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

-LYSOによるアクティブコンバーター試作機の性能評価-

Development of Photon Pair Spectrometer for Next Generation μ → eγ Experiment
- Performance Evaluation by Electron beam -

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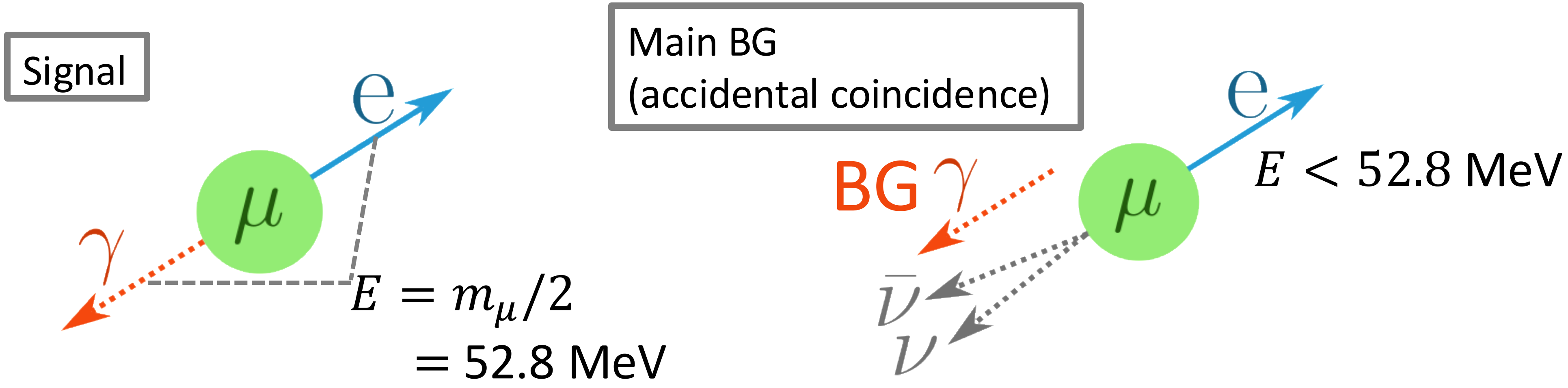
2025年9月18日　日本物理学会 第80回年次大会

$\mu \rightarrow e\gamma$ search

- One of the charged lepton flavor violation decay
  - Strongly suppressed ($Br \sim O(10^{-54})$) in SM + ν osc.
  - Measurable branching ratio ($Br \sim 10^{-14} - 10^{-11}$) in predicted in BSM (e.g. SUSY-GUT)
- $\mu \rightarrow e\gamma$ search experiment
  - Current UL : $Br(\mu \rightarrow e\gamma) < 1.5 \times 10^{-13}$ $(90\%\ C.L.)$ by MEG II @PSI
  - Target sensitivity of MEG II : 6×10^{-14}



- Strategy : precise measurement of kinematics

Future experiment for $\mu \to e\gamma$ search

Motivation

- Further search for $\mu \to e\gamma$ (target sensitivity $\mathbf{6 \times 10^{-14}}$ of MEG II → $\boldsymbol{O(10^{-15})}$)
- Precise measurement of $\mu \to e\gamma$ after discovery (BSM model selection)

Muon beam

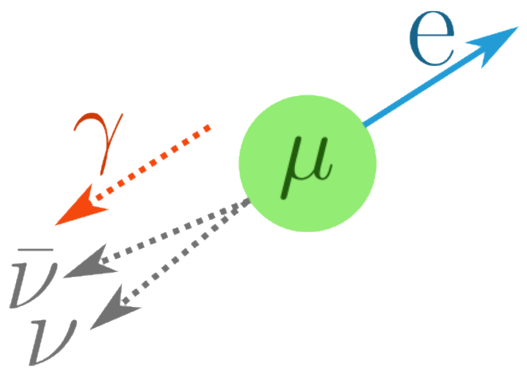
- Muon beamline upgrade planned at PSI, available from 2027-2028 (HiMB)
- $\sim\times\ 100$ muon beam rate (10^{10} μ / s)

Requirements for detector

- High resolution

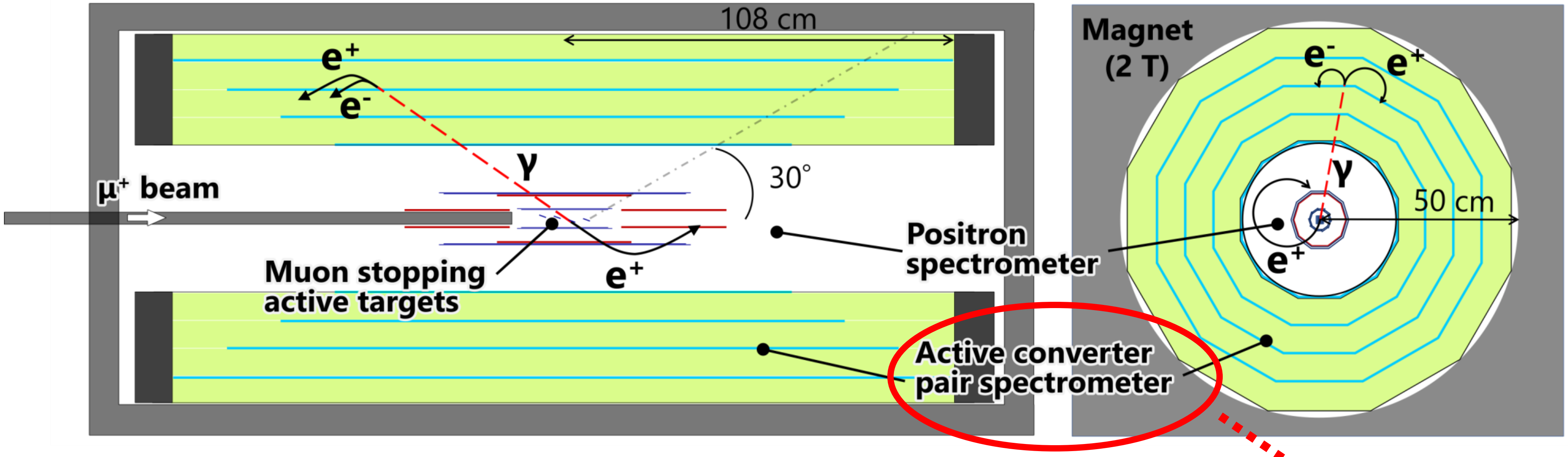
$$N_{\mathrm{acc}} \propto R_\mu^2 \cdot \Delta E_\gamma^2 \cdot \Delta p_e \cdot \Delta\theta_{e\gamma}^2 \cdot \Delta t_{e\gamma}$$

→ Resolution of gamma measurement is especially important



N_{acc} : Number of accidental background

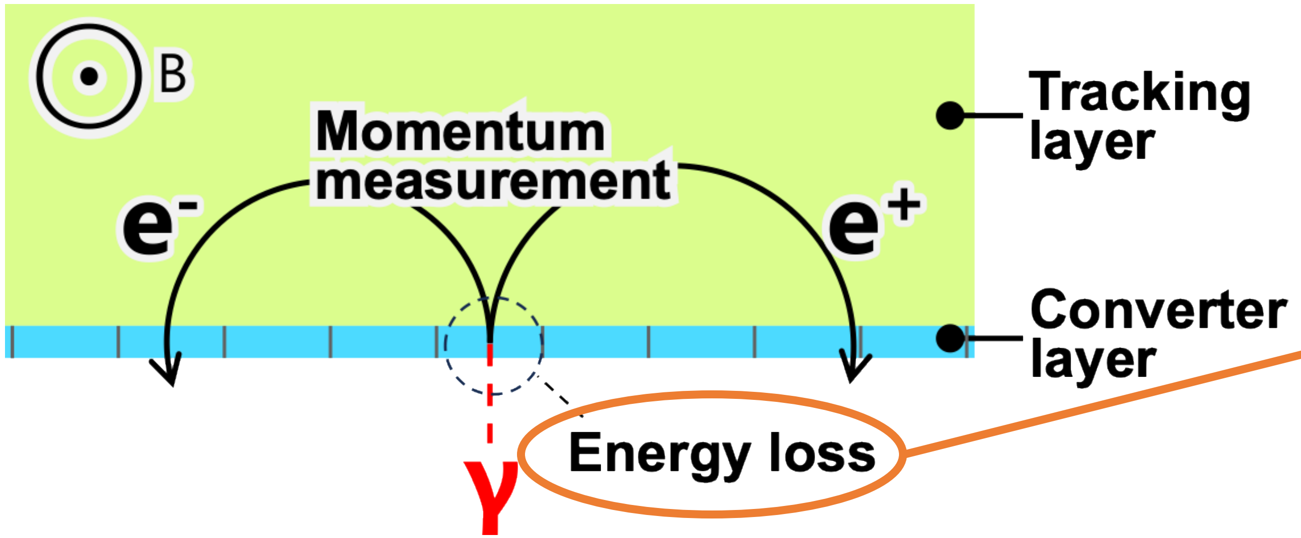
Detector concept

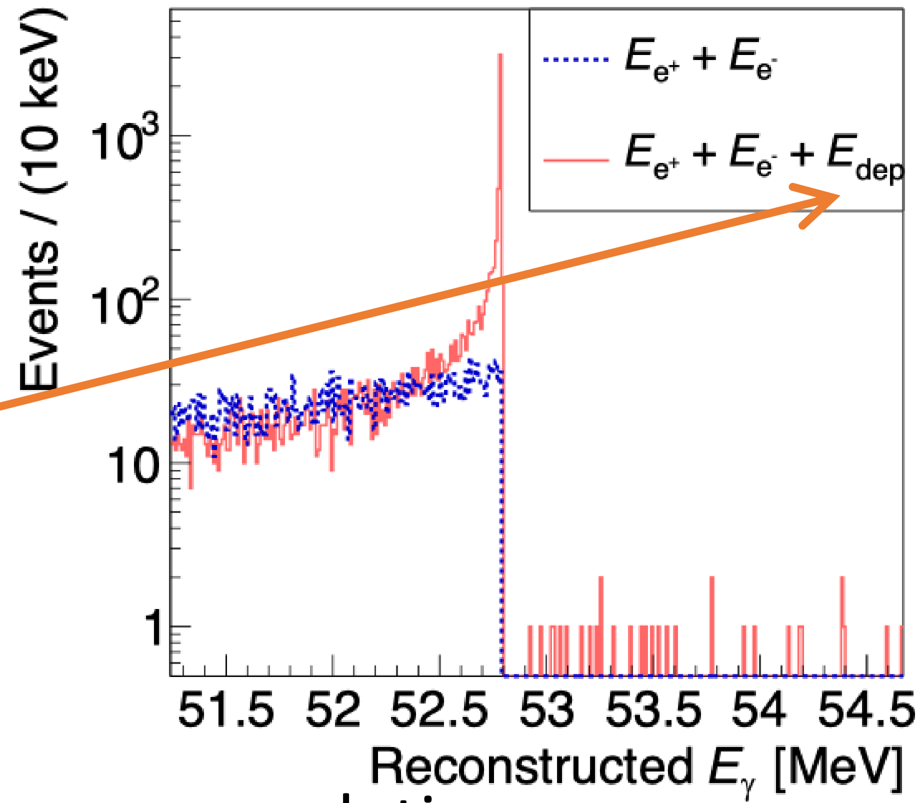


- 80-90% geometrical acceptance $(0 \leq \phi < 2\pi,\ 30° \leq \theta \leq 150°)$
- μ^+ stopping target : Active & split muon stopping target
- e^+ measurement : Spectrometer based on silicon sensor (HV-MAPS)
- γ measurement : **Pair spectrometer**

This talk!

