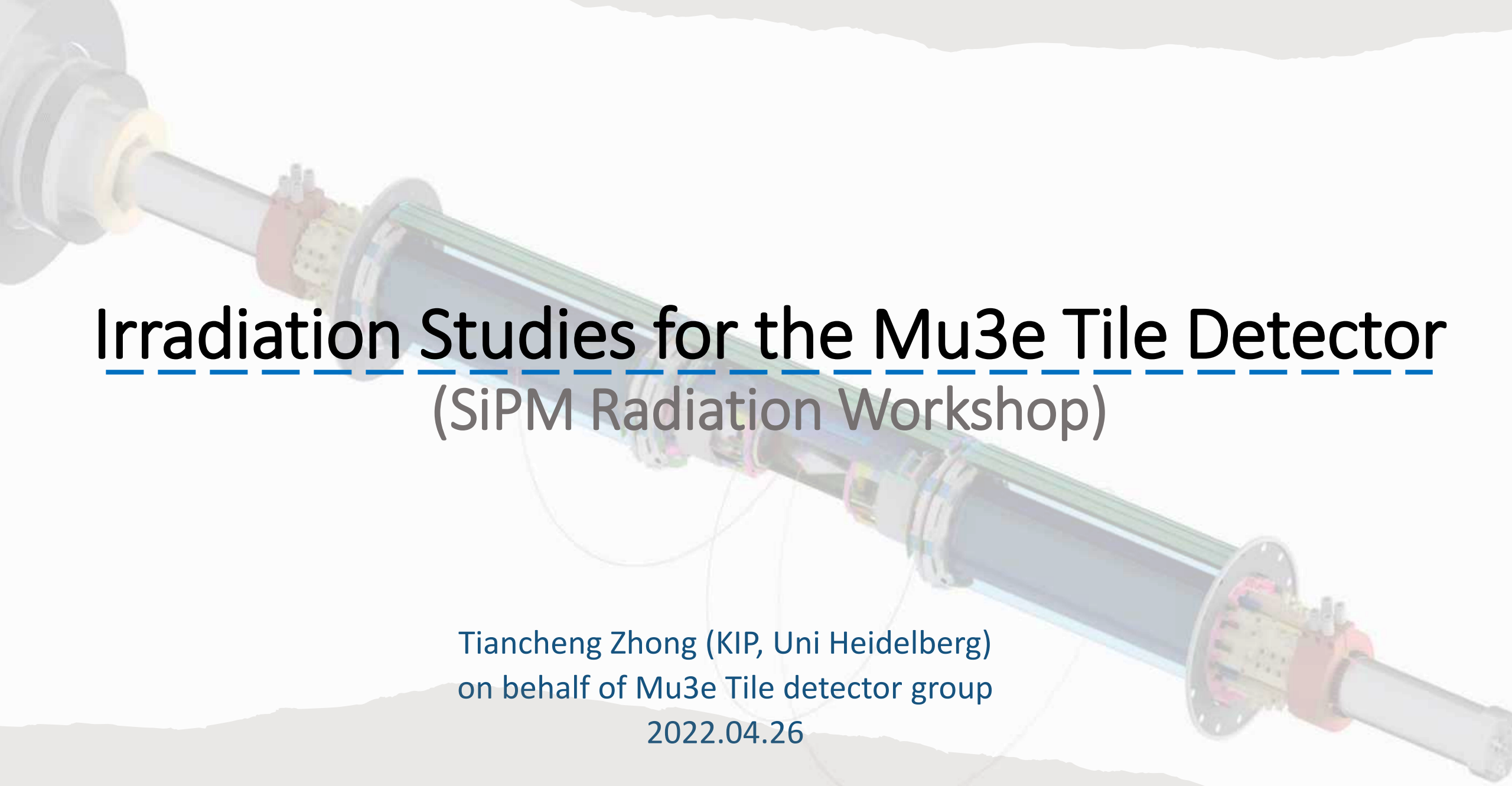


Irradiation Studies for the Mu3e Tile Detector

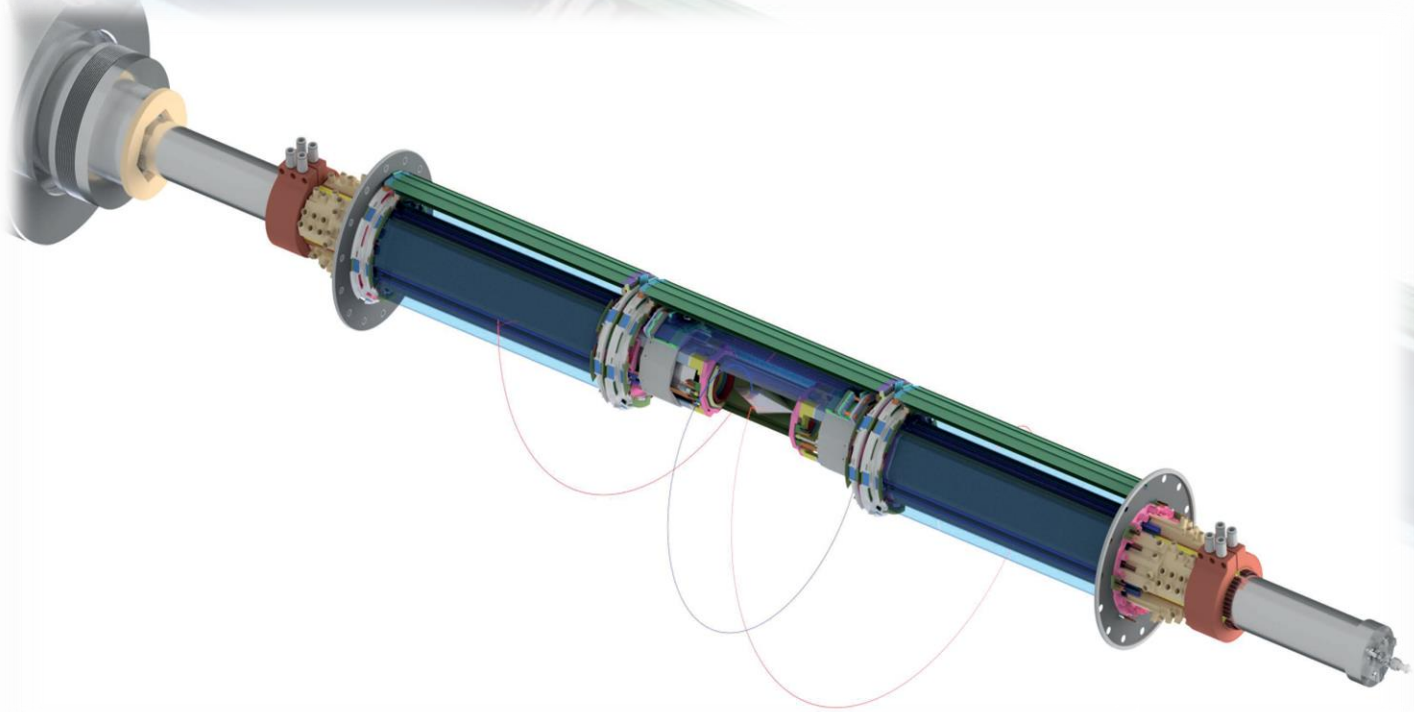
(SiPM Radiation Workshop)

Tiancheng Zhong (KIP, Uni Heidelberg)
on behalf of Mu3e Tile detector group

2022.04.26

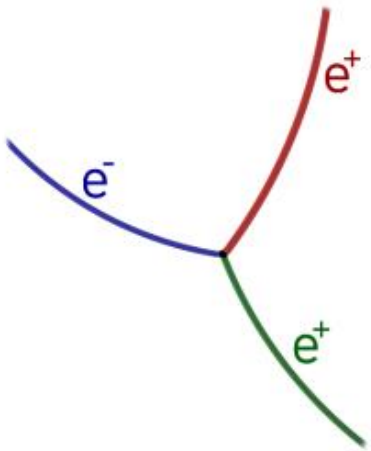
The Mu3e Experiment

- motivation: searching for $\mu^+ \rightarrow e^+e^+e^-$ (charged Lepton Flavor Violation decay)
  => would be a clear sign for new physics (SM: $B_{\mu\rightarrow 3e} < 10^{-50}$)
- goal: push upper limit of $B_{\mu\rightarrow 3e}$ to 10^{-16}(Current: 10^{-12} from SINDRUM, 1988)
- stopping target experiment at PSI in Switzerland (highest rate in the world: $\sim 10^8$ muon/s)



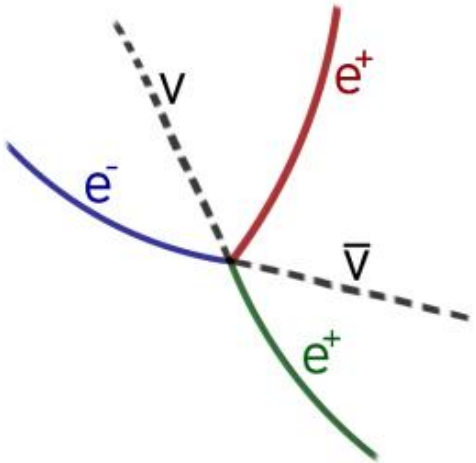
Signal and Background

Signal



$$\sum E_e = m_\mu \, , \sum \vec{p}_e = 0$$

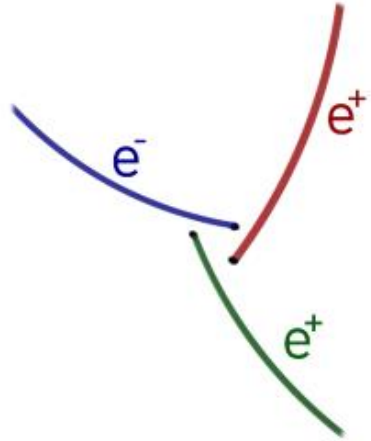
Internal conversion background



$$\sum E_e < m_\mu \, , \sum \vec{p}_e \neq 0$$

Good **momentum measurement**

Accidental background



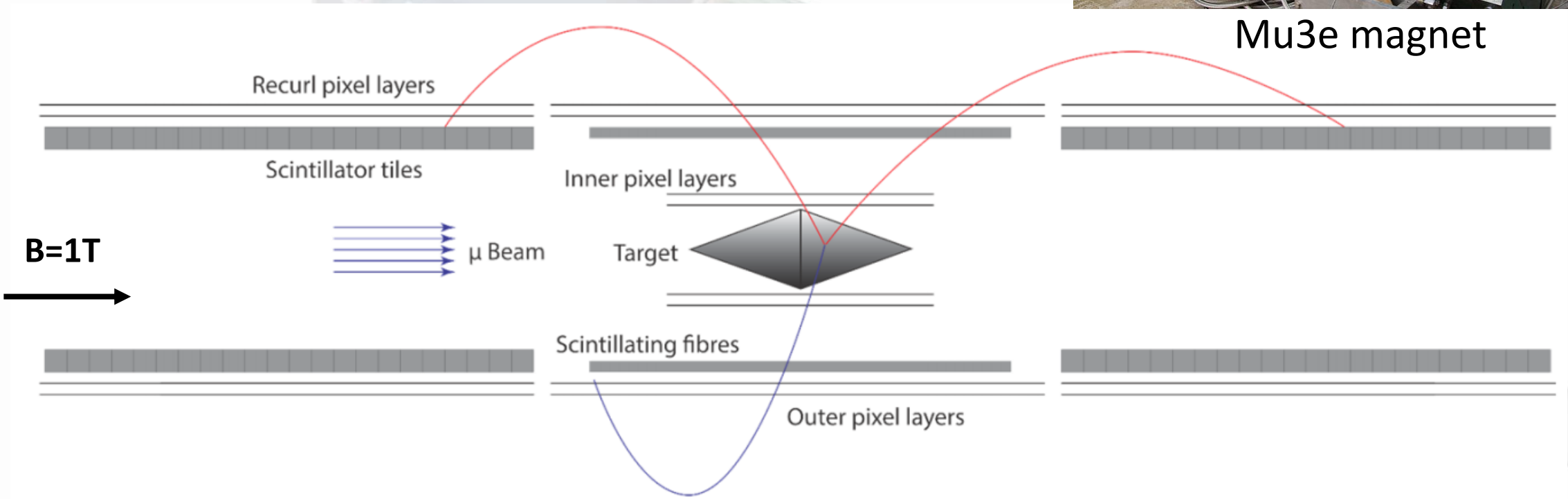
$$\sum E_e \neq m_\mu \, , \sum \vec{p}_e \neq 0$$
$$t_1 \neq t_2 \neq t_3, \vec{r}_1 \neq \vec{r}_2 \neq \vec{r}_3$$

