MEG II 実験陽電子タイミングカウンターの 2024 年ランにおける 改修後の運用結果と性能評価

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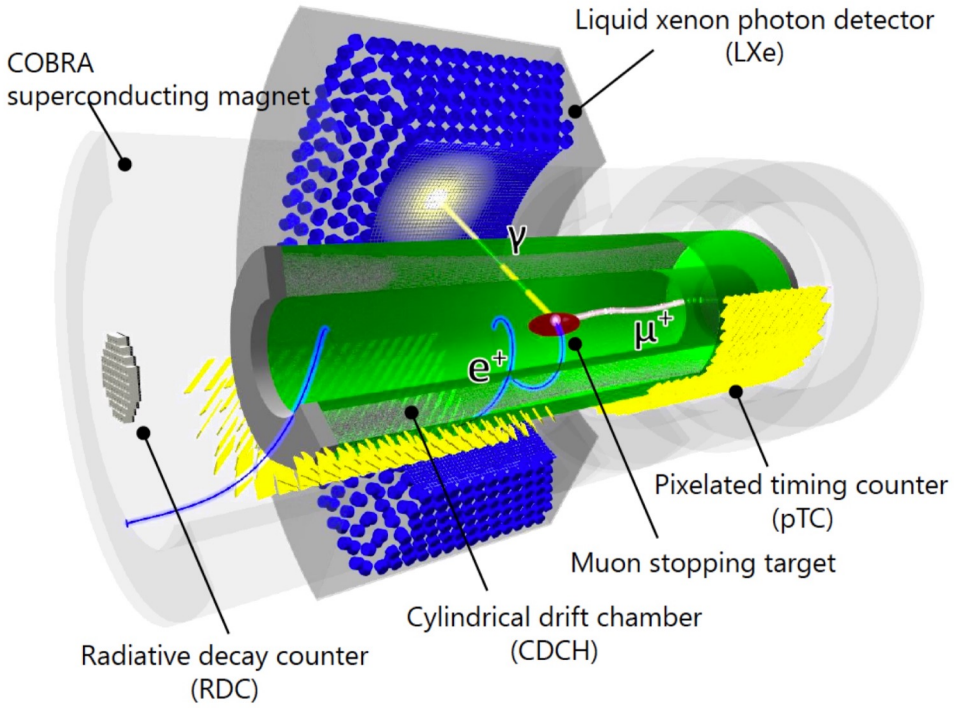
Introduction

MEG II experiment



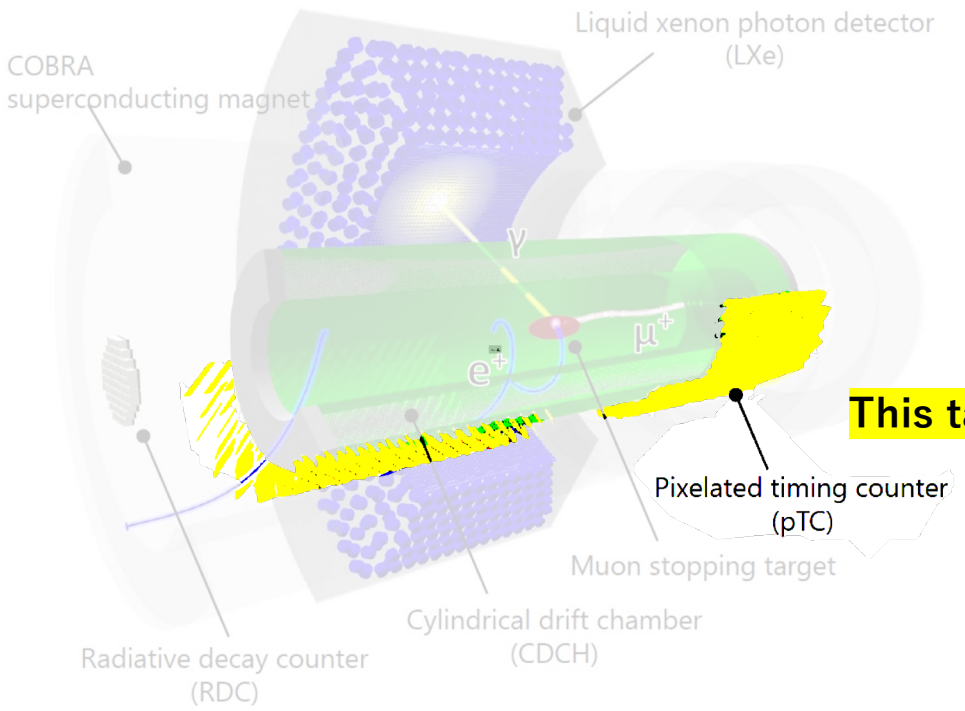
- **Mu to E Gamma phase II**
- MEG final result (2016):

  $\mathcal{B}(\mu \to e\gamma) < 4.2 \times 10^{-13}$ (MEG, full dataset)
- Search for the cLFV process $\boldsymbol{\mu \to e\gamma}$

  with one order better sensitivity: $\mathbf{6 \times 10^{-14}}$
- MEG II First result (2024):

  $\boldsymbol{\mathcal{B}(\mu \to e\gamma) < 3.1 \times 10^{-13}}$ (MEG II, 2021 data)
- Running since 2021 towards 2026
  - w/ the DC anti-muon beam $3 - 5 \times 10^7\ \mu^+/s$
  - @ Paul Scherrer Institute (PSI).

MEG II experiment



This talk !!

- **M**u to **E** **G**amma phase **II**
- MEG final result (2016):
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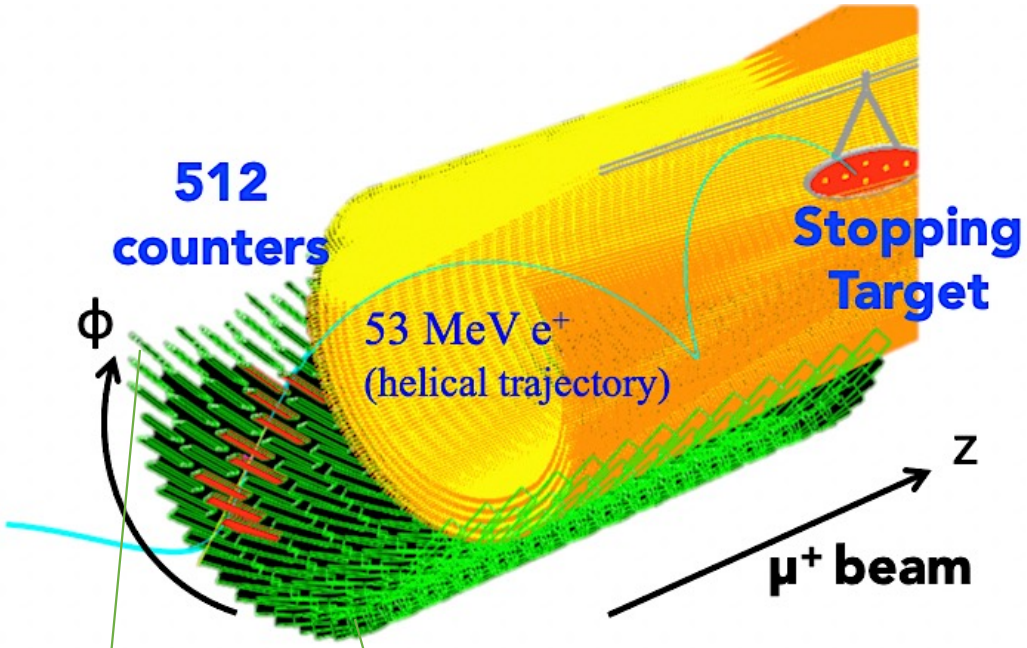
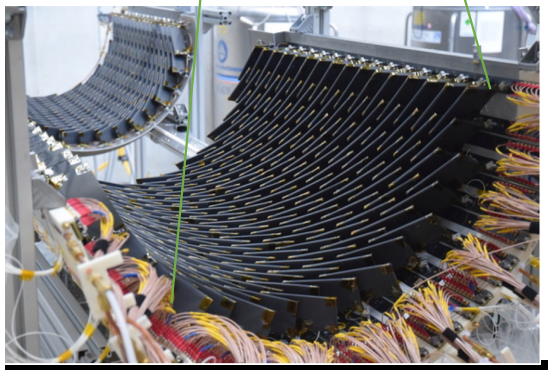
- Running since 2021 towards 2026
  - w/ the DC anti-muon beam $3 - 5 \times 10^7\ \mu^+/s$

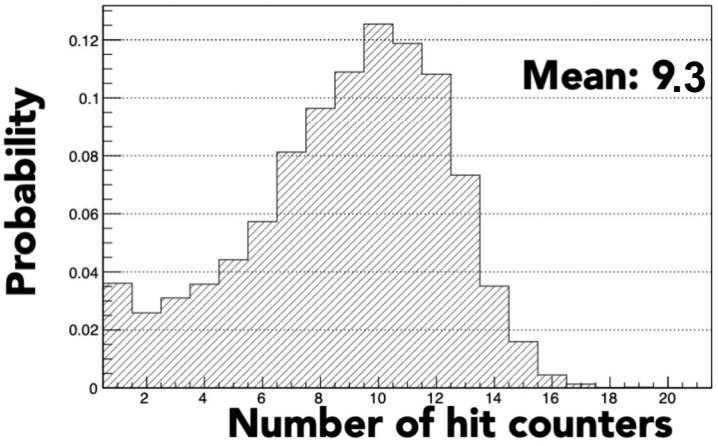
⇨ **Renovation of the pixelated Timing Counter for longer term operation & better positron timing detection.**

