次世代$\mu^+ \to e^+\gamma$崩壊探索実験のための光子ペアスペクトロメーターの開発

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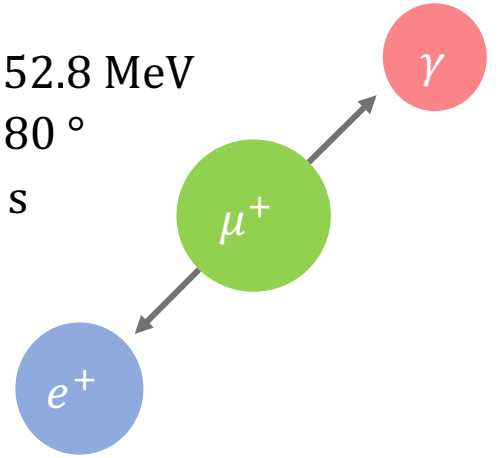
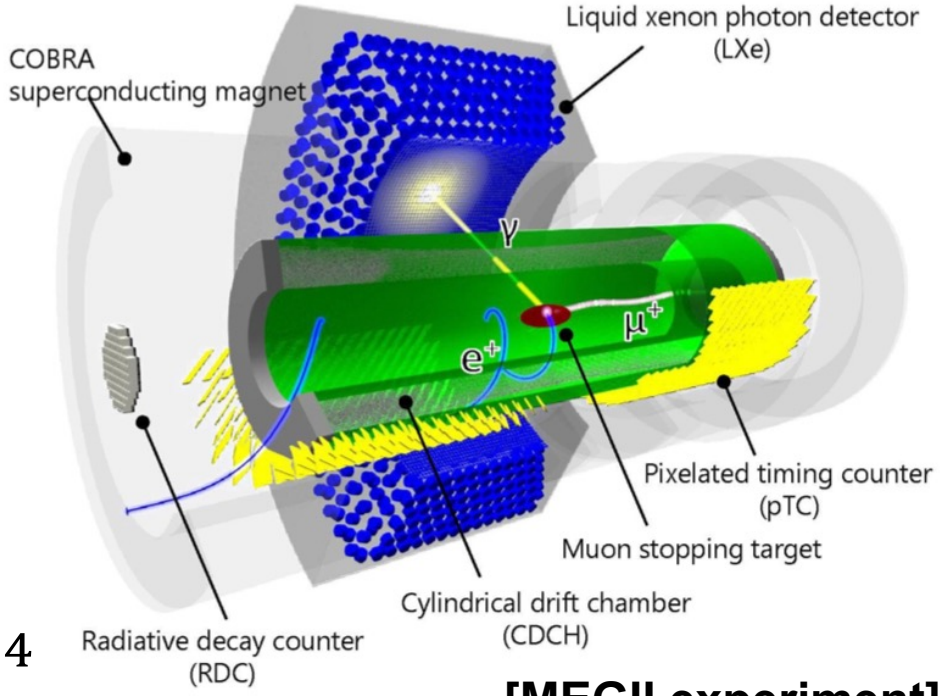
$\mu \rightarrow e\,\gamma$ Decay

$E_\gamma, E_e \sim 52.8\ \mathrm{MeV}$
$\theta_{\gamma,e} = 180\,°$
$t_{\gamma,e} = 0\ \mathrm{s}$



- Charged lepton flavor violation
  → strong evidence for BSM
- Characteristics of decay
  - same monochrome energy: $E_\gamma, E_e \sim 52.8\ \mathrm{MeV}$
  - back-to-back
  - same timing



[MEGII experiment]

- MEG II is searching for $\mu \rightarrow e\,\gamma$ decay at Paul Scherrer Institute (PSI)

Target sensitivity : $\mathbf{BR}_{\mu \rightarrow e\,\gamma} = 6\times10^{-14}$

New experiment for $\mu \rightarrow e\,\gamma$

- High-intensity muon beam is planned at PSI (2027-2028)