Good **time** and **vertex measurement**

Detector Design

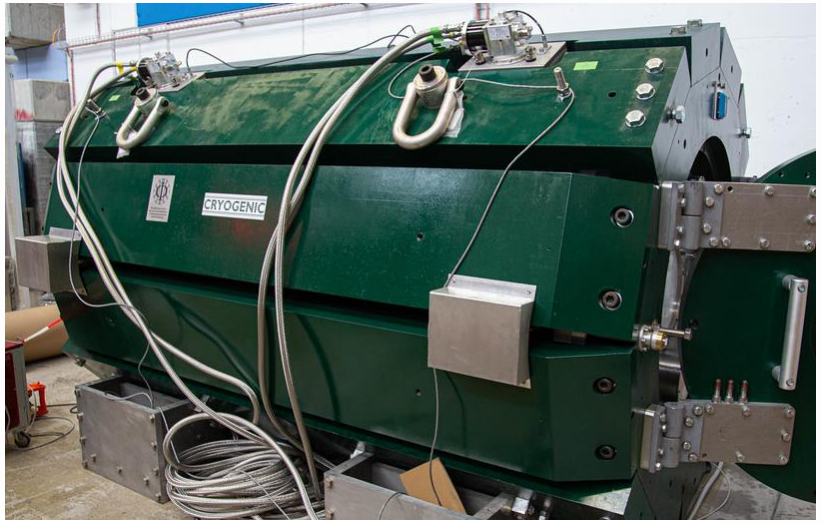
- located in B field: 1T

Mu3e magnet

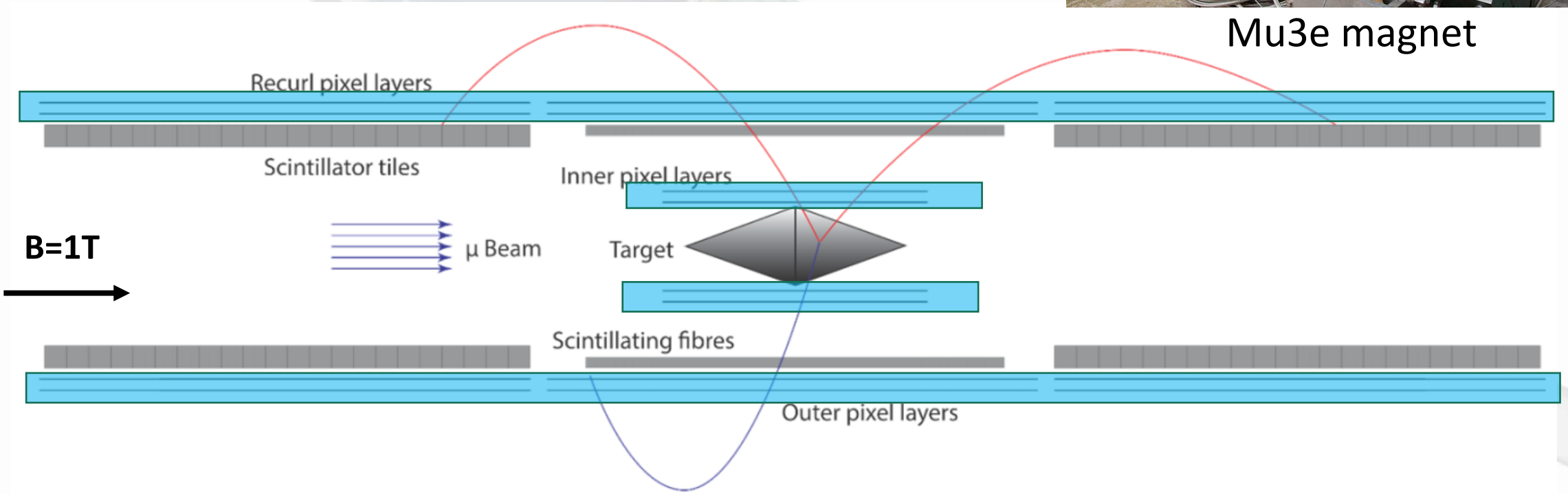


Detector Design

- located in B field: 1T
- pixel detector:
  - good **momentum** and **vertex** measurement



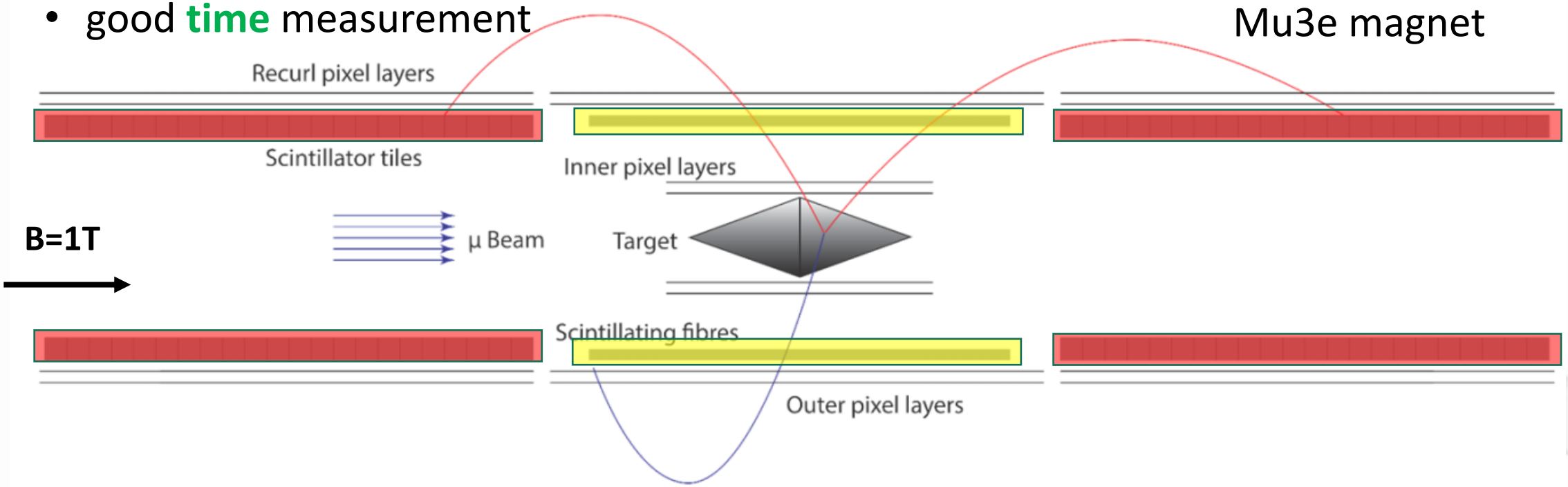
Mu3e magnet



Detector Design

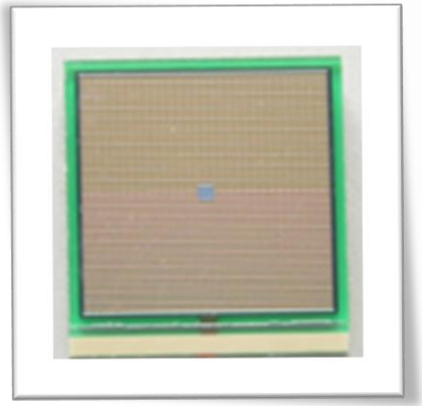
- located in B field: 1T
- pixel detector:
  - good **momentum** and **vertex** measurement
- fiber and Tile detector:
  - good **time** measurement

Mu3e magnet

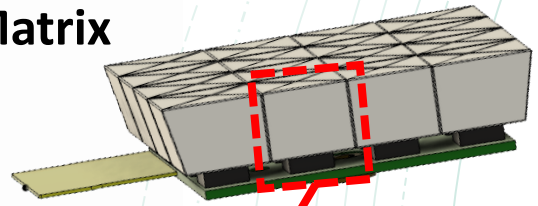


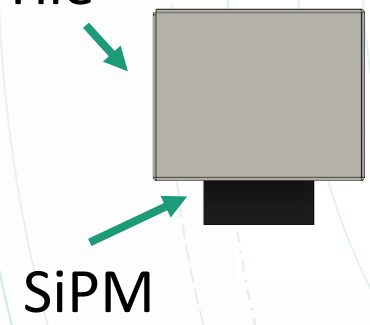
Mu3e Tile Detector

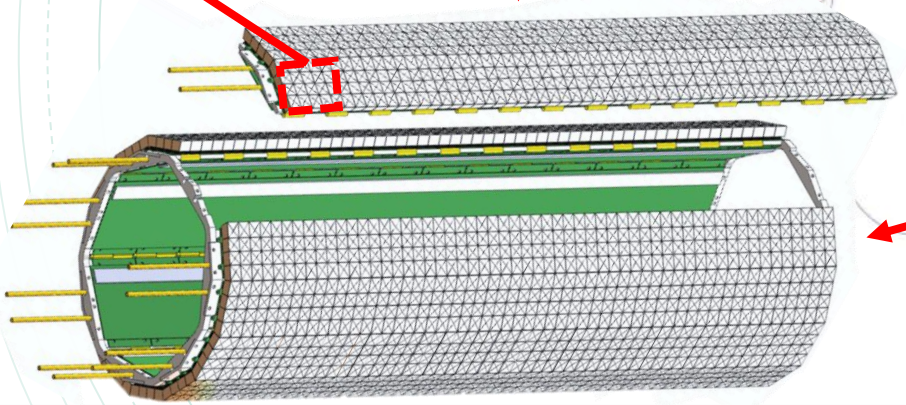
For **background suppression**:
timing resolution: **<100ps** (@~100% efficiency)



