MEG II実験2022年物理ランにおける液体キセノンガンマ線検出器光センサー較正および時間分解能評価

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日本物理学会 2023年春季大会

23aT3-6

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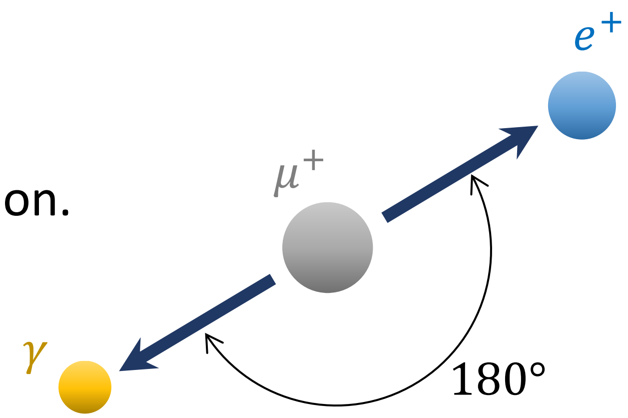
$\mu \to e\gamma$ search

- $\mu \to e\gamma$ is a charged lepton flavor violation decay.
- The decay is prohibited based on the Standard Model and ν oscillation.

  $\mathcal{B}(\mu \to e\gamma)\ :\ 10^{-54}$

  It can be observable in theories beyond SM.

  $\mathcal{B}(\mu \to e\gamma) : 10^{-11}{\sim}10^{-14}$



- Upper limit on the branching ratio was obtained by the MEG experiment.

  $\mathcal{B}(\mu \to e\gamma) < 4.2\times10^{-13}$ (90% C. L.)

<u>Signal of $\mu \to e\gamma$</u>

e^+ and γ are emitted
- simultaneously
- back-to-back
- at monochromatic energy (52.8 MeV)

MEG II experiment

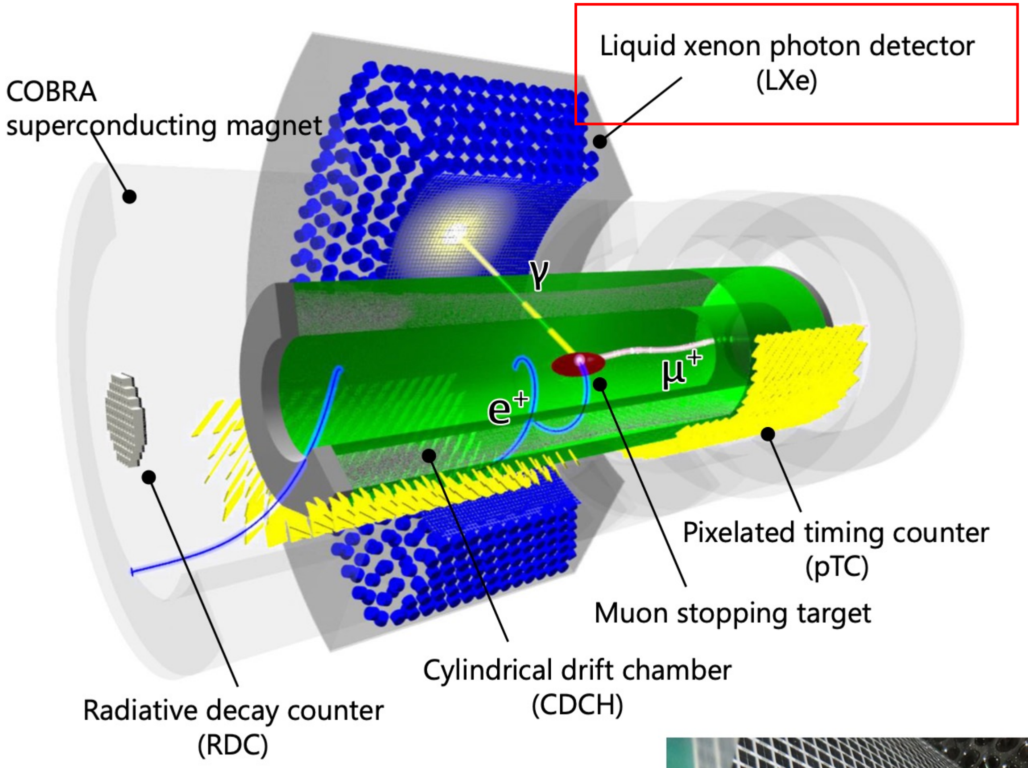
MEG II experiment searches $\mu \to e\gamma$.

Goal : $\mathcal{B}(\mu \to e\gamma) \sim 6 \times 10^{-14}$

Physics data taking started.

