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 -アクティブコンバーターの性能評価-

池田史 (東大理)

潘晟[A]，岩本敏幸[A]，松下彩華，森俊則[A]，大谷航[A]，内山雄祐[A]，山本健介，横田凜太郎

(東大理、東大素セ[A])

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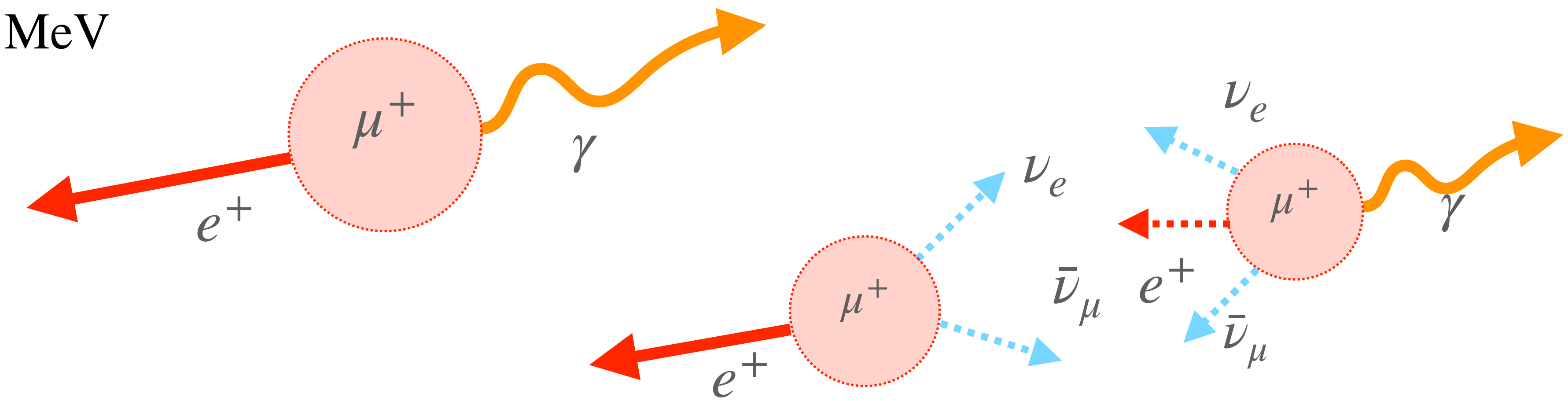
Outline

- **Introduction**
- **Measurements**
  - Requirements for active converter about energy and timing performance
  - Performance evaluation method
  - Setup
  - Results of energy performance
  - Results of timing performance
- **Summary**

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

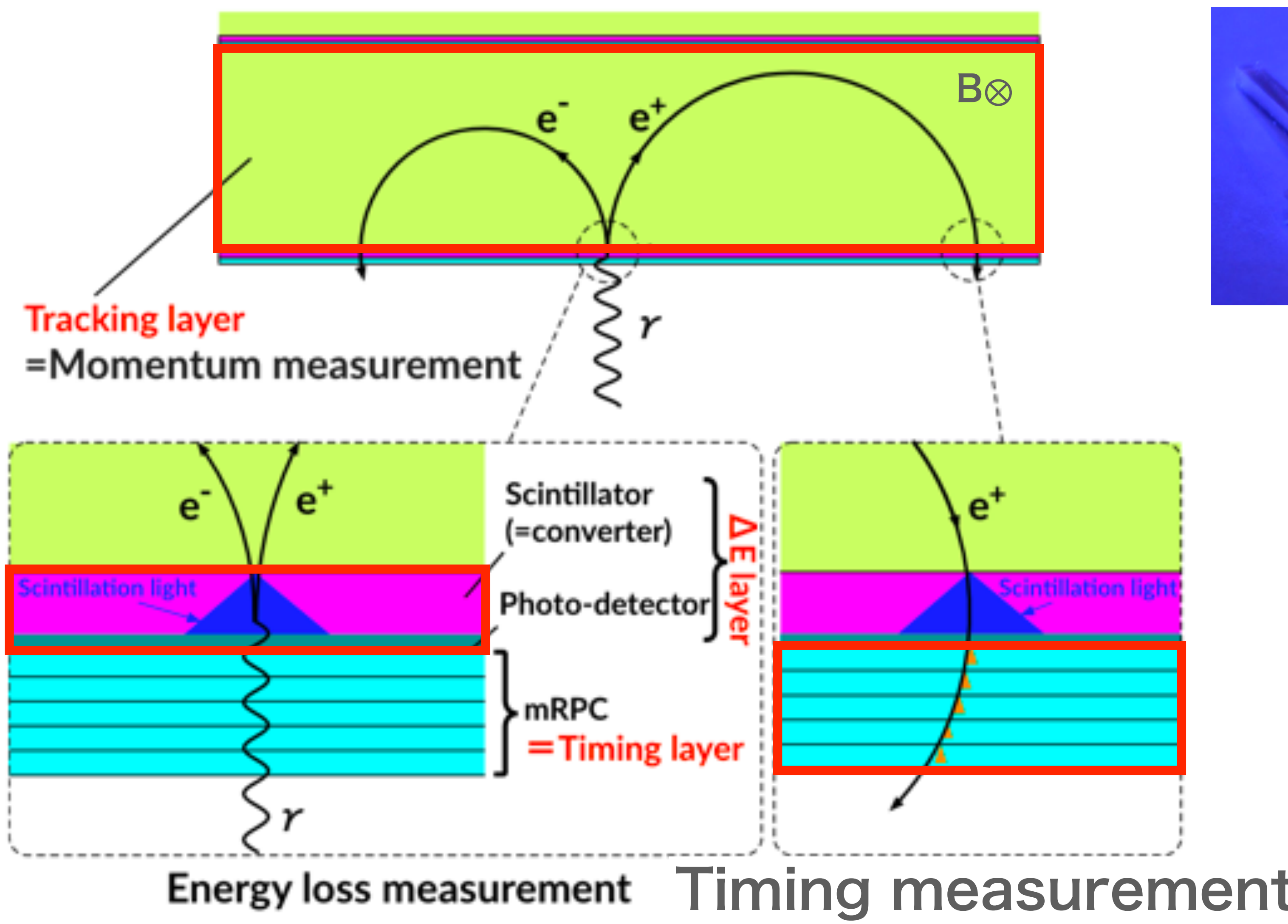
- Charged lepton flavor violation as a good probe into beyond-SM
- Signal
  - same energy of $52.8\,\mathrm{MeV}$
  - same timing
  - back-to-back
- Background
  - Accidental background is dominant

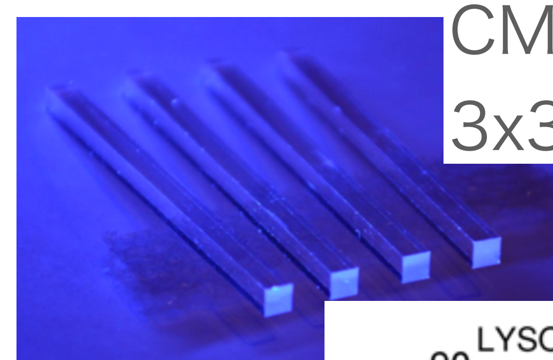


- The best limit is $\mathrm{B}(\mu \to e\gamma) < 4.2 \times 10^{-13}\,(90\,\%\,\mathrm{C.L.})$ by MEG experiment (2016) @PSI
- MEG II experiment @PSI is on progress with 6×10^{-14} as the goal
- Hight Intensity Muon Beam (HiMB) plan to be introduced in 2026-2027 @PSI
  - Upgraded muon beam by a factor of 100 $\to O(10^{10})\,\mu^+/\mathrm{s}$
  - Good opportunity to start new $\mu^+ \to e^+\gamma$ decay search
  - **Target sensitivity is $O(10^{-15})$**
- **Energy resolution is important for gamma-ray detector**

Pair Spectrometer with Active Converter

- **Energy loss in the converter material cannot be ignored**
  → Active material as a converter
- Target resolution $(E_\gamma, \vec{x}_\gamma, t_\gamma, \Theta_\gamma) = (0.4\,\%, 0.2\,\mathrm{mm}, 30\,\mathrm{ps}, 50\,\mathrm{mrad})$
- **Considering measuring timing with active converters**
  - CMS MIP timing detector achieved time resolution of 30 ps using LYSO bar + SiPM
  - Shape of the bar also has **advantages in terms of segmentation in ϕ-direction to reduce pile-ups** (see previous talk 7pA442-1 by R.Yokota)