Hamamatsu S13360-3050VE

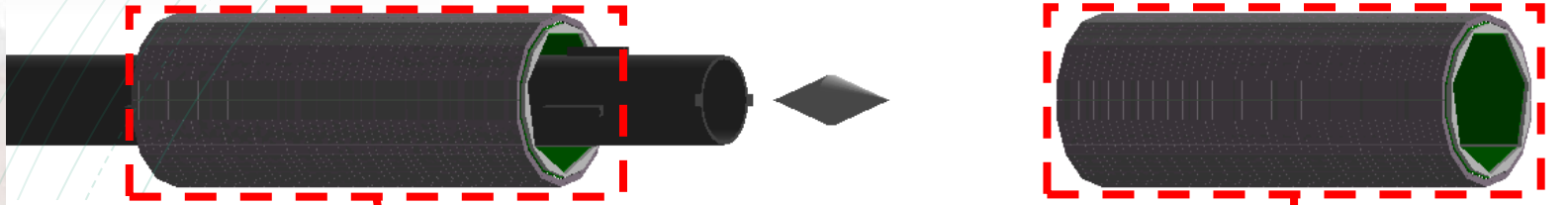




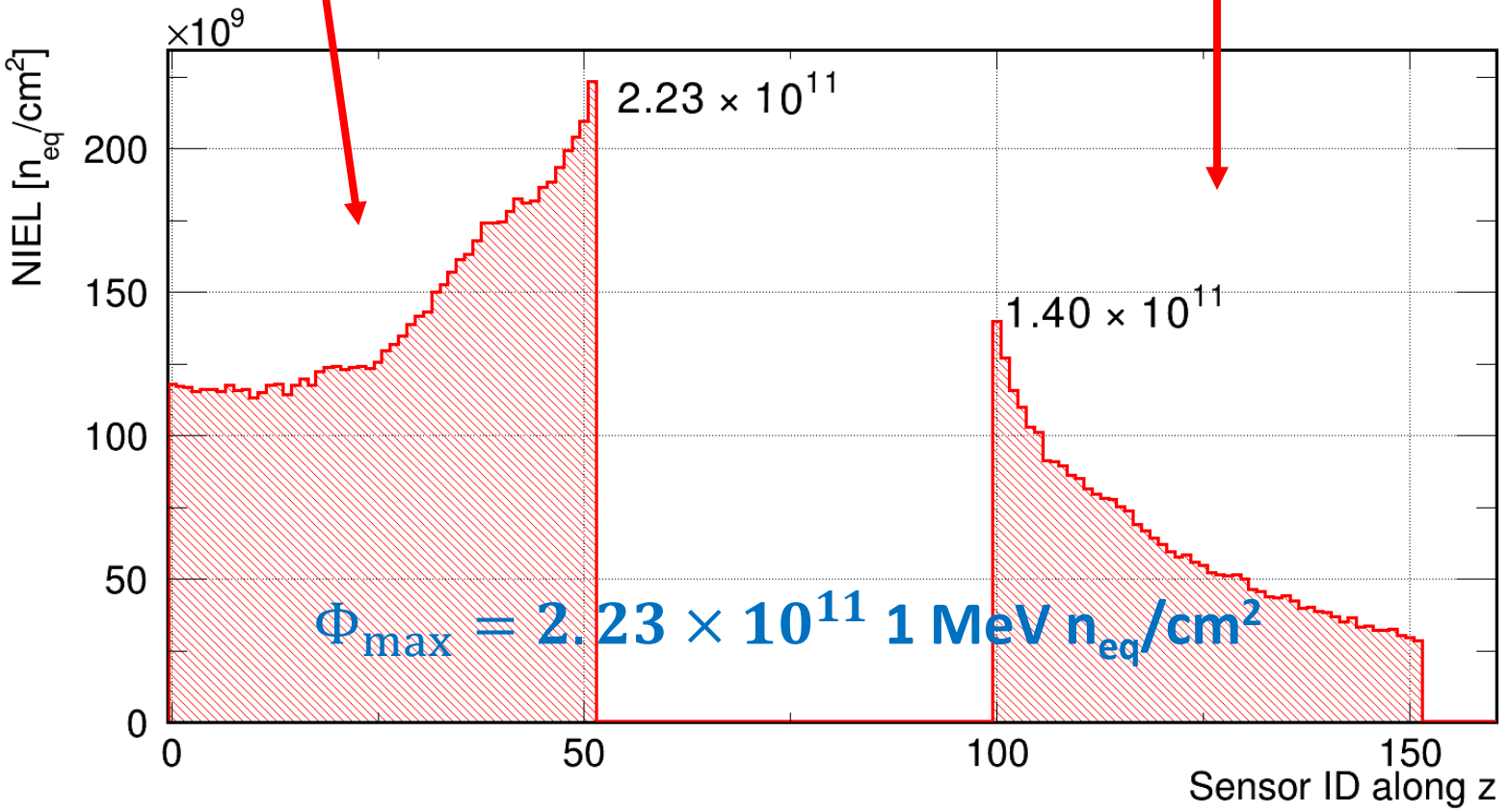


Irradiation in the Mu3e Tile detector

Muon beam

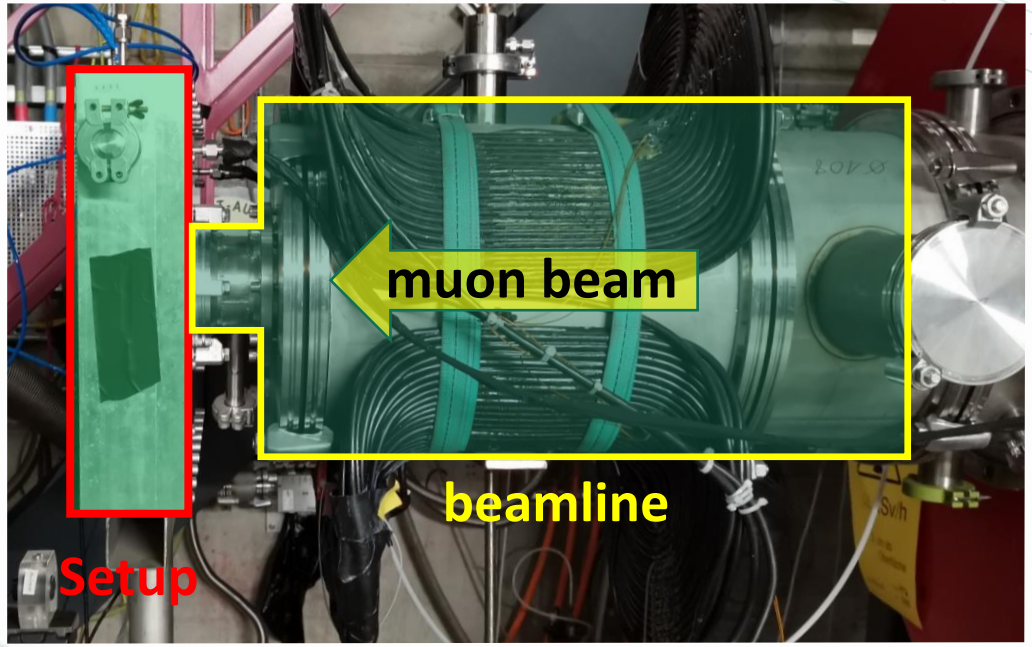


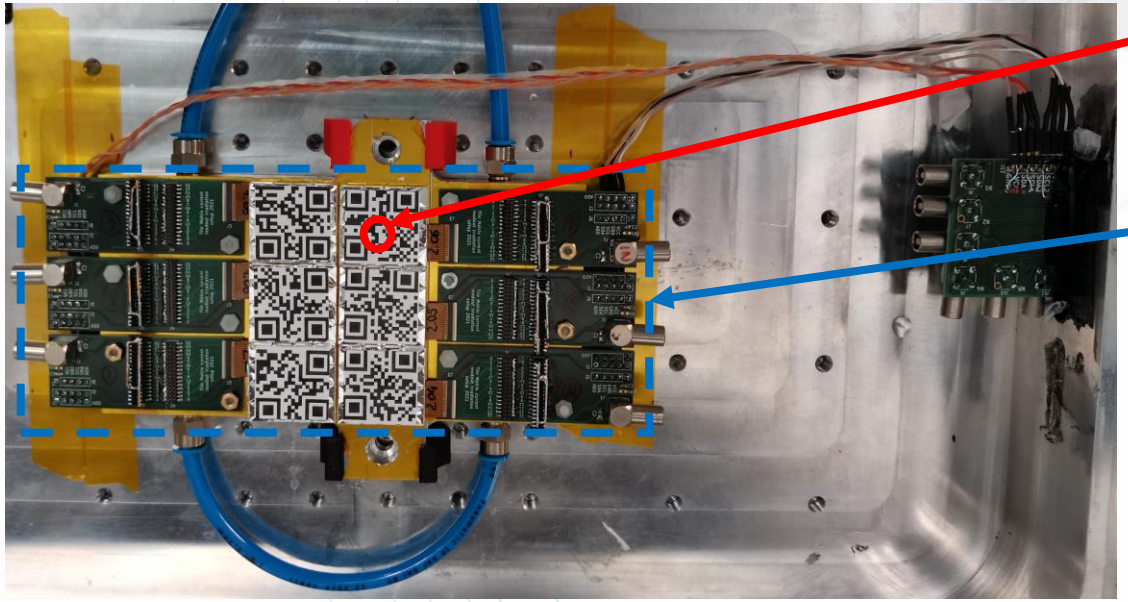
GEANT4 simulation

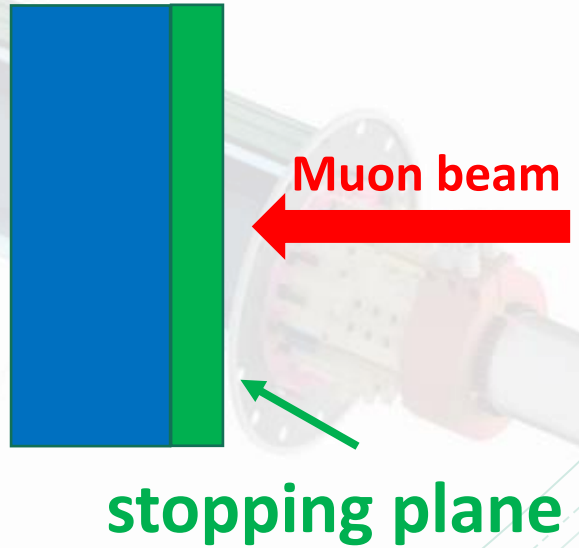


Testbeam setup

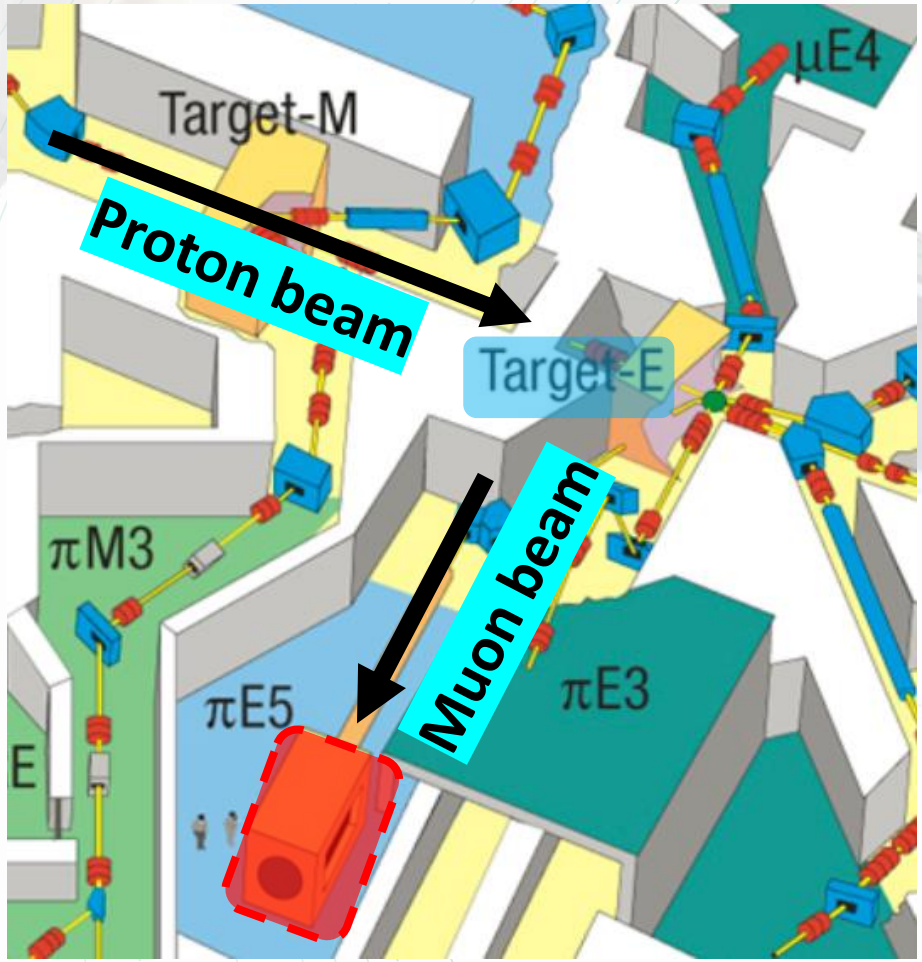
- period: 3 weeks in **April** 2021
- place: **PiE5** beam line at **PSI**
  - radiation by e^-/e^+ from Muon decay
  - **same beam line** for Mu3e experiment
- environment: water cooling @**13**℃





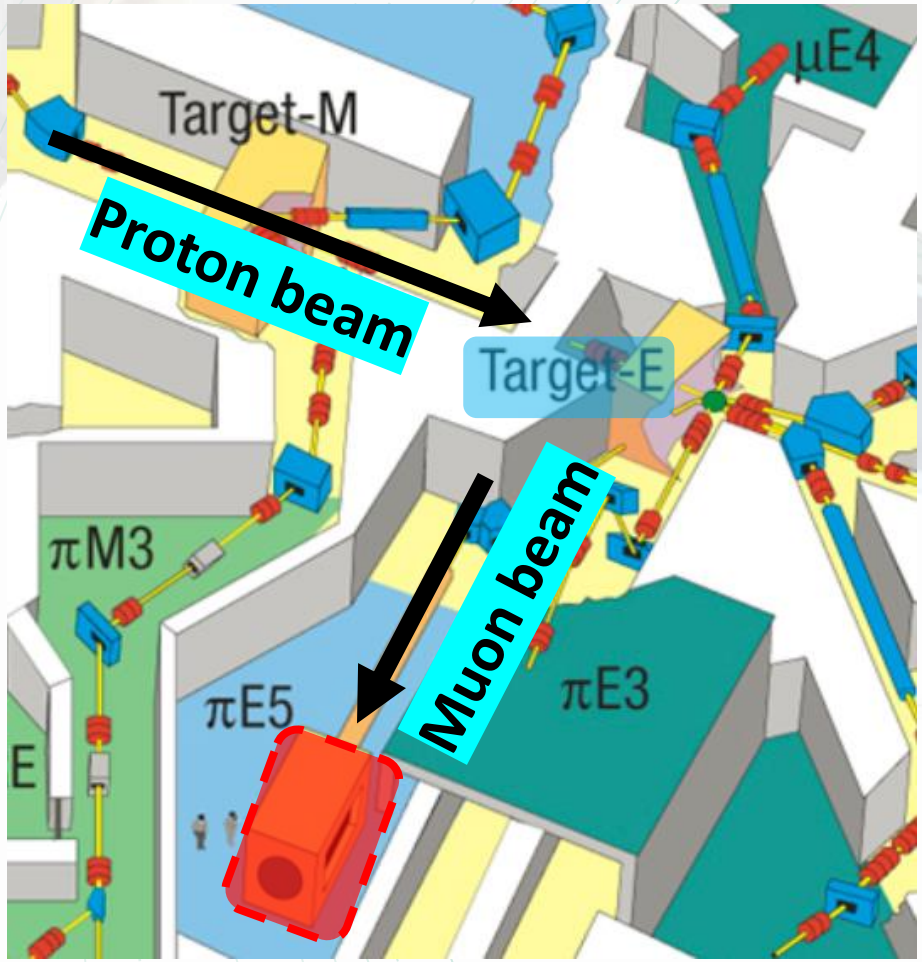


Beamline introduction



Beamline at PSI

Beamline introduction



Beamline at PSI

How much dose?

GEANT4: muon beam

No access to **muon beam** during the irradiation

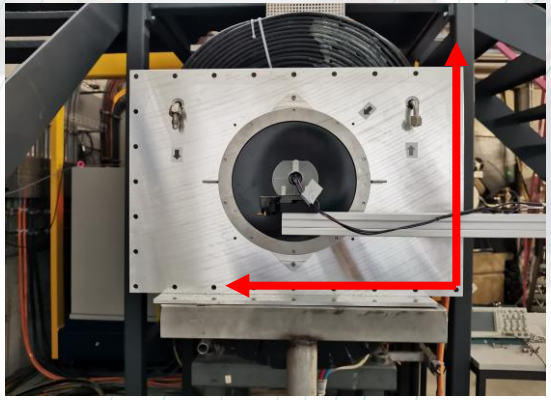
Proton beam
(during the test)

+

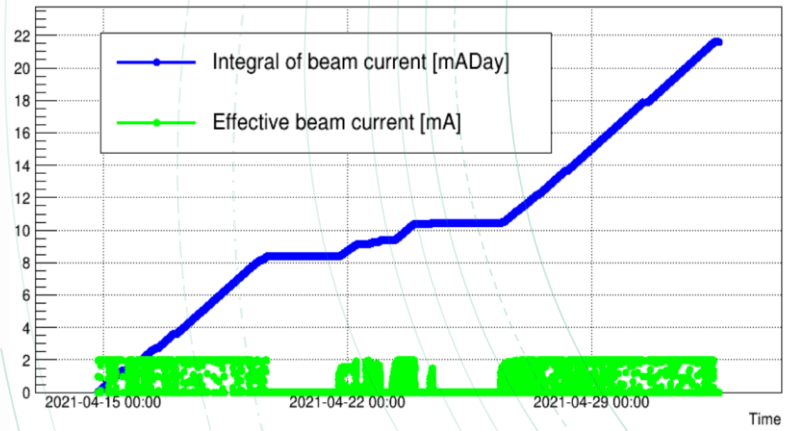
Coefficient:
Proton beam → **muon beam**
(before the test)

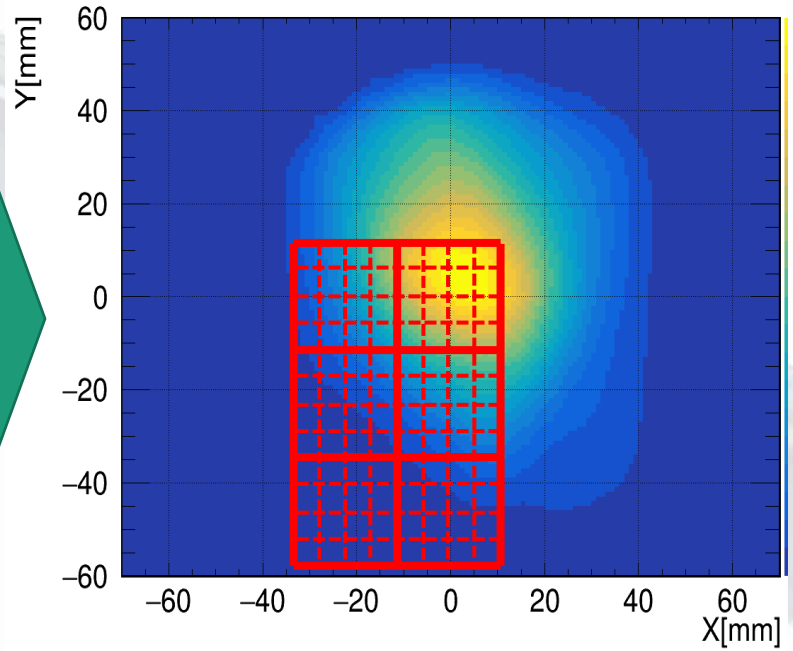
Dose estimation (testbeam)

Muon beam scan
(before irradiation)



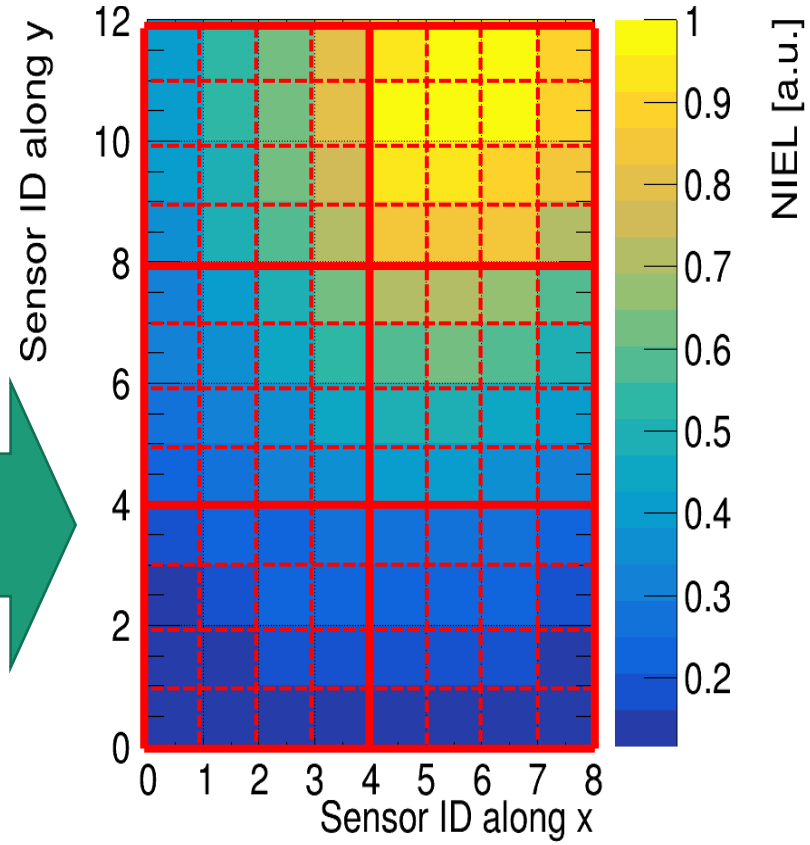
Proton beam log
(during irradiation)





