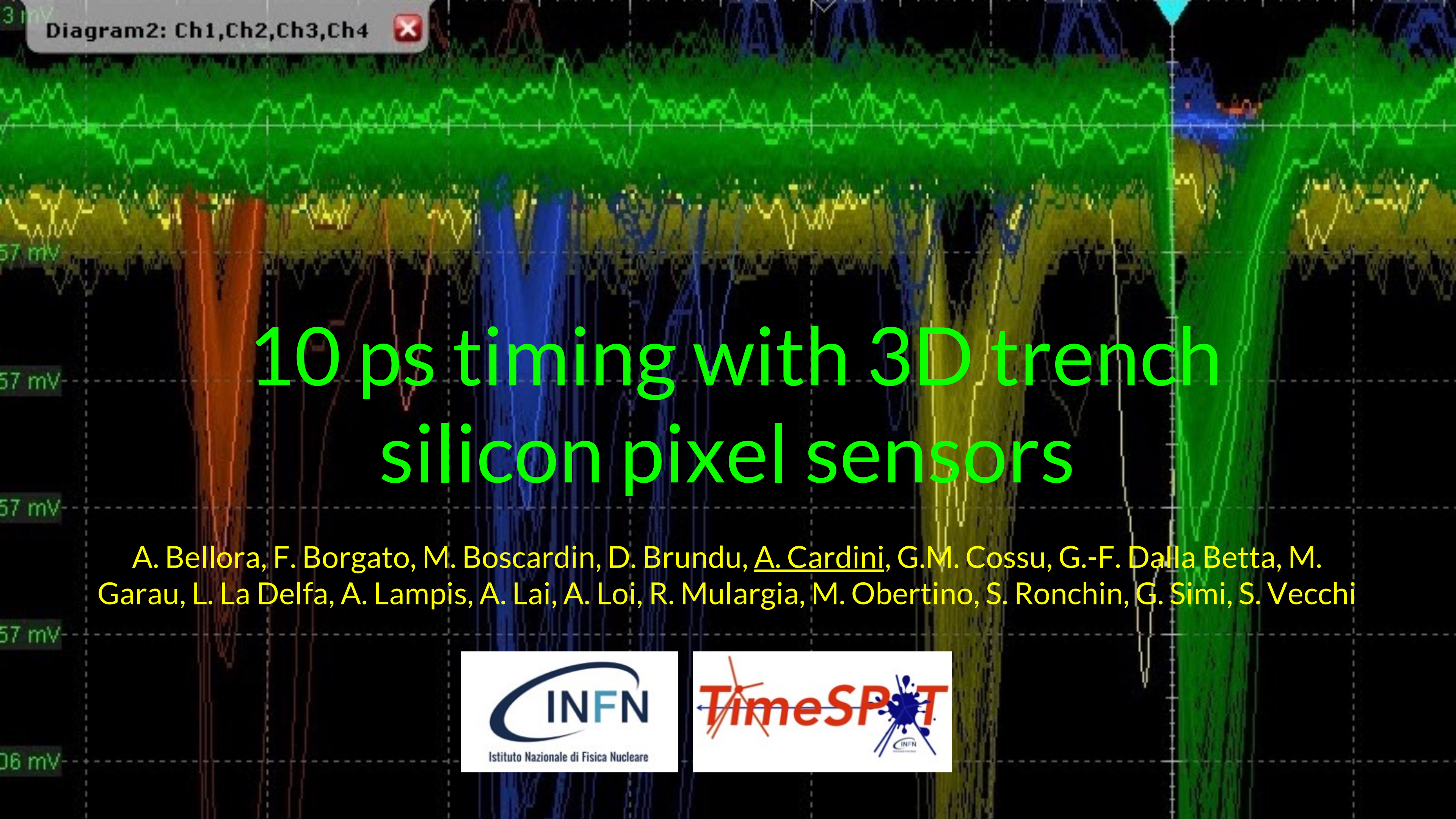


10 ps timing with 3D trench silicon pixel sensors

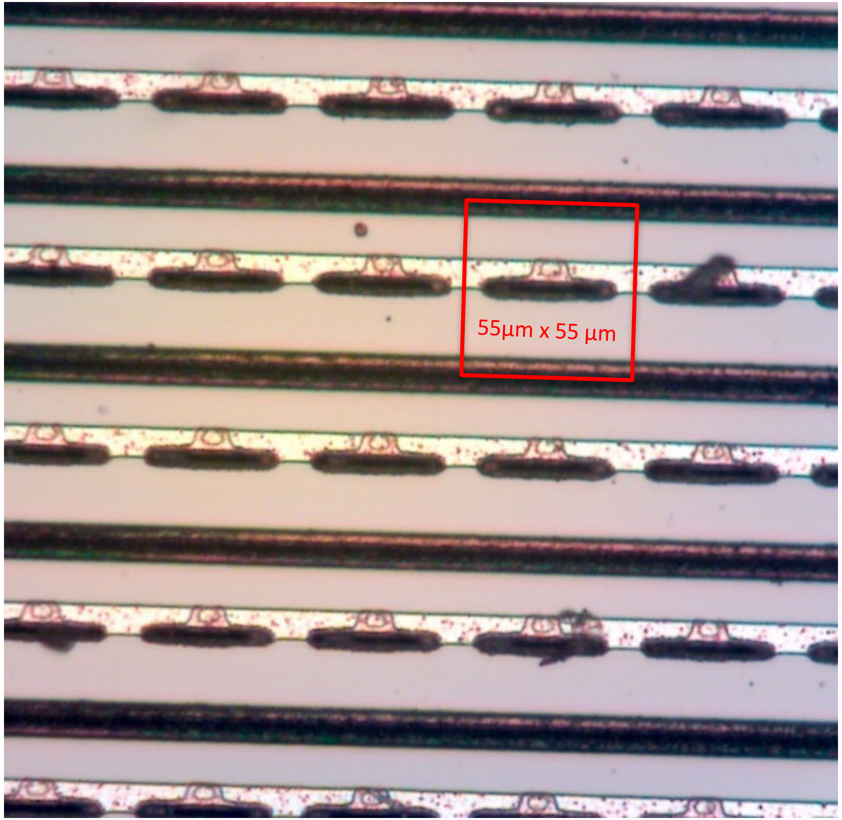
A. Bellora, F. Borgato, M. Boscardin, D. Brundu, A. Cardini, G.M. Cossu, G.-F. Dalla Betta, M. Garau, L. La Delfa, A. Lampis, A. Lai, A. Loi, R. Mulargia, M. Obertino, S. Ronchin, G. Simi, S. Vecchi

INFN Istituto Nazionale di Fisica Nucleare

TimeSPOT

Outline

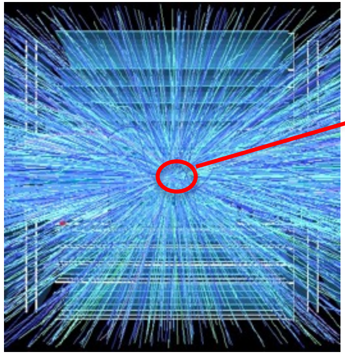
- Challenges in tracking at high luminosities
- The TimeSPOT 3D trench pixel design
- New experimental results
- Conclusions and outlook



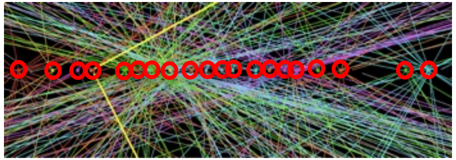
TimeSPOT 3D-trench pixels in a strip-like configuration

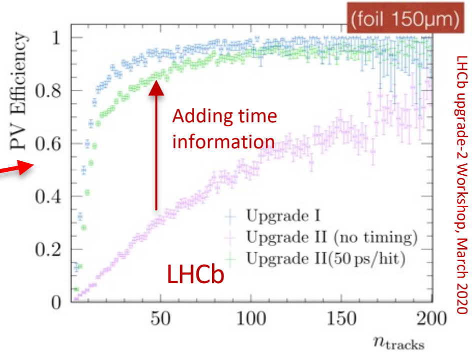
Present and future challenges in tracking

- 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
- ATLAS & CMS Phase-II upgrades (2026): mostly "traditional" tracker + single timing layer
  - $\sigma_t \approx 30$ ps, $\sigma_s \approx 100$-300 µm, F ≈ 10^{15} 1 MeV n_{eq}/cm^2
- LHCb Upgrade-2 (2030s): time information on each pixel
  - $\sigma_t = 30$-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
  - $\sigma_t = 10$-20 ps, $\sigma_s \approx 10$ µm, F = 10^{17} to 10^{18} 1 MeV n_{eq}/cm^2



Adding the track time information



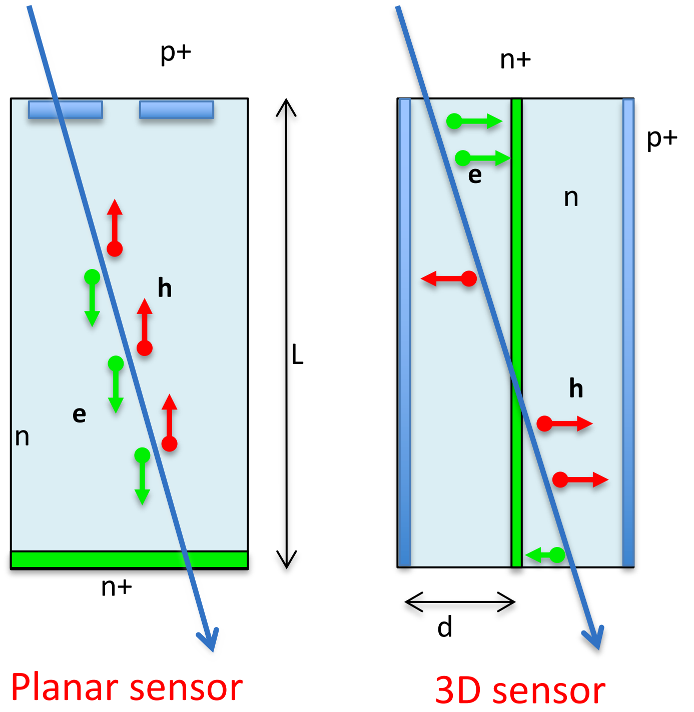


Spatial resolution, time precision and radiation hardness are <u>required at the same time!</u>

Why 3D sensors?