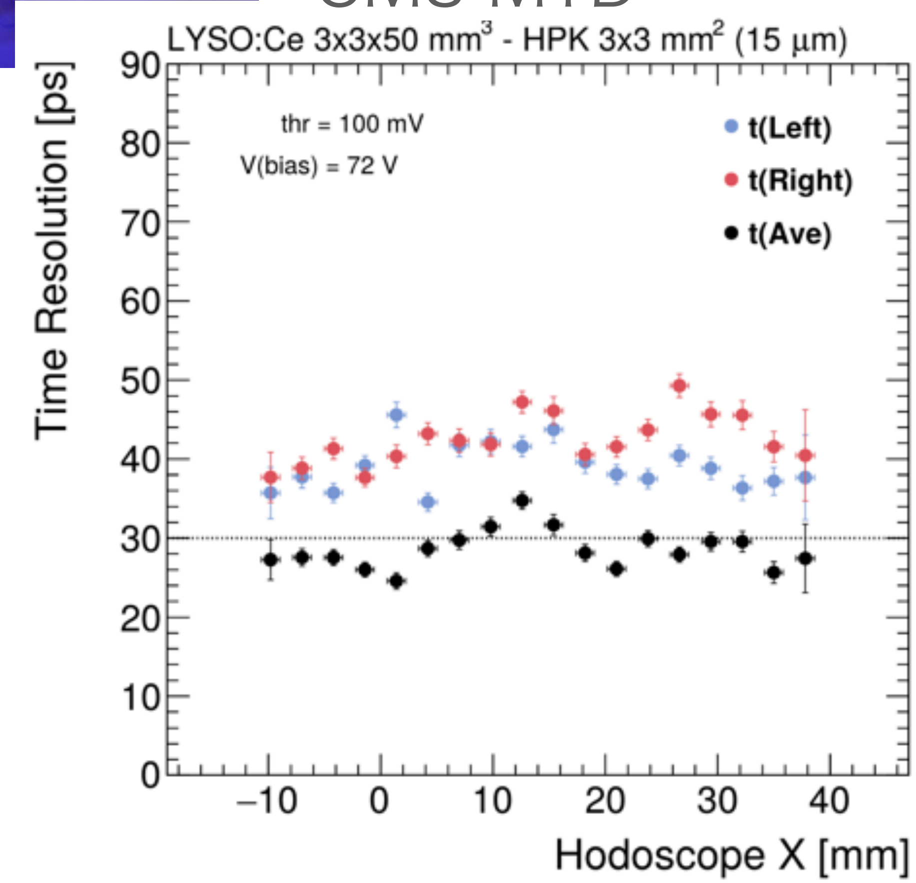




CMS MTD

3x3x50mm LYSO bar

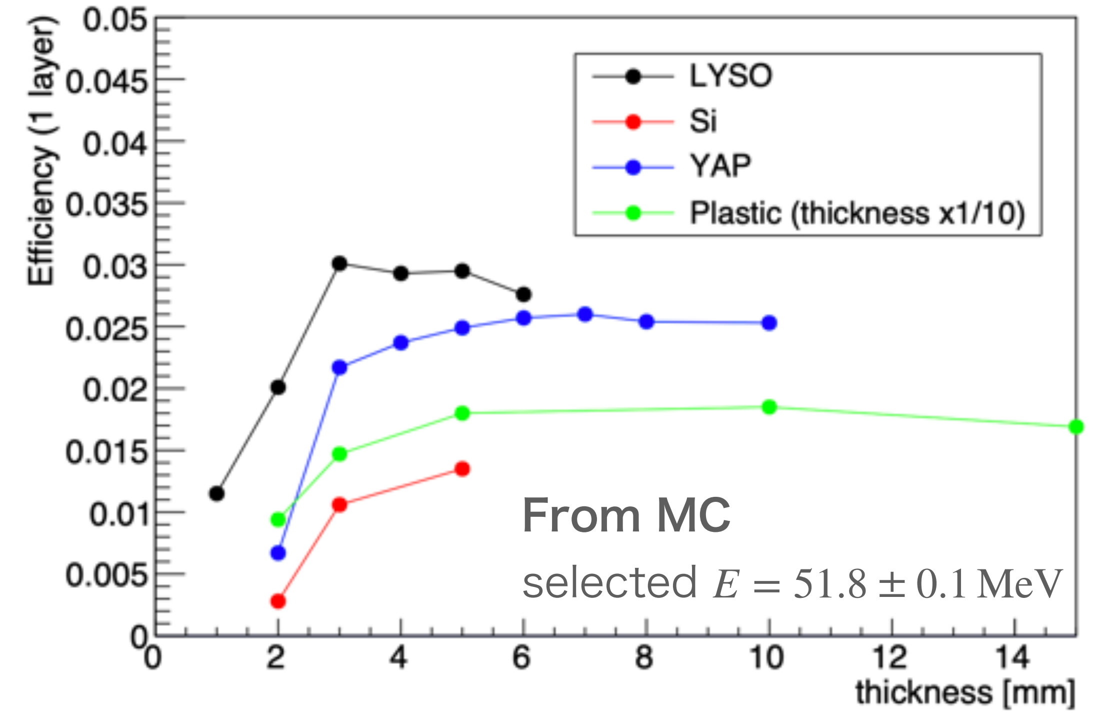
CMS MTD

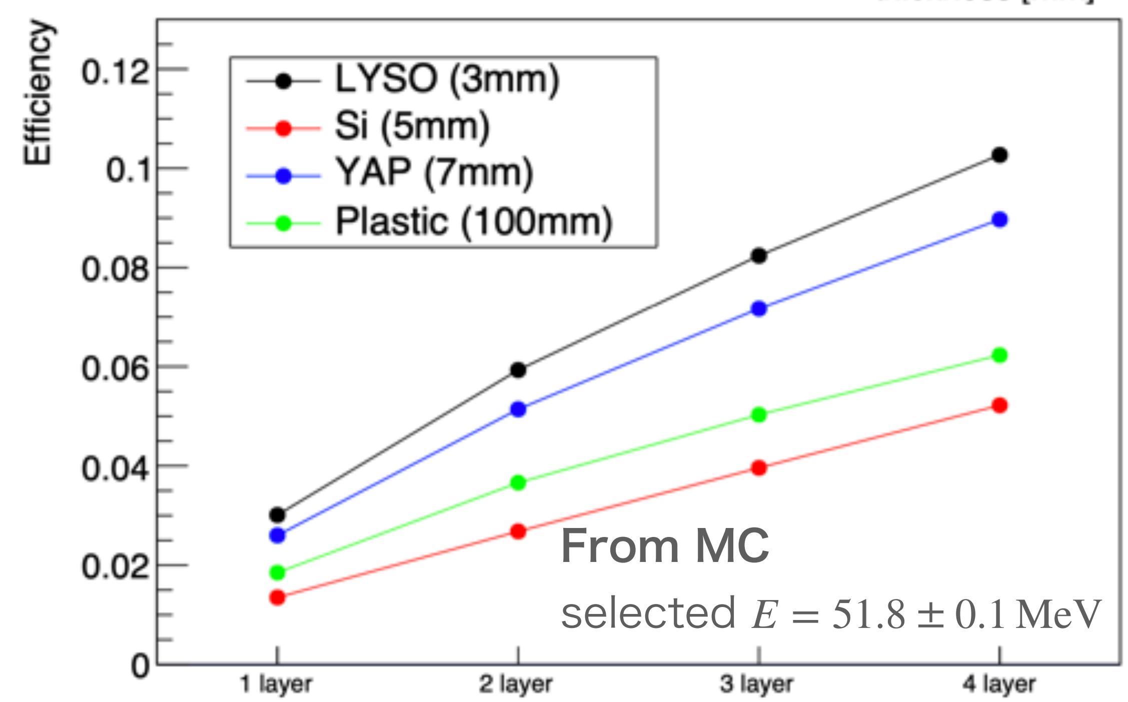


LYSO as Active Material

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.

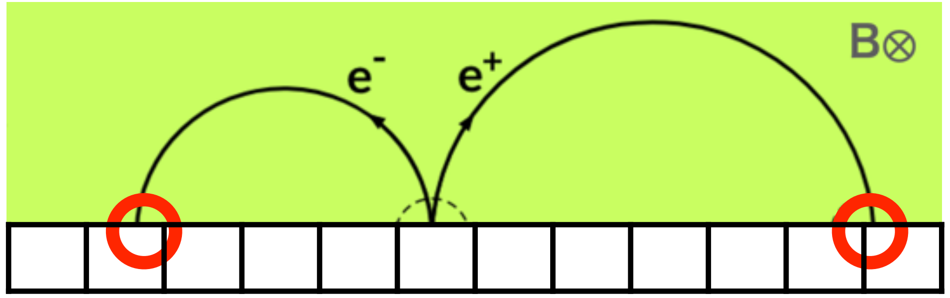




- Good light yields → **good energy resolution**
- Fast response → **good timing resolution**

Requirements for Active Converter

- **LYSO crystal as active material + SiPM as photo-sensor**
- Target performance of pair spectrometer and requirements for active converter
  - **About energy performance,**
    energy resolution of 0.4%@52.8 MeV, corresponding to 200 keV
    → If 4 mm thick LYSO, 200 keV corresponds to 3%@MPV of the energy deposited by 2 MIPs (e^+ and e^-)
    → Energy resolution ∝ 1/√p.e, so at least 1200 photo-electrons required for 2 MIP **(600 photo-electrons for 1 MIP)**
  - Position dependence of light yield can be corrected by the conversion point measured by the conversion pair tracks
  - **About timing performance,**
    time resolution of 30 ps for, by measuring timing of e^+, e^- independently
    → **40 ps. for 1 MIP**



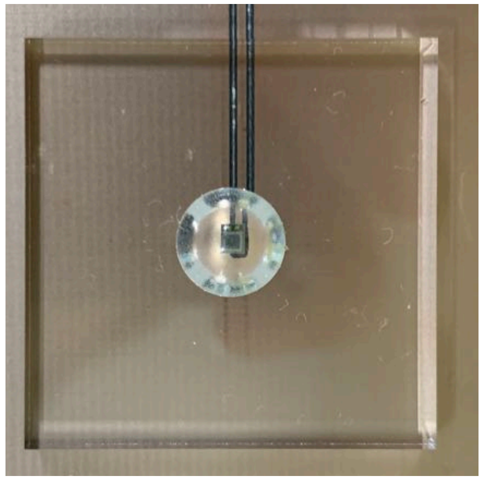
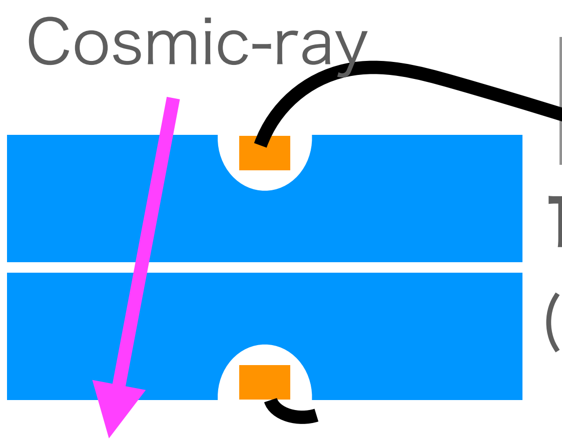
- What we want to know
  - **Average number of photo-electrons to 1 MIP**
  - **Average time resolution to 1 MIP**
    → **To consider specific designs of (LYSO + SiPM)**

Consideration of Performance Evaluation Method

- **Difficulty in giving energy to thin LYSO scinti. to the extent of 1 MIP**
  - Alpha-ray (Am-241) is mostly monochromatic (~ 5.4 MeV) and very easy to stop
    → Good for energy performance evaluation, and difficult for timing performance evaluation
  - Beta-ray (Sr-90) has the maximum Q-value of 2.2 MeV
    → Not enough energy for LYSO scinti. of ~ 3-4 mm (dE/dx ~ 1 MeV/mm)
  - **Cosmic-ray is a MIP and penetrate the LYSO scinti. of ~ 3-4 mm**
    → Can both energy and timing performance evaluations
    (But, Landau distribution is unavoidable)
- **LYSO scinti.** → **30x30x4mm, with a dimple**
  - Thickness → detection efficiency for gamma-ray
  - Size → # of chs
  - Dimple → convenience of mass production
    (this study started prior to the segmentation studies, so bar configuration not tested yet)
- **SiPM** → **three patterns**
  - Many parameters → pixel pitch, size, connection, coupling to the scinti.
    (Mainly to improve time resolution)

