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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 -要素技術の開発-

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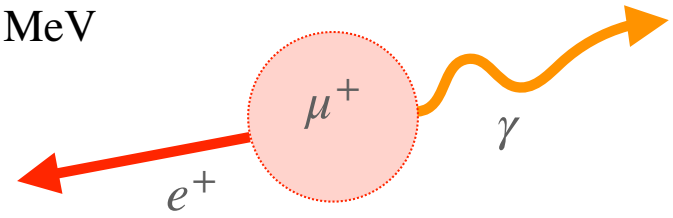
Outline

- Introduction
- Lab. Test
- Beam Test
  - Setup
  - Dataset
  - Analysis Flow
  - Results
- Summary

Introduction

$\mu^+ \to e^+\gamma$

- **Charged lepton flavor violation as a good probe into beyond-SM**
- Signal
  - Same energy of $52.8\,\mathrm{MeV}$
  - Same timing
  - Back-to-back



- Background
  - **Accidental background is dominant**
- The best limit is $\mathrm{B}(\mu \to e\gamma) < 4.2 \times 10^{-13}\,(90\,\%\,\mathrm{C.L.})$ by MEG experiment @PSI (2016)
- MEG II experiment @PSI has been started with 6×10^{-14} as the goal
- Hight Intensity Muon Beam (HiMB) @PSI plan to be implemented in 2027-2028
  - **Intensity increased by a factor of 100** $\to O(10^{10})\,\mu^+/\mathrm{s}$
  - Good opportunity to start new $\mu^+ \to e^+\gamma$ search
  - Target sensitivity is $O(10^{-15})$
- **Improvement of gamma-ray measurement is the key**

Calorimeter vs. Pair Spectrometer

Calorimeter

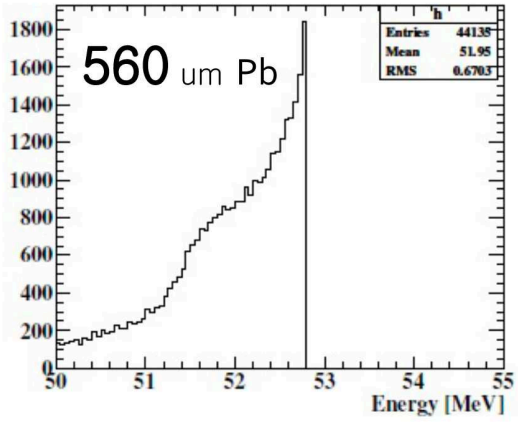
- **Higher efficiency**
- Moderate resolutions
- Moderate rate capability
- Using LXe, MEG (2009-2013) and MEG II (2022-now)

Pair Spectrometer

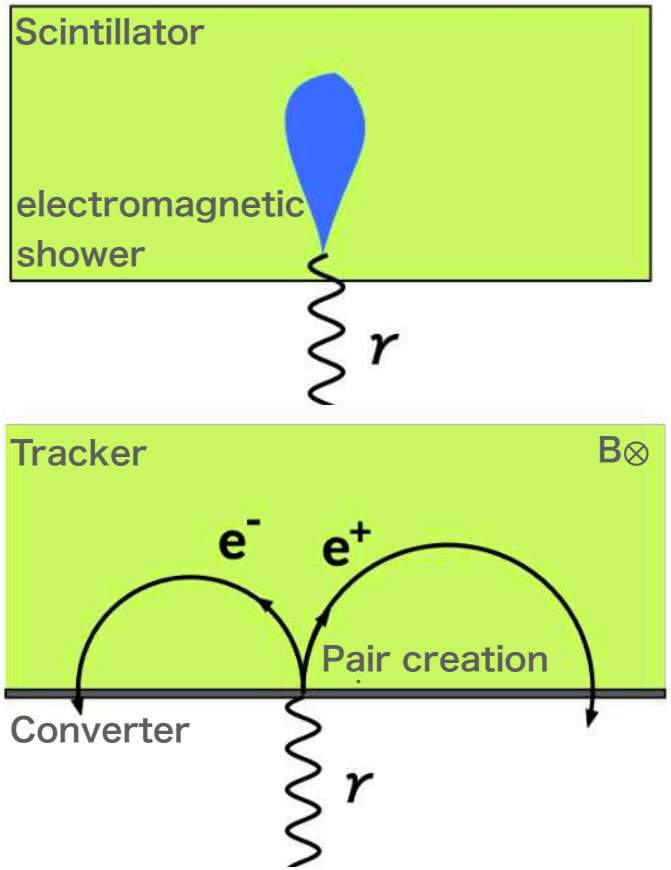
- **Higher resolutions**
- **Capable of measuring photon direction**

$$B_{\mathrm{acc}} \propto \Gamma_{\mu}^{2} \cdot \Delta E_e \cdot (\Delta E_\gamma)^2 \cdot \Delta T_{e\gamma} \cdot (\Delta \Theta_{e\gamma})^2 \cdot (\Delta \Theta_\gamma)^2$$

- Low efficiency
- Energy loss in converter
- Using Pb, MEGA (1985-1999)



E_{e^+,e^-} distribution in Pb (MC)



