Core-to-Core Program

Evaluation of Timing Resolution of MEG II Liquid Xenon Detector

14/03/2021, 14aT2-3

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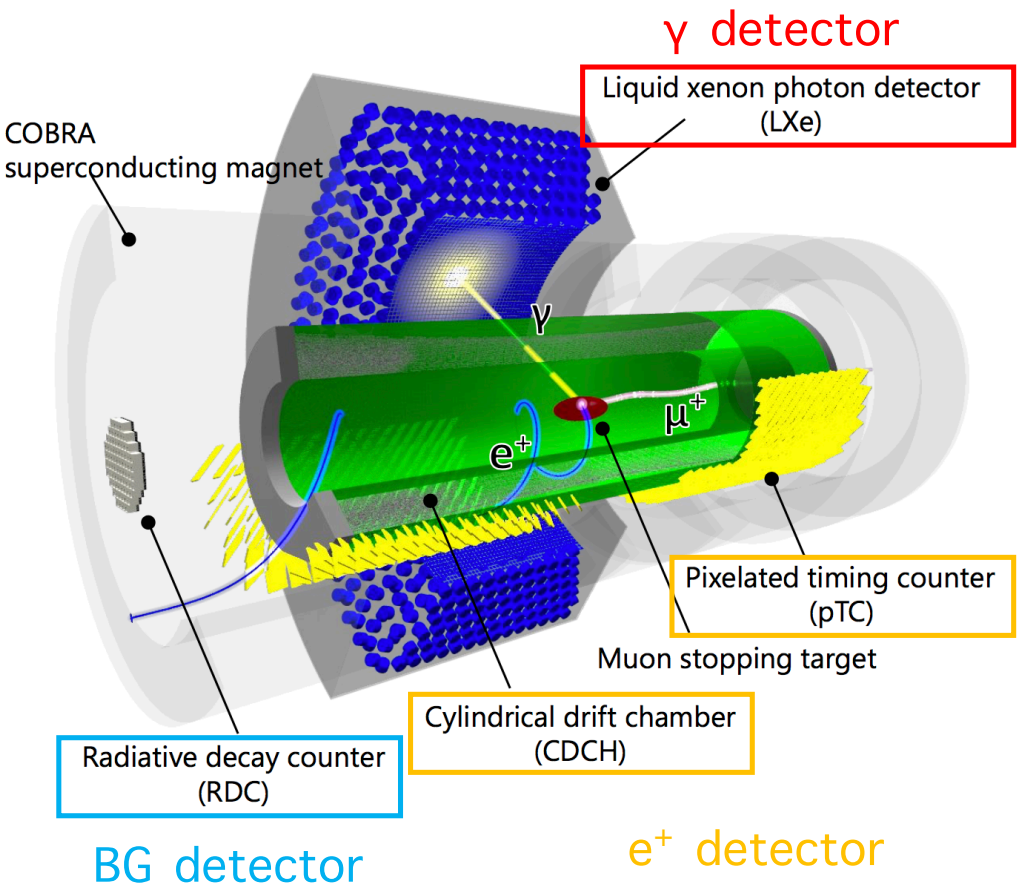
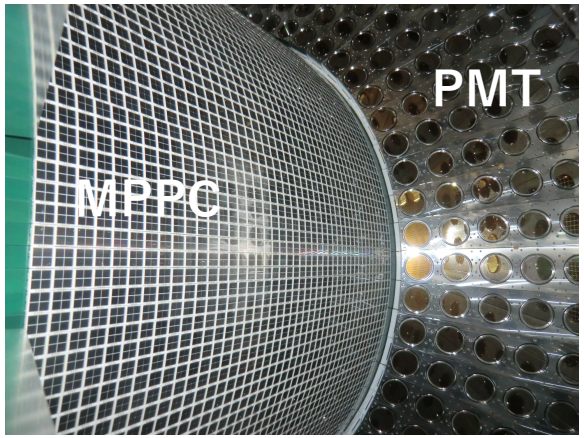
γ Detector of MEG II Experiment





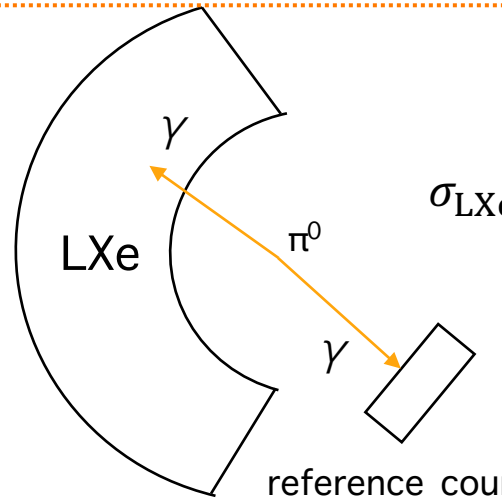
- MEG II experiment searches μ→ eγ decay, which is one of charged Lepton Flavor Violation.
- Liquid xenon photon detector (LXe) detects energy, position and timing of γ.
- Scintillation lights from liquid xenon are detected with PMTs and MPPCs.
- In this talk, the current status of evaluation of the LXe timing resolution will be reported.

Evaluation of Timing Resolution

The timing resolution can be evaluated with two methods:

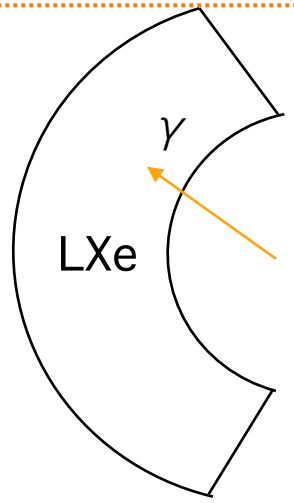
1. Absolute resolution
   - Use coincident 2 γ-rays from π^0 decay
   - Measure the timing of another γ with a reference counter
2. Intrinsic resolution
   - Use single γ-ray
   - Reconstruct γ timing with a half of channels (even, odd) separately

Absolute



$$\sigma_{\mathrm{LXe}} = \sigma(T_{\mathrm{LXe}} - T_{\mathrm{ref}}) \ominus \sigma_{\mathrm{ref}}$$

Intrinsic



$$\sigma_{\mathrm{LXe}} = \frac{\sigma(T_{\mathrm{even}} - T_{\mathrm{odd}})}{2}$$

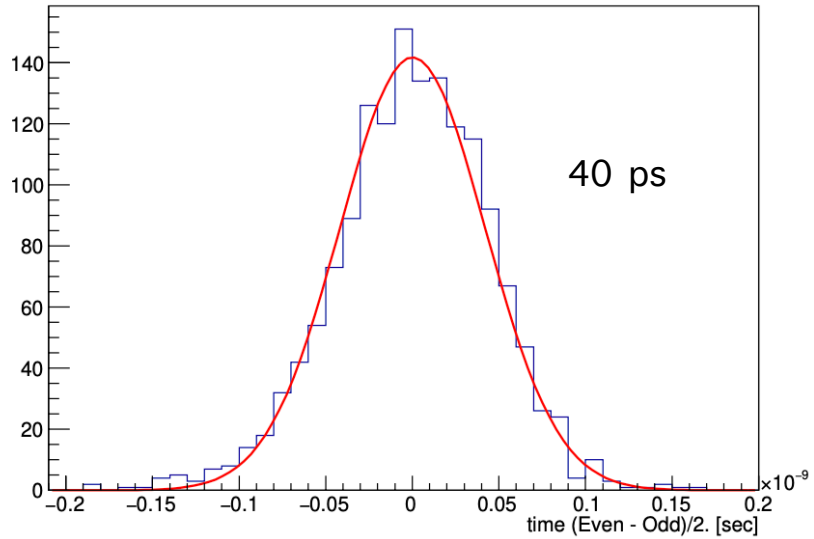
Previous Studies and Updates

- The intrinsic timing resolution has been evaluated with γs from μ beam.
- In 2019, ~40 ps was achieved for γs above 47 MeV.
  ← 30% improvement from MEG I

- The intrinsic timing resolution can be better than the absolute resolution because some effects can be reduced by even-odd subtraction:
  - Error from position reconstruction
  - Spread of shower
  - Coherence of electronics such as noise and synchronization