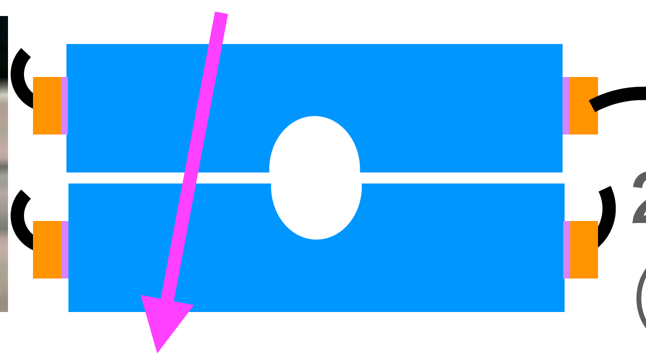
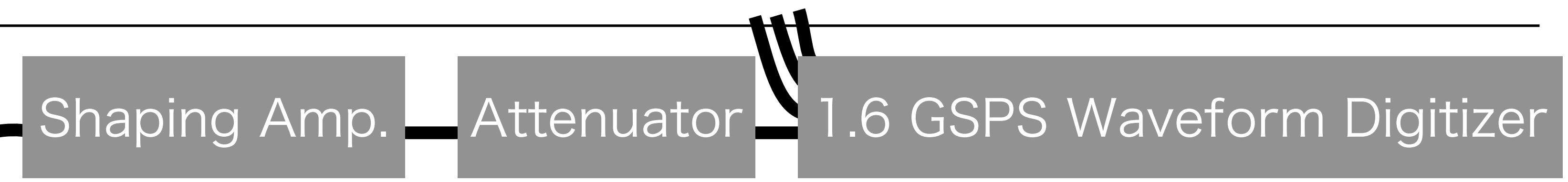
Setups

In all three patterns,
self-triggered by all ch coincidence

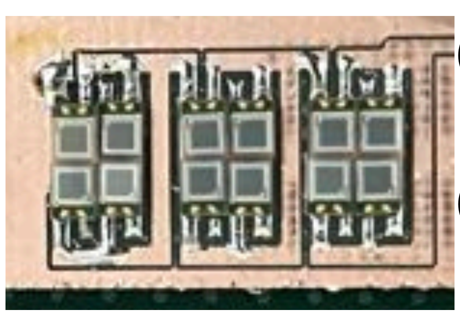
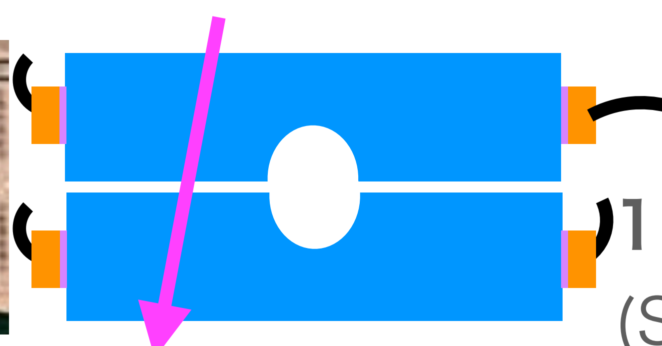
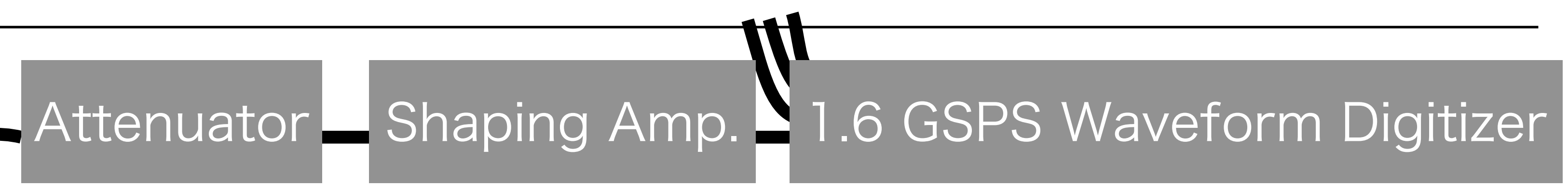
1.3x1.3mm 15μm SiPM x1, Vop = 42 [V]
(S14160-1315PS)

30x30x4mm with a dimple LYSO

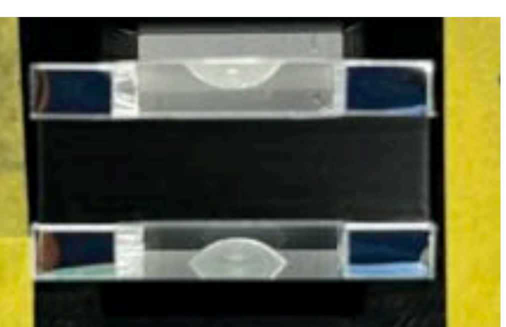
2.0x2.0mm 50μm SiPM x1, Vop = 52 [V]
(S13360-2050VE)

30x30x4mm with a dimple LYSO

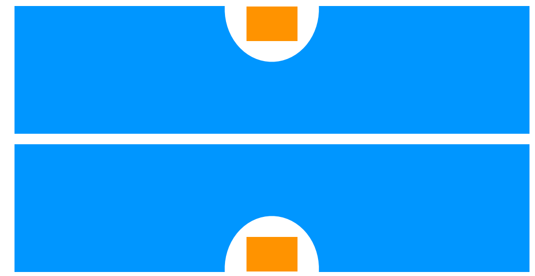




1.3x1.3mm 15μm SiPM x12, Vop = 126 [V]
(S14160-1315PS)
four in parallel, three in series
→ **To increase the photo-sensitive area**
and improve time performance by series connection

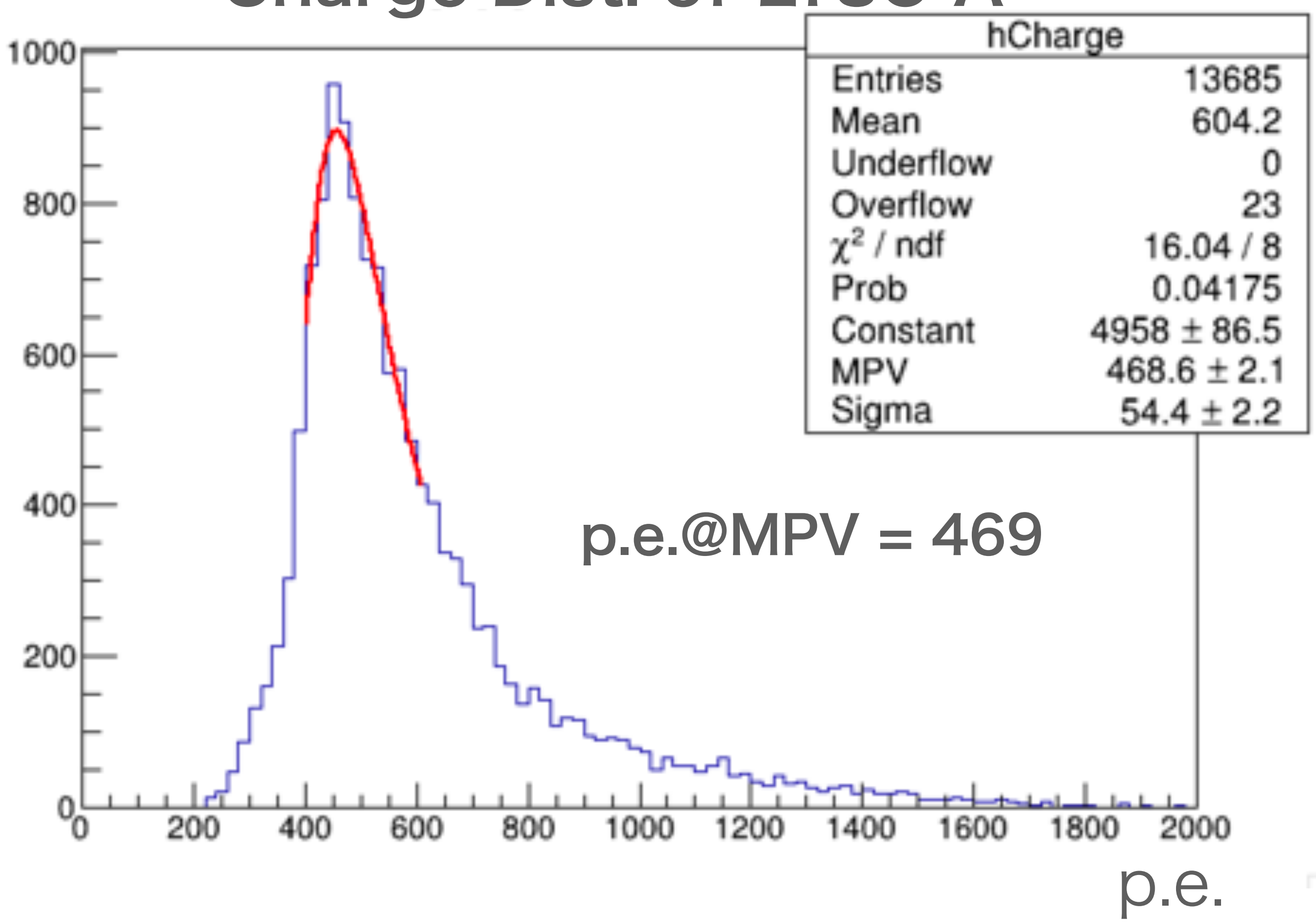
30x30x4mm with a dimple LYSO



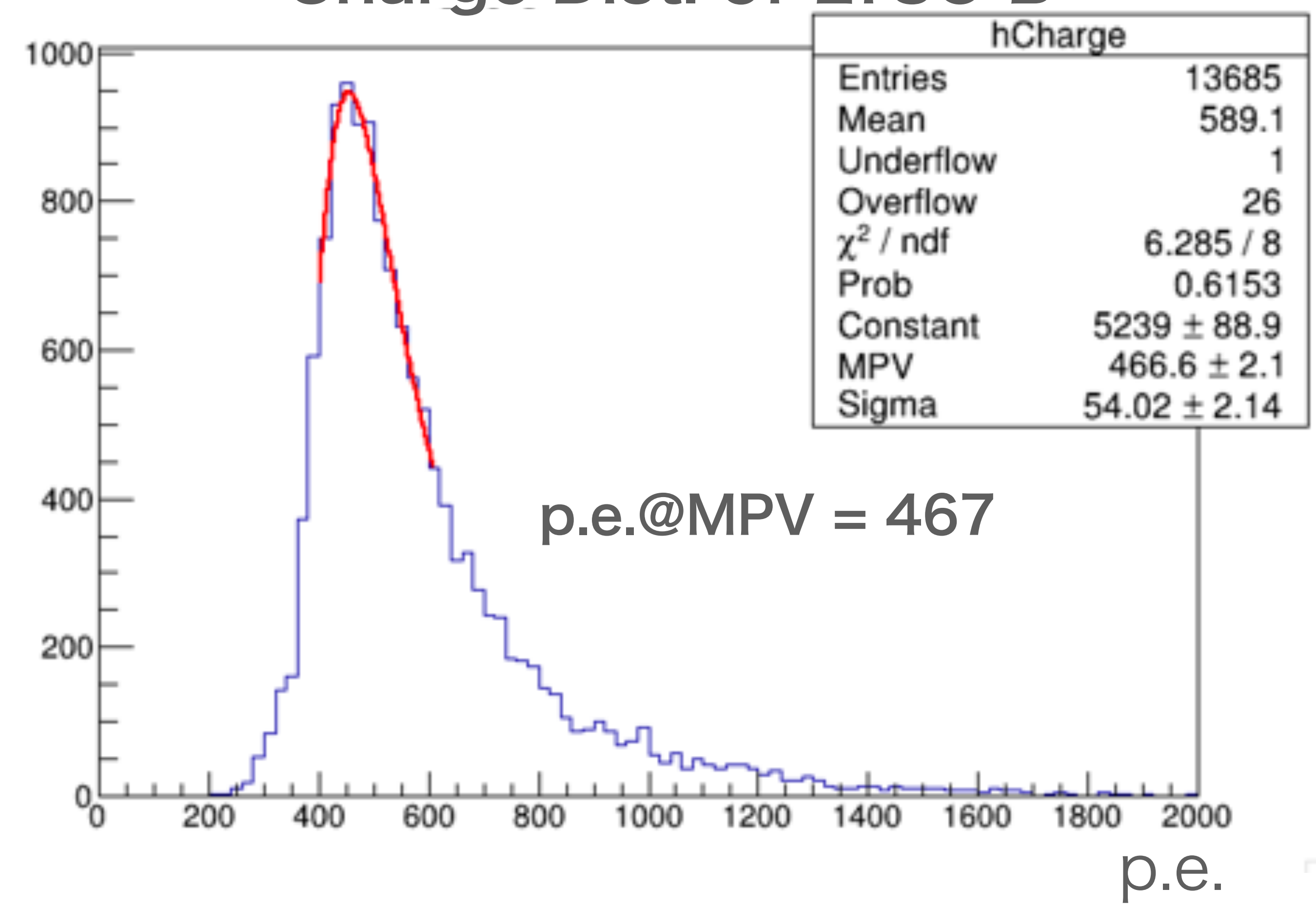
Charge Distributions (1.3x1.3mm 15μm SiPM x1, Dimple Readout)



