Picosecond timing resolution with 3D trench silicon sensors

<u>F. Borgato</u>, M. Boscardin, D. Brundu, A. Cardini, G.M. Cossu, G.-F. Dalla Betta, M. Garau, L. La Delfa, A. Lampis, A. Lai, A. Loi, R. Mulargia, M. Obertino, S. Ronchin, G. Simi, S. Vecchi

INFN PADOVA
Istituto Nazionale di Fisica Nucleare
Sezione di Padova

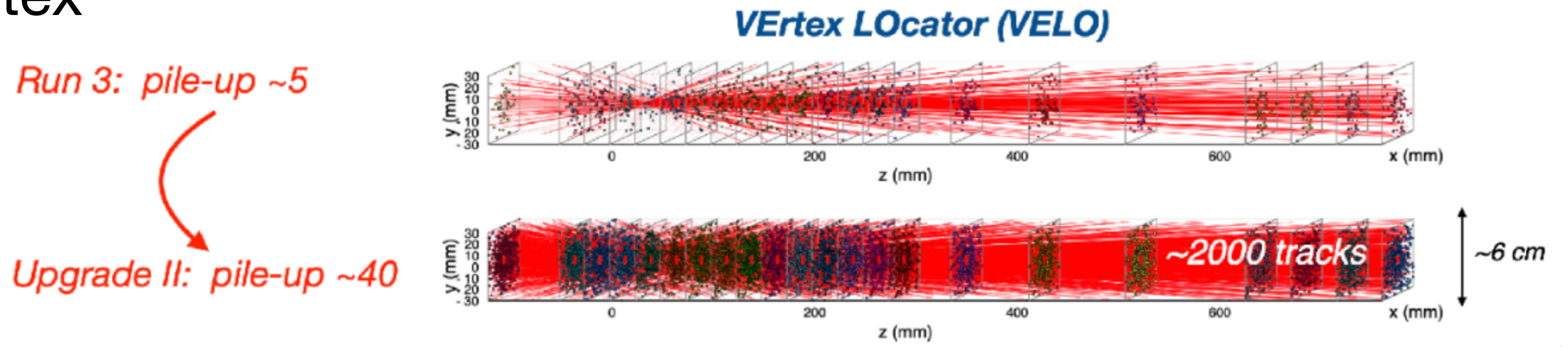
TimeSPOT

International Conference on High Energy Physics XLI
Bologna, 9th July 2022

High Luminosity and Future Colliders

Extremely high instantaneous luminosity planned at today's upgraded and future colliders:

- **High radiation damage** to tracking detectors
- **Difficult event reconstruction** due to large pile-up, implied by:
  - Association of traces to a certain Primary Vertex
  - Correct pattern recognition

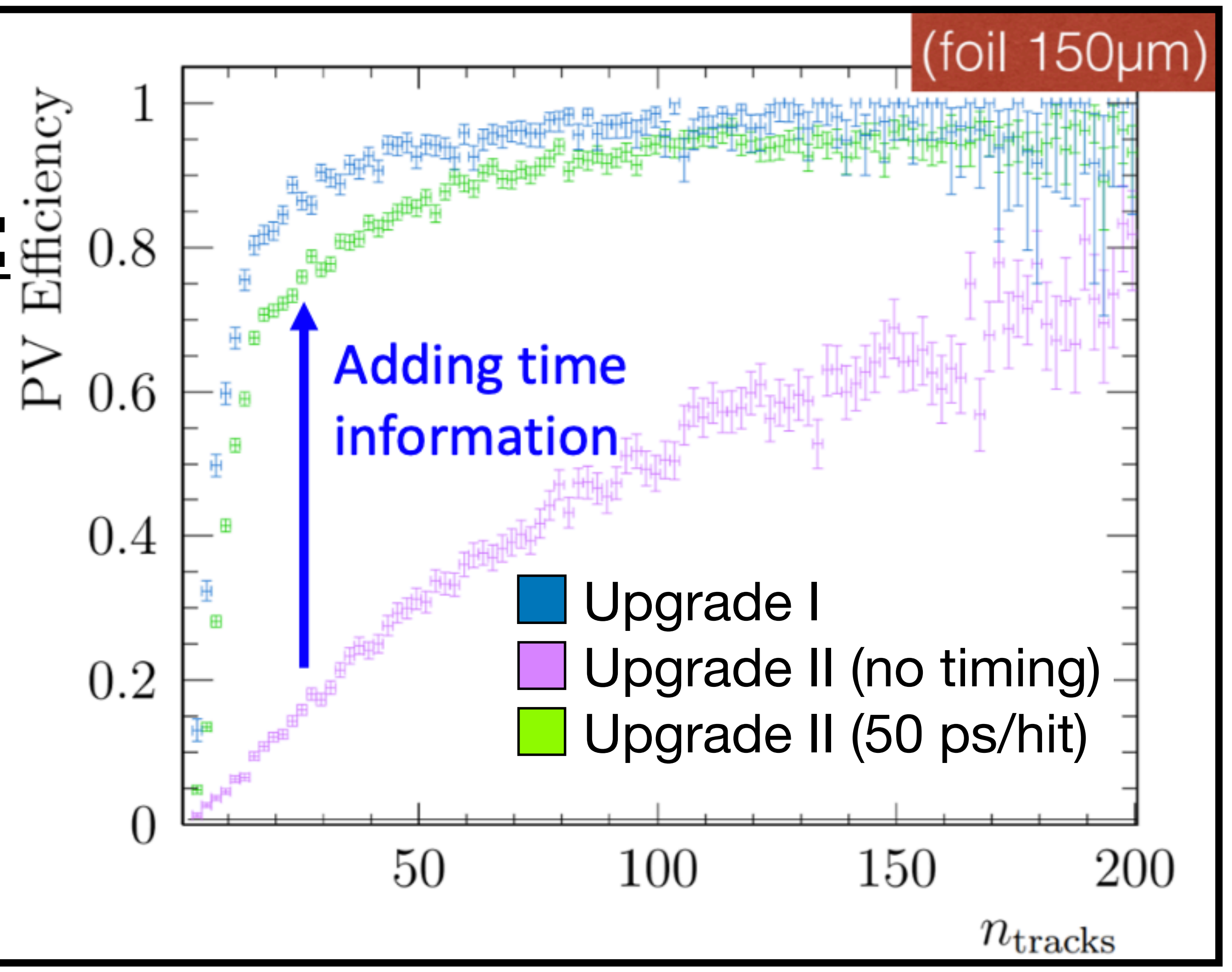


Spatial resolution
Time resolution
Radiation hardness

<u>All required at the same time!</u>

<u>LHCb Upgrade-2 (2030s) requirements:</u>

- σ_t = 30-50 ps
- σ_s = 10 μm
- F = 10^{16} to 10^{17} 1 MeV n_{eq}/cm^2

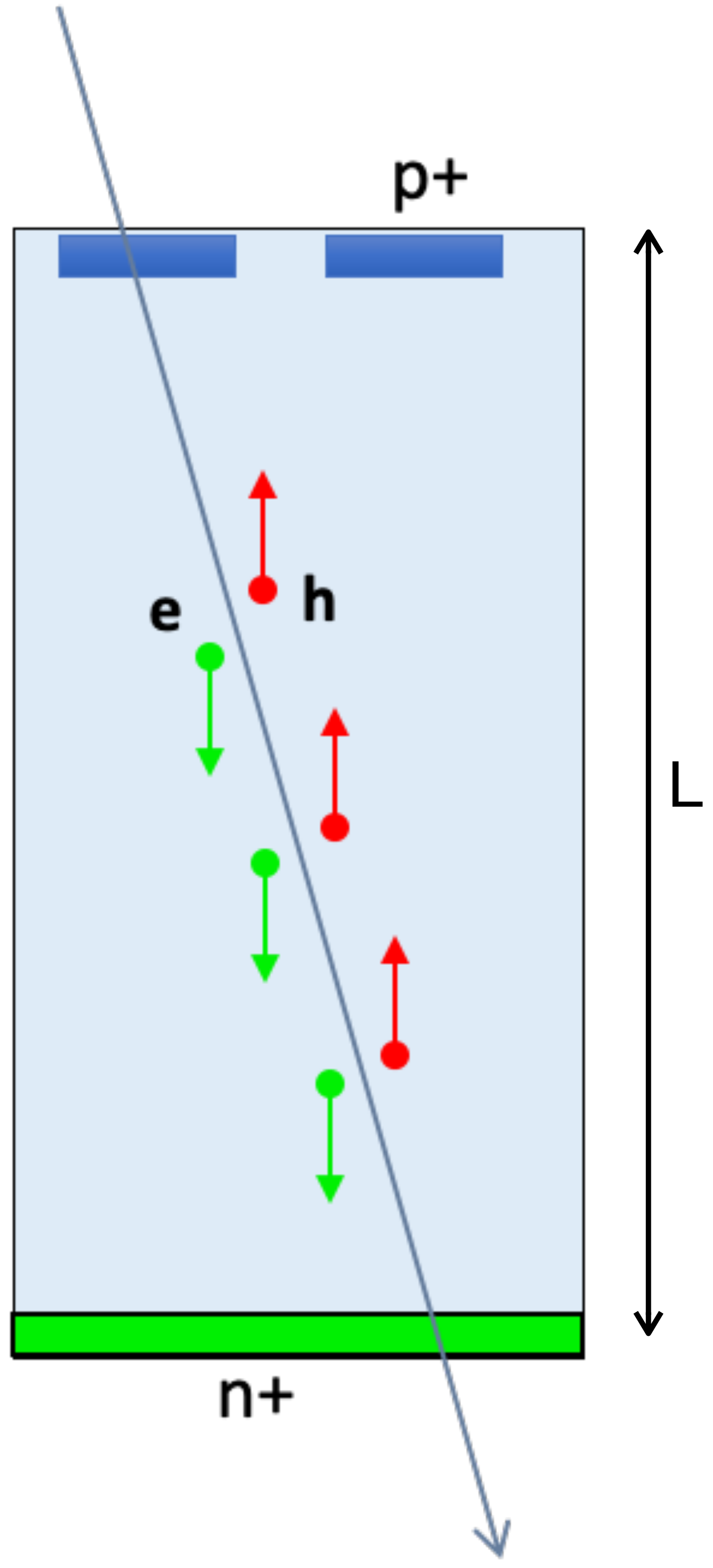


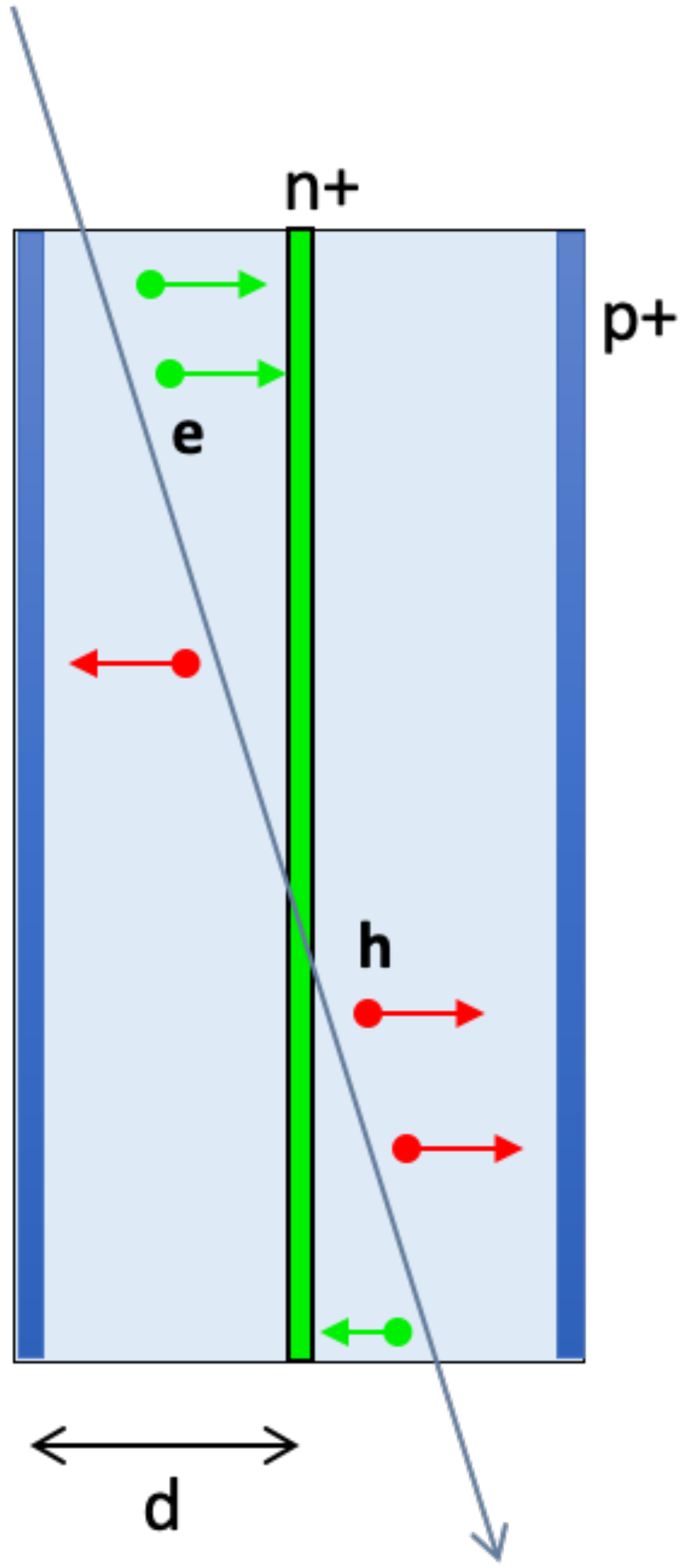
<u>FCC-hh (20??) requirements:</u>

- σ_t = 10-20 ps
- σ_s = 10 μm
- F = 10^{17} to 10^{18} 1 MeV n_{eq}/cm^2

Why 3D sensors?

Original idea by S. Parker, 1997





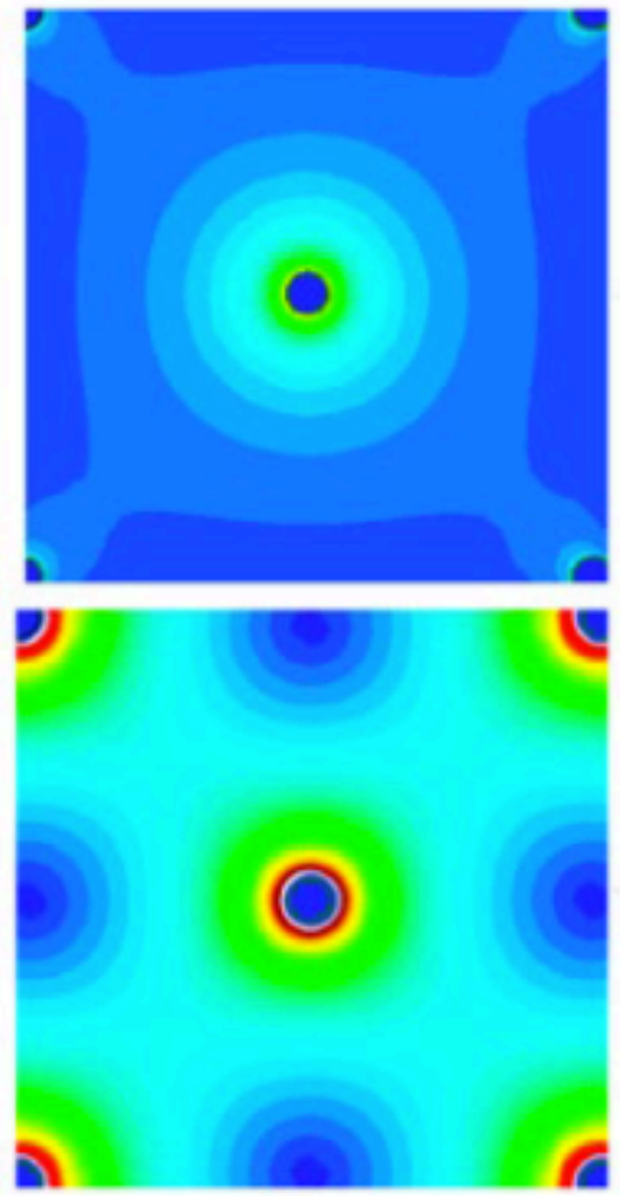
- Short inter-electrode drift distance: **extremely fast signals** (d<<L)
- Active volume and **electrode shape** can be **designed for maximum performance**
- **Unmatched radiation hardness** ($>10^{17}$ 1 MeV n_{eq}/cm^2) *NIMA, 979 (2020) 164458*
- 3D columnar geometry is a production-ready technology (ATLAS IBL, ATLAS-P2)

The optimized 3D sensor design

Current signal is defined as (Ramo's theorem):

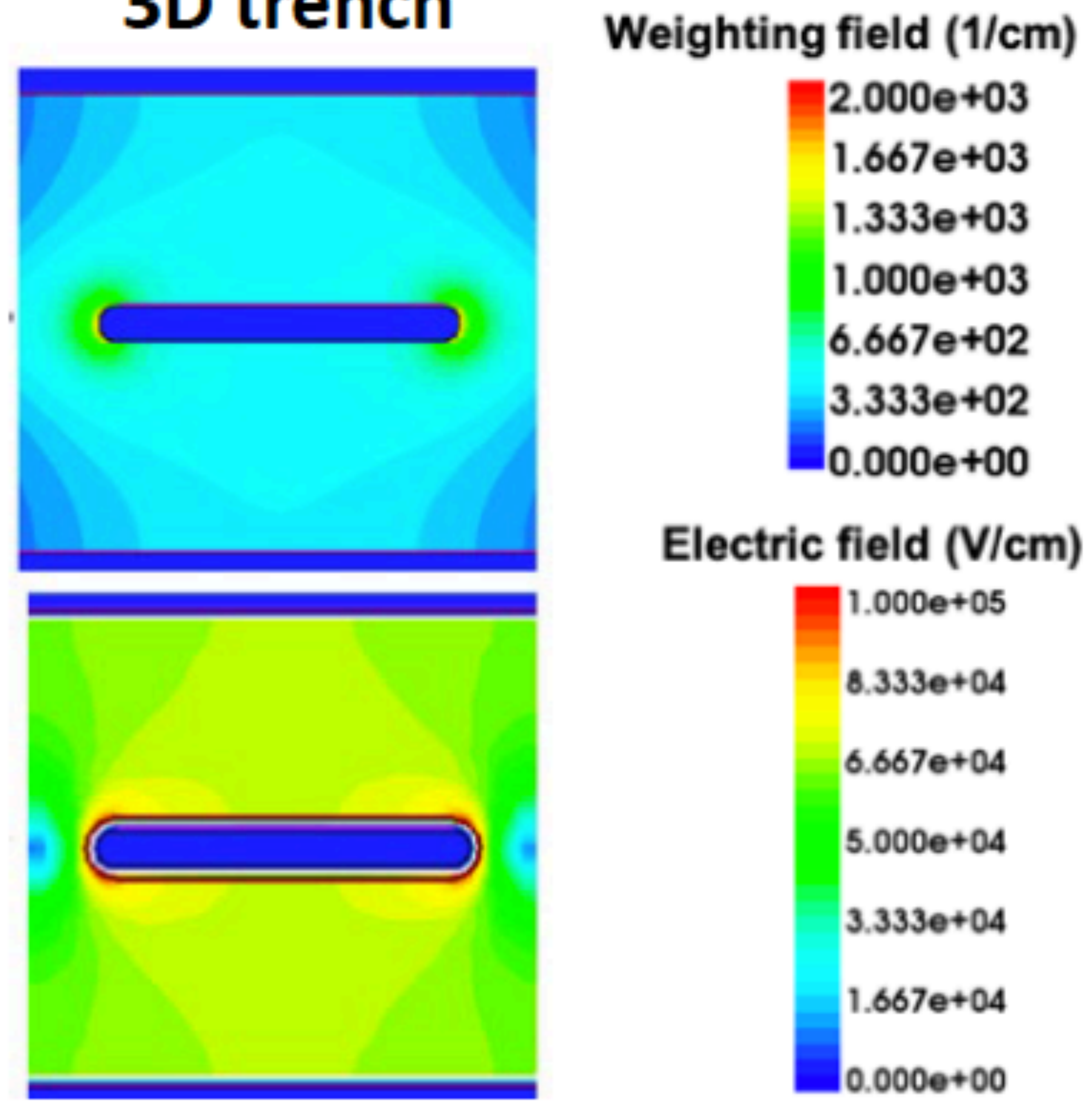
$$i = q\, \vec{E}_W \cdot \vec{v}_d$$

5 columns



Towards uniformity in both E_W and velocity

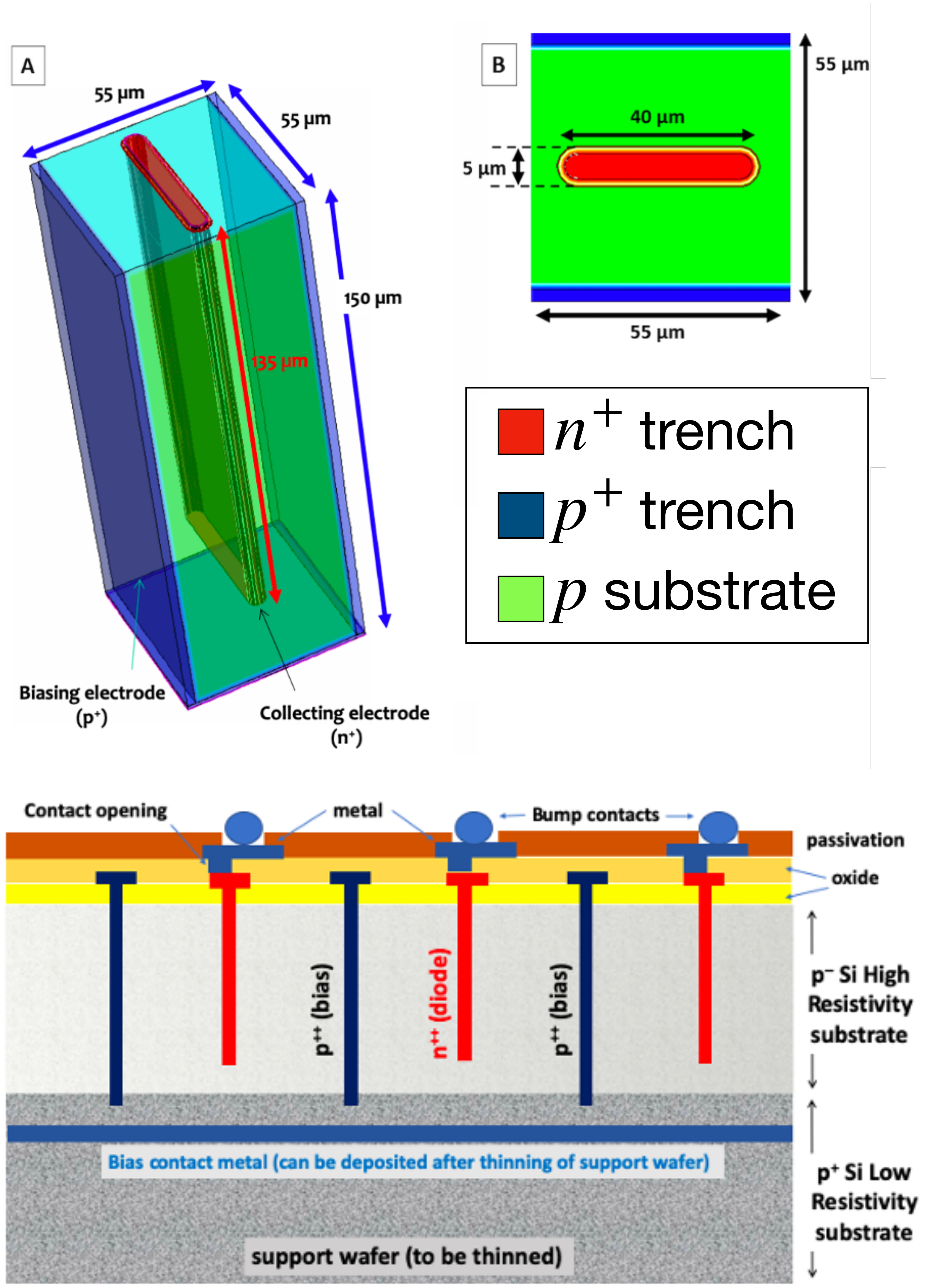
3D trench



TCAD simulation $V_{bias} = -150V$

Electrode shape optimization
allows the **signals** to be **independent of the hit position**

The trench-type TimeSPOT 3D sensors



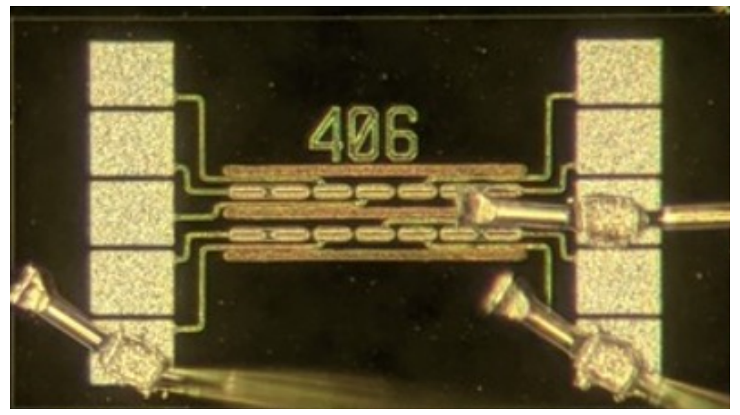
- **55x55 μm^2 pixels** (compatible with existing FEE)
- In each pixel a **40 μm long n++** trench is placed between the continuous p++ trenches for the bias
- **150 μm active thickness**, on a 350 μm-thick support wafer
- Collection electrode **135 μm deep**

The Fabrication Process

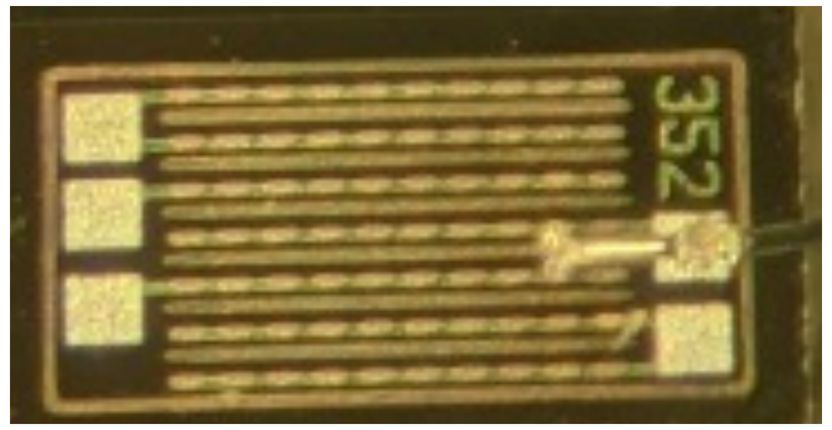
Two batches were produced in 2019 and 2021 at Fondazione Bruno Kessler (FBK, Trento, Italy) using the Deep Reactive Ion Etching (DRIE) Bosch process, 6” wafers.