  → 100 times higher intensity ~ 10^{10} μ/s

  → New concept experiment

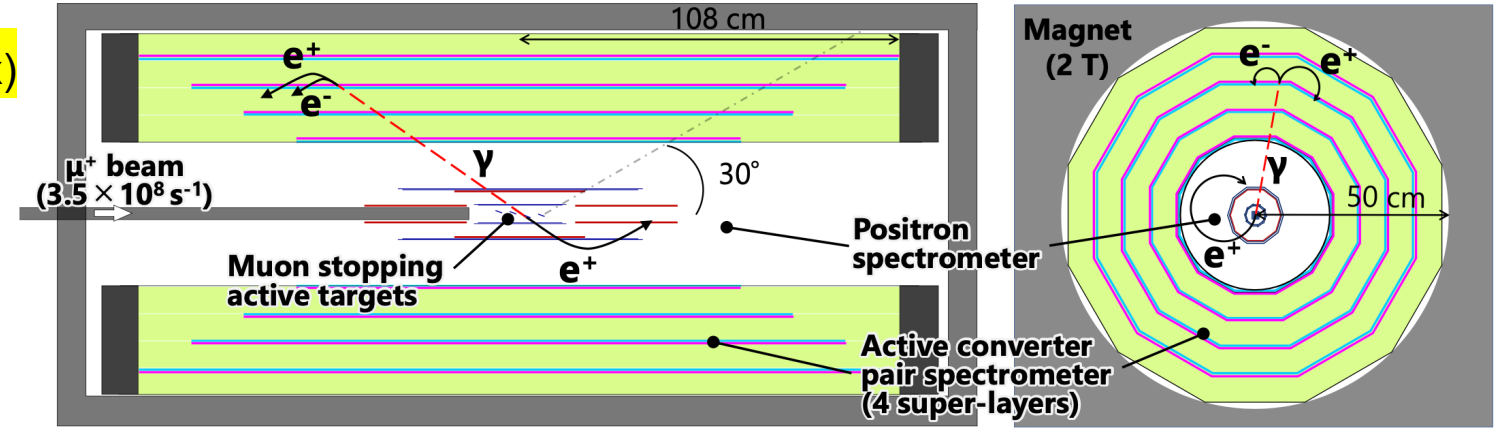
    ▪ high resolution and high rate capability

1. **Photon pair spectrometer**
   → higher resolutions (Δ E, Δ t, Δ x)

   angle measurement

2. **Positron spectrometer**
   → high rate capability

3. **Separate active targets**
   → higher vertex resolution, further BG suppression



[Concept of the new experiment]

⟹**Target sensitivity: BR** $_{\mu \rightarrow e\,\gamma} = \mathcal{O}\left(10^{-15}\right)$

