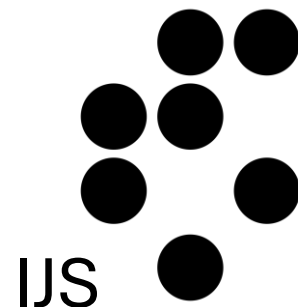


F9 Strategic Meeting

Characterisation of irradiated silicon photomultipliers



Boris
Gardinovački
29.9.2026.

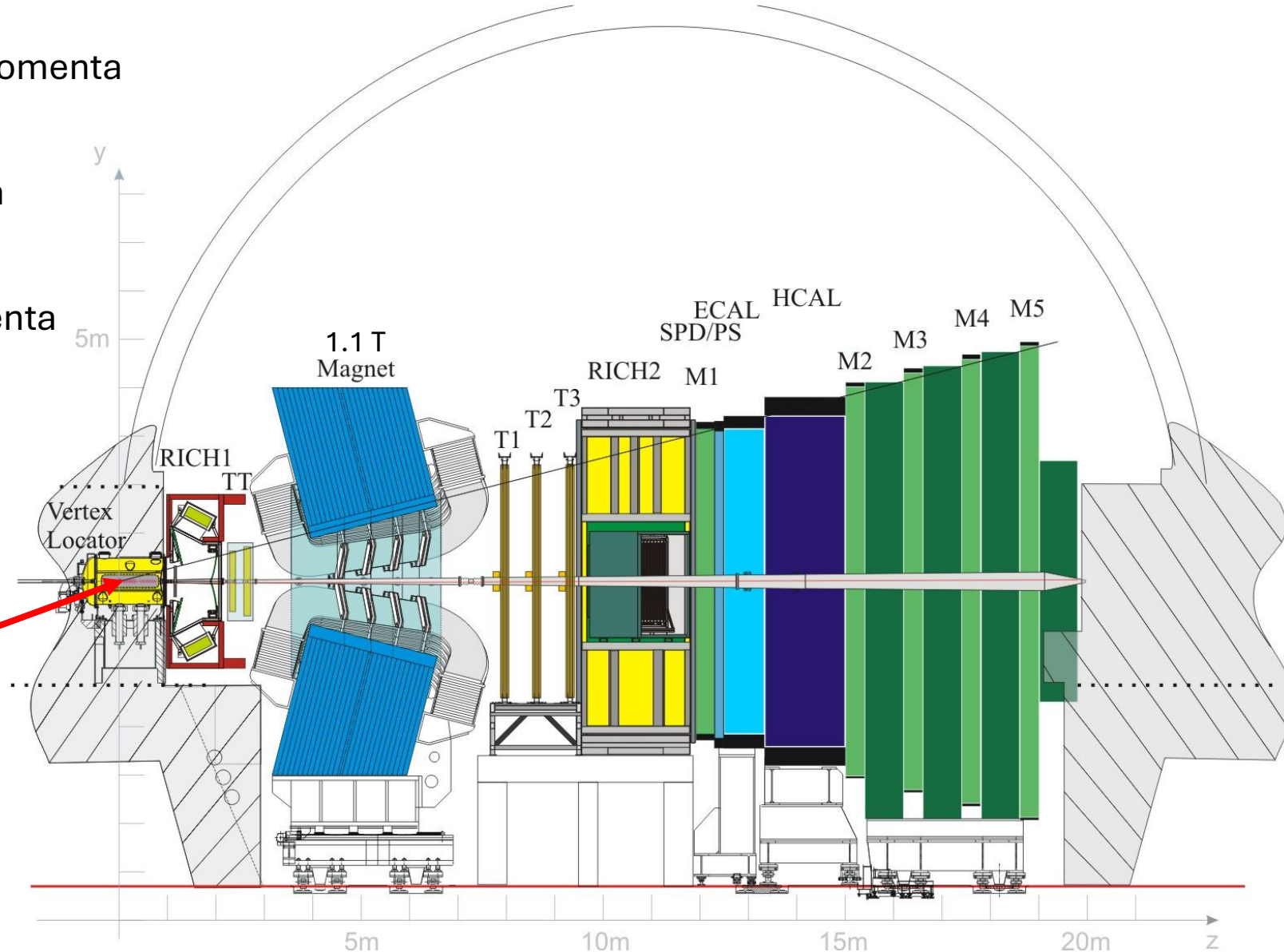


IJS

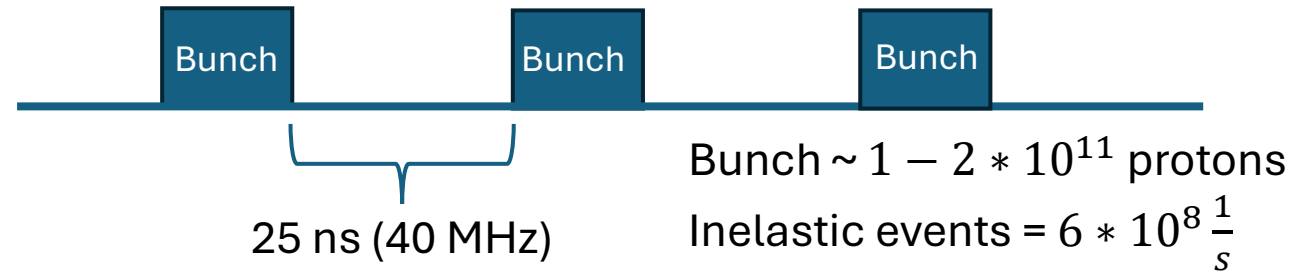
LHCb

- VERtex LOcator – Primary vertices and momenta
- RICH 1 – Low momentum PID
- Upstream tracker – Tracks and momenta
- Magnet – Momentum
- Downstream Tracker – Tracks and momenta
- RICH 2 – High momentum PID
- Calorimeters – Triggering and energy/momentum measurements
- Muon system – Triggering and muon ID

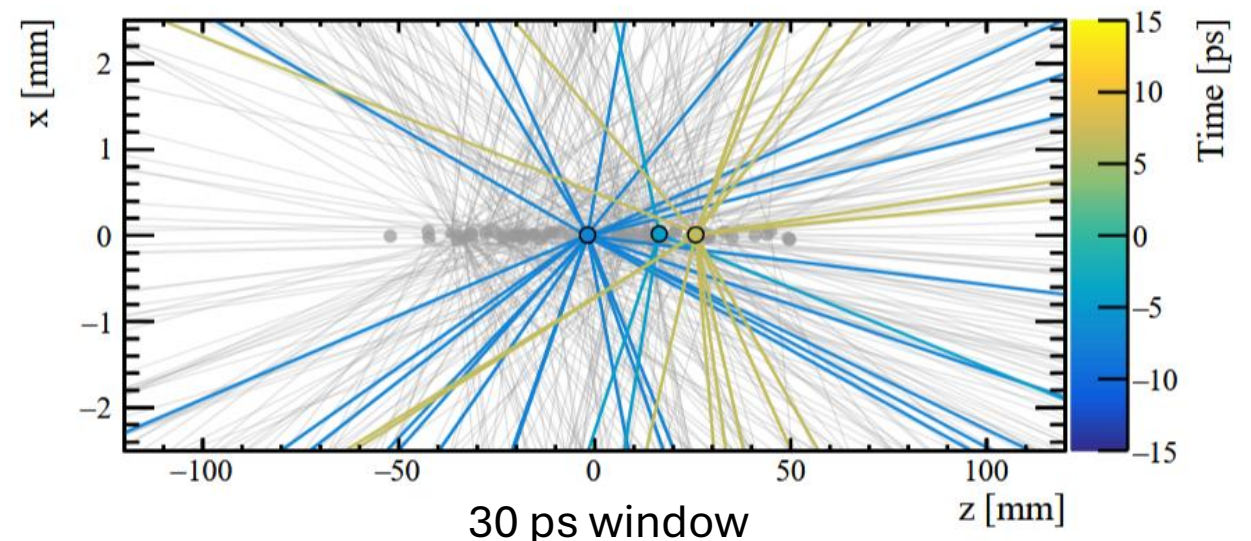
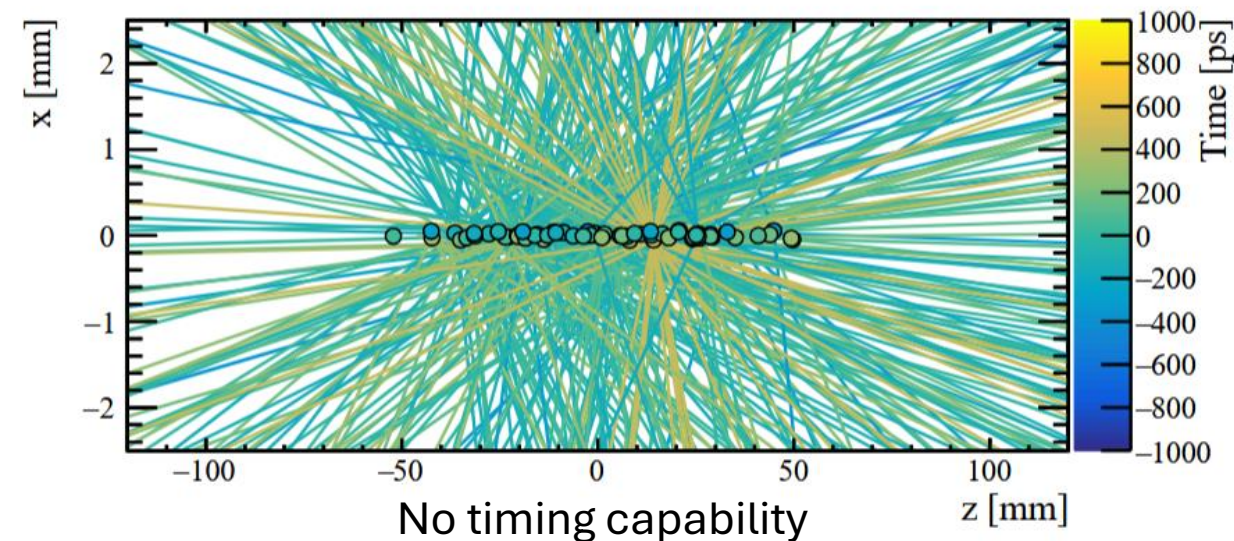
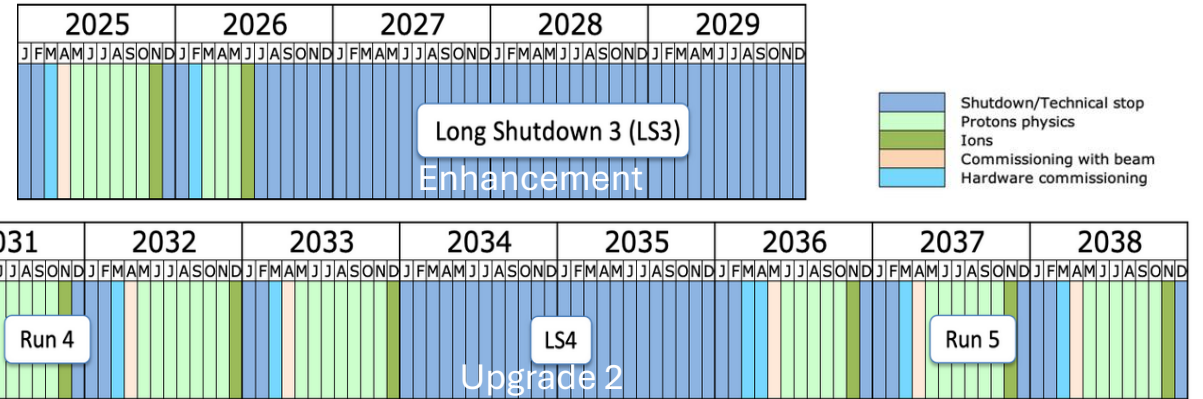
P-P
collisions