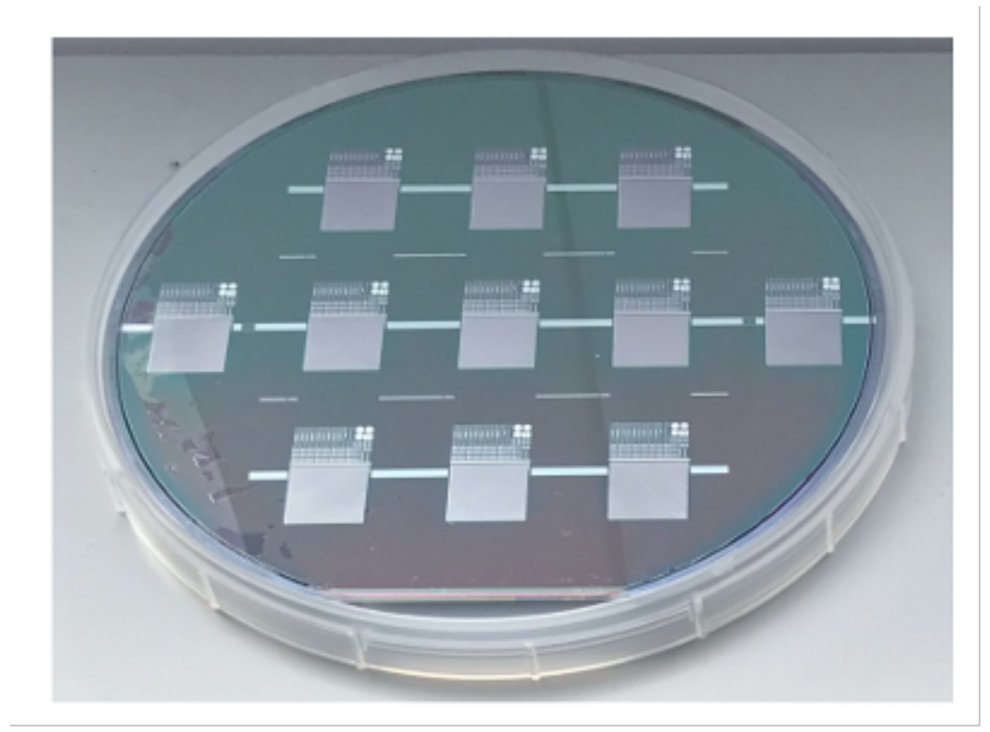
Many devices were designed and fabricated, such as:

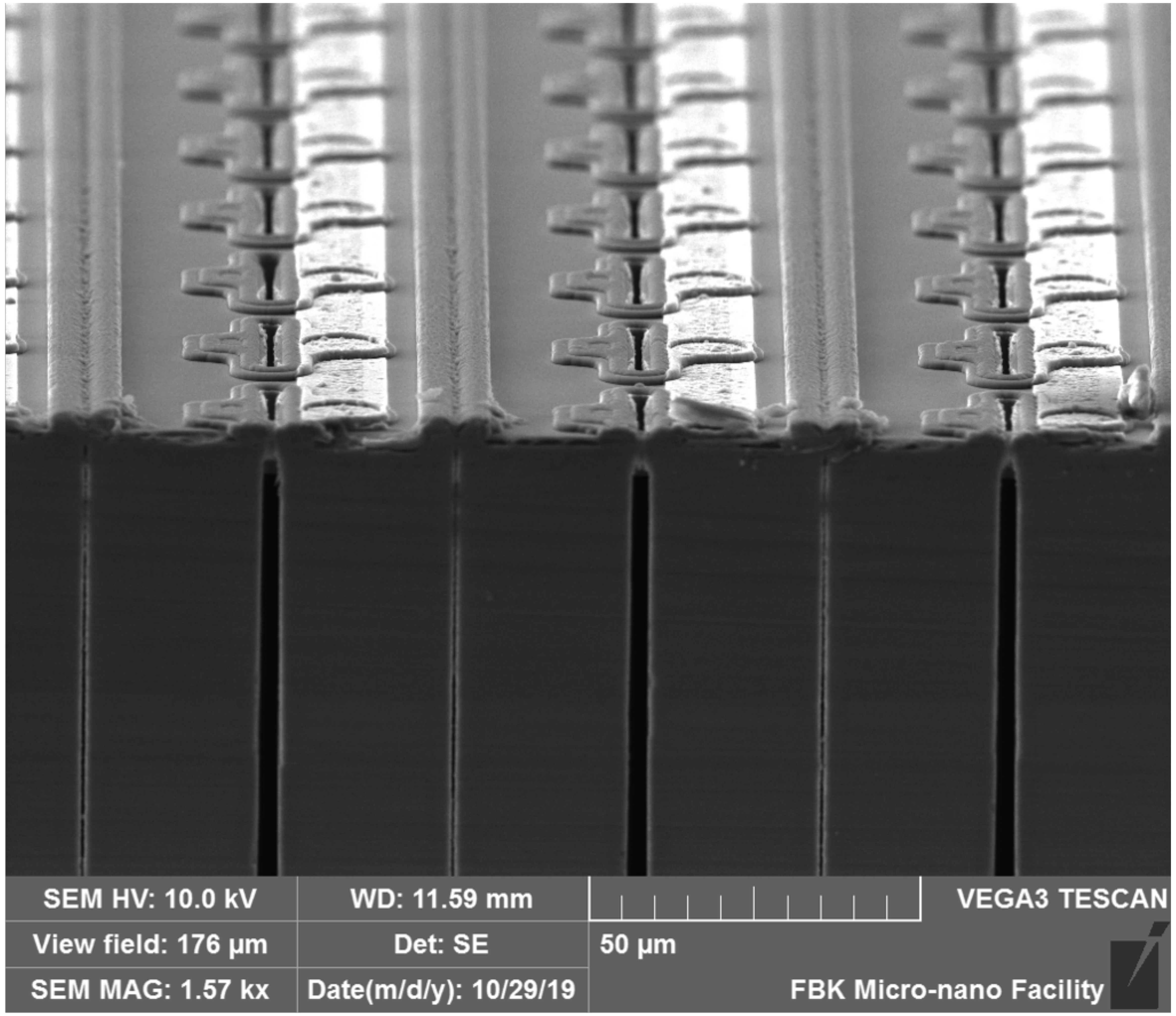
Pixels



Pixel strips

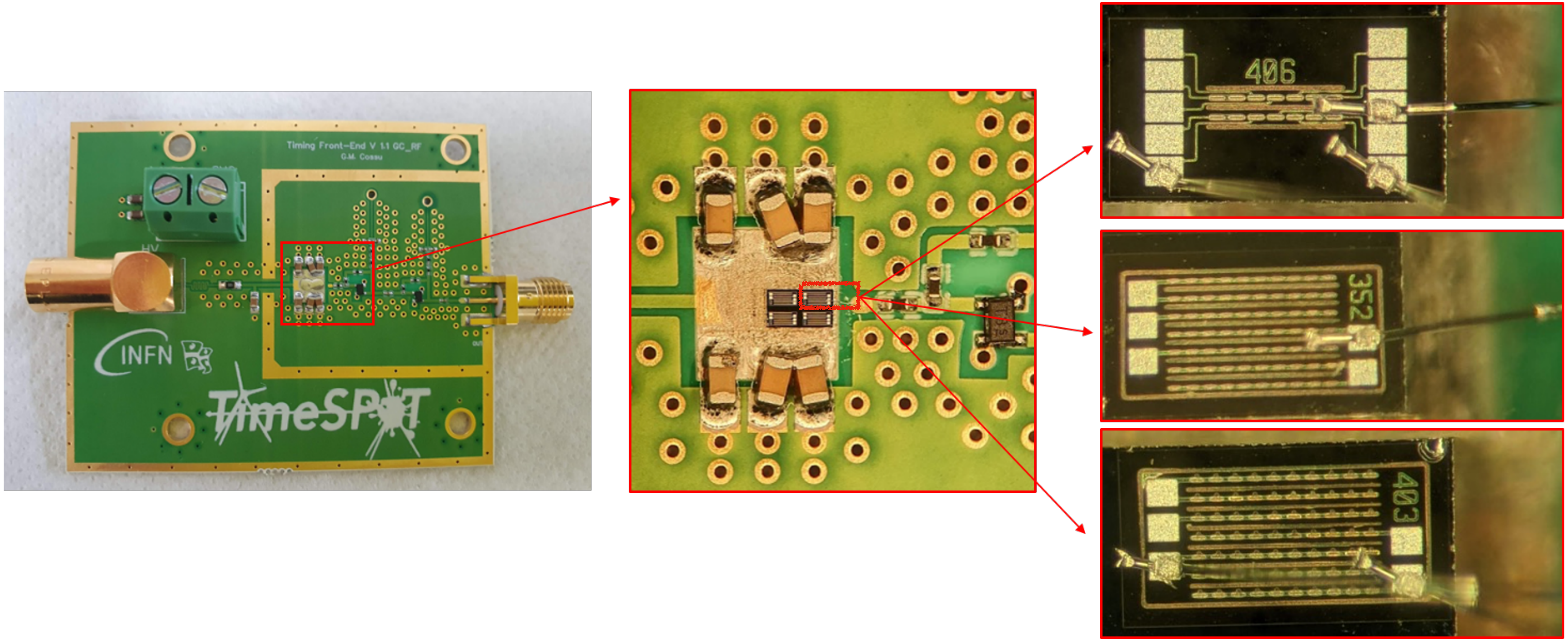






Tested devices: timing and efficiency

- Different devices were tested at **SPS/H8** (November 2021, May 2022)
- Custom made front-end electronic boards featuring a **two stage transimpedance amplifier**



1 PIXEL

1 STRIP (10 pixels)

3 STRIPs (30 pixels)

SPS beam test: Experimental Setup

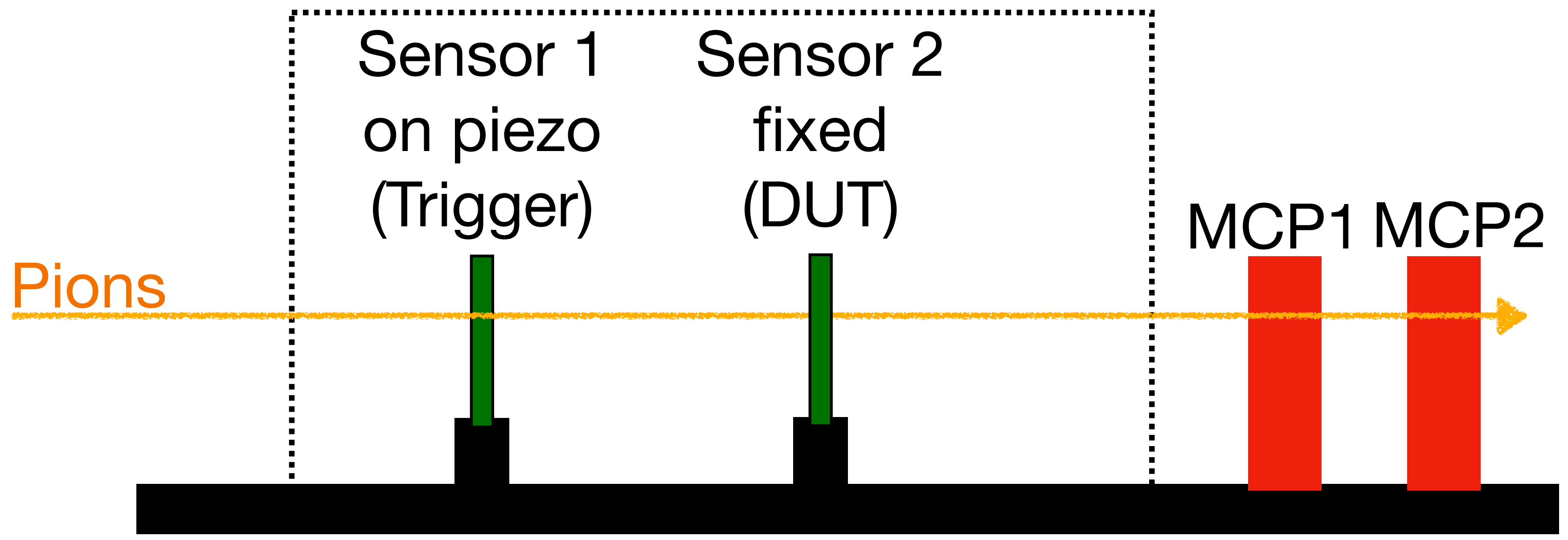
- **180 GeV/c π^+ beam,** 10^6 pions per spill on a beam spot of 8mm RMS transverse size

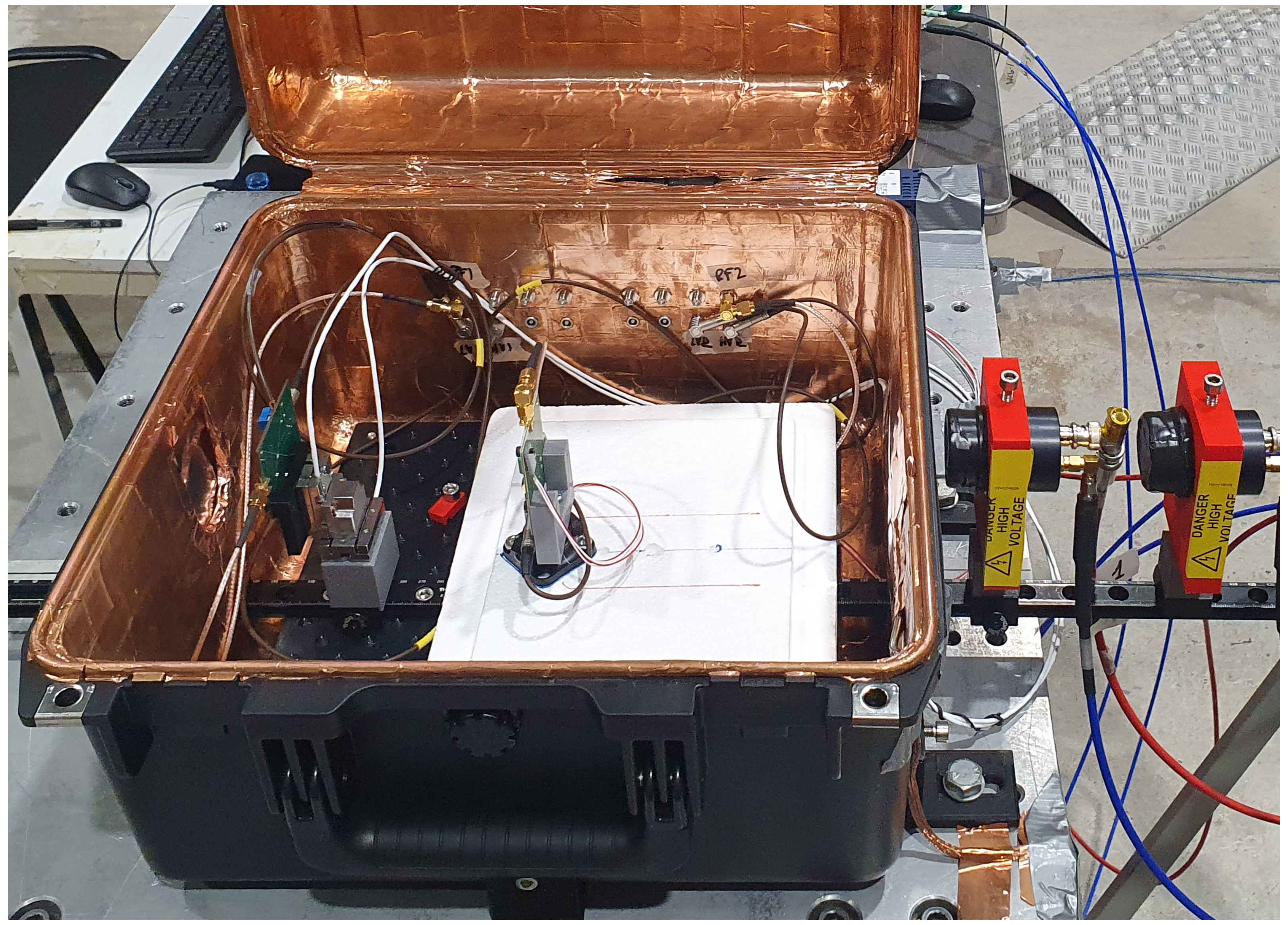
- 2 **MCP-PMTs** on the beam line to **time-stamp** the arriving particle (σ_{avg} = 5-7 ps)

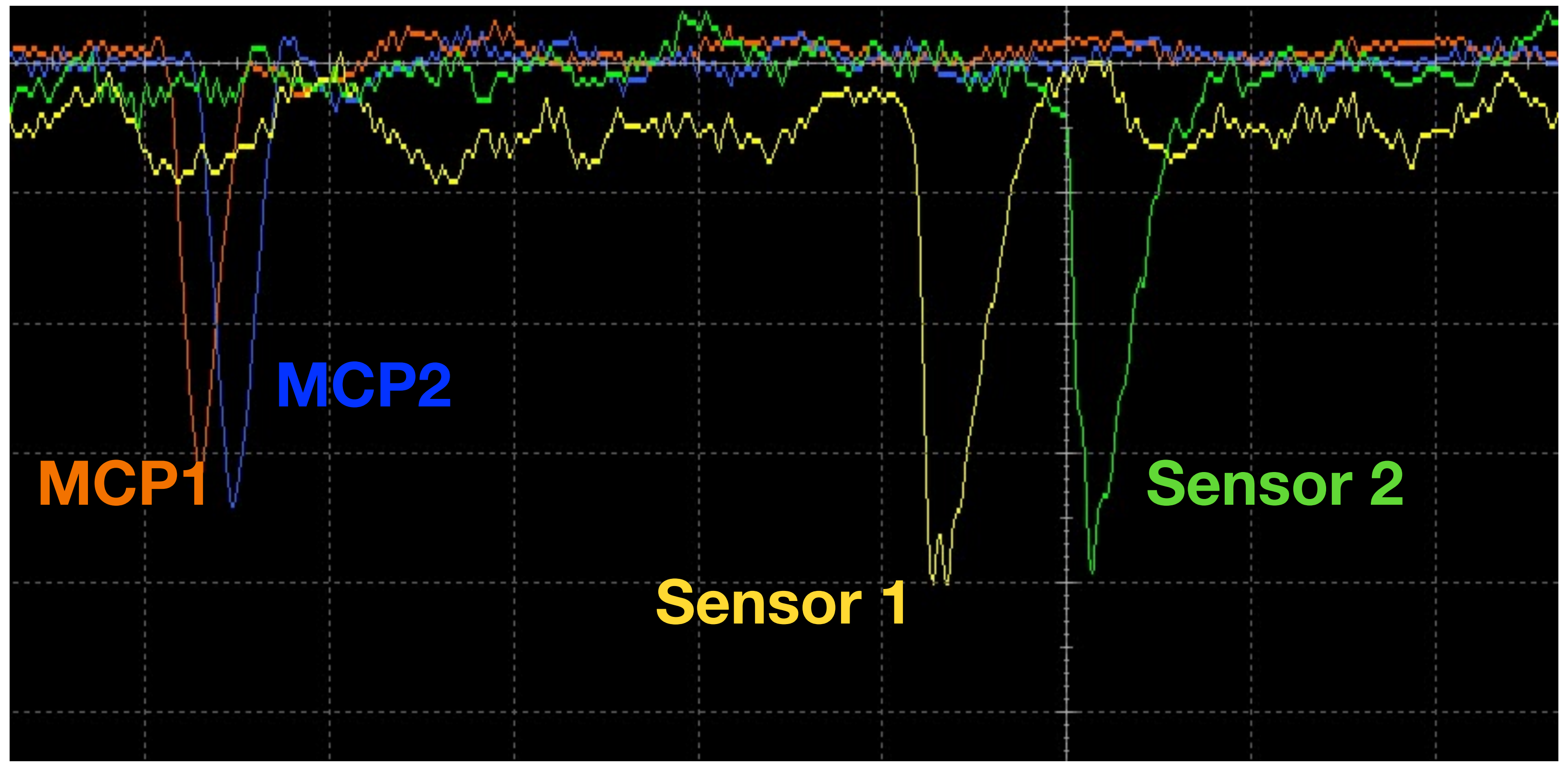
- One **sensor fixed** (sensor 1), one **sensor mounted on piezoelectric stages** (sensor 2) to precisely align the two 3D structures, all mounted in a RF-shielded box

- Possibility of operating the fixed sensor down to **-40°C** using dry ice to test **irradiated devices.**

- Readout with **8GHz bandwidth 20GS/s Scope**, trigger on the AND of one 3D sensor and one of the MCP-PMTs



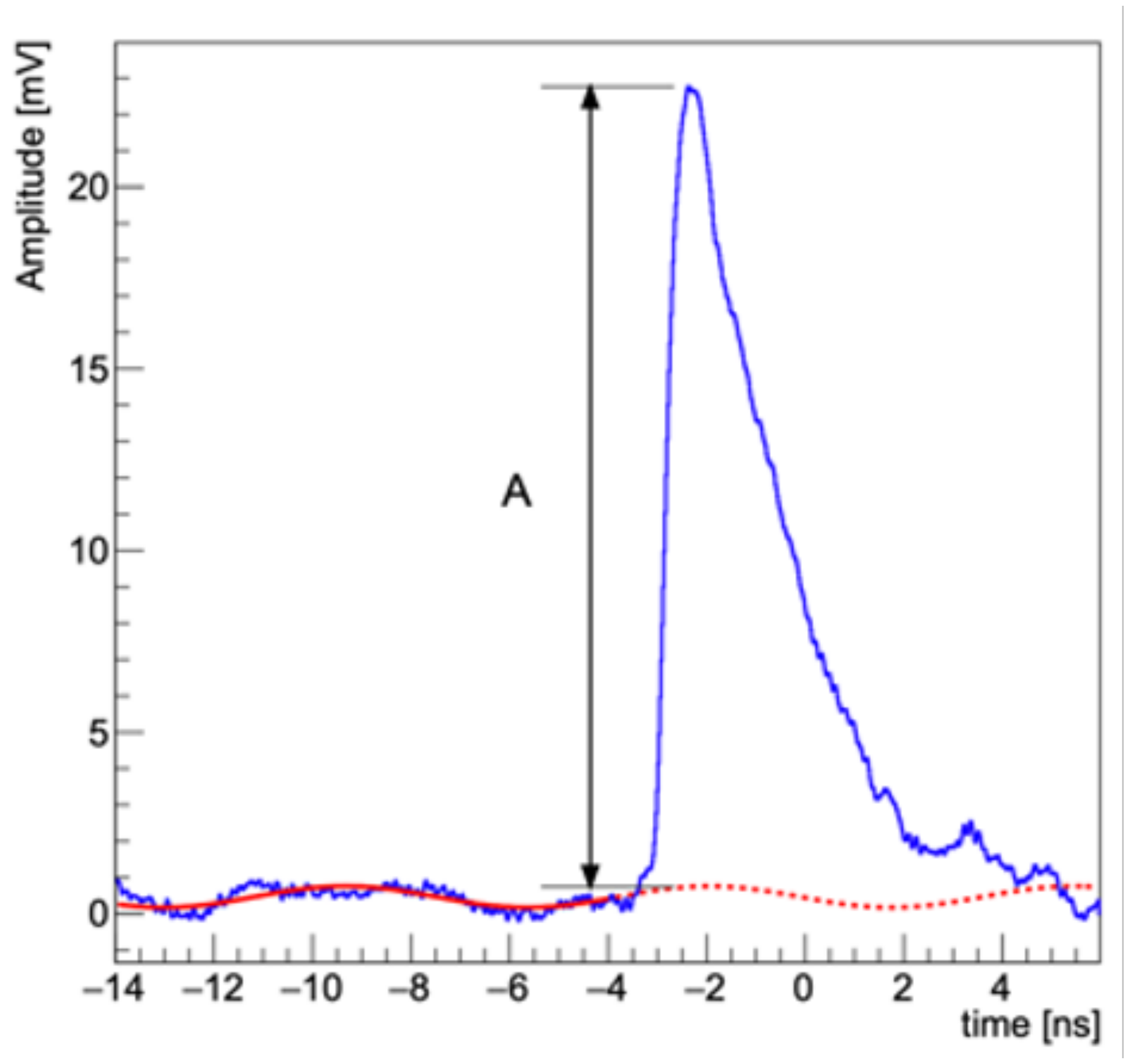


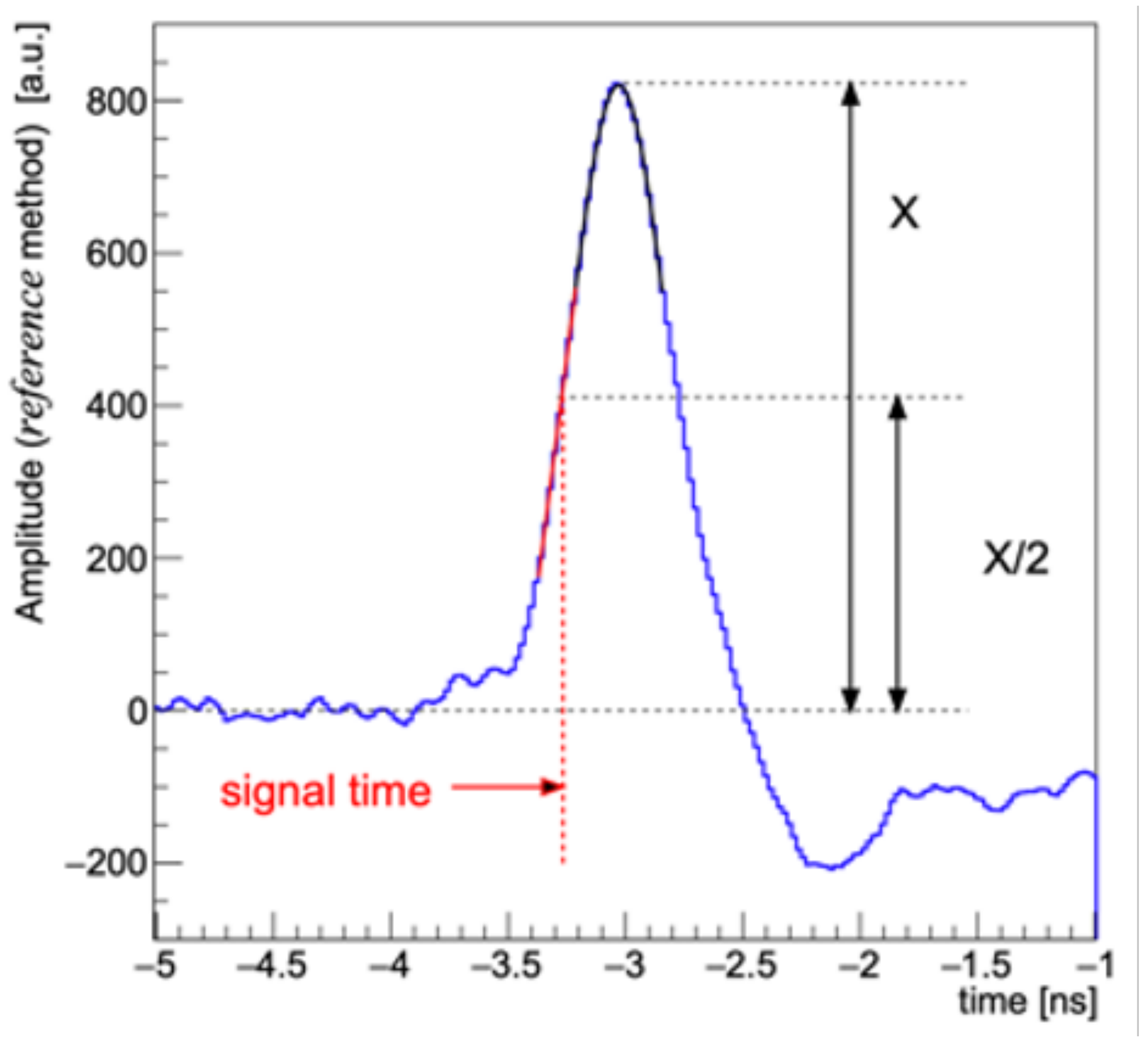


Waveforms Analysis

For each waveform:

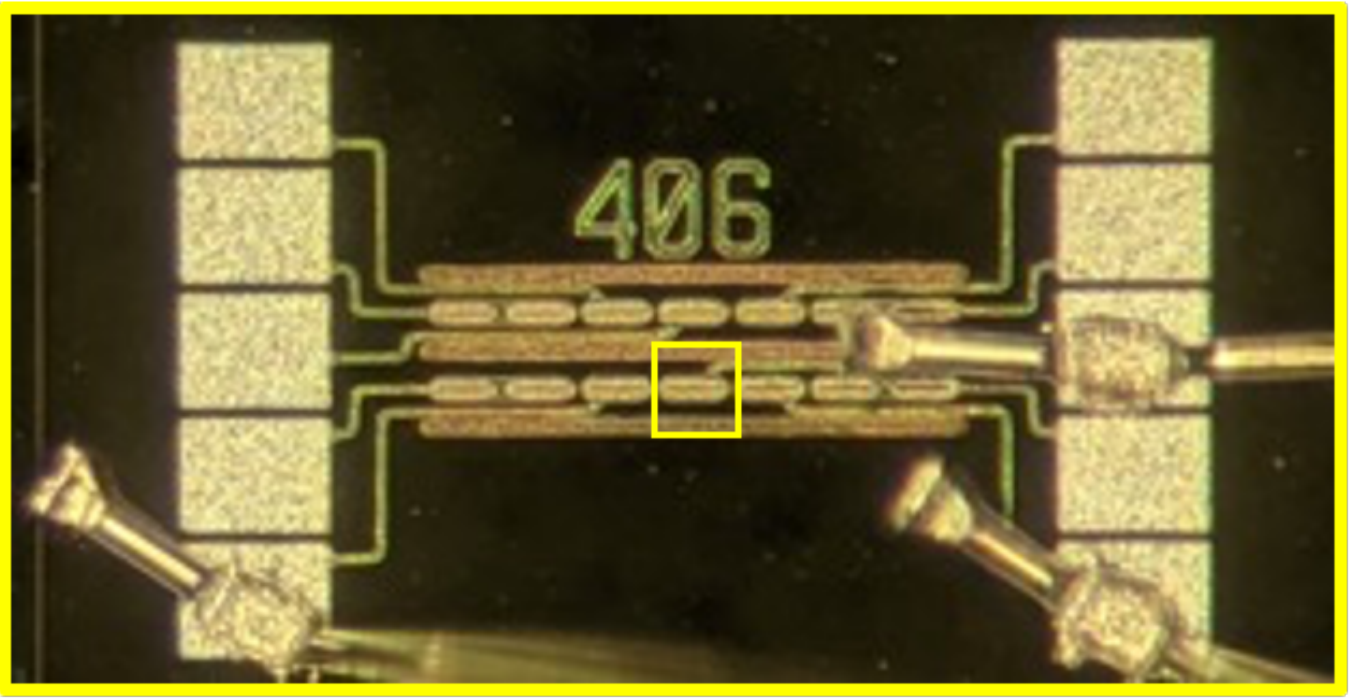
- Signal baseline is evaluated on an event-by-event basis
- The **signal amplitude A** is measured (w.r.t. to the baseline)
- Signal **time of arrival** evaluated with various methods:
    - **Leading edge:** time at 15 mV signal amplitude
    - **Spline:** a CFD at 35% with rising edge interpolated with a spline
    - **Reference:** subtract each waveform from a delayed (by half of the signal rise time) copy of itself, then on the resulting signal we trigger at X/2 height



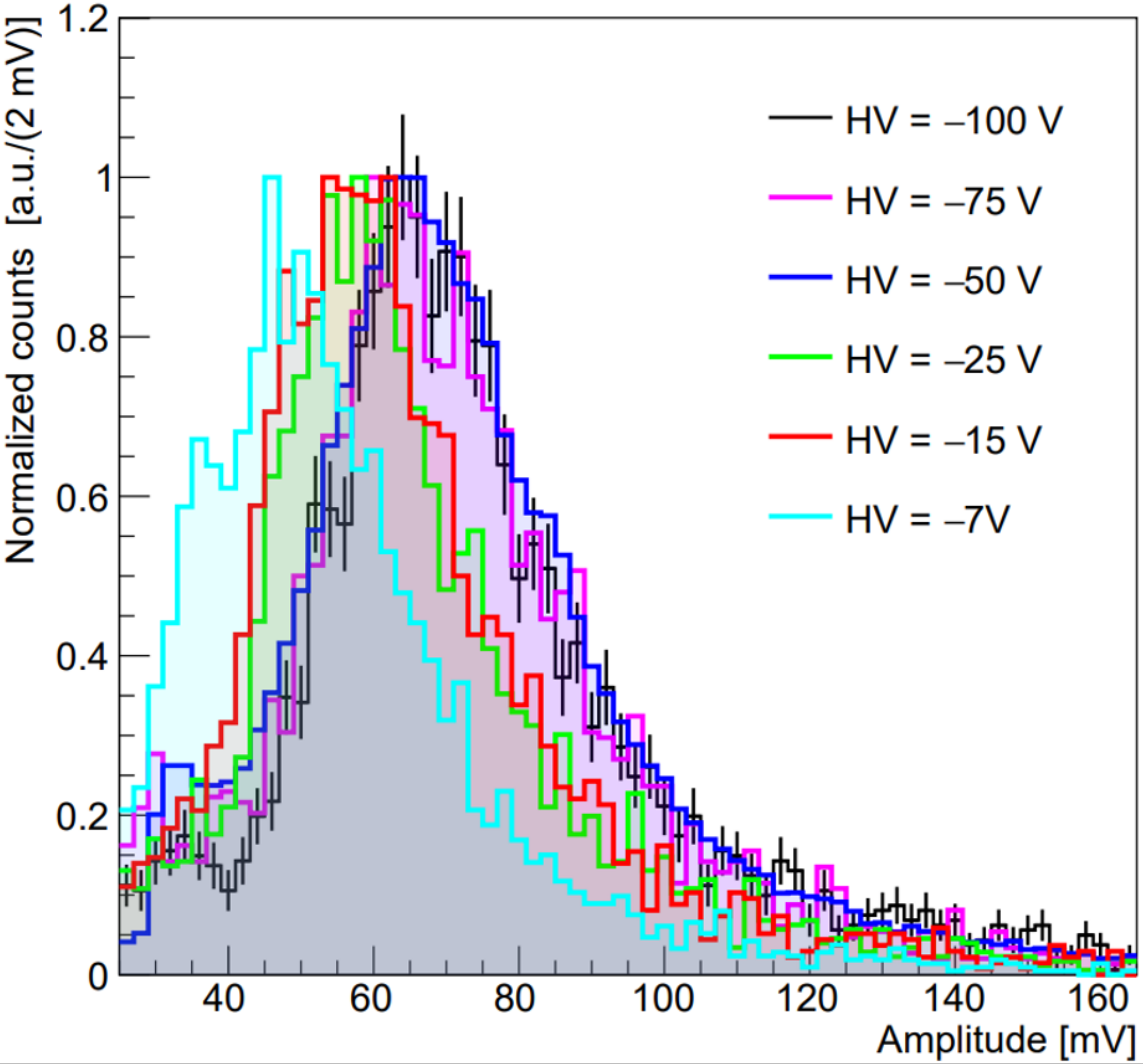


3D pixel: amplitude performance

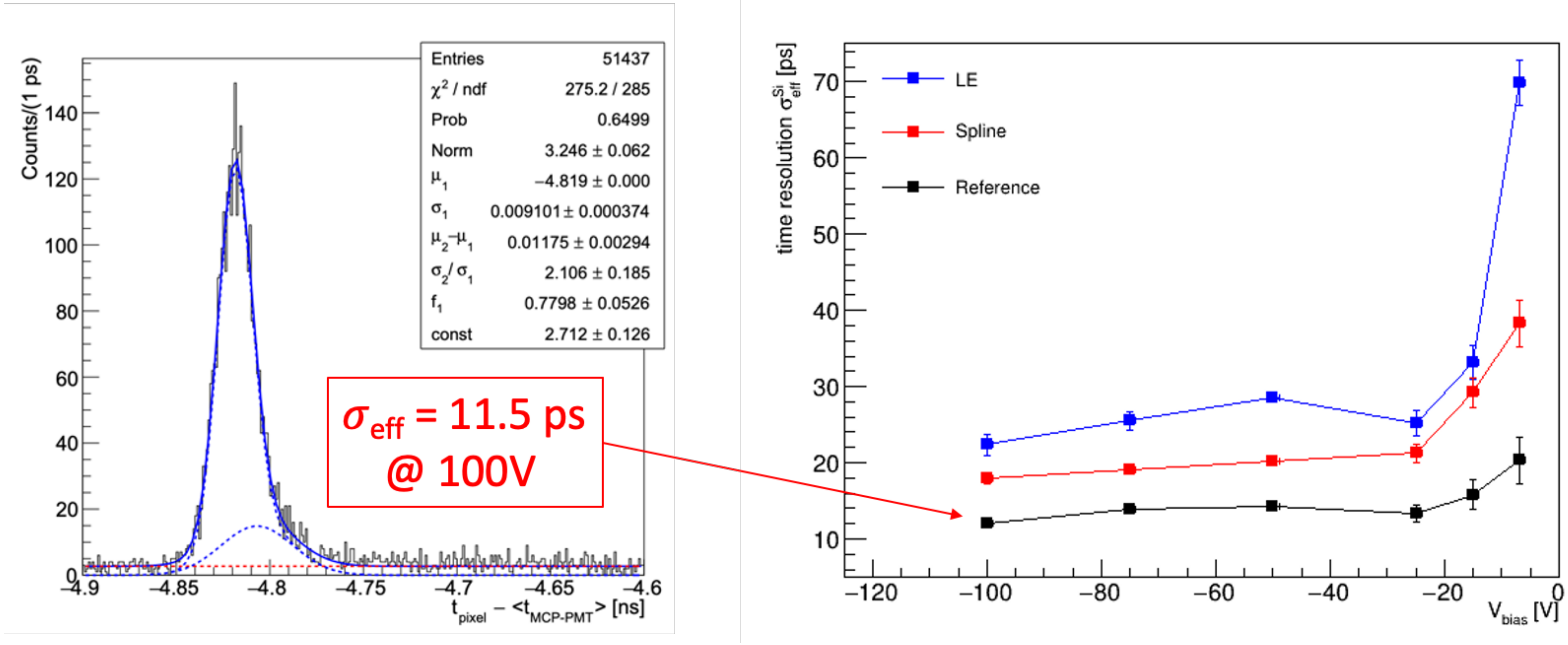
NON-IRRADIATED PIXEL



- Normal incidence
- The pixel (DUT) is **not on the trigger**
- **Good** sensor **performance** at **low bias voltage**



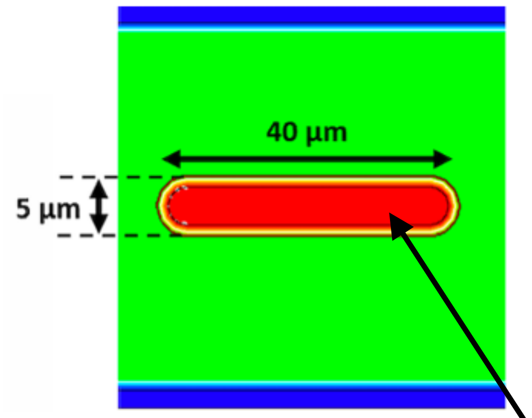
3D pixel: timing performance



- **Symmetric time distribution**, with only a **small tail** due to late signals
  ⟶ Time distribution fitted with two gaussians to include late signals contributions

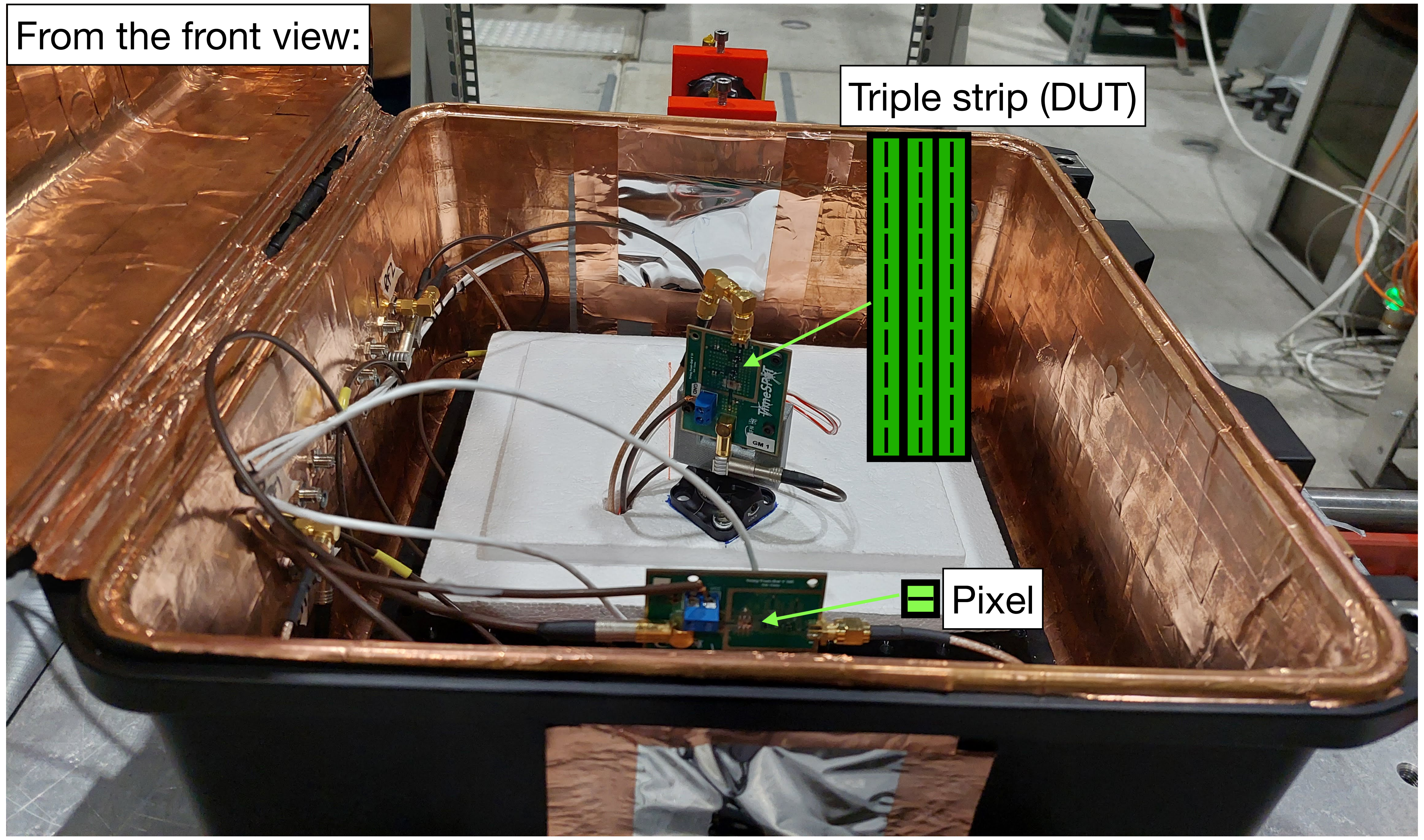
- **Excellent performance** with **CFD-based methods**, but also using **leading edge algorithm** (no time walk correction)

Efficiency tests: the setup



The **trenches** are **non-active volumes**:

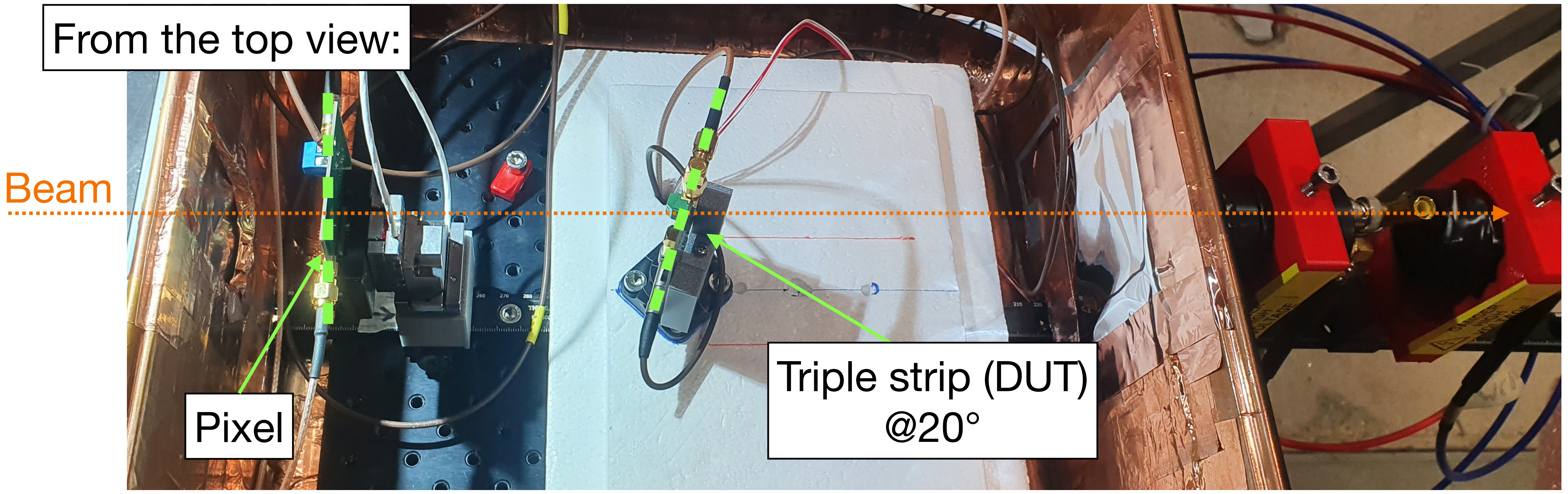
to **tilt the sensor** with respect to normal incidence is **needed** to **recover the geometrical efficiency**



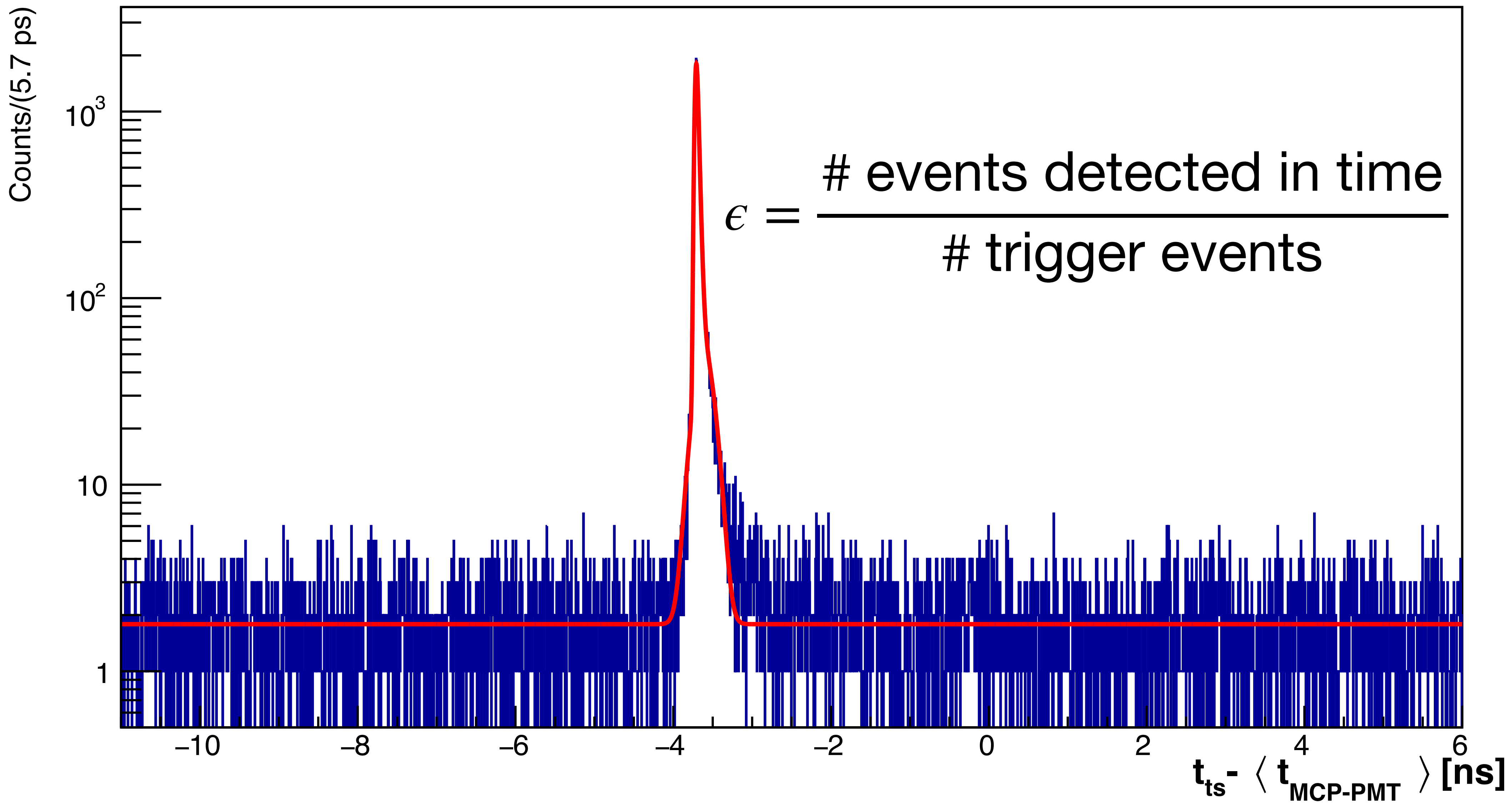
To **measure efficiency**:

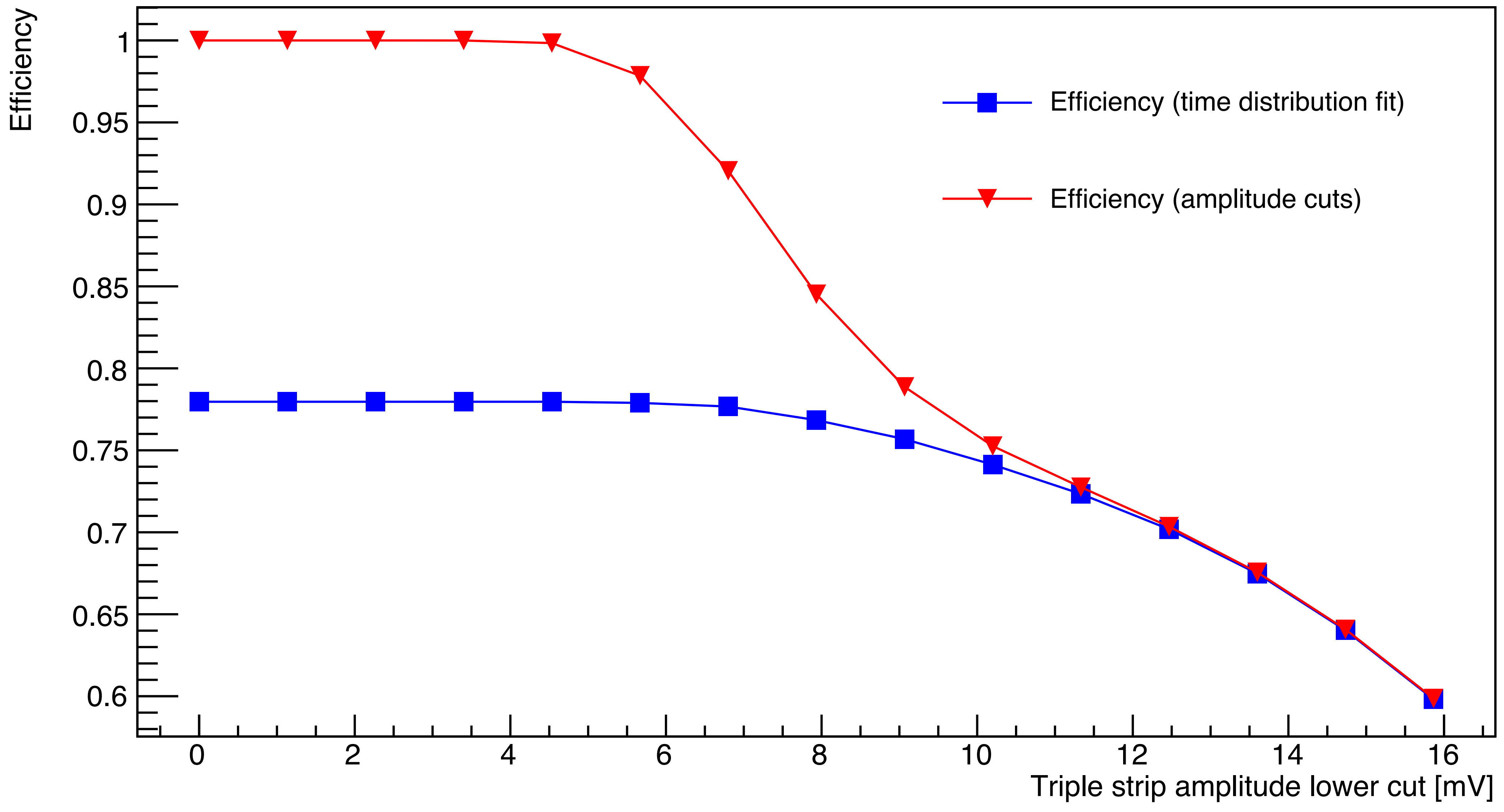
- Trigger on a **single pixel** ($55\text{x}55\mu\text{m}^2$) **centered** on a **triple strip** ($165\text{x}550\mu\text{m}^2$) and **counting the fraction of signals seen in the triple strip**

- The single **pixel** is mounted on the **piezoelectric stages**, the **triple strip** has fixed position but can **rotate around the trench direction**