1 month in 2021 engineering run

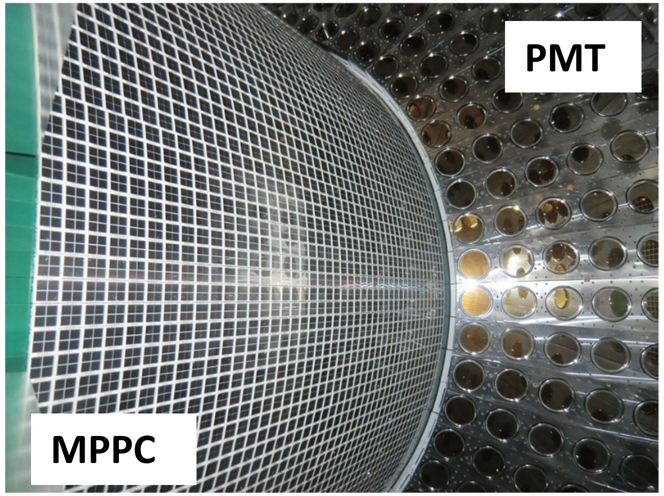
4 months in 2022 physics run



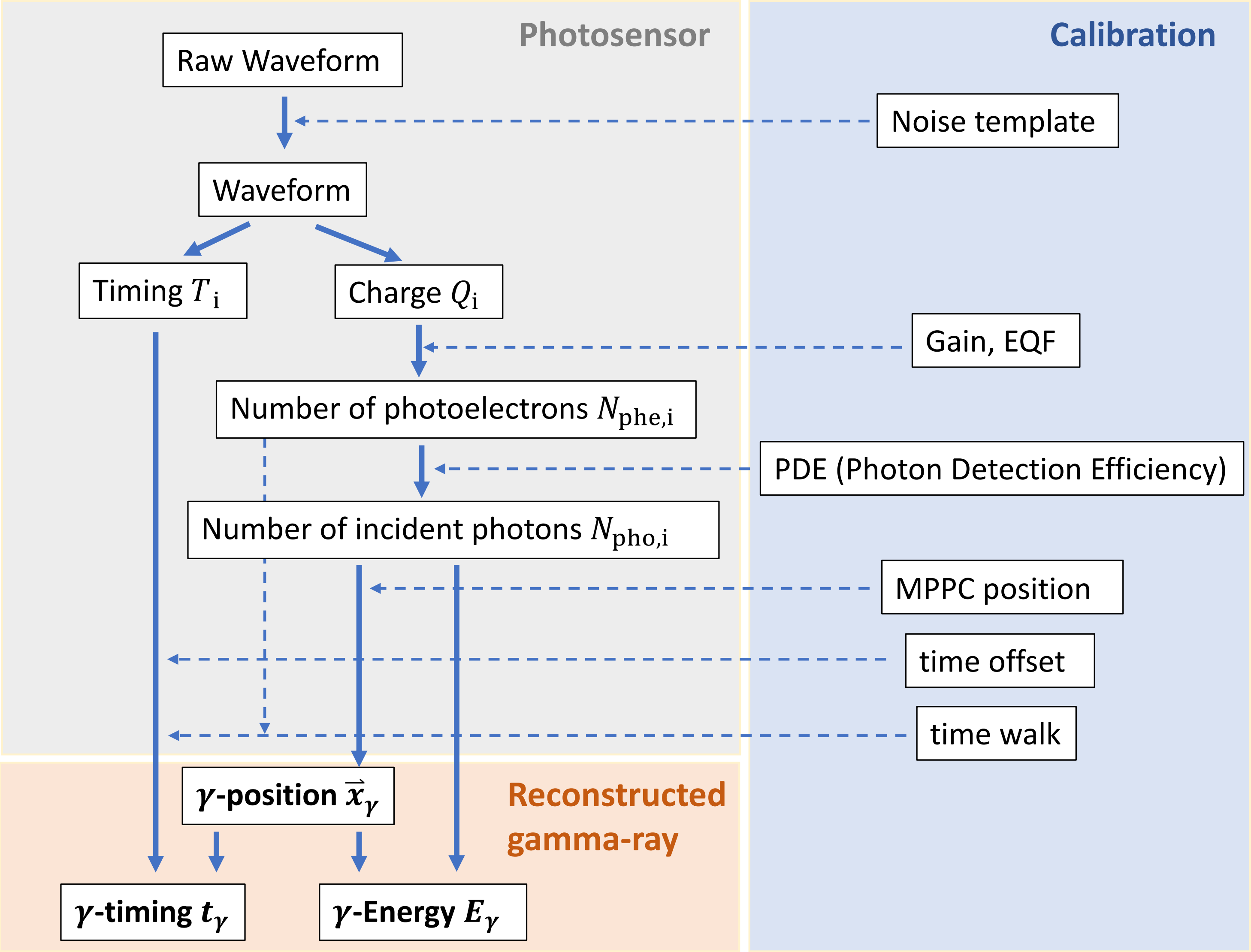
Liquid xenon (LXe) gamma-ray detector

LXe detector measures the position, energy and timing of the gamma-ray.

4092 VUV-sensitive MPPCs (entrance face) + 668 PMTs (other faces)



Event reconstruction in LXe detector



Waveform data for each channel is read out.

Gain, EQF, and PDE are calibrated.

$N_{pho,i}$ is calculated from charge of each sensor using calibration parameters.

Position and energy of gamma-ray is reconstructed using $N_{pho,i}$.

Excess Charge Factor (EQF)
Effect of cross talk and after pulse

$$N_{pho} = \frac{Q}{G \times PDE \times EQF}$$

Beam time in 2022

Run	Month	Event
MPPC annealing	Jun.	(13/Jun.) Detector commissioning start
RMD run (8.7×10^{5} μ^{+}/s)	Jul.	(14/Jul.) Physics run start
Physics run (3×10^{7} μ^{+}/s)	Aug.	(3/Aug.) PMT HV adjustment
	Sep.	(15/Sep.) PMT HV adjustment
	Oct.	(27/Oct.) muon beam rate change
Physics run (4×10^{7} μ^{+}/s)	Nov.	(7/Nov.) muon beam rate change
Physics run (5×10^{7} μ^{+}/s)		(17/Nov.) physics run end
pion beam run	Dec.	(4/Nov.) pion beam run start
		(16/Nov.) pion beam run end

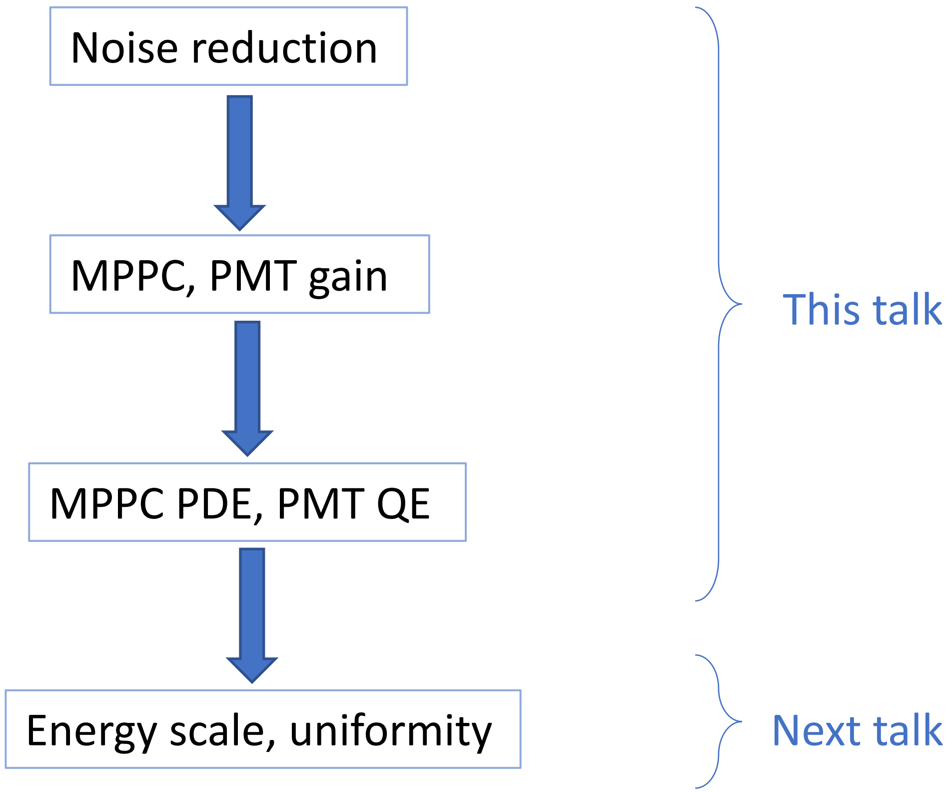
New LXe was added.
(LXe was not fully filled in 2021.)
→ Light yield drop due to impurities in new xenon.

To deal with gain decrease (PMT HV adjustments)
Continuous calibration is important!

pion beam run : dedicated run of LXe detector (calibration + performance evaluation)

Physics run for 4 months was achieved!

