MEG II実験陽電子タイミングカウンターの改修結果と運用経過

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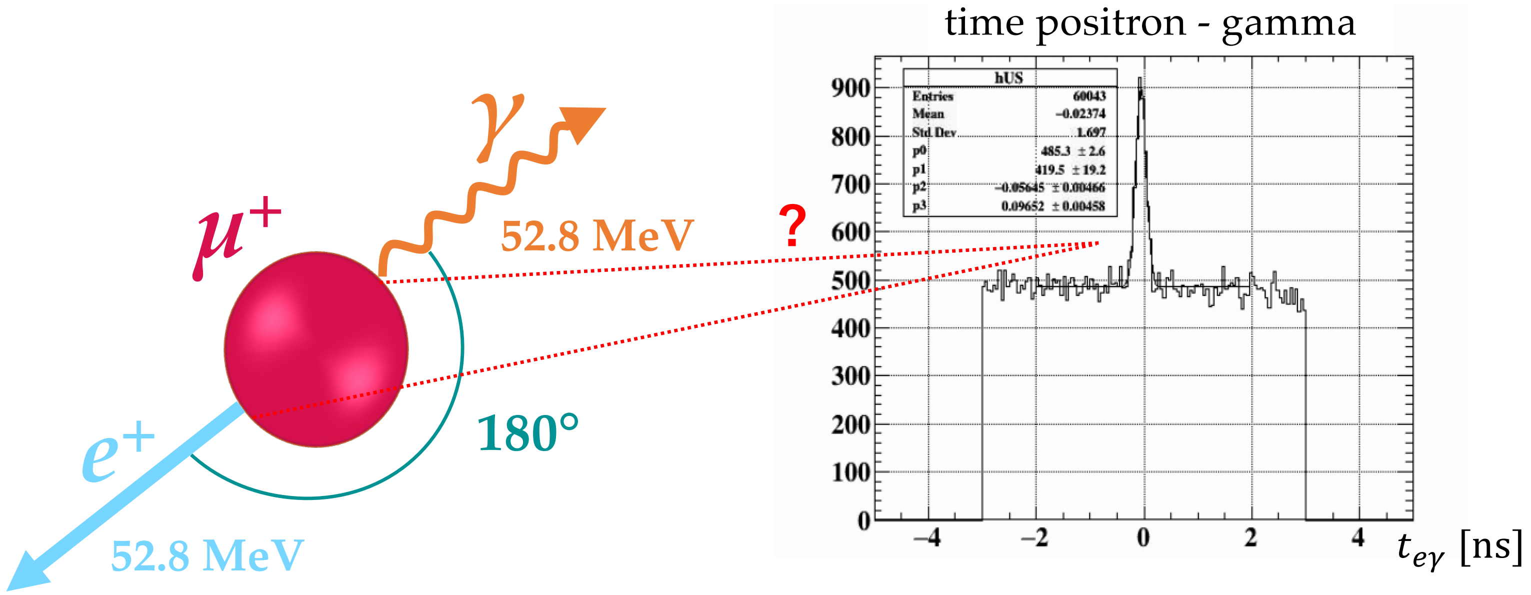
18aWB106-1

1. Introduction

Motivation – Mu to E Gamma

❑ Undiscovered charged lepton flavour violation (cLFV) process.



❑ **The Mu to E Gamma:** $\boldsymbol{\mu \to e\gamma}$, is hypothetical and one of the simplest cLFVs which emits only pair of positron and gamma ray at the same time and with the monochromatic energy.

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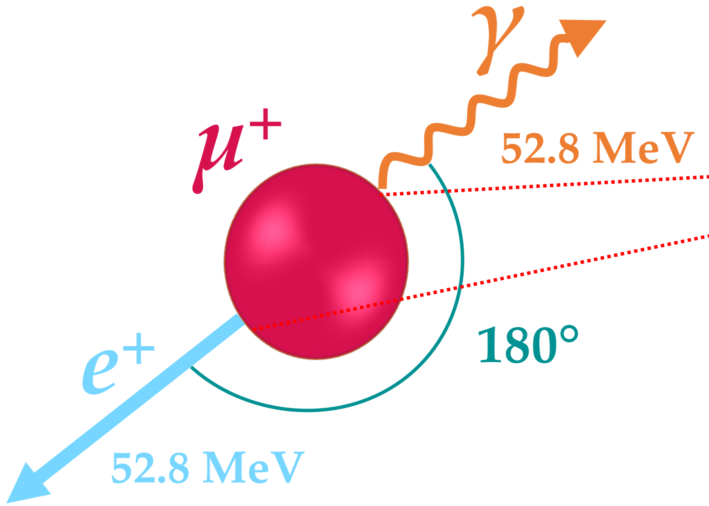
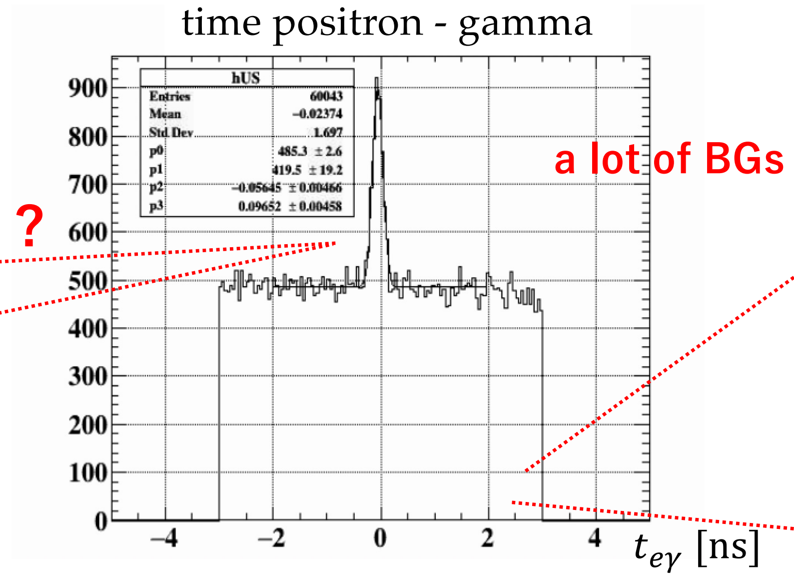
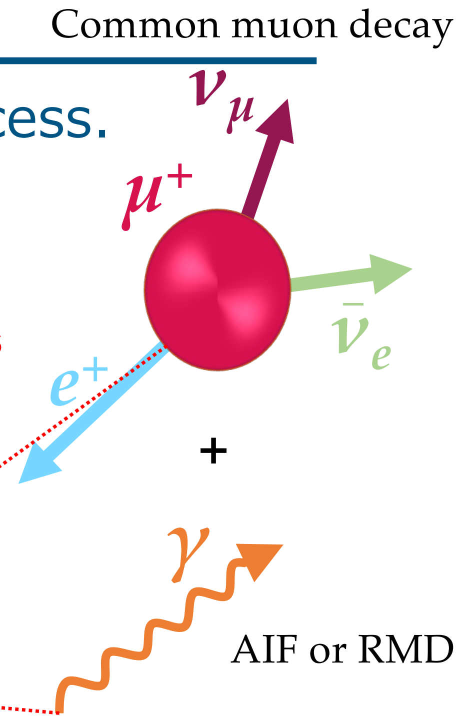
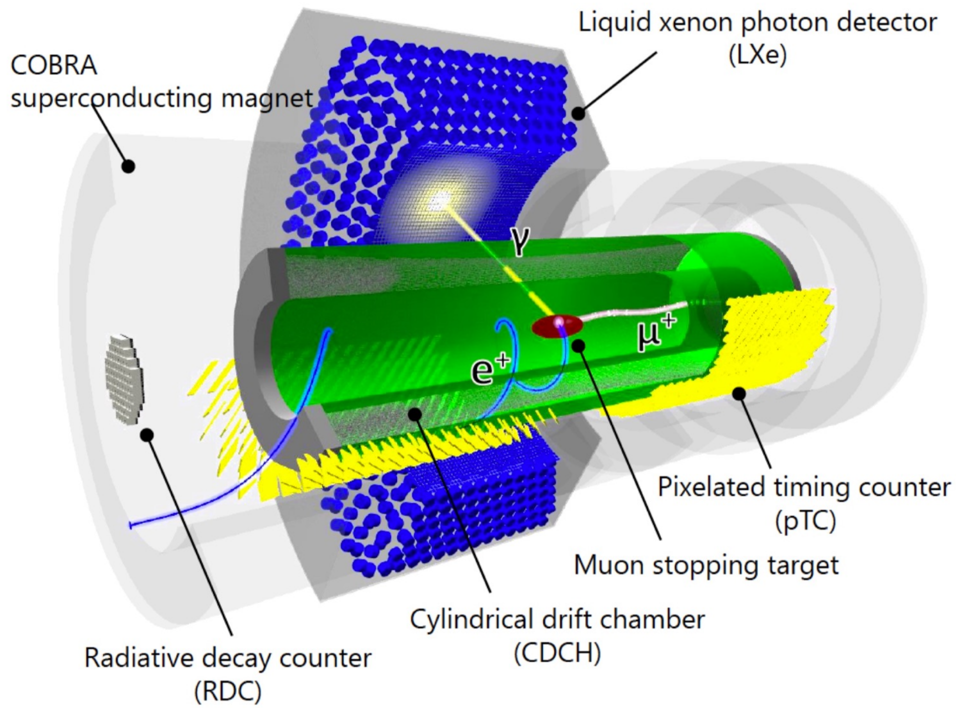






- ❑ **The Mu to E Gamma:** $\boldsymbol{\mu \rightarrow e\gamma}$, is hypothetical and one of the simplest cLFVs which emits only pair of positron and gamma ray at the same time and with the monochromatic energy.
- ❑ The most common muon decay mode: $\boldsymbol{\mu \rightarrow e\bar{\nu}\nu}$, accounts for ~100 % of muon decays.

Motivation – MEG II



- **M**u to **E G**amma phase **II** experiment
- Search for the cLFV process $\boldsymbol{\mu \to e\gamma}$ with aimed sensitivity: $\mathbf{6 \times 10^{-14}}$
- One order better than the UL:
  $\mathcal{B}\,(\mu \to e\,\gamma) < 4.2 \times 10^{-13}$ (MEG, 2016)
  -> $\boldsymbol{\mathcal{B}\,(\mu \to e\,\gamma) < 3.5 \times 10^{-13}}$ (MEG II, 2024)
- Running continually since 2021 with the DC anti-muon beam $> 10^7\ \mu^+/s$ at the Paul Scherrer Institute (PSI).

⇨ **Currently leading experiment in the search of $\mu \to e\gamma$ process !**

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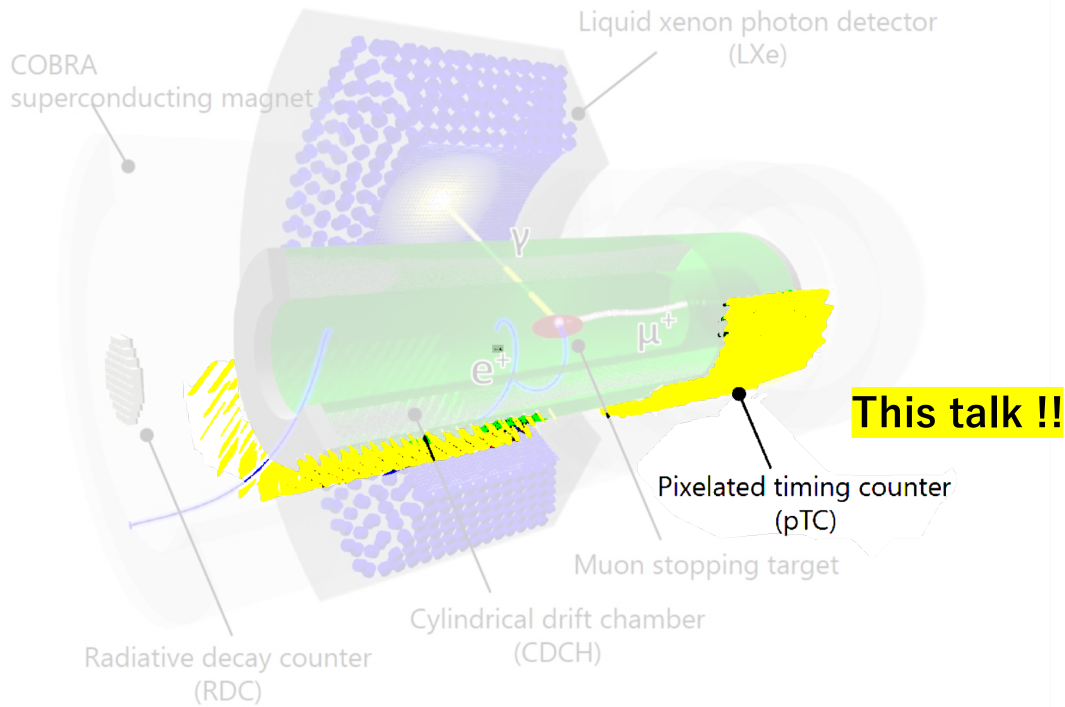

