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 ー電子ビームによる性能評価ー

Development of Photon Pair Spectrometer for Next Generation $\mu^+ \to e^+\gamma$ Experiment
- Performance Evaluation by Electron beam -

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2025年3月18日　日本物理学会春季大会

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Series talk

Detector R&D (This talk)

↓

Simulation study (next talk)

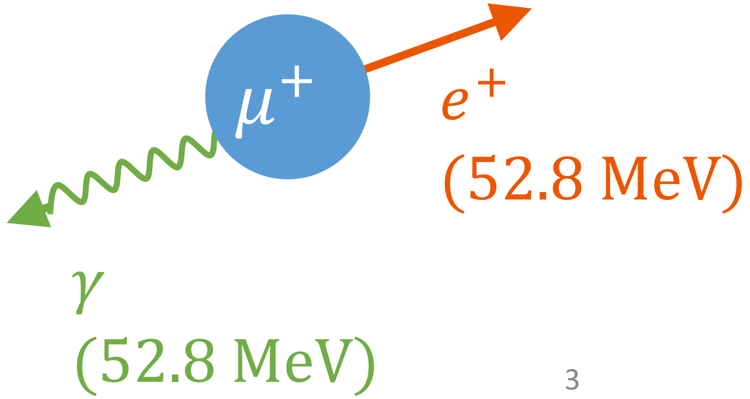
$\mu^+ \rightarrow e^+\gamma$ search

- Charged Lepton flavour violation decay
  - $\mathrm{Br}(\mu^+ \rightarrow e^+\gamma) \sim O(10^{-53})$ in SM + ν oscillation
  - $\mathrm{Br}(\mu^+ \rightarrow e^+\gamma) \sim O(10^{-11} \sim 10^{-15})$ predicted in BSM (e.g. SUSY)

Experiments

- MEG (2008 - 2013) & MEG II experiment (2021 – 2026 (planned)) @ PSI
  - Current UL : $\mathrm{Br}(\mu^+ \rightarrow e^+\gamma) < 3.1 \times 10^{-13}$ (90 % C. L.)
  - Target sensitivity : 6×10^{-14}

- Future $\mu^+ \rightarrow e^+\gamma$ experiment
  - Planning with the target sensitivity of $O(10^{-15})$



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

- Motivation
  - Further search for $\mu^+ \to e^+\gamma$ (if not found in MEG II)
  - Precise measurement of $\mu^+ \to e^+\gamma$ after discovery for BSM model selection

- Muon beam increase at PSI (HIMB project)
  - $\times 100$ muon beam rate ($R_\mu \sim O(10^{10})$) available from 2027—2028

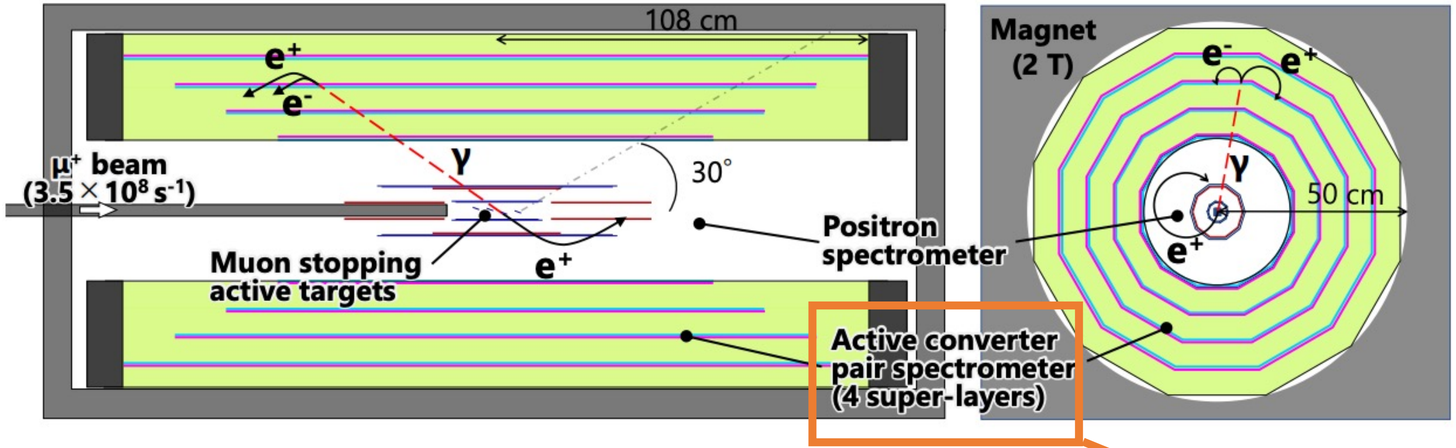
- Main background of $\mu^+ \to e^+\gamma$: accidental background

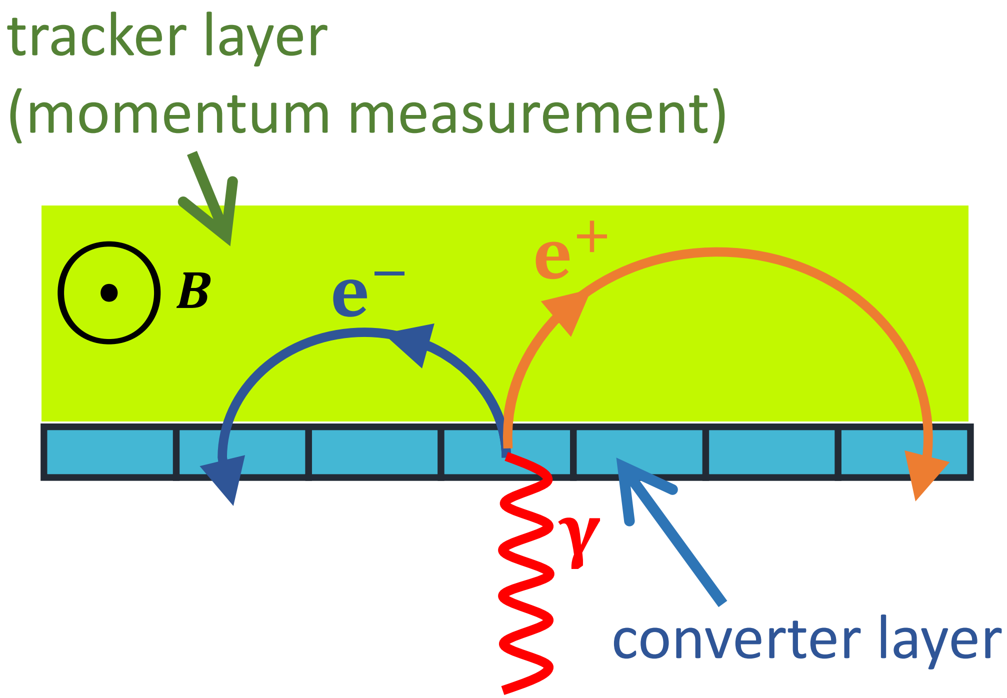
$$N_{\mathrm{acc}} \propto R_\mu^2 \cdot \Delta E_\gamma^2 \cdot \Delta p_e \cdot \Delta\theta_{e\gamma}^2 \cdot \Delta t_{e\gamma} \cdot T$$