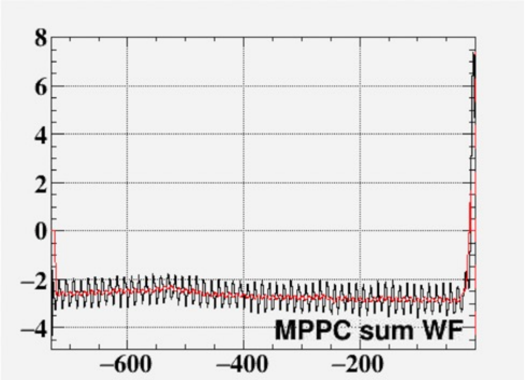
Calibration Flow



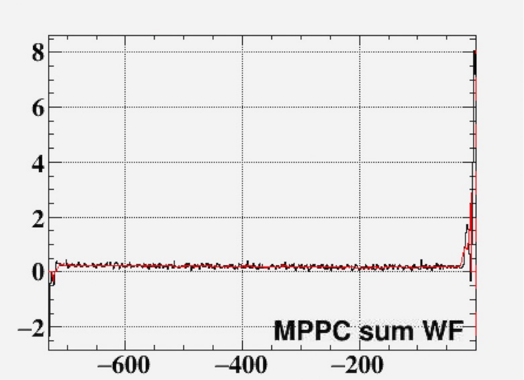
Sei Ban “MEG II experiment : calibration of the liquid xenon detector and annealing procedure for 2023 run” 23aT3-7

Noise evaluation in physics run

Noise templates are extracted from pedestal run.
(trigger issued periodically)
Update noise template as needed. (every 2~3 days)
Compensate for noise effects by subtracting noise templates in waveform analysis.

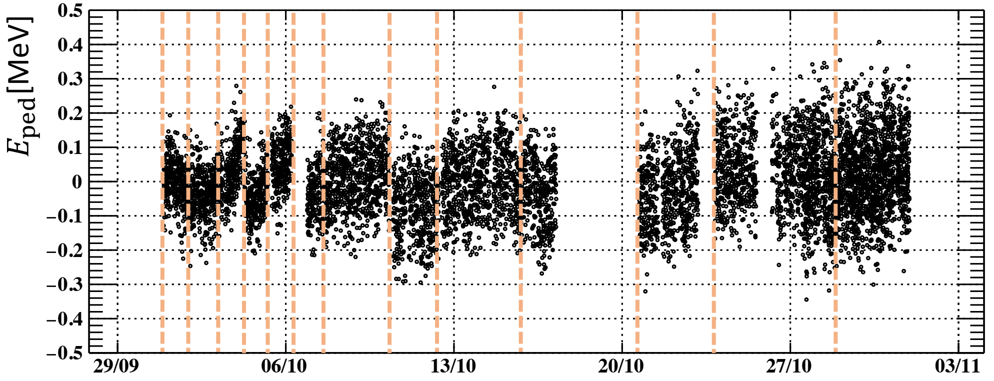


waveform before noise reduction

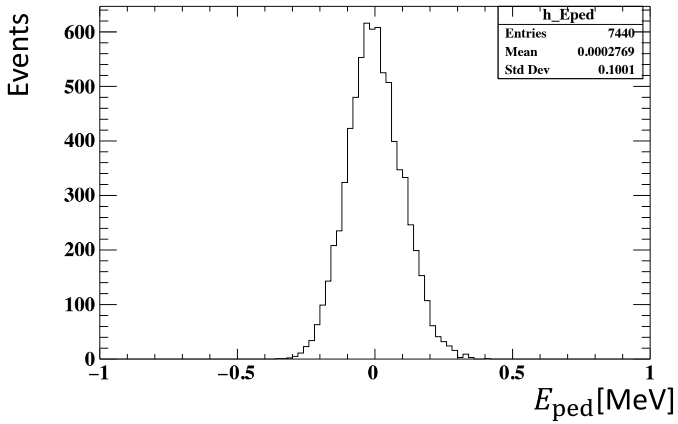


waveform after noise reduction

Reconstructed energy for pedestal events in physics run



Pedestal energy



0.1 MeV in standard deviation

Pedestal data is acquired periodically during physics run.
Average of the reconstructed energy for the pedestal events in physics runs.
The impact of noise on energy reconstruction is sufficiently small compared to the energy resolution(1.4 MeV).

PMT gain

PMT gain can be calculated from LED intensity scan data.

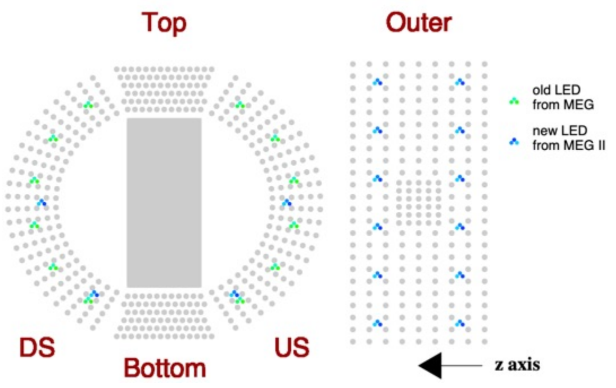
$$\sigma_q^2 = G \times e \times \bar{q} + \sigma_0^2$$