Pair spectrometer





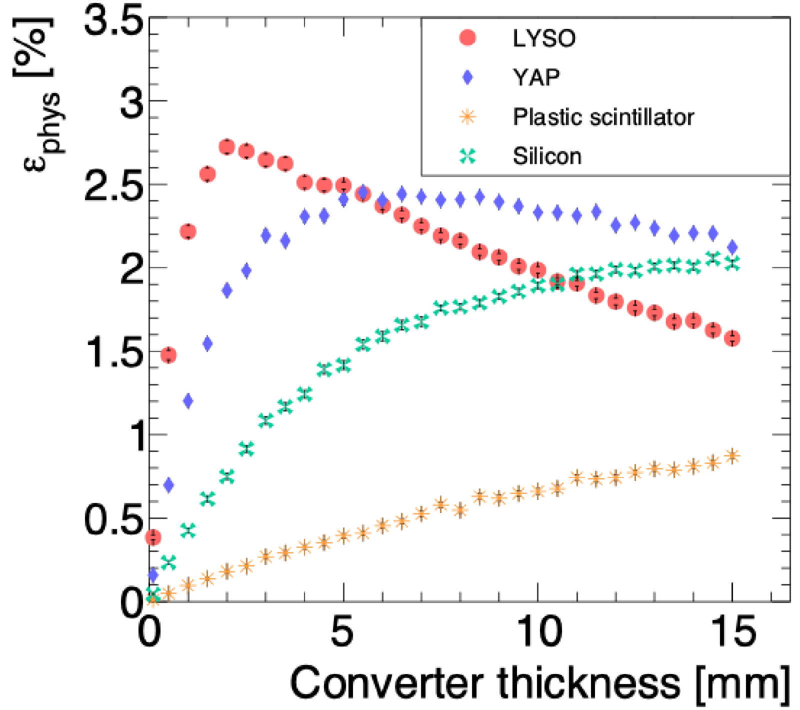
- High resolution & rate capability possible
- Energy loss inside the converter degrade energy resolution

Active converter
:measure energy (and also timing) by the converter itself

Converter geometry study by simulation

Converter material & thickness

Affects signal efficiency
which comes from <u>physical processes</u>

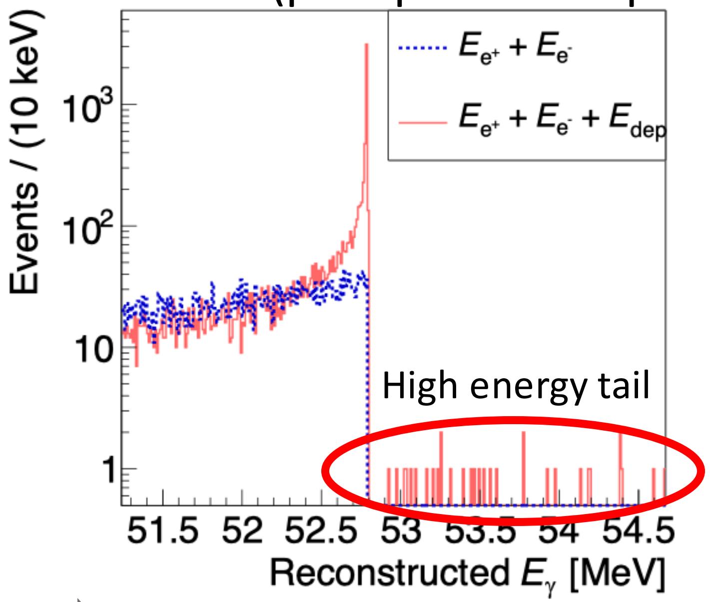


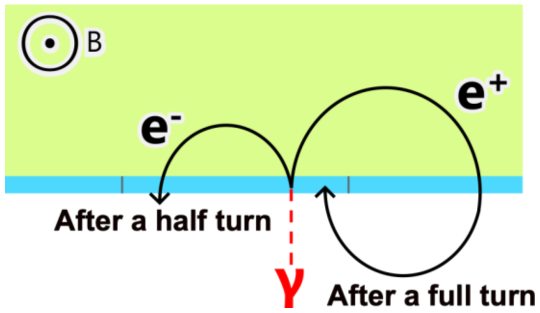
3 mm thickness LYSO has highest efficiency

Converter Segmentation

Affects signal efficiency
which comes from <u>topological features</u>

1. Conversion particle coming back to the same cell
2. (pileup from BG photon)





E_{dep} double count

5 mm × 50 mm cell size can suppress fraction of such topology enough

Motivation of beam test for LYSO converter

- Actual resolution of $3 \times 5 \times 50\ \mathrm{mm}^3$ LYSO cell needs to be confirmed
- Target

For **52.8 MeV γ** measurement

$$\Delta E_\gamma < 200\ \mathrm{keV}$$
$$\Delta t_\gamma < 30\ \mathrm{ps}$$

→

For **3 GeV electron beam** measurement

$$\text{Light yield} > 700\ \text{p.e.}$$
$$\Delta t < 40\ \mathrm{ps}$$

↘ Our goal for the beam test

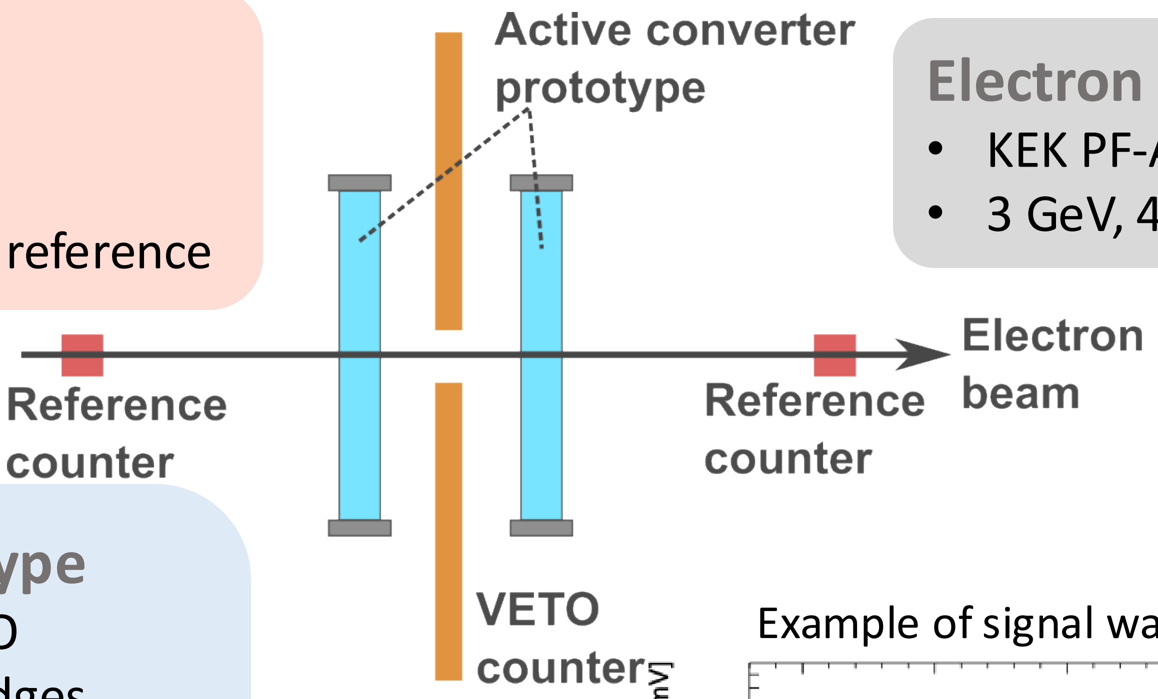
- Items to be studied in an electron beam test
  - Spatial uniformity within the LYSO cell
  - Performance with thinner LYSO (Described later)
  - Comparison of signal readout

Measurement setup

What is the actual performance of the LYSO bar?

Reference counters

- 3mm cube scintillator
  + SiPM readout
- Used for triggering & time reference



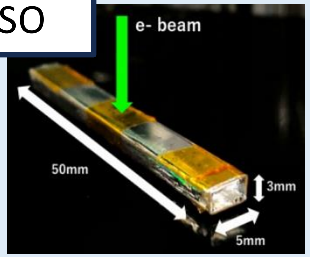
Electron beam line

- KEK PF-AR Test Beam Line
- 3 GeV, 4.5 kHz

Active converter prototype

- $3(1.5) \times 5 \times 50\ \mathrm{mm}^3$ LYSO
  + SiPM readout on both edges

LYSO



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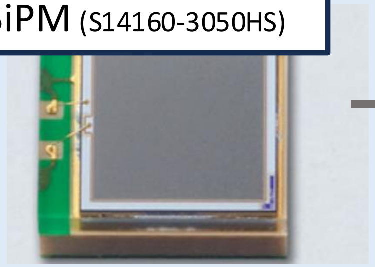
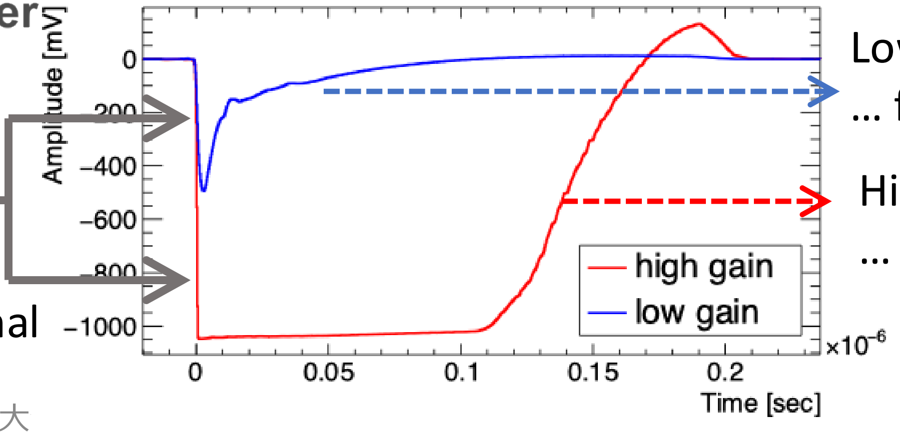
SiPM (S14160-3050HS)



Divide signal

Example of signal waveform



Low-gain
… for charge mes.