pixelated Timing Counter

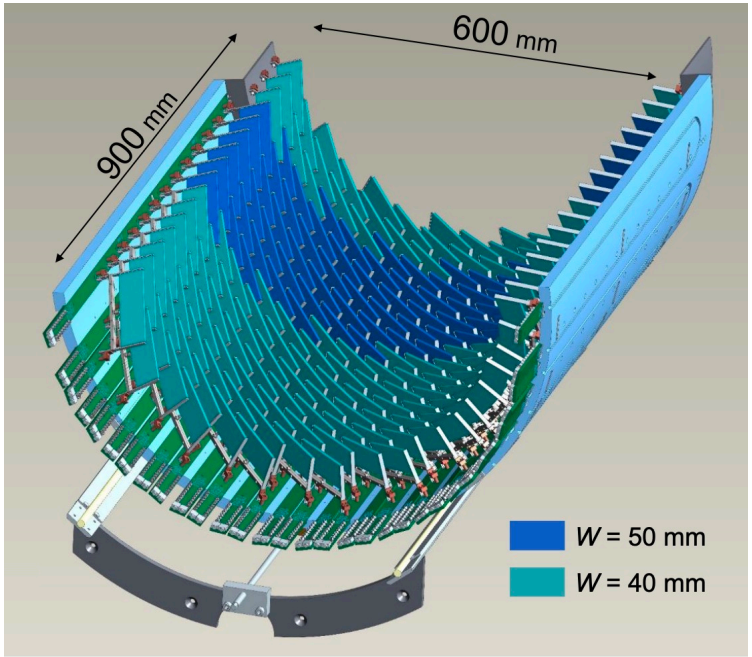


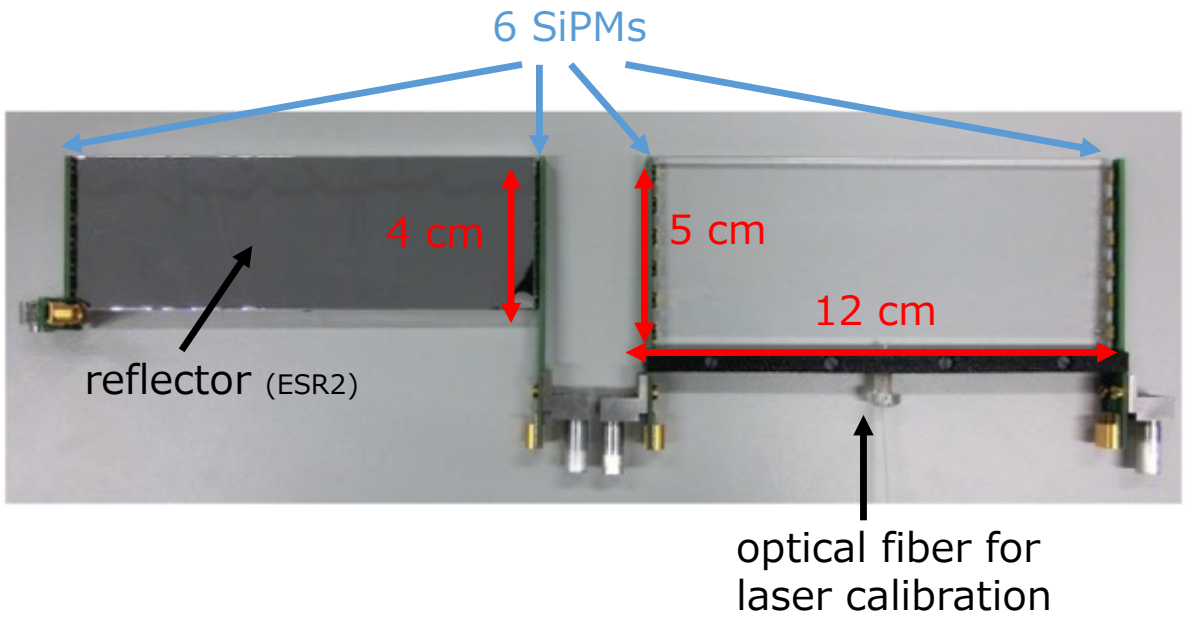


- Improve e^+ time resolution **by multiple-pixel-hit scheme.**
- 256 pixels on Upstream module
  256 pixels on Downstream module
  = **512 pixels**
- Mean ~ **9.3 hits** (MC, Signal e^+)



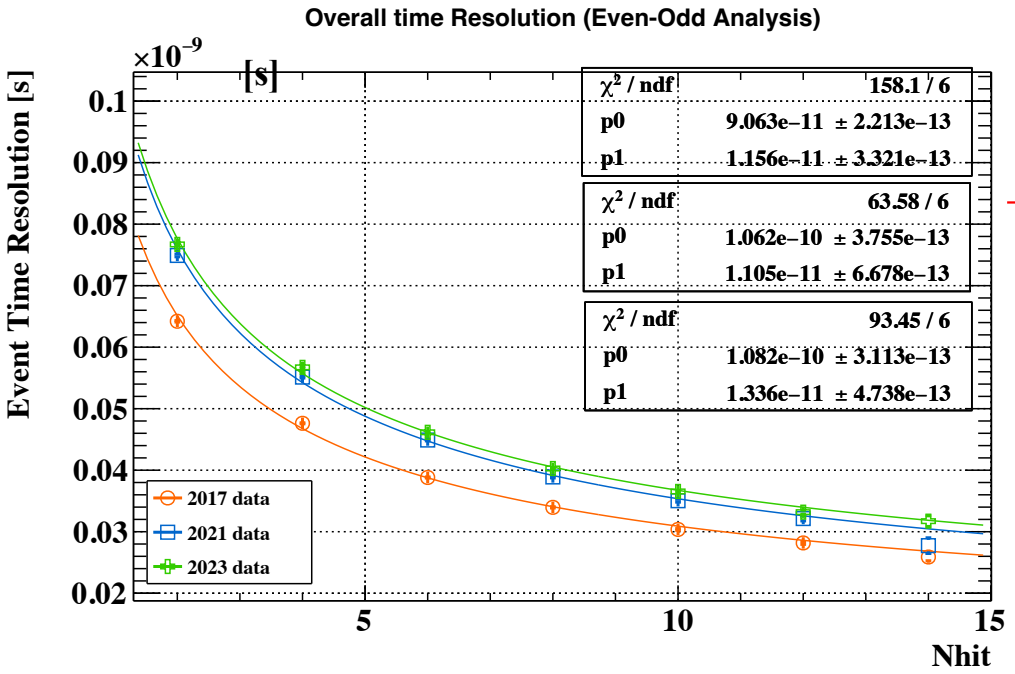
pTC geometry





- 90 cm x 60 cm semi-cylinder module. ($-165.8\,° < \varphi < +5.2\,°$)
- **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).

pTC performance so far (1)



for Michel e⁺ data in 2017, 2021, 2023

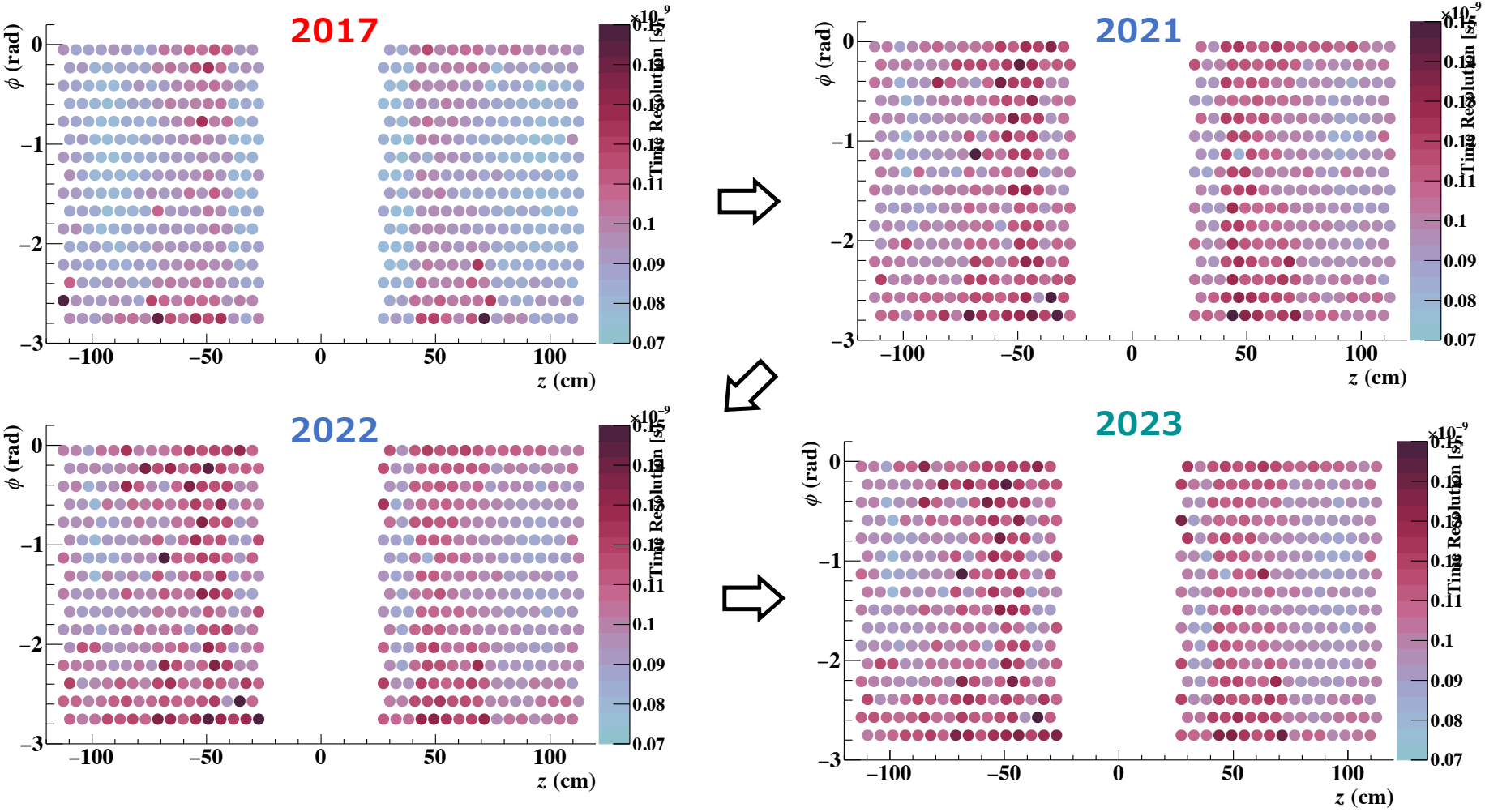
$$\sigma_{\mathrm{pTC}}(N_{\mathrm{hit}}) = \sqrt{\frac{p_0^2}{N_{\mathrm{hit}}} + p_1^2}$$

