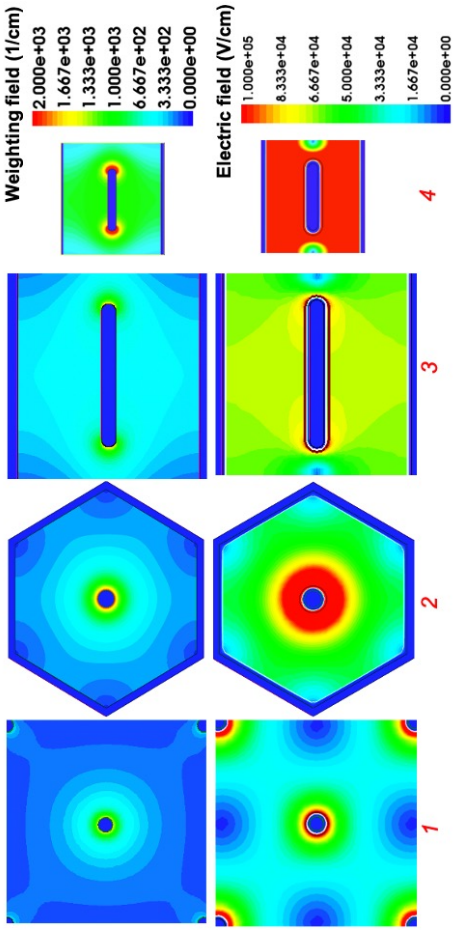
1st MONOLITH Workshop – UniGeneve, 5-6th September 2022

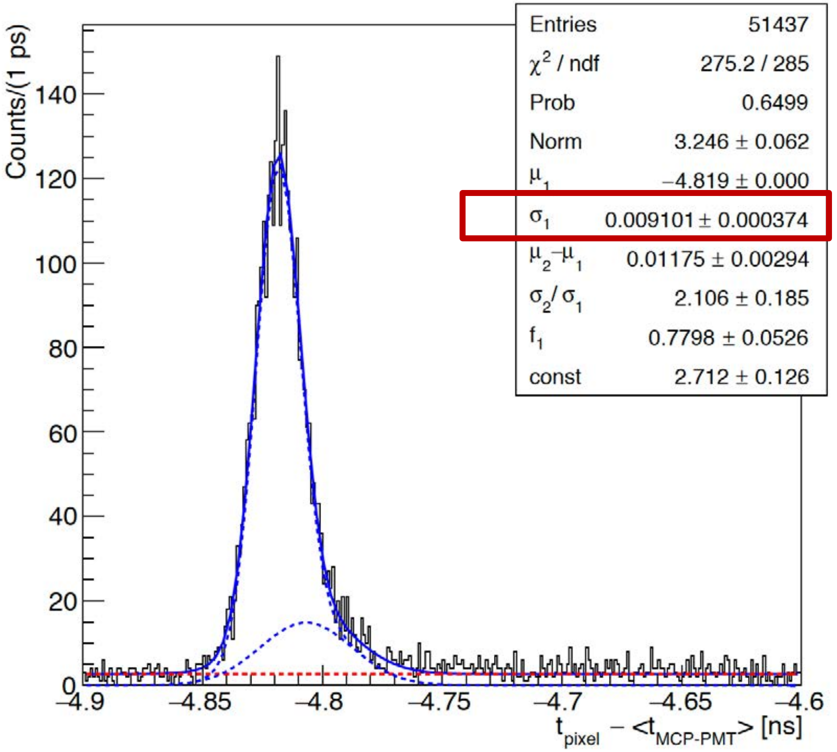
Studies and Tests on 4D pixel sensors

Adriano Lai,
INFN Cagliari



Talk Outline

1. *What we mean for 4D-pixel*
2. *Experimental/System Requirements*
3. *Study of pixel properties and simulation tools*
4. *Key-role of the electronics stage*
5. *Latest test results*
6. *Perspectives*



Definition of 4D pixel and scope of the developments

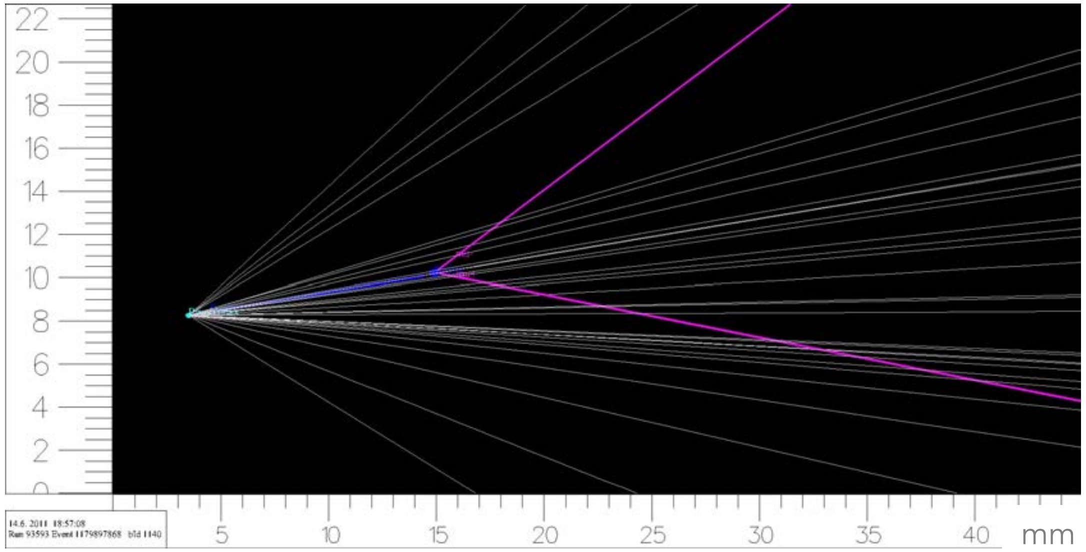
TimeSPOT results – A. Lai – 1st MONOLITH Wshop – UniGeneve, 5-6th September 2022

4D trackers/pixels: what do we mean for?

(beyond pile-up mitigation: when timing layers are not enough)

Plots from:
Considerations for the VELO detector at the LHCb Upgrade II – CERN-LHCb-2022-001

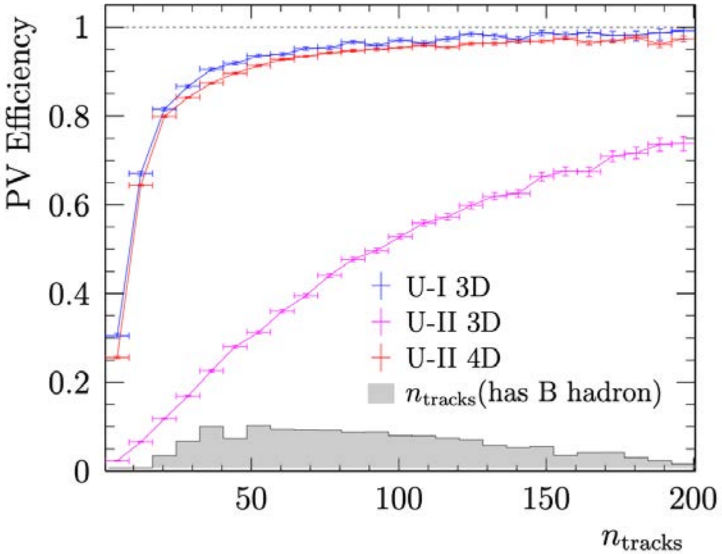
B_{0s} meson decaying into a μ^+ and μ^- pair



4D pixel:
A solid state pixel sensor (pitch ≈ 50 μm) bearing time information

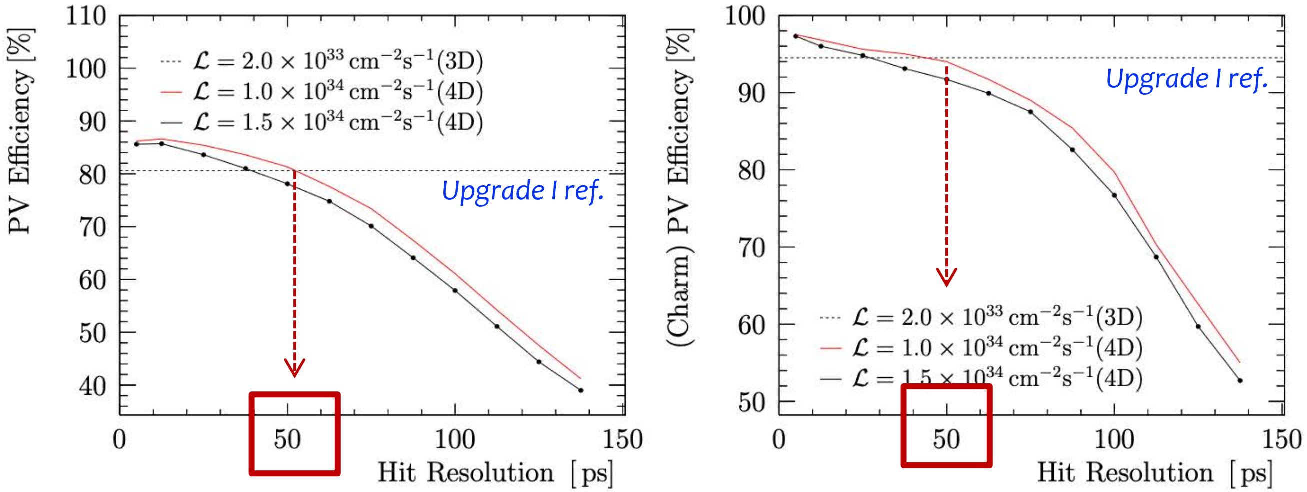
Track merging: bad Primary (and Secondary) Vertex reconstruction

Incorrect PV assigned to tracks: poorly measured lifetime (dominant sistematic effect for time-dependent analysis)



Reconstruction efficiency vs the number of tracks per primary vertex, comparing the Upgrade I 3D reconstruction in both data conditions, and a variant using timing information to resolve the primary vertices

PV reconstruction efficiency as as function of the single hit resolution, for all vertices (left) and for vertices where at least one of the decay products is a charm hadron (right).



50 ps per hit (corresponding to 20 ps per track) are sufficient to recover the Upgrade-I efficiency

Technical Requirements of 4D-Tracking

In the next generation of Upgrades

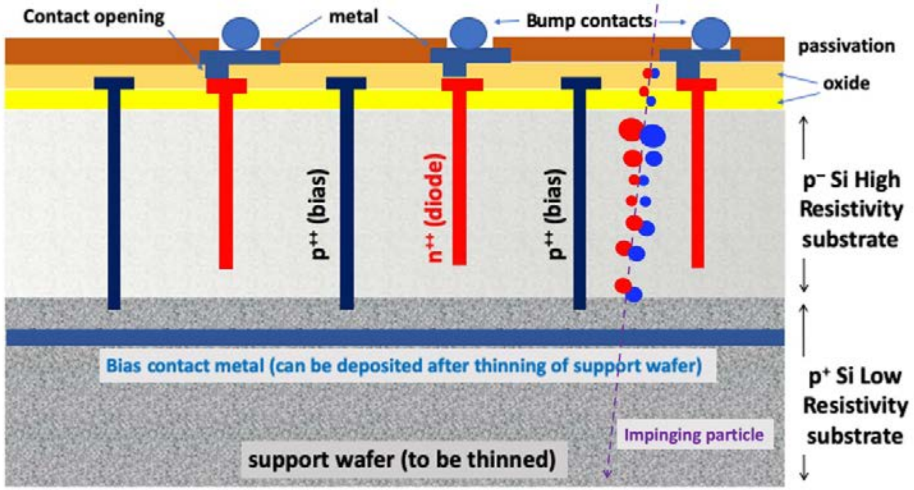
(LHCb run5, NA62 4x, CMS-PPS & ATLAS-AFP run4 … FCC - hh…)

1. **Space Resolution $\sigma_s \approx$ 10 µm (→ pixel pitch ≈ 40–60 µm)**
2. **Time Resolution $\sigma_t \leq$ 50 ps on the full chain ($\sigma_t = \sigma_{sensor} \oplus \sigma_{FE} \oplus \sigma_{TDC}$)**
3. **Radiation hardness to high fluences (for sensors) and high doses (for electronics).**
   Fluences $\Phi = 10^{16} \div 10^{17}$ 1 MeV n_{eq}/cm^2 and Doses > 1 ÷ 2 Grad
4. **A detection efficiency of ε > 99% per layer is tipically required (high fill factor)**
5. **The material budget must be kept below 1 ÷ 0.5 % radiation length per layer**

Very challenging front-end electronics must be developed:
high resolution @ 10s µW/pixel, huge data bandwidth ≈ 100 Gbps/cm².
Today a complete solution for that is FAR from being available.
Developments ongoing

A different approach: 3D silicon sensors

Gain? no thanks! go… Geometric !

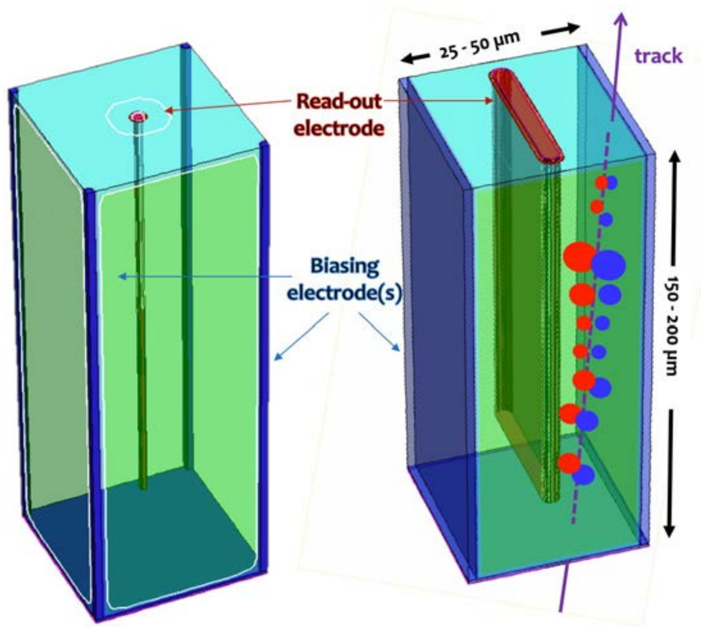


Deep Reactive Ion Etching
(MEMS technology)

Concept (S. Parker et al., 1997):
Perpendicular electrodes make
Inter-electrode distance d
independent of sensor thickness z

Sensitive volume and electrode shapes can be designed and modeled for maximum performance

High and uniform E field

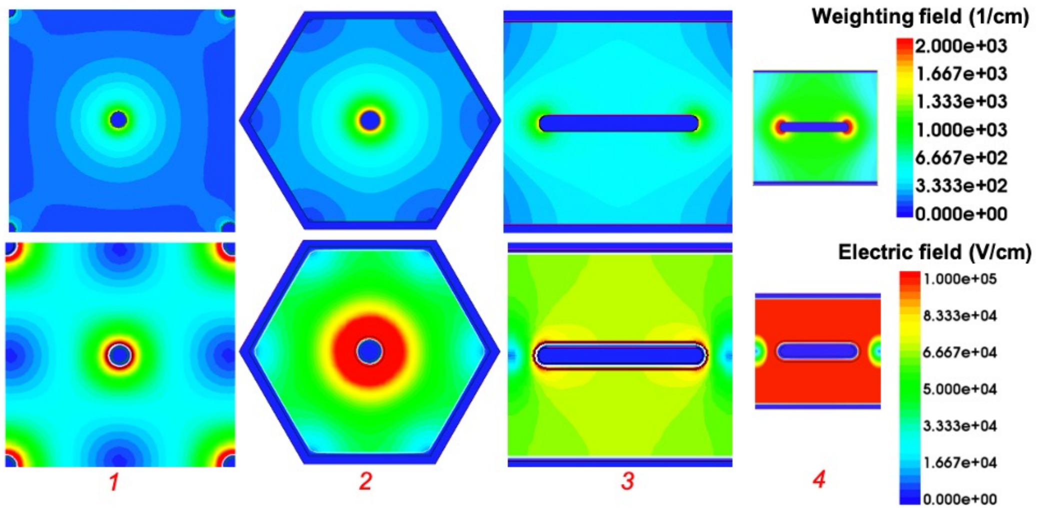


columns

trenches

Column or trench aspect ratio ≈ 30:1

$$i = qE_w \cdot v$$



TCAD Sentaurus output: 2D model simulation of three different electrode geometries at bias voltage V_{bias} = –100 V

