MEG II LXe calibration and resolution

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Outline

Calibration

Sensor Calibration

Gain calibration / PDE calibration

Energy Calibration

CW / NG

Resolution

CEX run

Timing / Energy Resolution

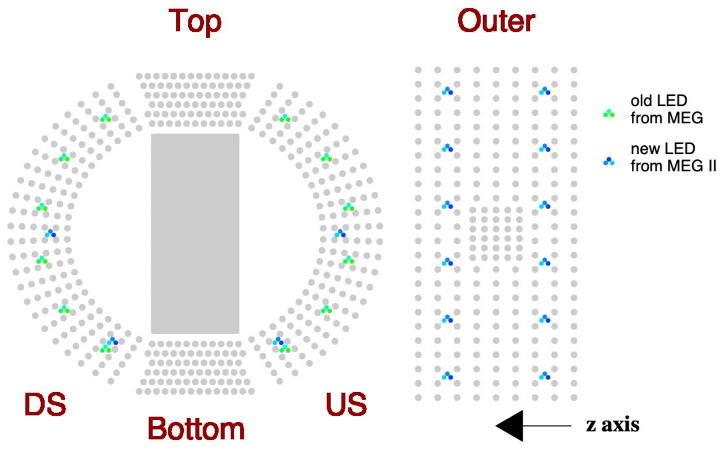
List of Calibration

Various parameters, such as gain and PDE, are required to reconstruct events in LXe detector.
Parameters fluctuate over time.
Calibration is necessary to continue physics data taking with sufficient energy resolution.

Run type	Frequency	Purpose
Pedestal	Once a day	Noise check. Update templates if necessary.
Strong LED	Once a day	PMT gain calibration
Beam blocker(BB) open/close	Every BB operation	Correction of gain shift during BB opening/closing
Weak LED	3 times a week	MPPC gain calibration
Alpha	Once a day	MPPC PDE calibration
Cosmic-ray	3 times a week	Energy scale check
17.6 MeV gamma-ray from $^{7}\mathrm{Li}(p,\gamma)\ ^{8}\mathrm{Be}$	3 times a week	Energy scale calibration
9 MeV gamma-ray from $^{58}\mathrm{Ni}(\mathrm{n},\gamma)^{59}\mathrm{Ni}$	3 times a week	Energy scale calibration

Long calibration (3 days/week) : ~120 min
Short calibration (4 days/week) : ~50 min

PMT Gain (Strong LED Run)



Position of LEDs installed inside detector

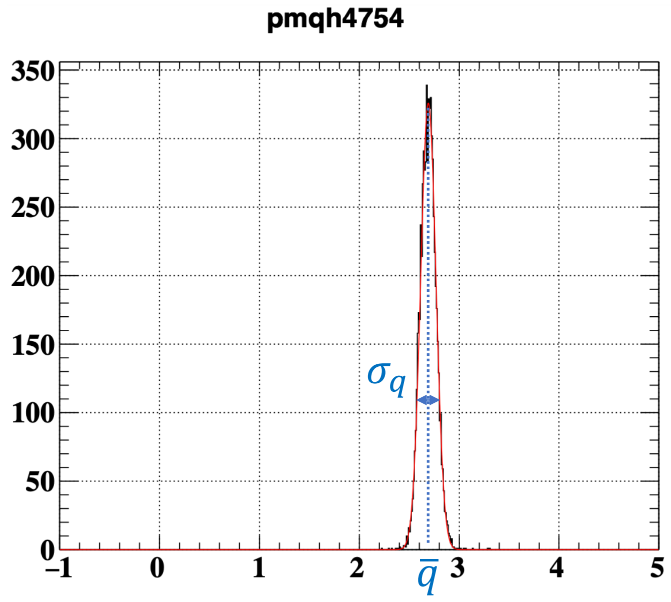
It is known from experience in MEG that PMT gain decreases.
LEDs are installed inside detector for gain calibration.
Calculate charge of each sensor at different LED intensities.

- Long calibration (22 different intensities) 3days/week
- Short calibration (4 different intensities) 4days/week

PMT gain can be calculated from the following equation.

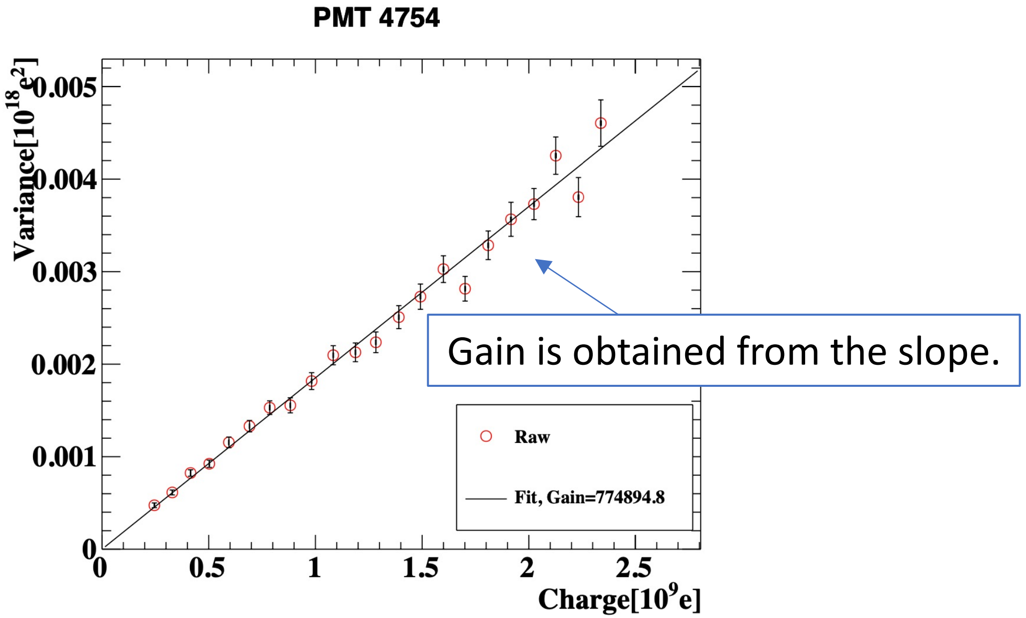
$$\sigma_q^2 = Ge\bar{q} + \sigma_0^2$$

(σ_q:spread of charge distribution, G:gain, e:elementary charge, $\bar{q}$:average charge)



Charge distribution of PM4754 for a given LED intensity

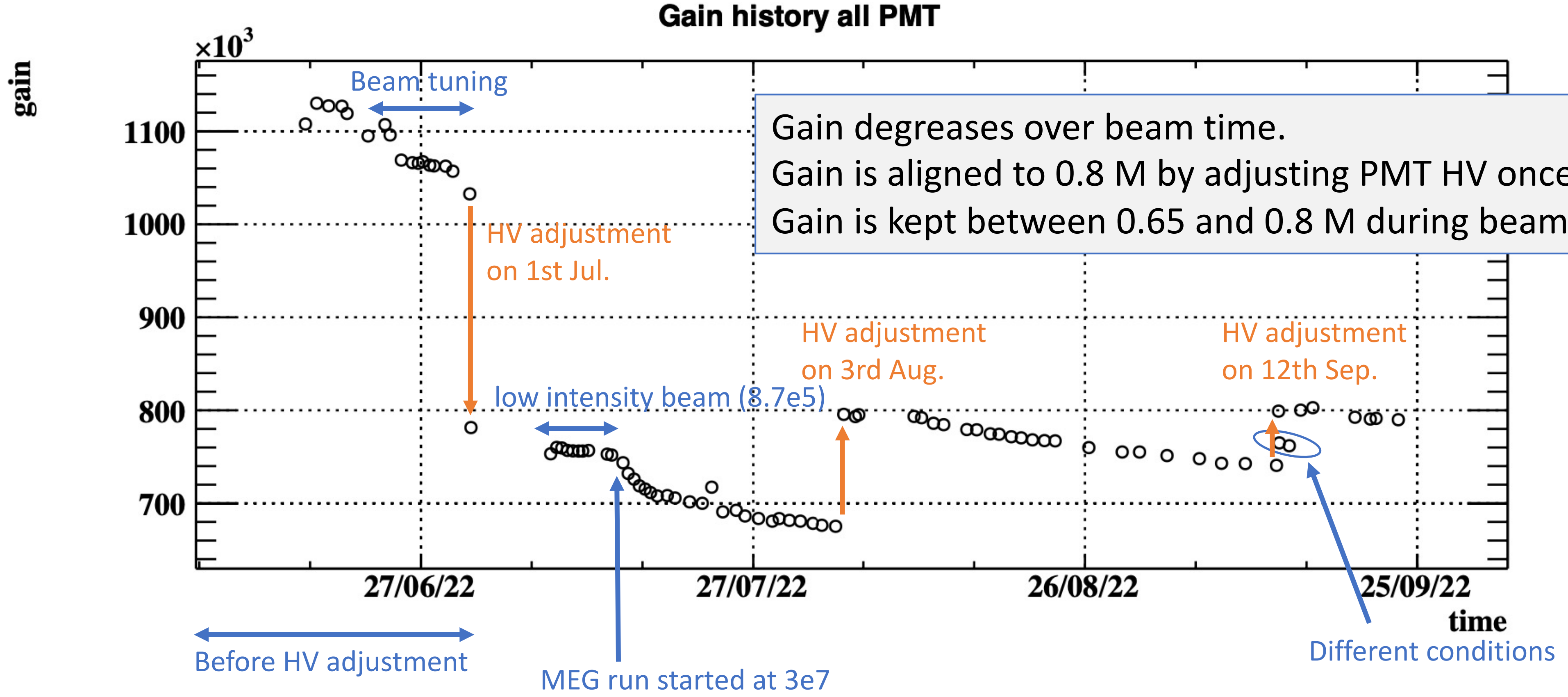
Calculate σ_q and $\bar{q}$ for different LED intensities

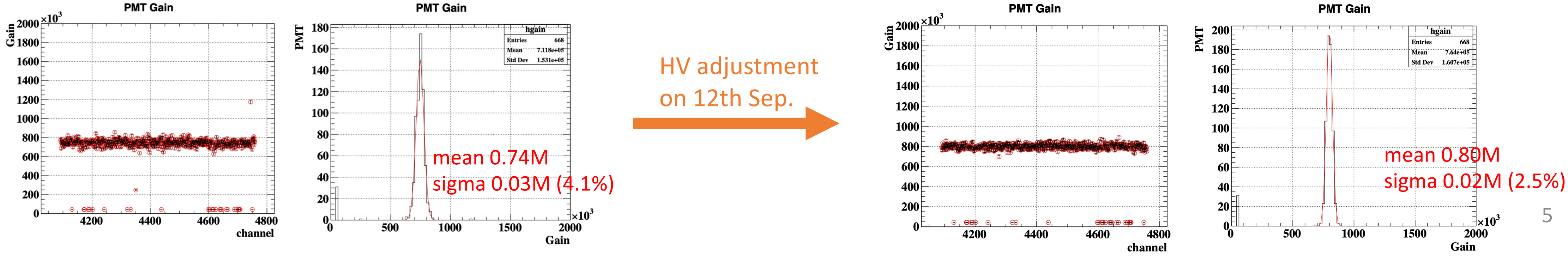


$\bar{q}$ and σ_q at different LED intensities

PMT Gain History in 2022 Beam Time

Gain degreases over beam time.
Gain is aligned to 0.8 M by adjusting PMT HV once a month.
Gain is kept between 0.65 and 0.8 M during beam time.