- Original idea: S. Parker, 1997

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



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 $\sim \frac{\sigma_{noise}}{Amplitude}$
- ✗ σ_{TDC} : an adequate TDC will make this term negligible

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

Toward an optimized 3D sensor design

- σ_{un}

The detector signal is produced by the drift of the charge carriers created along the path of the (charged) particle across the pixel volume, which creates an instantaneous current i defined as

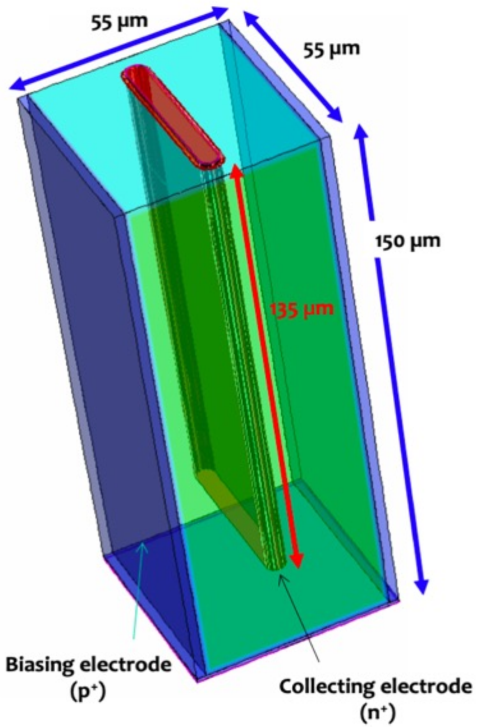
$$i = q\,\vec{E}_w \cdot \vec{v}_d$$

where $\vec{E}_w$ is the weighting field and $\vec{v}_d$ is the carrier's drift velocity. To have signals that do not depend on where the charged particle has crossed the detector ➔ (1) make $\vec{E}_w$ uniform by design and (2) work in a velocity saturation regime

- σ_{ej}

To fully exploit the sensor capabilities, one needs to reduce the front-end amplifier noise (increasing the sensor's thickness is usually not an option)

➔ TimeSPOT 3D trench-type silicon pixel detectors

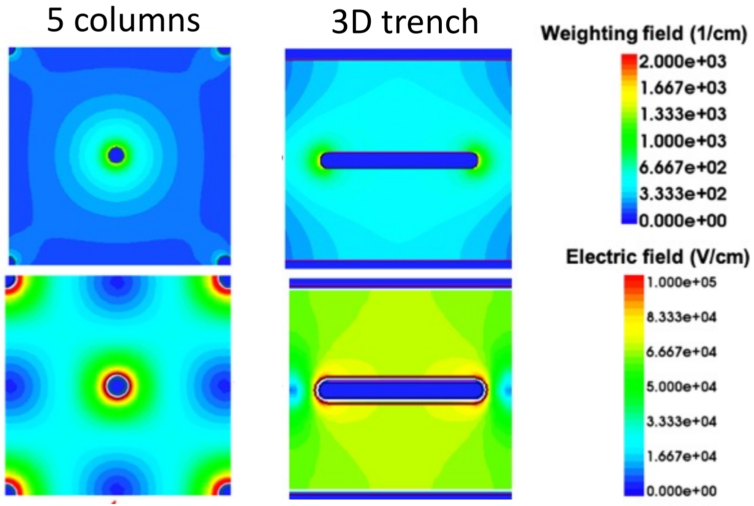


Comparison between 3D geometries

- Simulated weighting field and velocity maps are much more uniform in the trench geometry - both in magnitude and direction

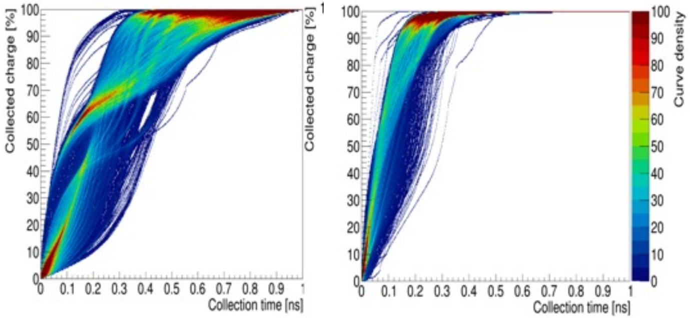
- This is essential to guarantee, via Ramo theorem, signals which are largely independent on where the charged particles crossed the detector

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

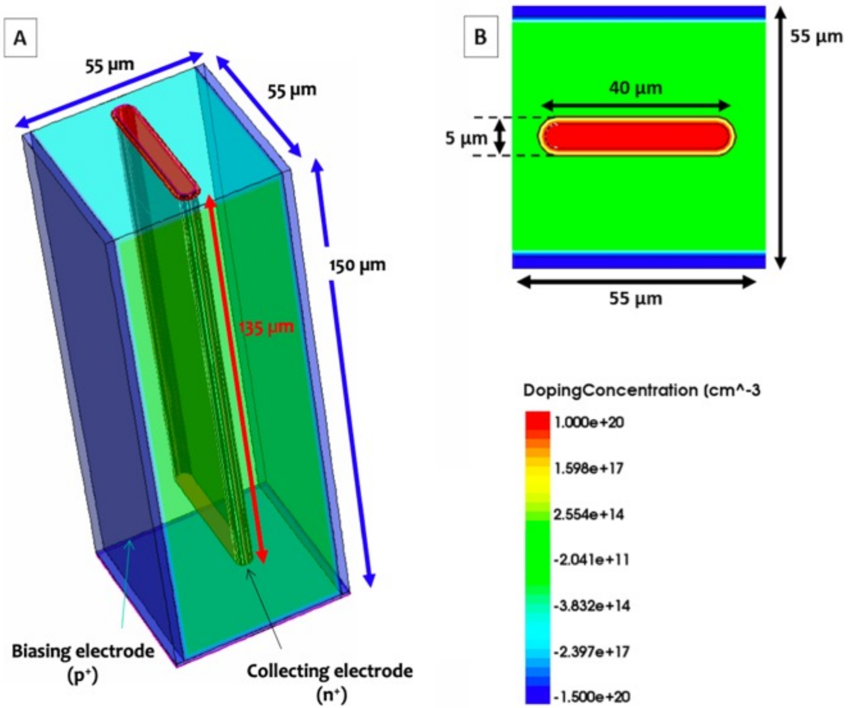


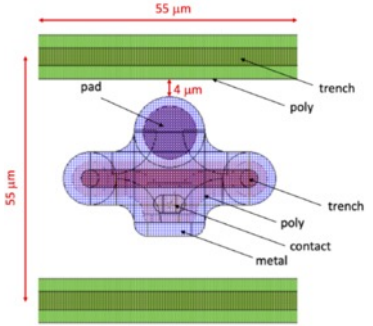
TCAD simulations, Vbias = – 150 V

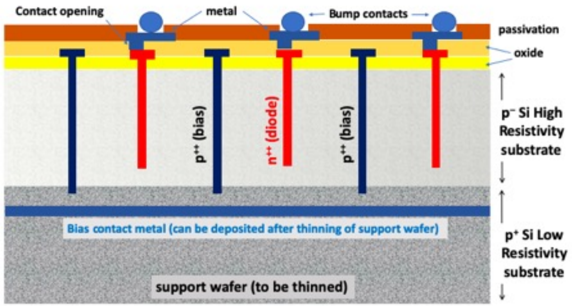
- Simulated charge collection curves for 3000 minimum ionizing particles uniformly crossing a pixel over its active area, in the two different 3D pixel geometries: shorter and much more uniform charge collection time for the 3D trench geometry



The trench-type TimeSPOT 3D pixels



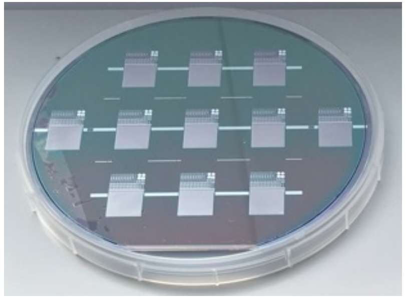


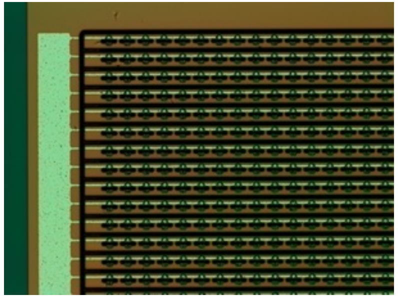


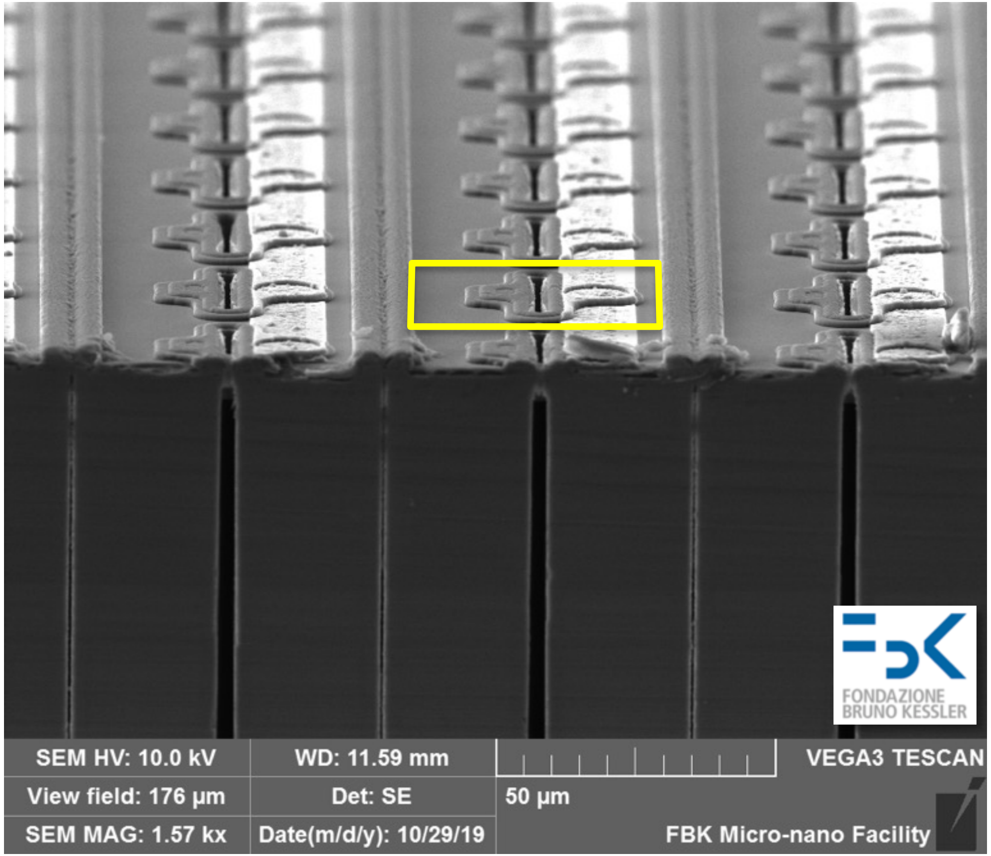
- 55 µm x 55 µm pixels (to be compatible with existing FEE, for example the Timepix family ASICs)
- In each pixel a 40 µm long n++ trench is placed between continuous p++ trenches used for the bias
- 150 µm-thick active thickness, on a 350 µm-thick support wafer
- The collection electrode is 135 µm deep

The TimeSPOT 3D sensors fabrication

- Single sided (Si-Si) process with a support wafer
- 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
- High aspect ratios (30:1) and good dimensional uniformity
- Photolithography performed with a stepper machine (min. feature size 350nm, alignment accuracy 80nm, max. exposure area 2x2cm^2)
- Many devices were designed and fabricated (single, double pixels, 10 pixel-strips, various pixel matrices, …)

