MEG II実験液体キセノンガンマ線検出器の2024年データ解析状況

馬越 隆成（東大理）、他MEG IIコラボレーション

日本物理学会第80回年次大会

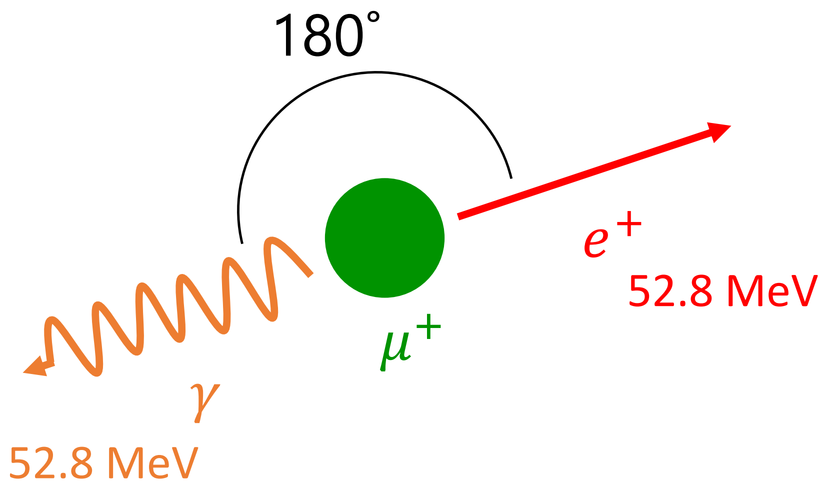
Core-to-Core Program

ICEPP The University of Tokyo

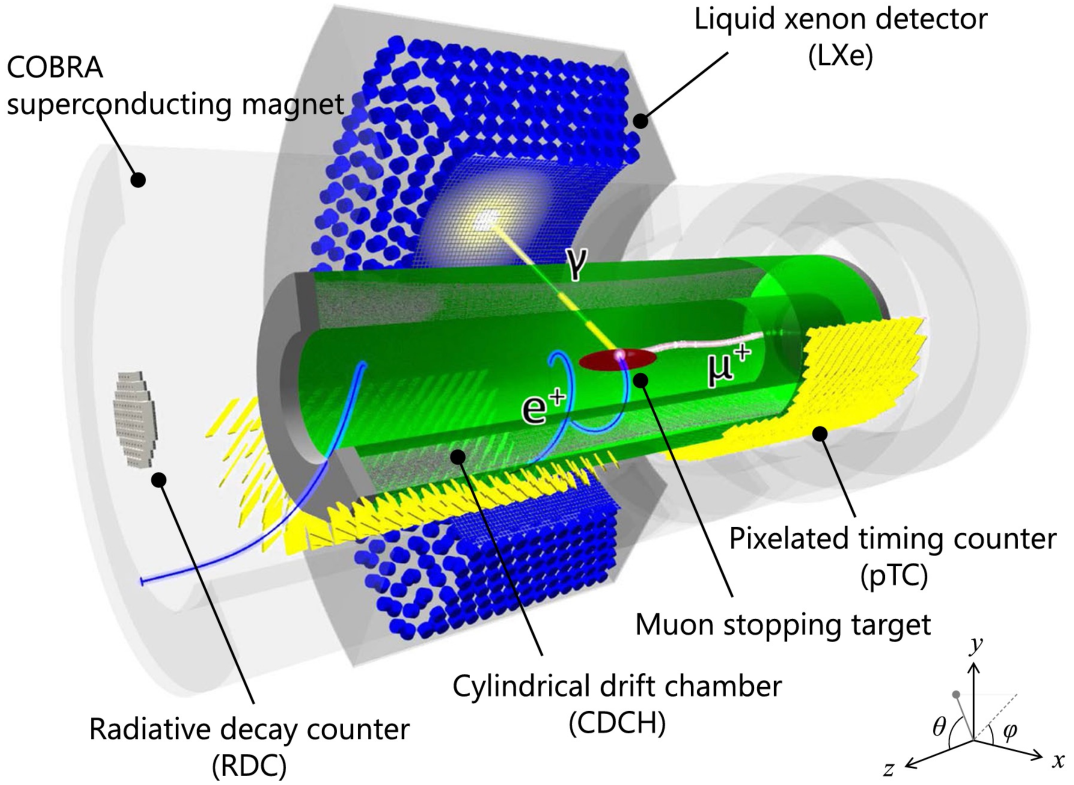
MEG II Mu - E - Gamma collaboration

MEG II Experiment

- MEG II Experiment
  - Search for $\mu^+ \to e^+\gamma$
    - charged Lepton Flavor Violation
    - with $2-5\times10^7\ \mu/s$ beam rate at Paul Scherrer Institute (PSI)
    - Data taking from 2021 to 2026
  - Expected branching ratio of $\mu \to e\gamma$ from SUSY-GUT: $\mathcal{O}(10^{-13}-10^{-14})$
  - Target sensitivity: 6×10^{-14}