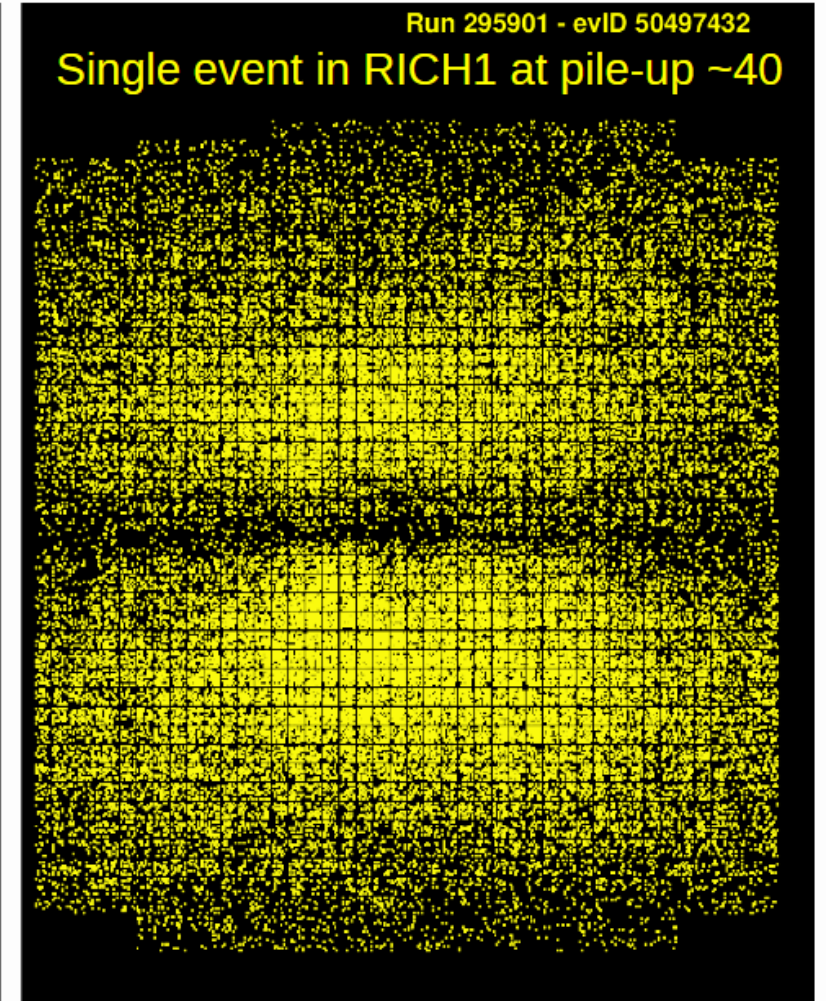
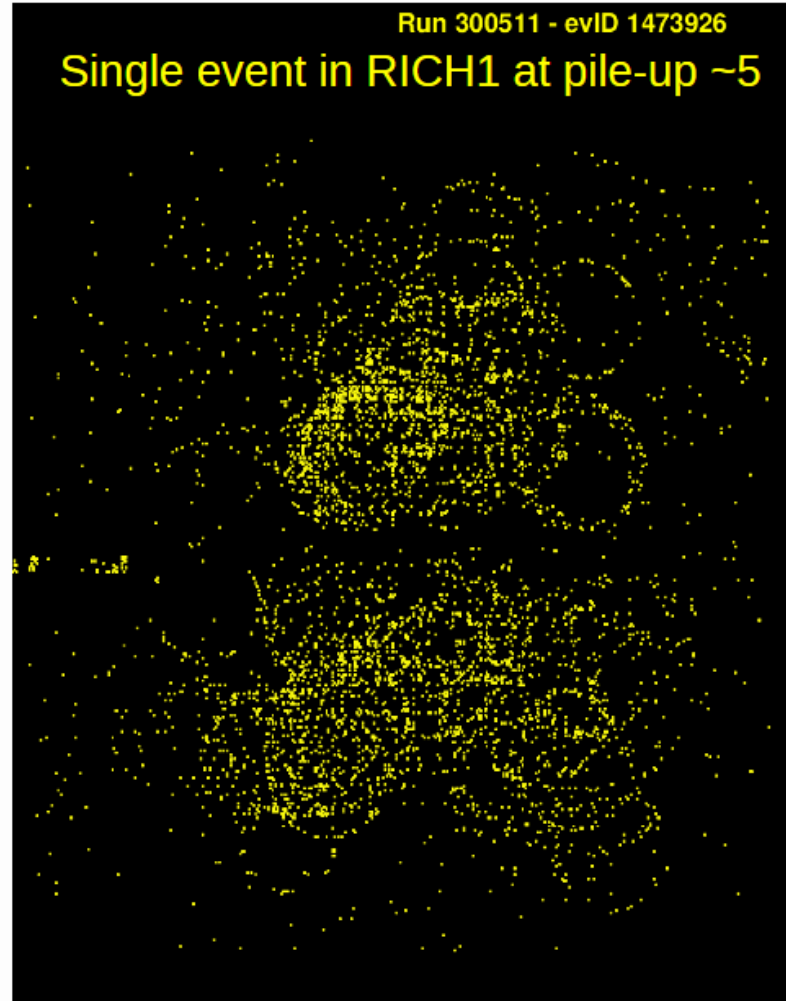
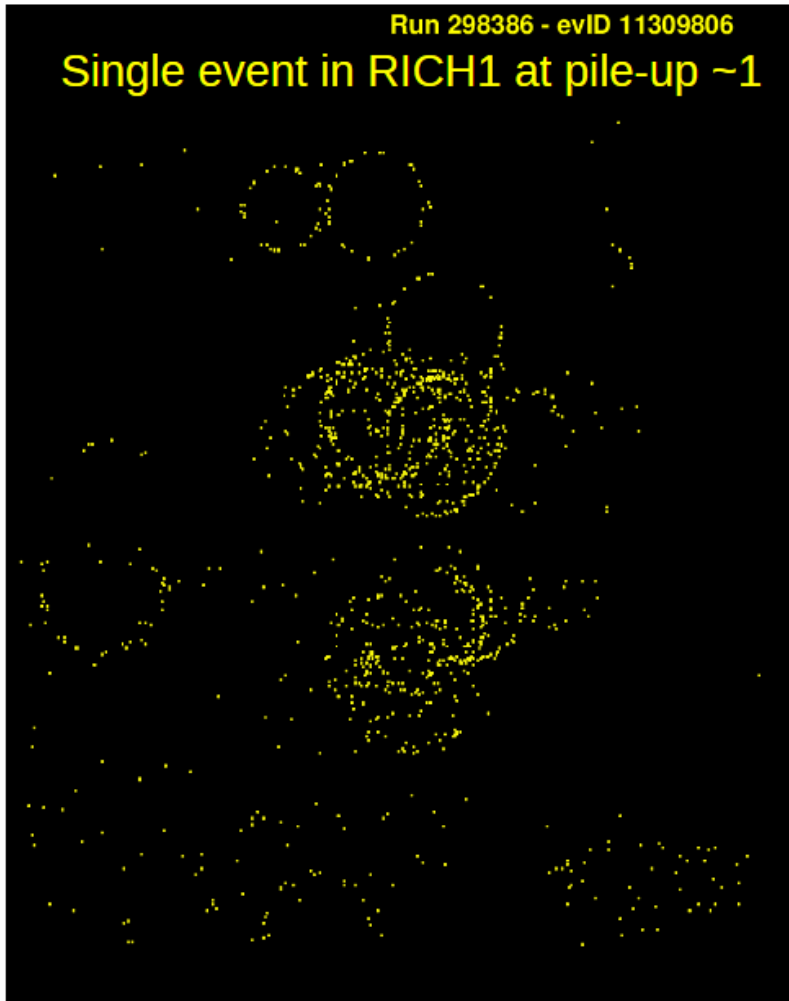
Upgrade II



- Instantaneous luminosity [$\frac{1}{cm^2s}$] - $2 * 10^{33} \rightarrow 1.5 * 10^{34}$
- Integrated luminosity [$\frac{1}{fb}$] - 25 $\rightarrow$ 300
- No. of i-type events = $L_{int} * \sigma_i$
- Pile-up [$\frac{\langle No. \rangle}{BX}$] - 2.5 $\rightarrow$ 40
- Radiation damage – detector dependent



Upgrade II – Photon detector



Photon detector requirements

	Required	Silicon Photomultiplier	Multi-Anode Photomultiplier Tube
Photon detection efficiency [%]	50	50 - 70	30-40
Timing resolution (FWHM) [ps]	50	<100	150
Cell size [mm ²]	1 x 1 – 2 x 2	1 x 1	2.8 x 2.8
Dark-Count rate [Hz/mm ²]		$10^5 - 10^7$	< 1
Operation voltage [V]		40 – 50	~1000
Magnetic sensitivity		NO	YES
Radiation hard [n_{eq}/cm^2]	$2 * 10^{13}$	NO	YES