σ_q: spread of integrated charge distribution

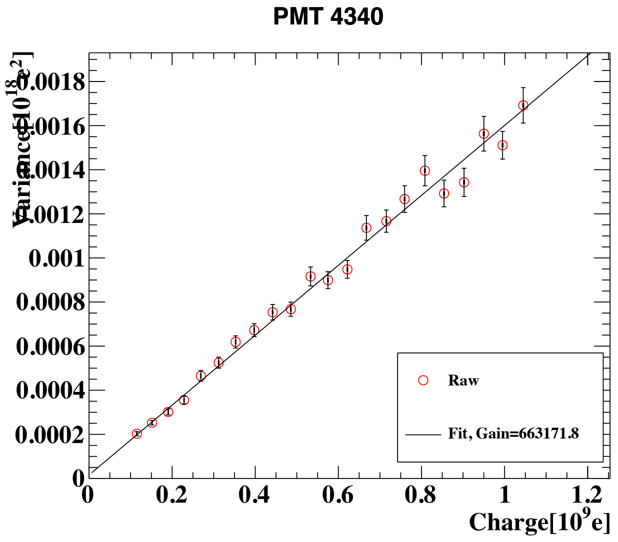
G: gain

e: elementary charge

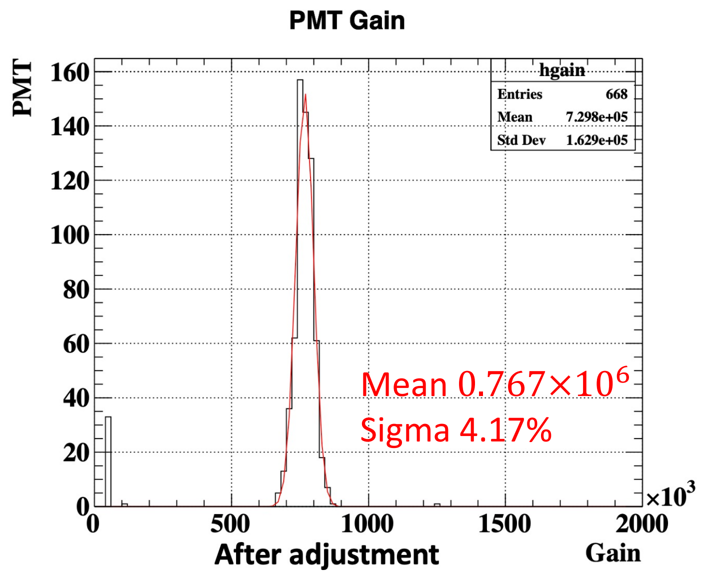
$\bar{q}$: mean of integrated charge



positions of LEDs inside LXe detector

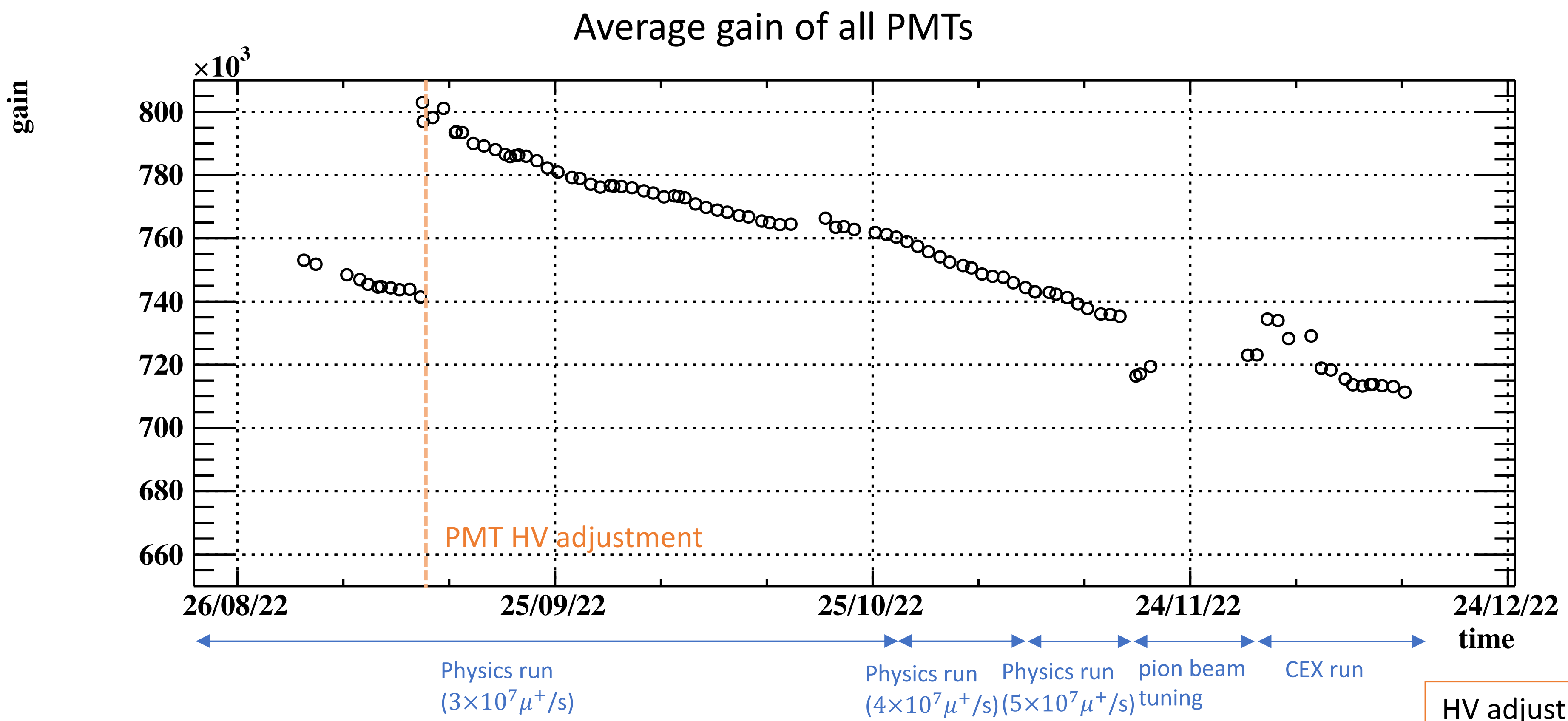


Result of LED intensity scan
Slope corresponds to gain.



PMT gain distribution

Gain history



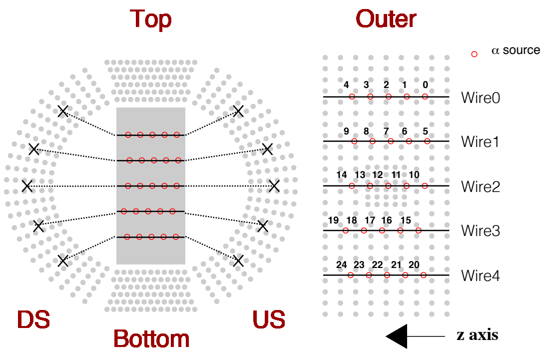
HV adjustment

$$G \propto (V - V_0)^k$$
$$V_0 = 100, k = 9.5$$

Gain has been steadily decreasing.

Applied voltage was adjusted because the gain decreases over beamtime.

MPPC PDE, PMT QE(Light yield)

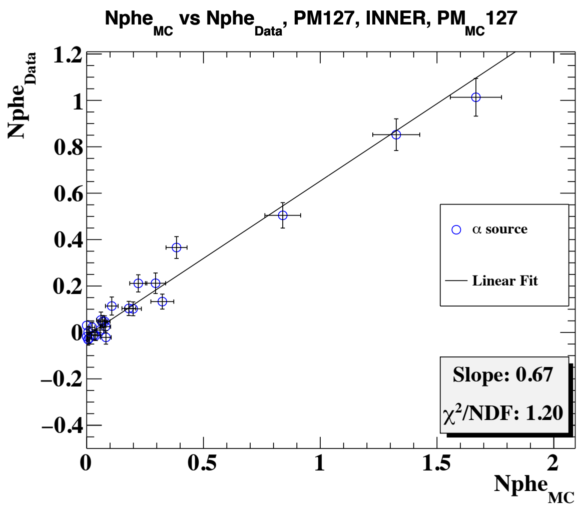


- It is known from the experience in MEG II experiment that PDE decreases during beamtime due to radiation damage.
- Since PMT QE does not fluctuate, light yield (LY) of LXe can be monitored from N_{phe} detected at PMT.