$$(p_0 \sim \sigma_t^{\mathrm{single}},\ p_1 \sim \sigma_t^{\mathrm{system}})$$

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

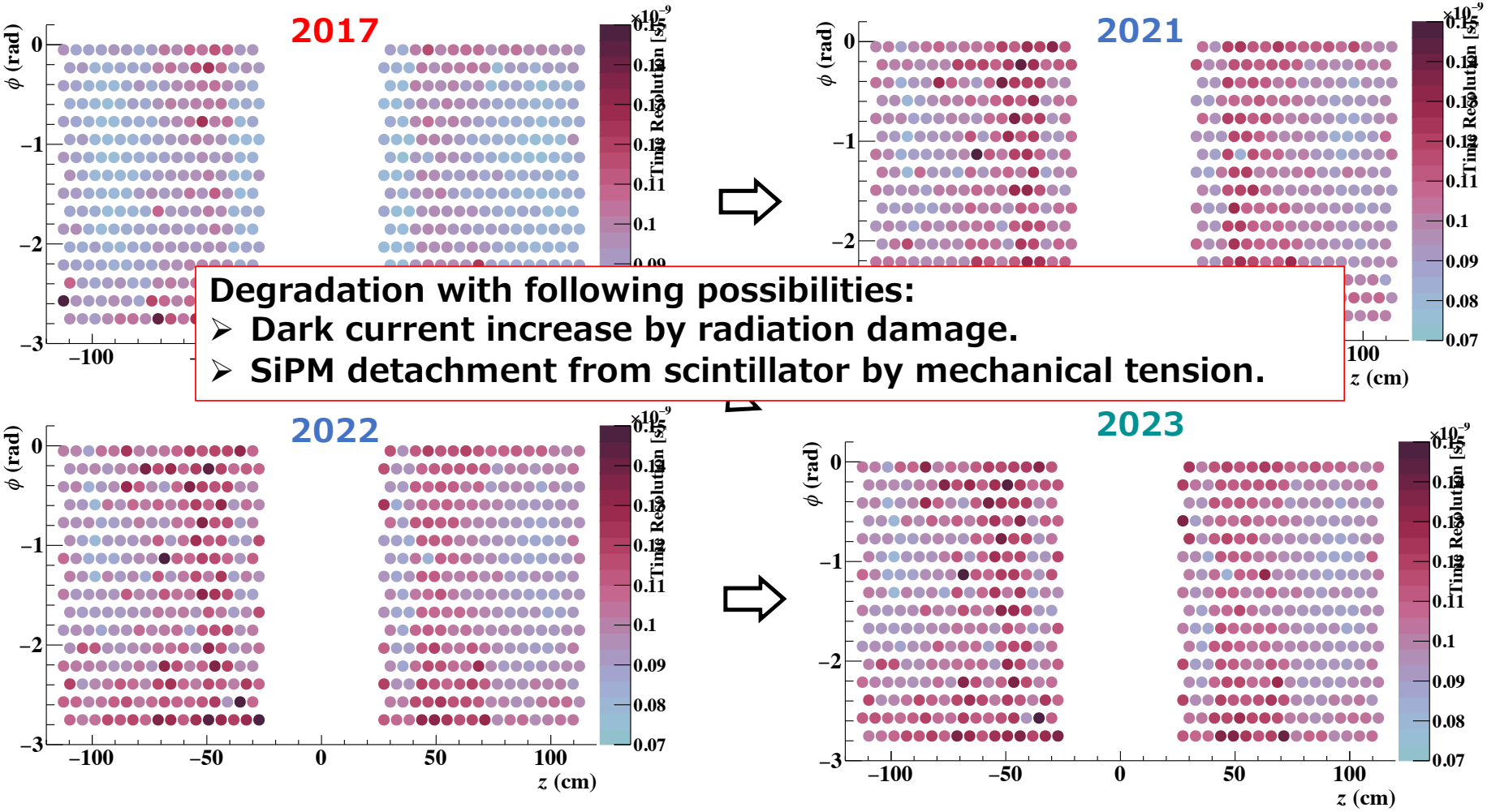
pTC performance so far (2)

*Timing resolution for Michel e+



pTC performance so far (2)

*Timing resolution for Michel e+

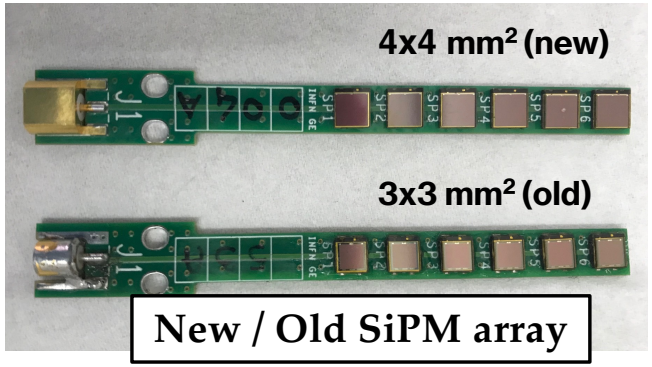


Degradation with following possibilities:

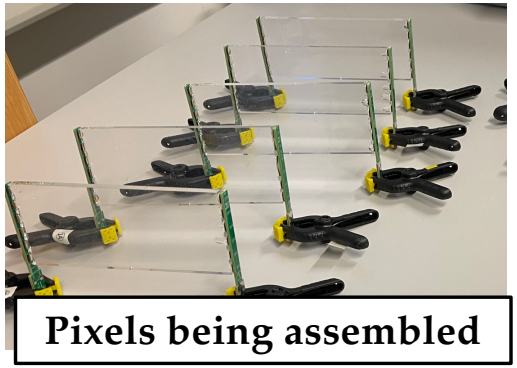
- **Dark current increase by radiation damage.**
- **SiPM detachment from scintillator by mechanical tension.**