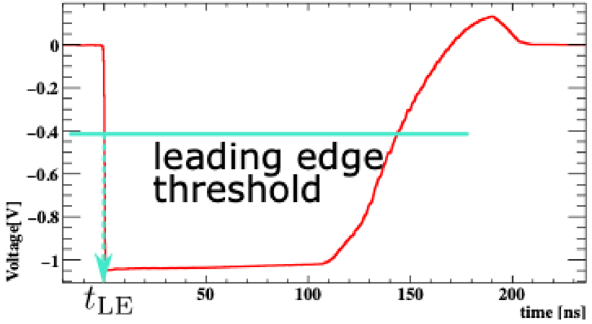
High-gain
… for timing mes.

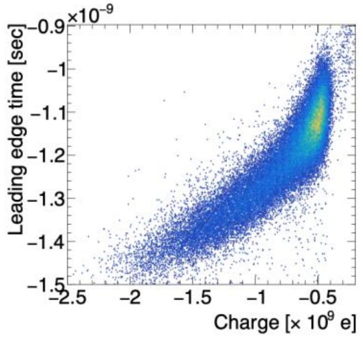
Analysis

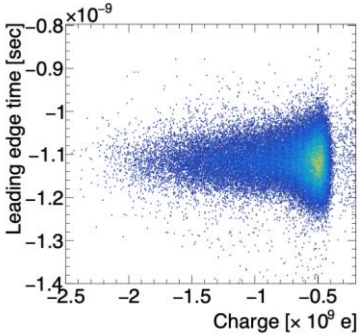
Time resolution

- Time pick-up by leading-edge method
  - Time-walk correction by charge
  - Threshold optimization

Before correction After correction



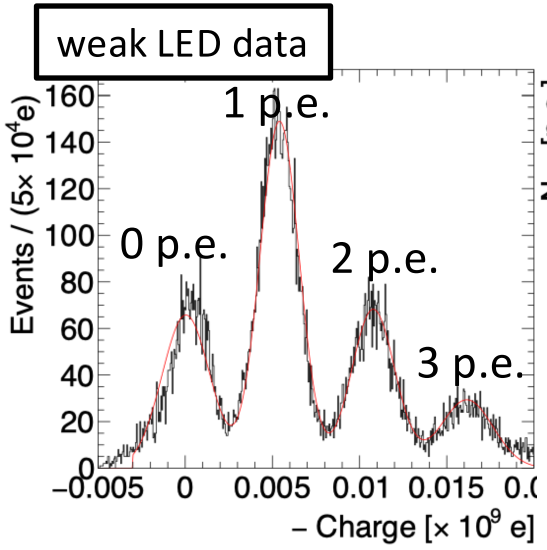


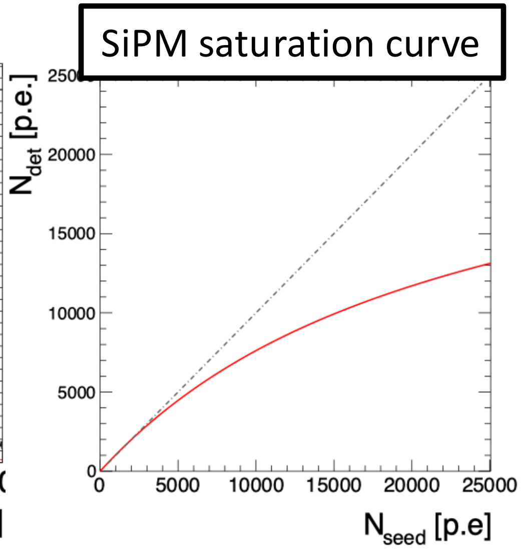


- Time resolution evaluation using reference time
  - $\sigma(t_{US\ LYSO} - t_{ref}) = \sigma_{US\ LYSO} \oplus \sigma_{ref}$
  - $\sigma(t_{DS\ LYSO} - t_{ref}) = \sigma_{DS\ LYSO} \oplus \sigma_{ref}$
  - $\sigma(t_{DS\ LYSO} - t_{US\ LYSO}) = \sigma_{US\ LYSO} \oplus \sigma_{DS\ ref}$

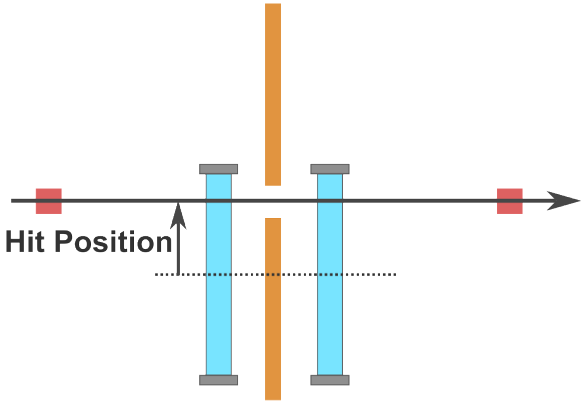
Light yield

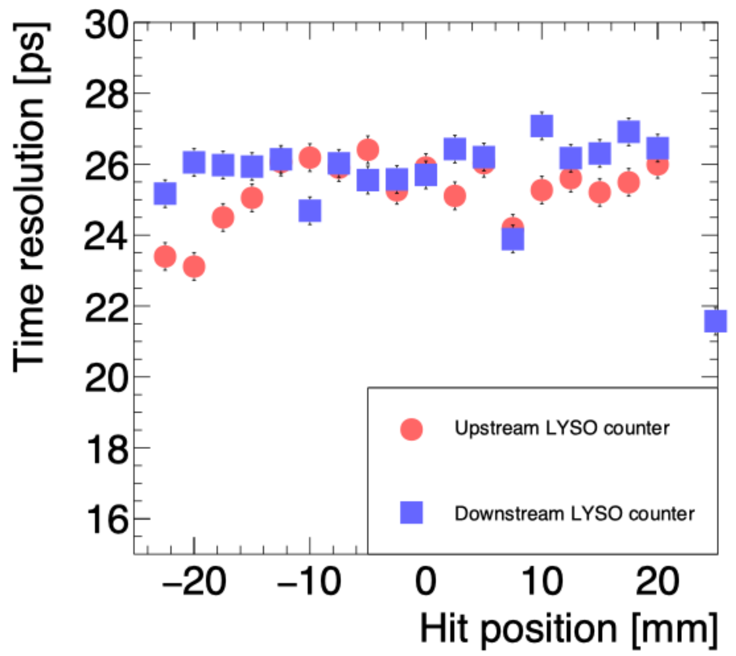
- Single photoelectron gain calibration with weak LED light
- Electronics gain calibration using exponential waveform output from function generator
- SiPM saturation correction with model (NIM A Volume 1064, July 2024, 169431)



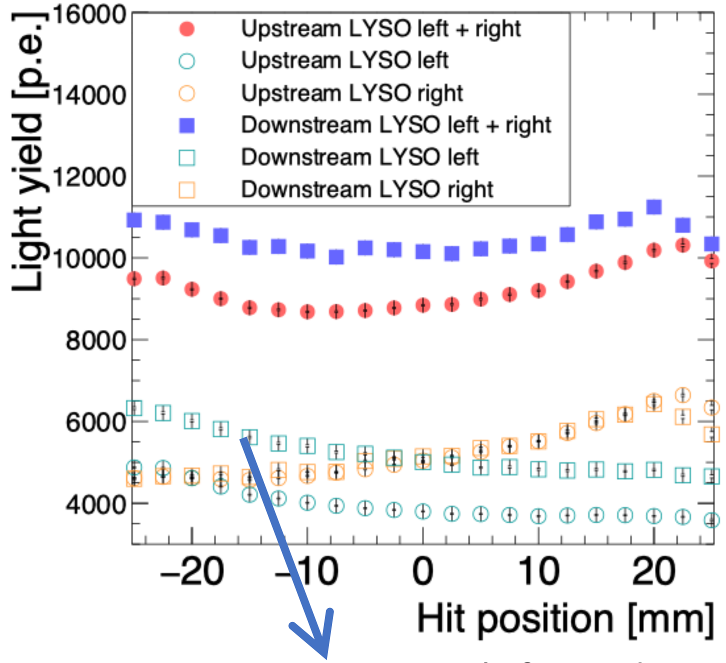


Position dependence





Event with light yield around MIP peak is selected



Downstream left readout channel had low light yield detection

→ Bad SiPM coupling quality?