Charge Dist. of LYSO A

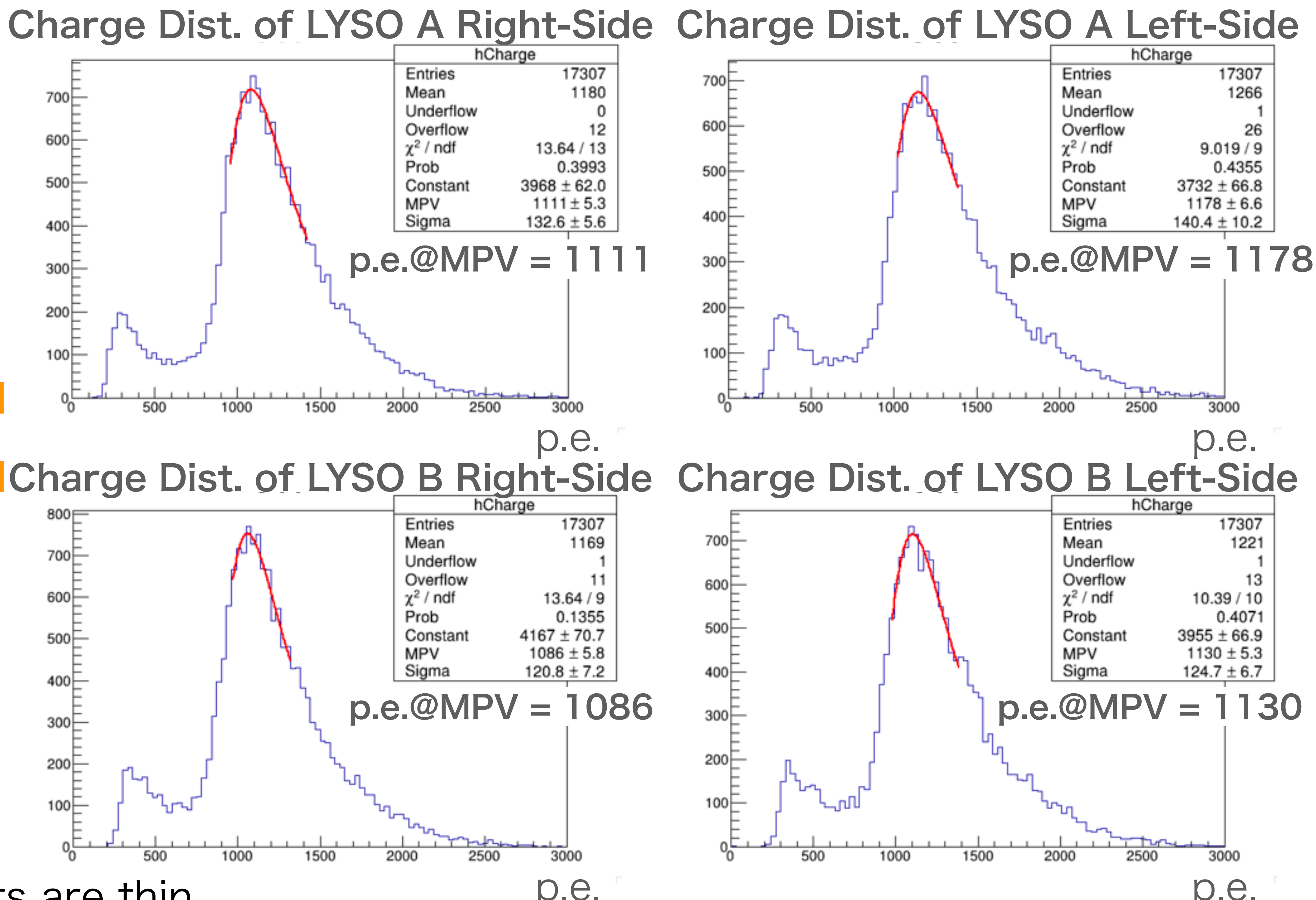


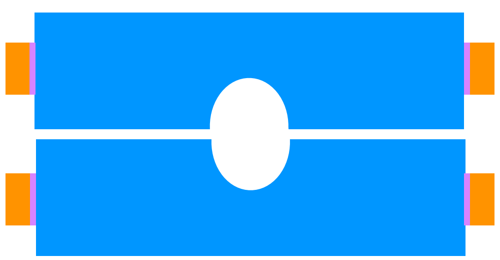
Charge Dist. of LYSO B



- Scintillators are thin
  → Charge distributions roughly form Landau distributions
- Detected photons ~ **470 p.e./counter** at MPV of Landau distributions

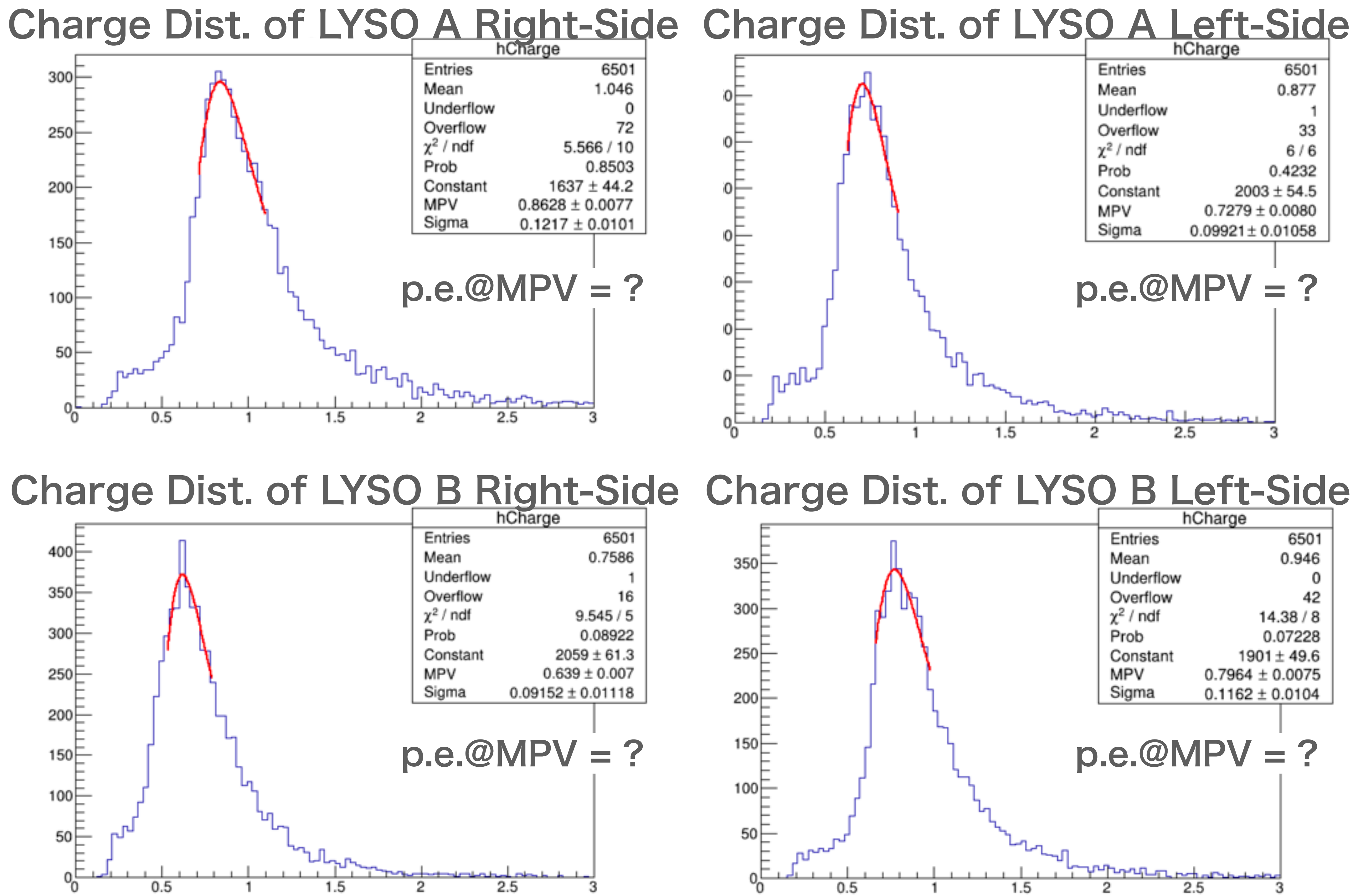
Charge Distributions (2.0x2.0mm 50μm SiPM x1, Double-Side Readout)

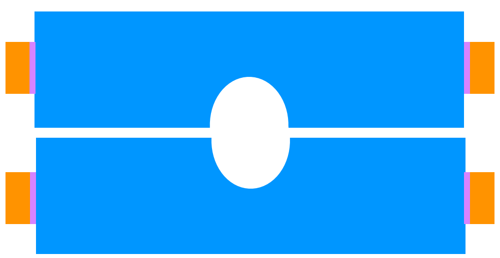




- Scintillators are thin
  → Charge distributions roughly form Landau distributions
- Detected photons ~ **1100 p.e./counter** at MPV of Landau distributions