Pair spectrometer with active converter

- Pair spectrometer for γ-ray measurement
  - **Advantages**

    High resolutions (energy, position)
    Direction of γ can be measured

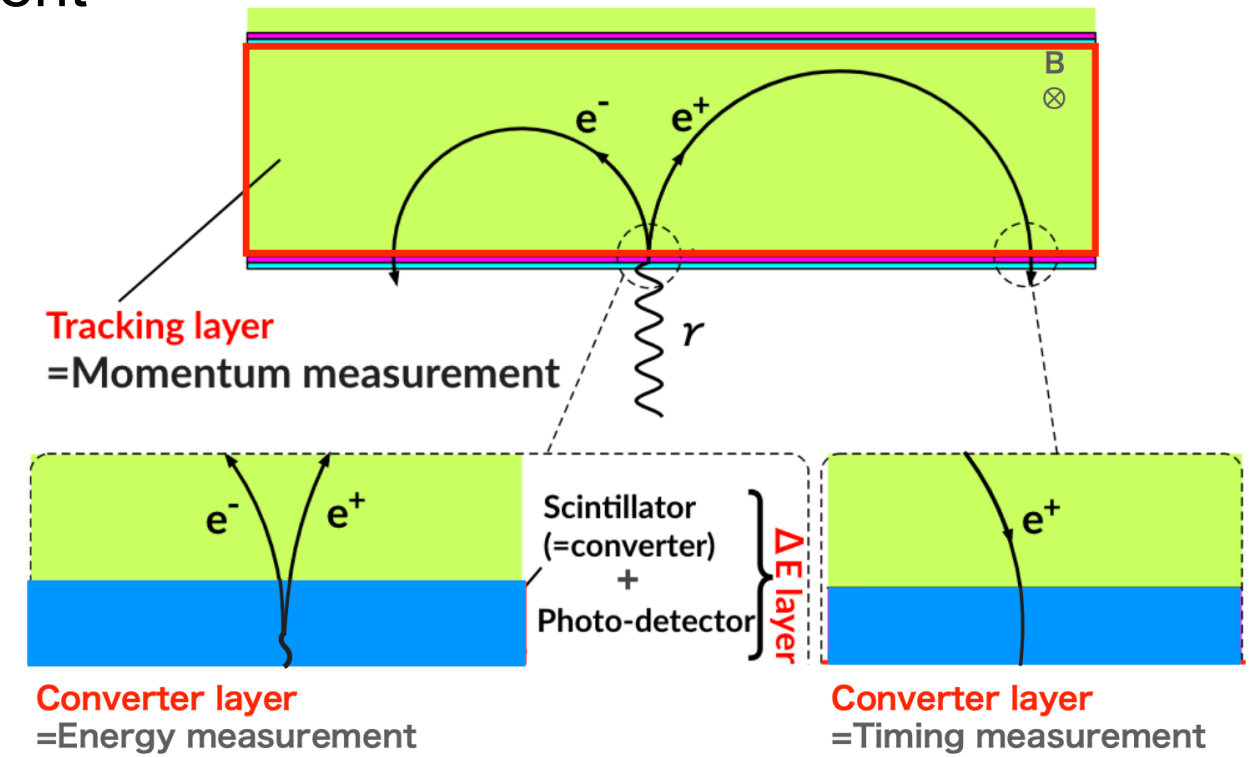
  - **Difficulty**

    Energy loss in convertor: invisible

    Low efficiency

→ active converter

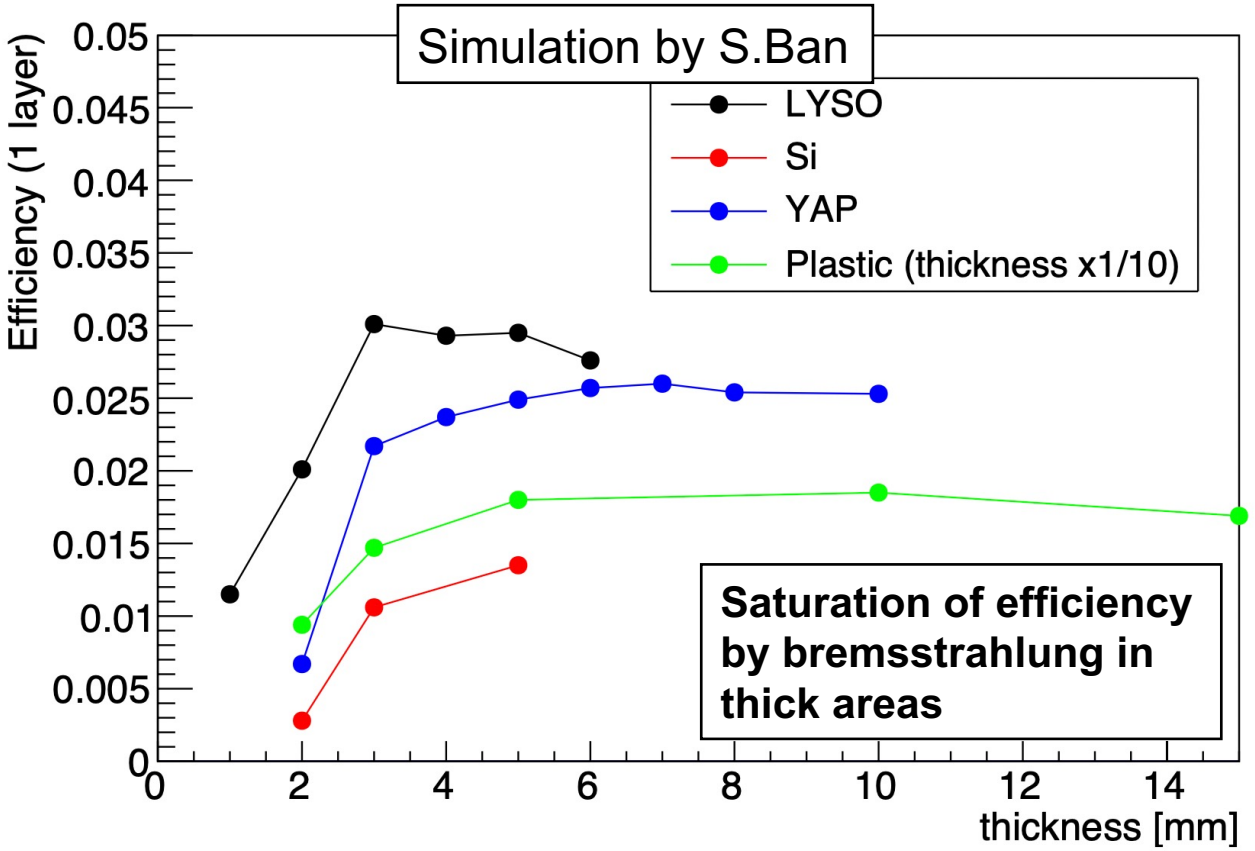
- Measure energy loss in convertor
- Measure timing



- Candidate technology for tracking layer

  TPC(Time projection chamber), Drift chamber

LYSO as active material



[LYSO]

Density [g/cm^3]	7.2
Light Yields [rel. to NaI]	75%
Emission Peak [nm]	420
Decay time [ns]	40
Radiation Length [cm]	1.1
Critical Energy [MeV]	12
Hygroscopicity	None

- High light yields → Good energy resolution
- Fast response → Good timing resolution

