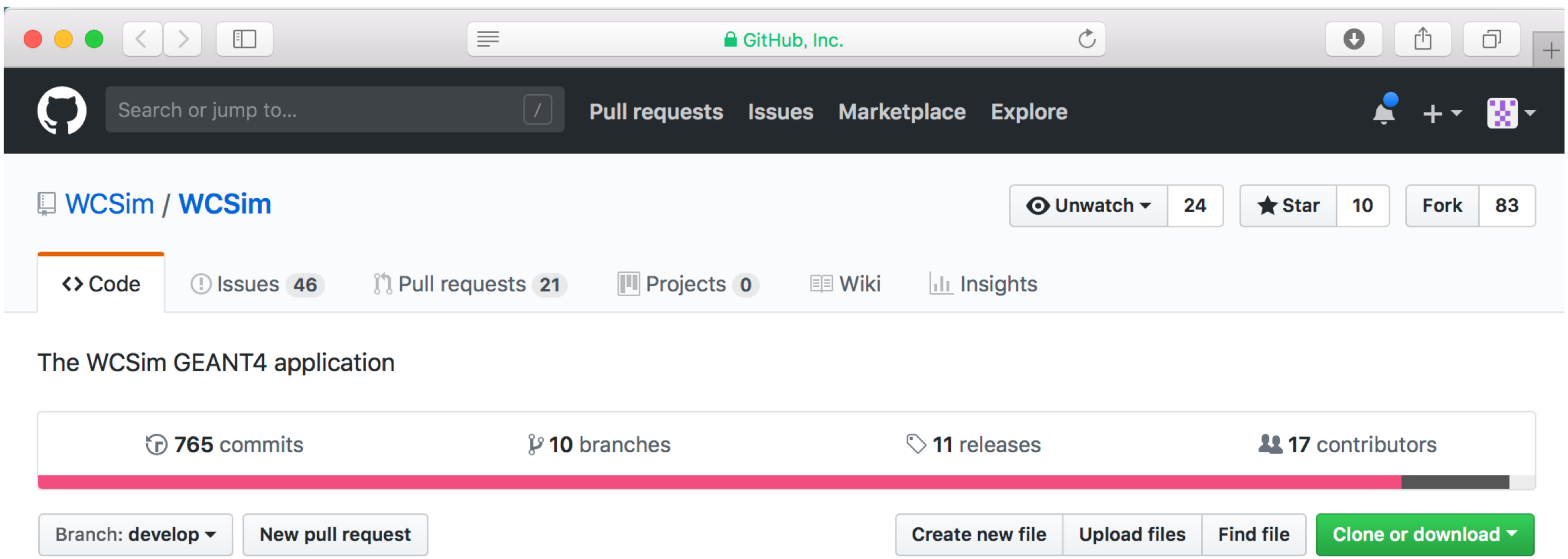
- Detector simulation **WCSim**
- Event reconstruction algorithm **fiTQun**





WCSim detector simulation

- Open-source flexible water Cherenkov detector simulation package based on Geant4
  - https://github.com/WCSim/WCSim
- Mainly developed by Hyper-Kamiokande collaborators

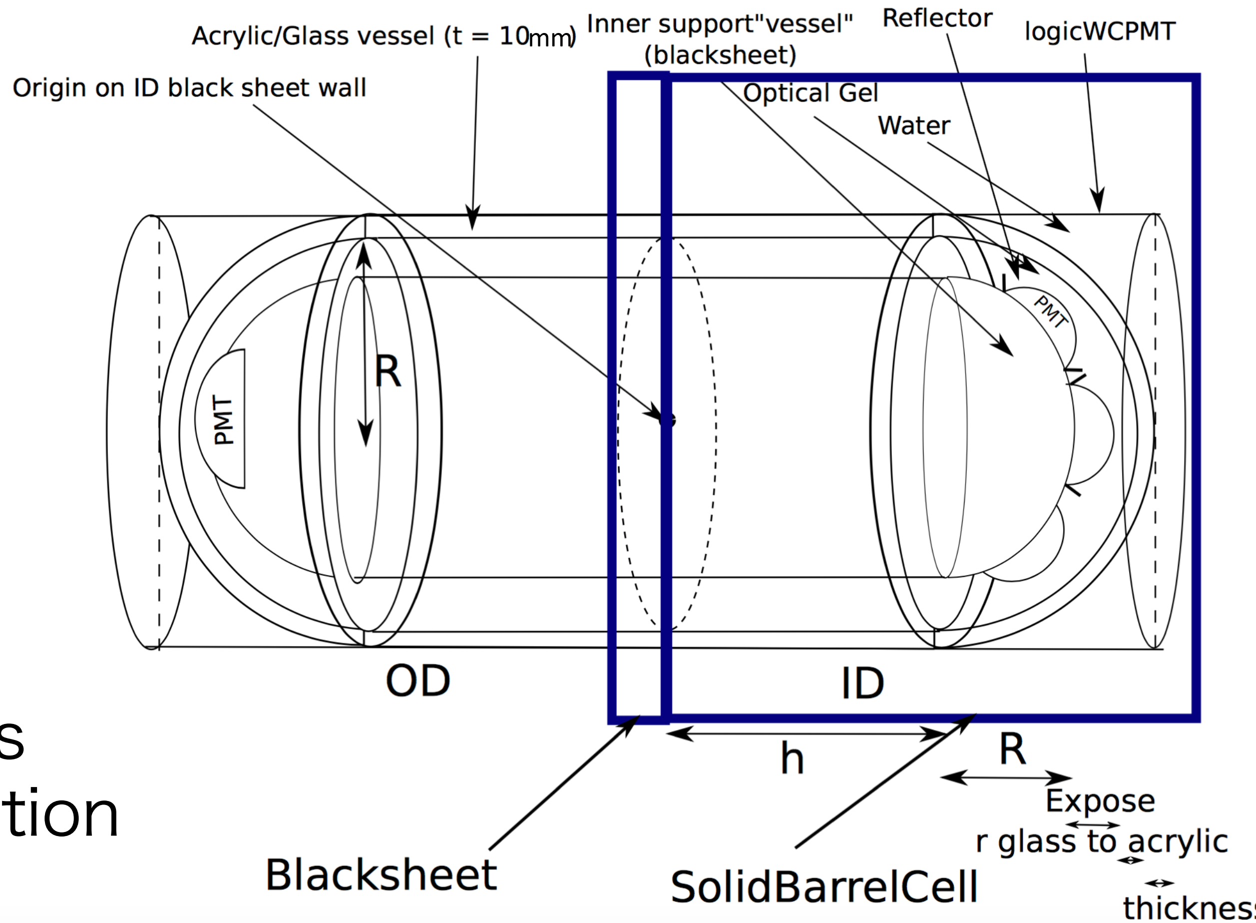


mPMT implementation

mPMT is implemented into E61 branch of WCSim
https://github.com/nuPRISM/WCSim

- Acrylic vessel
- Optical gel
- Aluminum reflector
- 3inch PMT
- Inner support structure