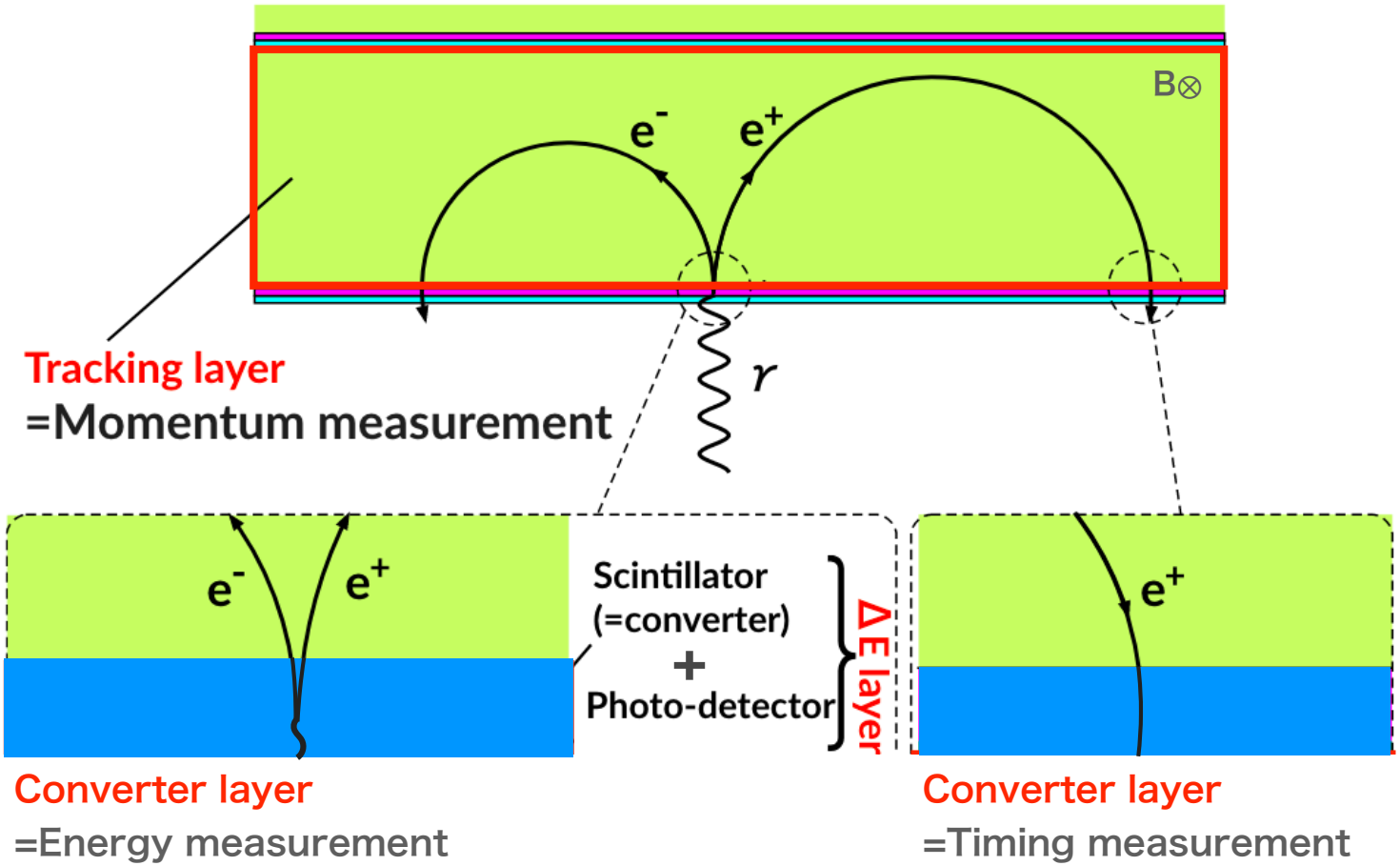
- Pair spectrometer would be more advantageous with much higher beam intensity
- Issues to be addressed
  - **Lower efficiency**
  - **Energy loss in converter**

→ **Active converter**

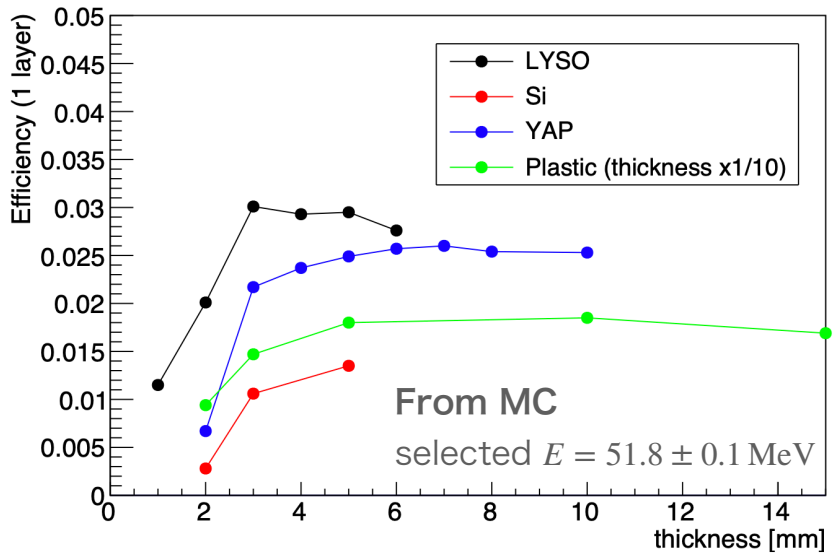
- **Heavy scinti. & multi-layer**

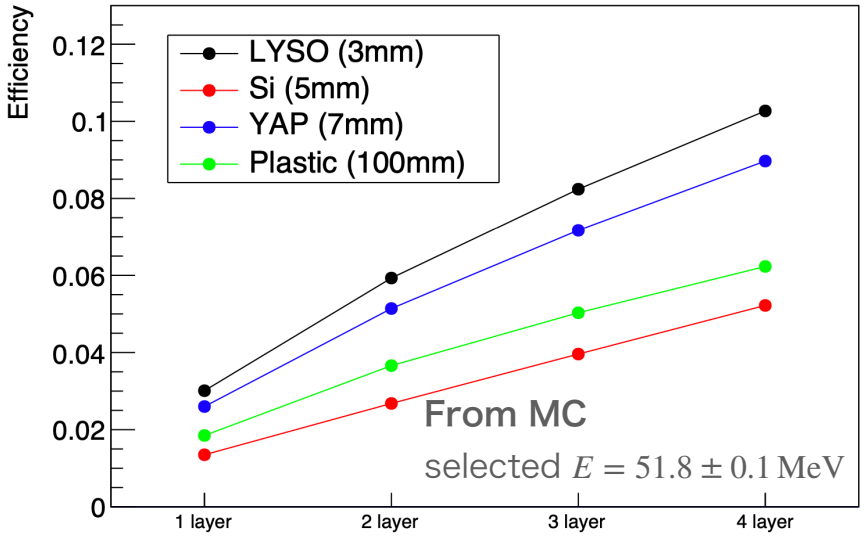
Pair Spectrometer with Active Converter

- Energy loss in the converter material cannot be ignored
  → Active material as a converter
- Active converter as timing layer
- Target resolution $(E_\gamma, \vec{x}_\gamma, t_\gamma) = (0.4\,\%, 0.2\,\mathrm{mm}, 30\,\mathrm{ps})$



LYSO as Active Material





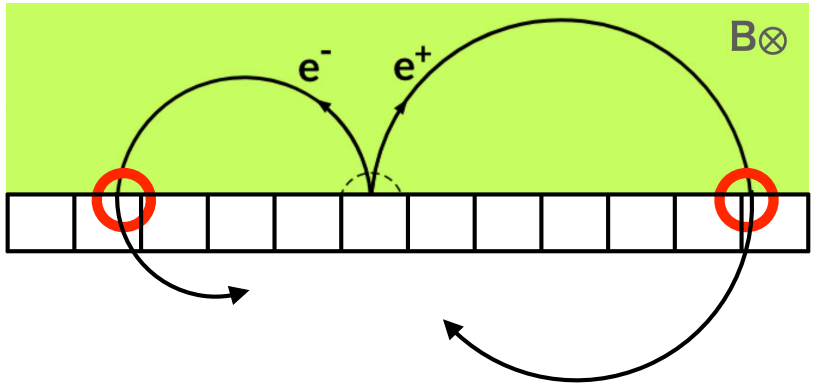
Density [g/cm^3]	7.2
Light Yields [rel. to NaI]	75%
Emission Peak [nm]	420
Decay time [ns]	40
Radiation Length [cm]	1.1
Critical Energy [MeV]	12
Hygroscopicity	None

Critical Energy: $E_c \propto 1/Z$, if E > Ec, ionization < brems.