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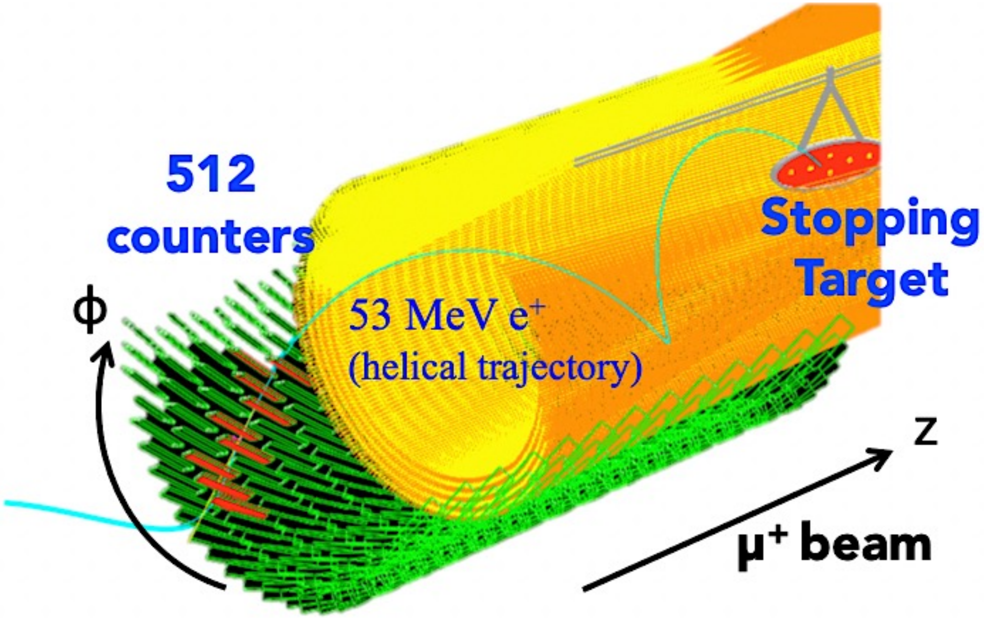
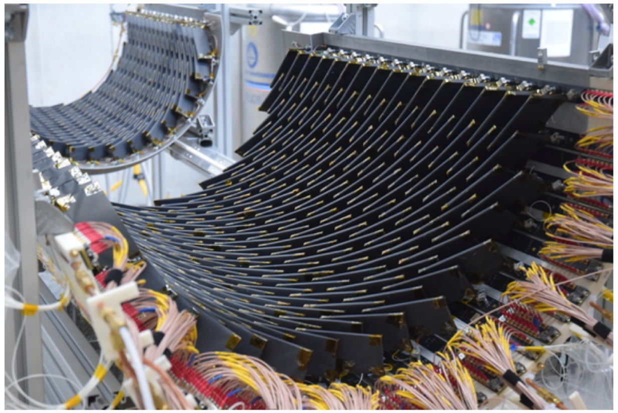
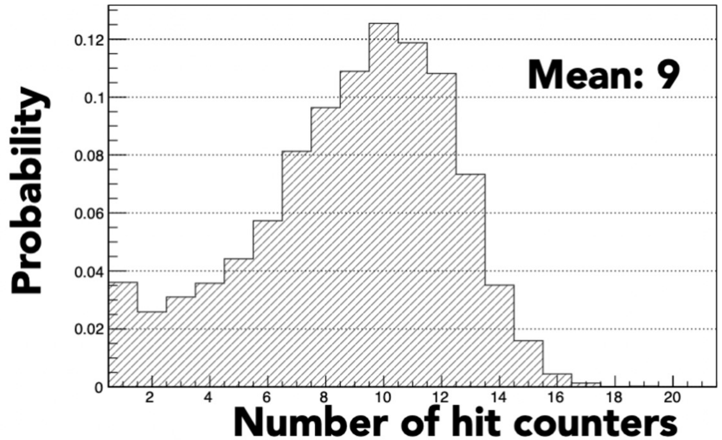
⇨ **Long term operation and renovation of the pixelated Timing Counter for positron timing detection.**

pixelated TC - concept

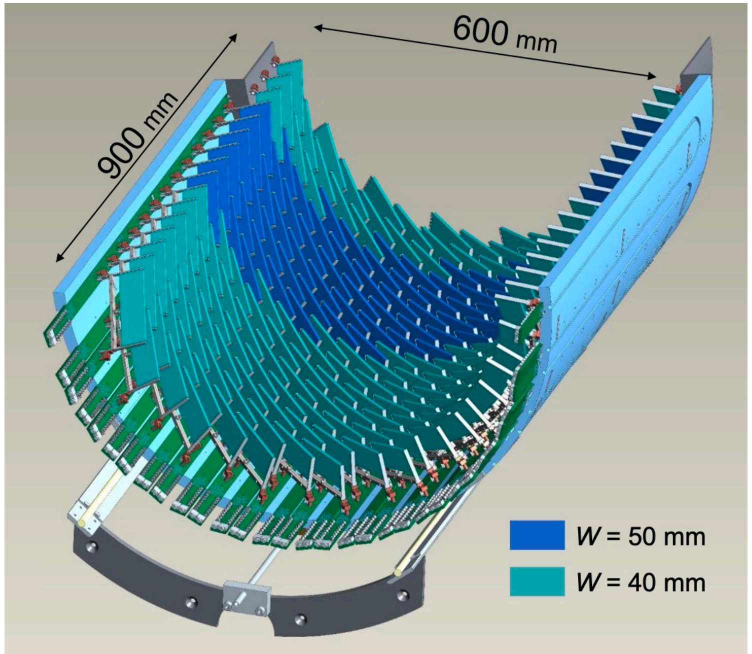


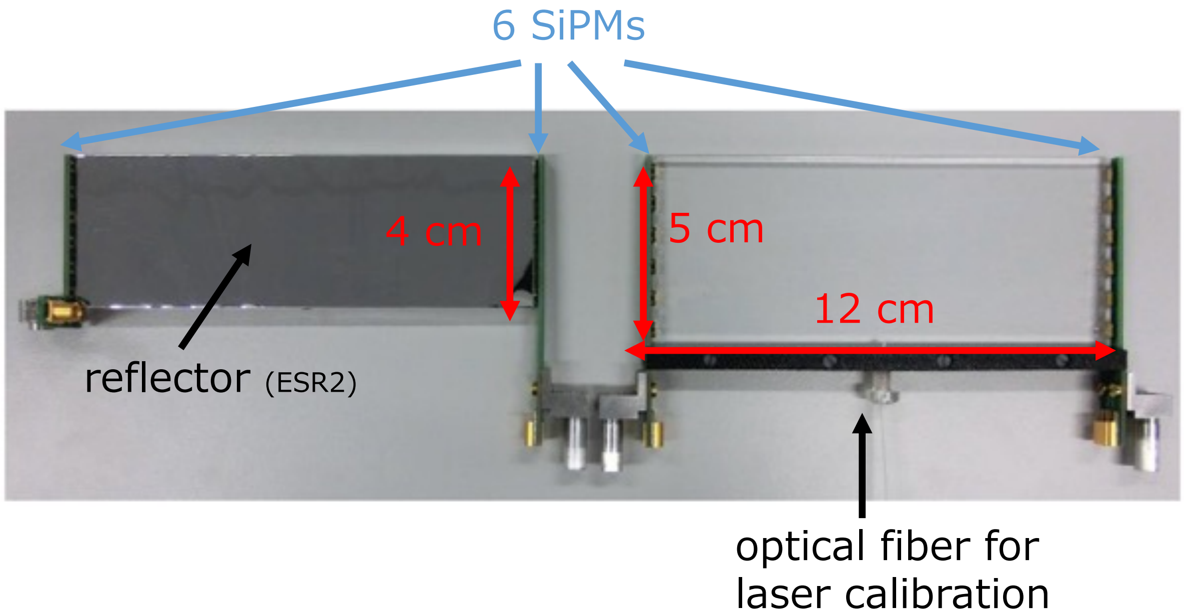


- ❑ **Improve e^+ time resolution by multiple-pixel-hit scheme.**
- ❑ Upstream 256 + Downstream 256 = **512 pixels**
- ❑ Mean ~ **9 hits** (MC, signal e^+)



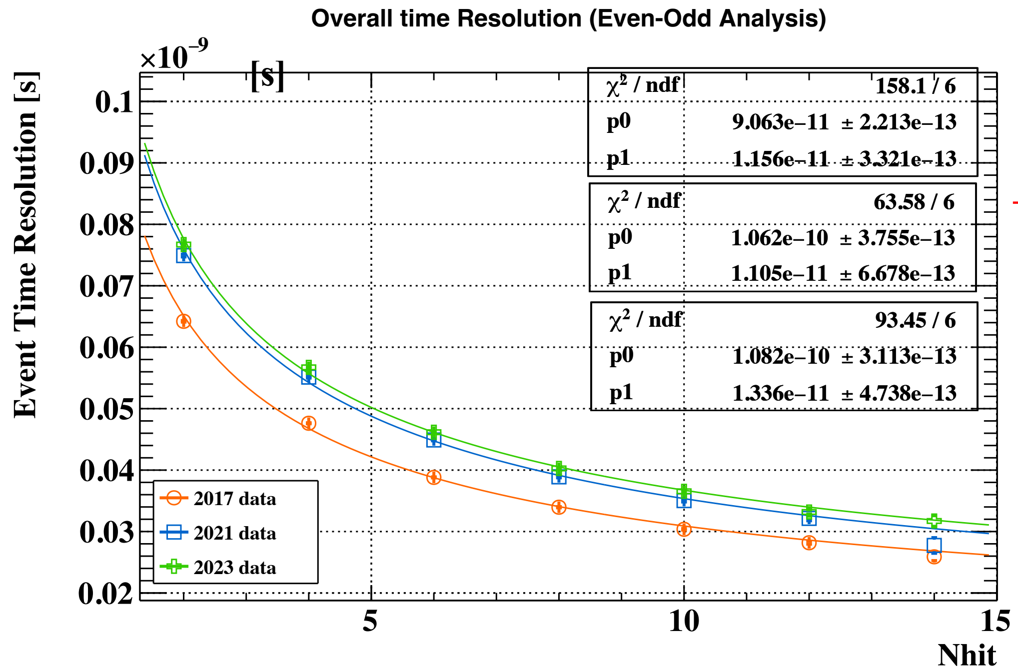
Detector geometry – pixels on semicylinder





- 90 cm x 60 cm semi-cylinder module. (−165.8 ° < φ < +5.2 °)
- **12 cm × 5 cm (4 cm) × 5 mm plastic scintillator** (BC422).
- Read by series connection of **6 SiPMs on both side.**
    - (AdvanSiD, ASD-NUV3S-P High-Gain, 3 x 3 mm^2, 50 x 50 μm^2, $V_{breakdown}$ ~ 24 V).

Detector performance so far



for Michel e⁺ data in 2017, 2021, 2023

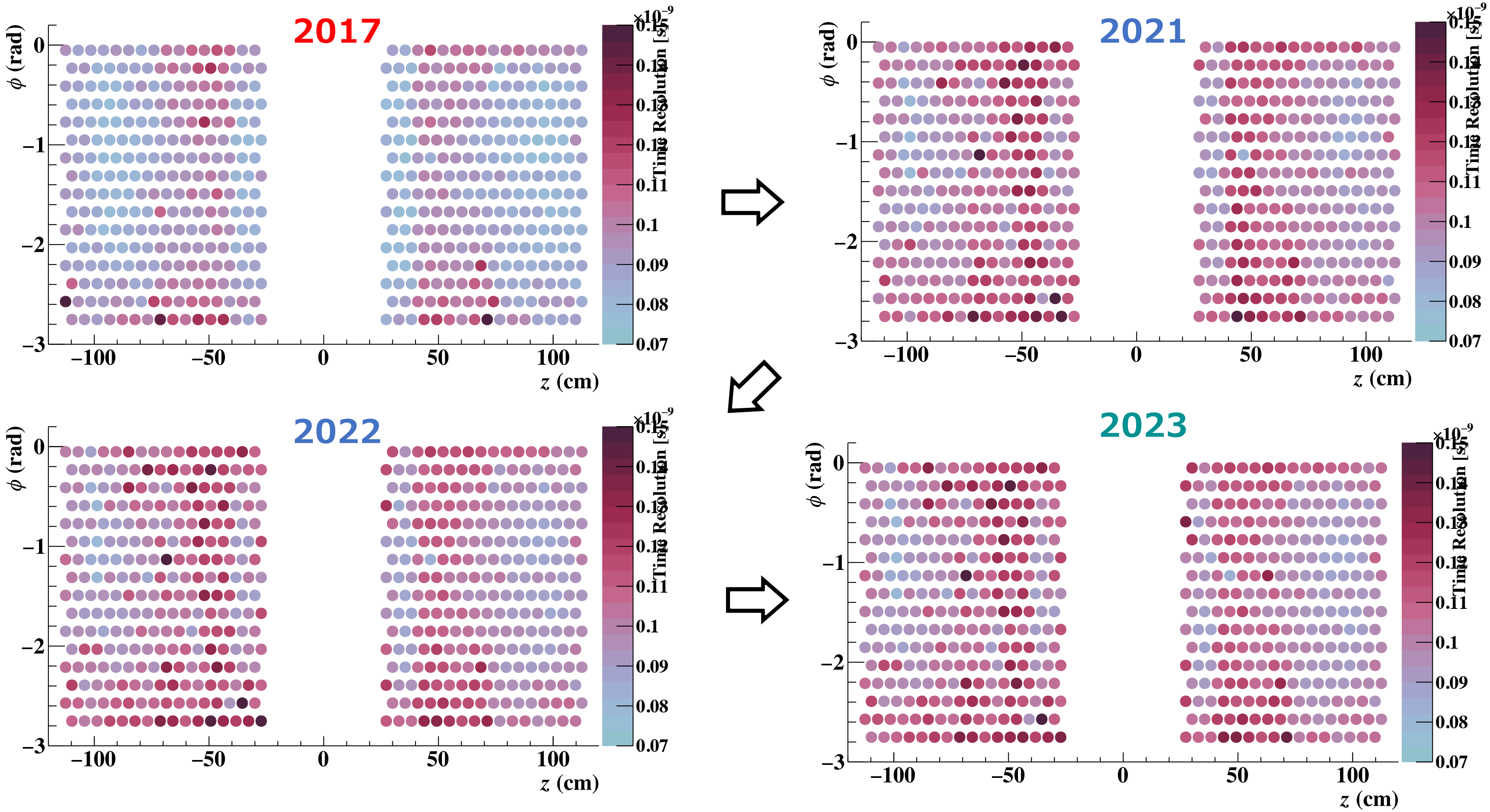
$$\boxed{\sigma_{\mathrm{pTC}}(N_{\mathrm{hit}}) = \sqrt{\frac{p_0}{N_{\mathrm{hit}}} + p_1}}$$

$$\left(p_0 \sim \sqrt{\sigma^2_{\mathrm{intrinsic}} + \sigma^2_{\mathrm{inter-pixel}}},\ p_1 \sim \mathrm{const.}\right)$$

Period	Single pixel time resolution (p_0)	pTC Overall time resolution ($\sum \sigma_{\mathrm{pTC}}(n) \times \mathrm{Prob}\ (N_{\mathrm{hit}} = n)$)	$\sigma_{\mathrm{pTC}}(N_{\mathrm{hit}} = 9)$
pilot run 2017 Nov.	90.6 ps	37.3 ps	32.3 ps
2021 Oct.	106.2 ps	42.9 ps	37.1 ps
2023 Jun.	108.2 ps	44.4 ps	38.5 ps

Detector performance so far (2)