→ $\sim$ 25 ps time resolution and $\sim 10^3$ p.e. light yield achieved over entire crystal region

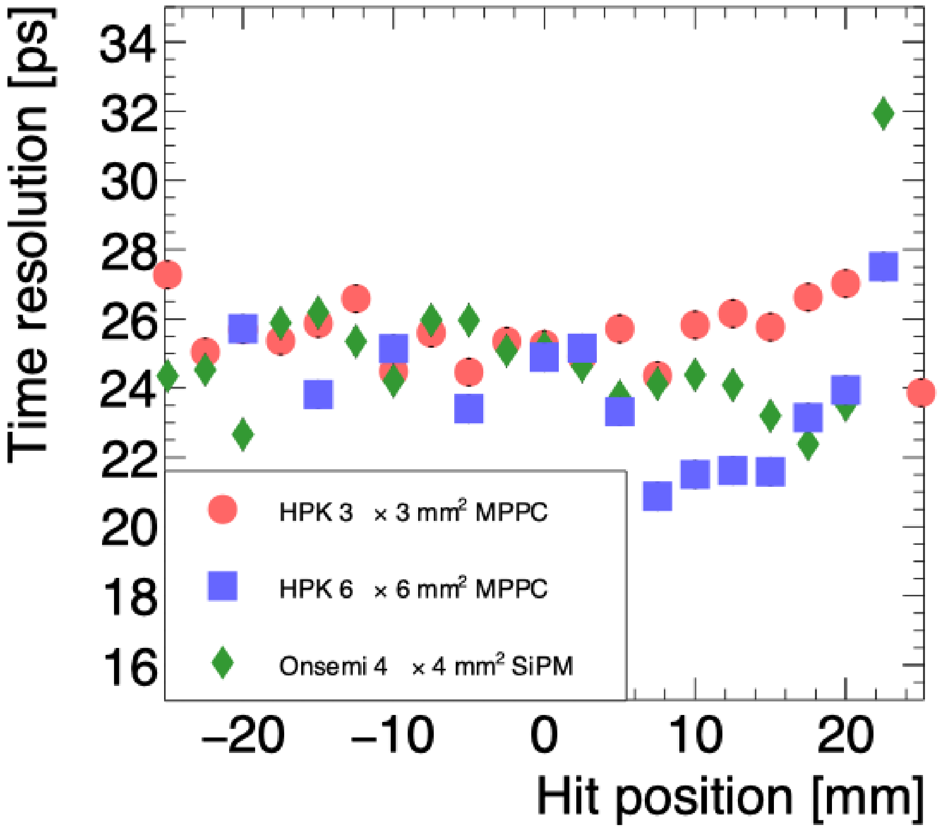
Comparison of readout SiPMs

SiPM model	Photosensitive area	Pixel pitch	Channels per side	Time resolution at center
S14160-3050HS	3×3 mm^2	50 μm	3 (series connected)	25.2 ± 0.4 ps
S14160-6050HS	6×6 mm^2	50 μm	1	24.9 ± 0.4 ps
MICROFJ-40025-TSV-TR1	4×4 mm^2	35 μm	1	25.2 ± 0.4 ps

S14160-6050HS

S14160-3050HS

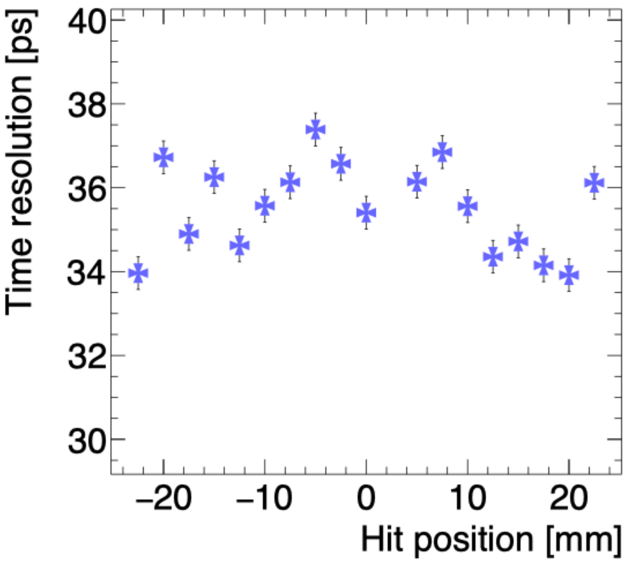
MICROFJ-40035-TSV-TR1

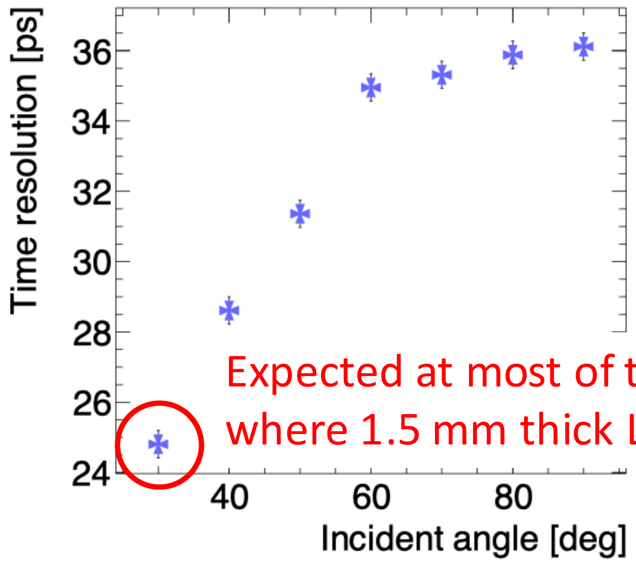


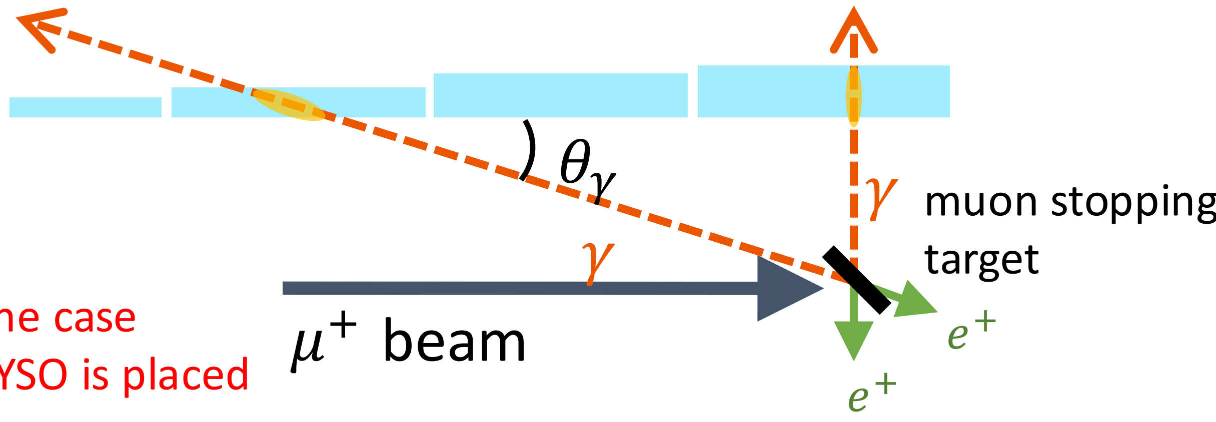
SiPM choise has little impact on time resolution

Performance of thin LYSO

- Converter segments in the outer part of the detector mainly receive photons with angle
- To make the effective path length equivalent, they will be made thin accordingly
  → Need to confirm the performance with thin LYSO







About $\times\sqrt{2}$ resolution compared to 3 mm thickness

Time resolution below 35 ps is achieved with thin LYSO

Discussions

- LYSO converter demonstrated excellent resolutions

<u>$3 \times 5 \times 50\ \mathrm{mm}^3$ LYSO readout by HPK $3 \times 3\ \mathrm{mm}^2$ MPPC</u>

	Target	Result
Light yield	> 700 p.e.	~ **10000 p.e.**
Time resolution	< 40 ps	~ **25 ps**

- Target resolution was achieved with all tested configurations as well

  → Almost no concern about resolutions in the design of LYSO converter

- A slight non-uniformity was observed across the crystal

  → Require careful calibrations

- Prospect : Demonstration of the measurement principle of pair-spectrometer
  - With gamma with monochromatic energy around 52.8 MeV
  - Evaluation of absolute energy resolution, conversion probability, …
  - Need preparation of pair-tracker

Summary

- Future $\mu \to e\gamma$ search experiment is planned with the target sensitivity $O(10^{-15})$
  - High rate capability & resolution required
  - Pair spectrometer with active converter is considered for photon measurement

- Simulation study was conducted to optimize the geometry
  - $5\ \mathrm{mm} \times 5\ \mathrm{mm} \times 3\ \mathrm{mm}$ LYSO was found to be the primary candidate in terms of signal efficiency, rate capability, number of readout channels etc.

- An electron beam test was conducted to confirm performance of LYSO
  - Excellent **time resolution below 25 ps** and **light yield over 10000 p.e.** was observed
  - Comfortably satisfy the target of 40 ps/MIP and 600 p.e./MIP

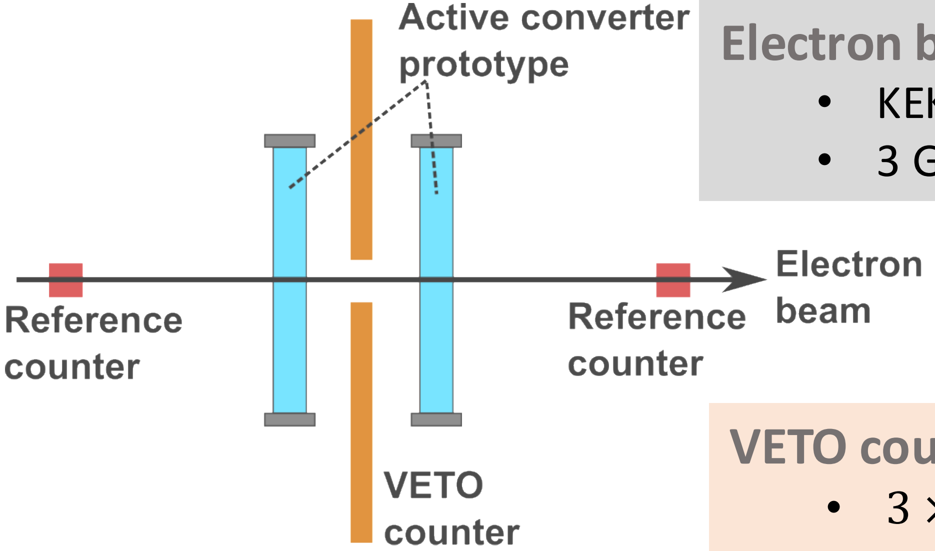
Backups

Measurement setup

What is the actual performance of the LYSO bar?