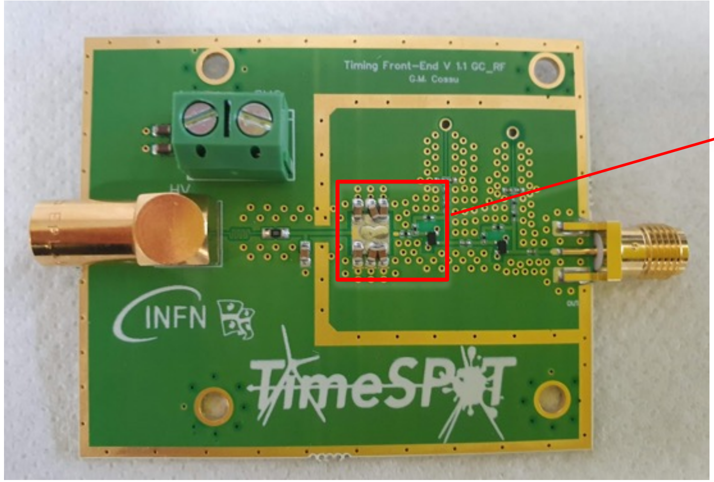


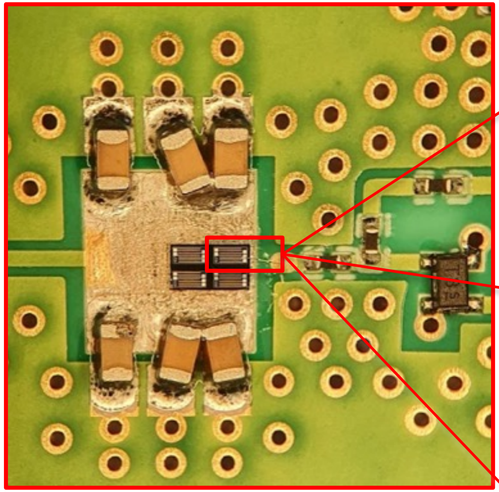


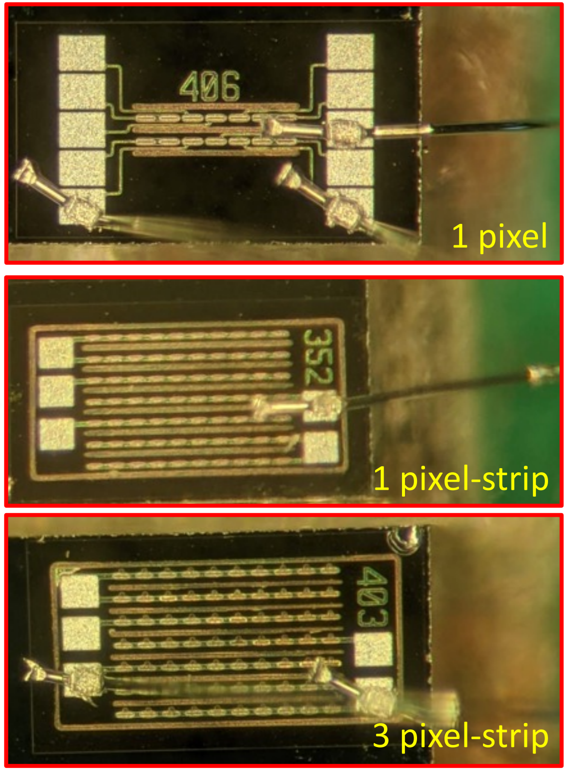


Beam characterization of 3D trench pixels

We have characterized single-pixels and various pixel-strips (10-30 pixels) test structures, connected to custom-made front-end electronics boards featuring a two-stage transimpedence amplifier made with fast SiGe BJTs - to fully exploit the sensor speed one needs to readout the sensor’s current

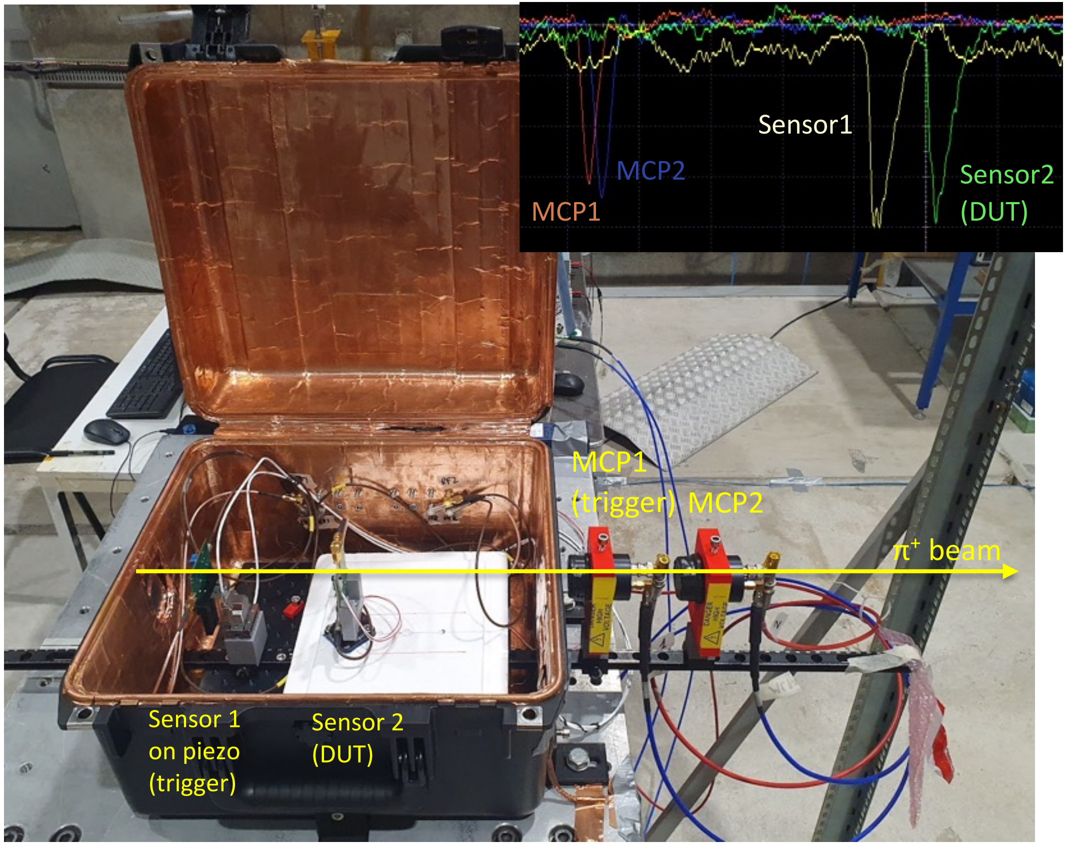


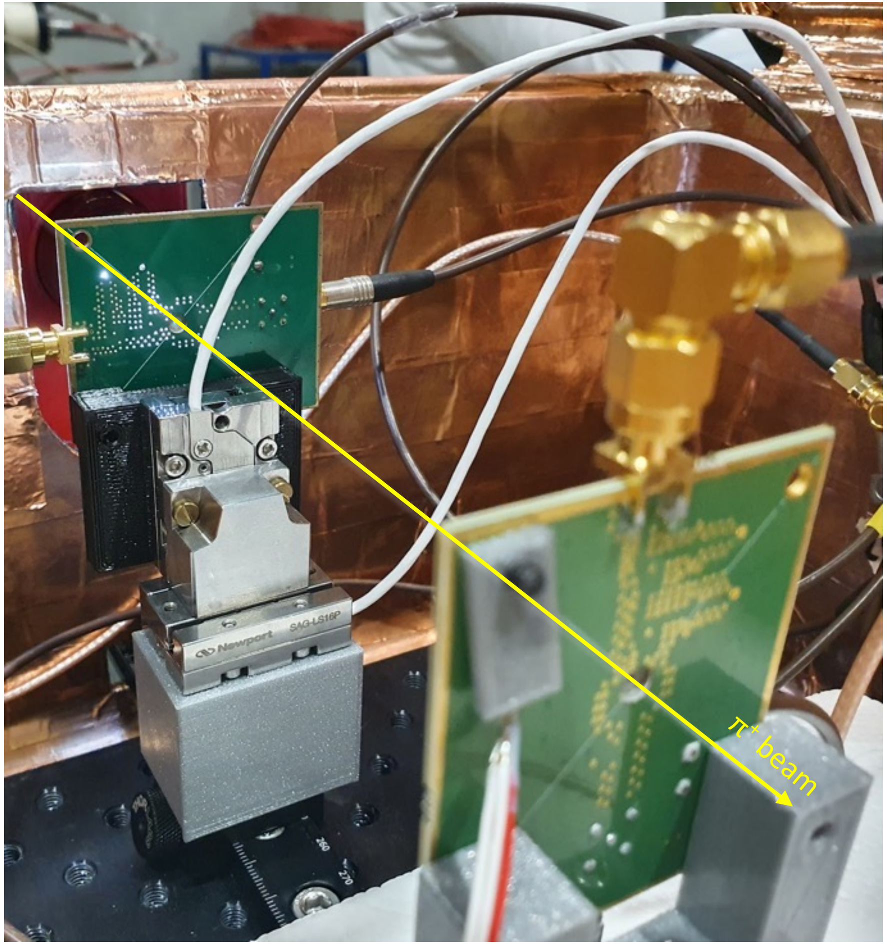


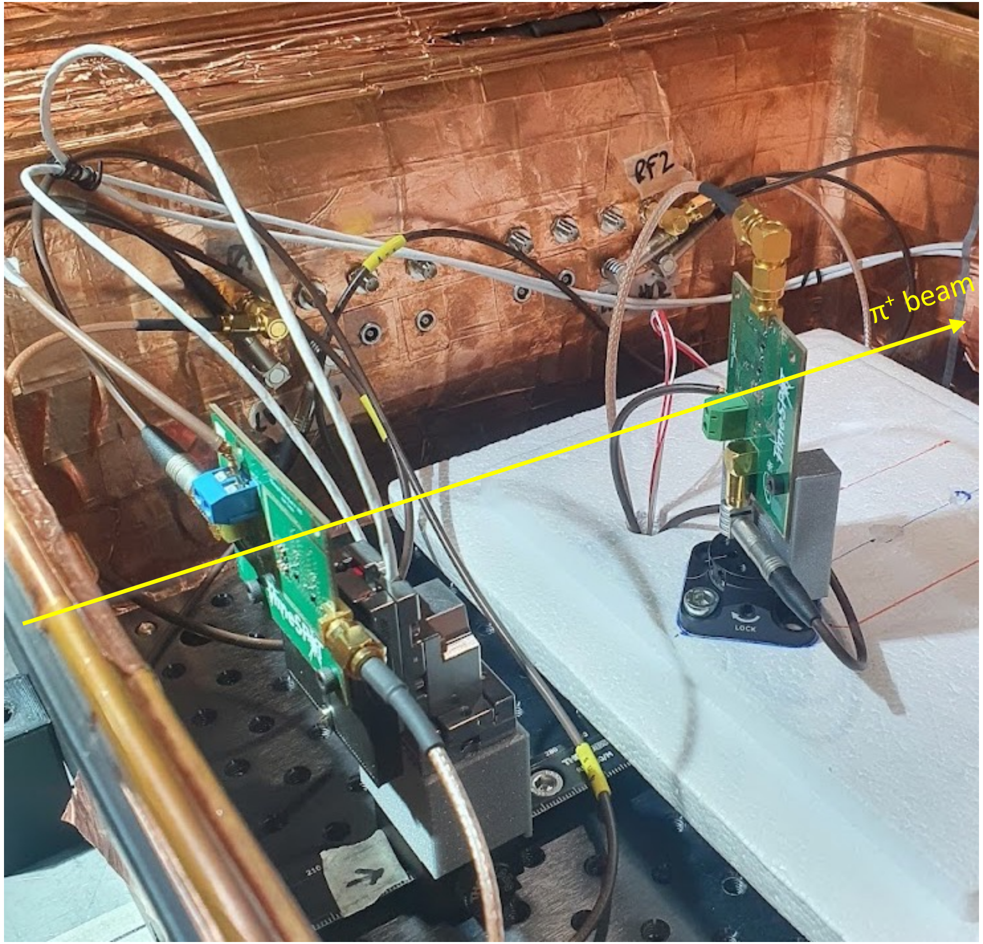


2022 SPS/H8 beam test (still ongoing)

- 180 GeV/C π^+ beam
- 10^6 pions per spill (4 sec.) 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 ps)
- One fixed sensor. Another sensor mounted on piezoelectric slides to precisely align the two 3D structures with beam, all mounted in a RF-shielded box
- Readout with 8 GHz bandwidth 20 GS/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