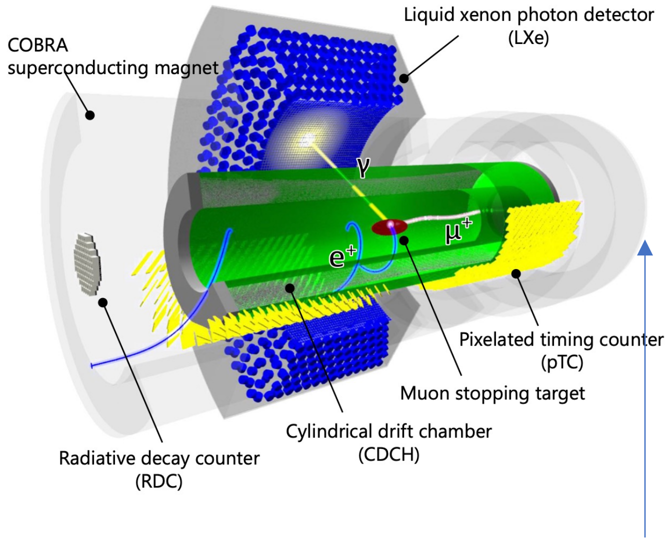


Gain Shift (BB Open/Close Run)

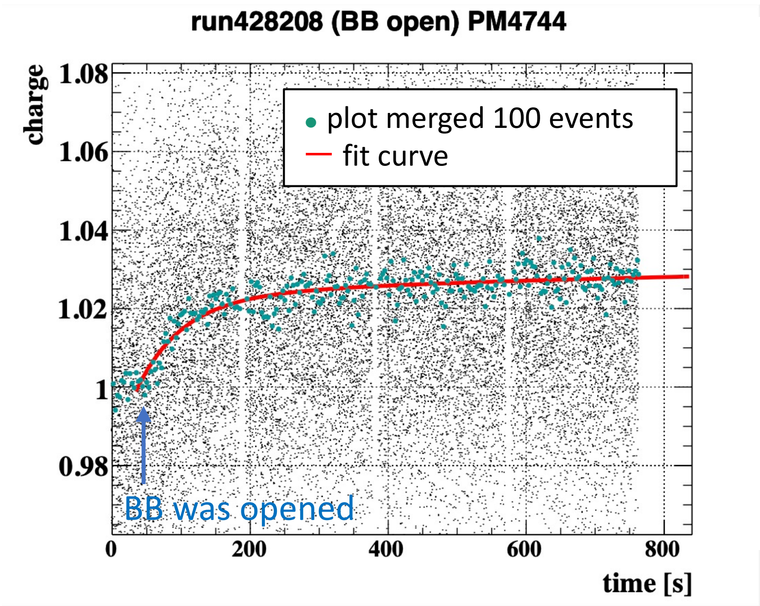
A beam blocker (BB) is installed upstream of the beam.
Beam is blocked by inserting BB into the beamline.

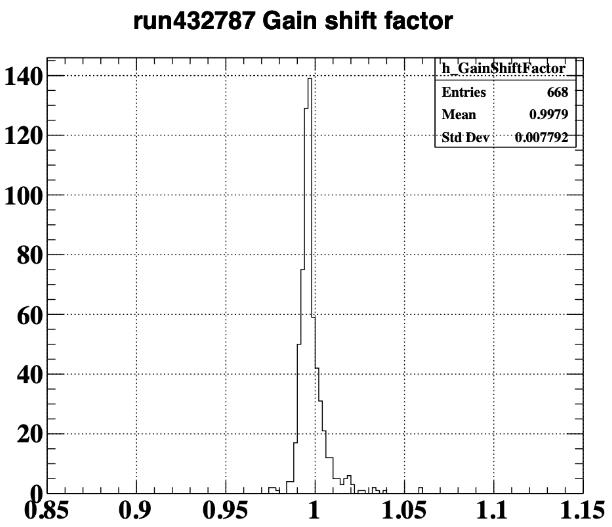
PMT gain fluctuates over a short period when BB opens or closes.
Energy scale can be modified due to gain shift.
It is necessary to correct gain shift to use the data just after BB is opened.

LEDs inside the detector are illuminated to monitor the fluctuation of the charge of each sensor when BB is opened or closed.



BB is placed on upstream side.





Fitting function

$$f(x) = 1 + A\left(1 - \exp\left(-\frac{t - t_{BB}}{\tau_1}\right)\right) + B\left(1 - \exp\left(-\frac{t - t_{BB}}{\tau_2}\right)\right) + C\left(1 - \exp\left(-\frac{t - t_{BB}}{\tau_3}\right)\right)$$

Gain shift factor (BB open) = $1 + A + B + C$
Gain shift factor (BB close) = 1 / Gain shift factor (BB open)

Most PMT gains don’t shift, but about 100 PMTs shift more than 1%.

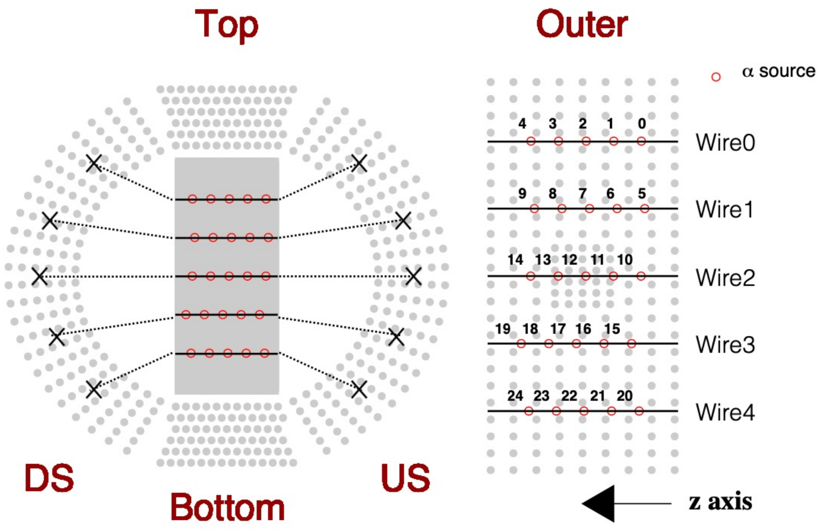
MPPC PDE / PMT QE

It was found in pre-engineering run that PDE decreases during beam time due to radiation damage.

(7.7 % → 5.6 % in 2021)

PDE of at least a few percent is required for DAQ for sufficient sensitivity.

→ Beam rate and beam time are limited by PDE.



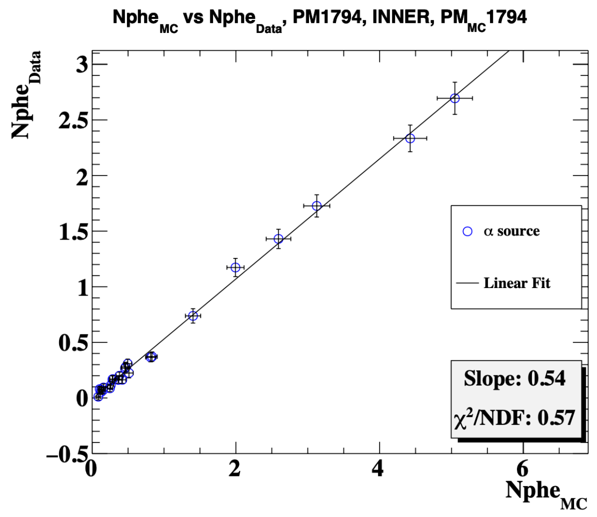
^{241}Am sources are installed inside the detector for PDE calibration.

PDE can be calculated from the number of photoelectrons using alpha-rays from ^{241}Am.

$$PDE_{\mathrm{data}} = PDE_{\mathrm{MC}} \times \frac{N_{\mathrm{data}}}{N_{\mathrm{MC}}} \times LY$$

N_{data}, N_{MC}: the number of photoelectrons in data or MC

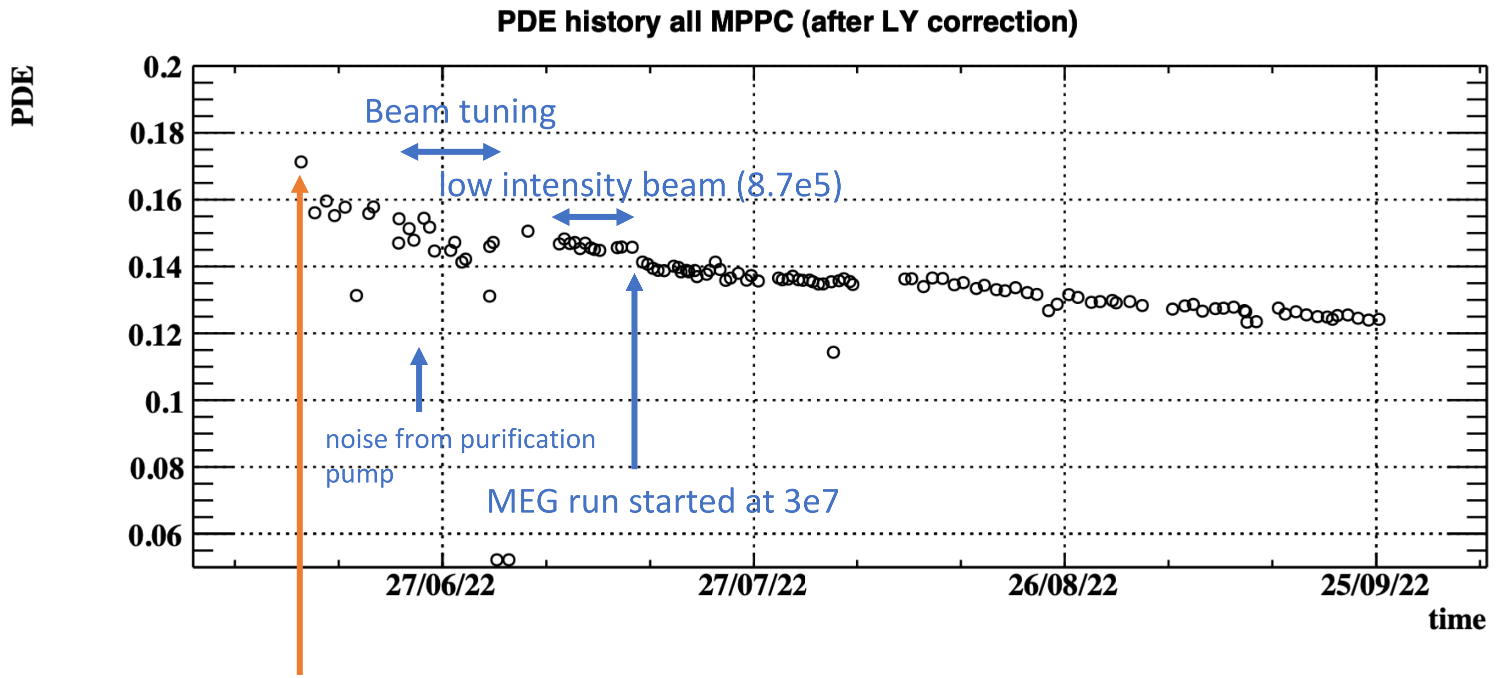
LY: Light yield



Assume PMT QE does not change.

→ Measured apparent QE fluctuation is due to LY.

MPPC PDE / PMT QE



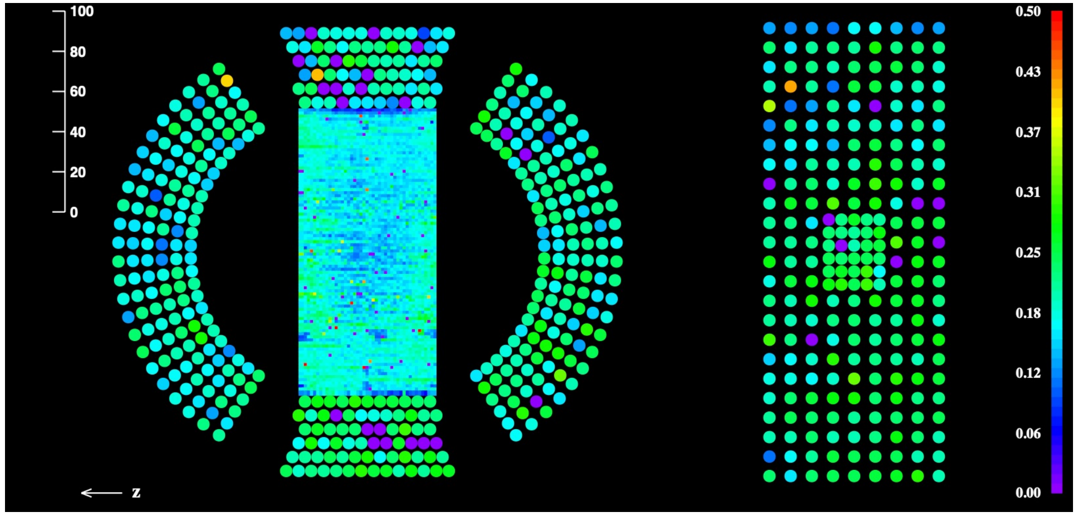
PDE was recovered to 17.7% after annealing.
(It is high enough to do DAQ this year.)

PDE history of 2022 physics run

PDE is monotonically decreasing after the start of DAQ.

(PDE before LY correction is unstable due to the large fluctuation of LY this year.)