Efficiency tests: the method



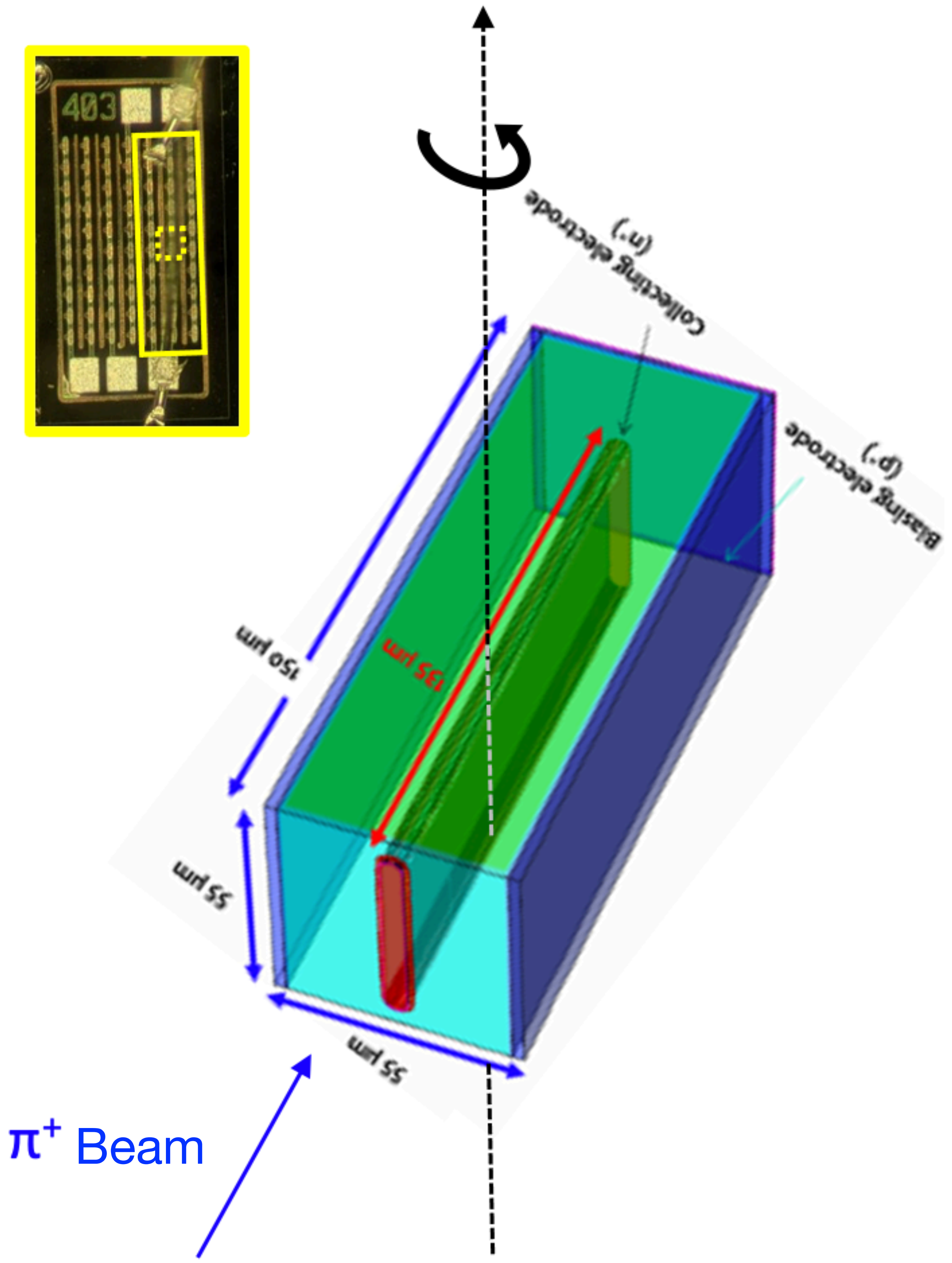


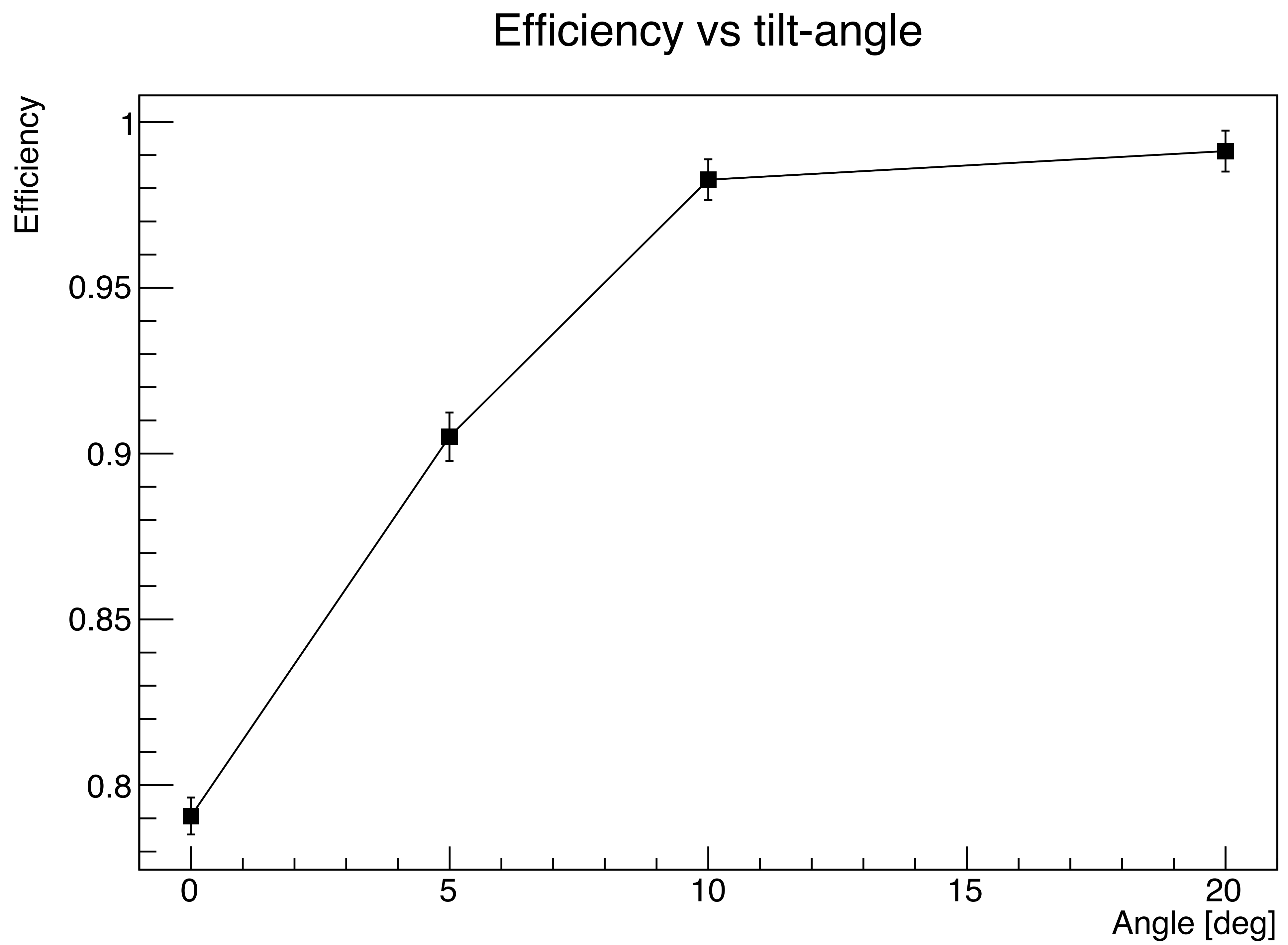
*Red line includes noise contribution

*no correction for the beam divergence

- From the **time distribution of the triple strip signals w.r.t the MCP-PMTs**, the **efficiency** is computed by the number of **events in time** (populating the peak) over the **total number of trigger events**
- **3D pixel detection (geometrical) efficiency** at normal incidence is in **agreement with calculated fraction of active area** ($\approx 80\,\%$)

Efficiency tests: the results

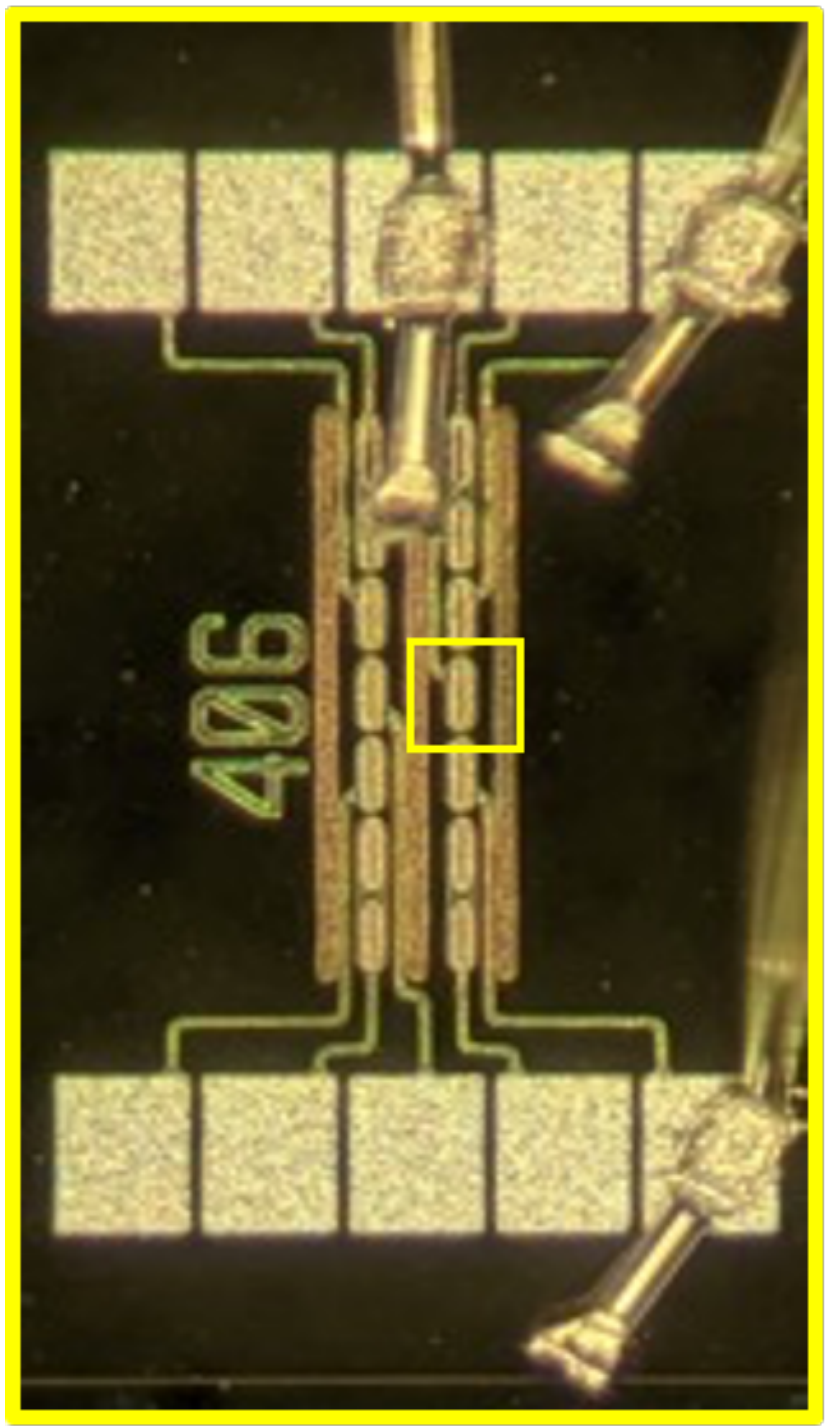


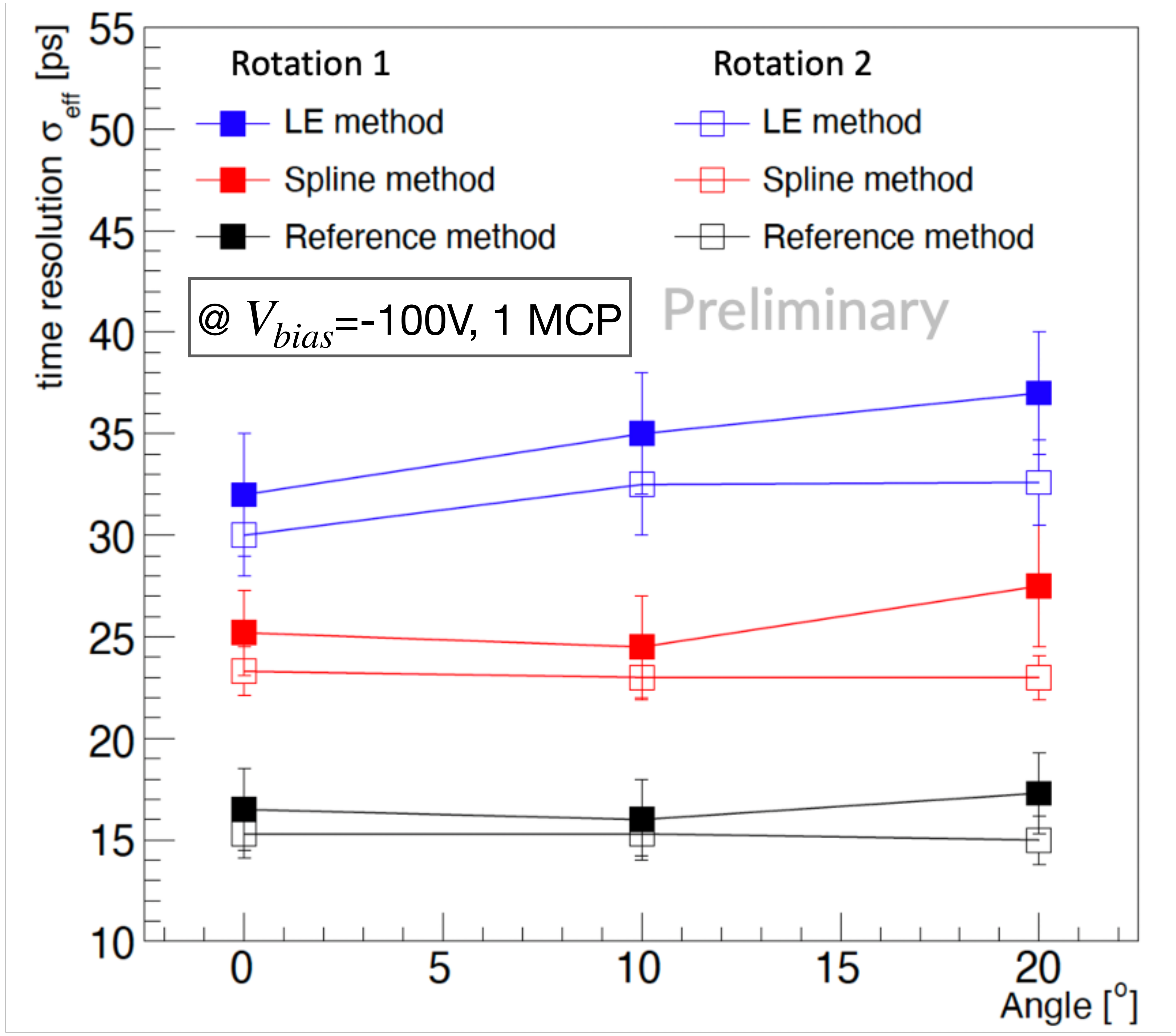


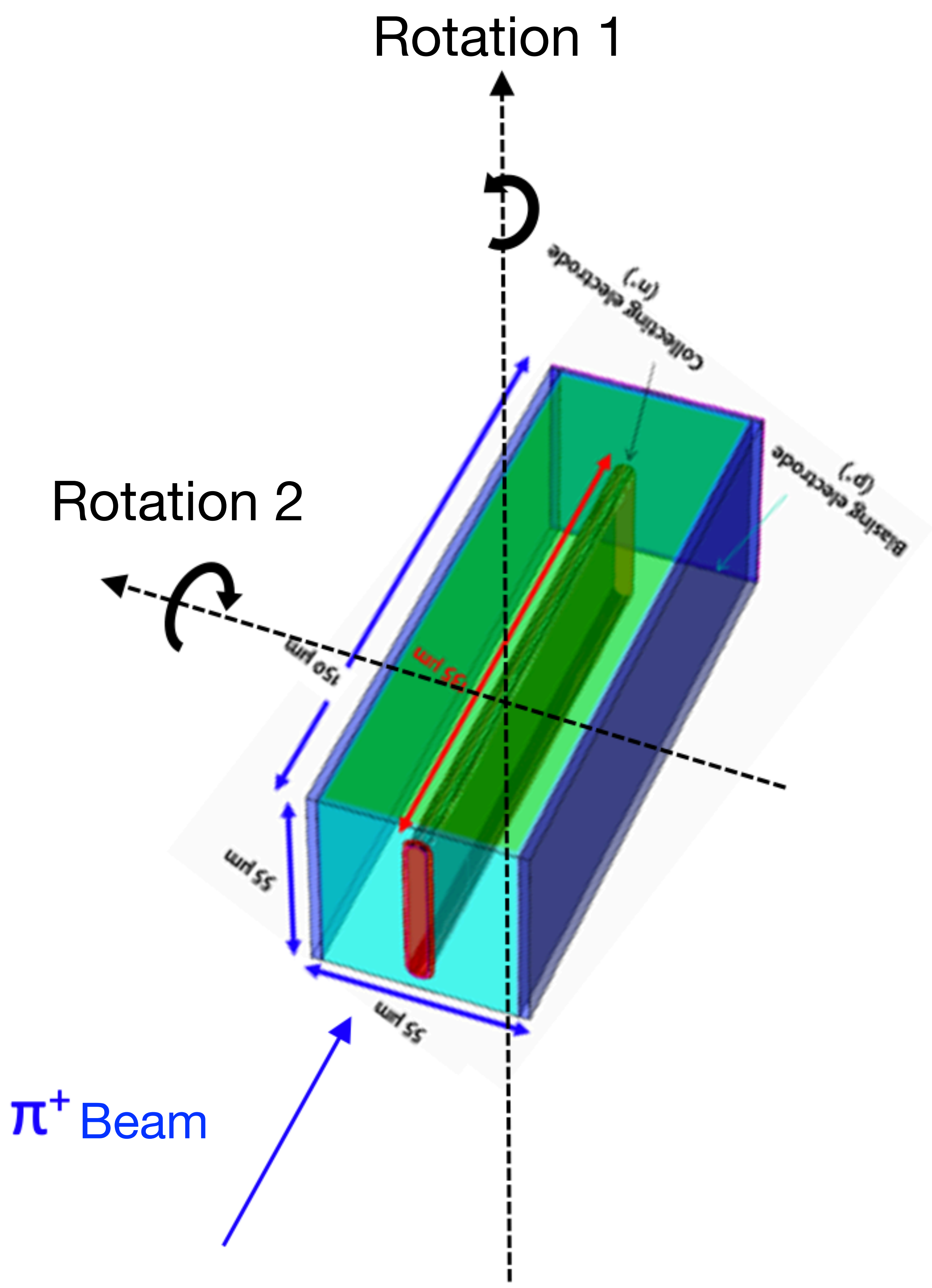
$$\epsilon = 99.1 \pm 0.6\,\% \quad @20°$$

The **inefficiency** (at normal incidence) due to the dead-area of the trenches is **fully recovered** by **tilting** the sensors around the trench axis **at angles larger than 10°**

Tilted sensors: timing performances







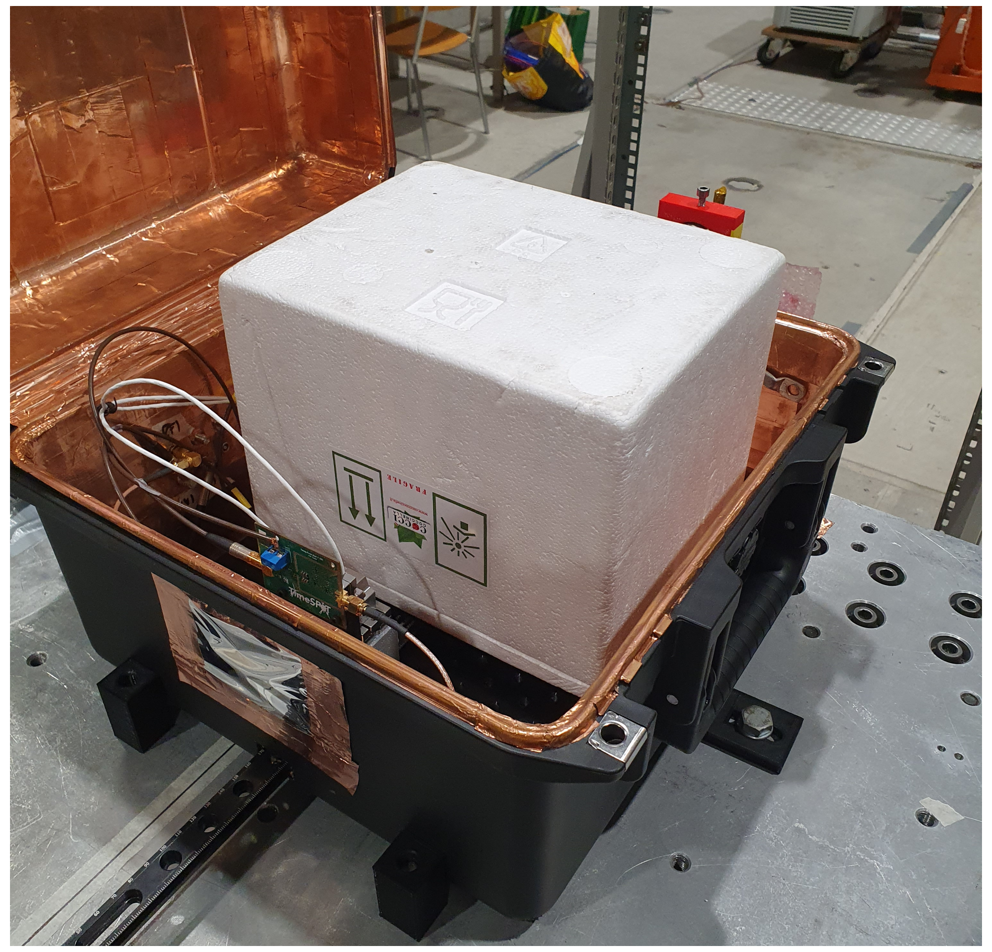
Radiation hardness of 3D-trench silicon sensor studies

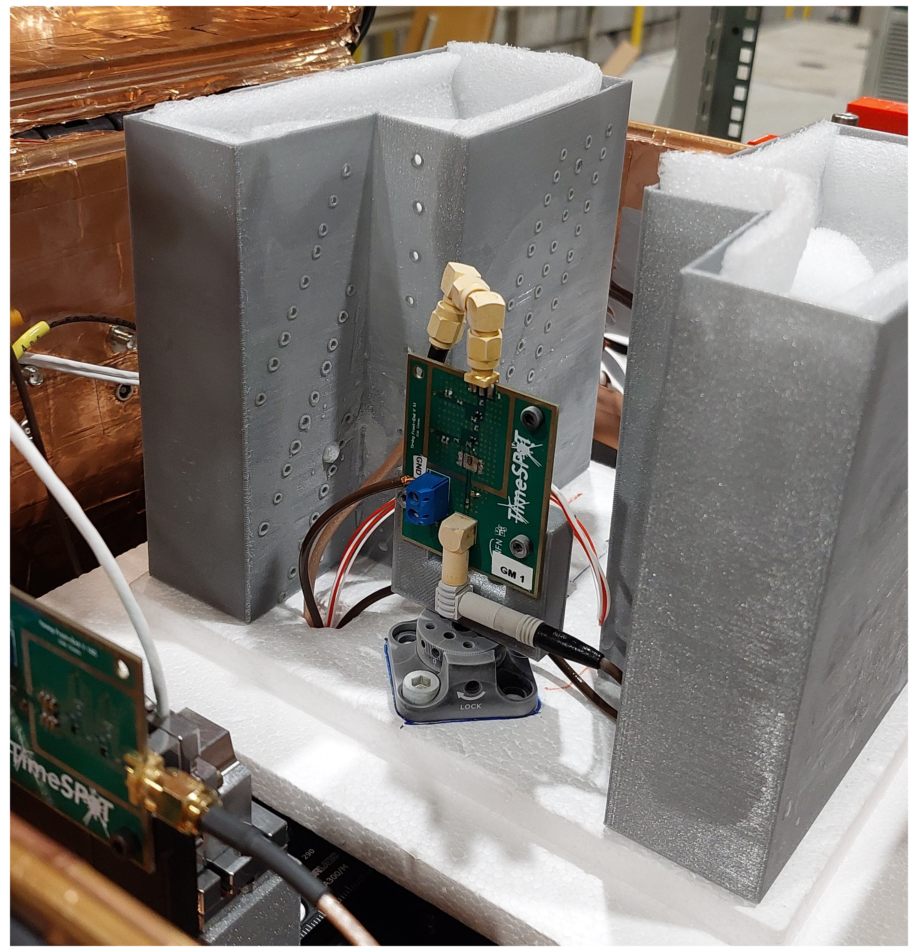
- **3D sensors irradiated** at the Triga Mark II reactor at the Jožef Stefan Institute in Lubjiana, Slovenia

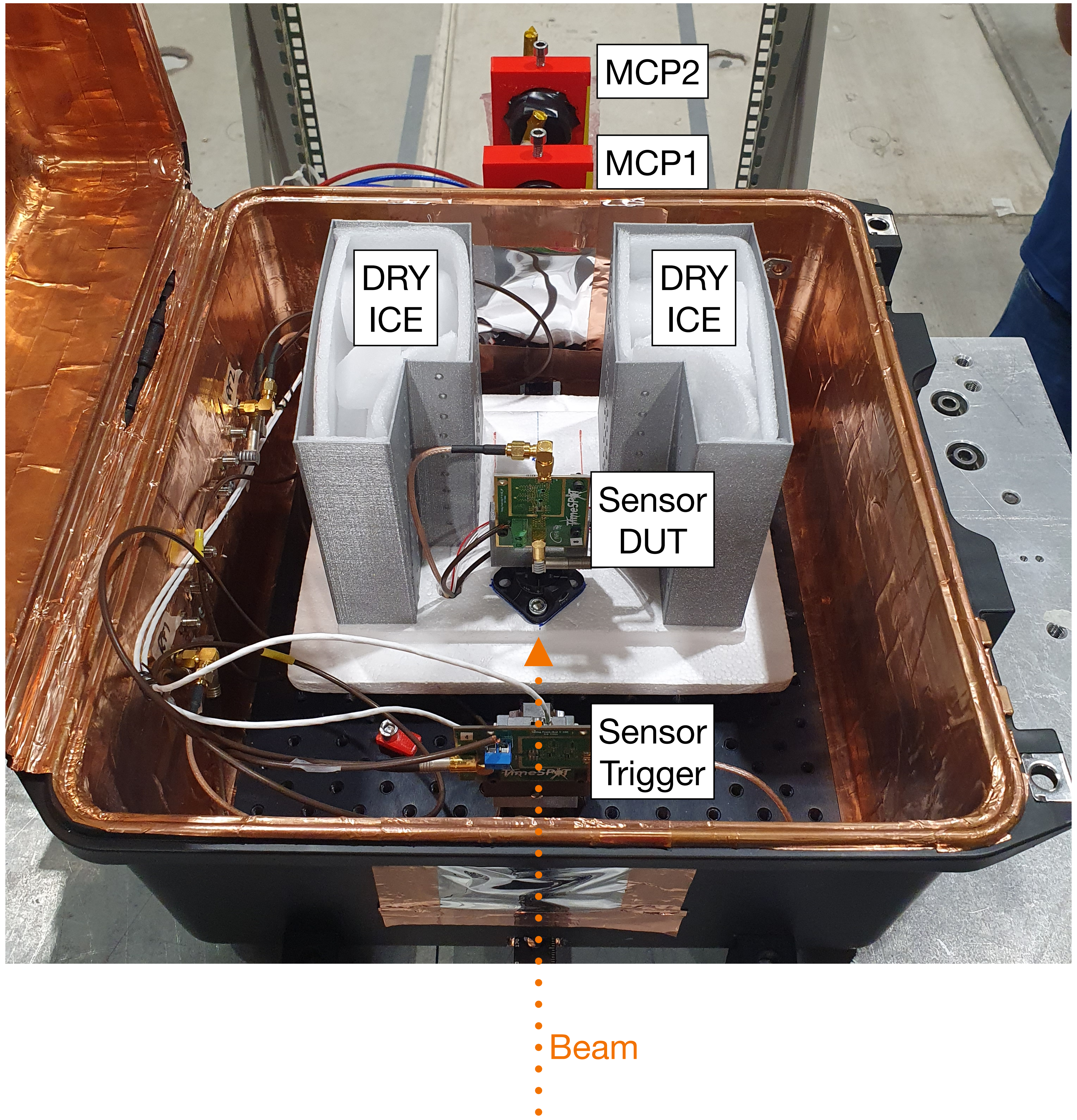
- **Fluences:** up to $2.5 \cdot 10^{16}$ 1 MeV n_{eq}/cm^2
  $\longrightarrow$ Almost expected **fluency on LHCb VELO after LHC Run5** on innermost detectors

- Sensors **tested below -20°C** to reduce **leakage current**

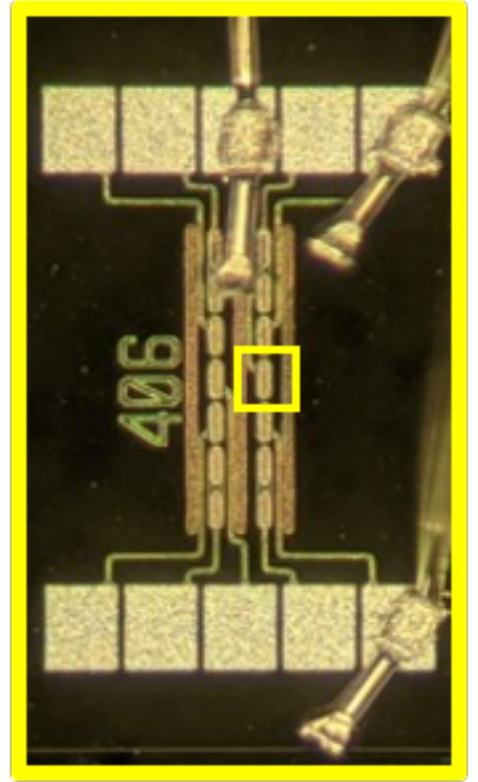
- **Efficiency and timing studies** performed in the irradiated sensors as well