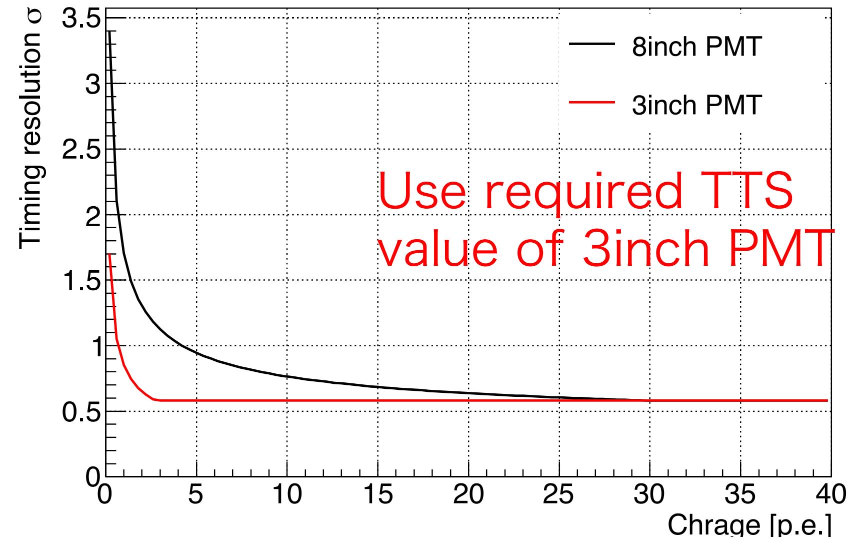
OD simulation is under construction

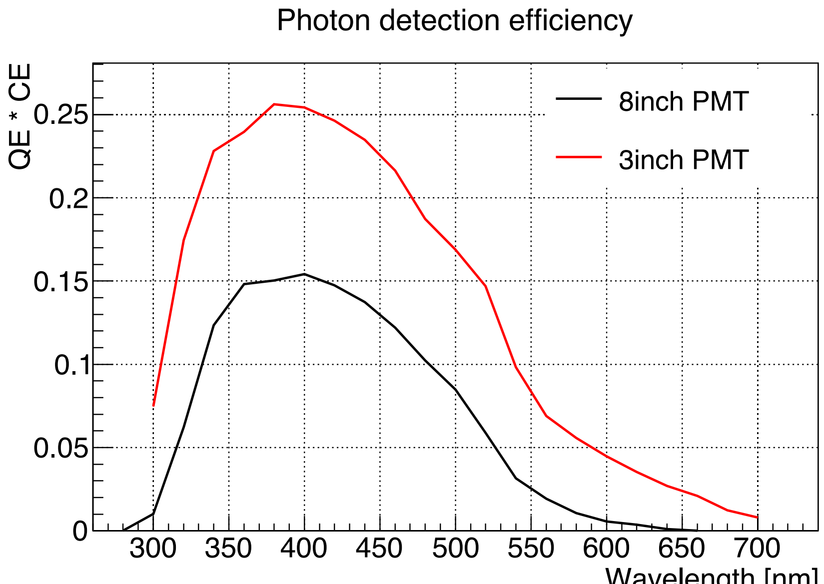


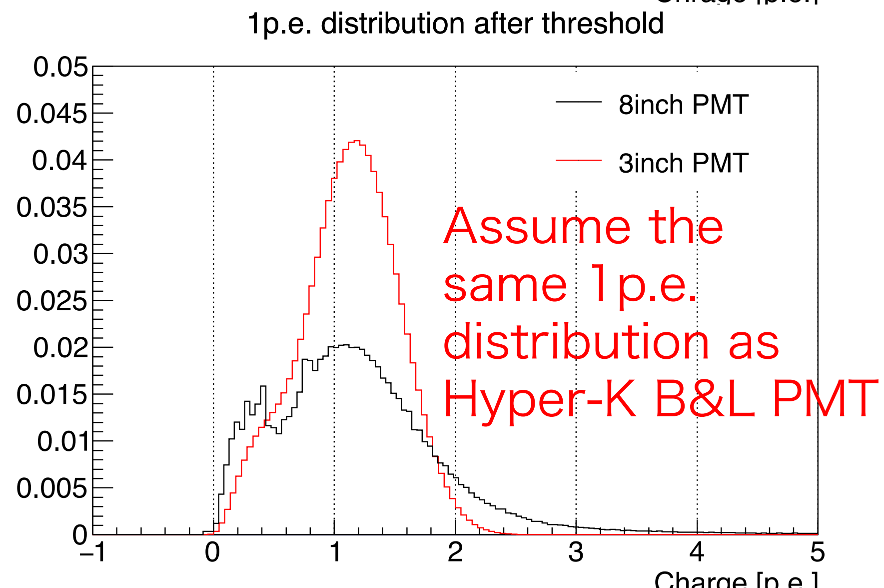
Implemented PMT properties

8inch PMT properties based on old LBNE measurements

QE is taken from KM3NeT measurement
doi: 10.1063/1.4902786







FiTQun event reconstruction

FiTQun is originally developed for T2K experiment, and is based on maximum likelihood method.