⇒ Detector resolution (especially γ) is important

to benefit from increased μ beam

Detector concept





- μ^+ stopping target ... Active & split
- e^+ measurement ... Silicon sensor (HV-MAPS)
- γ measurement ... Pair-spectrometer

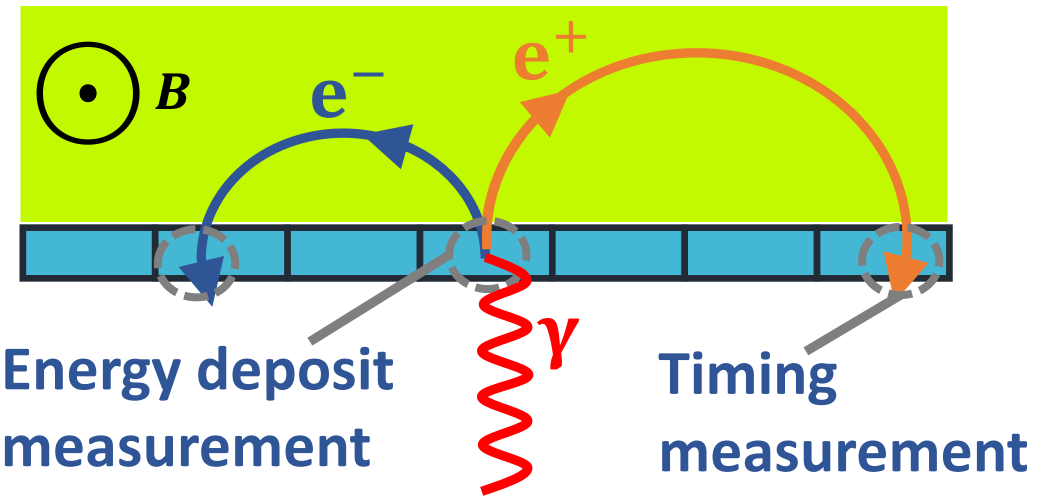
This talk!

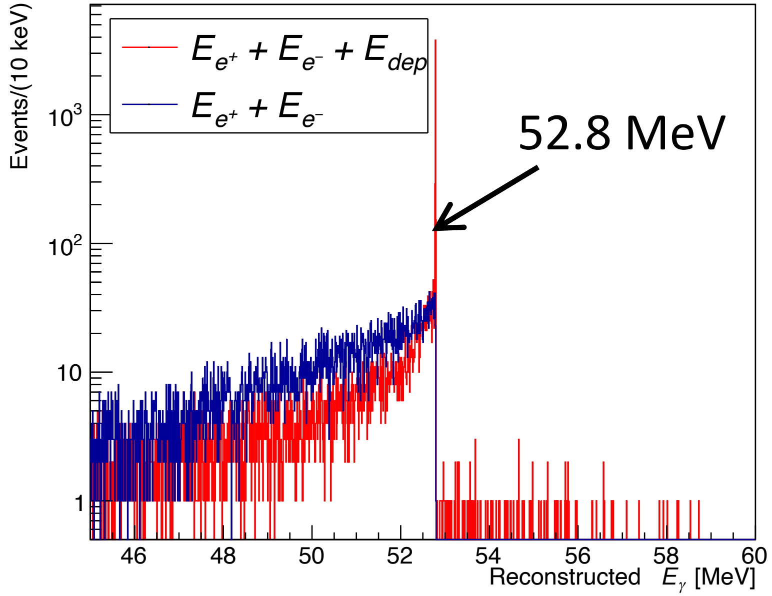
Pair spectrometer with active converter

Problem with conventional pair spectrometer

- Non-negligible energy loss inside the converter layer
- Too thin converter is not unacceptable… degradation of conversion efficiency

Solution: energy measurement by converter itself (active converter)





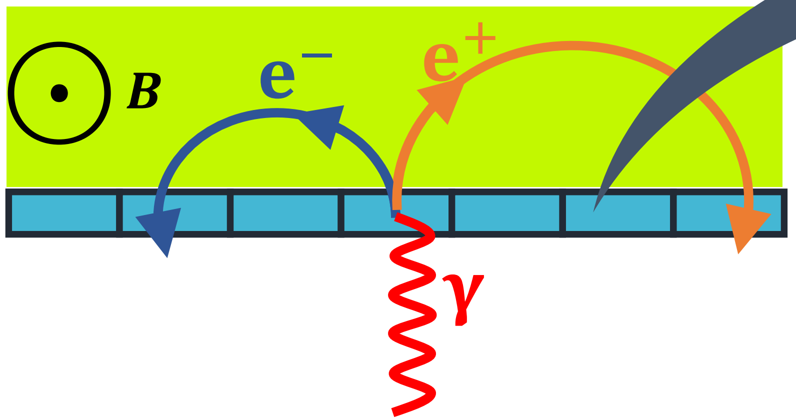
Requirements for active converter

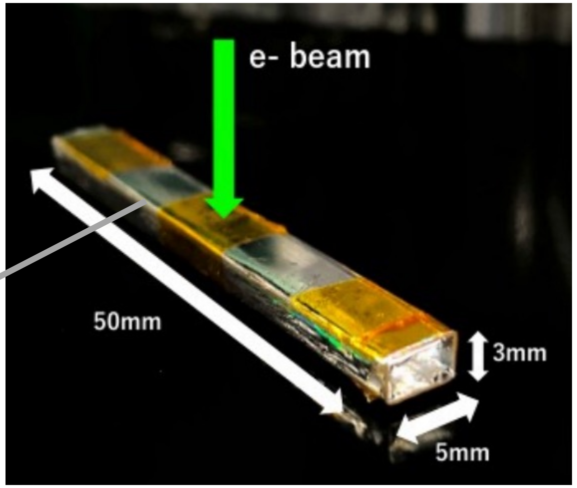
$\frac{\Delta E}{E} < 0.4\ \%$ at signal ($E = 52.8$ MeV) & $\Delta t < 30$ ps for pair spectrometer

$N_{\text{p.e.}} > 500$ p.e. (3mm thickness converter) & $\Delta t < 40$ ps for 1 MIP

Active converter prototype by LYSO

- Primary candidate & material for active converter : LYSO
- Made prototypes for one cell

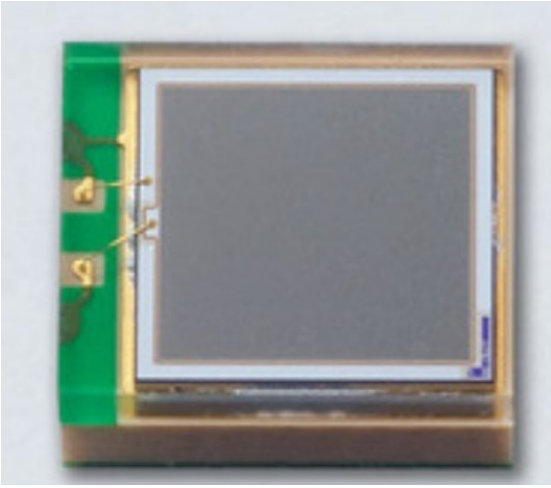




ESR wrapping

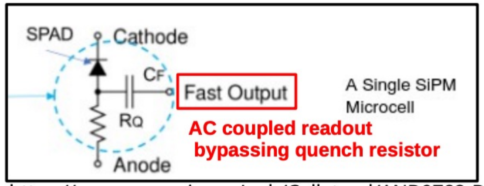
$3(1.5)\times5\times50\ \mathrm{mm}^3$ LYSO