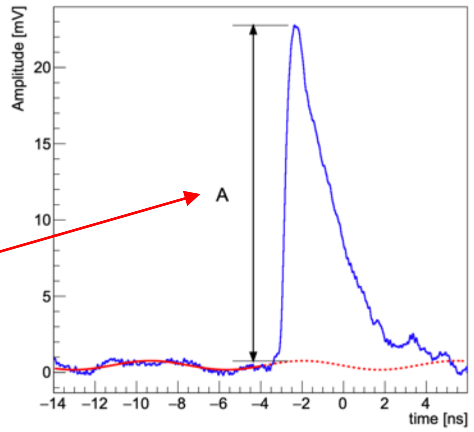


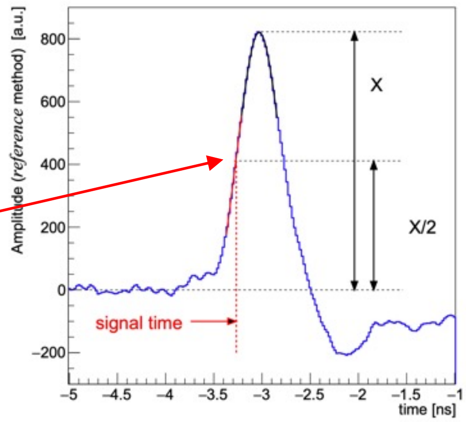

π+ beam
Newport
SAG-LS16P


π+ beam
RF2
LOCK

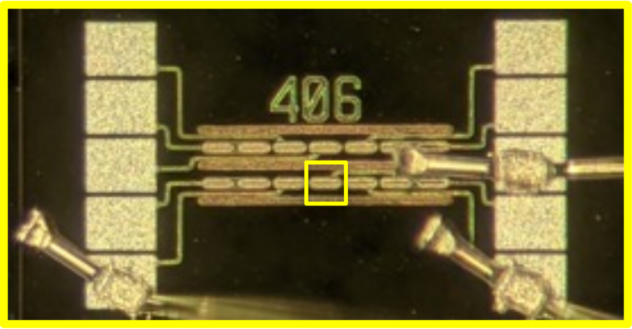
Pixel waveforms data analysis

- For each sensor's waveform:
  - 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:
    - Leading-edge: time at 20mV signal amplitude, linear interpolation around threshold
    - Spline: a traditional 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

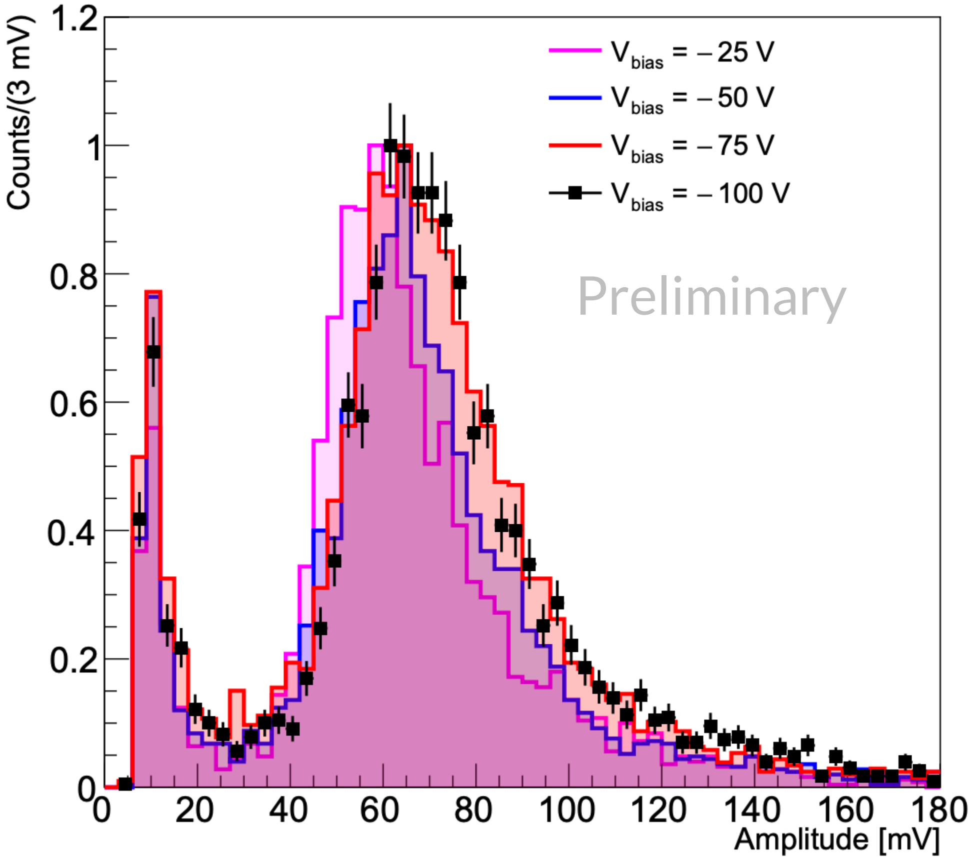




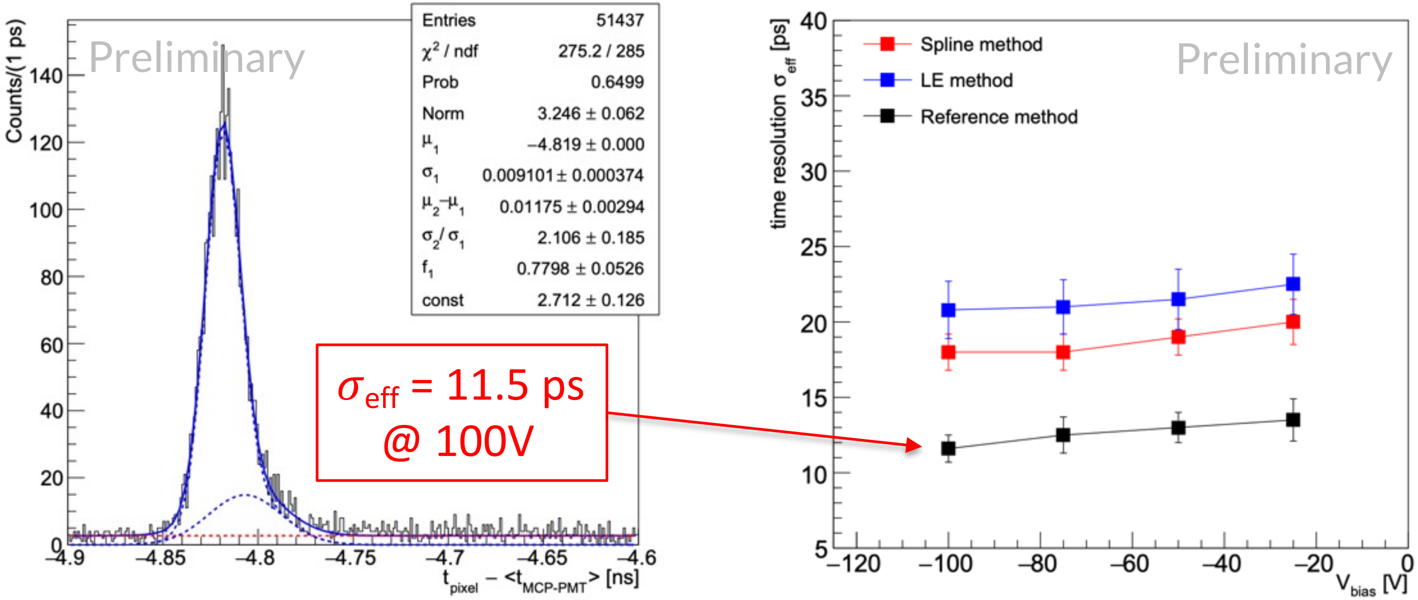
Single 3D pixel - amplitude



- Non-irradiated pixel
- Normal pion incidence
- Unbiased trigger – i.e. not on DUT
- The shape of the Landau distributions as a function of V_{bias} indicate a very good sensor performance even at low V_{bias}