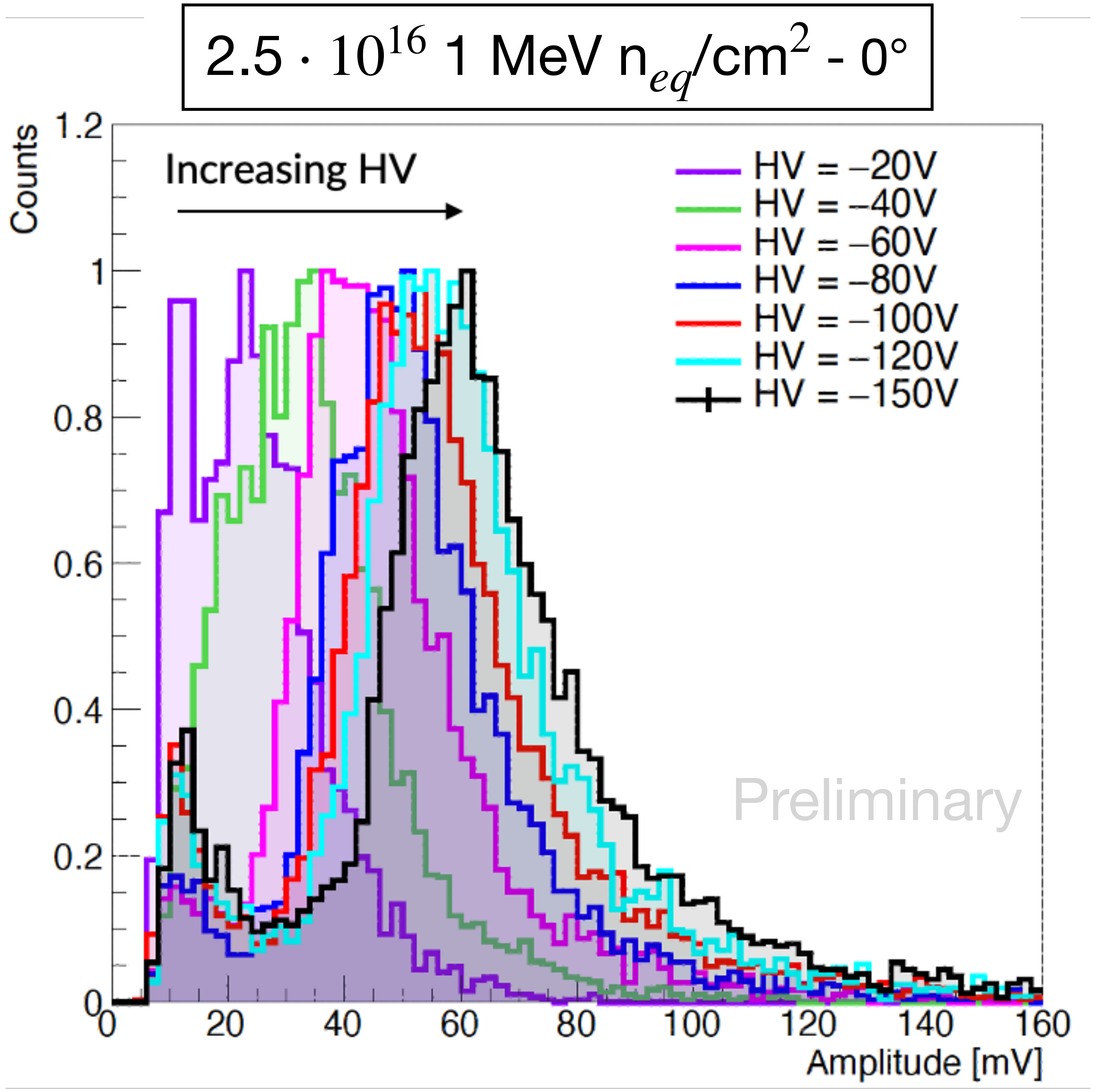


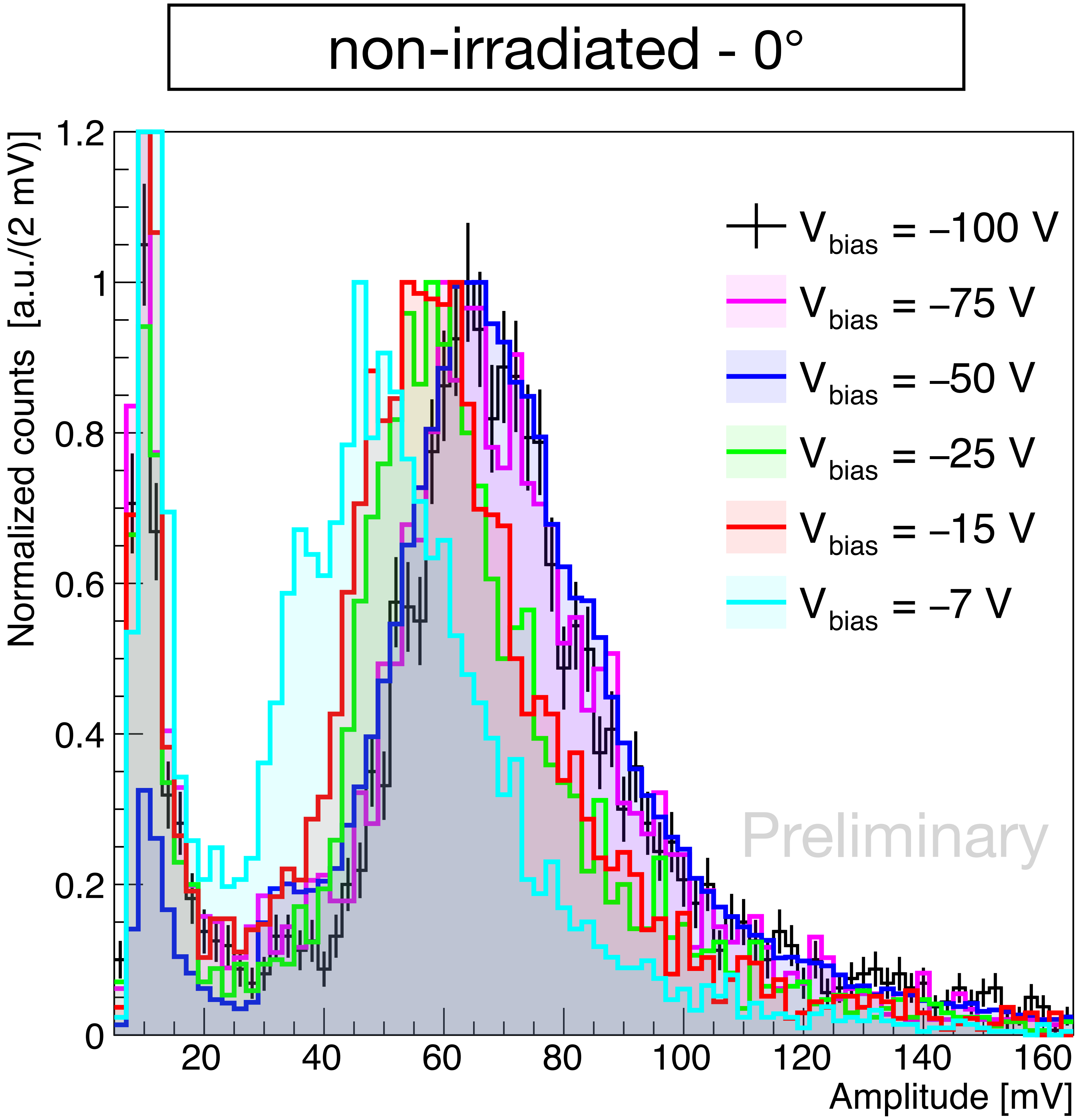




Irradiated sensors: amplitude performance

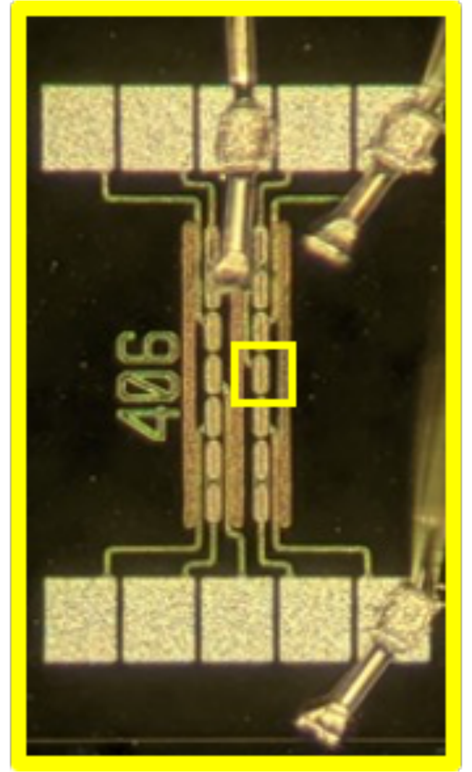




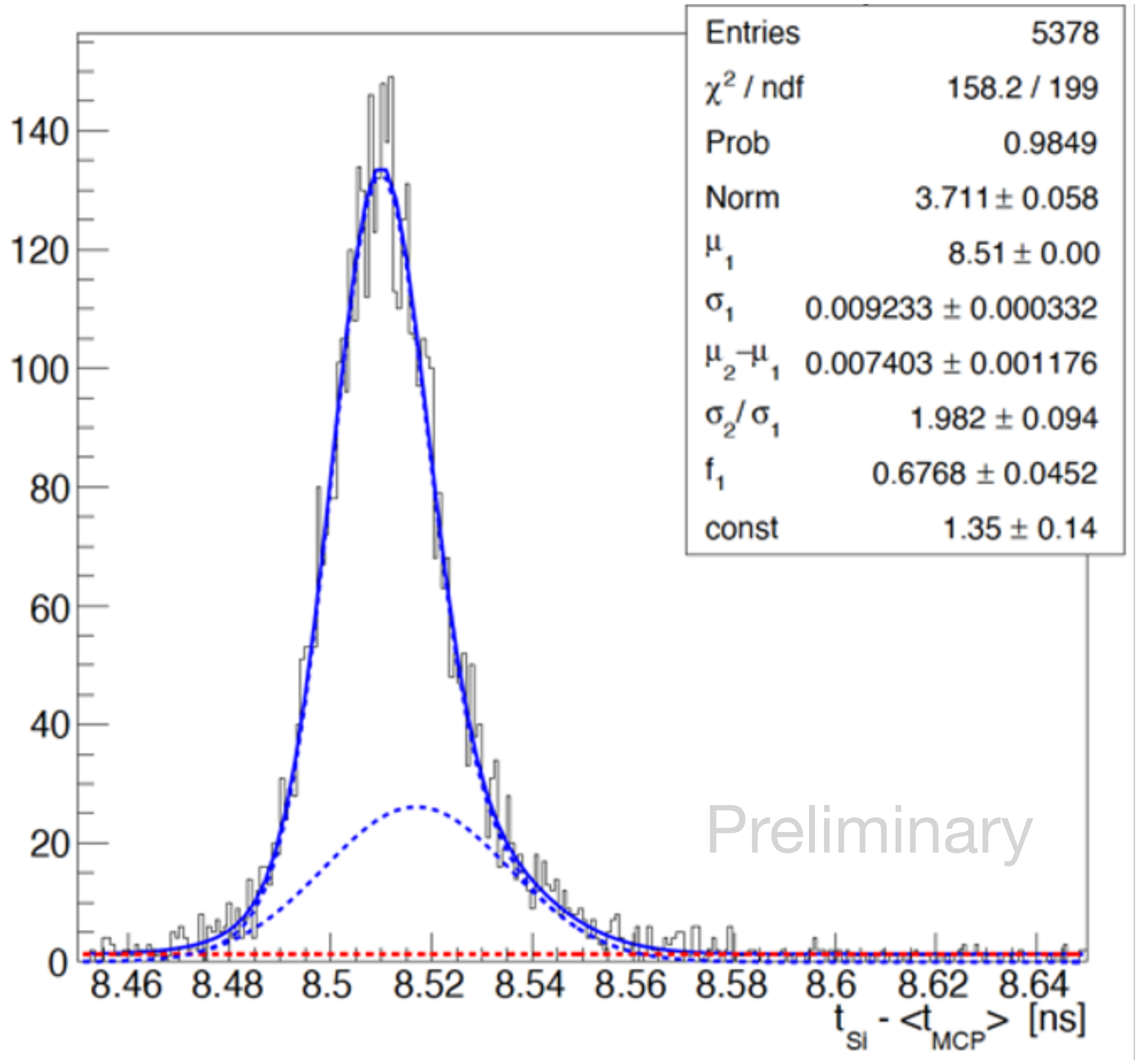


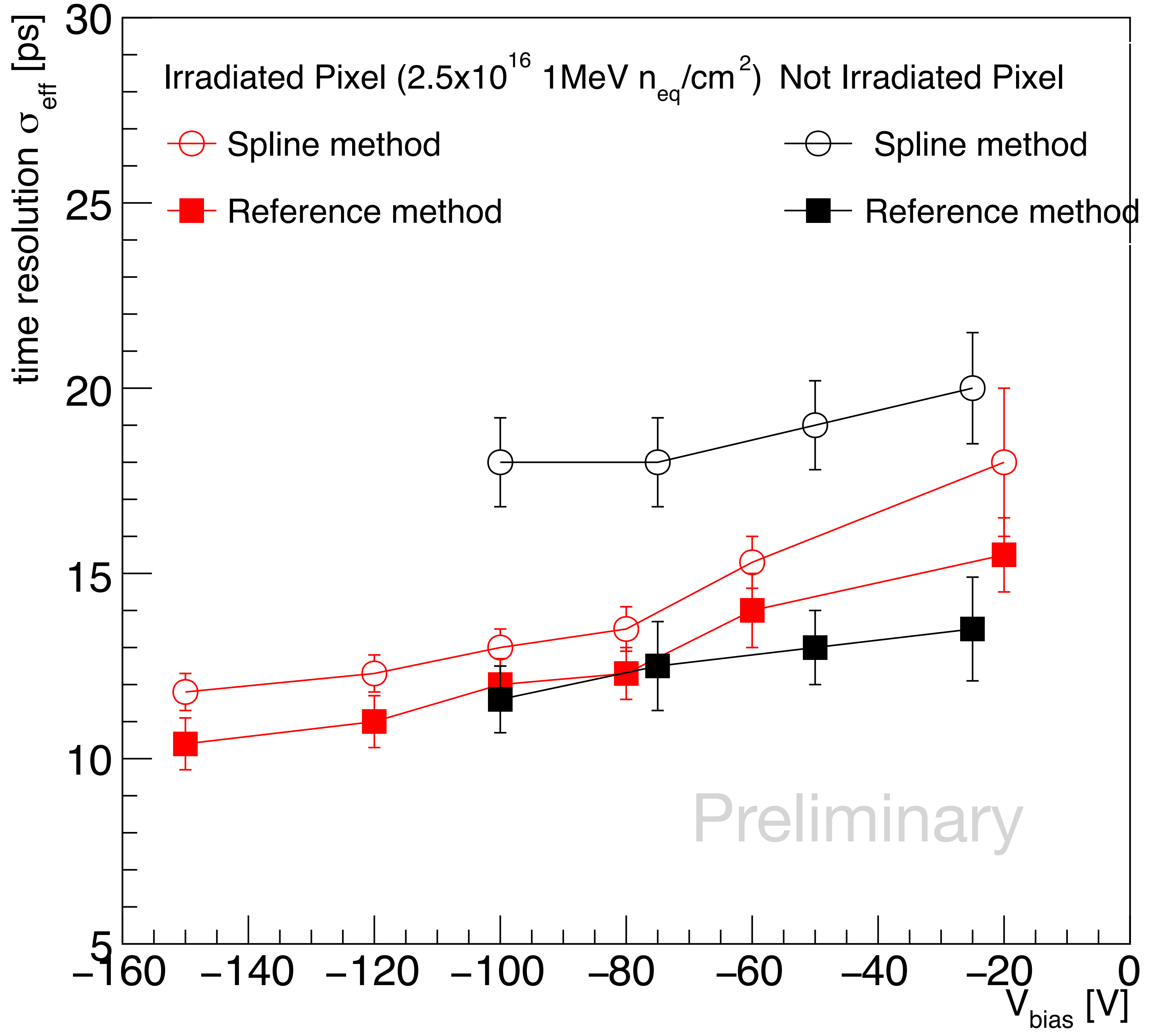
Larger bias voltage is required to **recover the signal amplitude** for irradiated sensors

Irradiated sensors: timing



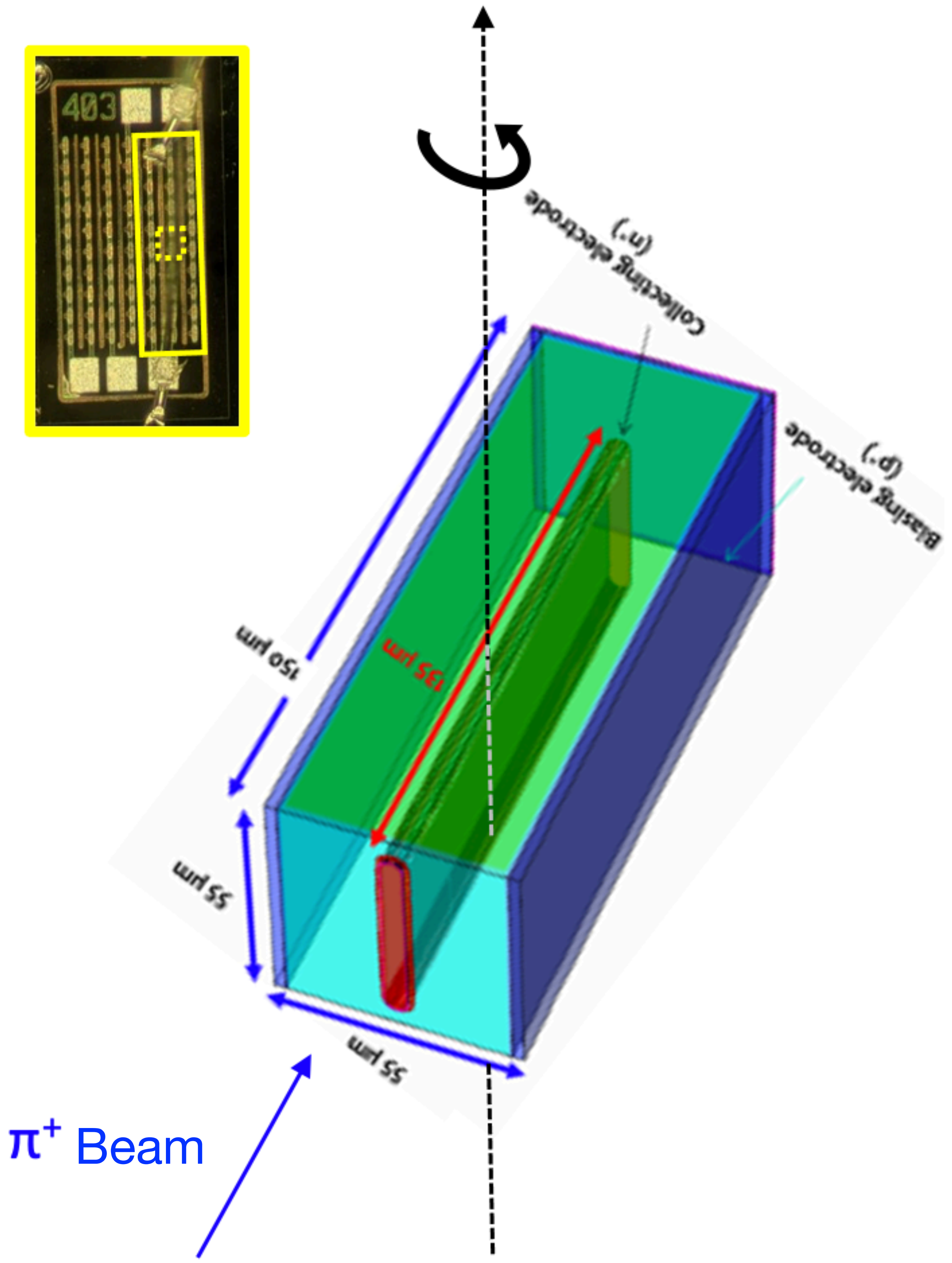
$2.5 \cdot 10^{16}$ 1 MeV n_{eq}/cm^2 - 0°

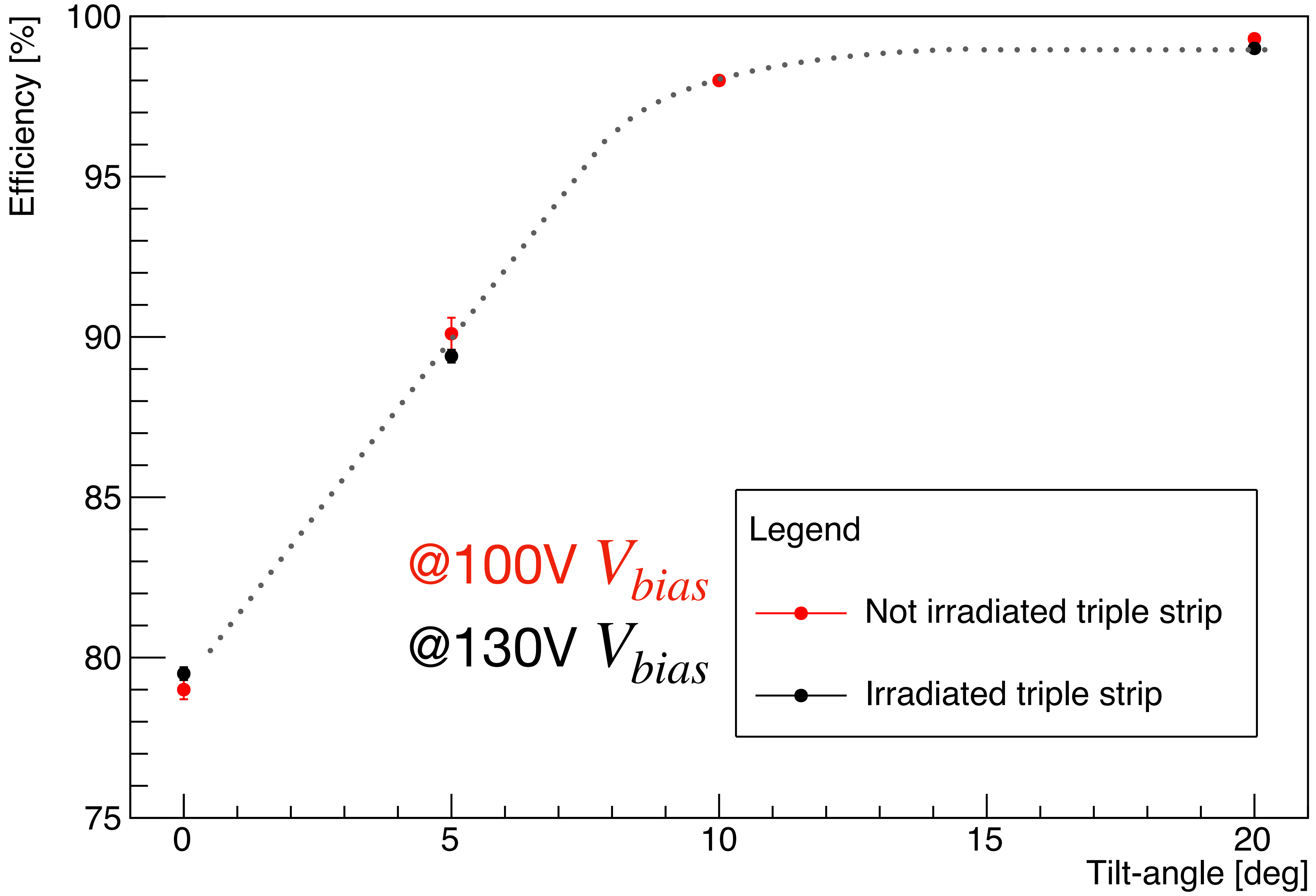




Excellent time resolution measured at 150V on single pixel irradiated $2.5 \cdot 10^{16}$ 1 MeV n_{eq}/cm^2 !