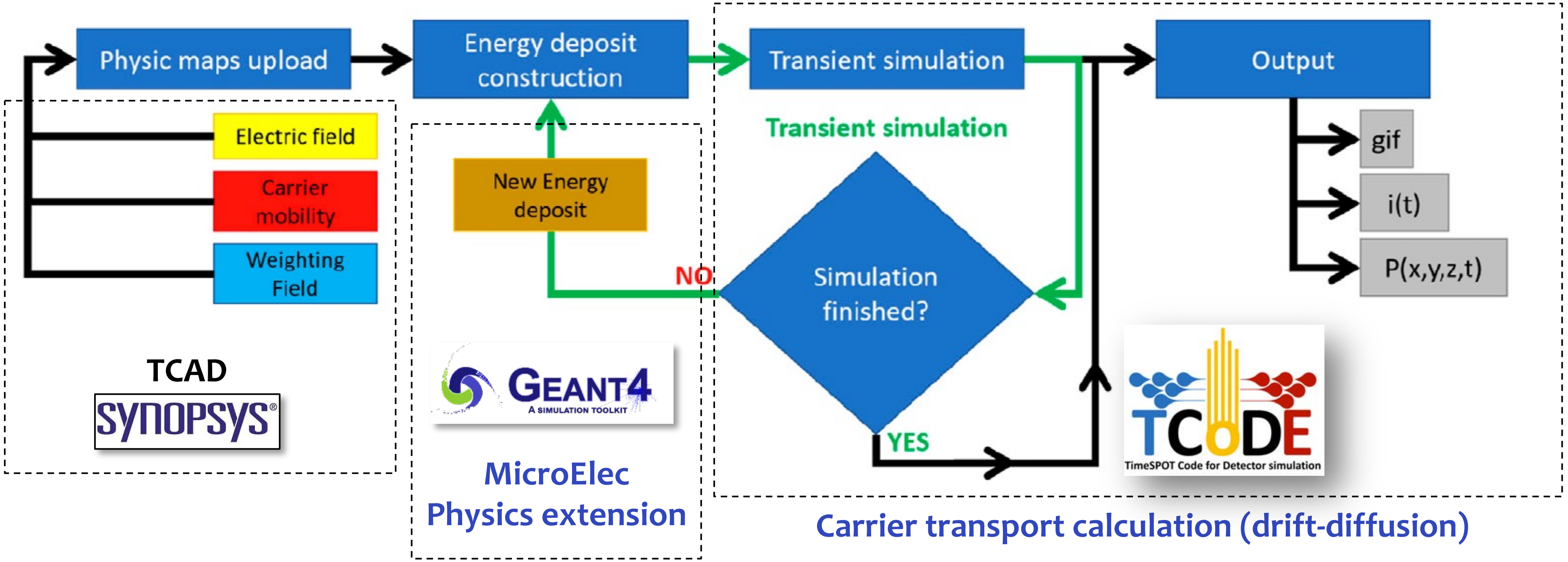
(3D) Sensor modeling and its impact in sensor design and understanding

The playgound and the game
CCT and current signals

https://github.com/MultithreadCorner/Tcode

GPL3 license

The TCoDe simulation flow



Physic maps upload

Energy deposit construction

Transient simulation

Output

Electric field

Carrier mobility

Weighting Field

TCAD

SYNOPSYS

New Energy deposit

NO

Transient simulation

Simulation finished?

YES

gif

i(t)

P(x,y,z,t)

GEANT4 A SIMULATION TOOLKIT

MicroElec Physics extension

TCoDe TimeSPOT Code for Detector simulation

Carrier transport calculation (drift-diffusion)

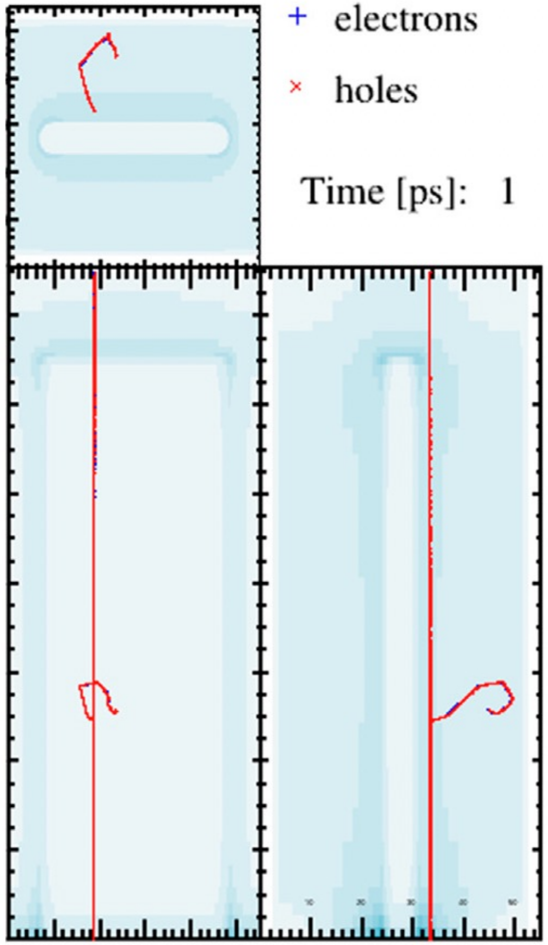
The **carrier motion** calculated using a 4th-order Runge–Kutta algorithm and the thermal diffusion equation.
The contribution of each carrier to the current induced on the readout electrode is determined with the **Ramo theorem** for each time interval.
Multi-threaded approach (Hydra libraries): each carrier is followed independently in a separate computing thread, either in CPU or GPU.

Brundu D, et al. (2022) Modeling of Solid State Detectors Using Advanced Multi-Threading: The TCoDe and TFBoost Simulation Packages. Front. Phys. 10:804752.

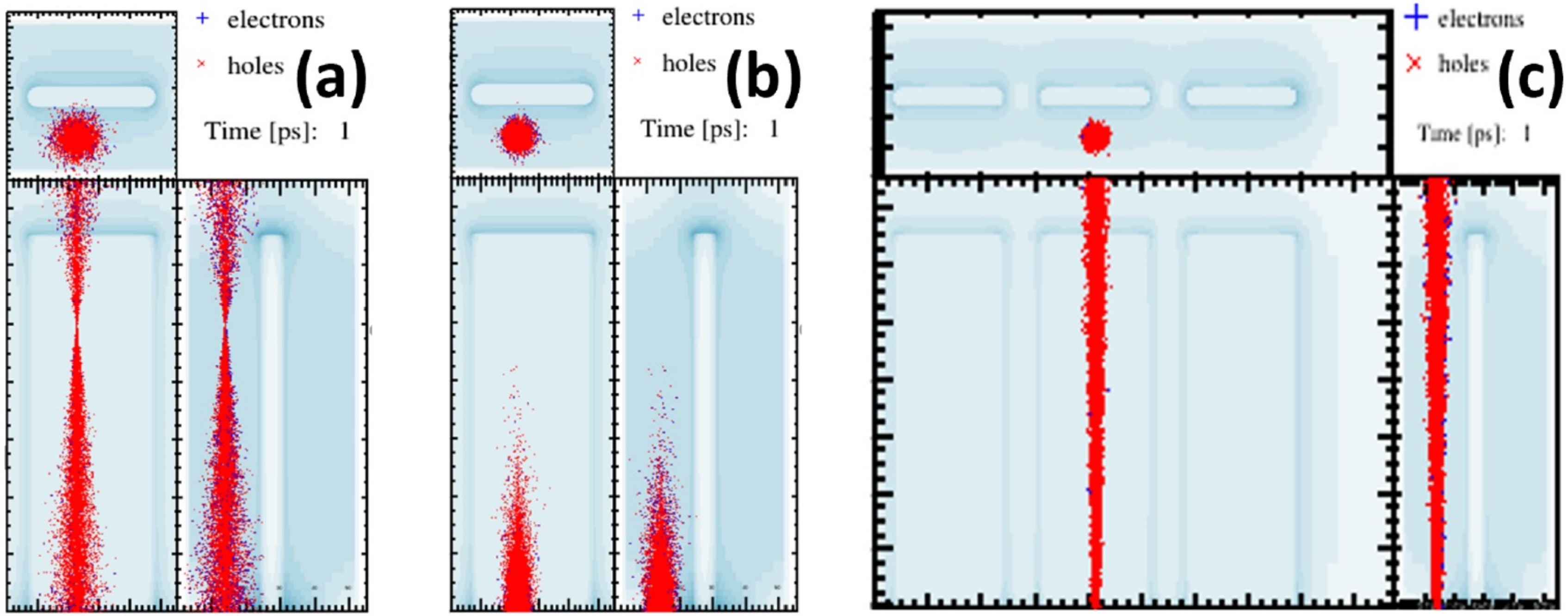
Loi A, Contu A, Lai A. Timing Optimisation and Analysis in the Design of 3d Silicon Sensors: the TCoDe Simulator. J Inst (2021) 16:P02011

Energy deposits

Geant4 and/or analytical



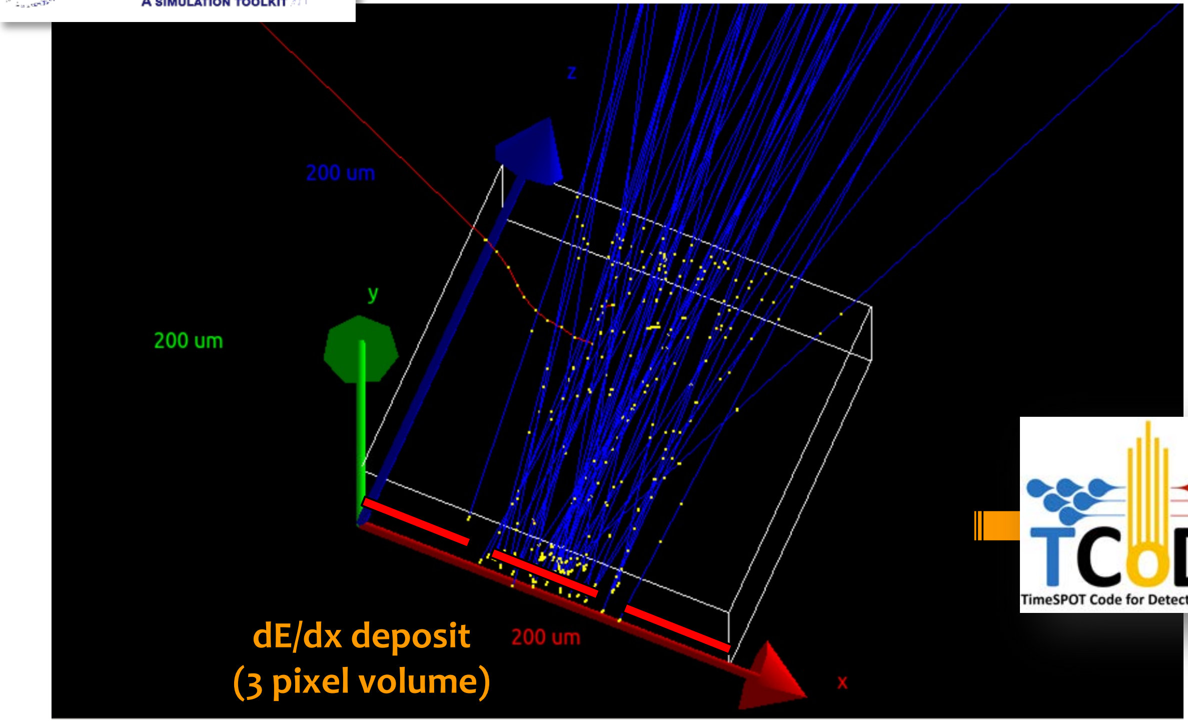
MIP deposit shape



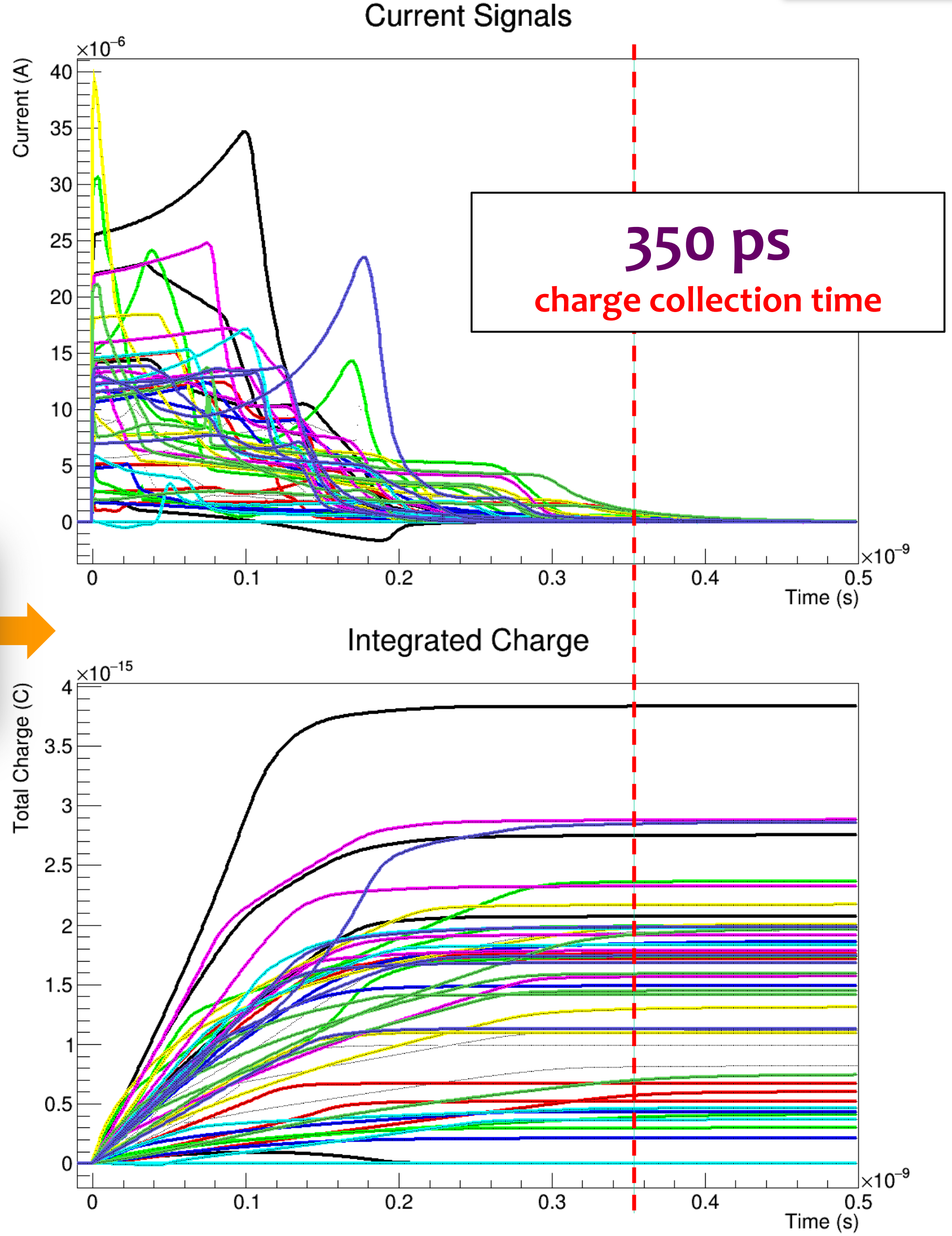
Examples of calculated energy deposit shapes **from laser sources** inside a TimeSPOT 3D-trench structure:

(a) Deposit with focus inside the active bulk.
(b) Deposit shape due to high absorption (655 nm wavelength)
(c) Deposit of IR laser source (1030 nm wavelength), emulating a MIP.