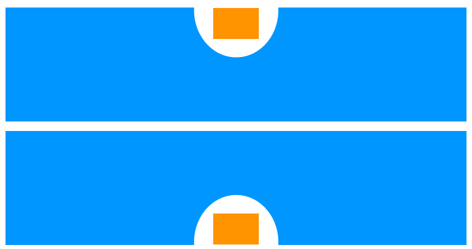
Charge Distributions (1.3x1.3mm 15μm SiPM x12, Double-Side Readout)

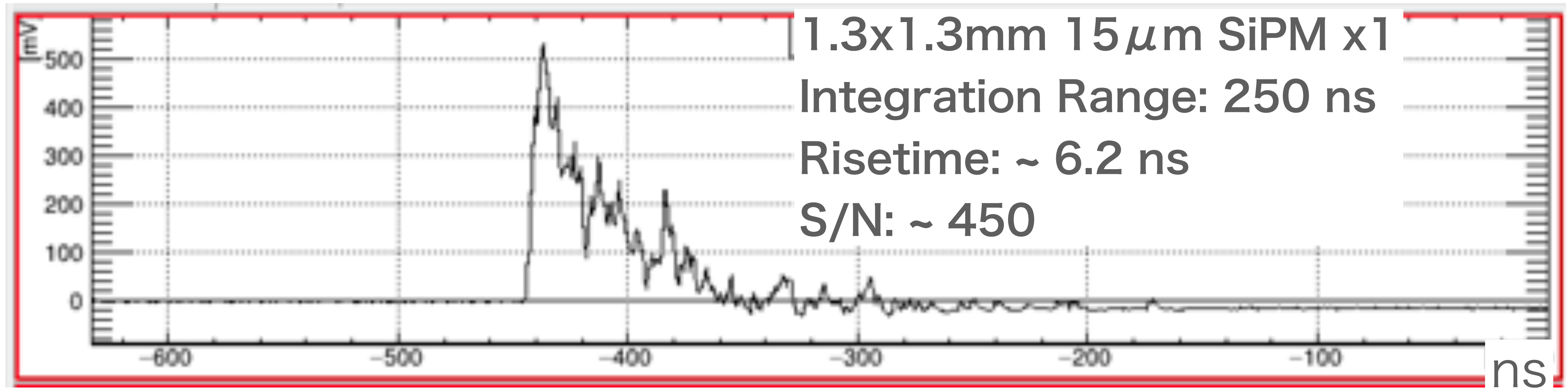




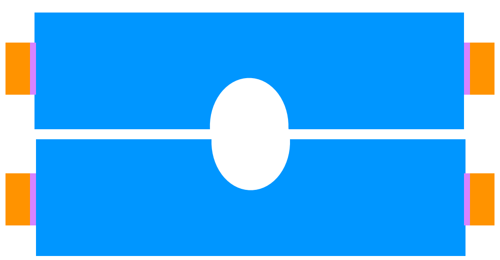
- Scintillators are thin
  → Charge distributions roughly form Landau distributions
- Unknown gains due to so small 1 p.e. waveforms, so unknown # of detected photons
  But, when estimated from photo-sensitive areas and PDEs, **~ 8800 p.e./counter**
- **The requirement of 600 p.e. is easily achievable** in all three readout patterns