- High light yield → Good energy resolution
- Fast response → Good timing resolution
- **The highest detection efficiency at about 3-4 mm**

Requirements for Active Converter

- **LYSO crystal as active material + SiPM as photo-sensor**
- Target performance of pair spectrometer and requirements for active converter
  - **Energy measurement**
    Energy resolution of 0.4%@52.8 MeV for a gamma
    → Corresponds to 3%@MPV of the energy deposited by e^+ and e^-
    → Energy resolution ∝ 1/√p.e, so, **600 photo-electrons required for 1 MIP**
    - Assuming the position dependence of light yield, position dependence can be corrected by the conversion point measured by the conversion pair tracks
  - **Timing measurement**
    Time resolution of 30 ps for, by measuring timing of e^+ and e^- independently
    → **40 ps. for 1 MIP**
- What we want to know
  - **Number of photo-electrons for 1 MIP**
  - **Time resolution for 1 MIP**

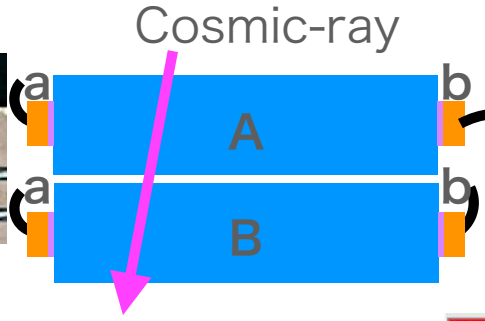


Lab. Test

Reported at previous JPS meeting(7pA442-2)

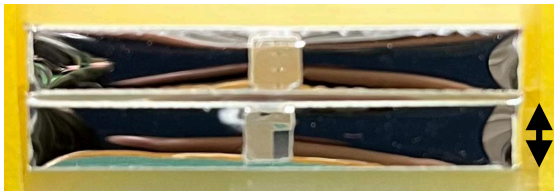
Lab. Test using Cosmic-ray

2x2mm^2



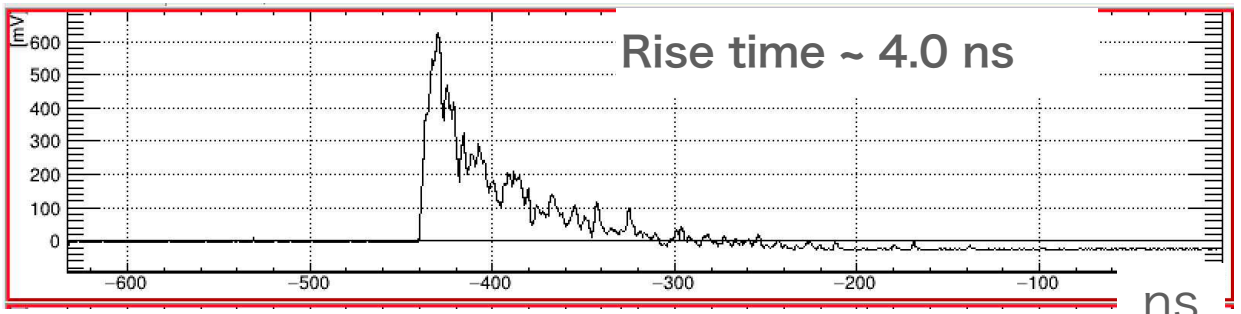
Shaping Amp. — Attenuator — 1.6 GSPS Waveform Digitizer

2.0x2.0mm 50μm SiPM 1/side, Vop = 52 V
(S13360-2050VE)



4mm

30x30mm^2



Attenuated by a factor of 0.50

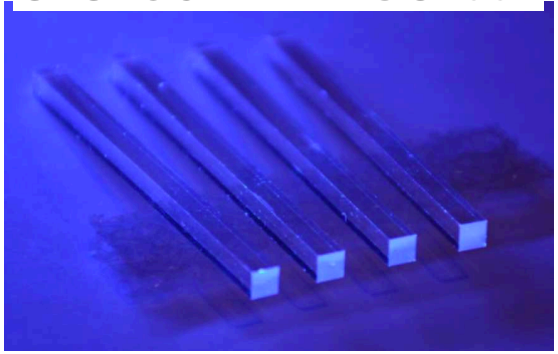
- Energy:
  - Detected photons ~ **2200 p.e./counter** at MPV of Landau distributions
    → **Photoelectron statistics are sufficient**
- Timing:
  - $\text{Time res.} = \sigma(t_{\text{counter A}} - t_{\text{counter B}})/\sqrt{2}$, $t_{\text{counter i}} = (t_{\text{side a}} + t_{\text{side b}})/2$, $(\text{i} = \text{A}, \text{B})$
  - Time information was obtained by constant fraction method
  - **Time resolution ~ 135 ps**
    → **Need further improvement**
    - **Crystal shape**
    - **Readout method**