TCoDe operation and statistics



dE/dx deposit
(3 pixel volume)



350 ps
charge collection time

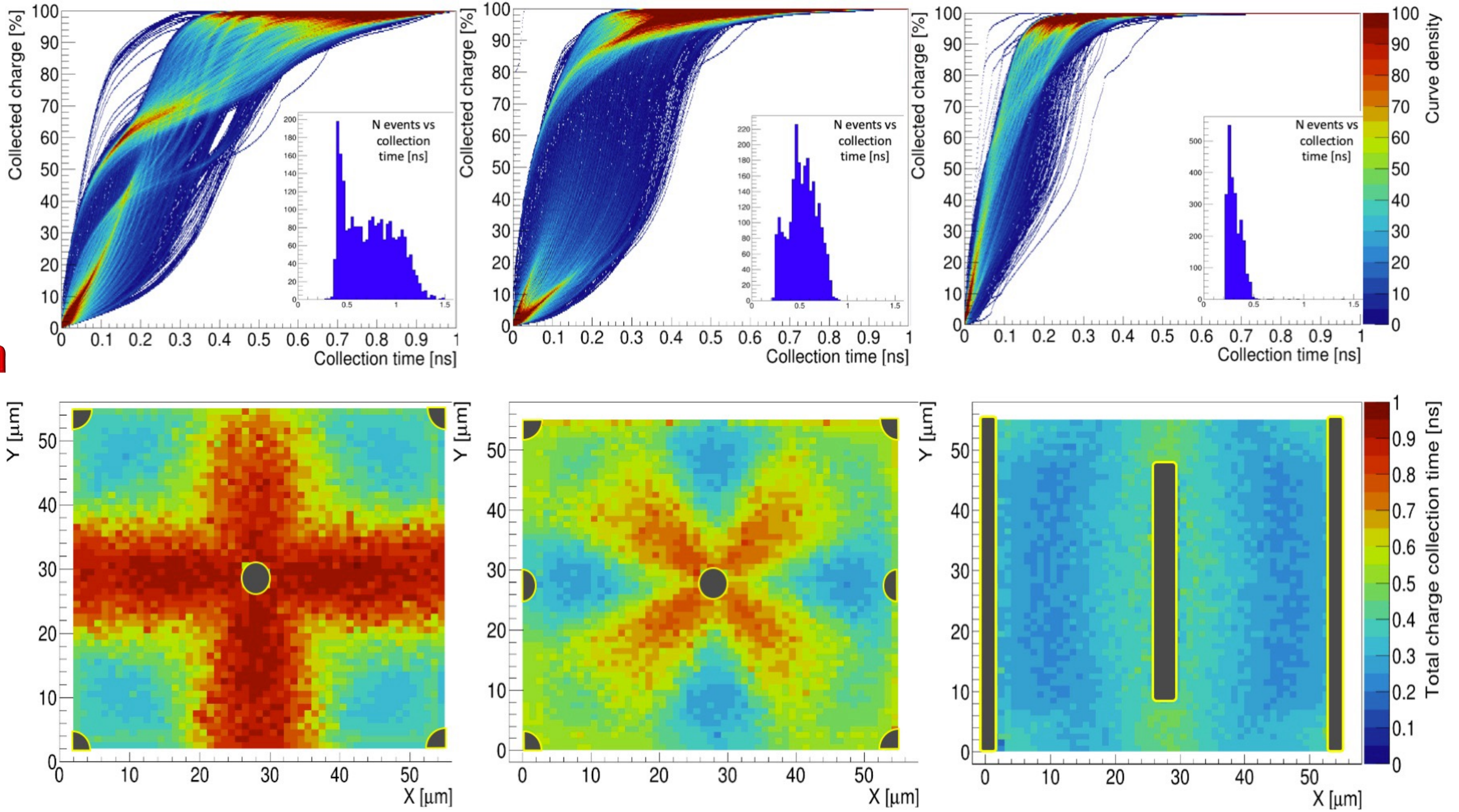
50 tracks
Induced current signals calculated by TCODE
(input to F/E electronics model)
1h40’ in ST (Intel®Xeon®CPU X5450 – 10 GB RAM)
1’40” on a gaming laptop in MT
2-3 months on TCAD (estimate)

A. Contu, A. Loi – INFN Cagliari

TimeSPOT results – A. Lai – 1st MONOLITH Wshop – UniGeneve, 5-6th September 2022

Charge Collection Time

Curves and maps



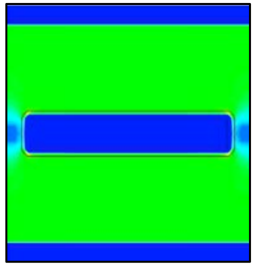
Time performance comparison among three different 3D geometries at V_{bias} = –100V (from left to right: five columns, nine columns and trench geometry). (Top) percentage of total charge collected on the electrodes versus time. (Top inserts) distribution of charge collection time for the three geometries. (Bottom) time for complete charge collection versus impact point for the same geometries. Each simulation is based on about 3 000 MIP tracks.

Sensor fabrication @ FBK

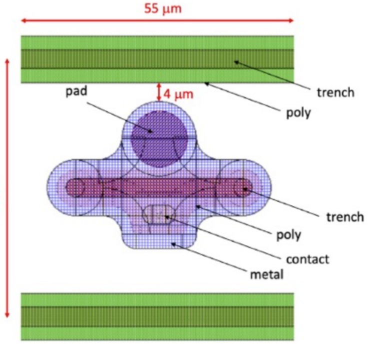
2 batches (2019 and 2020)

The optimal geometry

- 3D-trench
- 5 x 40 x 135 μm^3 trench
- 150 µm pixel depth



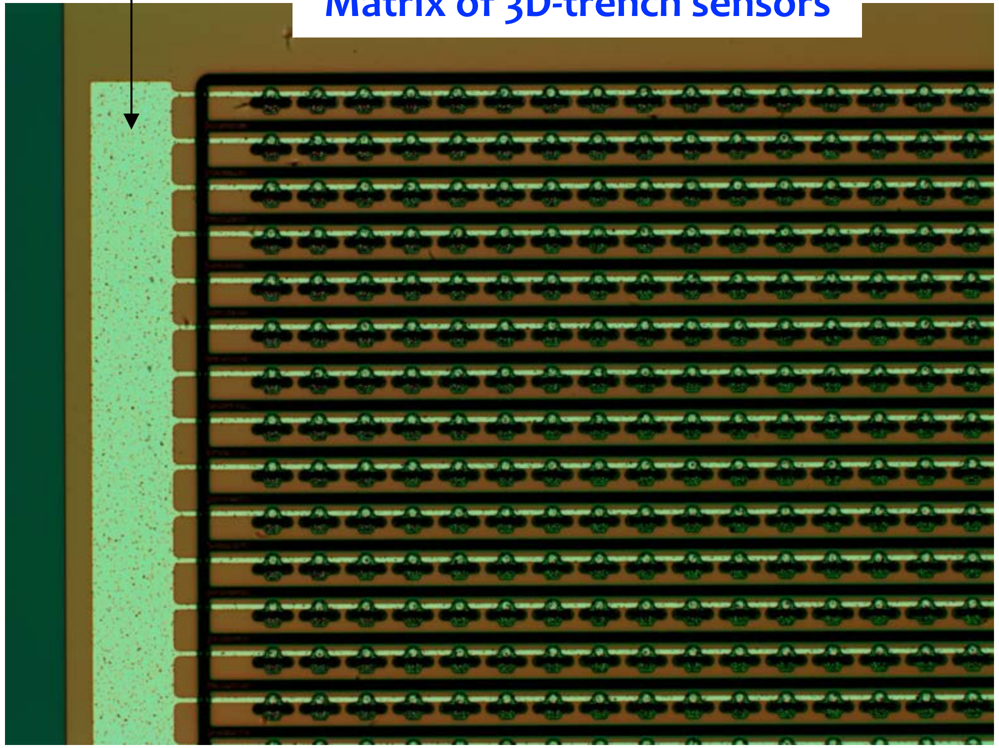
Pixel geometry



Pixel layout

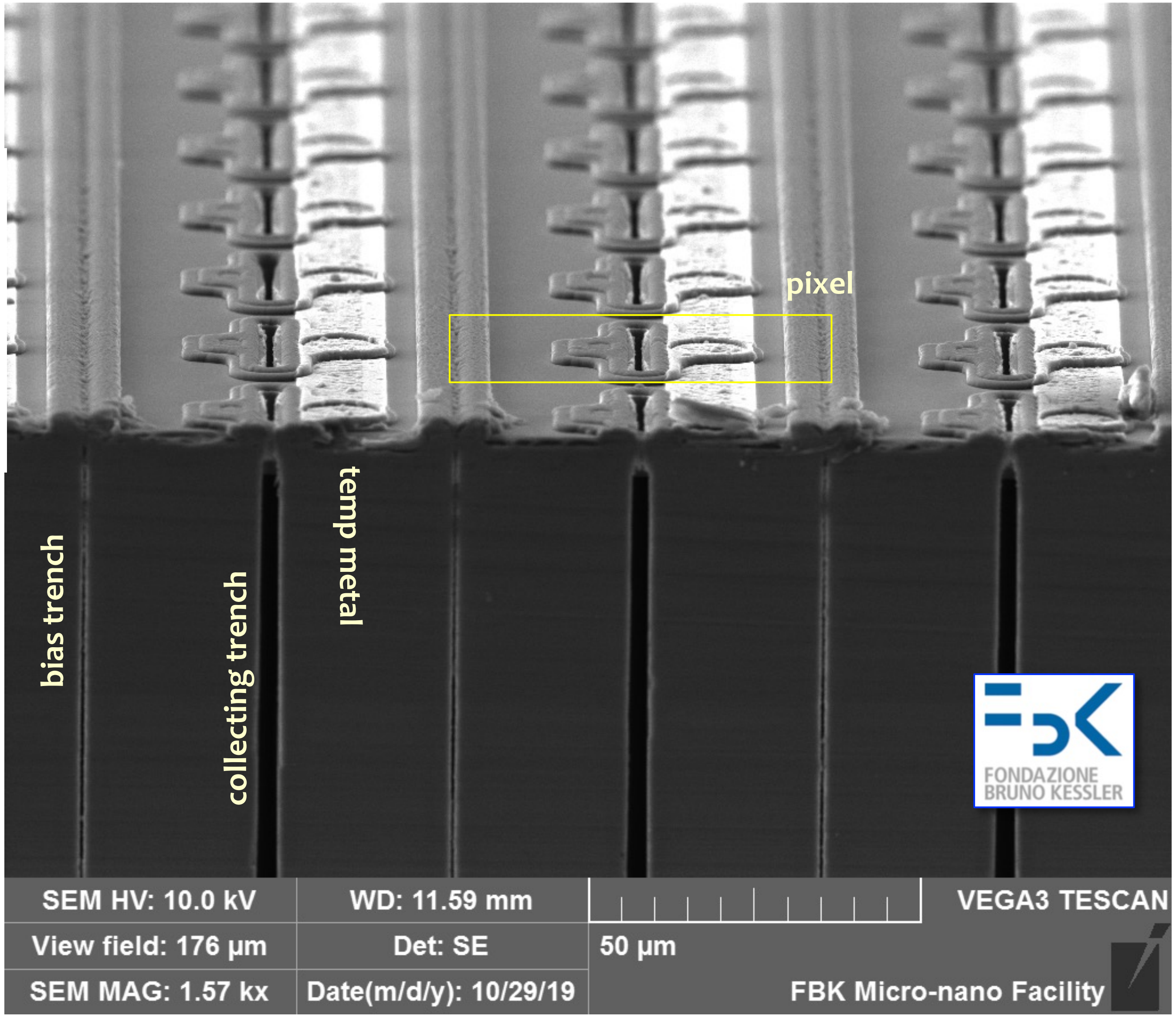
temp metal for static tests

Matrix of 3D-trench sensors



collecting trench

bias trench



Deep Reactive Ion Etching

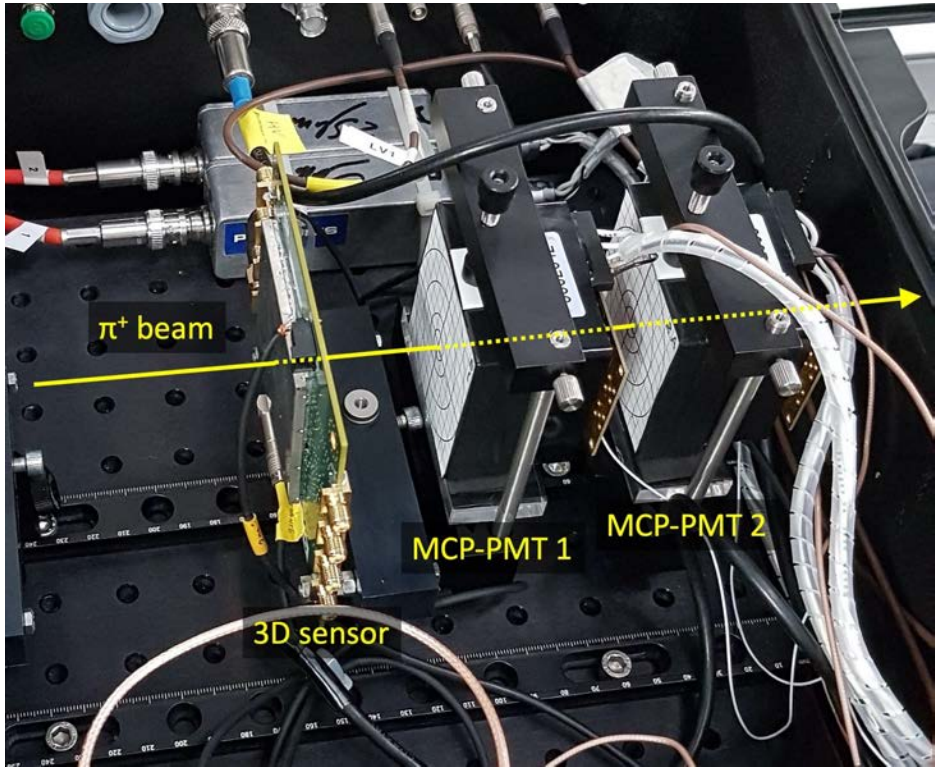
Bosch technology

(developed for MicroElectroMechanicalSystem technology)

First results on 3D-trench pixels at PSI (2019)

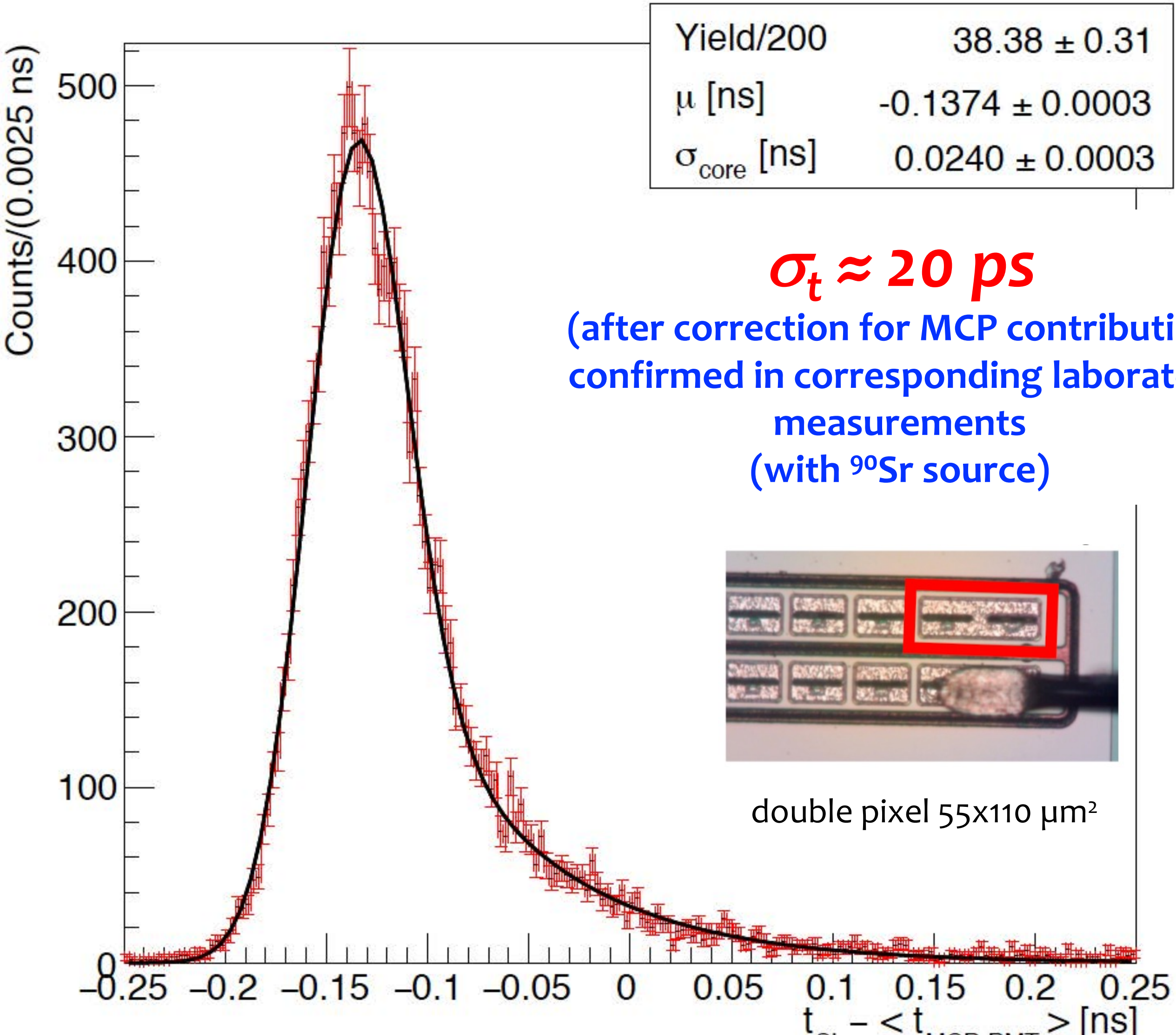
Time resolution of 3D-trench silicon pixels with MIPs (test-beam & lab) at room temperature