PDE decrease speed
0.00026 /day

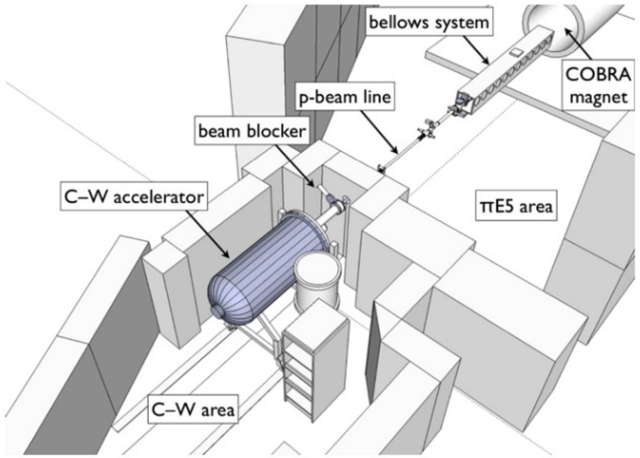


PDE Map

Energy Uniformity and Stability (CW run)

Energy scale and uniformity is monitored using a Cockcroft-Walton accelerator.

- Accelerate protons onto a $\mathrm{Li_2B_4O_7}$ target. (μ-target is removed in CW run.)
- Gamma-rays of 17.6 MeV from ${}^{7}_{3}\mathrm{Li}(p,\gamma){}^{8}_{4}\mathrm{Be}$ are used for energy scale monitoring.

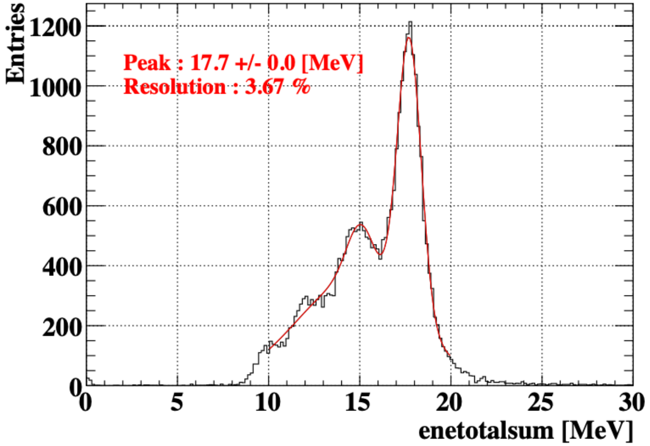


Energy uniformity is kept by correcting trigger weight using the result of CW runs.

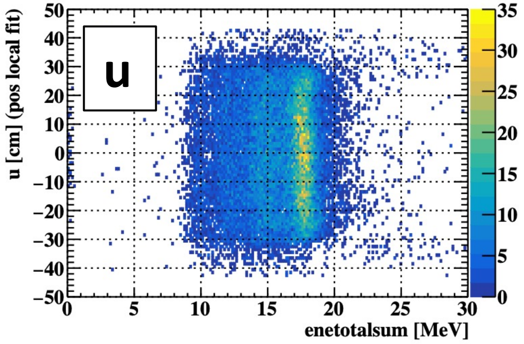
Offline energy resolution is 3.67%.

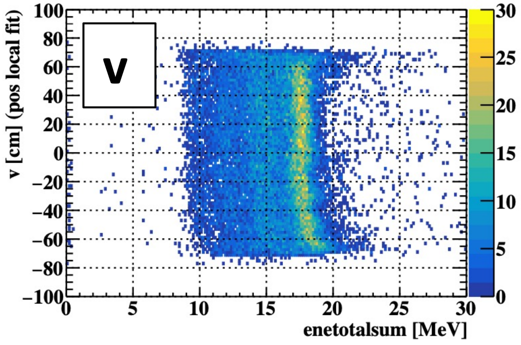
Online energy resolution at 4% also achieved.

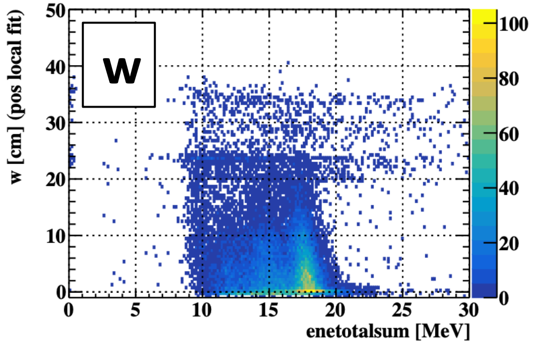
Energy scale is stable due to periodic trigger weight and scale factor updates.

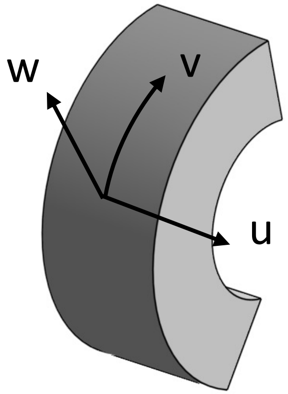


Energy uniformity in uvw-coordinate







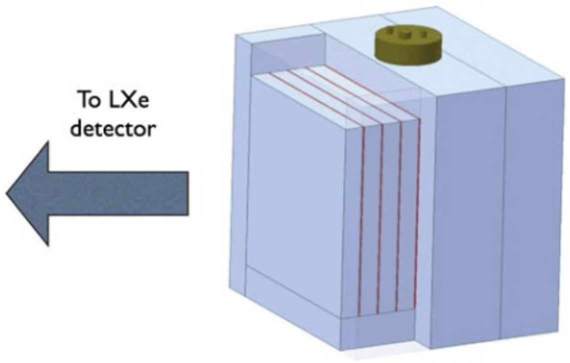


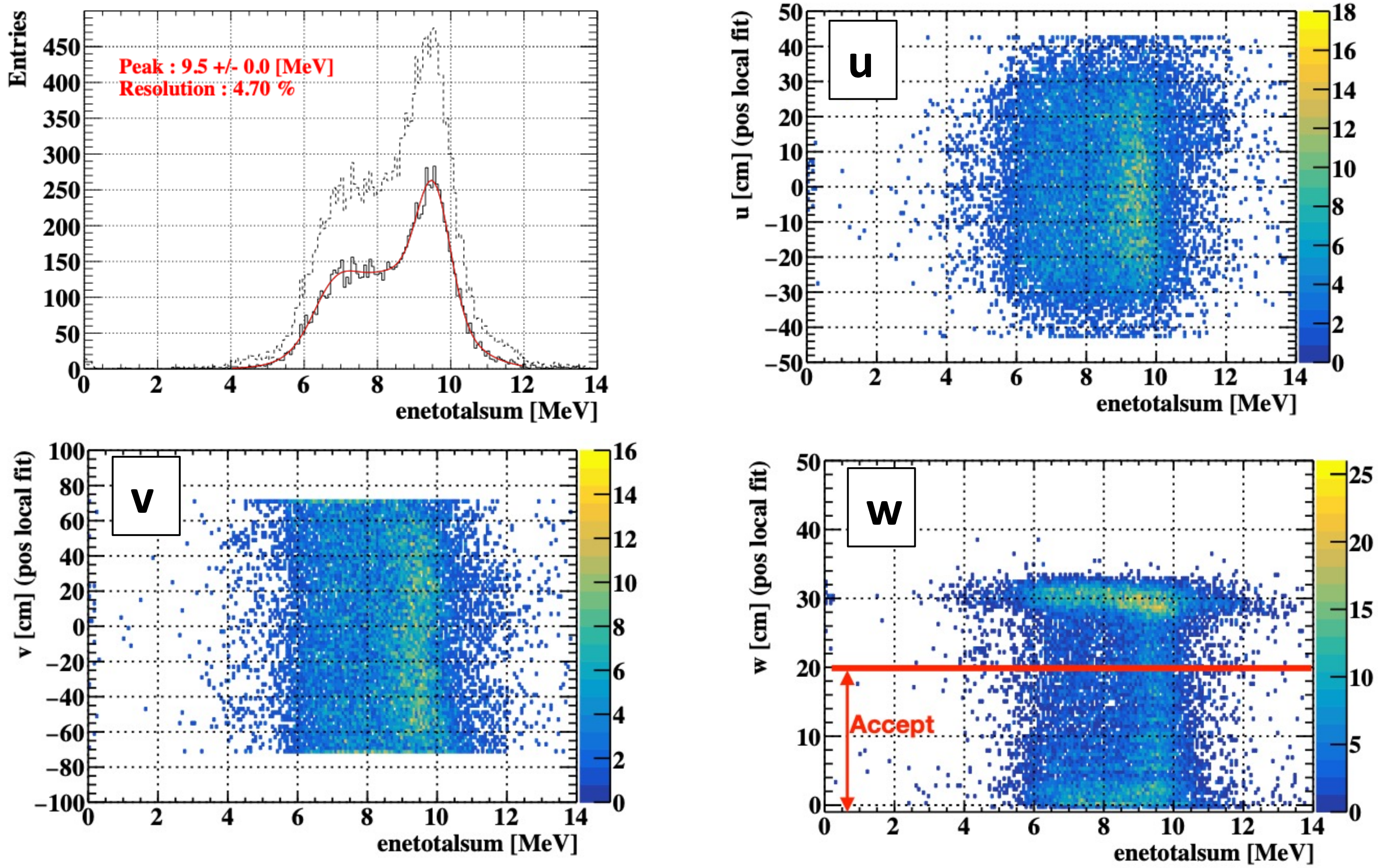
uvw-coordinate in LXe detector

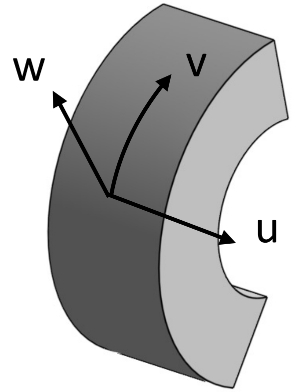
Energy Uniformity and Stability (NG run)

Energy scale can be monitored also using a neutron generator (NG).

- Gamma-rays of 9.0 MeV from capture of thermal neutrons in nickel $^{58}\mathrm{Ni}(\mathrm{n},\gamma)^{59}\mathrm{Ni}$
- This method can be used even with muon beam on.







uvw-coordinate in LXe detector

CEX Run

CEX run is used for the evaluation of timing and energy resolution of LXe detector.

Charge EXchange reaction (CEX)

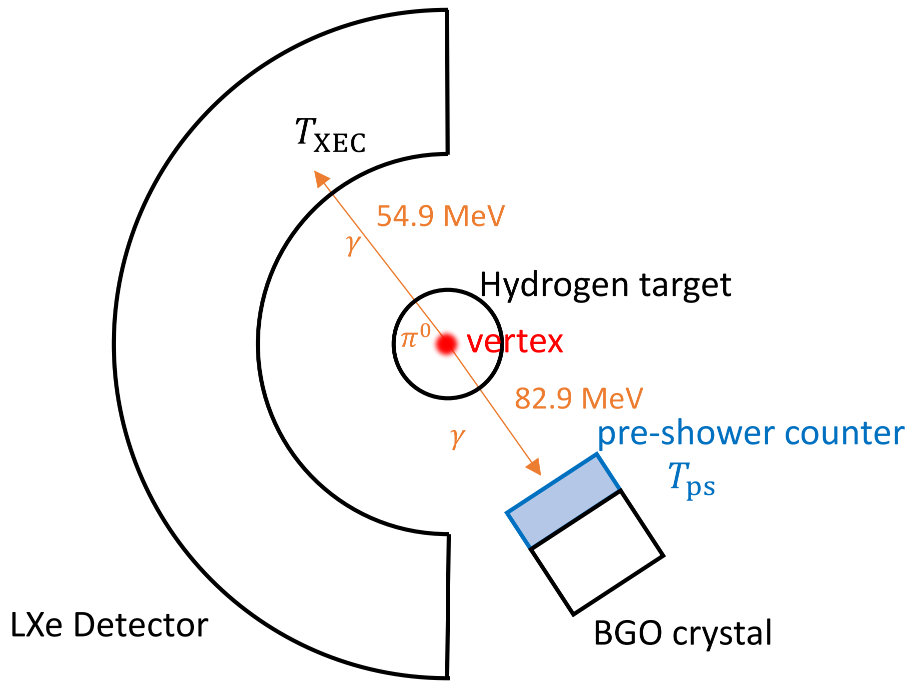
$$\pi^- p \rightarrow \pi^0 n$$

$$\pi^0 \rightarrow \gamma\gamma$$

π^- is injected into a liquid hydrogen target.