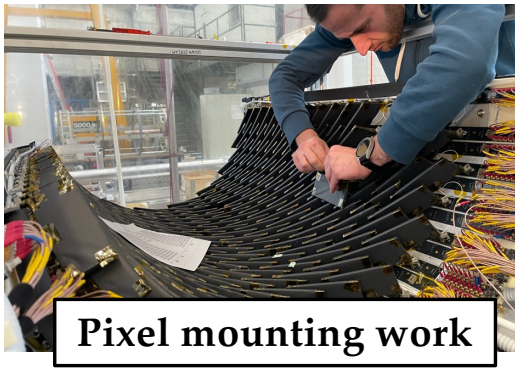
pTC refurbishment 2024

pTC refurbishment with new SiPMs



New / Old SiPM array


Pixels being assembled


Pixel mounting work

reported in JPS2024s

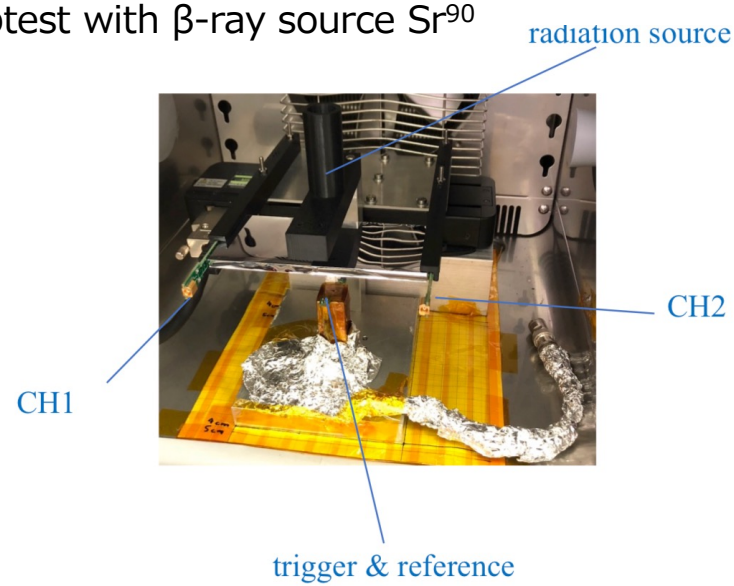
reported in JPS2024a

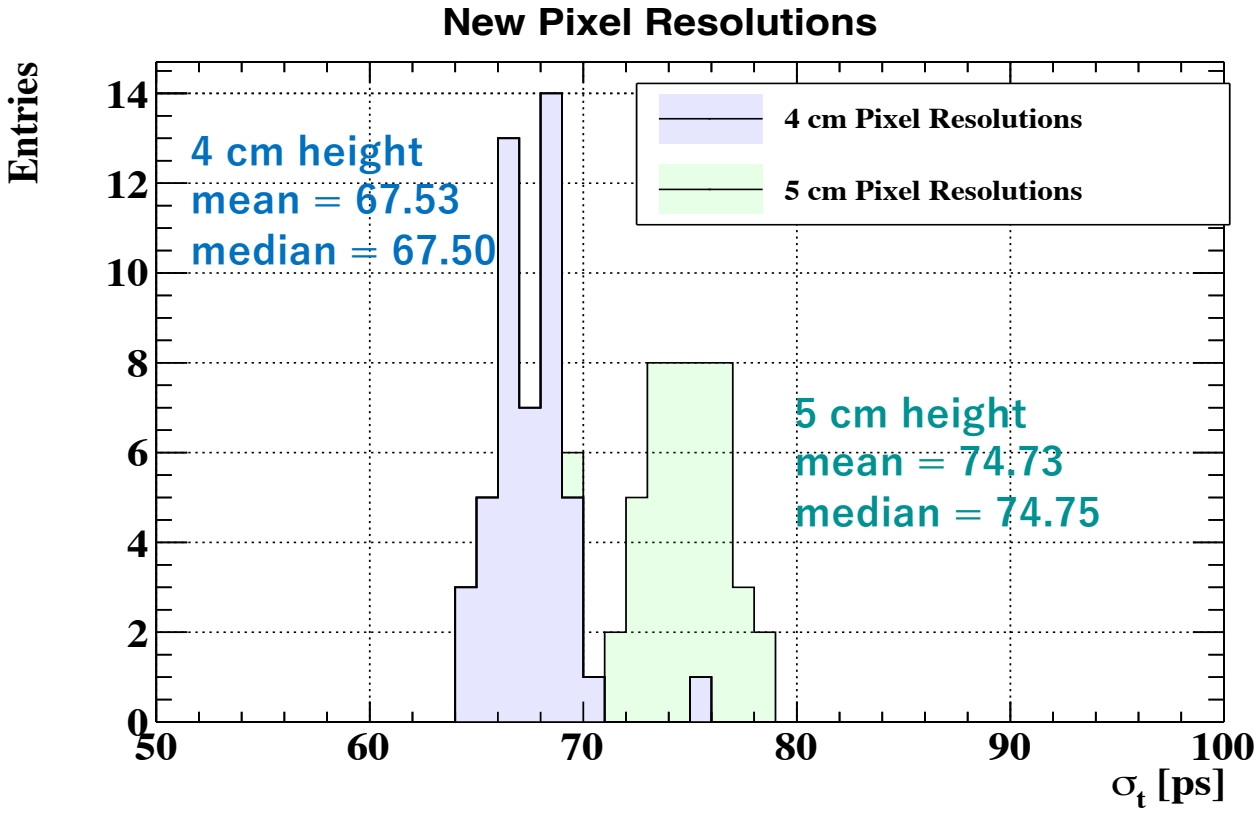
Soldering 6 SiPMs into series connection → SiPM array test of I-V & light yield → Pixel assembly → Pixel test of timing resolution → Pixel mounting on pTC

- 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 mm²** (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 $V_{breakdown}$+3.5 V / SiPMs (optimized by 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 only could **exchange 80 pixels on pTC.**
- Contribution of individual pixel exchange was evaluated as:

  - For 1 event which the exchanged pixel included:

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

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

  - For general:

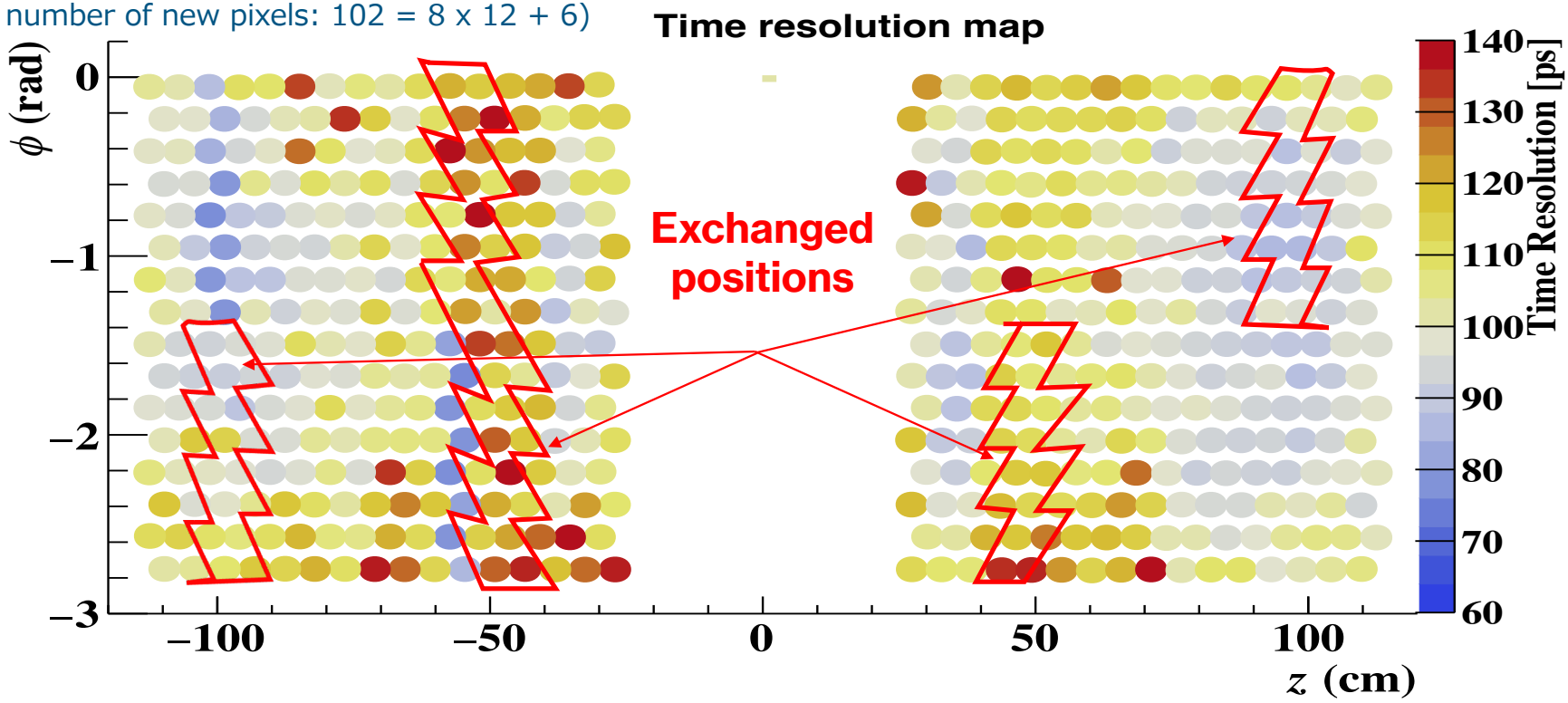
$$\hat{\sigma}_{t_{\mathrm{pTC}}}(n) \approx \sqrt{\boxed{\left(1-\frac{1-a^2}{n}\right)} \cdot r_n + 1 \cdot (1-r_n)} \cdot \frac{\hat{\sigma}_{\mathrm{single}}}{\sqrt{n}}$$

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

pTC refurbishment – geometry

- There were some constraints:
  - Exchange the ones with bad resolution > 130 ps, being suspected in a terrible aging.
  - 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 sharing a HV supply circuit, their HVs should be in range of +4V from V_{min}.

(Total number of new pixels: 102 = 8 x 12 + 6)

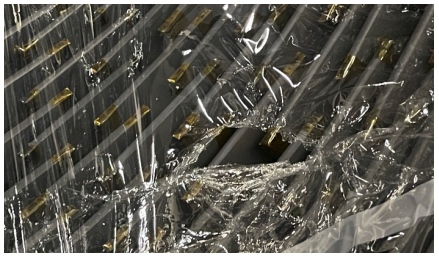


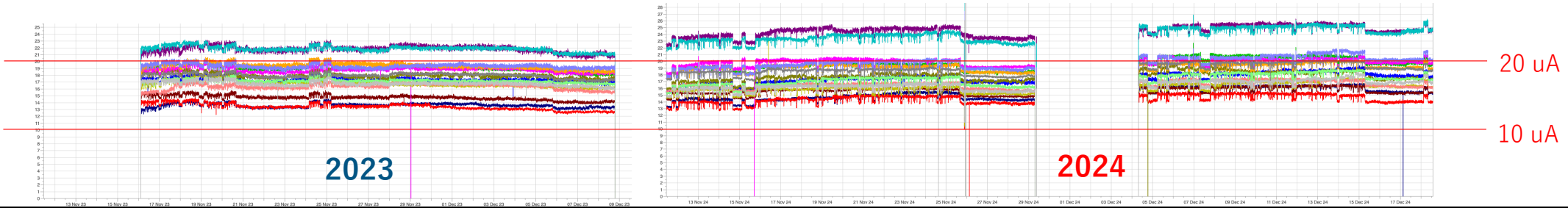
Performance evaluation

2024 MEG Run data samples & condition

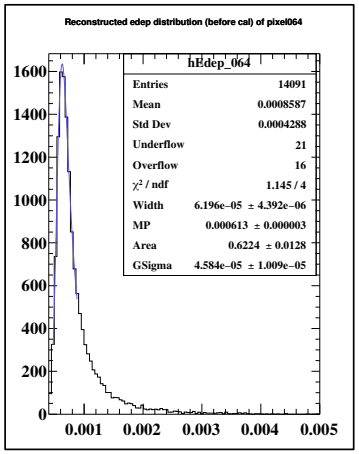
- Short beam time (11 Nov. – 18 Dec.)
  - Total ~16M muon events.
- Evaluated by **1.8M Michel positron events.**

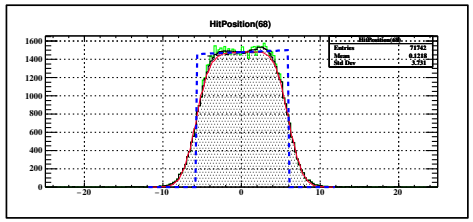
- pTC operation temperature was **at 17degC with uncontrolled humidity**.
  - Thin PE film to cover the pTC was broken.
    - The drawback of the refurbishment work.
    - Air circulation seemed not enough with a path to hole of film.
  - Sometimes attempted to cool down the temperature to 10 degC.
    - Failed with the warmer environment inside the experimental area, even in winter .
    - Many short-circuits happened, which seemed by condensed water.
  - Results in
    - **More dark currents by higher temperature:** ~ +1 uA than 2023
    - **Lower bias voltage:** due to higher breakdown voltage, missing changes of the HV configuration