… Based on simulation study (next talk)



SiPM (S14160-3050HS)

Comparison of readout SiPMs



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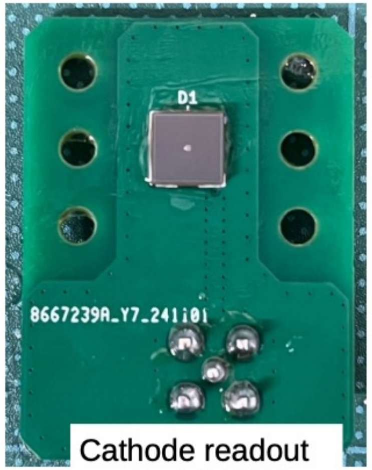
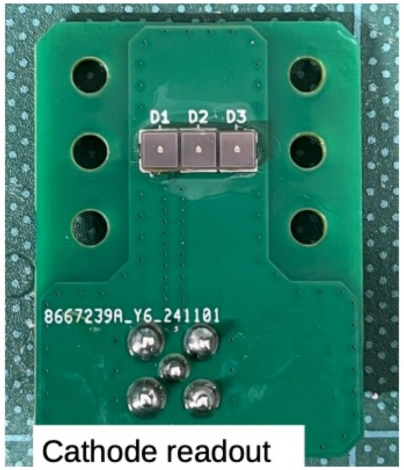
$6 \times 6\ \mathrm{mm}^2$ 50 μm pitch
Hamamatsu MPPC



S14160-6050HS

- 100 % coverage of LYSO cross section

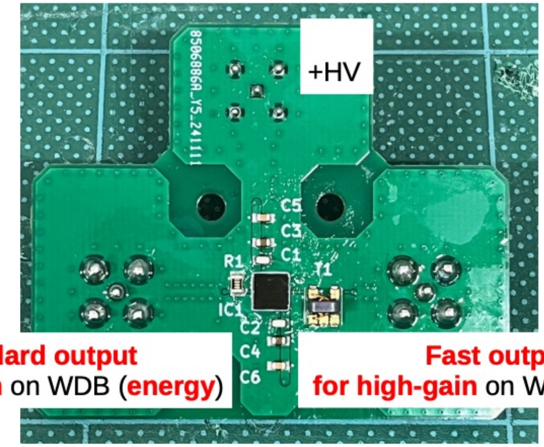
$3 \times 3\ \mathrm{mm}^2$ 50 μm pixel pitch
Hamamatsu MPPC



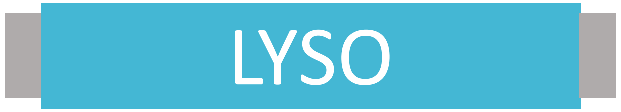
S14160-3050HS

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

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



MICROFJ-40035-TSV-TR1



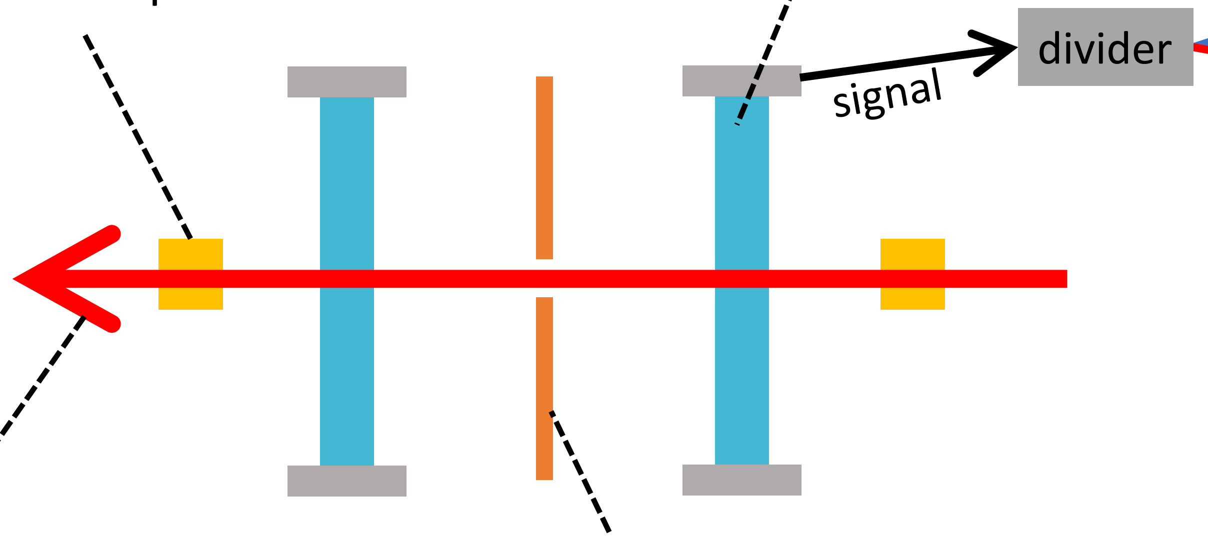
- Unique feature of having "fast output"

Overview of electron beam test of active converter

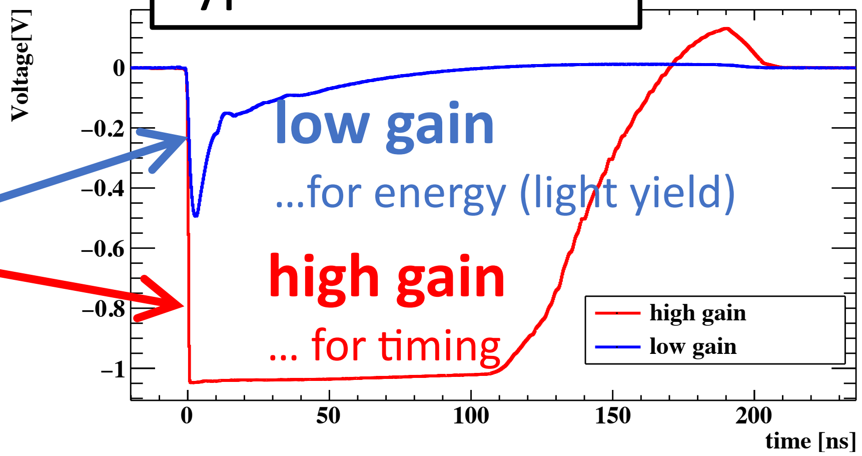
Reference Counter

- For DAQ trigger & time reference
- 5 mm cube plastic scintillator + SiPM

Active converter prototype



typical waveform



Electron beam

- KEK PF-AR TBL
- About 3 GeV, 3kHz
- ~ 2.7 MeV energy deposit in LYSO (3mm thickness)