Back-to-back γ-rays : 54.9 MeV and 82.9 MeV

Close to the energy of the signal event (52.8 MeV).

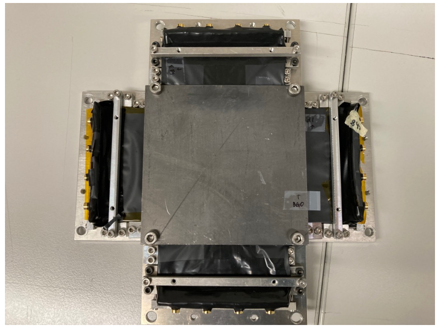


Timing measurement

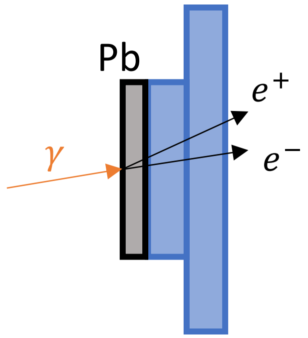
gamma-ray hit timing on pre-shower counter + LXe detector

Energy measurement

Energy in BGO crystal + LXe detector



pre-shower counter



Move BGO and scan the inner face of the detector.

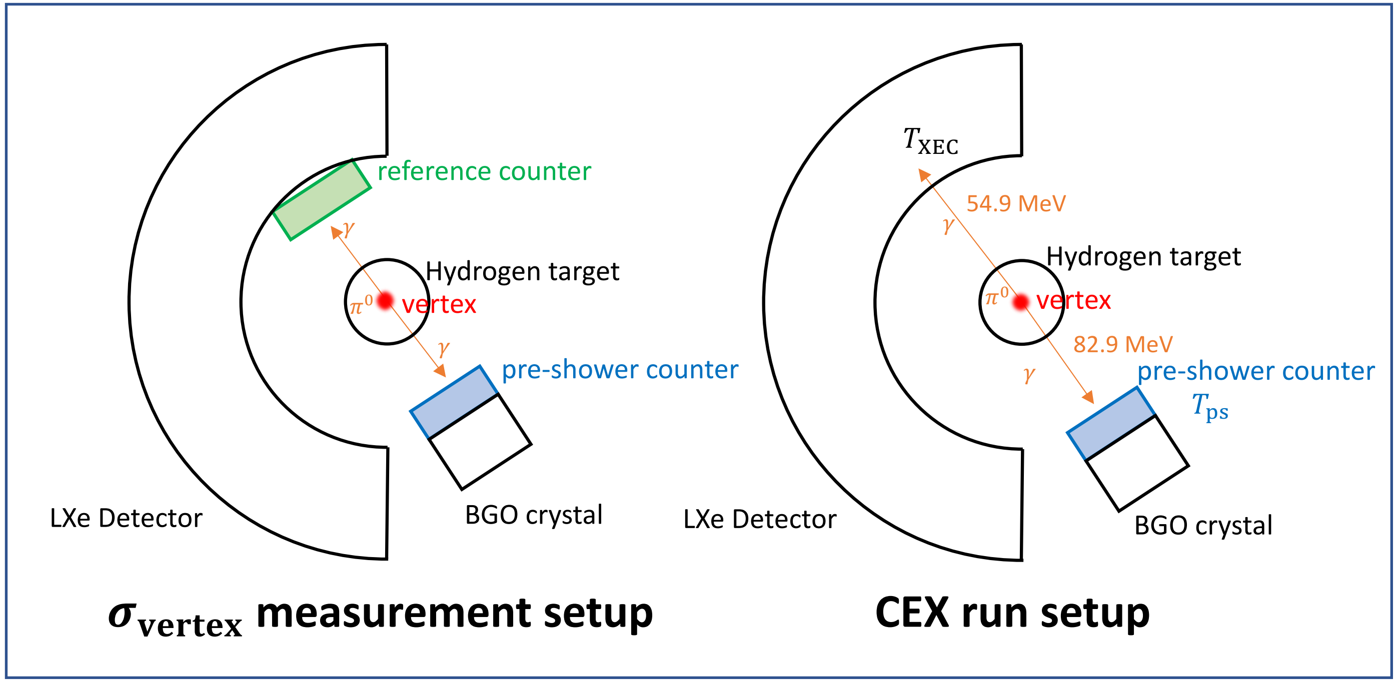
Timing Resolution

$$\boldsymbol{\sigma_{\mathrm{LXe}} = \sigma(T_{\mathrm{xec}} - T_{\mathrm{ps}} - T_{\mathrm{TOF}}) \ominus \sigma_{\mathrm{ps}} \ominus \sigma_{\mathrm{vertex}}}$$

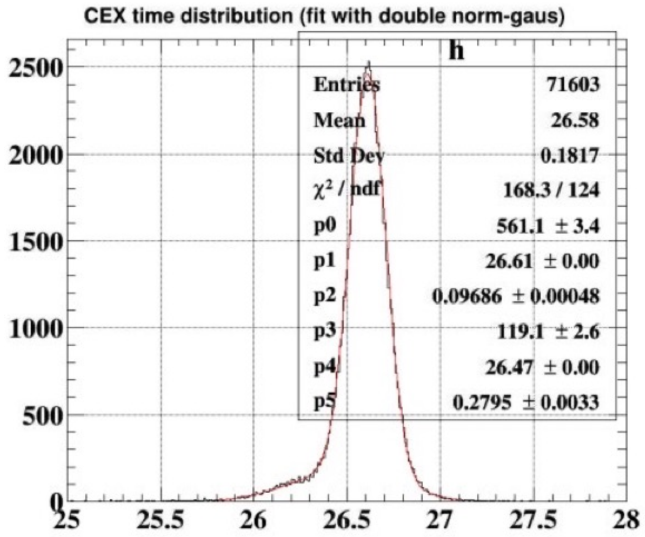
A reference counter was installed in front of LXe detector to measure σ_{vertex}.

Evaluate σ_{vertex} using the timing difference between pre-shower and reference counters.

$$\sigma_{\mathrm{vertex}} = \sigma(T_{\mathrm{ps}} - T_{\mathrm{ref}} - T_{\mathrm{TOF}}) \ominus \sigma_{\mathrm{ps}} \ominus \sigma_{\mathrm{ref}}$$



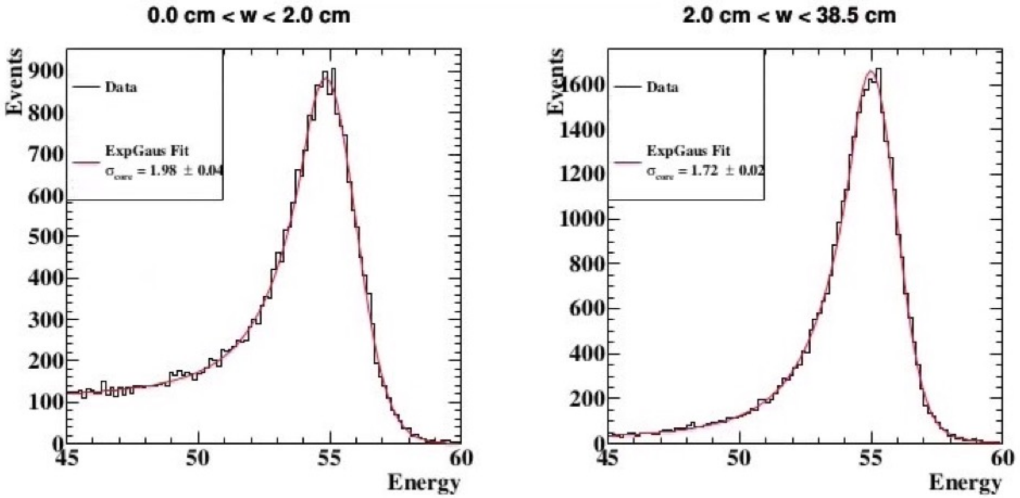
$\sigma(T_{\mathrm{xec}} - T_{\mathrm{ps}} - T_{\mathrm{TOF}})$	Time difference between pre-shower counter and LXe	96.9 ± 0.4 ps
σ_{ps}	Resolution of pre-shower counter	28.4 ± 0.2 ps
σ_{vertex}	Contribution of vertex	70.0 ± 5.7 ps
σ_{LXe}	Resolution of LXe detector	**60.7 ± 6.0 ps**



Energy Resolution

Energy resolution can be measured by CEX run.

$$\boldsymbol{\sigma_E = \sqrt{\sigma_{core}^2 - \sigma_{true}^2}}$$



Gamma-ray spectrum is fitted with exponential gaussian function.

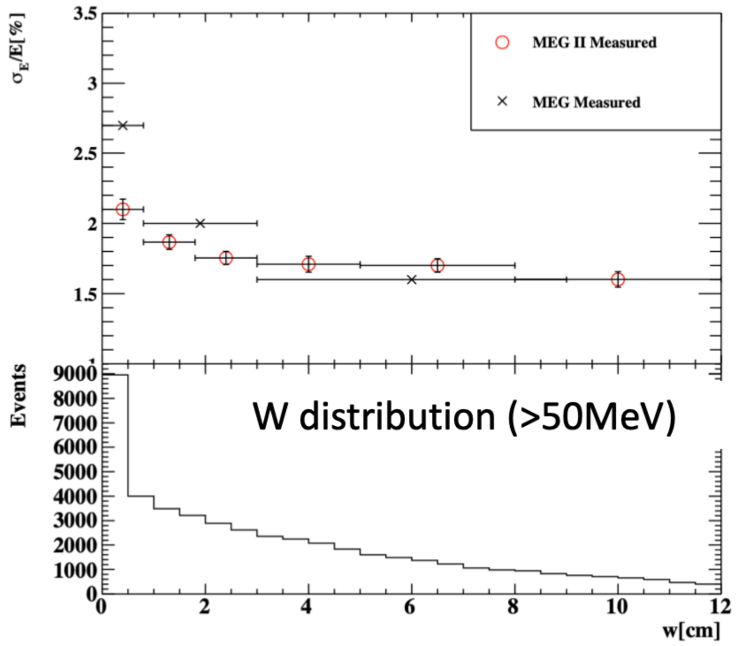
σ_E : Energy resolution of LXe detector

σ_{core} : Energy spread from fit result

σ_{true} : Spread of true energy deposit (= 0.4%)

σ_E (w < 2 cm) : 2.0 %

σ_E (w > 2 cm) : 1.7 %



Summary

- Calibration of the sensor and energy scale is necessary for the stable operation of LXe detector.

  PMT gain is measured by LEDs of some intensities, and HV is adjusted monthly.

  MPPC PDE is measured using alpha-ray and it is affected by LY.

  Energy uniformity and stability is monitored by CW run and NG run.

- Timing resolution and energy resolution are evaluated in CEX run.

  <u>Timing resolution</u>

  Timing resolution is measured by the time difference between pre-shower counter and LXe detector.

  Timing resolution of LXe detector is 60.7 ± 6.0 ps.

  <u>Energy resolution</u>

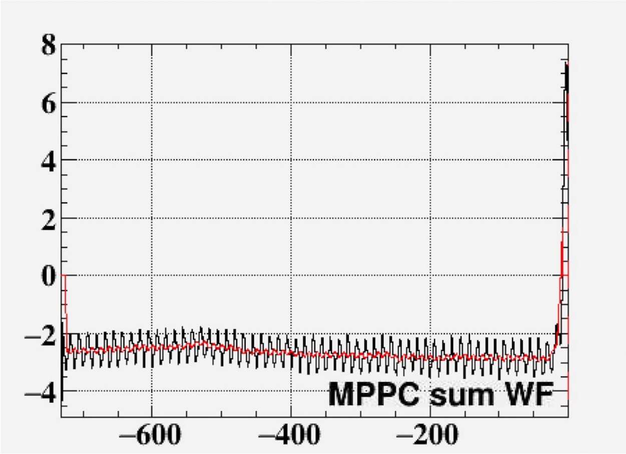
  Energy resolution is measured from the spread of gamma-ray spectrum from CEX reaction and the spread of true energy deposit.