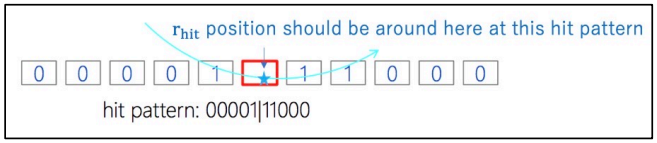


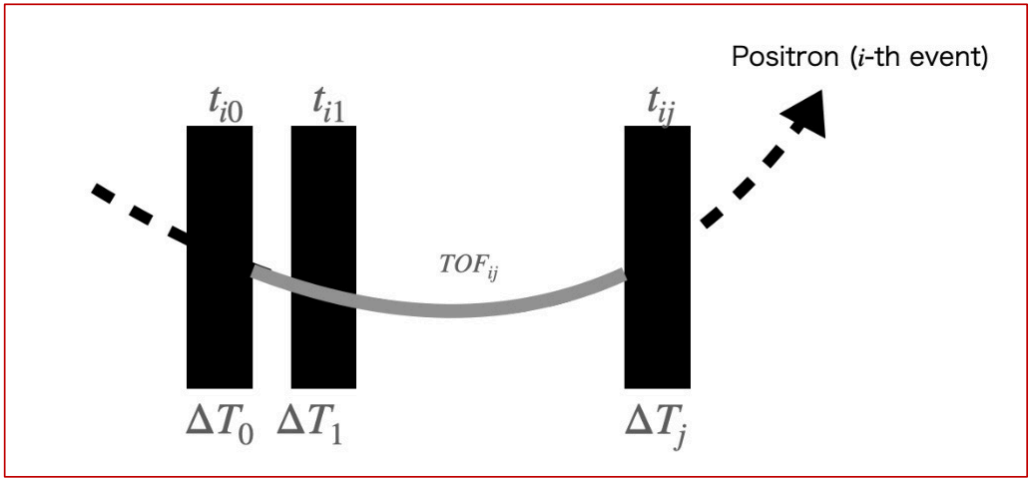


Performance evaluation scheme









- Energy calibration
  - Resolve gain difference according to MC simulation.
- Hit position (width direction) calibration
  - By ch0 - ch1 information.
- (Hit height estimation with cluster patern)

↓ **Energy, Hit plane information**

- **pTC-self tracking**

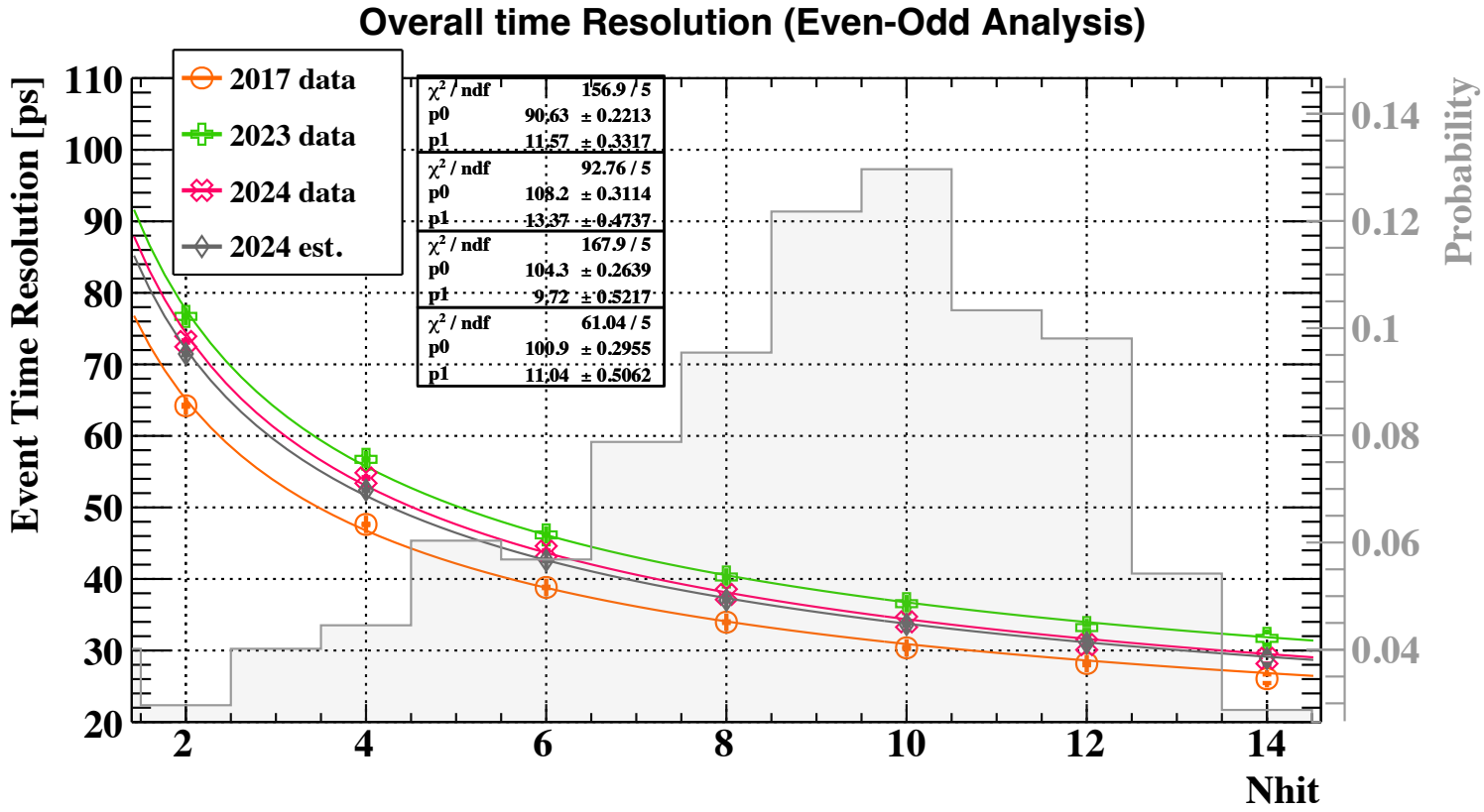
↓ **TOF information**

- **Timing calibration**

↓ **Other counters on the same track can be regarded as time reference**

- **Resolution evaluation**
  - Even-odd method
  - Single counter method

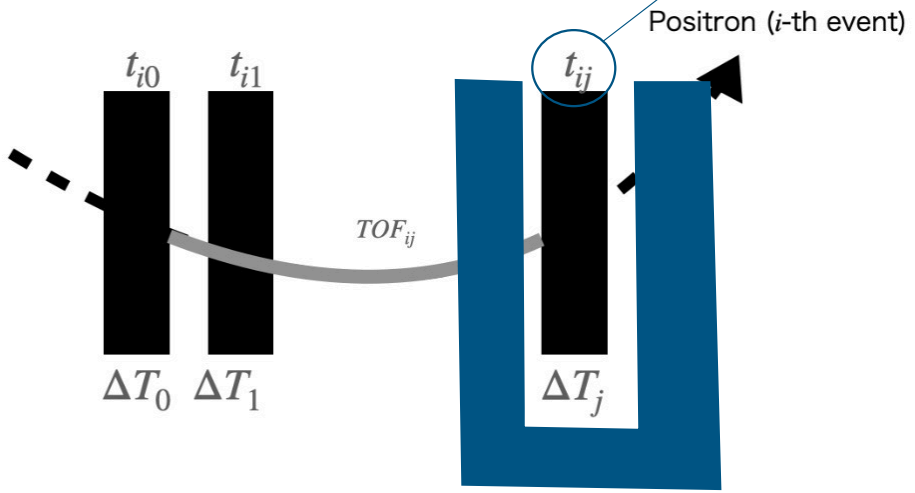
Refurbishment result (Even-odd)



- Single pixel parameter (σ_t^{single}): 108 ps (2023 data)
  - **-> 104 ps (2024 data, -3.7%)**
  - (Estimated = 101 ps, -6.5 %)
- **pTC Overall resolution: 44.3 ps (2023 data)**
  - **-> 41.8 ps (2024 data, -5.7%)**
  - (Estimated = 40.9 ps, -7.7 %)

Single counter method

$$\sum_{i-\text{track}} t_{ij} = t_{j-\text{th counter}} \sim N(0, \sigma_{t_j})$$

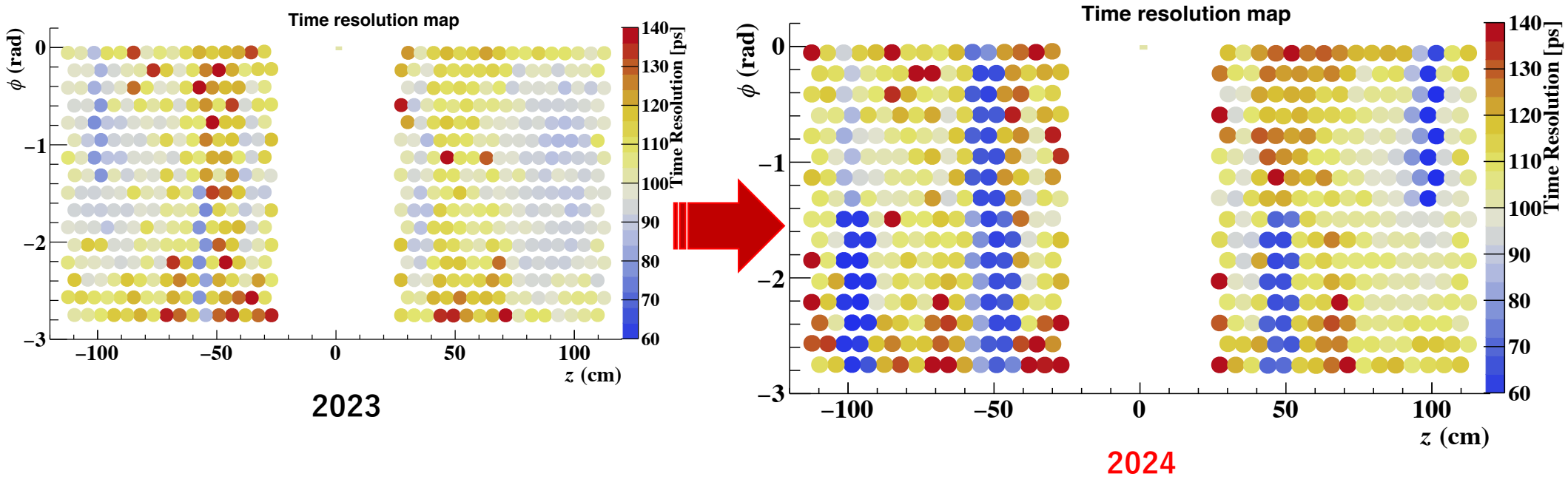


$$\sigma_t^{i-\text{th counter}} = \sqrt{\left(\sigma_{t_i}\right)^2 - \left(\sigma_{t_{\text{ref}}^i}\right)^2}$$