Irradiated sensors: efficiency





Increasing the **irradiated sensor bias voltage** to 130V allows to **fully recover** the **efficiency @20°** expected for **non-irradiated sensors**

Conclusions

- The **time resolution of a single 3D-trench pixel** sensor was measured at SPS with a 180 GeV/c π^+ beam and found to be about **11 ps @** V_{bias}=100V (sensor intrinsic + FEE noise)

- The sensor **detection efficiency** is **fully recovered** for incident **angles larger than 10°** with respect to normal incidence

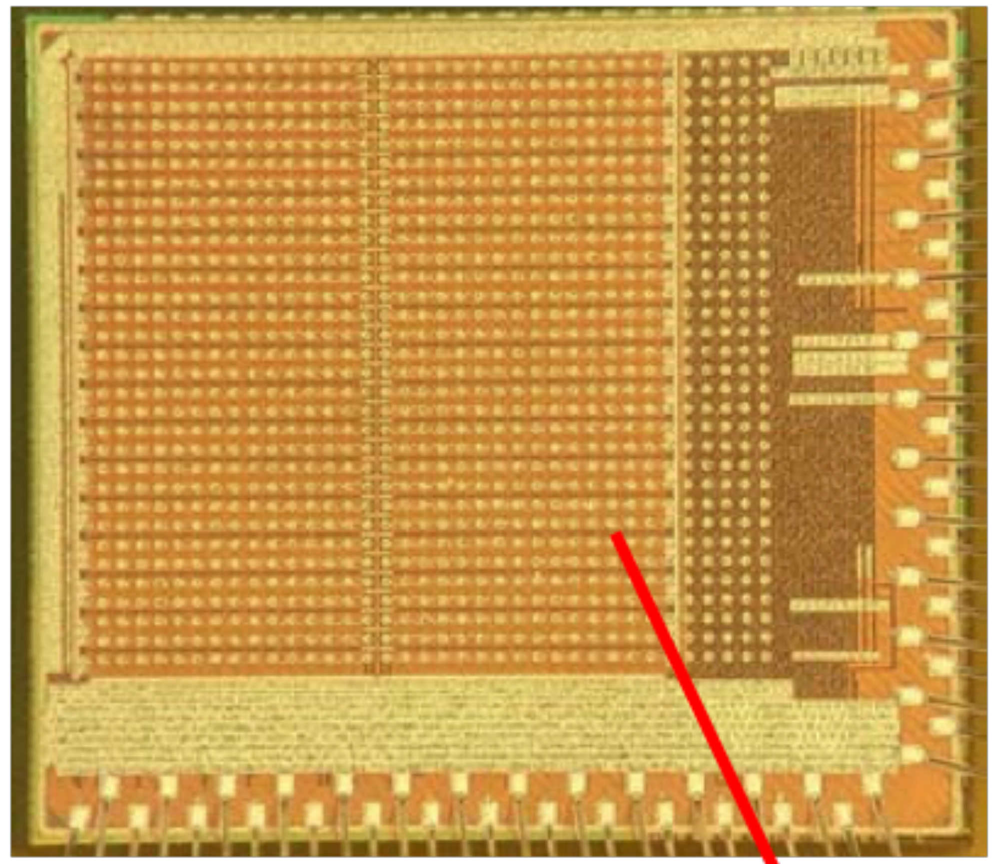
- **Sensors irradiated** at a fluence of $2.5 \cdot 10^{16}$ 1 MeV n_{eq}/cm^2 at V_{bias} exceeding 100V **perform as the non-irradiated sensors, both in timing performances and efficiency**

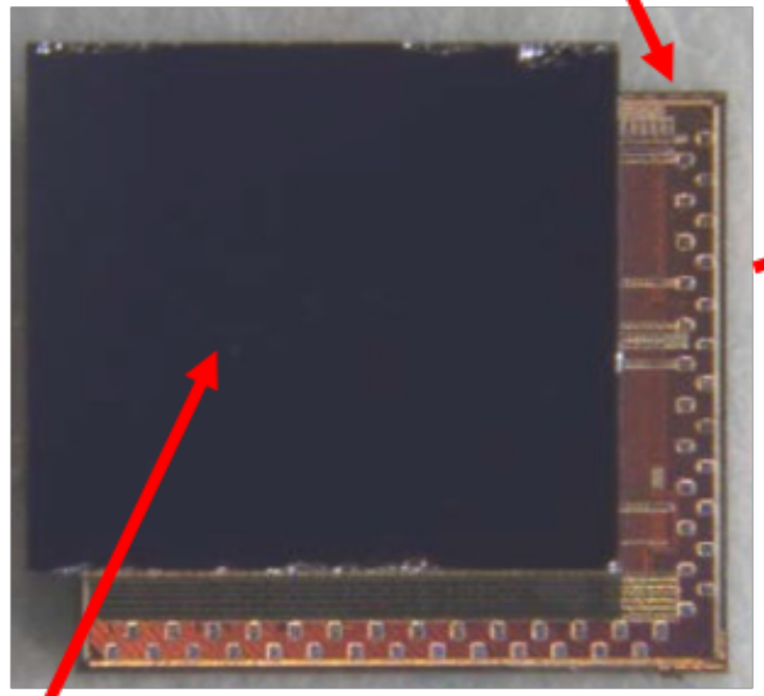
- **3D devices confirm** their theoretical **excellent performance** in timing and the trench geometry appears to be the right direction to go

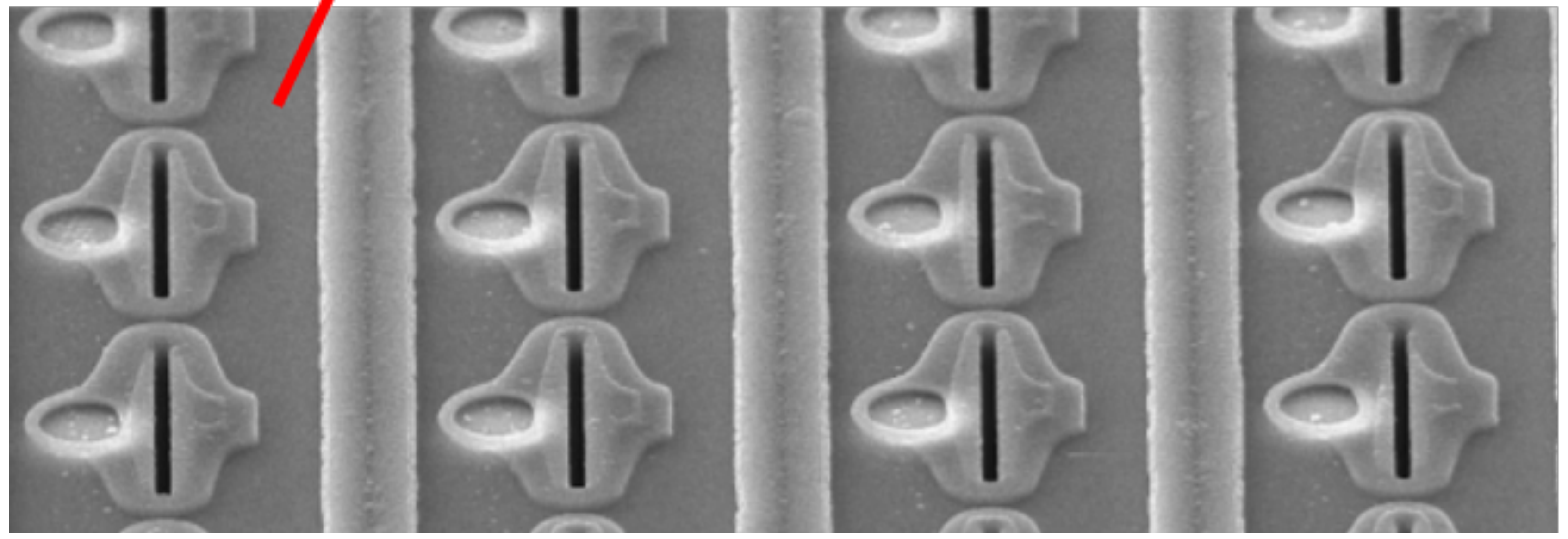
The front-end electronics is now the limiting factor to the system performance

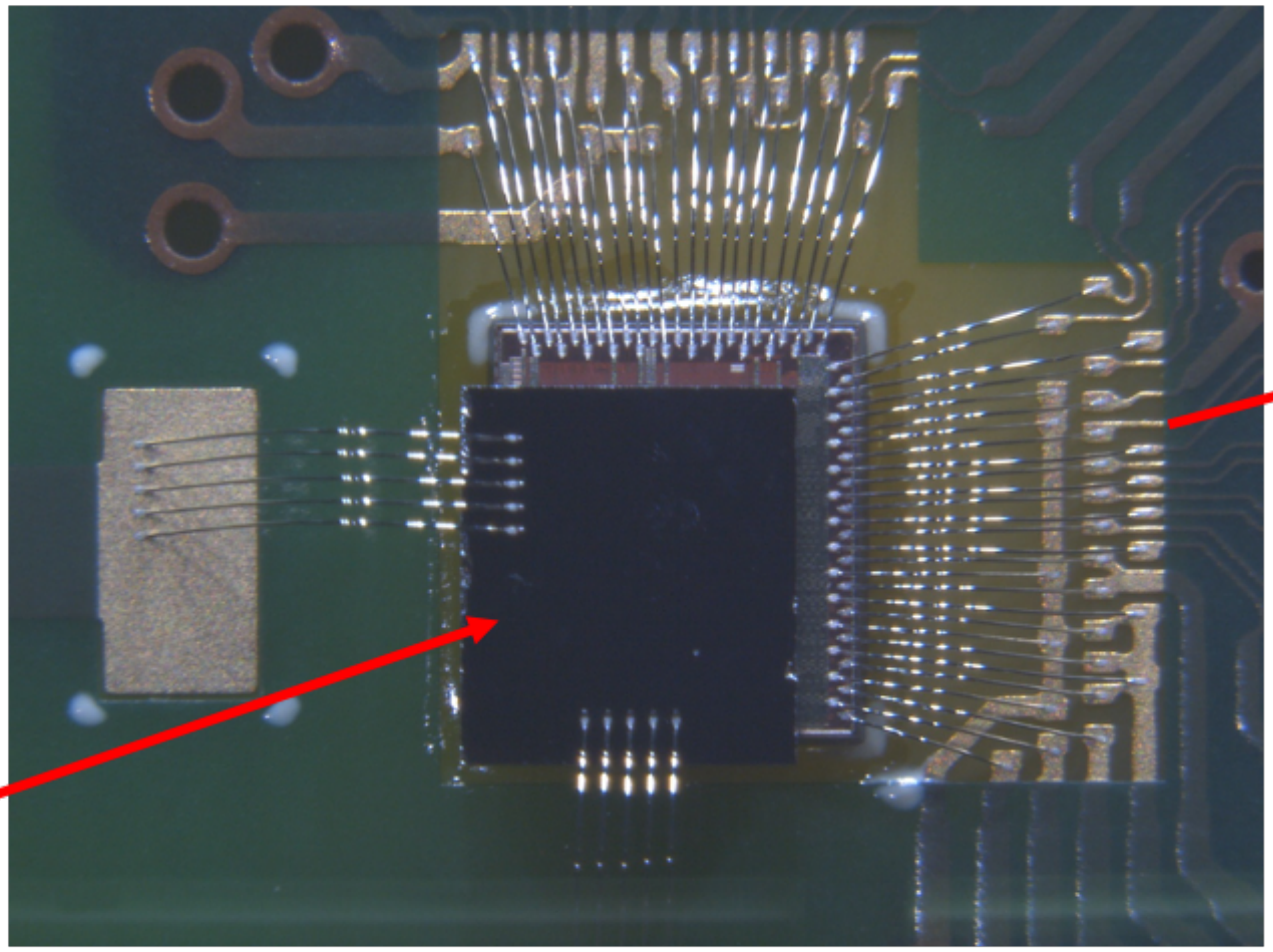
Outlook

TimeSPOT already developed the Timespot1 28-nm CMOS ASIC 32x32 matrix

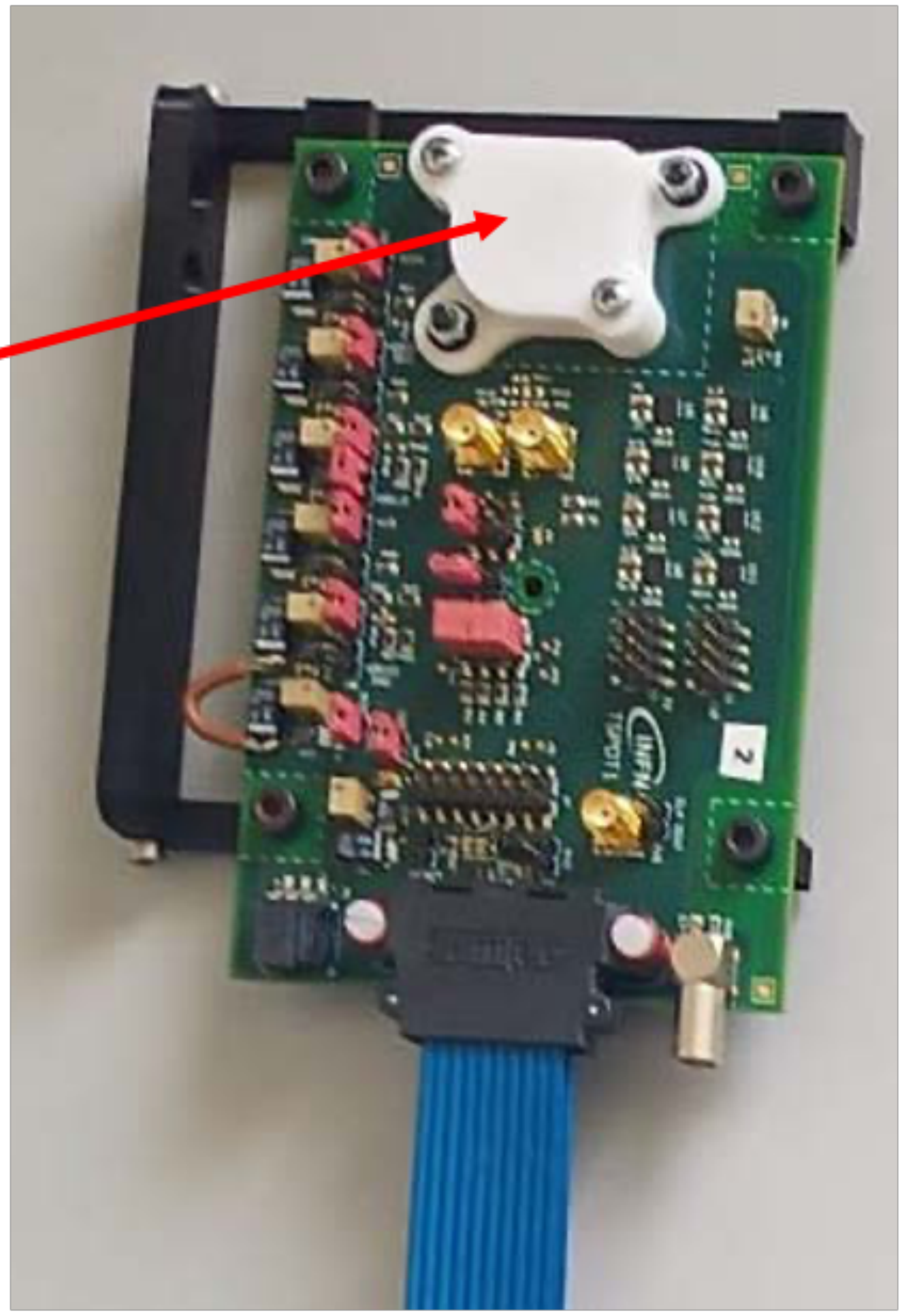








Timespot1 hybrid with 32x32 3D-trench silicon matrix



Beam test at the end of the year of 32x32 3D trench pixel matrices

Thank you for your attention!

Publications by the TimeSPOT Collaboration

- 3D trenched-electrode sensors for charged particle tracking and timing, NIM A, (2019)
- Simulation of 3D-Silicon sensors for the TIMESPOT project NIMA,936-, (2019)
- Development of 3D trenched-electrode pixel sensors with improved timing performance JINST,14-, C07011 (2019)
- Sensors, electronics and algorithms for tracking at the next generation of colliders NIMA,927-, (2019)
- Combined TCAD and Geant4 simulations of diamond detectors for timing applications NIMA,936-, (2019)
- A Timing Pixel Front-End Design for HEP Experiments in 28 nm CMOS Technology, 15thConference on Ph.D. Research in Microelectronics and Electronics, 2019
- First results of the TIMESPOT project on developments on fast sensors for future vertex detectors, NIMA, 2020
- Timing characterisation of 3D-trench silicon sensors, JINST, 2020
- Intrinsic time resolution of 3D-trench silicon pixels for charged particle detection, arXiv:2004.10881, JINST, 2020
- High-resolution timing electronics for fast pixel sensors, arXiv:2008.09867, to appear in JINST
- A. Loiet al., Timing Optimisation and Analysis in the Design of 3D silicon sensors: the TCoDeSimulator, JINST (2021) 16:P02011
- D. Brunduet al., Accurate modelling of 3D-trench silicon sensor with enhanced timing performance and comparison with test beam measurements, JINST 16 (2021) 09, P09028.
- L. Piccolo et al., First Measurements on the Timespot1 ASIC: a Fast-Timing, High-Rate Pixel-Matrix Front-End, arXiv:2201.13138
- BrunduD, et al. (2022) Modelingof Solid-State Detectors Using Advanced Multi-Threading: The TCoDeand TFBoostSimulation Packages. Front. Phys. 10:804752. doi: 10.3389/fphy.2022.804752

Backup

F. Borgato, M. Boscardin, D. Brundu, A. Cardini, G.M. Cossu, G.-F. Dalla Betta, M. Garau, L. La Delfa, A. Lampis, A. Lai, A. Loi, R. Mulargia, M. Obertino, S. Ronchin, G. Simi, S. Vecchi

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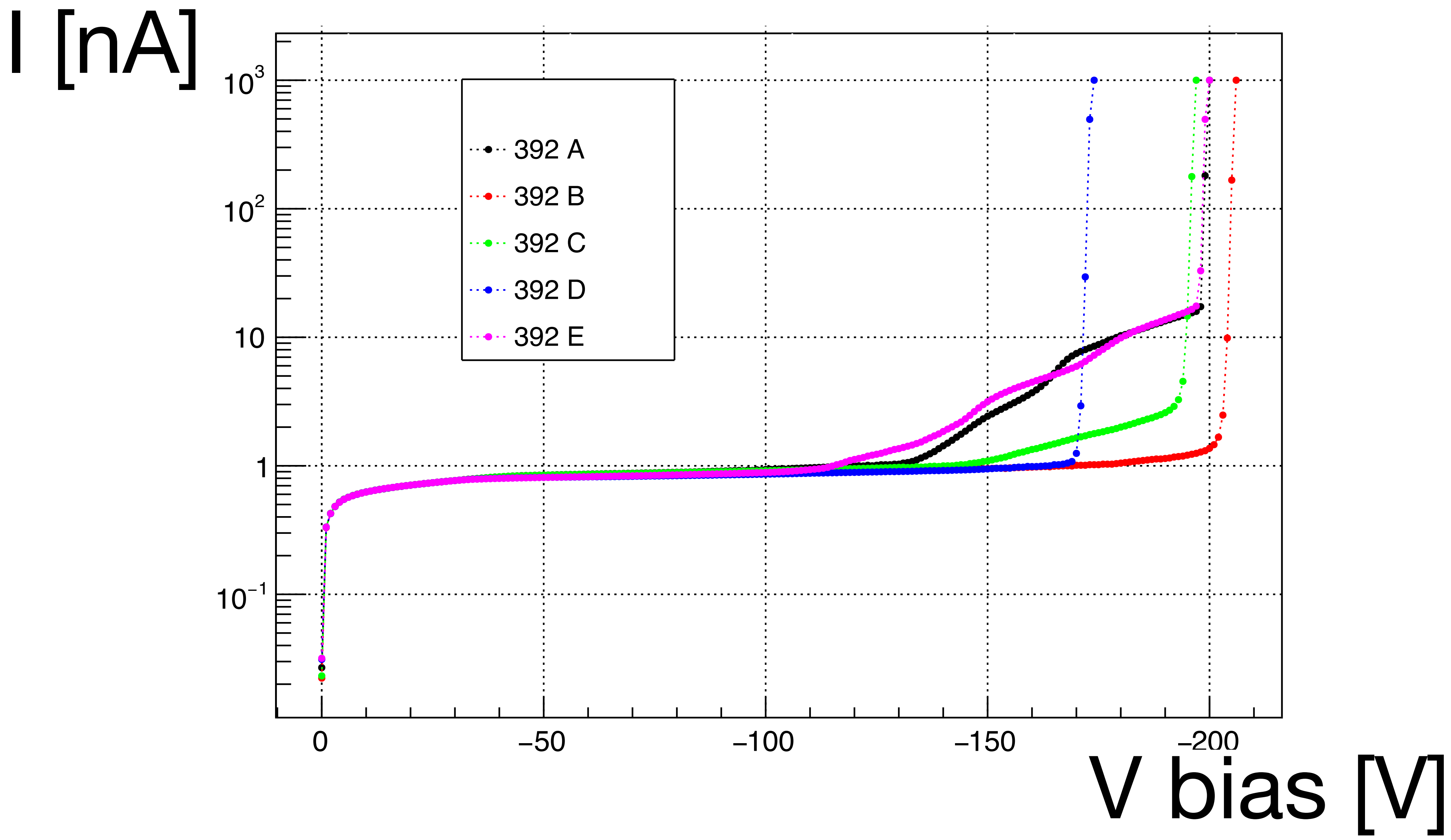
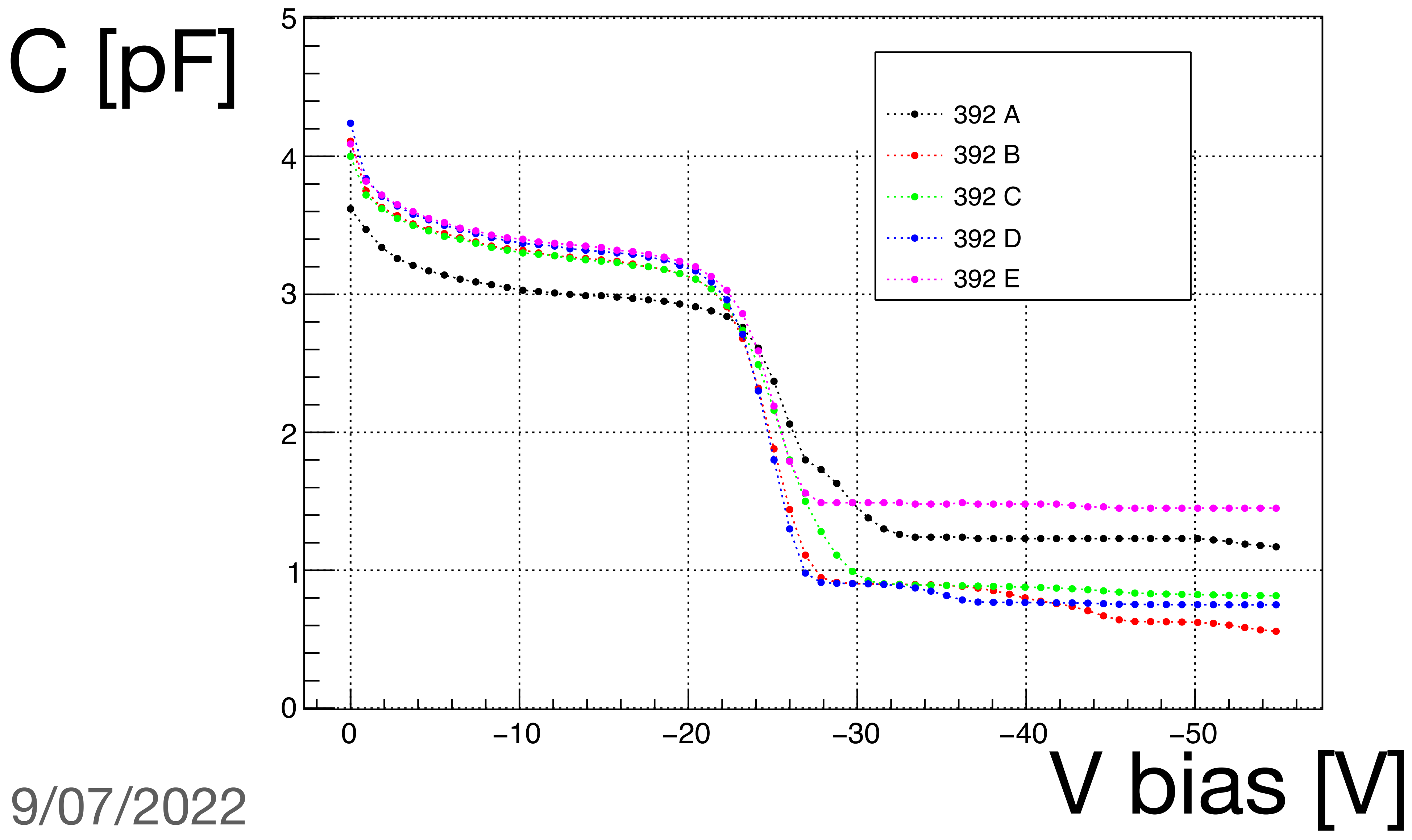
TimeSPOT

International Conference on High Energy Physics XLI
Bologna, 9th July 2022

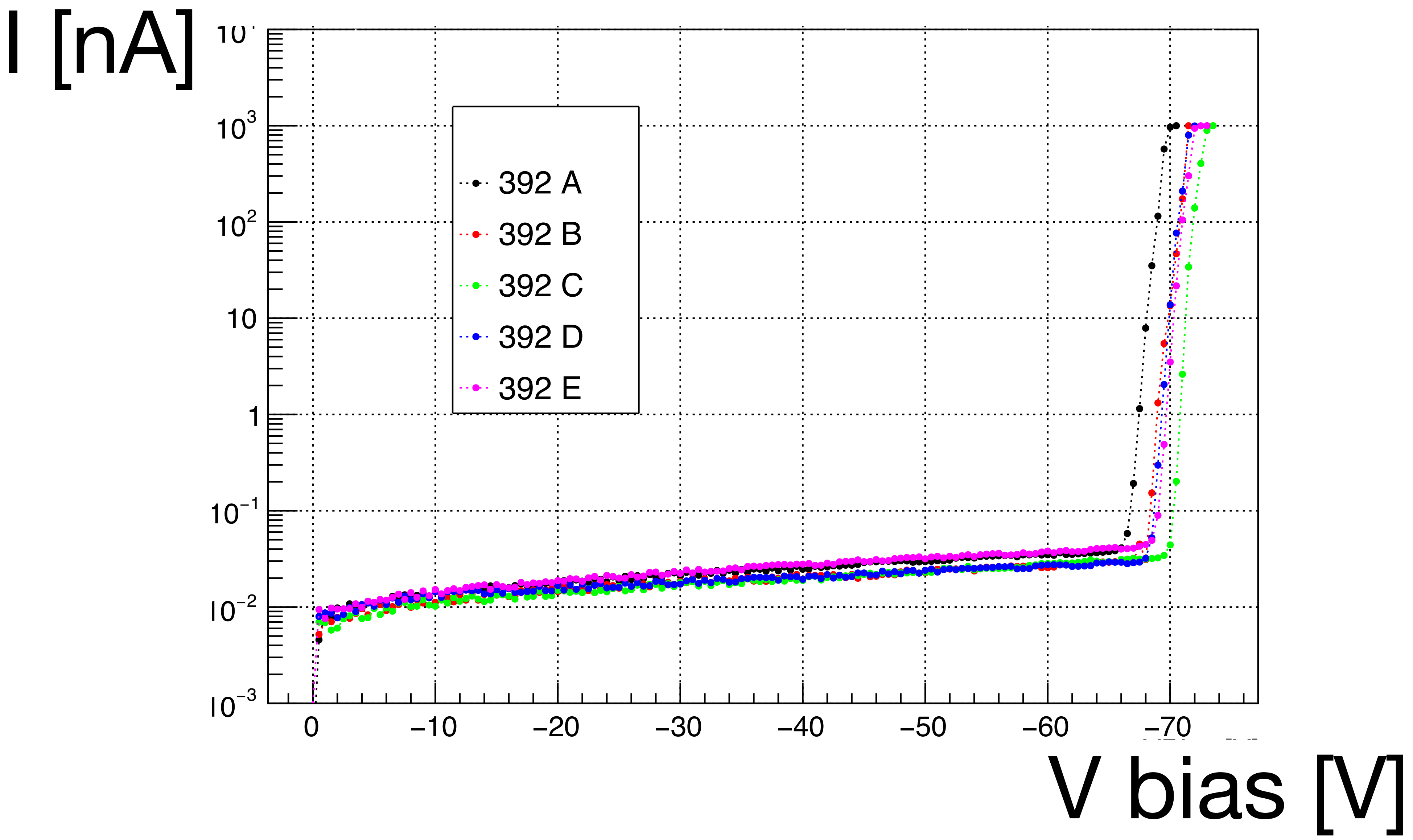
Static characterization of 3D-trench pixel strips

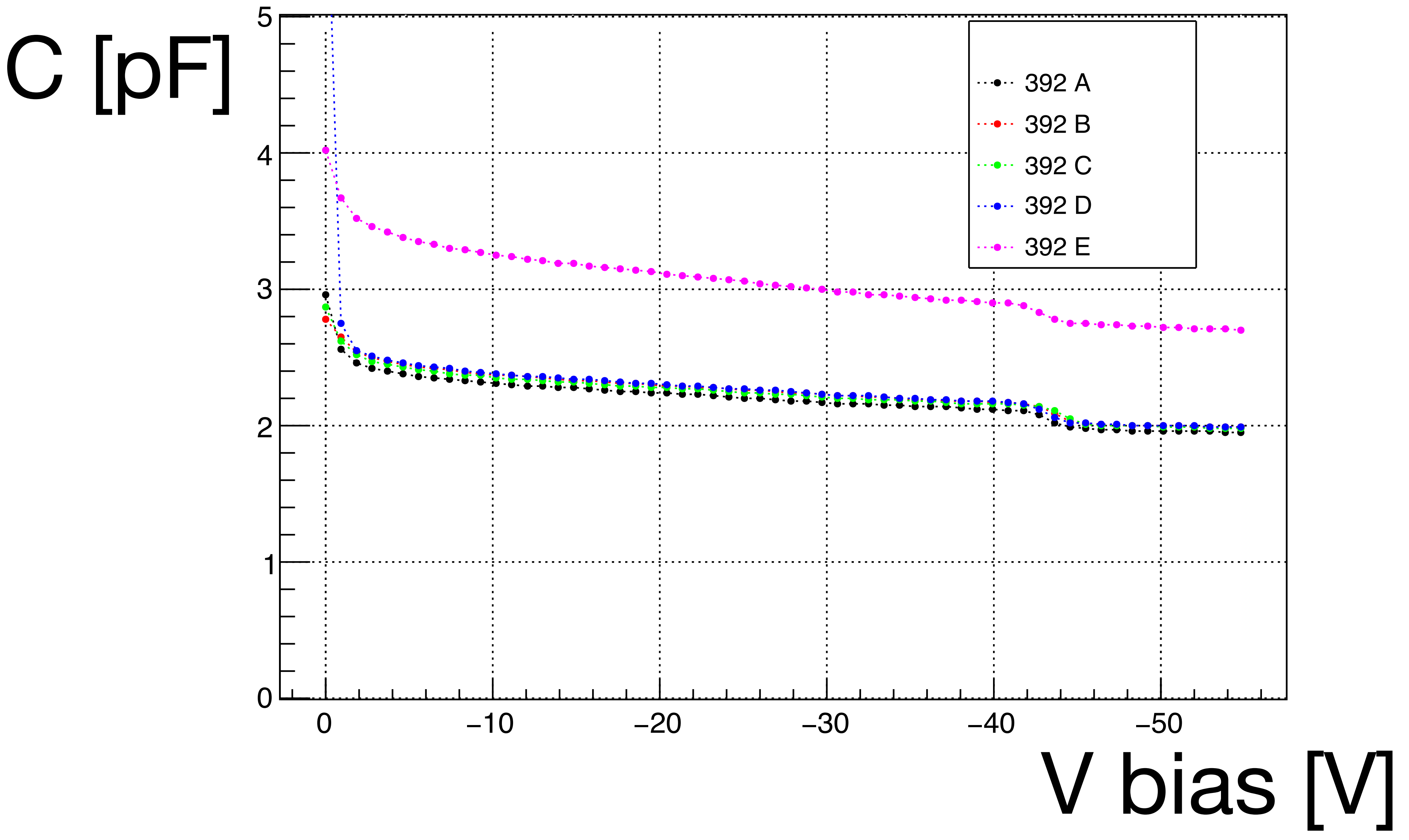
STRIP 392 (batch1, NO p-spray)