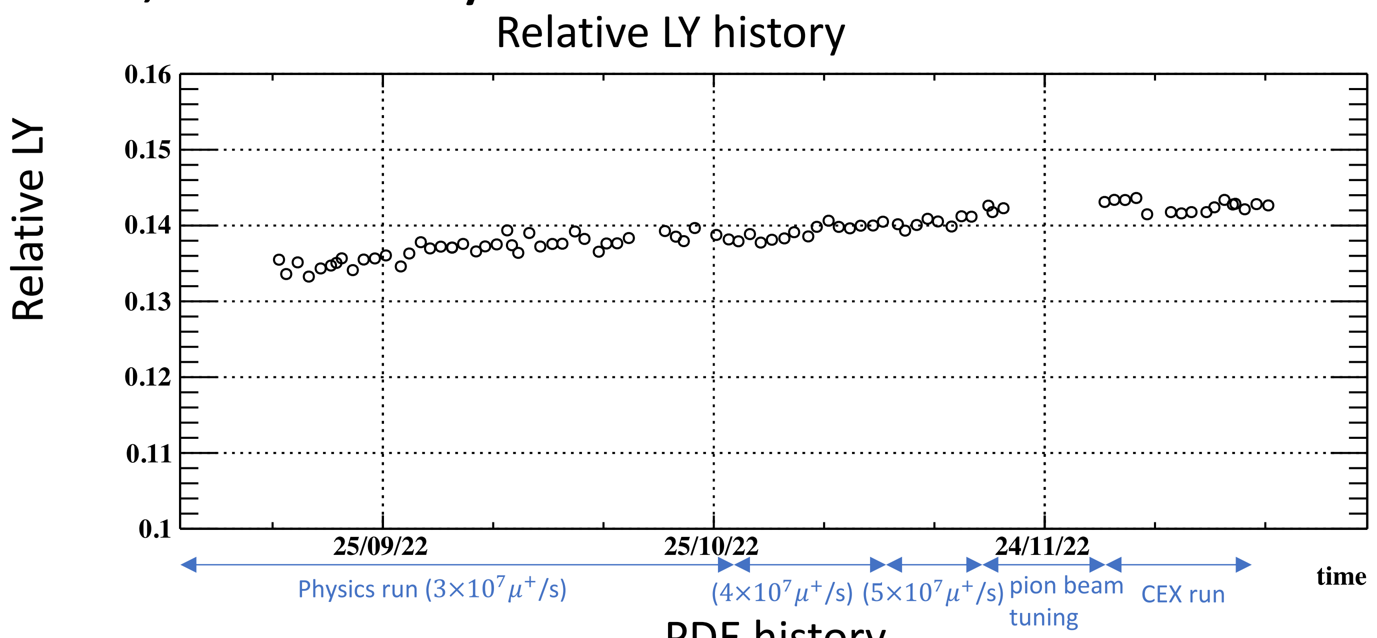
- Events from α sources are used for the calibration.
  PDE and QE are estimated by comparing N_{phe} assumed in MC simulation with N_{phe} actually detected.

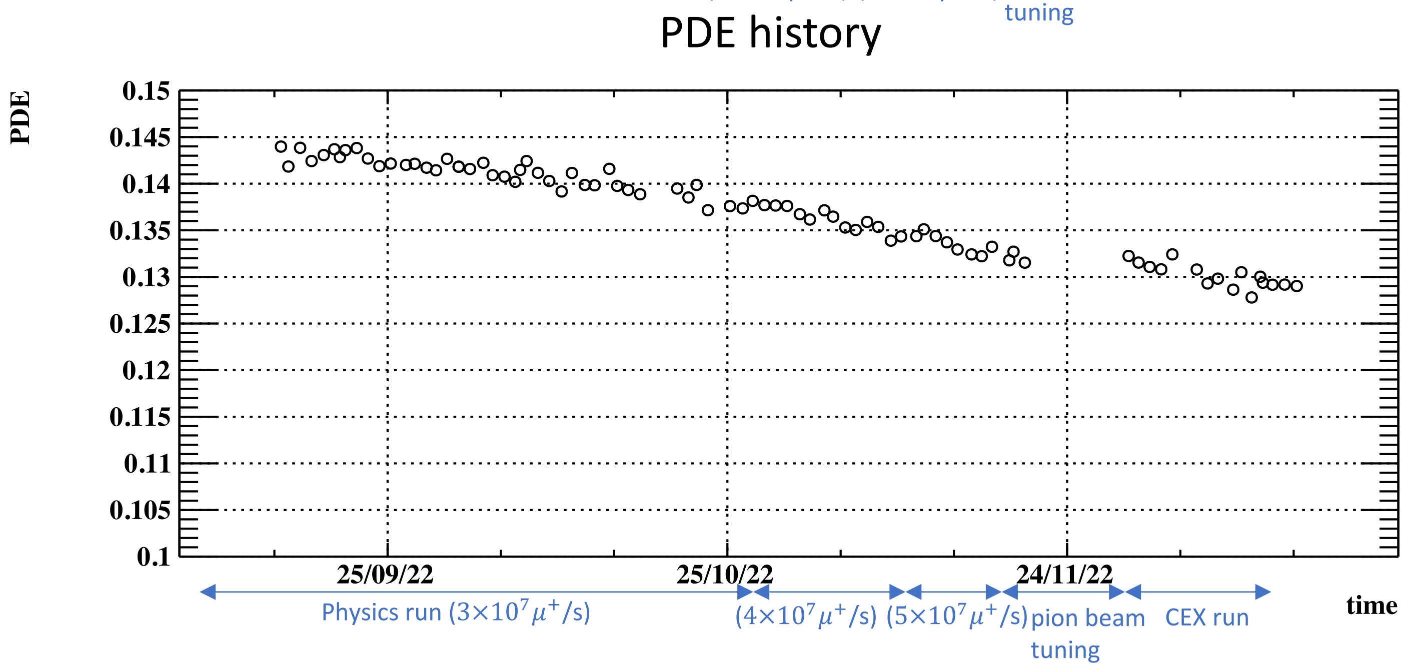
$$PDE_{\mathrm{data}} = PDE_{\mathrm{MC}} \times \frac{N_{\mathrm{data}}}{N_{\mathrm{MC}}} \times R_{\mathrm{LY}}$$

PDE_{data}: measured PDE
PDE_{MC}: PDE assumed in MC simulation
N_{data}: number of detected photoelectrons
N_{MC}: number of detected photoelectrons assumed as a result of MC simulation
R_{LY}: correction factor due to light yield variation



PDE, QE history





LY is increasing.
New xenon was added in the commissioning period in 2022 beamtime.
(LXe level had not reached the top of the detector during 2021 beamtime.)
LY recovery by purification of gaseous xenon