Reference resolution from neighbor hit

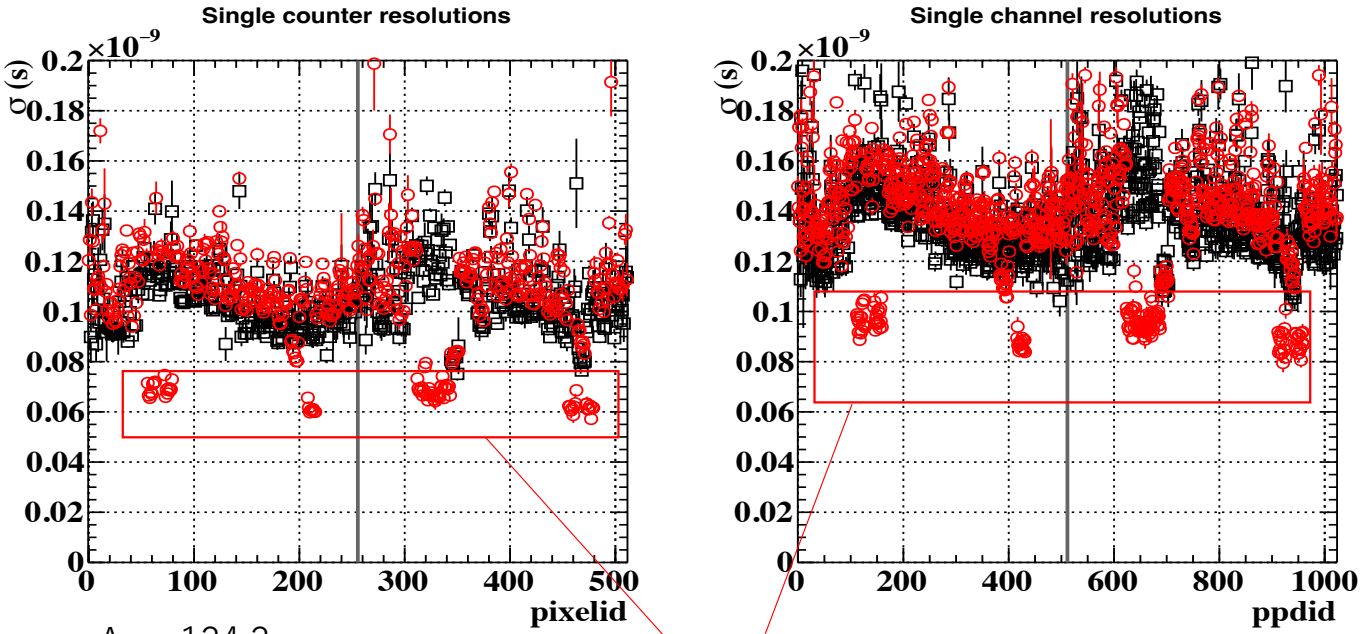
$$\sum_{i-\text{track}} \sum_{k=j\pm1}^{n_{\text{ref}}=4,6,8} t_{ik} = t_{\text{ref}}^{j-\text{th counter}} \sim N\left(0, \sigma_{t_{\text{ref}}^{i,n_{\text{ref}}}}\right)$$

Refurbishment result (single counter)



- New pixels (σ ~ 60 ps) are clearly seen.
- Old pixels' resolution got even worsen.
  - Higher temperature -> dark current, missed bias voltage.
  - Irradiation from 2023.
  - Outermost dead channels -> short circuit.

Refurbishment result (single counter)



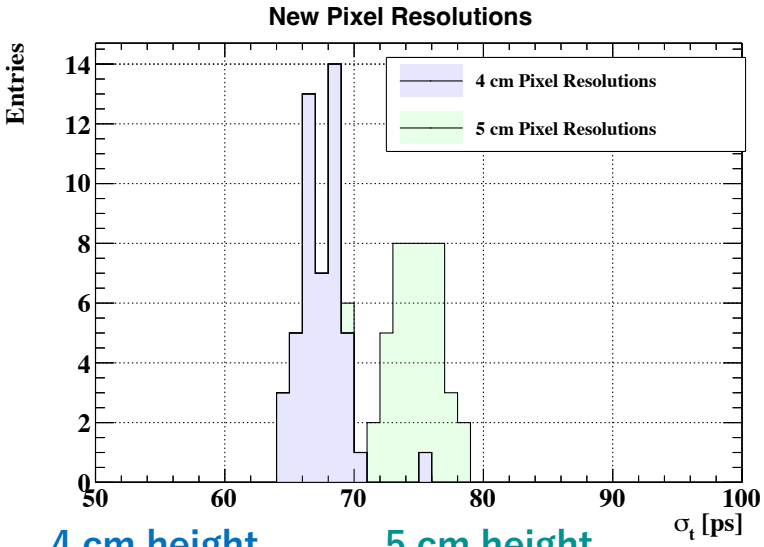
2023: black Ave. 134.3 ps
2024: red Ave. 93.9 ps

new pixels (channels)

- New pixels (σ ~ 60 ps) are clearly seen.
- Old pixels' resolution got even worsen.
  - Higher temperature -> dark current, missed bias voltage.
  - Irradiation from 2023.
  - Outermost dead channels -> short circuit.

Refurbishment result (single counter, new counters)

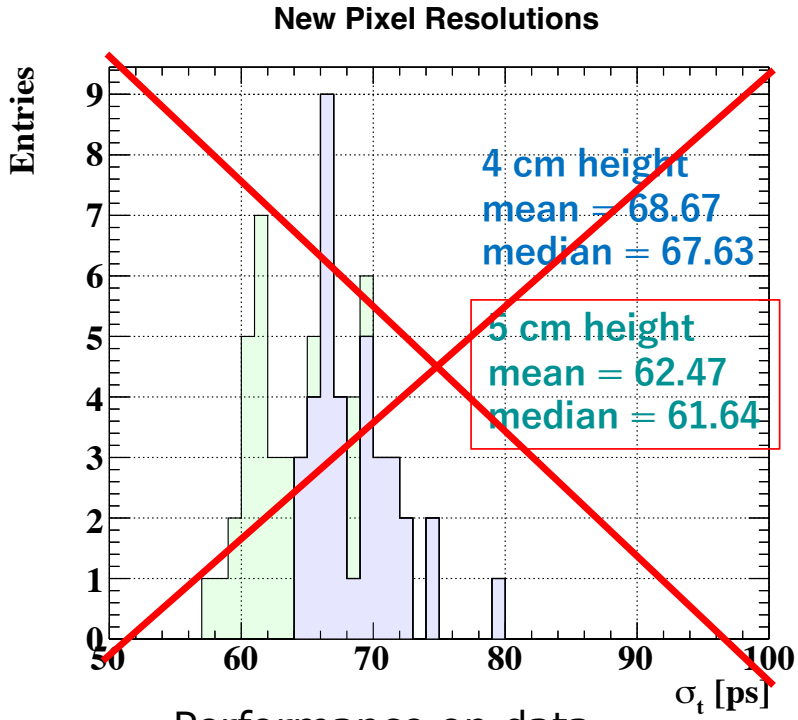
Errata



4 cm height
mean = 67.53
median = 67.50

5 cm height
mean = 74.73
median = 74.75

Labtest

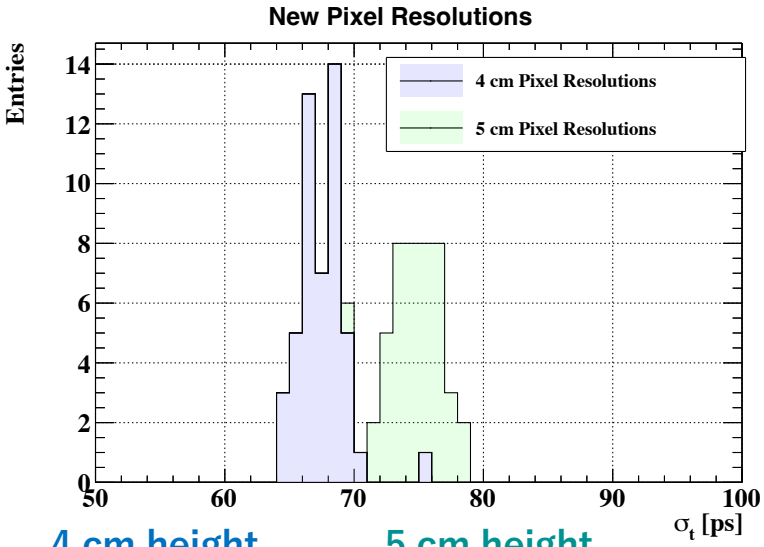


Performance on data

~~4 cm ~ equivalent with Labtest~~
~~5 cm ~ even better than Labtest~~
- ~~Statistics?~~
- ~~Reference quality?~~

Refurbishment result (single counter, new counters)