STRIP 392 (batch2, with p-spray)





Limits to the time resolution of a 3D sensor

$$\sigma_t = \sqrt{\sigma_{tw}^2 + \sigma_{dr}^2 + \sigma_{un}^2 + \sigma_{ej}^2 + \sigma_{TDC}^2}$$

Physics

- σ_{tw} : the time-walk effect can be eliminated by triggering at a constant fraction of the signal amplitude
- σ_{dr} : jitter due to delta-rays - negligible in a 3D sensor since all the charge deposits created at various depths contribute in the same way at the total signal because the charge collection occurs in a direction which is perpendicular to the charged particle path (and in general to the delta-rays produced)

Detector

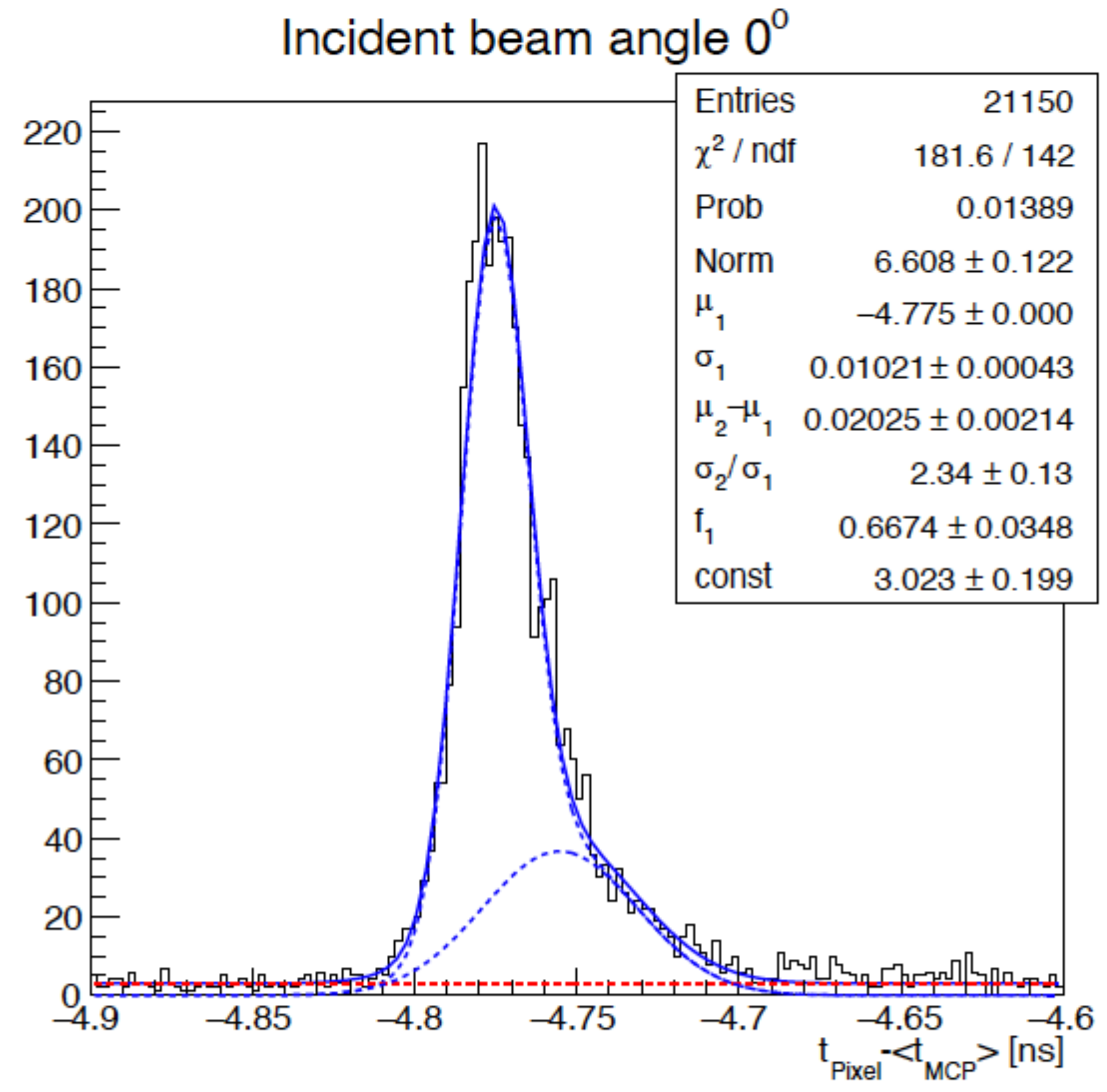
- σ_{un} : non-uniformities in the weighting field and charge carrier velocities inside the detector sensitive unit give the ultimate limit on the time resolution that can be achieved with a 3D sensor

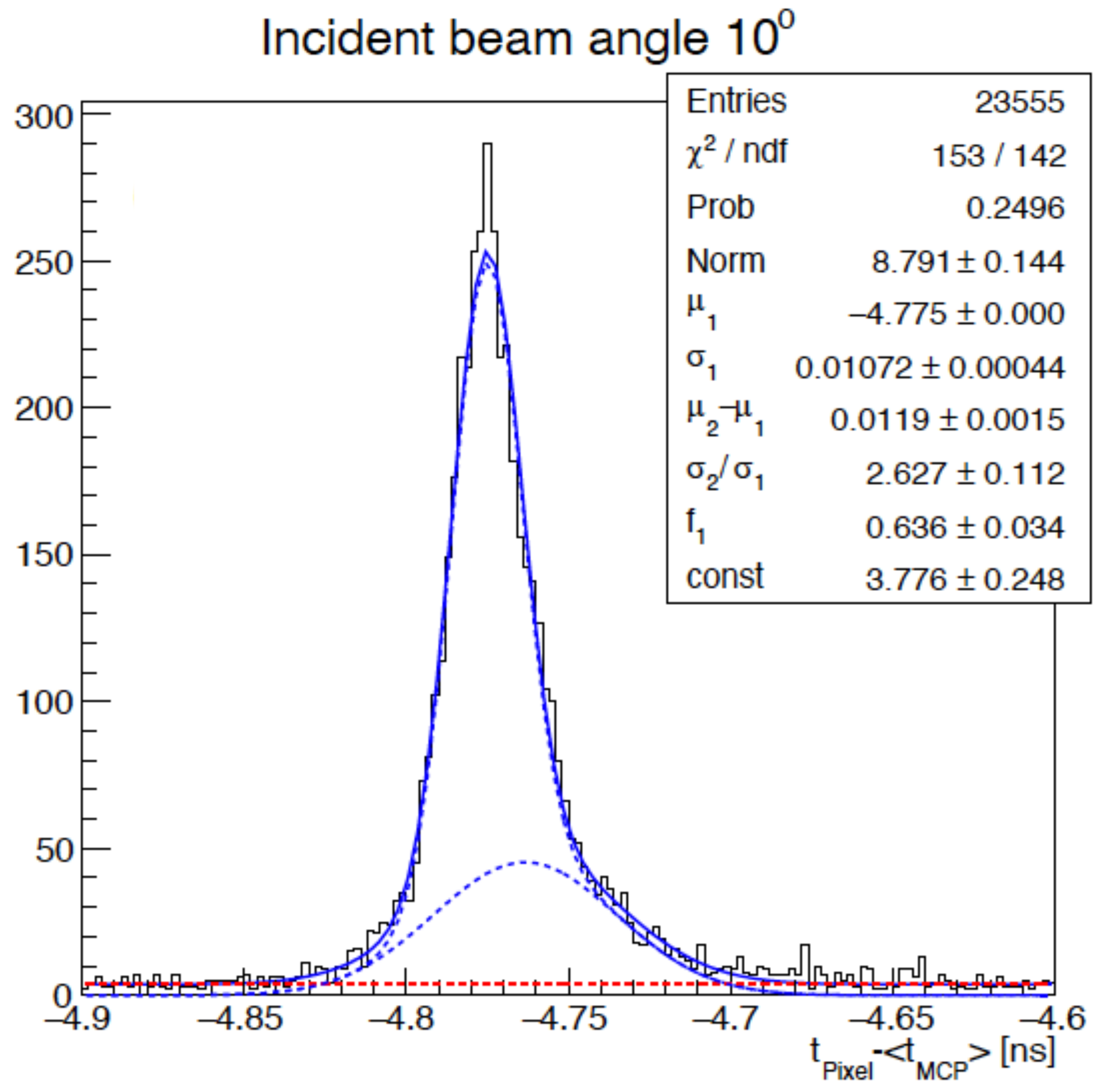
Electronics

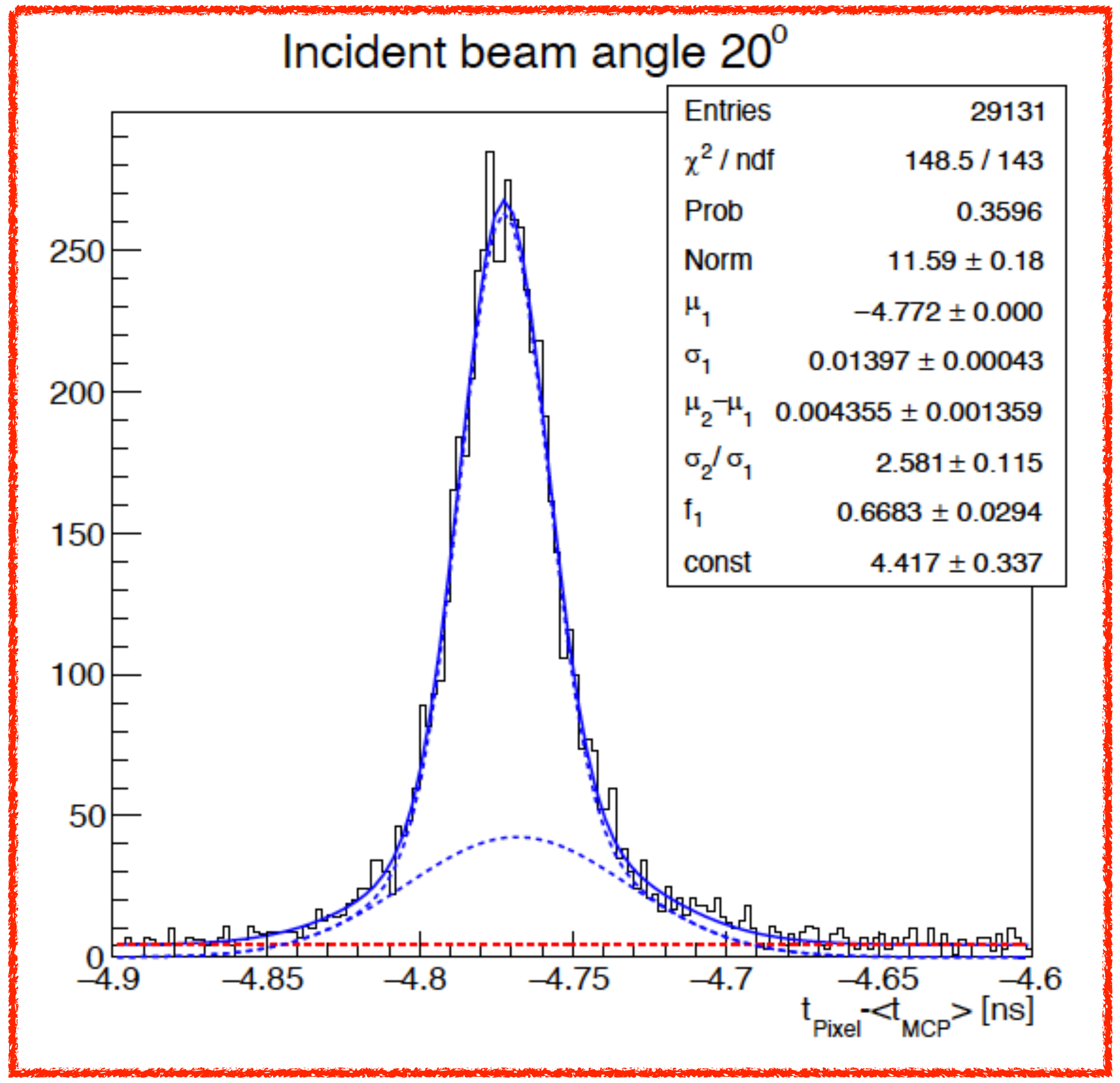
- σ_{ej} : the analog noise of the preamplifier limits the sensor's time resolution and scales as $\approx \frac{\sigma_{noise}}{Amplitude}$
- σ_{TDC} : an adequate TDC will make this term negligible

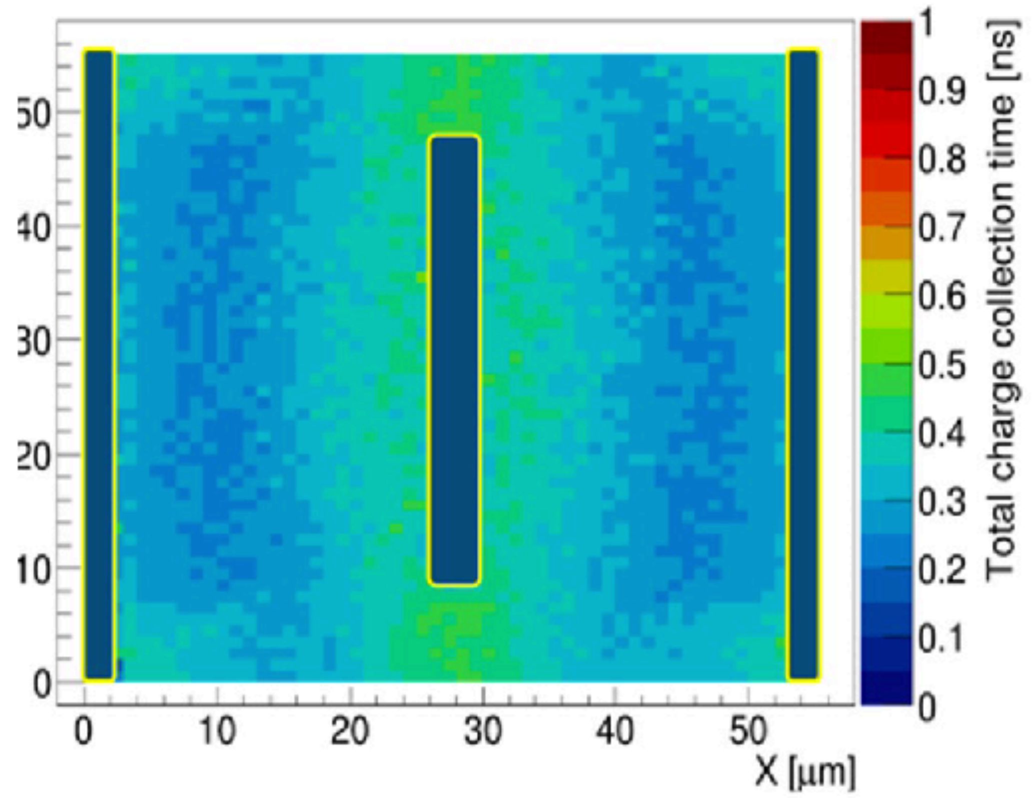
$$\boxed{\sigma_t \approx \sqrt{\sigma_{un}^2 + \sigma_{ej}^2}}$$

Tilted sensors: time distribution





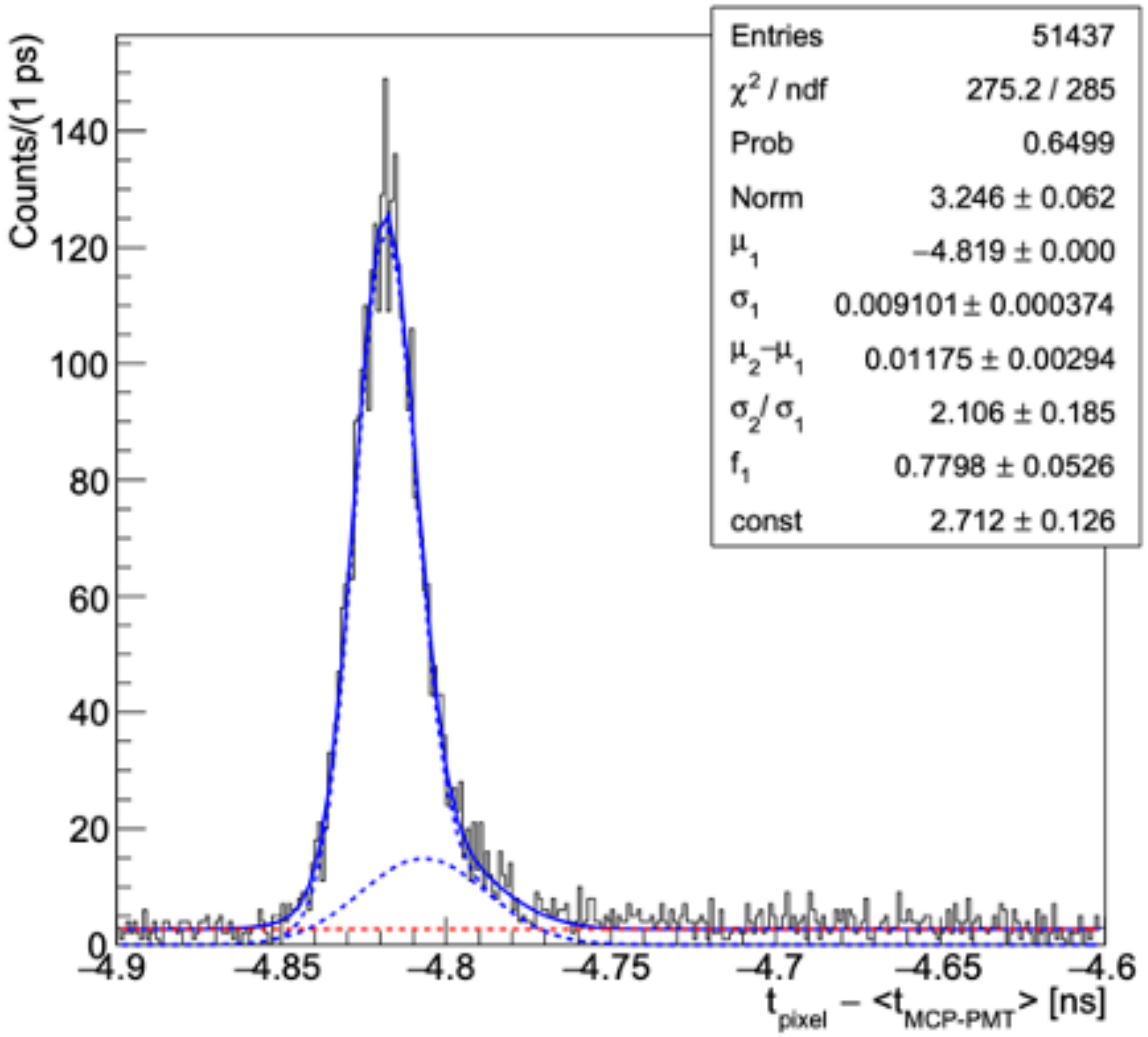




Simulated time of arrival map of a single 3D-trench pixel obtained in the lab by IR laser scan

In a tilted sensor, every charged track crosses both fast and less-fast regions of the pixels, thus providing a more uniform timing response

Fitting the time distribution: σ_{eff}



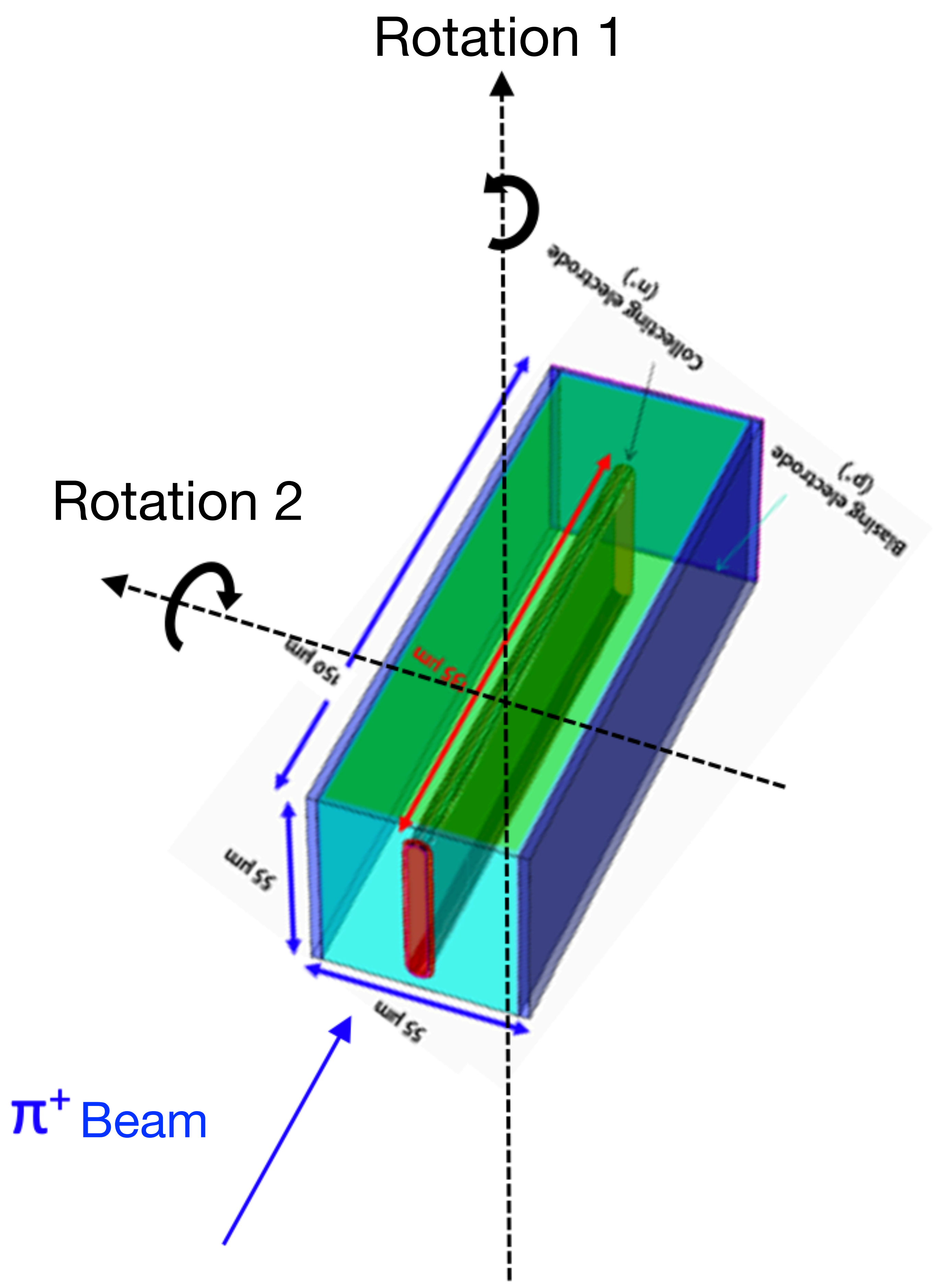
σ_{eff} is the standard deviation of the mixture distribution of two gaussians:

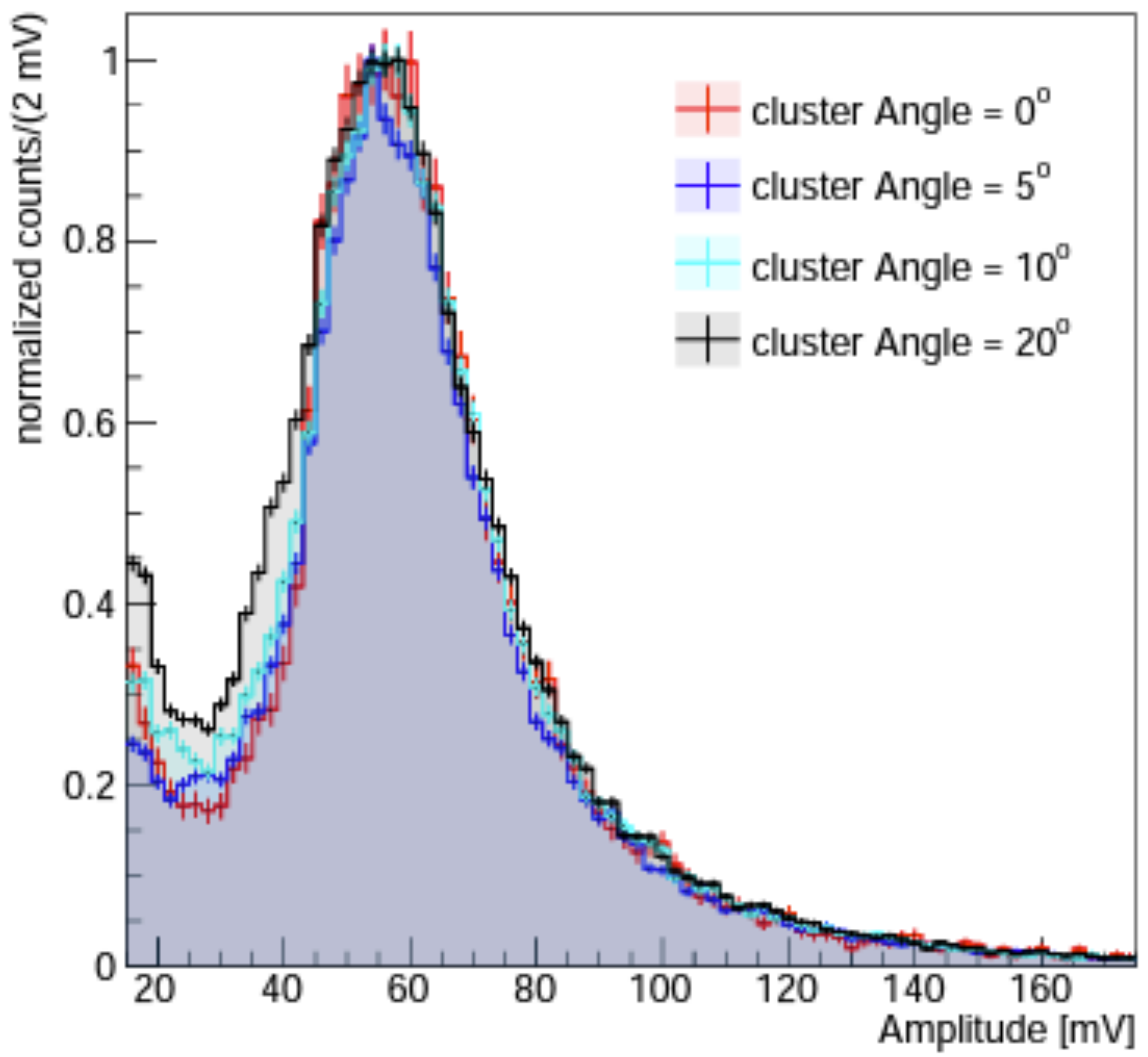
$$(\sigma_t^{eff})^2 = f_1 \cdot (\sigma_1^2 + \mu_1^2) + (1 - f_1) \cdot (\sigma_2^2 + \mu_2^2) - \mu^2$$