*Single pixel time resolution for Michel e+



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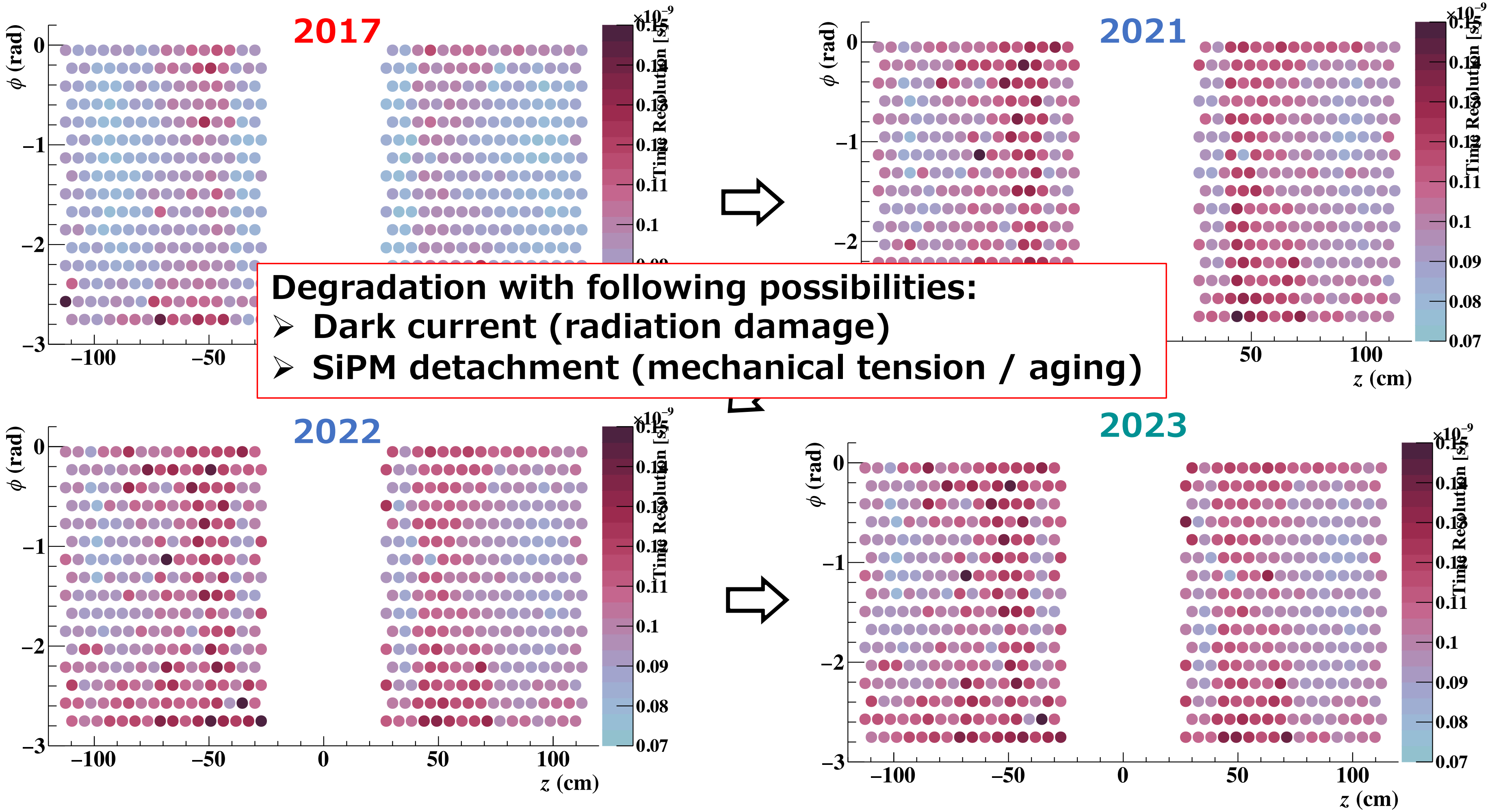
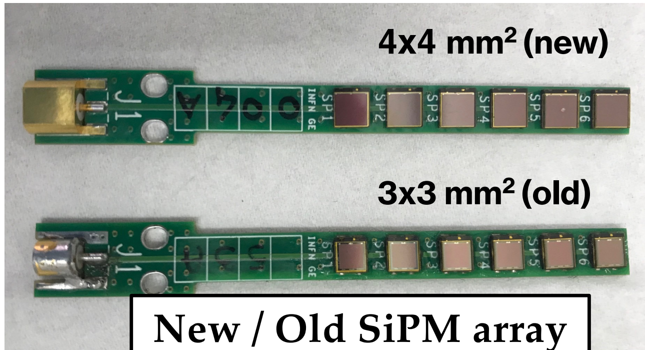


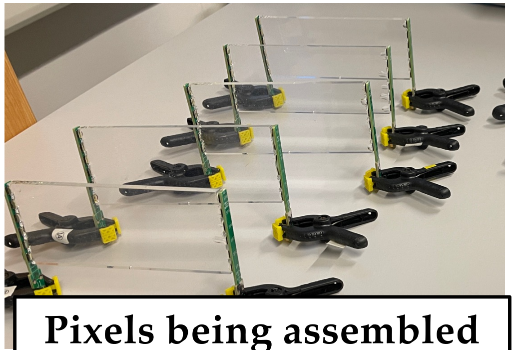
Degradation with following possibilities:
- **Dark current (radiation damage)**
- **SiPM detachment (mechanical tension / aging)**

2. pTC refurbishment

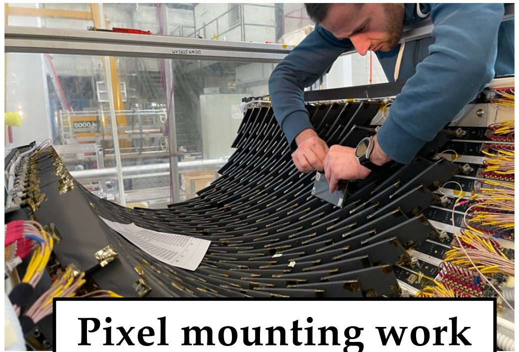
pTC refurbishment with new SiPMs



New / Old SiPM array



Pixels being assembled



Pixel mounting work

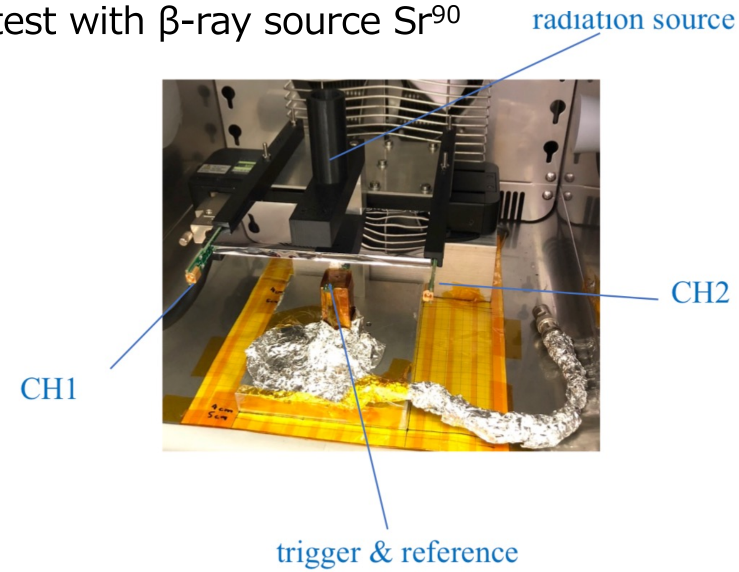
reported in JPS2024s

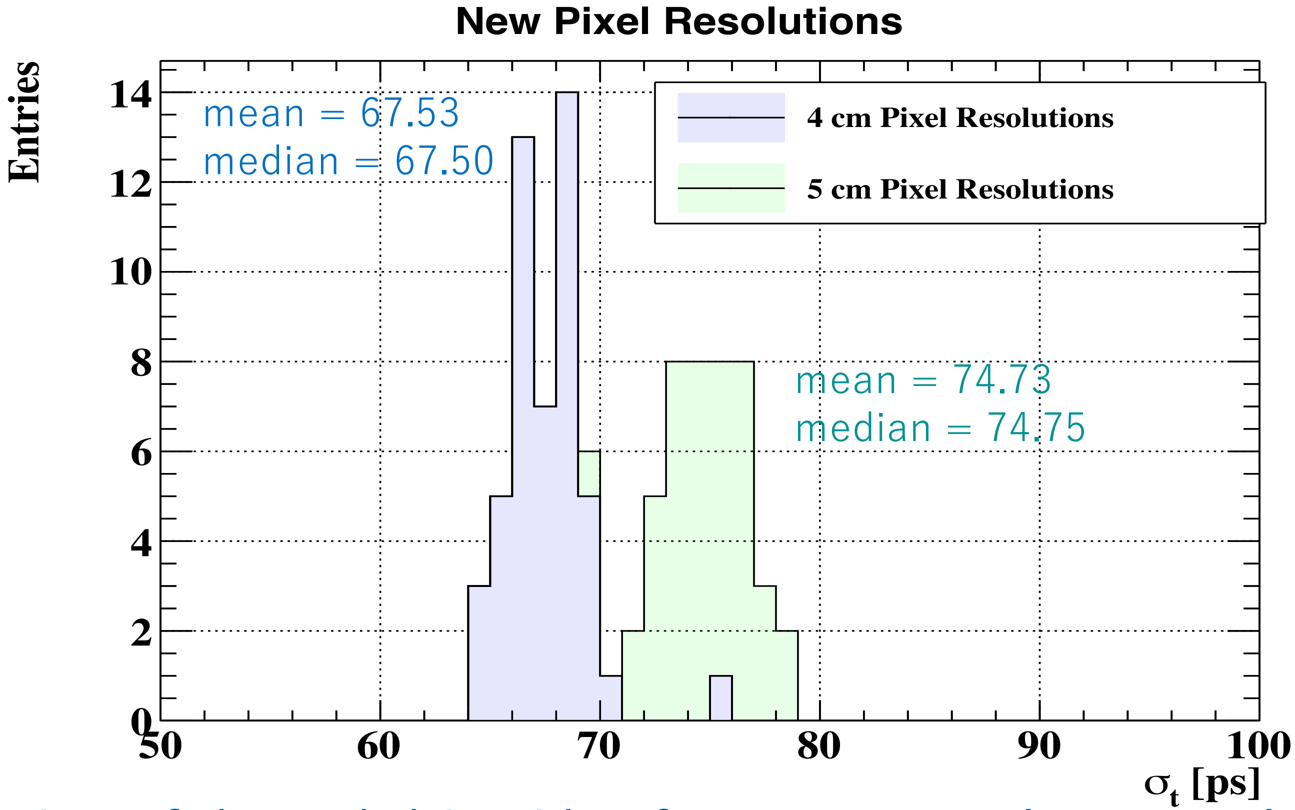
Soldering 6 SiPMs into series connection → SiPM array test of I-V & light yield → Pixel assembly → Pixel test of timing resolution → Pixel mounting on pTC

- For a still long-term operation towards 2026, we renovated the pTC.
- We produced **new 94 pixels** with spare scintillators & **new 1128 SiPMs with a larger sensitive area 4 × 4 mm^2** (ASD-NUV4S-P).

pTC refurbishment – time resolutions in labtest

Labtest with β-ray source Sr^{90}





- Evaluated time resolution by mean time of ch1 and ch2, with reference counter ($\sigma_{\mathrm{ref}} \sim 30$ ps)
- Operation voltages are set on $V_{\mathrm{breakdown}}$+3.5 V / SiPMs (scanned for 2 samples).
- Regard the average value $\bar{\sigma}_t = 67.5 / 74.7$ ps (4 cm / 5 cm) as new pixels' time resolution.

pTC refurbishment – performance expectation

- In 2024 maintenance period, we **exchanged 80 pixels on pTC.**
- Contribution of individual pixel exchange was evaluated as:
  - for 1 event which the exchanged pixel included:

$$\sqrt{\sum_{i=0}^{n}\left(\frac{\hat{\sigma}_{\mathrm{single}}}{n}\right)^2} \rightarrow \sqrt{\frac{n-1}{n^2}\hat{\sigma}^2_{\mathrm{single}} + \frac{1}{n^2}\left(a\hat{\sigma}_{\mathrm{single}}\right)^2} = \boxed{\sqrt{1-\frac{1-a^2}{n}}} \cdot \frac{\hat{\sigma}_{\mathrm{single}}}{\sqrt{n}}$$

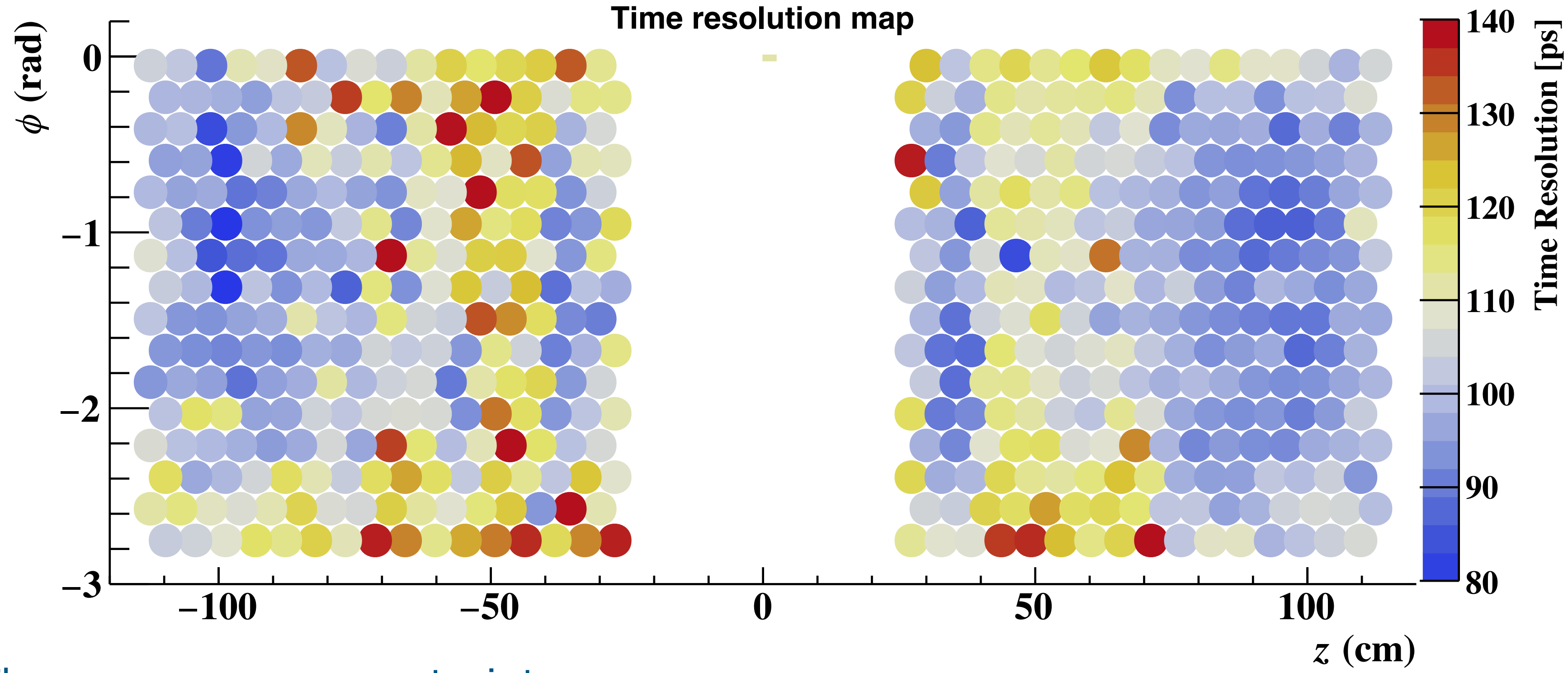
$$\left(a = \frac{\text{time resolution of the new pixel}}{\hat{\sigma}_{\mathrm{single}}}\right)$$

  - for a general event:

$$\hat{\sigma}_{t_{\mathrm{pTC}}}(n) \approx \sqrt{\boxed{\left(1-\frac{1-a^2}{n}\right)} \cdot r_n + 1 \cdot (1-r_n)} \cdot \frac{\hat{\sigma}_{\mathrm{single}}}{\sqrt{n}}$$