PMT unhit probability — PMT hit probability — PMT charge pdf — PMT timing pdf

$$L(\mathbf{x}) = \prod_{j}^{\text{unhit}} \underbrace{P_j(\text{unhit}|\mu_j)}_{\text{PMT unhit probability}} \prod_{i}^{\text{hit}} \underbrace{\{1 - P_i(\text{unhit}|\mu_i)\}}_{\text{PMT hit probability}} \underbrace{f_q(q_i|\mu_i)}_{\text{PMT charge pdf}} \underbrace{f_t(t_i|\mathbf{x})}_{\text{PMT timing pdf}}$$

$\mathbf{x} = (\boldsymbol{x}, t, p, \theta, \phi)$: Particle hypothesis

$\mu = \mu^{\text{dir}} + \mu^{\text{sct}}$: Poisson mean of predicted charge detected by each PMT, which is also a function of $\mathbf{x}$

Direct charge prediction

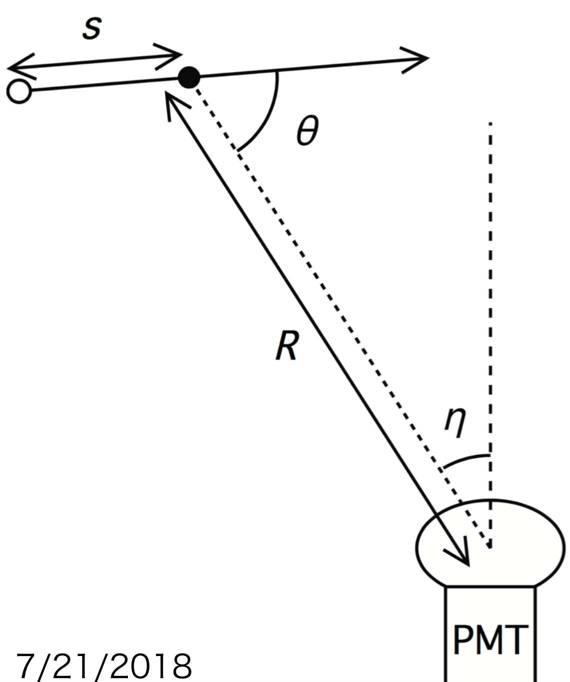
FiTQun predicts charge amount detected by each PMT

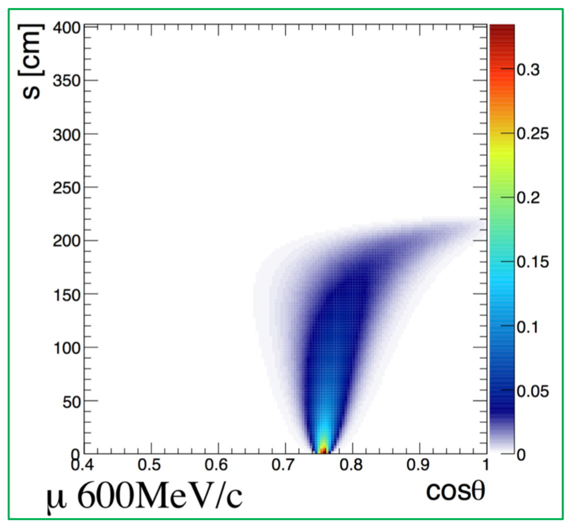
Normalization — Integration along the particle truck

$$\mu^{\text{dir}} = \Phi(p) \int ds\, g(p, s, \cos\theta)\,\Omega(R)\,T(R)\,\epsilon(\eta)$$

Cherenkov emission profile

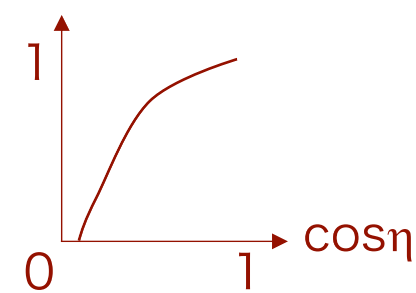
PMT solid angle at η=0 ~ R^{-2}





Light attenuation in water ~ $\exp(-R/L_{\text{attenuation}})$

PMT angular response

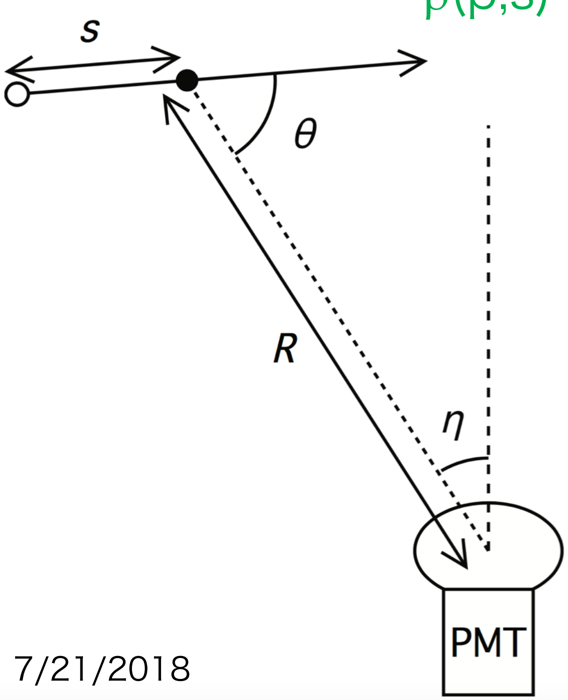


Indirect charge prediction

Indirect charge is predicted similar to direct light

$$\mu^{\rm sct} = \Phi(p)\int ds \frac{1}{4\pi}\rho(p,s)\Omega(R)T(R)\epsilon(\eta)A(s)$$

Cherenkov emission profile is integrates over angle.
ρ(p,s) is the fraction of photons emitted per unit track length.



$$\rho(p,s) \equiv \int g(p,s,\cos\theta)d\Omega$$

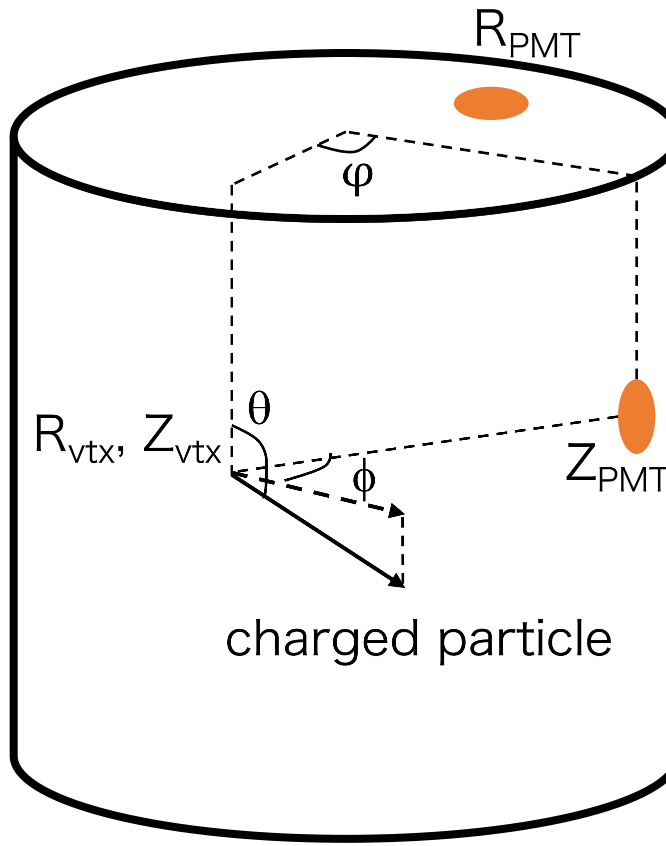
Scattering tables

$$A(x_{\rm PMT}, z_{\rm vtx}, R_{\rm vtx}, \varphi, \theta, \phi) = \frac{d\mu^{\rm sct}}{d\mu^{\rm iso,dir}}$$