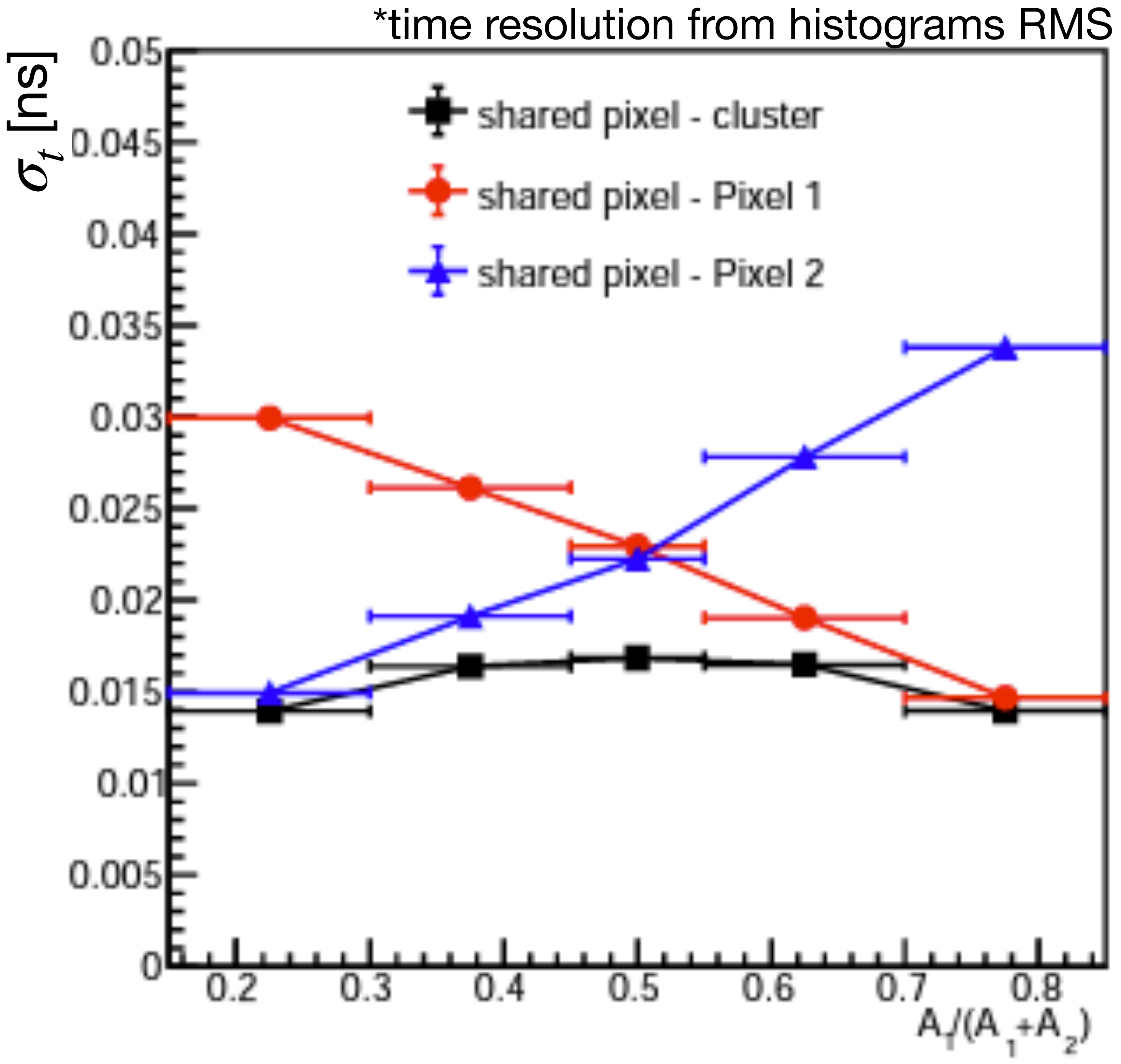
where f_1 is the fraction of the gaussian core and μ is defined as:

$$\mu = f_1 \cdot \mu_1 + (1 - f_1) \cdot \mu_2$$

Work in progress: charge sharing

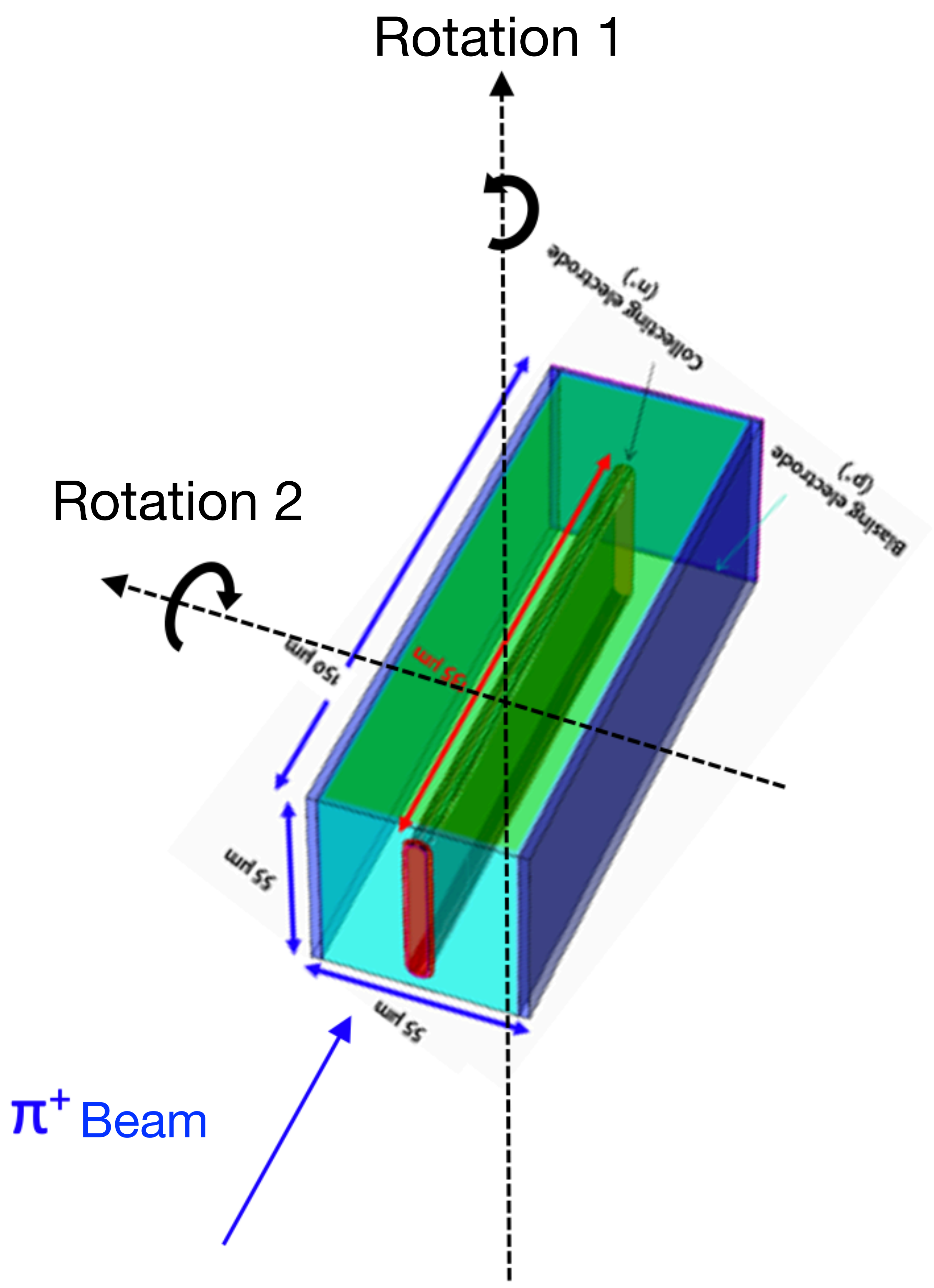


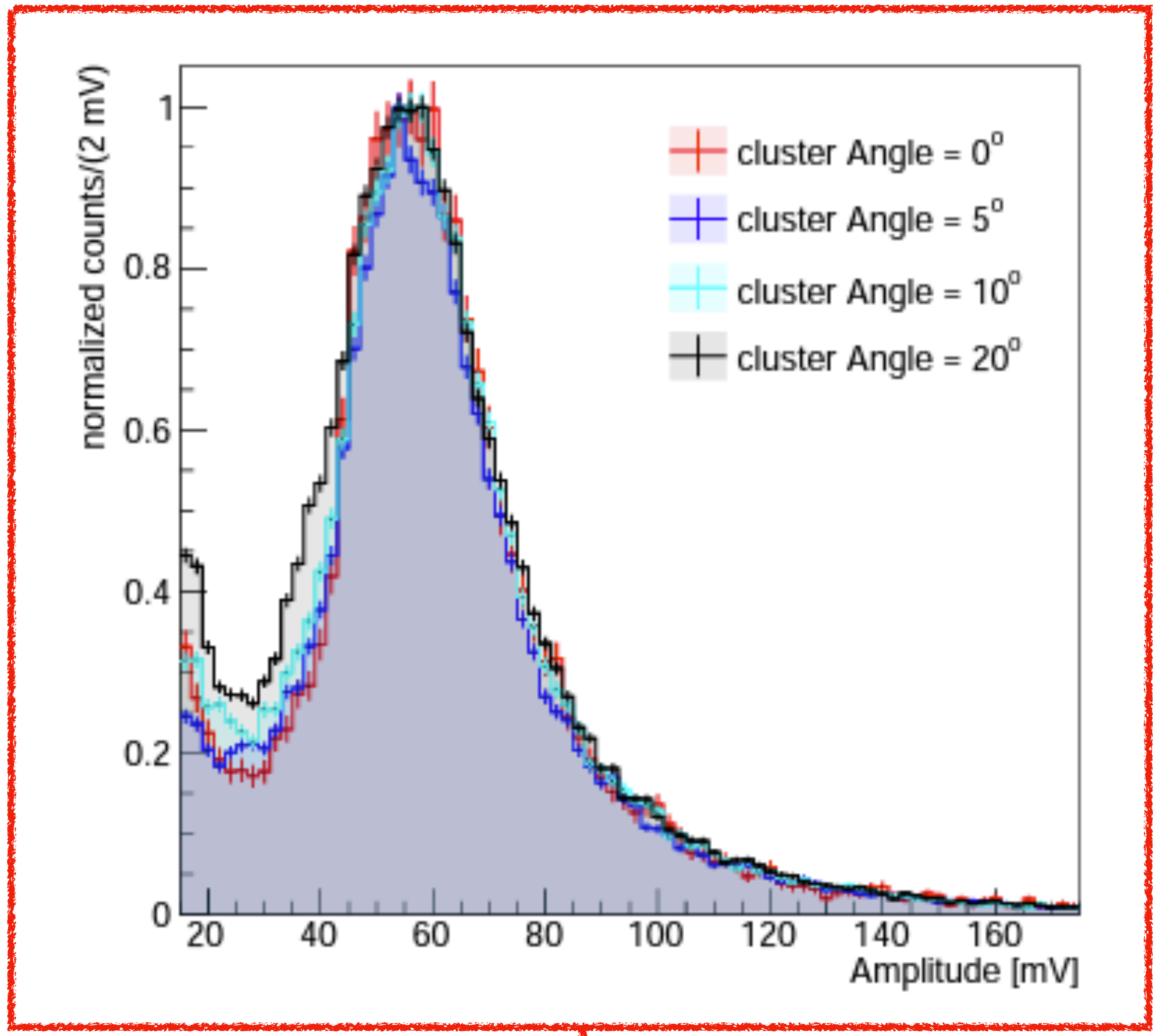


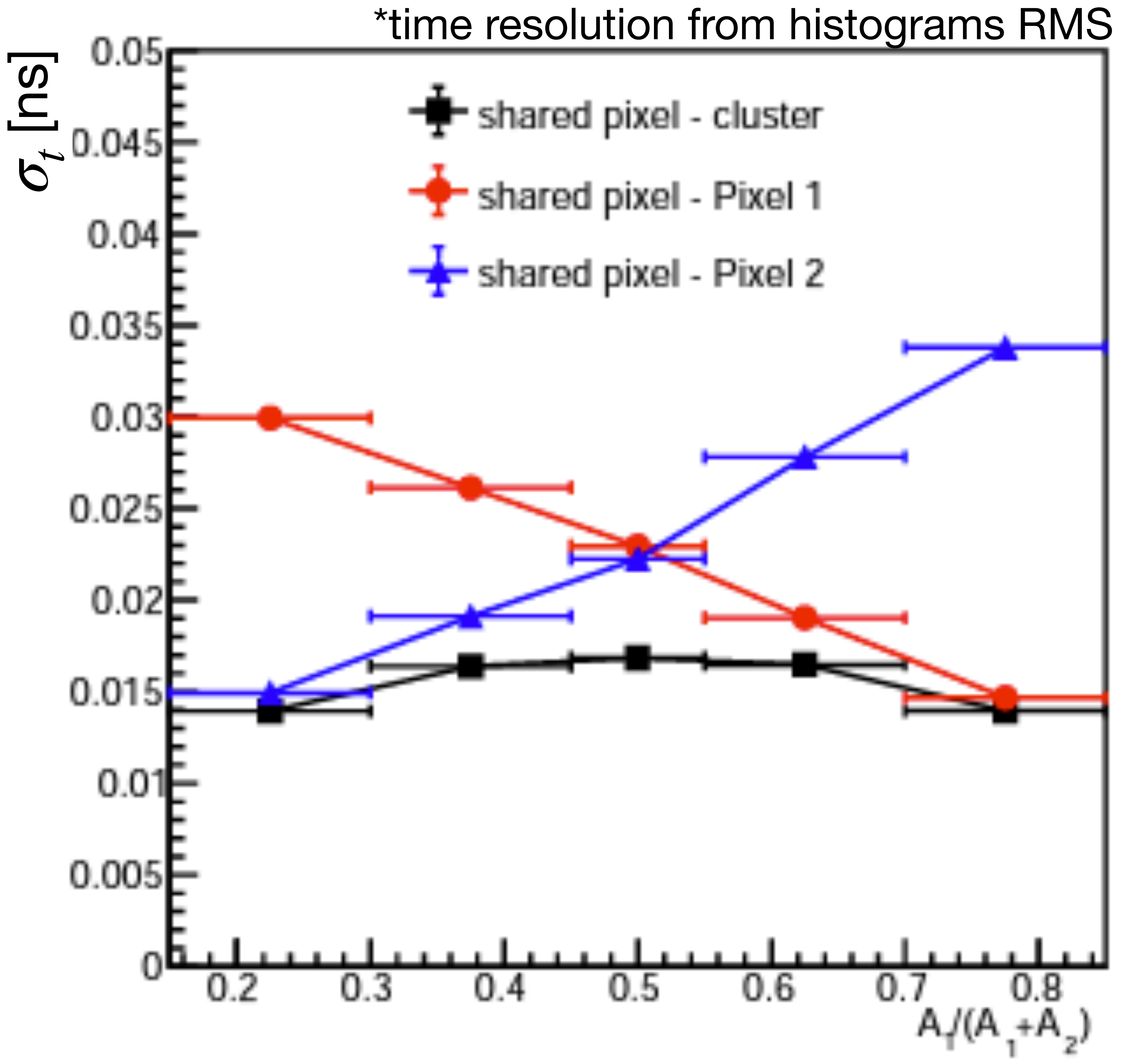


Tilting the sensor (Rotation 2) it is possible to study the **behavior of two pixels** (readout on different channels) when a **charged particle crosses both**.

Work in progress: charge sharing



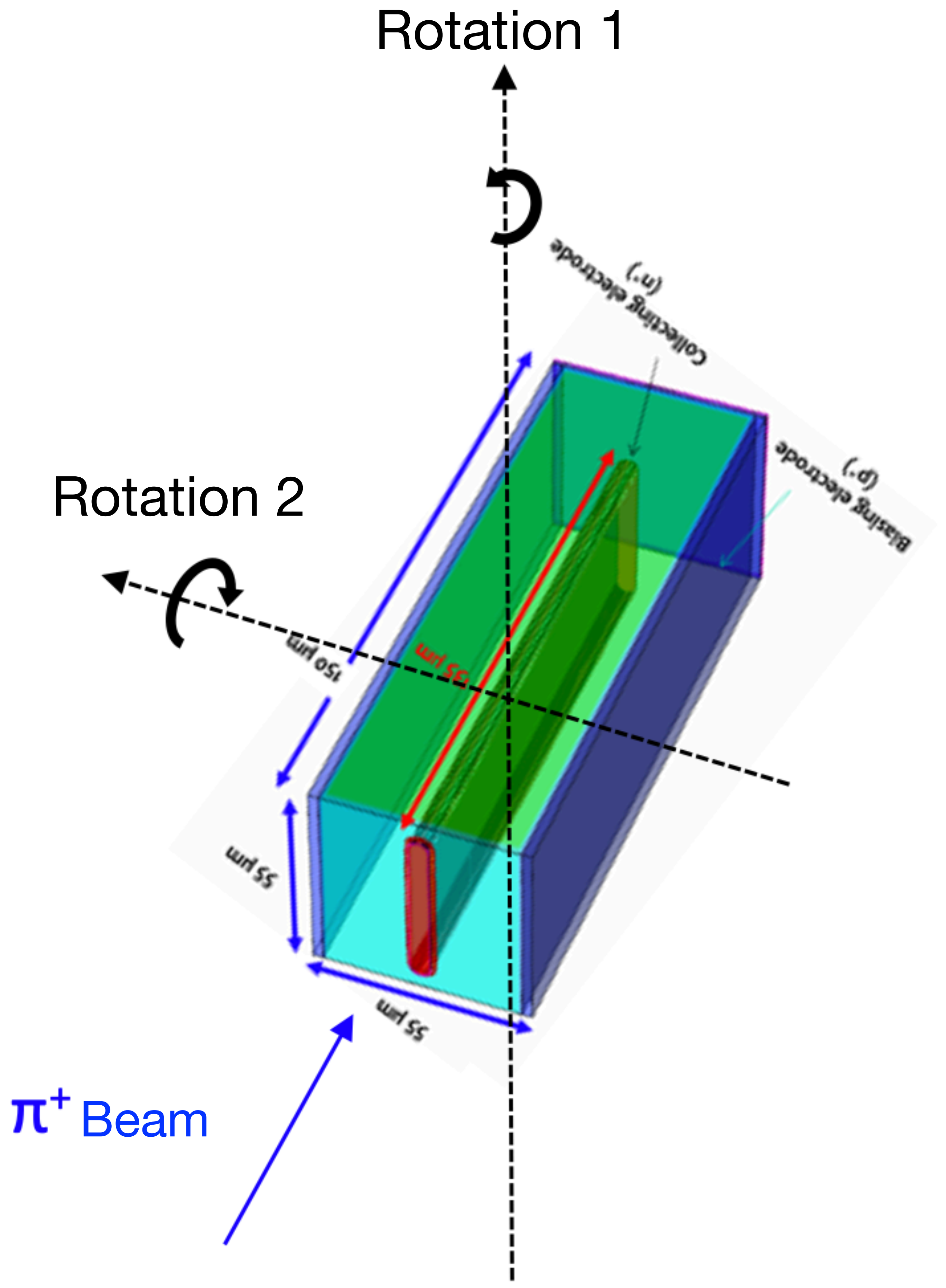


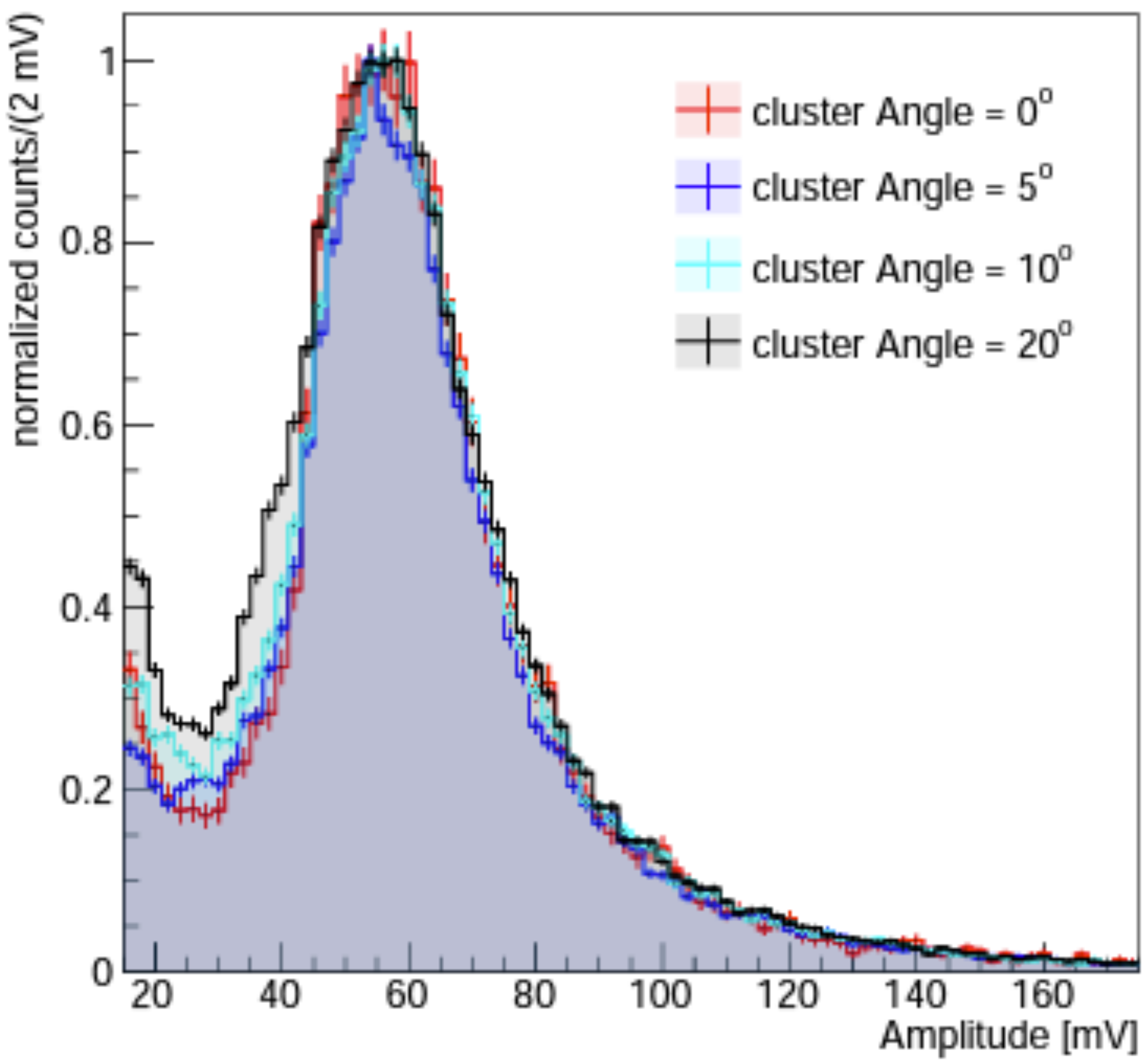


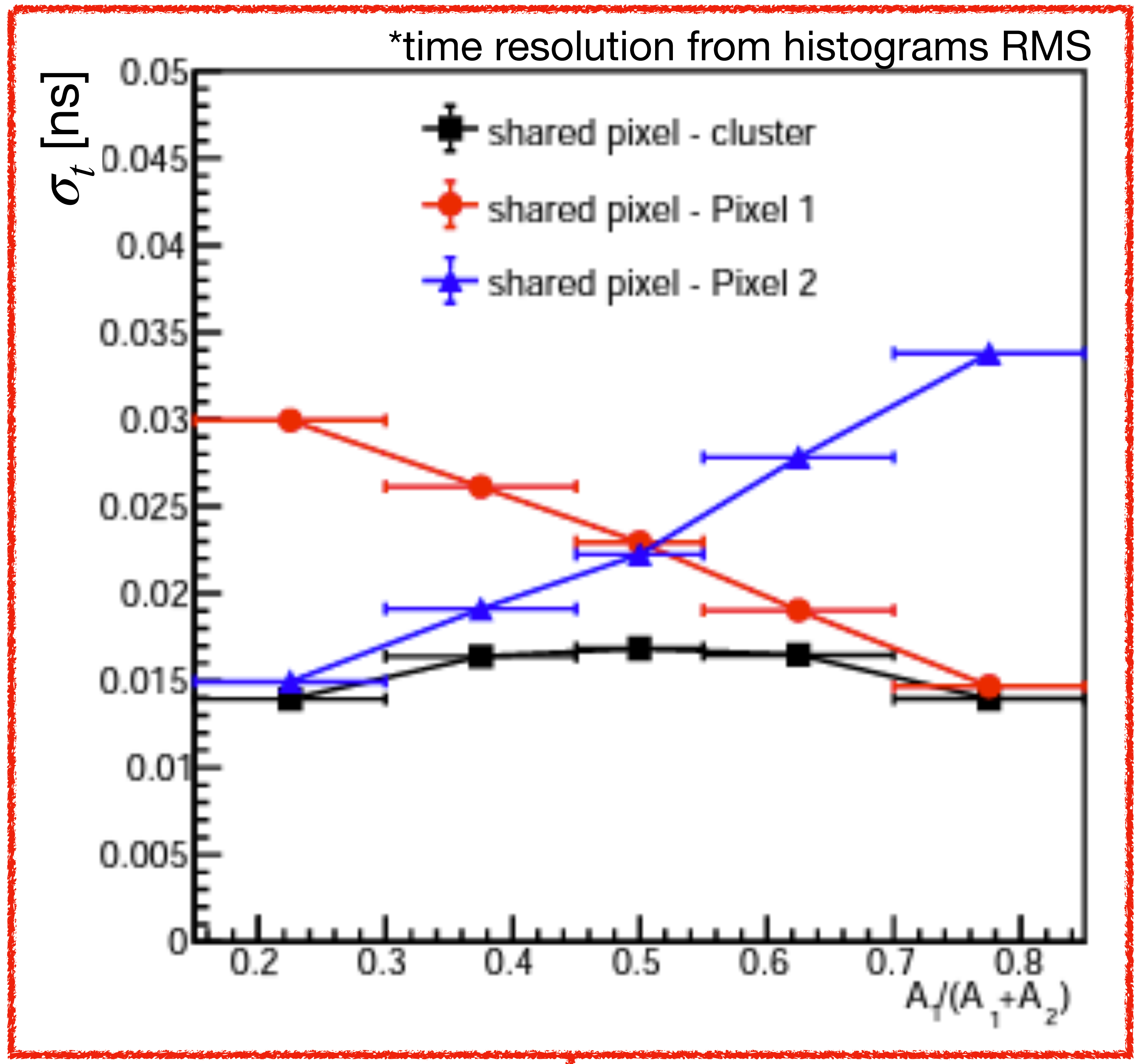
When a **particle crosses two pixels**, the **sum of the amplitudes** of the two signals is taken.

Combining the **whole cluster information** (tracks hitting only one pixel + tracks hitting two pixels) it is possible to **recover the amplitude distribution expected at normal incidence angle**

Work in progress: charge sharing







When a **particle crosses two pixels**, the ToA is the weighted sum on amplitudes of the ToA in the two pixels.

Considering **only the tracks hitting two pixels**, the σ_t from the **weighted mean improves** the **timing performance** when the tracks are equally shared by the two pixels