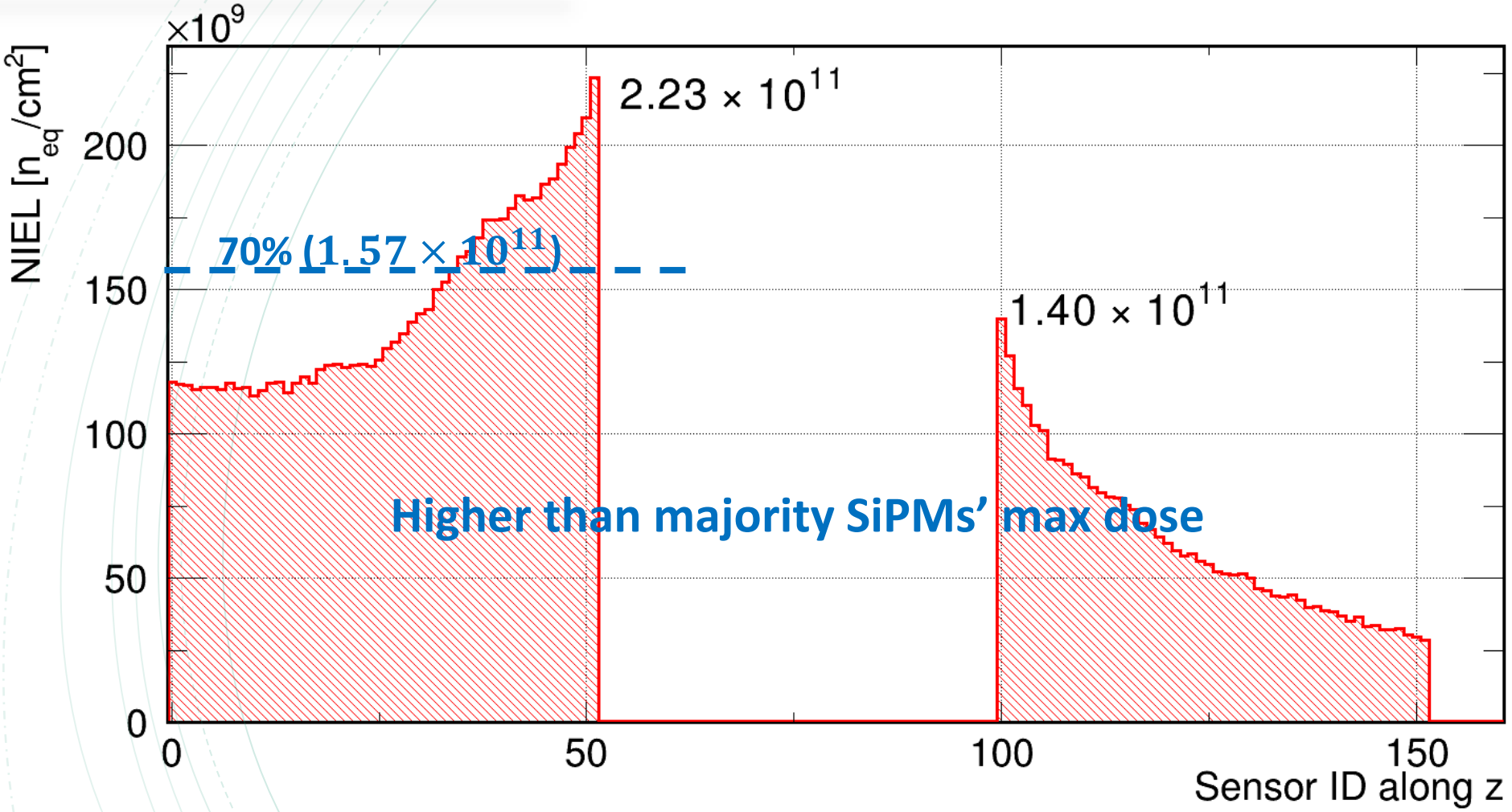
Muon beam profile
(red: position of Tile SiPMs)

Max dose: $1.57 \times 10^{11} n_{eq}/cm^2$



Dose distribution (simulation)

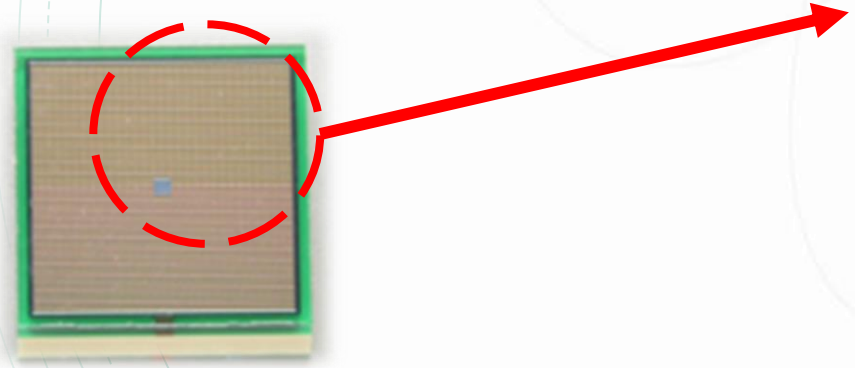
Dose estimation (testbeam)

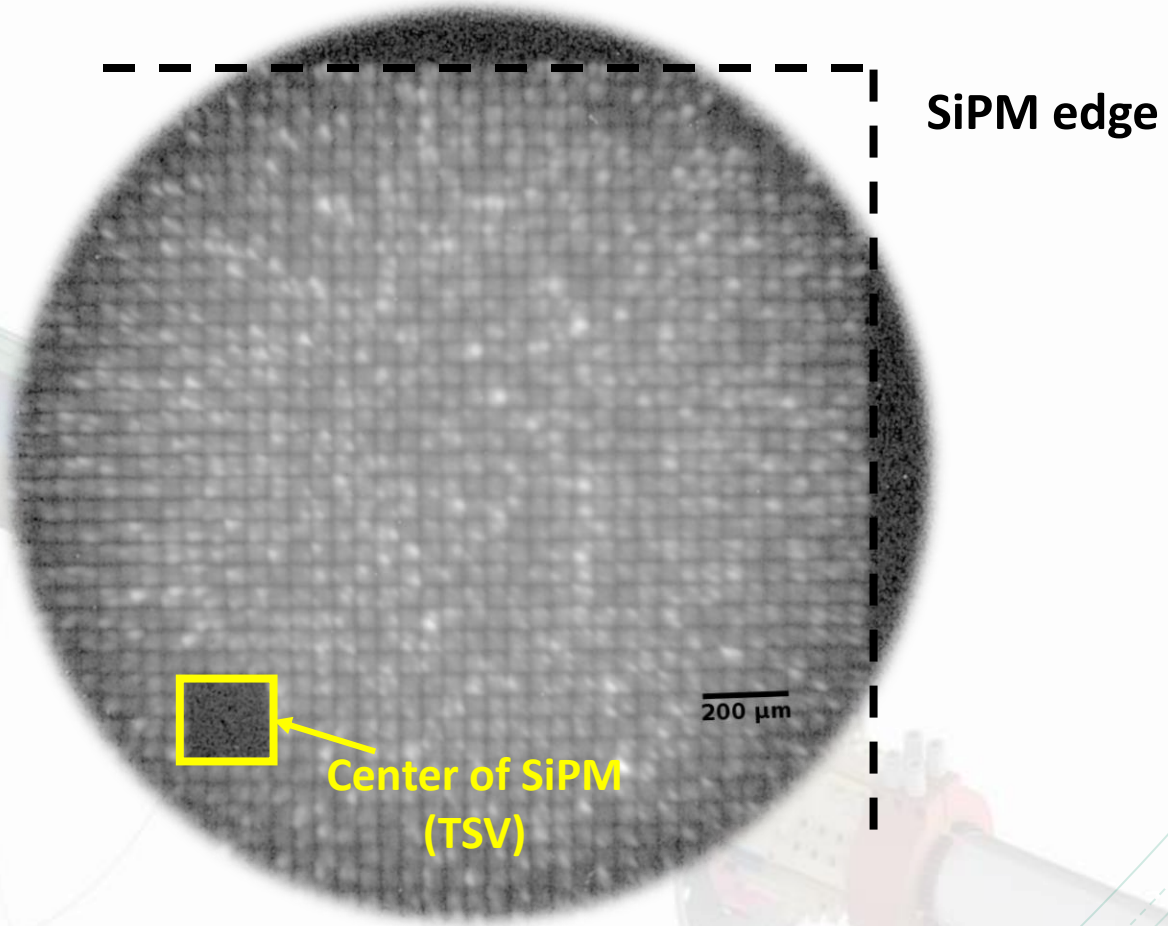


Direct look at damage distribution

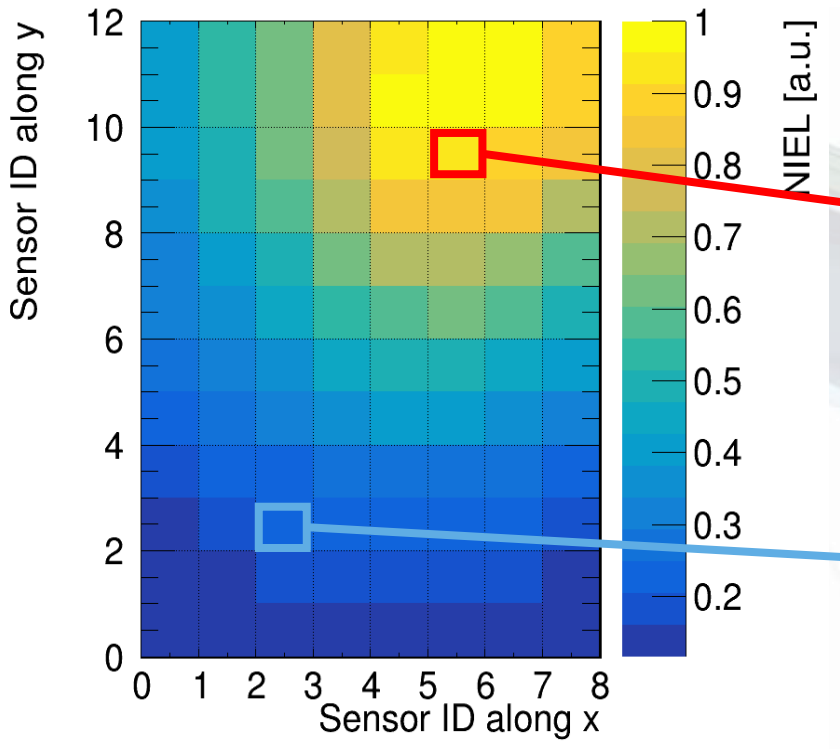
Photons from SiPM avalanche:

- low noise camera: SXVR-H18 (T: -15°C)
- scope lens amplification :X10
- SiPM: (HV=58V; water cooled @5°C)