(ref. *Intrinsic time resolution of 3D-trench silicon pixels for charged particle detection*, 2020 JINST 15 P09029)



PSI πM1, π^+ beam, 270 MeV/c

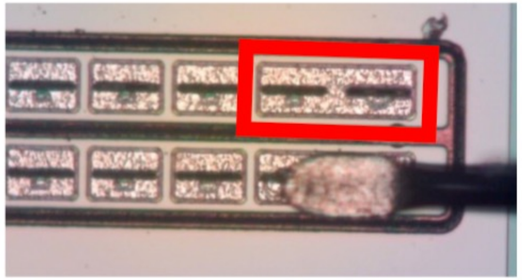
Fast but not optimised FE used



$\sigma_t \approx 20$ ps

(after correction for MCP contribution) confirmed in corresponding laboratory measurements (with ^{90}Sr source)

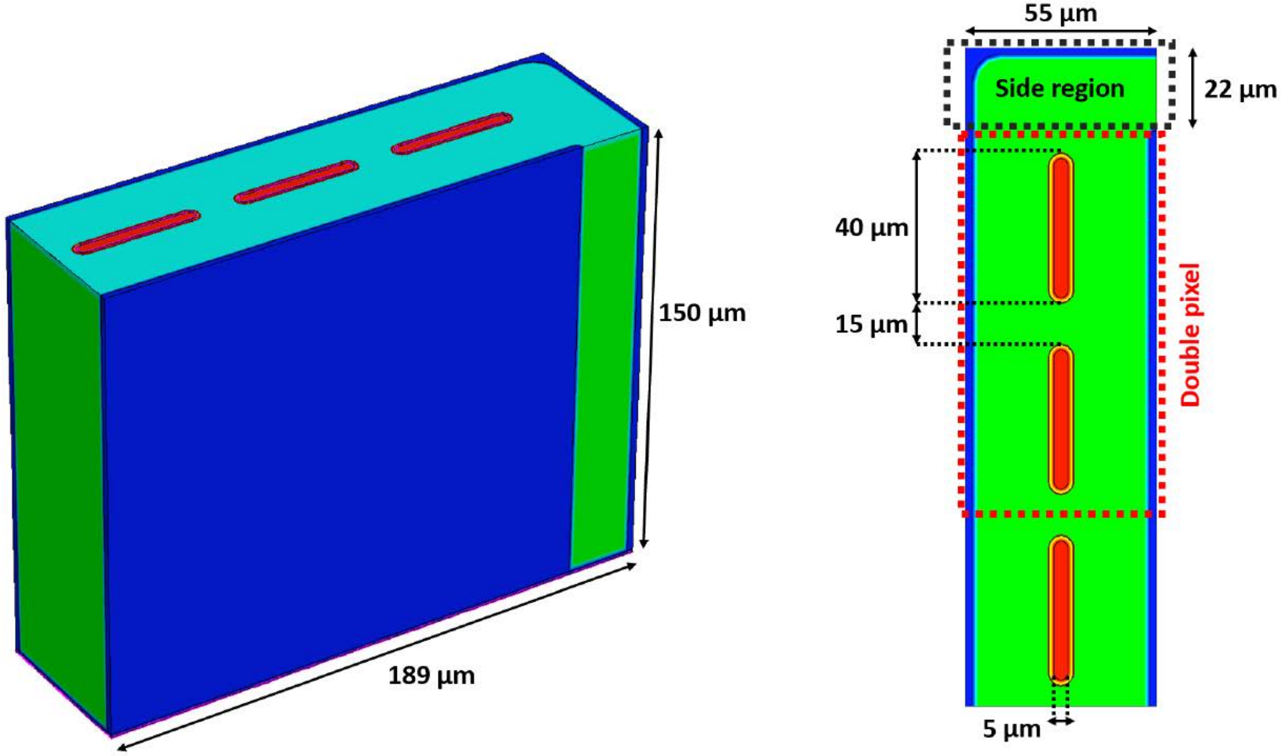
double pixel 55x110 μm²



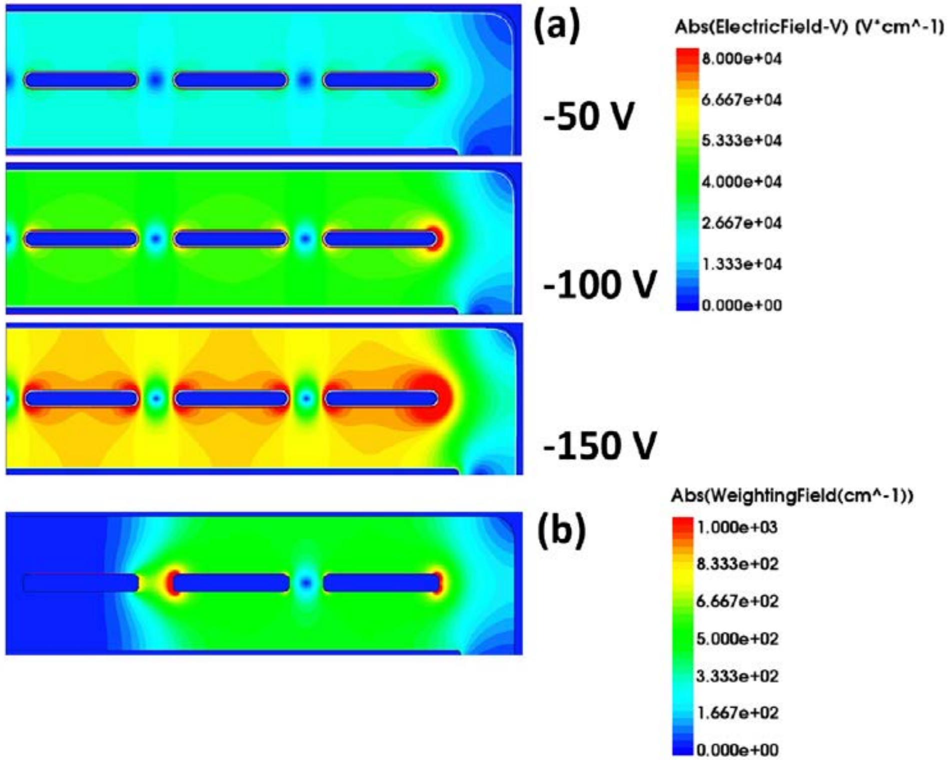
TCAD outputs

For detailed sensor charaterization

D. Brundu et al., *Accurate modelling of 3D-trench silicon sensor with enhanced timing performance and comparison with test beam measurements. JINST, 16, P09028*, 2021



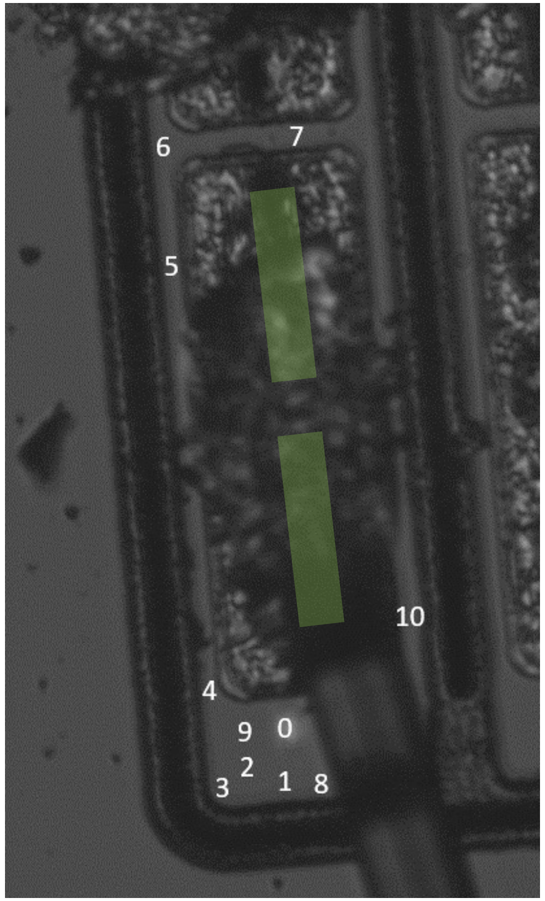
Layout of the simulated TimeSPOT test structure, including sections and sizes, designed using Sentaurus **TCAD**. The double pixel is indicated by the dotted-red line.



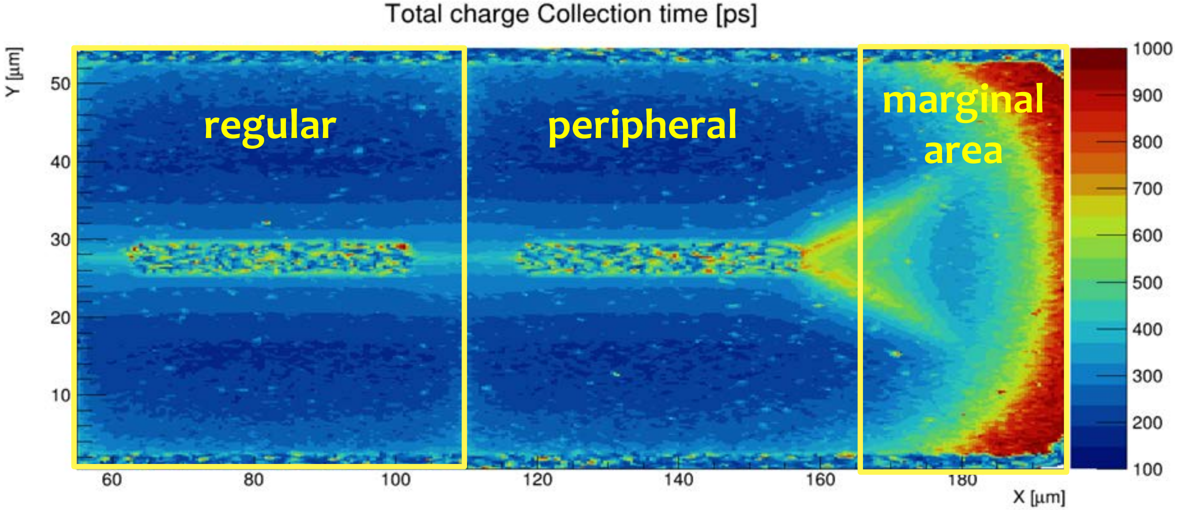
(a) Electric field amplitude at different bias voltages for the double-pixel test structure and
(b) weighting field

A virtual experiment on the DUT to identify tail contributions

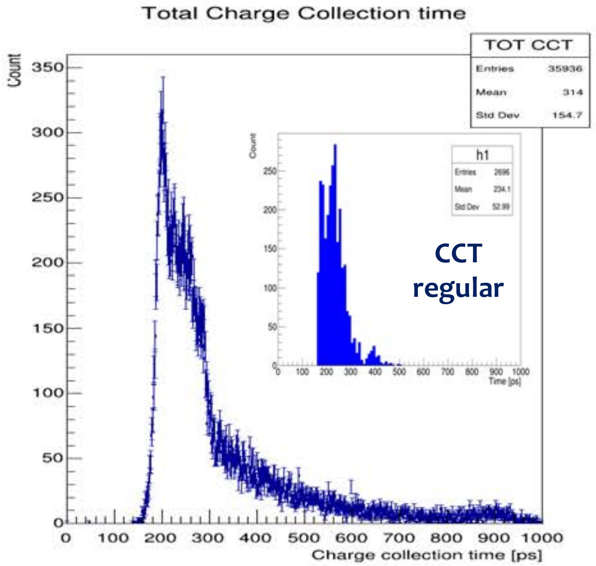
Charge Collection Time distributions from TCoDe



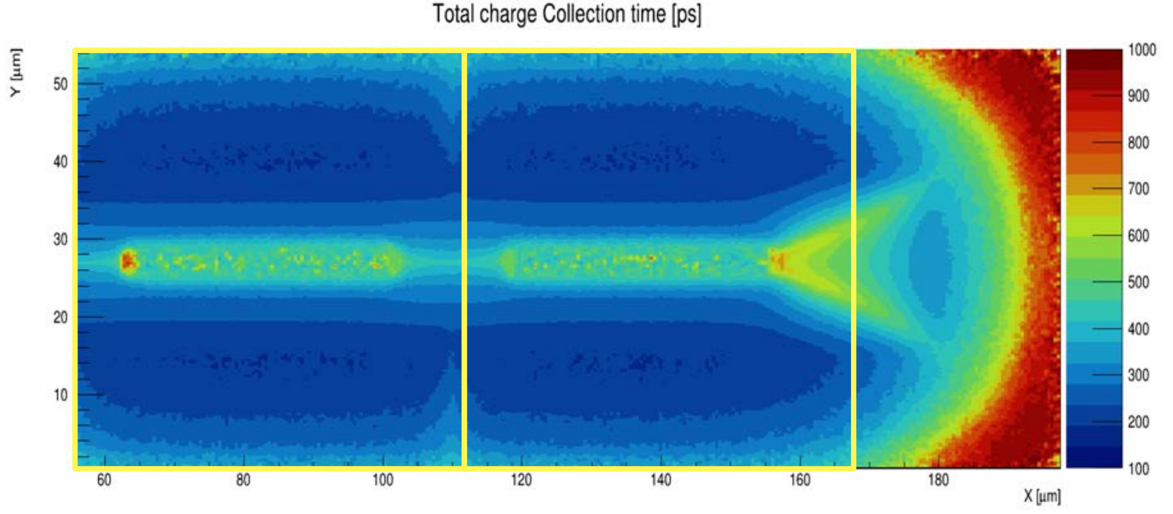
Double pixel structure under test @ PSI test-beam ($\sigma_t \approx 20$ ps + exponential tail)



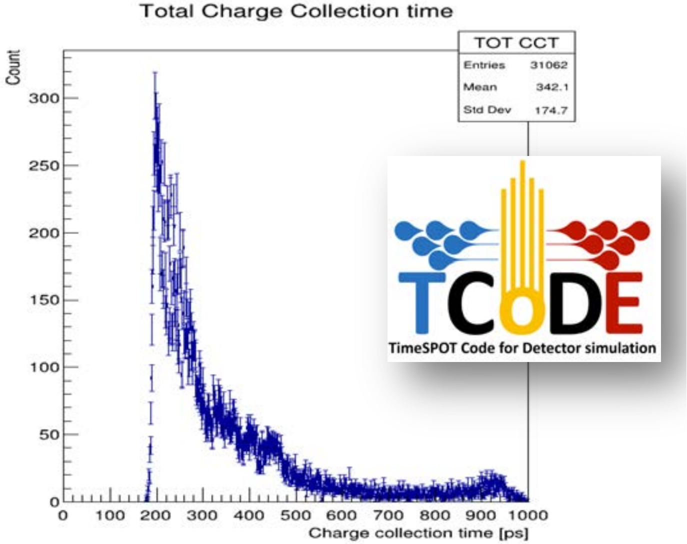
35k 270 MeV/c π^+ deposits **150 V bias**