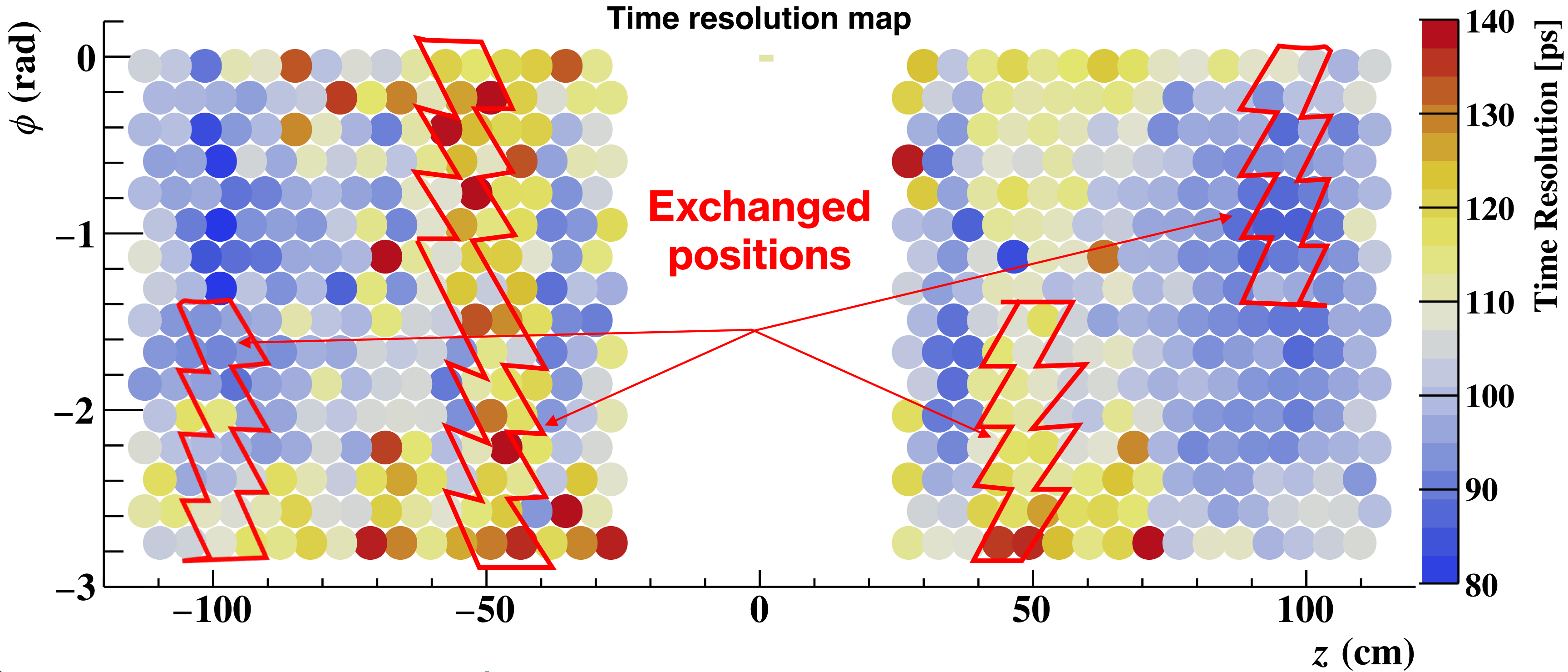
$$\left(r_n = \frac{\#\text{ of } n \text{ hit events with the new pixel}}{\#\text{ of all } n \text{ hit events}}\right)$$

pTC refurbishment – geometry



- There were some constraints:
  - Number of pixels: only 94.
  - Eager to pick up the extreme bad pixels: resolution > 130 ps, for investigation.
  - Pixel size (height = 4 or 5 cm): due to the number of spare scintillators and PCBs (40 (4 cm) + 56 (5 cm)).
  - Readout electronics configuration: 8 pixels on 1 readout board, their HVs should be in range of +4V from V_{min}.

pTC refurbishment – geometry



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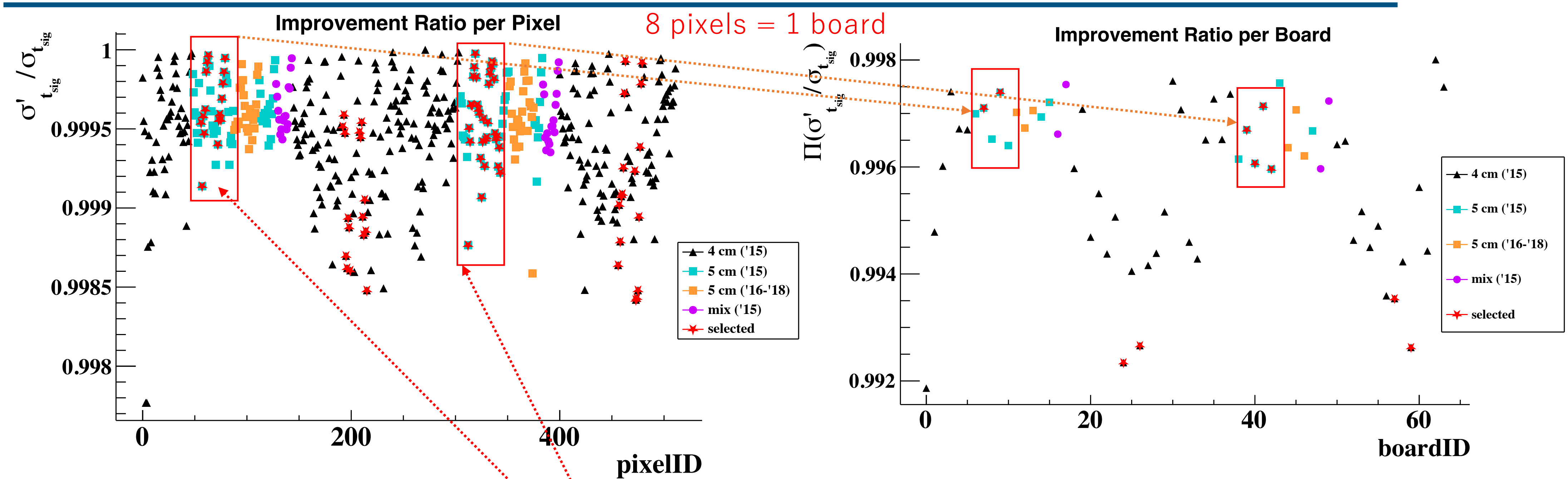
pTC refurbishment – pixel selection



- There were some constraints:
  - Number of pixels: only 94.
  - Eager to pick up the extreme bad pixels: resolution > 130 ps, for investigation (-> not reproduced in Lab.).
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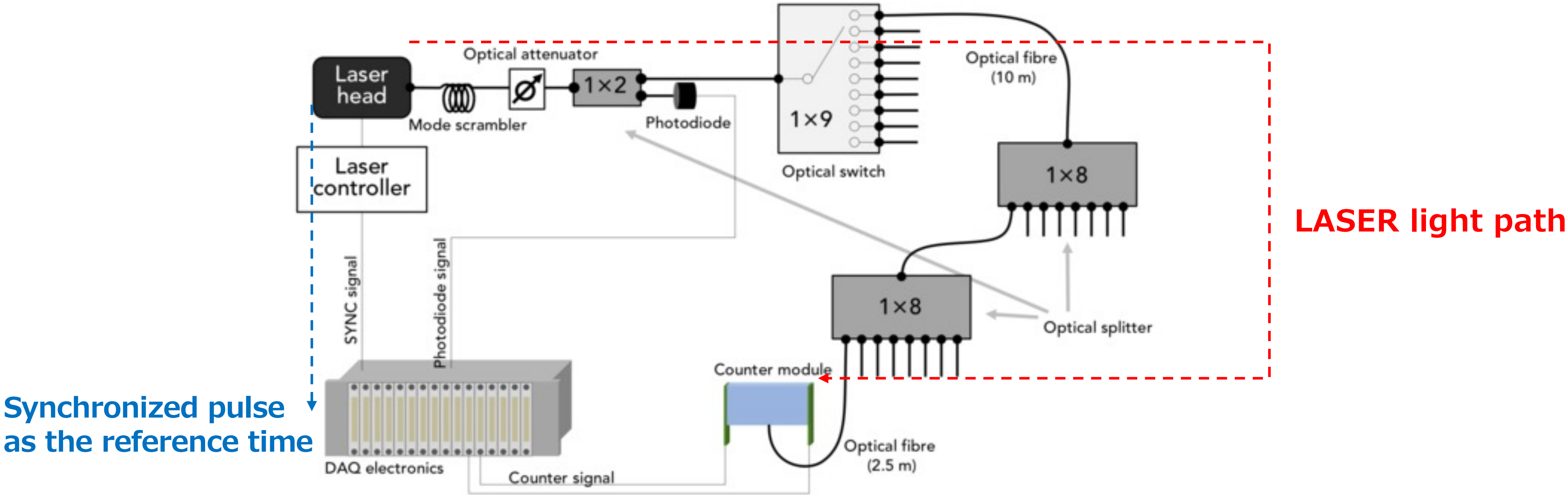
3. Performance

Performance evaluation

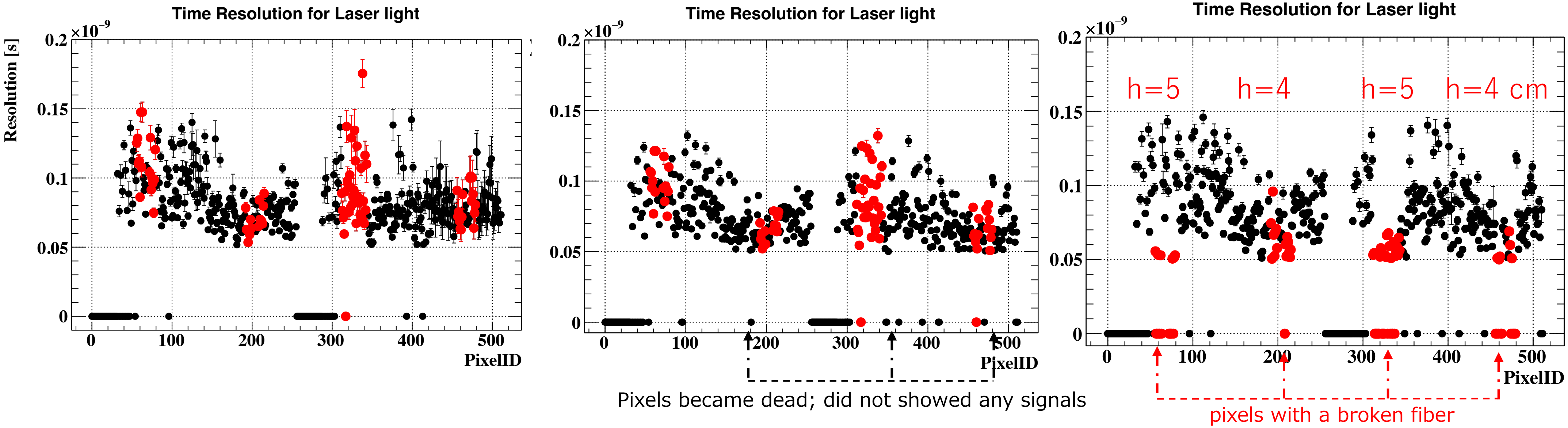
- With the laser system, which is usually used as a pTC calibration tool.



- For 2024, muon beam DAQ has not been available sufficiently.
  - pTC pixels were subject to summer humidity with poor wrapping after the maintenance.
  - troubles on the MEG beamline cooling system, expected be restarted from November.

Single pixel resolution with laser

*refurbished pixels in 2024 are highlighted

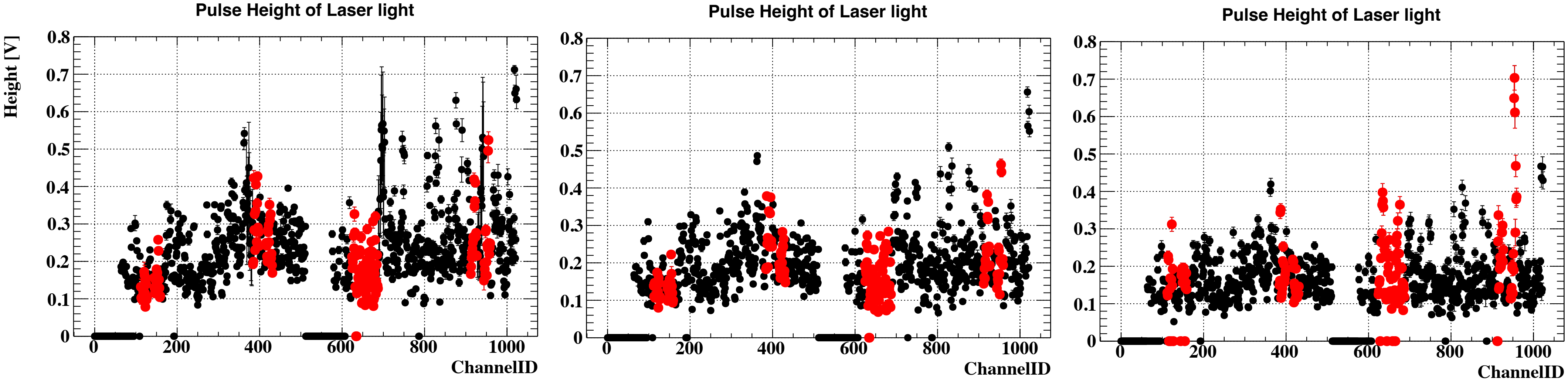


Start point of MEG II (2021) **after HV optimization (2023)** **after refurbishment (2024)**

- ❑ Timing resolutions with laser light (not fully reflecting the responses for e^+) show
  - ❖ for h = 5 cm pixels: 50-140 ps -> 50-70 ps
  - ❖ for h = 4 cm pixels: 50-100 ps -> 50-80 ps
- ❑ Because we re-plugged the fibers (even broke some) in 2024, the samples are not exactly the same.

Single pixel amplitude with laser

*refurbished pixels in 2024 are highlighted



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(preliminary; should be calibrated)

- The gain looks like increased more or less from 2023 to 2024.
  - The operation voltages of SiPMs in 2023 were optimized by local-maximization of S/N ratio.
  - The operation voltages of new SiPMs in 2024 are just +3.5 V from measured breakdownV.