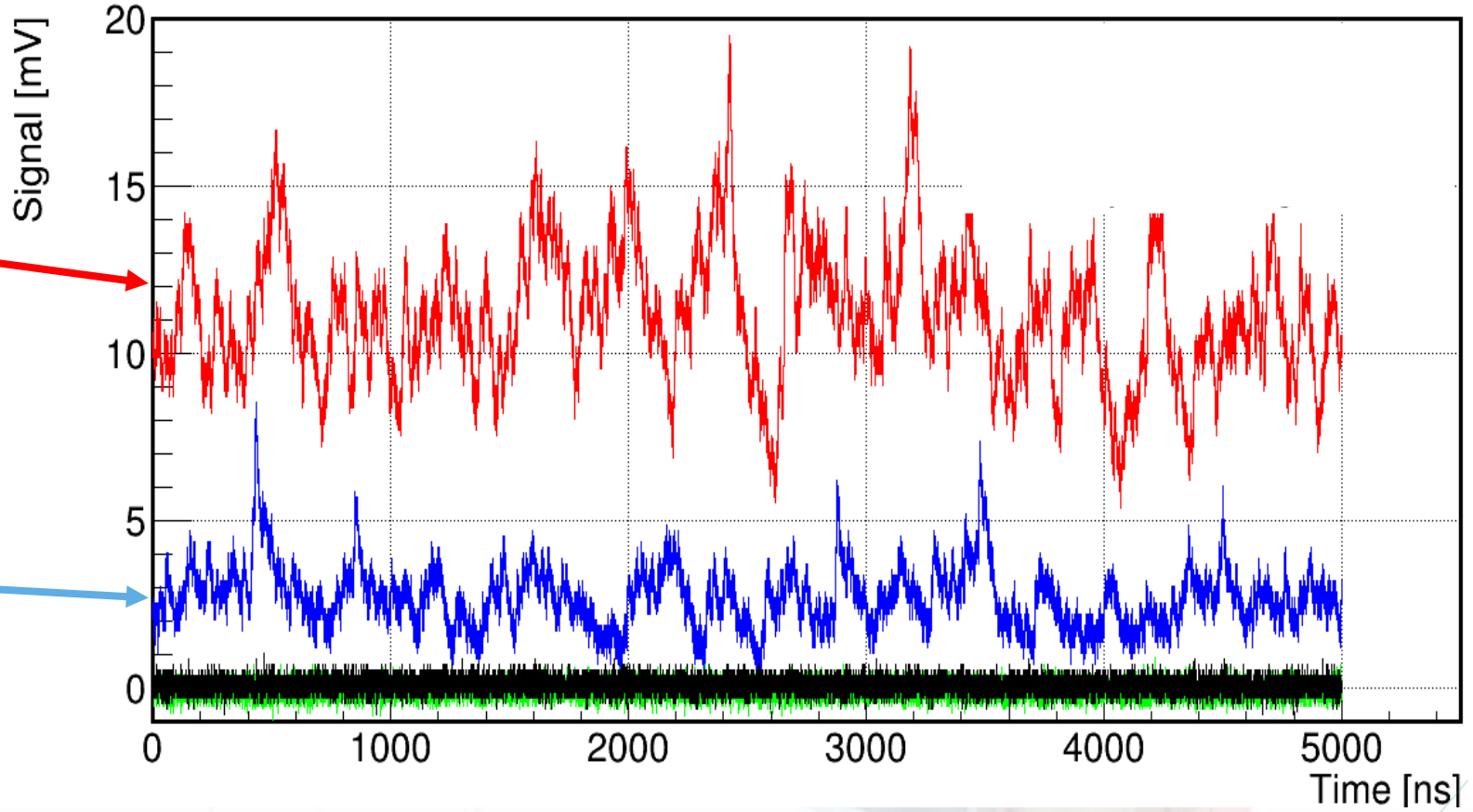




Dark signal measurement



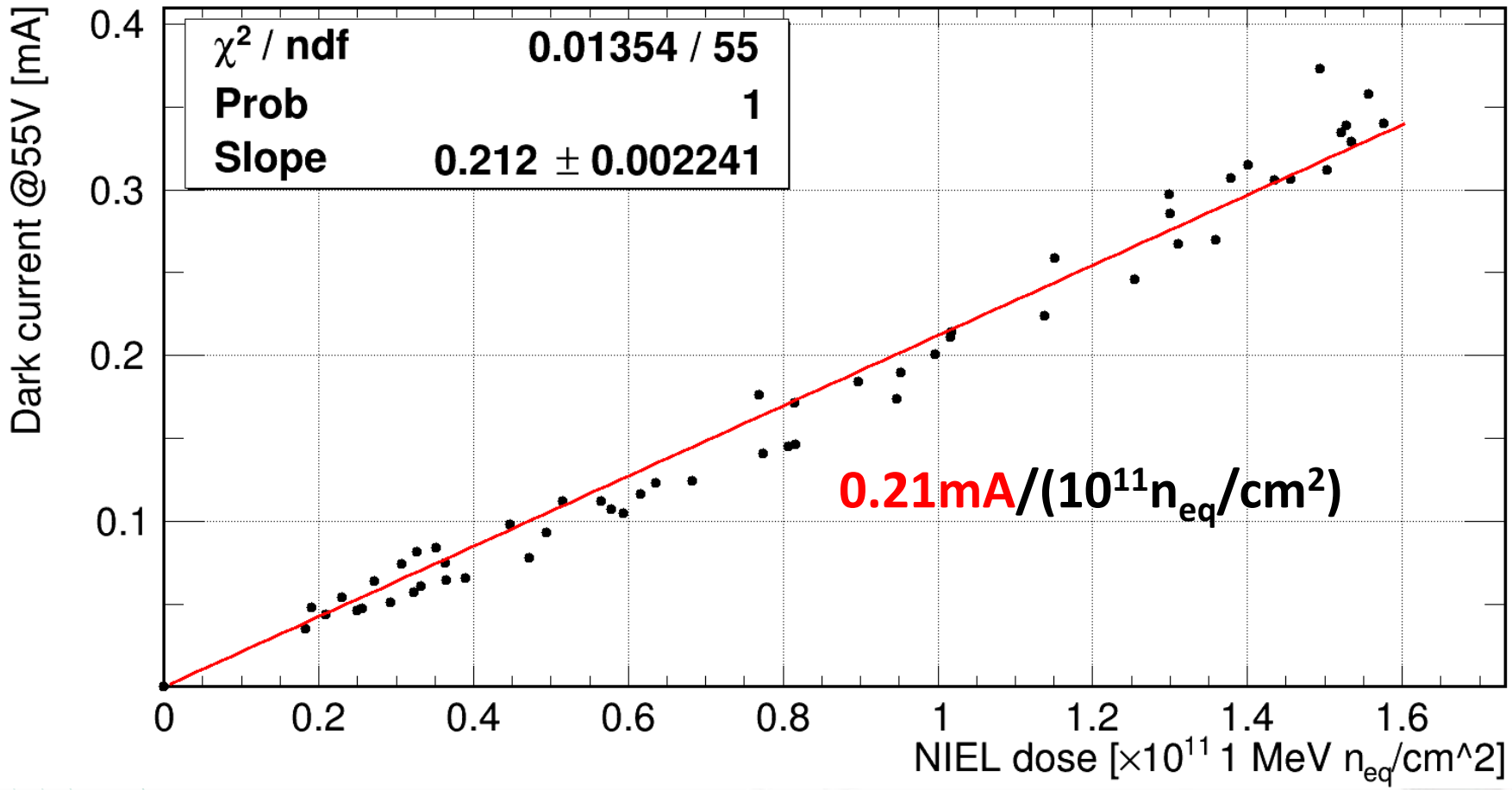
Dose distribution



Black: background

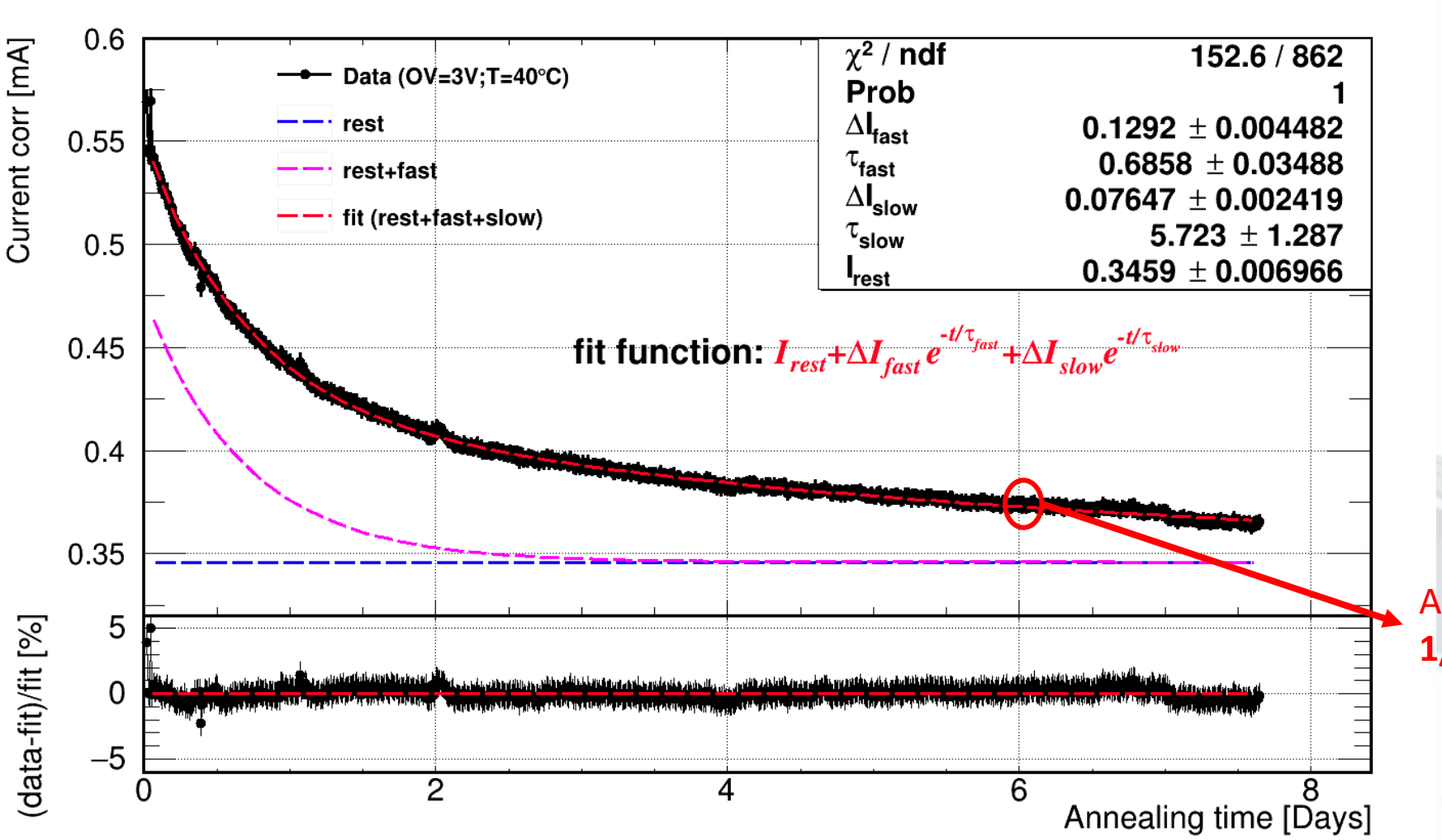
Green: new matrix **w/o irradiation**

Dark signal measurement



Dark current (DC) vs. NIEL dose

Annealing study

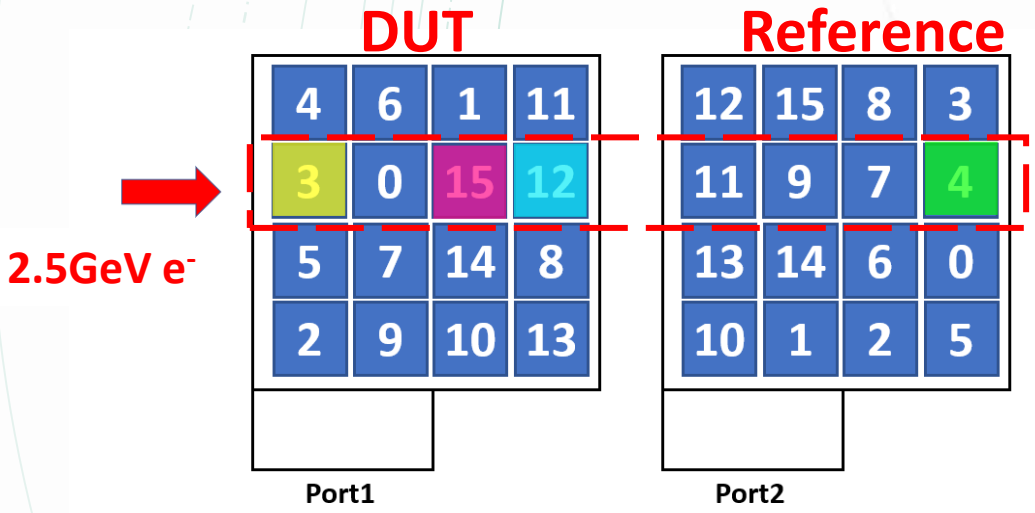


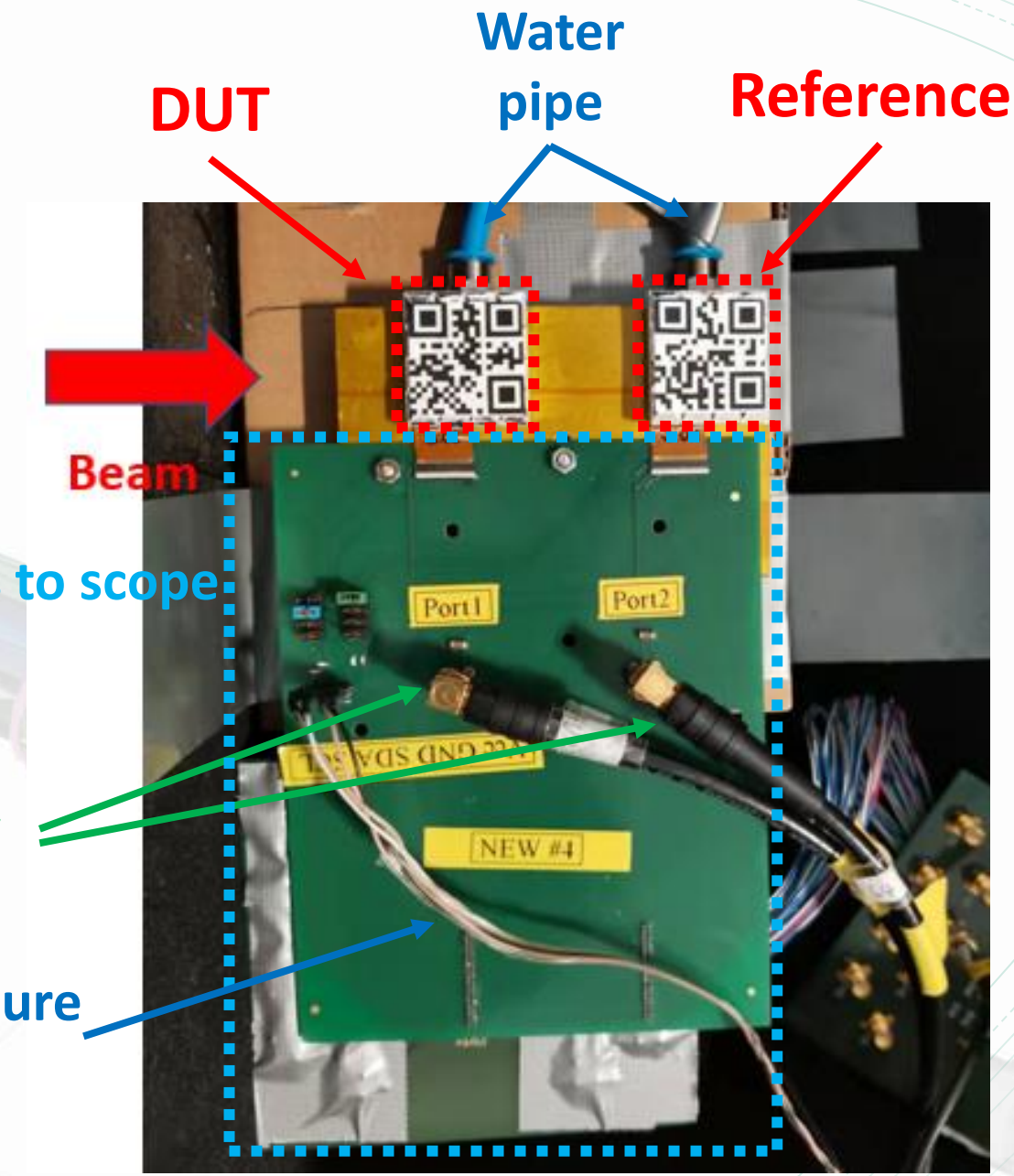
$\tau_{fast} = \mathbf{0.69}$ **days**
$\Delta I_{fast} = 0.129$mA [23.5%]
$\tau_{slow} = \mathbf{5.72}$ **days**
$\Delta I_{slow} = 0.076$mA [13.8%]

Annealing @T=**40°C** for about **6 days**:
1/3 of the dark current can be recovered

Testbeam @DESY

- Goal: timing of Tile+SiPM after irradiation
- time: Oct. 2021
- high-energy electron beam: ~2.5GeV
- cooled with water
- DUT matrices:
  - **6** irradiated + **1** non-irradiated

