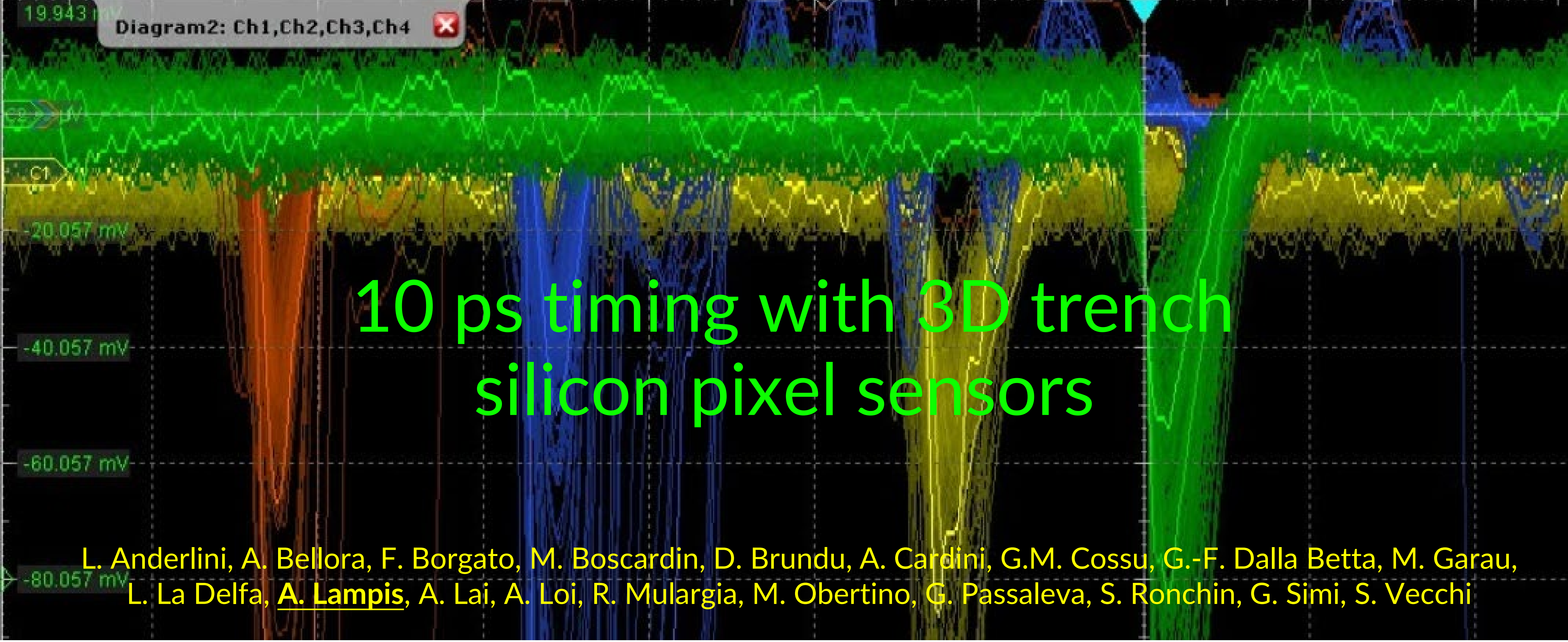


10 ps timing with 3D trench silicon pixel sensors

L. Anderlini, A. Bellora, 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, G. Passaleva, S. Ronchin, G. Simi, S. Vecchi

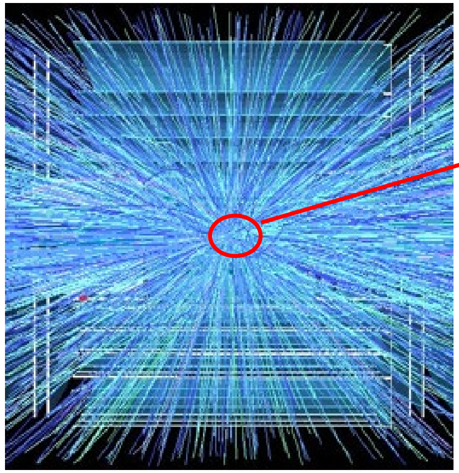
23rd International Workshop on Radiation Imaging Detectors
Riva del Garda, June 30th 2022

INFN CAGLIARI

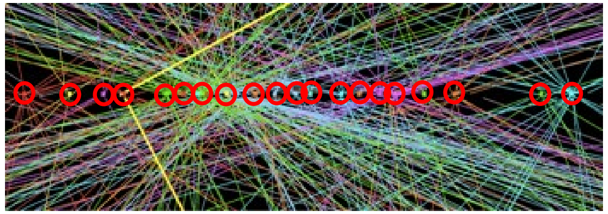
TimeSPOT

Present and future challenges in tracking

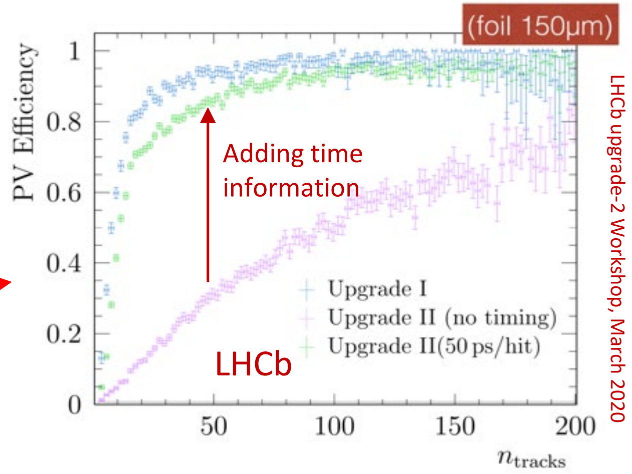
- Future and today's upgraded colliders will operate at extremely high instantaneous luminosities
  - Very important radiation damage to tracking detectors
  - Extremely difficult event reconstruction due to large pile-up ➔ adding the time information (at the track or hit level) will help recovering tracking and vertexing capabilities



Adding the track time information



- ATLAS & CMS Phase-II upgrades (2026): mostly "traditional" tracker + single timing layer
  - $\sigma_t \approx 30$ ps, $\sigma_s \approx 100\text{-}300$ µm, F ≈ 10^{15} 1 MeV n_{eq}/cm^2
- LHCb Upgrade-2 (2030s): time information on each pixel
  - $\sigma_t = 30\text{-}50$ ps, $\sigma_s \approx 10$ µm, F = 10^{16} to 10^{17} 1 MeV n_{eq}/cm^2



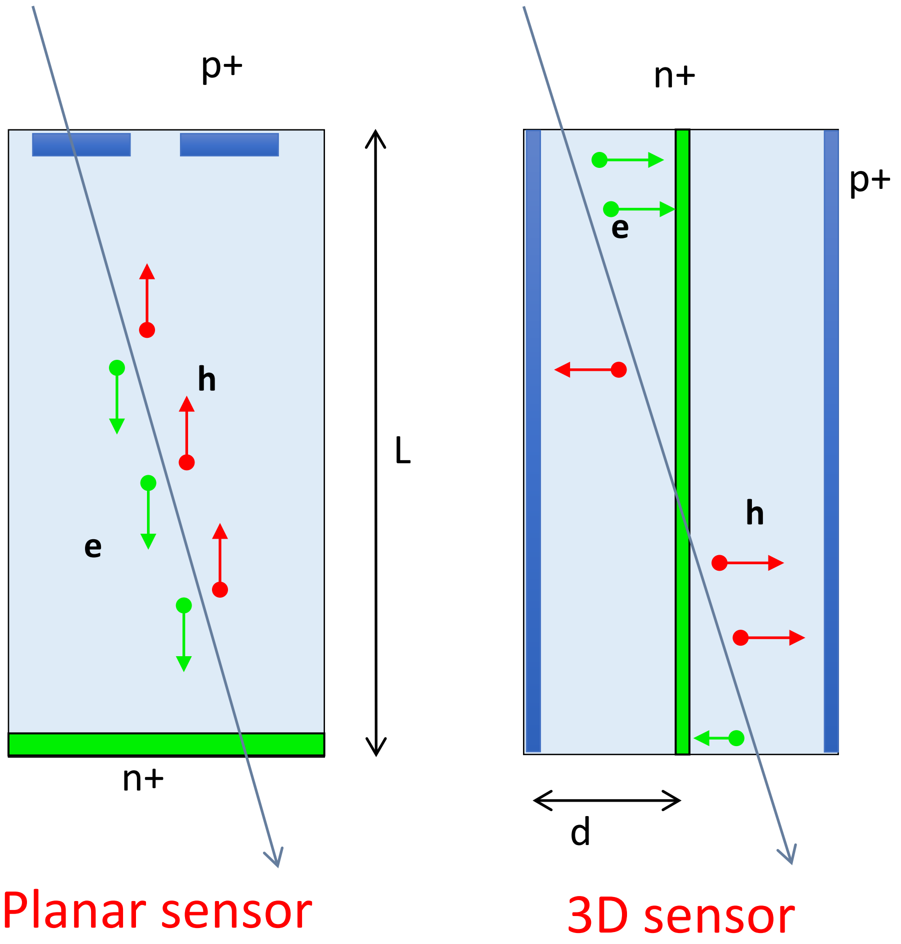
- FCC-hh (2040s ?): further improve the radiation hardness
  - $\sigma_t = 10\text{-}20$ ps, $\sigma_s \approx 10$ µm, F = 10^{17} to 10^{18} 1 MeV n_{eq}/cm^2

Excellent spatial resolution, time resolution and radiation hardness are **required at the same time!**

3D silicon pixel sensors

- Original idea: S. Parker, 1997

- Key points
  - Short inter-electrode drift distance (tens of µm) give rise to extremely fast signals (d<<L)
  - Unmatched radiation hardness (> 10^{17} 1MeV n_{eq}/cm^2, NIMA, 979 (2020) 164458)
  - Electrode shape can be designed for maximum performance
  - 3D columnar geometry is a production-ready technology (ATLAS IBL, ATLAS-P2)



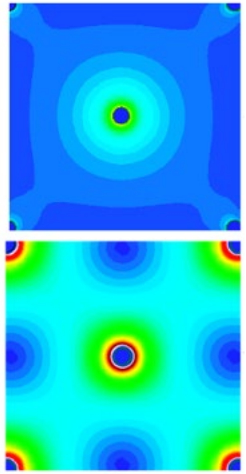
Toward an optimized 3D sensor design

Electrode shape optimisation to have signals that do not depend on where the charged particle has crossed the detector

Current signal is defined as

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

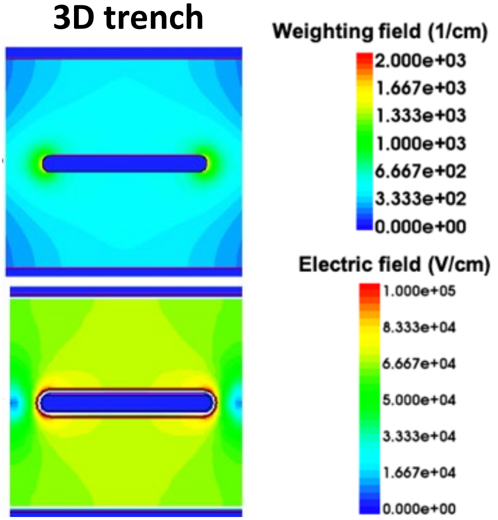
5 columns



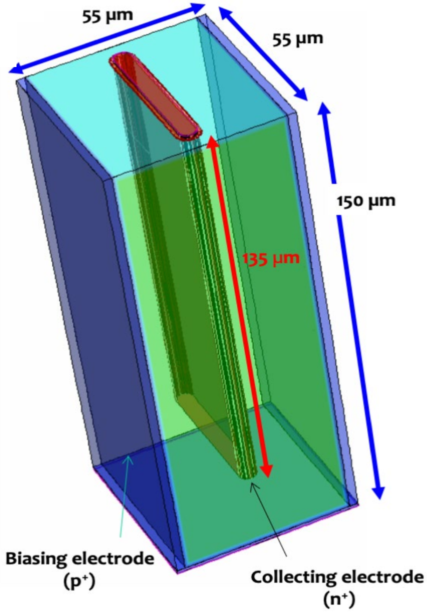
$\vec{E}_w$ **uniform by design**

Velocity saturation

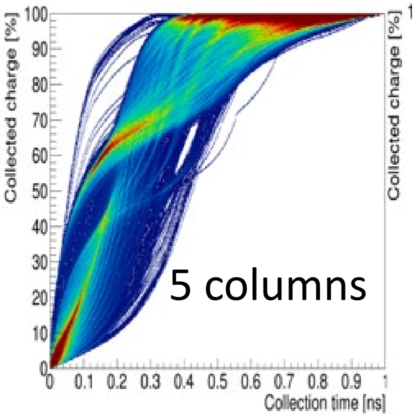
3D trench

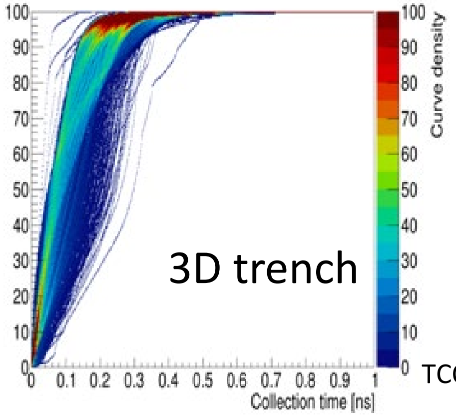


TCAD Simulations Vbias = – 150 V



Simulated charge collection curves for MIPs uniformly crossing a pixel over its active area