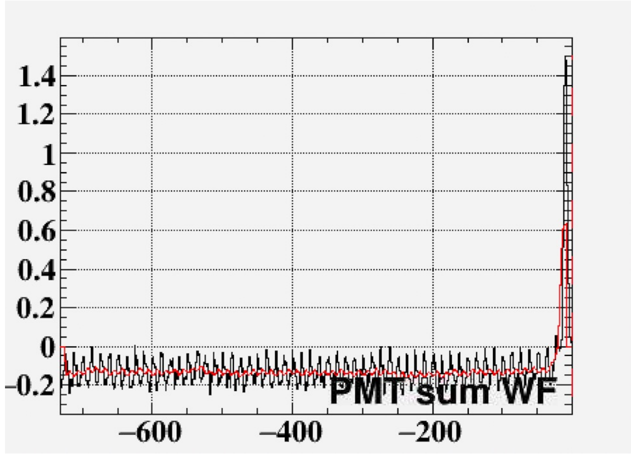
  Energy resolution of LXe detector is 2.0 %(w < 2 cm) / 1.7 %(w > 2 cm).

Backup

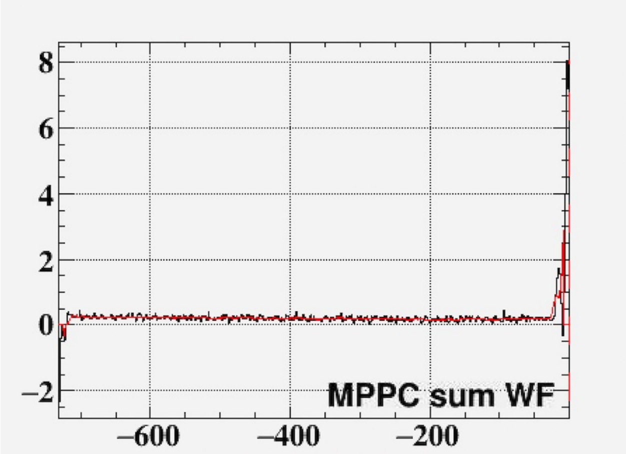
Noise Reduction (Pedestal Run)

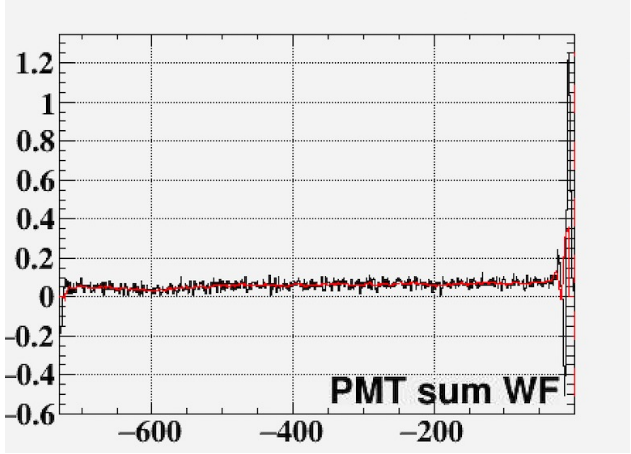
Before applying noise reduction





After applying noise reduction

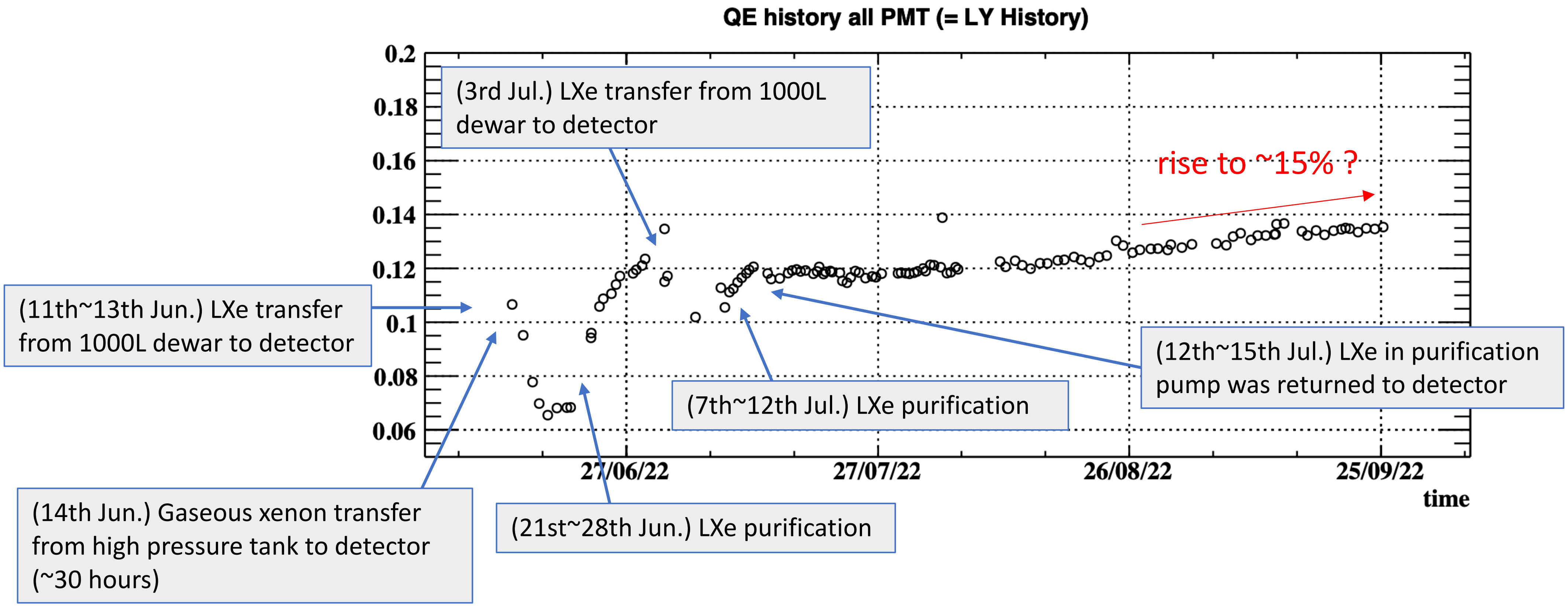




Make noise template from pedestal data.

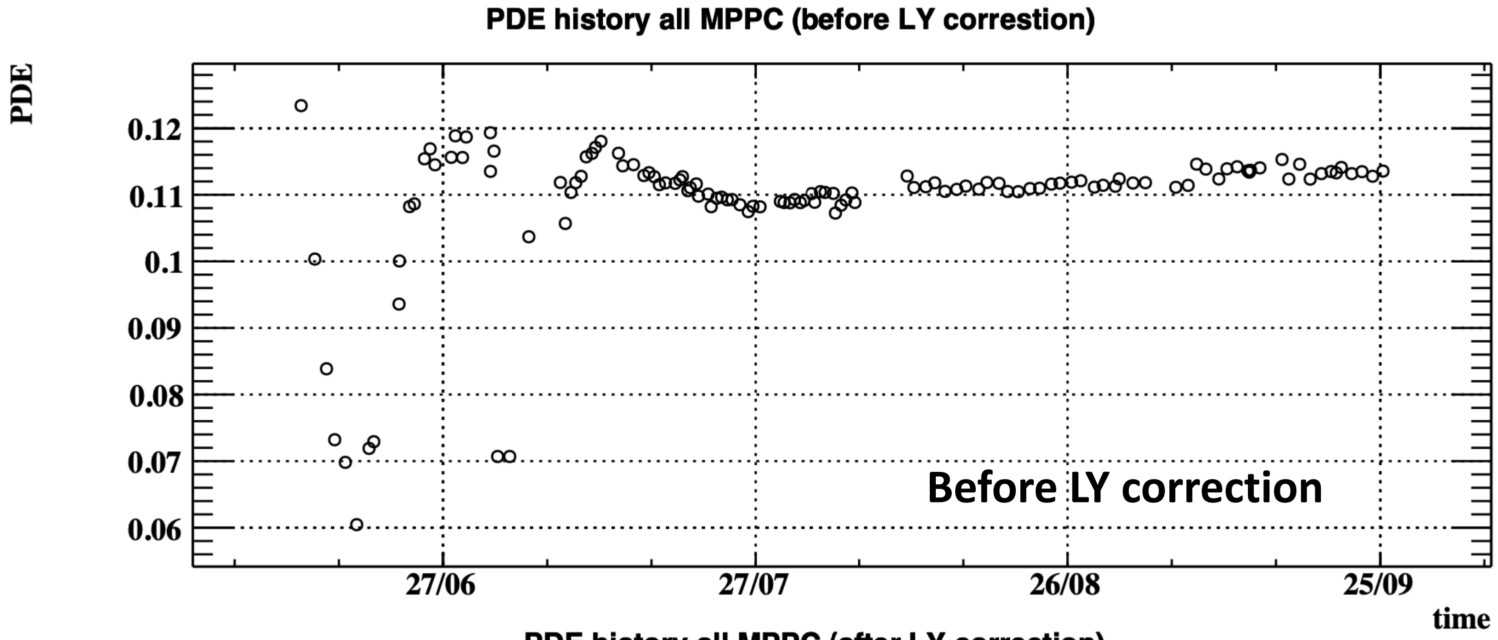
Charge of each sensor is calculated
by integrating the waveform.
Charge calculation is affected
if pedestal is displaced due to noise.

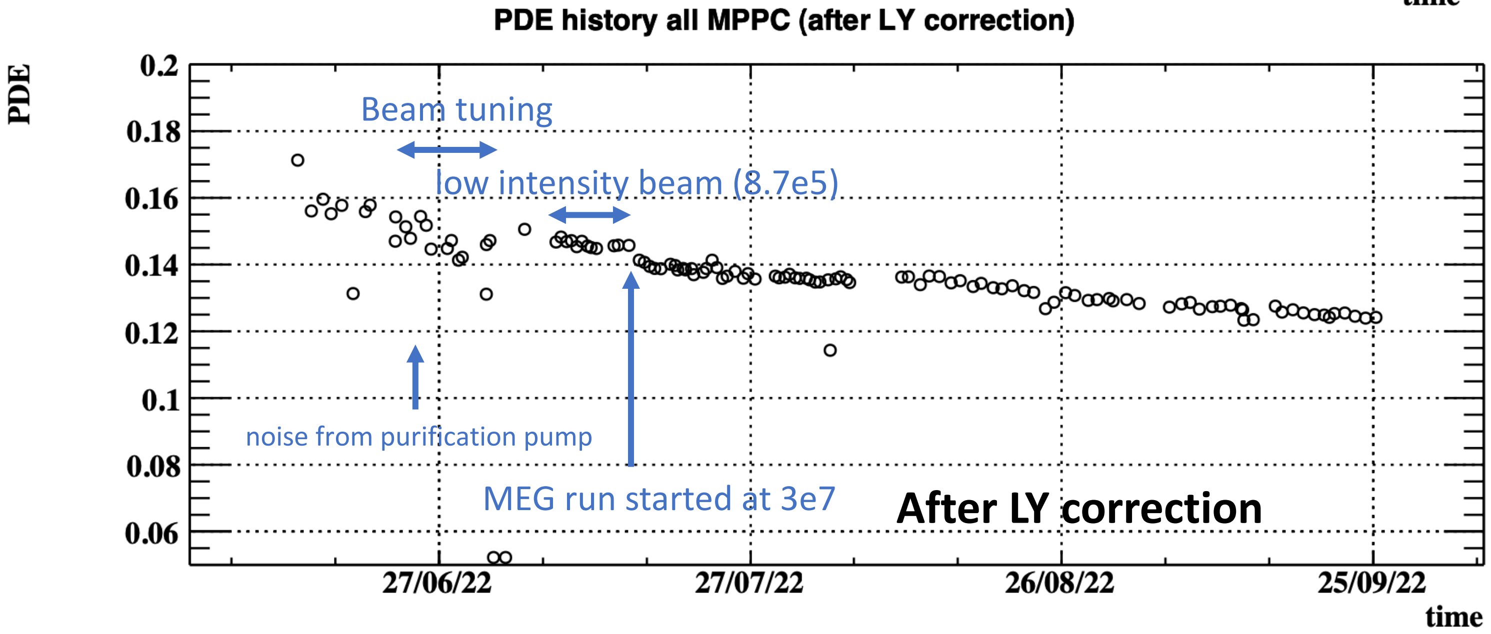
LY History



Assume PMT QE does not change. → Measured apparent QE variation is due to LY.
It was concluded that LY had recovered fully on 12th Jul. and LXe purification was finished.
LY has been rising since the end of Jul.
LY at the end of the last year's beamtime was 14.8%.
LY may continue to rise.
Impact of absorption need to be investigated.