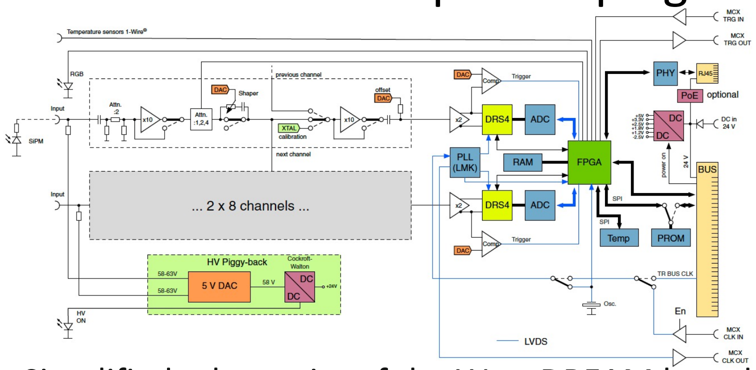
VETO counter

- For offline analysis (veto multiparticle events)
- Plastic scintillator + SiPM

DAQ

[WaveDREAM board]

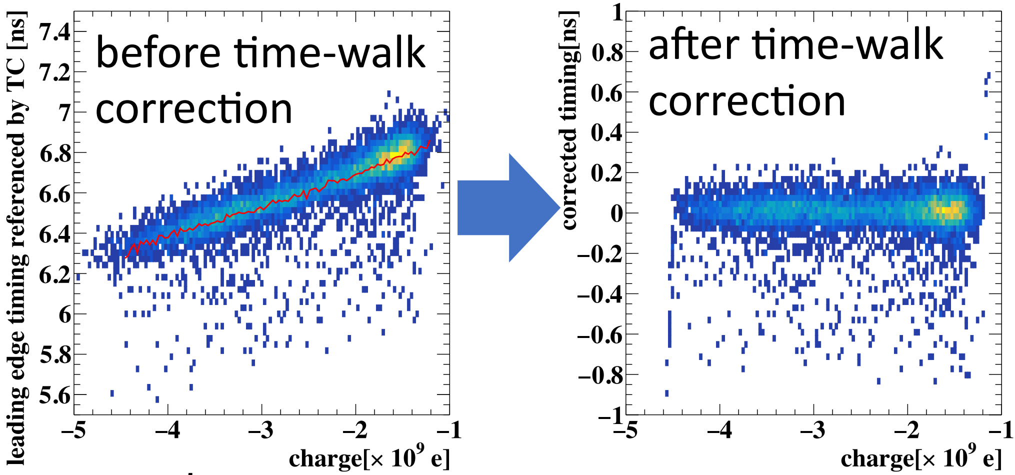
- Waveform WaveDREAM Board
- digitization by DRS4 chip (4-5 GHz sampling)
- Built-in amp & shaping



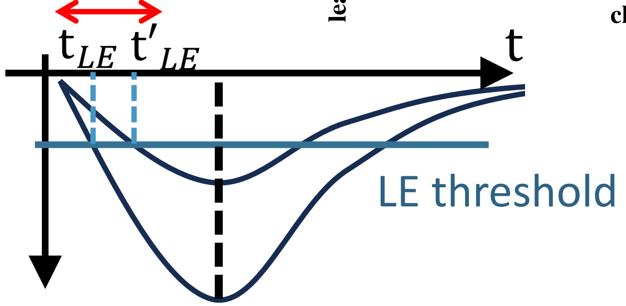
Simplified schematics of the WaveDREAM board

Time resolution analysis

- Time pickoff :
  leading edge method on high-gain channel
  - Threshold is scanned to find the optimal value



- Time walk correction :
  by charge on low-gain channel

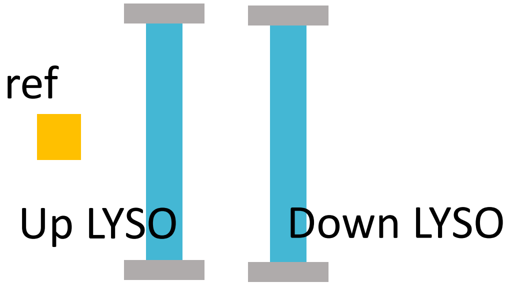


- Single counter time resolution

$$\sigma(t_{up\ LYSO} - t_{ref}) = \sqrt{\sigma(t_{up\ LYSO})^2 + \sigma(t_{ref})^2}$$

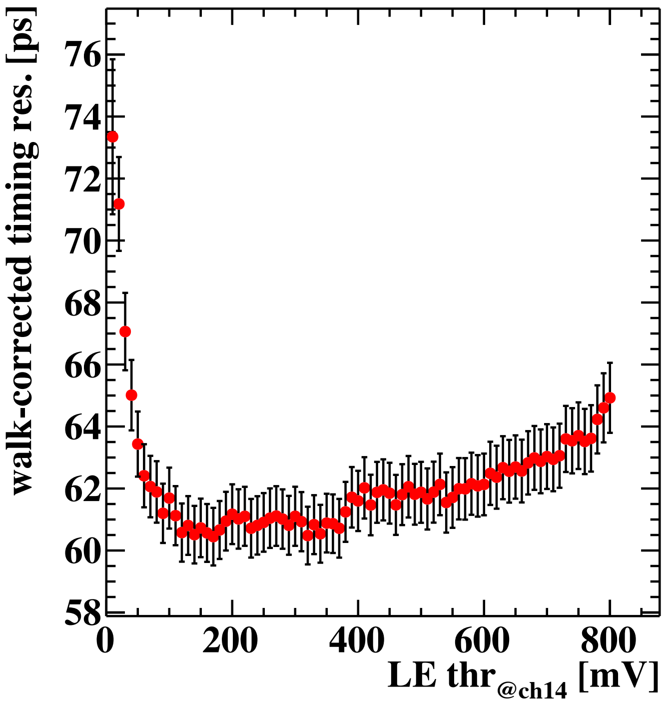
$$\sigma(t_{down\ LYSO} - t_{ref}) = \sqrt{\sigma(t_{down\ LYSO})^2 + \sigma(t_{ref})^2}$$

$$\sigma(t_{up\ LYSO} - t_{down\ LYSO}) = \sqrt{\sigma(t_{up\ LYSO})^2 + \sigma(t_{ref})^2}$$