Single pixel amplitude with laser

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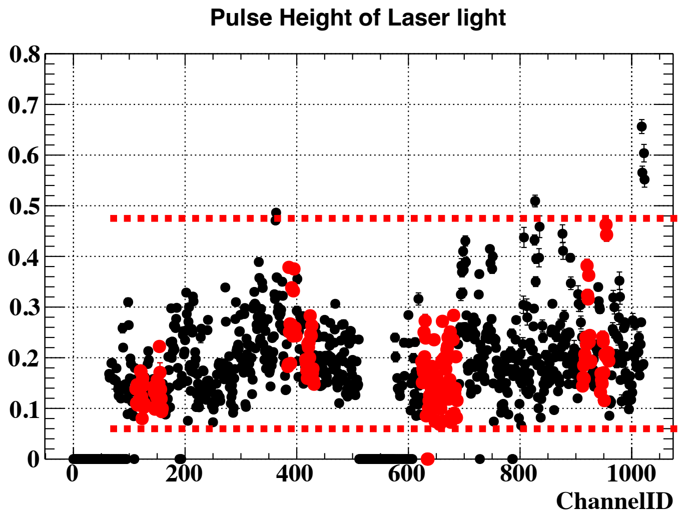
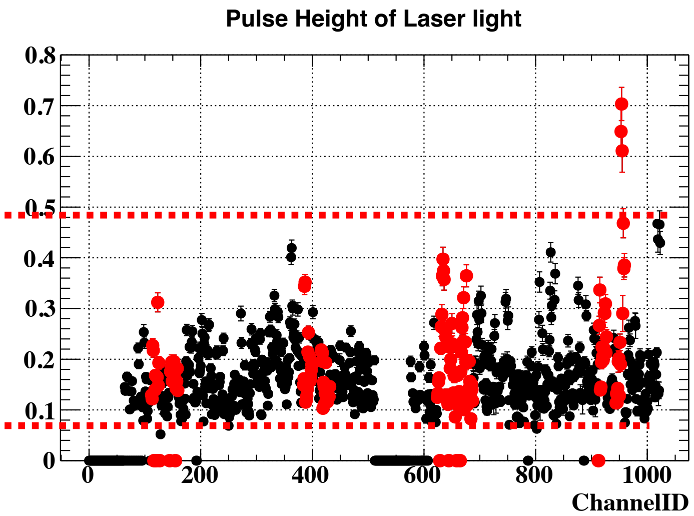


after HV optimization (2023)



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Outlook

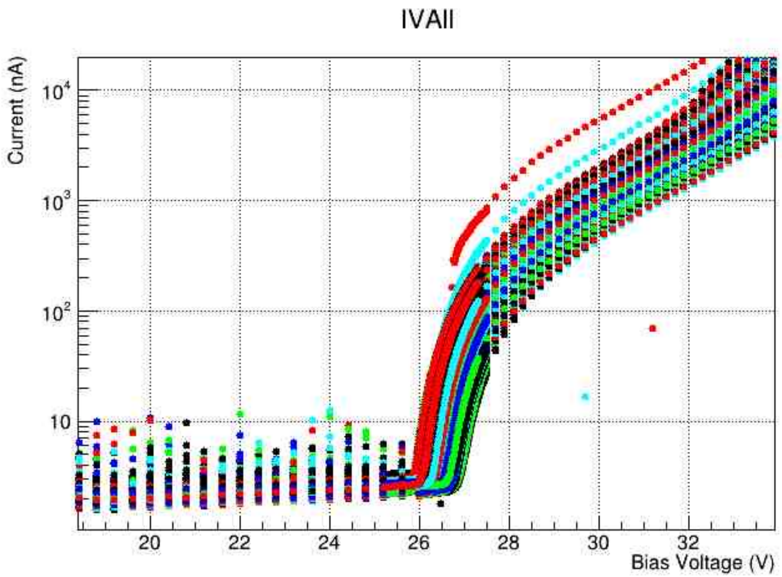
- MEG II timing counter has been on long-term operation since 2017.
  - Aiming to maintain good time resolution to detect time coincidence events.
  - Degradation with irradiation and aging had been reported.
- 80 pixels (out of 512) refurbishment was done.
  - Calculated the improvement factor for each pixel exchange.
  - Expected to improve the pTC overall time resolution for signal positron:

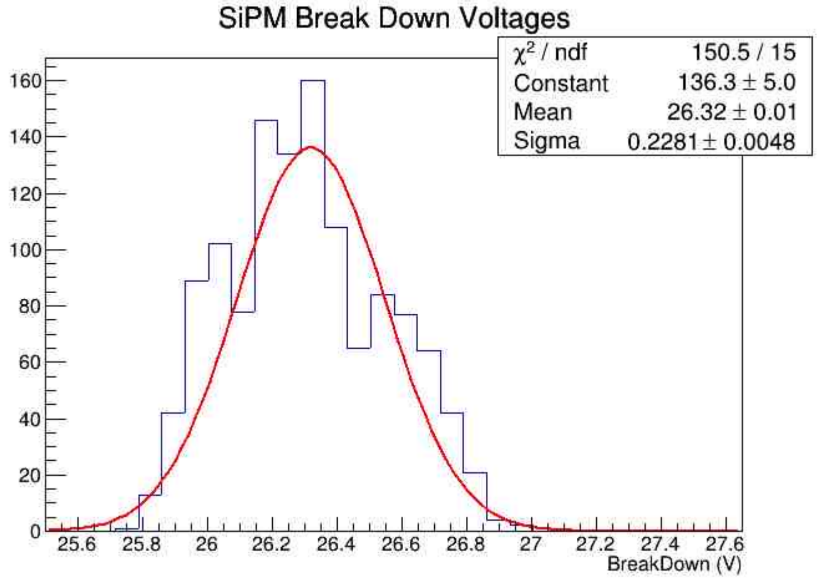
$$\Pi^{80}_{i\text{-th selected pixel}} \left(\frac{\hat{\sigma}^{2024}_{\mathrm{pTC}}(i)}{\sigma^{2023}_{\mathrm{pTC}}} \right) \sim 95.3\ \% \left(\simeq \frac{\left(432 + 80 \times \frac{67\ \mathrm{ps}}{110\ \mathrm{ps}} \right)}{512} \right)$$

- The renewed performance was evaluated only with laser light so far.
  - New pixels show a good time resolution with laser light (50-70 ps).
  - Their operation parameters should be more calibrated from labtest ones.
  - Still waiting for the more muon data in the coming period of 2024.
  - In return of refurbishment, we lose some laser fibers and airtightness to keep dry.

Back up

Single SiPMs - IV curve, grouping

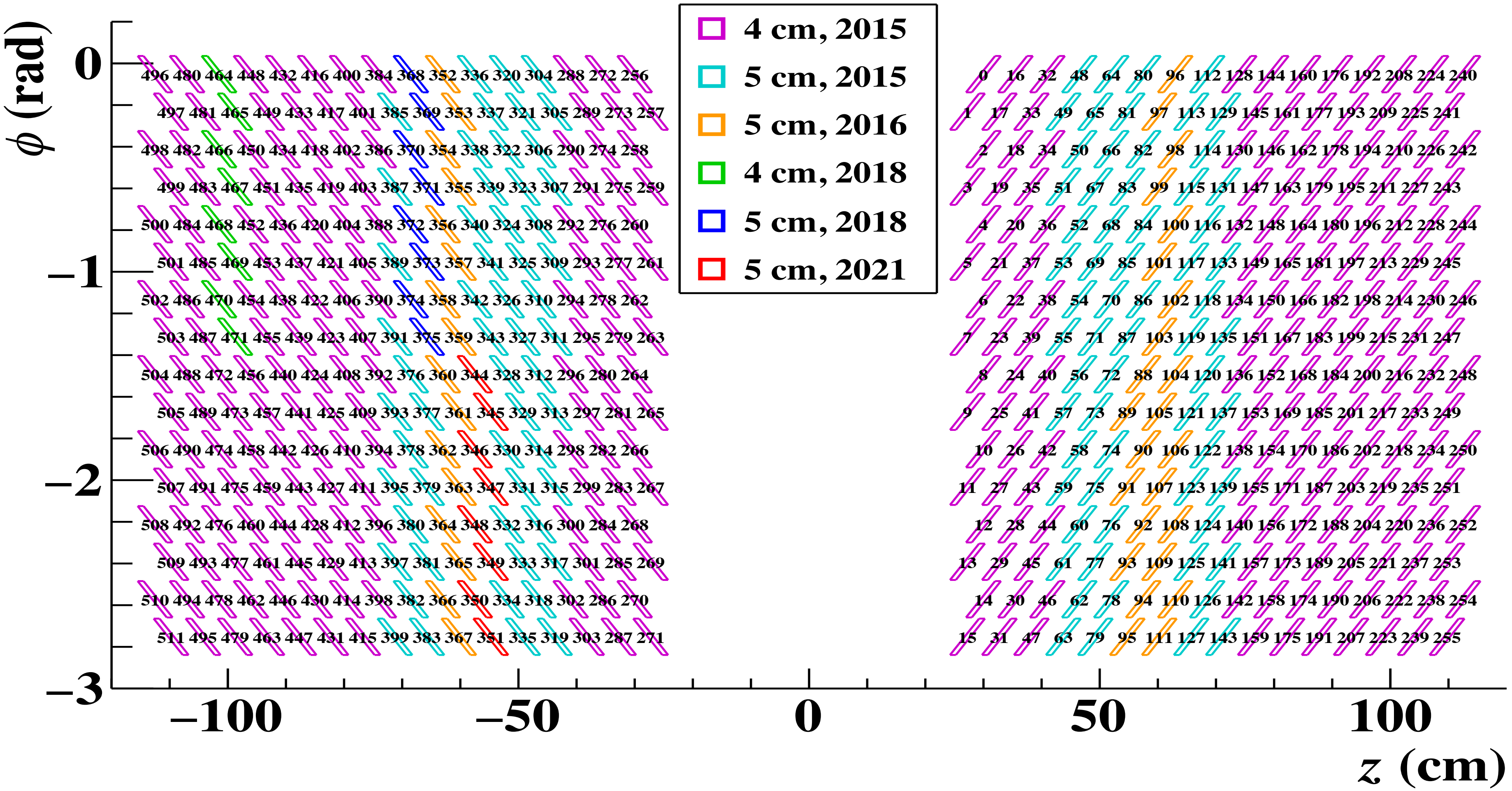




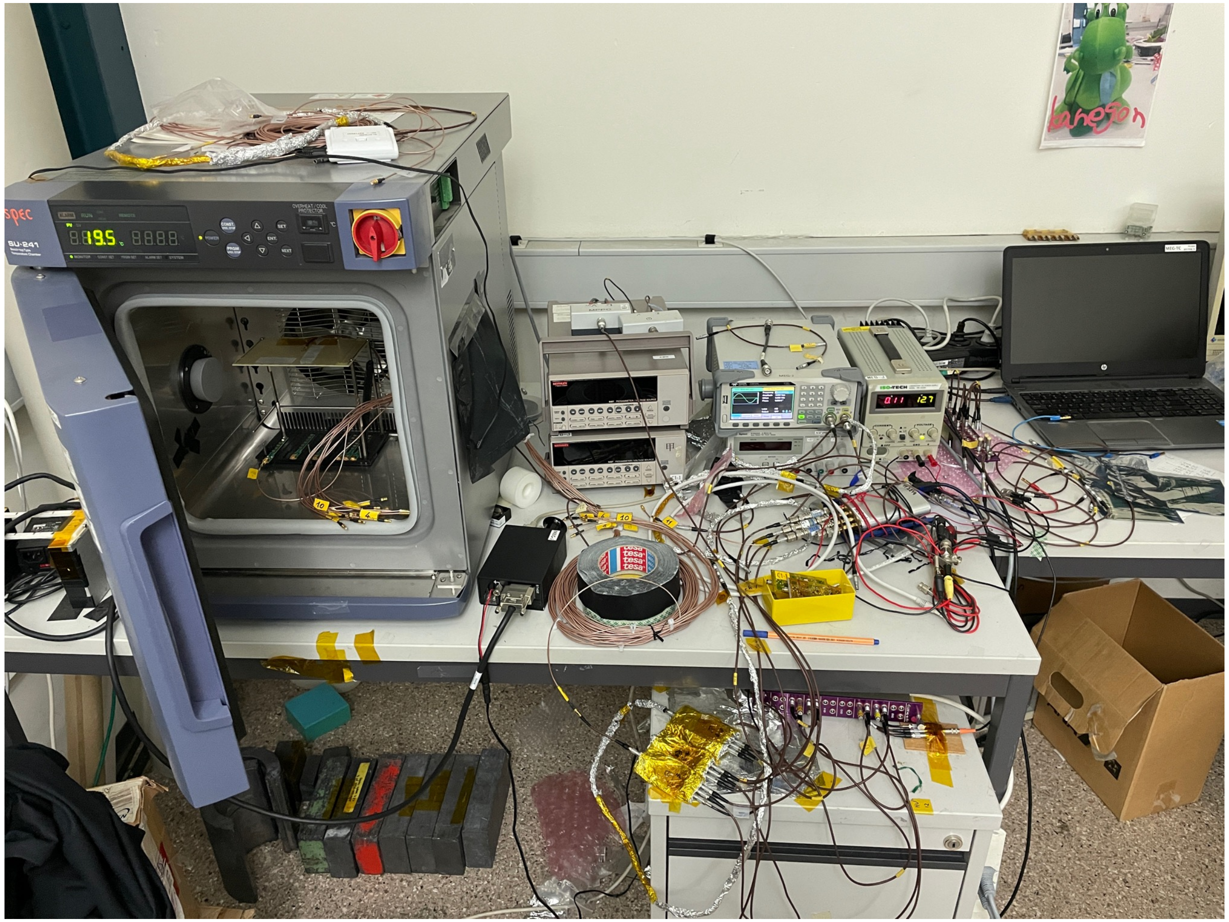
- All the SiPMs operate properly measured for I-Vs and BVs.
  - To be ordered a company to perform soldering the 6 pieces into one array.

- V_{BD} of single SiPM: 25.8 – 26.9 V

Detector geometry – pixels on semicylinder



LED test



Dark current history in 2021

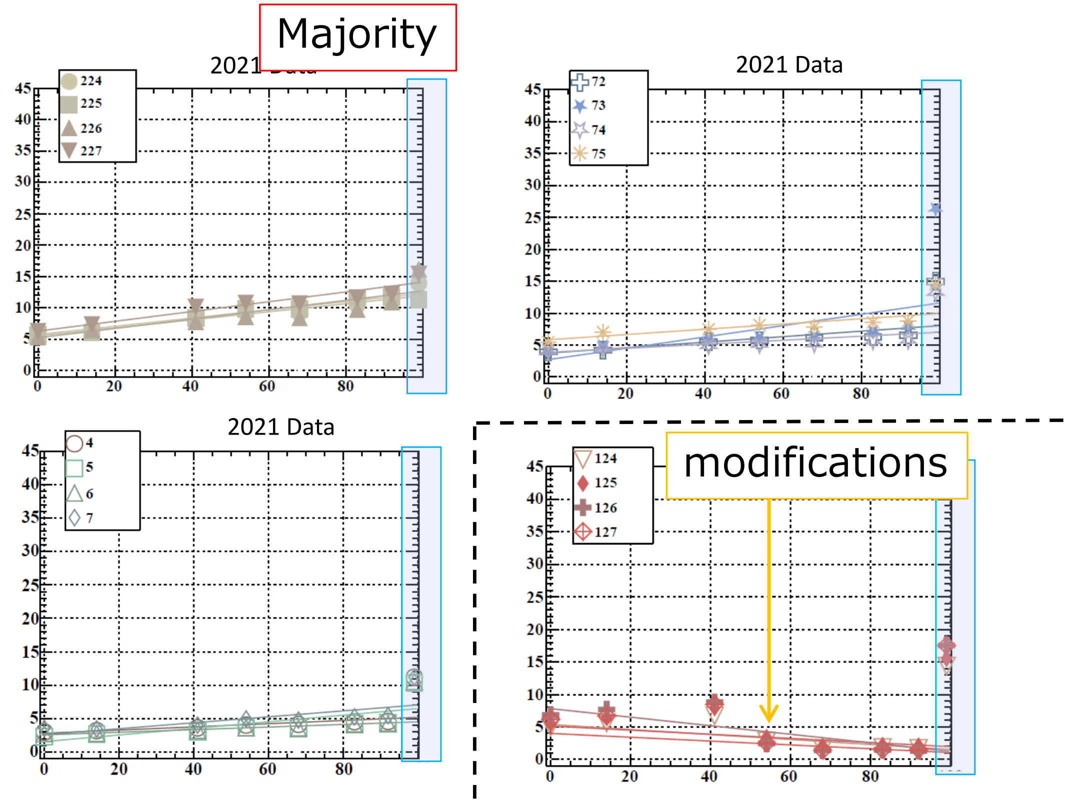
- ❑93 Days in 2021 + 1 Day ref. in 2023
  - ❖To follow in the same HV config.
  - ❖After 171 Days under muon beam. (108 in 2022 + 63 in 2023)

- ❑Almost all the pixels show the similar increment.
  - ❖**By +5 - 10 μA for 264 Days.**

- ❑Prediction (converted from 宇佐見@'17秋季大会)
  - ❖ +5 - 7.5 μA
  - ❖ 2 x 10^{10} ~50-MeV-positrons /cm^2 ~ 6 Gy
  - ❖ eff. NIEL -> 10^9 1-MeV-neutrons /cm^2

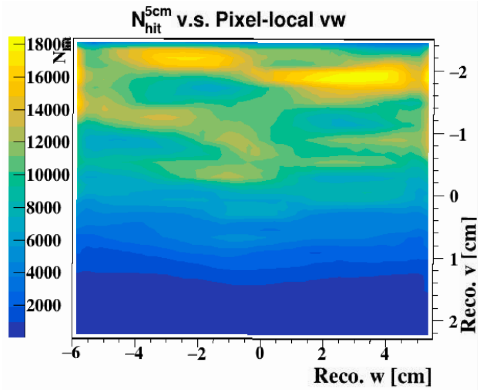
2021 Current + 2023 Current at 2021 HV conf.