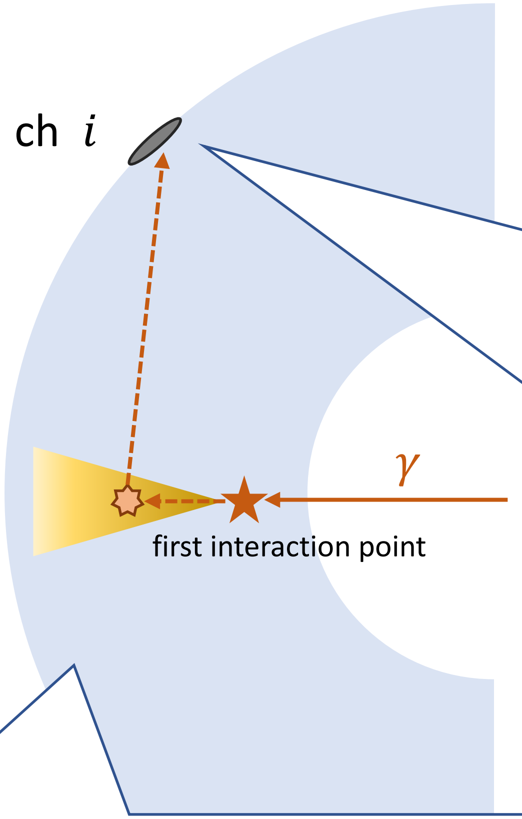
Before 2022 beamtime, MPPCs were annealed for PDE recovery.

Initially, a beam rate $3\times10^7\mu^+$/s was used.
Based on PDE monitoring results,
it was determined that a higher beam rate was available.

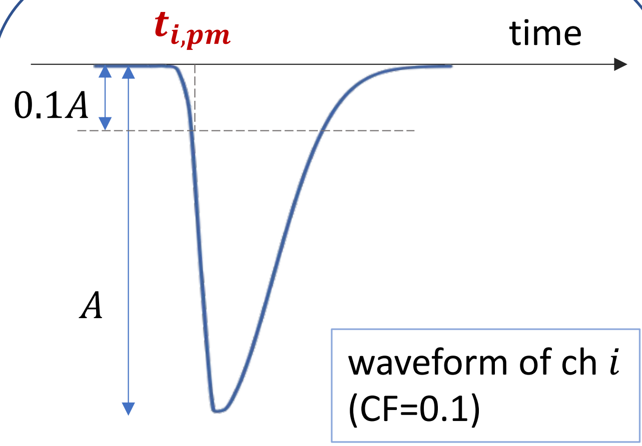
Timing reconstruction in LXe detector

Gamma-ray timing t_γ is reconstructed with χ^2 minimization fit.

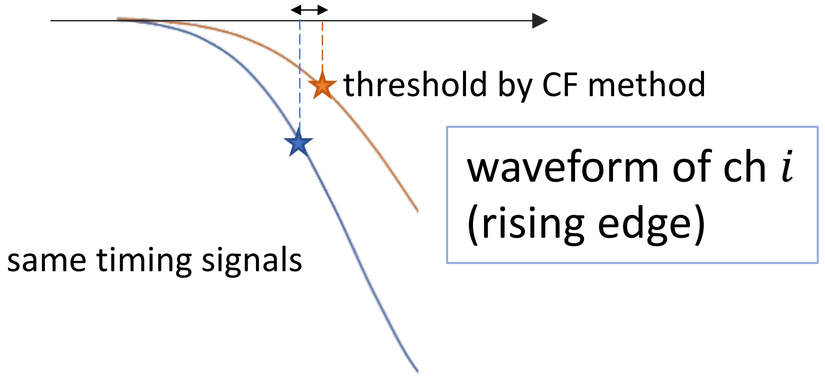
$$\chi^2 = \sum_{i \subset \mathrm{MPPC,PMT}} \left(\frac{t_{i,\mathrm{pm}} - t_{i,\mathrm{prop}} - t_{i,\mathrm{walk}} - t_{i,\mathrm{offset}} - t_\gamma}{\sigma_{i,\mathrm{pm}}} \right)^2$$



$t_{i,prop}$: Propagation time of scintillation light from the first interaction point to each sensor



$t_{i,\mathrm{pm}}$: the signal detection timing of each sensor



$t_{i,\mathrm{walk}}$: the time walk effect of each sensor
Calibrate the effect of time walk as a function of N_{phe}

$t_{i,\mathrm{offset}}$: the time offset of each sensor
Calibrated using pion beam run data based on the dedicated timing calibration counter

Timing resolution evaluation of LXe detector

Charge EXchange reaction (CEX)

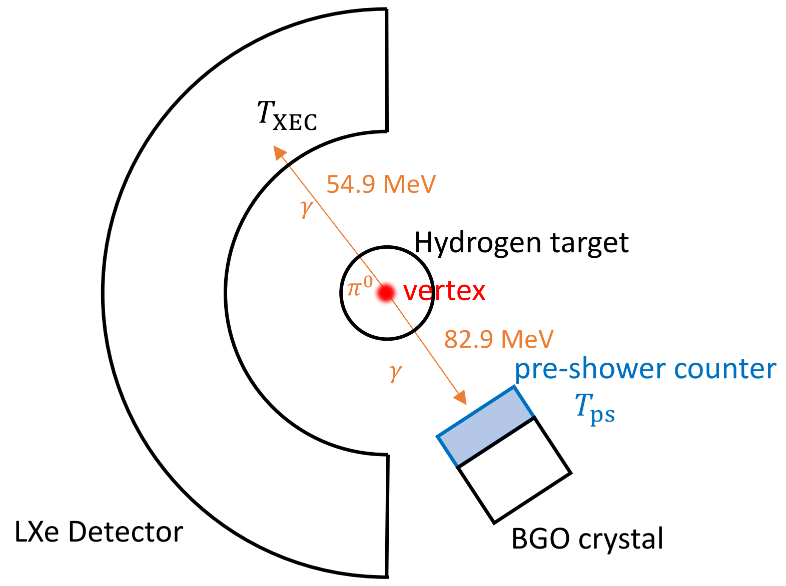
$$\pi^- p \rightarrow \pi^0 n$$

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

π^- is injected into a liquid hydrogen target.

Back-to-back γ-rays : <u>54.9 MeV</u> and 82.9 MeV

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

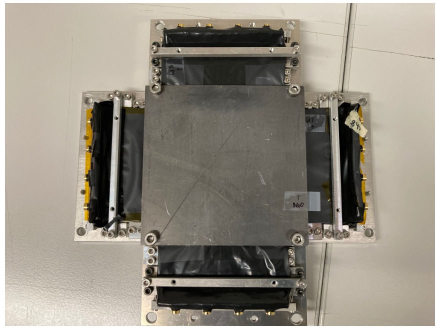


Gamma-ray hit timing on pre-shower counter is used as a reference.
Inner face is divided into 24 patches and scanned.

absolute timing resolution $\sigma_{\mathrm{abs}} = \sigma(T_{\mathrm{xec}} - T_{\mathrm{ps}}) \ominus \sigma_{\mathrm{ps}} \ominus \sigma_{\mathrm{vertex}}$

even odd timing resolution $\sigma_{\mathrm{evenodd}} = \sigma(T_{\mathrm{even}} - T_{\mathrm{odd}})/2$

It is necessary to measure σ_{vertex} to evaluate σ_{abs}.



pre-shower counter

Pb converter + two plastic scintillator plates
Signal waveforms are read out by MPPCs
from both ends of the plates

Evaluation of σ_{vertex}

Reference counter is installed in front of LXe in σ_{vertex} measurement.

