Development of an active converter pair spectrometer for the future search for $\mu^+ \to e^+\gamma$

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Abstract

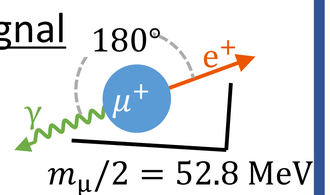
The search for $\mu^+ \to e^+\gamma$ requires a new gamma detector with high-beam capability and good resolution ($\Delta E/E = 0.4\ \%, \Delta t = 30$ ps).
To meet these requirements, we are considering a pair-spectrometer with an active converter. We tested a prototype of the active converter using a 3 GeV electron beam at the test beam line in KEK and confirmed that our design can achieve sufficient resolution.

1. $\mu^+ \to e^+\gamma$ search

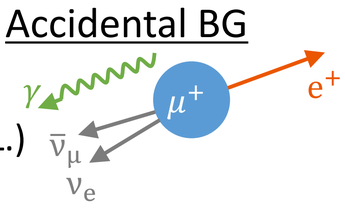
- $\mu \to e\gamma$: Charged Lepton Flavour Violation
  - SM + ν osc. → Effectively prohibited ($BR(\mu \to e\gamma) < 10^{-54}$)
  - BSM → Measurable value predicted

  Discovery of $\mu \to e\gamma$ would be a strong evidence of new physics

Signal



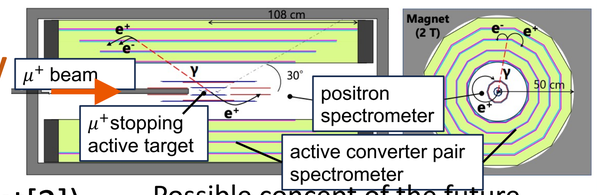
Accidental BG



- MEG II experiment[1] (@PSI, ~ 2026)
  Target sensitivity : $BR(\mu \to e\gamma) < 6 \times 10^{-14}$ (90% C.L.)

2. Future plans for $\mu^+ \to e^+\gamma$ search

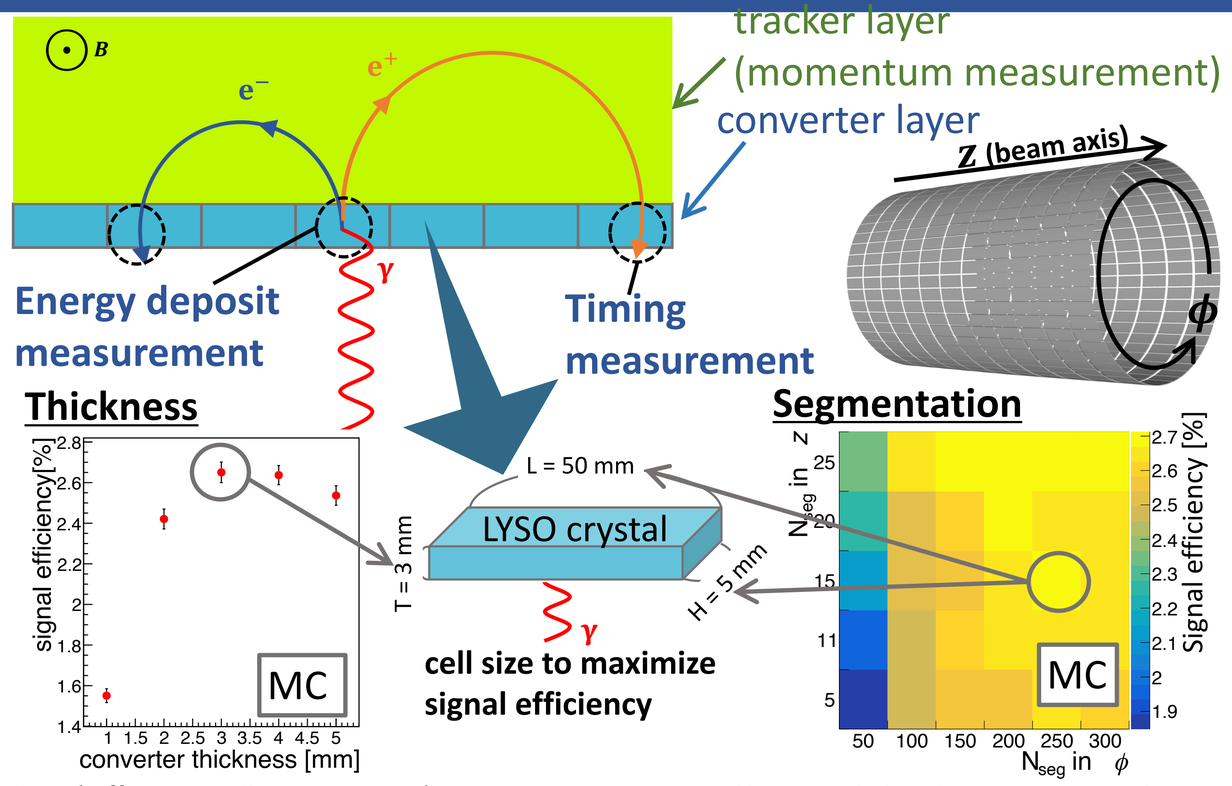
- Further search / precise measurement after discovery at $O(10^{-15})$ **sensitivity**
- ×100 μ^+ beam intensity available from 2028 at PSI (HiMB project[2])