Scattering tables

- FiTQun assumes that the ratio $\mu^{sct}/\mu^{iso,dir}$ does not depend on species and momentum of parent particles.
- FiTQun uses 3 scattering tables

  Each scattering table is for top/bottom/barrel PMTs
- Each of them is a 6D table



$$A(x_{\mathrm{PMT}}, z_{\mathrm{vtx}}, R_{\mathrm{vtx}}, \varphi, \theta, \phi) = \frac{d\mu^{\mathrm{sct}}}{d\mu^{\mathrm{iso,dir}}}$$

↑ R_{PMT} or Z_{PMT}

mPMT implementation

fiTQun treats signal from each PMT independently

→ Basically the same algorithm as Super-K is used

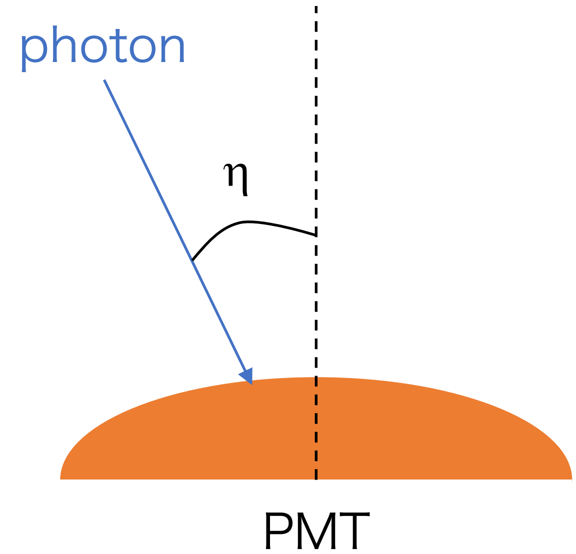
Reference pdf functions and tables are prepared using outputs of WCSim detector simulation

- $P_j(\mathrm{unhit}|\mu_j)$, $f_q(q_i|\mu_i)$
  ← Charge response of PMTs and electronics
- $f_t(t_i|\mathbf{x})$ ← Timing response of PMTs
- $\epsilon(\eta)$, $A(s)$ ← Detector geometry

mPMT implementation cont'd

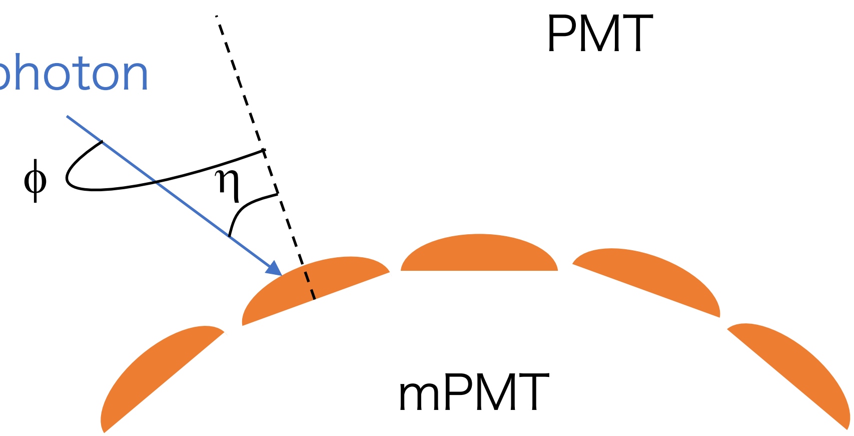
However, some parts of fiTQun assumes azimuthal symmetry of PMT that no longer holds in mPMT.

- Angular response function, $\epsilon(\eta)$
- Scattering table, $A(s)$



As a first step, these are averaged over ϕ.

Further study will be performed in future.



Detector performance study

The event reconstruction performance is evaluated using electron and muon particle gun MC.

- Electron: 30–1000 MeV
- Muon: 200–1200 MeV

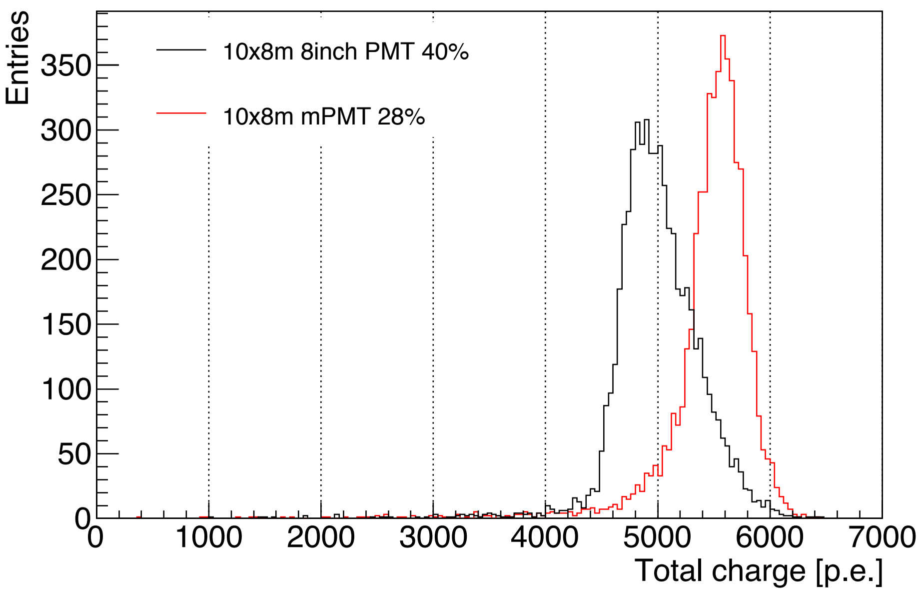
- Performance of mPMT configuration with 3inch PMTs (28% photo cathode coverage) is compared to that of 8inch PMT configuration (40% coverage), which was previous E61 nominal design.

