Laboratory characterization of 3D-trench silicon pixel sensors with a ^{90}Sr radioactive source

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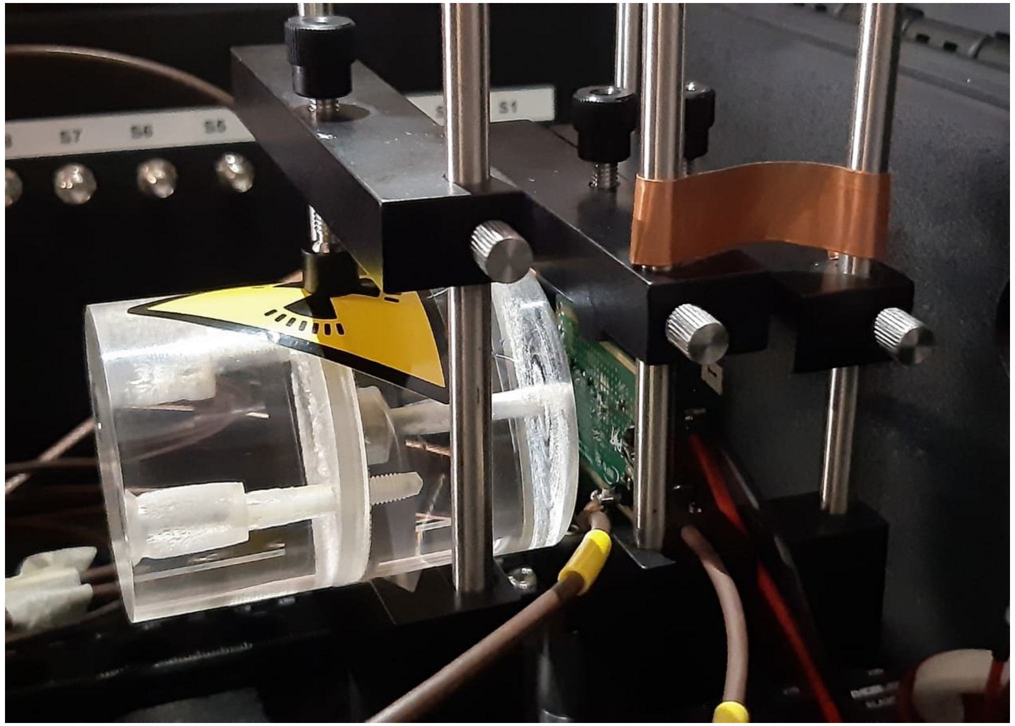
on behalf of the TimeSPOT team

18/02/2021
16th (Virtual) Trento Workshop on Advanced Silicon Radiation Detectors

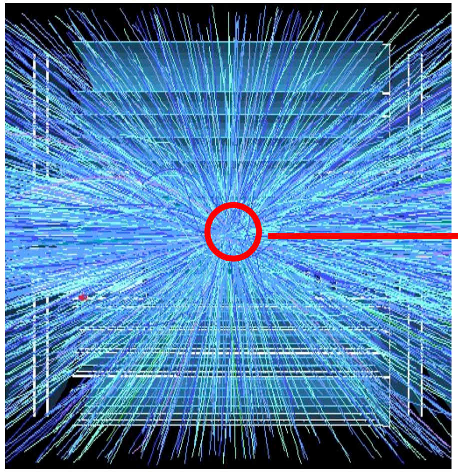
Outline

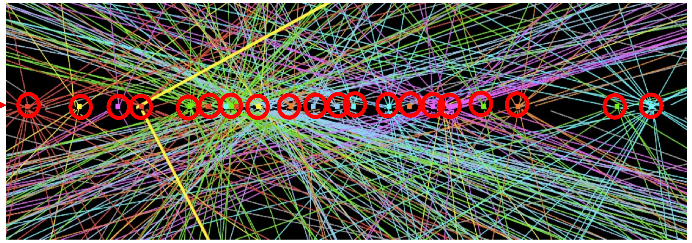
- High Luminosity at LHC
- The TimeSPOT 3D-trench pixel sensors
- Beam test like setup with a ^{90}Sr source
- Results
- Conclusions



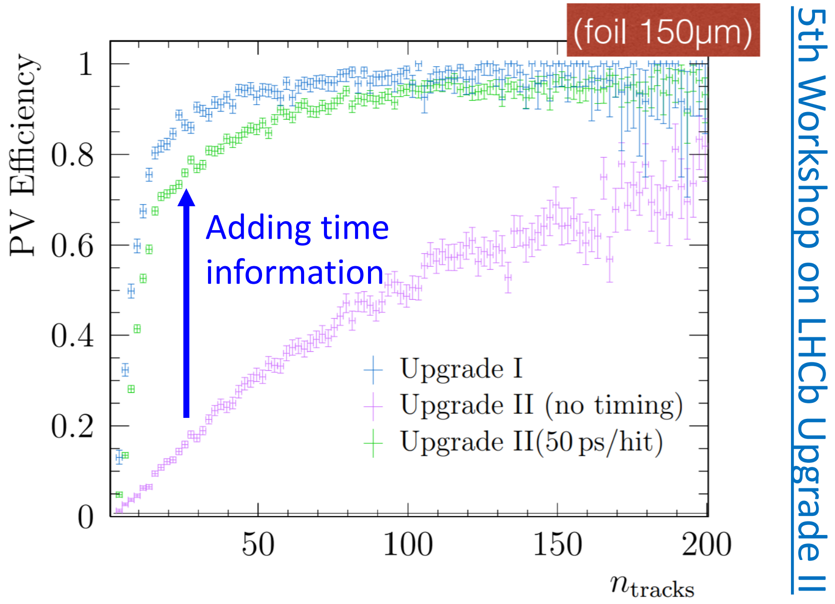
High Luminosity at LHC

- Extremely high instantaneous luminosity at upgraded LHC and future colliders
  - very high radiation damage to tracking detectors
  - very difficult event reconstruction due to large pile-up
    → addition of the **time information** per hit/track





- LHCb Upgrade-2 requirements:
  - Fluence 10^{16} - 10^{17} 1 MeV n_{eq}/cm^2
  - $\sigma_t \approx 30 - 50$ ps per hit
  - $\sigma_s \approx 10\ \mu m$

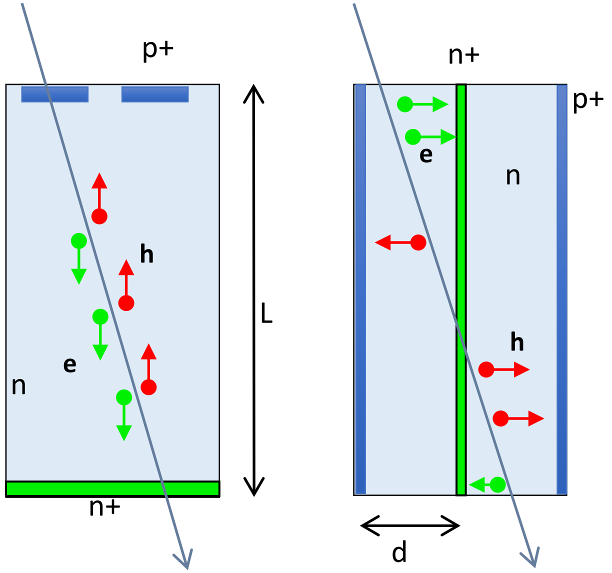


Very good spatial and time resolution, high radiation hardness are required **at the same time!**

3D technology is a very promising option

Why 3D sensors for fast timing?

- Proposed for the first time in 1997 by Sherwood Parker (S.I. Parker et al., NIMA 395(1997) 328)
- Short inter-electrode distance (d<<L) → extremly fast signals
- Unmatched radiation hardness > 10^{17} 1 MeV n_{eq}/cm^2 (M. Manna et al., NIMA 979(2020) 164458)
- 3D columnar geometry sensors already used (e.g. ATLAS IBL)
- The optimization of active volume and electrodes shape is possible



Planar sensor
d = L

3D sensor
d << L

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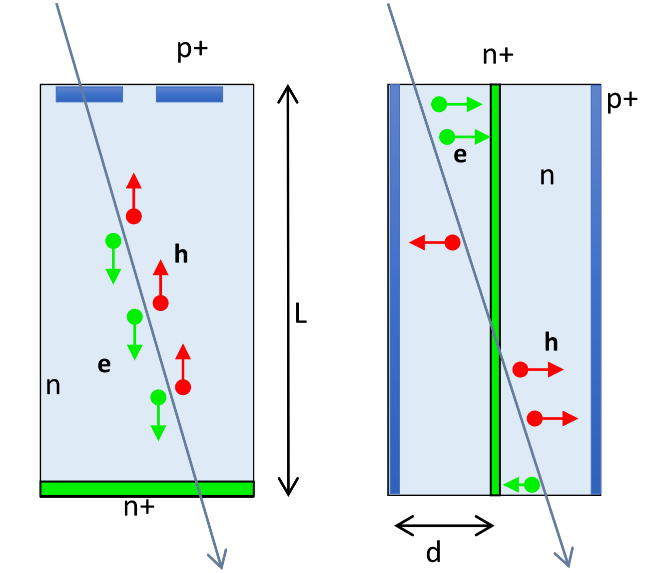