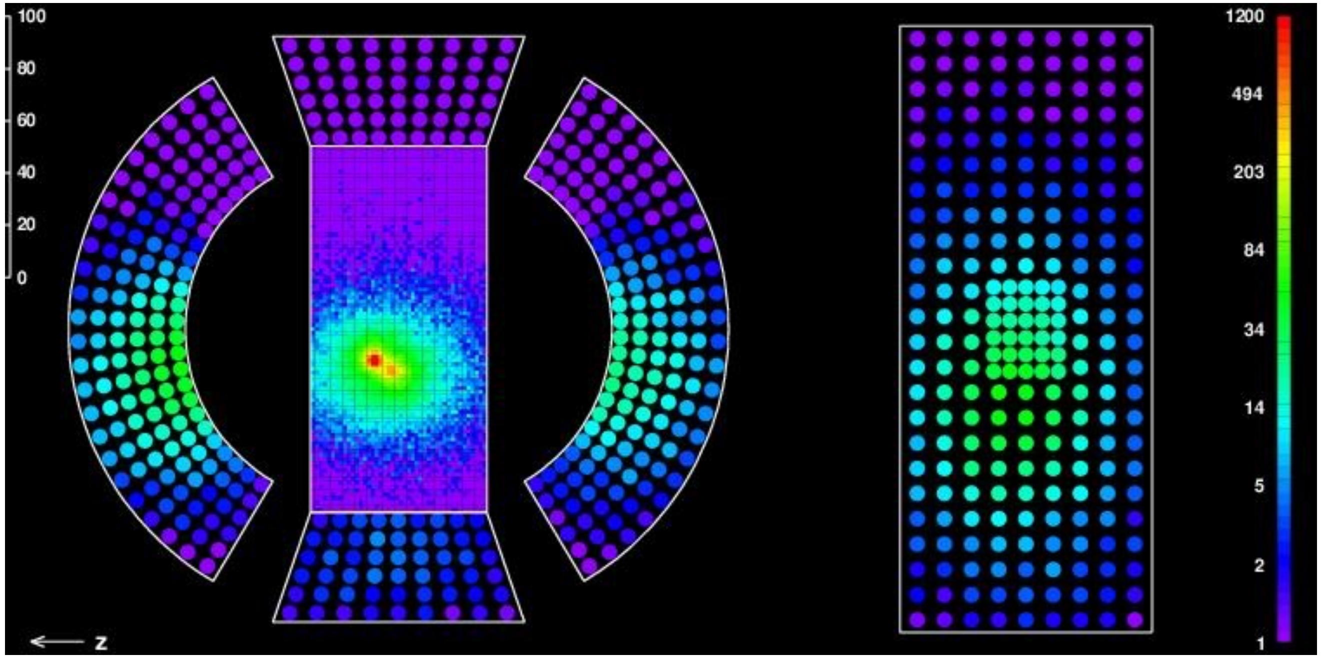


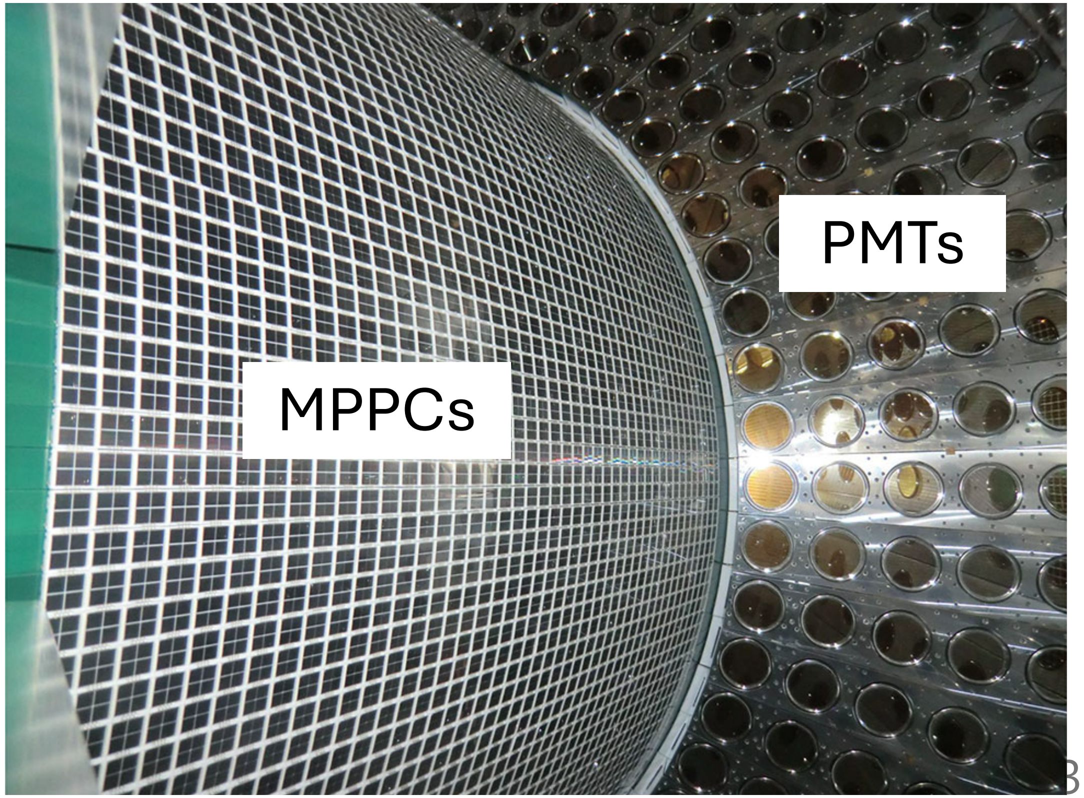
- MEG II Detector
  - CDCH: Tracking of e^+
  - pTC : Measure time of e^+
  - LXe detector: Measure position, time, energy of γ



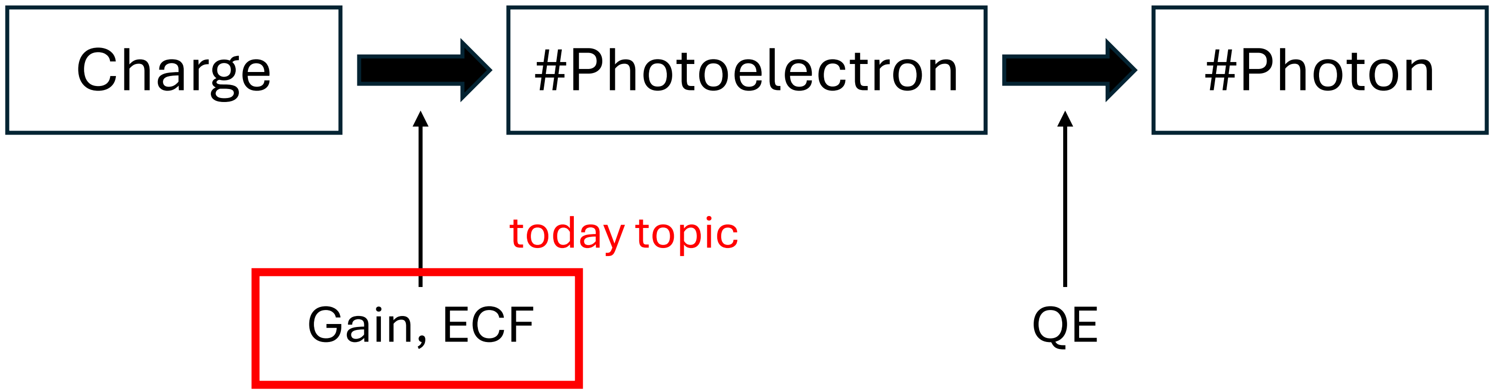
Liquid Xenon (LXe) Photon Detector

- LXe Detector
  - Used 900 L LXe as scintillator
    - Wavelength of scintillation light of LXe: $\lambda = 175\ \mathrm{nm}$ (Vacuum Ultraviolet (VUV) region)
  - Used PMTs and MPPCs which are sensitive to VUV light
    - 668 2-inch PMTs
    - 4092 MPPCs (MPPC size: $12 \times 12\ \mathrm{mm}^2$), MPPC is a kind of SiPM





Overview of Photon Analysis and Sensor Calibration in 2024



- PMT gain calibration
  - Take data which blinking LEDs to get PMT signals
  - But about 22% such calibration data were useless for calibration
  - Introduced a new method to compromise lost data

- MPPC gain and ECF calibration
  - Take data which blinking LEDs to get MPPC signals
  - Less #multiple photoelectrons was observed. But it does not affect to calibration analysis
  - It was due to less supplied intensity of LED
  - Introduced a online monitor of the intensity of LED in 2025

PMT Gain Calibration (Conventional)

- PMT which is used in the LXe detector could not detect 1 photoelectron
  - It is impossible to calculate the gain by the substraction of pedestal and 1 photoelectron peak charge

