MEG II実験
陽電子タイミングカウンターの分解能の詳細評価

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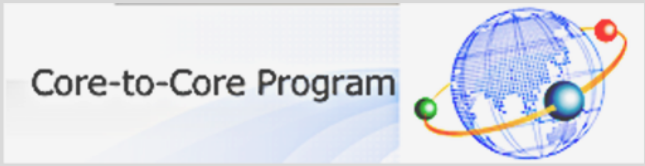
2023年3月23日(木) 日本物理学会2023年春季大会

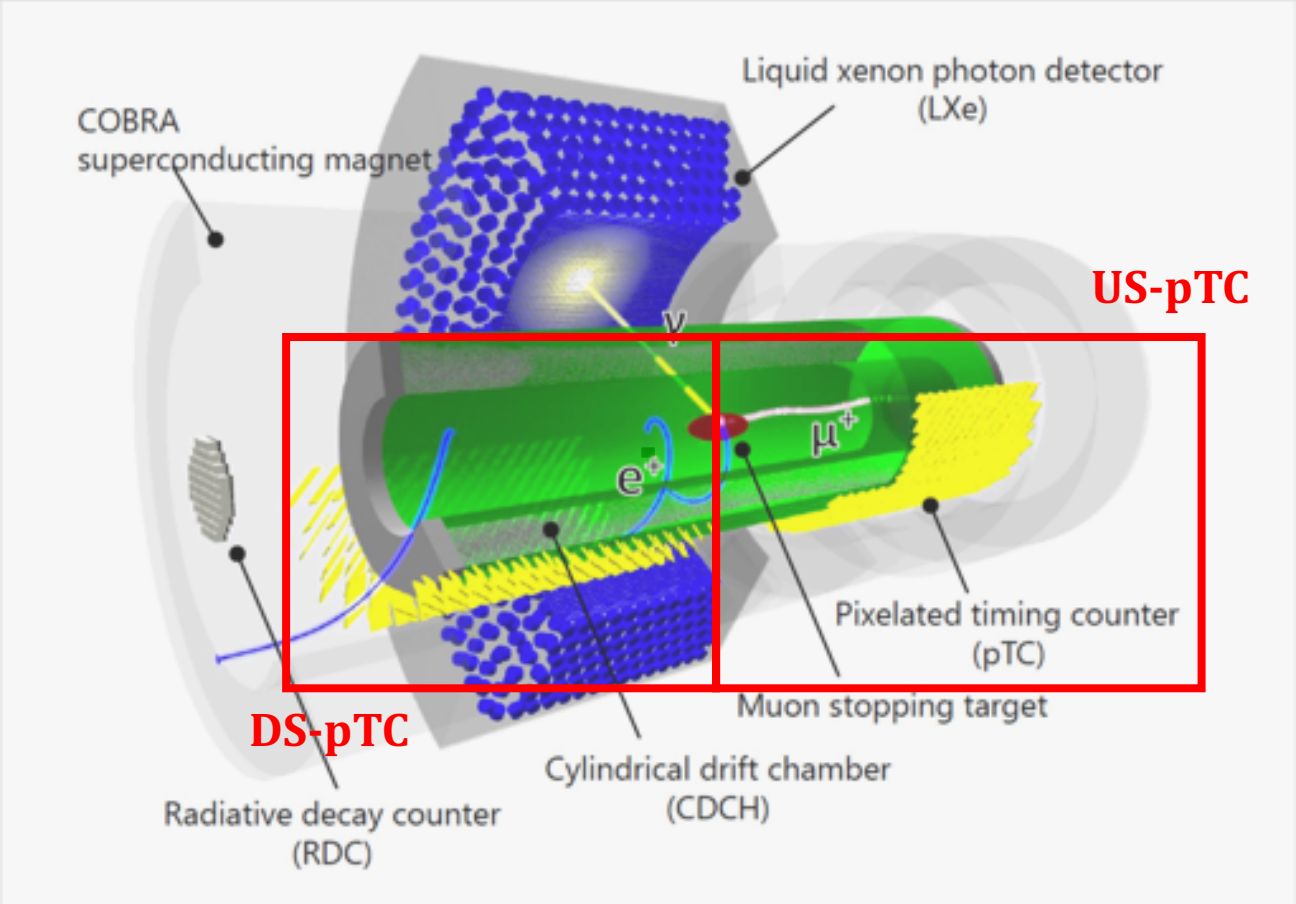
23aT3-2



Outline

- Introduction (MEG II, pTC)
- pTC in 2022
- Conclusion / Prospect

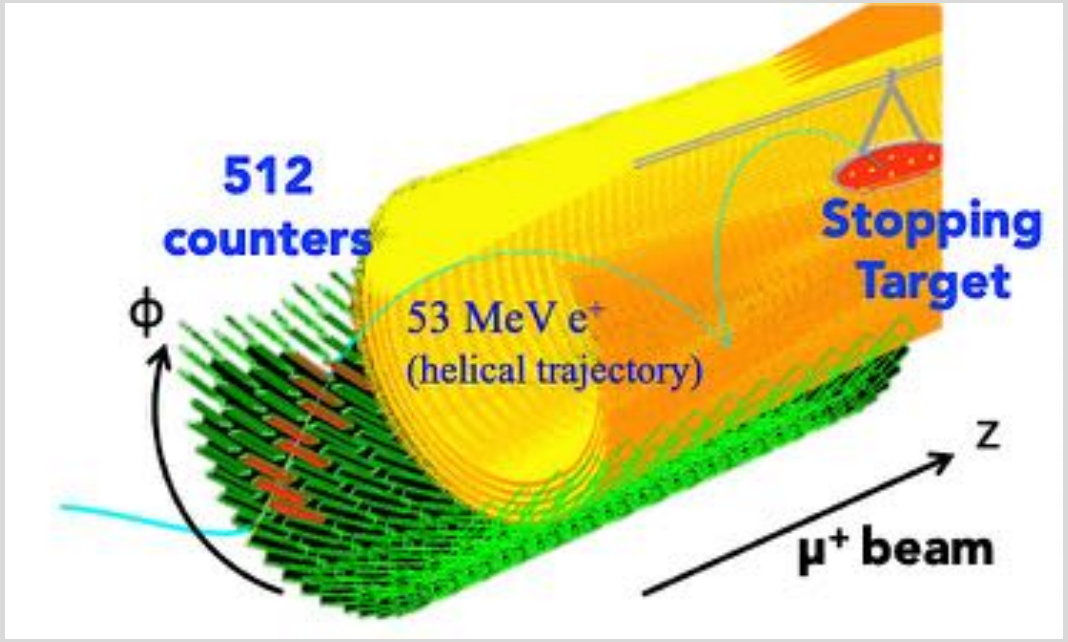
MEG II experiment

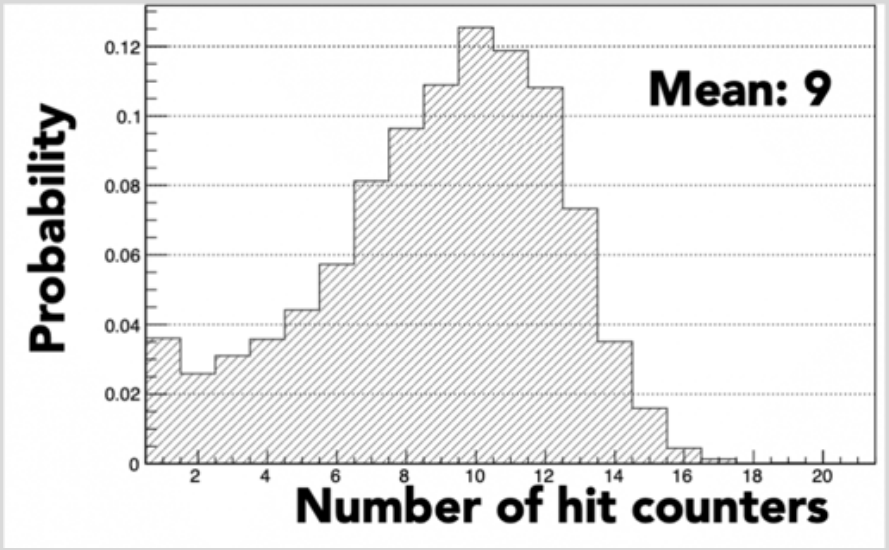


"The design of the MEG II experiment"
EPJ-C 78 (2018) 380

- Search for **cLFV** ($\mu \rightarrow e\,\gamma$) with aimed sensitivity: **6 x 10^{-14}**
- An order of magnitude better from the MEG result (2016) : $\mathcal{B}(\mu \rightarrow e\,\gamma) < 4.2 \times 10^{-13}$
- The physics data taking **ongoing** 2021 pilot run + 2022 -> 2023…

Pixelated / positron Timing Counter (pTC)

