次世代$\mu^+ \to e^+\gamma$崩壊探索実験のための研究開発
-ビームテストによるアクティブコンバータの研究-

Developing an experiment for a future search for $\mu^+ \to e^+\gamma$
: Beam test study of an active converter

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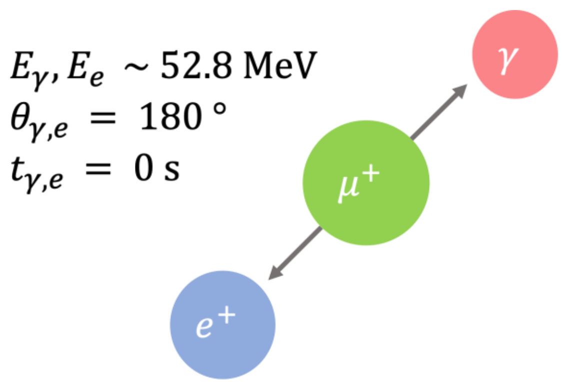
Abstract

- **Future experiments for $\mu^+ \rightarrow e^+\gamma$ decay search are planned.**
- **High-sensitivity gamma-ray detector**
  - **Pair spectrometer with active converter**
- **2023 Beam test at KEK to measure performance of converter materials**

Introduction

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

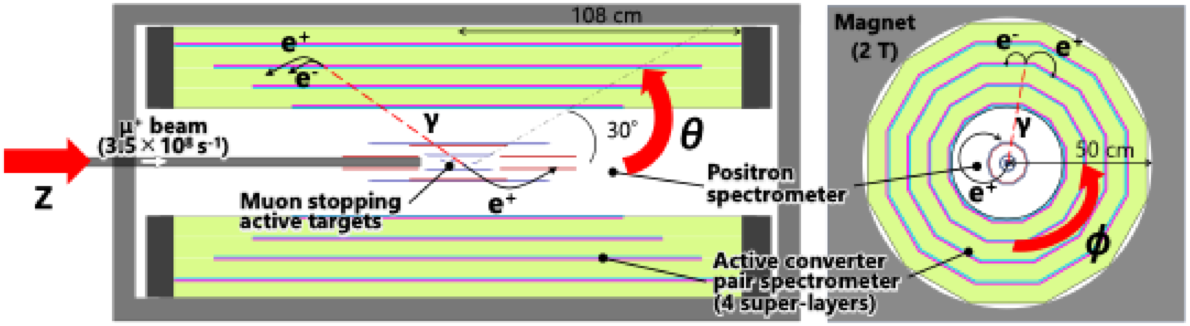
- **Charged lepton flavor violation as a prove of Beyond SM**
- **Characterization of the decay**



- **According to the new theory,** $\mathcal{B}(\mu^+ \to e^+\gamma)$: $\mathcal{O}(10^{-14}) \sim \mathcal{O}(10^{-11})$
- **MEG:** $\mathcal{B}(\mu^+ \to e^+\gamma) \leq 4.2 \cdot 10^{-13}$ **, MEGII goal :** $6 \cdot 10^{-14}$
- **Background**
  - accidental background is dominant: $N_{acc} \propto R_\mu^2 \cdot \Delta E_\gamma^2 \cdot \Delta P_e \cdot \Delta\theta_{e\gamma}^2 \cdot \Delta t_{e\gamma} \cdot T$
  - ΔE_γ is important for suppression of N_{acc}

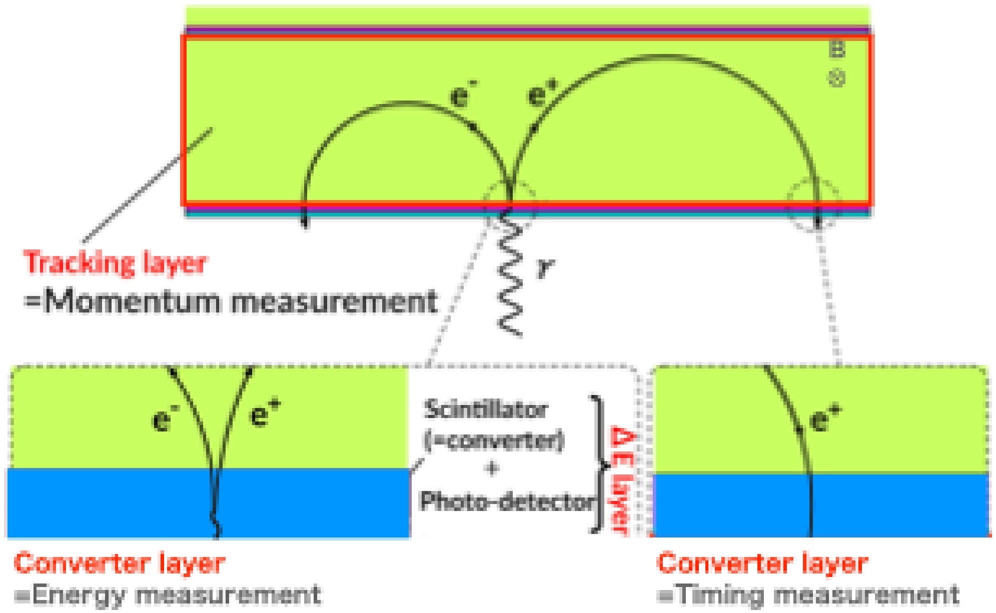
New experiment for $\mu^+ \to e^+\gamma$ search

- **Why $\mathcal{O}\left(10^{-15}\right)$?**
  - Search for $\mu^+ \to e^+\gamma$ with even higher sensitivity
  - Even if found by MEGII, precise measurement of $\mathcal{B}(\mu^+ \to e^+\gamma)$ is an important issue as model selection
- **High intensity muon beam is planed at PSI (2027-2028)**
- **Concept of New μ → eγ Experiment**



- **Gamma detector**
  - Photon pair spectrometer
    : high resolutions (E, x), angle measurement, high rate capability
- **positron detector**
  - Ultra-thin silicon sensor (HV-MAPS) technology
    : High rate capability

Pair spectrometer with active converter



- **Pair spectrometer vs LXe detector**

	Pros.	Cons.
Lxe detector	･High efficiency	･Moderate detector resolutions (E, x, t)
Pair spectrometer	･High resolution (E, x) ･Angle measurement ･High rate capability	･Low efficiency ･Energy loss in converter

Performance requirements

- **For pair spectrometer**
  : $\Delta E_{\gamma} = 210\ keV, \Delta t_{\gamma} = 30ps,\ \Delta x_{\gamma} = 0.2mm$

- **For active convertor (3mm, LYSO)**
  : $\Delta E_{\gamma} = 210\ keV \rightarrow$ 500photo-electrons per 1 electron (positron)
  $\Delta t_{\gamma} = 30\text{ps} \rightarrow$ 42ps per 1 electron (positron)

- **Motivation**

  : Investigation of suitable geometry for converters(Simulation)

  : Evaluation of converter performance by actual measurement(Beam test)