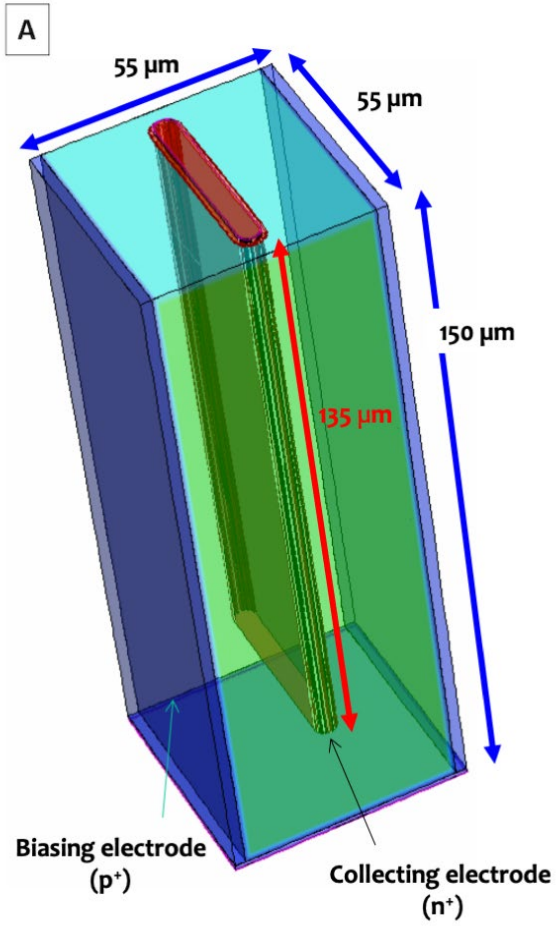


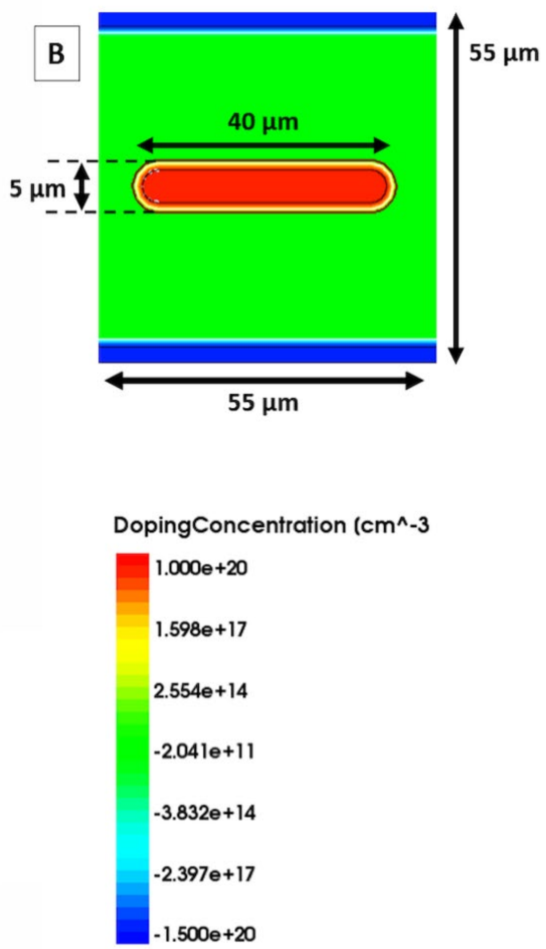


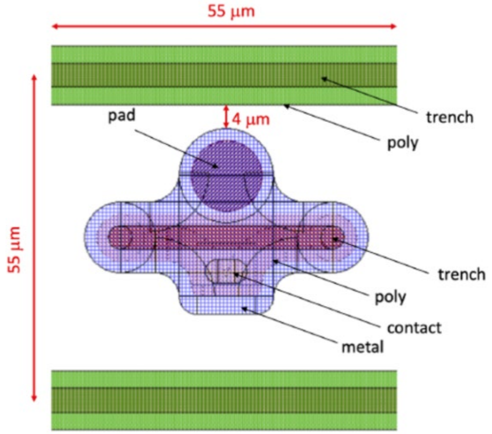
TCODE Simulations

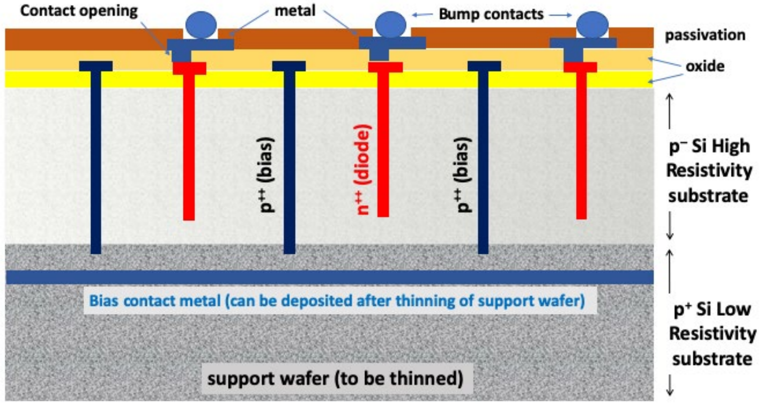
shorter and much more uniform charge collection time for the 3D trench geometry

The trench-type TimeSPOT 3D pixels







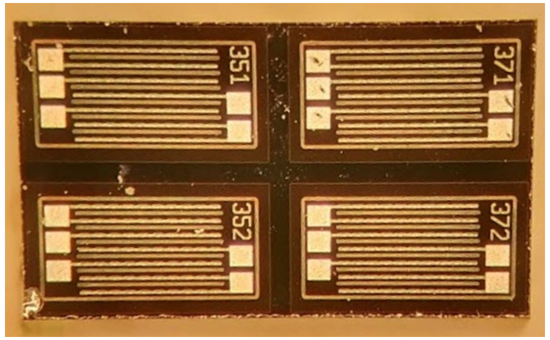


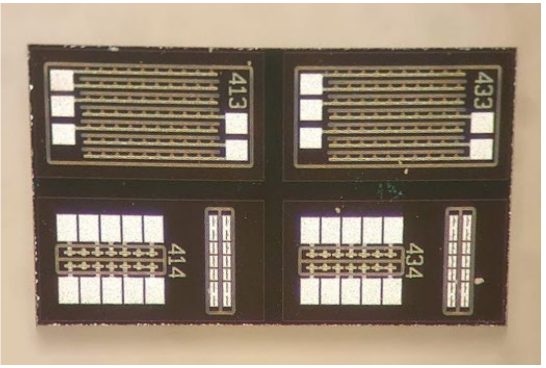
- 55µm x 55µm pixels (to be compatible with existing FEE, for example the Timepix family)
- In each pixel a 40µm long n++ trench is placed between continuous p++ trenches used for the bias
- 150µm-thick active thickness, on a 350µm-thick support wafer
- The collection electrode is 135µm deep

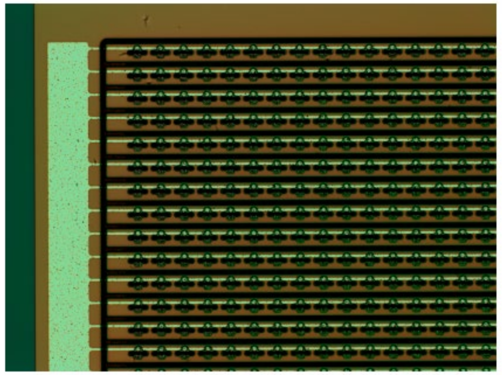
TimeSPOT silicon sensor

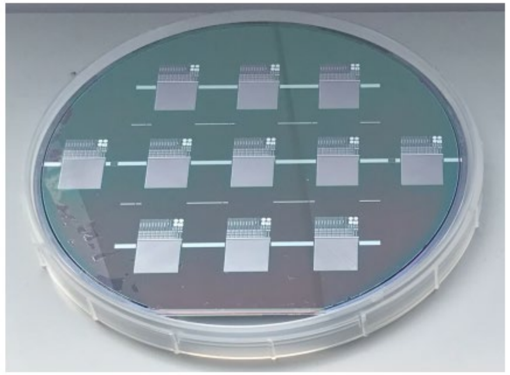
Two batches were produced in 2019 and 2021 at Fondazione Bruno Kessler (FBK, Trento, Italy) using the Deep Reactive Ion Etching Technique (DRIE) Bosch process, 6" wafers

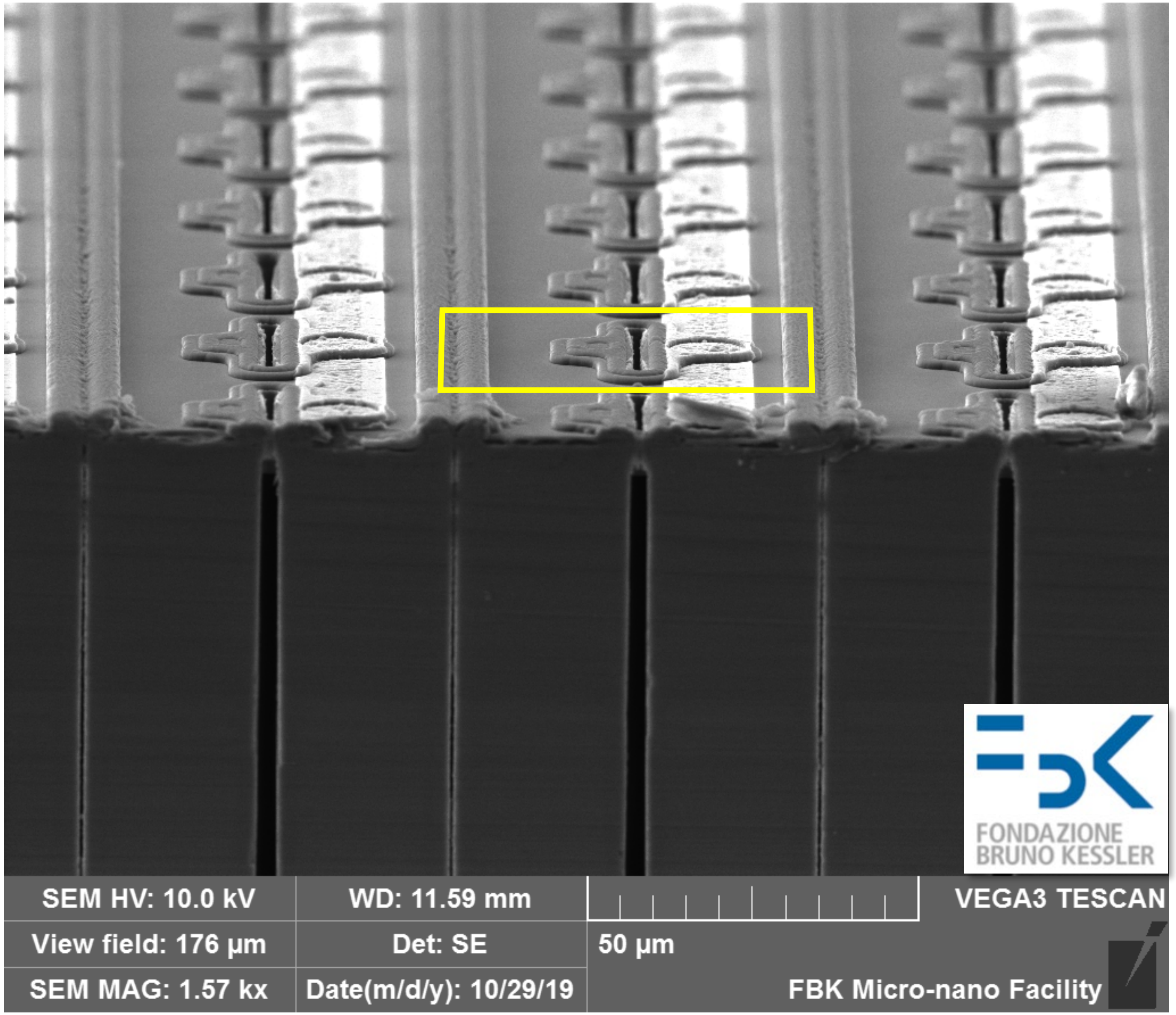
Many devices fabricated (single, double pixels, pixel-strips, pixel matrices)





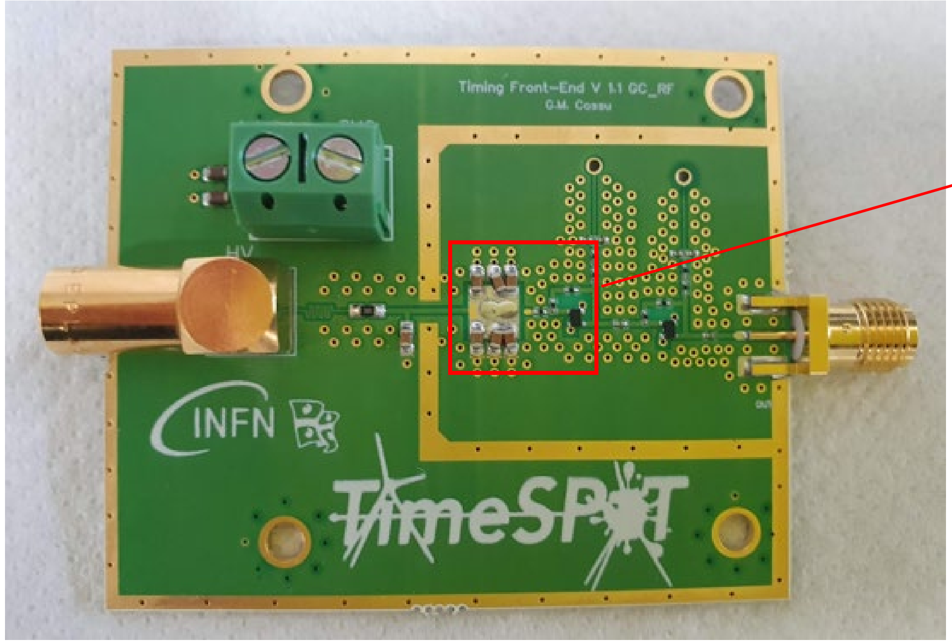


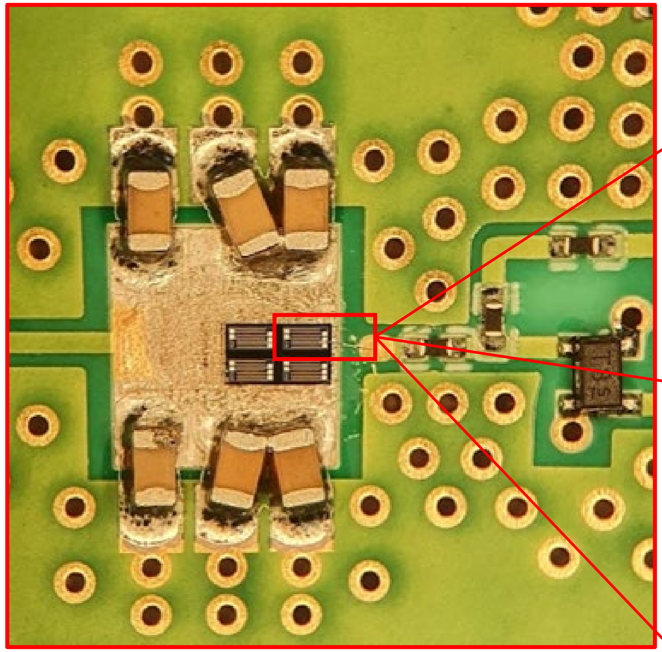


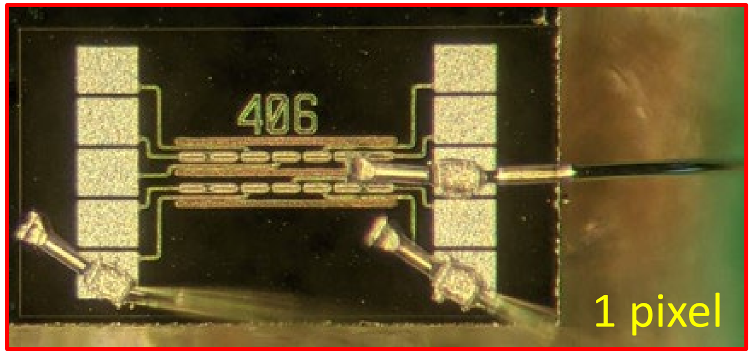


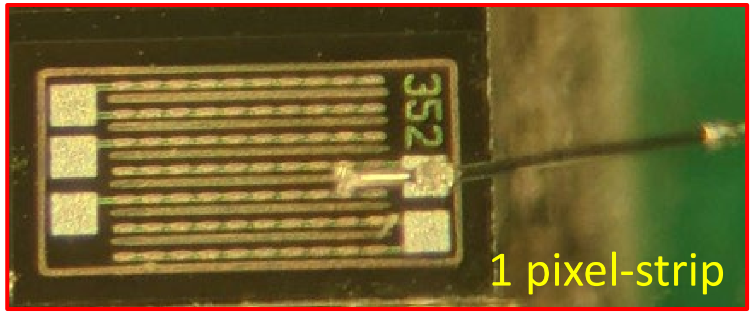
Beam characterization of 3D trench pixels