A. Loi – INFN Cagliari



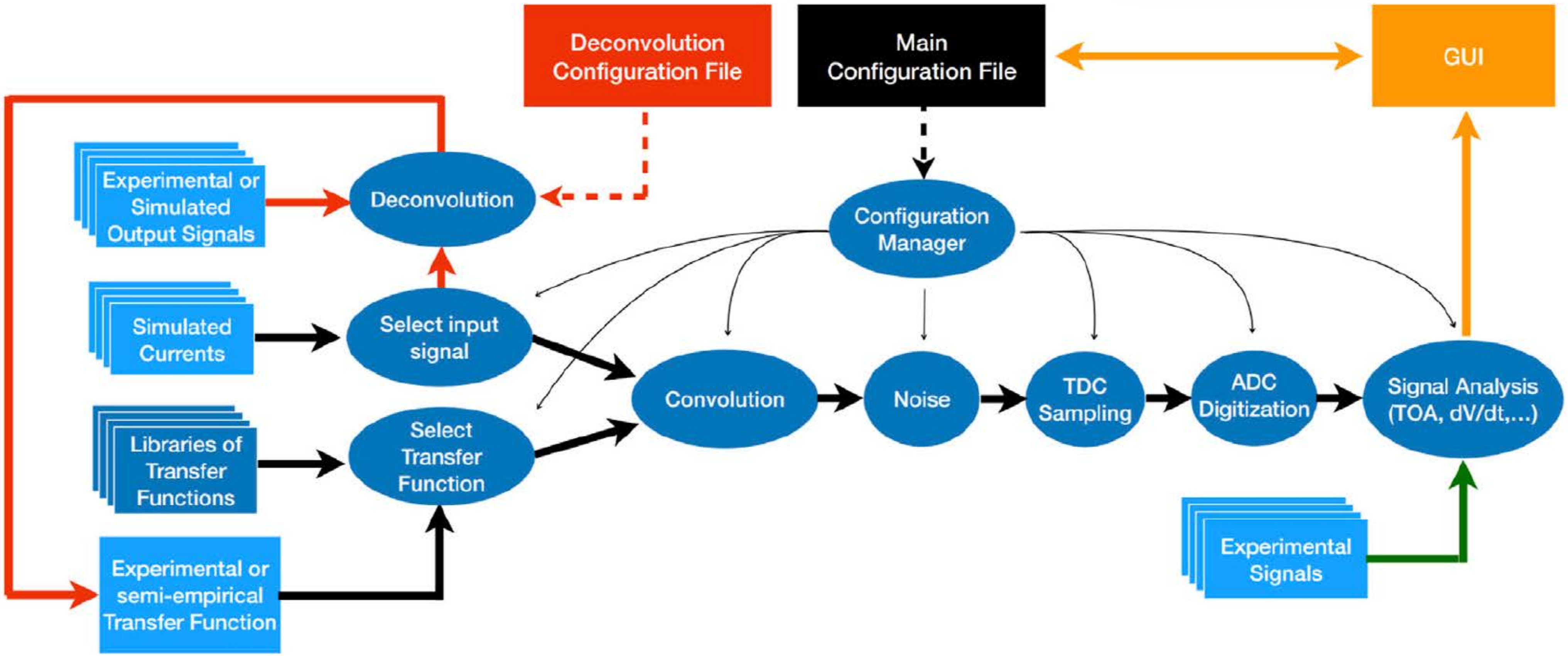
31k IR laser (MIP-like) deposits



Before convolution

F/E response? TFBoost!

TFBoost
TimeSPOT Front-end
Booster


Deconvolution Configuration File

Main Configuration File

GUI

Experimental or Simulated Output Signals

Deconvolution

Configuration Manager

Simulated Currents

Select input signal

Libraries of Transfer Functions

Select Transfer Function

Convolution

Noise

TDC Sampling

ADC Digitization

Signal Analysis (TOA, dV/dt,...)

Experimental Signals

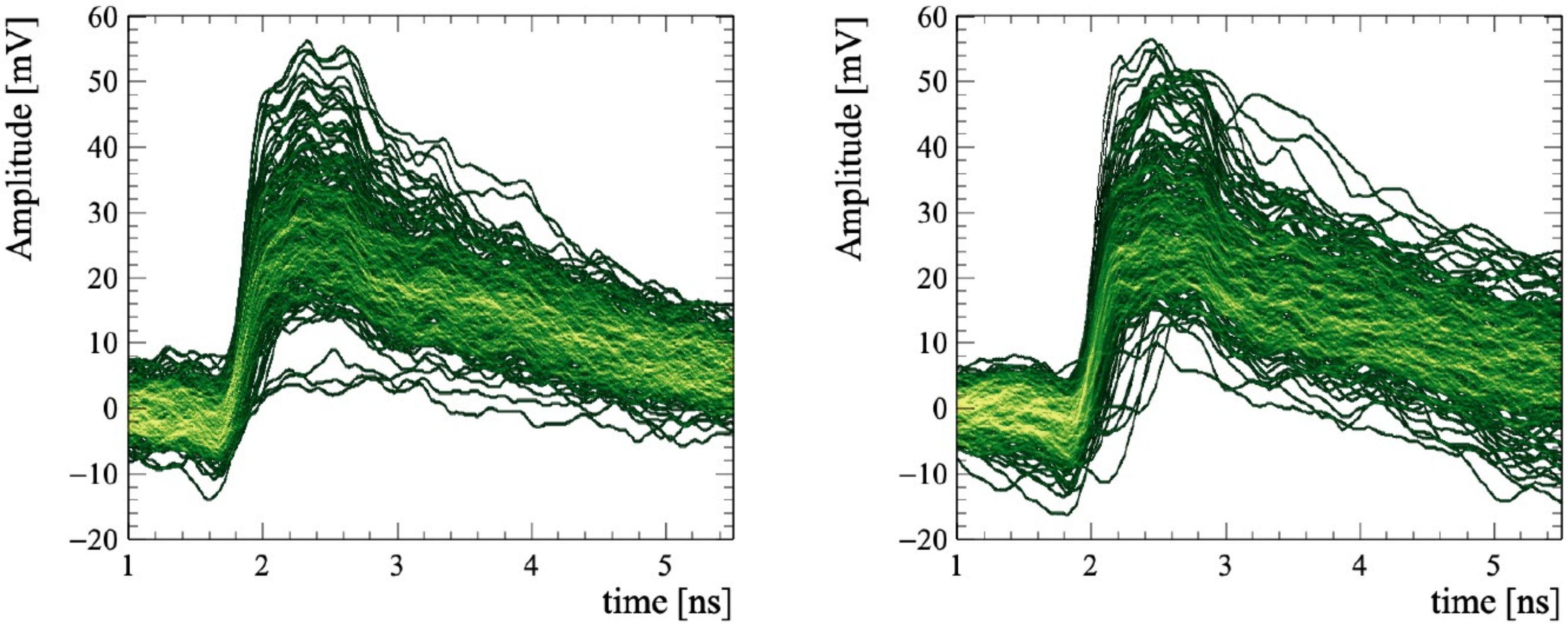
Experimental or semi-empirical Transfer Function

TFBoost simulations flow. The black path is the main simulation in which the convolution and the signal analysis are performed. The green path is followed if TFBoost is used as a pure signal analyzer, while the red path is followed to perform the deconvolution between an input current and an output signal.

Brundu D, et al. (2022) Modeling of Solid State Detectors Using Advanced Multi-Threading: The TCoDe and TFBoost Simulation Packages. Front. Phys. 10:804752.

Accurate re-analysis

And the origin of the tails: simulation outputs



Overlap of all silicon sensor waveforms (about 200) for (left) simulation and (right) test beam data

	V_{bias} [V]	Amp(P_{max}) [mV]	⟨S/N⟩	⟨N⟩ [mV]	rise time [ps]	dV/dt [mV/ns]
Simulation	−50	25.0	14.6	2.11	247	103
	−100	24.5	14.3	2.17	224	113
	−150	24.4	14.2	2.19	217	116
Data	−50	24.1	14.3	2.19	258	111
	−110	24.4	13.9	2.30	221	123
	−140	24.7	14.2	2.29	217	126

Maximum amplitude, average signal-to-noise ratio, noise, rise time (20–80%) and slew rate (dV/dt) of the 3D-trench silicon sensor response at different values of the bias for simulation and data.
The statistical uncertainties are below 1%.

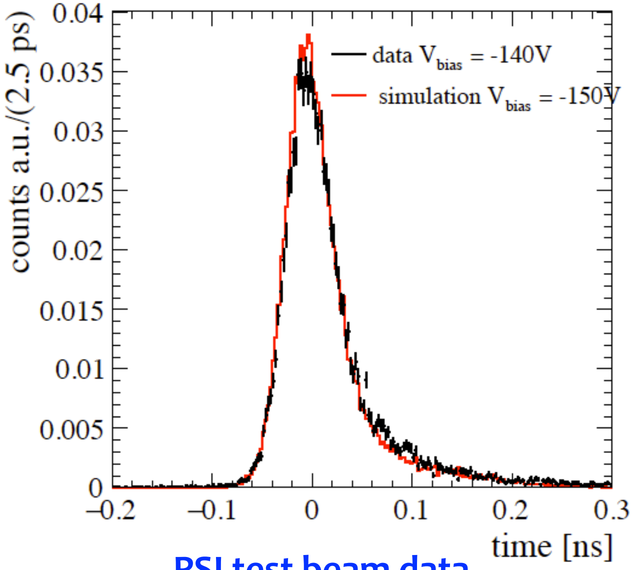
Brundu D, et al. Accurate Modelling of 3d-Trench Silicon Sensor with Enhanced Timing Performance and Comparison with Test Beam Measurements. J Inst (2021)16:P09028.

TimeSPOT results – A. Lai – 1st MONOLITH Wshop – UniGeneve, 5-6th September 2022

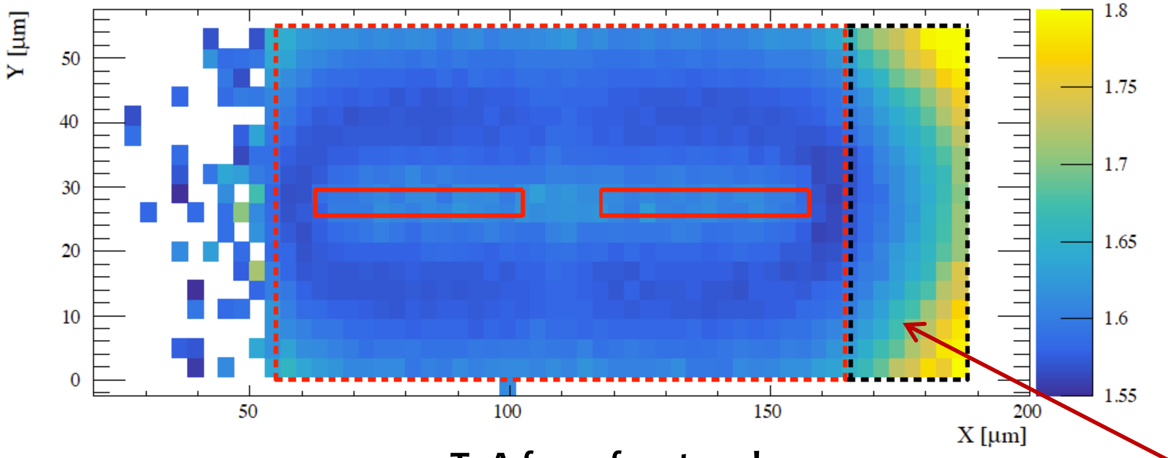
Final response about the slow tails

The very special case of the double pixel

D. Brundu et al., Accurate modelling of 3D-trench silicon sensor with enhanced timing performance and comparison with test beam measurements. *JINST, 16, P09028*, 2021

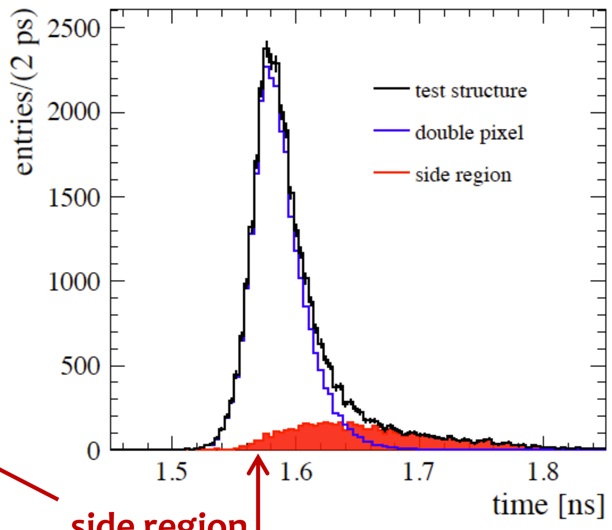


PSI test beam data



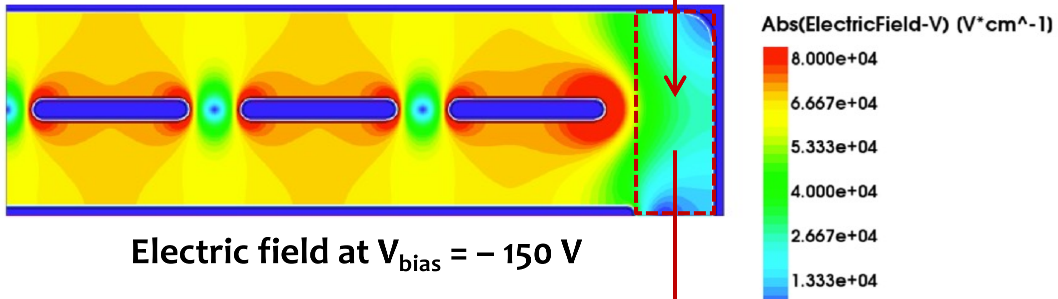
ToA from front-end

Simulated data

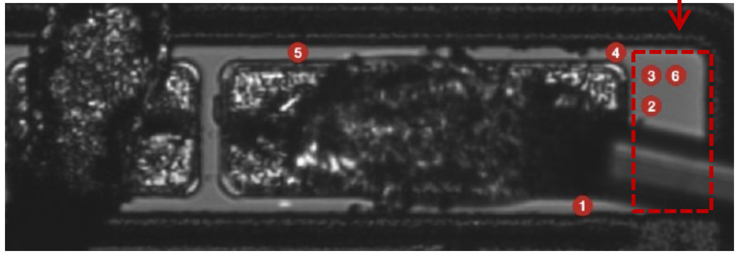


side region

Simulation			Measurement	
V_{bias} [V]	$\sigma_{intrinsic}$ [ps]	σ_t [ps]	V_{bias} [V]	σ_t [ps]
−50	9.6 ± 0.1	18.9 ± 0.2	−50	20.7 ± 0.3
−100	8.0 ± 0.1	16.7 ± 0.2	−110	19.8 ± 0.2
−150	7.0 ± 0.1	16.3 ± 0.2	−140	19.0 ± 0.2



Electric field at V_{bias} = – 150 V



Double pixel picture

Tails have been studied with very accurate pixel modeling, from the ionization process to the front-end output.
A clear assignation of the tail contribution was done to the (out)side region of the pixel (outside the nominal pixel area in this particular case).
As a by-product, simulations clearly indicate a better intrinsic performance of the sensor

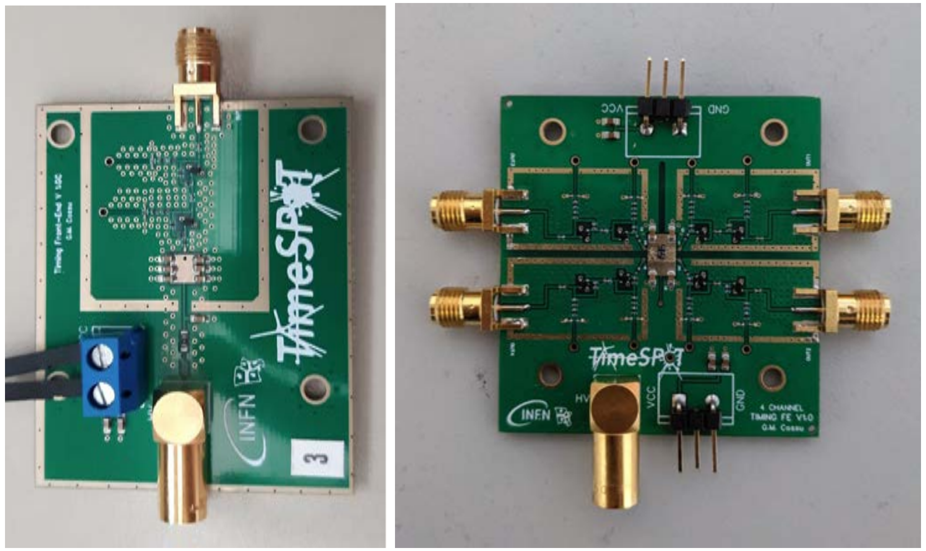
Measurements at test beams and 3D-trench sensor characterization