Beam test in KEK

PF-AR test beam line in KEK

10 Dec. – 17 Dec. 2023

- **Time and energy resolution results are preliminary**
- **Electron beam**
  - **beam momentum ~ 3GeV**
    - The energy deposit is similar to that of 0~52.8 MeV electrons by simulation
  - beam profile: thin vertically and spread horizontally
- **Purpose of the Beam Test**
  1. **Evaluate the performance of LYSO various sizes, scintillation light detection methods, position and angular dependence, and other conditions**
  2. **Determine the optimal converter design**

DAQ list and motivations

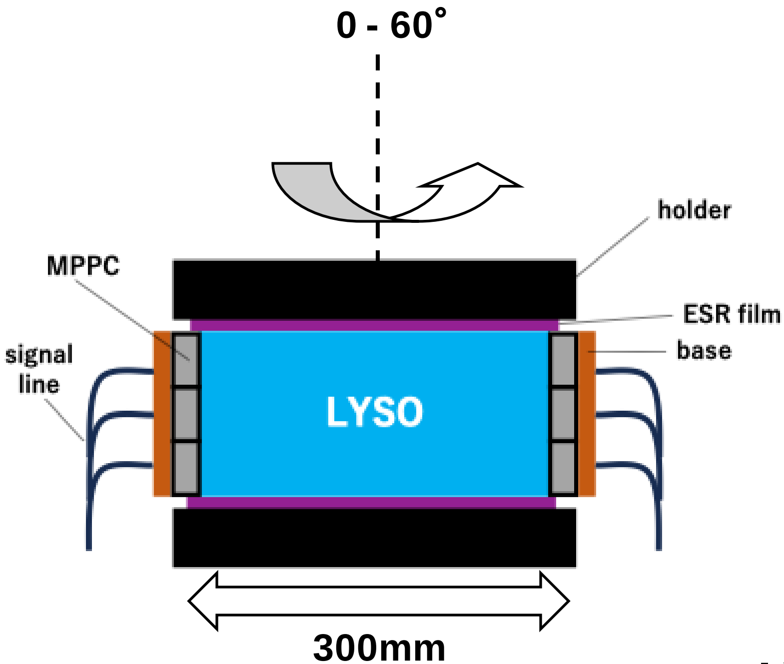
1. **LYSO size**
   - For segmentation studies and comparison of different light collection rates
2. **LYSO type**
   - For comparison of NORMAL and FTRL type
     - NORMAL: high light yield
     - FTRL: good time resolution
3. **MPPC pixel pitch & connection method**

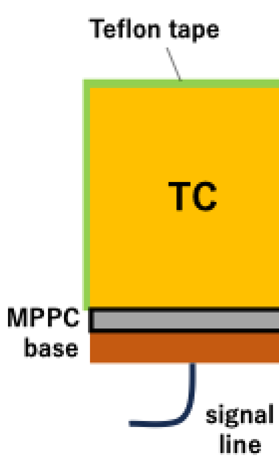
pixel pitch	gain	time resolution
small	small	good
large	large	bad

connection	gain	time resolution
independent	large	bad
series	small	good

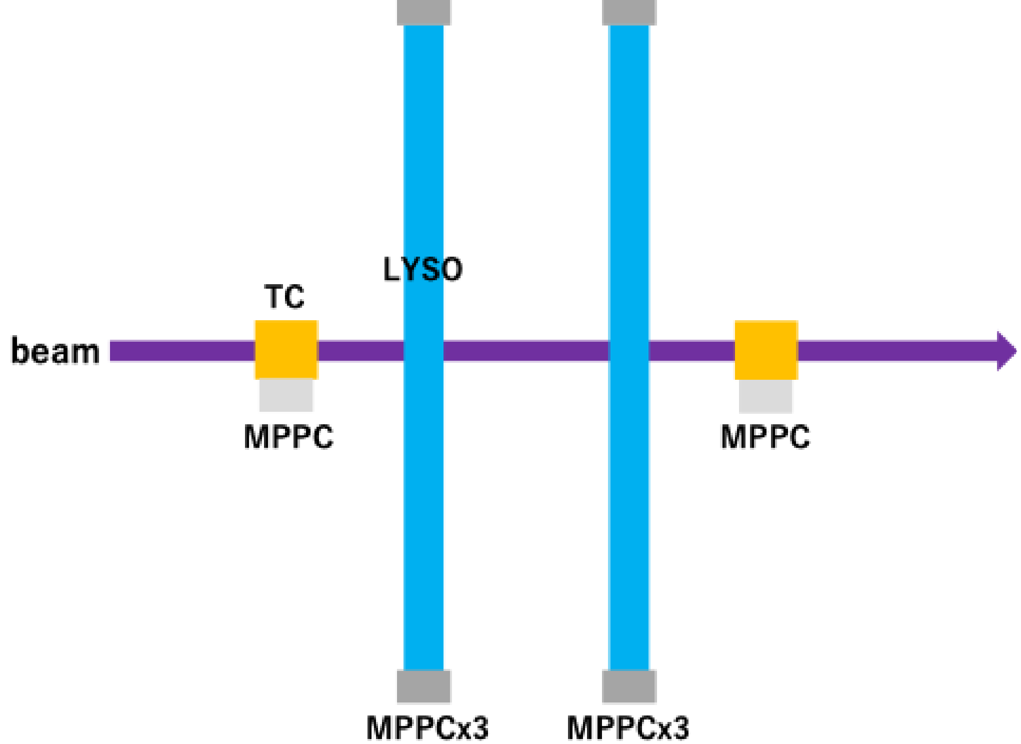
4. **Position and angle dependence**
   - For comparison of γ ray injection point and angle