Planar sensor
d = L

3D sensor
d << L

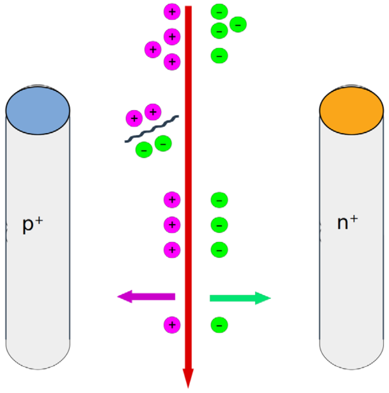
- 4 years INFN-funded project
- **Innovative 3D pixel sensors + readout**
    - space resolution O(10 μm)
    - time resolution < 50 ps per pixel
    - radiation hardness > 10^{16} 1 MeV n_{eq}/cm^2

TimeSPOT
TIME and SPace real-time Operating Tracker

The TimeSPOT sensor design

In a semiconductor detector the **signal**, due to the passage of a charged particle, is produced by the drift of the charge carriers, which induces on the electrodes an **instantaneous current** i defined as

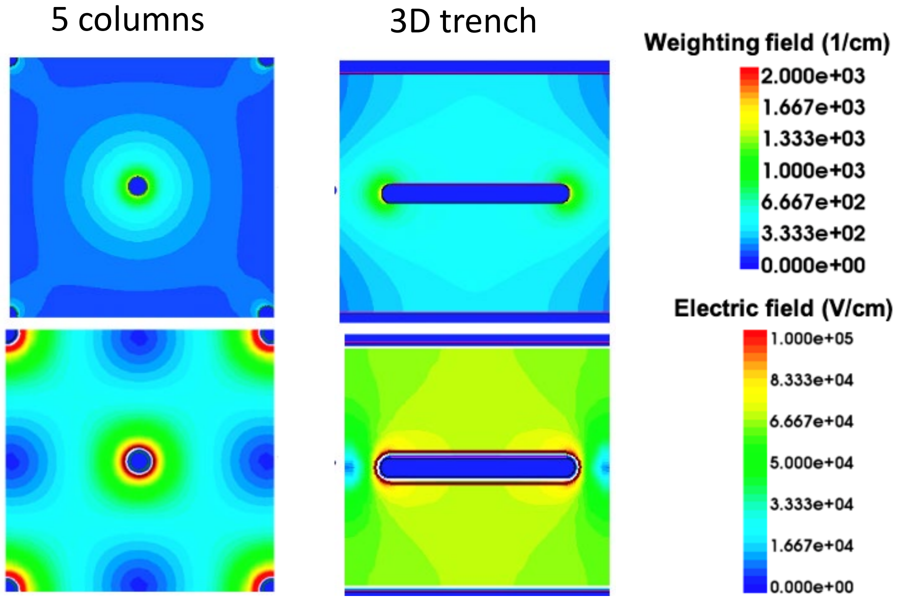
$$i = q\,\vec{E}_w \cdot \vec{v}_d$$



E_w *= weighting field,* ***v_d*** *= carrier's drift velocity*

We want a detector in which the signals are position independent → $\vec{E}_w \cdot \vec{v}_d$ has to be as uniform as possible

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



TCAD simulation

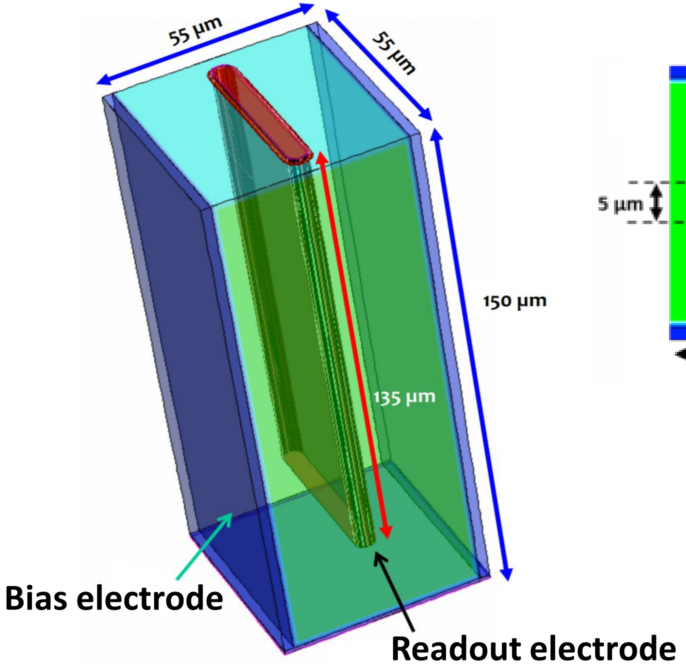
Weighting field and electric field maps **much more uniform** in the **trench geometry**

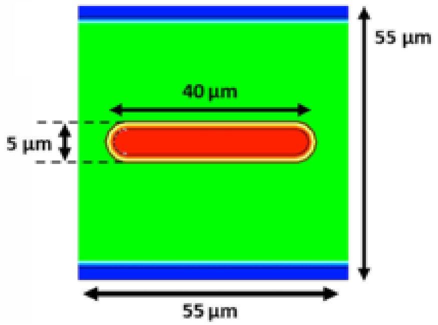
↓

This implies a fast and more uniform charge collection time

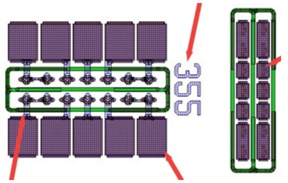
The TimeSPOT sensors

TIME and SPace real-time Operating Tracker

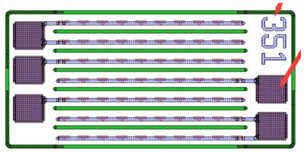




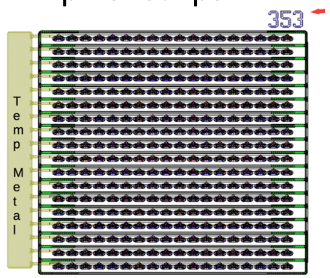
- **55x55 µm² ** pixels
- **150 µm** active thickness
- Collection electrode **135 µm** deep