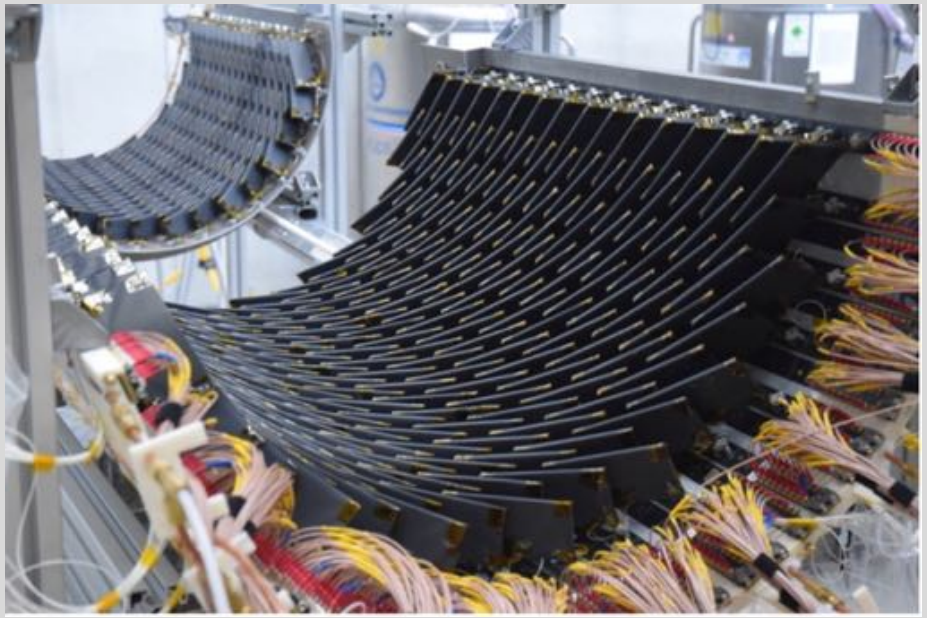


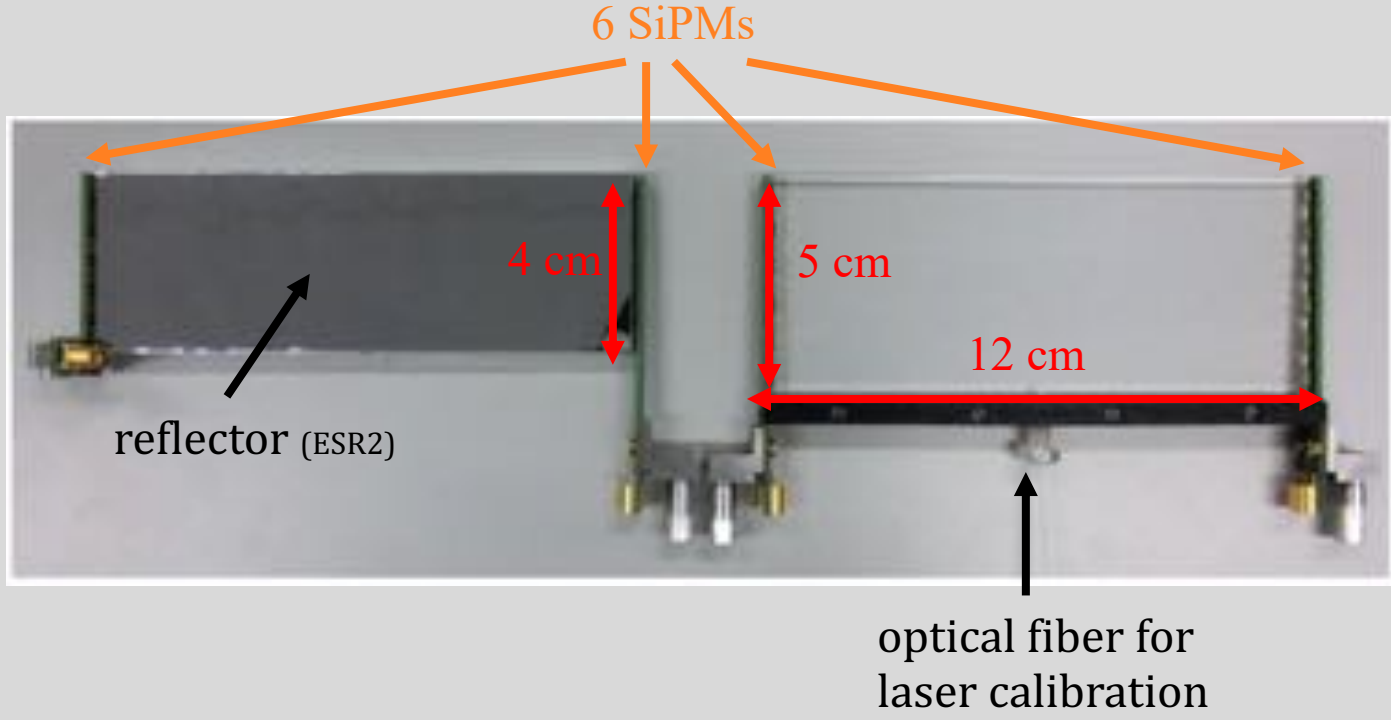


Concept

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

pTC: Pixels



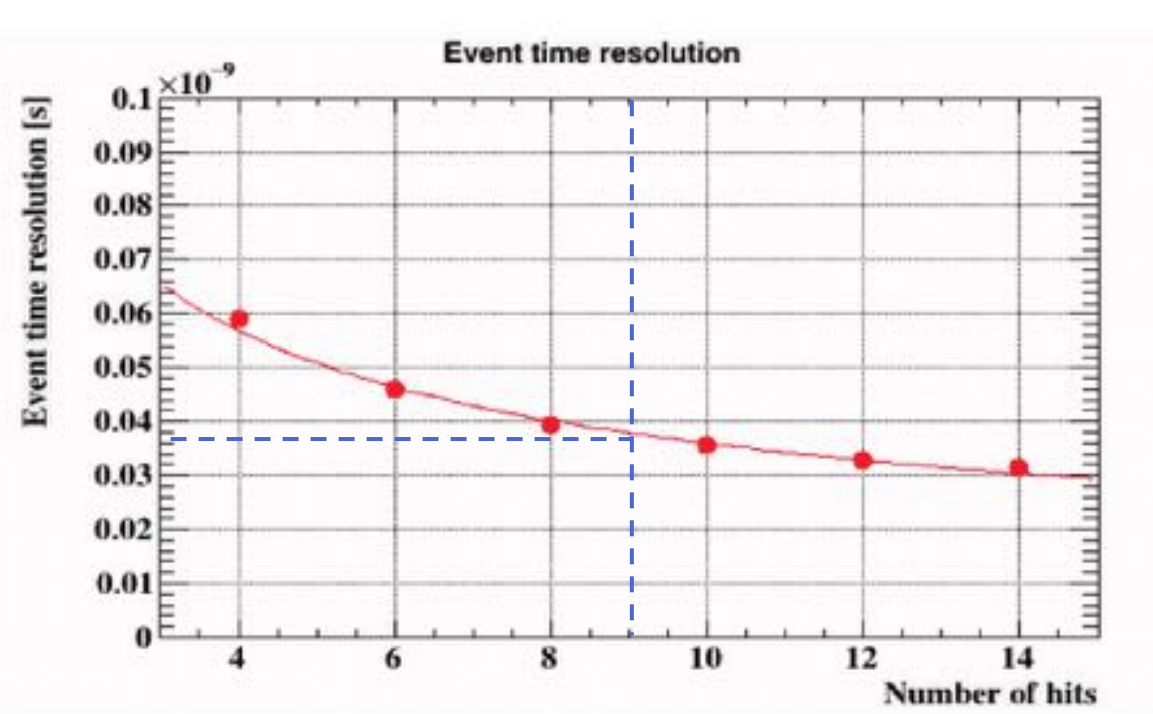


- **Upstream 256 + Downstream 256 = 512 pixels**
- **12 cm × 5 cm (4 cm) × 5 mm** plastic scintillator (BC422).
- Read by series connection of **6 SiPMs** on both side.

(AdvanSiD, ASD-NUV3S-P High-Gain, 3 x 3 mm^2, 50 x 50 μm^2, $V_{breakdown}$ ~ 24 V).

pTC: Time Resolution

$$\sigma_{\mathrm{pTC}}(N_{\mathrm{hit}}) = \sqrt{\frac{\sigma^2_{\mathrm{intrinsic}} + \sigma^2_{\mathrm{inter-pixel}}}{N_{\mathrm{hit}}}} + \mathrm{const.}$$



pTC time resolution in Even-Odd analysis
for Trigger-Timing positrons (November 2022)

- The estimated time resolution at 9 hits is **37 ps**.
- $\sqrt{\sigma^2_{\mathrm{intrinsic}} + \sigma^2_{\mathrm{inter-pixel}}} \sim$ **110 ps**

precision of the time calibration

Positron Reconstruction Scheme

pTC

Waveform analysis

Waveform time is obtained by **constant fraction method**

Intra-pixel (ch-ch) timing & charge (energy) calibration.

Hit reconstruction

Inter-pixel timing calibration.