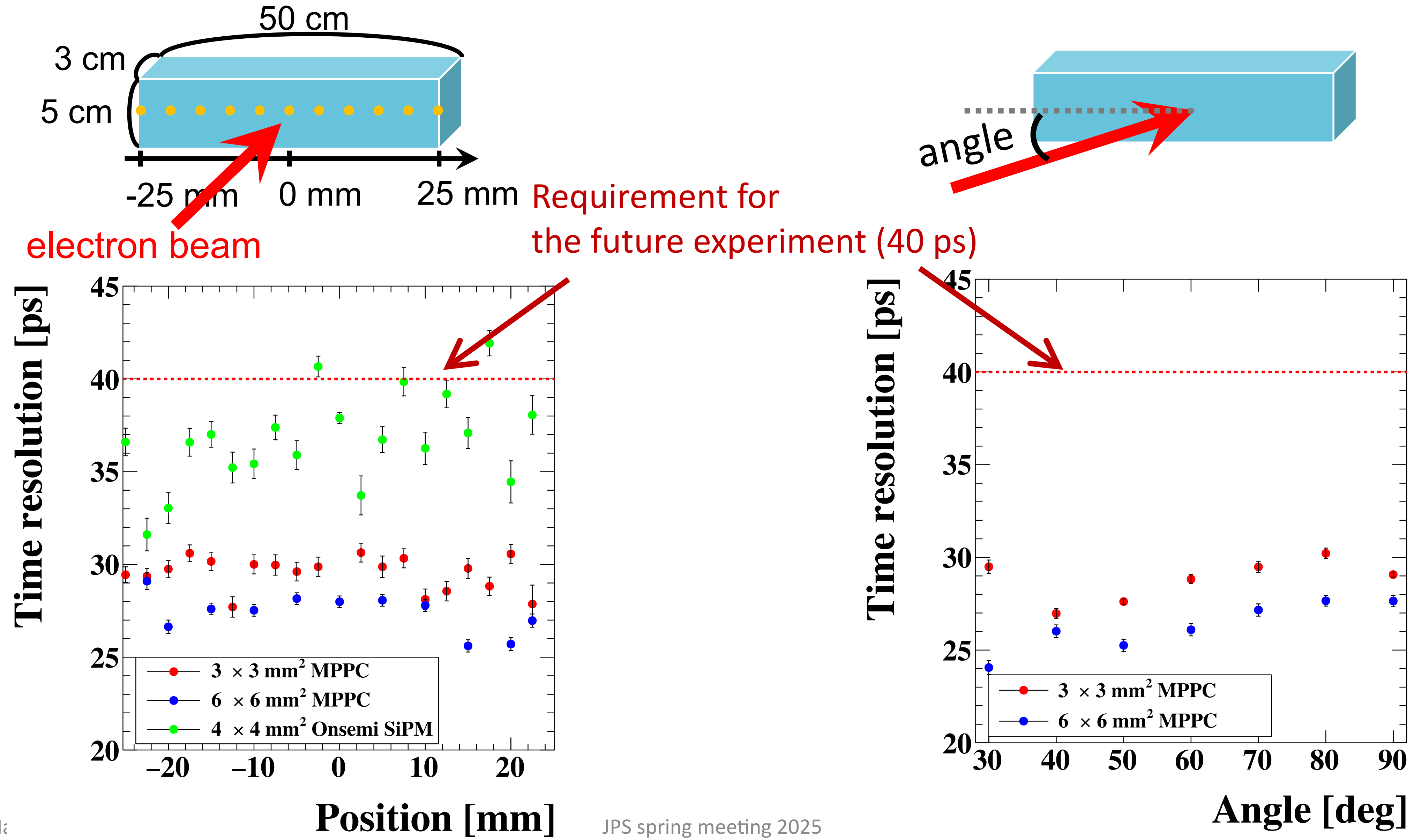


➡ Solve and obtain $\sigma(t_{up\ LYSO}), \sigma(t_{down\ LYSO}), \sigma(t_{ref})$