Charge and hits distributions

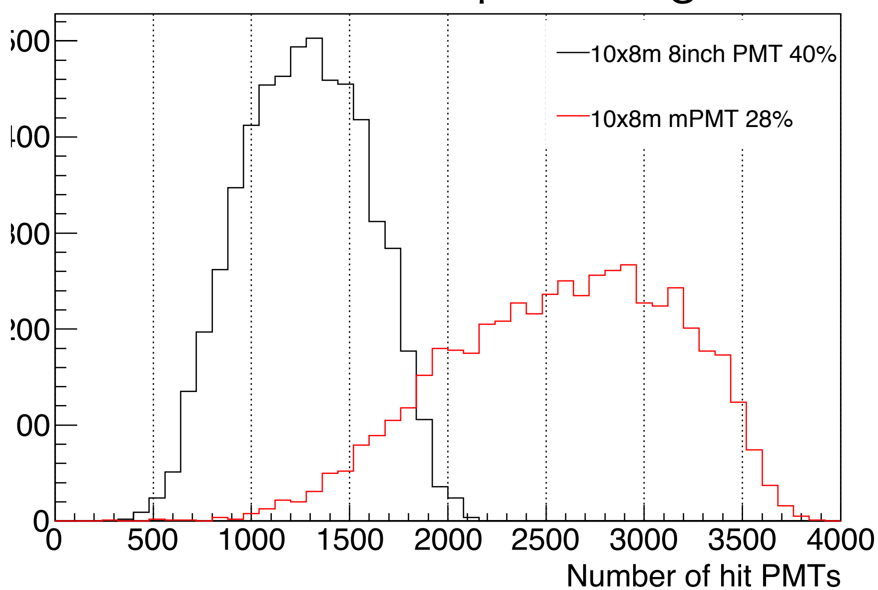
Similar or larger number of photons are detected in mPMT configuration.

- Increased QE (by ~28%) and CE (by ~30%)
- Photon collection by reflectors (~20%).

500MeV e^- particle gun



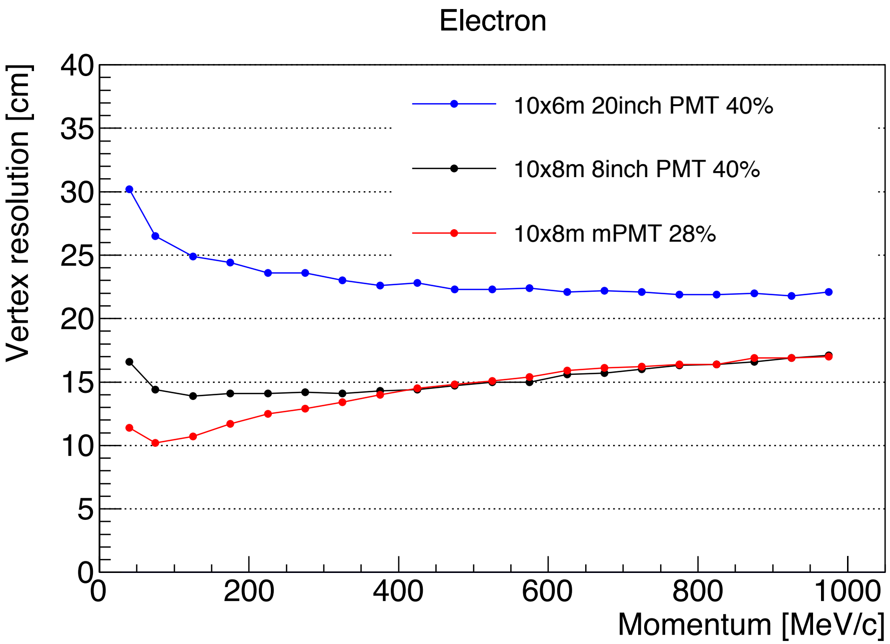
500MeV e^- particle gun

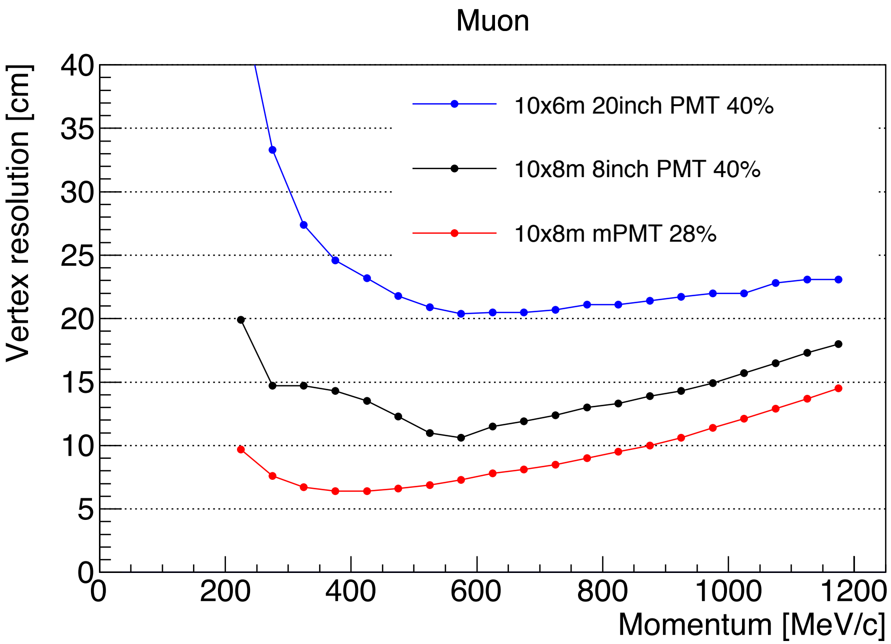


Vertex resolution

Vertex resolution is improved by using smaller PMTs.