Latest results

Test-beams Nov21 & May22 @SPS/H8

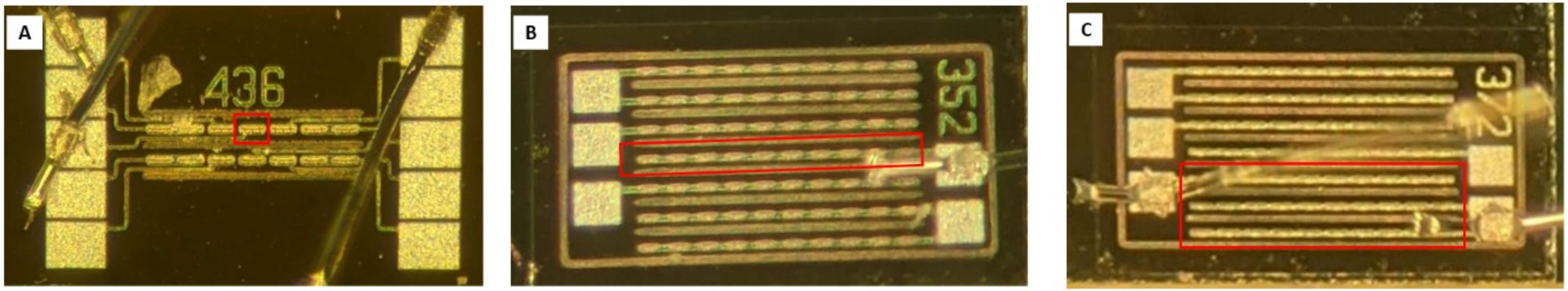
New faster dedicated front-end electronics

Si-Ge input stages $t_r \approx$ 100 ps. Measured *jitter* < 7 ps @ 2 fC
≈ 70 mW/channel



1. **Not-irradiated:**
   - **Landau distributions vs V_{bias}**
   - **Time resolution**
   - **Geometrical efficiency vs tilt angle**
   - **Time resolution vs tilt angle**
2. **Same with samples irradiated @ $\Phi = 2.5\ 10^{16}$ 1-MeV-n/cm²**
3. **First studies on charge sharing**

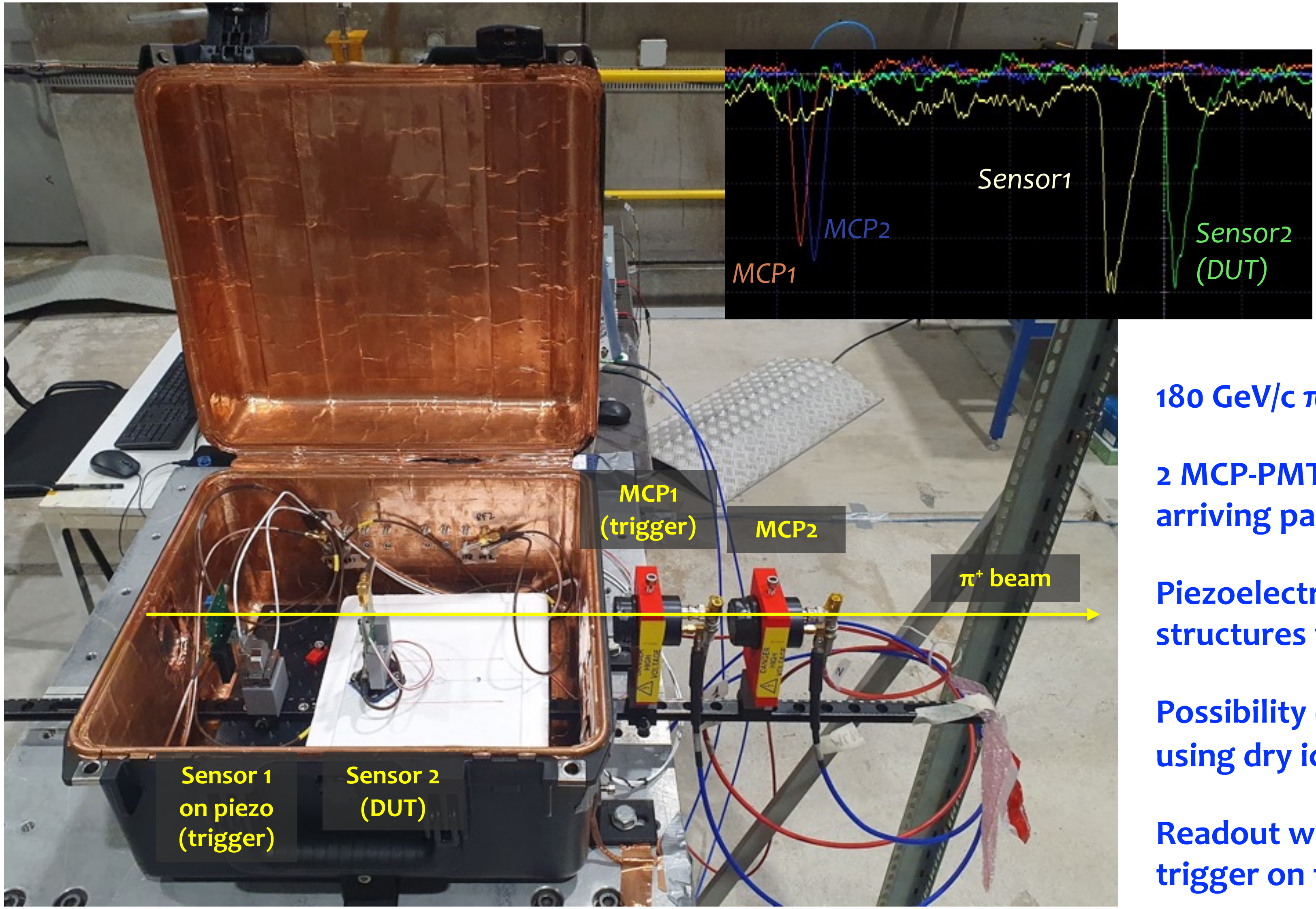
Tested structures. For each sensor the active area is shown in red.
(A) Single pixels sensor; (B) strip sensor; (C) triple strip sensor



Paper in preparation: *"New results on the TimeSPOT 3D-silicon sensors from measurements at SPS"* (Frontiers in Physics)

Experimental setup

Test-beams Nov21 & May22 @SPS/H8



180 GeV/c π^+ beam

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

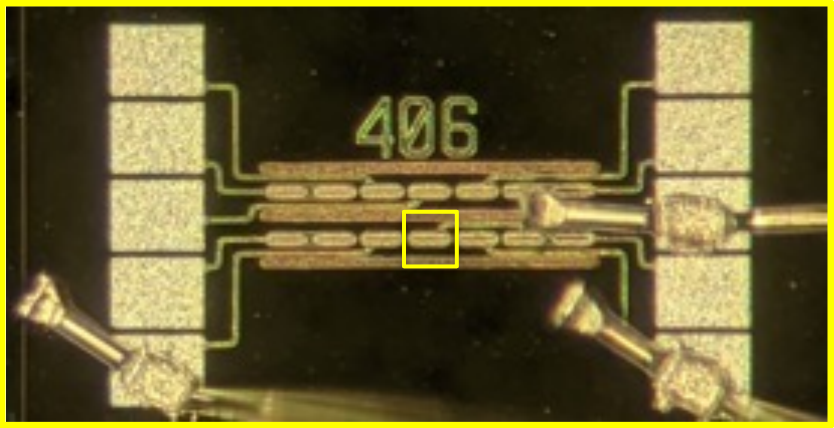
Piezoelectric stages to precisely align the two 3D structures with beam, all mounted in a RF-shielded box

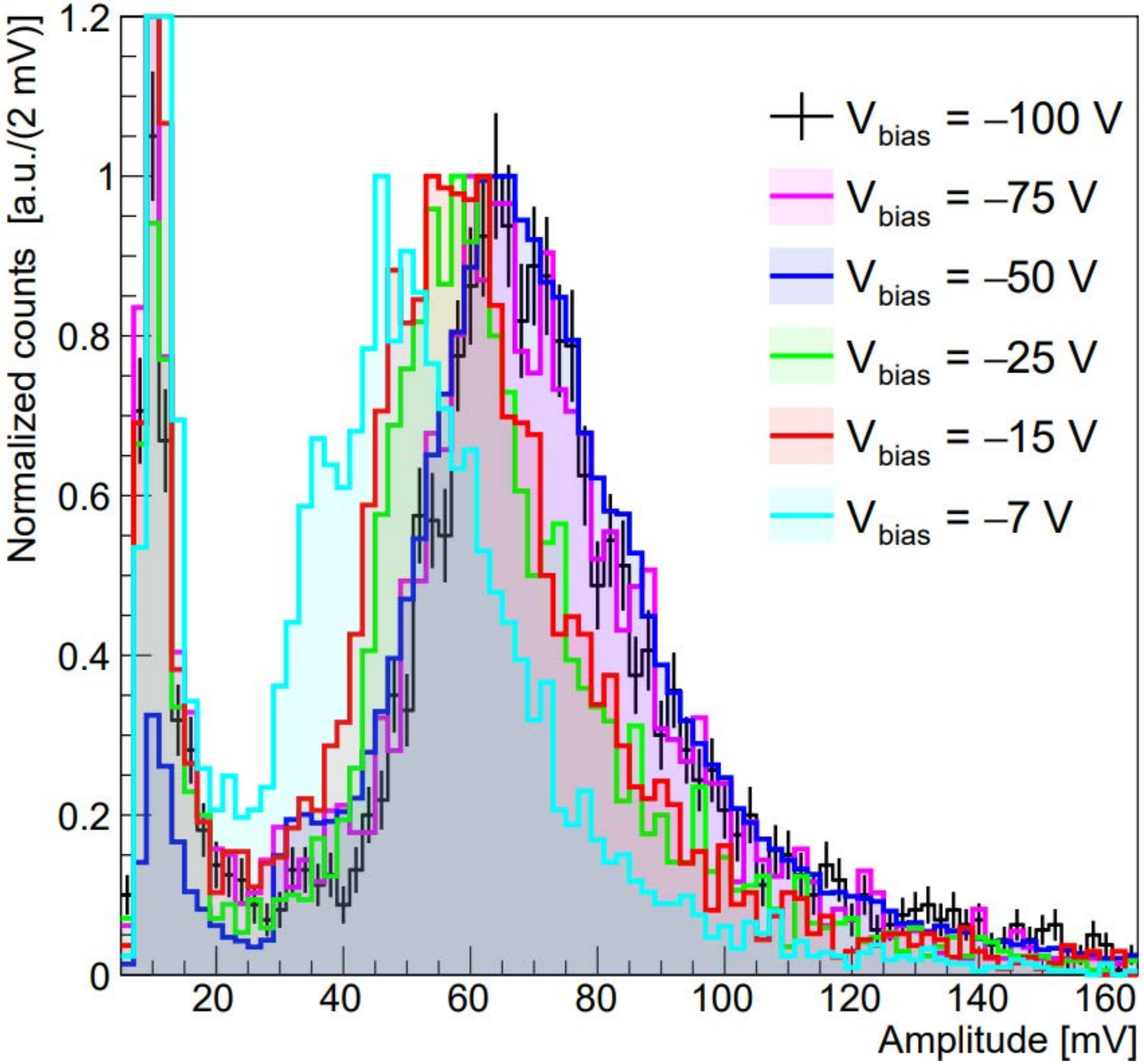
Possibility of operating the fixed sensor down to -40°C using dry ice to test irradiated sensors

Readout with an 8 GHz bandwidth 20 GSa/s scope: trigger on the AND of one 3D sensor and one MCP-PMT

Amplitude distributions vs bias

Single pixel, not irradiated





Normal pion incidence ($\alpha_{tilt} = 0^o$)

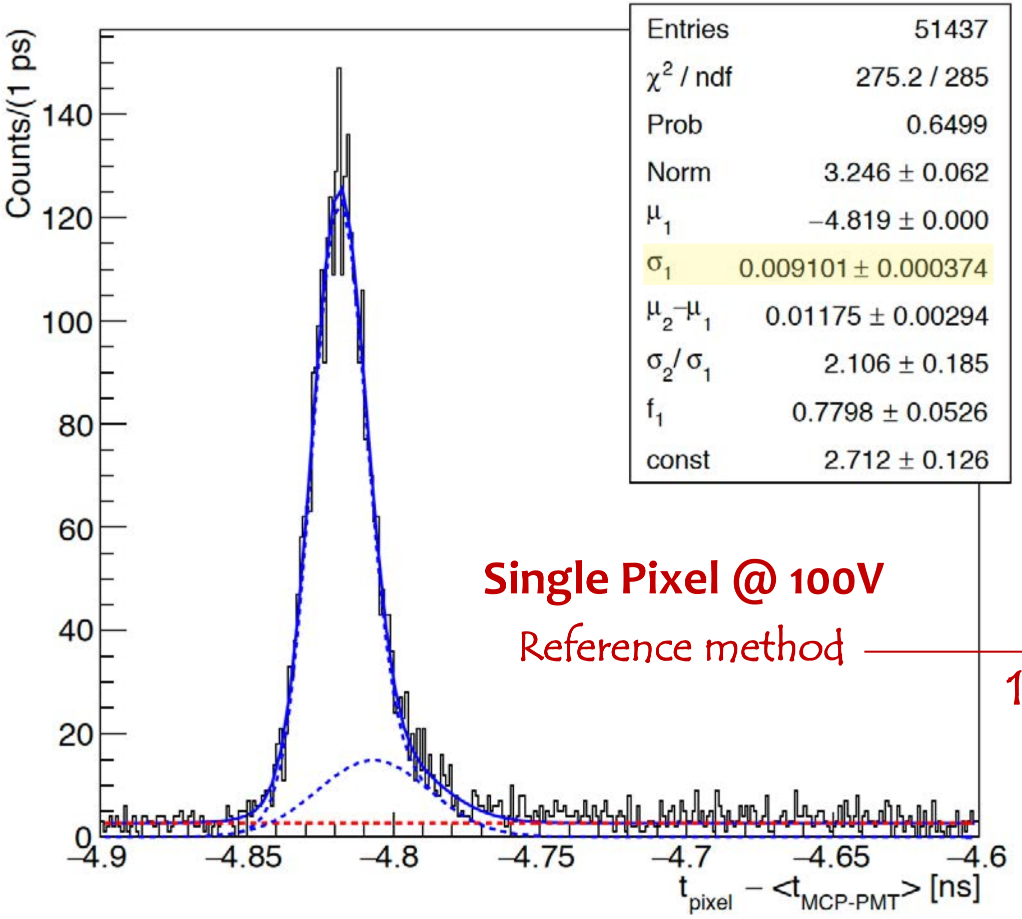
DUT not on the trigger

Very good sensor performance even at **low V_{bias}** (prompt full depletion)

Timing measurements

(single pixel @ α_{tilt} = 0°, not irrad.) SPS/H8 (Nov'21)

LE: Leading edge, NO ToT correction
LE: Leading edge, ToT correction
Spline: Classic CFD
Reference: Differentiation + CFD



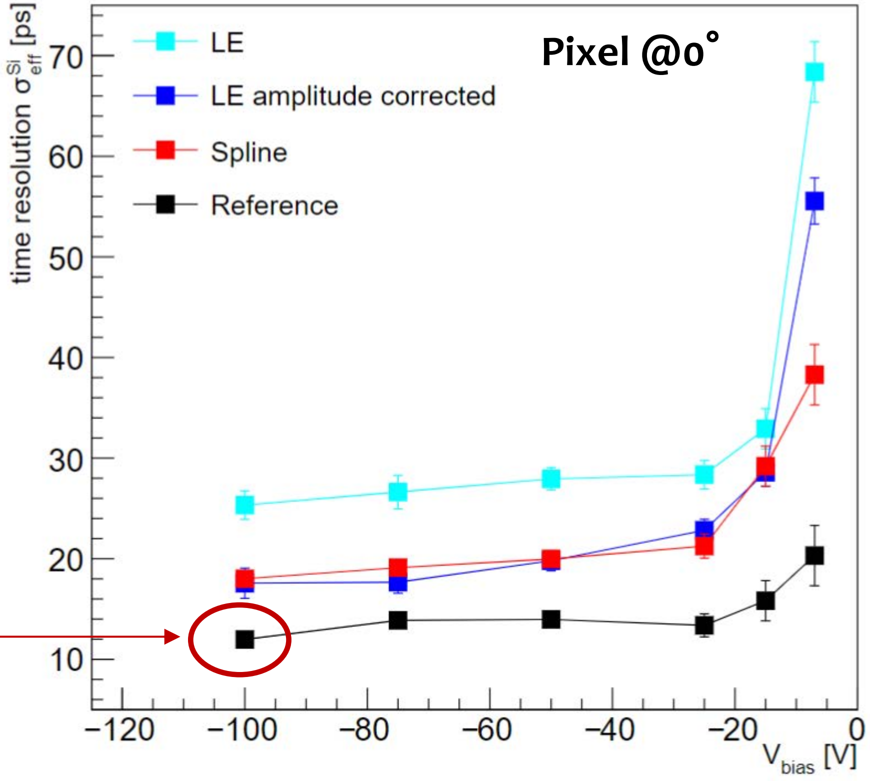
Entries	51437
χ^2 / ndf	275.2 / 285
Prob	0.6499
Norm	3.246 ± 0.062
μ_1	−4.819 ± 0.000
σ_1	0.009101 ± 0.000374
$\mu_2-\mu_1$	0.01175 ± 0.00294
σ_2/σ_1	2.106 ± 0.185
f_1	0.7798 ± 0.0526
const	2.712 ± 0.126

Single Pixel @ 100V

Reference method

σ_t^{eff}

11.5 ps



Distribution of the difference between the TOA of the single pixel and the time reference, $t_{pixel} - \langle t_{MCP-PMT} \rangle$, for the single pixel perpendicular to the beam at V_{bias} = −100 V with the reference method. The distribution is fit with the sum of two Gaussian functions (blue dashed lines) describing the signal, and a constant (red dashed line) modelling the background.