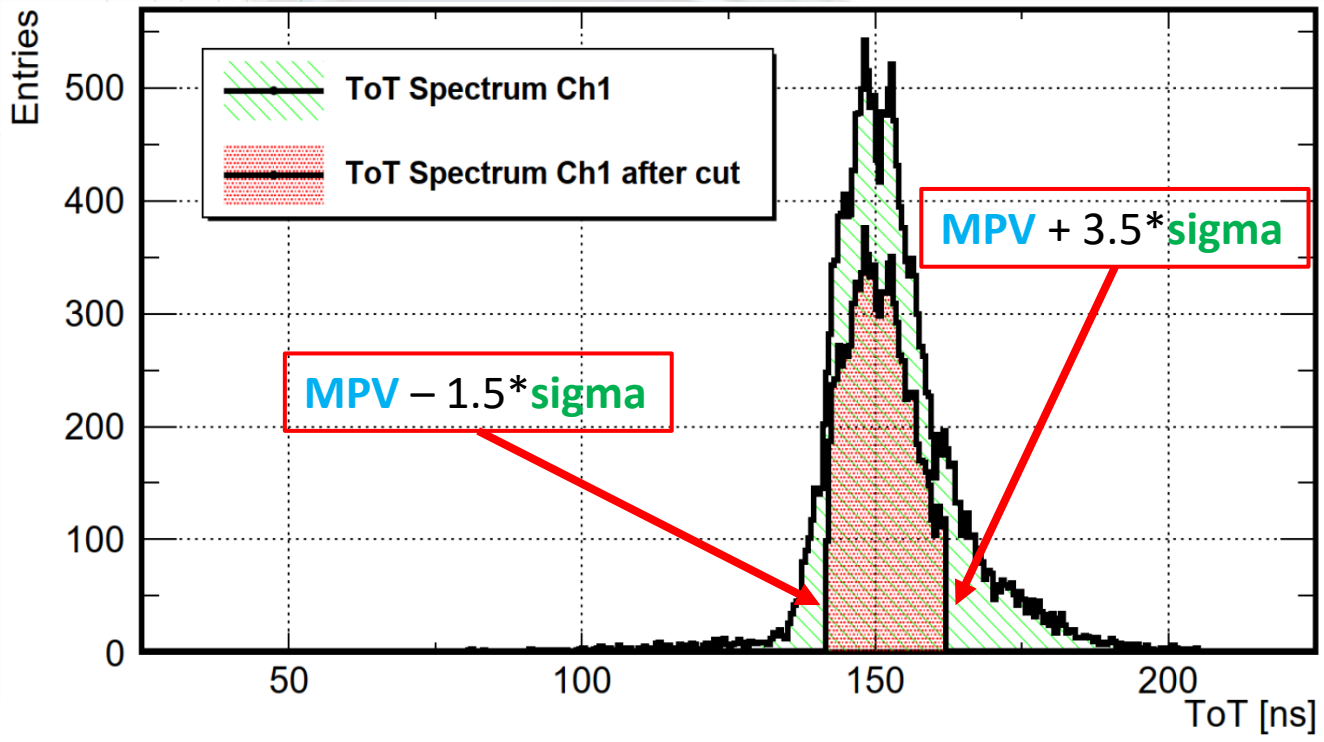




Timing analysis

Analysis:

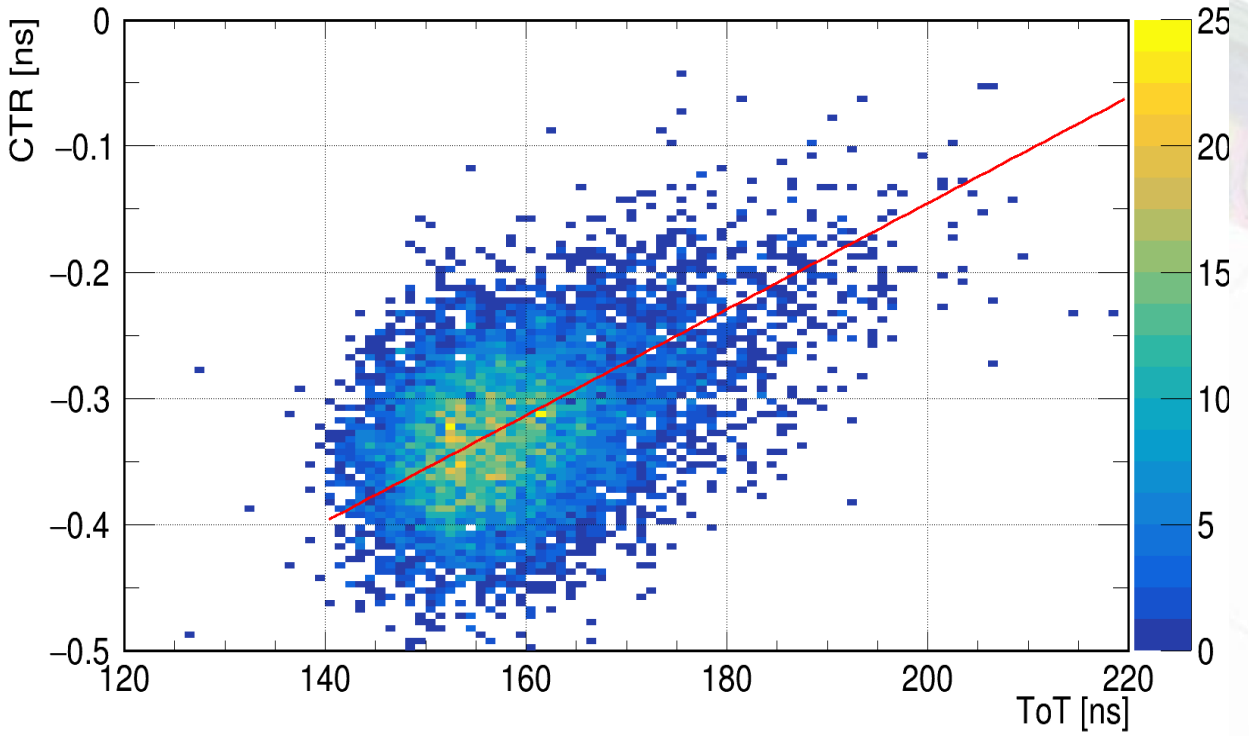
- high cut on reference channels ➔ suppress timewalk in reference channel

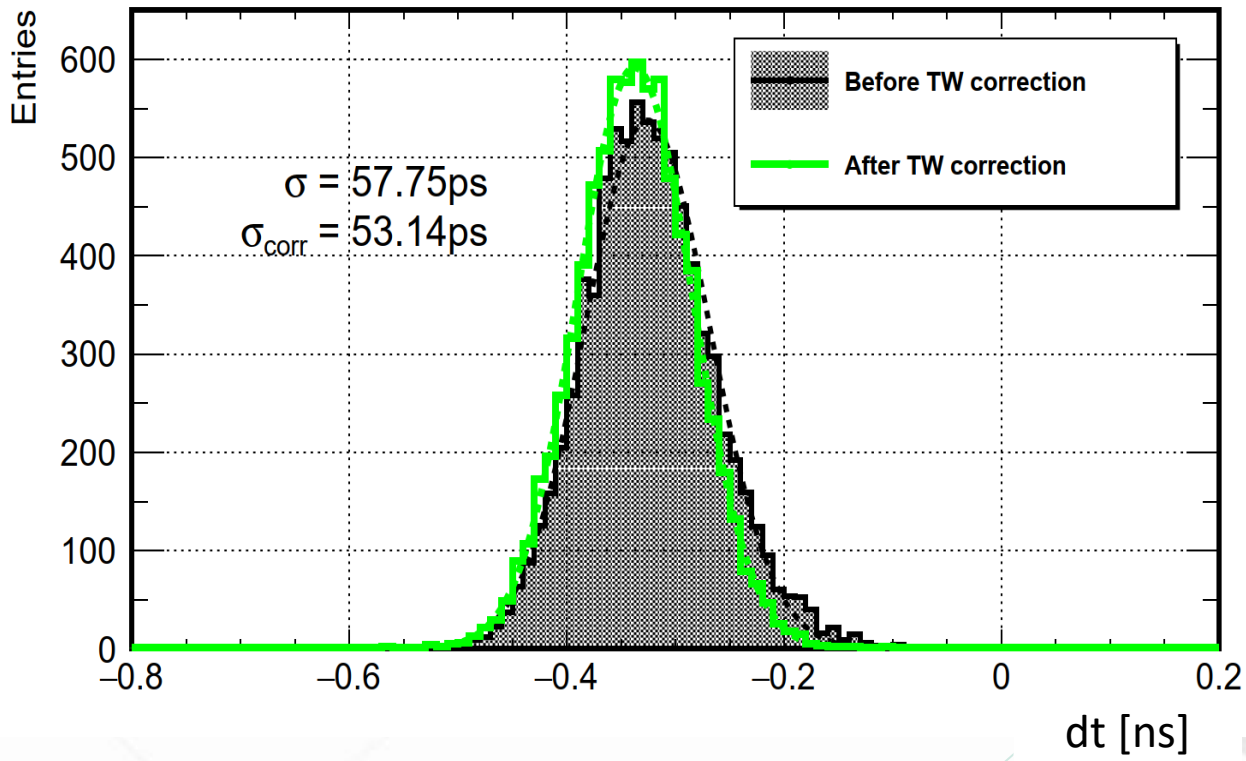


Timing analysis

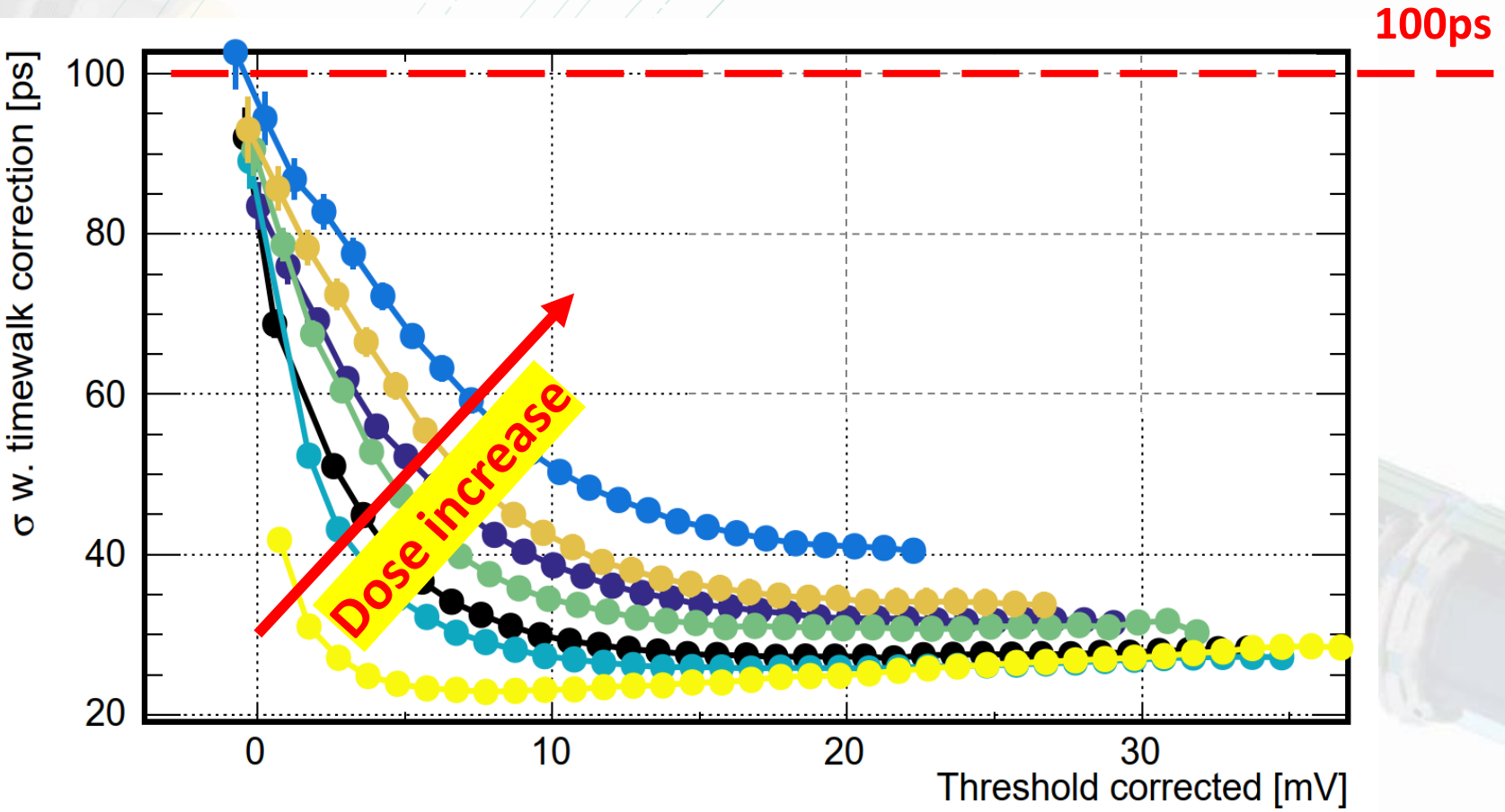
Analysis:

- high cut on reference channels ➔ suppress timewalk in reference channel
- coincident time difference to reference channels
- time walk correction applied