Setup





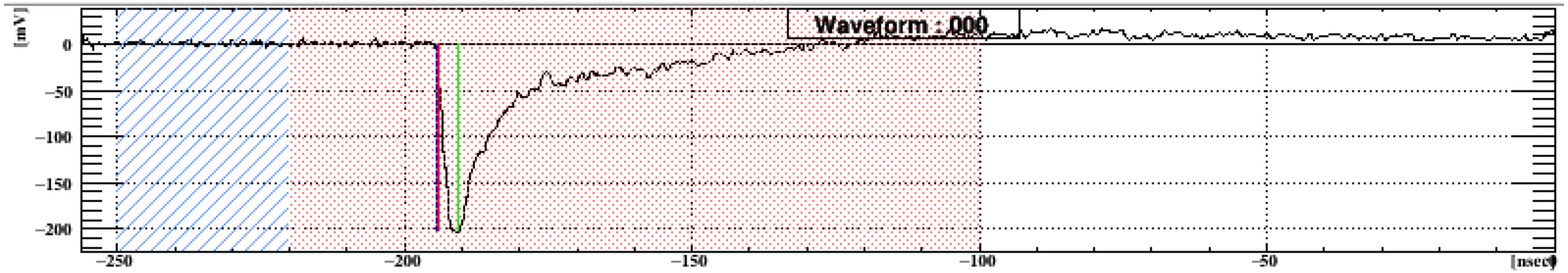
＜Counter Placement＞



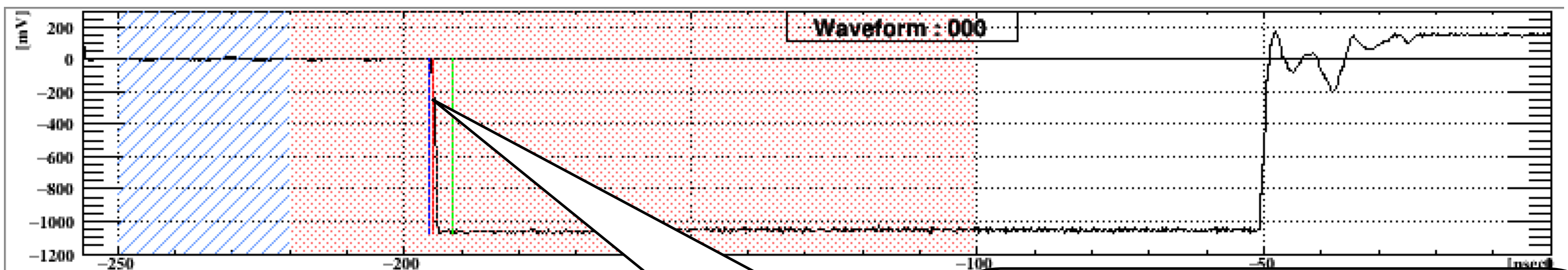
- **LYSO: 3ch MPPC/LYSO's side**
- **TC(timing reference counter, trigger counter) : 1ch MPPC/TC's side**
- **Optimize measurement parameters of readout instruments**
  - **Variable resistance for waveform shaping : max**
  - **waveform gain: 50x**
  - **HV of MPPC: Fixed optimum values for each board type**

Waveform, Timing

- **3x5x50, gain 0.5**



- **3x5x50, gain 50**



Key Points for Timing Measurement

1. Scintillation light arrives at MPPC with a certain time width
2. For good time resolution, we want to focus on early arrival photons

DAQ approach

- Amplify the waveform and focus on the early arrival photon

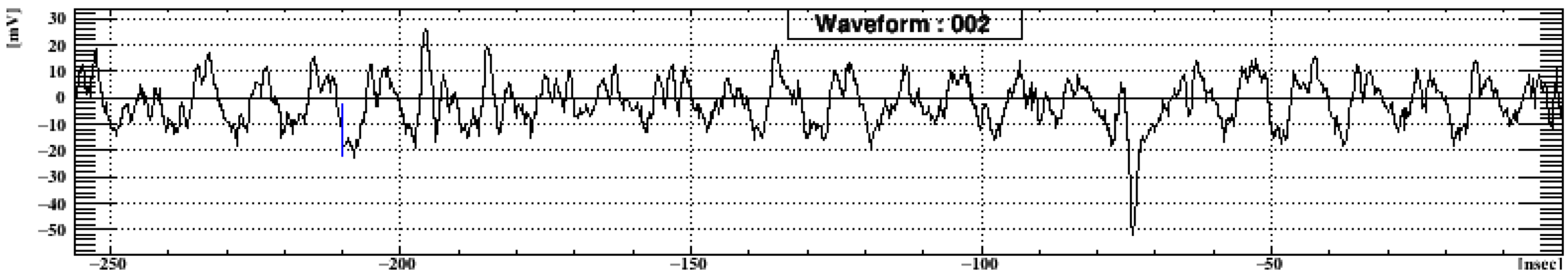
- LE method
  : the rise time of a signal as the time it exceeds a certain threshold
- **Time resolution:**

$$\sigma_{t_{LYSO}} = \sigma\left(\frac{t_{right} - t_{left}}{2}\right)$$

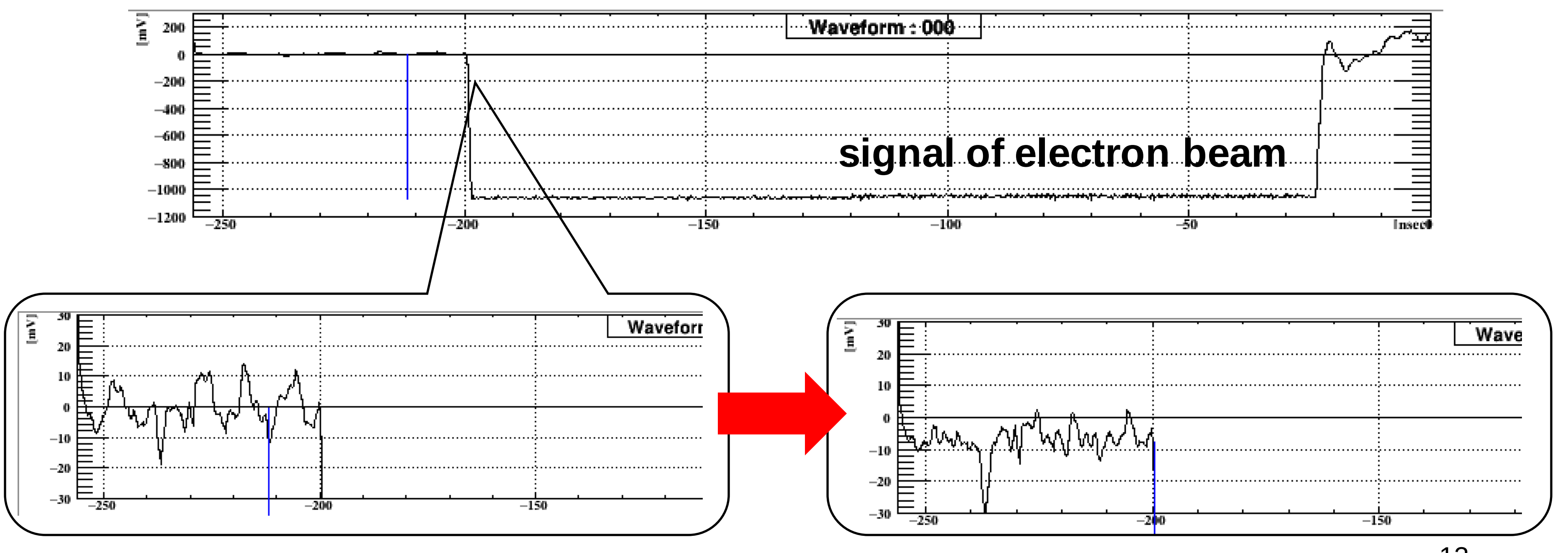
  - $t_{right/left}$: Time taken at the right (left) end of LYSO