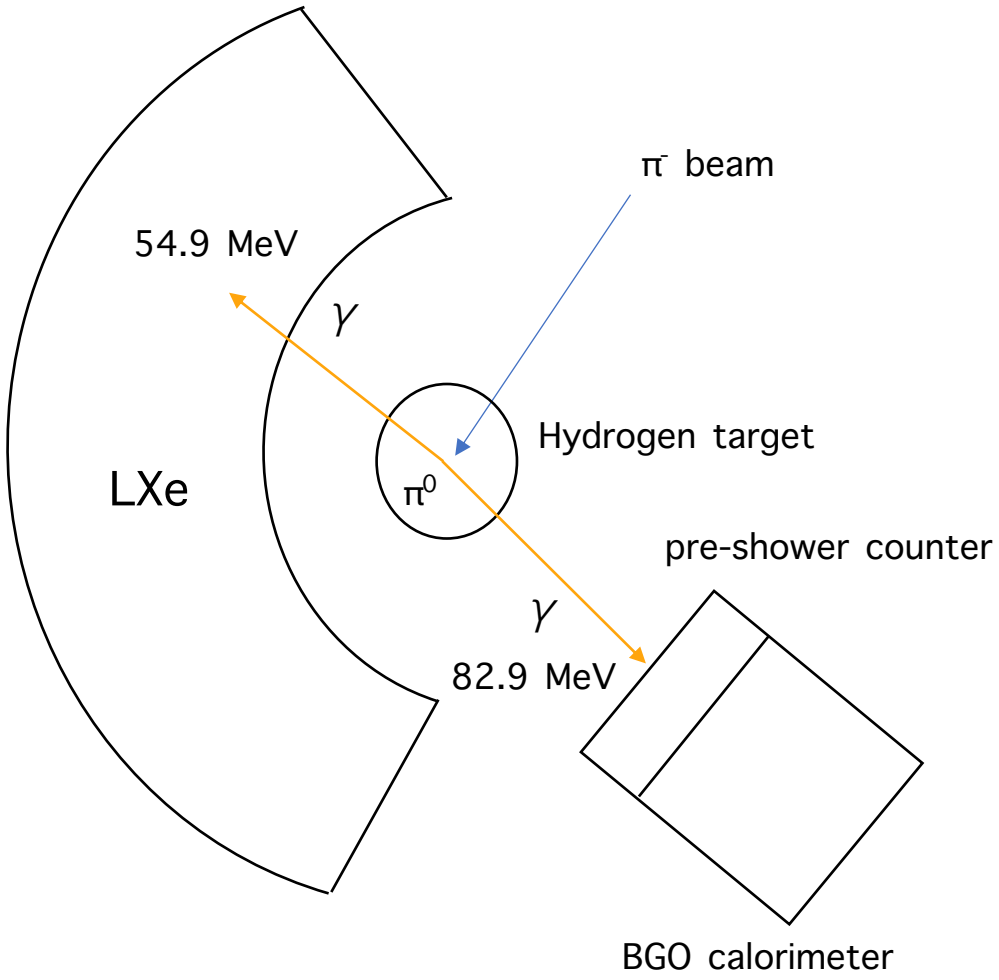
  → The absolute timing resolution must be evaluated.

$(T_{\mathrm{even}} - T_{\mathrm{odd}})/2$



- In 2020, we performed DAQ for evaluation of the absolute timing resolution.
- This is the first result about the absolute timing resolution of LXe for the MEG II experiment.

Evaluation of Timing Resolution with CEX



- The absolute timing resolution can be evaluated using back-to-back γ-rays from charge exchange reaction of π^-:

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

- The pre-shower counter was placed in the opposite side of LXe to measure the reference timing.

- LXe timing resolution can calculated using time difference with the pre-shower counter by

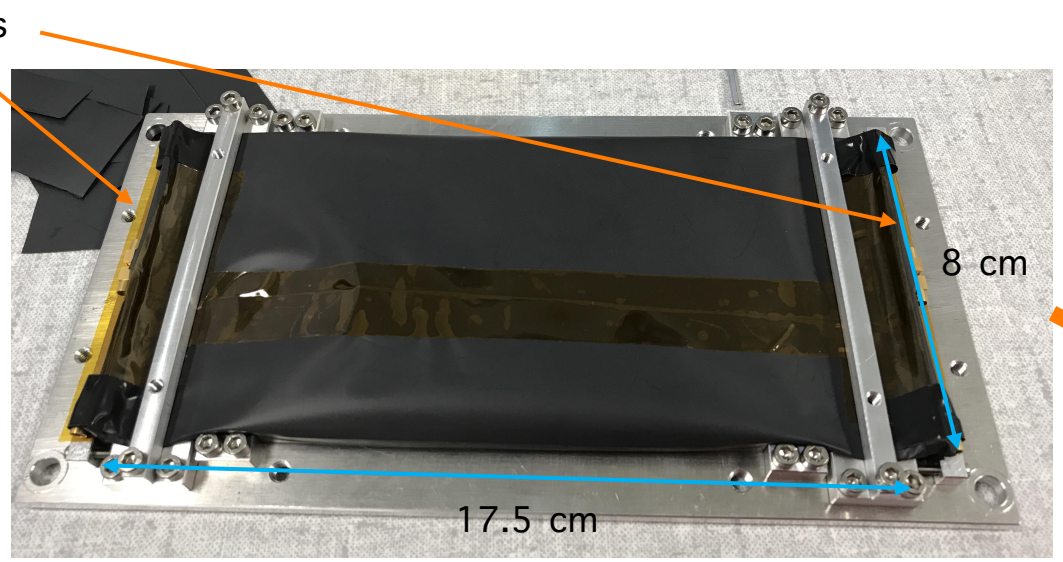
$$\sigma_{\mathrm{LXe}} = \sigma(T_{\mathrm{LXe}} - T_{\mathrm{ref}}) \ominus \sigma_{\mathrm{ref}}$$

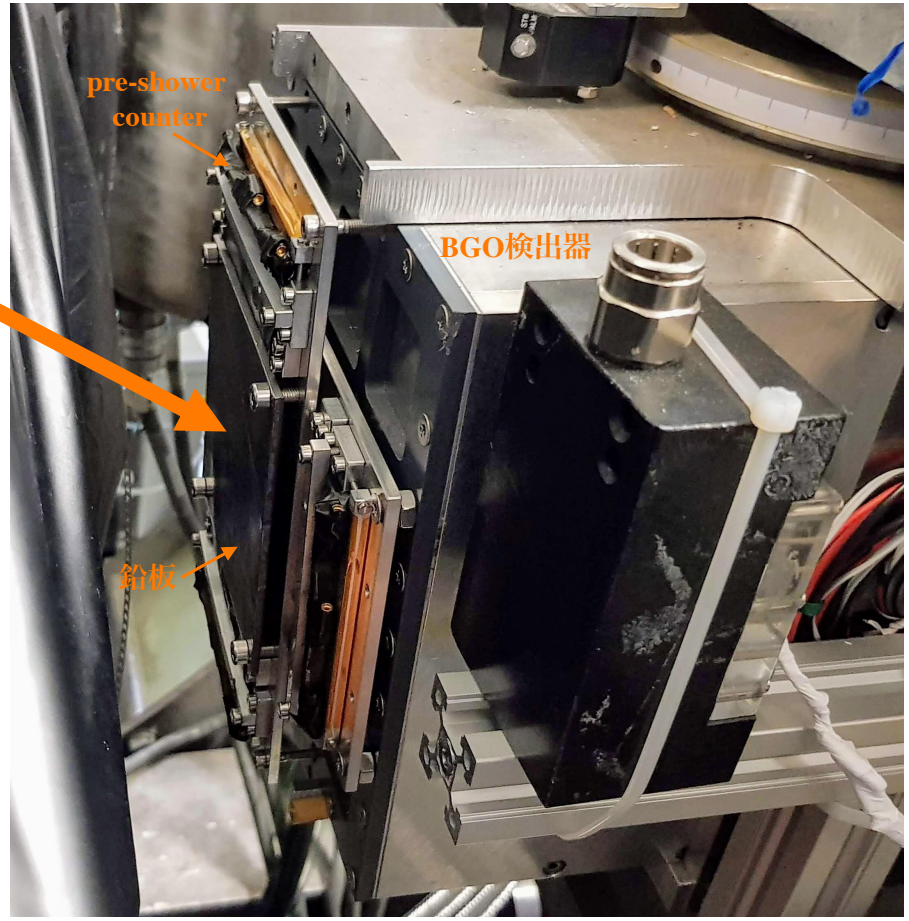
$$T_{\mathrm{ref}} = T_{\mathrm{ps}} + T_{\mathrm{TOF}}$$

$$\sigma_{\mathrm{ref}} = \sigma_{\mathrm{ps}} \oplus \sigma_{\mathrm{vertex}},$$

where T_{ps} is the measured timing and σ_{ps} is the contribution of the pre-shower counter, T_{TOF} is the time of flight, σ_{vertex} is the uncertainty of the vertex position.