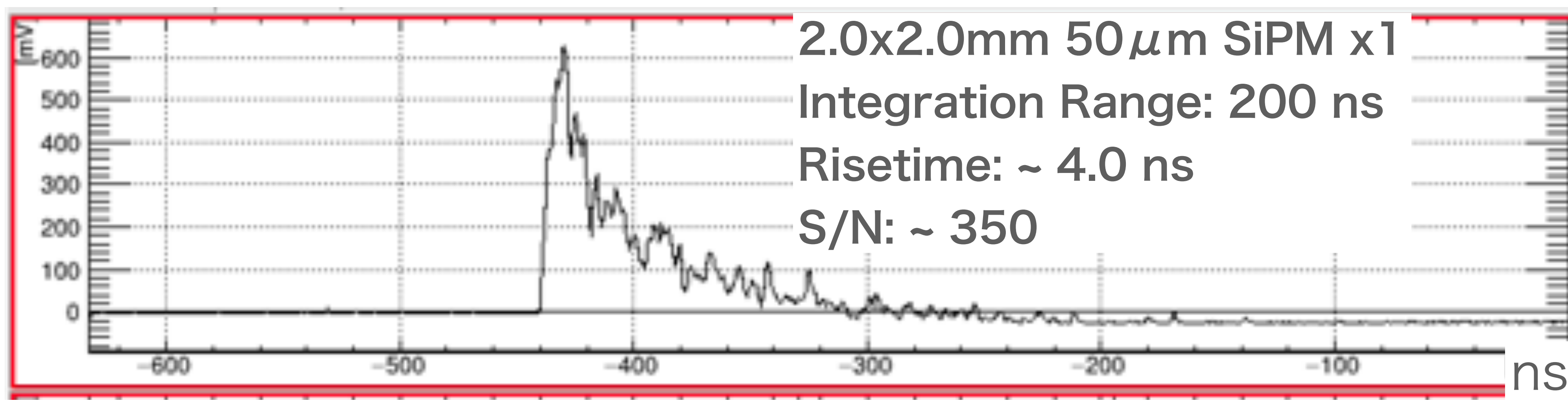
Waveforms



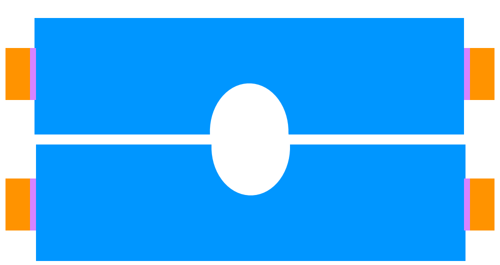


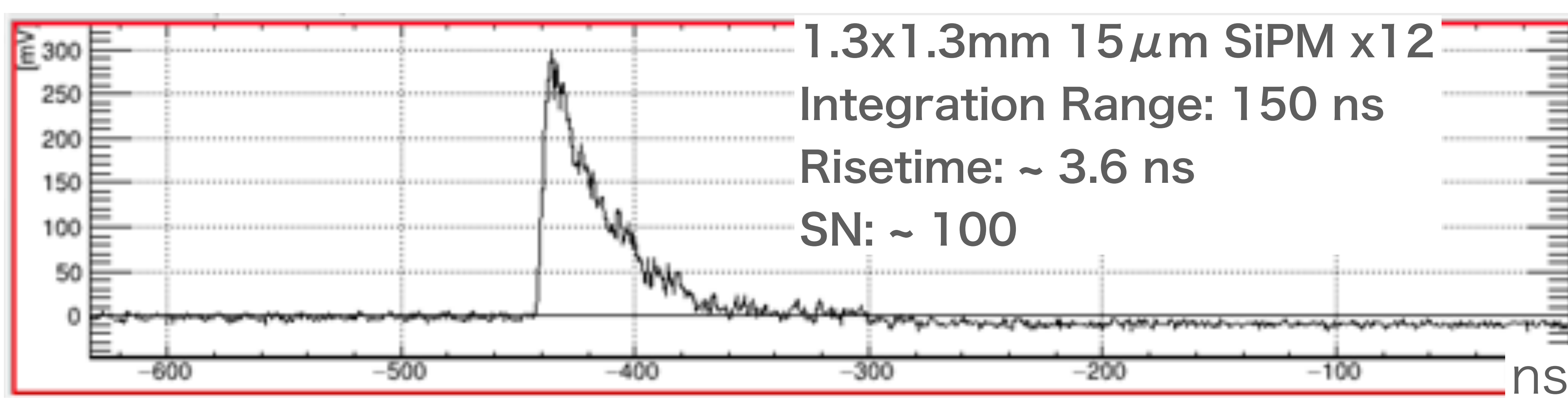
Attenuated by a factor of 0.71





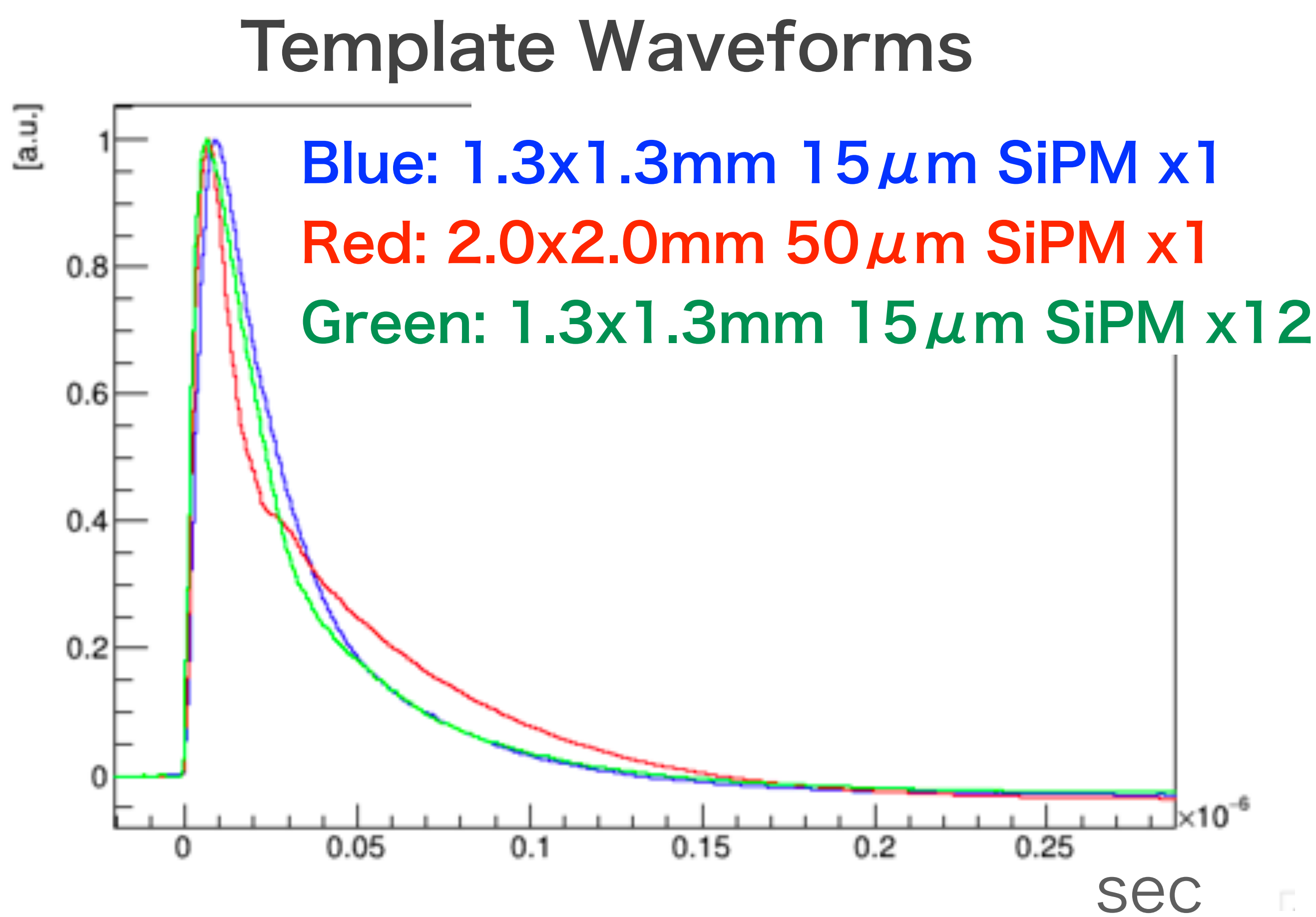
Attenuated by a factor of 0.50

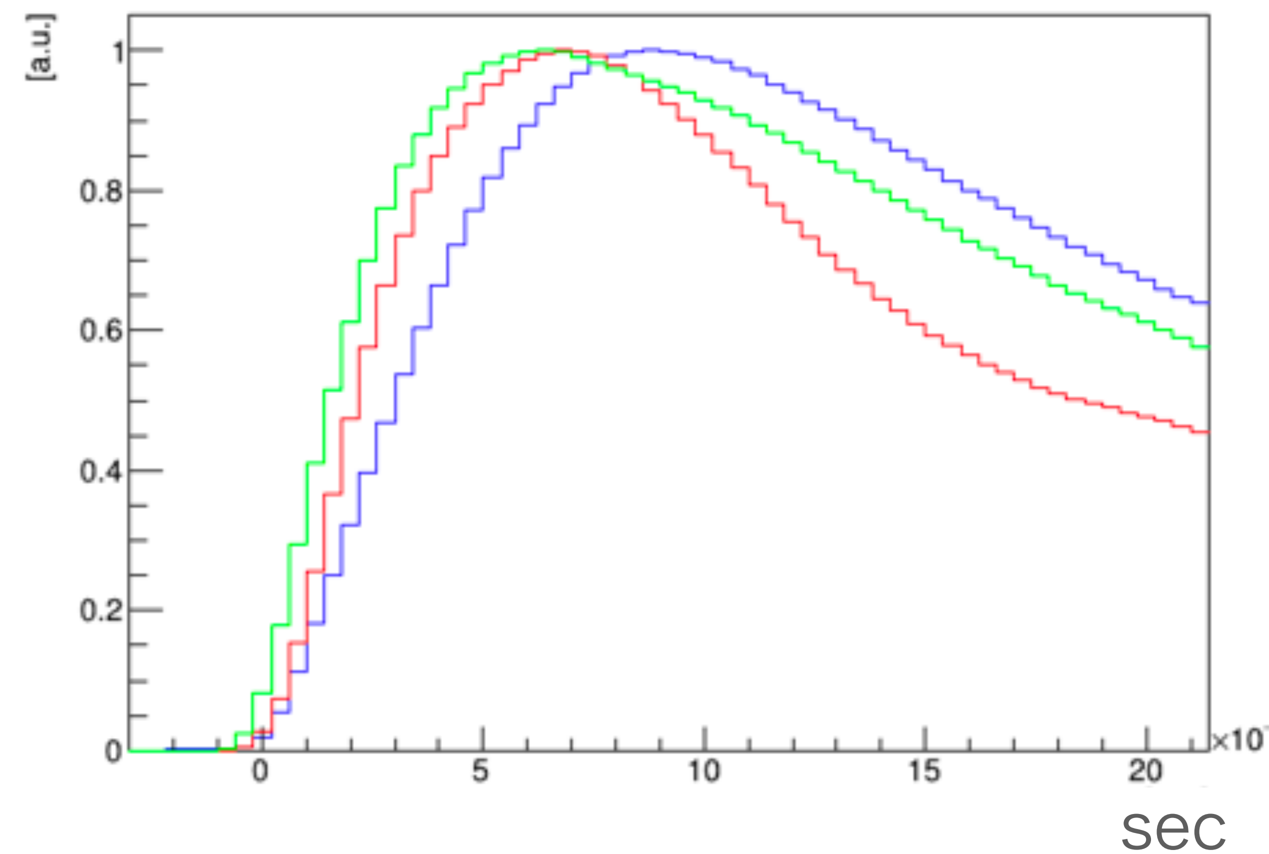




Attenuated by a factor of < 0.32

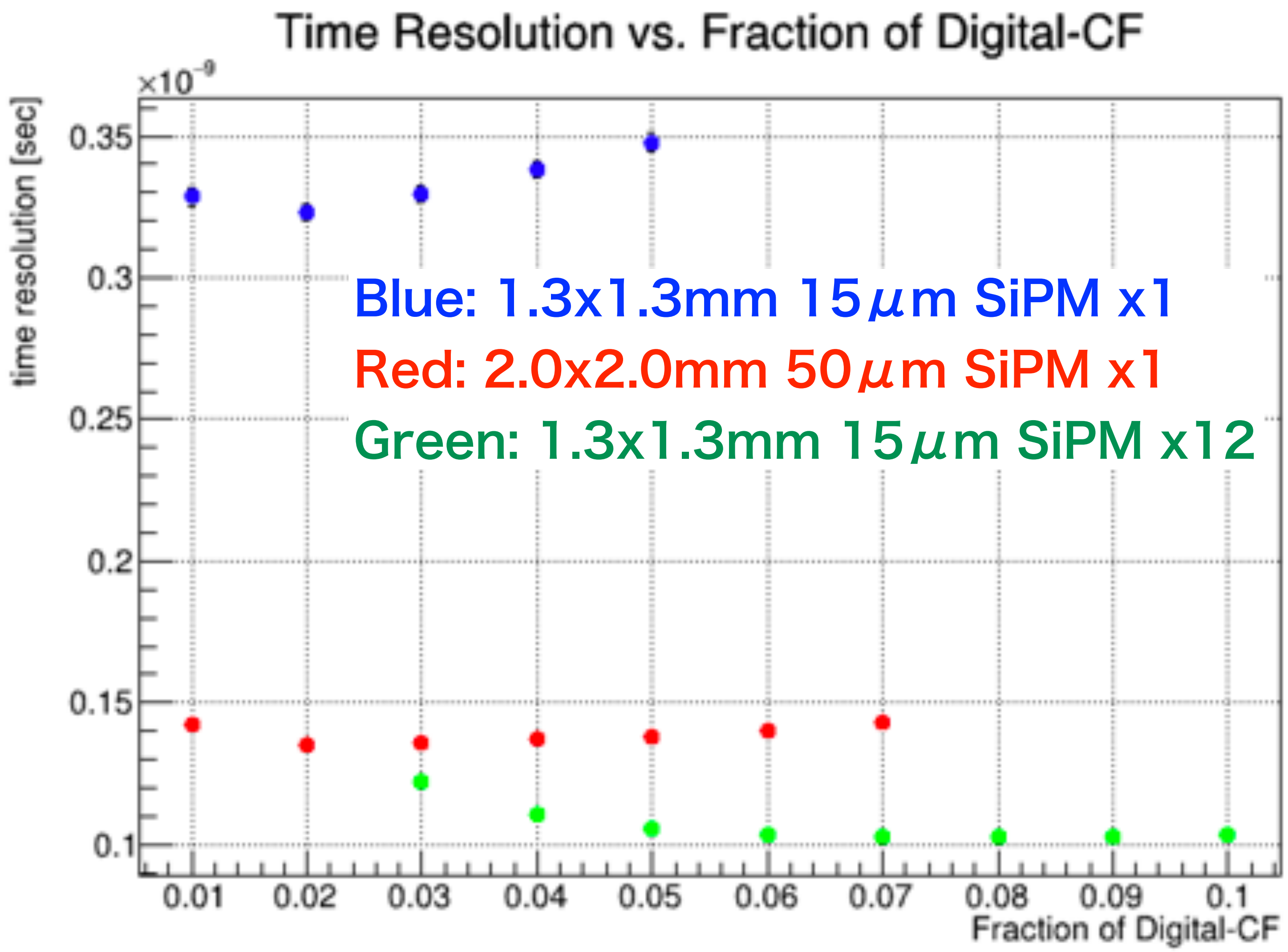
Template Waveforms





- For the same pixel pitch (15μm)
  → **series connection** has a **shaper waveforms** and **rise faster**
- For the different pixel pitches (15μm and 50μm)
  → **smaller pixel pitch** has a **shaper waveforms**

Time resolution



- time resolution $= \sigma(t_{\text{counter A}} - t_{\text{counter B}})/\sqrt{2}$
  - If double-side readout, $t_{\text{counter i}} = (t_{\text{right SiPM}} - t_{\text{left SiPM}})/2\,, (\text{i} = \text{A}, \text{B})$
- Detection time was obtained by applying the digital constant fraction method to the waveform
- Fraction parameters were scanned
  - 0.02 was optimal for both 1.3x1.3mm x1 and 2.0x2.0mm x1
  - 0.07 was optimal for 1.3x1.3mm x12 → **S/N may limit time resolution**

Table of Summary

	This study			CMS MTD BTL
Scinti.	30x30x4mm with a dimple LYSO			3x3x50mm LYSO
Readout	Dimple	Double-Side	Double-Side	Double-side
SiPM	1.3x1.3mm15μm x1	2.0x2.0mm 50μm x1/side	1.3x1.3mm15μm x12/side	3x3mm 15μm x1/side
p.e.@MPV	468 p.e.	2252 p.e.	8800 p.e. scaled by photo-sensitive area and PDE	12000 p.e.
Time Resolutions	323 ps	135 ps	102 ps	30 ps
Time Resolutions@1000 p.e. Scaled by ∝ 1/√L.Y.	221 ps	203 ps	**303 ps**	**104 ps**
Risetime	~ 6.3 ns	~ 3.8 ns	~ 4.0 ns	
S/N	~ 450	~ 350	~ 100	

- **The target value of 600 p.e. can be easily achieved**
- Time performance seems **to be slightly better for double-side readout** than for dimple readout
- **The best time resolution was 102 ps, which does not meet the requirement yet**
    - Poor S/N
    - Geometry of scinti. and coverage by photo-sensitive area