Crystal Shape

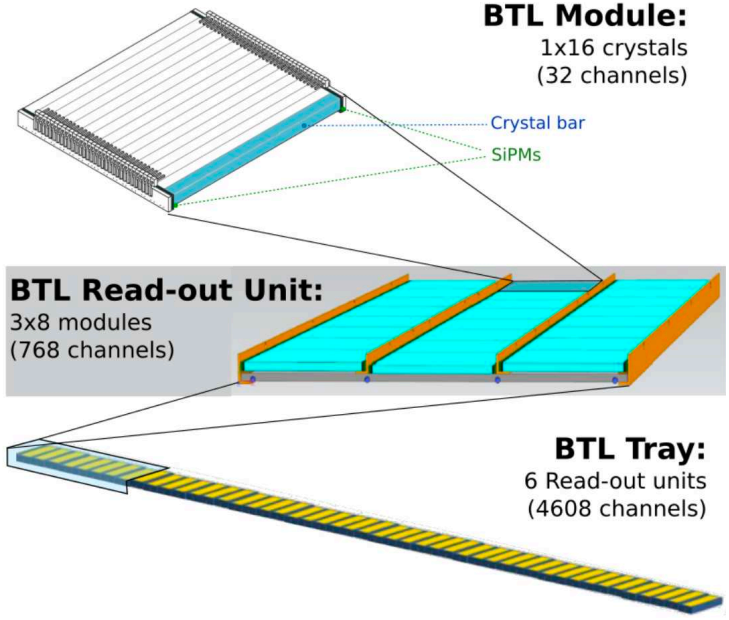
- Tile → **Bar**
  - Segmentation
    - Fine segmentation in the ϕ direction is expected **to mitigate pileups**
  - CMS MIP Timing Detector (MTD)
    - **Excellent time resolution of about 30 ps has been achieved, using bar**

CMS MTD

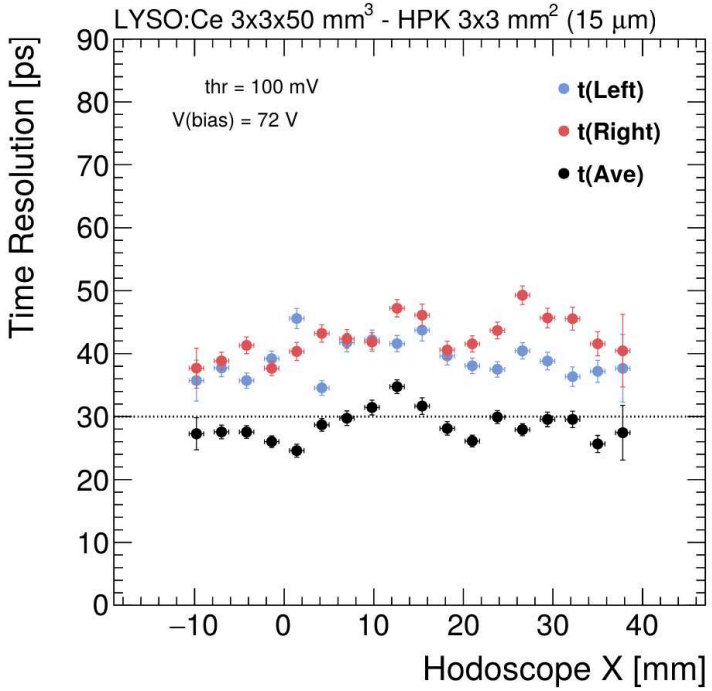
3x3x50mm LYSO bar



CMS MTD



CMS MTD



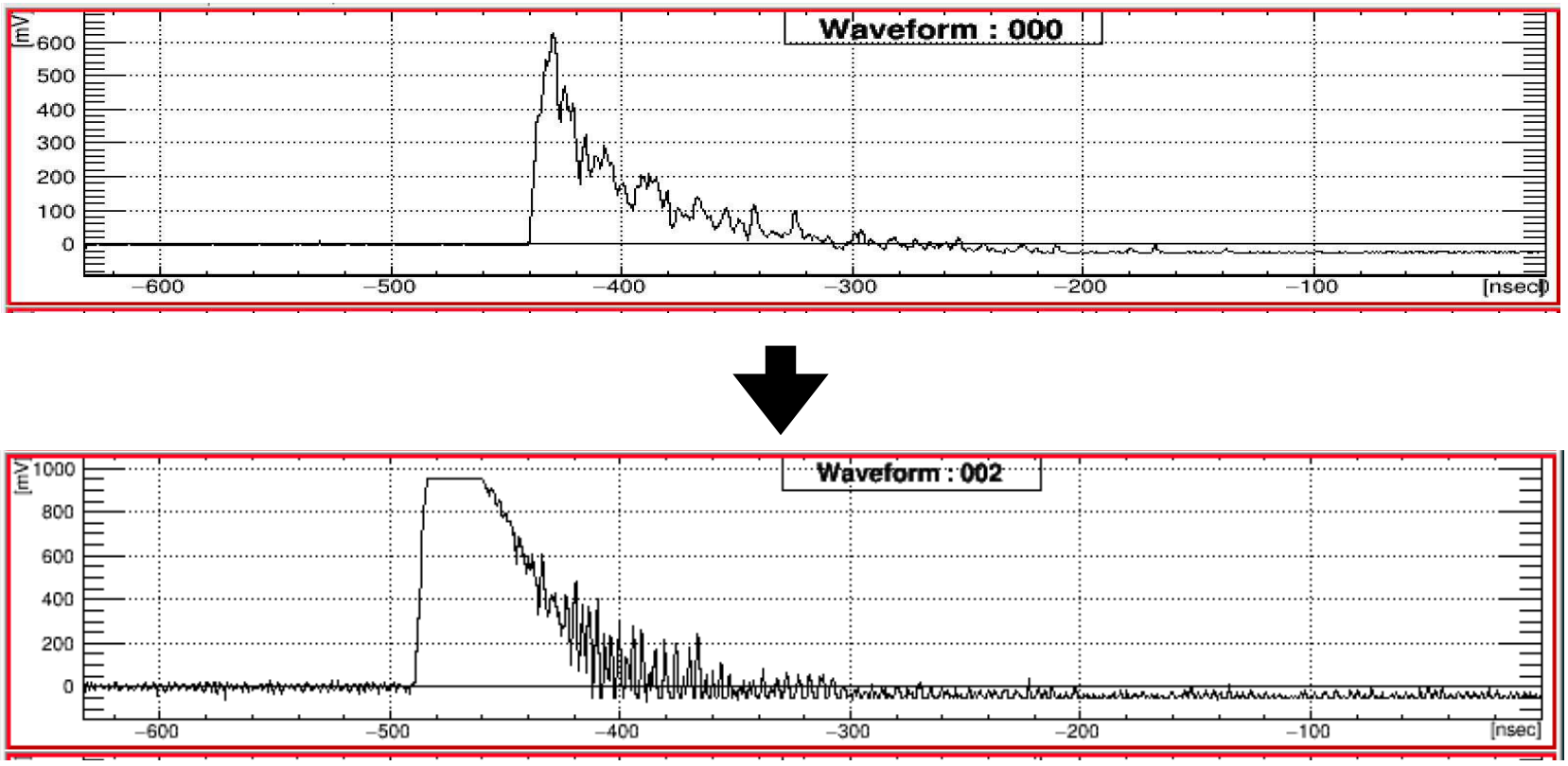
CERN-LHCC-2019-003, CMS-TDR-020

Readout Method

- **It seems that timing resolution in lab. test was limited by S/N**
- **Important to use early-arrival photons for time pickup**