Possible concept of the future experiment[2]

- $N_{\rm acc} \propto \boldsymbol{R_\mu^2 \cdot \Delta E_\gamma^2} \cdot \Delta p_e \cdot \Delta\theta_{e\gamma}^2 \cdot \Delta t_{e\gamma} \cdot T$
  → **γ energy measurement resolution is important** for BG suppression
  → Pair spectrometer with active converter

3. Active converter



Signal efficiency ...Conversion prob vs
- Energy loss by bremsstrahlung
- Loss of low energy $e^\pm$

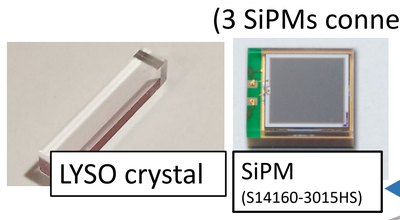
Need to distinguish energy deposit from
- re-entering $e^\pm$
- BG γ conversion

4. Electron beam test

What is the actual performance (time & energy resolution) of the converter?

Active converter

LYSO crystal + SiPM readout
(3 SiPMs connected in series on both sides)



Reference timing counter

- Plastic scintillator + SiPM
- 30–40 ps time resolution
- Also used for triggering

Electron beam

- KEK PF-AR test beam line
- 3 GeV, 1.5 kHZ

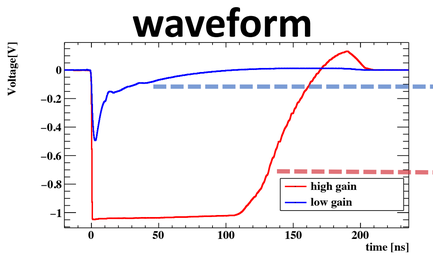
Veto counter

- Plastic scinti. + SiPM
- For multi-particle vetoing

DAQ

- Waveform digitization by WaveDREAM board (built-in shaping & amps)
- Split SiPM signal and record with high gain & low gain at the same time

waveform



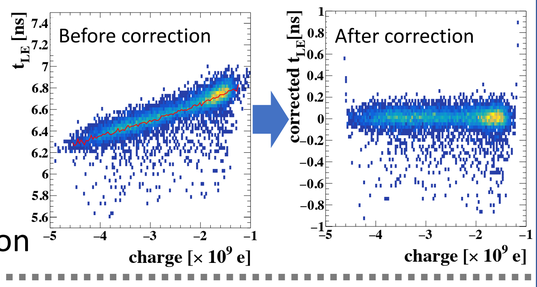
Low gain channel
- for energy measurement