Errata

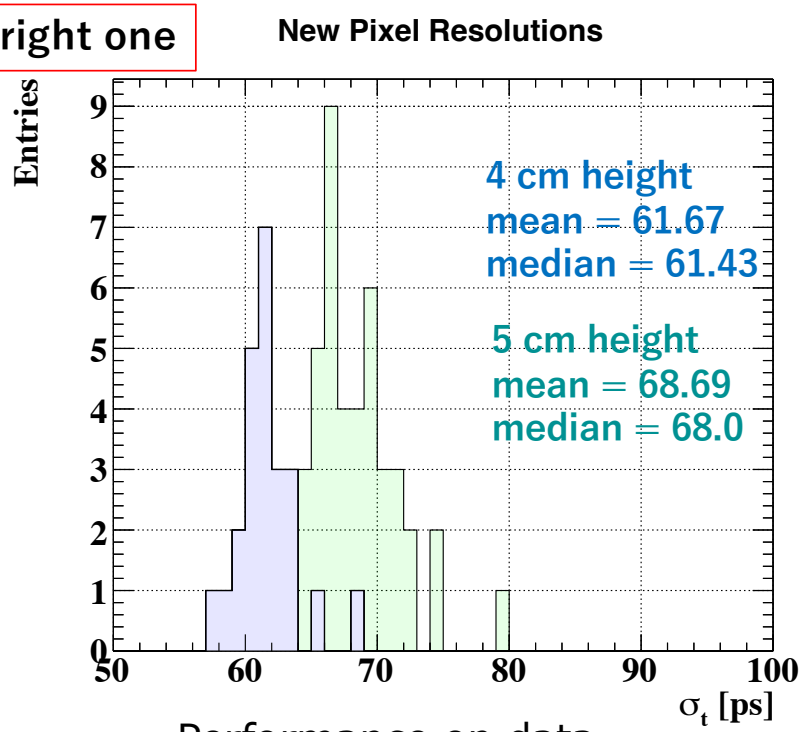


4 cm height
mean = 67.53
median = 67.50

5 cm height
mean = 74.73
median = 74.75

Labtest

right one



Performance on data

~~4 cm ~ equivalent with Labtest~~
~~5 cm ~ even better than Labtest~~
- ~~Statistics?~~
- ~~Reference quality?~~

Resolution of reference counter in Labtest:
well-estimated as 27.52 ps / 29.43 ps
from 4 cm / 5 cm counter's differences.

Summary & prospect

- Major replacement work on the MEG II pixelated Timing Counter was done.
  - For 80 pixels out of 512, done before 2024 run
    - Single improvement ratio / fraction of hit probabilities per nHit are combined to choose the positions.
  - Pre-estimation from MEG II 2023 dataset,
    - Estimated 7.7% improvement from 2023 for pTC overall time resolution.
    - c.f. 80/512 ~ 15% exchange, with 70/100 (ps/ps) ~ 30% better resolution counters = 4.5 %
  - Performance in MEG II 2024 dataset,
    - **Resulted in 5.7% improvement from 2023**.
    - Higher operation temperature with uncontrolled humidity would affect on dark current & bias voltage.

Dataset	$\sigma_t^{\mathrm{single}}$	$\sigma_t^{\mathrm{system}}$	N_{hit}-overall time resolution
2017 commissioning	90.6 ps (100%)	11.6 ps	37.3 ps (100%)
2023 data	108.2 ps (119%)	13.4 ps	44.3 ps (119%)
2024 pre-estimation	101.0 ps (111%)	10.5 ps	40.8 ps (109%)
2024 data	104.3 ps (115%)	9.7 ps	41.8 ps (112%)

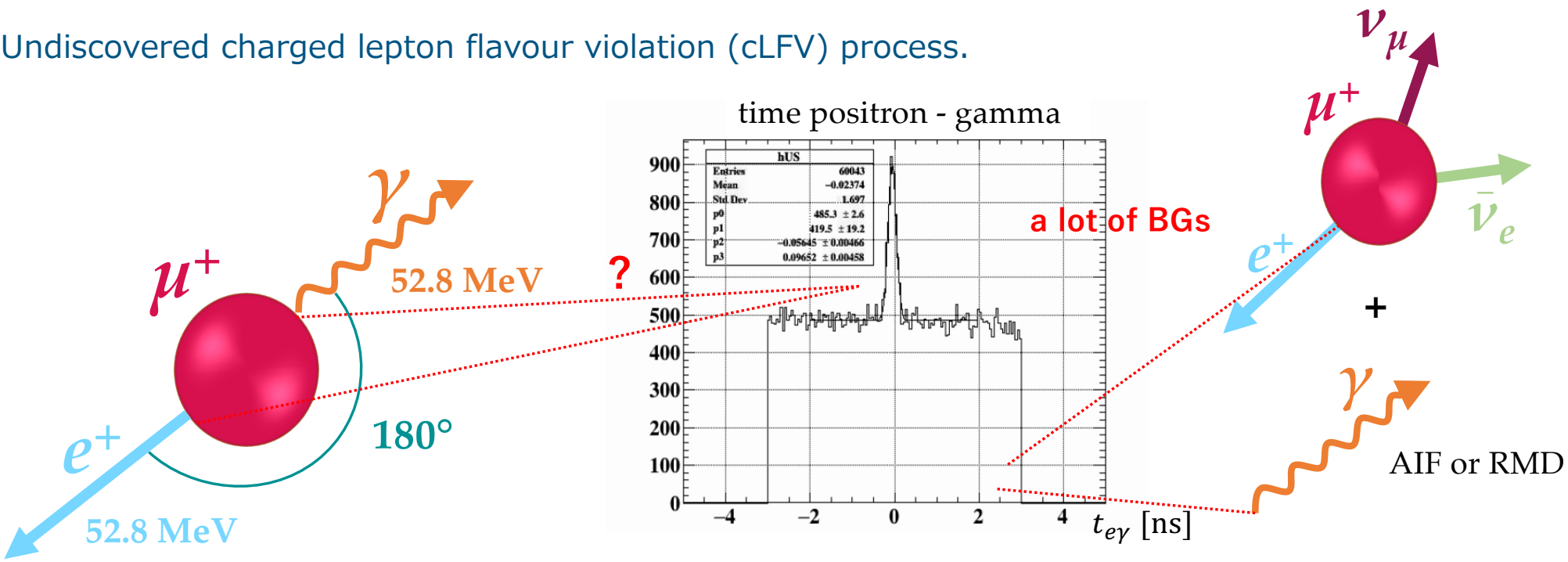
- For 2025 and future,
  - Before 2025 run, we already mounted 12 new pixels out of rest 14.
  - With more air-tight PET (Mylar) film to cover the pTC, we expect full operation of cooling system in 10 degC.

Back up

Motivation – Mu to E Gamma

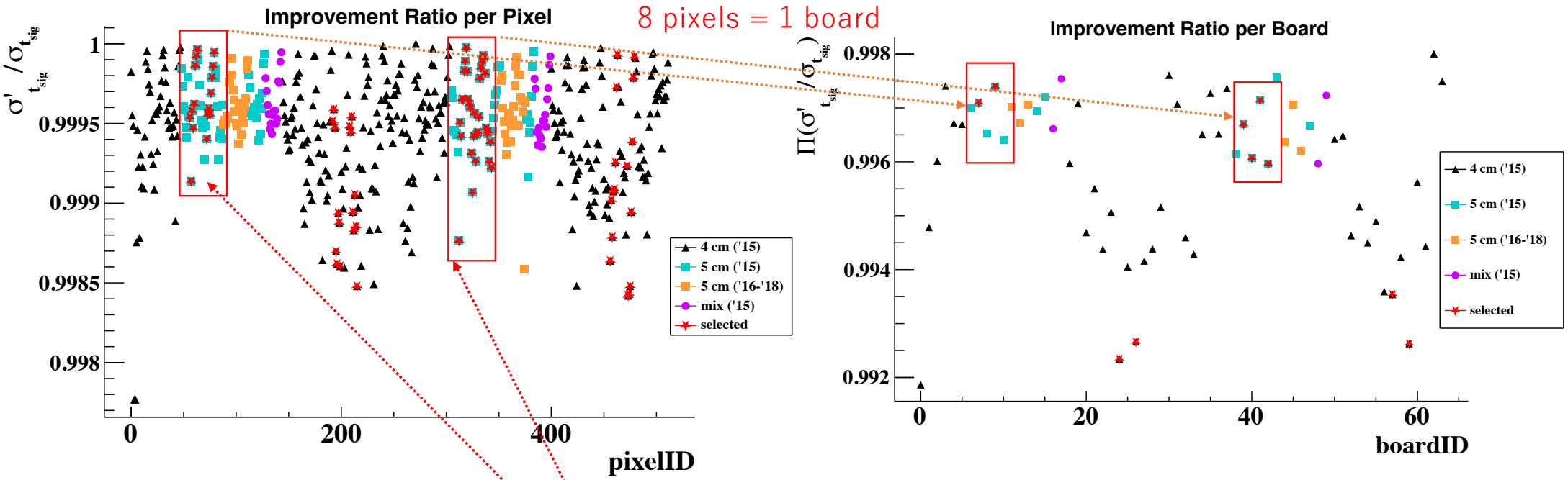
Common muon decay

- Undiscovered charged lepton flavour violation (cLFV) process.