PDE (Before/After LY Correction)





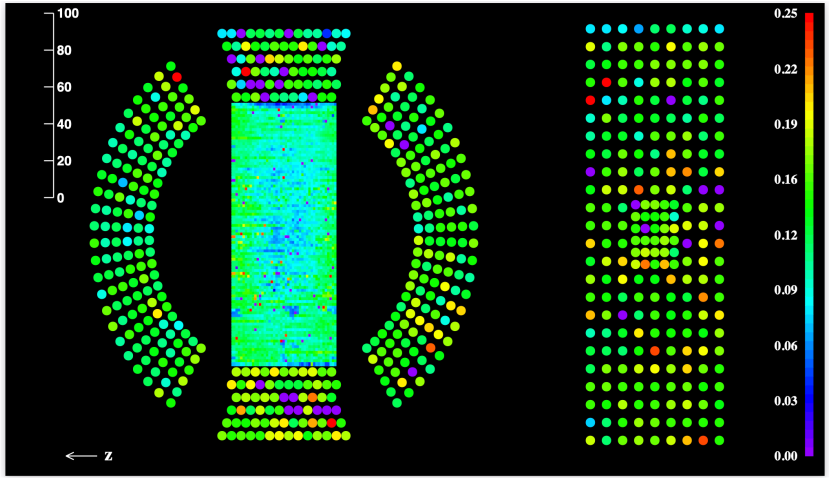
PDE measurements are affected by LY. Apparent measured PDE increases when LY increases.

Some data in commissioning period are not well fitted due to noise caused by liquid purification pump.

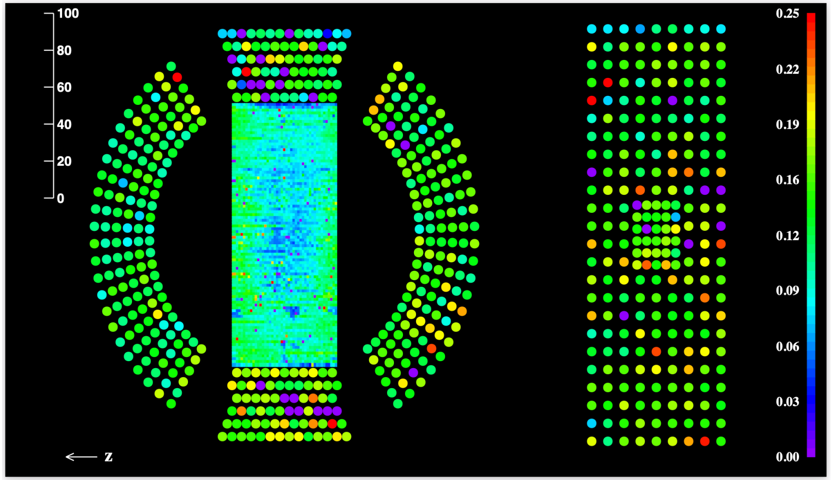
PDE after LY correction is decreasing.

Estimated PDE Map

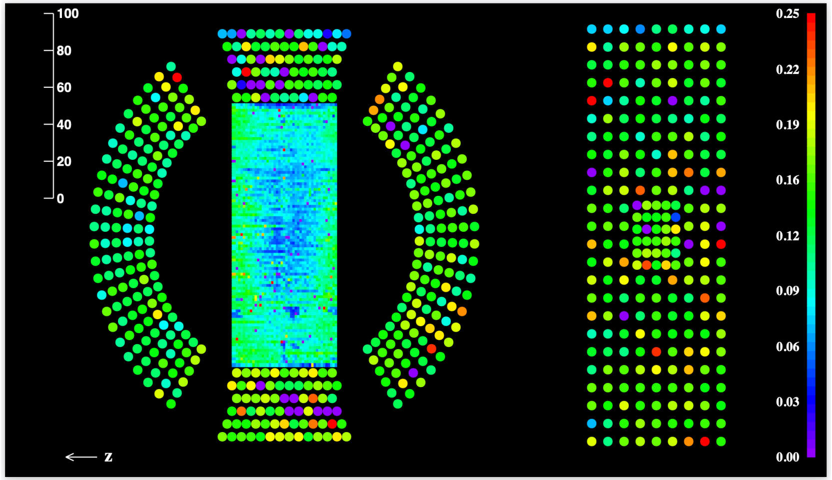
at the end of physics data taking with 3e7 beam



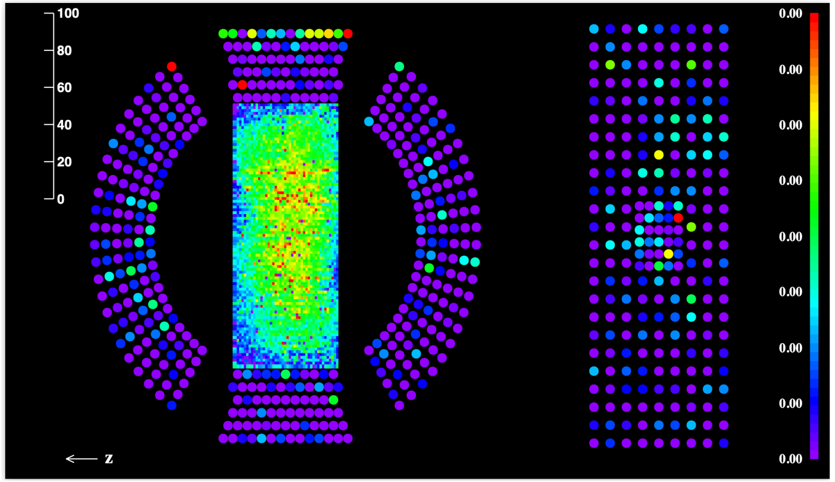
at the end of physics data taking with 4e7 beam



at the end of physics data taking with 5e7 beam



PDE decrease speed



Level of LXe

LXe may not have reached the top of the detector in the last year's run.
LXe level in last year : 83 cm

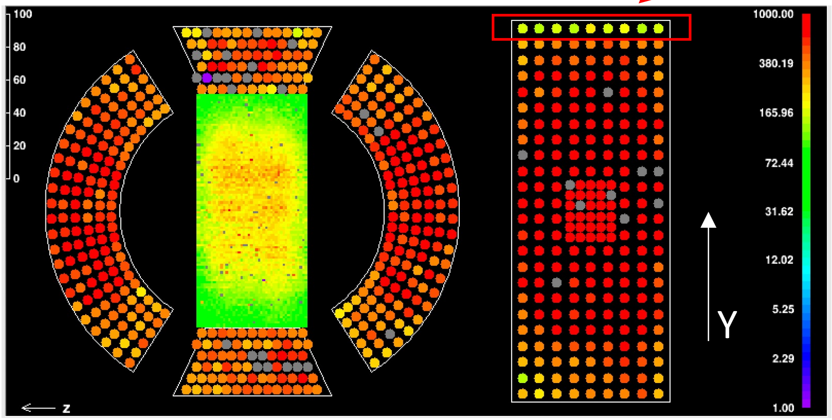
Low LXe level may cause non-uniformity in light collection efficiency.

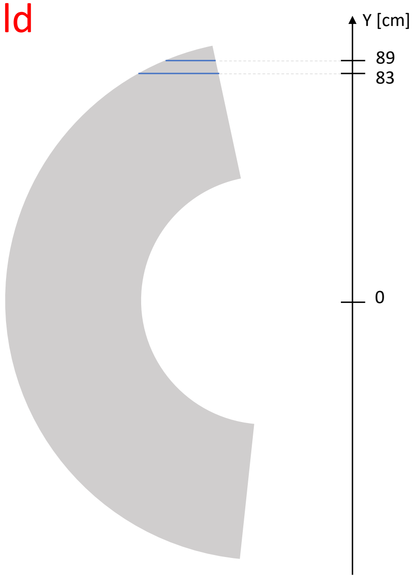
Xenon was added to raise the liquid level, and LXe level rose.

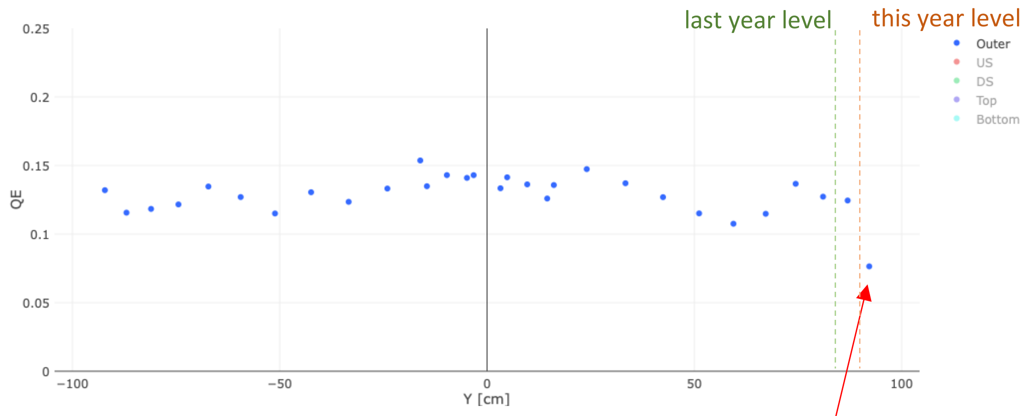
Top part of the detector (a PMT row) is not filled with LXe.
LXe level in this year : 89 cm
→ Symmetry of energy response is expected to improve.

Response of the senser when LEDs installed inside the detector is turned on.