Requirements for active converter

Active converter = LYSO crystal as active material + SiPM as photo-sensor

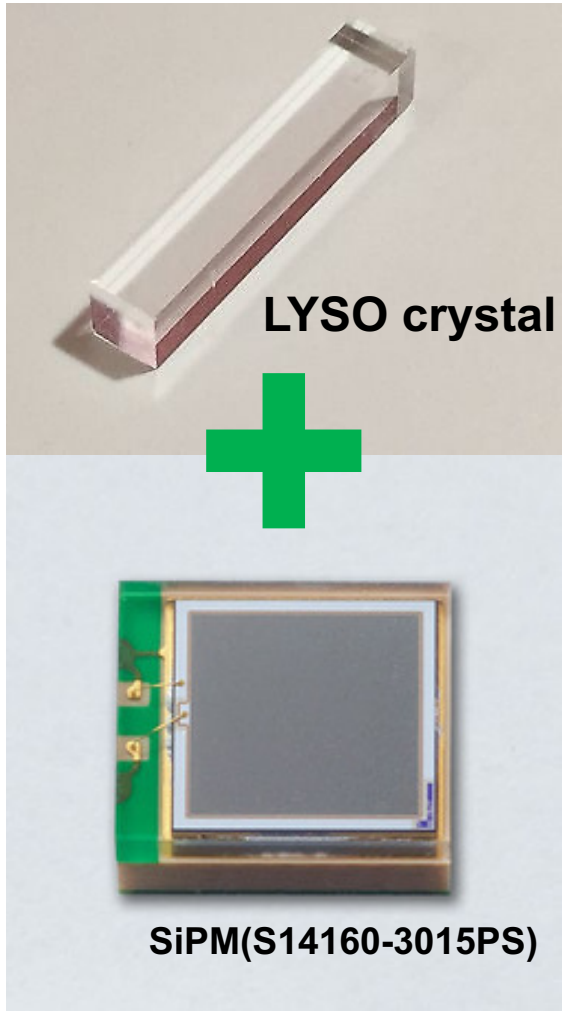
- Energy measurement
  - Target resolution : ΔE/E= 0.4% for 52.8MeV γ → ΔE~200keV
  - Maximum energy loss in 3mm-thick LYSO ~ 6.72MeV

  → Requirement for energy resolution at LYSO ~200keV/6.72MeV ~3%
  (ignoring tracker resolution)

  → Requirement for photoelectron statistics ~560 p.e. for 1MIP
  (if 1.5mm, the required p.e. number is ~140 for 1MIP)
- Time measurement

  Δ t = 30ps, by measuring timing of e- and e+ independently

  → 40ps for 1 MIP
- What we want to study
  1. Number of p.e for 1 MIP
  2. Time resolution for 1 MIP



Previous study

- Energy measurement (In KEK)

Detected photons (3x5x50mm LYSO + SiPM)

: ~ 2000p.e.

→ **Photoelectron statistics are sufficient**

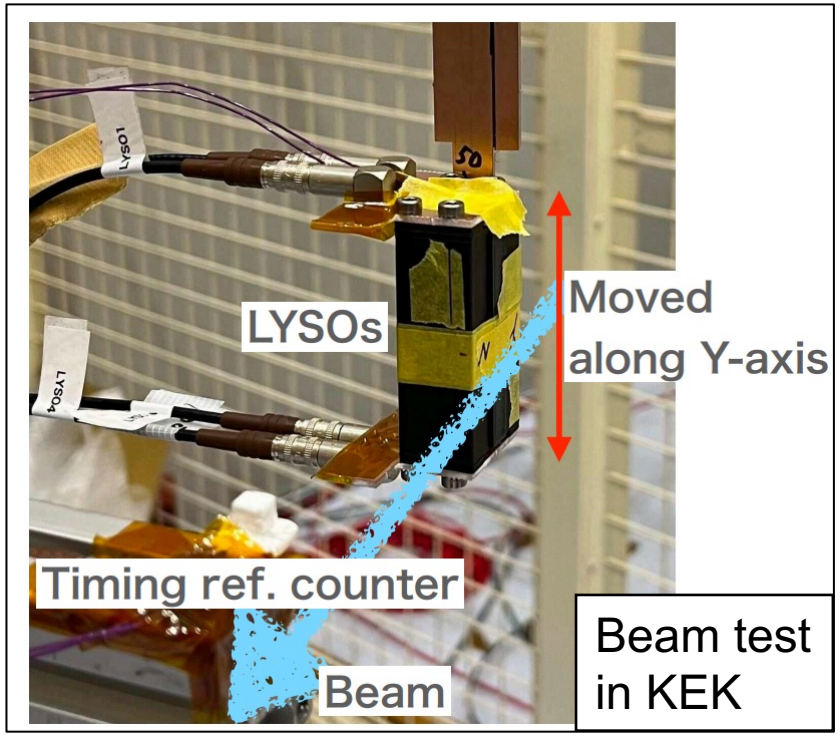
F.Ikeda (2022 Autumn JPS)

- Timing measurement (In KEK)

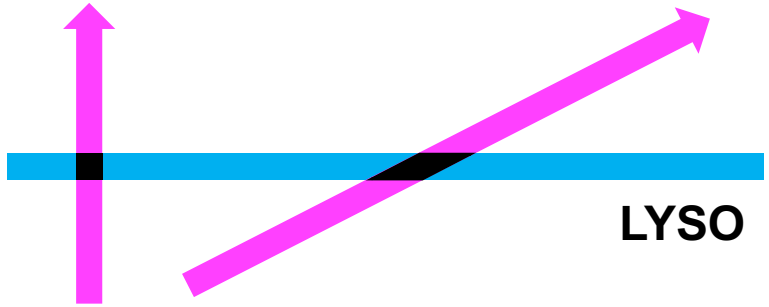
Good timing resolution: 40-50 ps (3x5x50mm LYSO + SiPM)

→ **Preliminary, but it looks promising**

F.Ikeda (2023 Spring JPS)