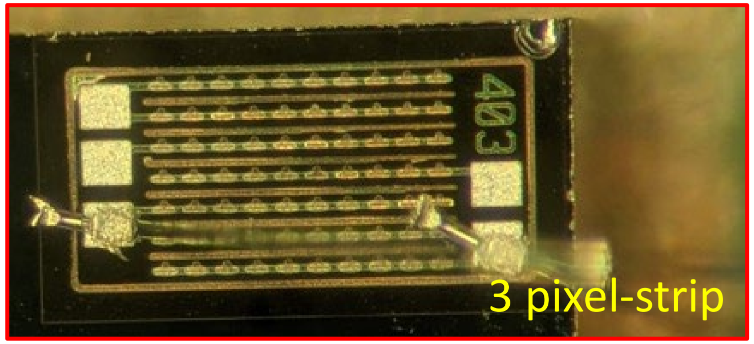
- We have characterized single-pixels and various pixel-strips (10-30 pixels) test structures
- Custom-made front-end electronics boards featuring a two-stage transimpedence amplifier made with fast SiGe BJTs





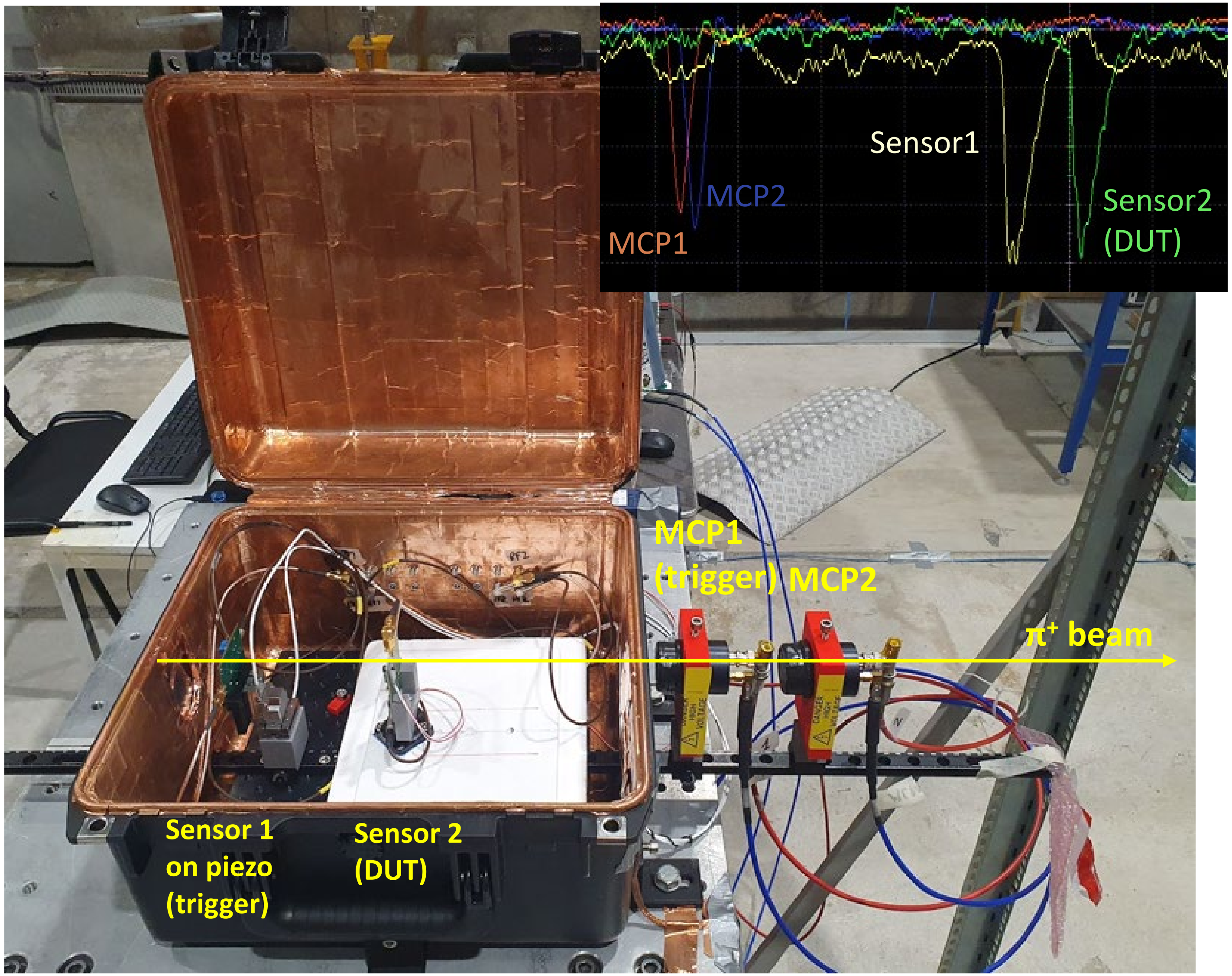






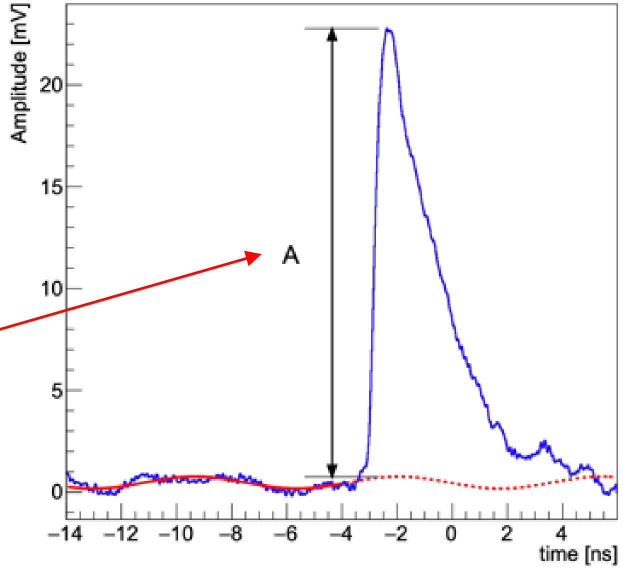
2021/2022 SPS beam test

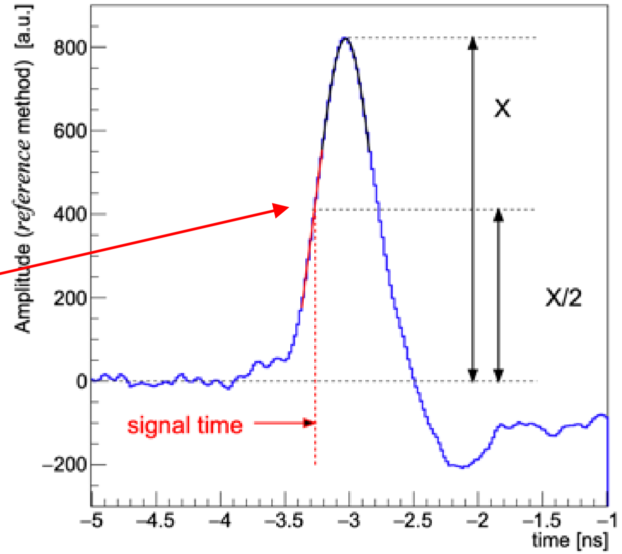
- 180 GeV/c π^+ beam
- 2 MCP-PMTs on the beam line to time-stamp the arriving particle (σ_{avg} = 5 ps)
- Piezoelectric stages to precisely align the two 3D structures with beam, all mounted in a RF-shielded box
- Readout with 8 GHz bandwidth 20 GSa/s scope: trigger on the AND of one 3D sensor and one MCP-PMT
- Possibility of operating the fixed sensor down to -40°C using dry ice to test irradiated sensors



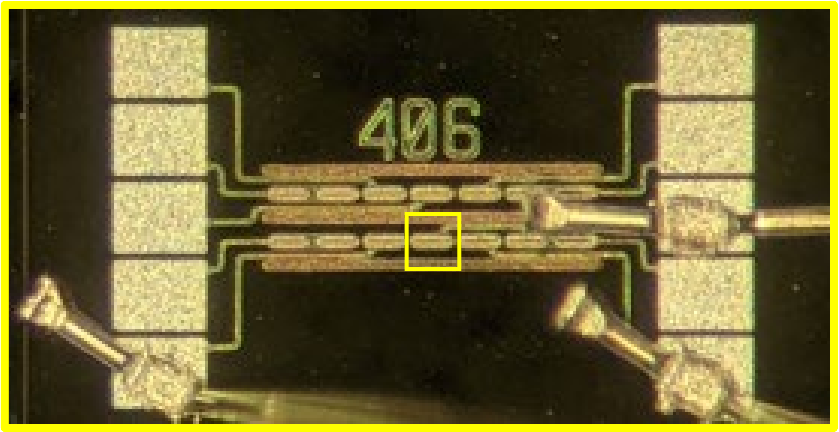
Waveforms analysis

- <u>For each sensor's waveform:</u>
  - Signal baseline (red-dashed line) is evaluated on an event-by-event basis
  - The **signal amplitude** A is measured (w.r.t. to the event baseline)
  - **Signal time of arrival** evaluated with various methods:
    - <u>Leading-edge</u>: time at 15 mV signal amplitude, linear interpolation around threshold
    - <u>Spline</u>: a CFD at 20% with rising edge interpolated with a spline
    - <u>*Reference*</u>: subtract each waveform from a delayed (by about half of the signal rise time) copy of itself, then on the resulting signal we trigger at X/2 height