Leading-edge threshold scan

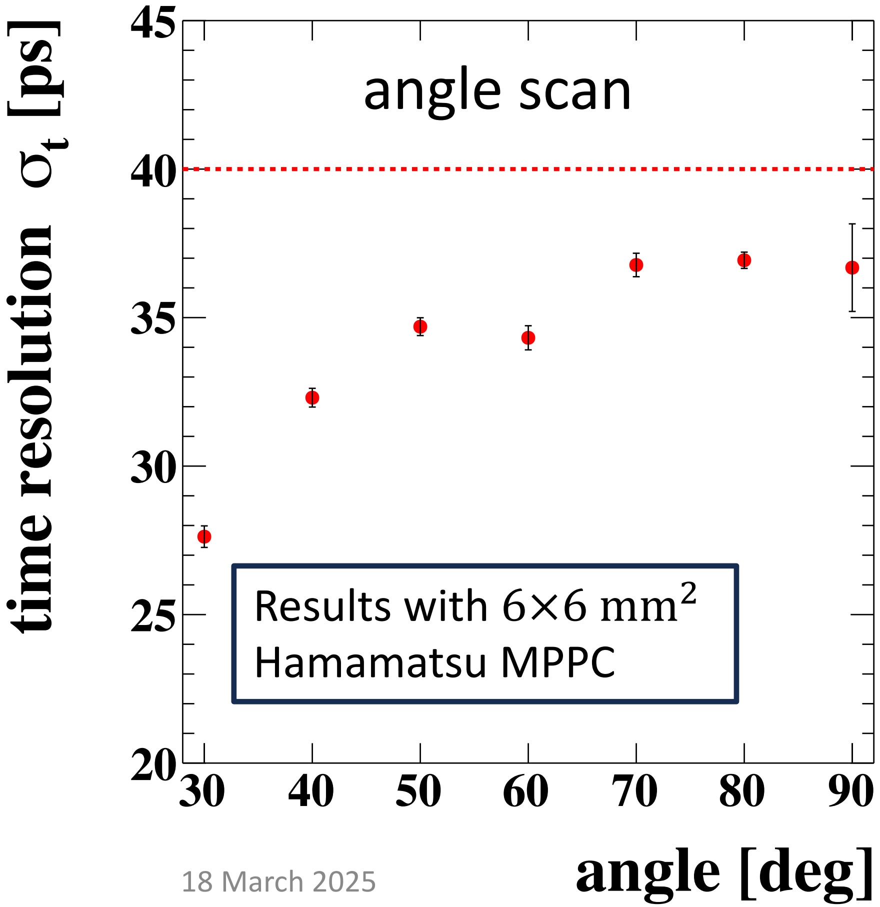


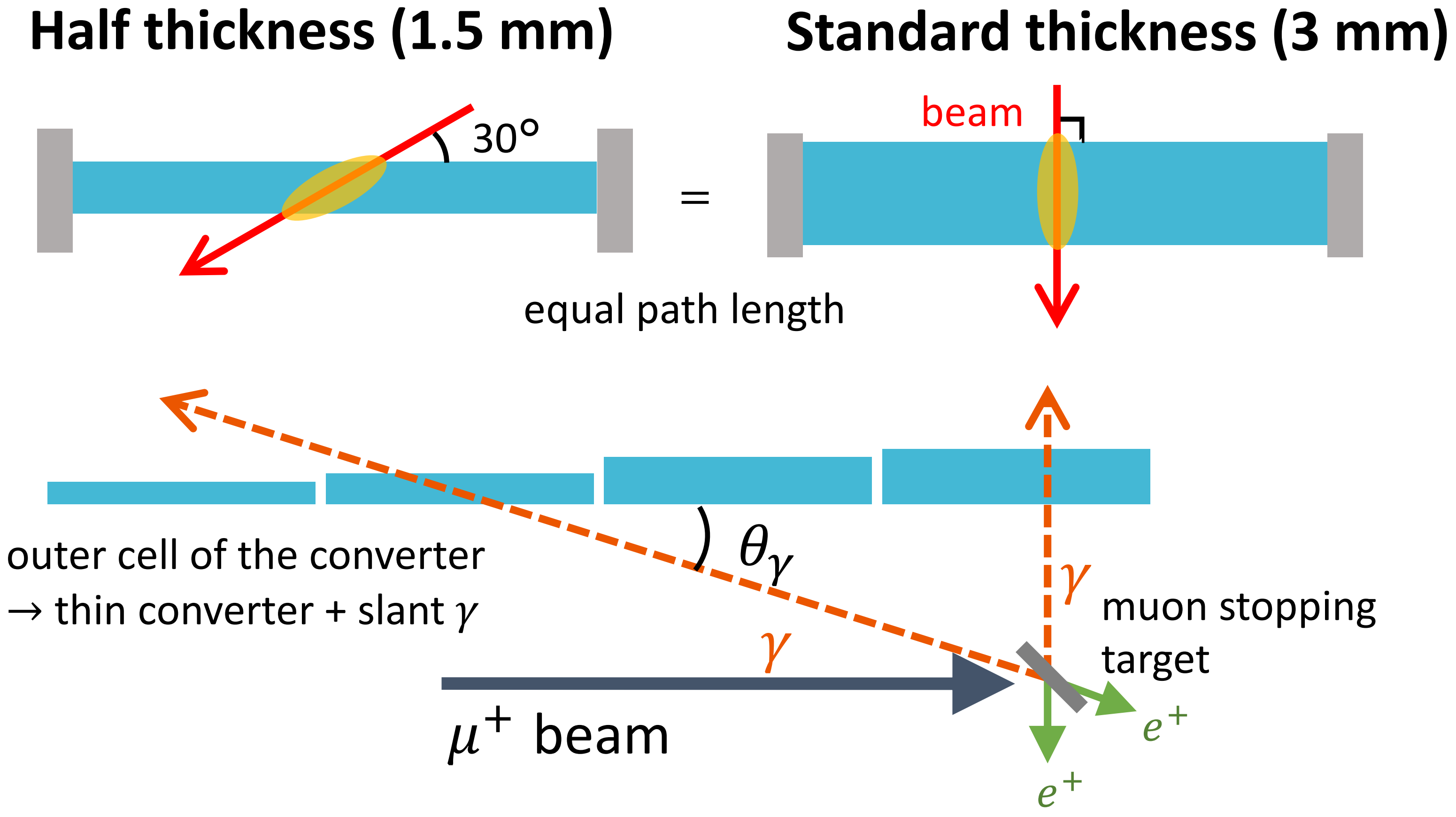
Time resolution results



Time resolution with half thickness LYSO

- Also tested with LYSO of half thickness (1.5 mm)
- Sufficient time resolution with thin converter + slanting incident beam

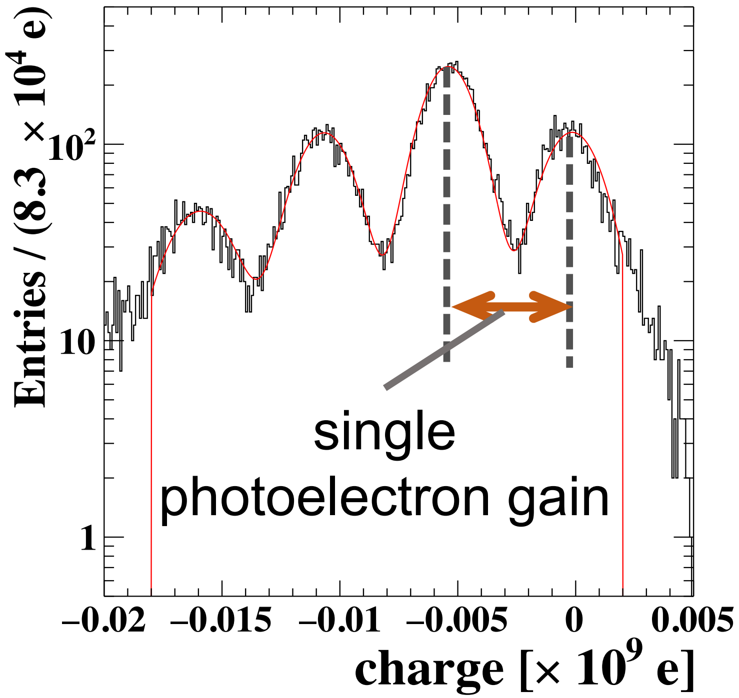


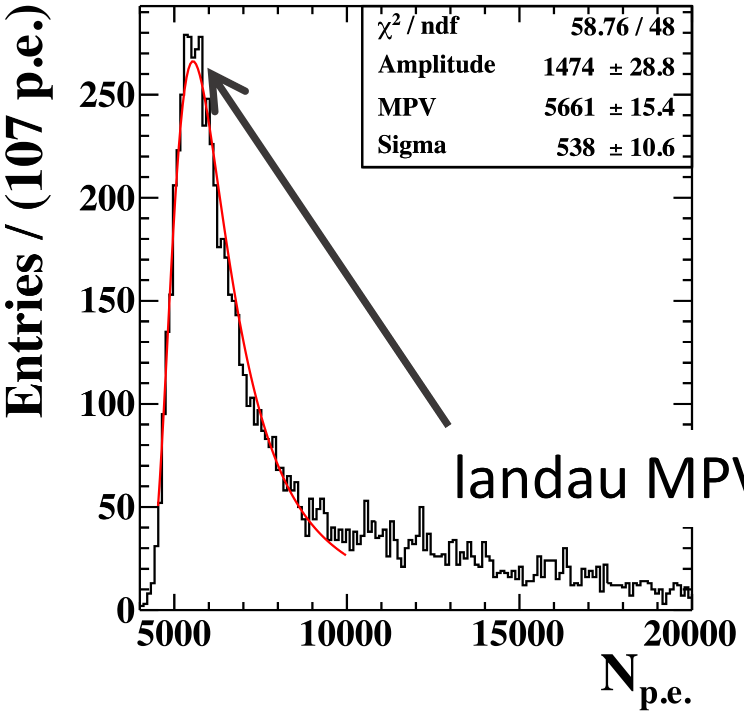


Light yield analysis

Conversion from charge Q -> photoelectron $N_{\mathrm{p.e.}}$

$$N_{\mathrm{p.e.}} = \frac{Q \text{ at low gain}}{\text{single photoelectron gain at high gain}} \times \frac{\text{high gain}}{\text{low gain}}$$