Pre-shower Counter

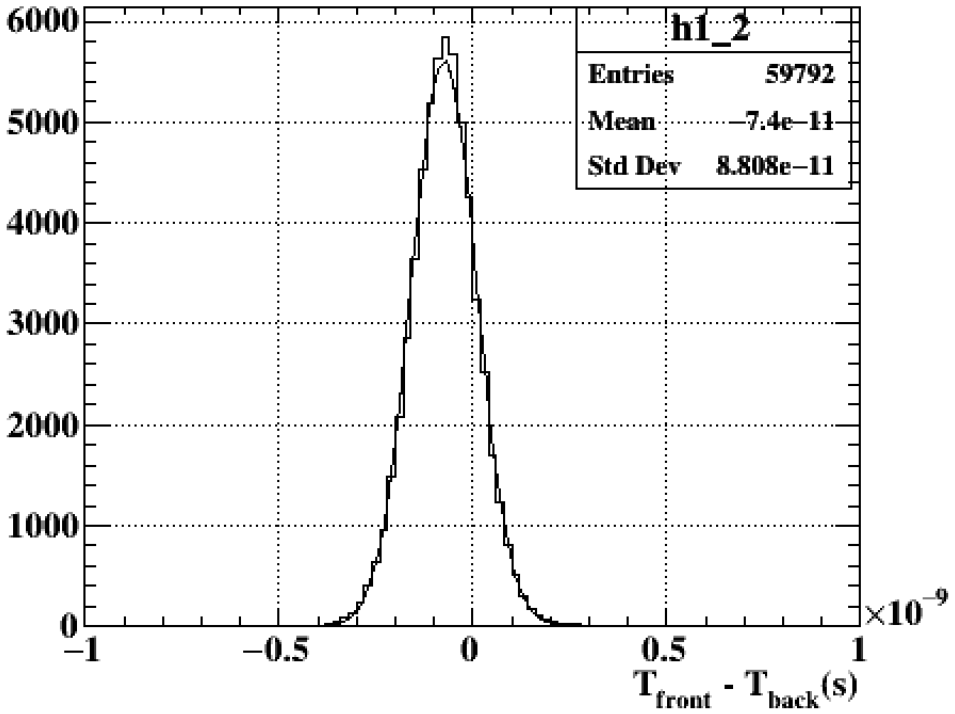




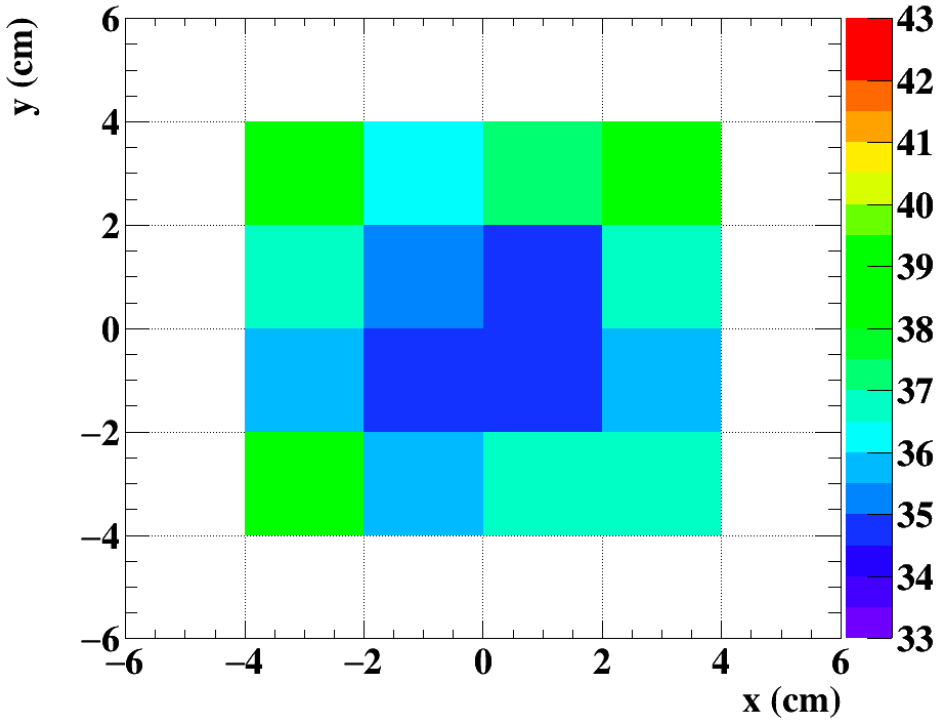
- The pre-shower counter consists of two plastic scintillators readout by 16 SiPMs (8 SiPMs × 2 sides) respectively.
- The two scintillators were placed orthogonally in the front of the BGO calorimeter.
- A Pb converter with 4 mm thickness was placed in the front to convert γ-rays.

Pre-shower Timing Resolution

Time Difference between Two Plates



Position Dependence of Timing Resolution

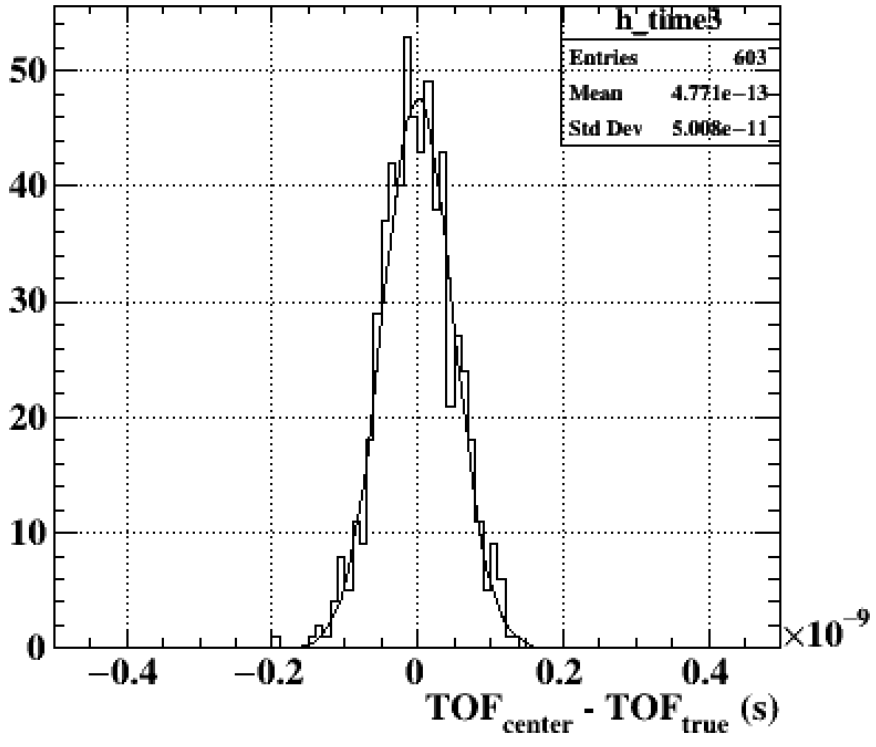


- Time resolution can be evaluated by time difference of two plates.
- Overall time resolution: ~36.8 ps.
- Position dependence is smaller than 5 ps in the 40×40 mm^2 analysis region.

Uncertainty from Vertex

- TOF is corrected assuming π_0 decays at the vertex center.
  $\leftrightarrow$ The vertex distributes with a certain width.
- The contribution from the vertex uncertainty can be estimated using MC.
- The estimation was done calculated based on the measured beam profile:
  - vertex center: (x, y, z) = (0, 0, 6.8 cm)
  - vertex size: (σ_x, σ_y, σ_z) = (7.6 mm, 6.8 mm, 10 mm)
- The uncertainty is 48.4 ± 1.6 ps.

Uncertainty from TOF Estimation



Timing Reconstruction of LXe

The timing of γ hit, t_γ, is reconstructed with χ^2 minimization fit:

$$\chi^2 = \sum_{\mathrm{pm}} \frac{(t_{\mathrm{pm}} - t_{\mathrm{corr}} - t_\gamma)^2}{\sigma_{\mathrm{pm}}^2}$$

$$t_{\mathrm{corr}} = t_{\mathrm{prop}} + t_{\mathrm{walk}} + t_{\mathrm{offset}}$$

t_{pm} : the extracted timing of each photosensor

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

t_{walk} : the time walk effect

t_{offset} : the time offset from electronics and cable length

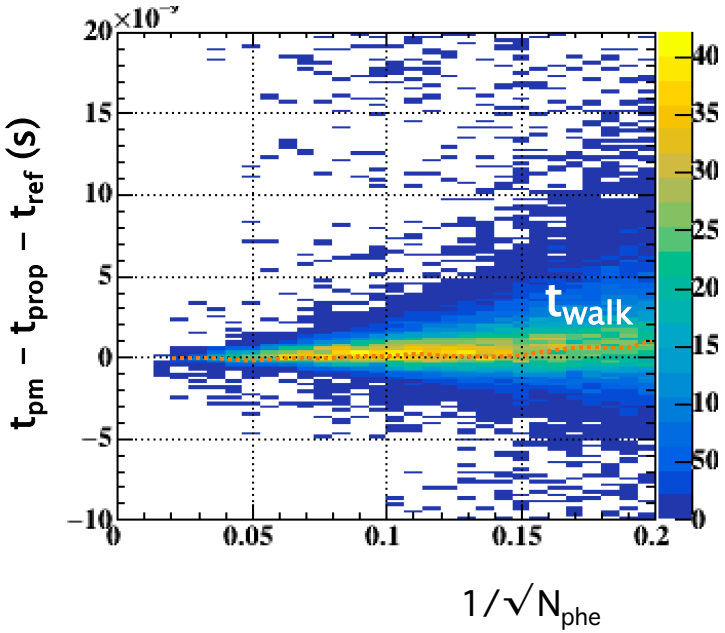
σ_{pm} : the timing resolution of each photosensor