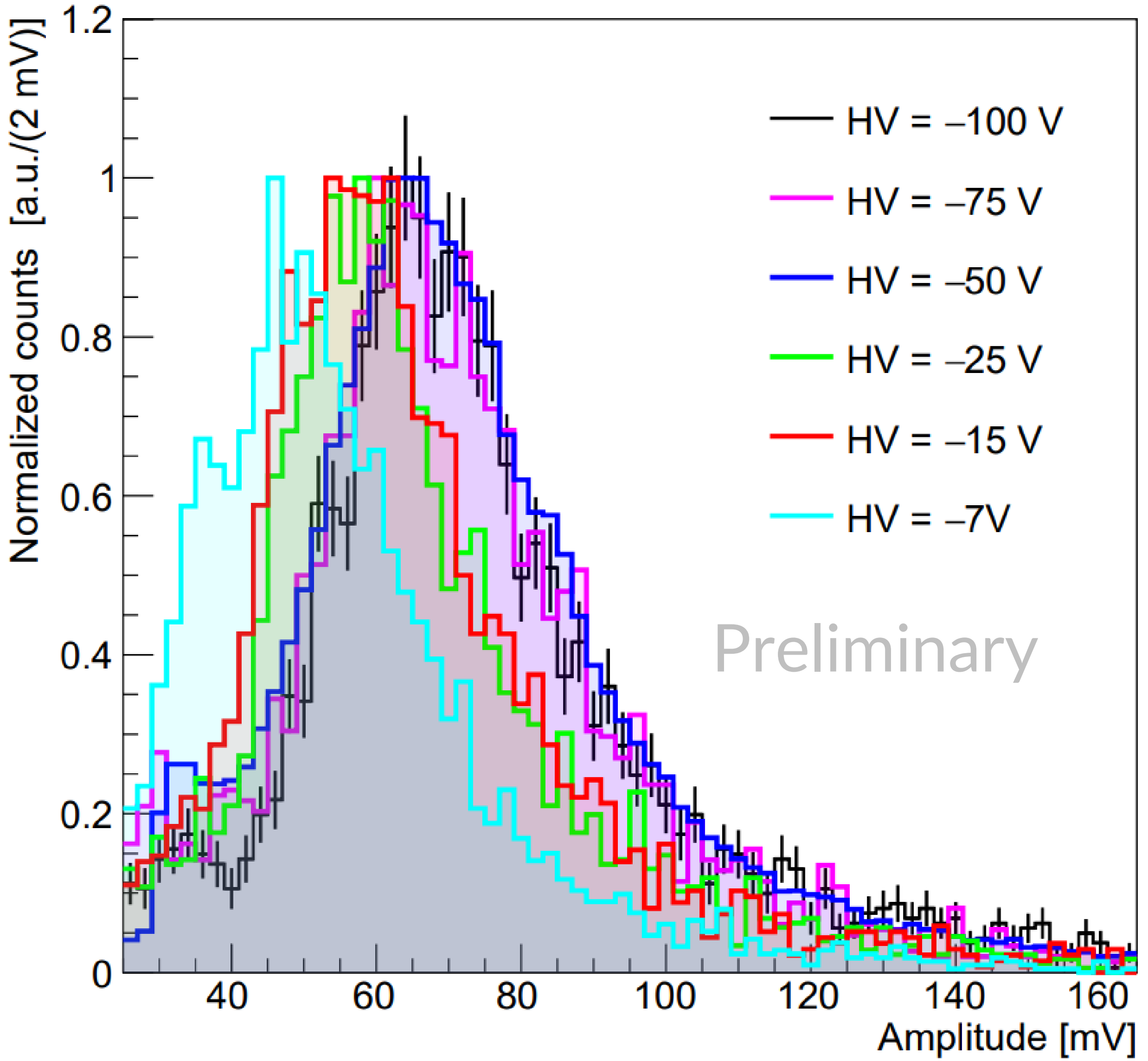




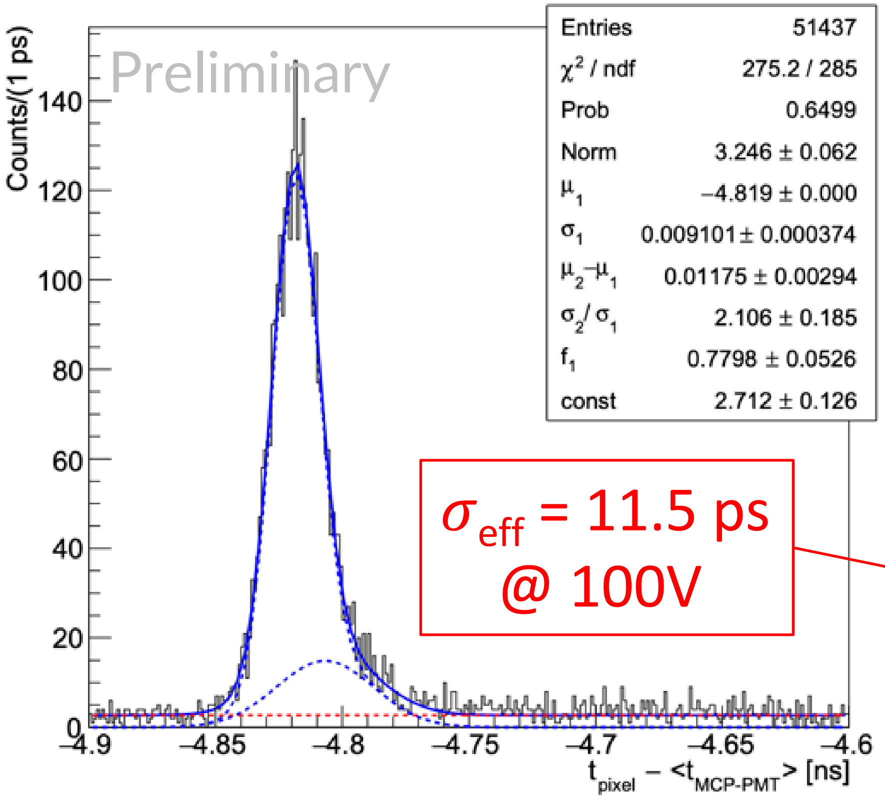
Single 3D pixel - amplitude

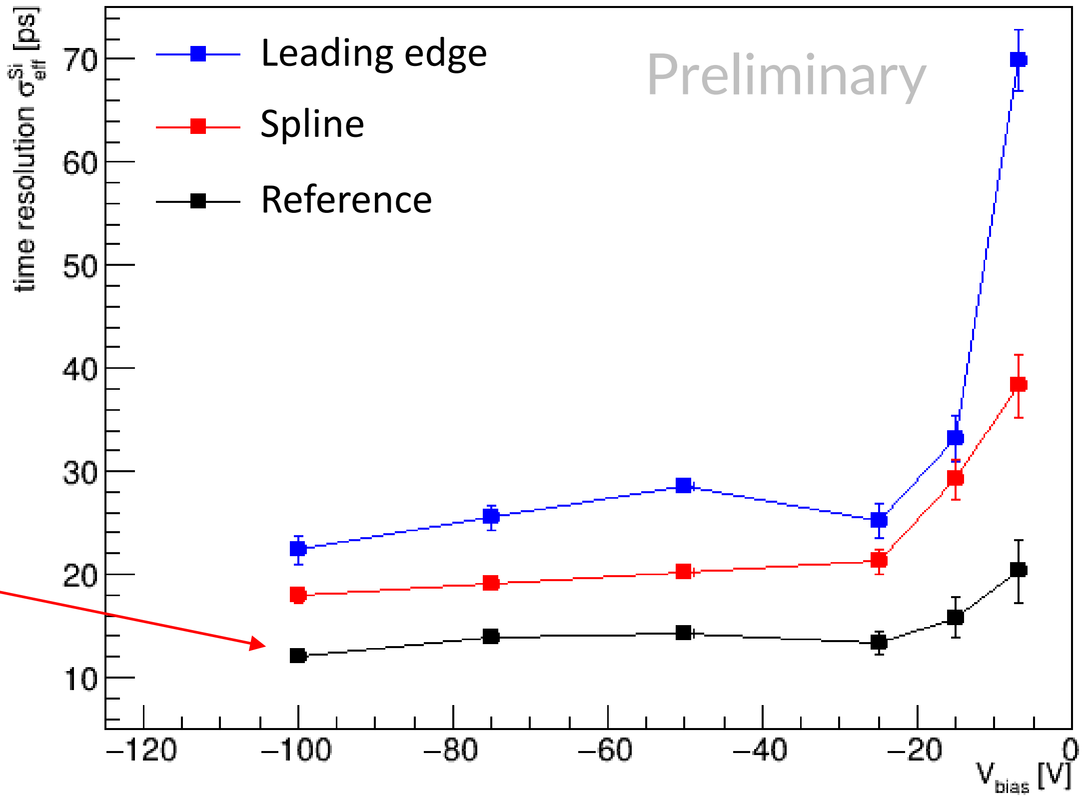


- Non-irradiated pixel
- Normal pion incidence
- **<u>DUT not on the trigger</u>**
- <u>Good sensor performance even at low V_{bias}</u>



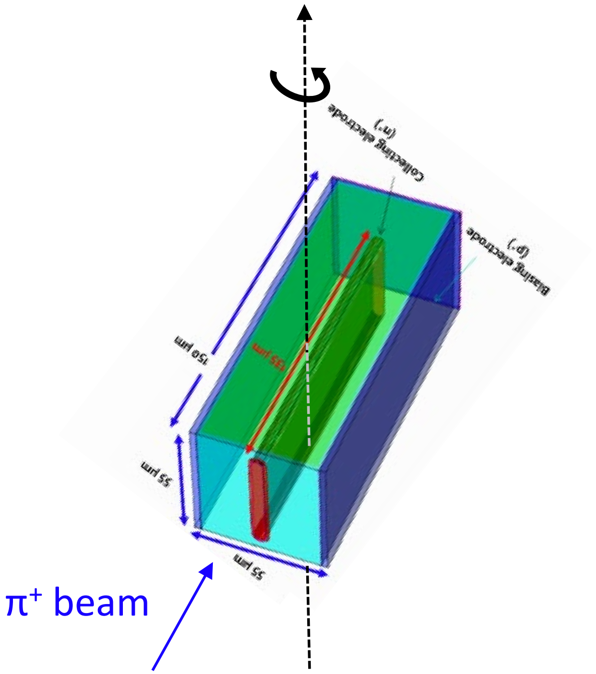
Single 3D pixel – timing performances



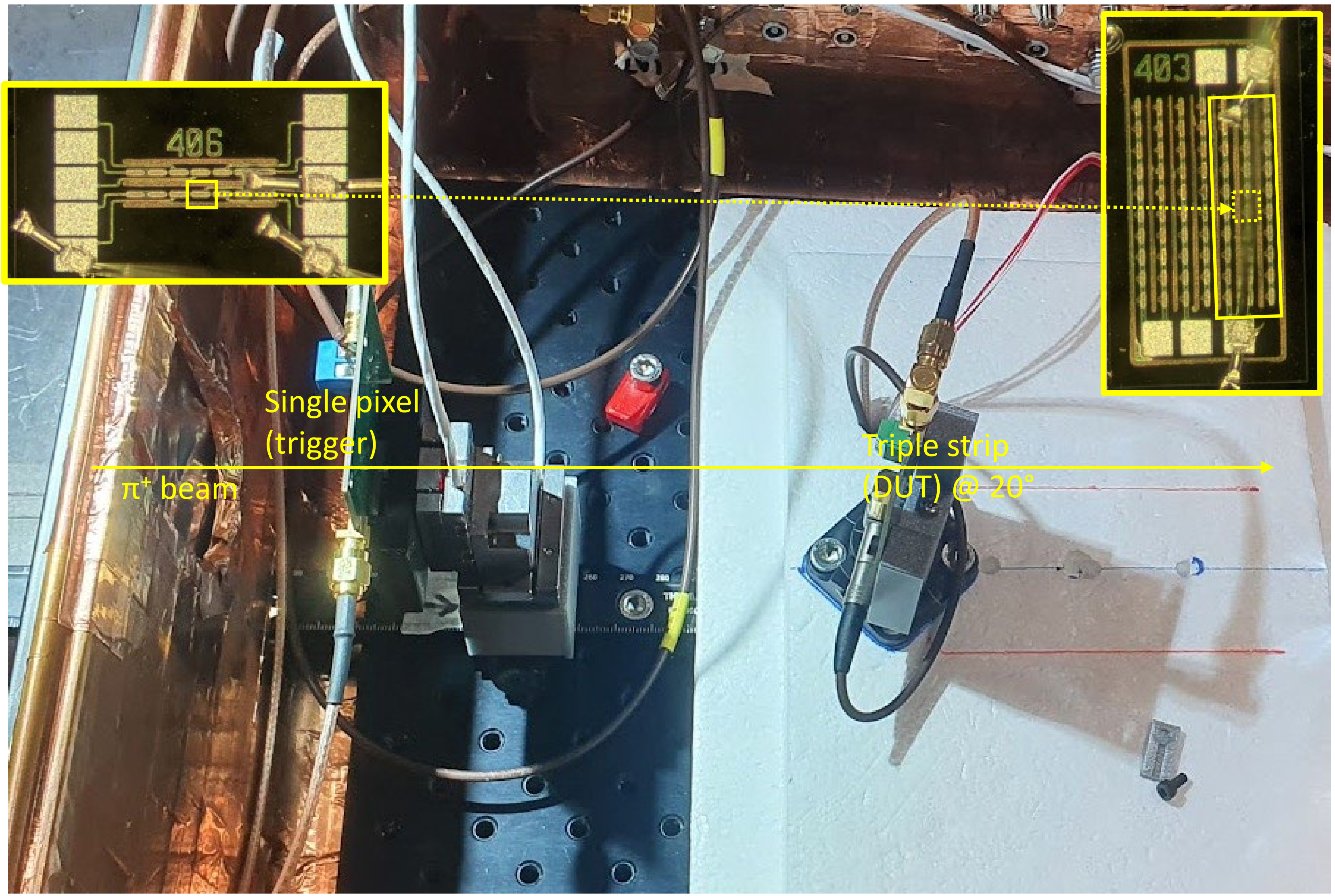


- 3D pixel time distribution w.r.t MCP-PMTs: symmetric with only a small tail due to late signals
- Time distribution fitted with two gaussians, to include small tail contributions
- Excellent timing performances with CFD-based methods, but also with leading edge algorithm (**<u>no time walk correction</u>**)

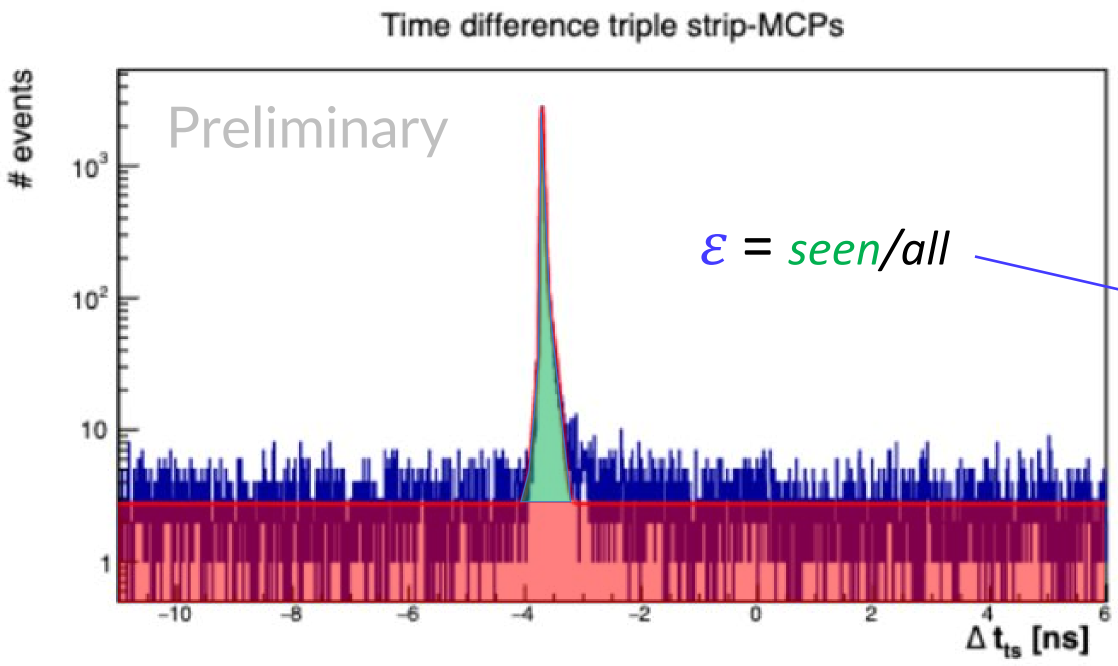
Efficiency: setup



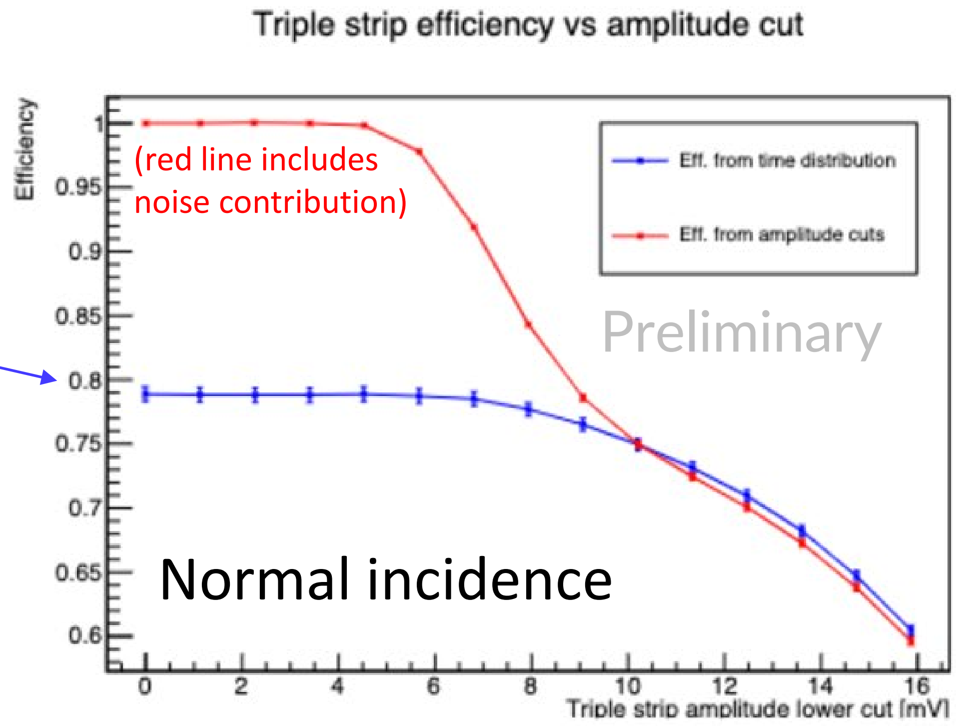
- Trenches (5 μm wide) are non-active volumes, channeled particles will not be detected
- **Tilt the sensors** with respect to normal incidence should allow **to recover geometrical efficiency**
- Trigger on one pixel (55 μm x 55 μm, on piezos) centered on a triple strip (165 μm x 550 μm, DUT) and counting the fraction of signals seen in the triple strip (on a single FE channel)
- Rotate the DUT around the trench direction