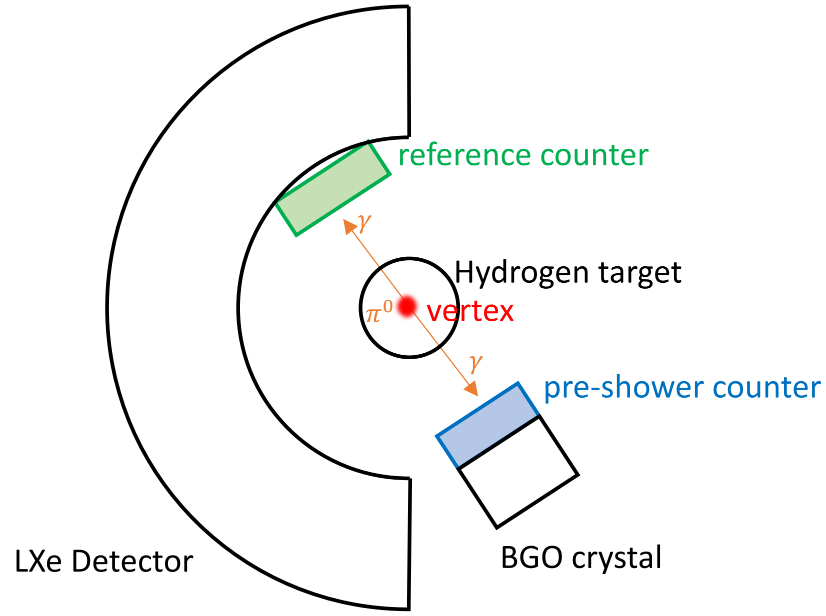
Timing resolution of a counter can be estimated from the time difference between two plates.

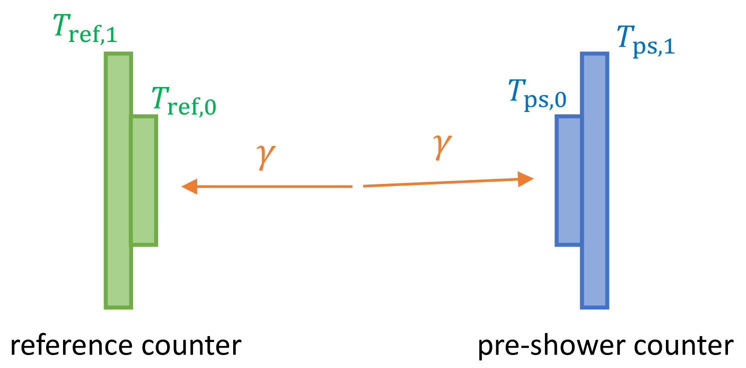
$\boldsymbol{\sigma_{\mathrm{vertex}}}$ can be calculated from the time difference between two counters.

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

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

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





<u>Result of σ_{vertex} measurement in 2022</u>

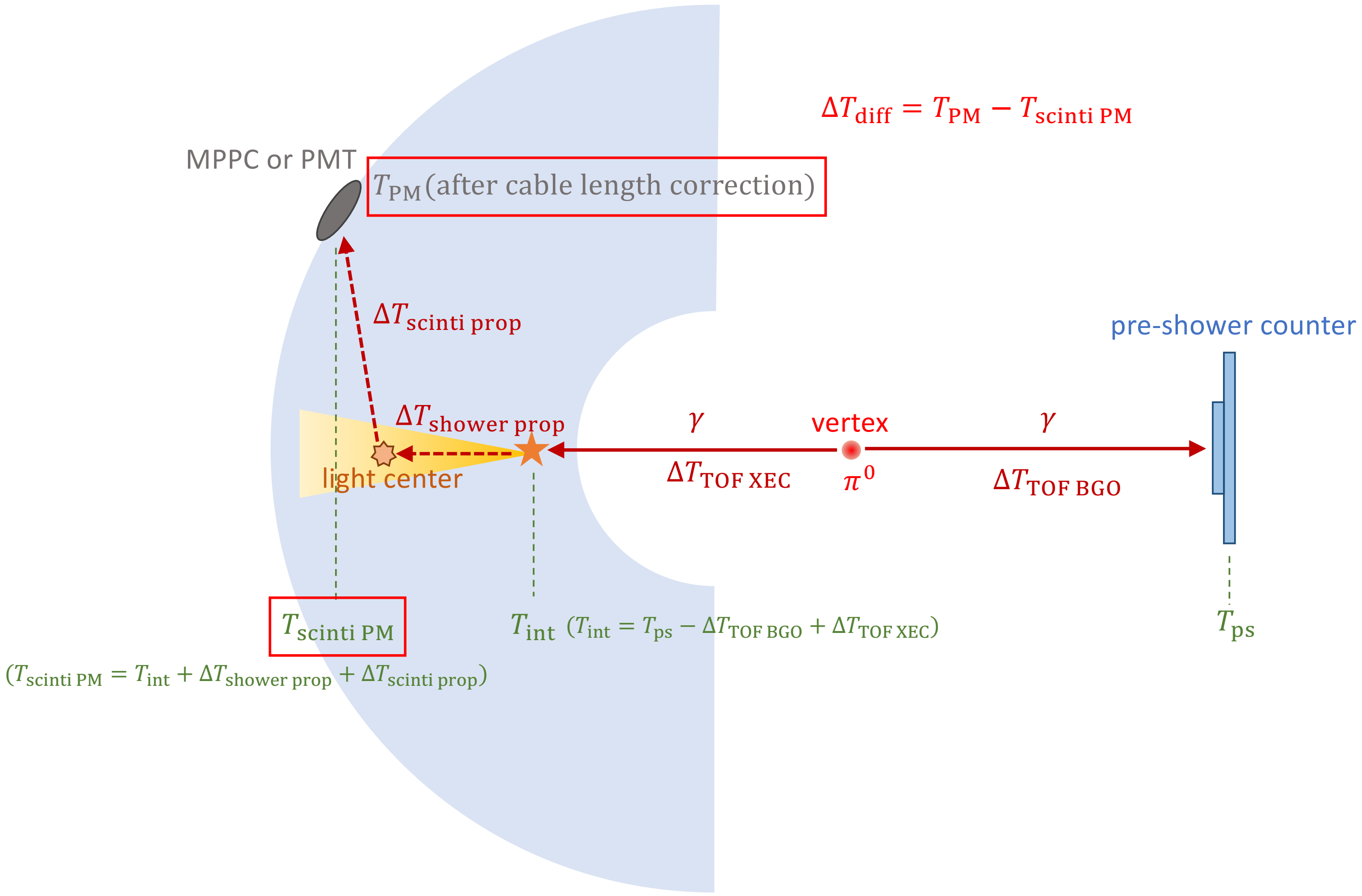
parameter	Value [ps]
$\sigma(T_{\mathrm{ps}} - T_{\mathrm{ref}})$	92.0 ± 1.3
σ_{ps}	84.7 ± 1.3
σ_{ref}	84.3 ± 1.4