Low light yield

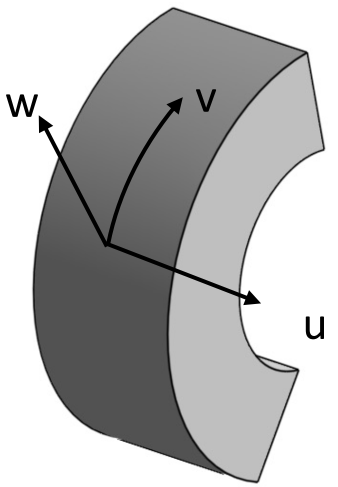




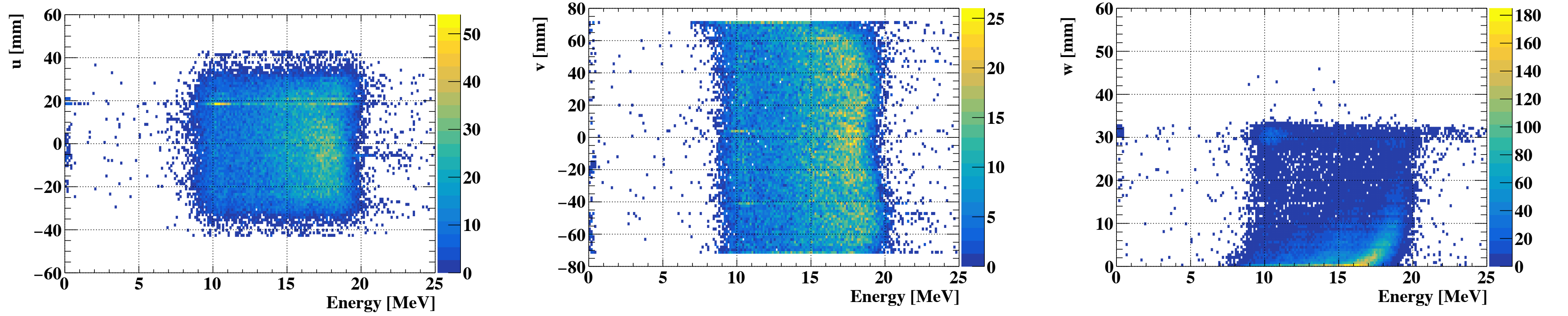


small apparent QE

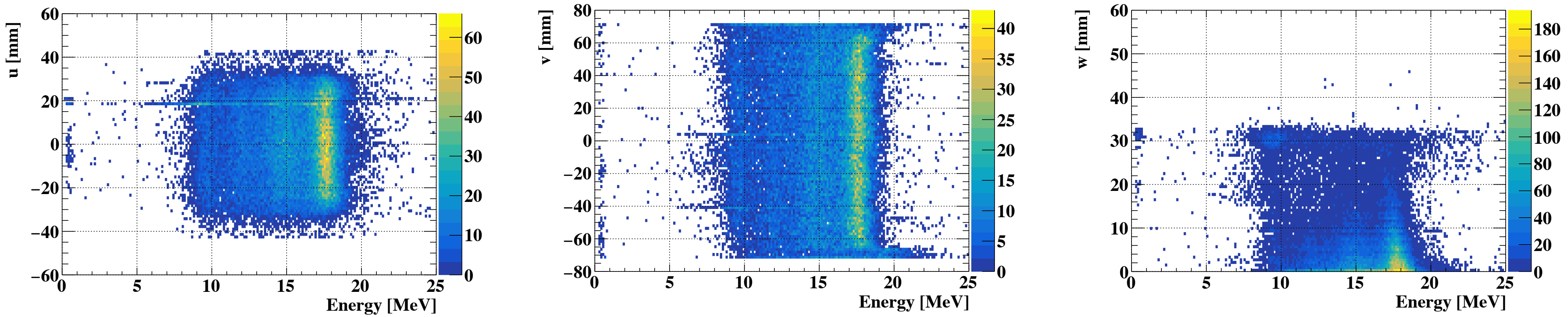
Energy Uniformity and Stability



Before weight correction

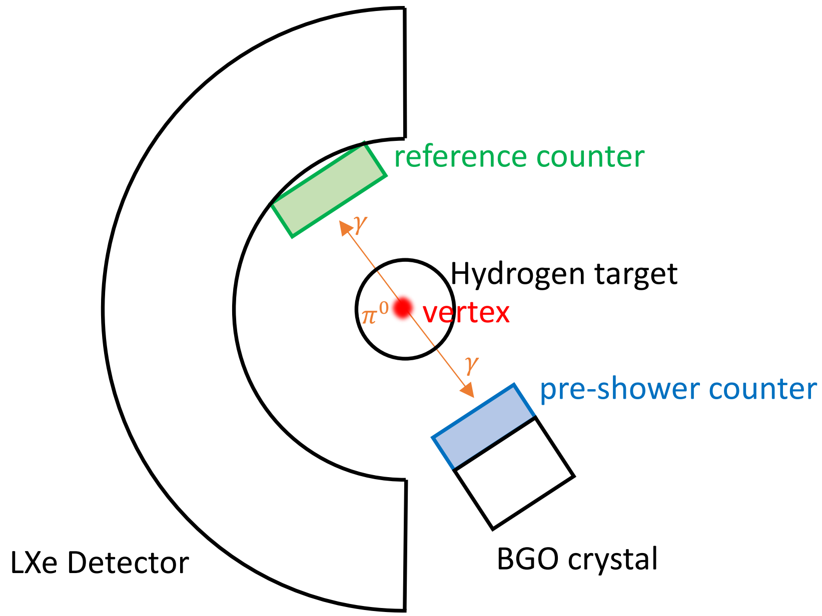


After weight correction

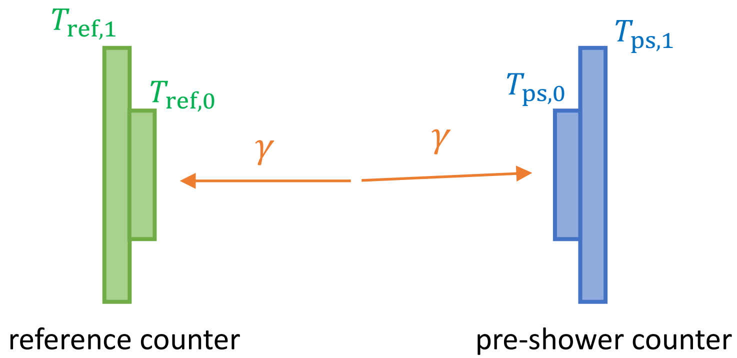


Calculation of σ_{vertex}

A reference counter was installed in front of LXe detector to measure σ_{vertex}.
The timing resolution of each counter is known. (~ 40 ps in a lab test)
Evaluate σ_{vertex} using the hit time on each plate.



$$
\begin{cases}
\sigma\left(\frac{T_{\mathrm{ps},0}+T_{\mathrm{ps},1}}{2}-\frac{T_{\mathrm{ref},0}+T_{\mathrm{ref},1}}{2}\right)=\frac{\sigma_{\mathrm{ps},0}\oplus\sigma_{\mathrm{ps},1}\oplus\sigma_{\mathrm{ref},0}\oplus\sigma_{\mathrm{ref},1}}{2}\oplus\sigma_{\mathrm{vertex}} \\
\sigma(T_{\mathrm{ps},0}-T_{\mathrm{ref},0})=\sigma_{\mathrm{ps},0}\oplus\sigma_{\mathrm{ref},0}\oplus\sigma_{\mathrm{vertex}} \\
\sigma(T_{\mathrm{ps},1}-T_{\mathrm{ref},1})=\sigma_{\mathrm{ps},1}\oplus\sigma_{\mathrm{ref},1}\oplus\sigma_{\mathrm{vertex}} \\
\sigma(T_{\mathrm{ps},0}-T_{\mathrm{ref},1})=\sigma_{\mathrm{ps},0}\oplus\sigma_{\mathrm{ref},1}\oplus\sigma_{\mathrm{vertex}} \\
\sigma(T_{\mathrm{ps},1}-T_{\mathrm{ref},0})=\sigma_{\mathrm{ps},1}\oplus\sigma_{\mathrm{ref},0}\oplus\sigma_{\mathrm{vertex}}
\end{cases}
$$

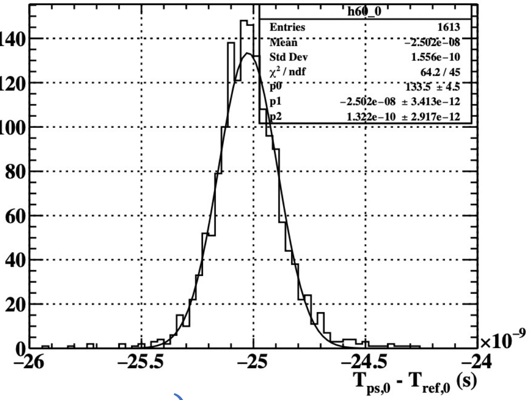


From the above equations, σ_{vertex} is expressed as

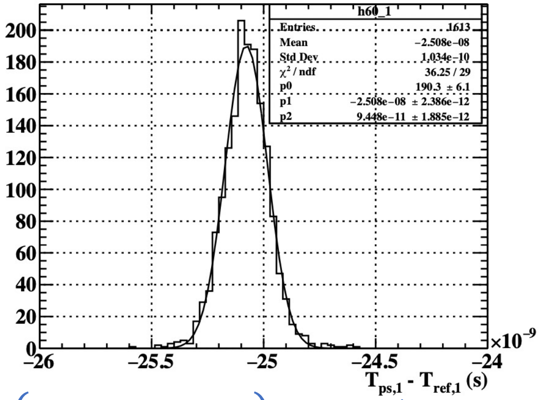
$$
\sigma_{\mathrm{vertex}}^2=2\sigma^2\left(\frac{T_{\mathrm{ps},0}+T_{\mathrm{ps},1}}{2}-\frac{T_{\mathrm{ref},0}+T_{\mathrm{ref},1}}{2}\right)-\frac{\sigma^2(T_{\mathrm{ps},0}-T_{\mathrm{ref},0})+\sigma^2(T_{\mathrm{ps},1}-T_{\mathrm{ref},1})+\sigma^2(T_{\mathrm{ps},0}-T_{\mathrm{ref},1})+\sigma^2(T_{\mathrm{ps},1}-T_{\mathrm{ref},0})}{4}
$$

Result of Vertex Measurement

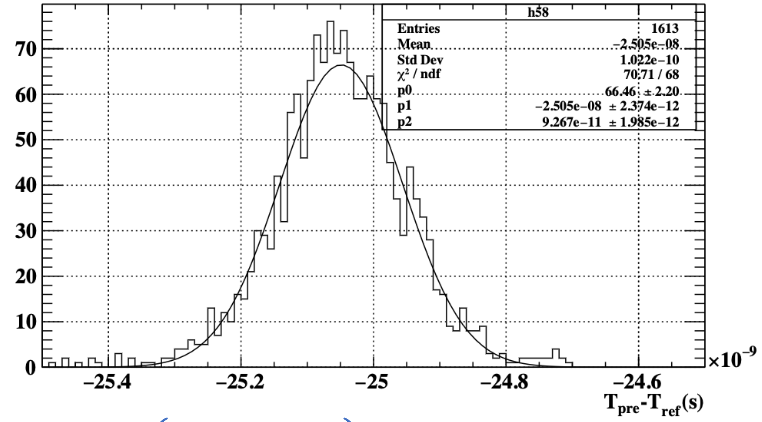
$$\sigma_{\mathrm{vertex}}^2 = 2\sigma^2\left(\frac{T_{\mathrm{ps},0}+T_{\mathrm{ps},1}}{2} - \frac{T_{\mathrm{ref},0}+T_{\mathrm{ref},1}}{2}\right) - \frac{\sigma^2(T_{\mathrm{ps},0}-T_{\mathrm{ref},0}) + \sigma^2(T_{\mathrm{ps},1}-T_{\mathrm{ref},1}) + \sigma^2(T_{\mathrm{ps},0}-T_{\mathrm{ref},1}) + \sigma^2(T_{\mathrm{ps},1}-T_{\mathrm{ref},0})}{4}$$



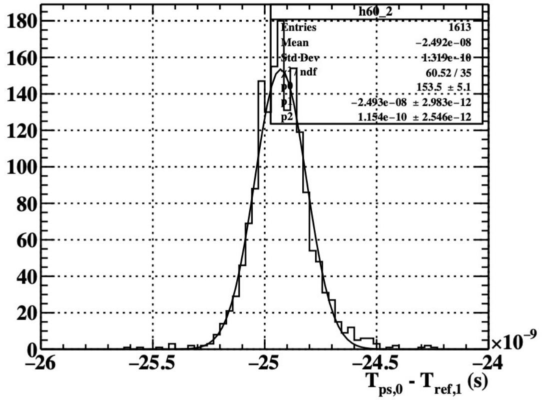
$\sigma(T_{\mathrm{ps},0} - T_{\mathrm{ref},0}) = 132.2 \pm 2.9$ ps



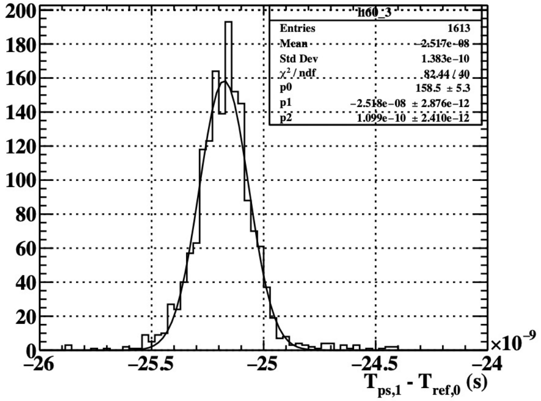
$\sigma(T_{\mathrm{ps},1} - T_{\mathrm{ref},1}) = 94.5 \pm 1.9$ ps



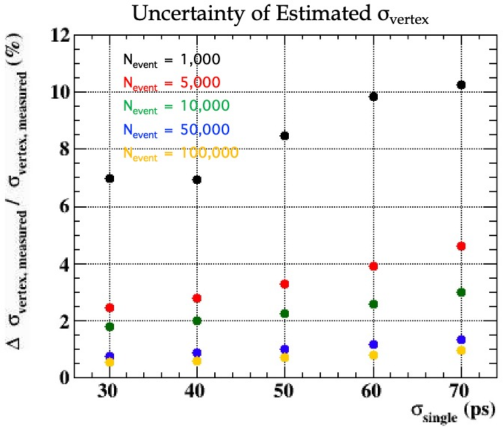
$\sigma(T_{\mathrm{ps}} - T_{\mathrm{ref}}) = 92.7 \pm 2.0$ ps



$\sigma(T_{\mathrm{ps},0} - T_{\mathrm{ref},1}) = 115.4 \pm 2.6$ ps



$\sigma(T_{\mathrm{ps},1} - T_{\mathrm{ref},0}) = 109.9 \pm 2.4$ ps



To estimate σ_{vertex} with 3-5 % precision, 5000 events are needed.

$\boldsymbol{\sigma_{\mathrm{vertex}} = 65.0 \pm 6.1\ \mathrm{ps}\ (9.8 \pm 0.9\ \mathrm{mm})}$

The number of the events obtained is about 1600 due to the limitation of the beamtime and the target stability.

The effect of the electronics used for DAQ has not been considered.

Timing Calibration of LXe Detector

The calibration parameters must be extracted to estimate the gamma hit timing.