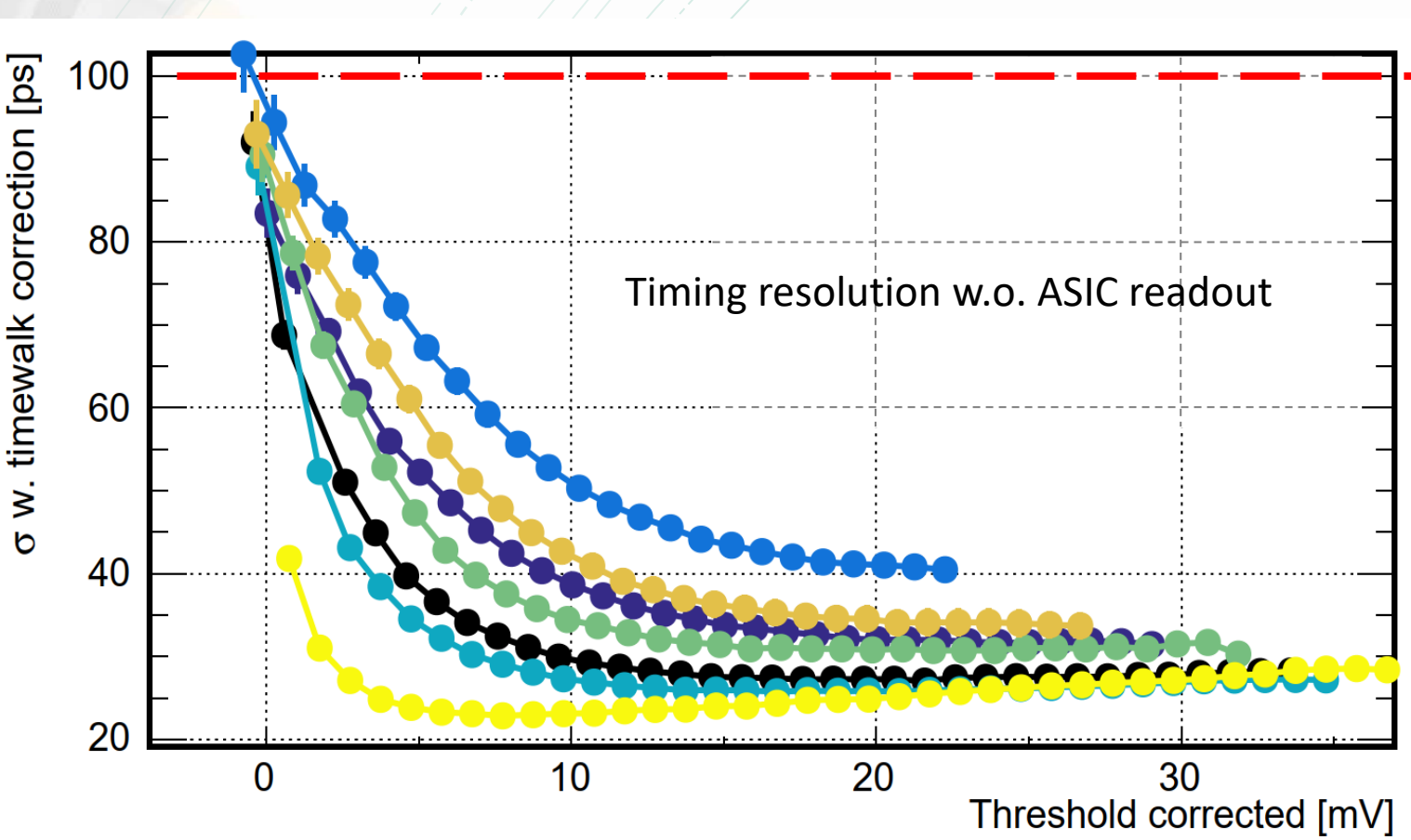
Timing analysis



Timing resolution(**TR**):

- **@low threshold**: dominated by **signal fluctuation**
- **@high threshold**: dominated **by photon statistic uncertainty**

Timing analysis



Low threshold:

➔ Worse efficiency due to large dead time

➔ Worse timing resolution

High threshold:

➔ better efficiency

➔ Better timing resolution

After irradiation:

ASIC needs to be capable to set threshold accordingly!

Summary

Mu3e Tile detector:

- dose up to $1.57*10^{11}$ n_{eq}/cm^2 was irradiated at PiE5 at PSI (mu3e beamline).
- characterization has been done both in lab and DESY:
  - significant dark current increasing due to DCR.
  - bigger fluctuation on base line.
  - timing resolution will still fulfill the requirement.

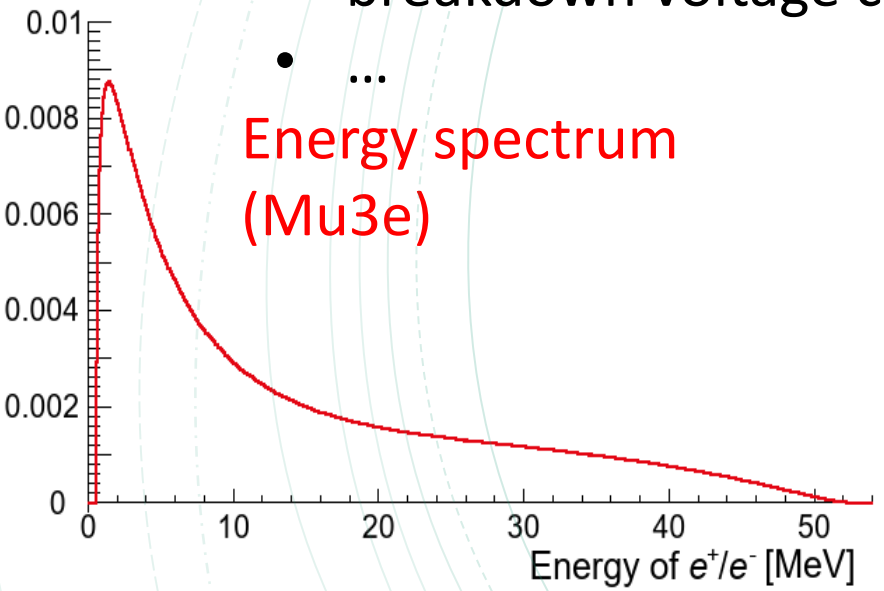
Thanks for you time and attention!!

Backup slides

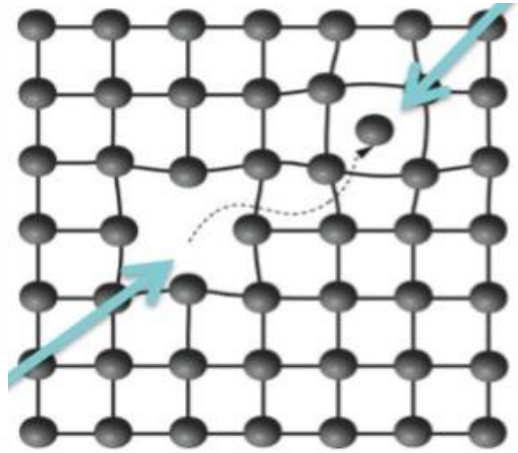
Irradiation damage in SiPMs

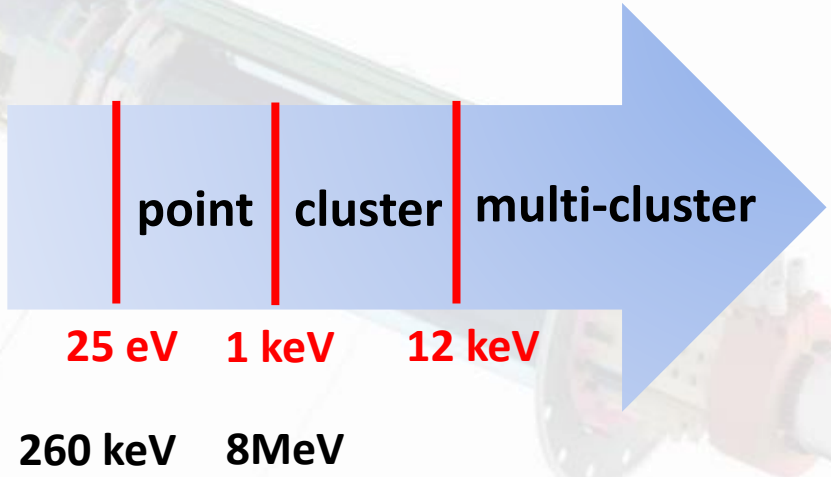
Bulk damage dominates:

- source: electron, proton, neutron, gamma…
- mechanics: atom in lattice relocated
- effects:
  - dark count rate (DCR) increase
  - breakdown voltage changes
  - …

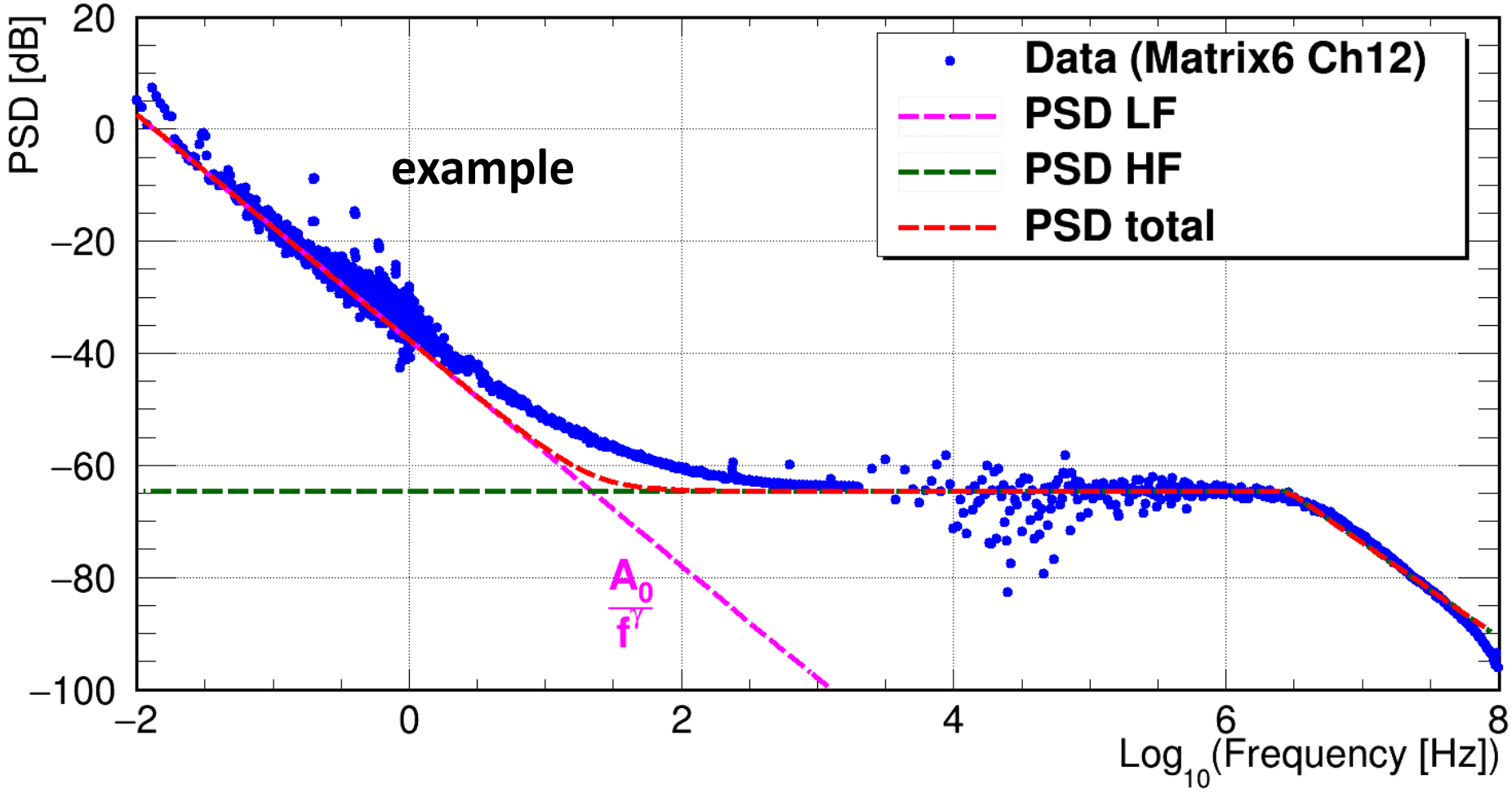


Energy spectrum (Mu3e)