Clustering

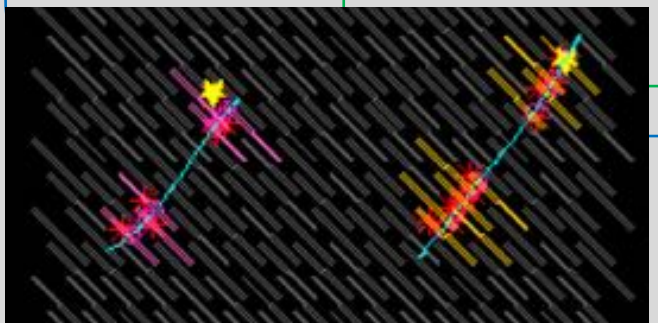
Initial time

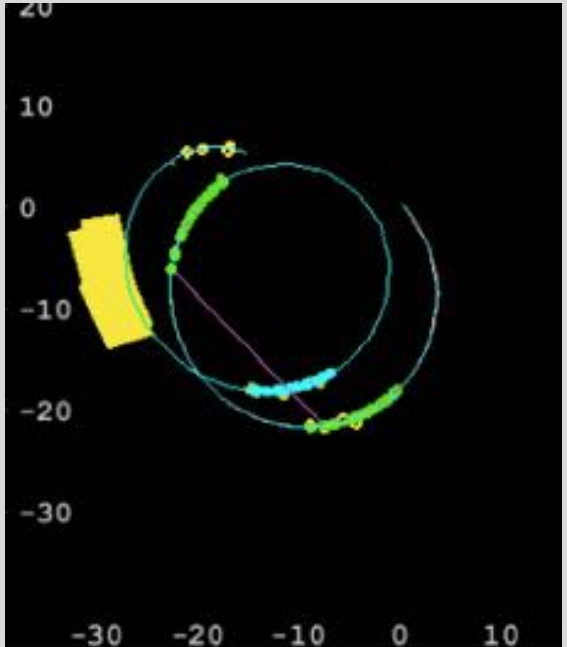
Positron track from CDCH

pTC self track

Positron reconstruction

Positron spectrometer





pTC Overview in 2022

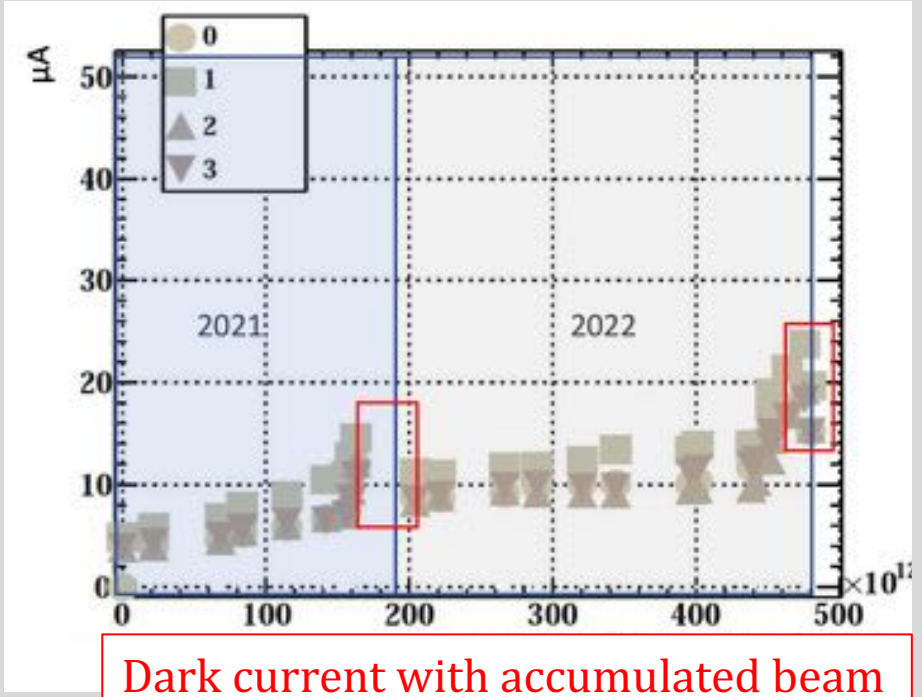
- **NO Dead Channels** during the beamtime.

  4 channels were found to be dead at the commissioning period.
  (Despite alive during the maintenance ’21 -> ’22)

- **Radiation Damage on SiPM** is accumulated.

  It is reflected on increment of Dark Currents in SiPM.

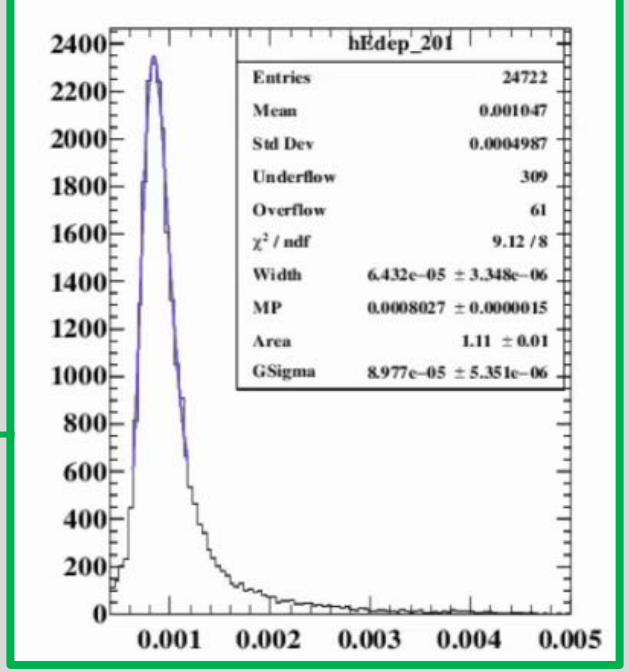
- Cooling & Drying were successfully done.
- Bias voltages were scanned & optimized.
- Calibration flow was integrated.



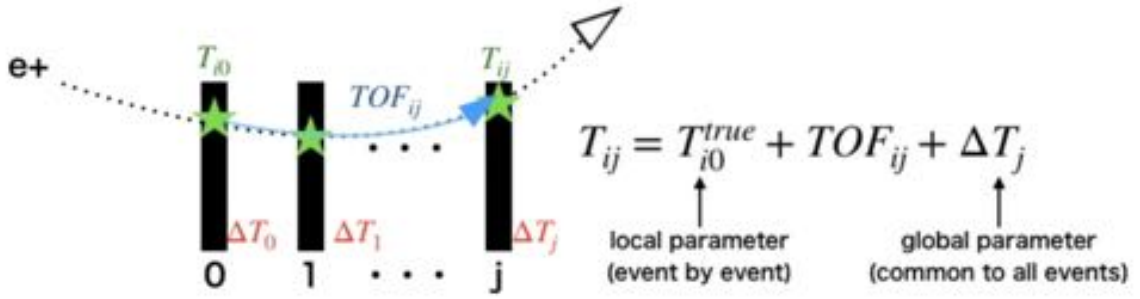
Dark current with accumulated beam

Calibrations on pTC

- The deposited energy (<- integrated charge) in a pixel
  - ➢ The MPV (most probable energy loss) is adjusted.



$$\chi^2 = \Sigma_i^{event}\Sigma_j^{hit}\left(\frac{T_{ij} - (T_{i0}^{true} + TOF_{ij} + \Delta T_j)}{\sigma}\right)^2$$



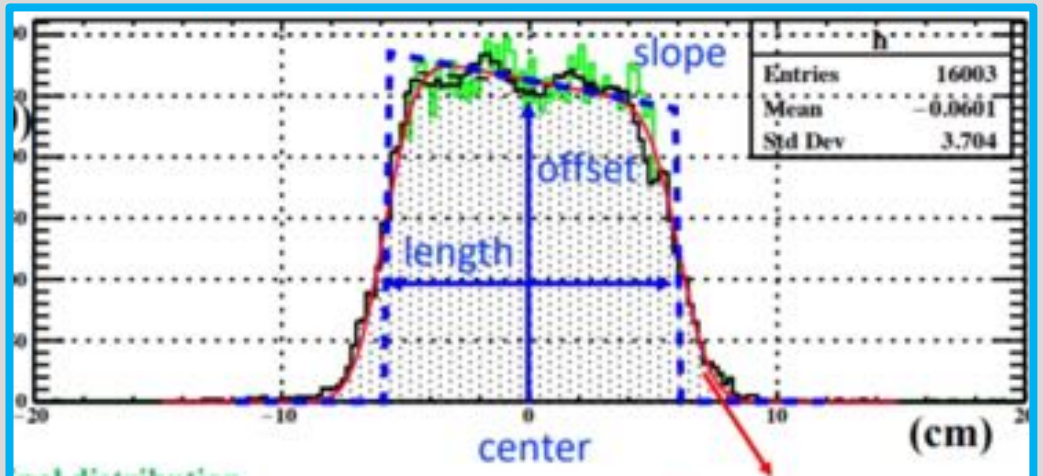
$$T_{ij} = T_{i0}^{true} + TOF_{ij} + \Delta T_j$$

local parameter (event by event)

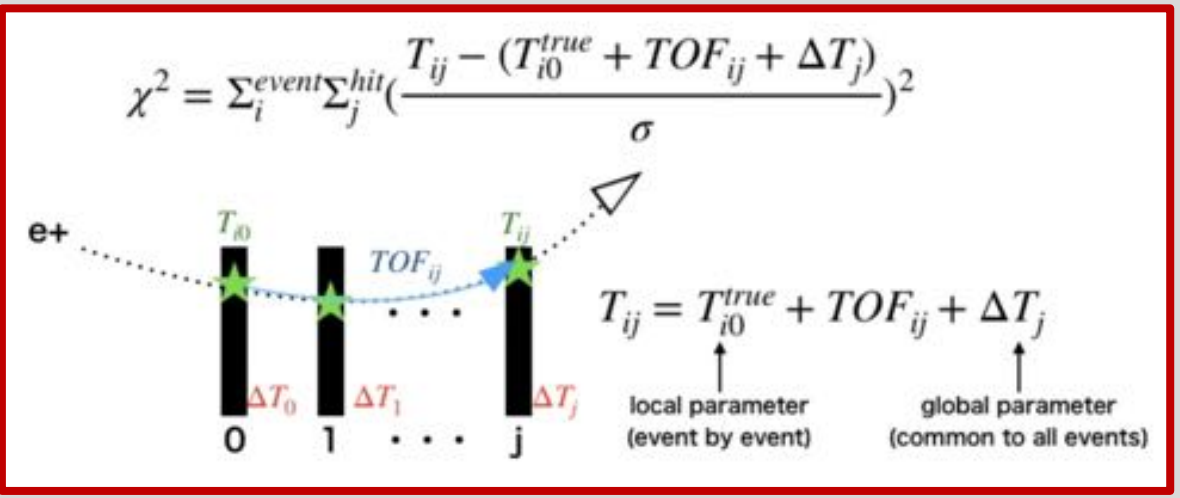
global parameter (common to all events)

- Inter-pixel (pixel - pixel) Timing
  - ➢ Based on e^+ track from Michel decay; Laser measurements eliminates geometry dependence.