Noise reduction

- wave form of the clock noise in WDB



- effect of noise reduction



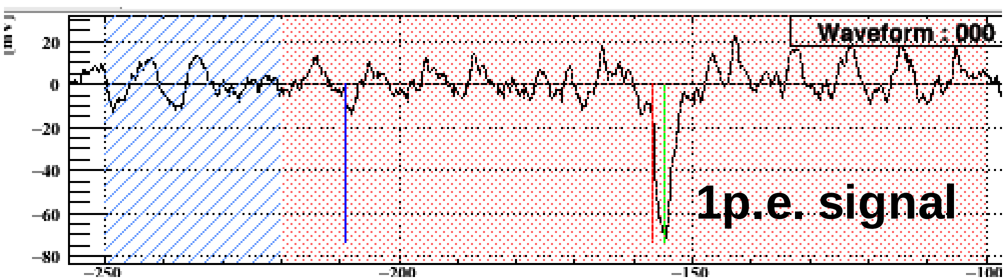
before **after**

Result

Light yield

Calculation method

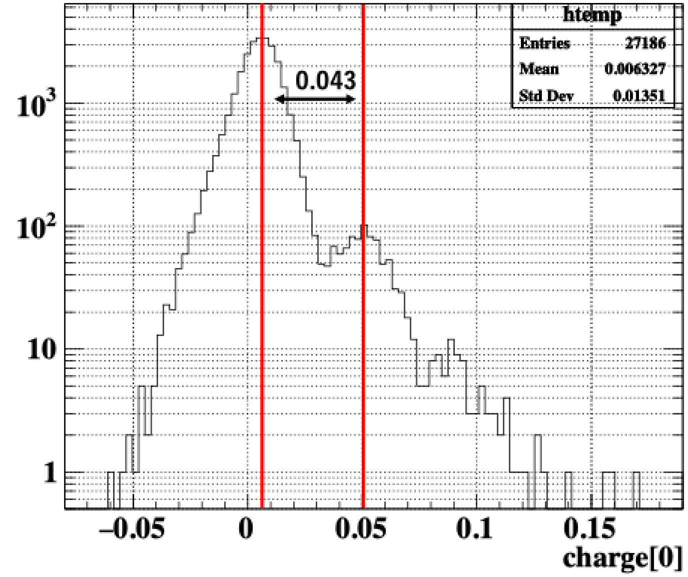
- Calculate the charge of one photon using MPPC's Dark Count (gain 50x)



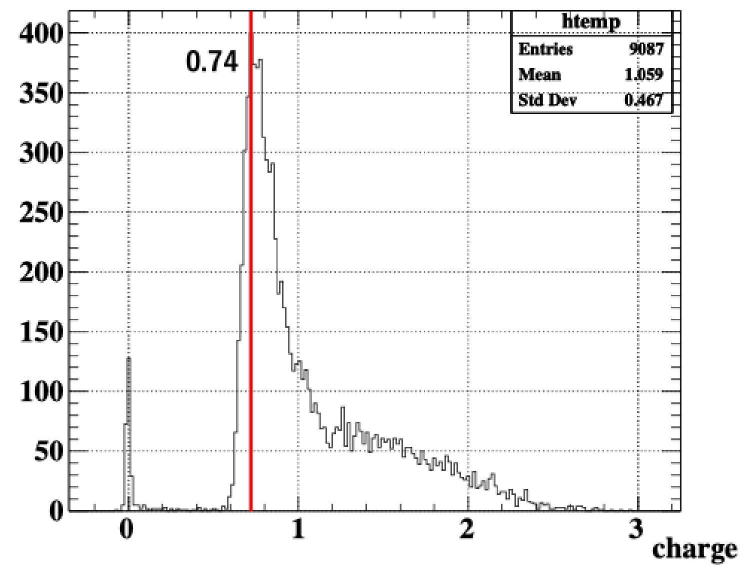
- Obtain signal charge distribution from low-gain (0.5x) data where the entire waveform falls within the range
- Calculate the number of photoelectrons by dividing the peak value of the charge distribution by the charge of one photon

ex) 3x5x50(FTRL), independent connection

$$\mathrm{charge[p.e]} = \frac{0.74}{0.043} \cdot \left(\frac{50}{0.5}\right) \sim 1720\ \mathrm{p.e.}$$



charge dis. of dark count



charge dis. of LYSO

Light yields

- Light yields for all LYSO sizes were sufficient to meet the required light yield of 500 p.e. (130 p.e. at 1.5 mm) and energy resolution of 210 keV for active converters

▪Type

	[p.e.]	σ(E) [keV]
3x5x50(FTRL)	1720	130
3x5x50(NORMAL)	2160	120

NORMAL light yield was greater than FTRL

▪Thickness

	[p.e.]	σ(E) [keV]
3x5x50(FTRL)	1720	130
1.5x5x50(FTRL)	978.0	110

At 1.5mm thickness, light yield decreased in proportion to thickness

▪Length

	[p.e.]	σ(E) [keV]
3x5x50(FTRL)	1720	130
3x5x100(FTRL)	1560	140

100mm length can have low light yield due to scintillation light attenuation

▪Width

	[p.e.]	σ(E) [keV]
3x5x50(FTRL)	1720	130
3x10x50(FTRL)	2210	120

The 10mm width has a small MPPC insensitive area ratio to LYSO sides. The wider width and higher light yield

Time resolution ※data of center injection

- 3mm LYSO (FTRL) achieved 42ps required time resolution for all sizes
- Results generally consistent with light yield with respect to size differences
  - LYSO is a material with high light yield and good time resolution due to its large p.e. number