- Instead the PMT gain calculated by the following formula

$$\sigma_Q^2 = G_I \cdot e \cdot \bar{Q} + \sigma_0^2$$

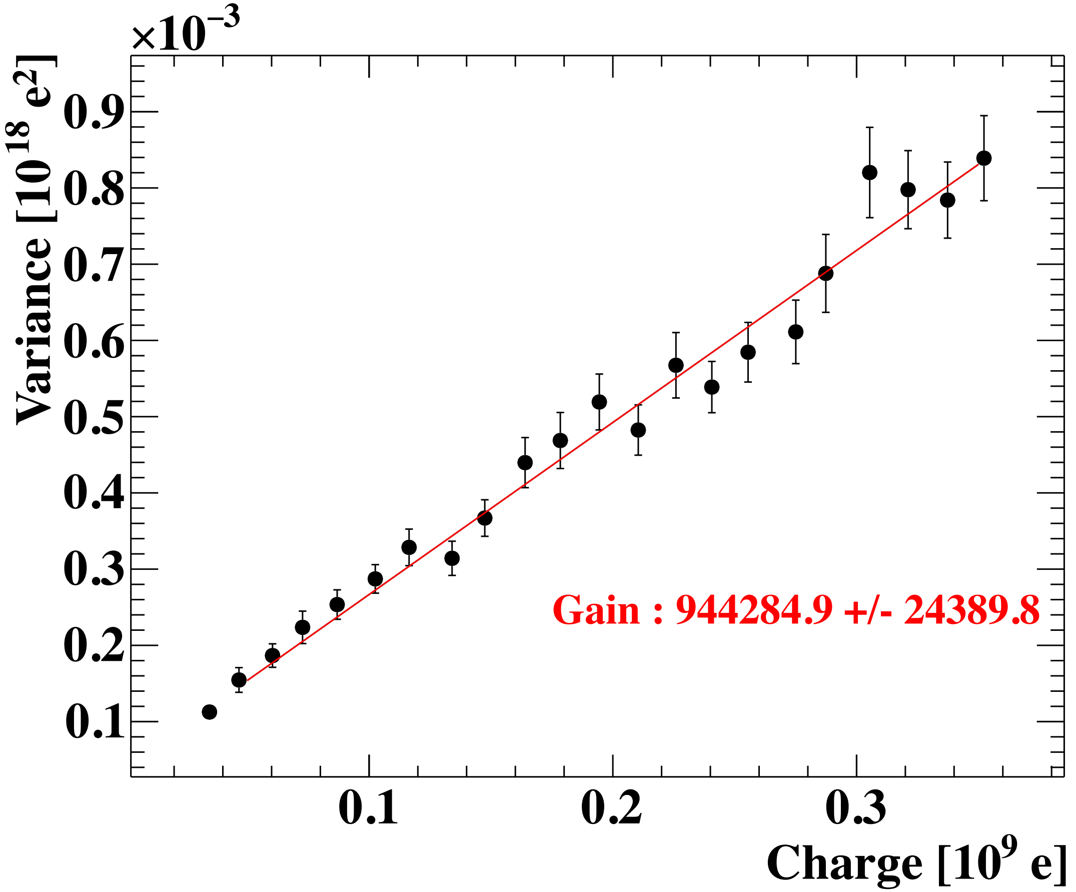
σ_Q: Variance of charge distribution

G_I : PMT Gain

e : Elementary charge

$\bar{Q}$: Mean of PMT charge

σ_0 : Noise of readout electronics



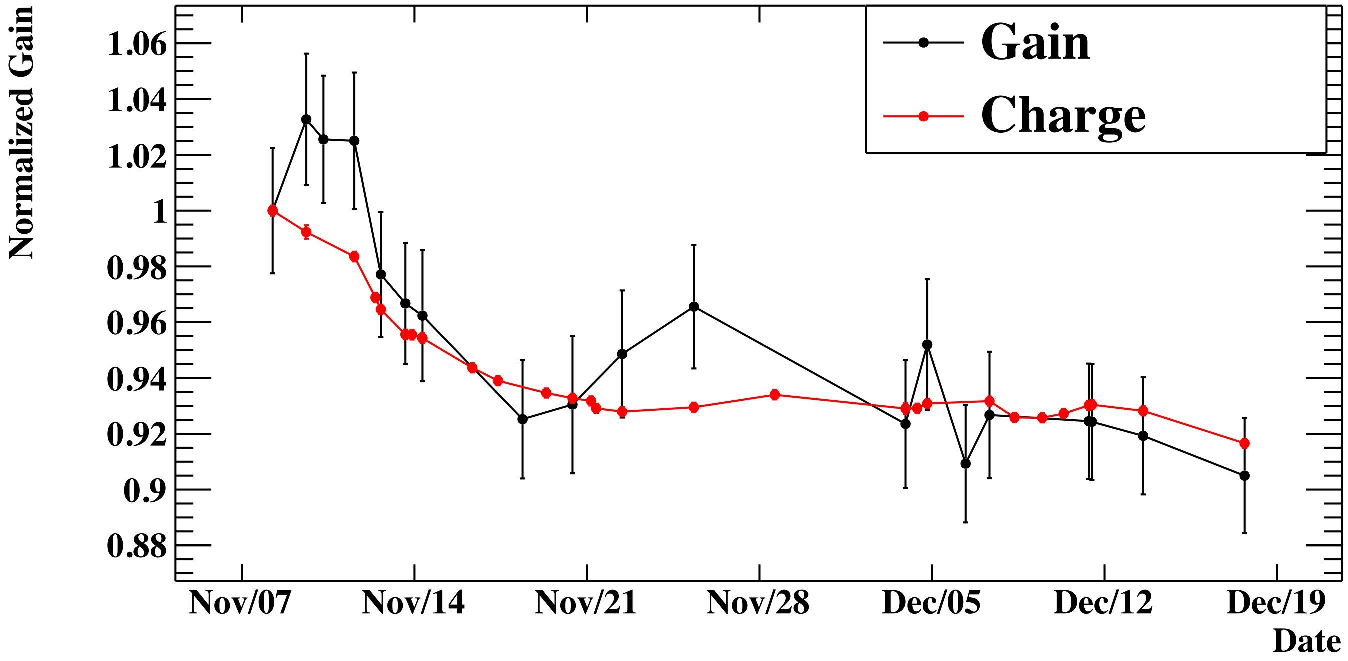
- To calculate G_I, blinking LED with several intensities and measure PMT charge (called *intensity scan*)

PMT Gain Calibration (Conventional)

- The gain of PMT in the LXe detector decreased due to the irradiation of muon beam

- PMT gain can be calculated only by the intensity scan
  - But calculated gain by this method has large uncertainty due to a noise of readout electronics

- On the other hand, PMT charge has less uncertainty. Scale PMT charge to gain to get more realistic PMT gain



PMT Gain Calibration (Conventional)

- Gain based on charge $G_{Q,i}$ is calculated to minimize the subtraction of $G_{I,i}$ and $G_{Q,i}$