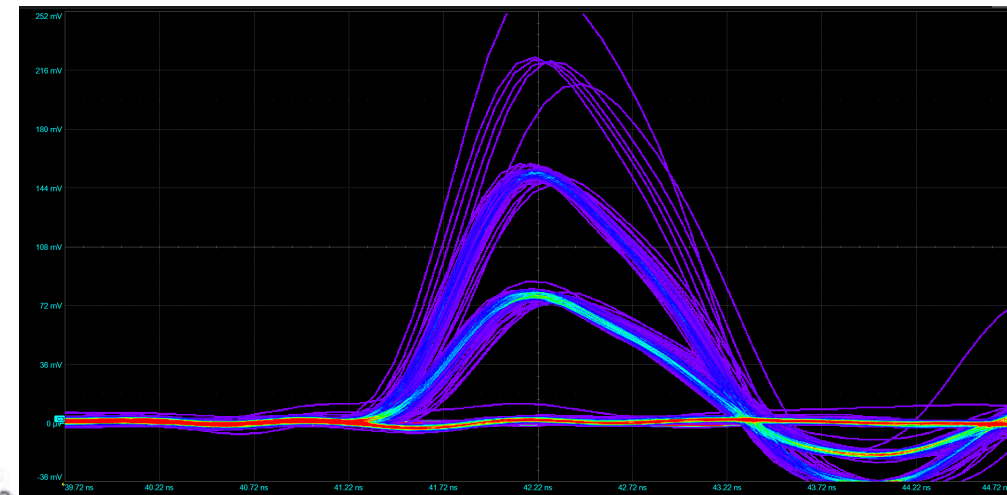
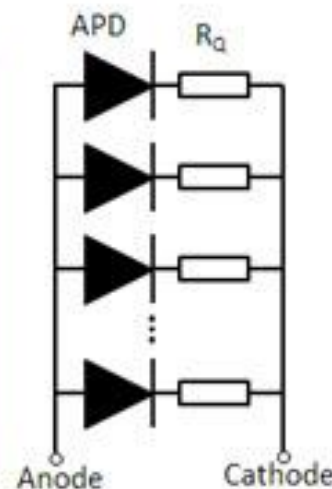
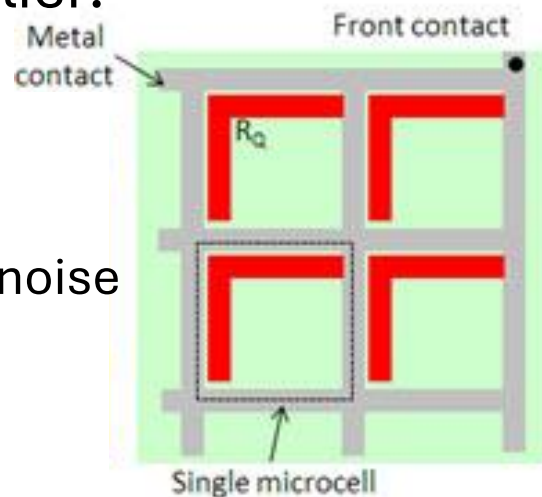
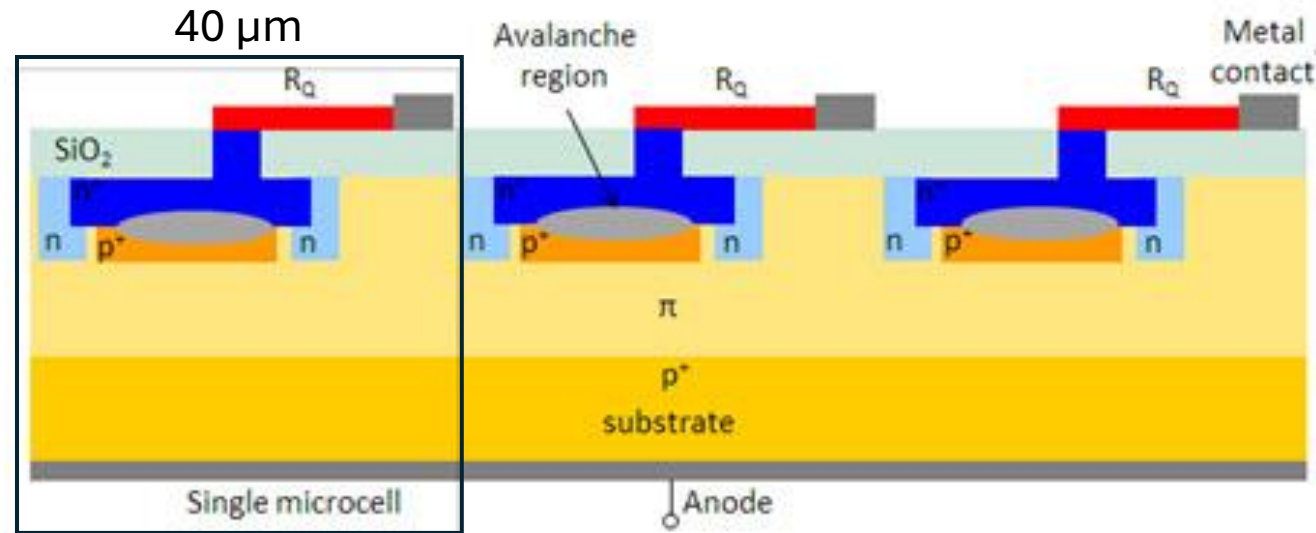
Silicon Photomultiplier (SiPM)

- Single Photon Avalanche Diode (SPAD):

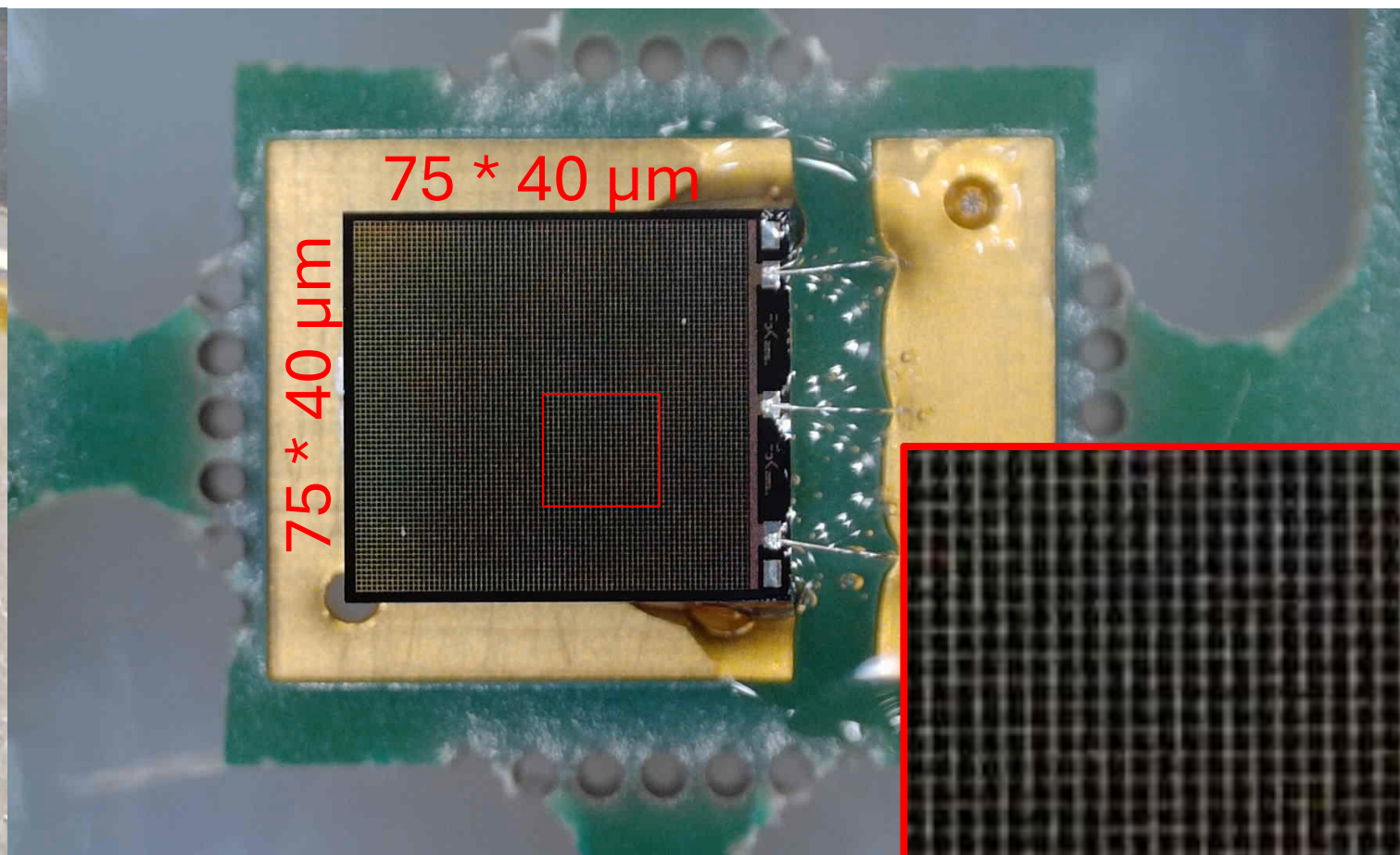
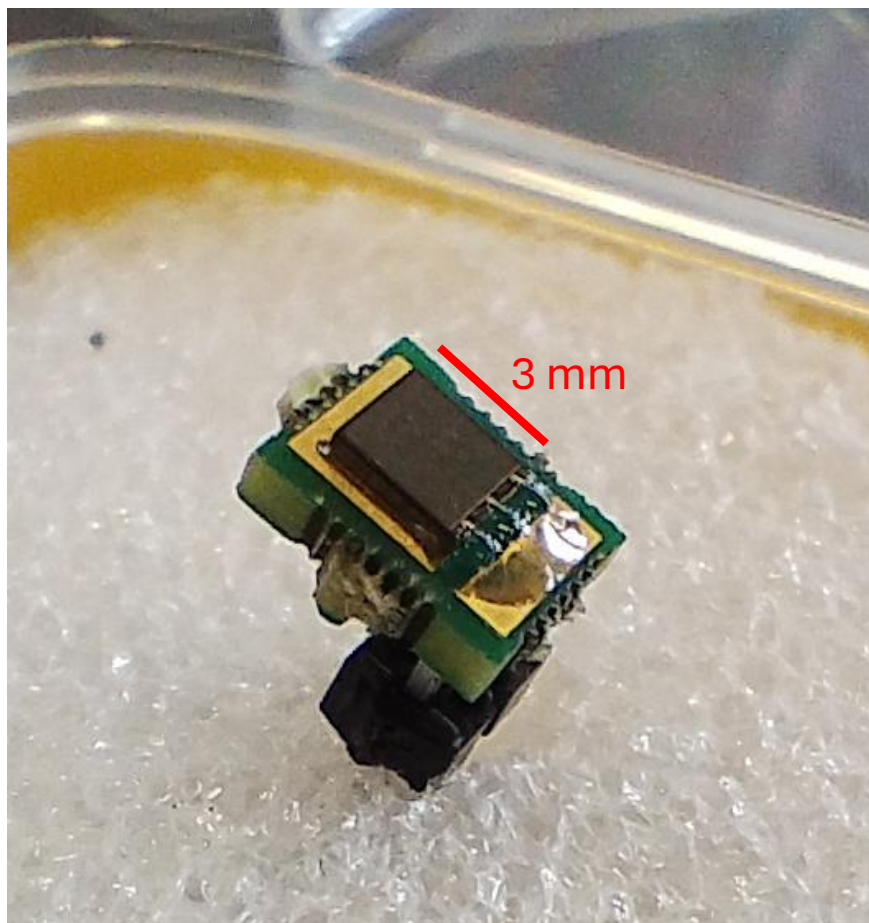
- PN junction
- Reverse external E field
- Electron-hole pairs
- Avalanche - > Gain
- Quenching resistor