・Type

	time resolution[ps]
3x5x50(FTRL)	37
3x5x50(NORMAL)	45

FTRL time resolution is better than NORMAL

・Thickness

	time resolution[ps]
3x5x50(FTRL)	37
1.5x5x50(FTRL)	49

1.5mm Light yield is lower than 3mm thickness, and time resolution is also worse

・Length

	time resolution[ps]
3x5x50(FTRL)	37
3x5x100(FTRL)	40

Time resolution may be worse by light attenuation in the longitudinal direction

・Width

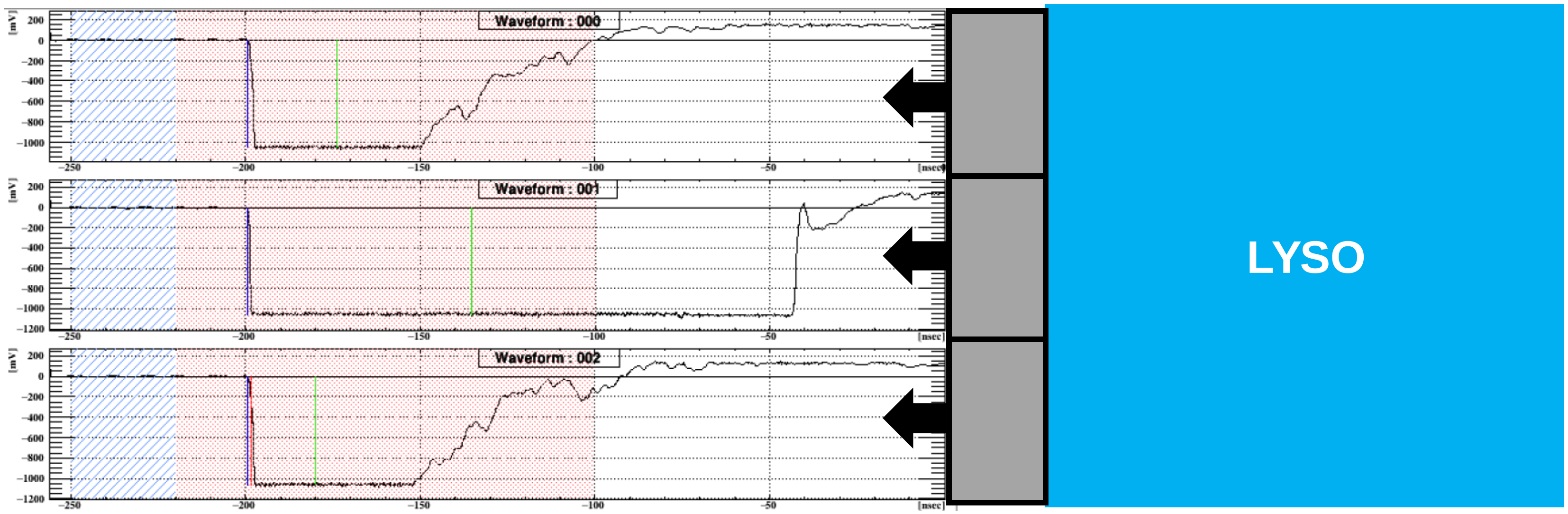
	time resolution[ps]
3x5x50(FTRL)	37
3x10x50(FTRL)	29

Possibility of good time resolution due to small ratio of MPPC insensitive area to LYSO side and high light collection rate

MPPC pixel pitch and connection

LYSO 3x10x50 (FTRL)	independent[ps]	series [ps]
10um	62.7	56.2
15um	42.3	38.1
50um	28.5	25.6

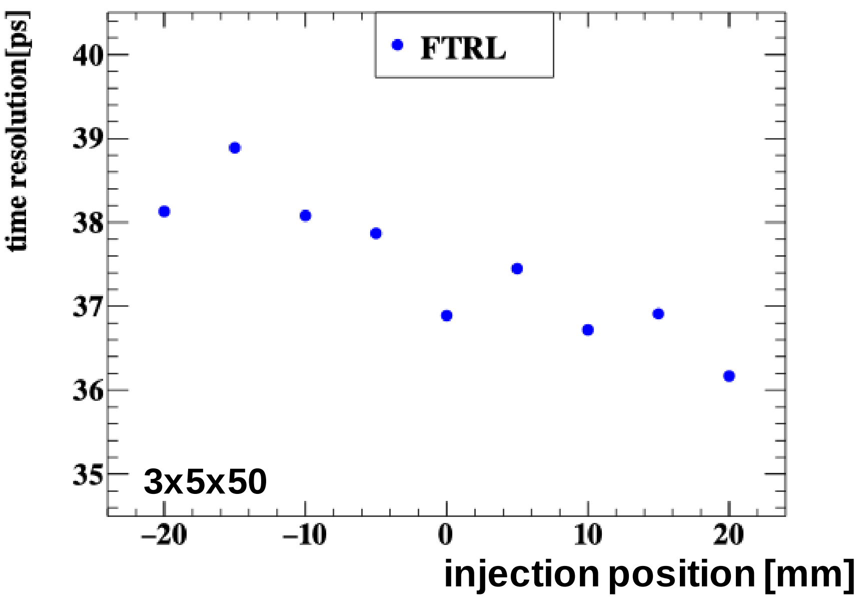
- The best readout method was a combination of 50um pixel size with large gain & series connection with good time response.
- Series connection has less deviation in waveform height than independent connection -> smaller effect of time walk (but may remain the same depending on time walk correction)



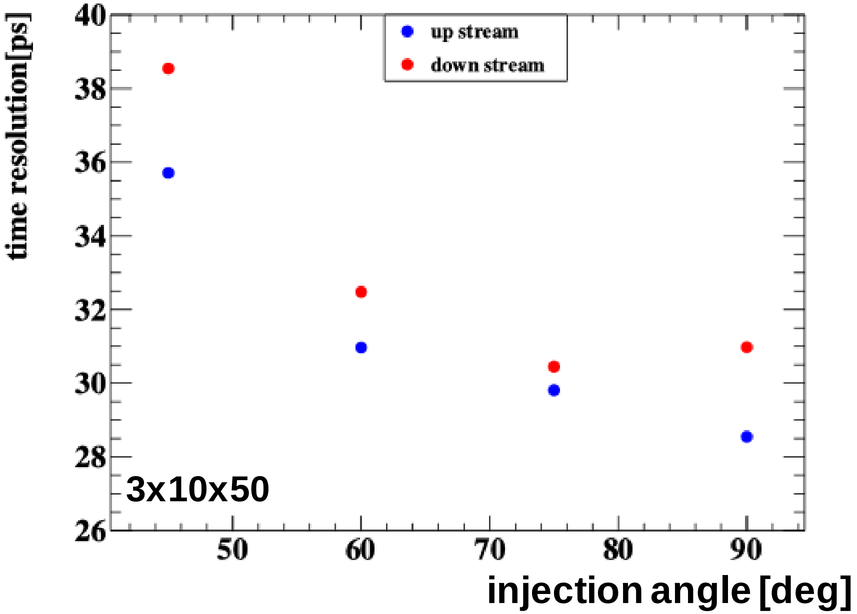
waveform of independent connection

Position & Angle dependence

- **position dependence**



- **angle dependence**



- Neither dependency has been accurately analyzed for its trend in a simple analysis
- Need to identify these dependencies through further detailed analysis

Summary

- Future experiments for $\mu^+ \to e^+\gamma$ decay search are planned.
- Pair spectrometer with active converter is being considered as a highly sensitive gamma detector
- In the beam test, many measurement conditions were evaluated to obtain the performance of the converter under optimum measurement conditions.
- The results showed that under the optimal measurement conditions, **the energy and time resolutions required by future experiments were satisfactorily achieved**

$\rightarrow$ The results obtained from simulations and beam tests will be very important information for the future design of active converters

Prospect

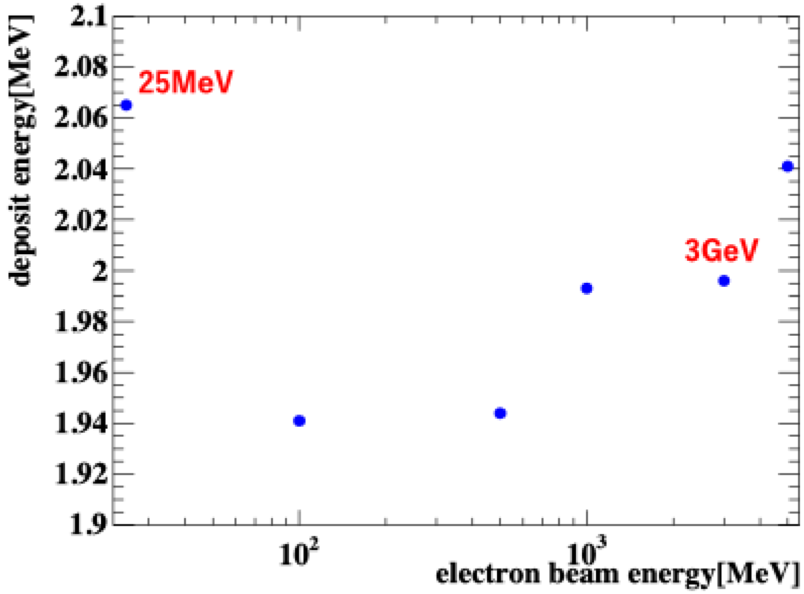
- Correction of time walk due to variations in wave height is also necessary.
- The positional and angular dependence of time resolution has not been adequately analyzed, and needs further investigation through detailed analysis.