High gain channel (saturated waveform)
- for timing measurement

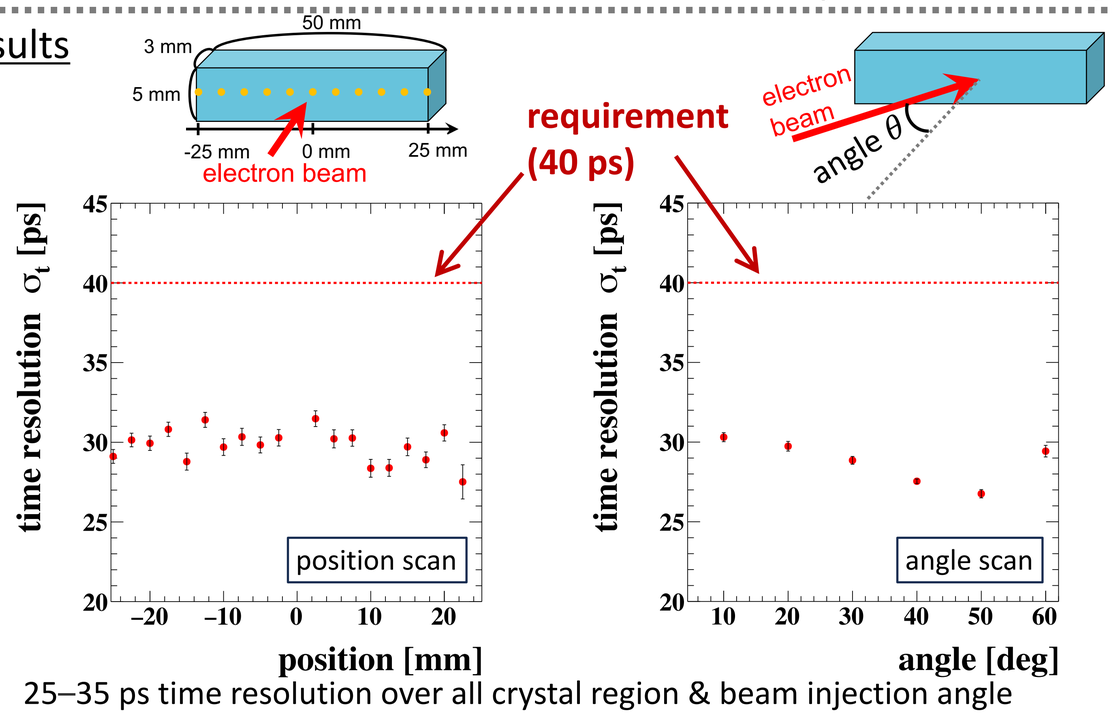
5. Timing resolution

Analysis method

- Time pick-up: leading edge method
  - Threshold for the leading edge is scanned and set to the optimal value
- Time-walk correction: use the charge information



Results



- 25–35 ps time resolution over all crystal region & beam injection angle
- Requirement for the future experiment (40 ps/MIP) is achieved

6. Energy resolution

Requirement

$$\frac{\Delta E}{E_{\rm signal} = 52.8\ \rm MeV} = \mathbf{0.4\ \%} \xrightarrow{\Delta E = \mathbf{200\ keV}} \frac{\Delta E}{2\times E_{\rm deposit} \simeq 7\ \rm MeV} = 3\ \% > \frac{1}{\sqrt{2\times N_{\rm p.e.}}} \Rightarrow \boldsymbol{N_{\rm p.e.} > 500}$$

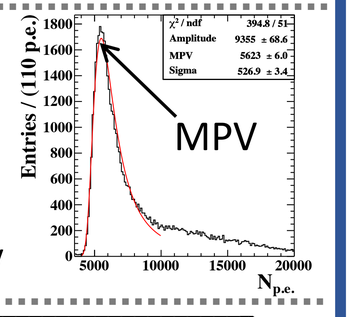
$E_{\rm deposit}, N_{\rm p.e.}$: energy deposit and light yield per MIP

Light yield analysis method

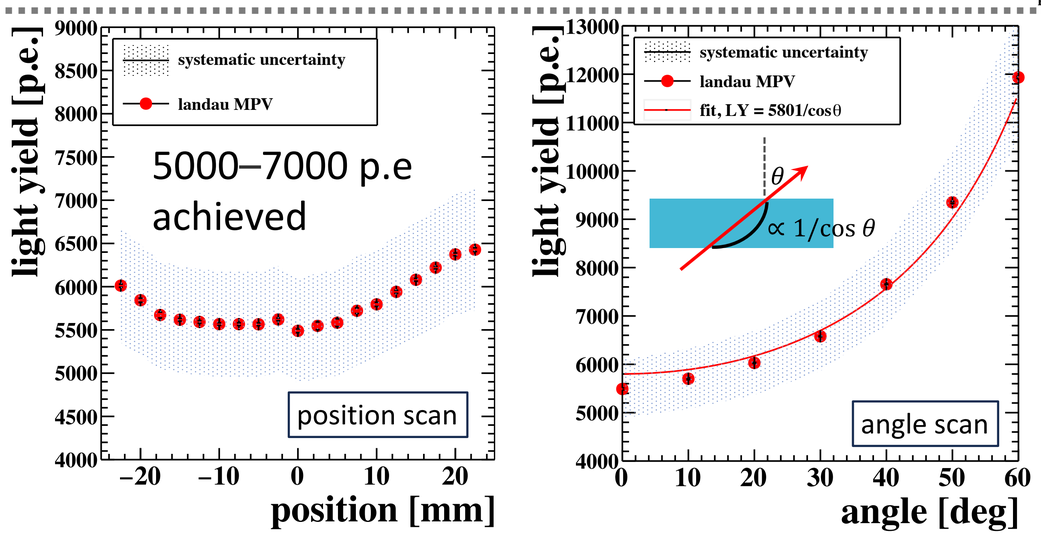
- Measure single photoelectron using weak LED light
- Conversion from charge → p.e.

$$N_{\rm p.e.} = \frac{\rm charge}{\rm 1\ p.e.\ gain}$$

- Fit with landau function + gaussian smearing and obtain MPV



Results



7. Conclusion

- A pair spectrometer with active converter is considered for the gamma detector in the future $\mu^+ \to e^+\gamma$ experiment.
- Signal efficiency with respect to the converter geometry and materials was investigated by MC simulation.
- Converter prototypes with LYSO crystal and SiPM readouts was tested with an electron beam test, and excellent performance more than required (time resolution: 25–35 ps, light yield: 5000–7000 p.e.) was confirmed.

Reference

[1] A.M. Baldini et al., "The design of MEG II experiment",Eur.Phys.J.C, 78, 380 (2018)

[2] Aiba, M et al.,"Science Case for the new High-Intensity Muon Beams HIMB at PSI", arXiv:2111.05788 [hep-ex] (2021).