Define the reference time t_{ref} as follows.

$$t_{\mathrm{ref}} = t_{\mathrm{ps}} + t_{\mathrm{TOF}}$$

1. The time difference dt is calculated for each photosensor **for each group of the photosensors**.

$$dt = t_{\mathrm{pm}} - t_{\mathrm{prop}} - t_{\mathrm{offset}} - t_{\mathrm{ref}}$$

the offset effect from the length of the cables

2. The time difference dt is calculated for each photosensor **for each photosensor**.

$$dt = t_{\mathrm{pm}} - t_{\mathrm{prop}} - t_{\mathrm{offset}} - t_{\mathrm{ref}}$$

the offset effect from the length of the cables

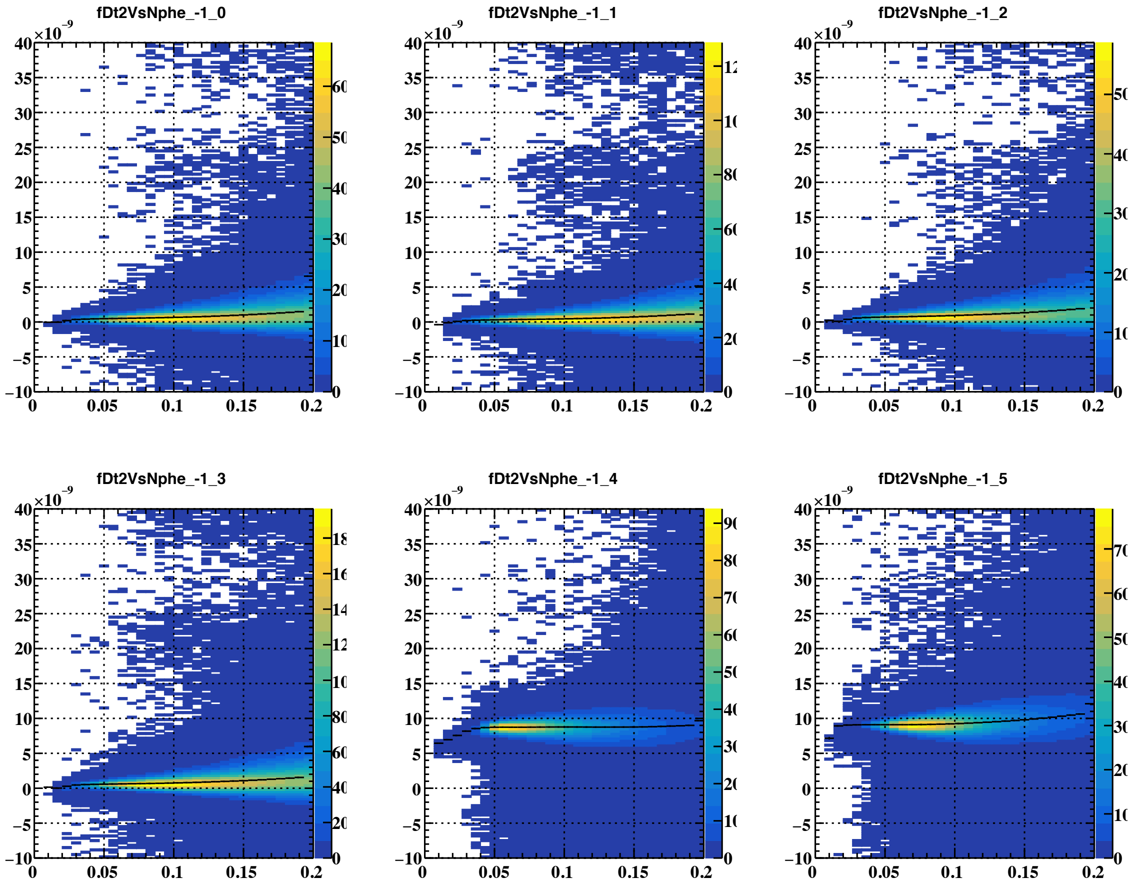
3. The time difference dt is calculated for each photosensor **for each group of the photosensors**.

$$dt = t_{\mathrm{pm}} - t_{\mathrm{prop}} - t_{\mathrm{offset}} - t_{\mathrm{ref}}$$

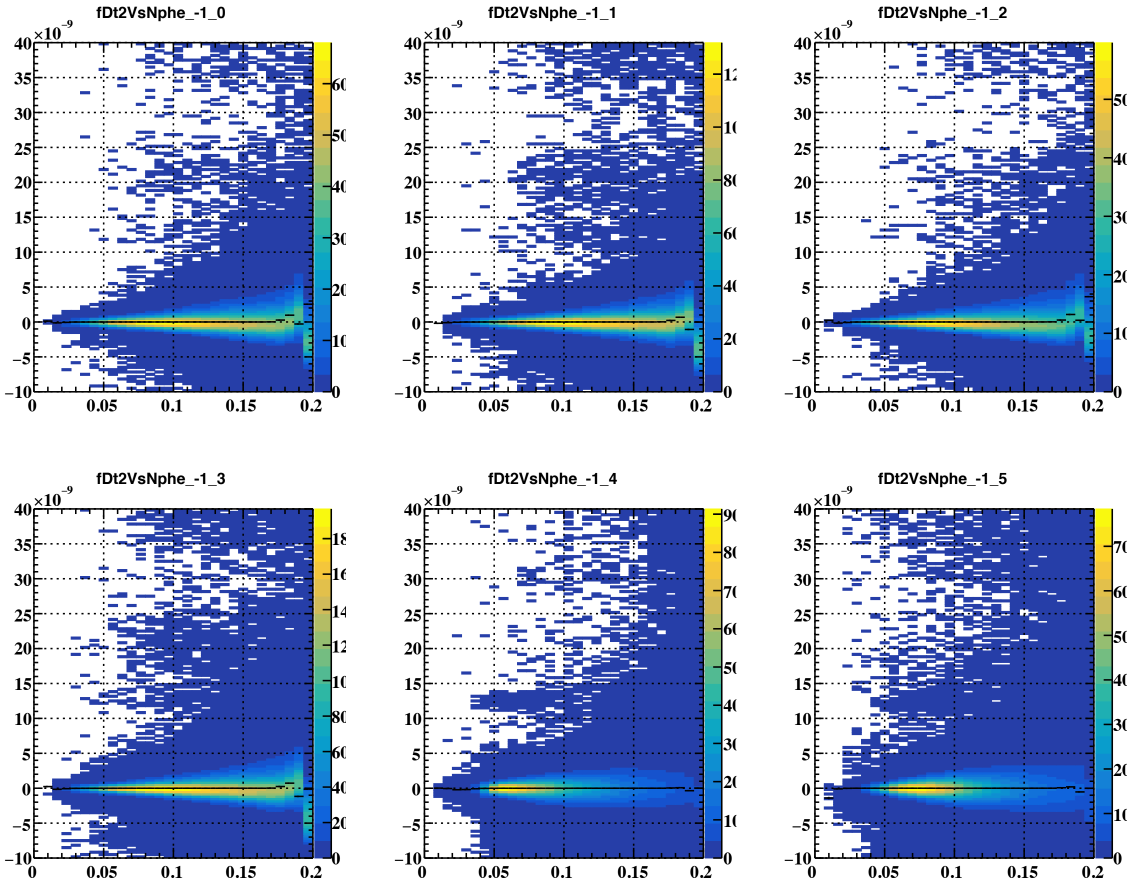
the offset effect from the length of the cables and the rest offset effect

Time Fit

Before the timing calibration



After the timing calibration



Timing Reconstruction in LXe Detector

Gamma hit timing T_{XEC} is reconstructed with χ^2 minimization fit.

$$\chi^2 = \sum_{\mathrm{MPPC,PMT}} \left(\frac{t_{\mathrm{pm}} - t_{\mathrm{walk}} - t_{\mathrm{prop}} - t_{\mathrm{offset}} - T_{\mathrm{XEC}}}{\sigma_{\mathrm{pm}}} \right)^2$$

t_{pm}: the timing of each photosensor

t_{walk}: the time walk effect

t_{prop} : the propagation time of scintillation light from γ hit position to each photosensor

t_{offset} : time offset of each channel

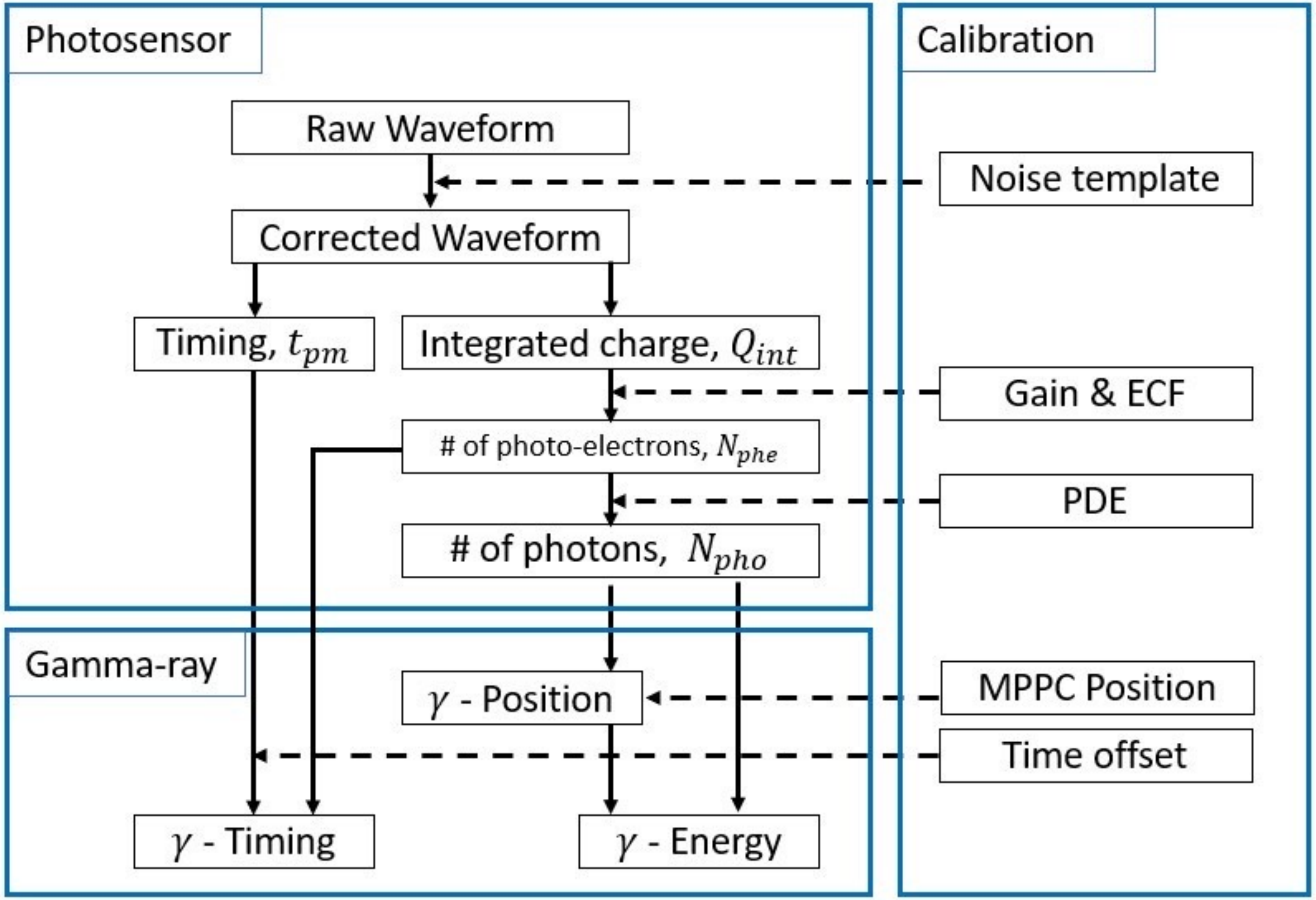
T_{XEC}: the gamma hit timing (fitting parameter)

extracted from data in the timing calibration

Resolution of LXe Detector

	Resolution in MEG II
Position resolution[mm] u, v, w (w<2 cm)/(w>2 cm)	2.7/4.6, 2.5/3.9, 2.7/5.9
Energy resoluiton[%] (w<2 cm)/(w>2 cm)	2.0/1.7
Timing resolution[ps]	61

LXe Reconstruction



Position Resolution

Collimator is installed in position measurement.

Position resolution is measured by using collimated 17.6 MeV gamma-rays from ${}^{7}_{3}\mathrm{Li}(p,\gamma){}^{8}_{4}\mathrm{Be}$.