Backup

Estimation of energy deposit in LYSO

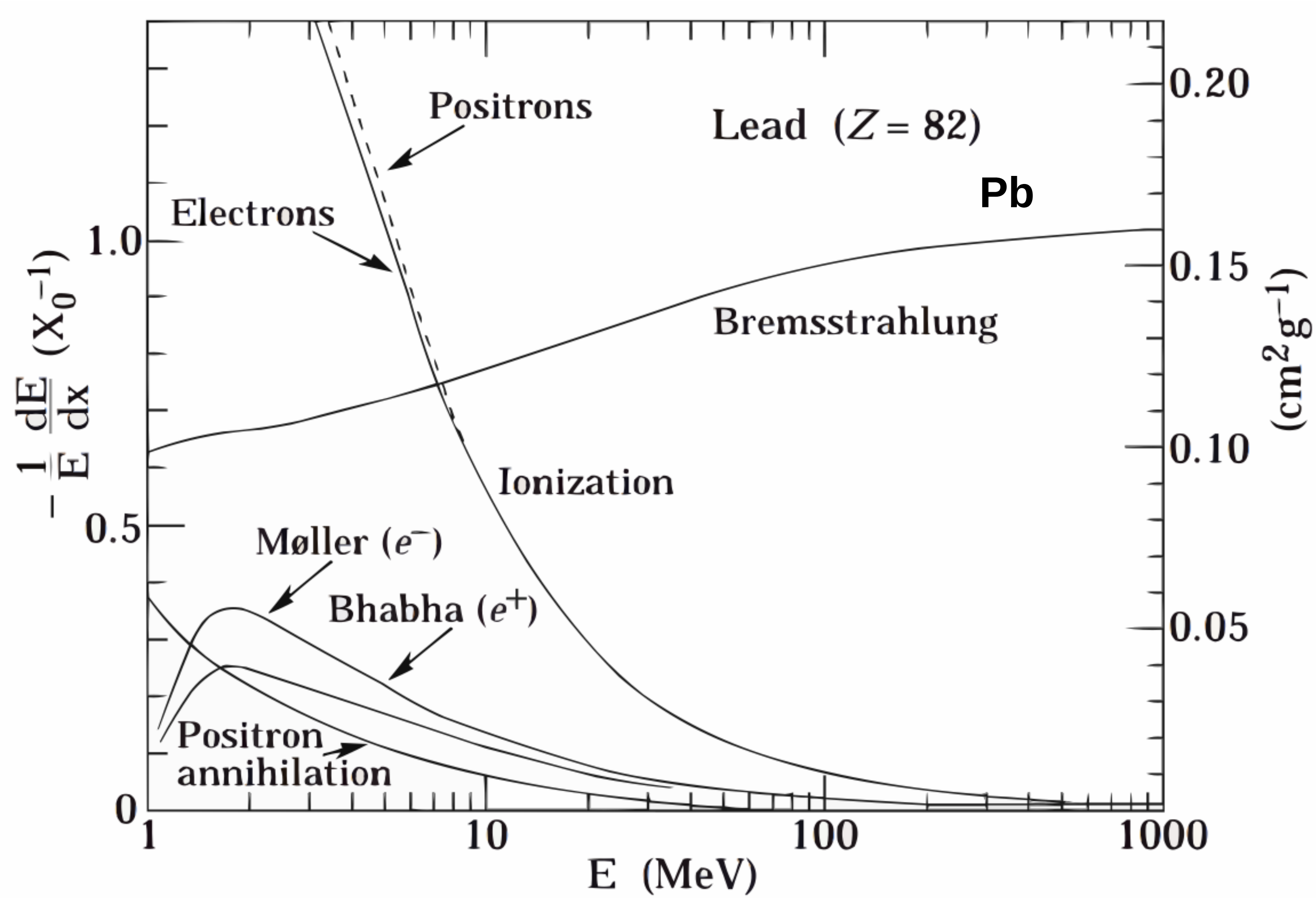
- **The light yield of 3 GeV (beam test) and ~52 MeV (electrons of $\mu^+ \to e^+\gamma$) may be different**

  → Deposit energy is compared by simulation



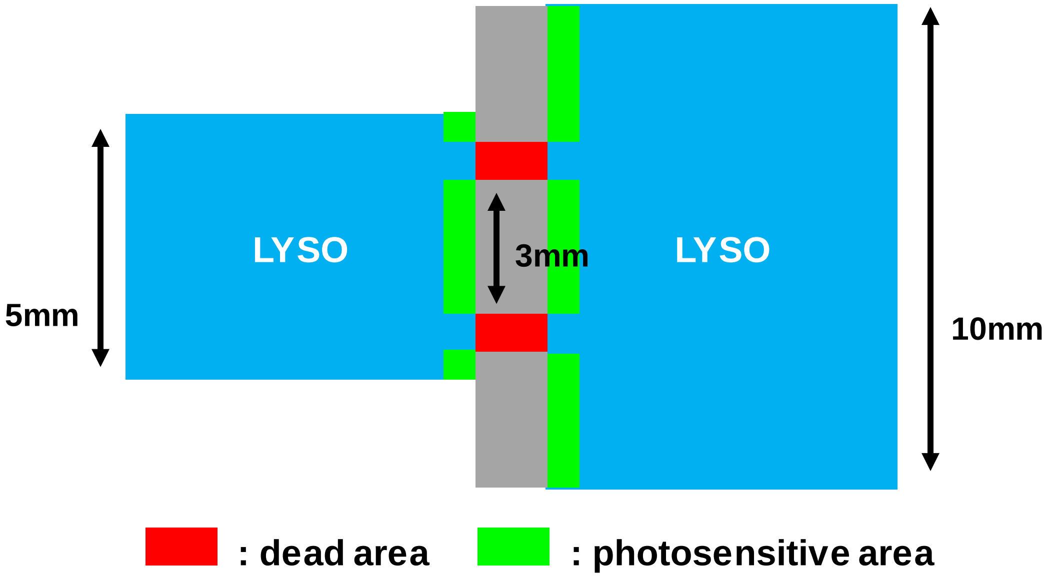
- **The difference in deposit energy between 25 MeV and 3 GeV is small**
- **Beam test results can be adapted to conversion pairs in future experiments**