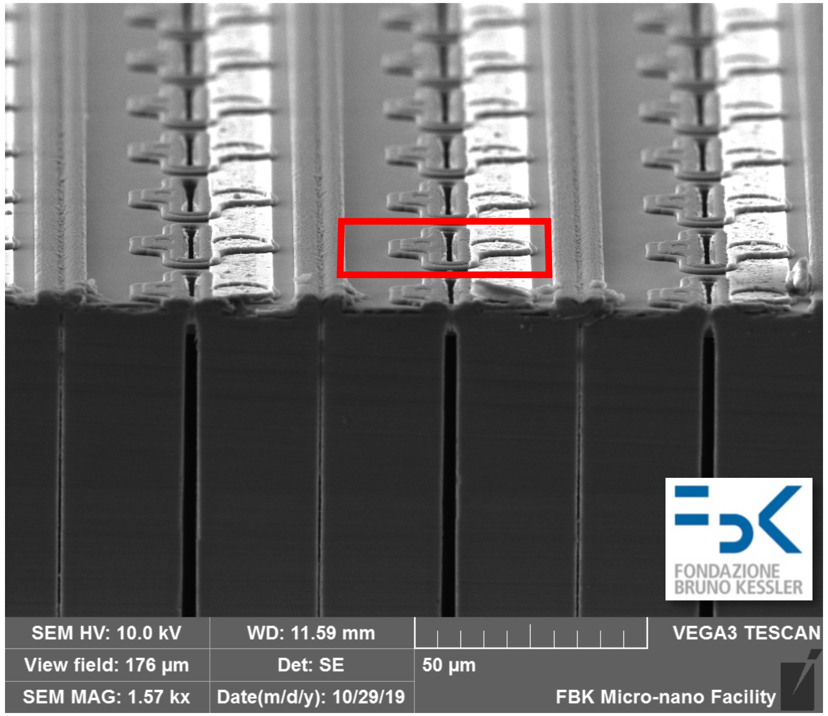
single and double pixels



pixel-strips



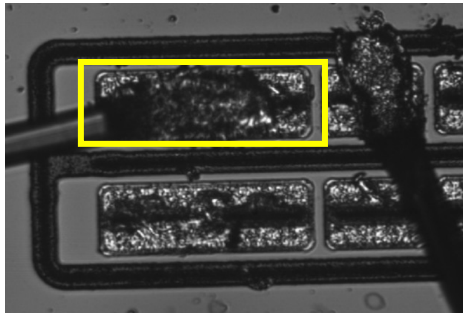
18x18 pixel matrix



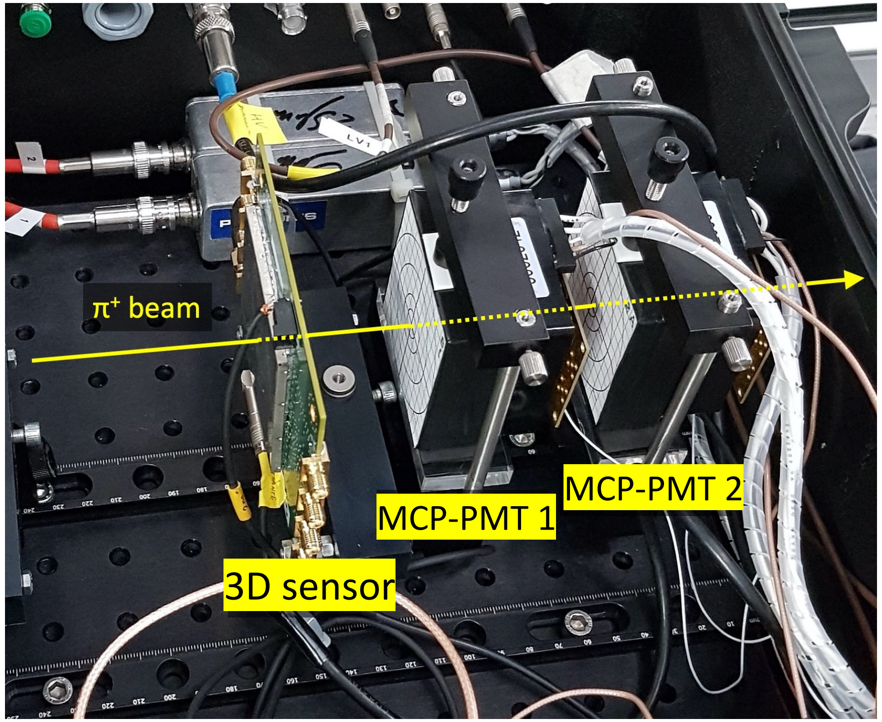
- The **first batch** of TimeSPOT sensors was produced in **2019** at Fondazione Bruno Kessler (FBK, Trento, Italy)
- Several devices designed and fabricated (single and double pixels, 10 pixel-strips, 18x18 and 256x256 pixel matrices, etc.)

The first TimeSPOT beam test

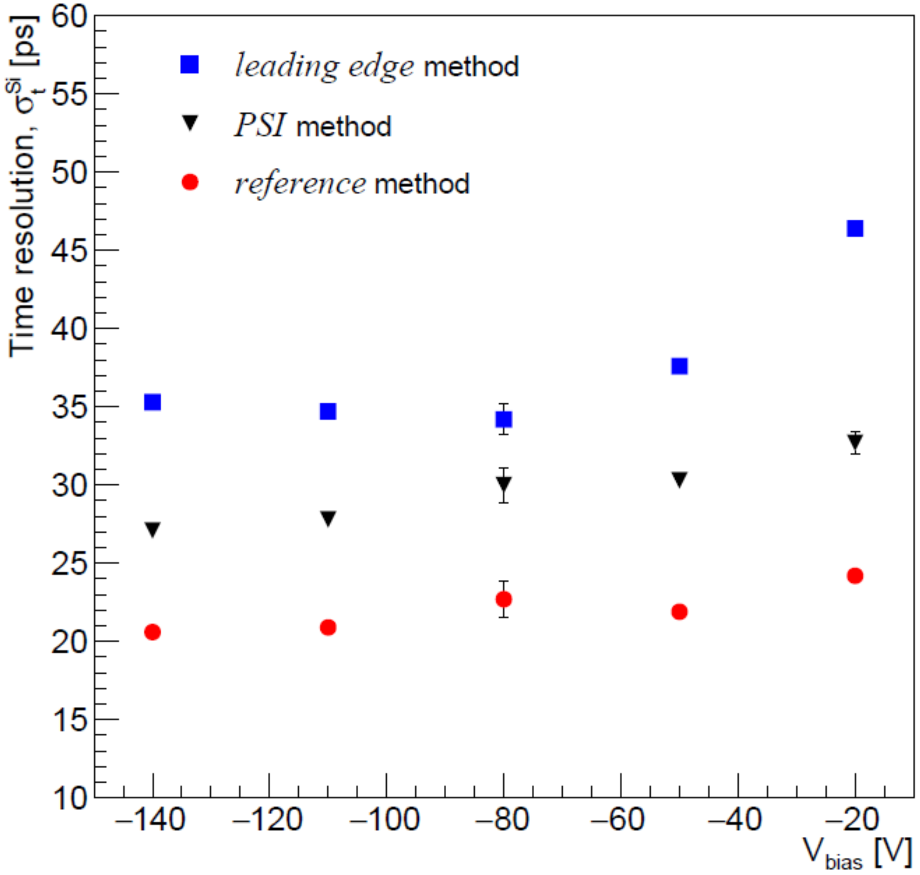
- Paul Scherrer Institut (**PSI**) πM1
- $\boldsymbol{\pi^+}$ beam, $\mathbf{270}\ \boldsymbol{MeV/c}$
- Structure tested: **double pixel**



L. Anderlini et al., "*Intrinsic time resolution of 3D-trench silicon pixels for charged particle detection*", 2020 *JINST* 15 P09029 https://doi.org/10.1088/1748-0221/15/09/P09029



Time accuracy of the time reference $\sim \mathbf{12}\ \boldsymbol{ps}$



Time resolution contributions

At a first order simplified analysis, the time resolution of a system sensor + read-out electronics is

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

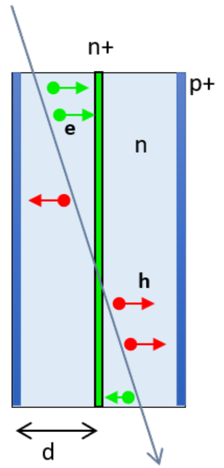
~~$\boldsymbol{\sigma_{tw}}$~~: signal amplitude fluctuation event by event → time-walk jitter → constant fraction discriminator

~~$\boldsymbol{\sigma_{dr}}$~~: delta rays → signal amplitude and shape variations → negligible in a 3D sensor

$\boldsymbol{\sigma_{un}}$: non-uniformities in the charge collecting field and carrier velocities → different signal shape

$\boldsymbol{\sigma_{ej}}$: noise of the preamplifier used to readout the sensor

~~$\boldsymbol{\sigma_{TDC}}$~~: digital resolution of the electronics used to measure the signal → adequate TDC



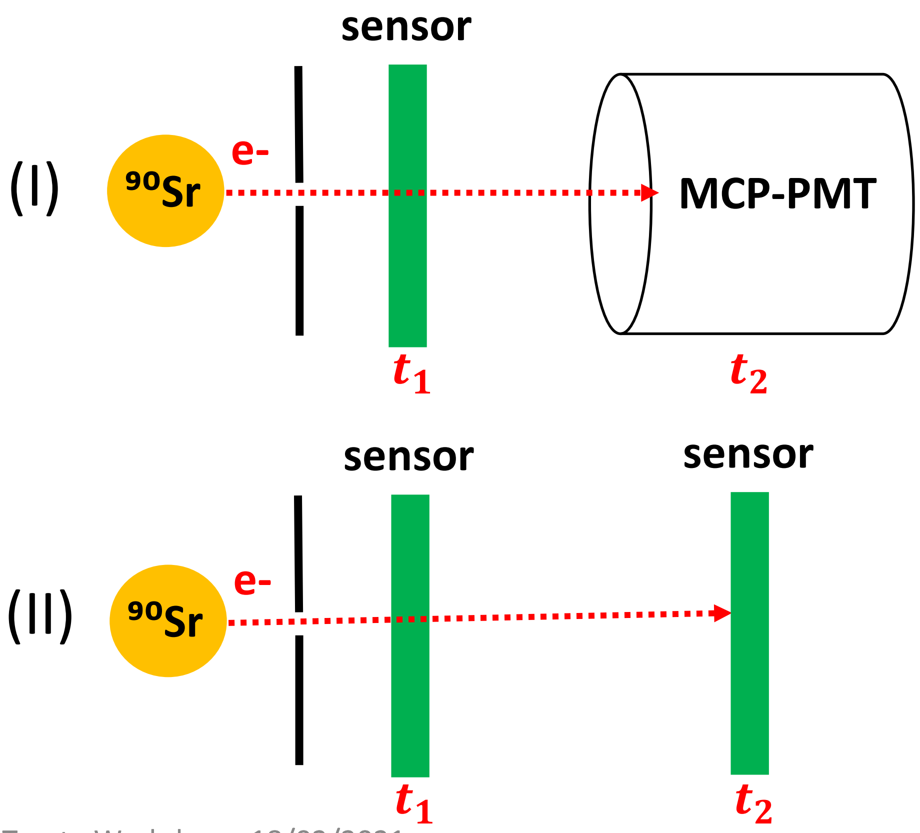
For a 3D sensor ⇒ $\sigma_t \cong \sqrt{\sigma_{un}^2 + \sigma_{ej}^2}$