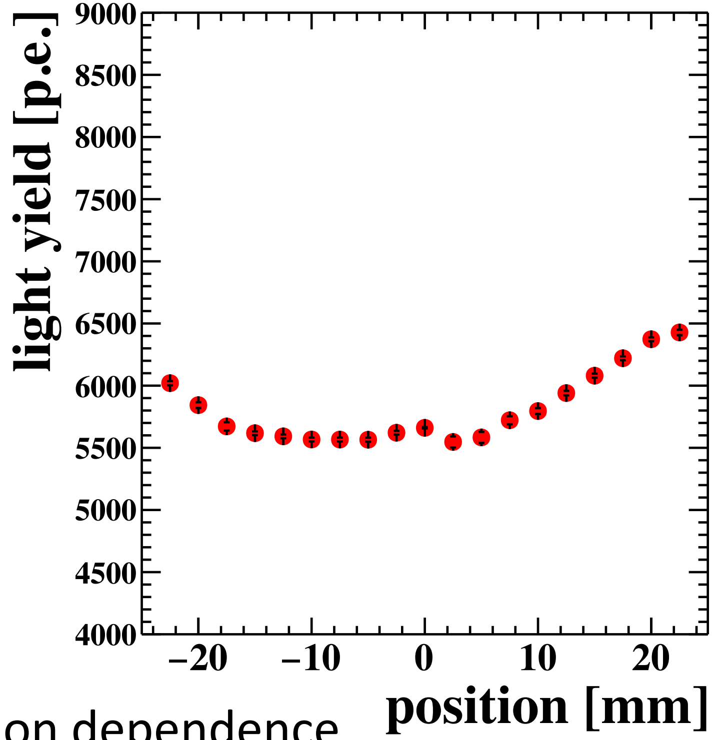
landau MPV = "light yield"

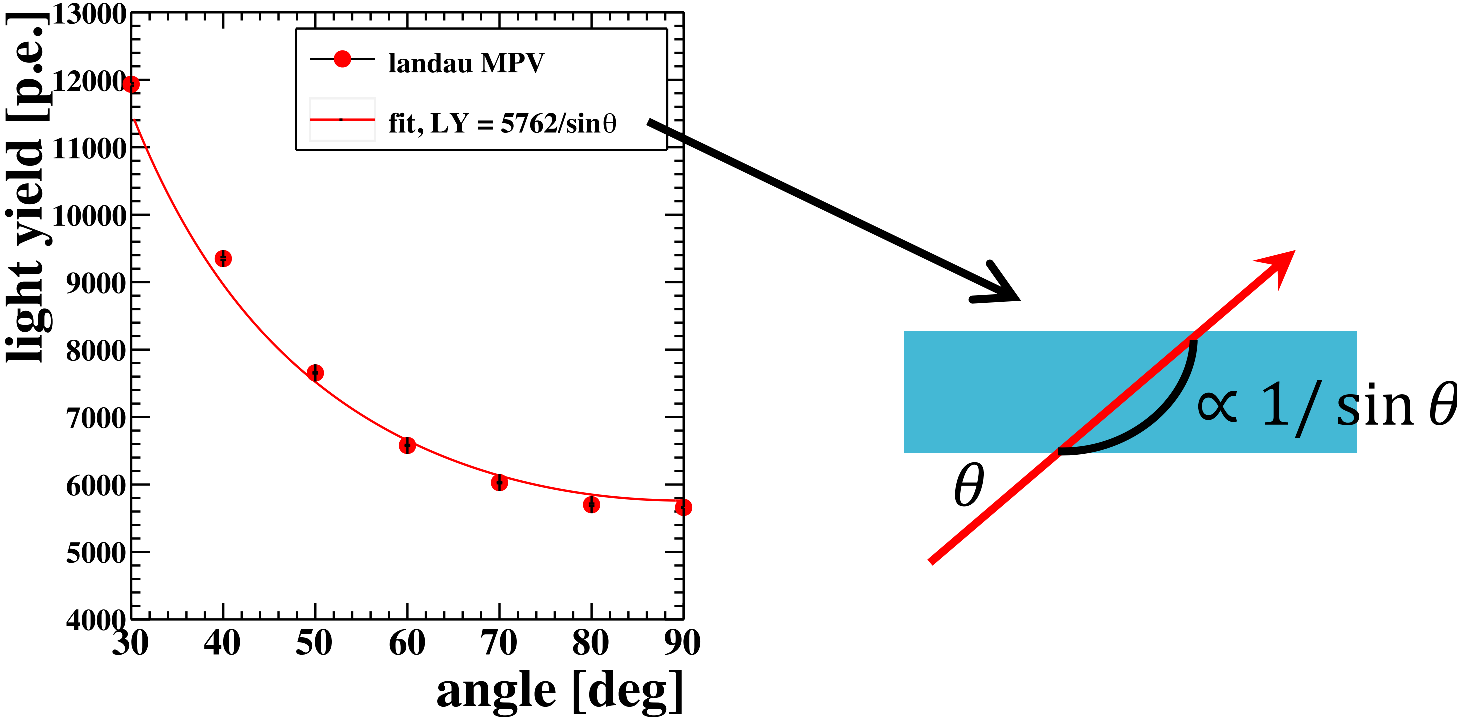
large uncertainty (34—42)

…frequency dependence of the amp

Light yield results

- Result with 3 mm MPPC : $N_{p.e.} = 5000 - 7000$ over all crystal region (perpendicular injection)
- Requirement for future experiment ($N_{\mathrm{p.e.}} > 500$) has been achieved





Position dependence
… change in the run condition (e.g. temperature) may be relevant

Summary

- R&D for a photon pair-spectrometer with active converter for the future $\mu^+ \rightarrow e^+\gamma$ search experiment is underway.

- Prototypes of the active converter made of LYSO with SiPM readout were tested with an electron test beam

- Excellent time resolution of 25—35 ps and light yield of 5000—7000 photoelectrons were confirmed.

  ➡ Meet the resolution requirements for the future $\mu^+ \rightarrow e^+\gamma$ experiment

- Active converter with LYSO + SiPM readout is a strong candidate for the conversion layer.

Prospect

- Improvement of the analysis
  - Unexpected behavior of the waveform was observed in some datasets … still under investigation
  - Further investigation of the position dependence of the light yield

- Validation of the measurement principle of a pair spectrometer
  - Develop a prototype of superlayer (converter + tracker)
  - Test beam campaign with gamma ray