$$FCN = \sum_i \frac{\left(G_{I,i} - G_{Q,i}\right)^2}{\sigma^2_{G_{I,i}}}$$

$G_{I,i}$: Gain based on intensity scan

$\sigma^2_{G_{I,i}}$: Variance of $G_{I,i}$

- Where $G_{Q,i}$ is given by

$$G_{Q,i} = Q_i(p_0 + p_1 t)$$

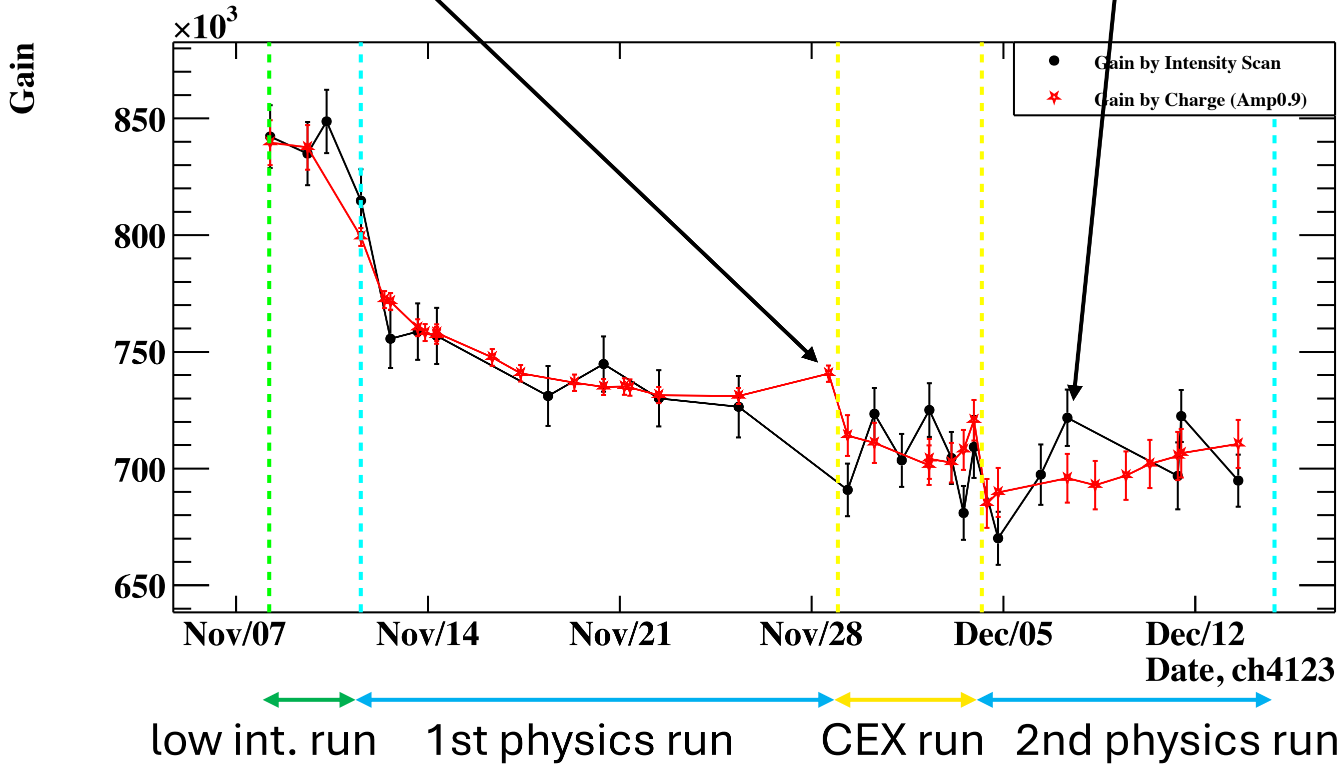
Q_i : PMT charge

p_0, p_1: minimization parameters

t : time

Red point is the gain $G_{Q,i}$ by the charge to an intensity LED

Black point is the gain $G_{I,i}$ by Intensity scan



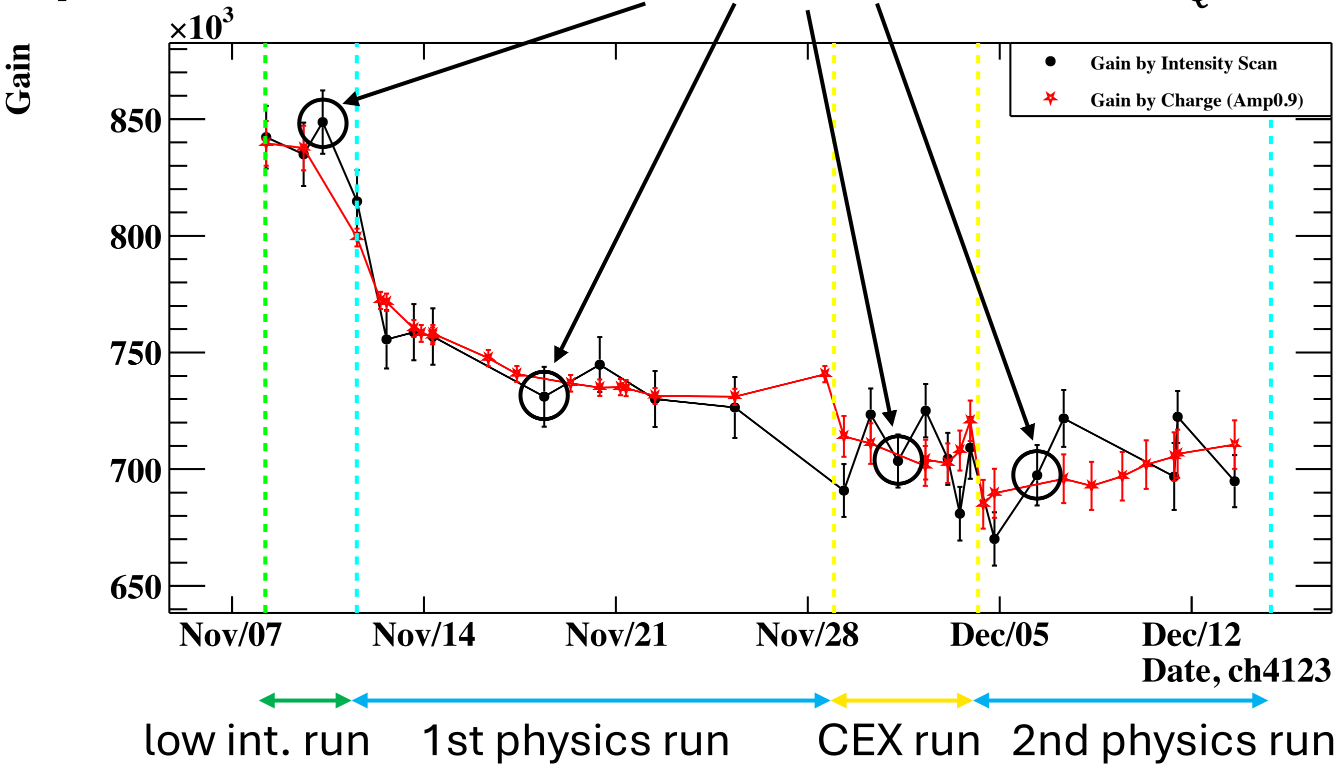
The minimization was done by each run period

Affect of Bad LED Data to PMT Gain Calibration

- 22% LED data for PMT gain calibration are useless
  - For those data LED intensities did not change properly due to a problem of LED driver controller
  - It happend only in 2024 and resolved for the MEG II data taking in 2025

- It causes unprecise minimization between G_Q and G_I due to the lack of G_Q data points

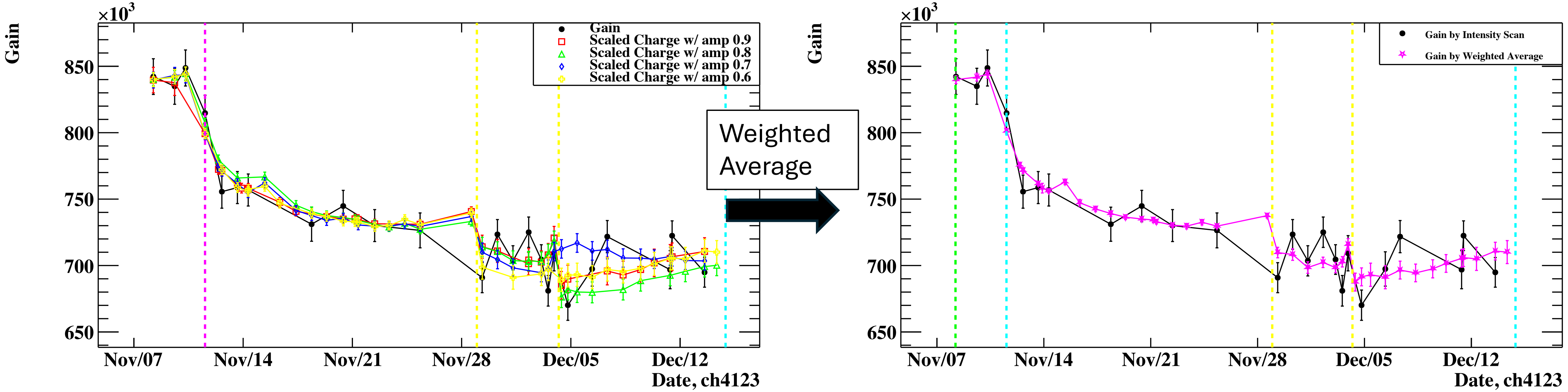
G_Is are not included in the minimization between G_Q and G_I