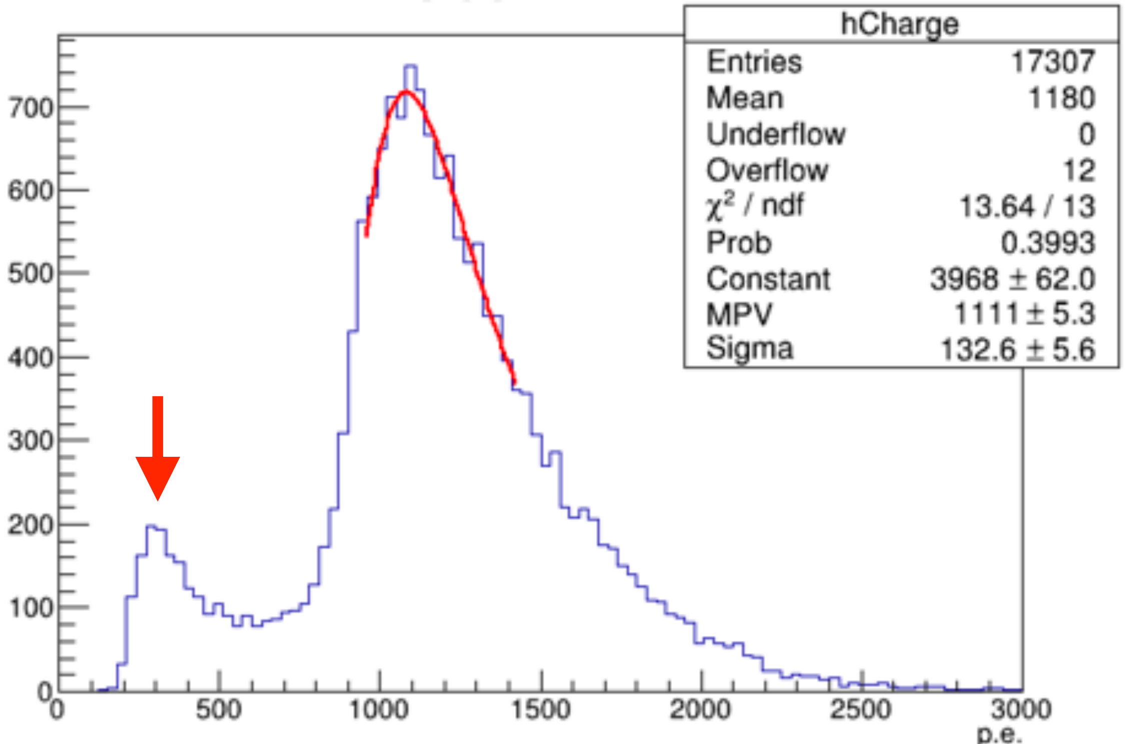
Summary and Prospects

- In future $\mu^+ \to e^+\gamma$ decay search experiment, **pair spectrometer with active converter** are being considered for gamma-ray detector
- As an active material, **LYSO crystal** is being considered for use in terms of efficiency
- Also considering using active converters as **timing layer**
- Average response of (30x30x4mm LYSO + SiPM) to MIP was investigated
  - **About energy performance,**
    The required light yield to achieve 0.4% as pair spectrometer found to be achievable
    Position dependence of light yield will be measured
  - **About timing resolution**
    The timing resolution of 102 ps has been achieved.
    It should be further improved.
- It is planned to test using **LYSO bar to improve timing performance**
  - Also to test Fast-type LYSO expected to have a good time response

Backup

Charge Distributions (2.0x2.0mm 50μm SiPM x1, Double-Side Readout)

Charge Dist. of LYSO A Right-Side



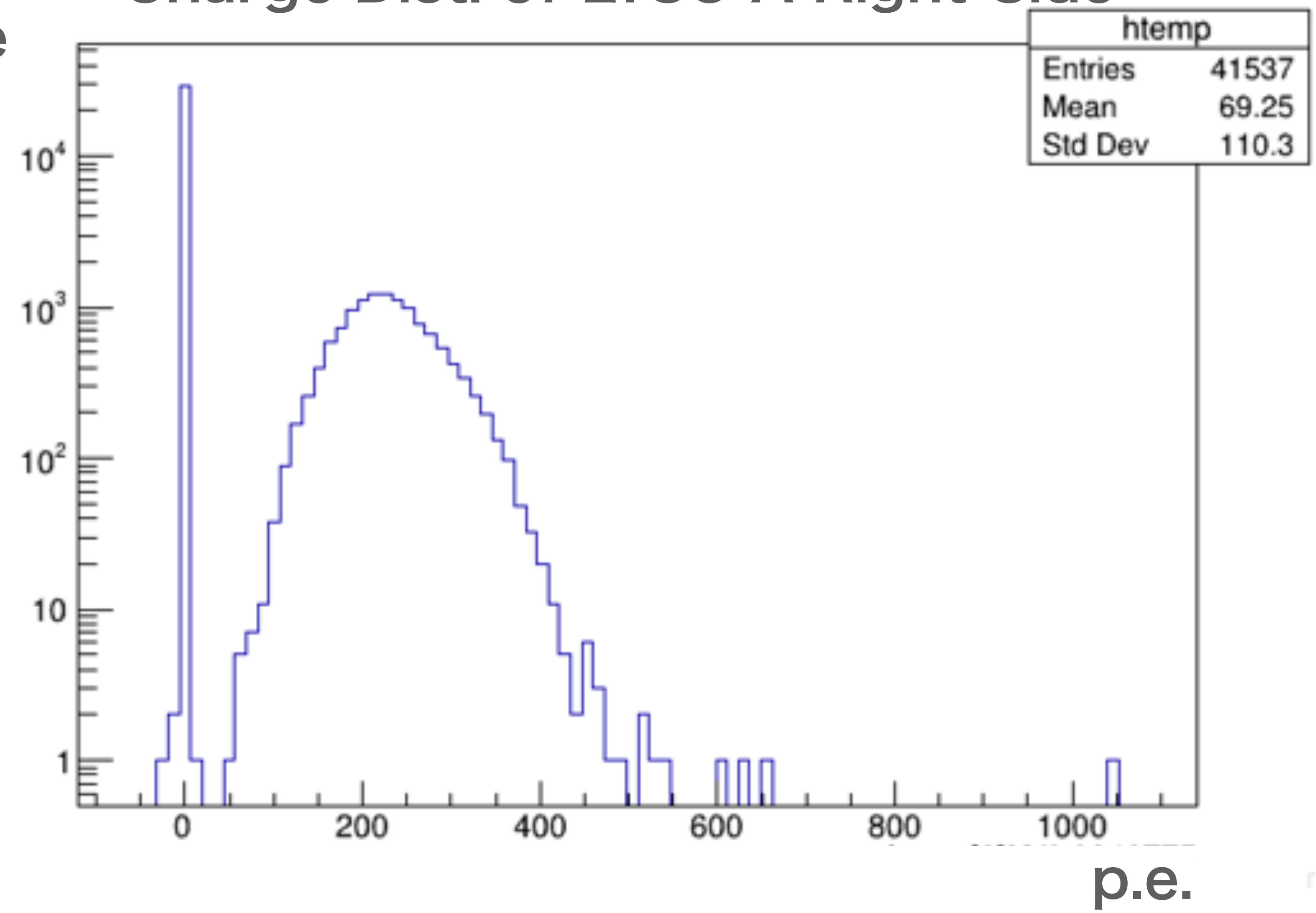
Cosmic data with high threshold coincidenced w/ SiPM of the other 3 chs (coincidence gate = TOT)

Trigger rate ~ 1 Hz

Also, when applied higher Vop, w/ same thr.
Trigger rate ~ 380 Hz (>> cosmic-ray's rate)

→ self-radiations?

Charge Dist. of LYSO A Right-Side



Self-radiations data with low threshold
no coincidence

Trigger rate > 500 Hz (limited by digitizer)

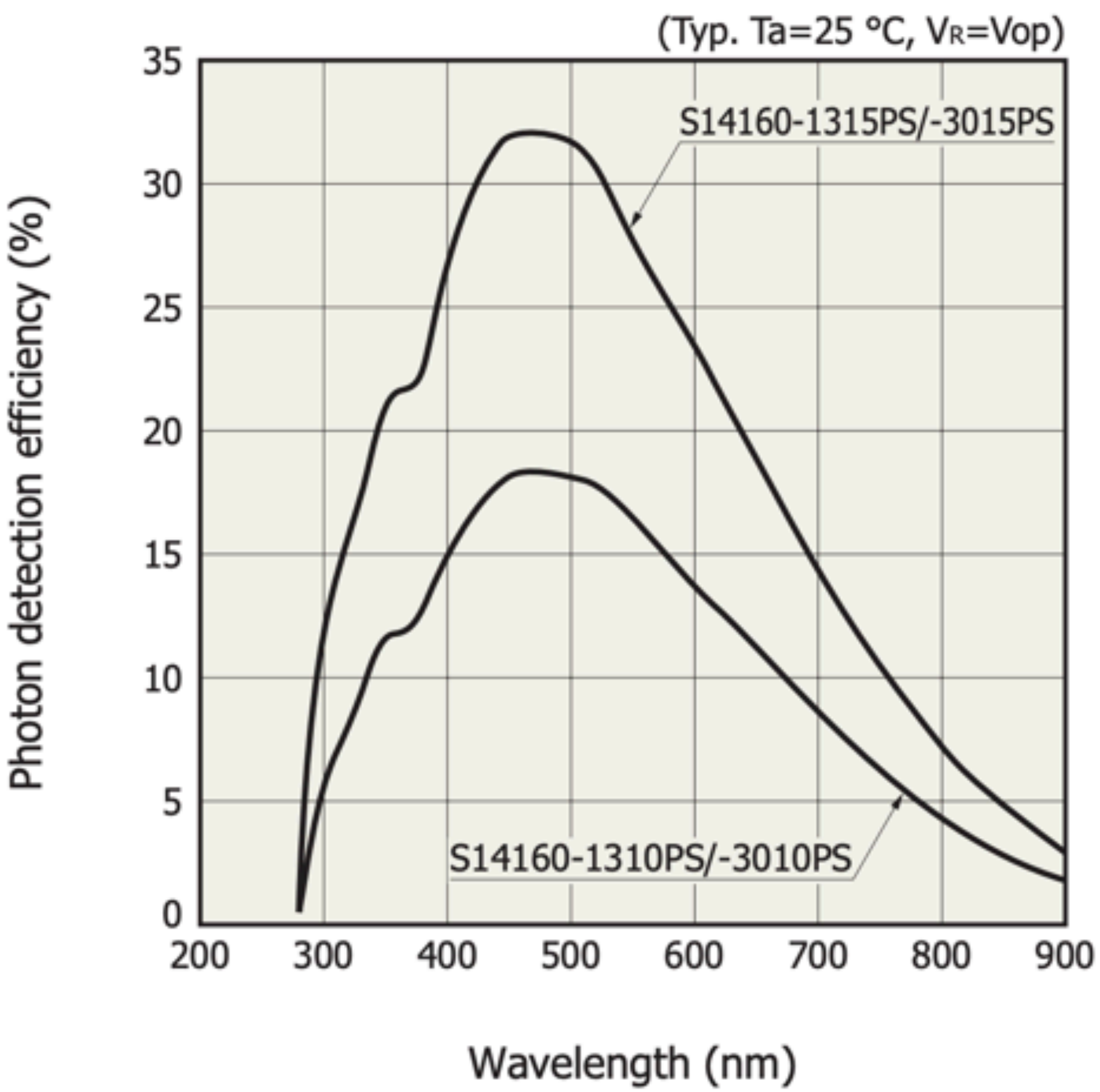
More investigations are needed to conclude whether self-radiations is the cause