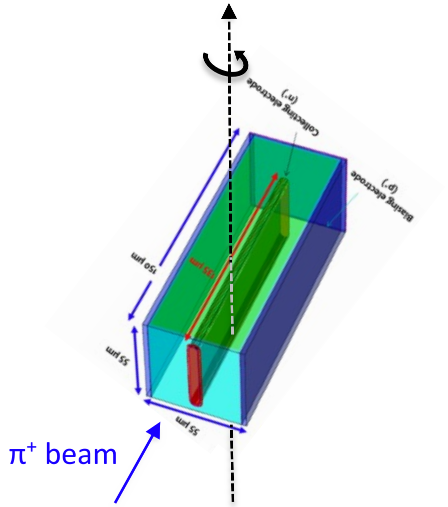


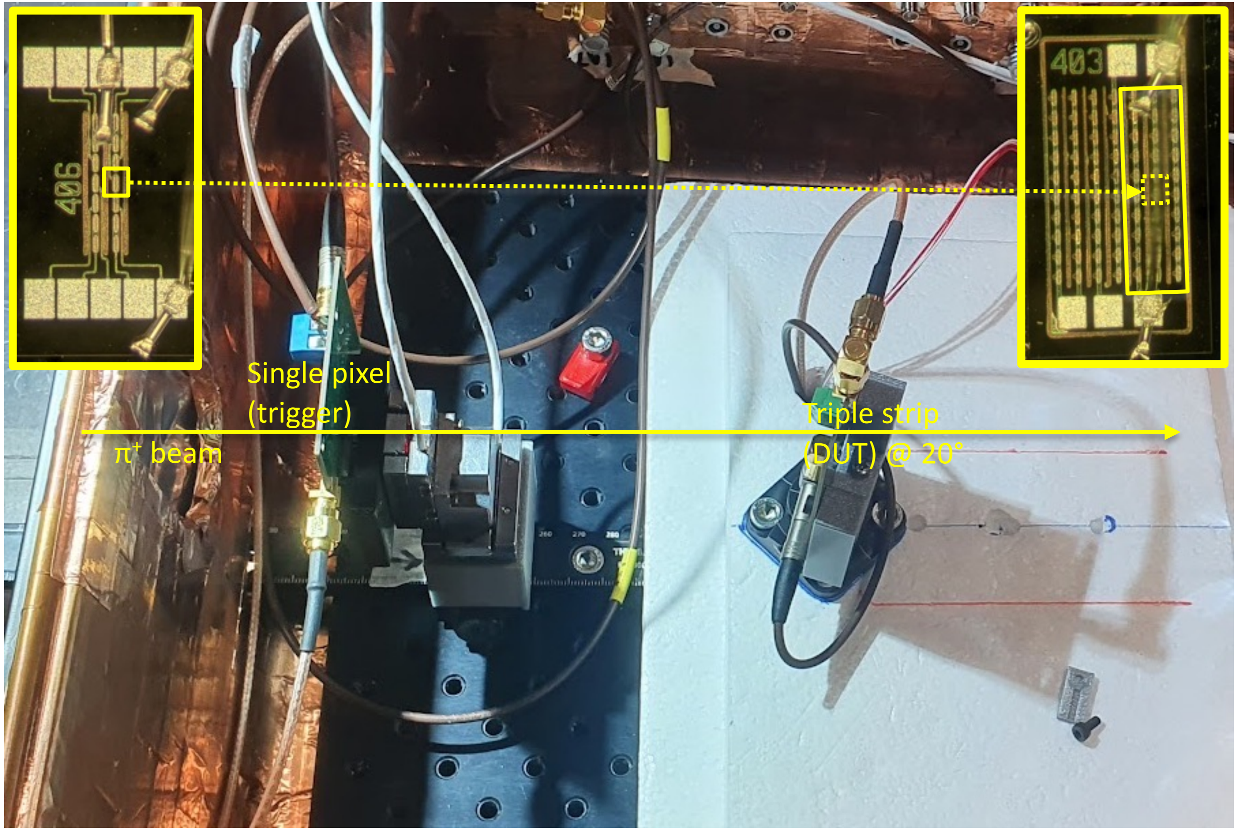
Single 3D pixel – timing performances



- 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, slightly time shifted, to include late signal contributions
- Excellent timing performances with CFD-based methods, but also using a leading edge algorithm

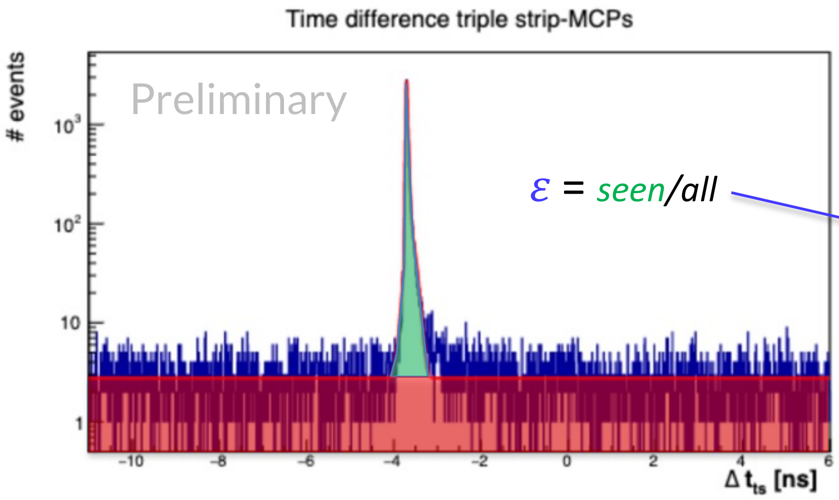
Efficiency: setup



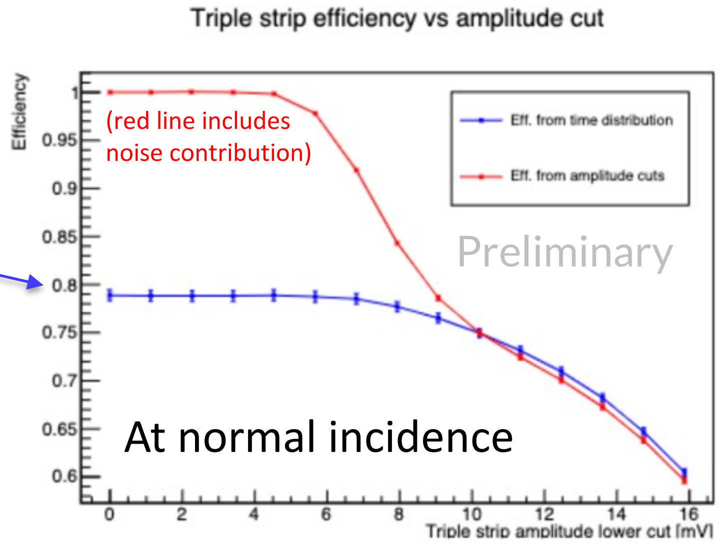


- Trenches (5 μm wide) are non-active volumes, channeled particles will not be seen
- Tilt the sensors with respect to normal incidence to recover geometrical efficiency
- Efficiency is measured by triggering on one pixel (55 μm x 55 μm, on piezos) centered on a triple strip (165 μm x 550 μm, the DUT) 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

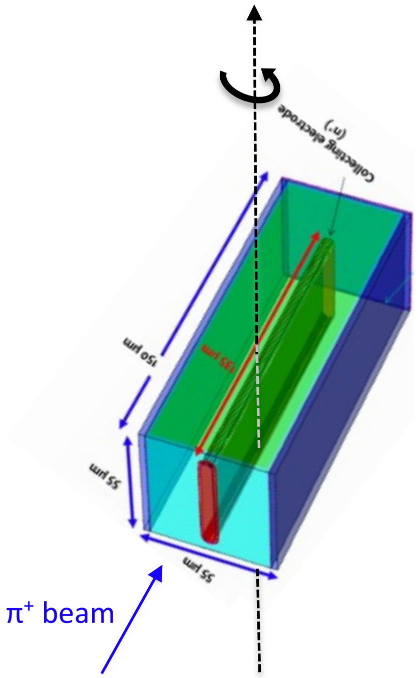


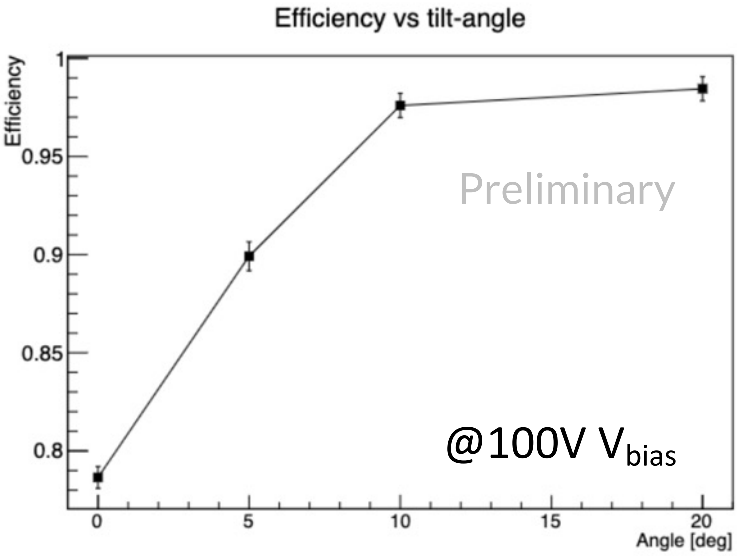
ε = *seen*/*all*

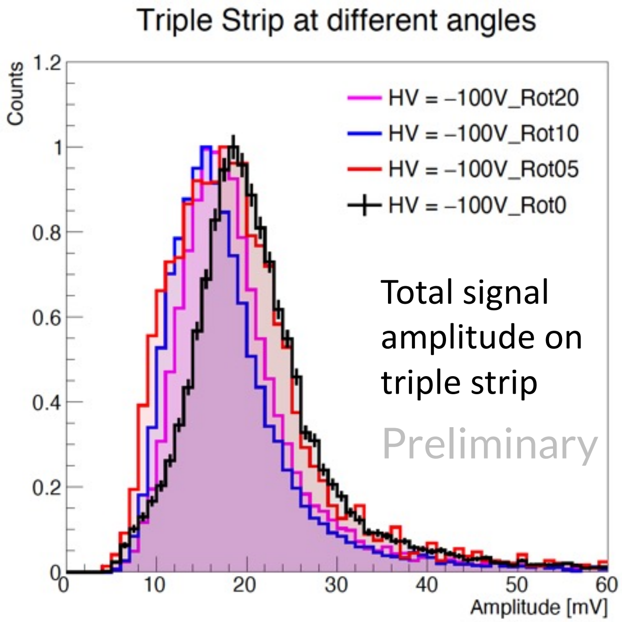


- Plot the time distribution of **all triple-strip signals** w.r.t. MCP-PMTs and count as 'seen' the ones under the peak
- 3D pixel detection (geometrical) efficiency at normal incidence is in agreement with calculated fraction of active area

Efficiency: results

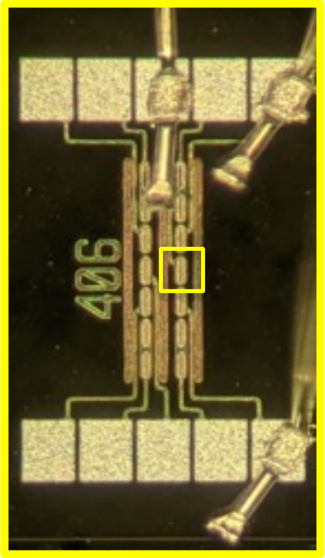




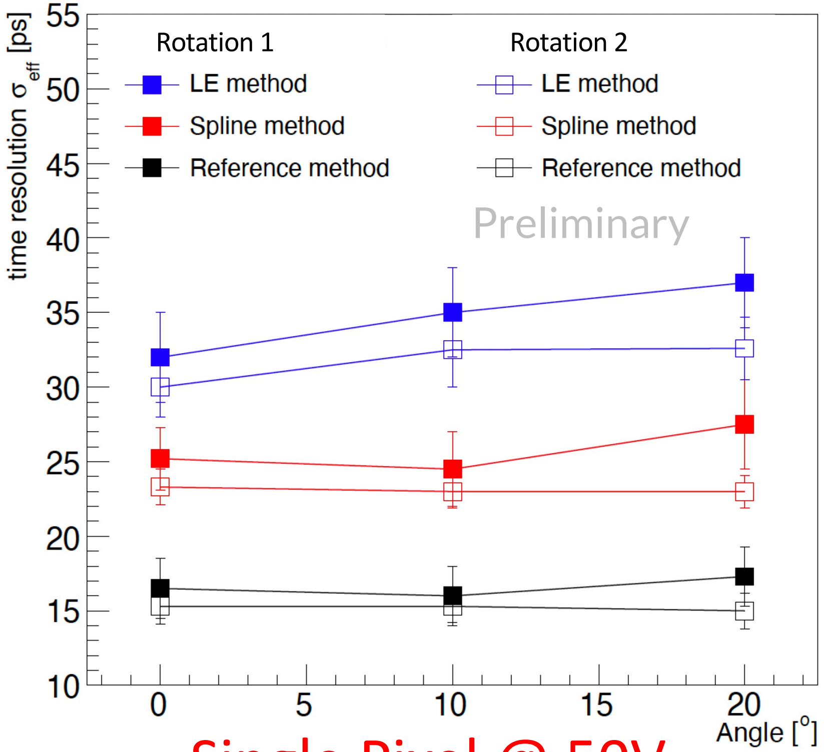


- The inefficiency (at normal incidence) due to the 3D pixel dead-area of the trenches is fully recovered by tilting the sensors around the trench axis at angles larger than 10°