Beam test setup in laboratory

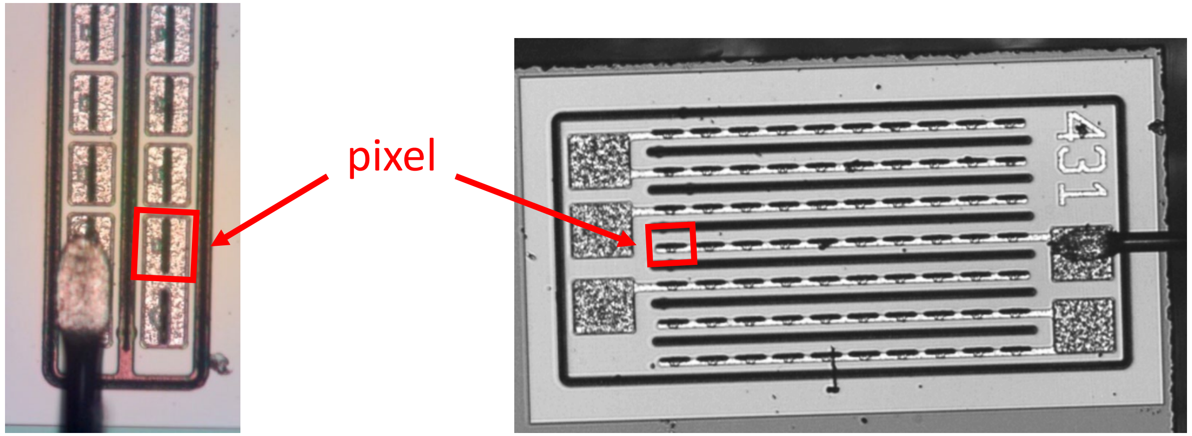
- To perform accurate time resolution measurements **in our laboratory** with minimum ionizing particles
- Beta emitter ^{90}**Sr**, (0.546 - 2.28) MeV
- Two setup configurations:

  (I) with an external time reference detector

  (II) measure of the time of arrival in one sensor with respect to another



- Test structures tested:
  - double pixel
  - pixel strip (not measured at the PSI 2019 beam test)

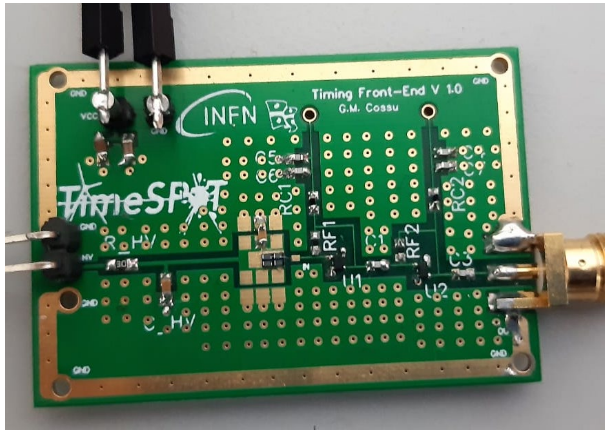


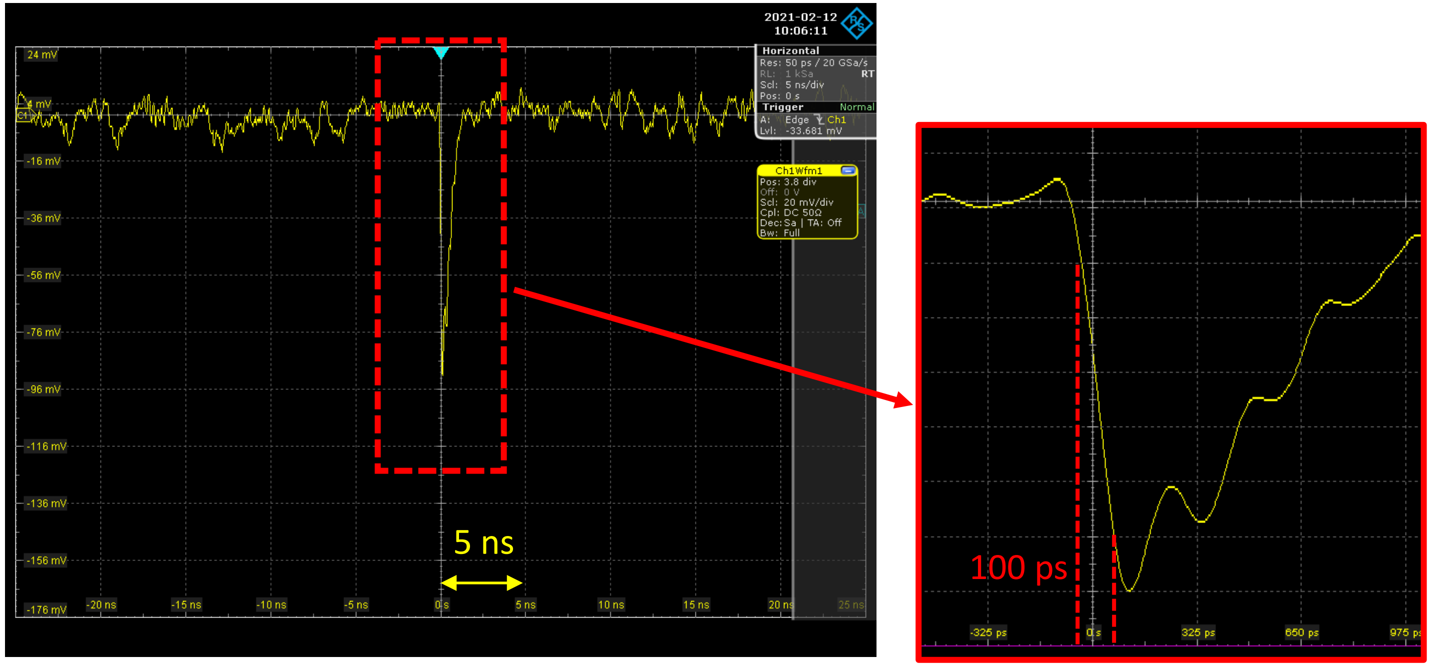
Double pixel **Pixel strip**

Setup I

FEE electronic board

- FEE optimised for the TimeSPOT sensor
- Two stages of transimpedance amplifier with ultra low-noise SiGe BJT
- Noise ~ 3 mV
- Rise time ~ 100 ps