Reference counters

- 3mm cube scintillator + SiPM readout
- Used for triggering, event selection, and time reference



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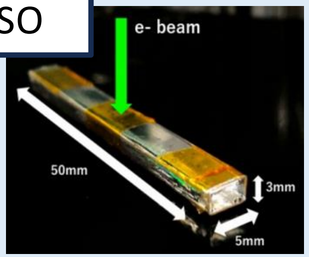
LYSO



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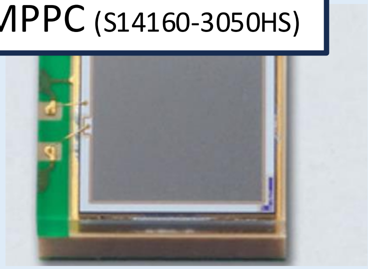
MPPC (S14160-3050HS)



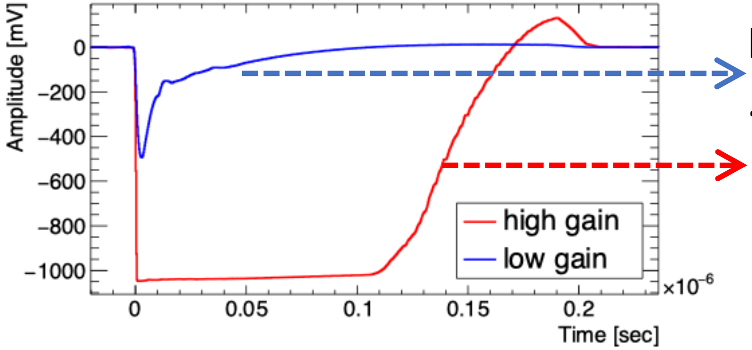
VETO counter

- $3 \times 30 \times 60\ \mathrm{mm}^3$ plastic scintillator + SiPM readout
- For multi-particle event rejection

DAQ

- Digitization with WaveDREAM board
- Split signal and record with with high-gain and low-gain
- 4-5GHz sampling, trigger rate ~ 25 Hz

Example of signal waveform



Low-gain
… for charge (energy) mes.

High-gain
… for timing mes.

LYSO Properties

JTC's Scintillation Product Information

Properties	Ce:FTRL	Ce:LYSO	YSO
Coincident Time Resolution(ps) 2mm cube	96	125	
LO (Ph/MeV)	30000±10%	36000±10%	27000
Decay Time (ns)	31	40	70
Energy Resolution	8-10%	8-10%	11%
Hygroscopic	No	No	No
Wavelength of Max Emission (nm)	420	420	420
Refractive Index	1.81	1.81	1.8
Density (g/cm3)	7.2	7.2	4.5

Comparison of readout SiPMs

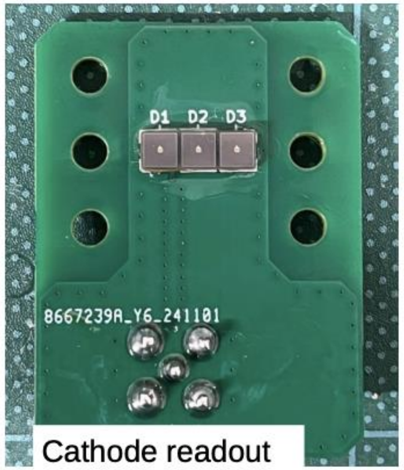
$6 \times 6\ \mathrm{mm}^2$ 50 μm pitch
Hamamatsu MPPC

Cathode readout
output & +HV

S14160-6050HS

- 100 % coverage of LYSO cross section

$3 \times 3\ \mathrm{mm}^2$ 50 μm pixel pitch
Hamamatsu MPPC

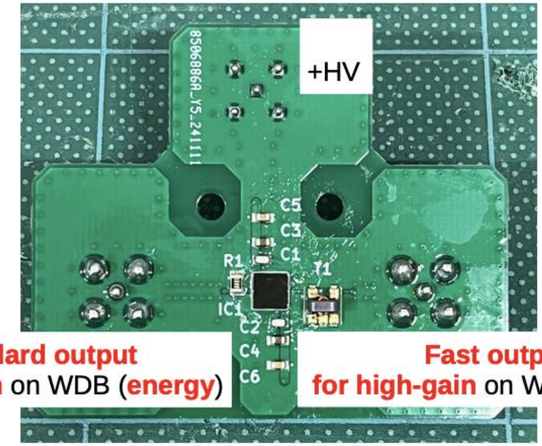


Cathode readout
output & +HV

S14160-3050HS

- Connected in series
- Small inactive area (gap between MPPCs)

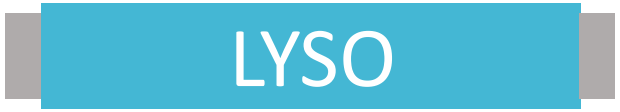
$4 \times 4\ \mathrm{mm}^2$ 35 μm pixel pitch
Onsemi SiPM



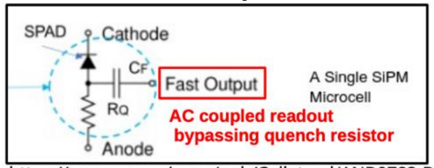
Standard output for low-gain on WDB (**energy**)

Fast output for high-gain on WDB (**timing**)

MICROFJ-40035-TSV-TR1

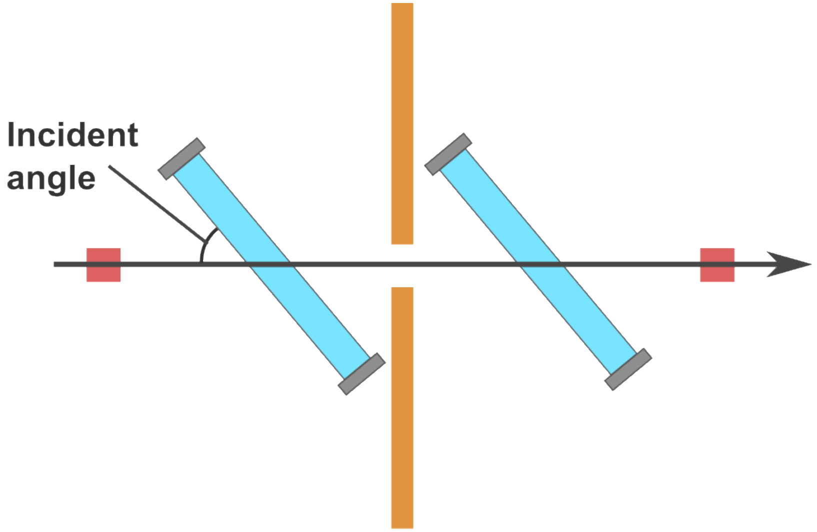


- Unique feature of having “fast output”

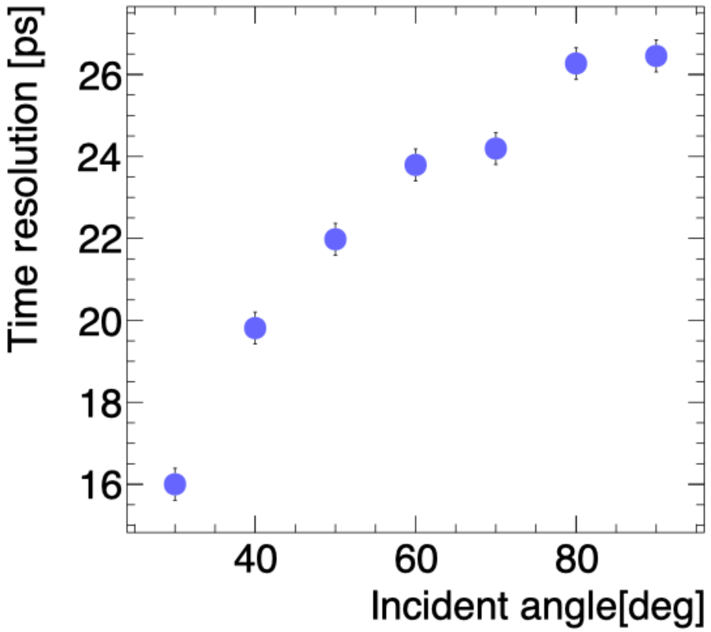


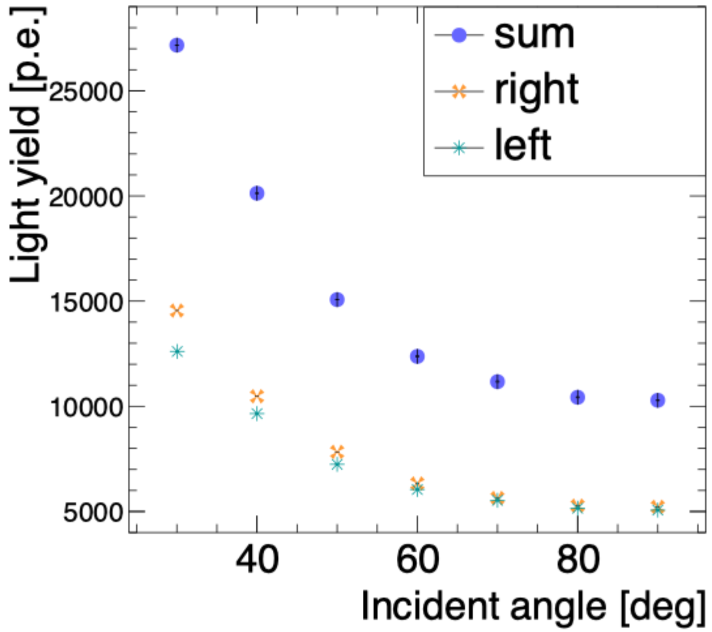
https://www.onsemi.com/pub/Collateral/AND9782-D.PDF