→ **Significantly increase readout gain**

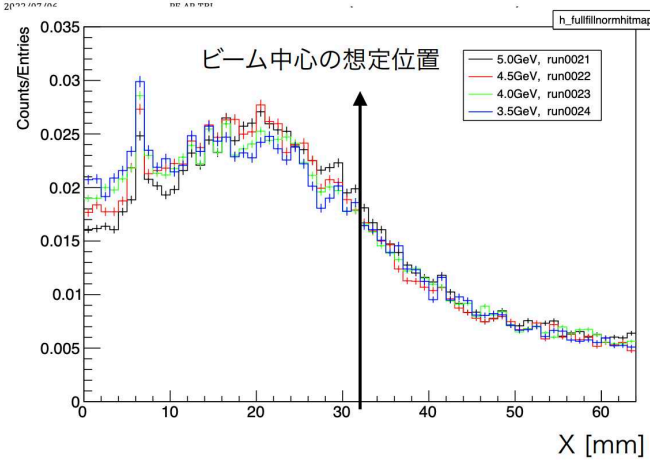
- Signal well beyond dynamic range
- Time walk correction with Time-Over-Threshold (TOT)

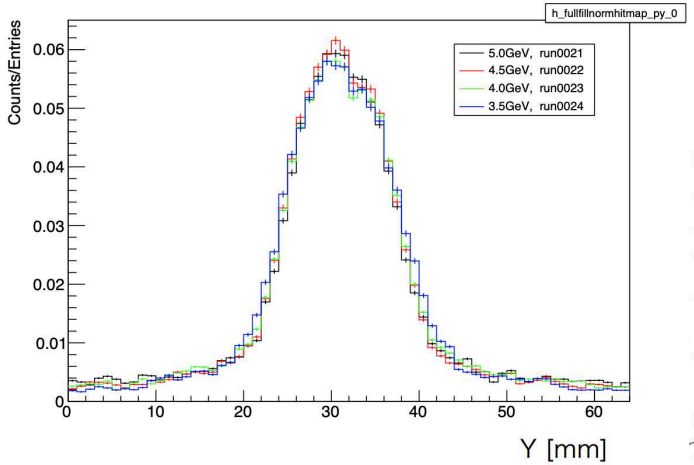


Beam Test.

PF-AR Test Beam Line@KEK

- 16 Nov. - 21 Nov., 2022
- **MIP-electron beam**
  - Beam momentum ~ 0.5-5.0 GeV/c
  - Beam rate ~ 150-200Hz, dependent on target wire position
  - Beam profile is **thin vertically** and spread horizontally

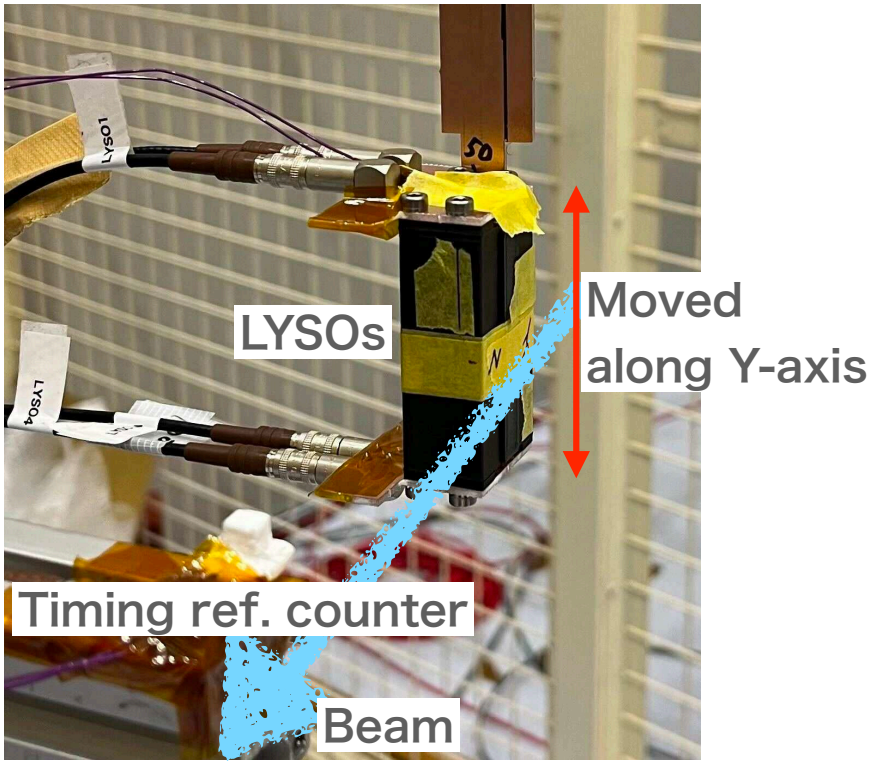


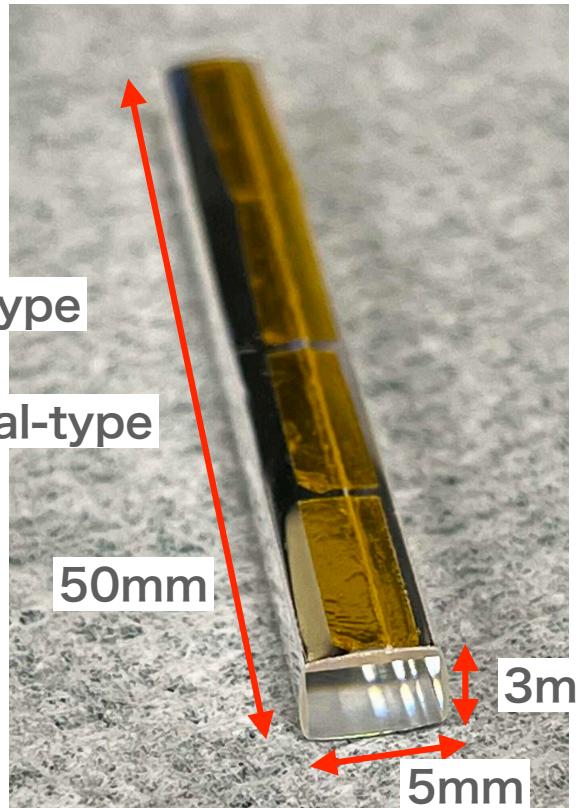


Courtesy of Hanagaki-san

Setup

- Two types of LYSOs
  - **Normal-type and Fast-type (FTRL)**, made by Suzhou JT Crystal
  - Size: **3x5x50mm^3**
  - **Readout by SiPMs placed on both sides of LYSO**
    - Photosensitive area of 3x3mm and pixel pitch of 15/50um (S14160-3015PS/S14160-3050HS)
    - Wrapped by Reflector (ESR)
- **Timing reference counter**
  - Plastic scinti. of 5x5x5mm read out by one SiPM (S14160-6050HS)
- All signals are read by shaping amp. and then input to 5 waveform digitizers (DRS4 Evaluation Board)
  - Sampling speed of 1.6GSPS