Timing Calibration

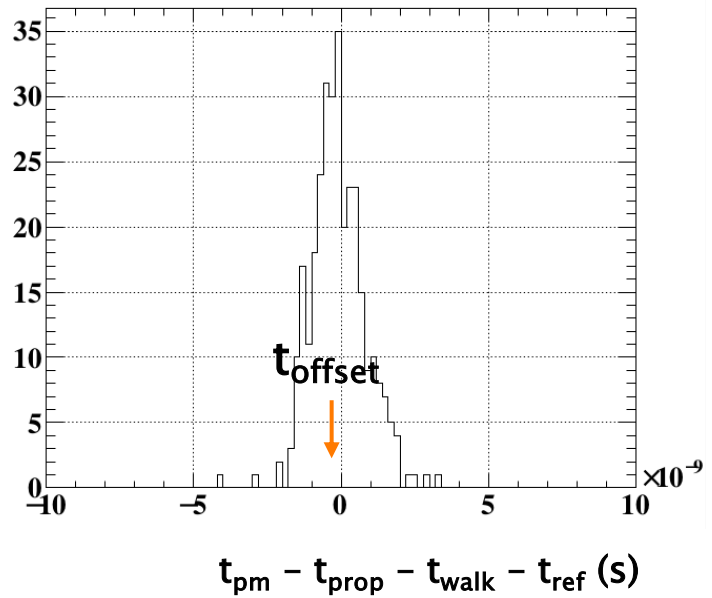
The correction parameters are estimated beforehand using the timing of the pre-shower counter as reference.

1. The time walk effect was extracted from the time difference of $\mathbf{t_{pm} - t_{prop} - t_{ref}}$ as a function of $1/\sqrt{N_{phe}}$. (N_{phe} : the number of photoelectrons)
2. The time offset t_{offset} was defined by the mean of the time difference of $\mathbf{t_{pm} - t_{prop} - t_{walk} - t_{ref}}$.
3. The channel timing resolution was defined by the uncertainty of the time difference of $\mathbf{t_{pm} - t_{prop} - t_{walk} - t_{offset} - t_{ref}}$ as a function of $1/\sqrt{N_{phe}}$.

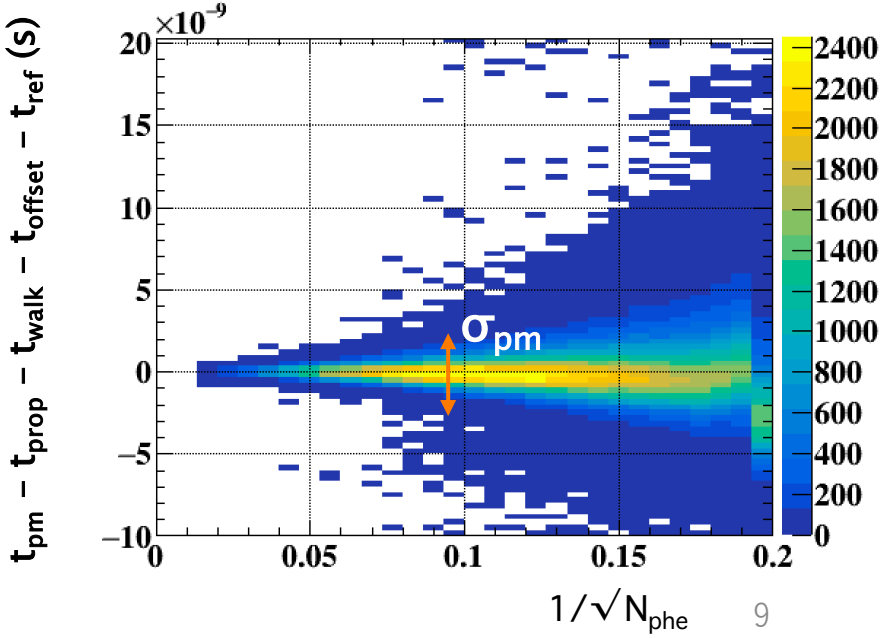
Extraction of Time Walk



Extraction of Time Offset

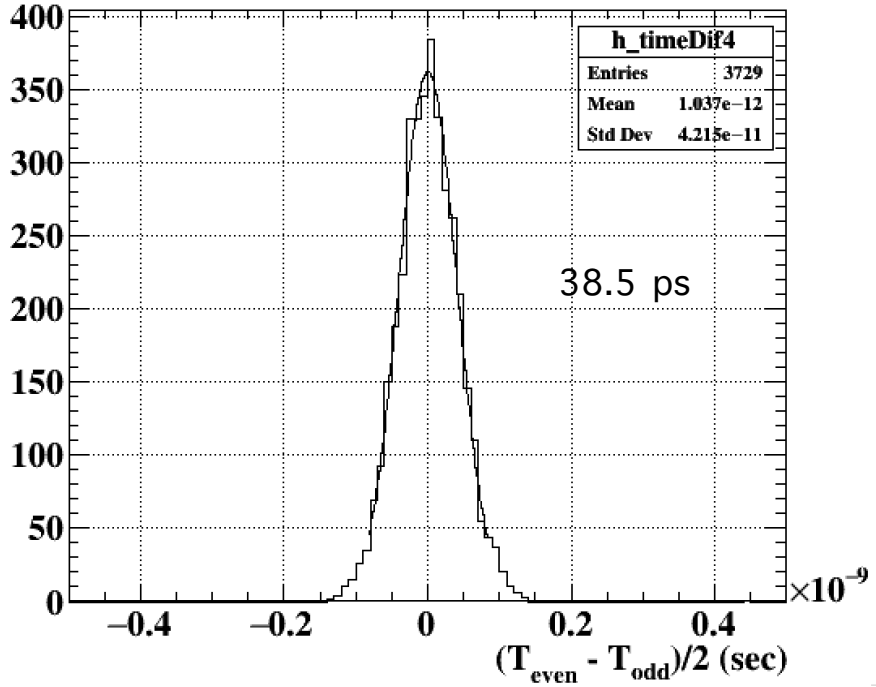


Extraction of Channel Resolution

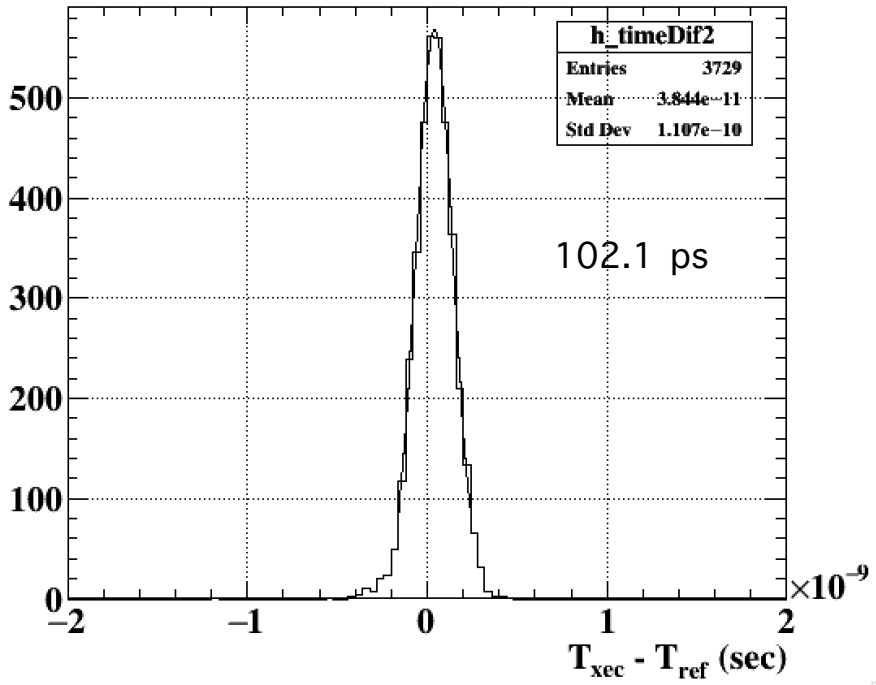


Timing Resolution @ 55 MeV

Intrinsic Resolution



Absolute Resolution



- The intrinsic timing resolution was 38.5 ps, which is consistent with the previous result.
- The absolute timing resolution was 82.0 ps after subtracting $\sigma_{\mathrm{ref}} = \sigma_{\mathrm{ps}} \oplus \sigma_{\mathrm{vertex}}$ = 36.8 ps $\oplus$ 48.4 ps.