Same beam configuration as patch scan

$$\sigma_{\mathrm{vertex}} = \sigma(T_{\mathrm{ps}} - T_{\mathrm{ref}}) \ominus \sigma_{\mathrm{ps}} \ominus \sigma_{\mathrm{ref}} = 68.1 \pm 1.7 \text{ ps}$$

$(1.02 \pm 0.03 \text{ cm})$

Sensor timing calibration



Time offset and time walk are calibrated in pion beam run.

$$\Delta T_{\mathrm{diff}} = T_{\mathrm{PM}} - T_{\mathrm{scinti\ PM}}$$

T_{PM} : Signal detection time in each sensor obtained from waveform analysis

$T_{\mathrm{scinti\ PM}}$: Time when scintillation light reaches the sensor calculated using T_{ps} as a reference

Time offset calibration

Average of ΔT_{diff} at each sensor is extracted.

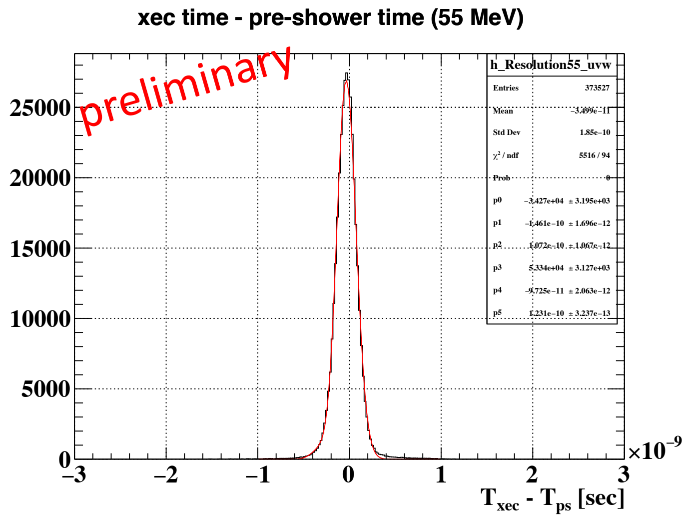
Time walk calibration

Sensors are divided 6 groups.

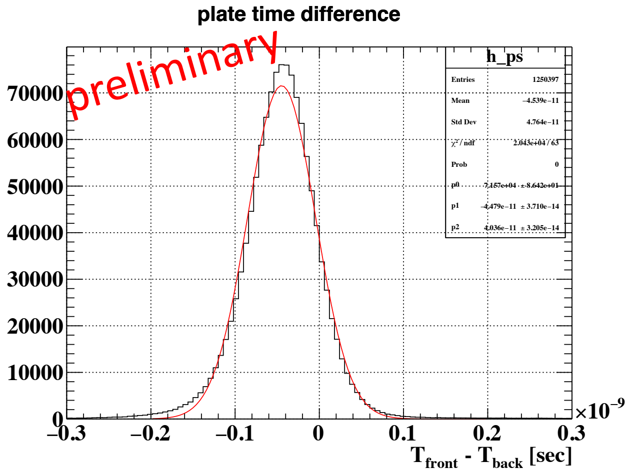
Dependence of ΔT_{diff} on N_{phe} is extracted.

These parameters are calibrated iteratively.

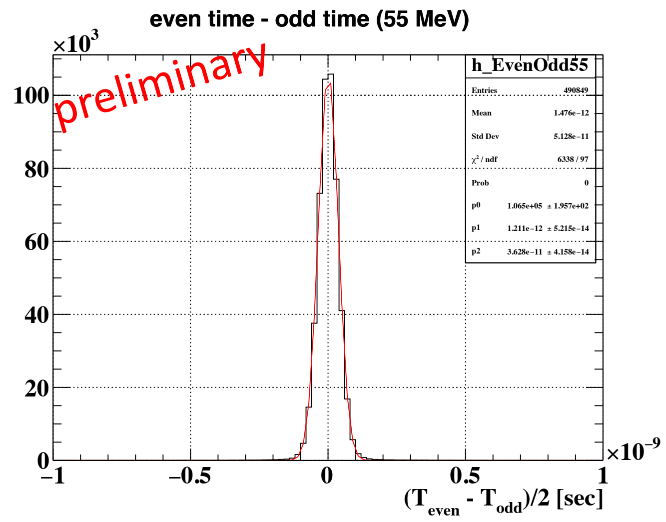
Timing resolution of LXe in 2022



$\sigma(T_{\mathrm{XEC}} - T_{\mathrm{ps}} - T_{\mathrm{TOF}}) = 104.1 \pm 0.2$ ps



$\sigma_{\mathrm{ps}} = 40.4 \pm 0.0$ ps



$\sigma_{\mathrm{evenodd}} = 36.3 \pm 0.0$ ps

$$\sigma_{\mathrm{abs}} = \sigma(T_{\mathrm{XEC}} - T_{\mathrm{ps}} - T_{\mathrm{TOF}}) \ominus \sigma_{\mathrm{ps}} \ominus \sigma_{\mathrm{vertex}}$$
$$\sigma_{\mathrm{evenodd}} = \sigma((T_{\mathrm{even}} - T_{\mathrm{odd}})/2)$$

$\sigma_{\mathrm{abs}} = 67.6 \pm 1.7$ ps
$\sigma_{\mathrm{evenodd}} = 36.3 \pm 0.0$ ps

Complete scan of inner face of LXe detector

(Data for some areas were not taken in 2021 due to instability of liquid hydrogen target.)

Sufficient statistics were obtained.

Detailed analysis is in progress.
- Detailed sensor calibration
- Optimization of analysis parameters
- Time dependence
- Position dependence correction of time offset

Summary & prospect

- Physics run was accomplished over four-month in 2022 beamtime.

Sensor calibration

- Impact of noise on energy reconstruction is less than energy resolution.
- PMT gain decreased during beamtime but was stable by adjusting HV as needed.
- LY recovery due to purification of gaseous xenon is observed.
- Sensor calibration for the second half of the beamtime is ready, and calibration for the first half of the beamtime is continued.

Timing resolution evaluation in pion beam run

- Sufficient statistics were obtained for the entire detector area in 2022 pion beam run.
- Preliminary timing resolution of LXe detector in 2022 pion run data is 67.6 ± 1.7 ps and detailed analysis is ongoing.