PMT Gain Calibration (Updated in 2024)

- To compromise lost G_Q data, take weighted average of several G_Qs to different intensity's LED
  - 4 different intensities' LED are taken
  - Exclude outliers of G_Qs for the weighted average

- PMT gain calibration was successfully done



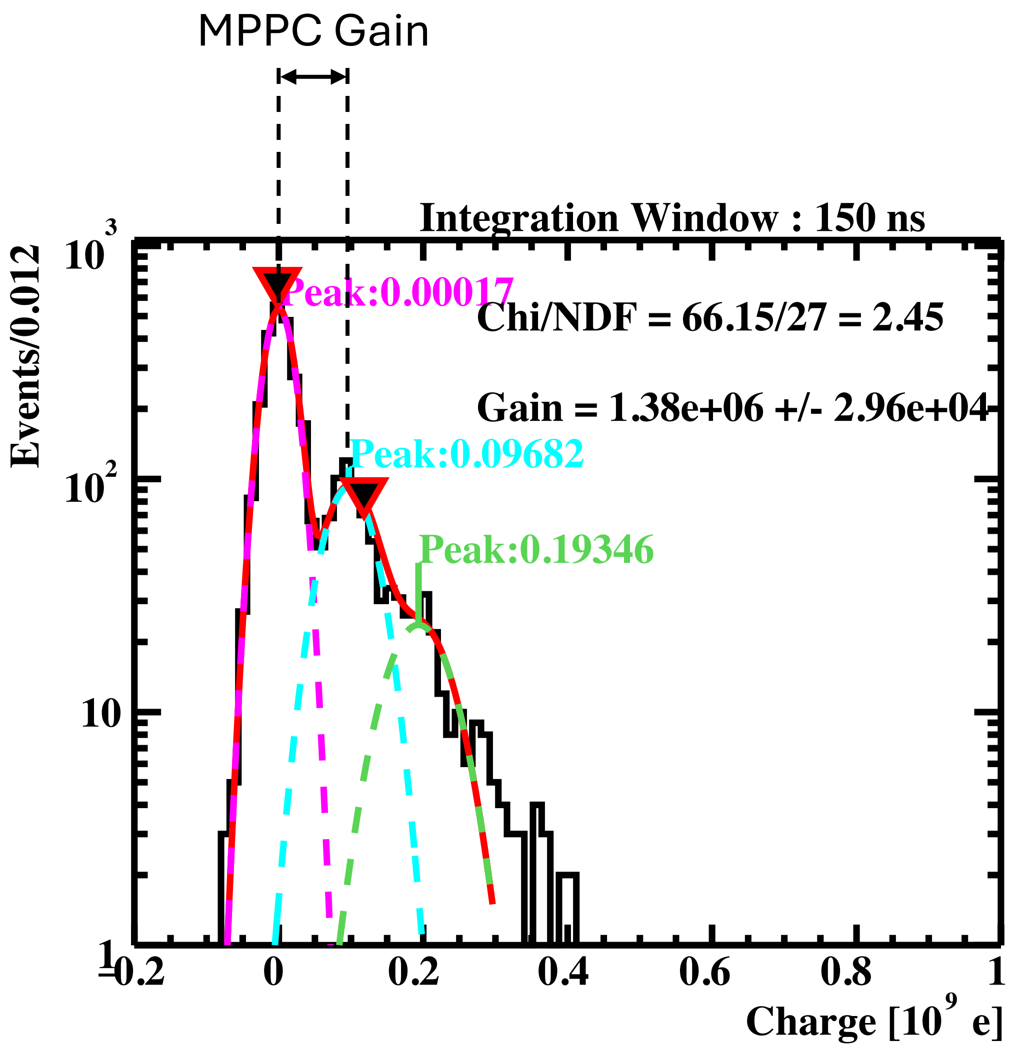
MPPC Gain Calibration (Conventional)

- MPPC gain is calculated by the subtractioin of pedestal and 1 photoelectron peak
- Charge distribution is fitted with a triple gaussians
- Observed #photoelectron of VUV-MPPC is larger than the real #photoelectron which folows Poission distribution
  - Due to noises such as cross talk and after pulse
- Represents it ECF (Excess Charge Factor) and it is given by

$$ECF = \frac{\bar{Q}}{e \cdot G \cdot \langle N_{\mathrm{phe}} \rangle},$$

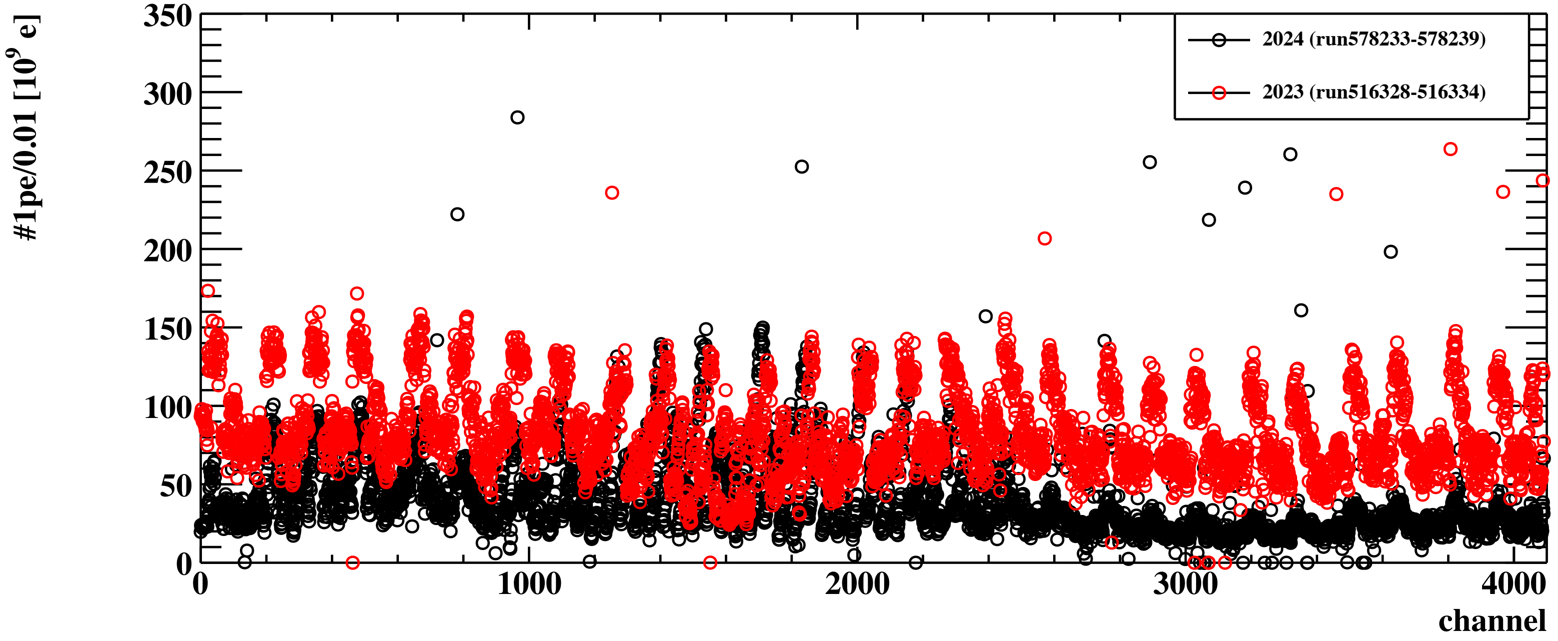
$$\langle N_{\mathrm{phe}} \rangle = -\log\left(\frac{N_{0\mathrm{pe}}}{N_{\mathrm{total}}}\right),$$

where $N_{0\mathrm{pe}}$ is #pedestal which follows Poisson distribution and N_{total} is total #photoelectron