Discrepancy of Timing Resolution

- The absolute timing resolution can be worse than the intrinsic resolution because some effects can be reduced by the even-odd subtraction:
  - Error from position reconstruction
  - Spread of shower
  - Coherence of electronics such as noise and synchronization
- The difference between the absolute and intrinsic resolution can be 42.5 ps according to MC.
  ↔ 72.4 ps for data

Timing Resolution (E_γ = 55 MeV)

	Intrinsic	Absolute	Absolute ⊖ Intrinsic
Data	38.5 ps	82.0 ps	72.4 ps
MC	38.4 ps	57.3 ps	42.5 ps

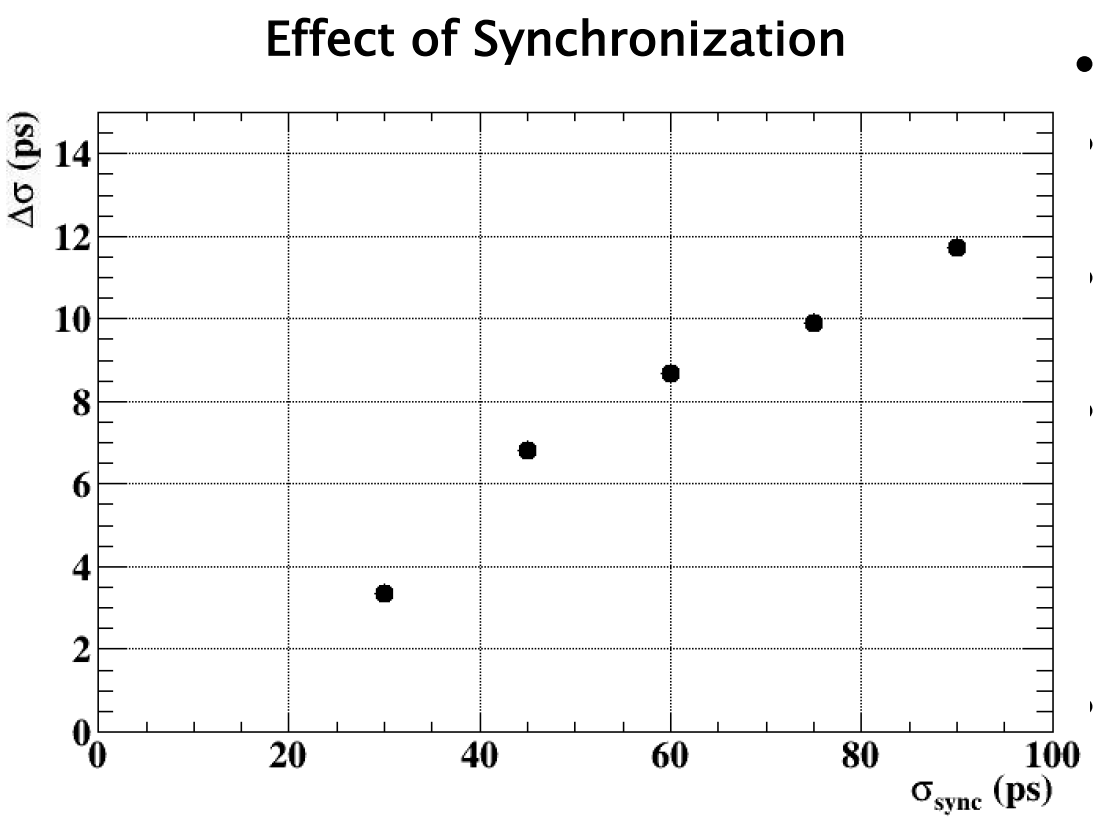
Possible Cause of the Discrepancy

The cause of the discrepancy is under investigation.

1. Some effects are erased by even-odd subtraction.
   - Electronics noise, synchronization, calibration
   - Bias from analysis

2. Some effects are added to the absolute timing resolution.
   - Vertex uncertainty
     - If the size of vertex is larger than expected, the uncertainty of vertex becomes larger.
     - $(\sigma_x, \sigma_y, \sigma_z)$ = (7.6 mm, 6.8 mm, 10 mm) → (11 mm, 11 mm, 10 mm), for example
   - Timing resolution of pre-shower counter
     - Not likely because the timing resolution is consistent b/w Sr90 and γ results.

Effect of Synchronization



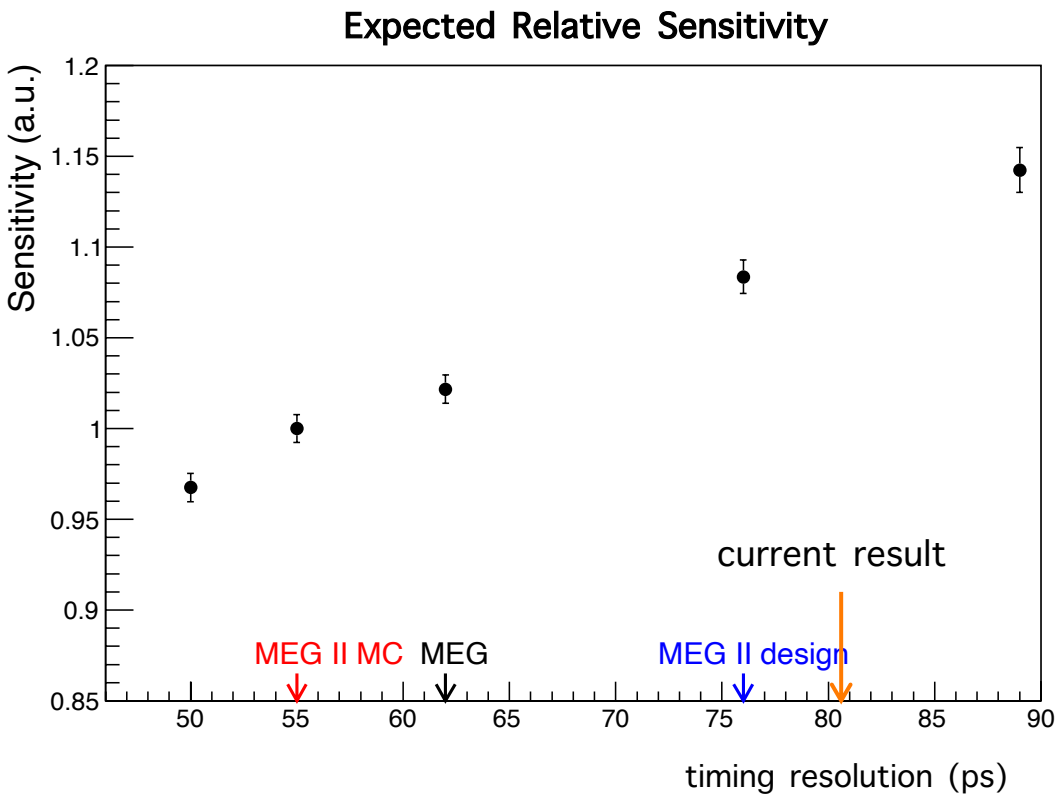
- The 8 channels are readout with one electronics' chip.
- The chips are synchronized using clock waveforms.
- The precision of synchronization b/w two chips was measured to be σ_{sync} ~45 ps.
- In addition, the precision of timing calibration of electronics within one chip was measured to be σ_{calib} ~25 ps.
- To estimate the effect of synchronization, the timing was reconstructed adding the fluctuations to MC:

$$t_{pm,\ sync} = t_{pm,\ truth} + \mathrm{Gaus}(t_{chip},\ (\sigma_{sync} \ominus \sigma_{calib})/\sqrt{2})$$

$$t_{chip} = \mathrm{Gaus}(0,\ \sigma_{calib}/\sqrt{2})$$

- The resolution gets worse as the precision of synchronization gets worse.
- The effect can be ~7 ps (@ σ_{sync} ~ 45 ps).
  → small effect: 82.0 ps → 81.7 ps

Expected Sensitivity



- The current absolute timing resolution is ~81.7 ps, which is worse than that of MC.
- The worse timing resolution can deteriorate the sensitivity by ~10%.