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

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

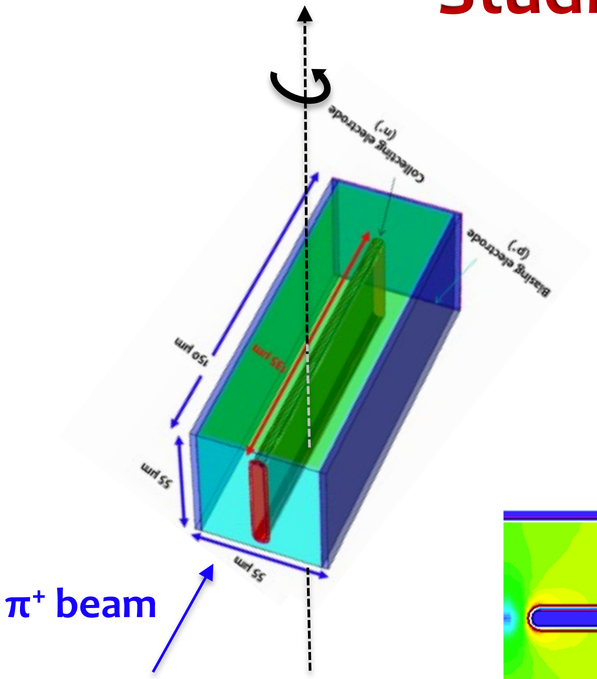
$$\mu = f_1 \mu_1 + (1 - f_1) \cdot \mu_2$$

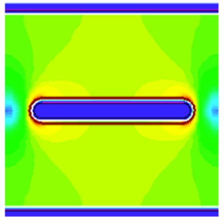
σ_t^{eff} **takes into account the two-Gaussian behaviour**

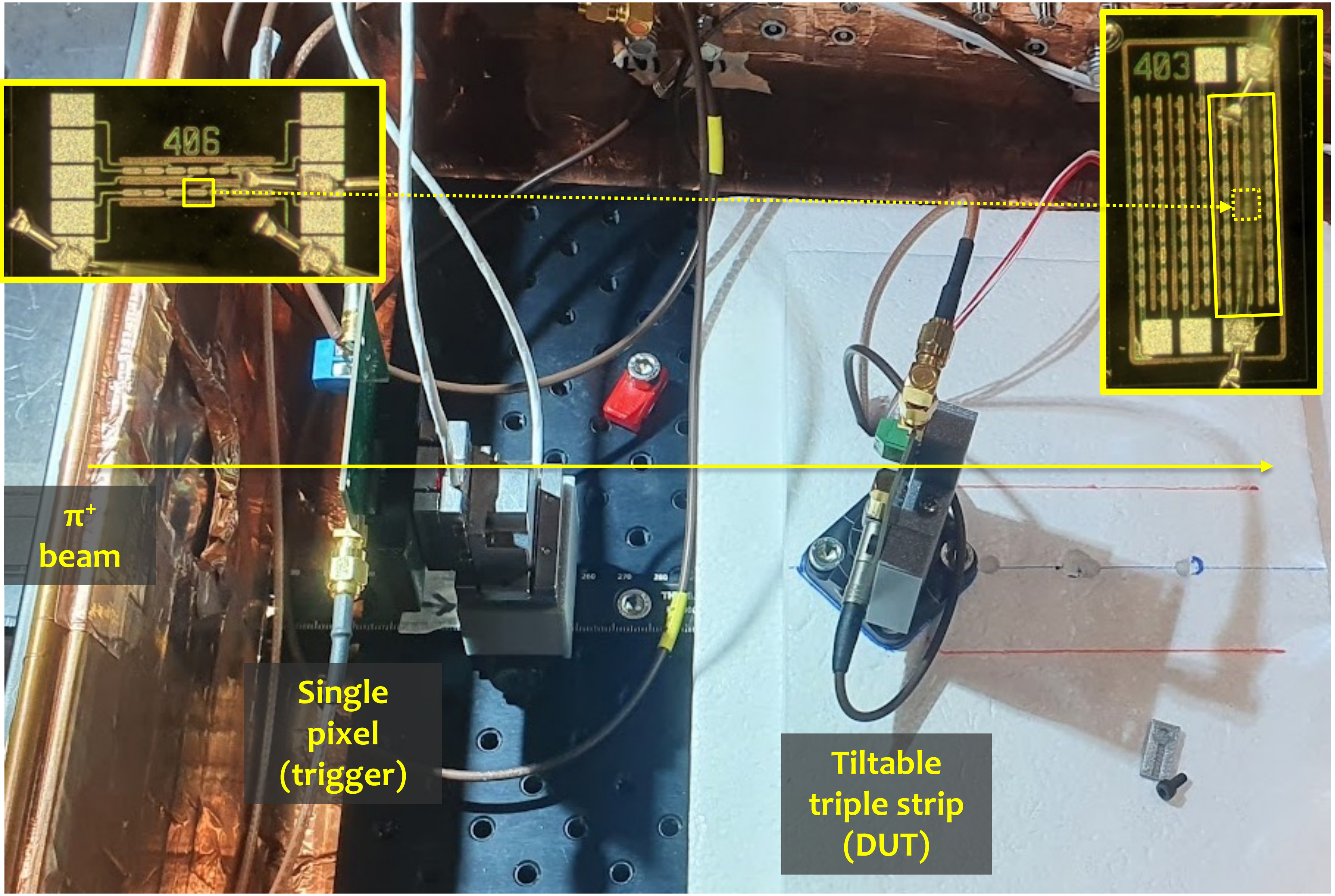
Paper to be submitted soon to Frontiers in Physics:
"New results on the TimeSPOT 3D-silicon sensors from measurements at SPS"

Studies of Geometric Efficiency: setup

Single pixel, not irradiated





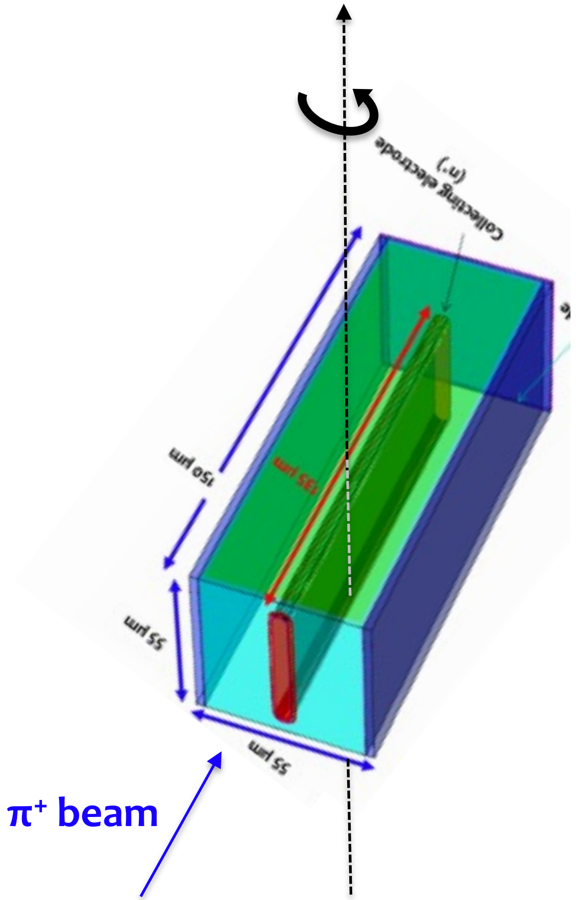


Tilting the sensors with respect to normal incidence should allow **to recover geometric efficiency**

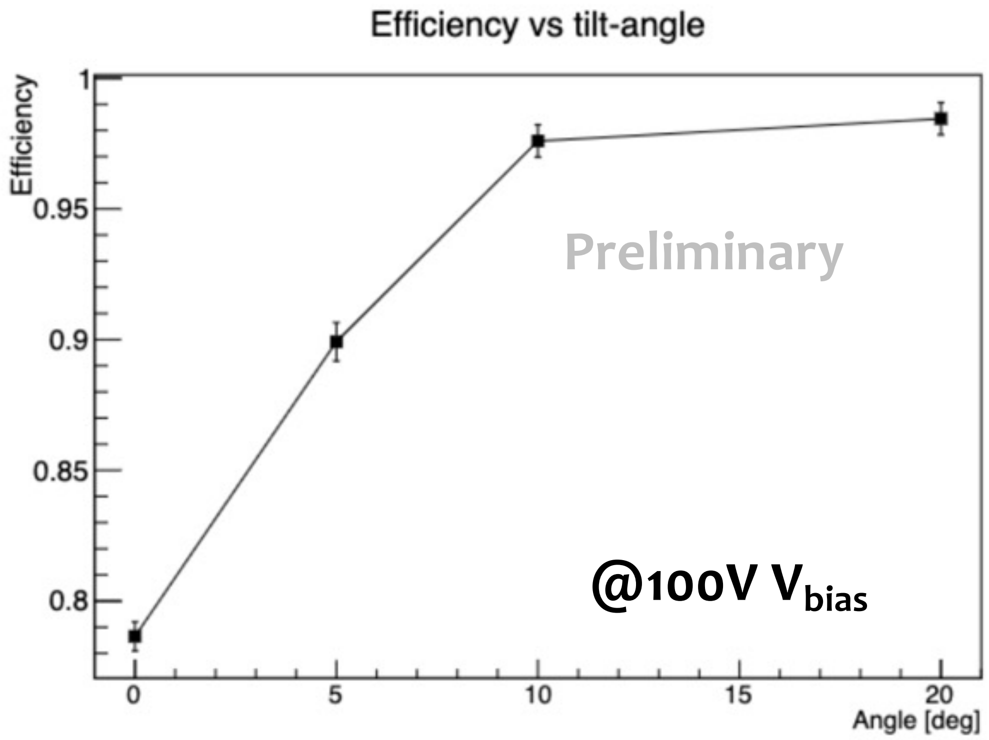
Trigger on one pixel (55 µm x 55 µm, on piezos) centered on a triple strip (165 µm x 550 µm, DUT) and **counting the fraction of signals seen in the triple strip** (on a single FE channel)