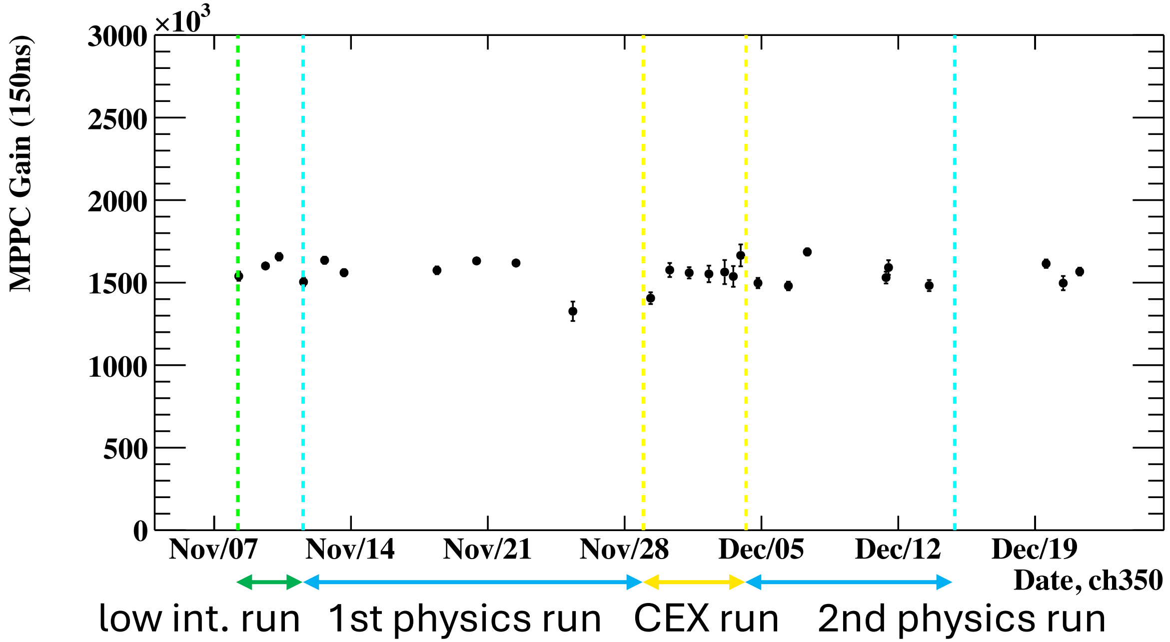
Less #1 photoelectron for MPPC Gain Calibration Data

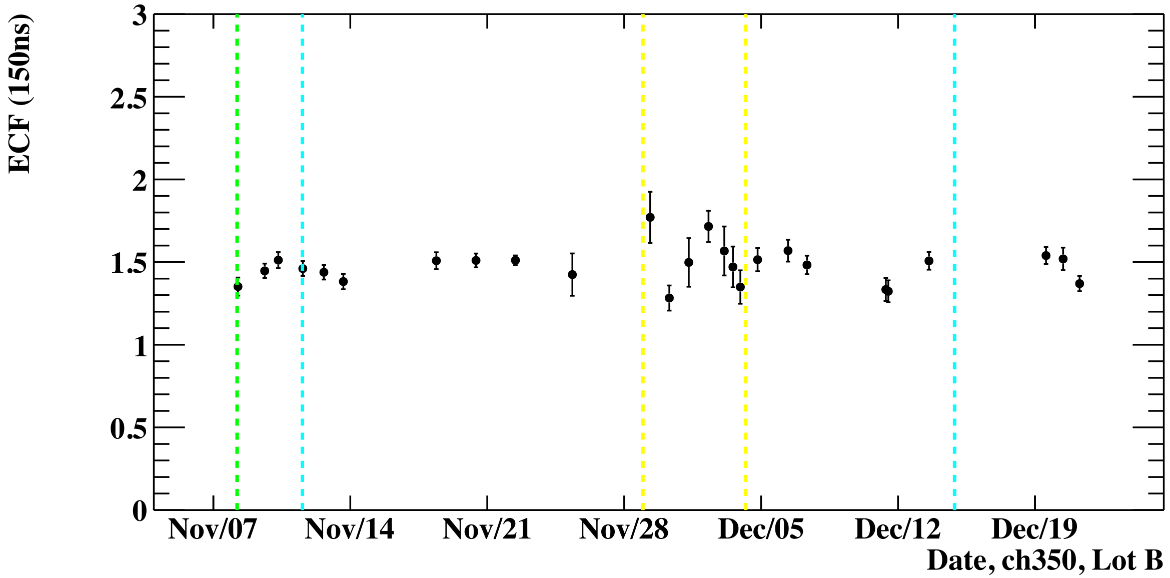
- #1 photoelectron for MPPC gain calibration data in 2024 was a bit less than 2023
- It does not affect to the MPPC gain calibration but might be a problem in the future
- Found out that the cause of less #1 photoelectron is less intensity of LED.
- Introduced a online monitor of the LED intensity for MPPC gain calibration data in 2025



MPPC Gain Calibration (Conventional)

- Calculated MPPC gains and ECFs by the conventional method for whole MEG II run in 2024
- Overall these values are stable as expected
- Dedicated MPPC gain and ECF calibrations are ongoing





Summary

- Due to about 22% bad calibration data for the PMT had to introduce new calibration method to calculate accurate PMT gains
- Took weighted average for several PMT gains based on its charge and successfully calculated accurate PMT gains
- Calculated MPPC gains and ECF
- Found out that the cause of less #1 photoelectron for MPPC gain calibration data in 2024 and introduced a online monitor to insure the quality of MPPC gain calibration
- Dedicated LXe detector photosenser's calibration in 2024 are ongoing

Backup

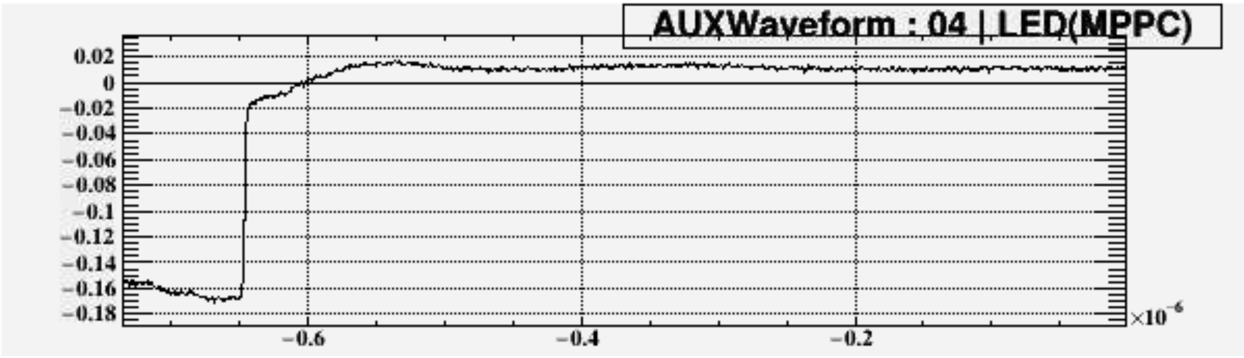
Constant Fraction Time of LED Input Pulse