- Silicon Photomultiplier:

- SPAD Array
- Parallel connection (Sum of signals)
- Excellent signal-to-noise

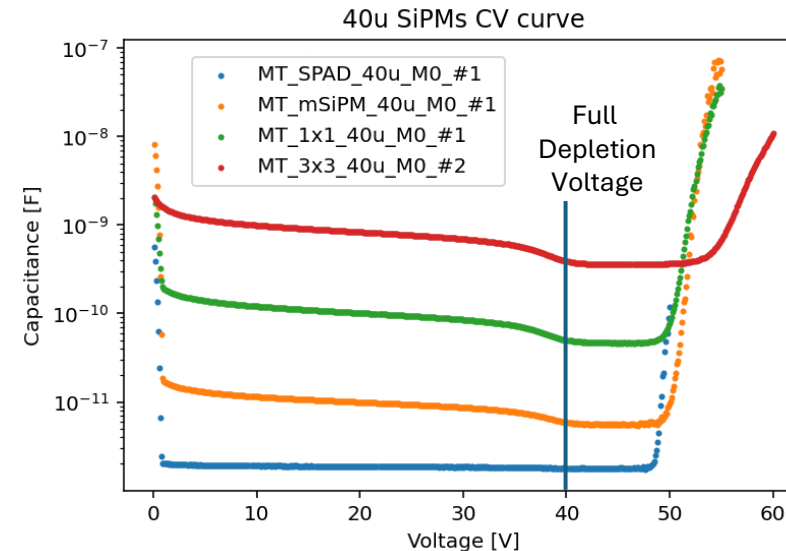
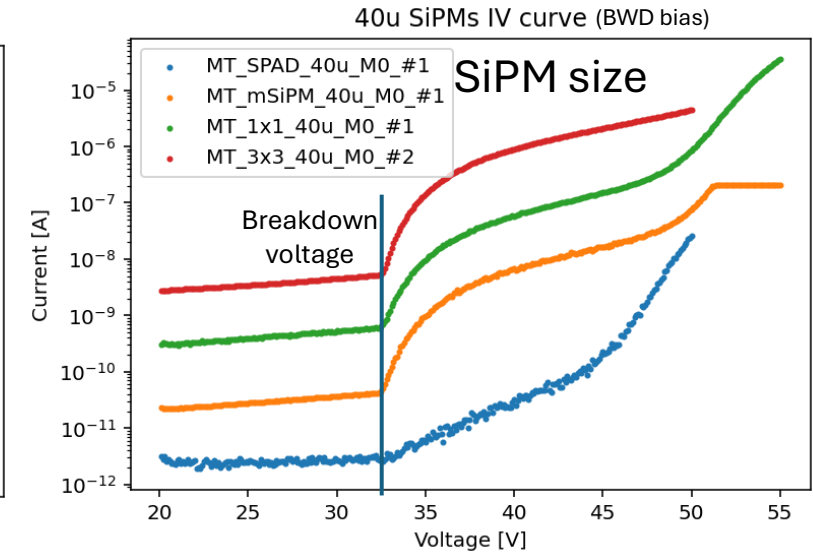
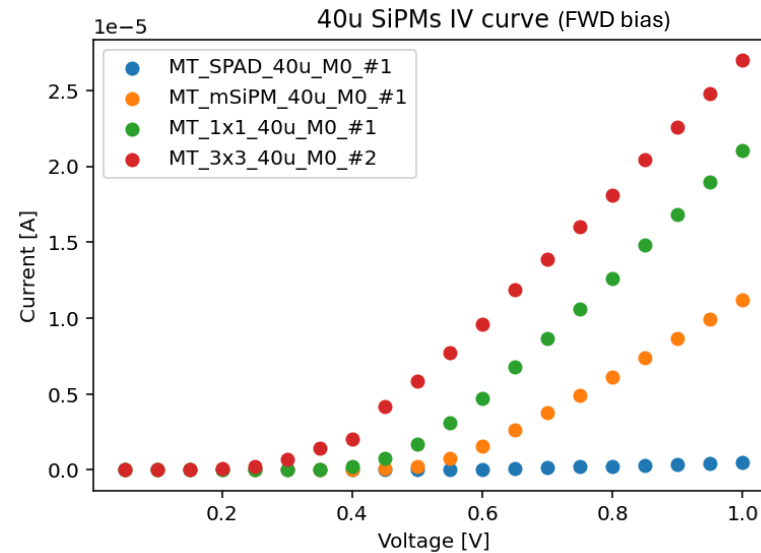


Silicon Photomultiplier (SiPM)



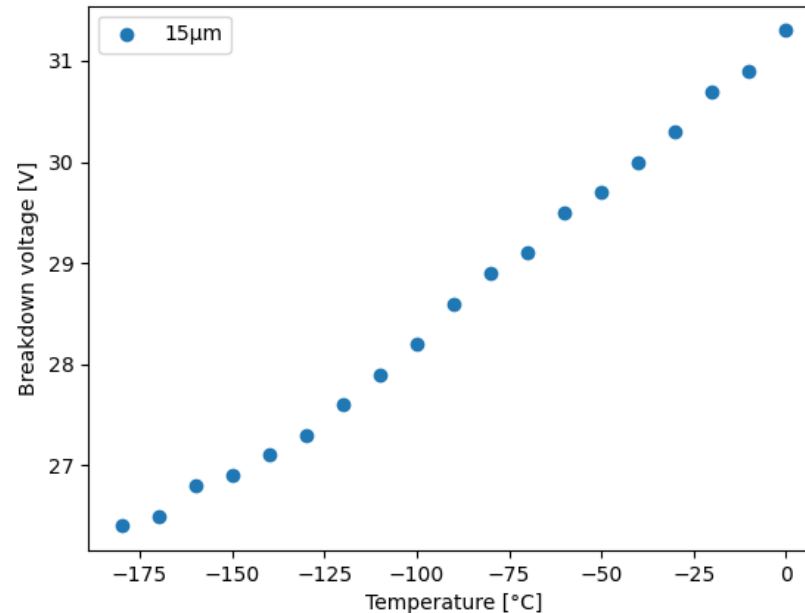
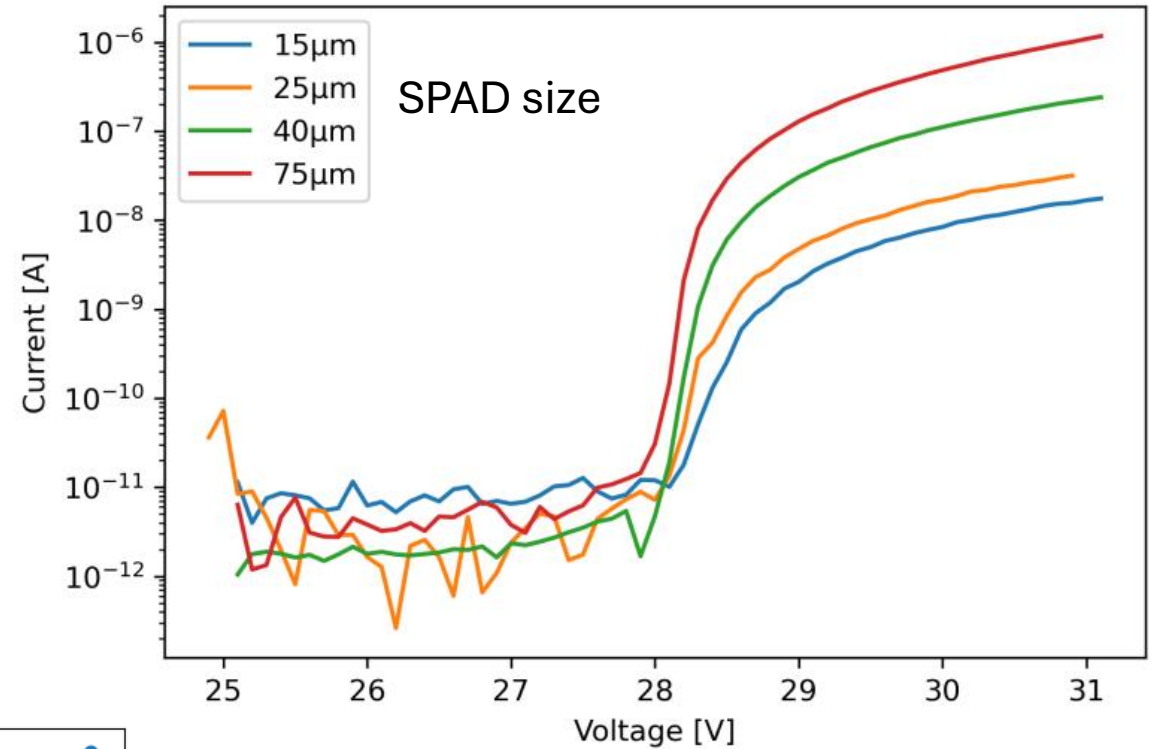
SiPM characterization

- Current-Voltage
 - Breakdown voltage
- Capacitance-Voltage
 - Full depletion voltage