Motivation of this study



- **Time measurement performance for LYSO of different sizes** using MIP

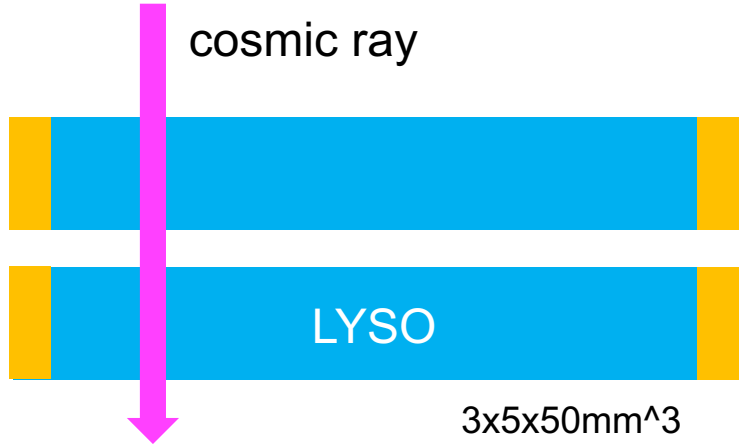
1. Thinner LYSO
   - Need to use thinner LYSO at outer region
   - Possibility to use even thinner LYSO to mitigate worsening of angular resolution due to multiple scattering
2. Longer LYSO
   - To reduce the number of readout channels

[Different LYSO samples]
Thickness: 1.5 and 3 [mm]
Width: 10 and 5 [mm]
Length: 50 and 100 [mm]
Type: normal and fast

→ **Study light yield, timing performance, position dependence**

Setup

※No trigger counter is used.
Incident position and angle are random.



Due to time constraints, cosmic rays are used as MIP instead of KEK's beam in the university lab.

- LYSO

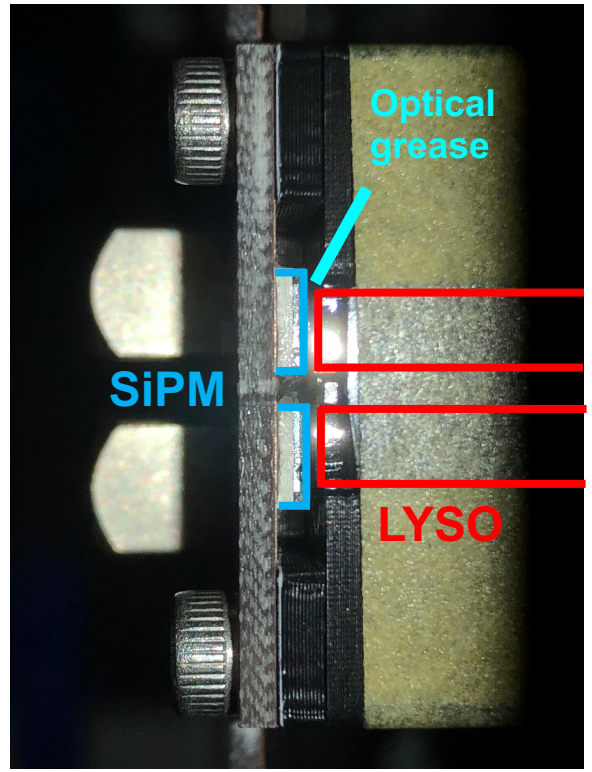
  Fast-type (FTRL-Suzhou JT Crystal)
  Wrapped by Reflector (ESR)

- Readout

  SiPM: both sides of LYSO's length

  - S14160-3015PS (Photosensitive area: 3x3mm, pixel pitch: 15um)

  Using Amplifier and Waveform digitizer



LYSO TYPE	THICKNESS [mm]	WIDTH [mm]	LENGTH [mm]
3x5x50	3.0	5.0	50
Thinner	1.5	5.0	50
Longer	3.0	5.0	100