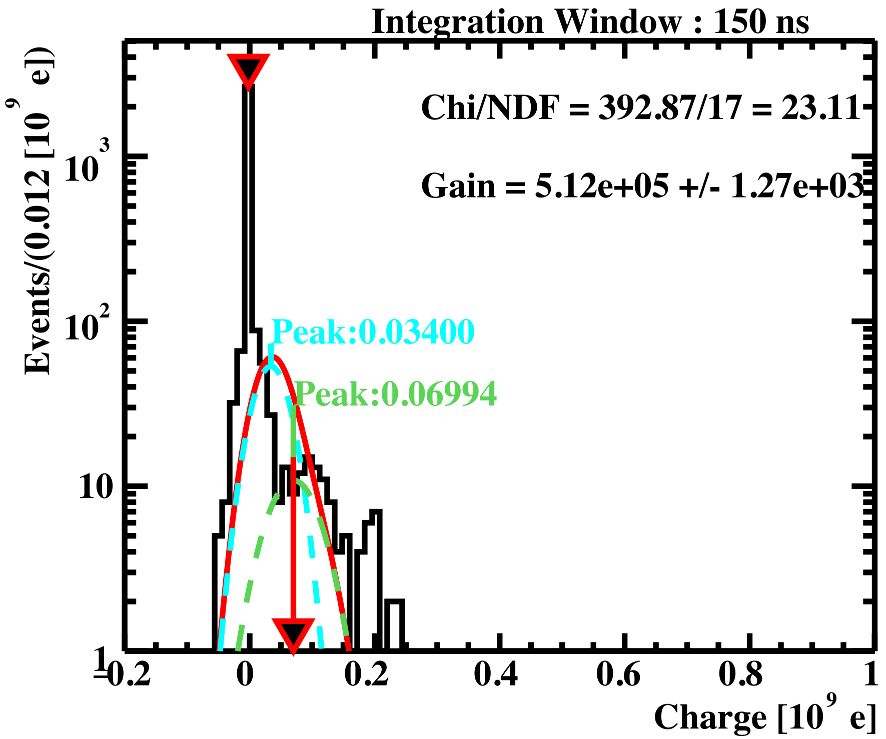
- Constant fraction time of LED input pulse is used for a reference time of MPPC signal integration range

- But for some events the LED input pulse is out of the dynamic range so that unproper constant fraction time can be used as the reference time of MPPC integration range

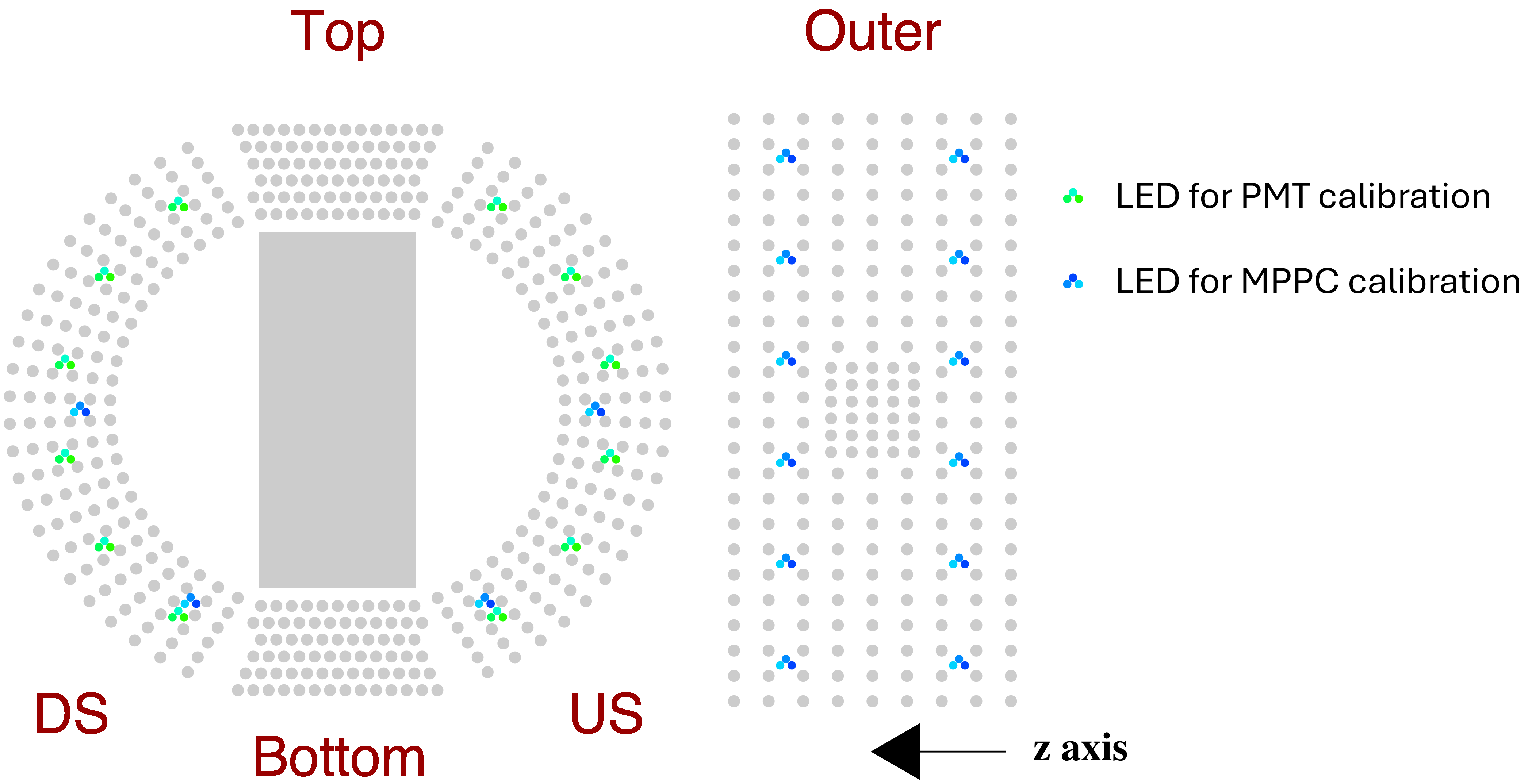
- It causes a sharp pedestal peak on charge distribution and affects gaussian fitting negatively

- To avoid this case set a constant fraction condition to fullfil only properly calculated MPPC charge in the histogram
  - $-740 \text{ ns} < \text{constant fraction time} < -600 \text{ ns}$