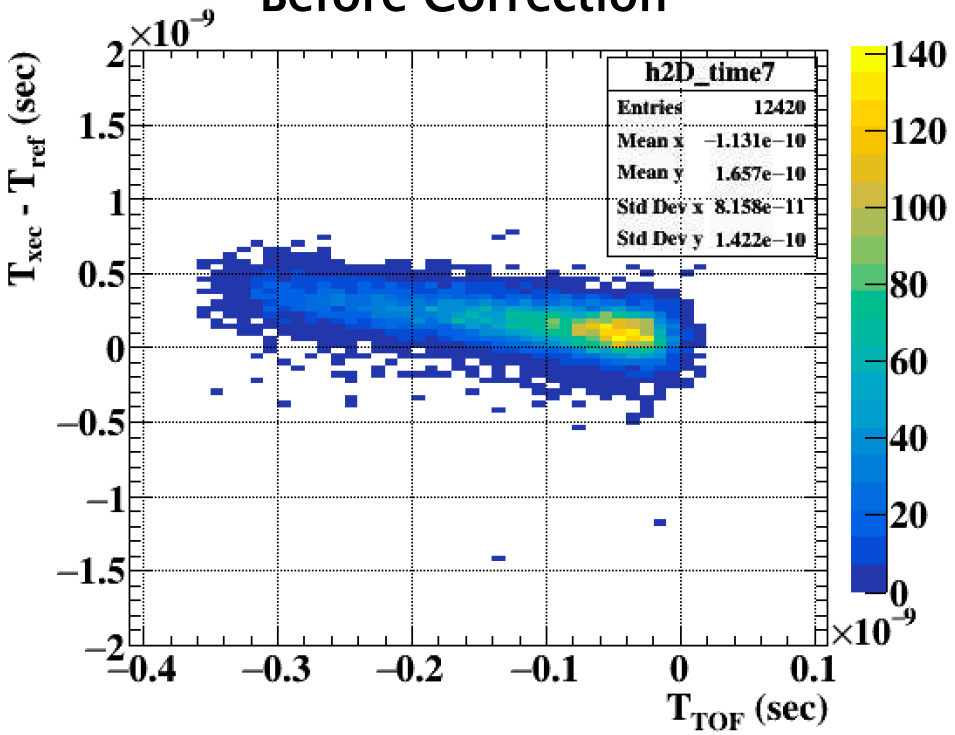
Summary

- CEX DAQ was performed in 2020.
- The timing resolution of LXe was evaluated to be
  - Absolute: 81.7 ps
  - Intrinsic: 38.5 ps
- The absolute timing resolution was worse than expected.
- The cause of the discrepancy is under investigation.
- If the resolution cannot be improved, it can deteriorate the sensitivity by ~10%.