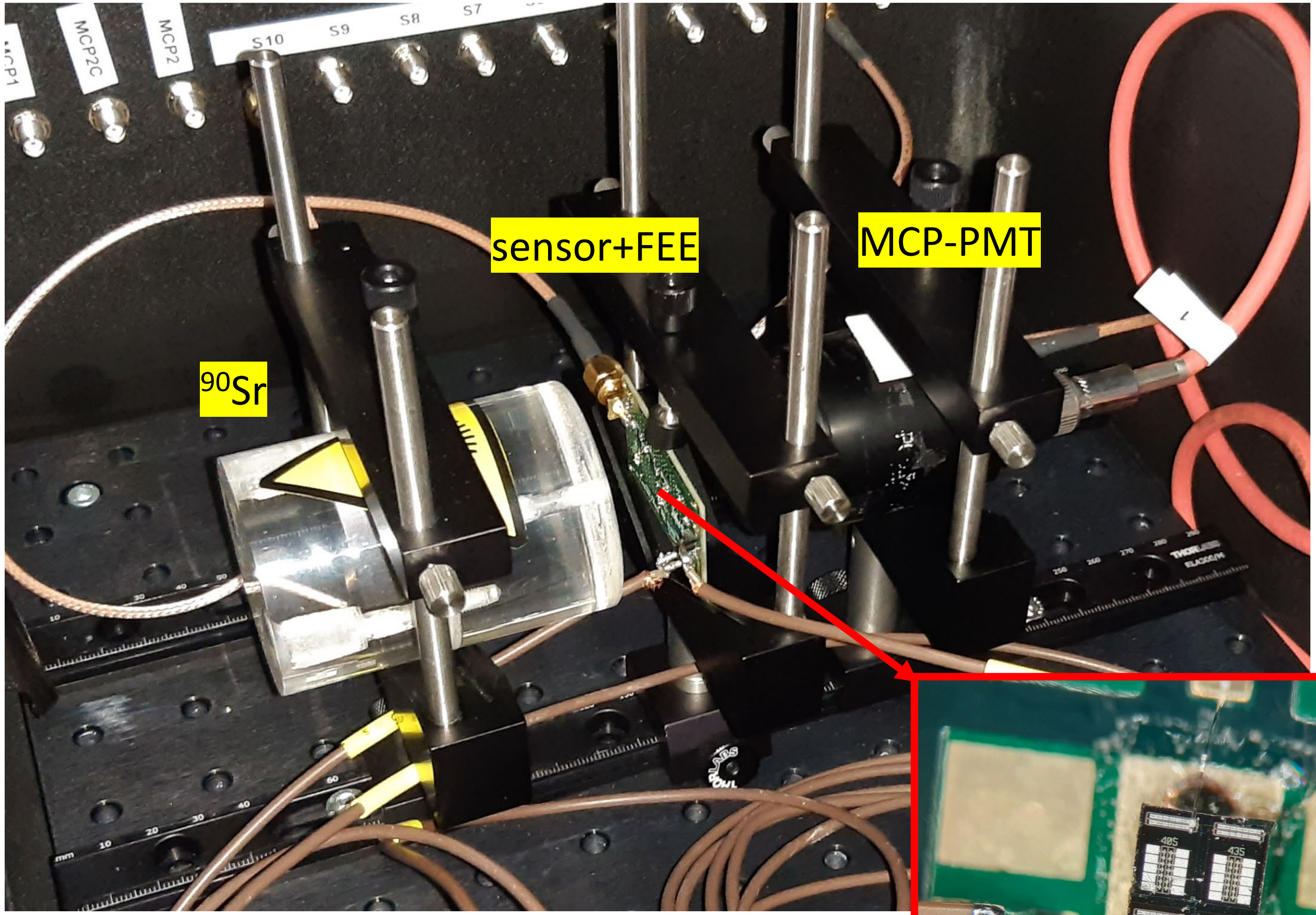
Time reference

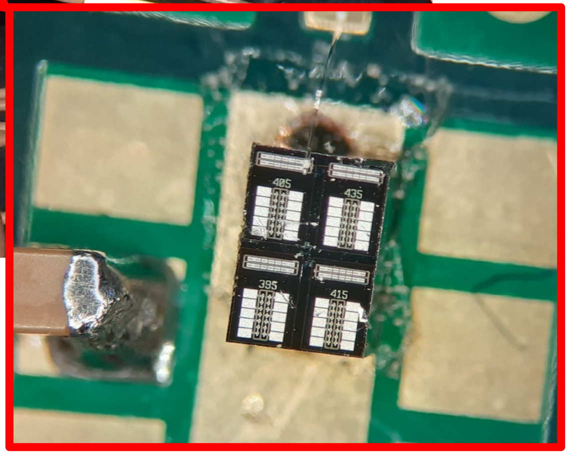
Microchannel plate PMT - Photonis PP0365G

- Input window diameter 18 mm
- ~ 40 ps Transit Time Spread (TTS) in single photon condition
- 2 MCP, chevron
- 6 µm channel size, L:D 50:1

Setup I

The setup is inside a **light tight black box**.

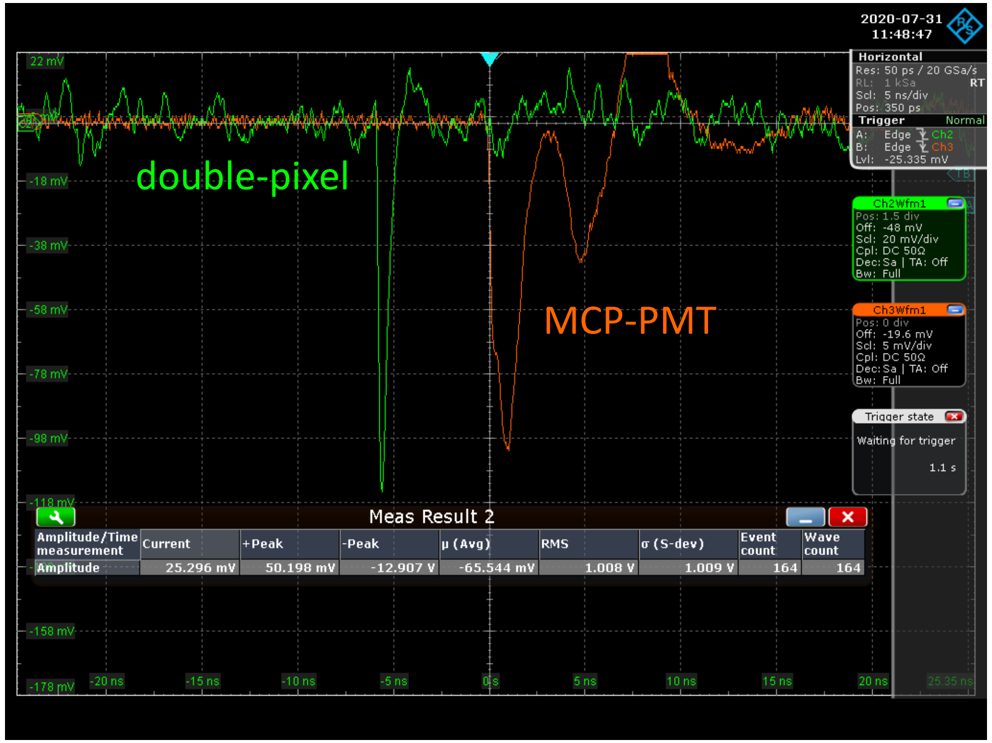




The pad in which the sensor is taped has an hole to avoid the electrons from losing energy in the PCB.

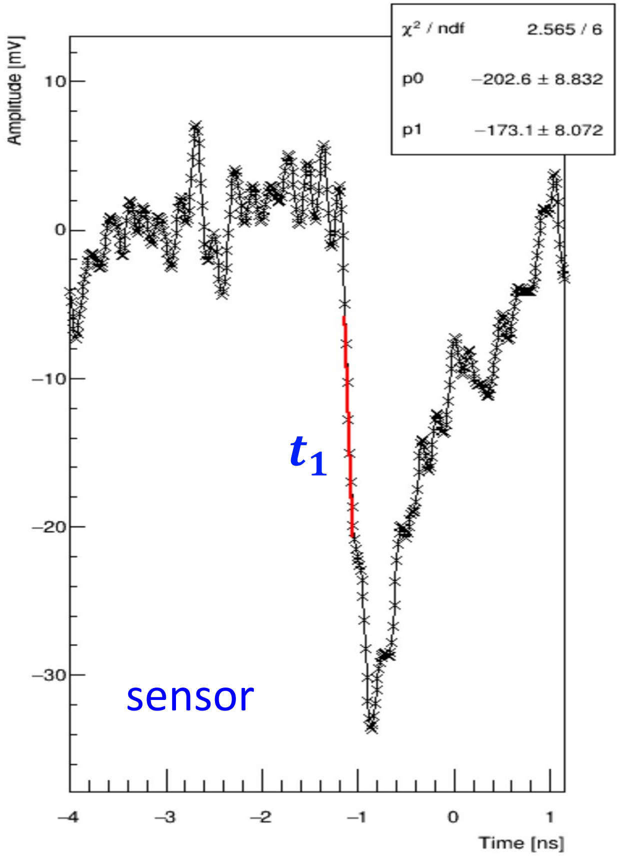
Analysis

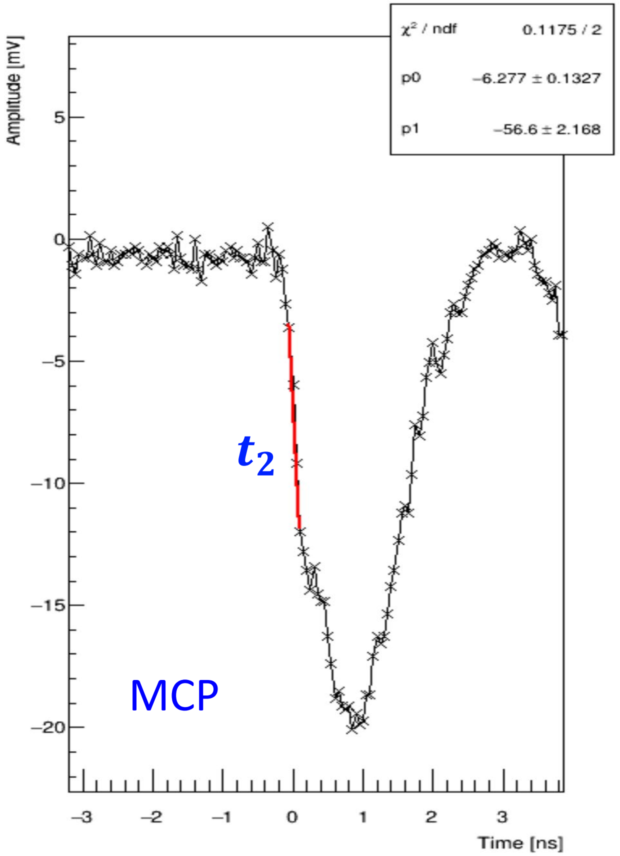
A typical event seen at the oscilloscope



$$\Delta t = t_{sensor} - t_{mcp} \longrightarrow \sigma_{sensor}$$

- Offline analysis of the waveforms acquired with the oscilloscope
- Offline interpolation
- Constant fraction algorithm to determine the ToA