- Location of each photon is decided more precisely

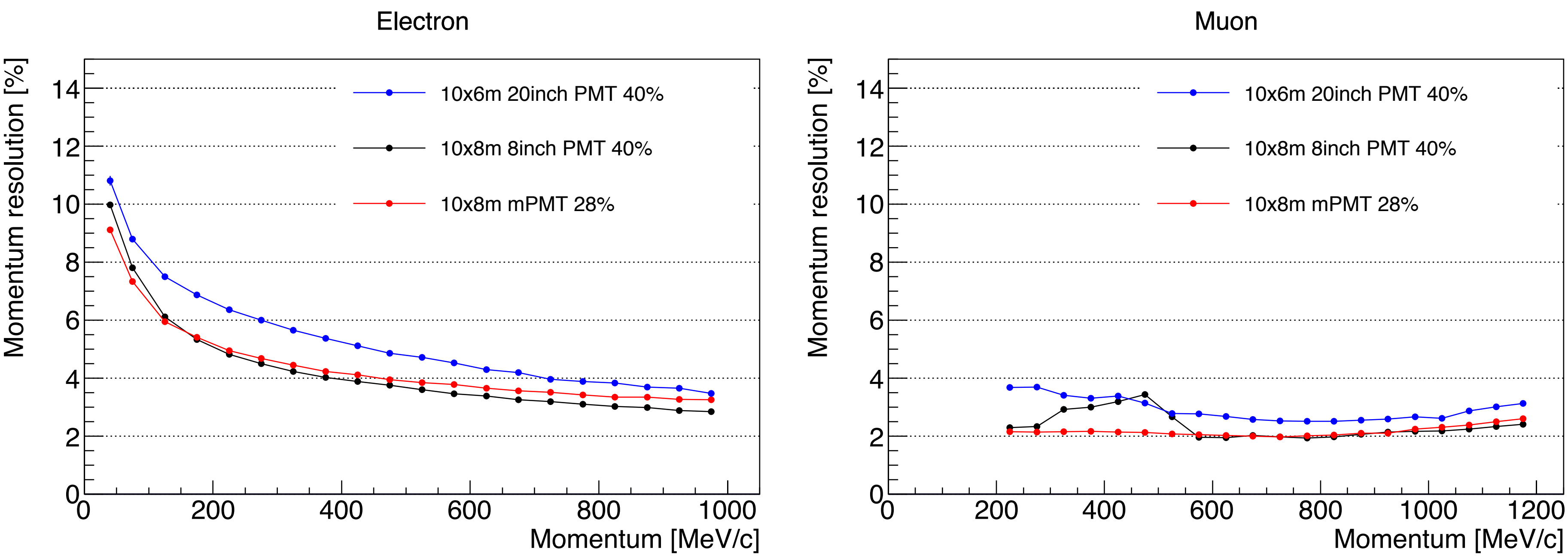




Momentum resolution

Similar momentum resolution is achieved with smaller photo-cathode coverage

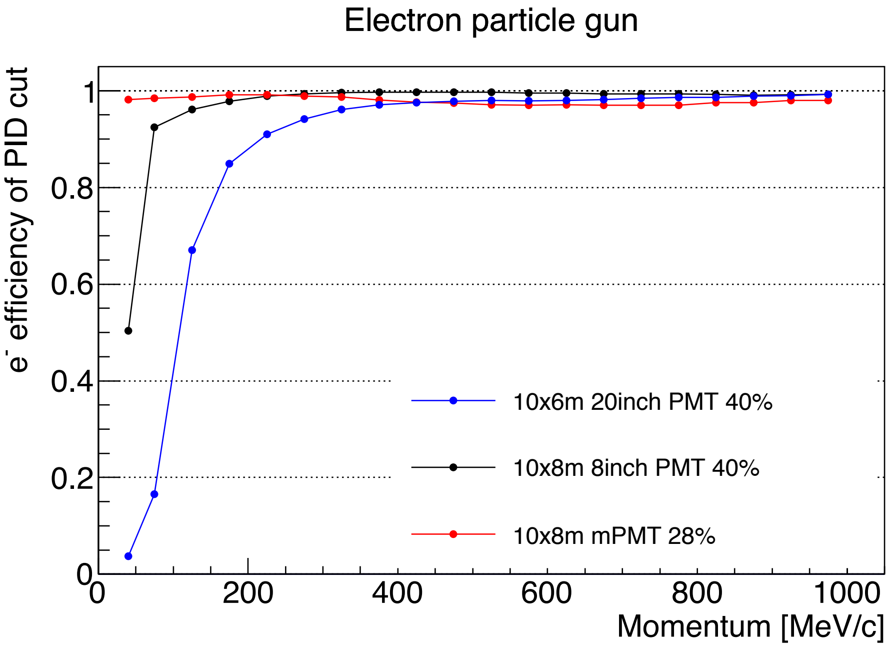
- Photon collection is improved

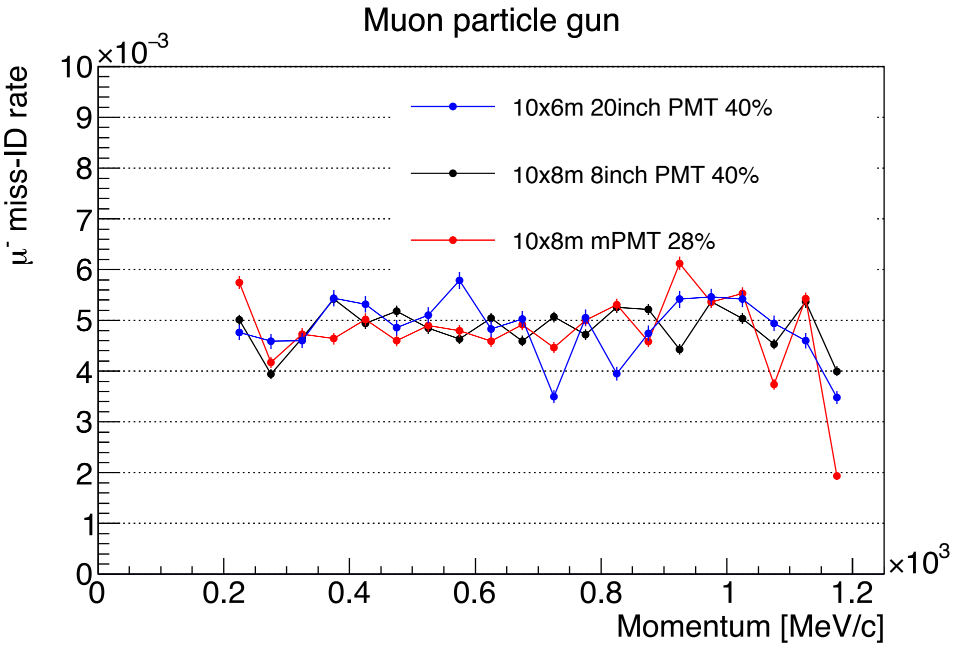


Particle identification

Electron selection efficiency is compared with the same muon rejection of 99.5%.

- An improvement is expected at lower momentum region





Future software improvements

- Development of outer detector simulation is in progress in Hyper-K collaboration.
- Precise measurements of PMTs and optical mPMT materials are ongoing in E61 collaboration. These measured properties will be implemented in future.
- FiTQun improvements are also ongoing

FiTQun improvements: Use PMT direction more

- In Super-K like configuration, all the PMT faces the direction perpendicular to detector wall.
- In mPMT, all the PMTs look different direction.