- **The Mu to E Gamma:** $\mu \to e\gamma$, 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.
- The most common muon decay mode: $\mu \to e\bar{\nu}\nu$, accounts for ~100 % of muon decays.

pTC refurbishment – pixel selection

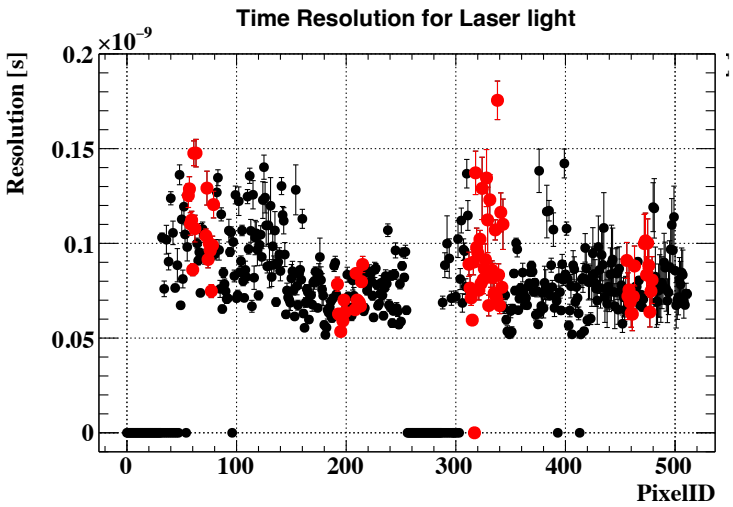


❑There were some constraints:

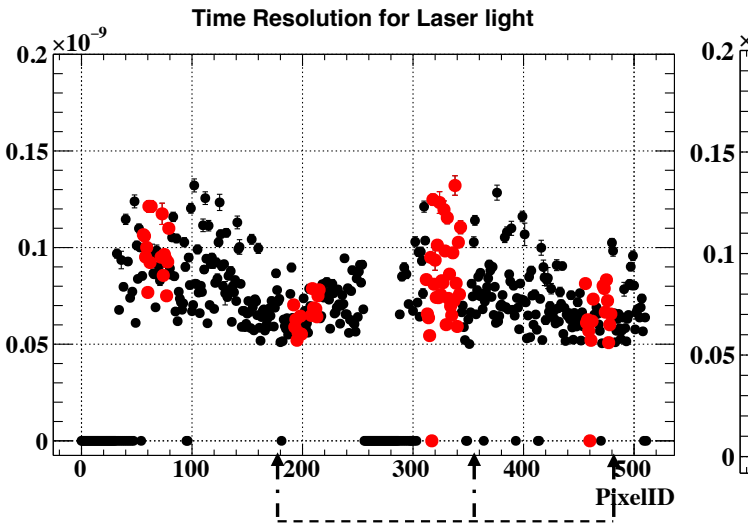
- Number of pixels: only 94.
- Eager to pick up the extreme bad pixels: resolution > 130 ps, for investigation (-> not reproduced in Lab.).
- Pixel size (height = 4 or 5 cm): due to the number of spare scintillators and PCBs (40 (4 cm) + 56 (5 cm)).
- Readout electronics configuration: 8 pixels on 1 readout board, their HVs should be in range of +4V from V_{min}.

Single pixel resolution with laser

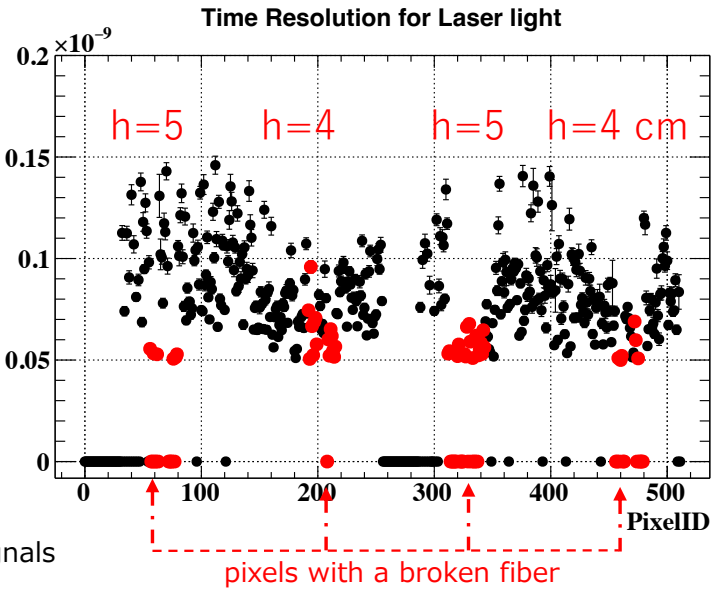
*refurbished pixels in 2024 are highlighted



Start point of MEG II (2021)



after HV optimization (2023)

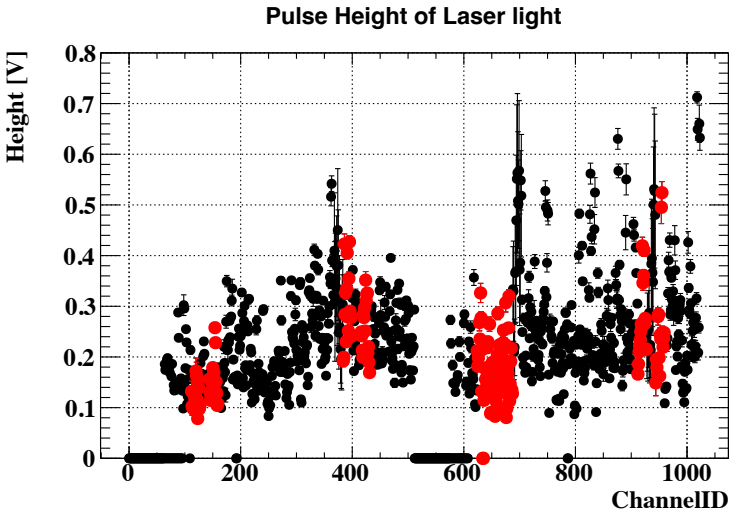


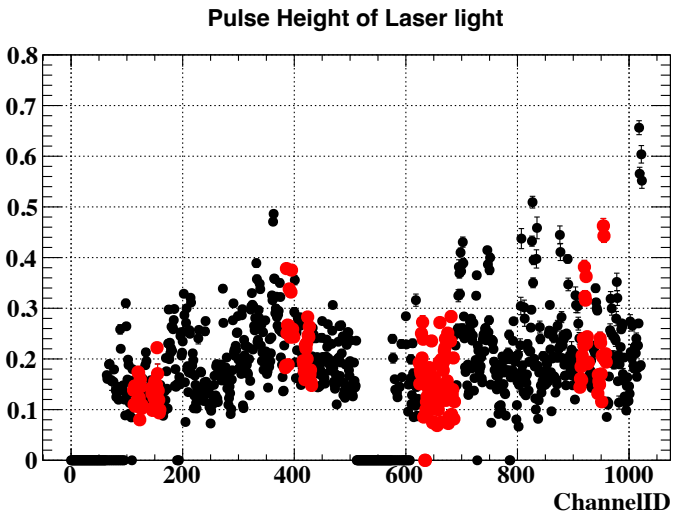
after refurbishment (2024)

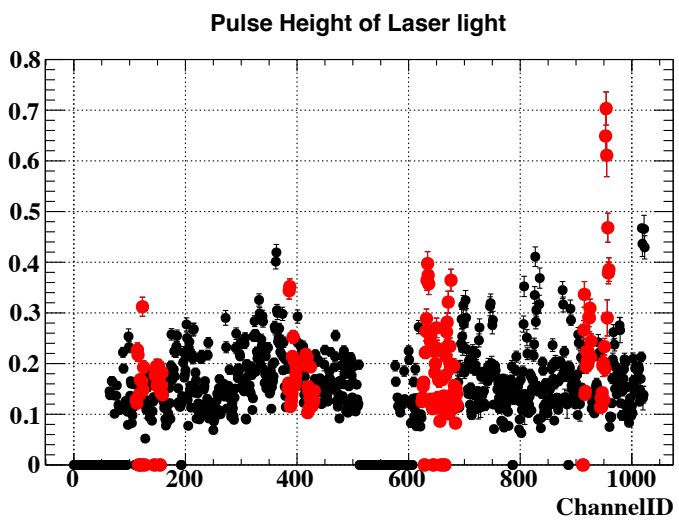
- Timing resolutions with laser light (not fully reflecting the responses for e^+) show
  - for h = 5 cm pixels: 50-140 ps -> 50-70 ps
  - for h = 4 cm pixels: 50-100 ps -> 50-80 ps
- Because we re-plugged the fibers (even broke some) in 2024, the samples are not exactly the same.

Single pixel resolution with laser

*refurbished pixels in 2024 are highlighted







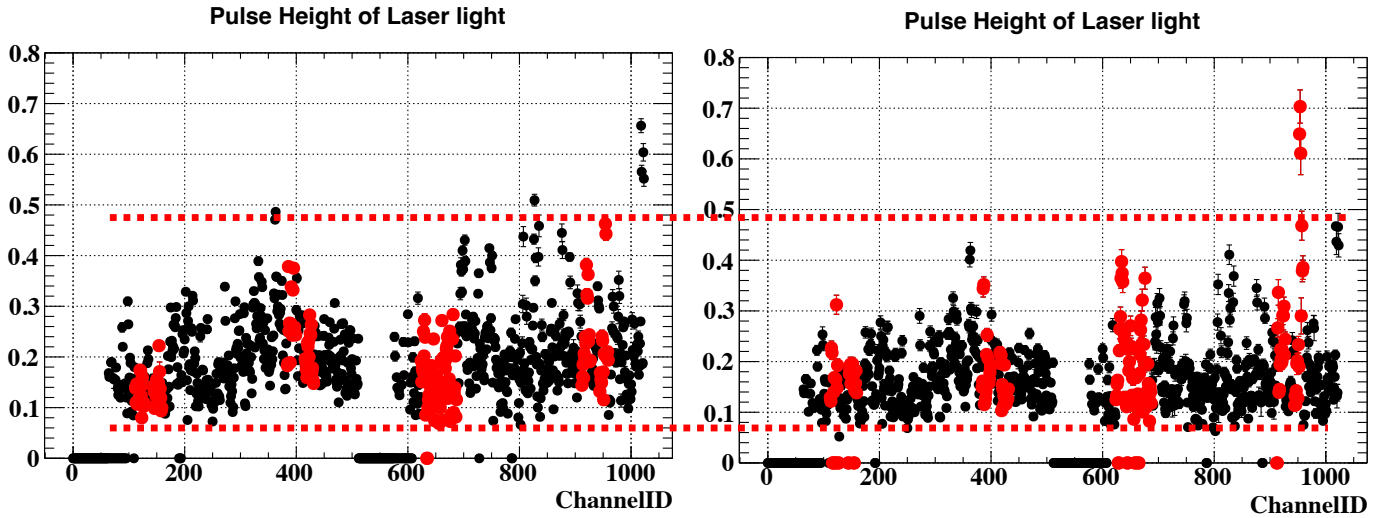
Start point of MEG II (2021) **after HV optimization (2023)** **after refurbishment (2024)**

(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 resolution with laser

*refurbished pixels in 2024 are highlighted



after HV optimization (2023)

after refurbishment (2024)

(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.
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