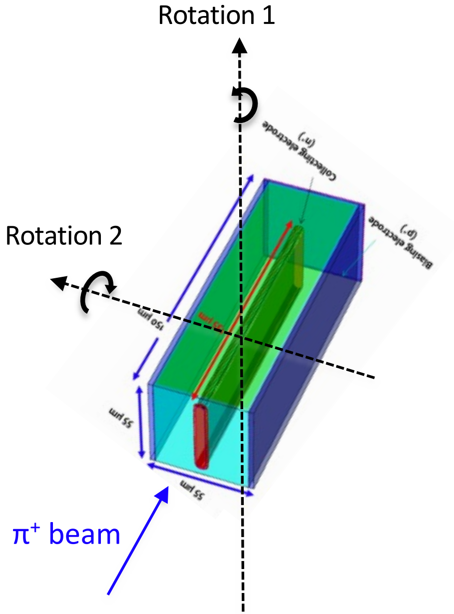
Tilted sensors: timing performances



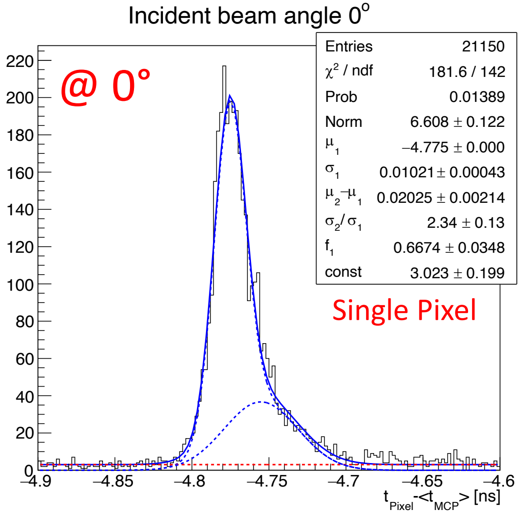
Does some tilt (rot. 1) slightly improves the time resolution?

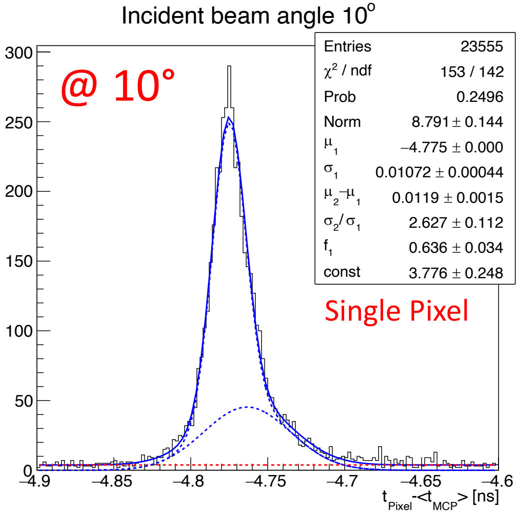


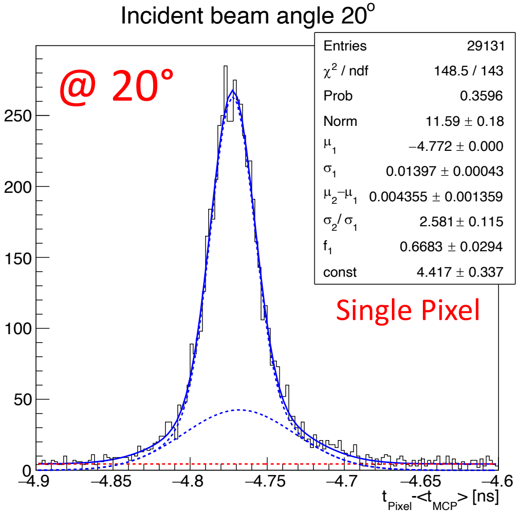
Single Pixel @ 50V

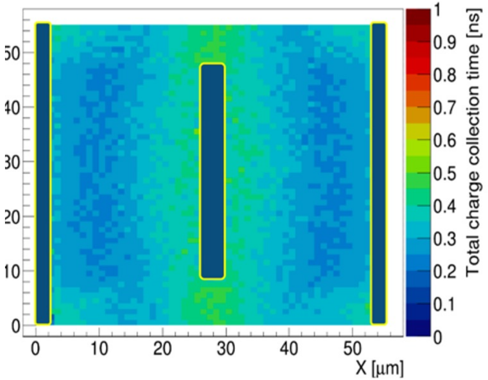


Tilted sensors - time distributions





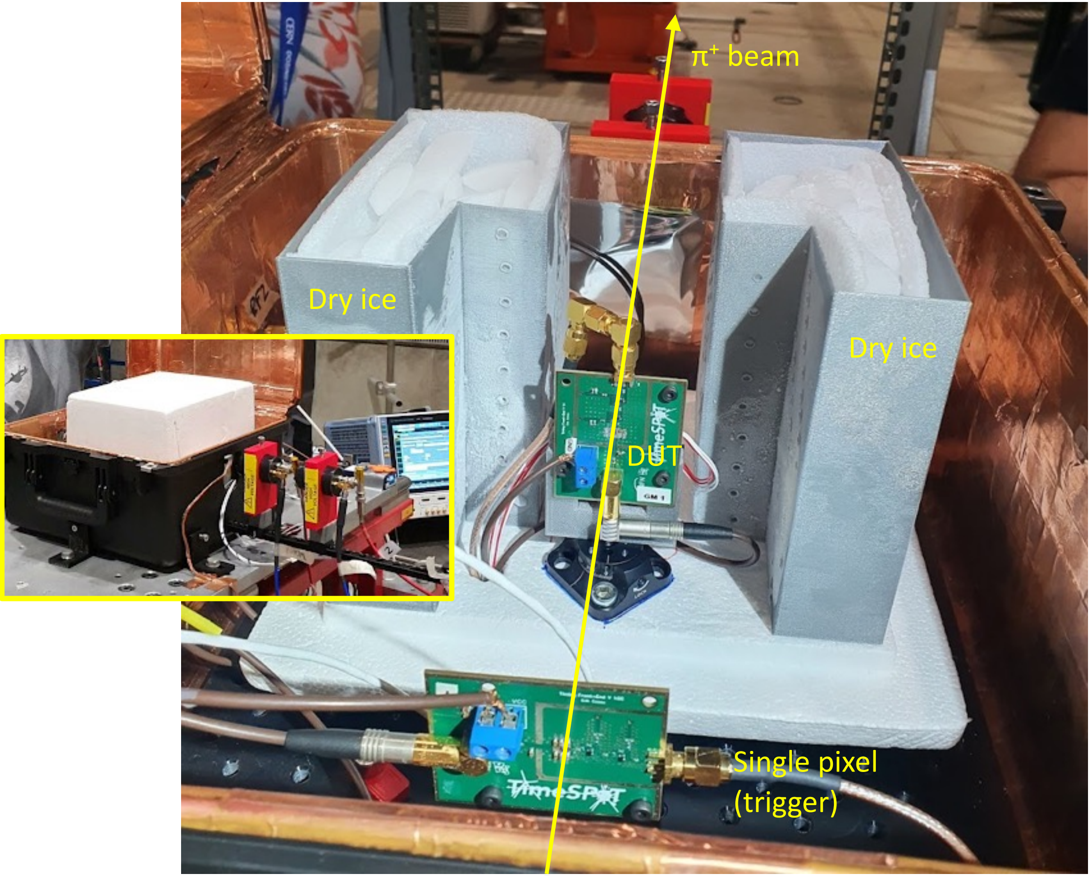




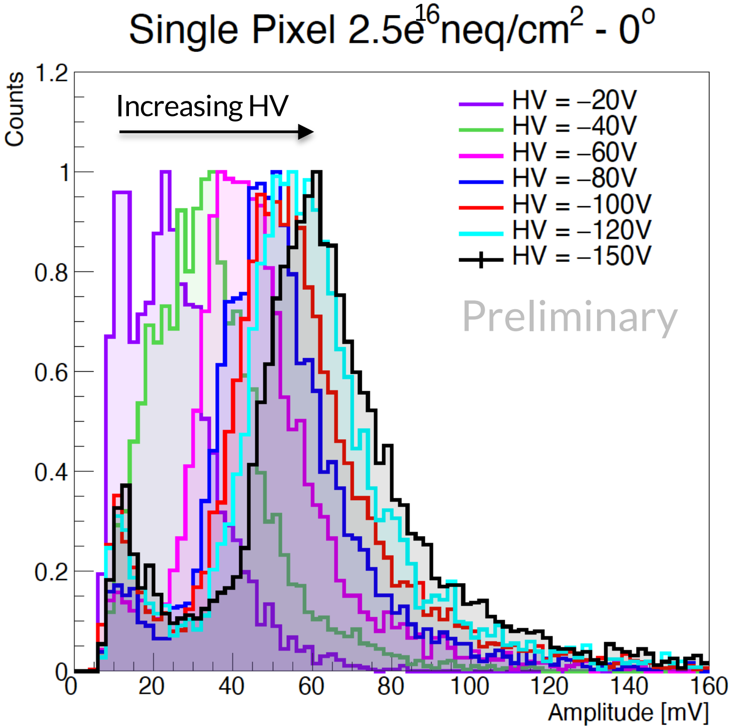
- In a tilted sensor, every charged track crosses both fast and less-fast regions of the pixels, thus providing a more uniform timing response
- Note that 3D detectors are required to be operated titled w.r.t normal incidence to recover the detection efficiency

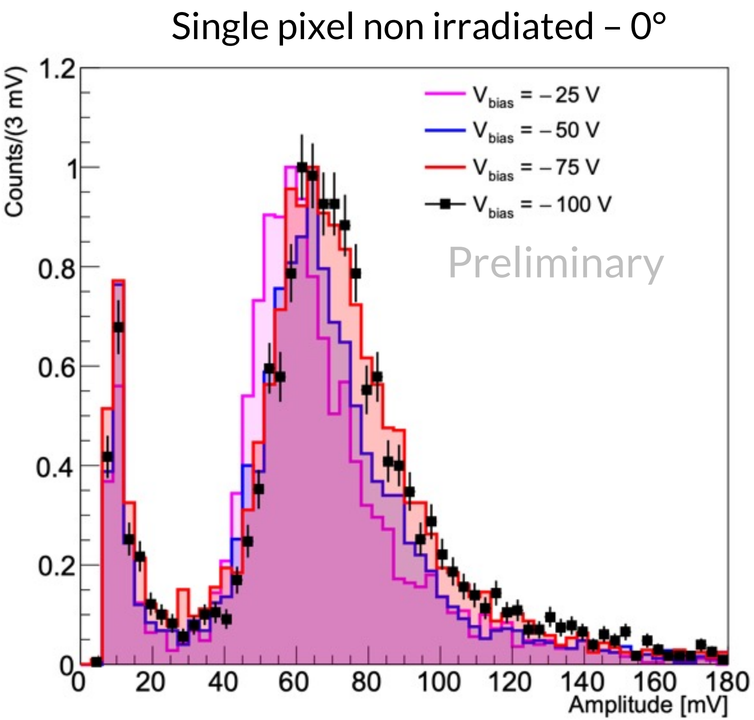
Irradiated sensors – the setup

- 3D sensors were irradiated at the Triga Mark II reactor at the Jožef Stefan Institute in Lubjiana, Slovenjia
- Fluences: 10^{15}, 10^{16} and $2.5 \cdot 10^{16}$ 1MeV n_{eq}, sensors not annehaled
- $2.5 \cdot 10^{16}$ 1MeV n_{eq} is what one would expect on LHCb vertex detector after LHC Run5 on innermost sensors
- Irradiated sensors tested below -20°C to reduce leakage current
- Characterization of irradiated single pixels and triple-pixel-strips structures