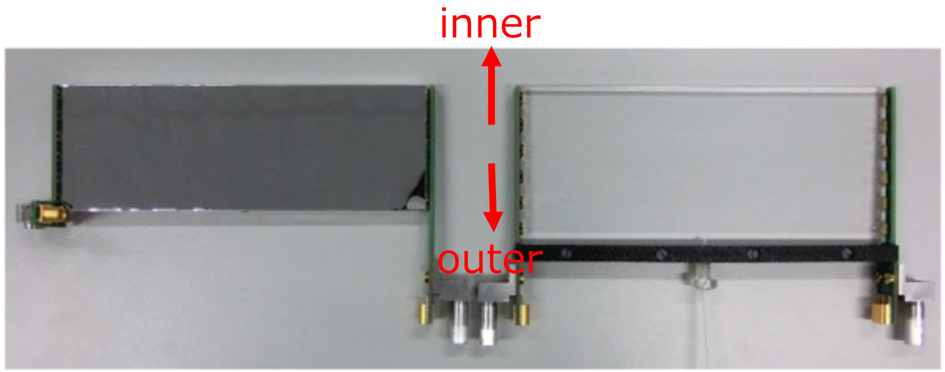
from 16 Aug. to 17 Nov. (2021) + on 9 Aug. (2023)



Development in analysis side

❑Radiation damage accumulates more on the inner side of SiPMs.





❑It causes a difference of the response of pixel, on the hit position of a passing particle.

❖Regard as time offsets depending on the hit position.

❖Offset correction resolves the problem.

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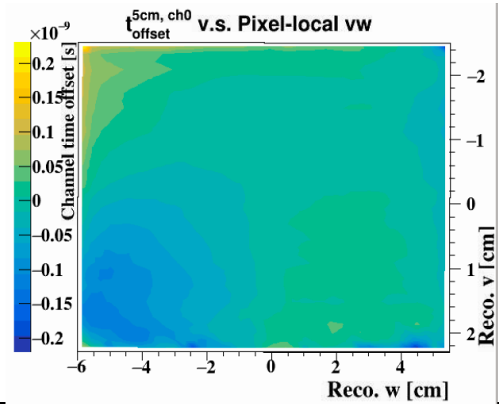
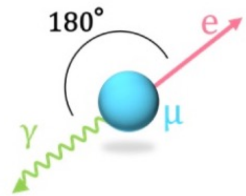


MuEGamma Decay



- One of charged lepton flavor violating (cLFV) decays, which is forbidden in the Standard Model.

- Many of the new physics beyond the Standard Model (BSM) predict that the branching ratio is $\mathcal{O}(10^{-13})$ – $\mathcal{O}(10^{-14})$ where an undiscovered particle in $\mathcal{O}(10)$ TeV mediates the process.

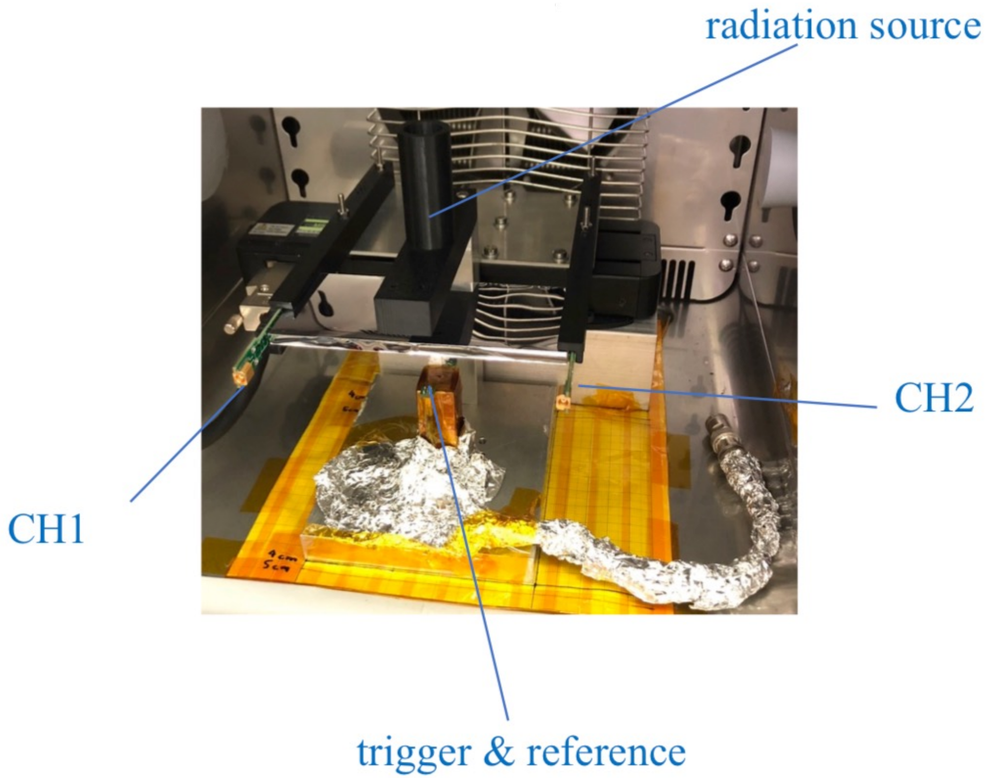
- Upper limit on the branching ratio was obtained by the MEG experiment: $\mathcal{B}(\mu \to e\ \gamma) < 4.2 \times 10^{-13}$ (90% C.L.)

Resolution Lab. test

- Set a pixel to the moving stage in a thermal chamber (~30 degC).
- Apply V_{bd} + 24 V to each PCB.
- Triggered with β-ray source (Sr^{90}) and reference counter, to obtain time resolution for

$$t = (t_1 + t_2)/2 - t_{ref}$$

at three positions.



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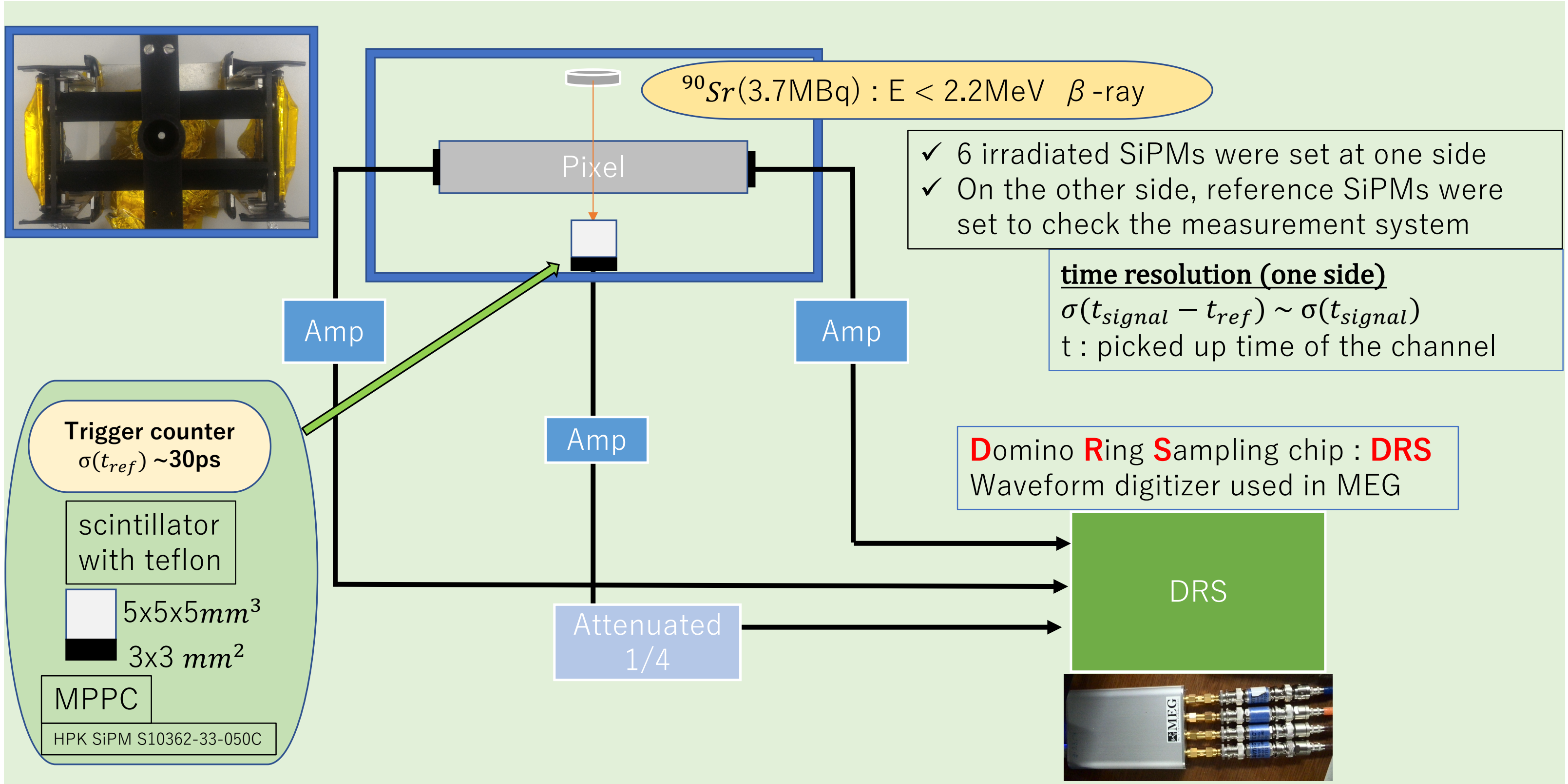


Time resolution evaluation

- $t_{\mathrm{ave}} := \frac{1}{n_{\mathrm{hit}}} \sum (t_i^{\mathrm{reco}} - t_0^{\mathrm{reco}} - TOF_{i,0})$

(single pixel / channel)

- $t_{\mathrm{even}} := \frac{1}{n_{\mathrm{hit}}/2} \sum (t_{2i}^{\mathrm{reco}} - t_0^{\mathrm{reco}} - TOF_{2i,0})$

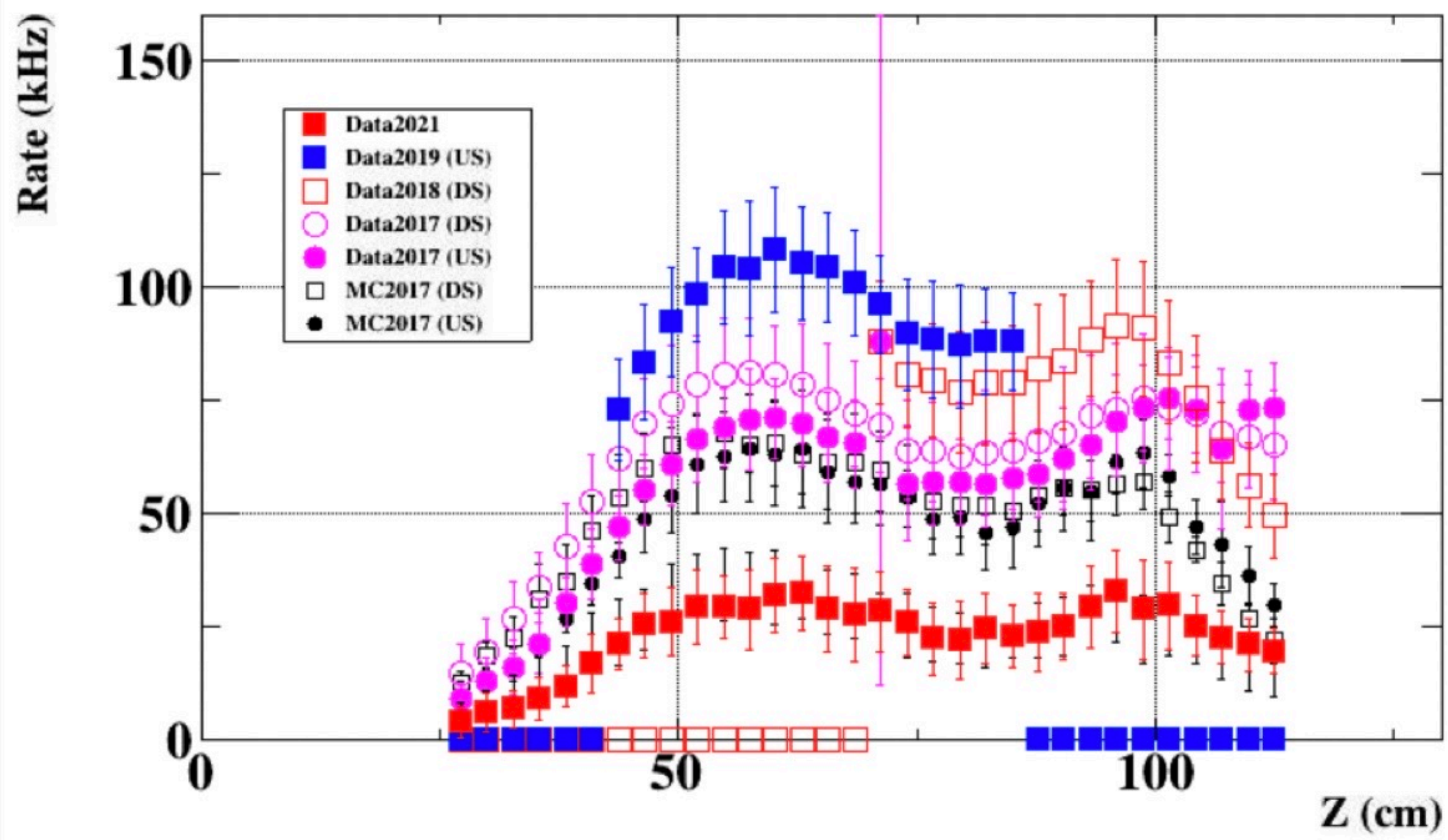
  $t_{\mathrm{odd}} := \frac{1}{n_{\mathrm{hit}}/2} \sum (t_{2i+1}^{\mathrm{reco}} - t_0^{\mathrm{reco}} - TOF_{2i+1,0})$

  $\sigma(N_{\mathrm{hit}}) = \sigma(t_{\mathrm{even}} - t_{\mathrm{odd}})$ **(even-odd)**

❑2 complemental methods.