Efficiency: method

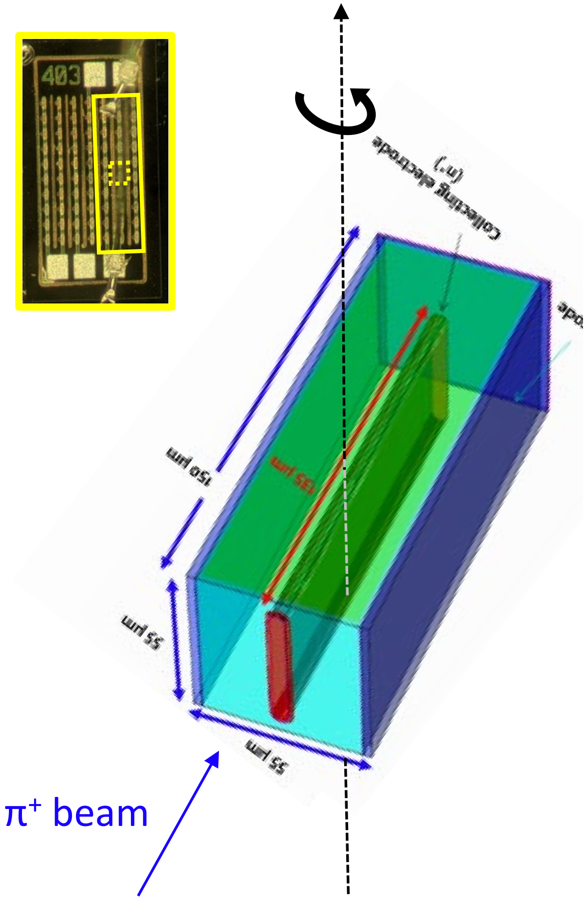


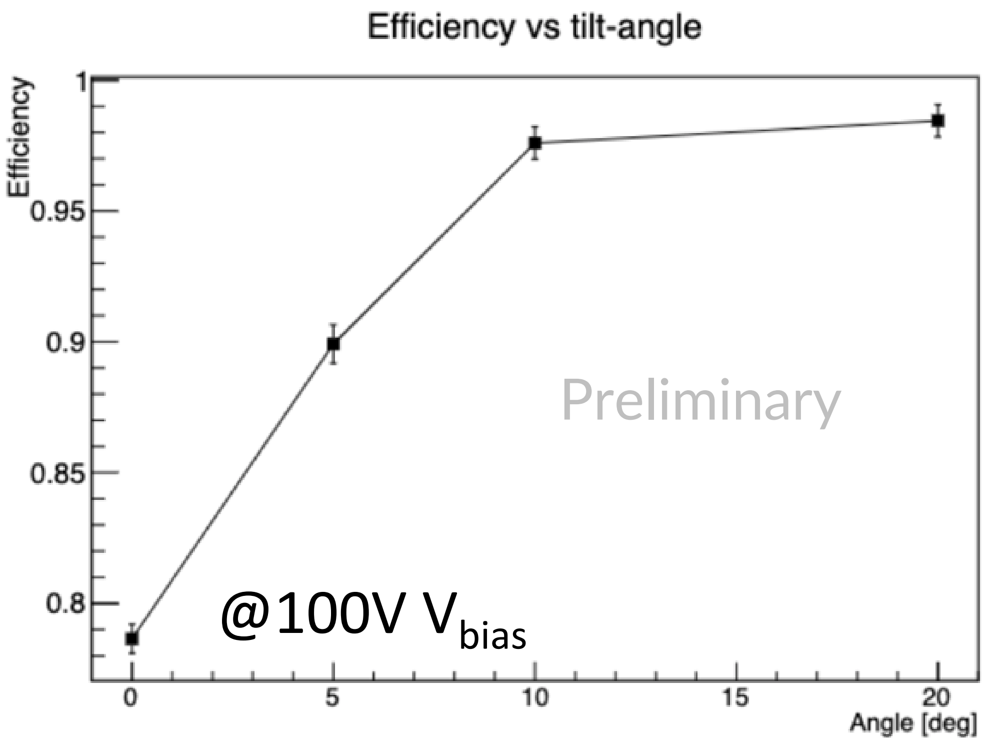
ε = *seen*/*all*

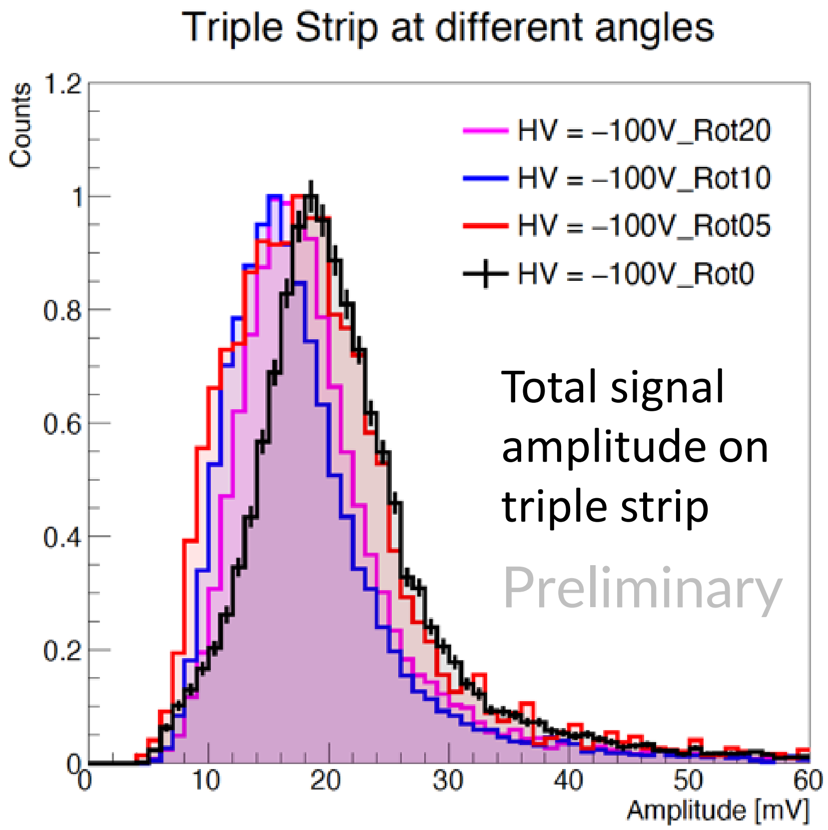


- Time distribution of **all triple-strip signals** w.r.t. MCP-PMTs and count as 'seen' the ones under the peak
- 3D pixel detection (geometrical) efficiency at normal incidence is in agreement with calculated fraction of active area