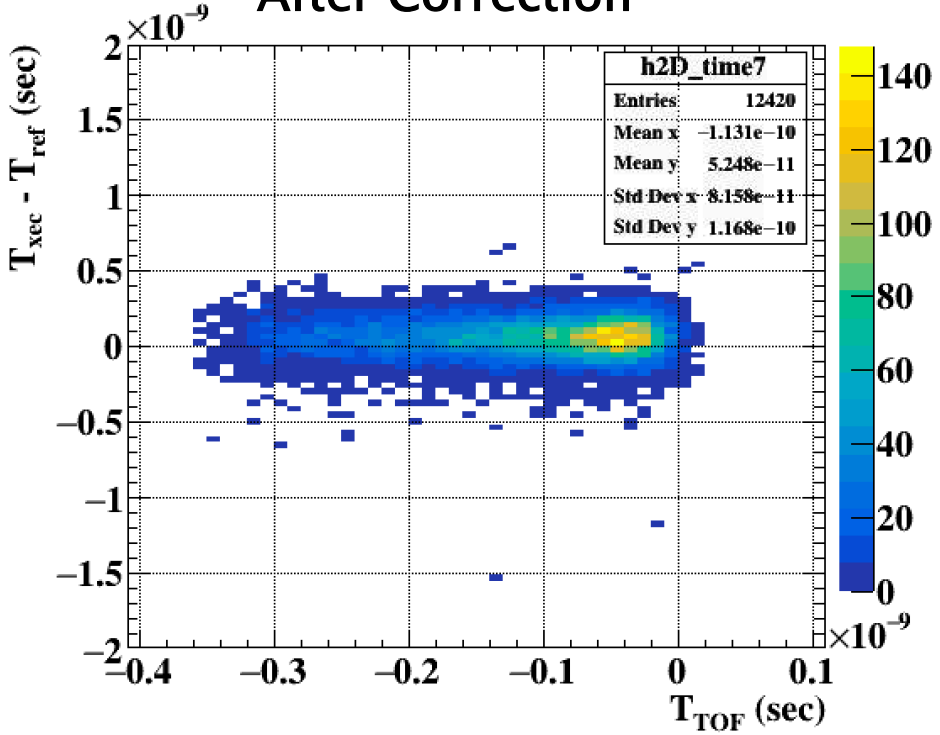
Backup Slides

TOF Correction

Before Correction

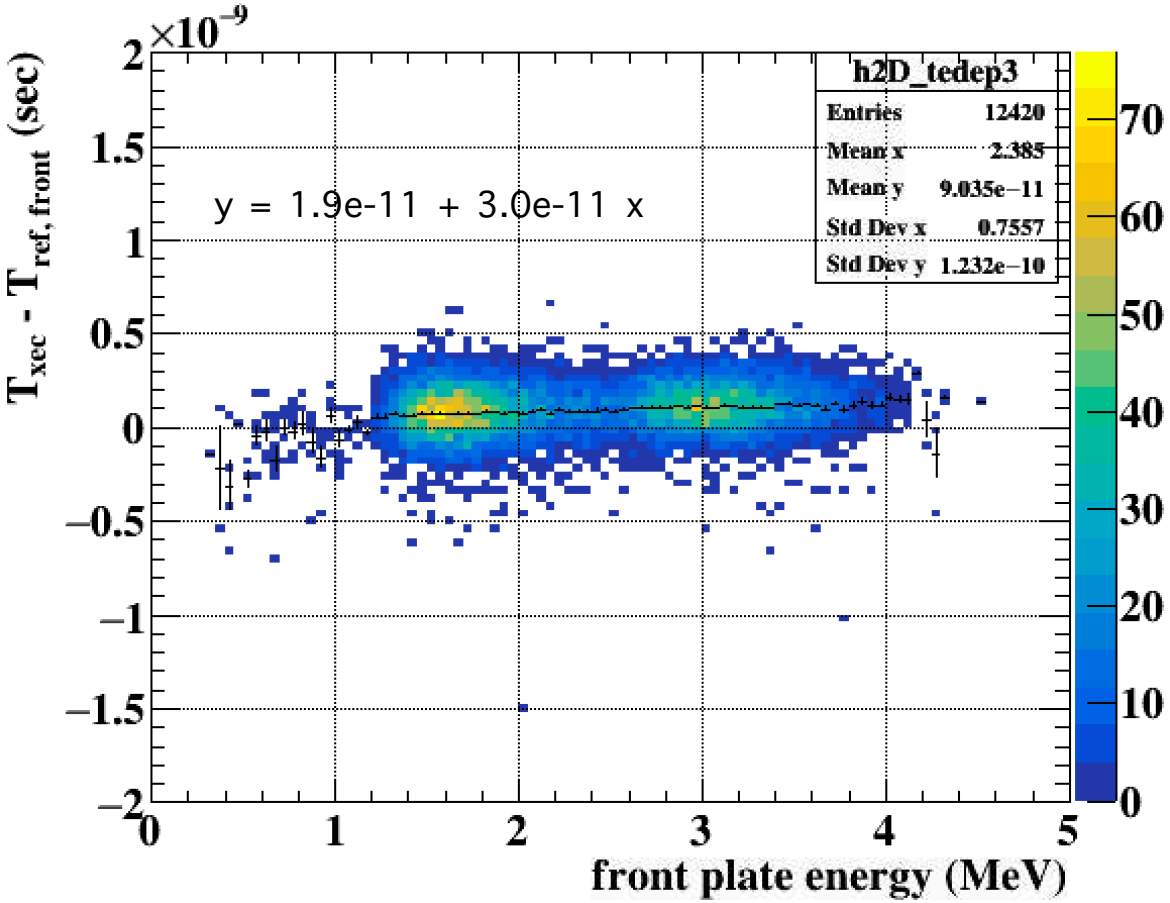


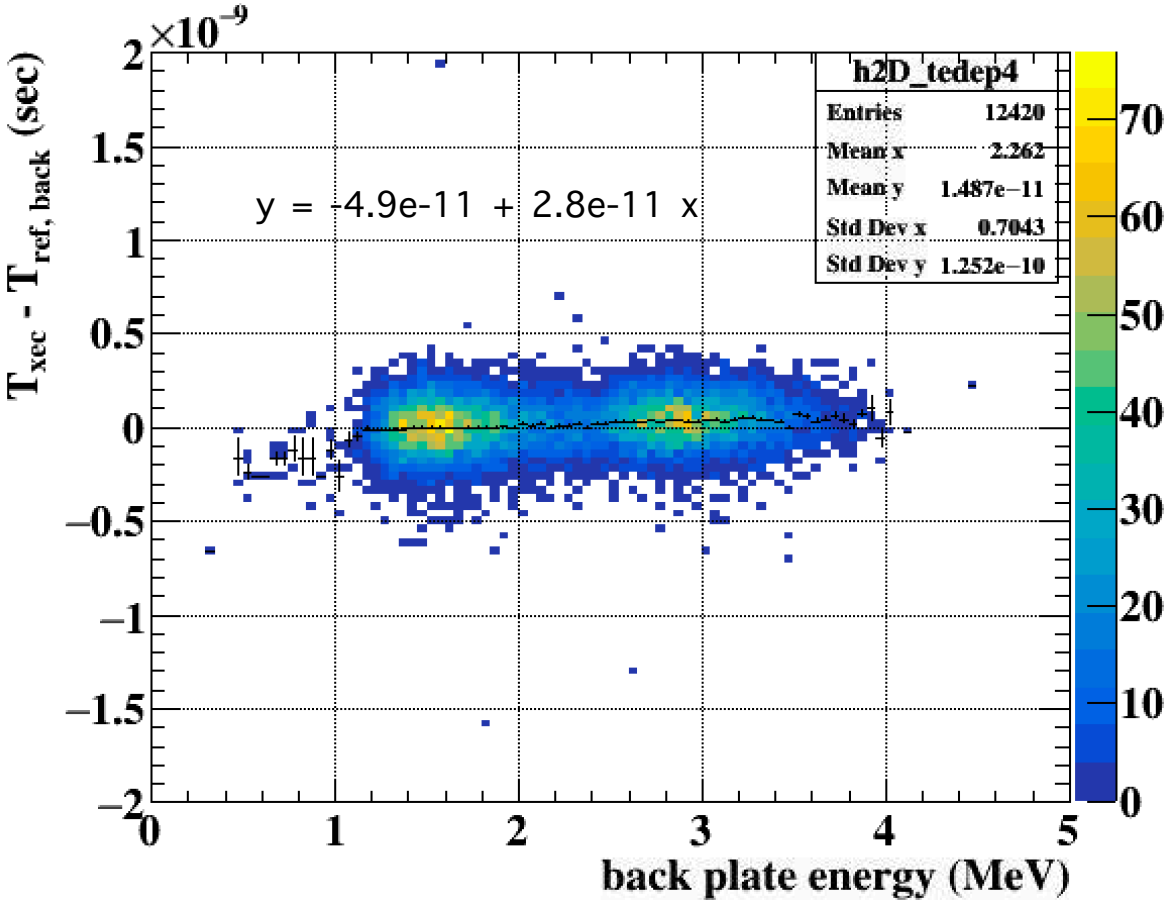
After Correction



- The time of flight was calculated using the reconstructed hit positions of LXe and the pre-shower counter.
- The vertex is assumed to be the beam center.

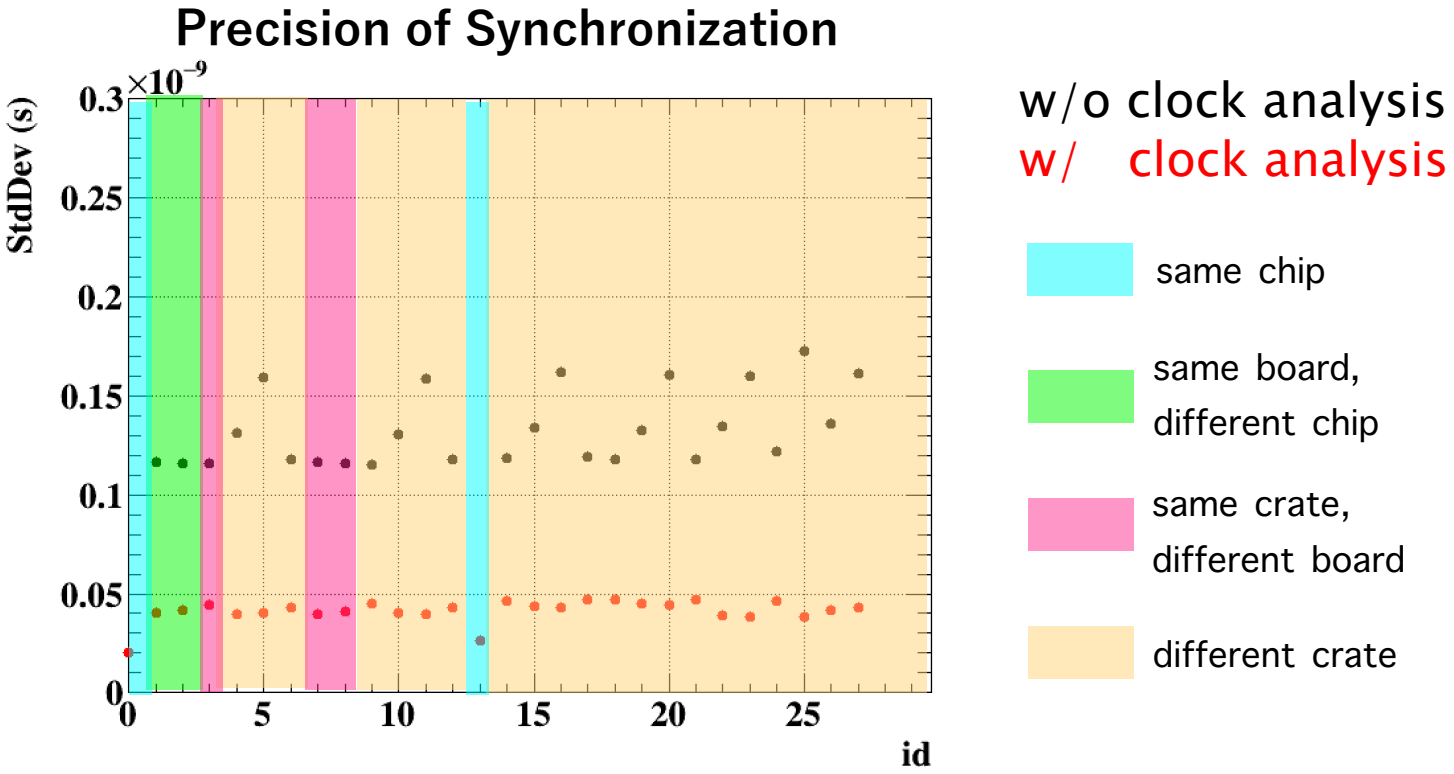
Time Walk of Pre-shower





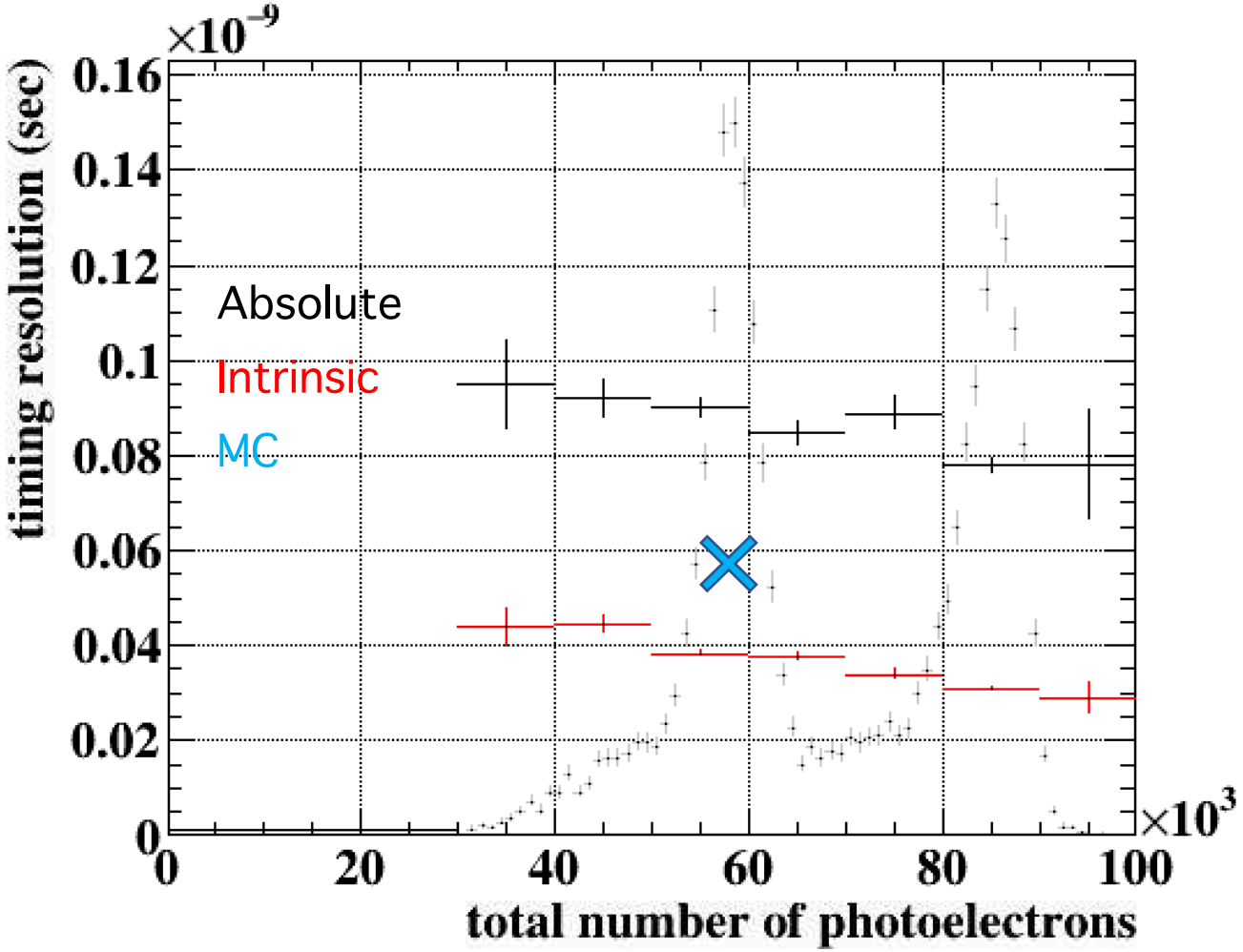
The dependence was subtracted.