Current fiTQun for mPMT uses PMT direction information partially in charge prediction.

$$\mu^{\text{dir}} = \Phi(p) \int ds g(p, s, \cos\theta) \Omega(R) T(R) \boxed{\epsilon(\eta)}$$

PMT angular response function

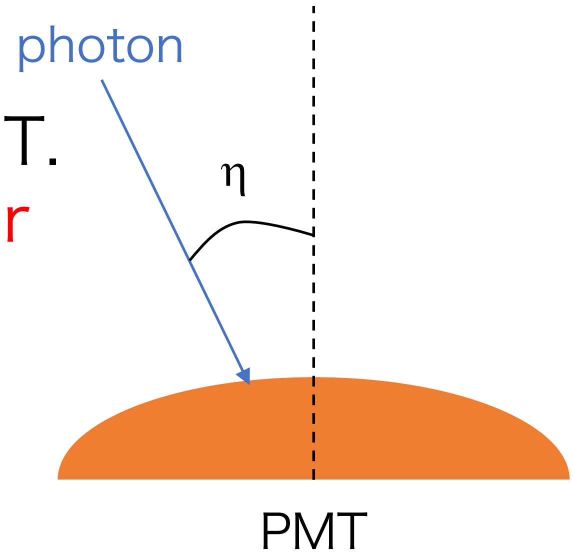
$$\mu^{\text{sct}} = \Phi(p) \int ds \frac{1}{4\pi} \rho(p, s) \Omega(R) T(R) \boxed{\epsilon(\eta)} A(s)$$

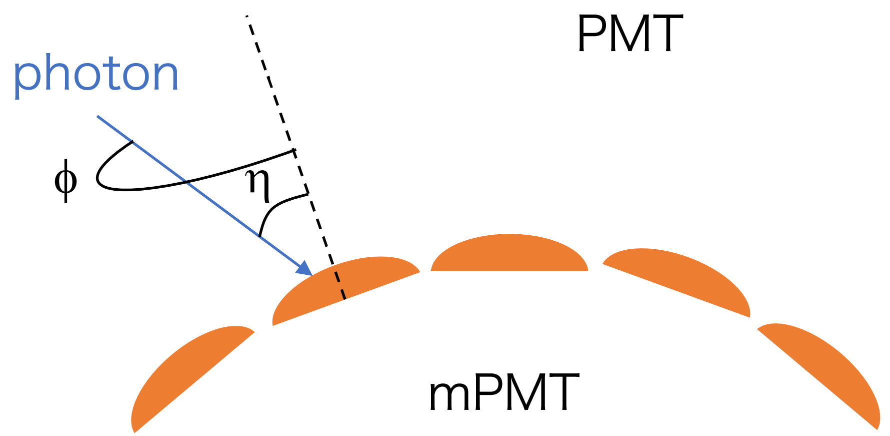
This additional PMT direction information has potential to tell us photon emission point.
Two ideas are shown in following slides.

PMT angular response in 2D

Current PMT angular response function is a 1D function of η. Azimuthal symmetry of PMT is assumed.

However, that is not the case of mPMT. Shading by nearby PMTs and detector wall depends on ϕ.
→ 2D angular response function
is a possible option

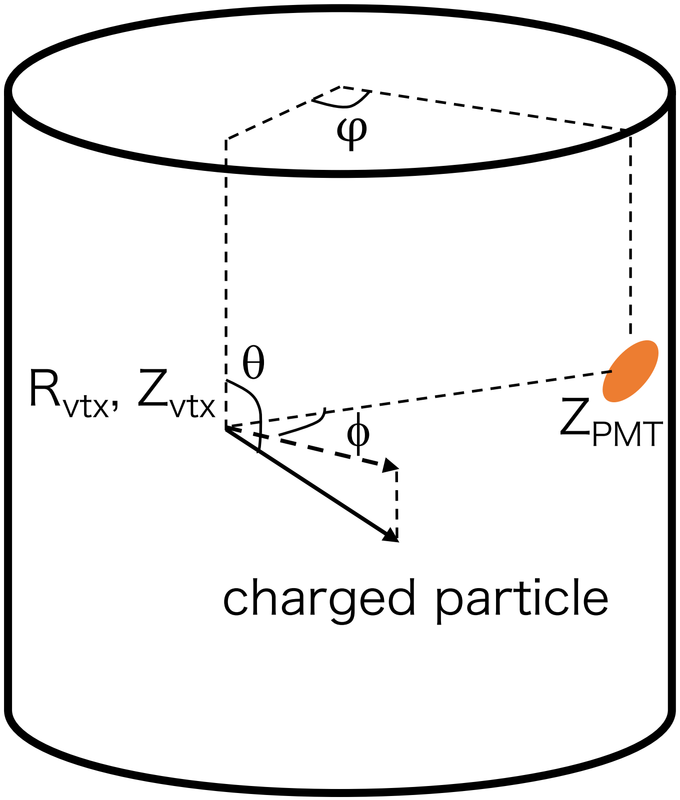




PMT direction in scattering tables

- PMT direction is not explicitly implemented in scattering tables as for now.
- PMT direction is indirectly considered by using positional relationship of PMT and photon production point, but this method ignores direction difference of PMTs in one module.

The ratio μ^{sct}/μ^{dir} should depend on PMT direction.
→ Adding another dimension of PMT direction information might improve reconstruction.