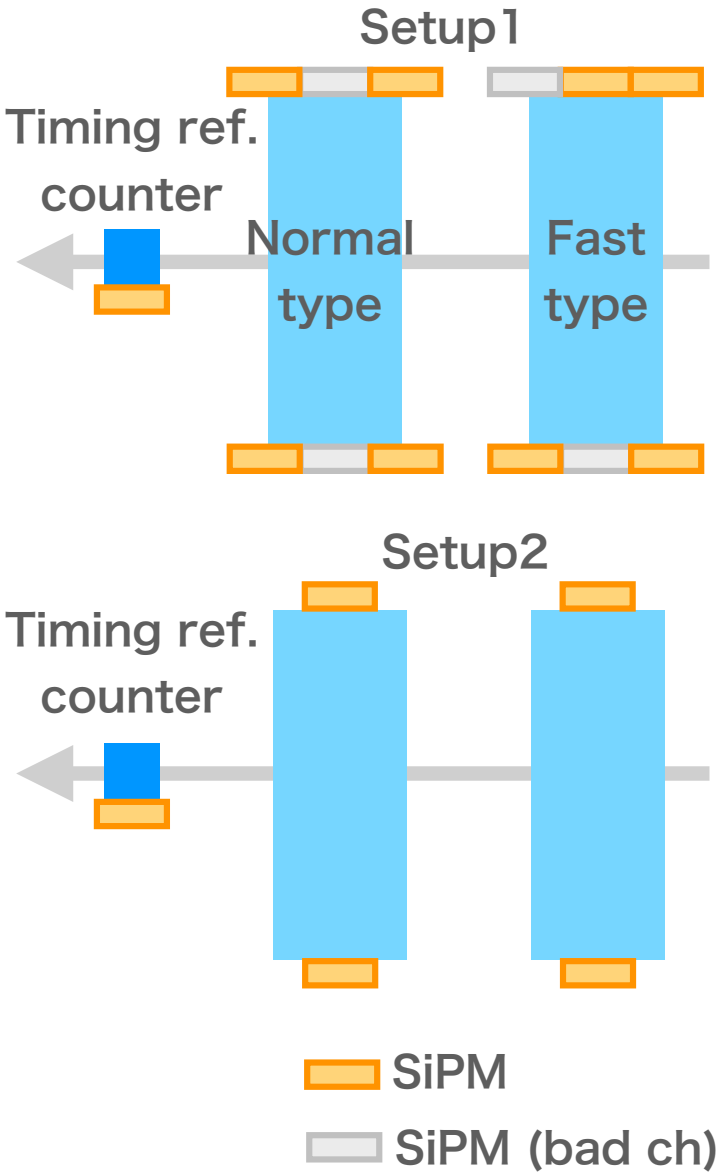




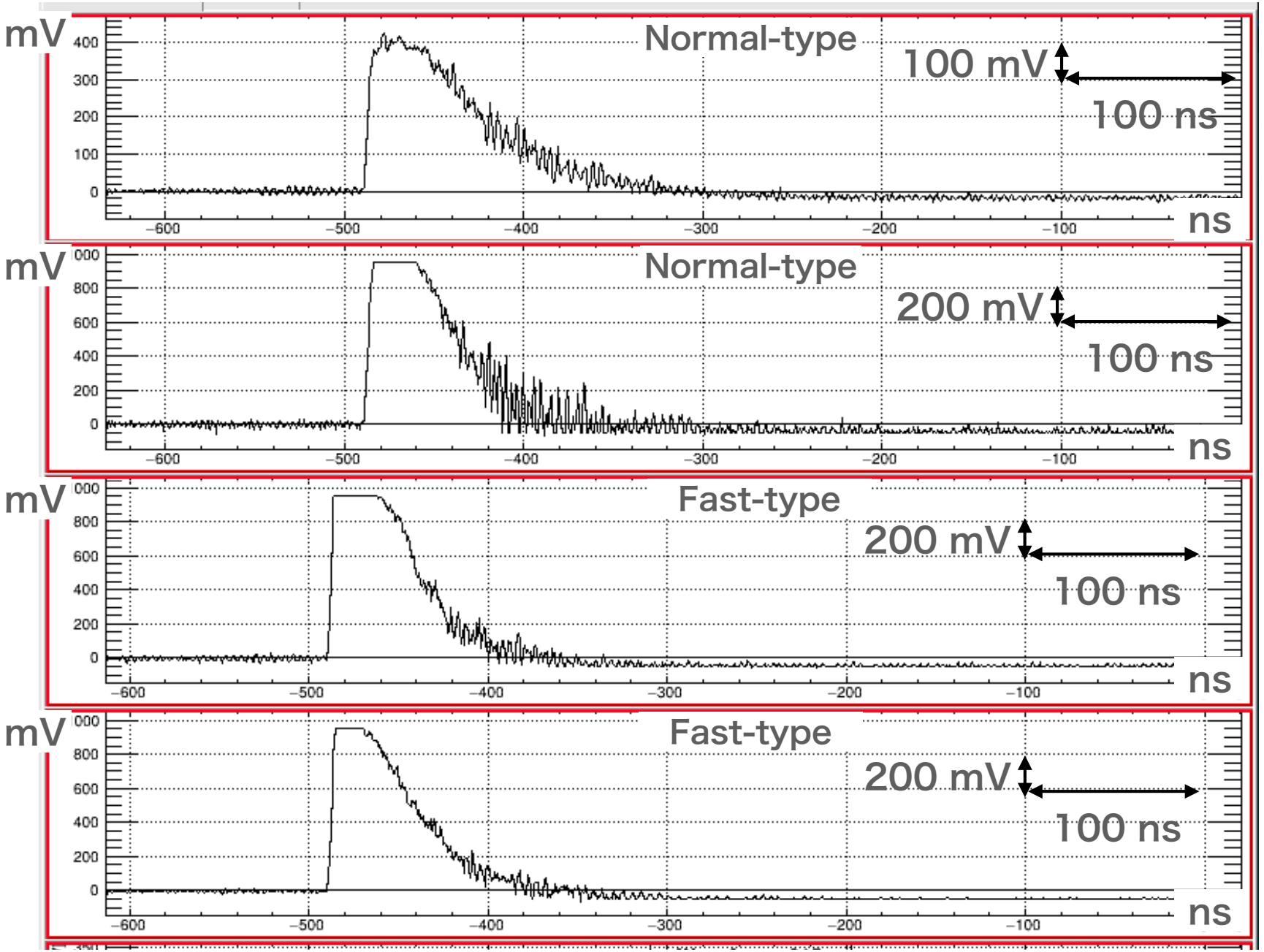
Setup

- Setup1: 50um pitch SiPMs (8 chs readout in total)
  - Data 1
    - Position scan (center, ±10mm, ±20mm)
    - Nominal SiPM gain
  - Data 2
    - 2 points position scan (center, +15mm)
    - Higher than nominal SiPM gain
- Setup2: **15um pitch SiPMs** (4 chs readout in total)
  - Data 1