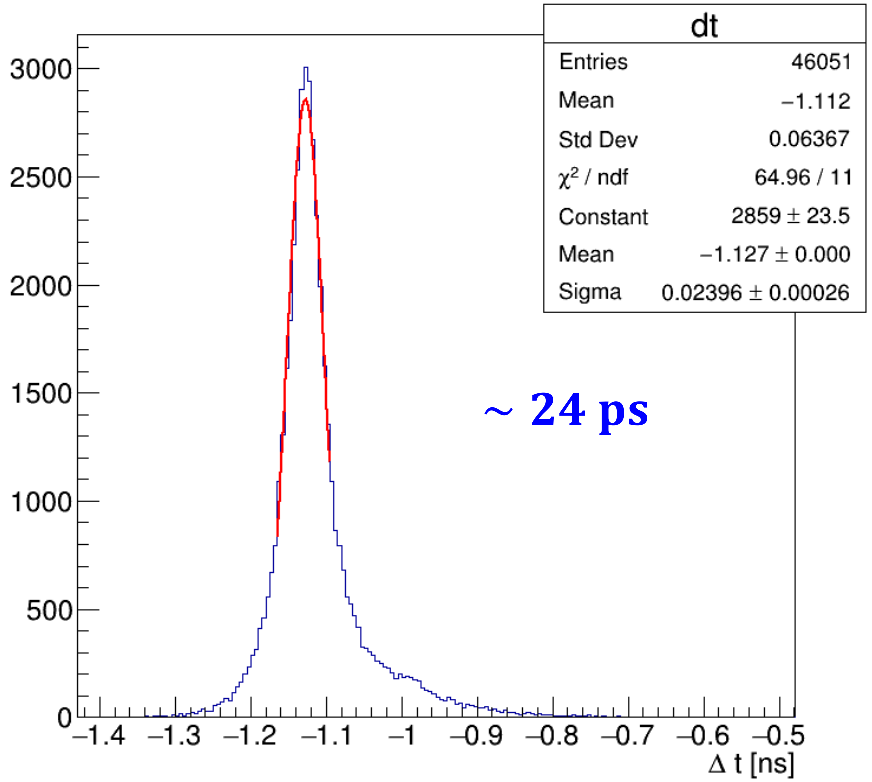


Time resolution – setup I

$$\Delta t = t_{sensor} - t_{mcp}$$

TimeSPOT 3D **double pixel**

V_{bias} = -100 V



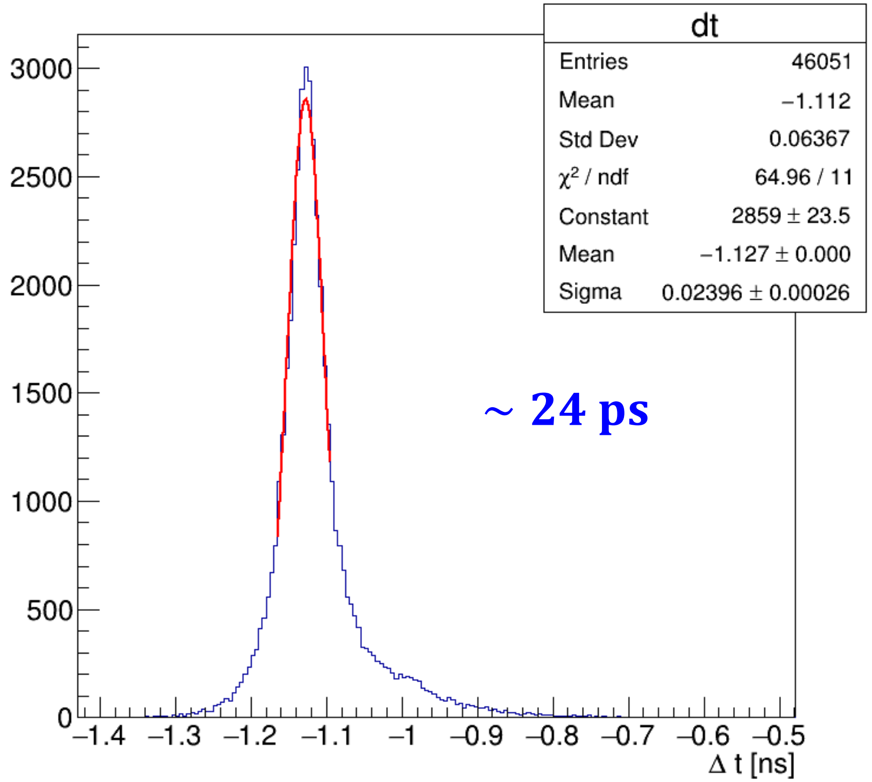
Compatible with the beam test results

Time resolution – setup I

$$\Delta t = t_{sensor} - t_{mcp}$$

TimeSPOT 3D double pixel

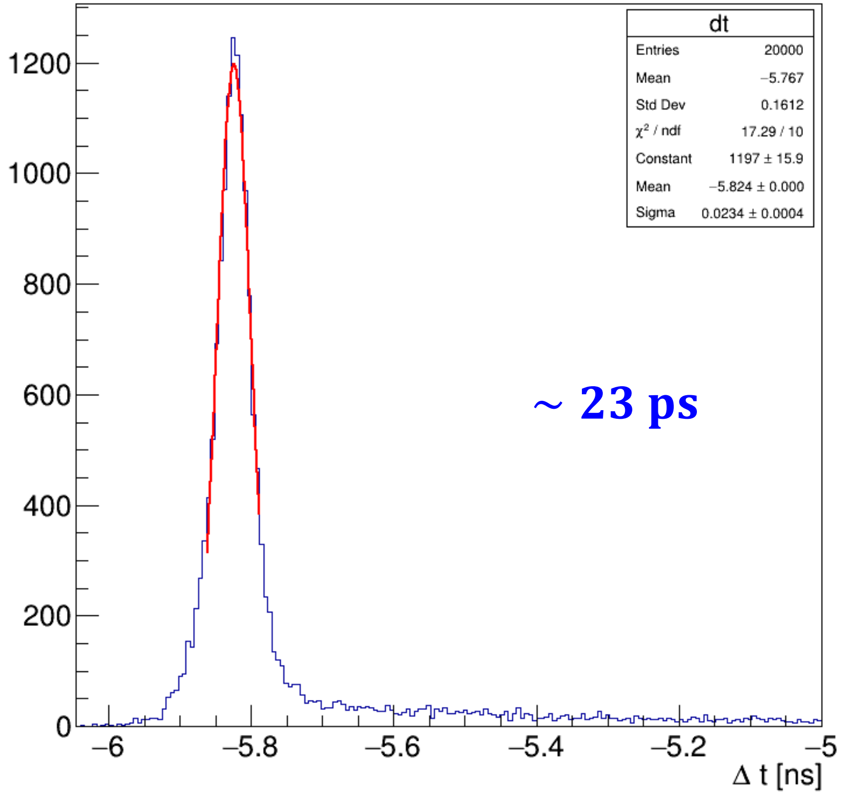
V_{bias} = -100 V



Compatible with the beam test results

TimeSPOT 3D strip pixel

V_{bias} = -100 V

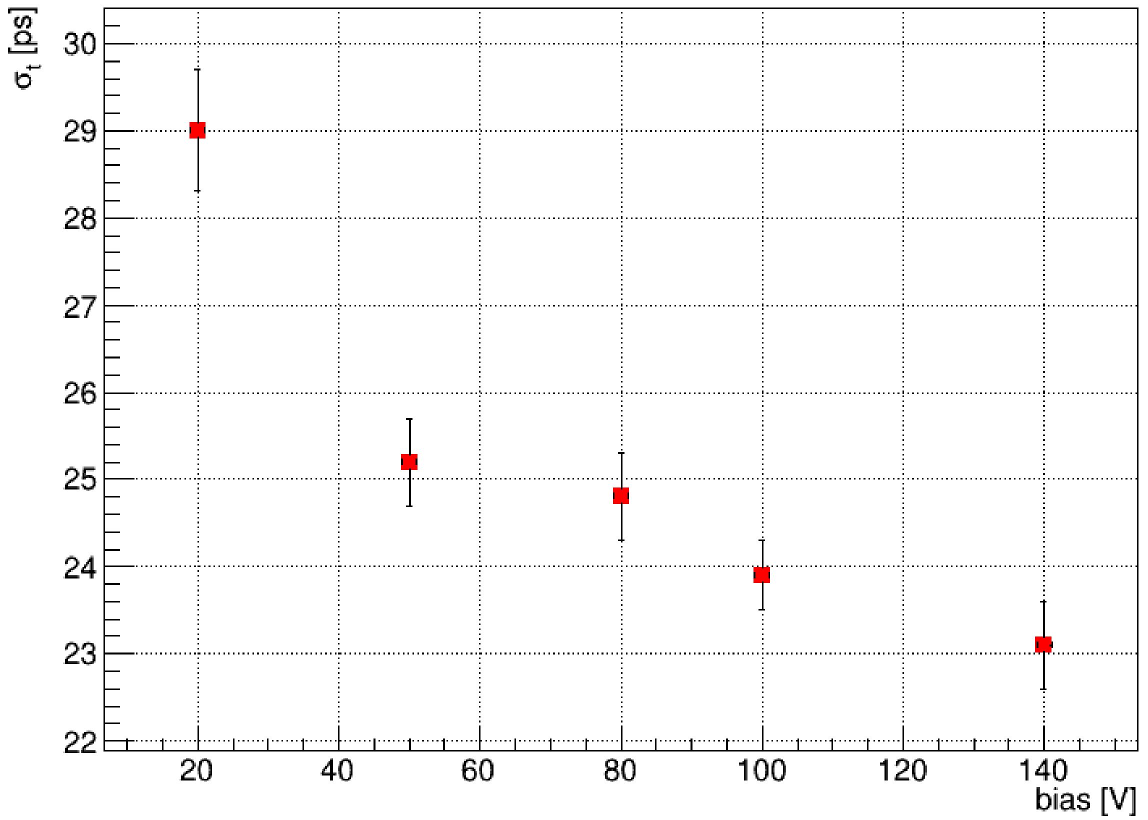


Not measured at the beam test!