backup

Update from the last beam test

Electron beam test in 2023 | reported in JPS 2024 autumn , 16aWB106-01

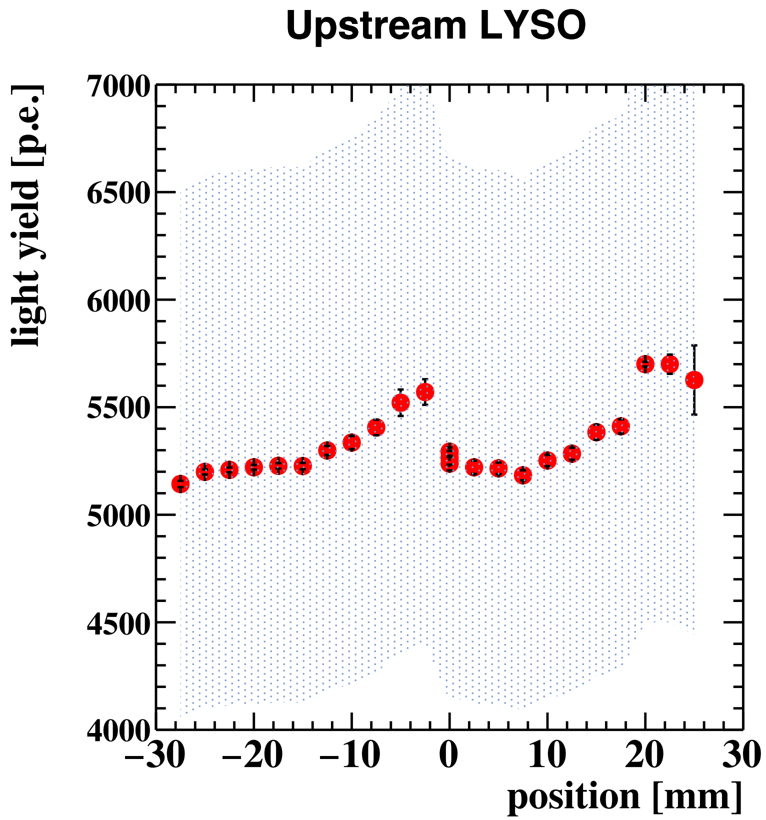
…Mainly focused on the time resolution

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

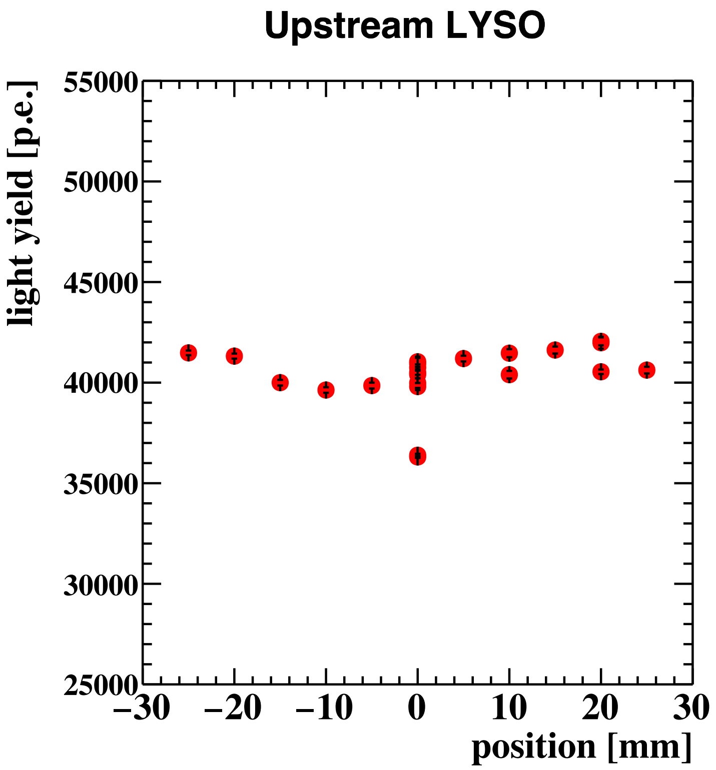
Electron beam test in 2024 | This talk

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

4 mm Onsemi SiPM



6 mm MPPC



Requirements for the future experiment

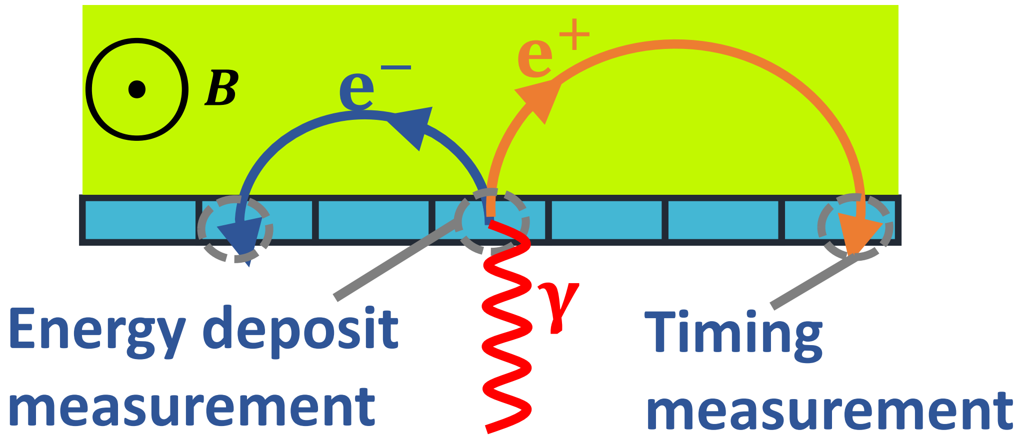
Energy resolution : 0.4% at signal energy (52.8 MeV)

- $\frac{\Delta E}{E_{\mathrm{signal}}=52.8\ \mathrm{MeV}} = 0.4\ \%$ ➡ $\Delta E = 200$ keV required
- $\frac{\Delta E=200\ \mathrm{keV}}{2\times E_{\mathrm{deposit}}\simeq 7\ \mathrm{MeV}} = 3\ \% > \frac{1}{\sqrt{N_{\mathrm{p.e.}}}}$ ➡ $N_{\mathrm{p.e.}} > 500$ required per MIP

The fluctuation of energy includes (at least)
the fluctuation of light yield governed by Poisson statistics

Time resolution : 30 ps for one gamma)

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

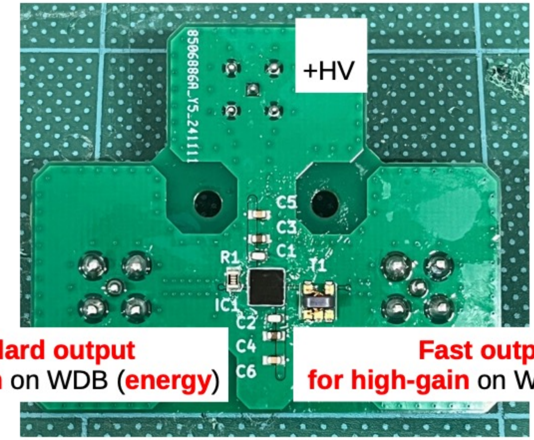


LYSO Properties

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

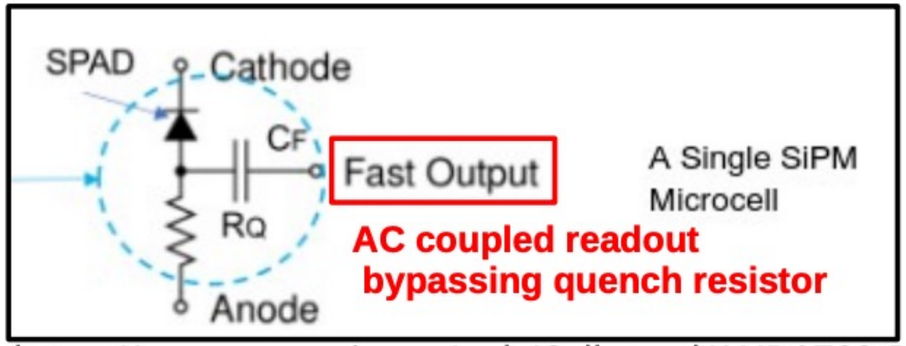
Onsemi SiPM fast-output



MICROFJ-40035-TSV-TR1
Onsemi

4x4 ㎟ / 35 um pitch

Fast output for timing measurements



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Energy deposit by MC

- 3 GeV electron injected to 3 mm LYSO