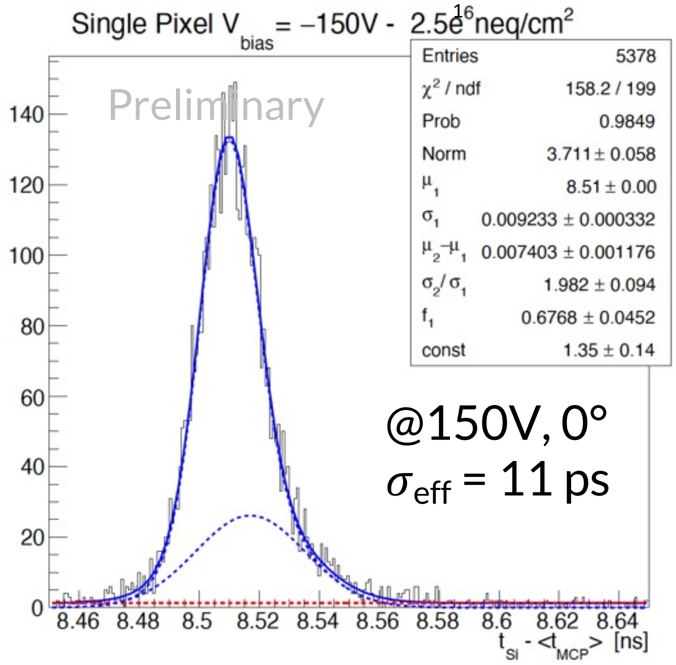
Irradiated sensors – working point

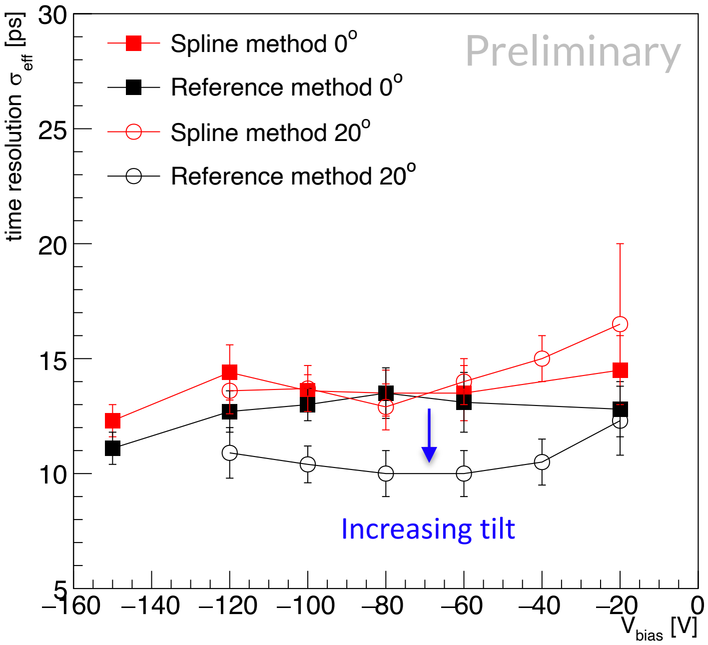




- A larger bias voltage is required to recover the signal amplitude for irradiated sensors

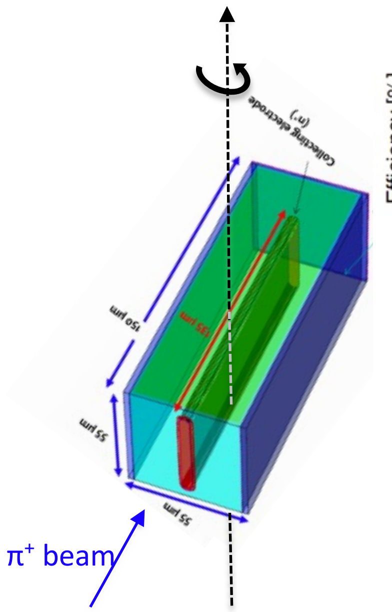
Irradiated sensors – timing performance

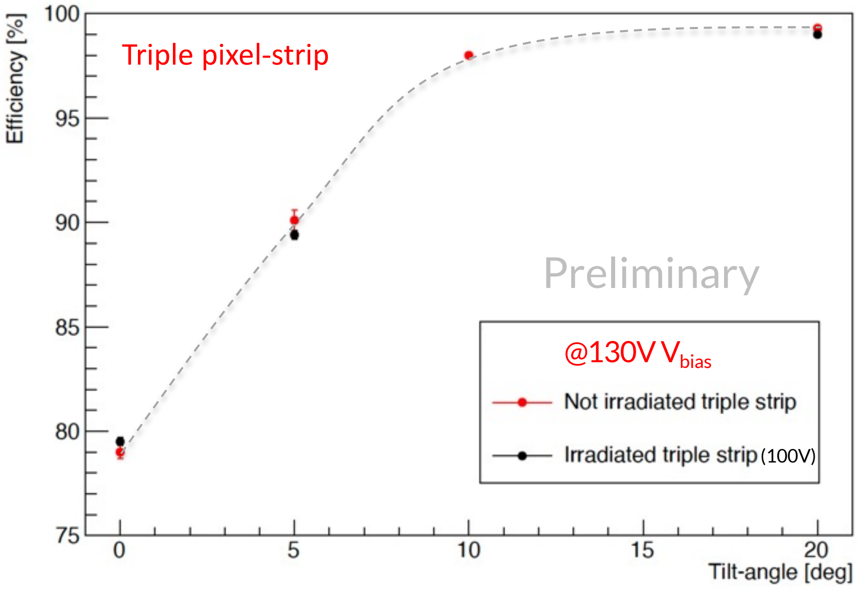


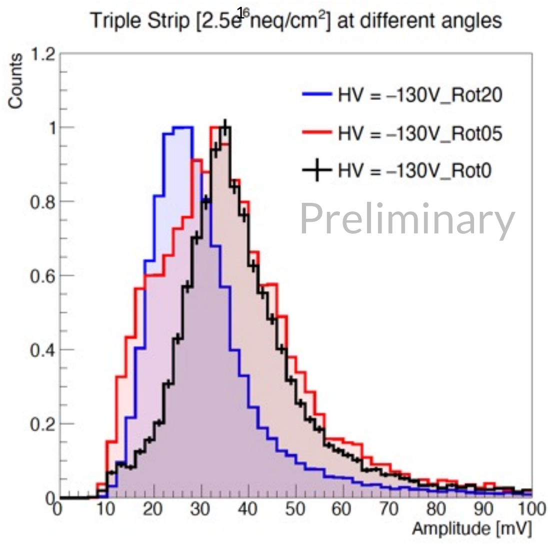


- Excellent time resolution (σ_{eff} = 11 ps) measured at 150V on single pixels irradiated with fluences of $2.5 \cdot 10^{16}$ 1-MeV neutron equivalent
- Again, there are indications that a tilted sensor even performs slightly better than at normal incidence

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 <u>also for sensors irradiated with fluences of $2.5 \cdot 10^{16}$ 1-MeV neutron equivalent</u>

Conclusions

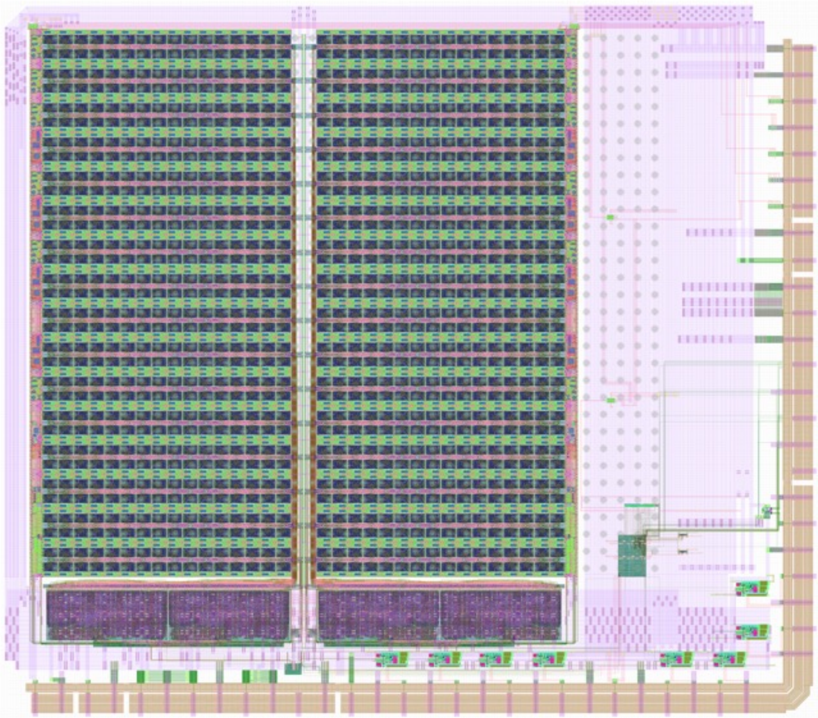
- Unprecedented results on trench 3D trend silicon pixels timing performances have been presented
- The time resolution of a single 3D trench pixel sensor was measured at SPS/H8 with a 180 GeV/c π^+ beam and found to be of about 11ps @ V_{bias} = 100V (sensor intrinsic + FEE noise)
- The sensor detection 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 neq 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
- **VERY IMPORTANT**: The front-end electronics is now the limiting factor to the system performance

… and Outlook

- The TimeSPOT collaboration has developed an ASIC (CMOS 28nm) to read a small pixel matrix → see A. Lai poster *"Timespot1: an ASIC for high-resolution timing and high-rates in 28-nm CMOS technology"* on Friday

- 3D pixel matrices has just been bump-bonded to ASICs by IZM and the assemblies will be tested in the next months in the laboratory and on the beam at SPS/H8 in October 2022

- More news soon… stay tuned!