- Intra-pixel (channel – channel) Timing
  - ➢ Timing b/w each end reflects the center of the trapezoid of the hit distribution.



Time calibration method



initial value

Laser method → **Track-based method** → Iteration

old

new

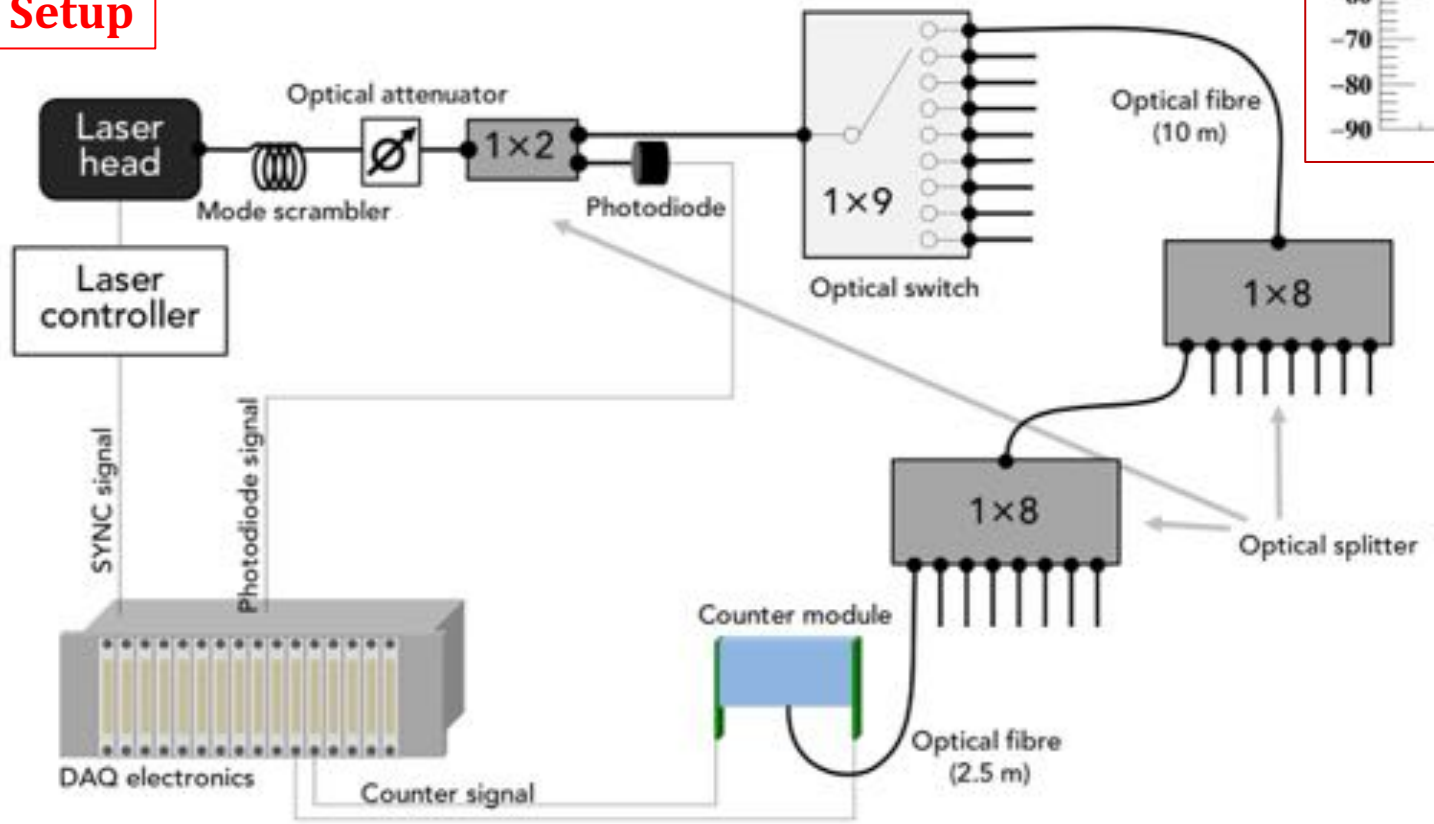
Laser method → CF corrected result → correction → Iteration

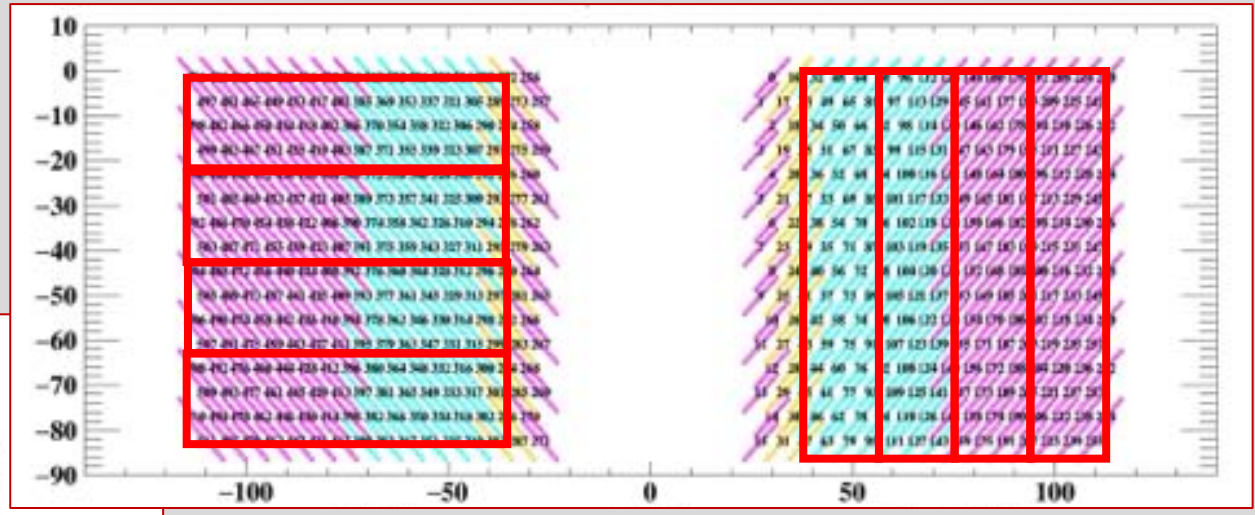
Track-based method → Results:
- US-DS separated
- Bias on Z & phi

- Inter-pixel (pixel - pixel) Timing
  - Based on e^+ track from Michel decay; Laser measurements eliminates geometry dependence.