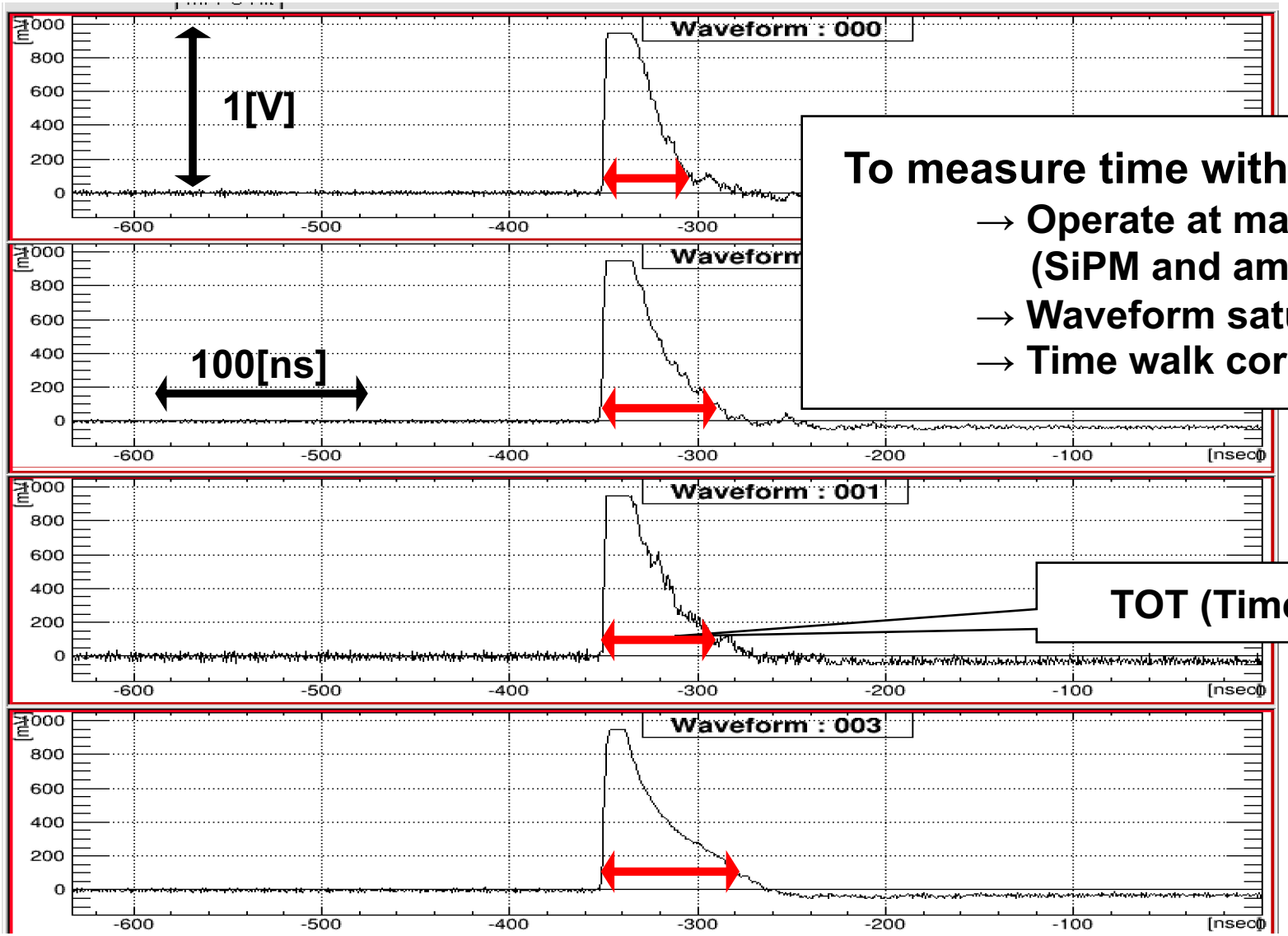
Waveform

LYSO1 side a

LYSO1 side b

LYSO2 side a

LYSO2 side b



To measure time with early-arrival photons

→ Operate at maximal signal gain (SiPM and amplifier)

→ Waveform saturated

→ Time walk correction by TOT

TOT (Time over threshold)