Efficiency: results



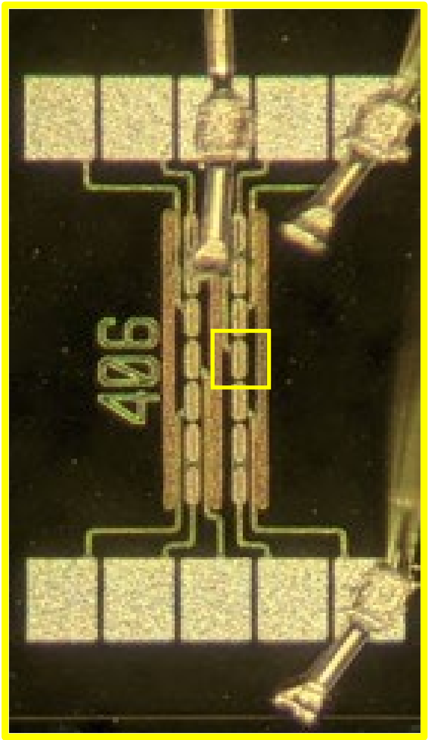


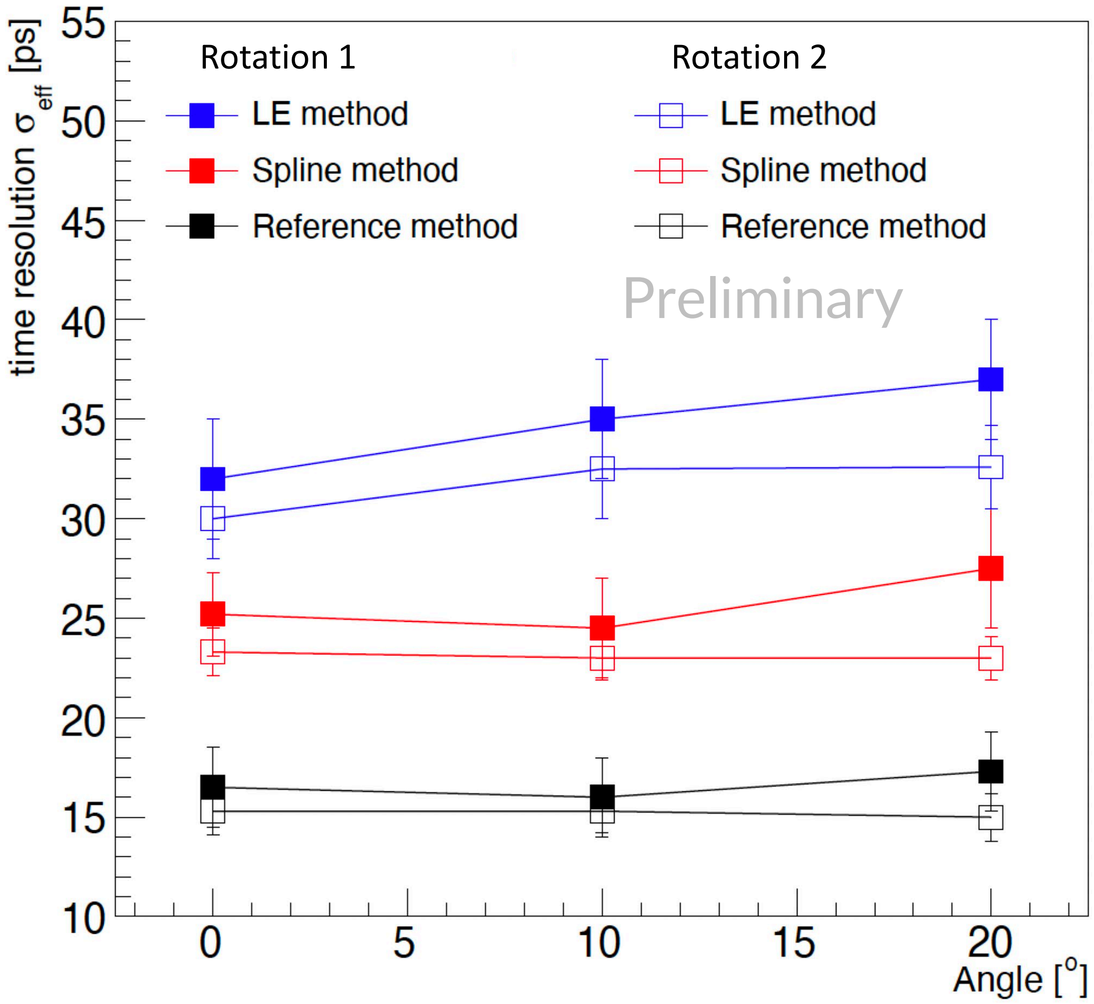


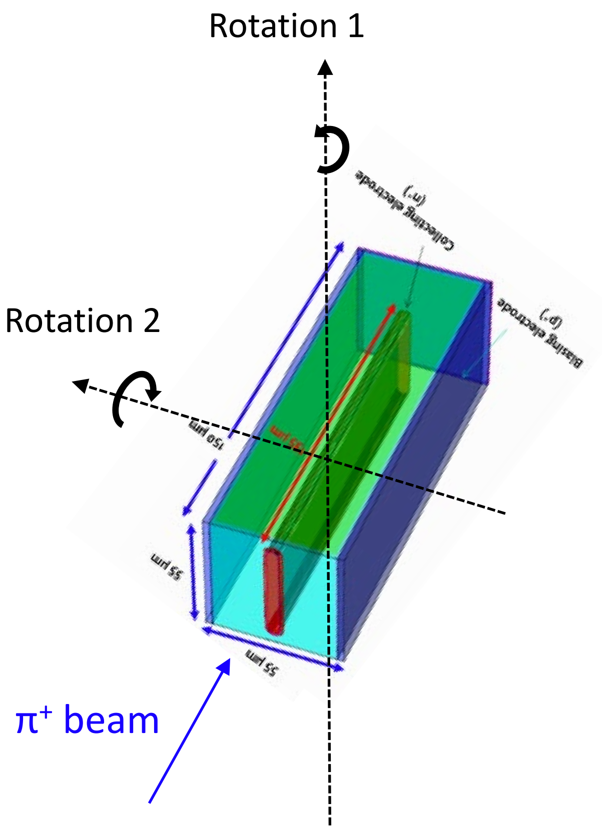
$$\epsilon = (99.1 \pm 0,6)\% \ @20°$$

- 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



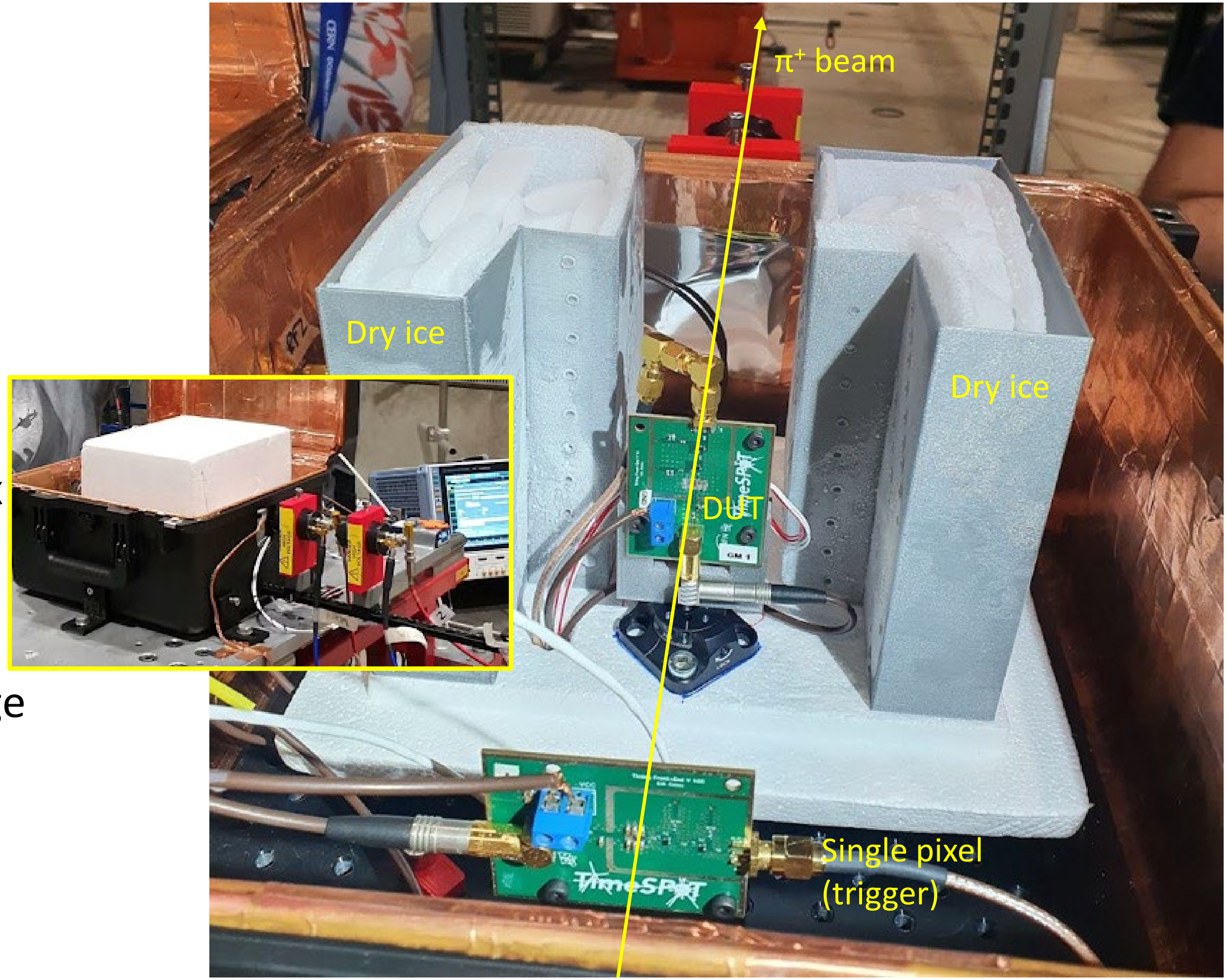




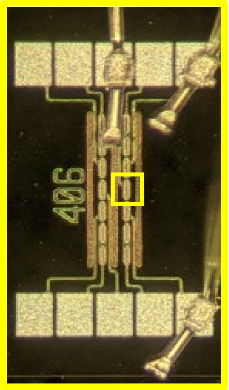
Excellent time resolution also for tilted sensors

Irradiated sensors – the setup

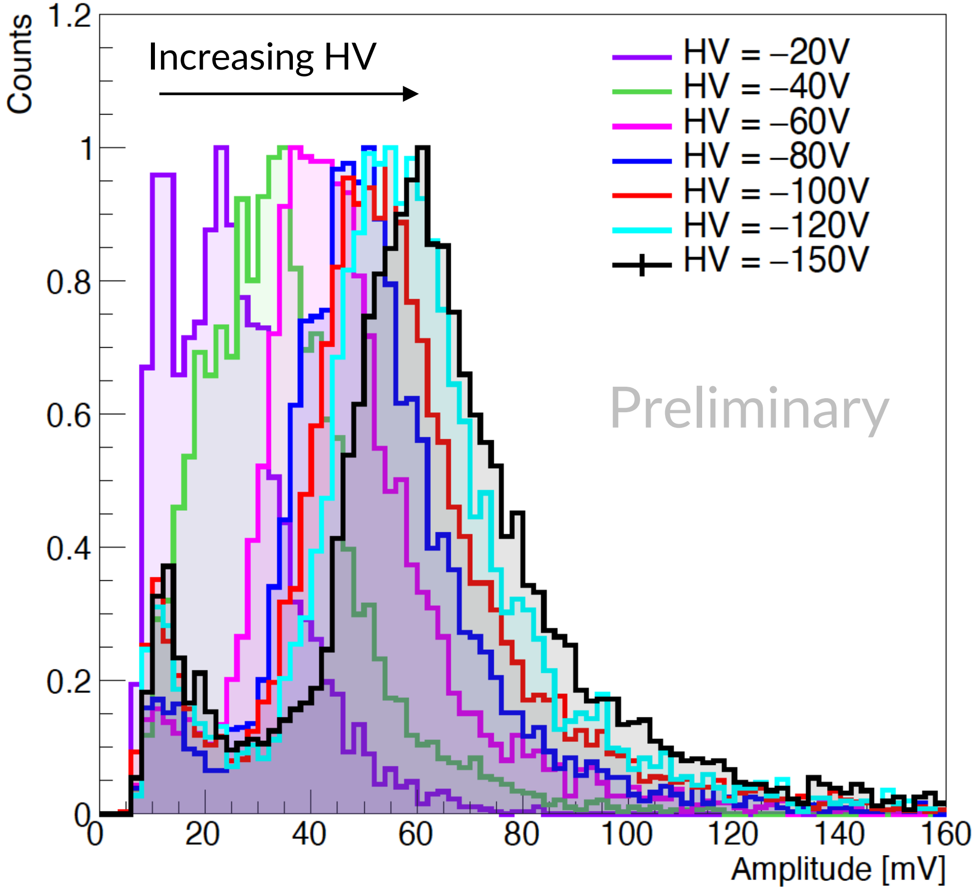
- 3D sensors irradiated at the Triga Mark II reactor at the Jožef Stefan Institute in Lubjiana, Slovenjia
- Fluences: up to $2.5 \cdot 10^{16}$ 1MeV n_{eq}/cm^2 sensors not annealed
- Almost the expected fluence on LHCb vertex detector after LHC Run5 on innermost sensors
- Sensors tested below -20°C to reduce leakage current
- Characterization of irradiated single pixels and triple-pixel-strips structures



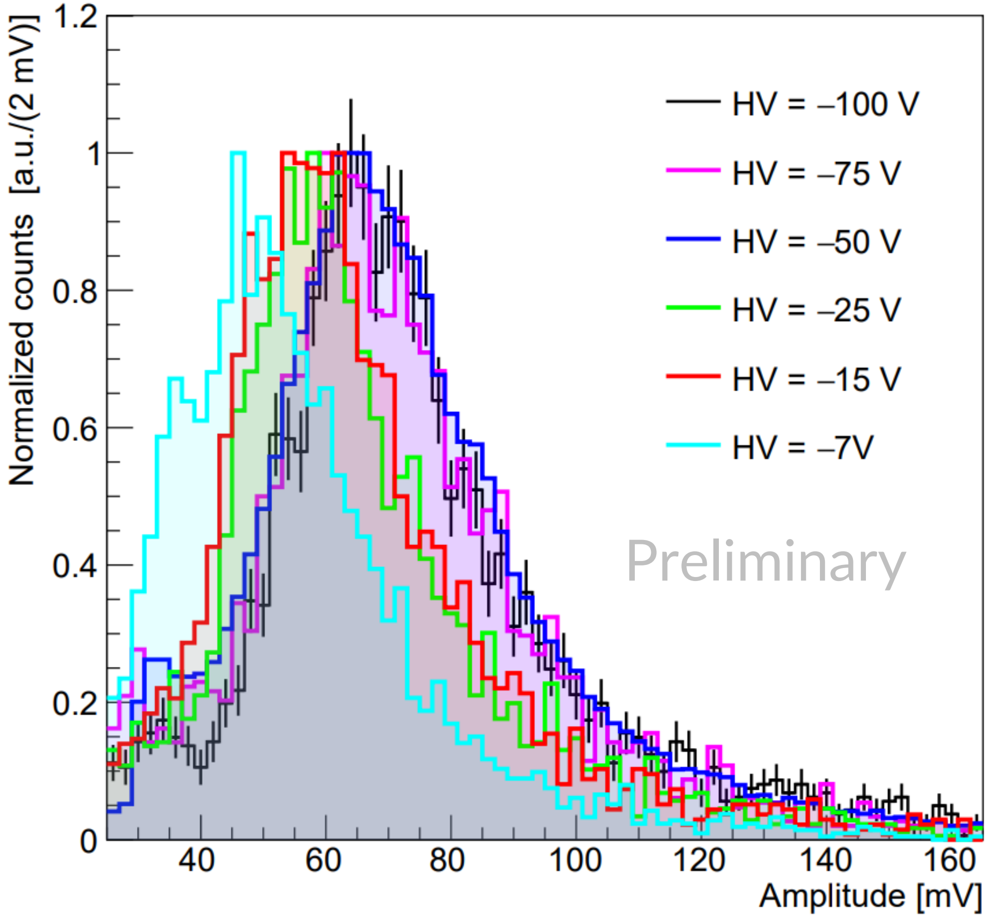
Irradiated sensors – working point



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

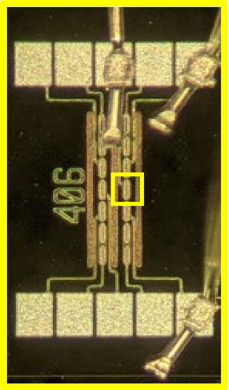


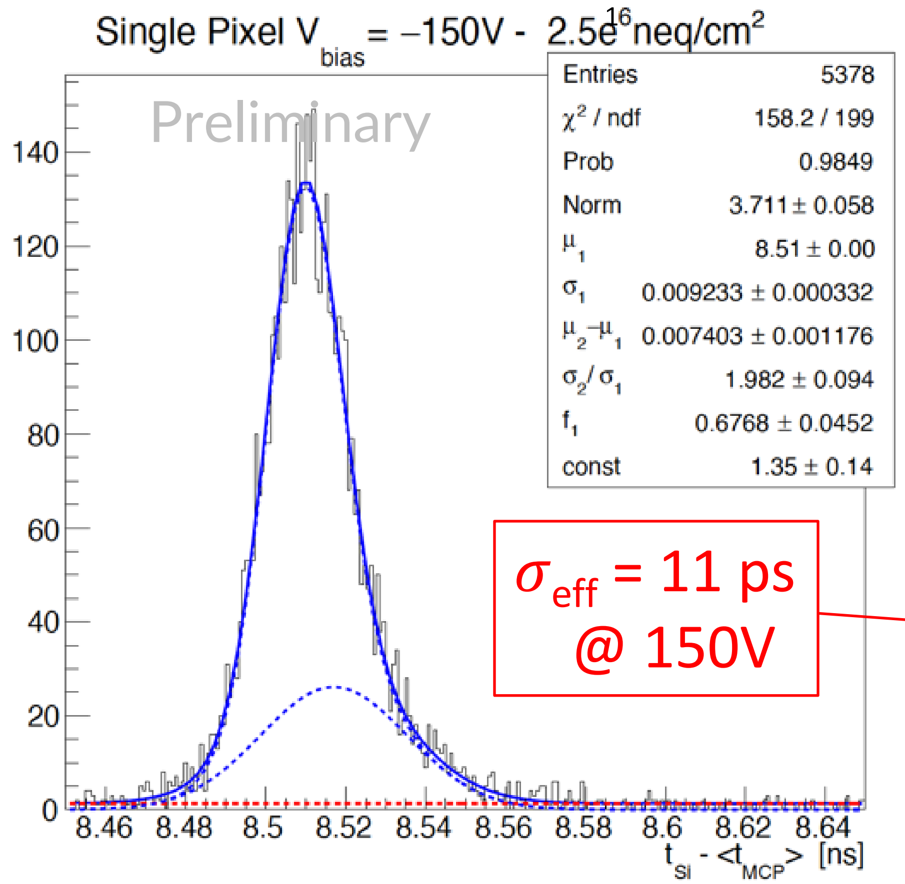
UNIRRADIATED PIXEL – 0°

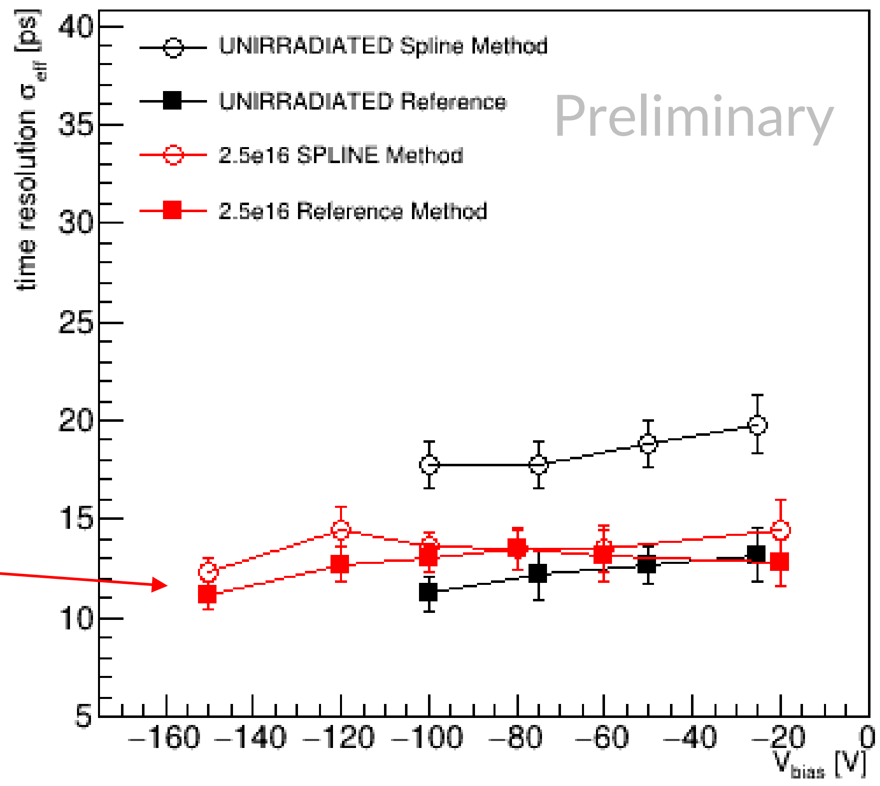


- A larger bias voltage is required to recover the signal amplitude for irradiated sensors