pTC Laser System

Setup

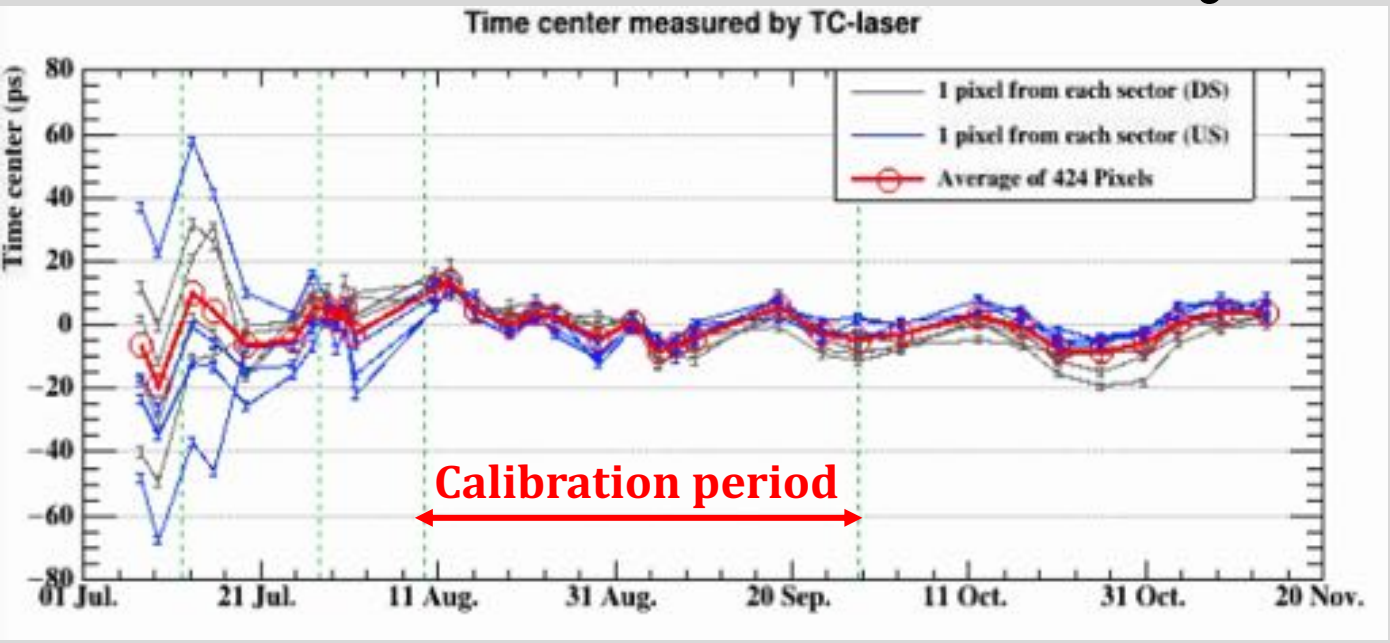


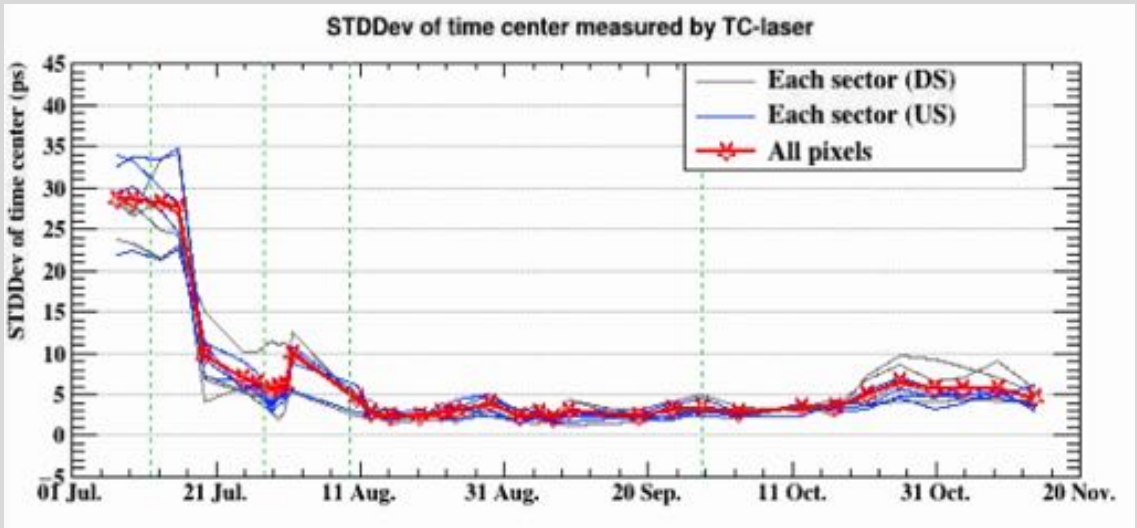


Upstream **Downstream**

- 8 switch channels x (8 x 8) splitters
- Can measure the time centers of pTC pixels with a common SYNC signal.
- NO position dependence, NO beam, 64 pixels at the same time.

Pixel Time Center by Laser





- DS, US pixel

  (1 example from each sector)

- Averaged all the pixels

$$\frac{1}{n}\sum T_{\mathrm{ofs}}^{\mathrm{pixel}}(t) =: \bar{T}_{\mathrm{ofs}}(t)$$

$$\mathrm{STDDev} = \sqrt{\frac{1}{n}\sum (T_{\mathrm{ofs}}^{\mathrm{pixel}}(t) - \bar{T}_{\mathrm{ofs}}(t))^2}$$

shown as a measure of the **stability**

(< 10 ps from 11 Aug.)

(< 40 ps in July)

pTC Event-Time analysis

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

  $\sigma_i = \sigma(t_{\mathrm{ave}} - t_i^{\mathrm{reco}})$ **(single pixel / channel)**

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

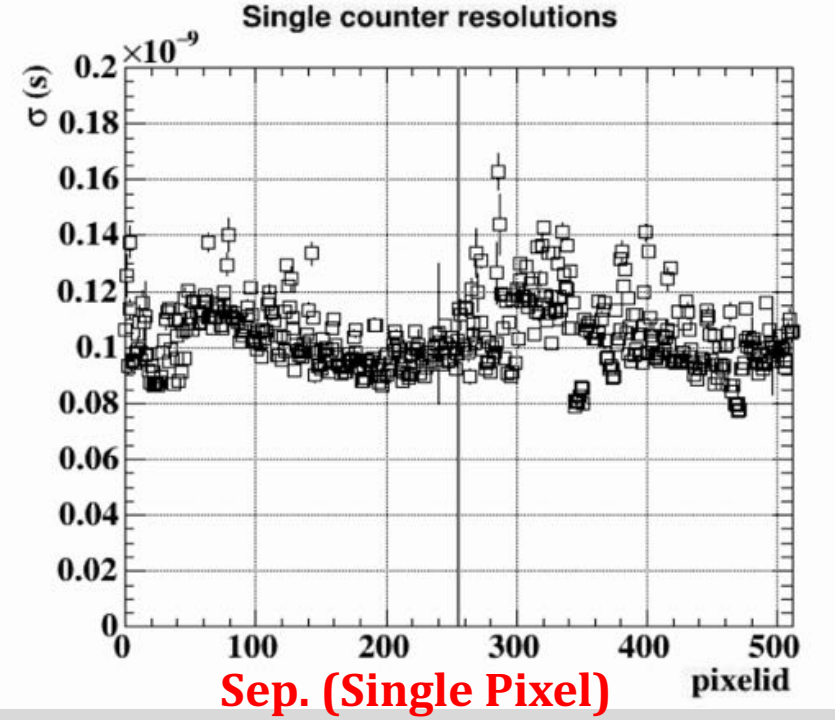
  $t_{\mathrm{odd}} := \frac{1}{n_{\mathrm{hit}}/2} \sum (t_{2i+1}^{\mathrm{reco}} - t_0^{\mathrm{reco}} - TOF_{2i+1,0})$

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

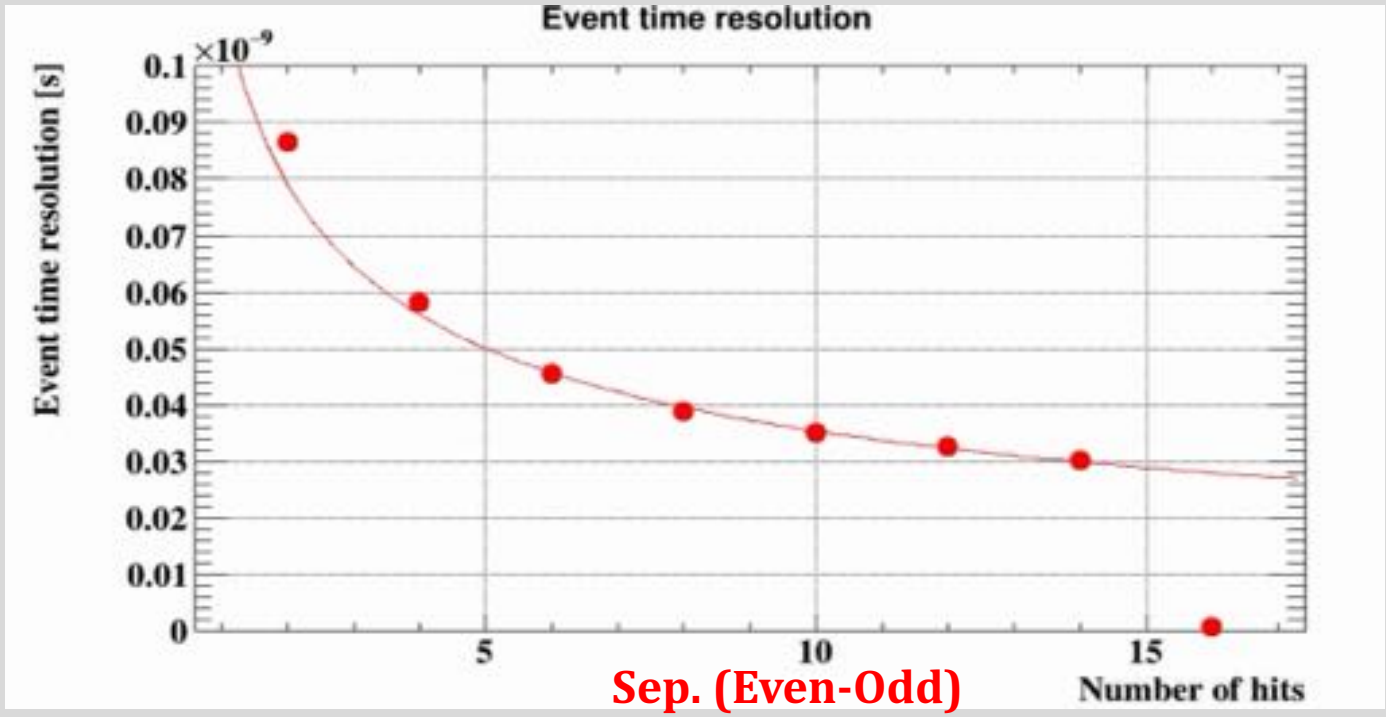
$$\sigma_{\mathrm{pTC}}^{\mathrm{Overall}} = \sum_{N_{\mathrm{hit}}} Rate(N_{\mathrm{hit}}) \times \sigma_{\mathrm{pTC}}(N_{\mathrm{hit}})$$

Resolution Evaluation in 2022

	Single Pix./Ch	1-hit (EvenOdd)	Overall (Even-Odd)
Sep.	102 ps / 132 ps	112 ps	43.5 ps
Oct. (3e7)	102 ps / 132 ps	113 ps	43.8 ps
Nov. (4e7)	102 ps / 133 ps	114 ps	44.2 ps
Nov. (5e7)	102 ps / 133 ps	114 ps	44.5 ps



Sep. (Single Pixel)



Sep. (Even-Odd)