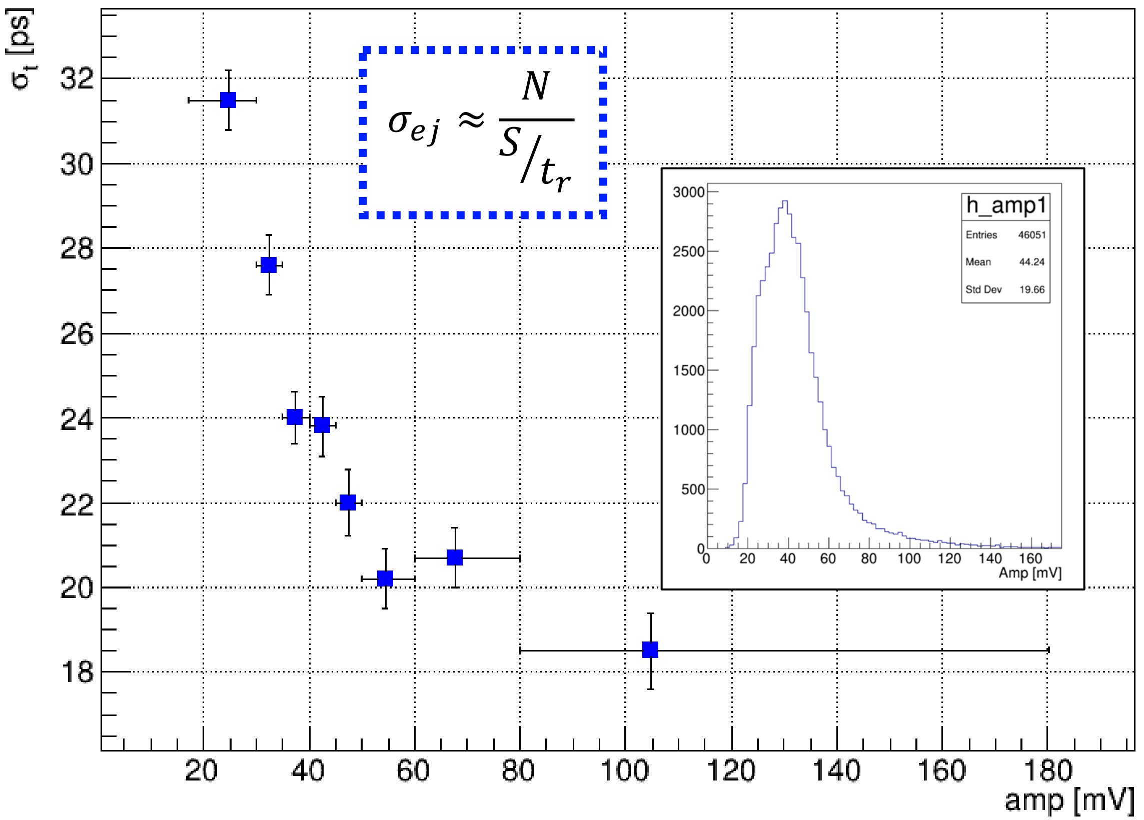
Time resolution – setup I

$$\Delta t = t_{double-pixel} - t_{mcp} \longrightarrow \boldsymbol{\sigma_t} \qquad \sigma_t \cong \sqrt{\sigma_{un}^2 + \sigma_{ej}^2}$$

Time resolution VS bias



Time resolution VS signal amplitude



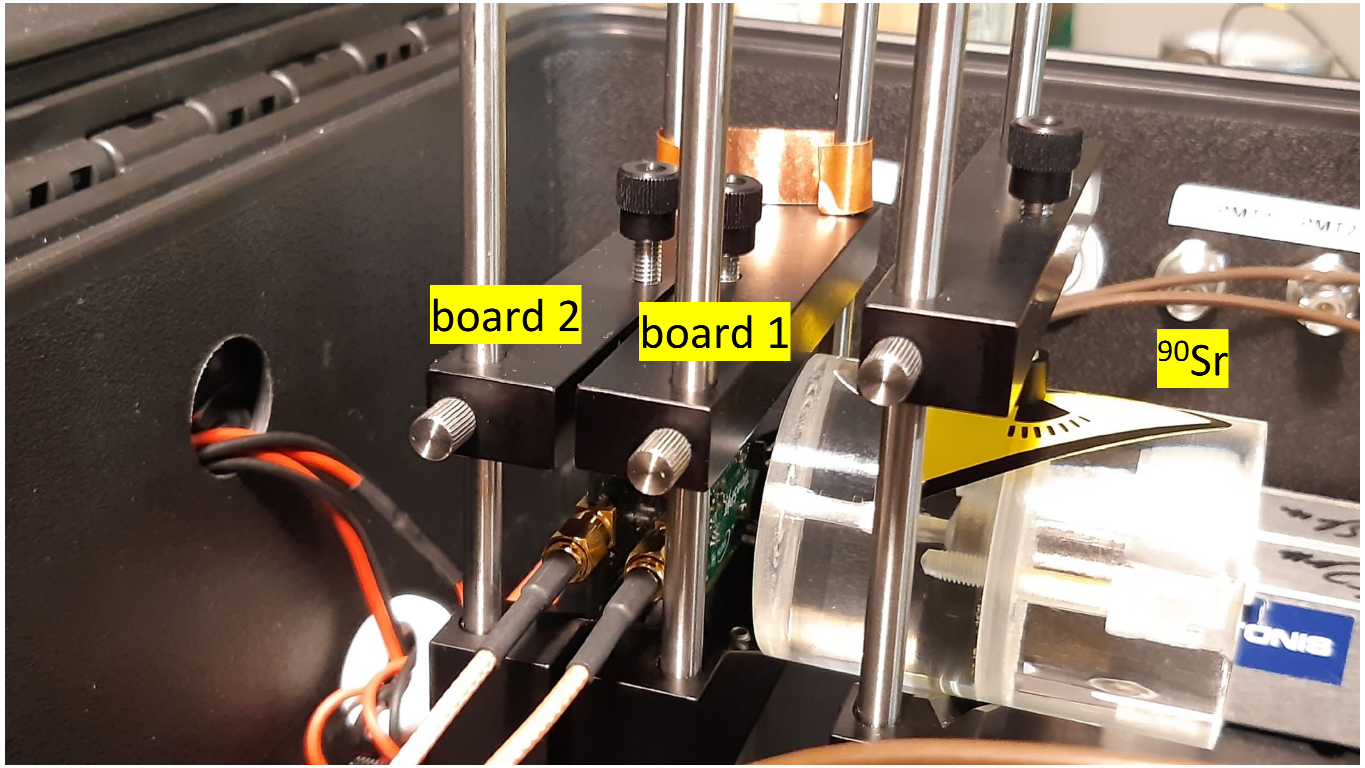
V_{bias}
-140V

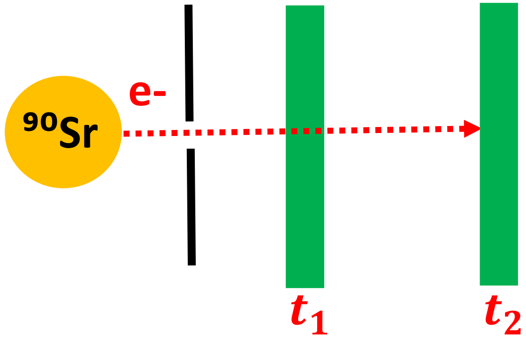
Same trend expected and observed also at the beam test.

With an amplitude scan we can study the impact of the front-end electronics to the time resolution.