Analysis

- Time pickup: **leading-edge method (LE)**

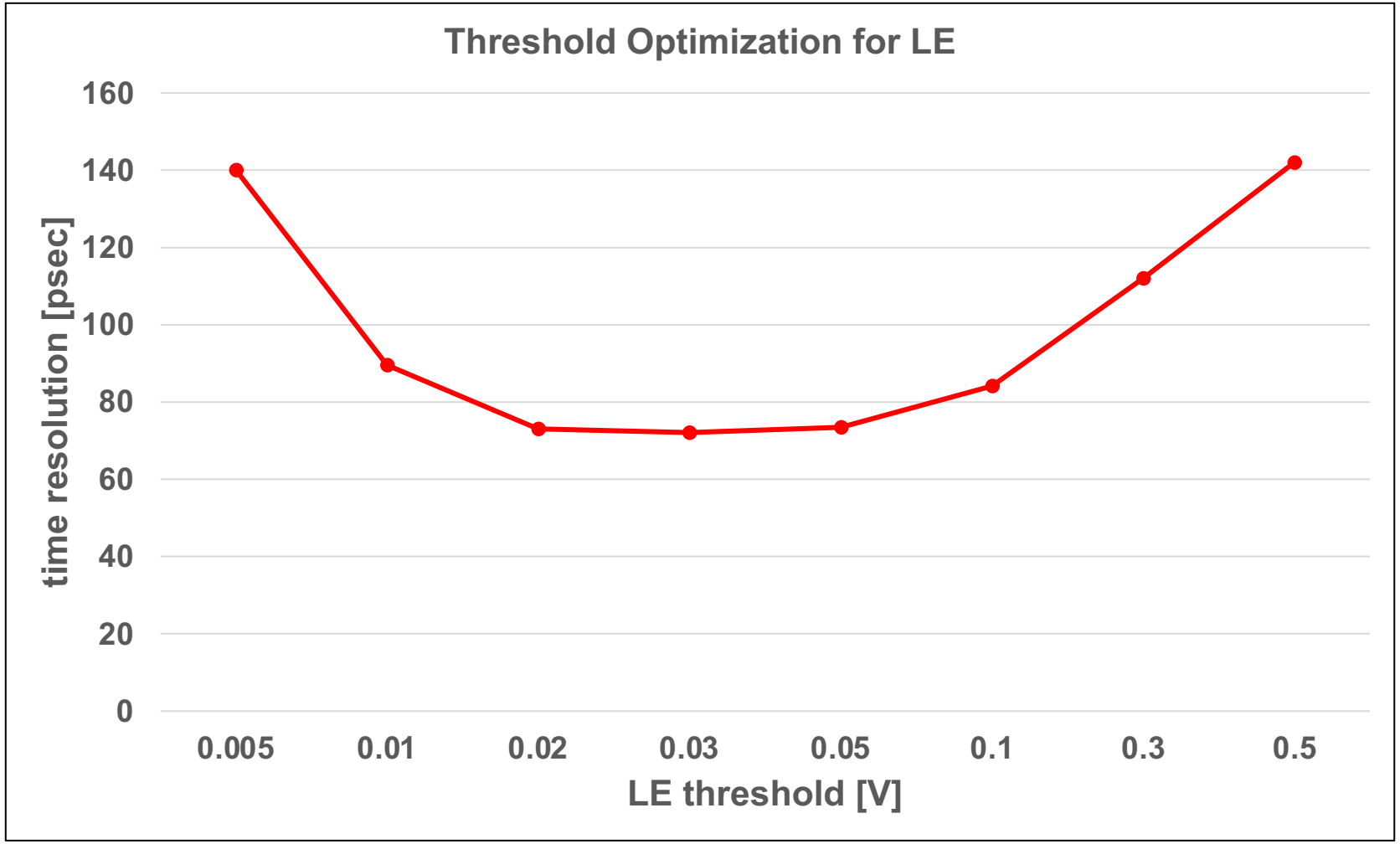
  Threshold for LE is optimized
- Time-walk correction: **Using TOT**

- Time resolution can be calculated from

$$\frac{1}{\sqrt{2}}\sigma\left(\frac{t_{LYSO1a}+t_{LYSO1b}}{2}-\frac{t_{LYSO2a}+t_{LYSO2b}}{2}\right)$$