Angle dependence



Results with the LYSO placed on the downstream side



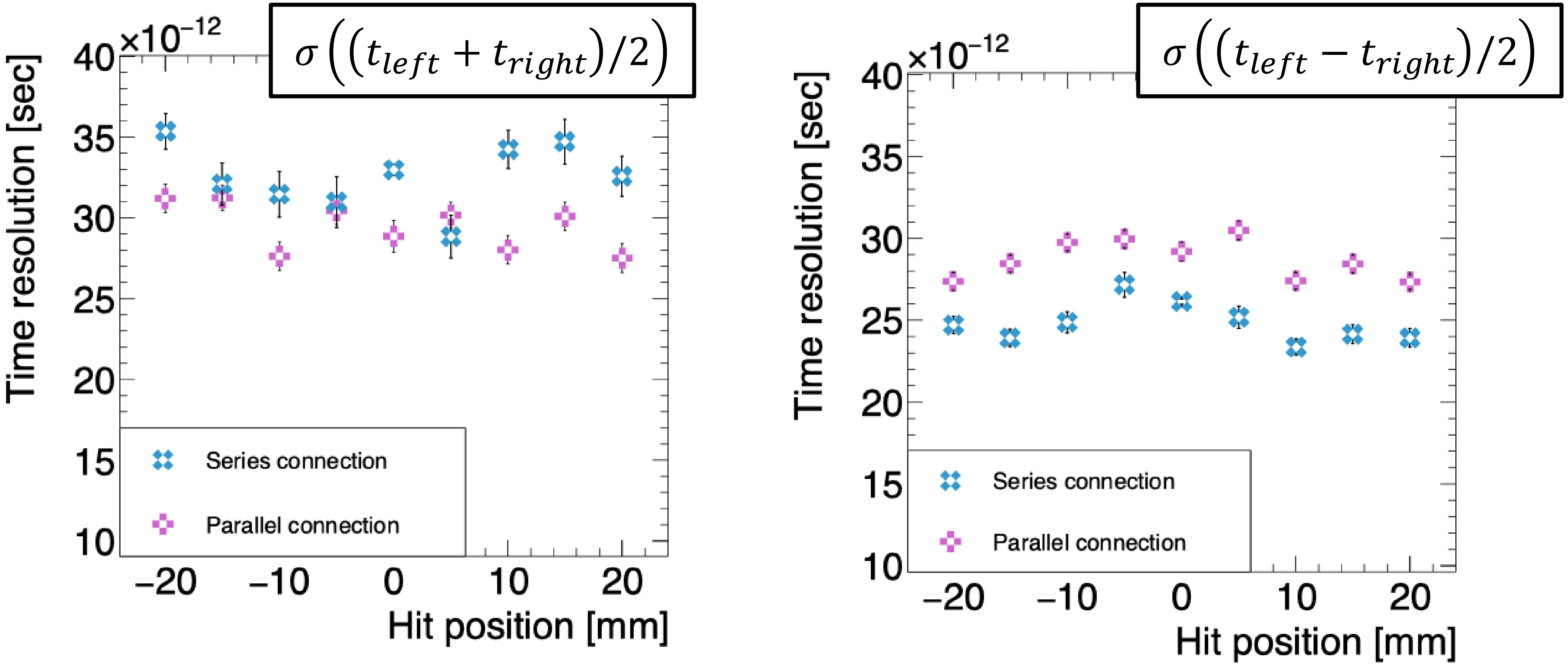


- Path length of the beam inside the converter scales as $\propto 1 / \sin\theta$
- Time resolution improves with the increase of light yield

Expected behavior observed in beam injection with angle

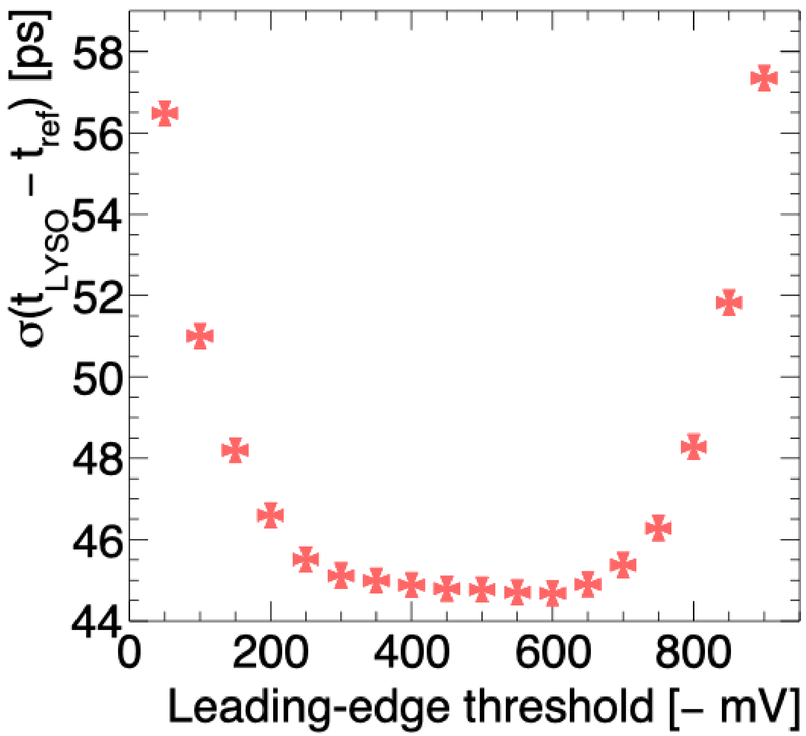
Comparison of SiPM connection method

- Compared in beamtest 2023 … low gain data not taken → walk correction with TOT
- Imperfect walk correction
  - Time resolution gets better when evaluated by $\sigma\left((t_{left} - t_{right})/2\right)$ than $\sigma\left((t_{left} + t_{right})/2\right)$
- Comparing $\sigma\left((t_{left} - t_{right})/2\right)$, series connection performs better

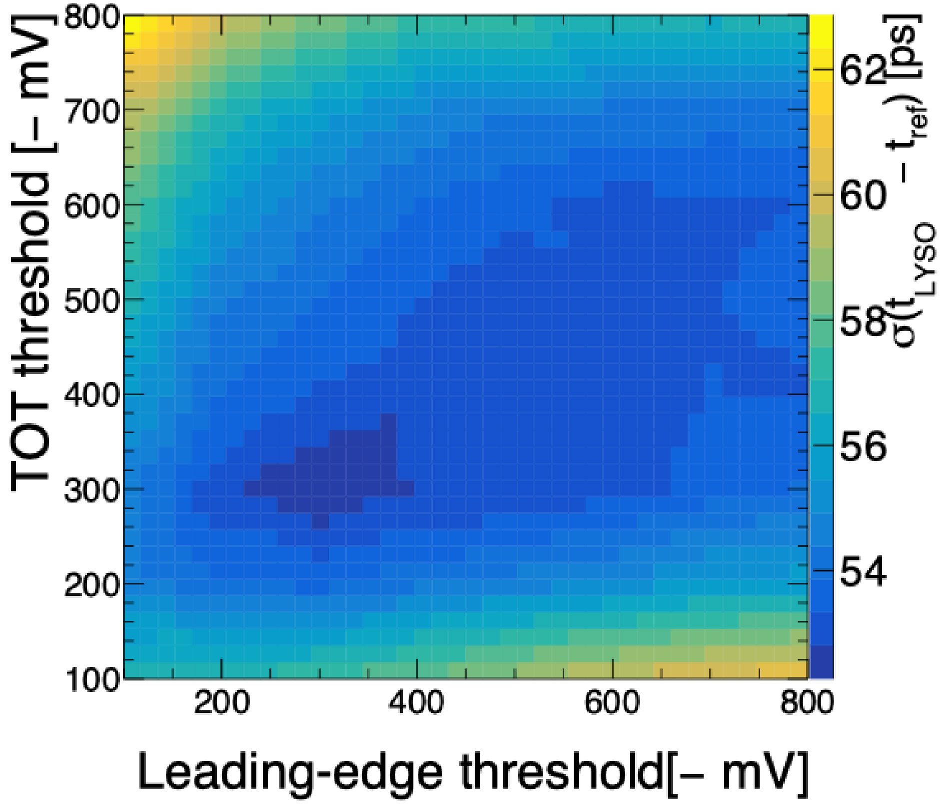


Threshold optimization for time analysis

Leading-edge
(when charge was used for walk correction)



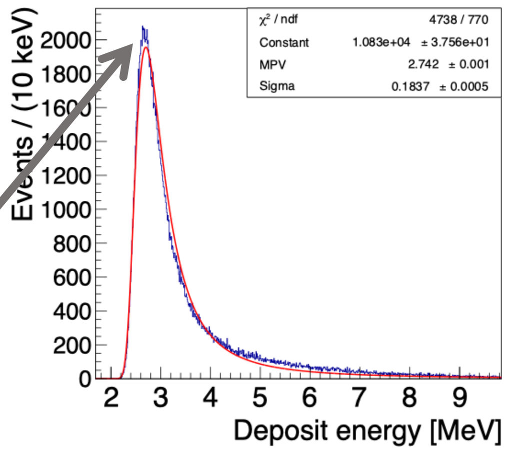
Leading-edge & TOT
(when TOT was used for walk correction)



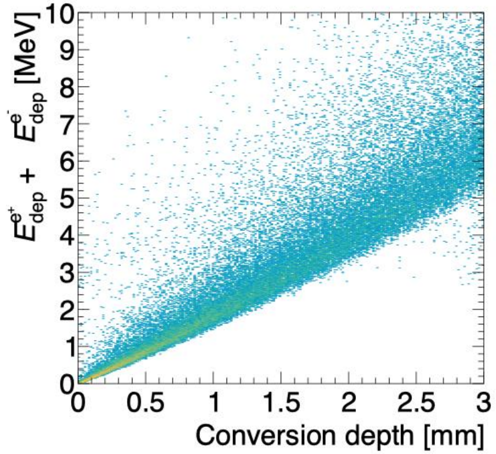
Requirements for the future experiment

Energy resolution : 0.4% at signal energy (52.8 MeV)

- Maximum 10 MeV energy deposit / pair
  → 2% energy resolution at 10 MeV
  is required for the active converter
  → $\frac{1}{\sqrt{N_{\mathrm{p.e.}}}} < 2\%$
  i.e., $N_{\mathrm{p.e.}} > 2500$ required at 10 MeV deposit
- $N_{p.e.} > 700$ required at 2.7 MeV deposit



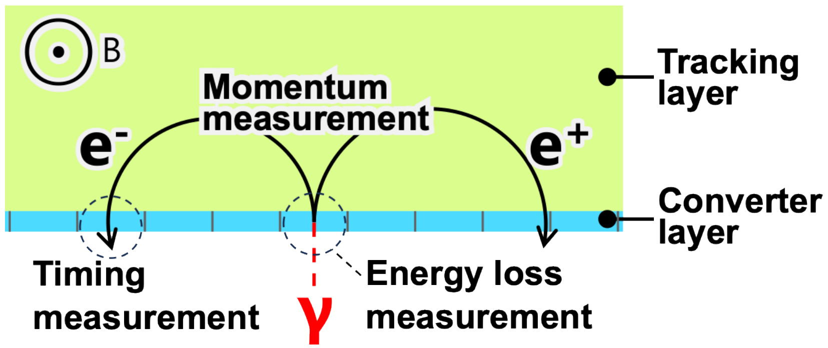
Energy deposit in LYSO by a 3 GeV electron beam



Energy deposit in LYSO by conversion pair

Time resolution : 30 ps for one gamma)

- $t_\gamma = (t_{e^+} + t_{e^-})/2$
- $\Delta t_\gamma < 30\ \mathrm{ps}$ ➡ $\Delta t_{e^\pm} < 30\ \mathrm{ps} \times \sqrt{2} = 40\ \mathrm{ps}$