dE/dX

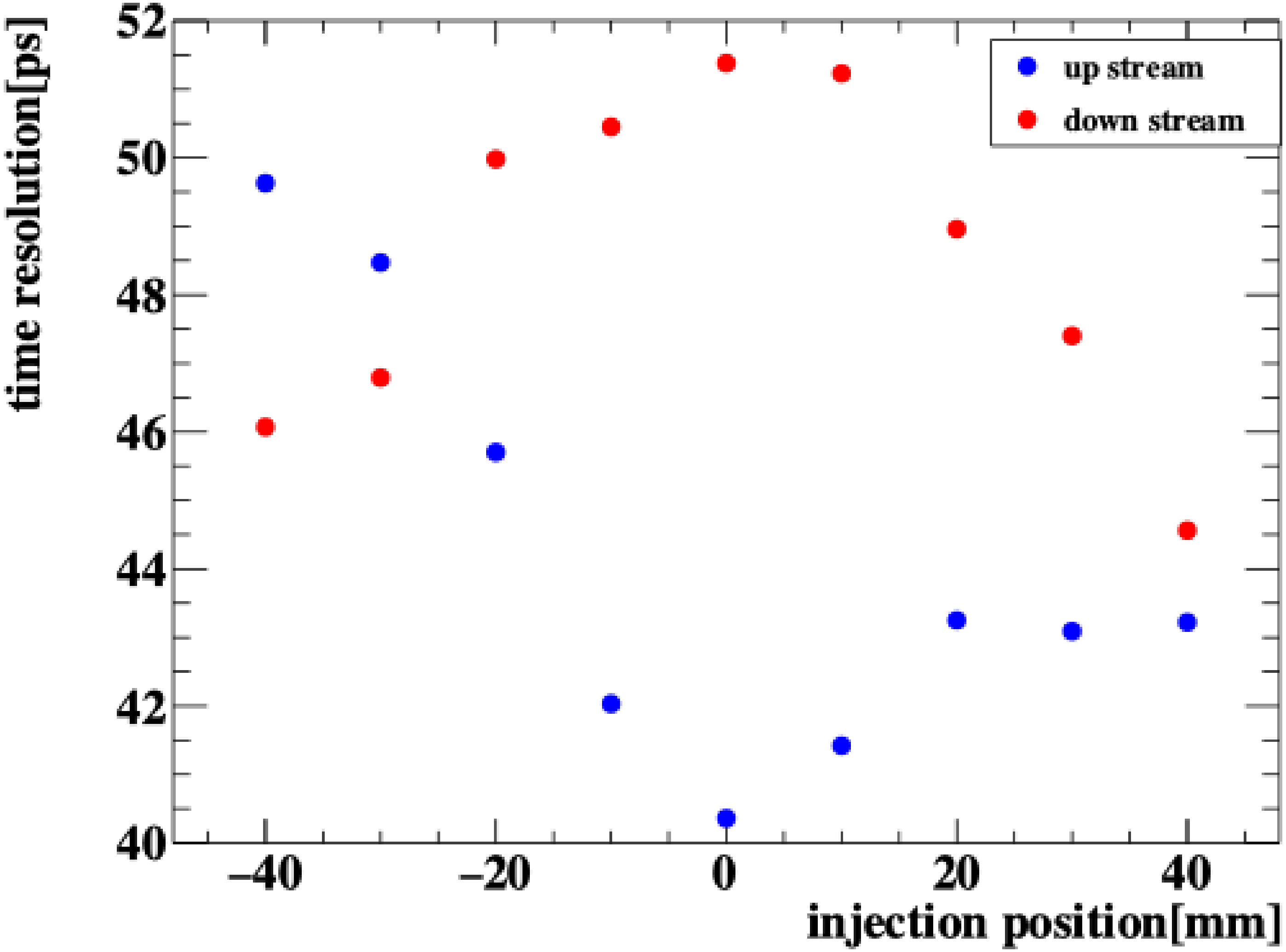


Positrons
Lead (Z = 82)
Pb
Electrons
1.0
0.20
0.15
0.10
0.05
Bremsstrahlung
Ionization
0.5
Møller (e⁻)
Bhabha (e⁺)
Positron annihilation
0
1
10
100
1000
E (MeV)
$-\frac{1}{E}\frac{dE}{dx}$ (X_0^{-1})
($cm^2 g^{-1}$)

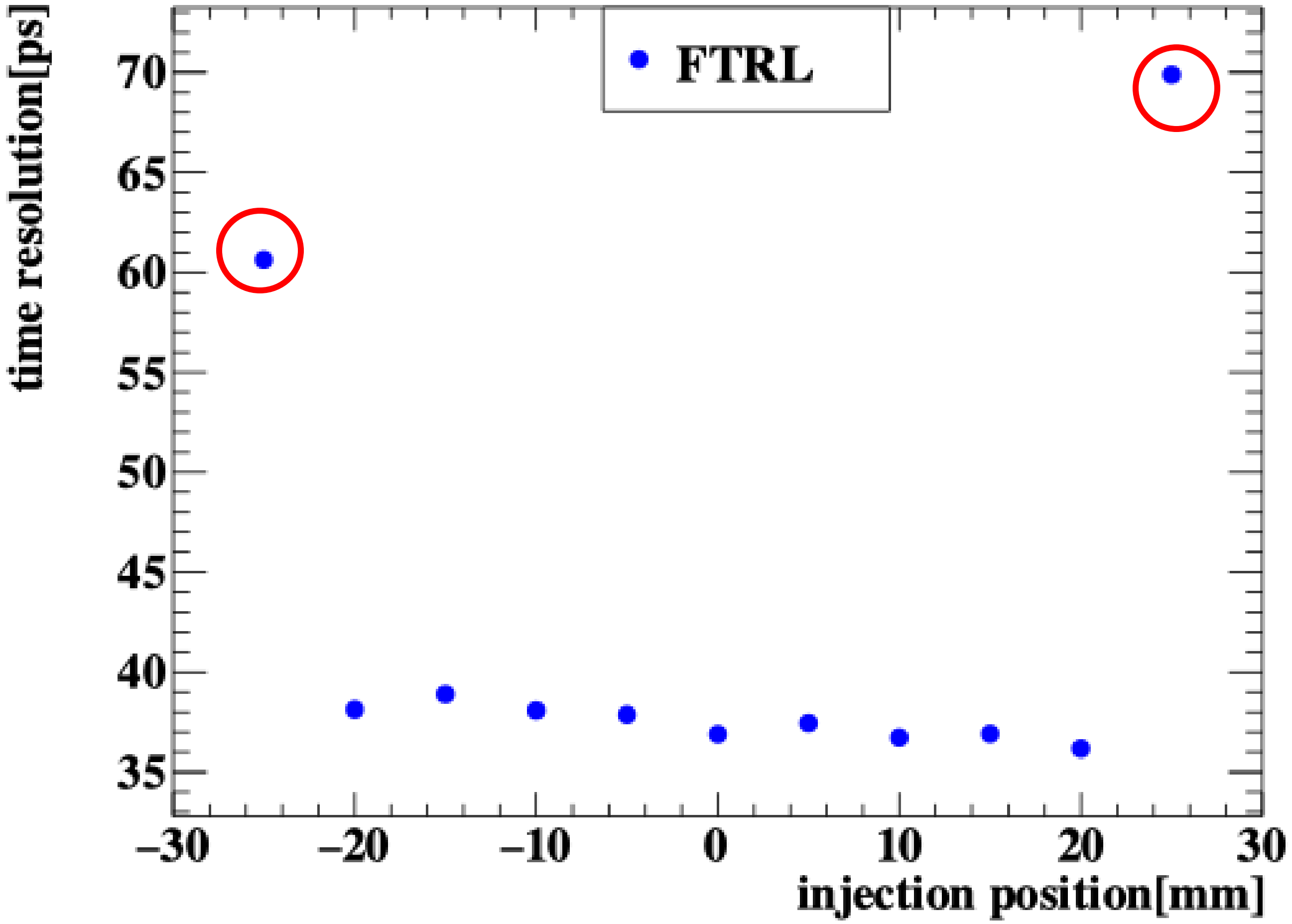
Difference in ratio of photosensitive area to LYSO sides for 10mm and 5mm widths