※Assume LYSO1 and 2 have the same time resolution

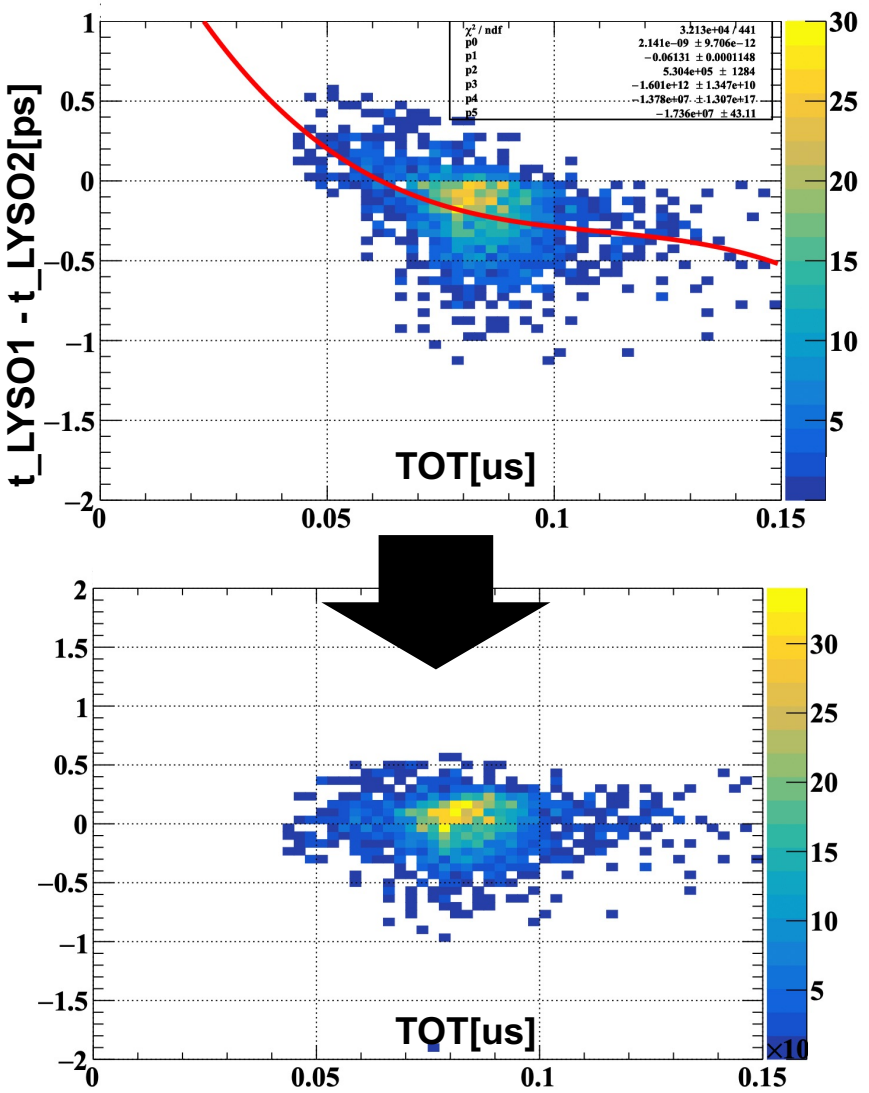
Threshold optimization for LE

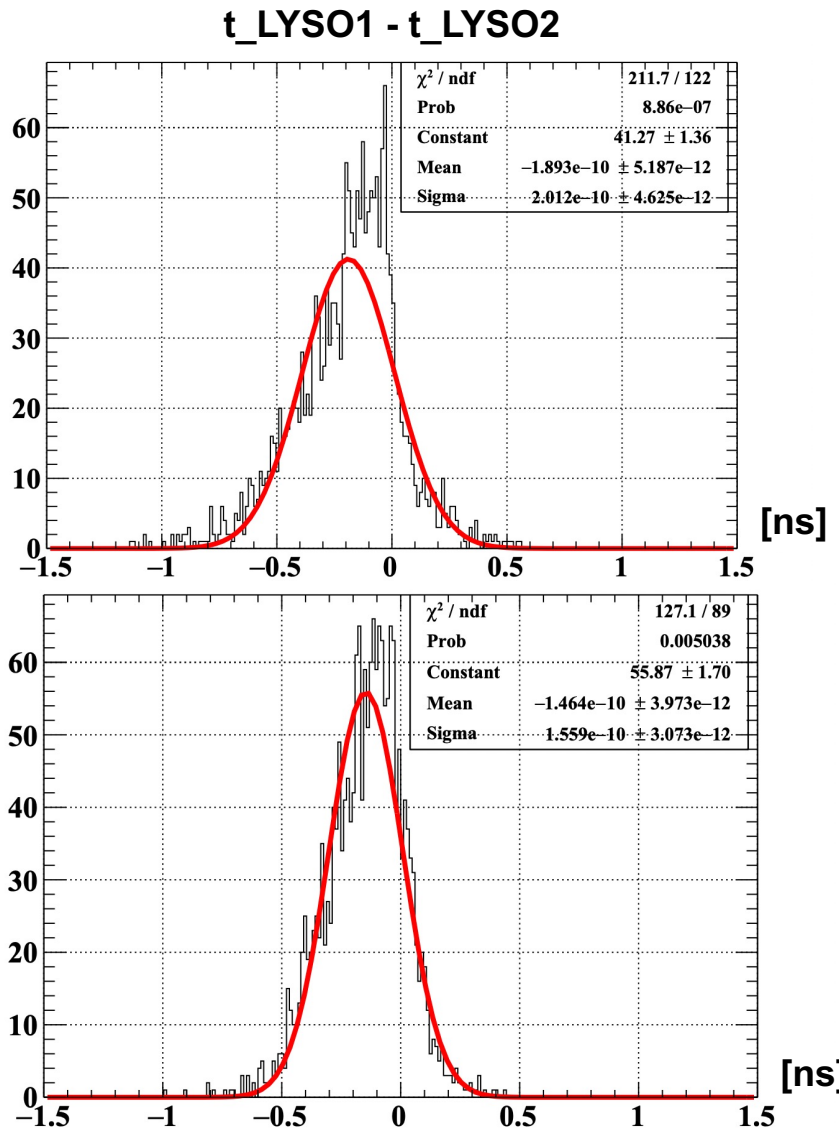


[3x5x50 type]

Time-walk correction by TOT

- Fit: 5th order polynomial for the distribution of $t_{SiPM1} - t_{SiPM2}$ vs TOT





Results

LYSO TYPE	THICKNESS [mm]	WIDTH [mm]	LENGTH [mm]	Time resolution [psec]	Number of p.e(MPV)/counter for 1MIP	Requirement of p.e.
3x5x50	3.0	5.0	50	72	~1000	~560
Thinner	1.5	5.0	50	124	~600	~140
Longer	3.0	5.0	100	101	~600	~560

Comparison with previous measurement at beam test

- Number of p.e. : sufficient, but much less than previous measurements at KEK beam test
  - -> Need investigation
  - -> worse time resolution due to smaller # p.e.?

Comparison between three samples

- Best time resolution with 3x5x50
- Thinner: worse time resolution due to smaller # p.e.?
- Longer: worse time resolution due to position dependence?

Summary and prospects

Summary

- Development of pair spectrometer with active converter for $\mu \rightarrow e\ \gamma$ new experiments.
- Performance measured with LYSO with different sizes
  - Much smaller # of p.e. -> need investigation
  - Best time resolution with 3x5x50
  - Worse time resolution for thinner and longer samples probably due to smaller # of pe and position dependence

Prospects

- More efficient and detailed study in beam test including other sizes and types of LYSO