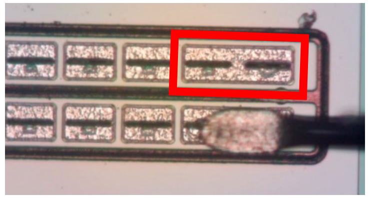
Setup II

- It simplifies the setup, making the measurement independent of the MCP-PMT
- This measurement wasn't done at the PSI 2019 beam test



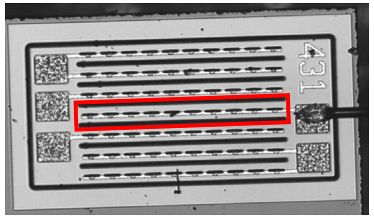


board 1 → double pixel



55x110 μm^2

board 2 → strip pixel



55x550 μm^2

The sensors are very small, but the multiple scattering in the first sensor makes the alignment not so critical.

Time resolution - Setup II

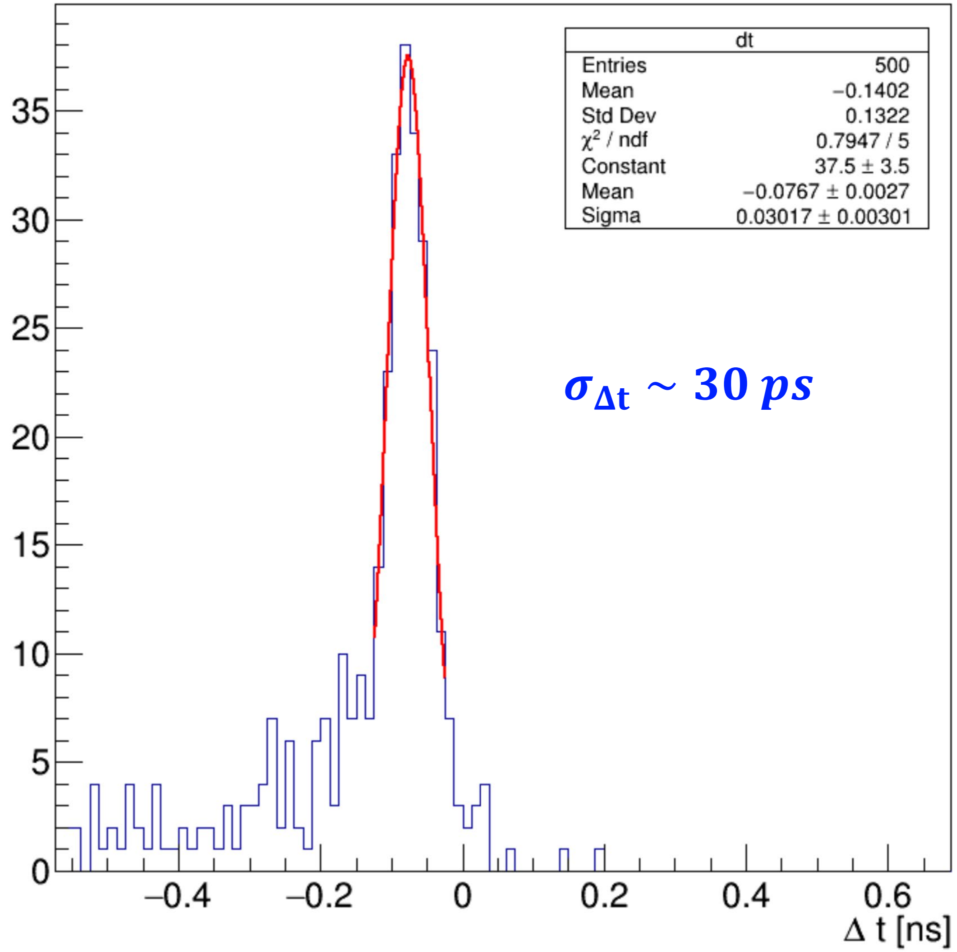
A typical event at the oscilloscope

- Acquisition of the waveforms with the oscilloscope
- Offline analysis
- Constant fraction algorithm described before to determine the ToA of each signal

Time resolution - Setup II

A typical event at the oscilloscope

$$\Delta t = t_{double-pixel} - t_{strip}$$



- Acquisition of the waveforms with the oscilloscope
- Offline analysis
- Constant fraction algorithm described before to determine the ToA of each signal

Comparison with the PSI beam test

Three measurements:

- $t_{double\text{-}pixel} - t_{mcp}$
- $t_{strip} - t_{mcp}$
- $t_{double\text{-}pixel} - t_{strip}$

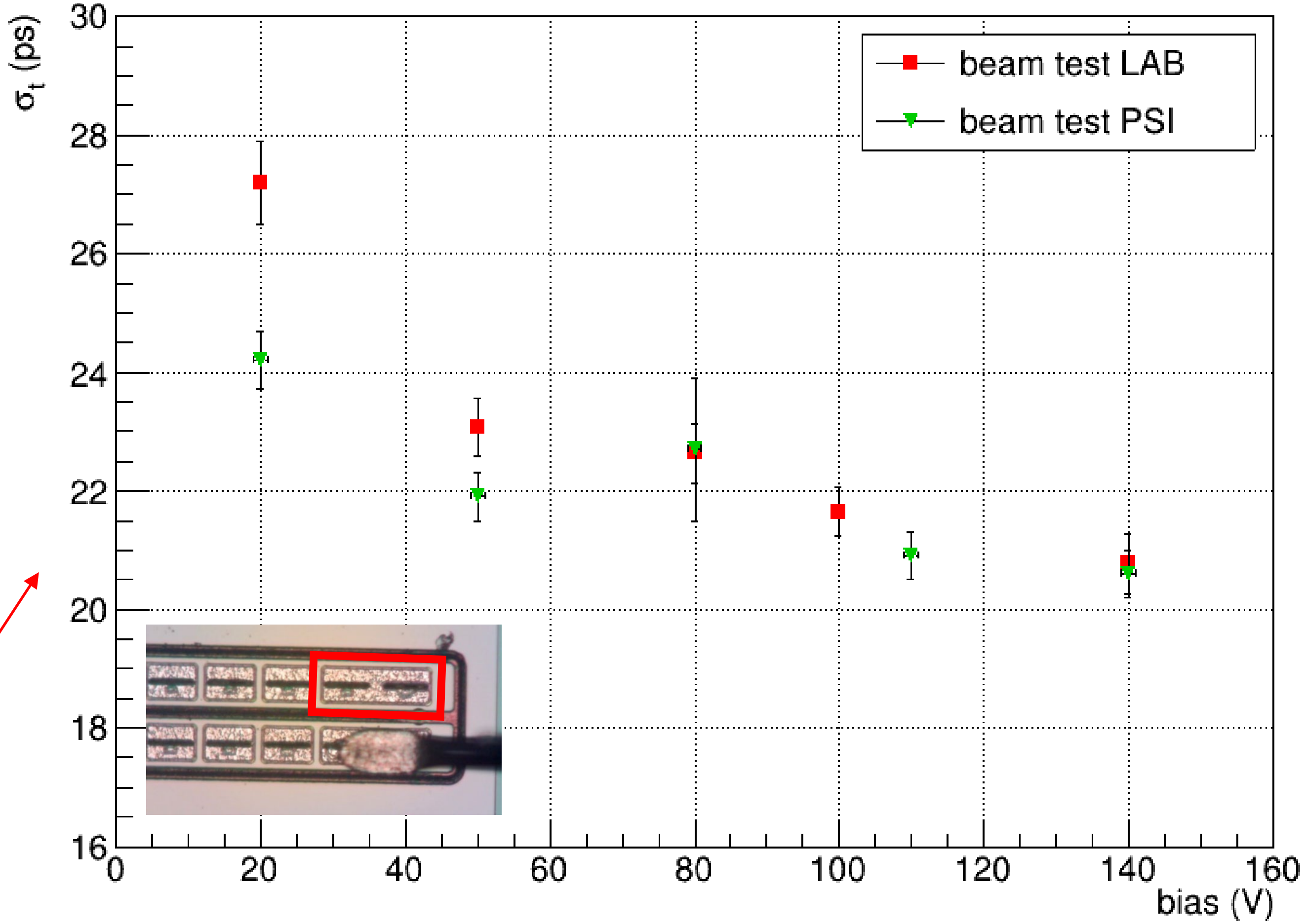
We can derive the time resolution of each detector…

$$\sigma_{mcp} \sim 10.3\ ps$$

$$\sigma_{double-pixel} \sim 21.6\ ps$$

$$\sigma_{strip} \sim 21.0\ ps$$

and subtract the contribution of the MCP.



Conclusions and outlook

- Beam test like setup with a ^{90}Sr source
- **Very good agreement** with the PSI beam test results → about 21 ps time resolution
- **Irradiated TimeSPOT sensors** tests are planned
- Soon second TimeSPOT sensors batch and two more performant MCP-PMT
- The results obtained with this setup do not give information about the efficiency of the pixel → a **microscopic** amplitude and time characterization is mandatory to study the detailed sensors response (see Andrea's talk, following)