Irradiated sensors – timing performance

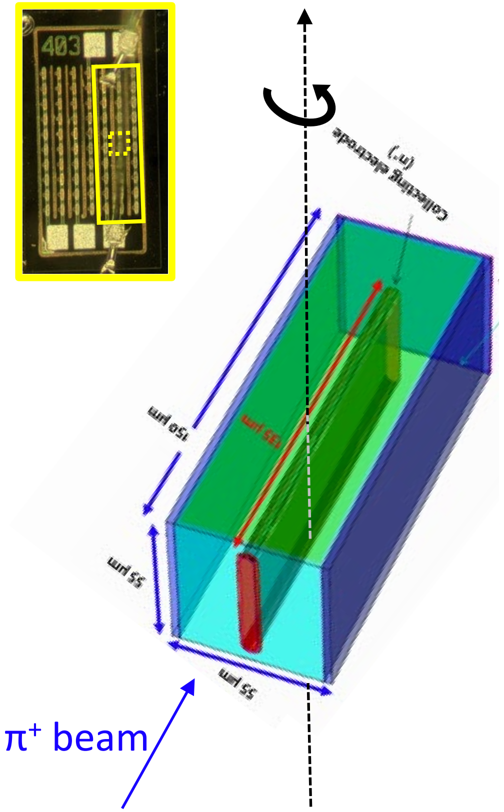


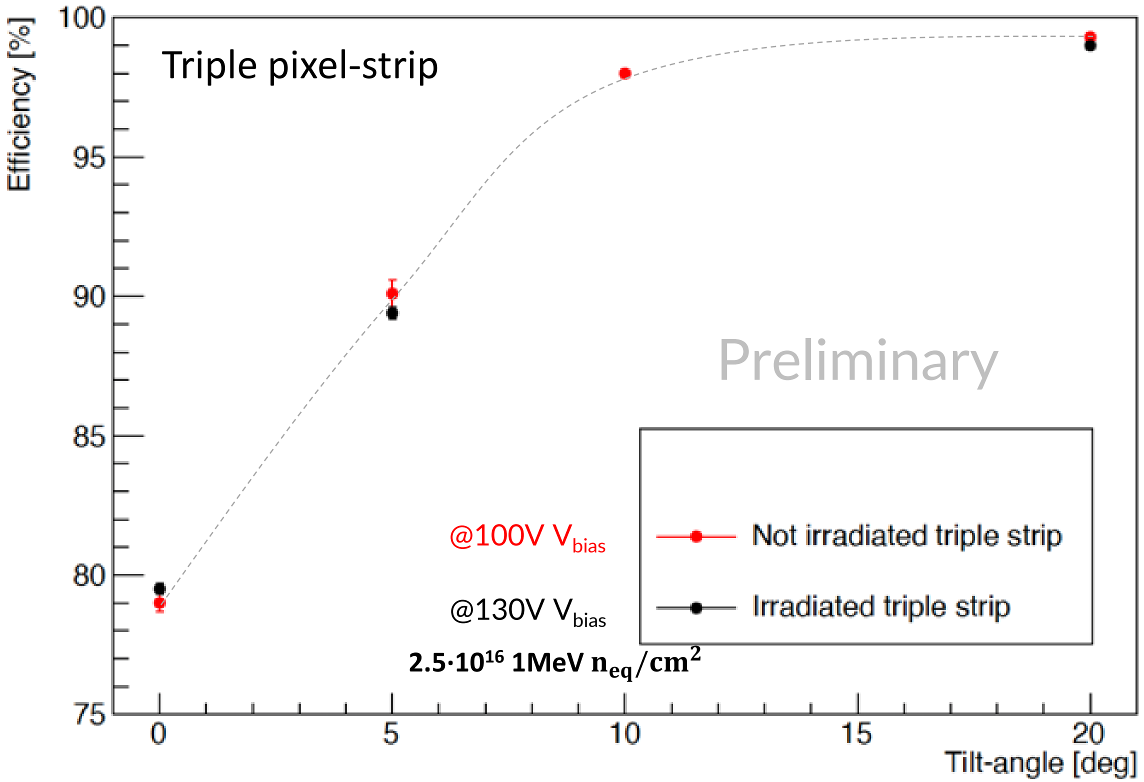


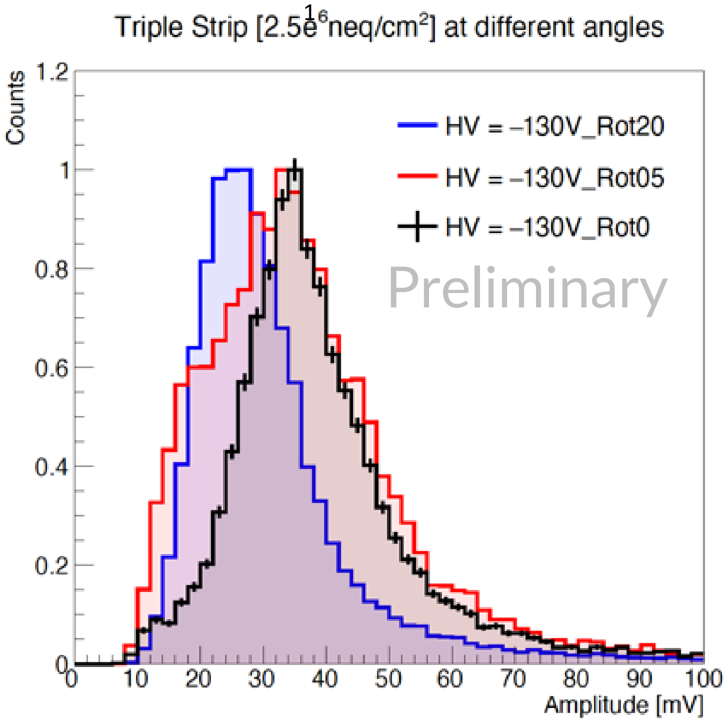


- **Excellent time resolution** (σ_{eff} = 11 ps) measured at 150V on single pixel irradiated at **$2.5\cdot10^{16}$ 1MeV n_{eq}/cm^2**
- Exceeding a bias of 100 V irradiated pixel has the **<u>same time resolution of an unirradiated pixel</u>**

Irradiated sensors – efficiency







- The inefficiency (at normal incidence) due to the dead-area of the trenches is fully recovered by tilting the sensors around the trench axis **also for sensors irradiated at $2.5 \cdot 10^{16}$ 1MeV n_{eq}/cm^2**

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} = 100 V (sensor intrinsic + FEE noise)

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

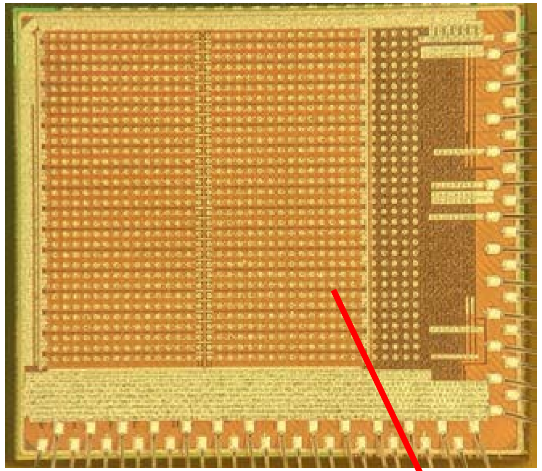
- Sensors irradiated at a fluence of $2.5 \cdot 10^{16}$ $1\text{MeV}\ \mathrm{n_{eq}/cm^2}$ at V_{bias} exceeding 100V **perform as the non-irradiated sensors, both in timing performances and in efficiency**

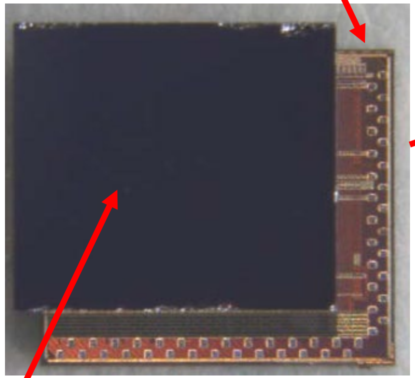
- 3D devices confirm their theoretical excellent performance in timing and the trench geometry appears to be the right direction to go

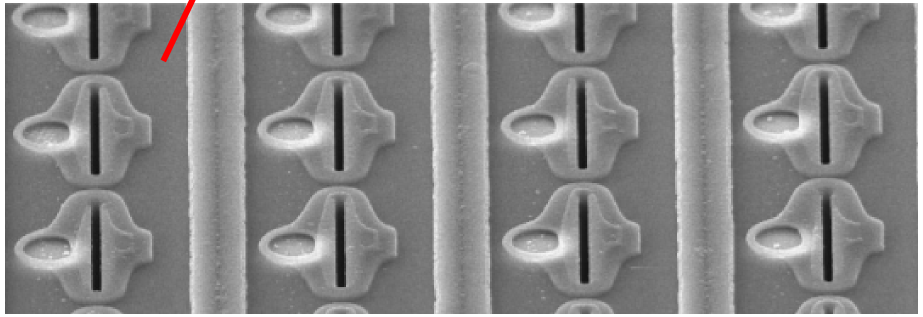
The front-end electronics is now the limiting factor to the system performance…