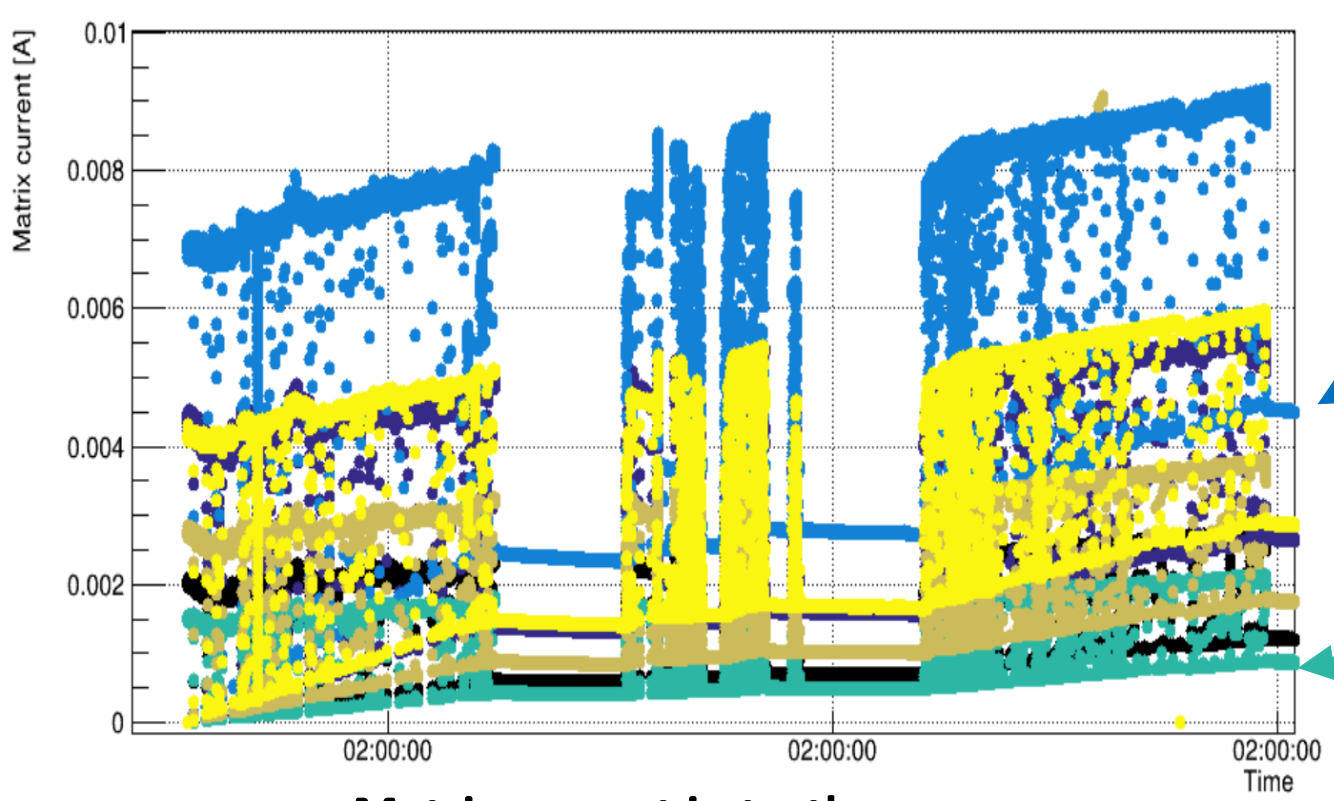




Noise model based on PSD analysis



Dose estimation

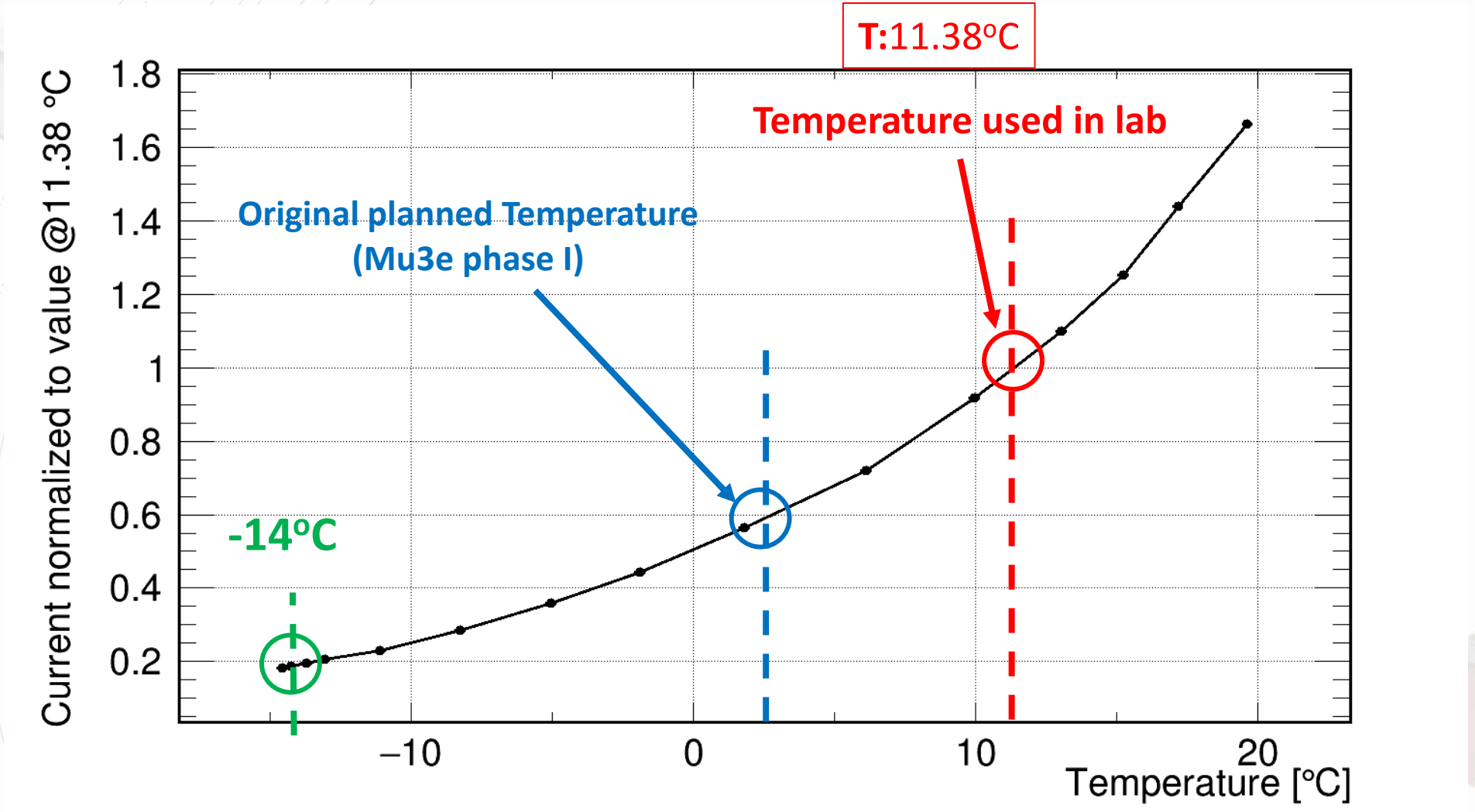


Matrix current in testbeam

Dark current: 0.86mA/matrix to **4.5mA/matrix**

(@$16 \pm 1°C, 55\ V$ after 12h annealing at 16°C)

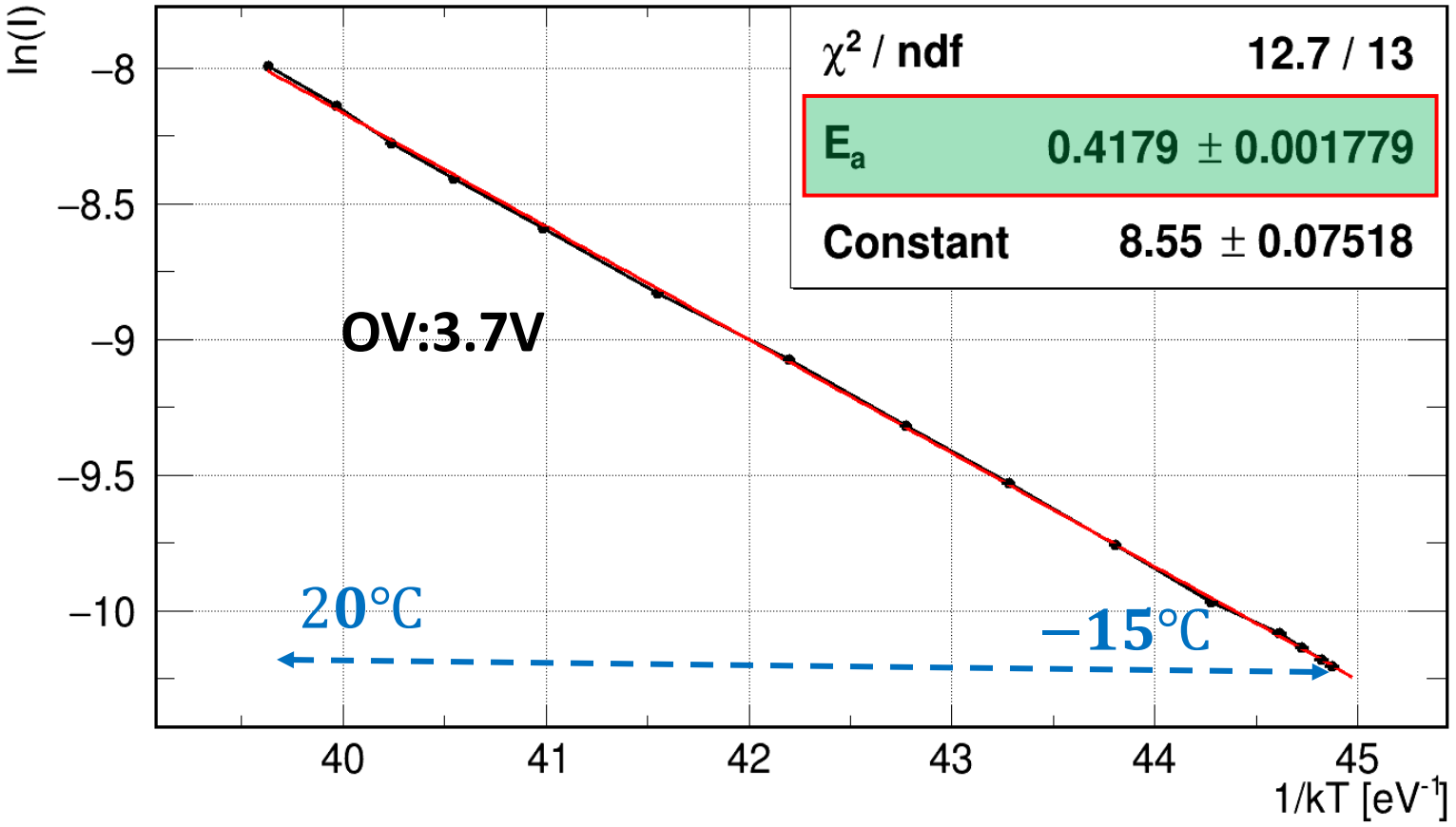
Temperature dependence



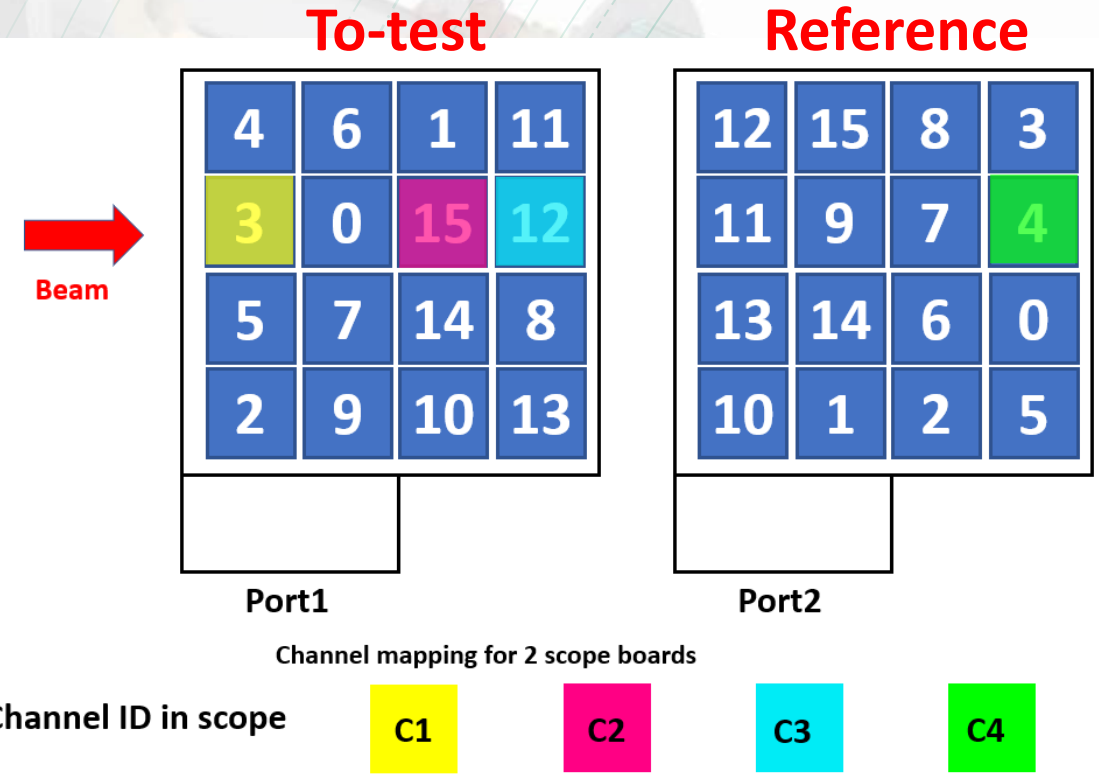
If work **@-14°C**, the max power needed will be7.5x20%= **1.5W@60V**

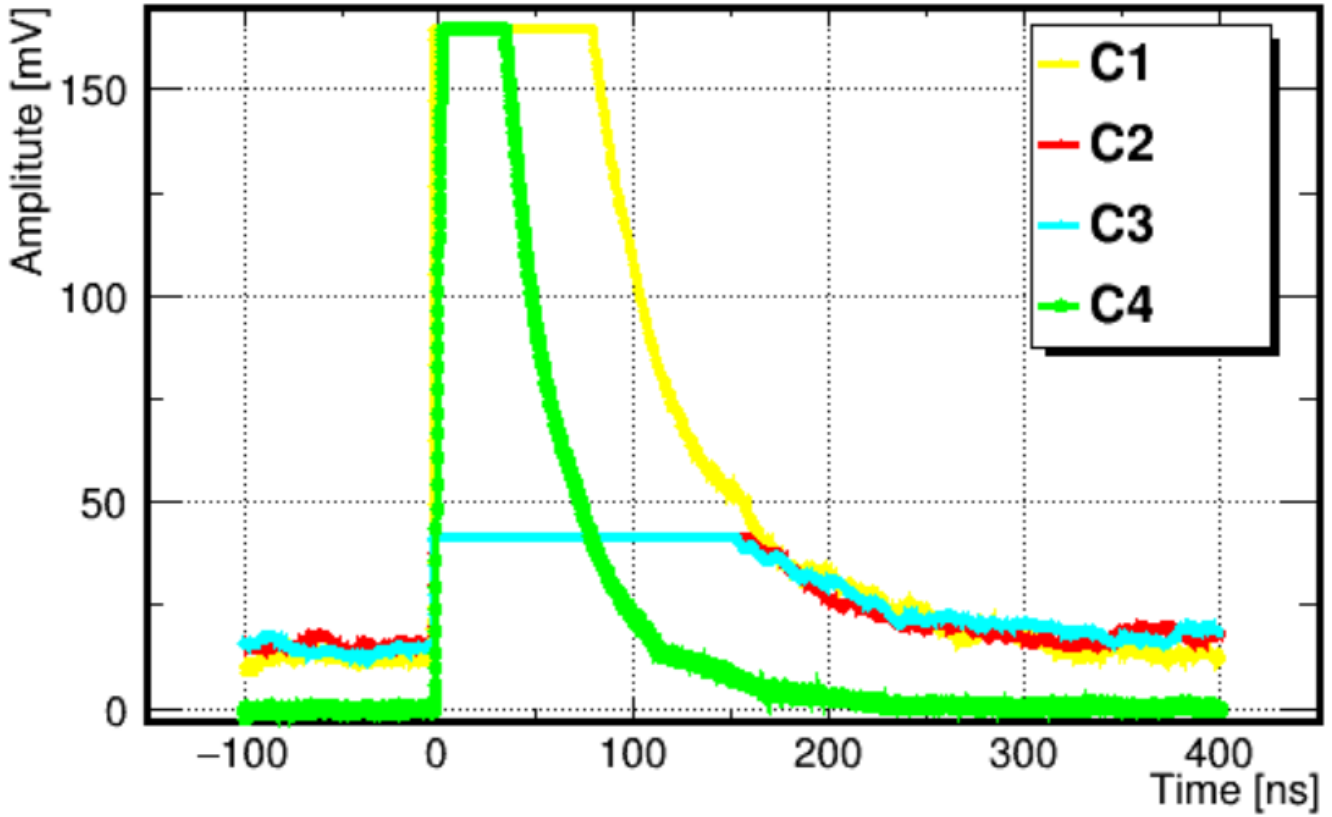
Arrhenius plot of irradiated SiPM

Irradiated SiPMs: generation current will dominate in a larger temperature range



Timing analysis





Trigger condition:

- C1 and C4 have big signal (>100mV)

Scope configuration:

- Horizontal:
  - Sampling rate: **10GS/s**
  - Range: -100ns to **400ns**
- Vertical:
  - Range: **0-160mV** (C1&C4); **0-40mV** (C2&C3)