    - Beam injection position at center only
    - Nominal SiPM gain
  - **Data 2**
    - 3 points position scan (**center**, ±15 mm)
    - Higher than nominal gain of SiPMs

- Self-triggered using LYSO's signals



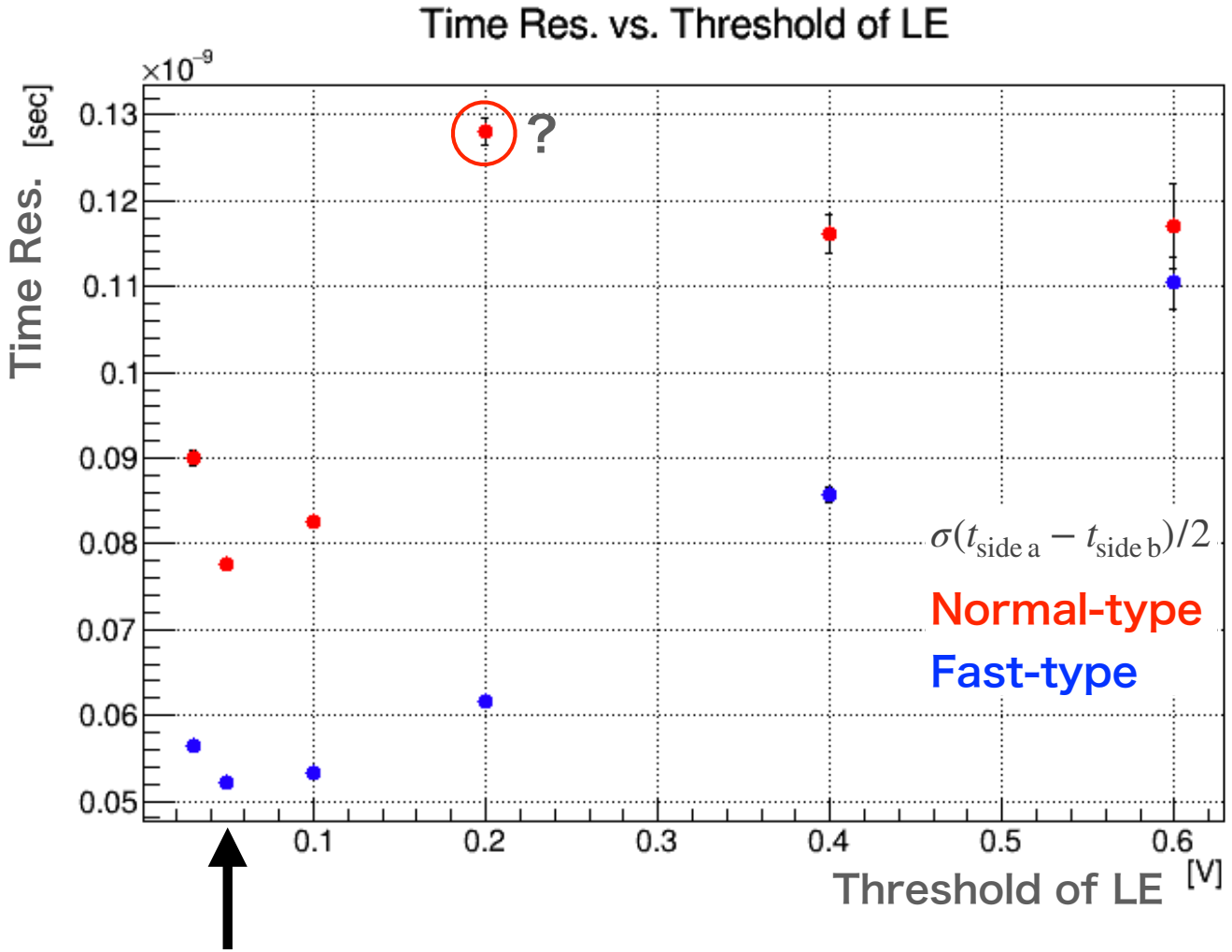
Waveforms


mV
Normal-type
100 mV
100 ns
ns
mV
Normal-type
200 mV
100 ns
ns
mV
Fast-type
200 mV
100 ns
ns
mV
Fast-type
200 mV
100 ns
ns