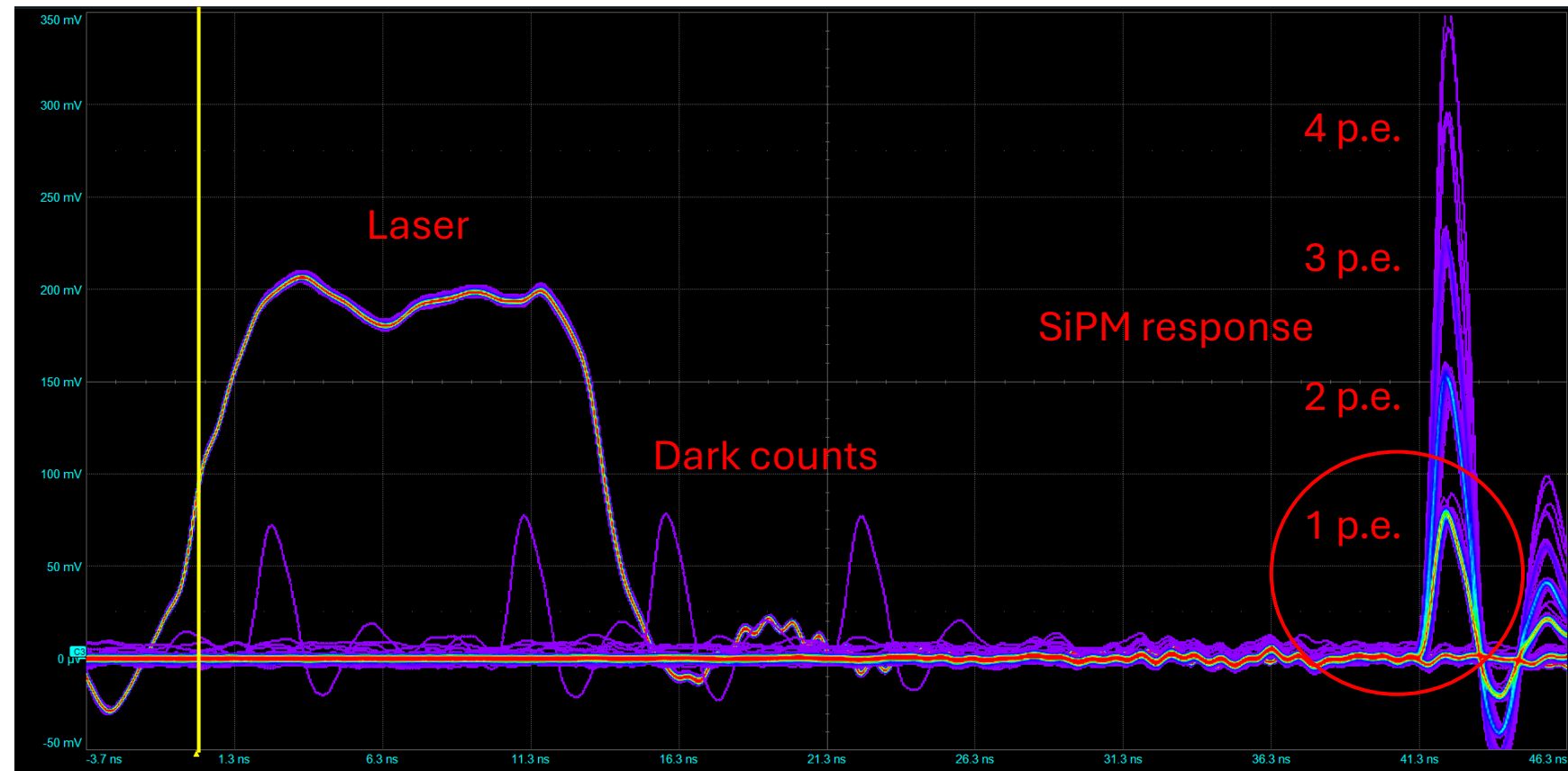
SiPM characterization

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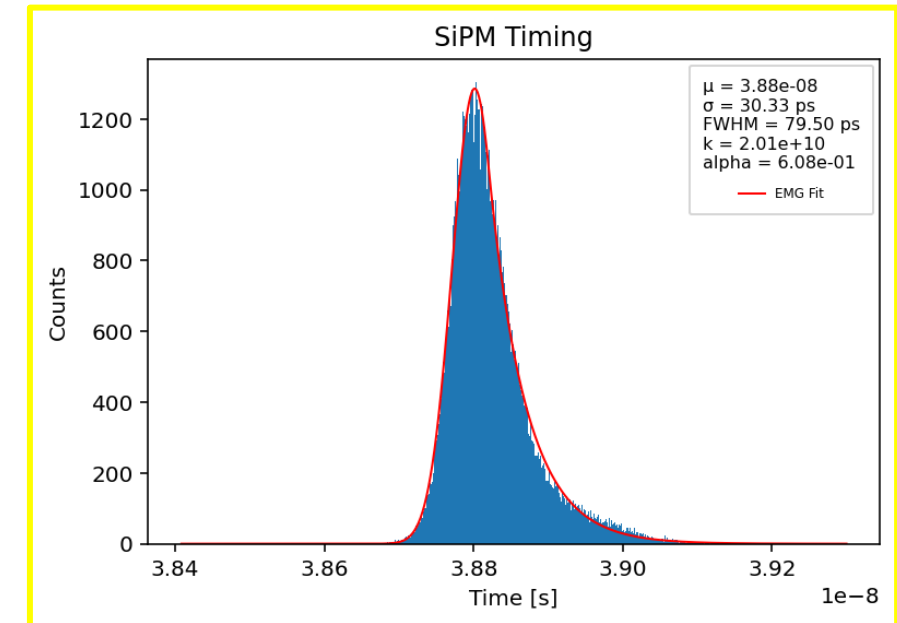
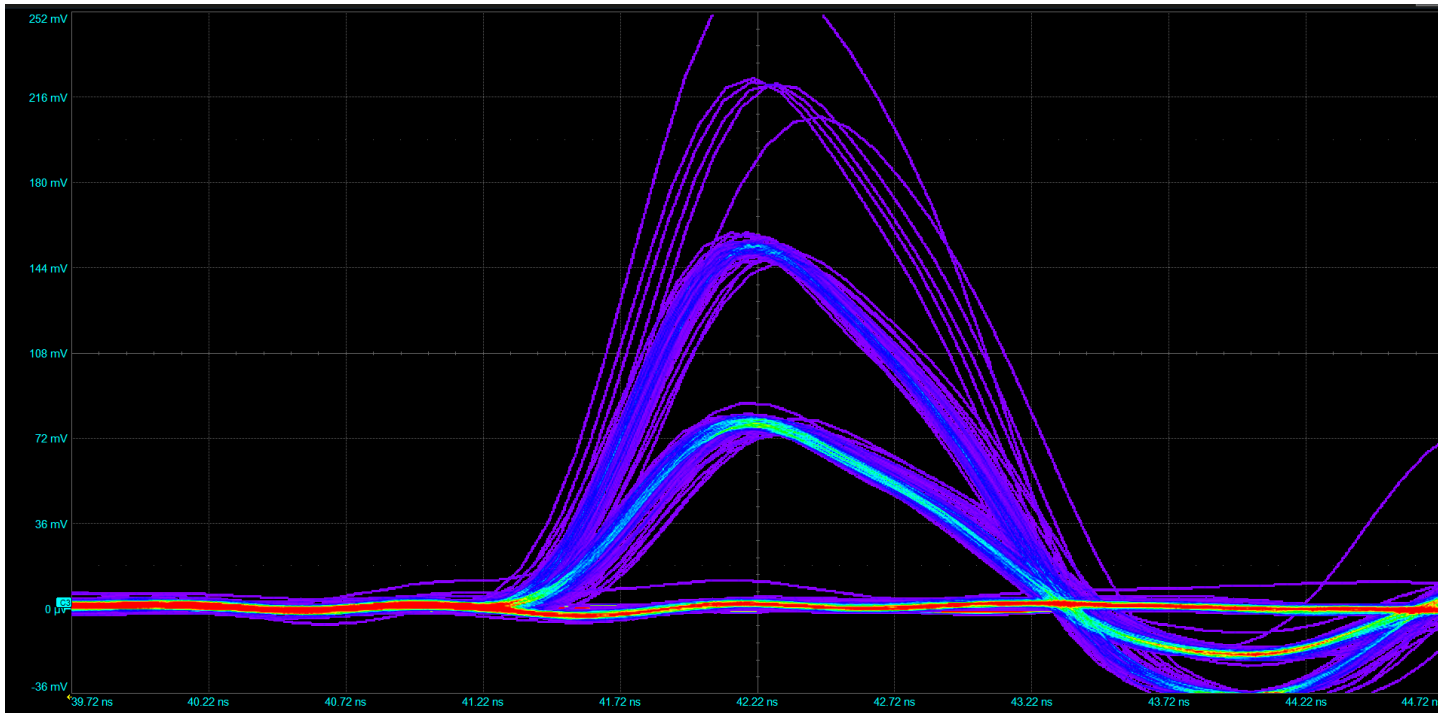
SiPM characterization

- Laboratory setup
 - Pulsing laser
 - Oscilloscope
- Event analysis
 - Photon counting
 - SiPM Timing
 - Noise characterization
 - Efficiency scan