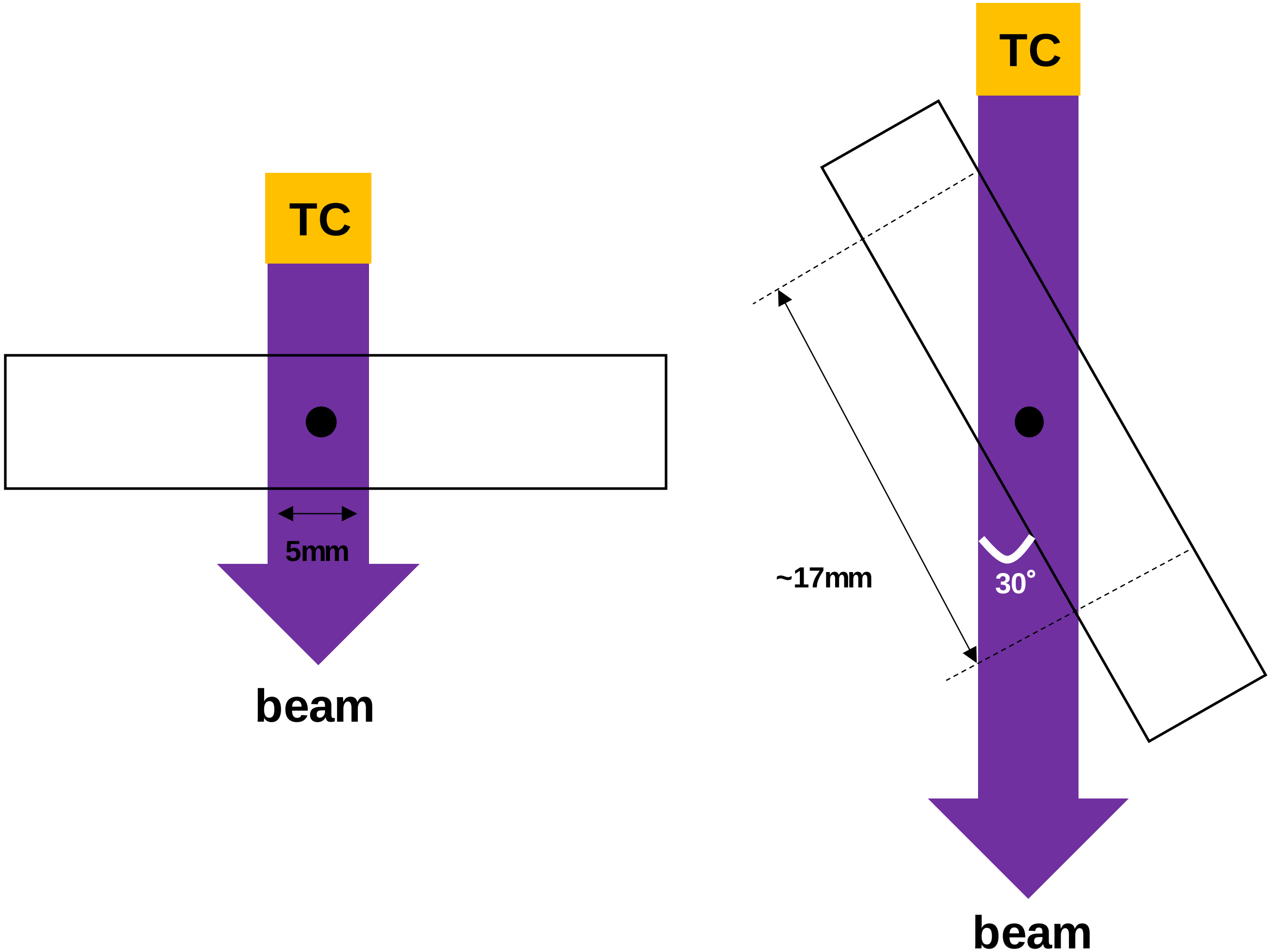
Difference of up stream and down stream



Anomaly of edge data



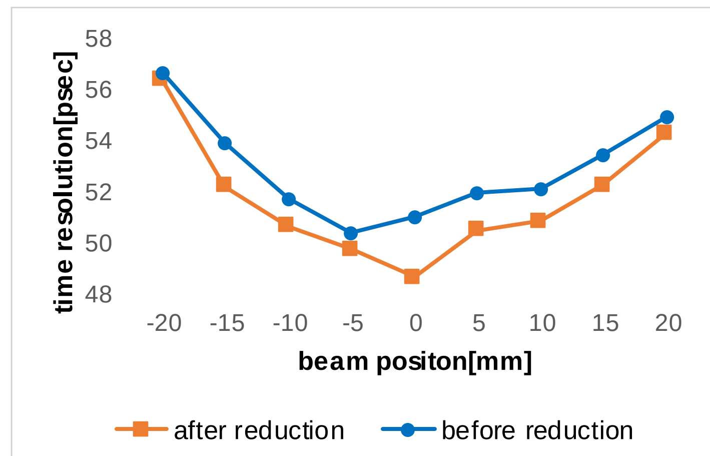
Difference in scintillation light spread



Effect of noise reduction

- **Time resolution was better, but only slightly, about 1 or 2 ps.**
- **The position-angle dependence was basically the same trend.**
  - **Still difficult to understand position angle dependence through noise reduction**

noise reduction	before	after
pitch		
10um, series	56.79	58.26
15um, series	38.76	38.12
50um, series	25.69	25.64
size(独立)		
FTRL	36.89	36.13
NORMAL	44.59	44.86
10w	28.55	28.5
1.5t	50.99	48.62
100l	40.36	39.6



ex) 1.5mm thickness
3ch independent connection