Update from the last beam test

Beam test in 2023 Dec.

reported in JPS 2024 autumn , 16aWB106-01

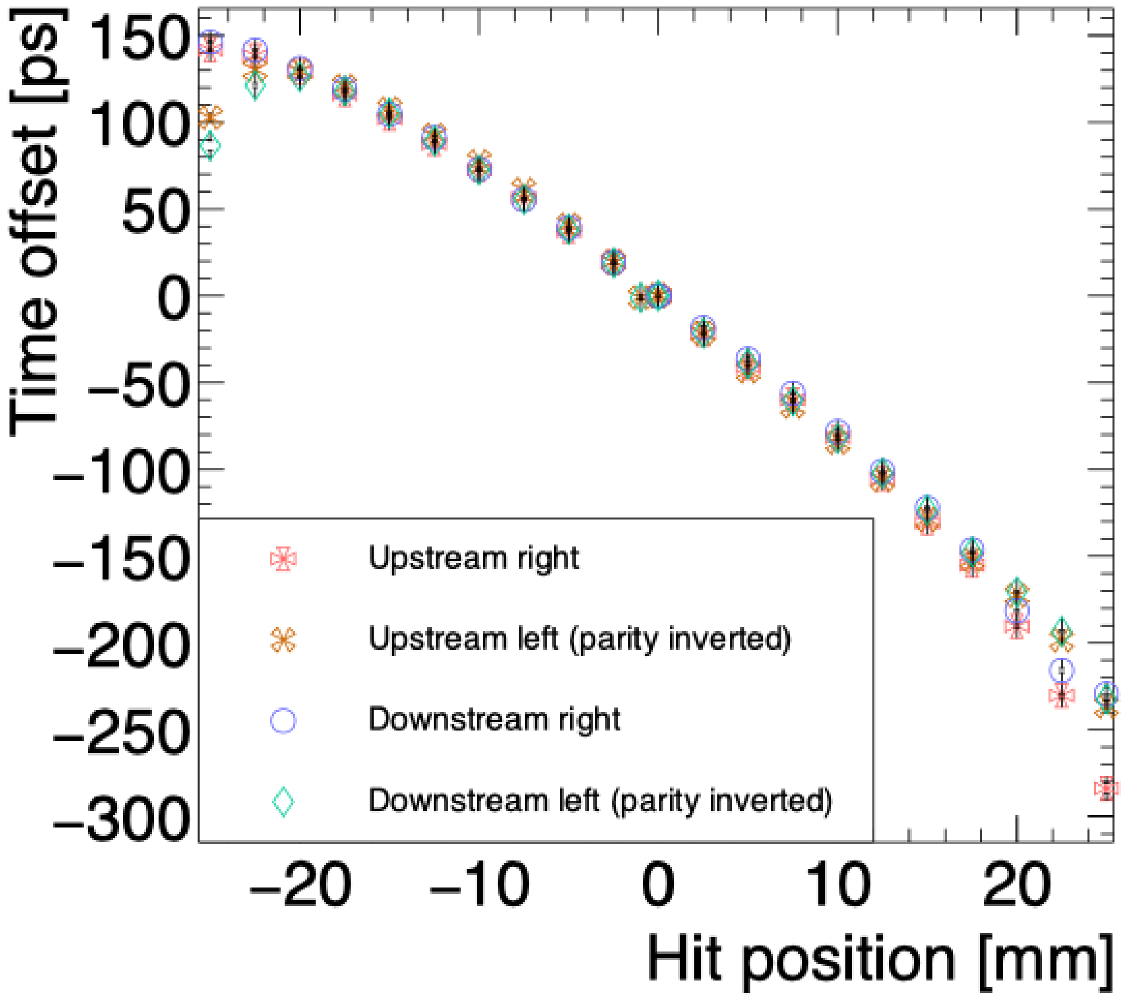
- Demonstrated time resolution of 30-35 ps & $O(10^3\ \mathrm{p.e.})$ light yield
- However, several rooms for improvements left
  - The signal was recorded only with high (or low) gain
  - Time walk correction by TOT → Remaining effect of time walk observed
  - Other details (out-sourcing readout board etc)

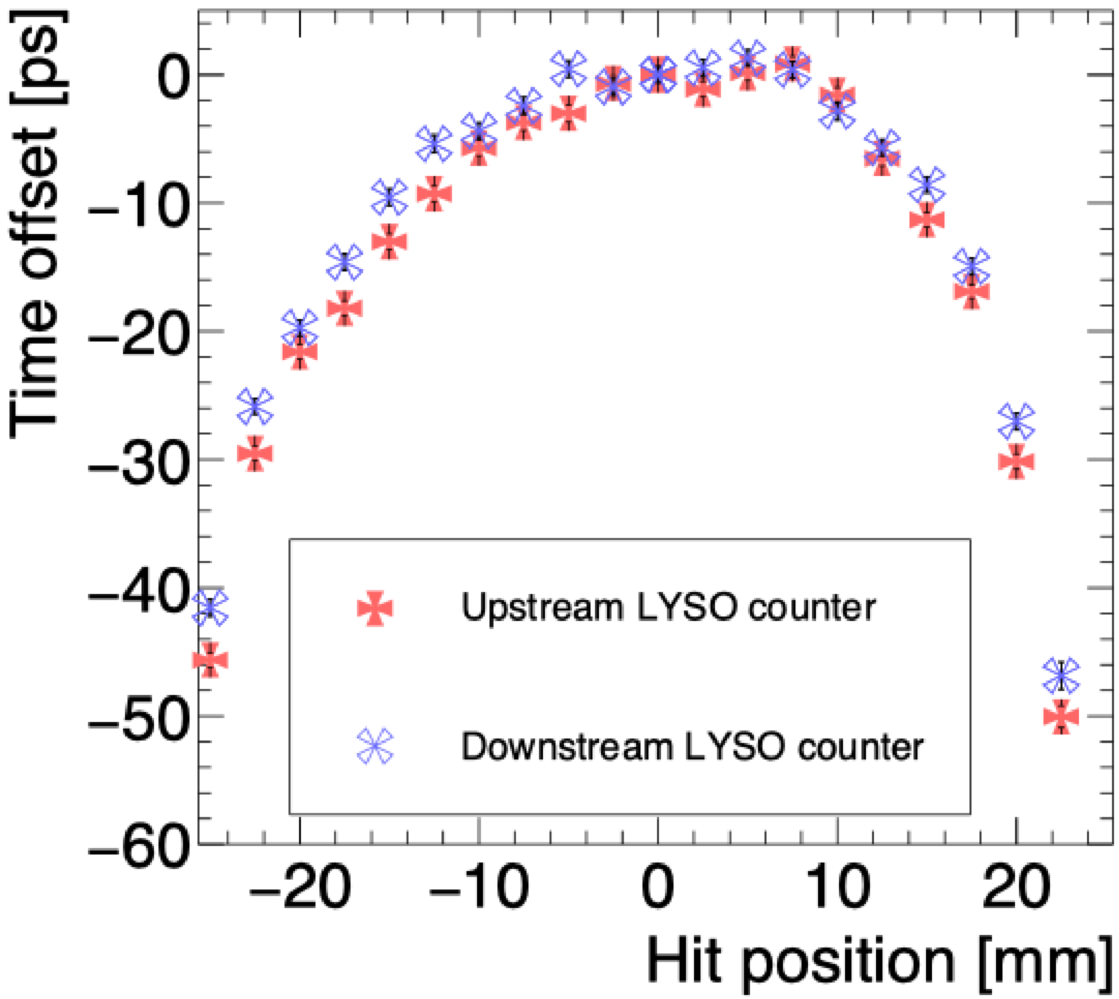
Beam test in 2024 Dec.

This talk

- Simultaneous DAQ with high & low gain
  - For better time walk correction
  - Towards the actual experiment (Both timing and energy must be measured)
- Trial with different types of SiPMs
- Introduction of the VETO counter