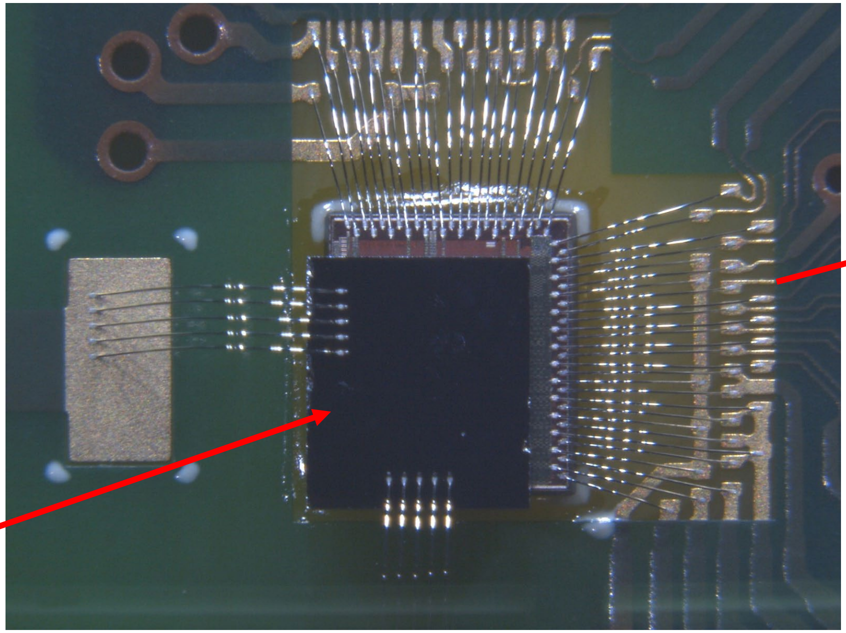
Outlook

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

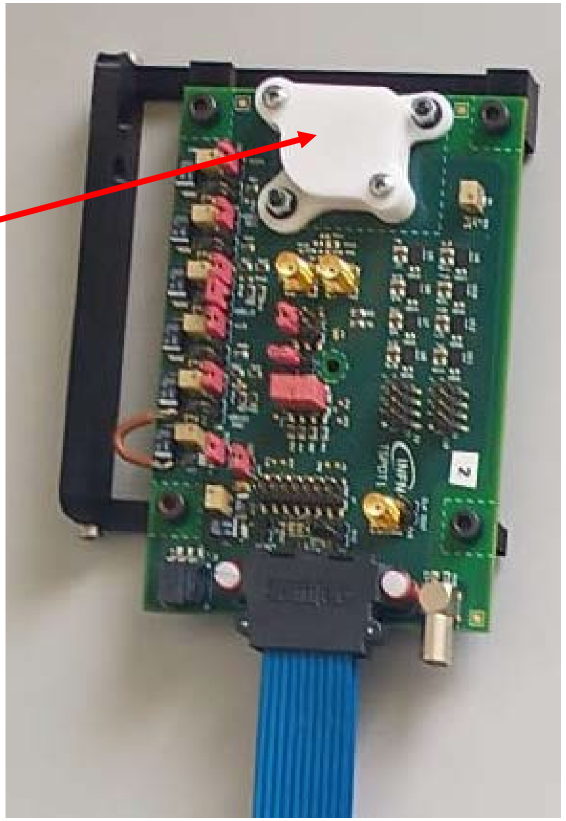








Timespot1 hybrid with 32x32 **3D-trench silicon** matrix



BEAM TEST of 32x32 3D trench pixel matrices at the end of the year

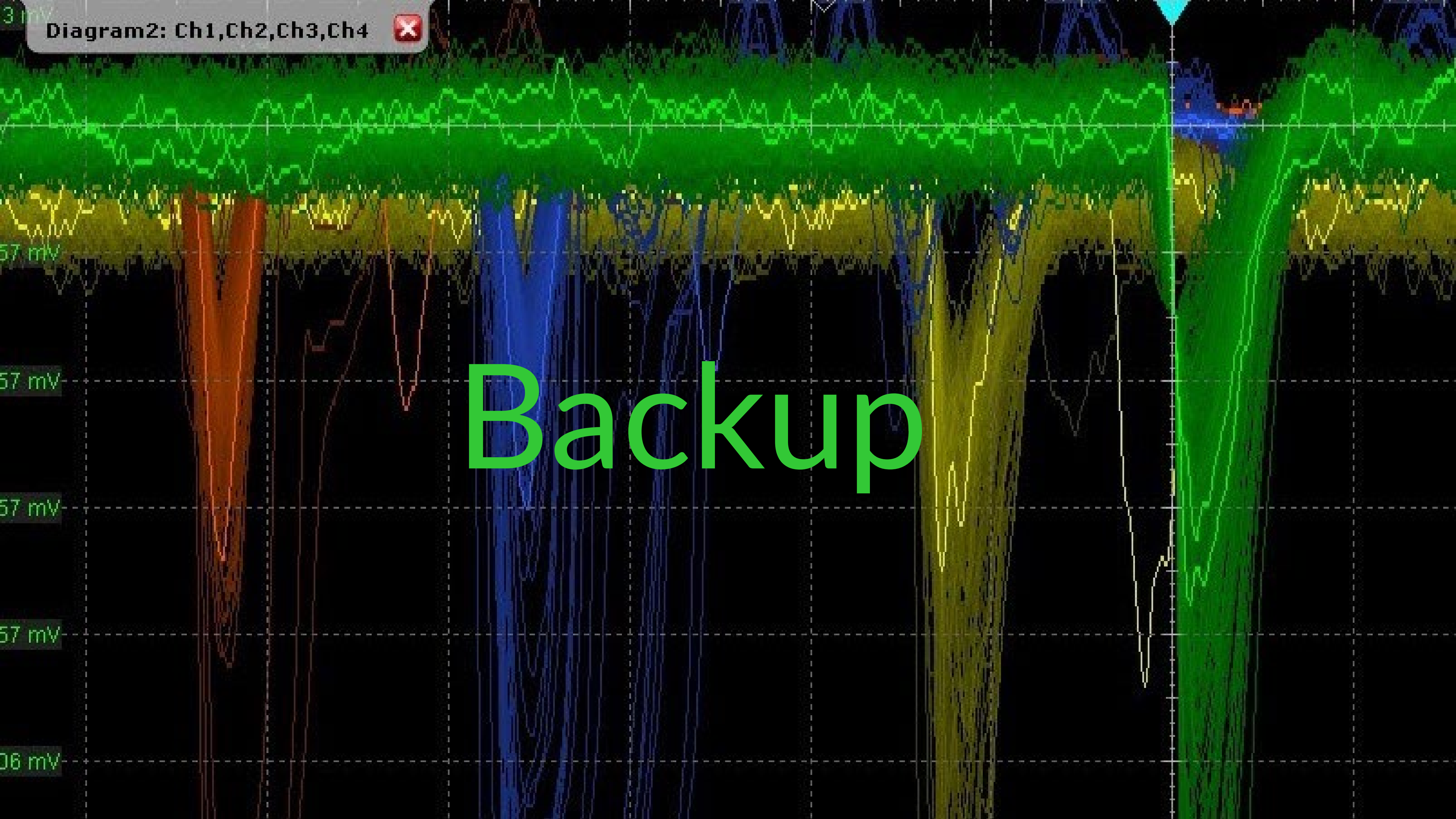
Stay tuned!

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, 15th Conference 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. Loi et al., Timing Optimisation and Analysis in the Design of 3D silicon sensors: the TCoDe Simulator, JINST (2021) 16:P02011
- D. Brundu et 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
- Brundu D, et al. (2022) Modeling of Solid-State Detectors Using Advanced Multi-Threading: The TCoDe and TFBoost Simulation Packages. Front. Phys. 10:804752. doi: 10.3389/fphy.2022.804752

Backup



Limits to the time resolution of a 3D sensor

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

physics

- σ_{tw} : the time-walk effect can be suppressed 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

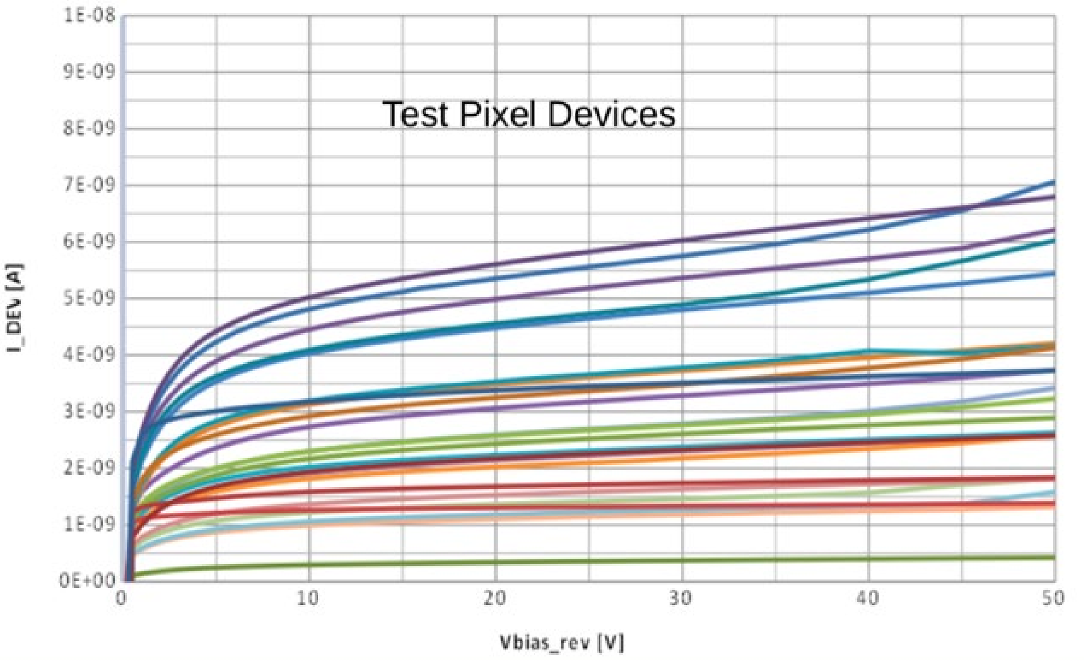
- σ_{un} : non-uniformities in the weighting field and charge carrier velocities inside the detector sensitive unit give the ultimate limit on the time resolution that can be achieved with a 3D sensor

electronics

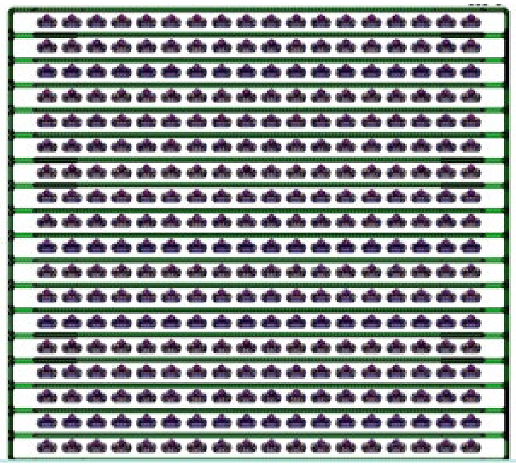
- σ_{ej} : the analog noise of the preamplifier limits the sensor's time resolution and scales as $\sim \frac{\sigma_{noise}}{Amplitude}$

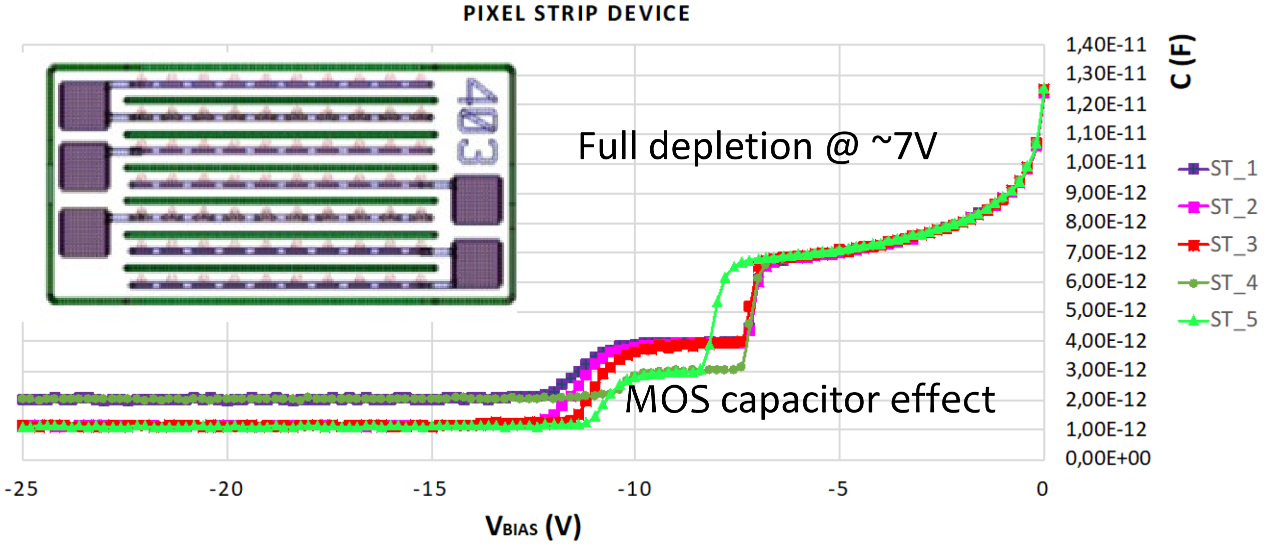
$$\sigma_t \cong \sqrt{\sigma_{un}^2 + \sigma_{ej}^2}$$

DC electrical characterization of 3D trench pixels



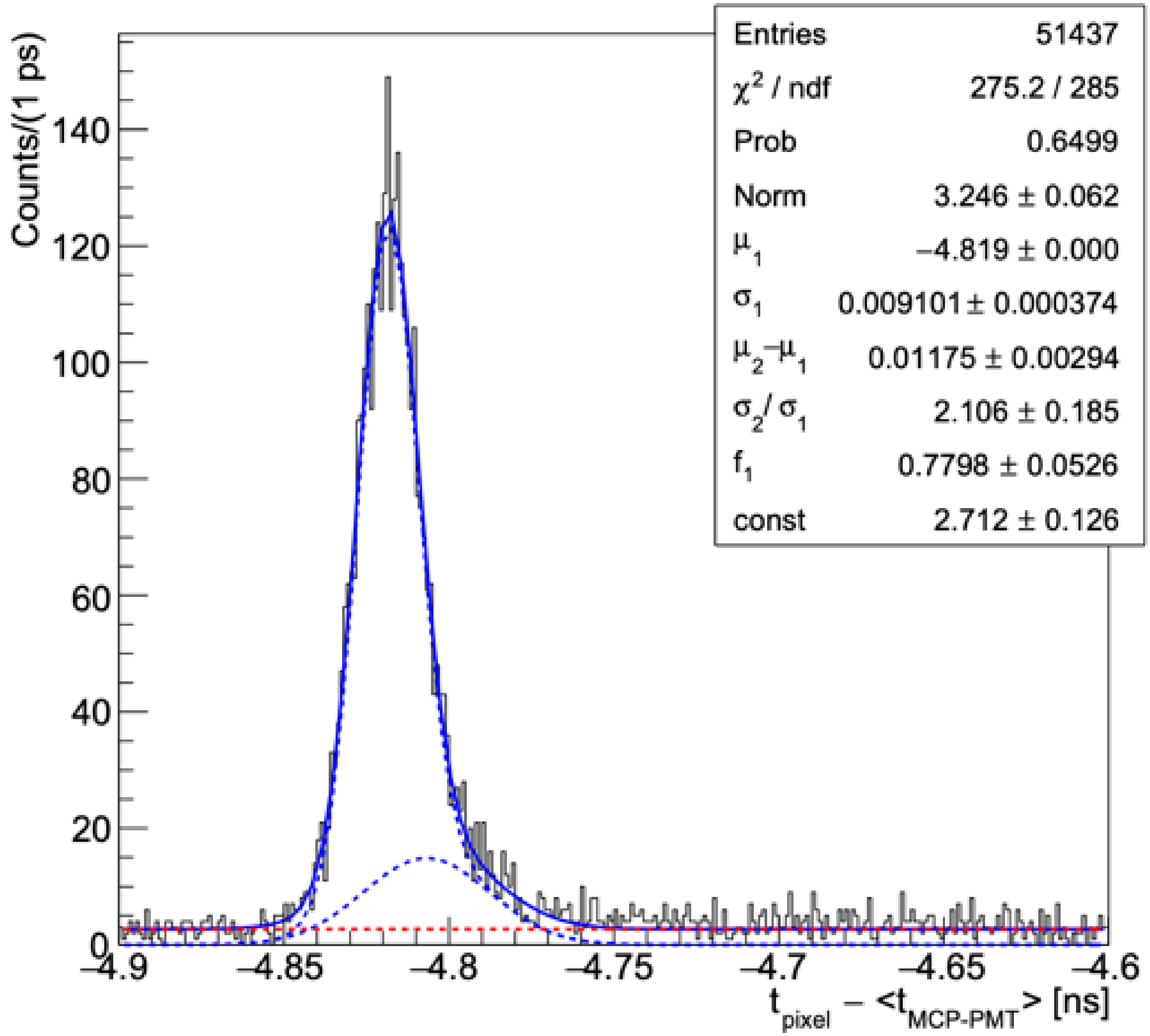
IV-curves on 18x18 pixel matrices (pixels connected with temporary metal): ~10 pA/pixel – good!





Measured capacitance ~100 fF/pixel, in agreement with simulation

Fitting the time distribution: $\boldsymbol{\sigma}_{\text{eff}}$



Mixture distribution

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

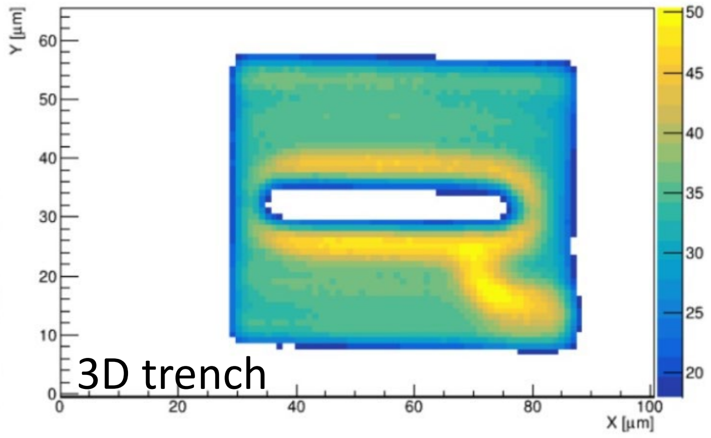
where f_1 is the fraction of the Gaussian core and μ is defined as

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

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

TCT-IR SCANS

Amplitude



Time of Arrival