- ❖Single counter resolution evaluation, depends on the tave from nearby counters.
- ❖Even-odd analysis is not sensitive to 1st order of i-th systematics on the tracking.

Hit rate

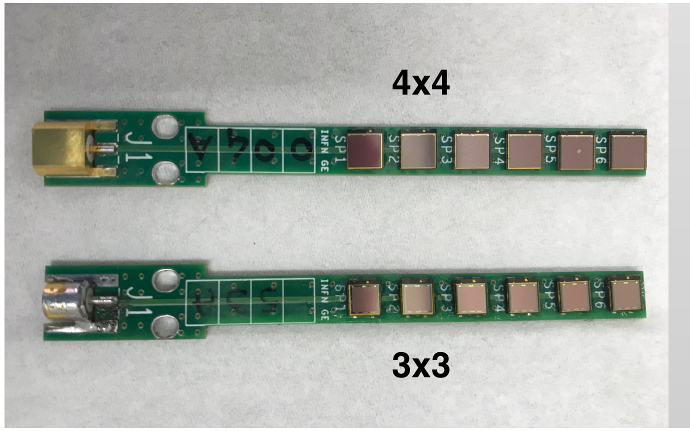


❑ 2017 -> 2021: generally, 1/2

Pixel refurbishment plan

- ❑SiPM: ASD-NUV3S-P (3x3 mm^2 active area)
  -> ASD-NUV4S-P (**4x4 mm^2 active area**)

- ❑50/48 pixels (4/5cm) will be newly produced.



- ❑Performance of pixels

Counter Producion	SiPM model	note	Time resolution in Lab. test	# of counters installed	Time resolution in pTC operation
2016	ASD-NUV3S-P	50x50 um^2 pitch	~ 85 ps	448	~ 95 ps
2018, 2021	ASD-NUV3S-P	40x40 um^2	~ 70 ps	40	~ 80 ps
2023	ASD-NUV4S-P	40x40 um^2	~ 70 ps	16	N.A.
2024	ASD-NUV4S-P	40x40 um^2	~ 70 ps	8	N.A.

Presumed increment

- Muon beam
  - 2021: 93 Days (16 Aug – 17 Nov)
  - 2022: 108 Days (1 Aug – 17 Nov)
  - 2023: 63 Days (7 Jun - 9 Aug)

❑ Presumed increment

- ❖~100 uA (from 2017 commissioning)
- ❖525 days, 30 degC

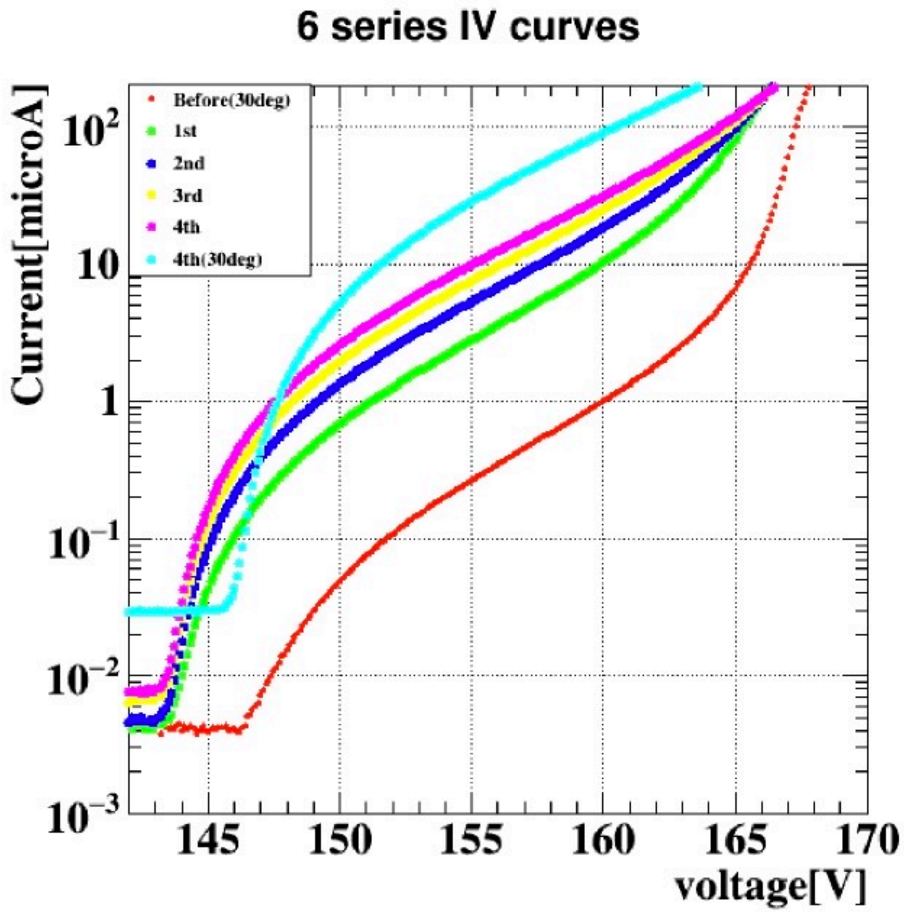
$$0.2346\ \mu A \times \frac{24 \text{ hours}}{31 \text{ hours} + 55 \text{ min}} \times 7 \text{ days} \times (25 \times 3) \text{ weeks} \sim 93 \mu A \tag{5.1}$$

Irradiation test ('16-'17)

- ❑ equivalent to

  +100 uA increment for 160V

  -> +30 uA @ 10 degC



pTC: performance so far

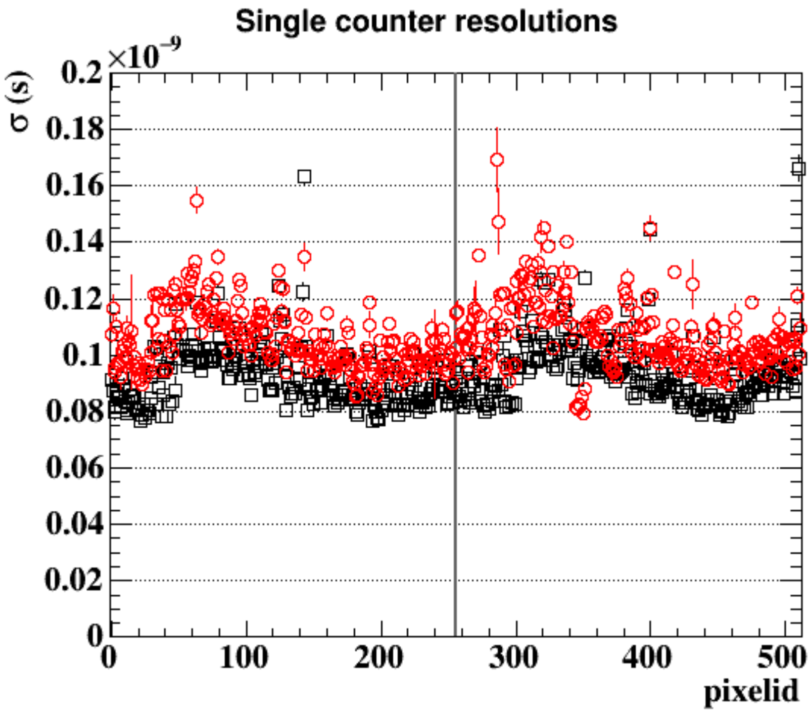


Figure 1: Single counter resolutions in 2017 (black) and in 2021 (red). The bumps in resolution around pixel id equal 50 and 300 are due to presence of 5 cm wide pixels.

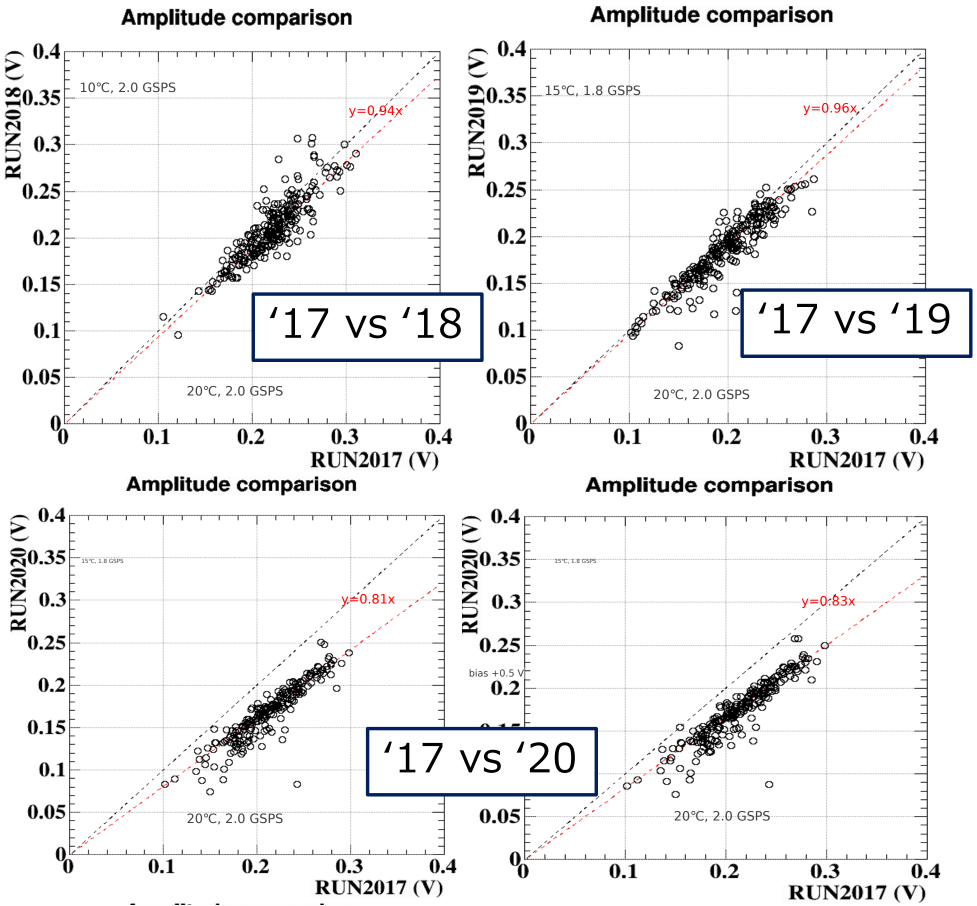
- Single counter resolutions estimated with a reference time from other counters on the same Michel e⁺ tracks.

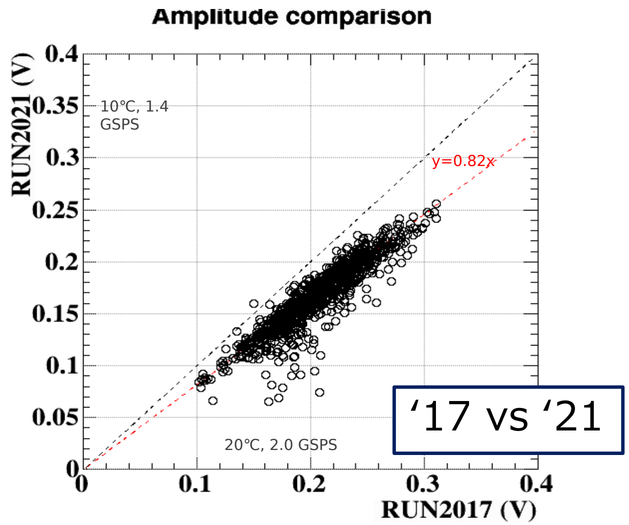
$$\sigma_{\text{single}}^{\text{new}} = \sqrt{\sigma^2(t_{\text{hit}} - t_{\text{ref}}) - {\sigma_{\text{ref}}^{\text{old}}}^2}$$

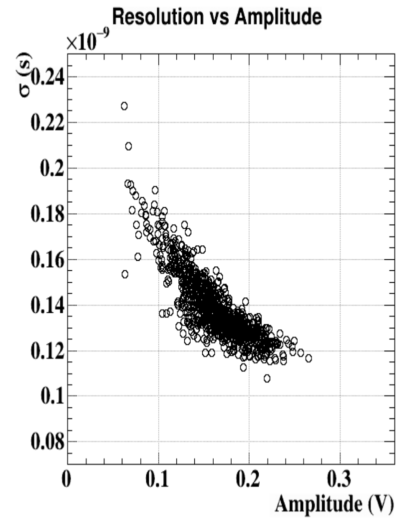
- General degradation from 2017 (black) to 2021 (red) was observed as well.

"Operational results with the pixelated Time Detector of MEG II experiment during the first year of physics data taking"
Nucl. Instrum. and Methods A 1046, 167751 (2023)

pTC: performance so far (pulse height)



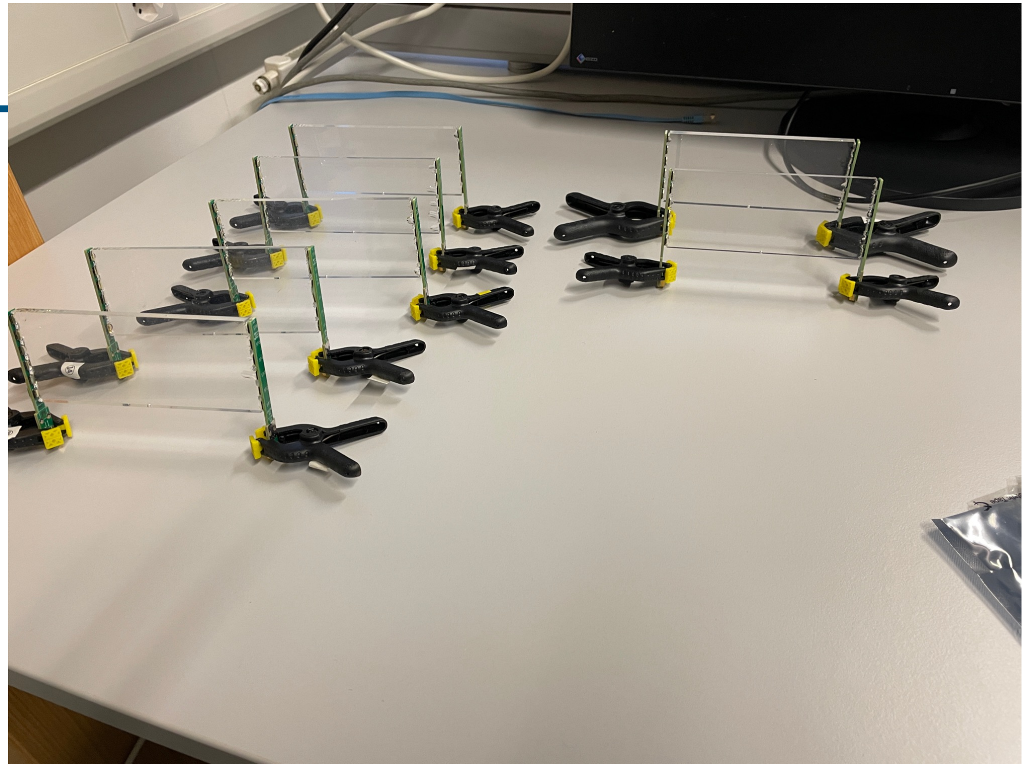
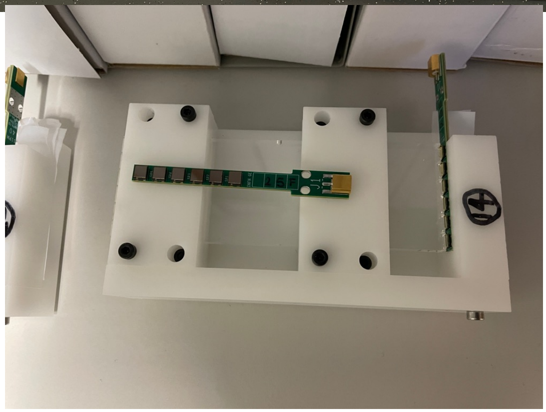




- Pulse height (=light yield) on each SiPM array has decreased.
- It strongly correlates to its time resolution.