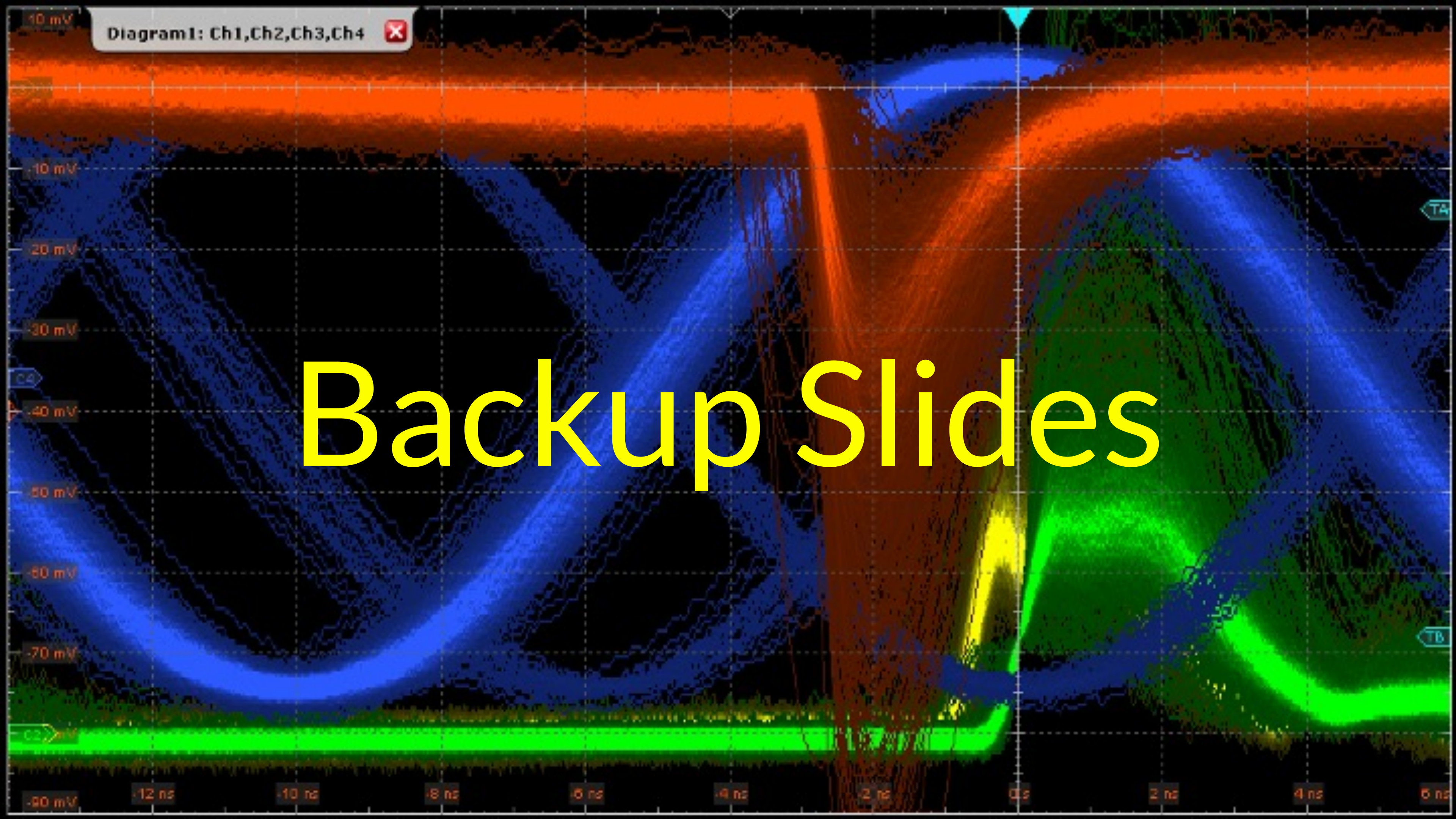


Thank you very much!

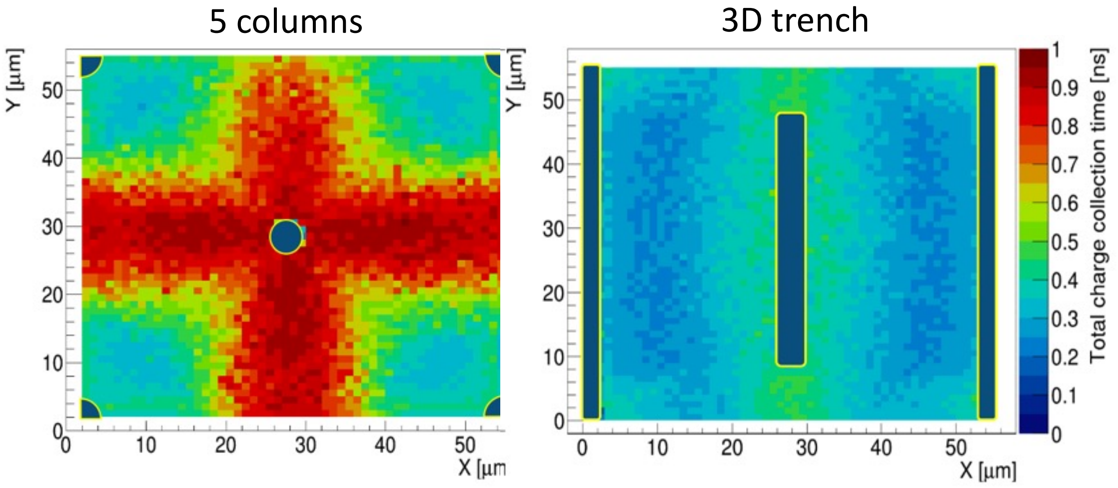
Publications by the TimeSPOT Collaboration

- 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 Slides



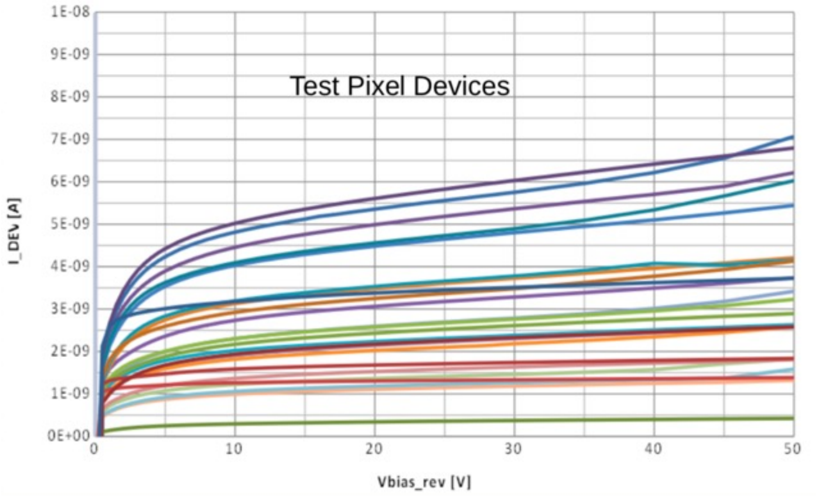
Comparison between 3D geometries



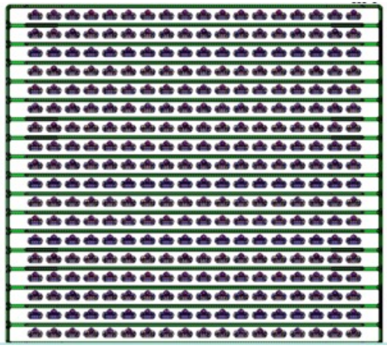
TCAD simulations, Vbias = – 150 V

- The time for total charge collection varies strongly as a function of the particle impact point on the pixel in the 5 columns geometry
- <u>This dispersion will strongly affect the overall pixel time resolution</u>
- The ”planar” trench design provides a very fast and uniform charge collection time

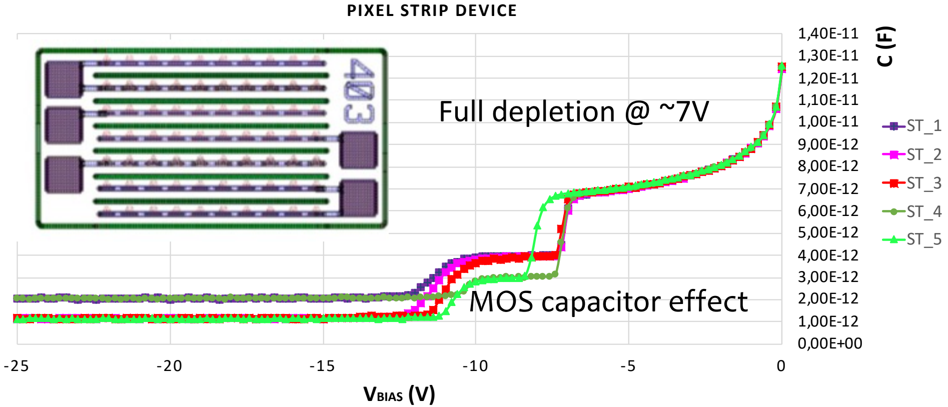
DC electrical characterization of 3D trench pixels



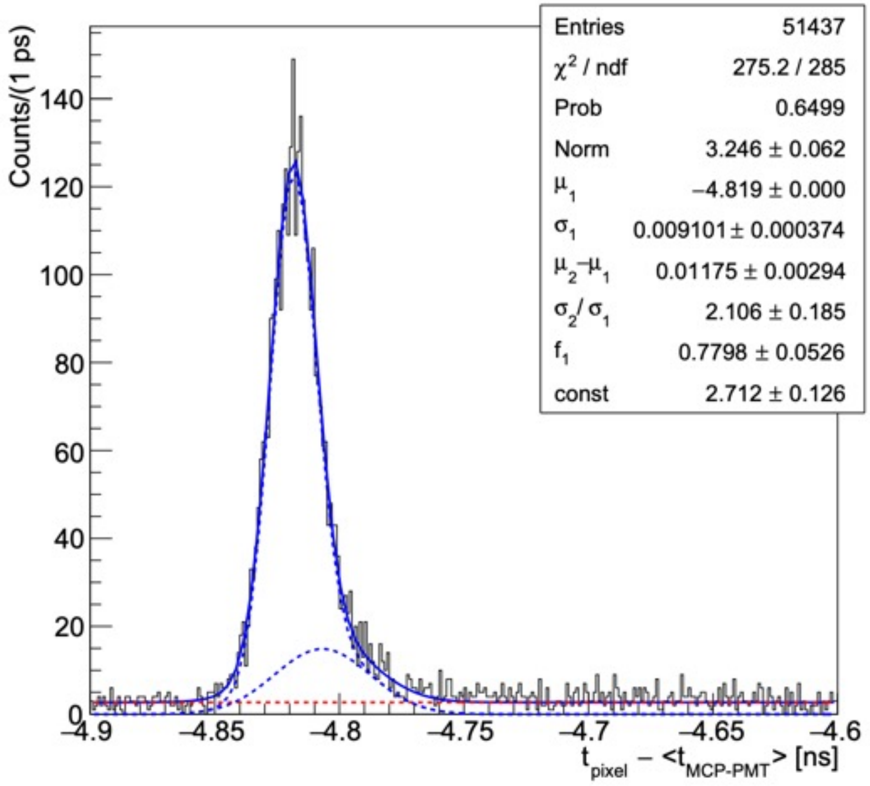
IV-curves on 18x18 pixel matrices (pixels connected with temporary metal): ~10 pA/pixel – good!



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



Fitting the time distribution: σ_{eff}



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

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} takes into account the two-Gaussian behaviour