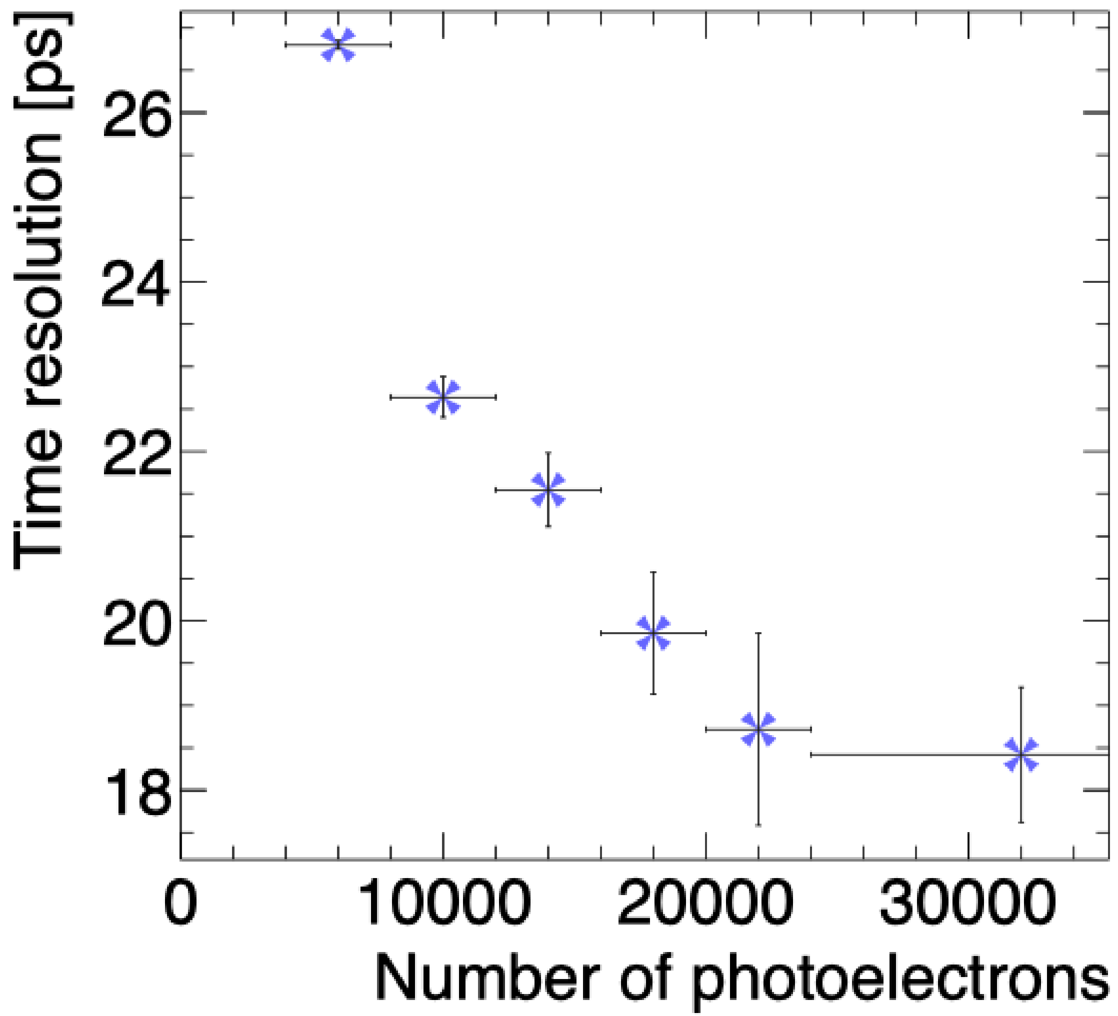
Position dependence of the time-offset



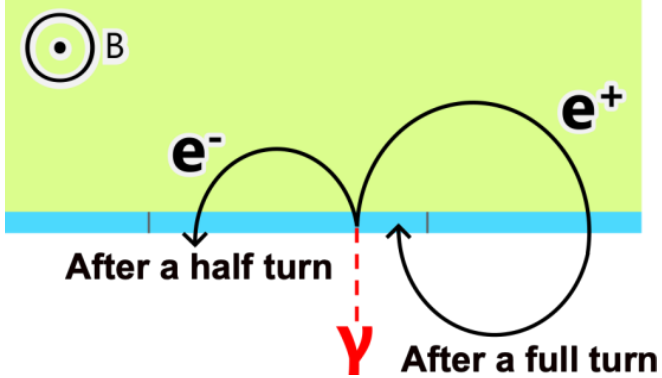


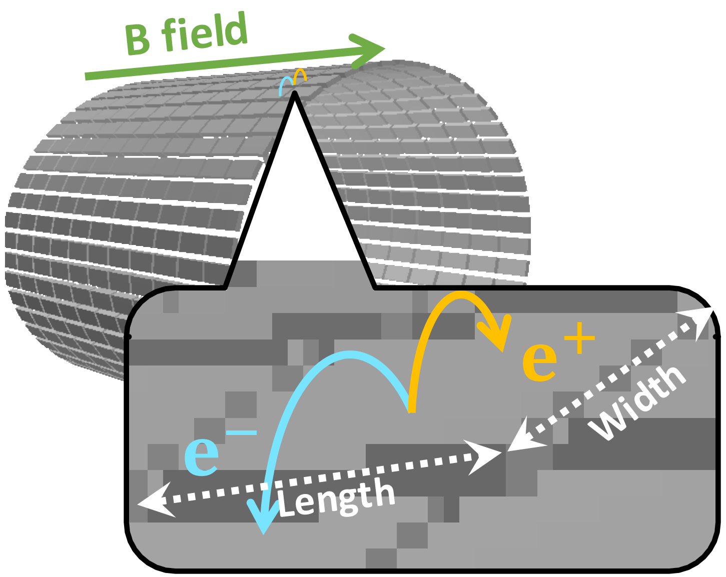
Time resolution dependence on light yield

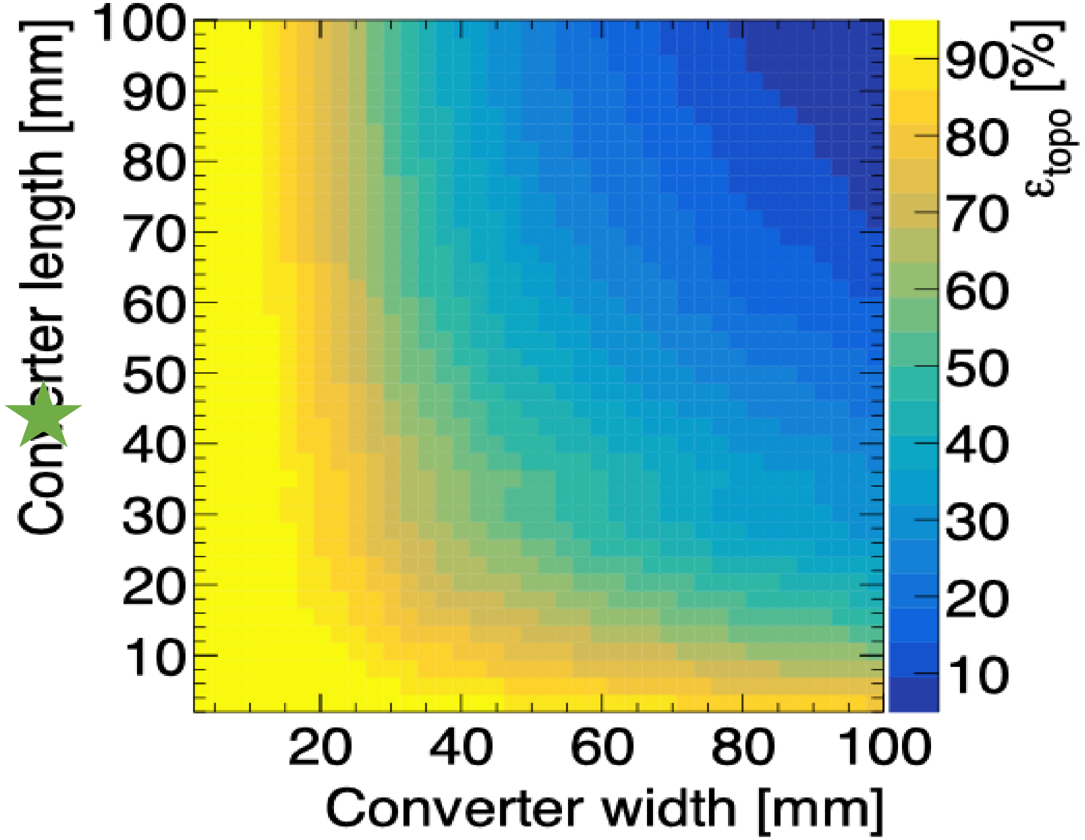
- Time resolution depends strongly on the number of photoelectrons detected
- Time resolution analysis is done with the events around MIP peak



Converter segmentation scan

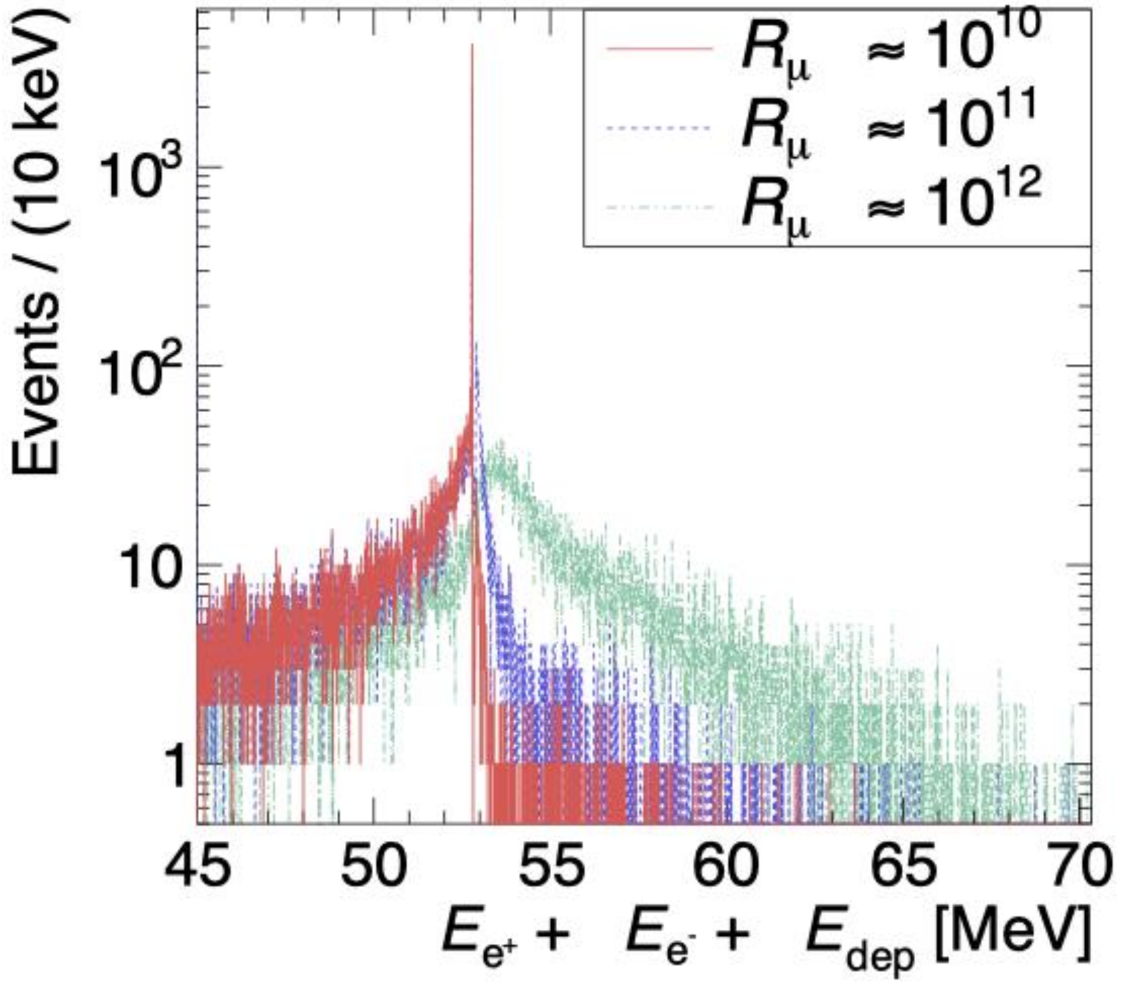






Rate capability

- The converter segmentation size affects the rate capability
- No severe distortion on the signal energy spectrum observed up to $R_\mu \sim 10^{10} \mu/s$ (planned at HiMB), with $3 \times 5 \times 50\ \mathrm{mm}^3$ converter



Effect of converter segment on BG spectrum

- Spectrum of radiative decay photon, simulated for > 45 MeV
- Severe high energy tail with bad segmentation