Conclusion

- MEG II pixelated TC performed the event time resolution in 2022

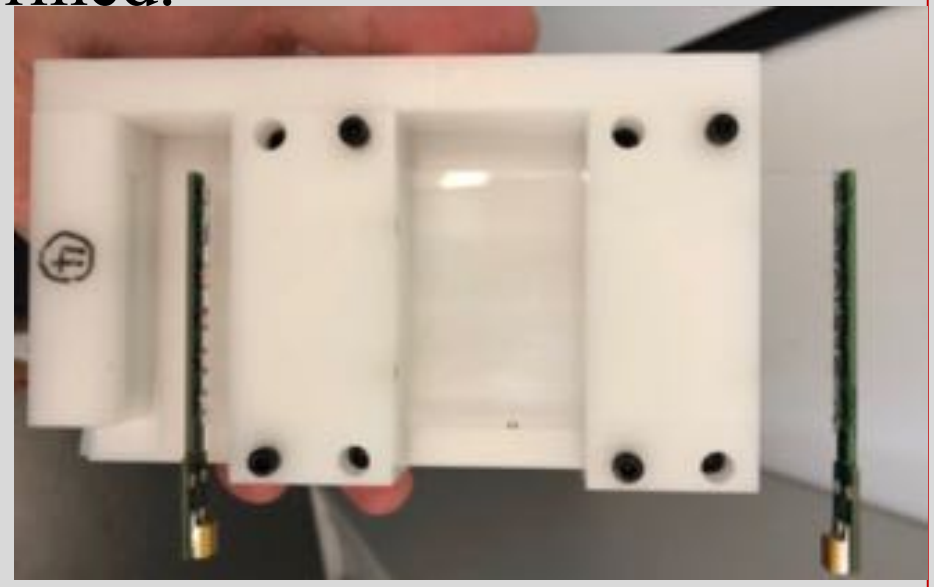
  $\overline{N_{\mathrm{hit}}} = 9$: 37 ps

  Overall Estimation : 44 ps

- Increment of the SiPM dark currents which reflects the radiation damage was found to be seriously accumulated.

Future prospect

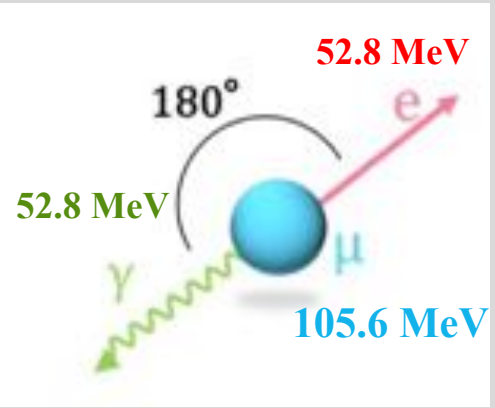
- Refurbishment of pTC is decided to be performed.
  - ➢ with 100 new pixels.
  - ➢ Assembly & Test ongoing.
  - ➢ Planned to be replaced after ‘23 run.



- Improvement and refinement on analysis algorithms.
  - ➢ weight on resolution of each pixel / channel by N_{photon}

Back up

MuEGamma Decay

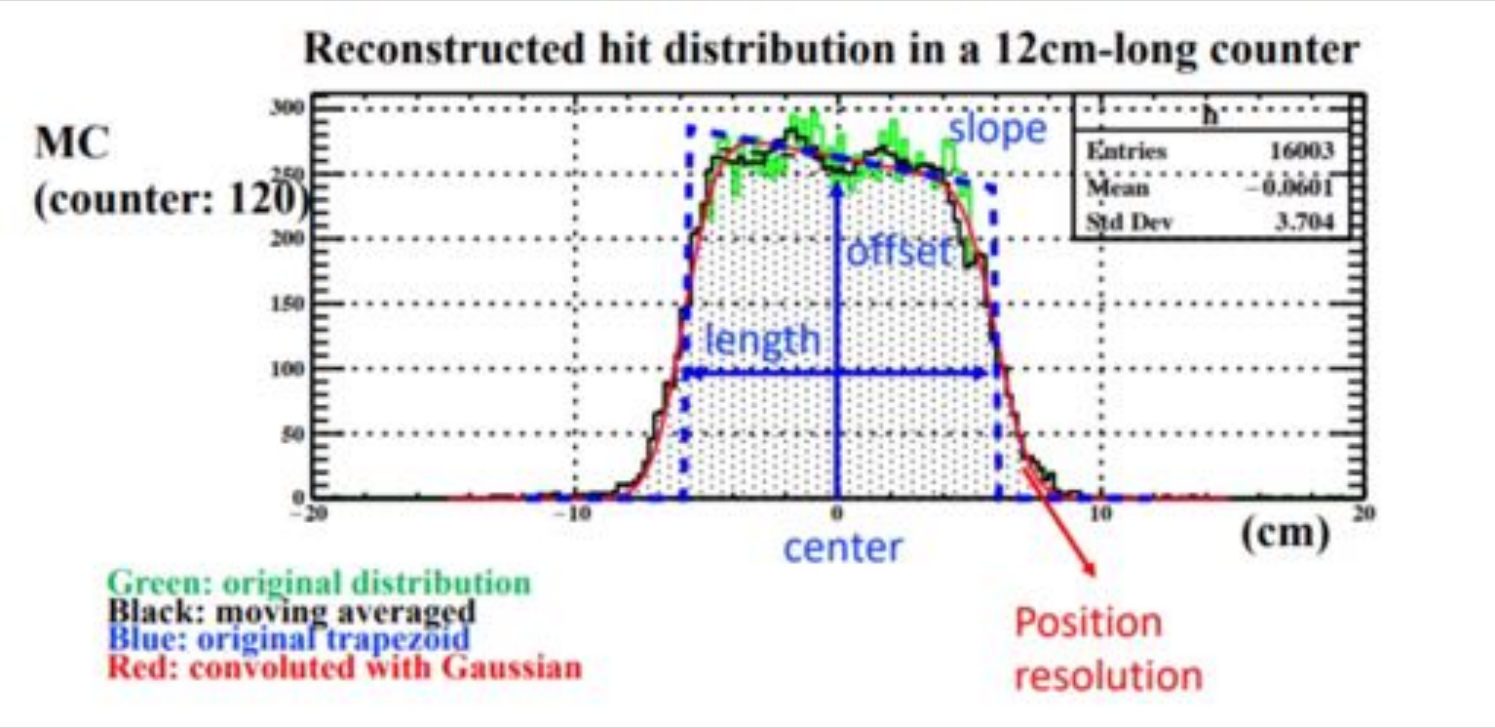


- One of charged lepton flavor violating (cLFV) decays, which is forbidden in the Standard Model.

- 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: $\mathcal{B}(\mu \rightarrow e\,\gamma) < 4.2 \times 10^{-13}$ (90% C.L.)

SPXPositionCalibration



5 parameters (initial value)

p0: center (μ)
p1: length (FWHM)
p2: height (linear const. b)
p3: slope (linear const. a)
p4: sigma (σ)

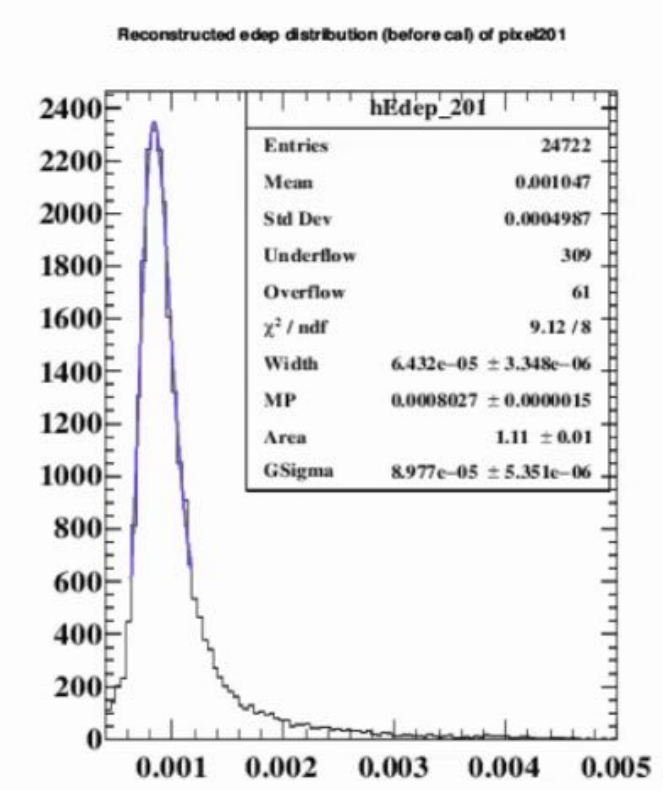
1. Moving average for the mean of the histogram $\pm$ 5 cm
2. Linear fit to the MAv histogram. (a * (x $-$ μ) + b)
3. Least square for the convolution of the linear function & a gaussian

SPXEnergyCalibration

$$C_{\text{Energy scale}} = \frac{E_{\text{MC}}^{\text{mean}}}{\sqrt{Q_{\text{ch1}}^{\text{MPV}} Q_{\text{ch2}}^{\text{MPV}}}}$$

explicitly $\sqrt{\left(E_{\text{MC}}^{\text{mean}}\right)^2}$

* Geometrical mean gives a better energy deposit reconstruction than an arithmetic mean, found in the past study.