Synchronization of Electronics



- Signals generated with a function generator were divided and input to 8 channels on several chips.
- The precision of synchronization can be calculated by StdDev of time difference of two channels.
- After clock analysis, the precisions of synchronization became 40-50 ps.
- Synchronization works well.

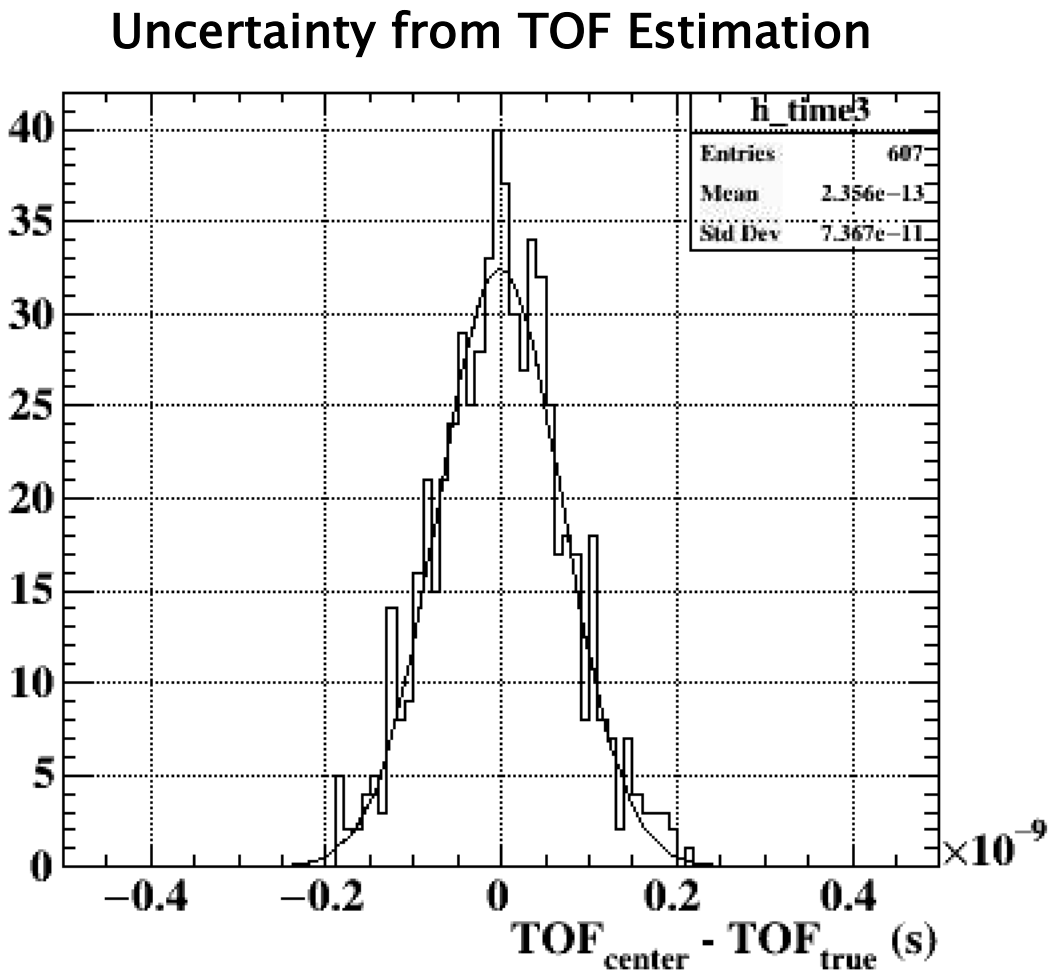
Energy Dependence



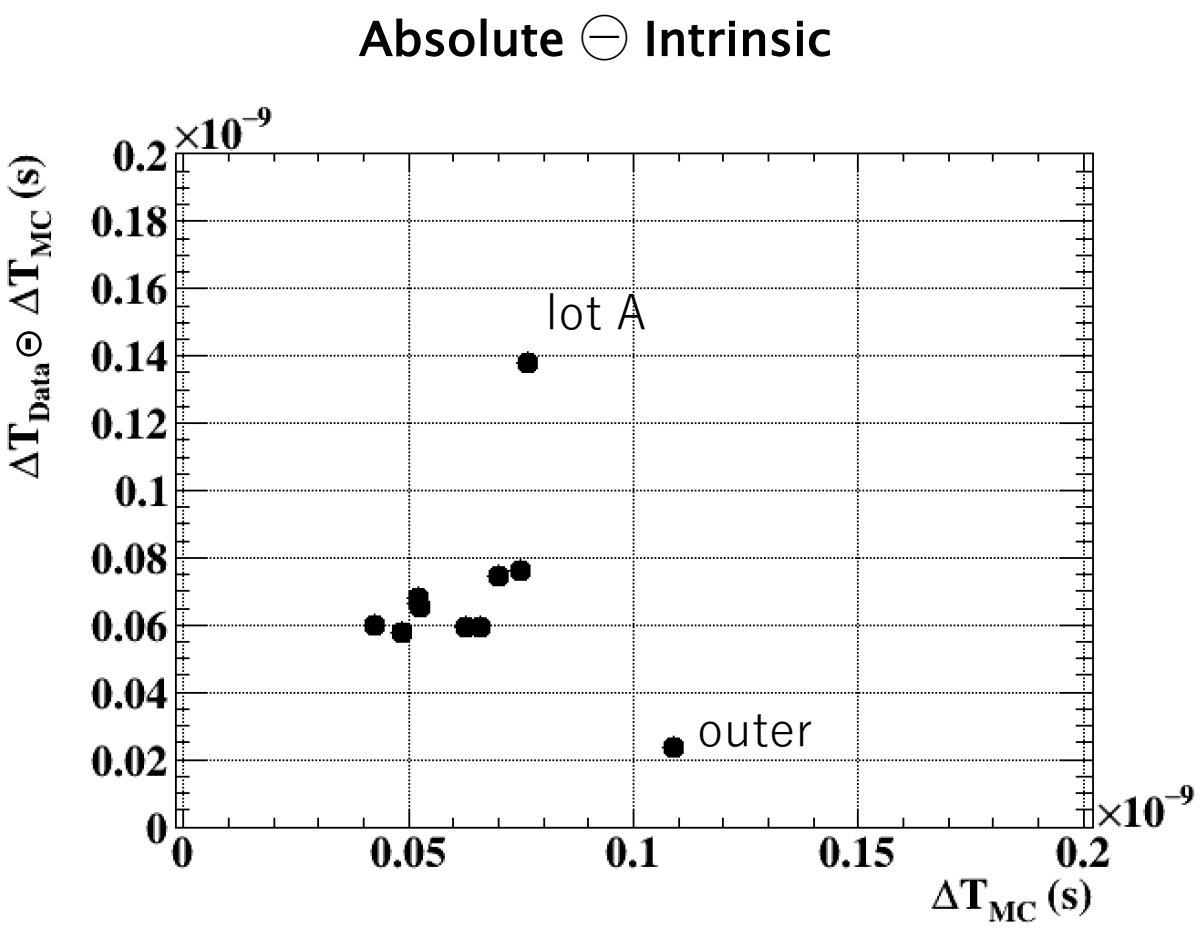
- The timing resolution improves as the number of photoelectrons increases.
- The improvement of the absolute timing resolution is limited.

Uncertainty from Vertex

- The contribution from the vertex uncertainty can be estimated using MC.
- It was estimated to be 58 $\pm$ 2 ps in MEG.
  - (x, y, z) = (0, 0, 0)
  - (σ_x, σ_y, σ_z) = (1 cm, 1 cm, 1 cm)
- The estimation was done with the configuration of this year.
  - (x, y, z) = (0, 0, 6.8 cm)
  - (σ_x, σ_y, σ_z) = (1.1 cm, 1.1 cm, 1 cm)
- The uncertainty is 70.8 $\pm$ 2.7 ps.



Absolute ⊖ Intrinsic



- We have seen the difference b/w the absolute and intrinsic timing resolutions is not constant both for data and MC.
- The difference of data is consistently larger by ~60 ps except for lot A, lot C and outer.