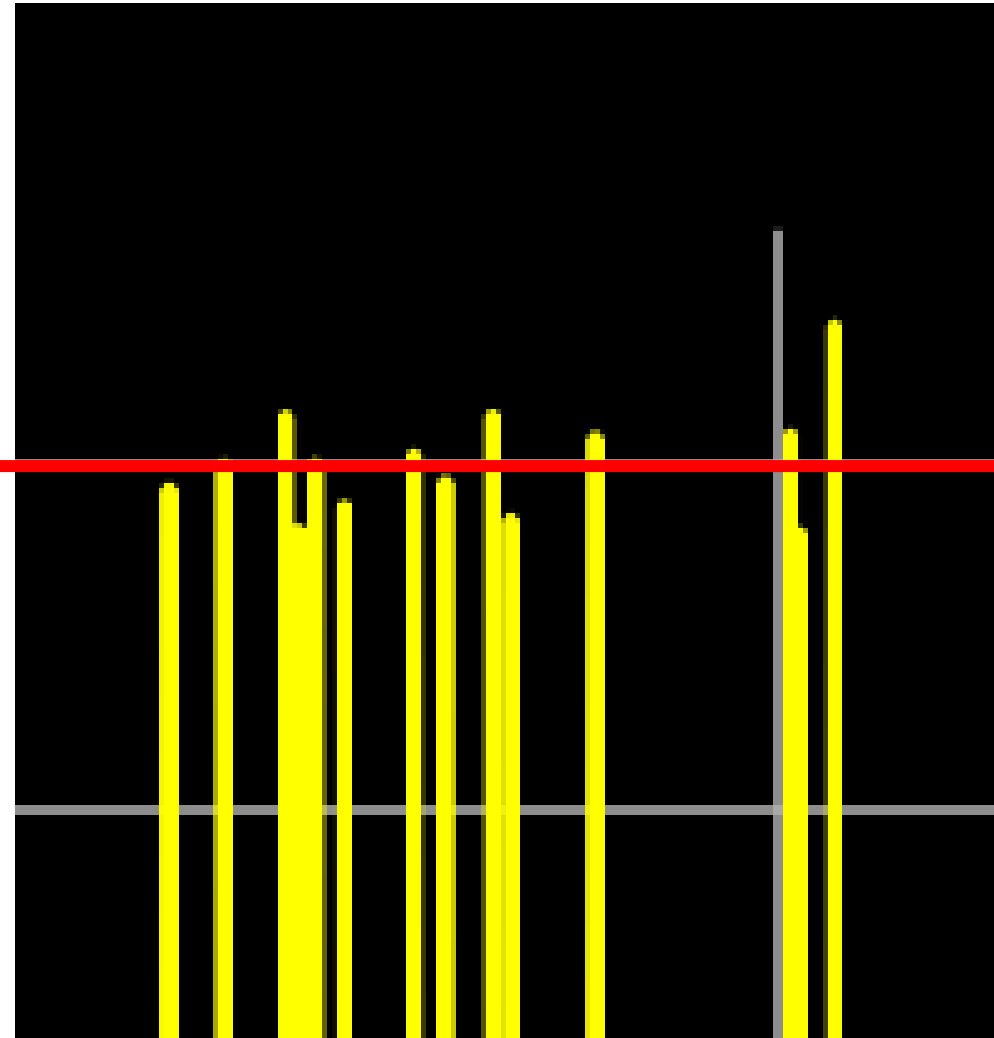
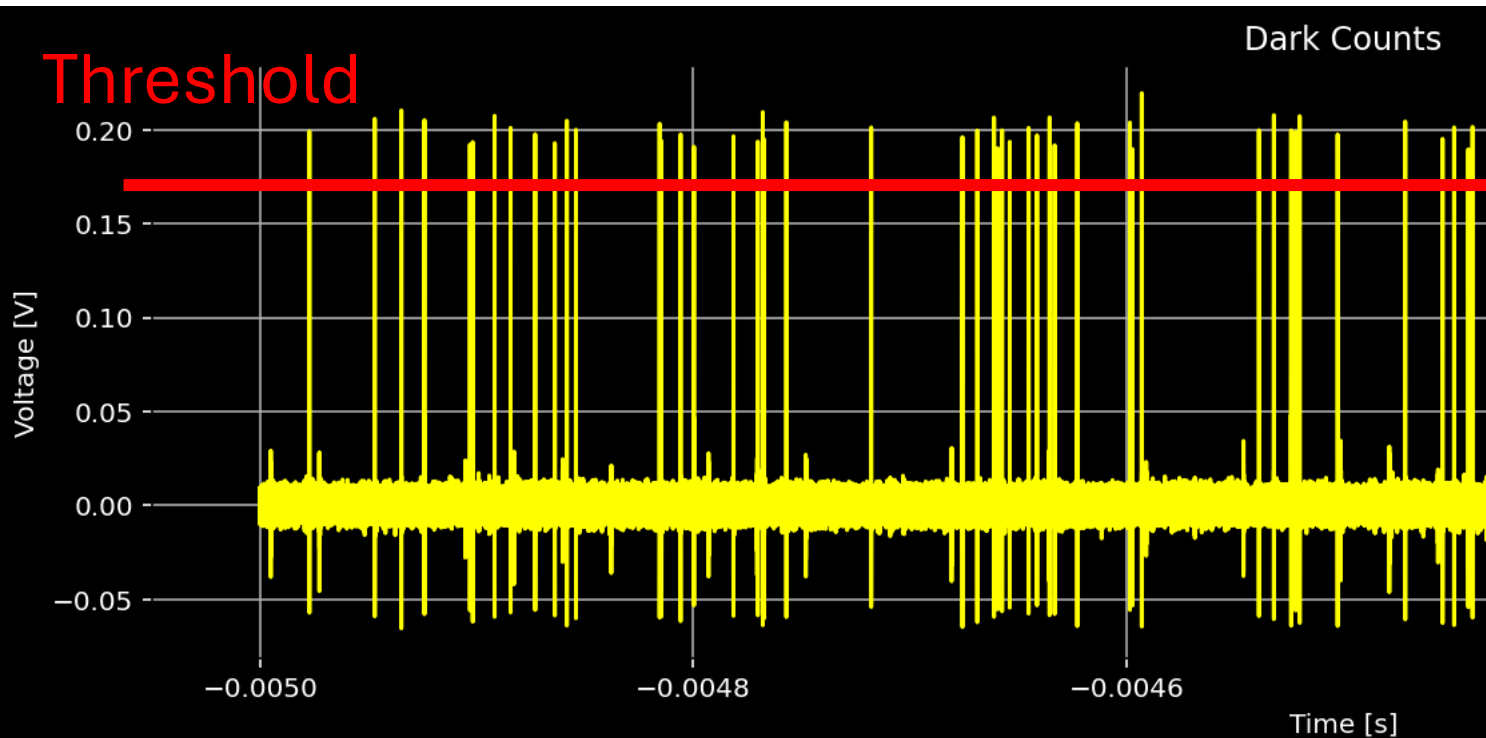
Single Photon Timing Resolution

- Timing resolution
 - Full-Width-Half-Max of time of arrival distribution



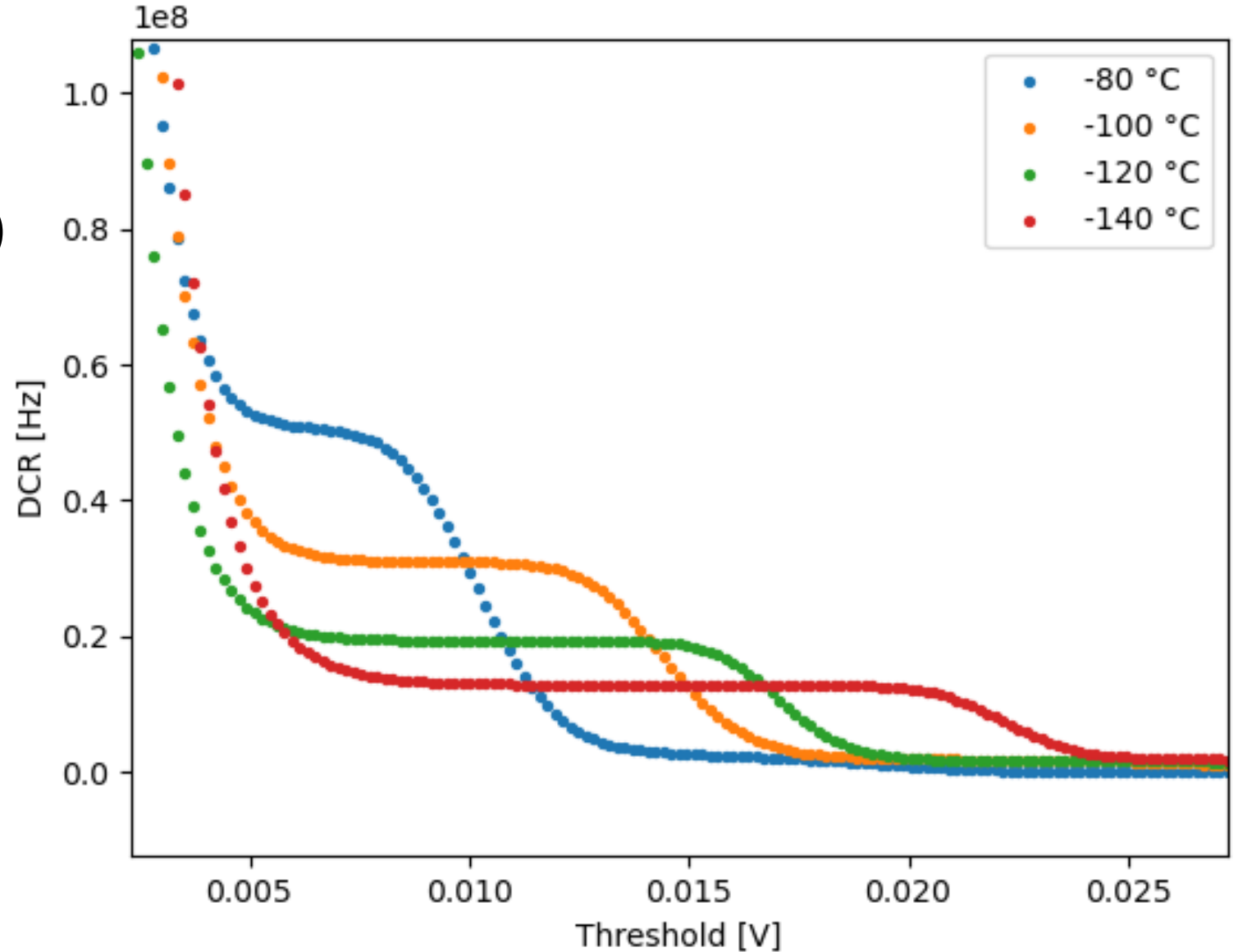
Noise characterization

- Threshold scan
- Dark Count Rate (DCR)



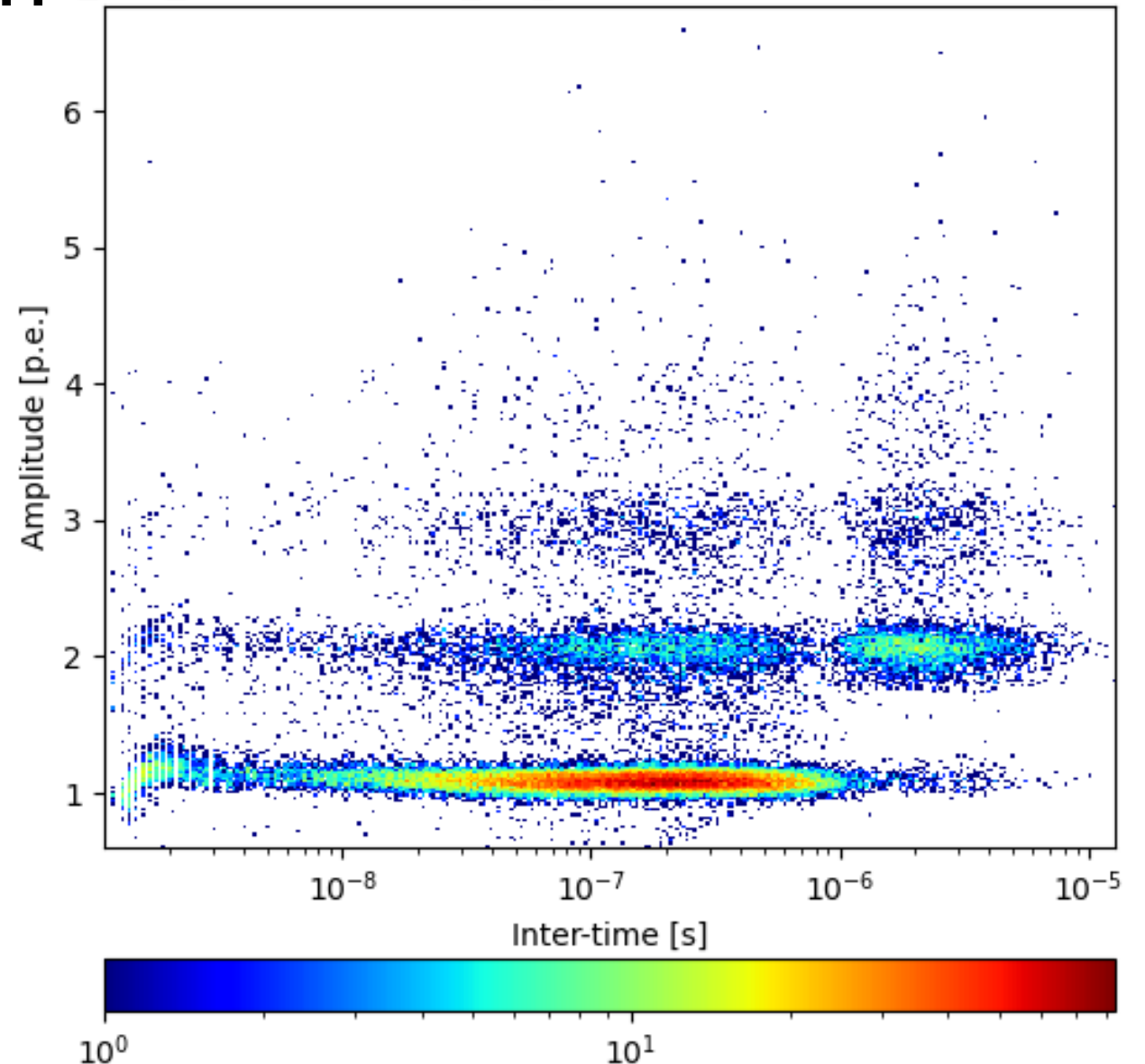
Noise characterization

- Threshold scan
- Dark Count Rate (DCR)