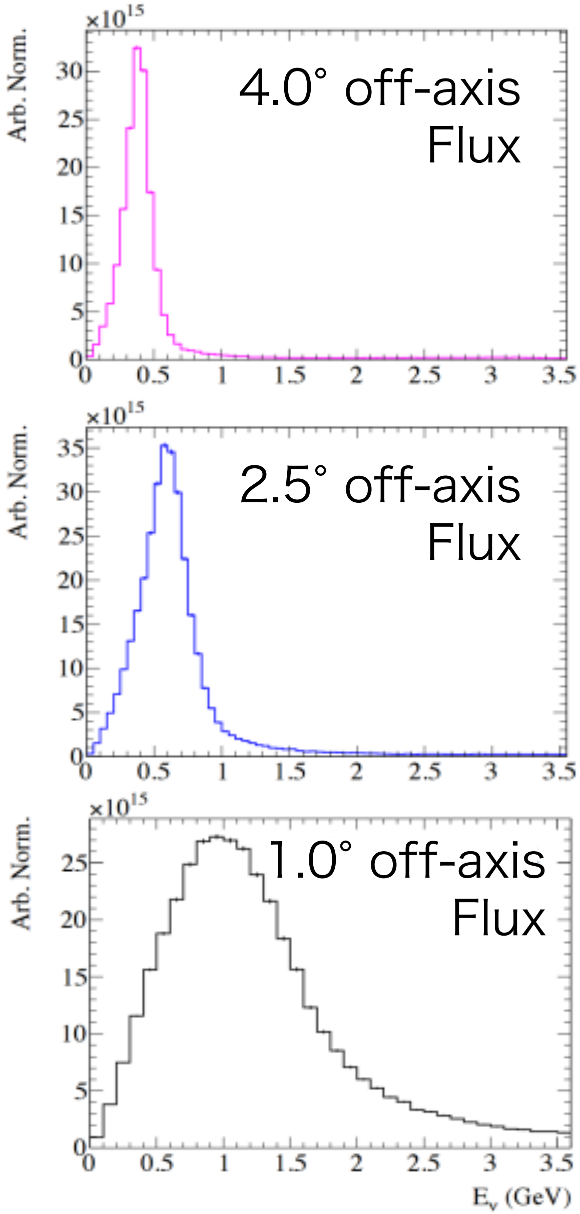


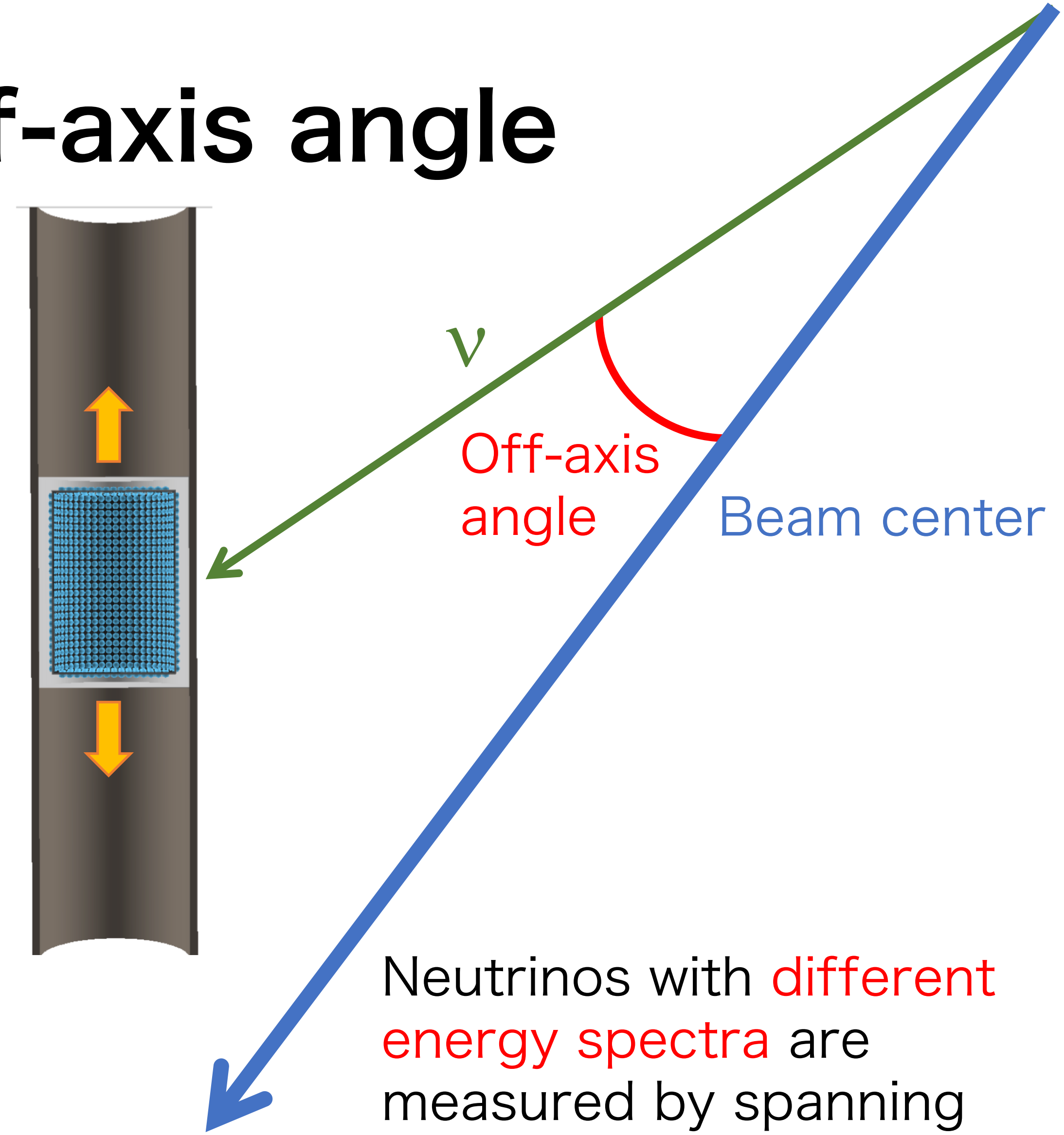
Summary

- J-PARC E61 is proposed to reduce systematics related to neutrino-nucleus interaction
- The initial version of full detector simulation and event reconstruction algorithm were developed for E61 detector equipped with mPMT modules.
- Further software improvements are ongoing in both detector simulation side and event reconstruction side.

Back up

Spanning off-axis angle





Neutrinos with different energy spectra are measured by spanning off-axis angle

$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2E_\pi(1-\beta_\pi\cos\theta)}$$

WCSim physics processing

- Kinematics of particles emitted by neutrino interaction or entering the detector are the input to WCSim.
- Physics processes of particles after the neutrino interaction are simulated by Geant4.
  - Particle track in water, interaction with nuclei, and Cherenkov radiation
- Geant4 also tracks Cherenkov photons.
- Many parameters describing material properties are taken from Super-K calibration and simulation
  - Water, black sheet, glass

PMT description in WCSim

When a photon reaches PMT surface, output signal is simulated according to PMT properties.

- PMTs are described by some functions and parameters
  - Overall efficiency for a photon to register a charge, including the quantum efficiency and collection efficiency
  - Single photo-electron distribution
  - Timing response function
  - Dark noise rate
- Users can modify PMT properties easily

Electronics in WCSim

- As dark noise, add random 1 photo-electron hit to each PMT at a given rate
- Convert hits by real photon and dark noise, and then digitize the hits
  - PMT-by-PMT threshold is applied
  - Timing and charge smearing can be applied
- Issue triggers by using number of digitized hits in a given sliding timing window