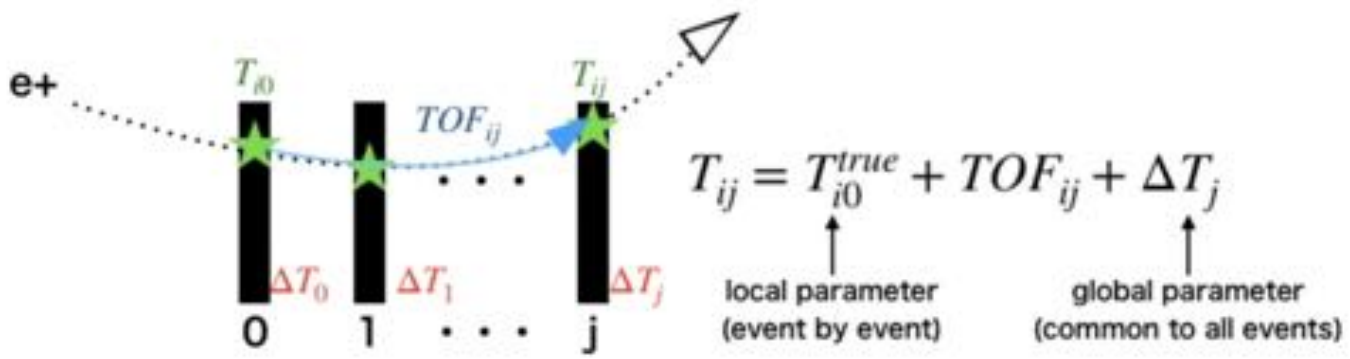
- The most probable energy loss (MPV; the peak of landau-gauss dist.) for each counter is adjusted to the $E_{\text{MC}}^{\text{mean}}$.

  $E_{\text{MC}}^{\text{mean}} = 0.085$ MeV is used now, as the MC mean of all the pix.

- Difference in incident angle (mostly depending each location) is ignored.

SPXTimeCalibration / Michel calibration; MiCa

$$\chi^2 = \Sigma_i^{event} \Sigma_j^{hit} \left(\frac{T_{ij} - (T_{i0}^{true} + TOF_{ij} + \Delta T_j)}{\sigma} \right)^2$$



1. config/offline_second_MiCa.xml -> loose clustering data
   - only SPXMichelCalibration task
     - Track selection, make 'Mille' file (.bin)
     - SPXmethod, GL Parameter, … are SPs.

2. Run 'Pede' for calculate to time offset.

millepedeII/

|-- Mille.cc
|-- Mille.h

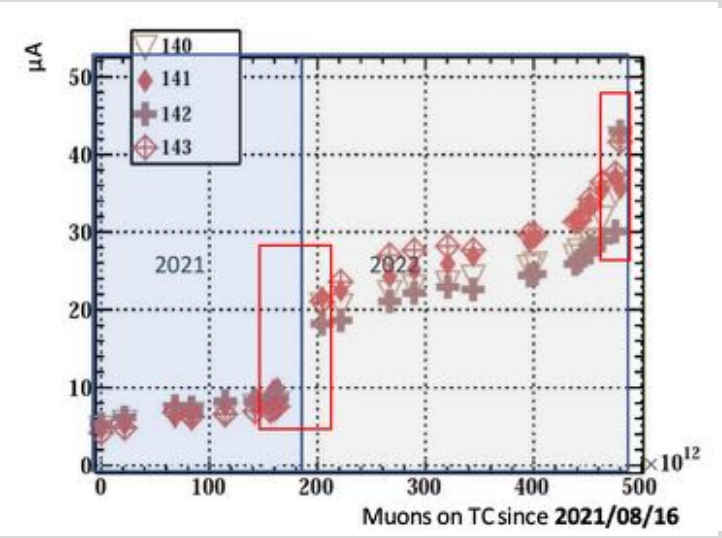
Mille to make binary file ~.bin .
(in macro, #include<Mille.cc>)

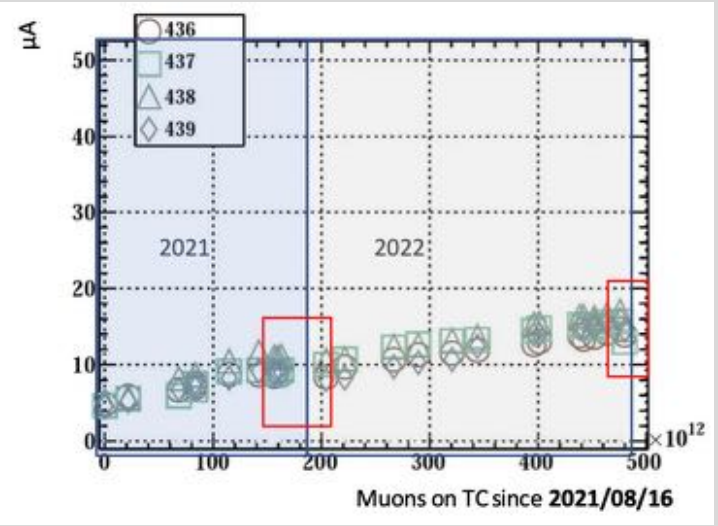
`-- others → Pede to optimize data as the matrix
(= solve the linear least squares)

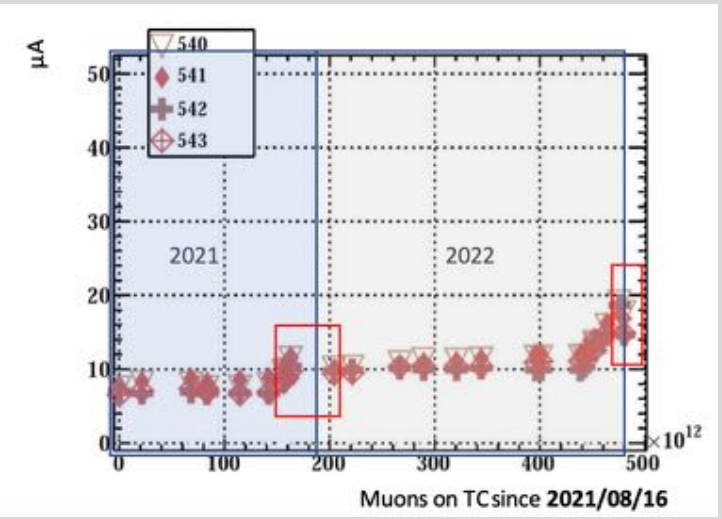
3. z-phi, US-DS correction with the laser calibration result.

4. Need 1 iteration for "not loose" clustering

Dark currents(1)