"Operational results with the pixelated Time Detector of MEG II experiment during the first year of physics data taking"
Nucl. Instrum. and Methods A 1046, 167751 (2023)

Pixel assembly

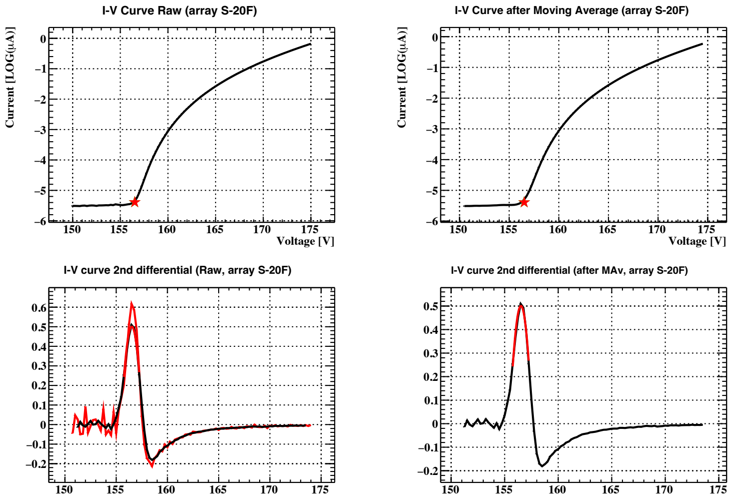




SiPM arrays IV curve

V_{BD} of array ~ 156 -160 V

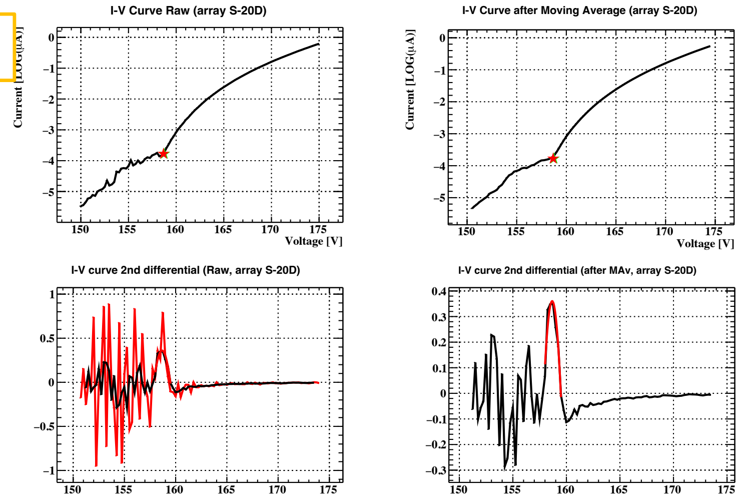
Normal

S-20F



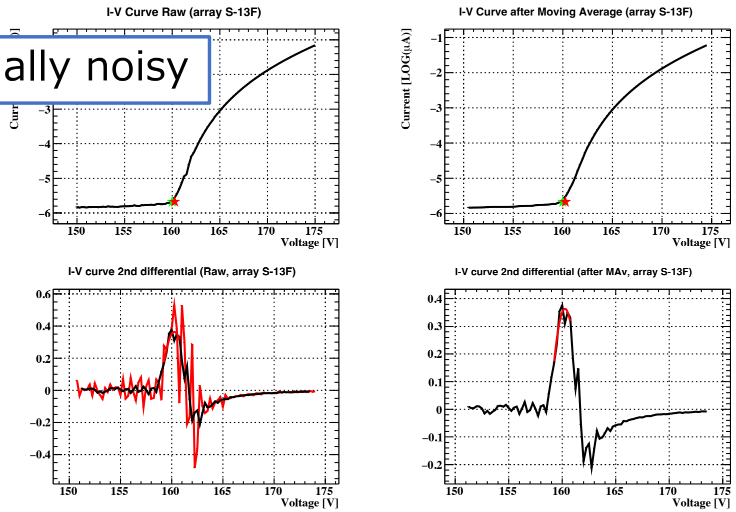
Strange

S-20D



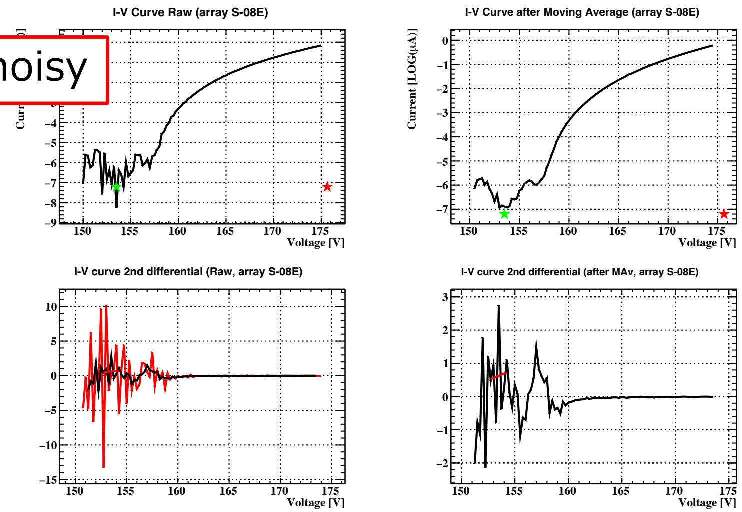
Occasionally noisy

S-13F



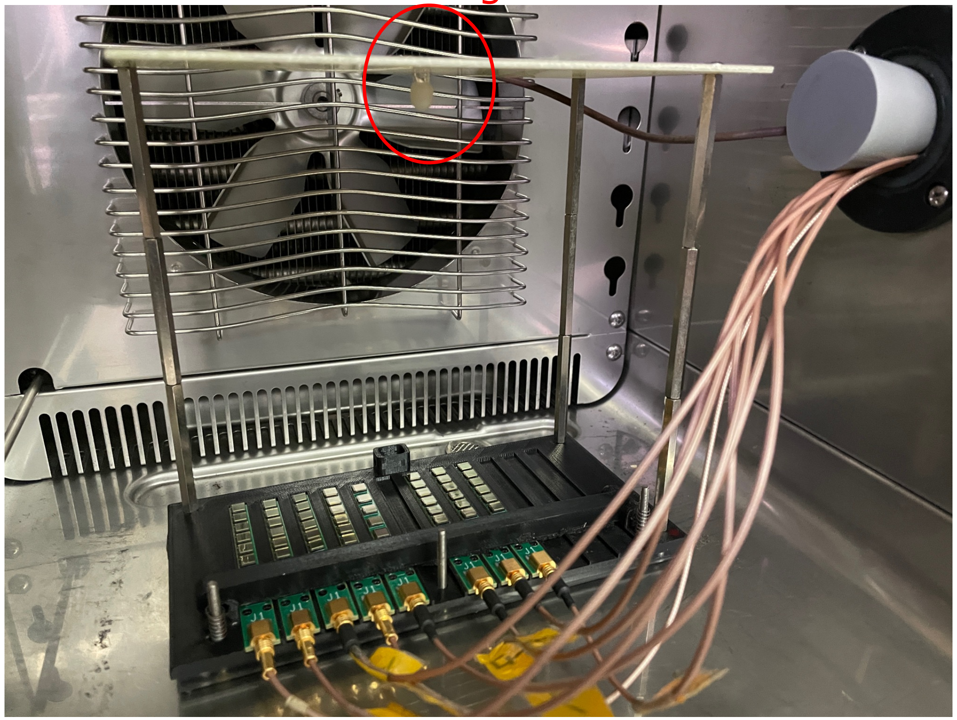
Fatally noisy

S-08E

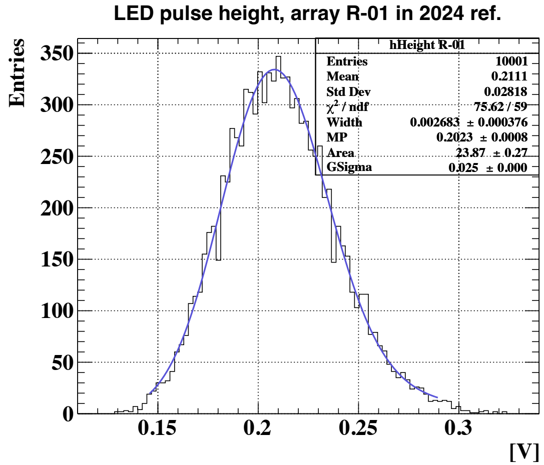


Light yield check

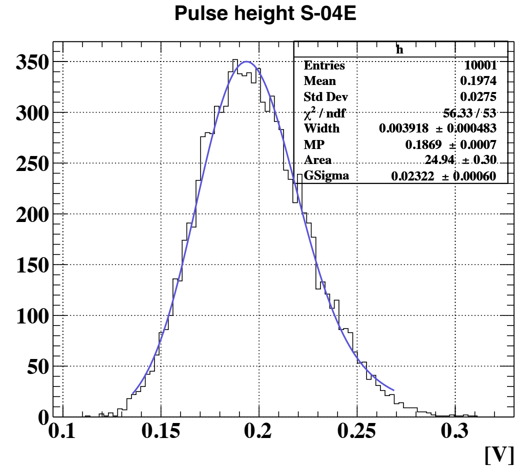
LED light



SiPM arrays



Prototype in 2023 measured in 2024 as ref.

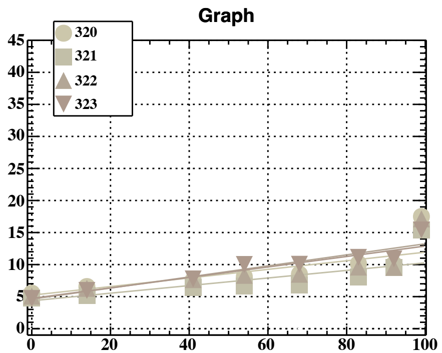


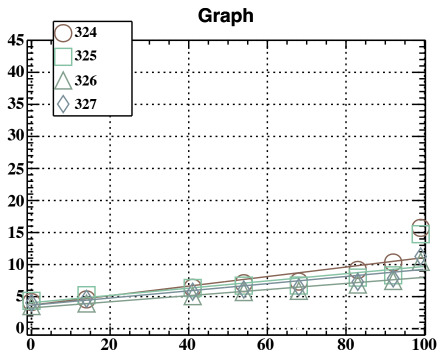
New array in 2024

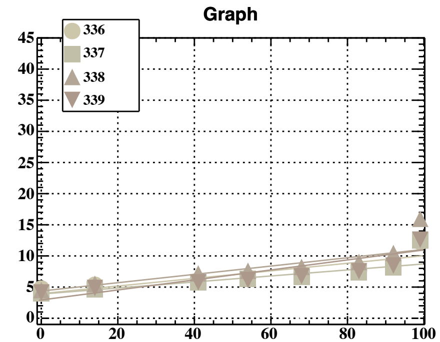
Examples (1, DS-pTC)

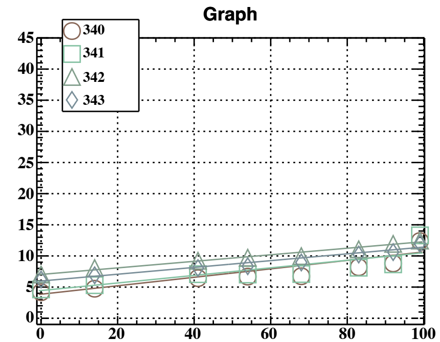
- Number = channel No.

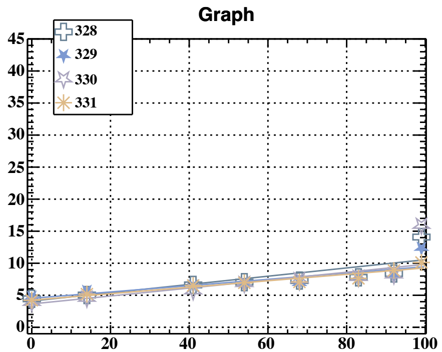
  (e.g. pixel 0 contains ch0-1, pixel 1 contains ch2-3)

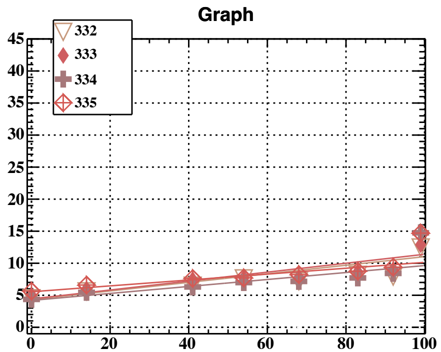


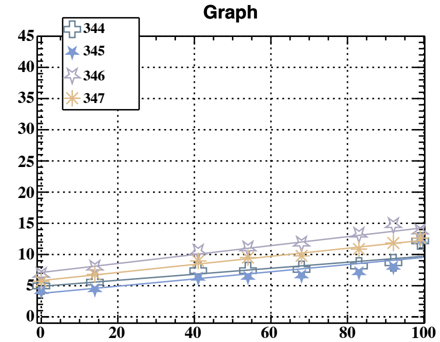


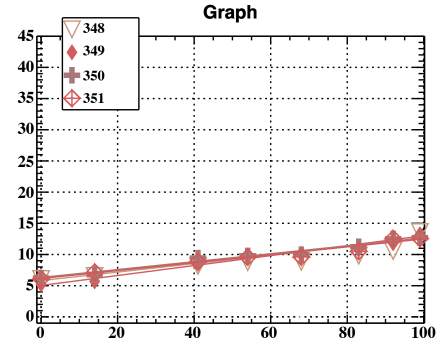












Examples (2, US-pTC)

- Number = channel No.

  (e.g. pixel 0 contains ch0-1, pixel 1 contains ch2-3)