JT Crystal Technology's LYSO

	Ce:LYSO	Ce:FTRL (or so-called Fast-LYSO)
Density [g/cm^3]	7.2	7.2
Light Yields	8-10%	8-10%
Energy Resolution	36000±10%	30000±10%
Emission Peak [nm]	420	420
Decay time [ns]	40	31
Coincidence Time Resolution [ps] (2mm cube)	125	96
Refractive Index	1.81	1.81
Hygroscopicity	None	None

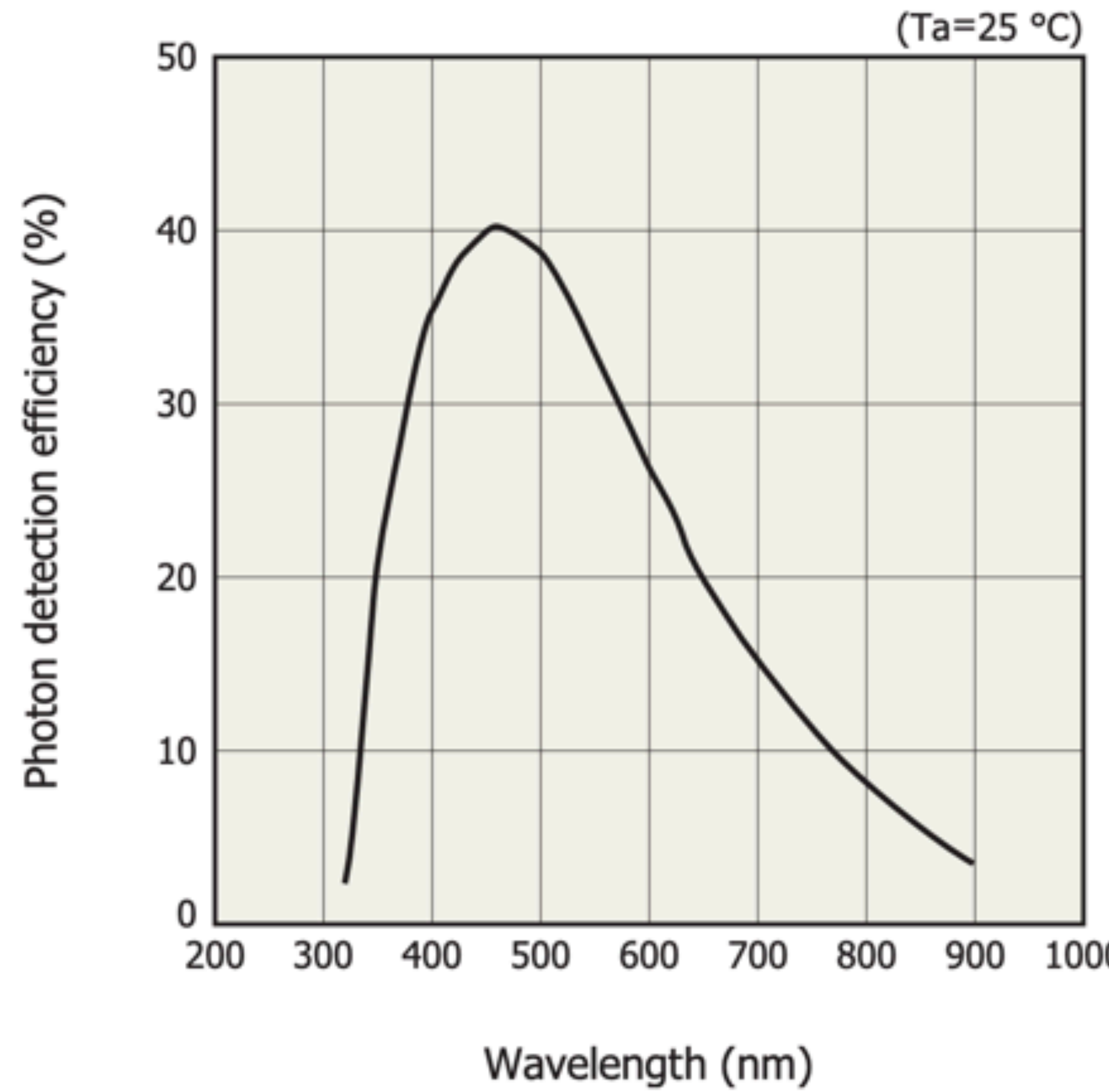
PDE Comparison

Photon detection efficiency vs. wavelength



S14160-1315PS
~ 27%@420

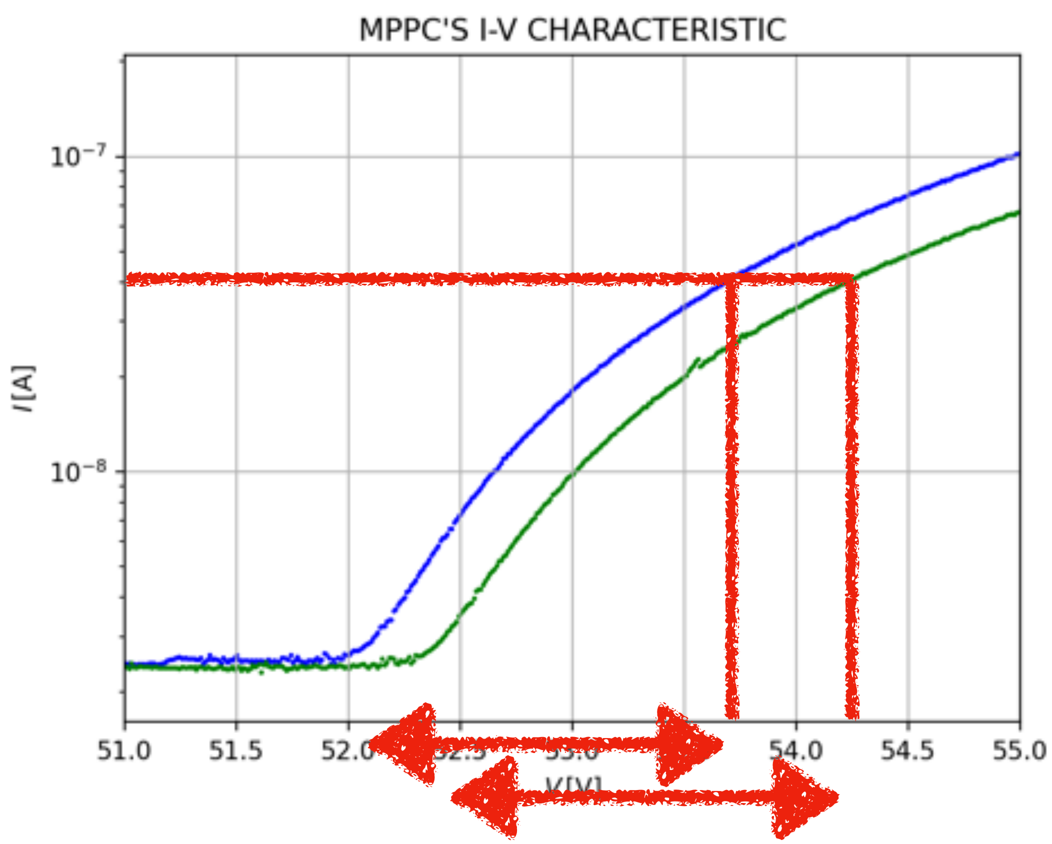
Photon detection efficiency vs. wavelength (typical example)



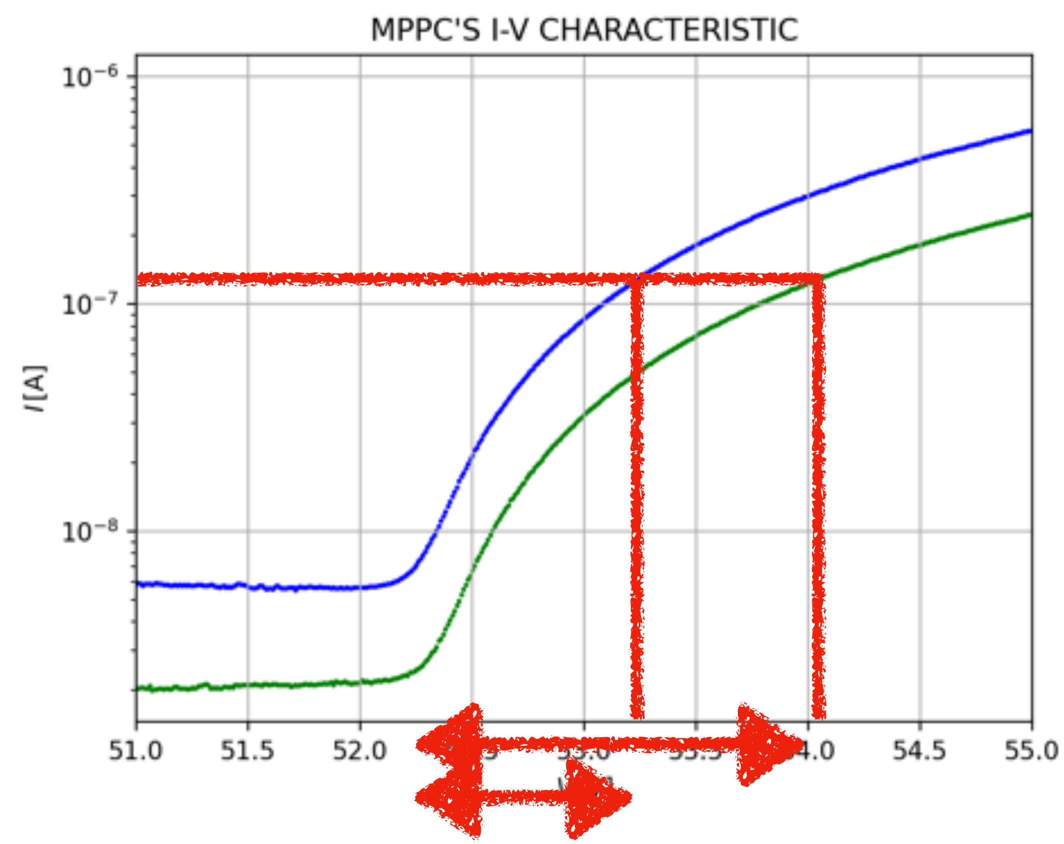
S13360-2050VE
~ 35%@420

Series Connection of SiPMs and Their Gains

- Voltage is distributed to each SiPM so that a common current flows
- Then, if the I-V characteristics are similar, V_{over} **(and also gain) will be equal in each SiPM**
- Where similar I-V characteristics mean the similar outlines of the graphs and the similar levels of current values



$\Delta V_1 \simeq \Delta V_2$



$\Delta V_1 \neq \Delta V_2$