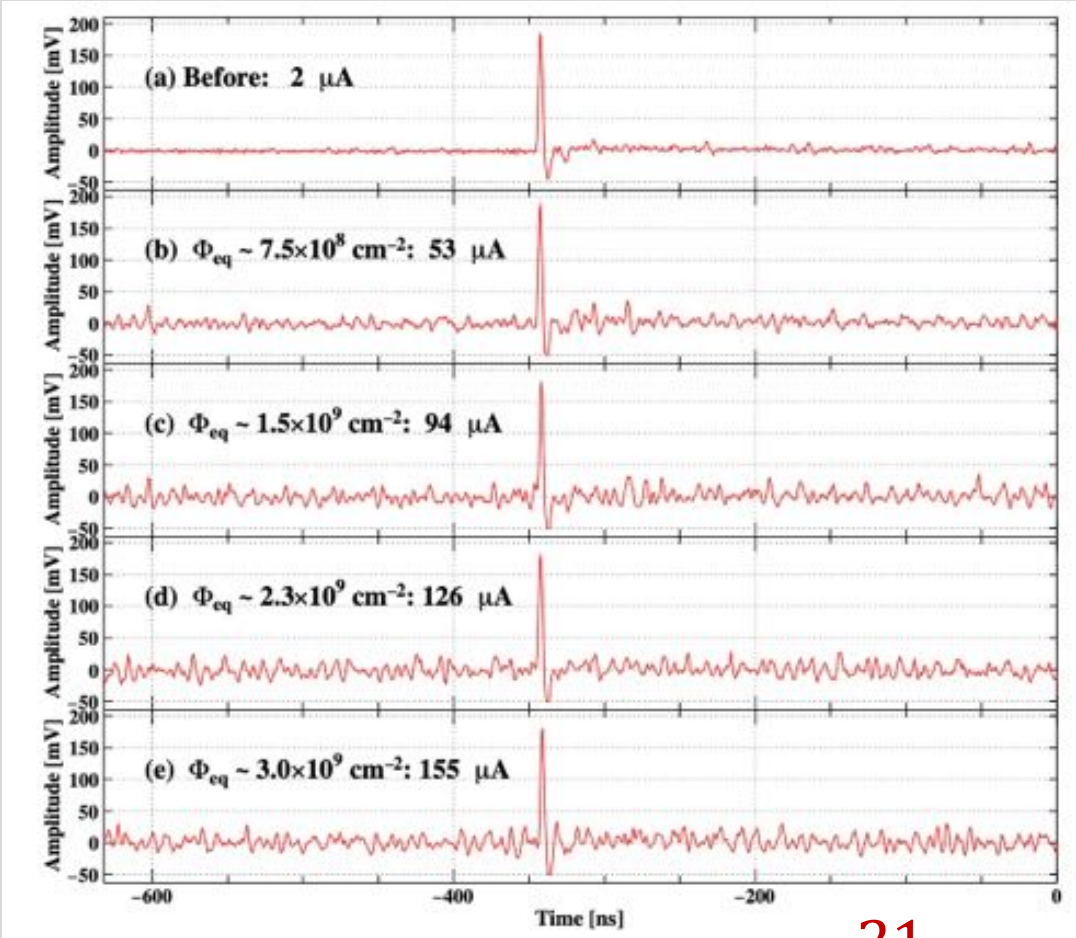
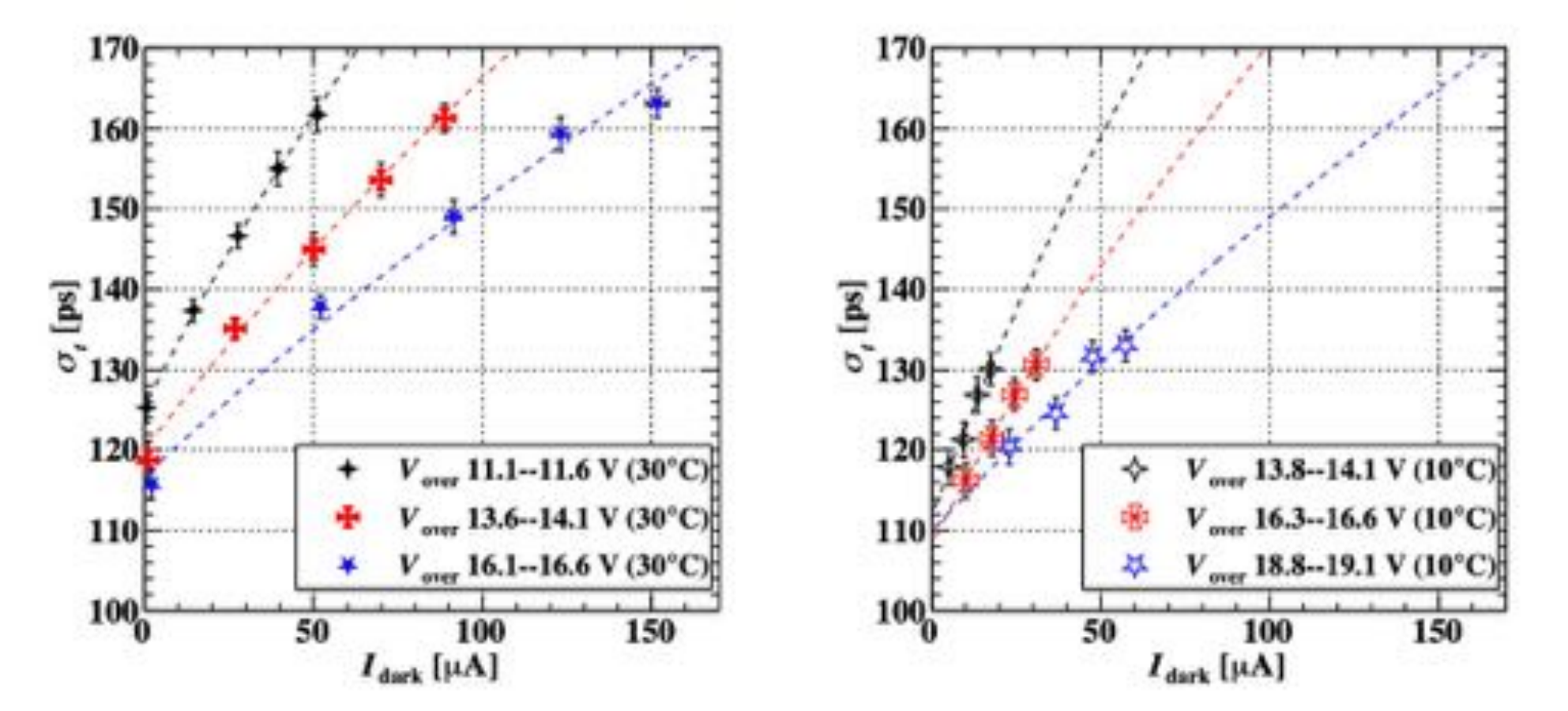


Fig. 3.5: The example of the waveform at each damage level.

Dark currents(2)



10 uA increment means < 10 ps effects on σ

pTC Time Center variation

Item	Coefficients (ps/K)	Effect
Fibre (2.5 m)	+0.45 ± 0.02	+
Fibre (10 m)	+1.00 ± 0.04	+
Optical splitter	+0.24 ± 0.11	+
Scintillator counter	+1.24 ± 0.04	+
Counter signal cable	−4.1 ± 0.1	−
SYNC signal cable	−0.08 ± 0.02	+
Total	−1.3 ± 0.2	−

”The laser-based time calibration system for the MEG II pixelated Timing Counter”

https://elog.psi.ch/elogs/Publication+List/134

Thermal expansion/shrink cannot fully explain the time variation.

- ± 1°C makes 1.3 ps difference for optical components.

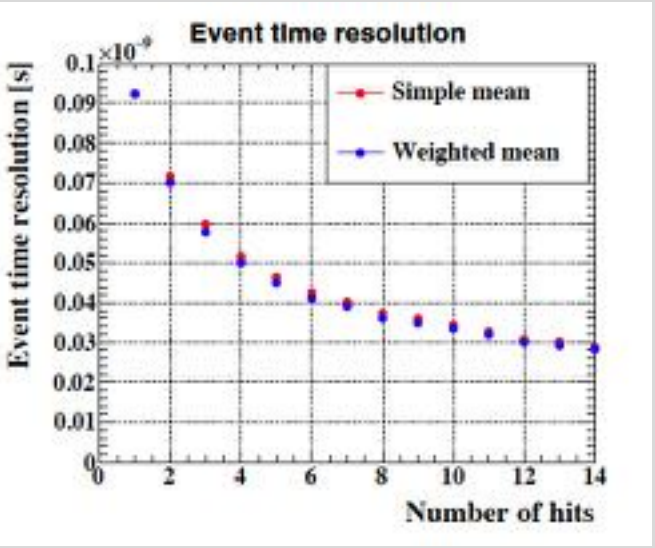
- The reported reproducibility ~11 ps

  -> some agreement

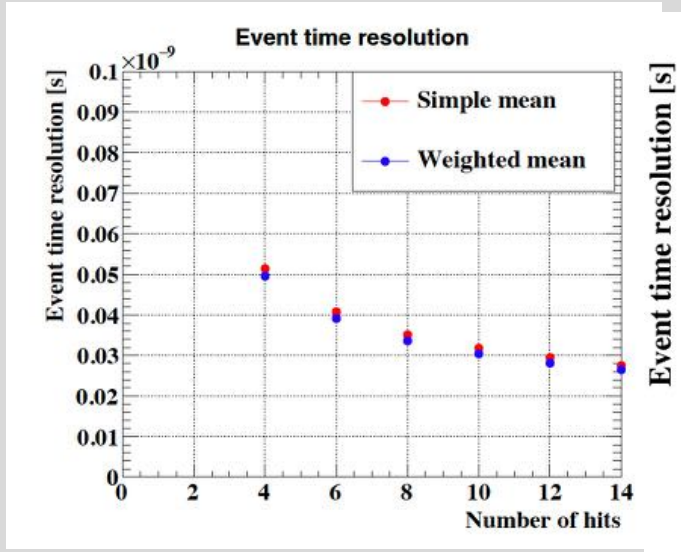
Time Correction Studies

Apply a weight by $1/\sigma^2$ on each channel (for v,w) and each pixel (for E)

preliminary

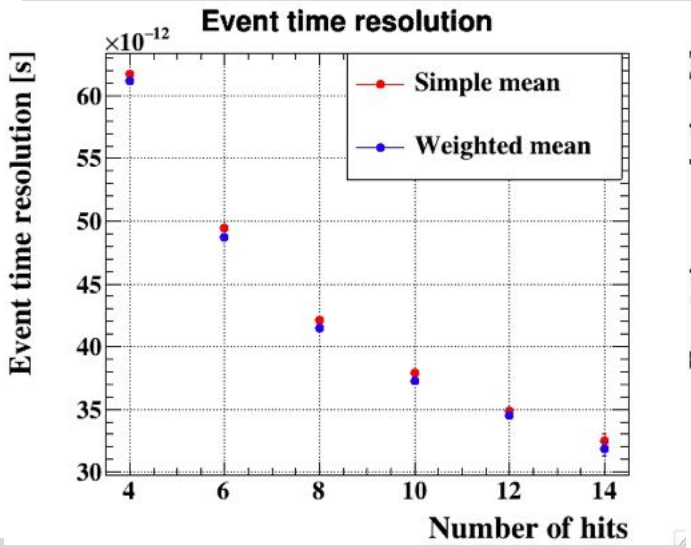


Kosuke (MC, 2019)

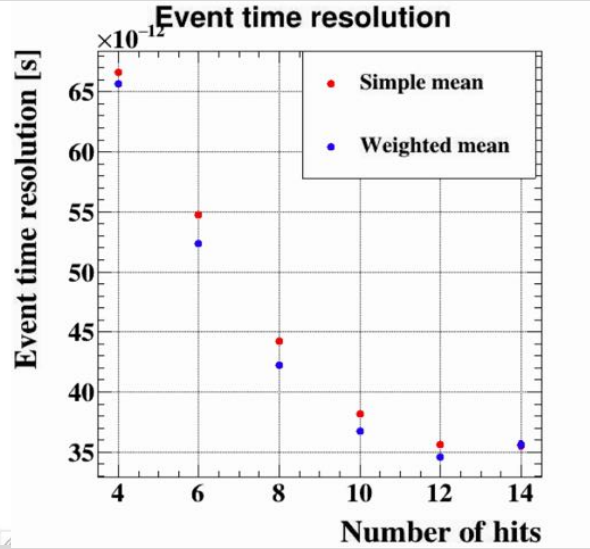


Kosuke ('17 commissioning, 2019)

JPS 2019 annual



Taku ('19 commissioning, 2021)



Taku ('22 MuEGamma, 2023)

JPS 2021 autumn