LED Positions inside LXe Detector



PMT Gain Calibration

- PMT gain $G_{Q,i}$ by Q_i is calculated from

$$G_{Q,i} = Q_i(p_0 + p_1 t)$$

p_0, p_1: minimization parameters

- Minimization function

$$FCN = \sum_i \frac{(G_{I,i} - G_{Q,i})^2}{\sigma^2_{G_{I,i}}}$$

$G_{I,i}$: Gain based on intensity scan

$G_{Q,i}$: Gain based on charge

- Formulation of uncertainty of $G_{Q,i}$

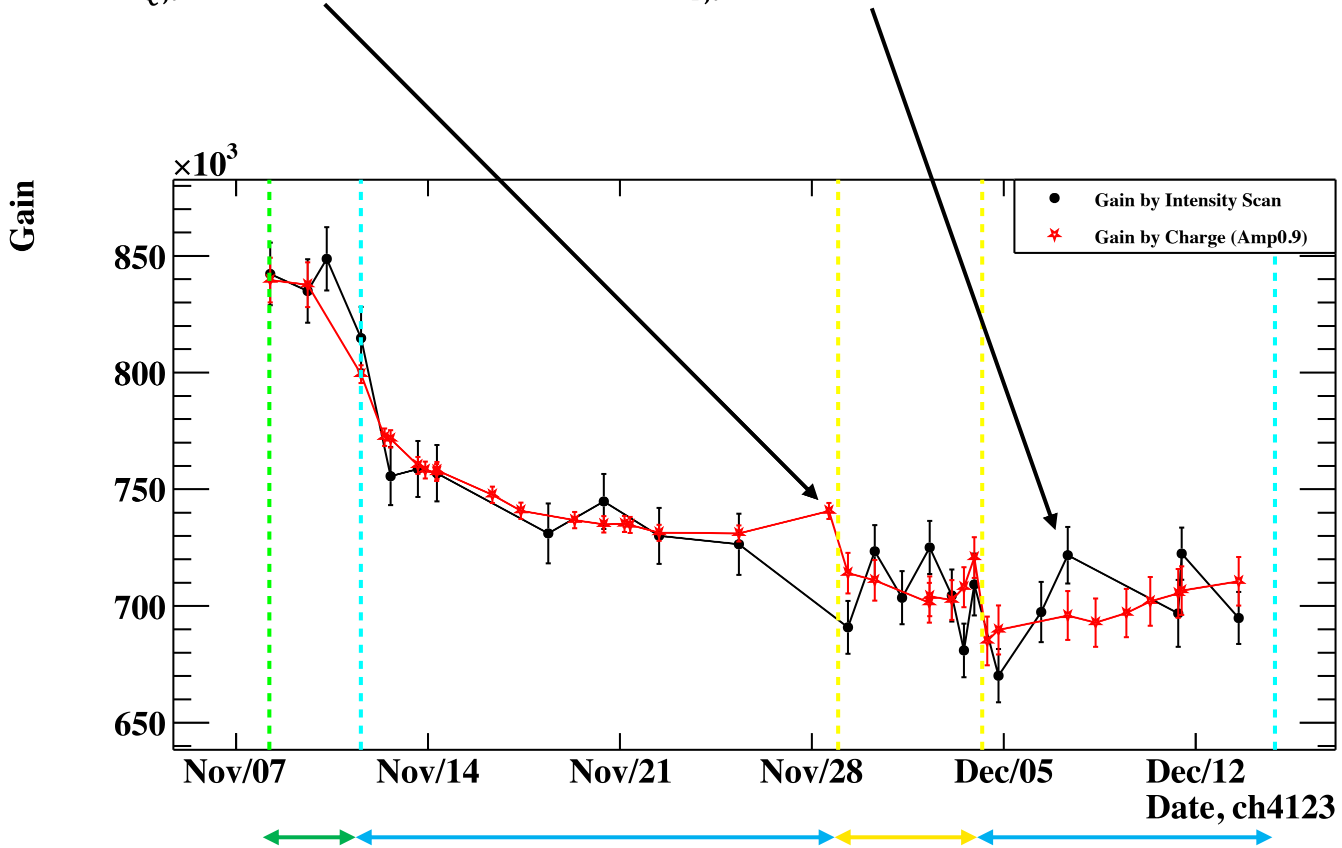
$$\sigma_{G_{Q,i}} = \sqrt{\sigma^2_{Q_i}(p_0 + p_1 t)^2 + Q_i^2 \sigma^2_{p_0 + p_1 t}},$$

where $p_0 \gg p_1 t$ ($p_0 = O(10^{-3}), p_1 t = O(10^{-5})$)

So that time dependency of $\sigma_{G_{Q,i}}$ is negligible

Red point is the gain $G_{Q,i}$ by amp 0.9 LED data

Black point is the gain $G_{I,i}$ by Intensity scan



low int. run | 1st physics run | CEX run | 2nd physics run

The minimization was done by each run period

Gaussian Fitting Function

- LED input pulse in 2024 is smaller than in 2024, but figured out there is still a few 2p.e. peak in charge distribution
- Use triple gaussian as fitting function

$$N \underbrace{\exp(-\lambda)}_{\text{ped. factor which follows Poisson dis.}} \times \text{binwidth} \times \frac{1}{\sigma_{\text{ped}}\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{x-\mu_{\text{ped}}}{\sigma_{\text{ped}}}\right)^2\right)$$

$$+N\lambda \underbrace{\exp(-\lambda)}_{\text{1p.e. factor which follows Poisson dis.}} \times p \times \text{binwidth} \times \frac{1}{\sigma_{1\text{pe}}\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{x-\mu_{1\text{pe}}}{\sigma_{1\text{pe}}}\right)^2\right)$$

$$+\left\{\frac{\lambda^2}{2} \underbrace{\exp(-\lambda)}_{\text{2p.e. factor which follows Poisson dis.}} \times \left(p^2 + 2p(1-p)\right) + \underbrace{\lambda \exp(-\lambda)}_{\text{1p.e. factor which follows Poisson dis.}}\right\} \times \text{binwidth} \times \frac{1}{\sigma_{2\text{pe}}\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{x-\mu_{2\text{pe}}}{\sigma_{2\text{pe}}}\right)^2\right)$$

N : total number of entries of histogram

p : conversion factor to multiple p.e. by CTAP, 0<p<1

λ : Expected #p.e. which follows Poisson distribution

μ_{ped} : result of peak search

$\mu_{1\text{pe}}$: set result of peak search as initial value.

$\mu_{2\text{pe}}$: given by $2\mu_{1\text{pe}} - \mu_{\text{ped}}$

σ_{ped} : sigma of pedestal gaussian

$\sigma_{1\text{pe}}, \sigma_{2\text{pe}}$: sigma of 1p.e. and 2p.e. gaussians given by $\sigma_{1\text{pe}} = \sqrt{\sigma_{\text{ped}}^2 + \sigma^2}$, $\sigma_{2\text{pe}} = \sqrt{\sigma_{\text{ped}}^2 + 2\sigma^2}$, respectively. σ is a fitting parameter

Fitting Functions for Gain and ECF etc

- Gain G given by $\mu_{\mathrm{1pe}} - \mu_{\mathrm{0pe}}$;

$$G = p_0 \left\{1 - \exp\left(-\frac{x - p_1}{p_2}\right)\right\}$$

- Gain G_{eff} incl. CTAP given by $\langle Q \rangle - \mu_{\mathrm{ped}}$;

$$G_{\mathrm{eff}} = p_0 \left\{1 - \exp\left(-\frac{x - p_1}{p_2}\right)\right\}$$

- Charge Mean $\langle Q \rangle$;

$$\langle Q \rangle = p_0 + p_1 \left\{1 - \exp\left(-\frac{x - p_2}{p_3}\right)\right\}$$

- Lambda λ;

$$\lambda = p_0 + p_1 \left\{1 - \exp\left(-\frac{x - p_2}{p_3}\right)\right\}$$

- ECF F_{ECF} given by G_{eff}/G;

$$F_{\mathrm{ECF}} = p_0 + p_1 \left\{1 - \exp\left(-\frac{x - p_2}{p_3}\right)\right\}$$

CFTime of LED Input Pulse in 2024

- During CEX run, the cftime of LED input pulse is not within 15ns which is defined by triggering. There are 2 peaks in cftime distribution only for CEX run's weak LED data
- But the number of plausible cftime during CEX is same as during physics run
- In priciple it does not negatively affect to integration range of MPPC signal unless the height of LED pulse is stable for whole 2024 run