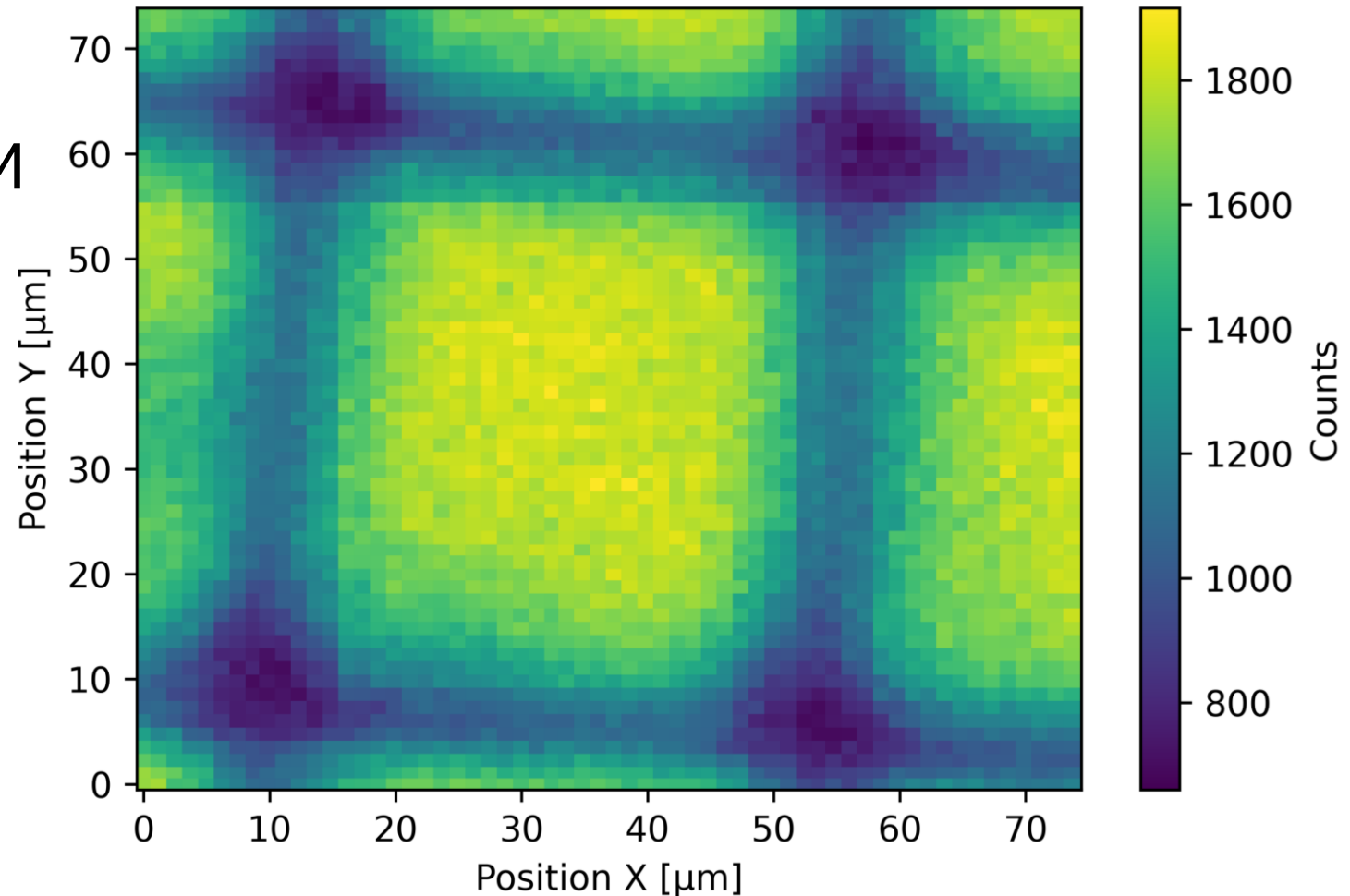
Noise characterization

- Threshold scan
- Dark Count Rate (DCR)
- Dark count statistics
 - Cross-talk probability
 - After-pulse probability



XY scan

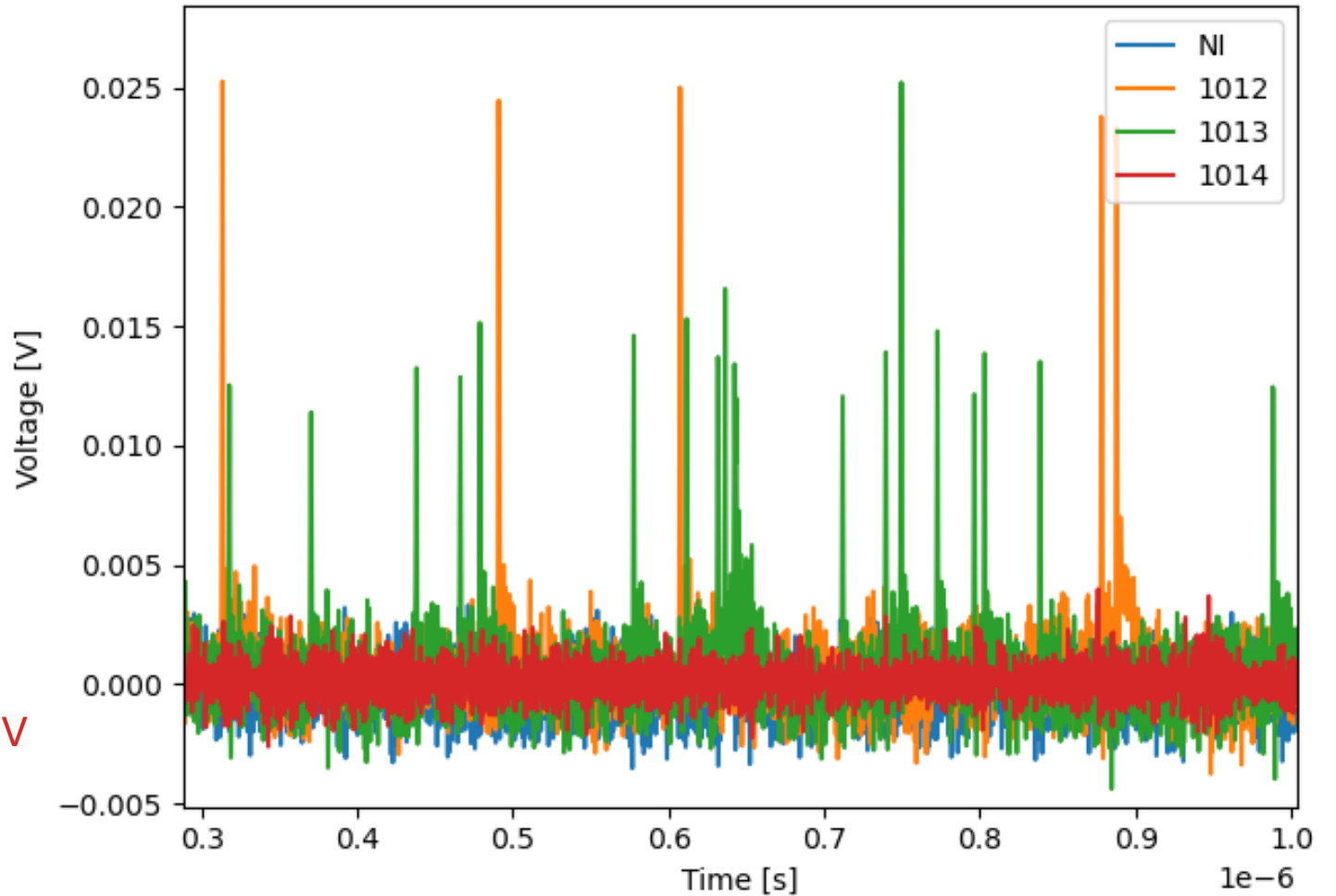
- Event counting efficiency across SiPM surface
- $\sim 3\text{-}5\text{ }\mu\text{m}$ laser point FWHM



Radiation damage

- Equivalent neutron fluence
 - LHCb: $2 * 10^{13} \frac{n_{eq}}{cm^2}$
- Increased DCR
- Decreased peak height