Analysis

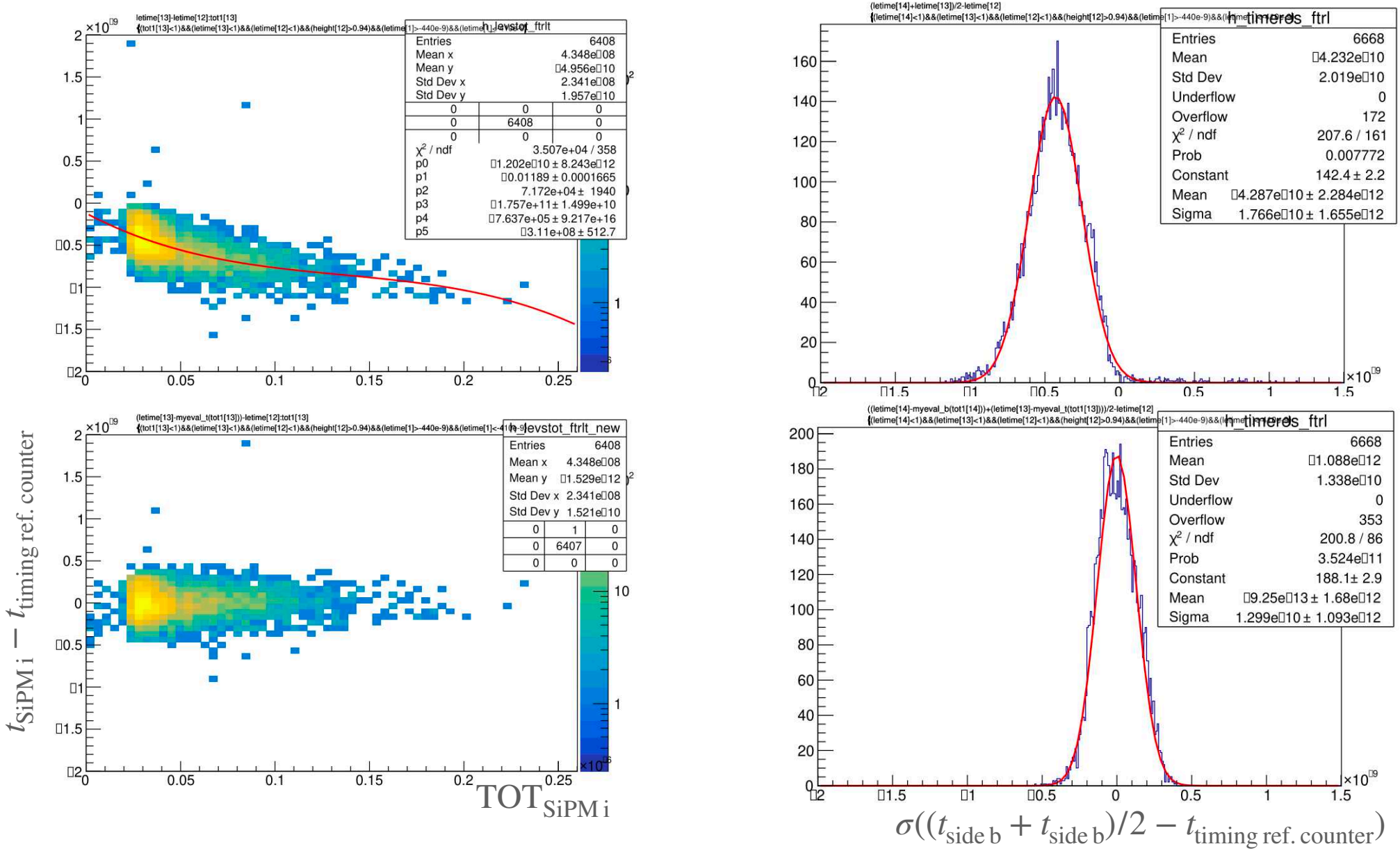
- Events were selected by requesting hits on timing ref. counter
- Time pickup was performed using leading-edge method (LE)
  - Threshold for LE scanned and optimized
- Time-walk correction was performed using TOT
- Time resolution can be calculated in two ways
  - $\sigma(t_{\text{side a}} - t_{\text{side b}})/2$
  - $\sigma((t_{\text{side b}} + t_{\text{side b}})/2 - t_{\text{timing ref. counter}})$

Threshold Optimization for LE



- LE threshold of 50 mV, which gave the best time resolution, was used in subsequent analyses

Time-walk Correction by TOT



- Walk correction was made by fit with a 5th order polynomial, for the distribution of $t_{\mathrm{SiPM\,i}} - t_{\mathrm{timing\ ref.\ counter}}$ vs . $\mathrm{TOT}_{\mathrm{SiPM\,i}}$

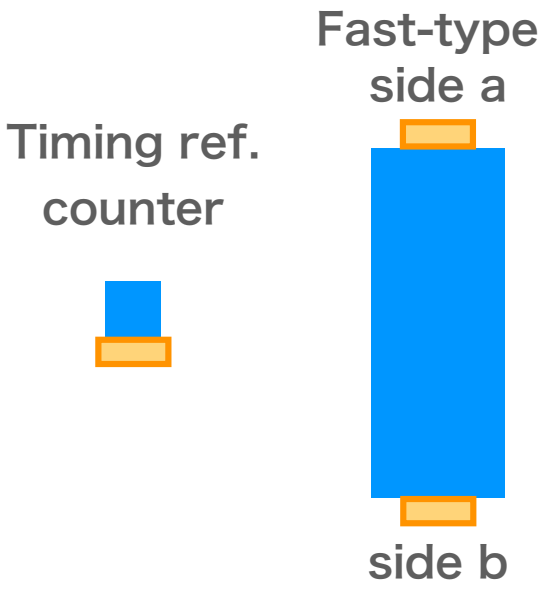
Time Resolution

Preliminary

- **Time resolution was calculated in two ways**
  - **Difference between the two sides**
    - $\text{Time res.} = \sigma(t_{\text{side a}} - t_{\text{side b}})/2$
    - Time res. of **Fast-type ~ 52 ps**
  - **Sum of the two sides**
    - Get $\sigma(t_{\text{side a}} - t_{\text{side b}})$, $\sigma(t_{\text{side b}} - t_{\text{timing ref. counter}})$ and $\sigma(t_{\text{timing ref. counter}} - t_{\text{side a}})$

      The, find $\sigma(t_{\text{side a}})$, $\sigma(t_{\text{side b}})$ and $\sigma(t_{\text{timing ref. counter}})$ that satisfy the above 3 conditions

      -> $\text{Time res.} = \sigma((t_{\text{side b}} + t_{\text{side b}})/2 - t_{\text{timing ref. counter}}) \ominus \sigma(t_{\text{timing ref. counter}})$
    - Time res. of **Fast-type ~ 43 ps**
      ($\sigma(t_{\text{side a}})$ ~ 81 ps, $\sigma(t_{\text{side b}})$ ~ 66 ps, $\sigma(t_{\text{timing ref. counter}})$ ~ 66 ps)



Summary

Summary

- For future $\mu^+ \to e^+\gamma$ search experiment, **pair spectrometer with active converter** is being considered for gamma-ray detector
- **LYSO crystal** as an active material
  - **Hight efficiency**
  - **Hight light yield**
  - **Good timing performance → Can also work as timing layer**
- From lab. test, **photoelectron statistics found to be good enough to achieve 0.4% energy resolution**
- Response of (3x5x50mm LYSO + SiPM) to MIP is being evaluated by MIP electron beam data
  - **Good timing resolution of 40-50 ps (for Fast-type) has been achieved**
- Prospects
  - Continue to analyze data
    Check for consistency of results, use of other data sets, etc.
  - Select technology and evaluate performance of trackers for conversion pair
  - Study overall design of pair spectrometer