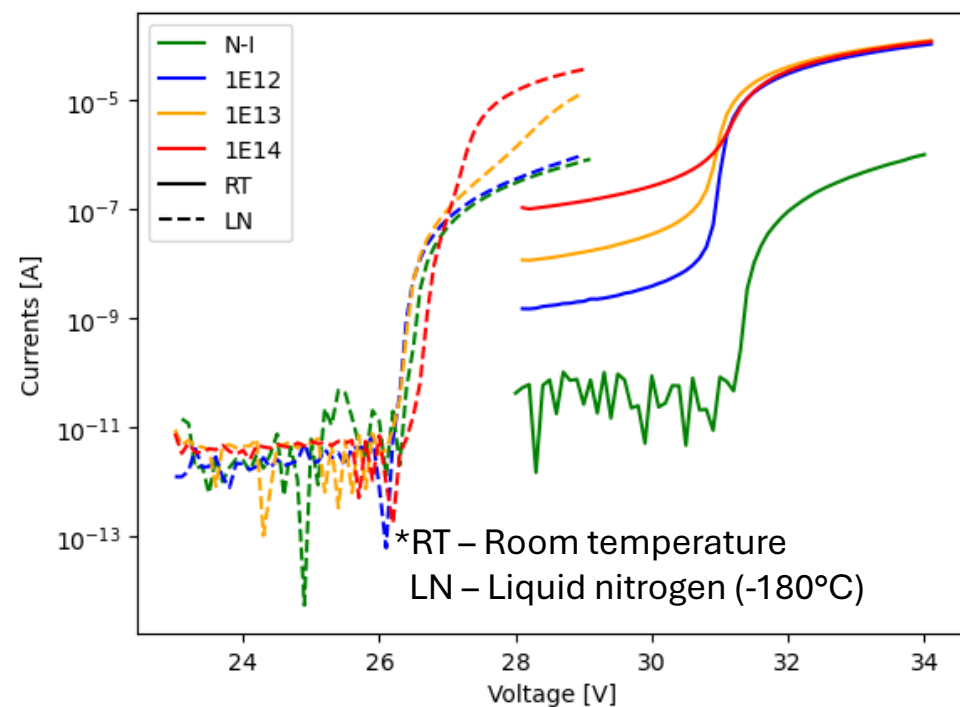
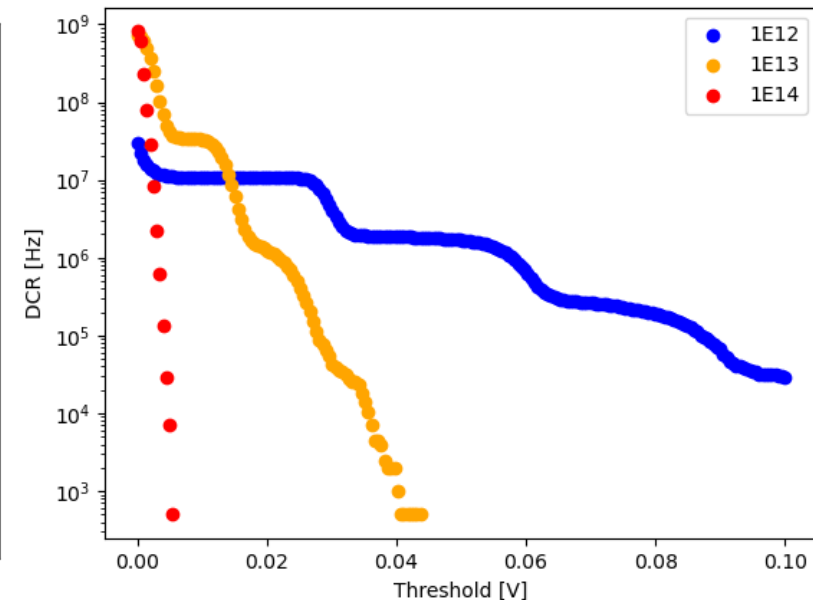
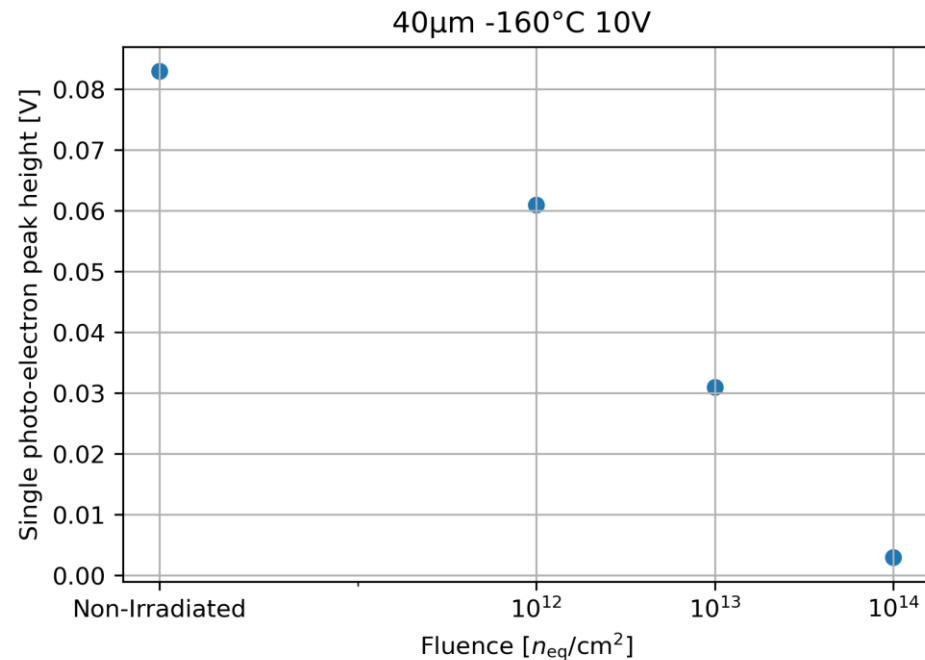
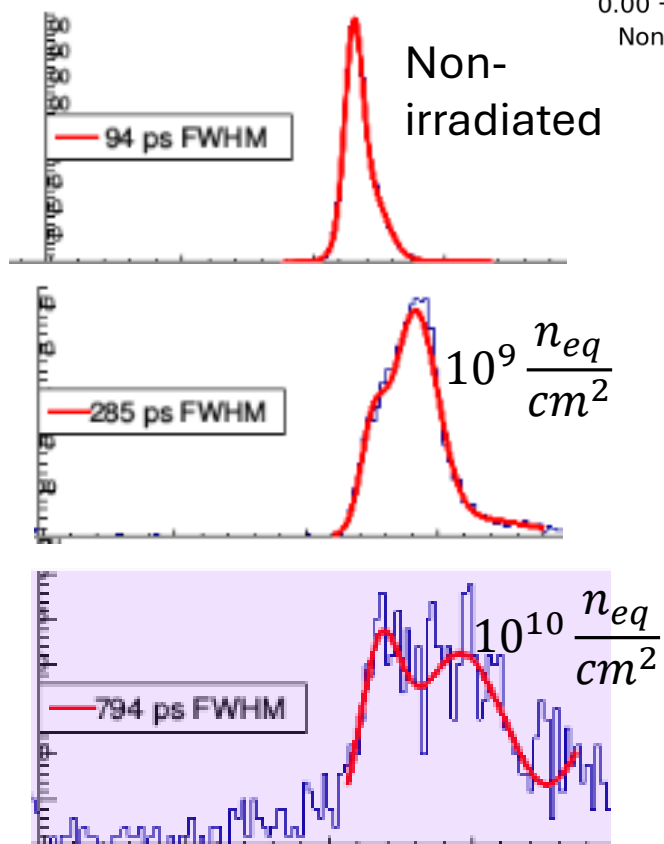
1E14
Peaks height ~ 3 mV



Radiation damage

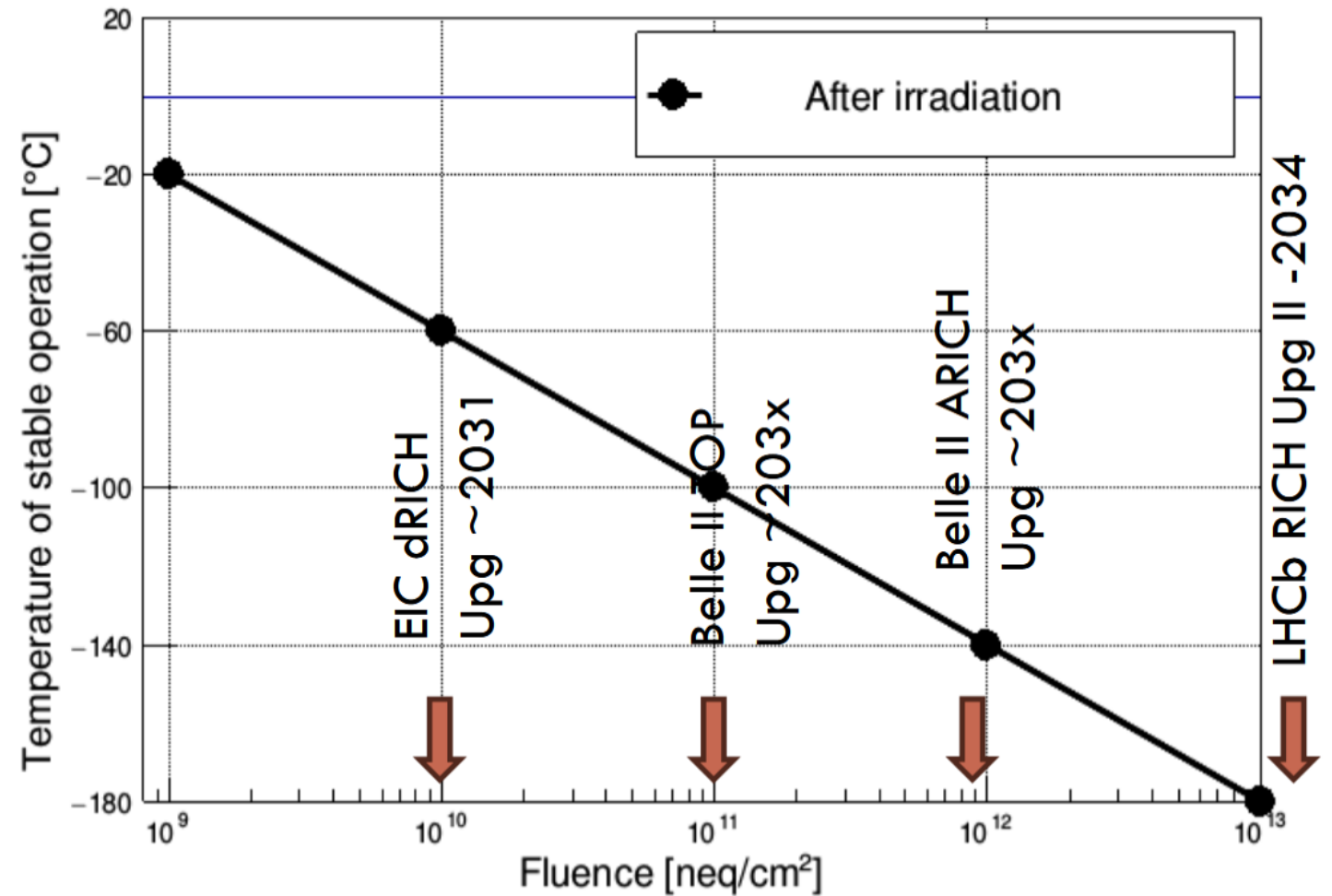
- Equivalent neutron fluence

- LHCb: $2 * 10^{13} \frac{n_{eq}}{cm^2}$



Radiation damage

- Equivalent neutron fluence
 - LHCb: $2 * 10^{13} \frac{n_{eq}}{cm^2}$



Radiation damage mitigation

- Cooling
 - Liquid nitrogen temperature (-196°C)
- Annealing
 - Recrystallization of silicon

Conclusions

- Silicon photomultipliers – good candidate

- Spatial resolution
- Timing resolution
- Radiation hardness
 - Noise
 - Resolution loss
 - Counting loss

- Upgrade 2 – R&D plan

- Operational parameters & best practices
 - Characterization
 - Measurement
 - Analysis
 - Radiation damage mitigation



Thank you