The DUT is rotated around the trench direction

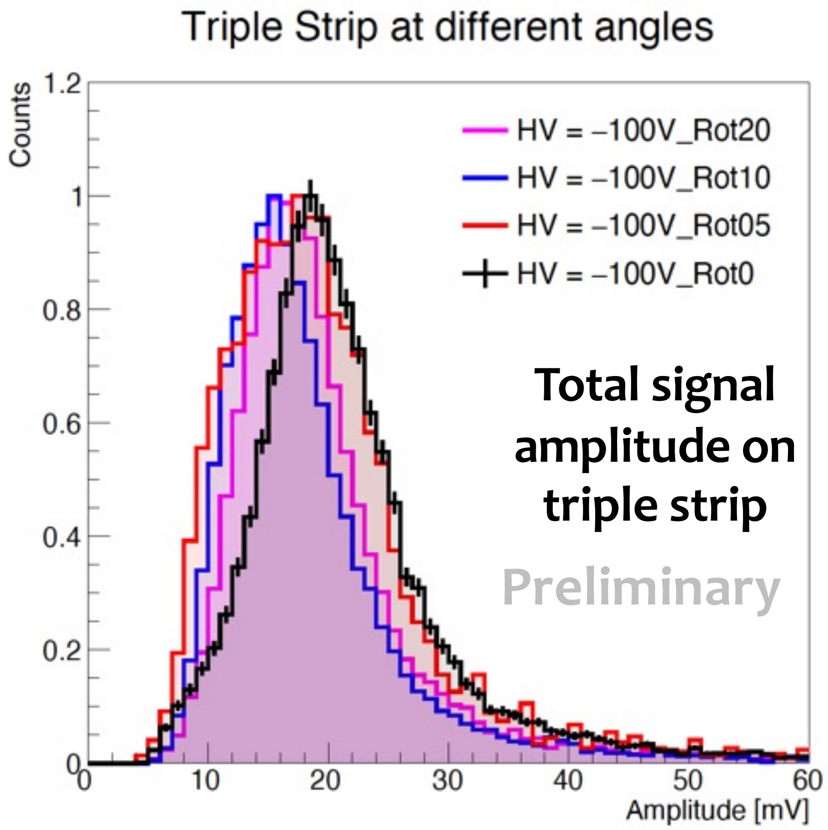
Efficiency: results



π^+ beam



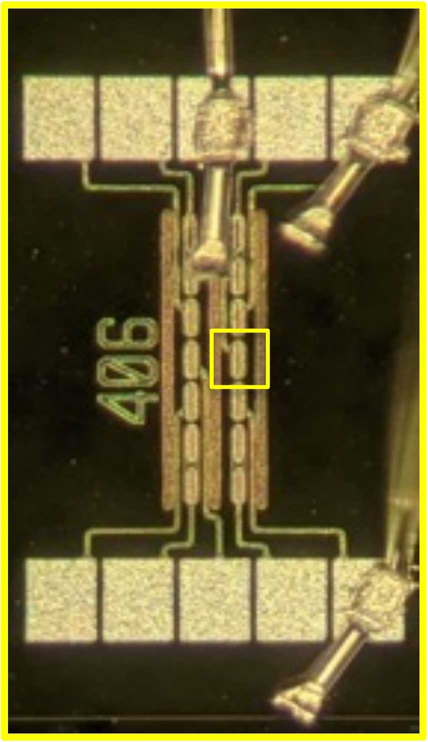
@100V V_{bias}

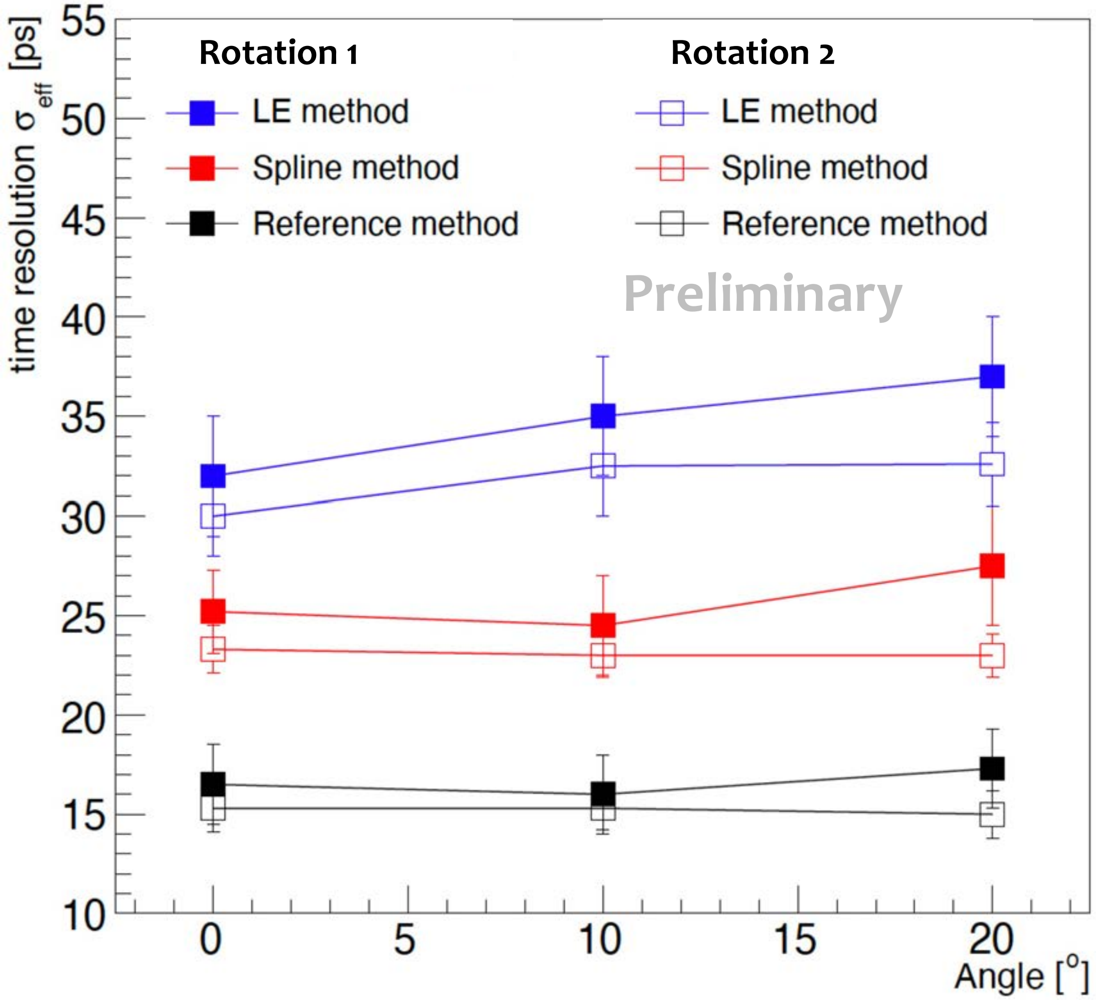


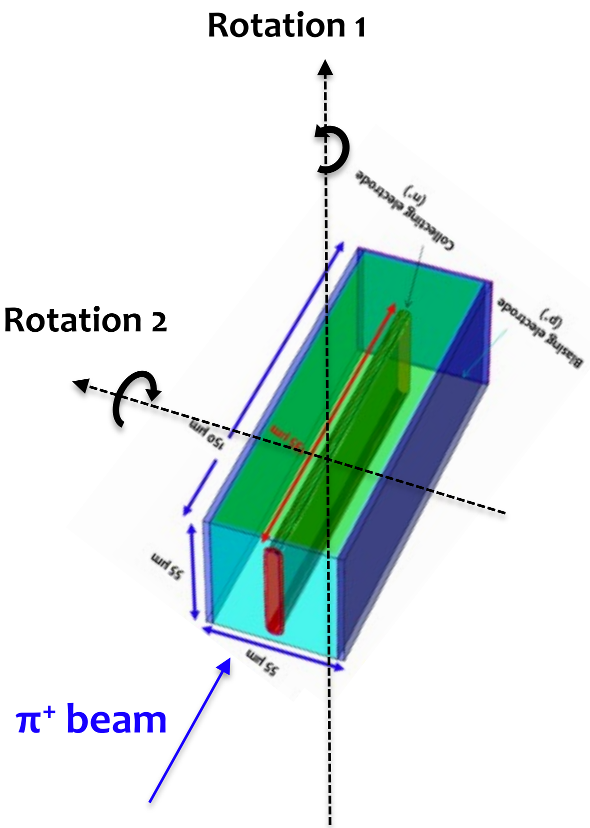
Total signal amplitude on triple strip

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 performance





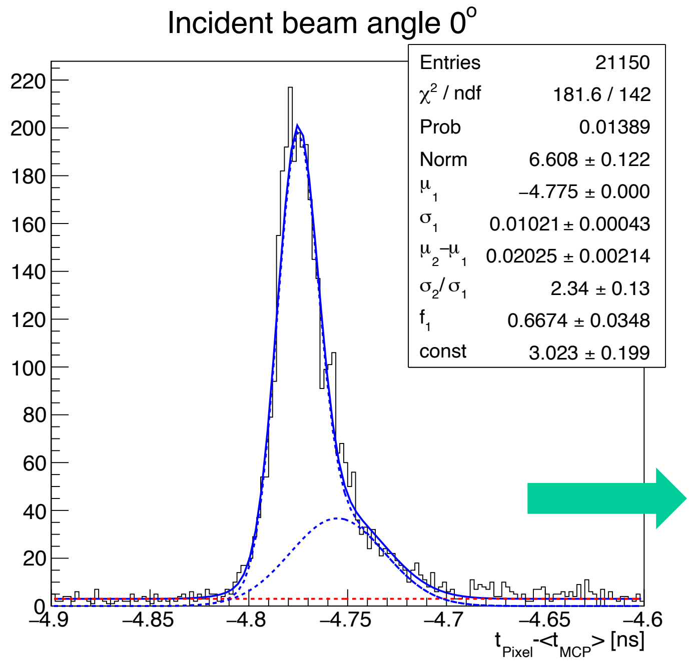


Single Pixel @ 50V

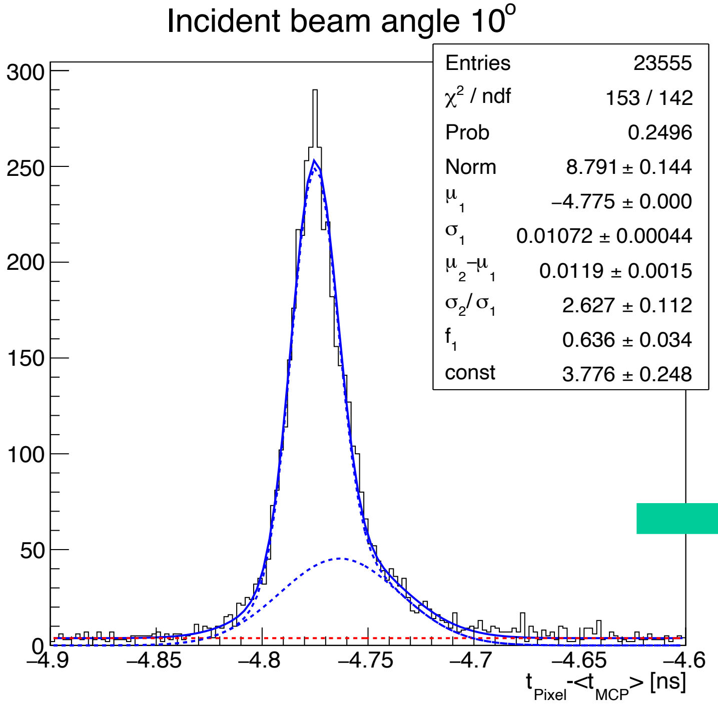
Effect of tilting on distribution shapes

Spline method, SPS/H8 (Nov'21)

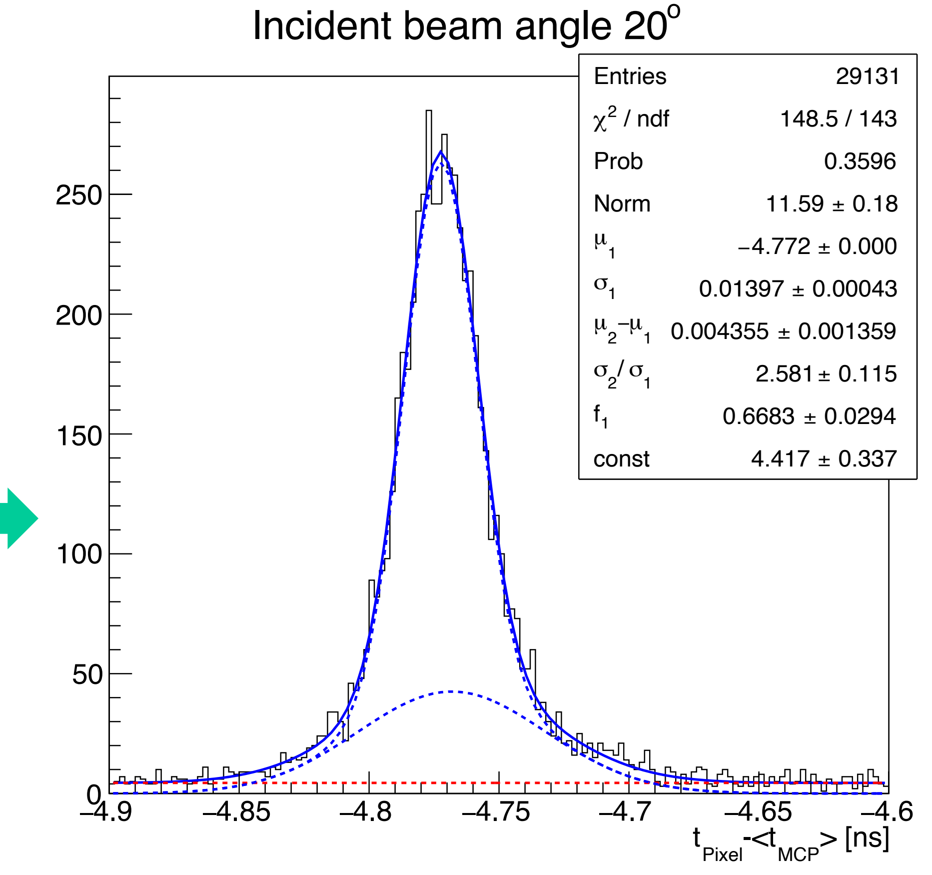
Single Pixel @ 50V


Incident beam angle 0°

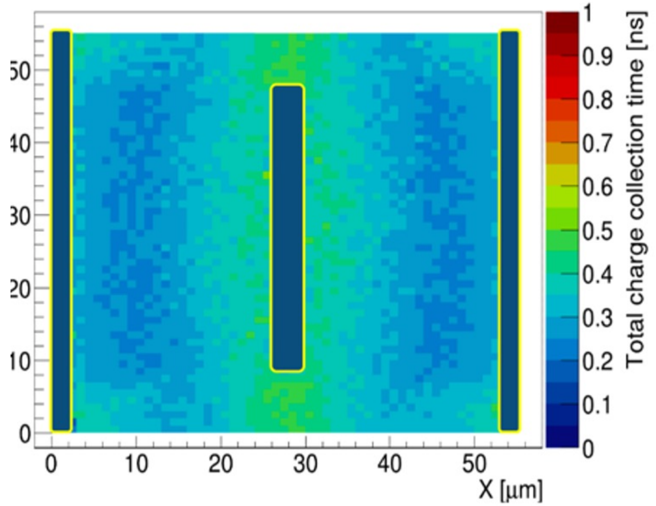
Entries	21150
χ^2 / ndf	181.6 / 142
Prob	0.01389
Norm	6.608 ± 0.122
μ_1	−4.775 ± 0.000
σ_1	0.01021 ± 0.00043
$\mu_2-\mu_1$	0.02025 ± 0.00214
σ_2/σ_1	2.34 ± 0.13
f_1	0.6674 ± 0.0348
const	3.023 ± 0.199


Incident beam angle 10°

Entries	23555
χ^2 / ndf	153 / 142
Prob	0.2496
Norm	8.791 ± 0.144
μ_1	−4.775 ± 0.000
σ_1	0.01072 ± 0.00044
$\mu_2-\mu_1$	0.0119 ± 0.0015
σ_2/σ_1	2.627 ± 0.112
f_1	0.636 ± 0.034
const	3.776 ± 0.248


Incident beam angle 20°

Entries	29131
χ^2 / ndf	148.5 / 143
Prob	0.3596
Norm	11.59 ± 0.18
μ_1	−4.772 ± 0.000
σ_1	0.01397 ± 0.00043
$\mu_2-\mu_1$	0.004355 ± 0.001359
σ_2/σ_1	2.581 ± 0.115
f_1	0.6683 ± 0.0294
const	4.417 ± 0.337

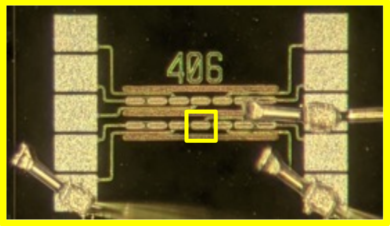


Simulated CCT map of a single 3D-trench sensor pixel scan (α_{tilt} = 0°)

Tilting has the effect of «mixing up» the fast and less-fast regions of the pixels, thus uniforming the timing response

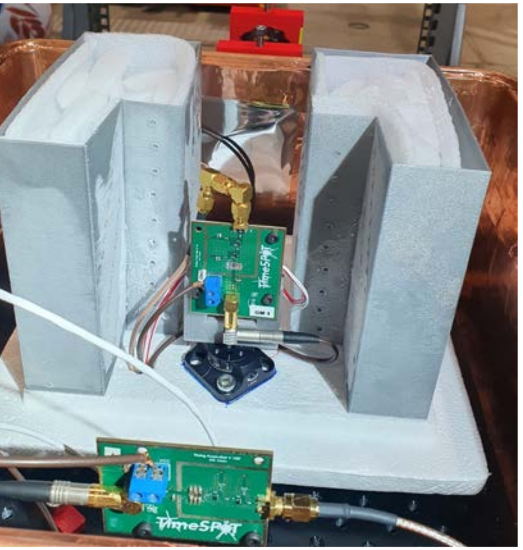
As a result, the shapes are more Gaussian at increasing α_{tilt}

Notice that, due to detection efficiency, α_{tilt} = 20° is the normal working condition of a 3D in a detecting system

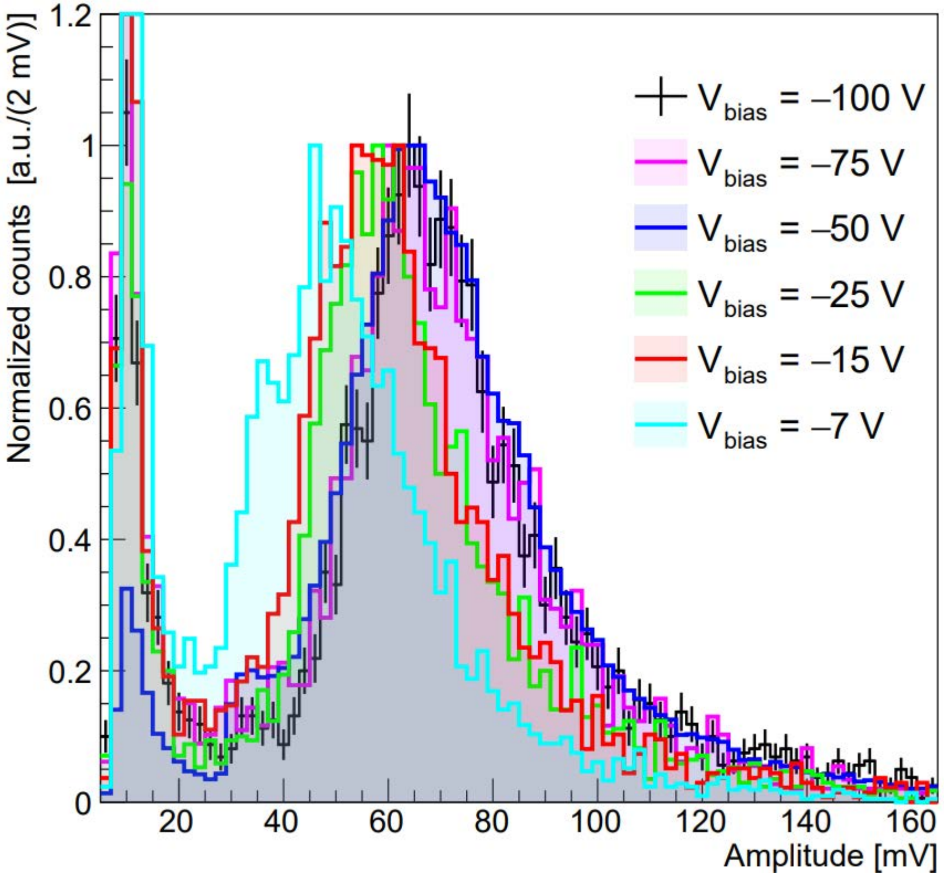


Amplitude distributions vs bias

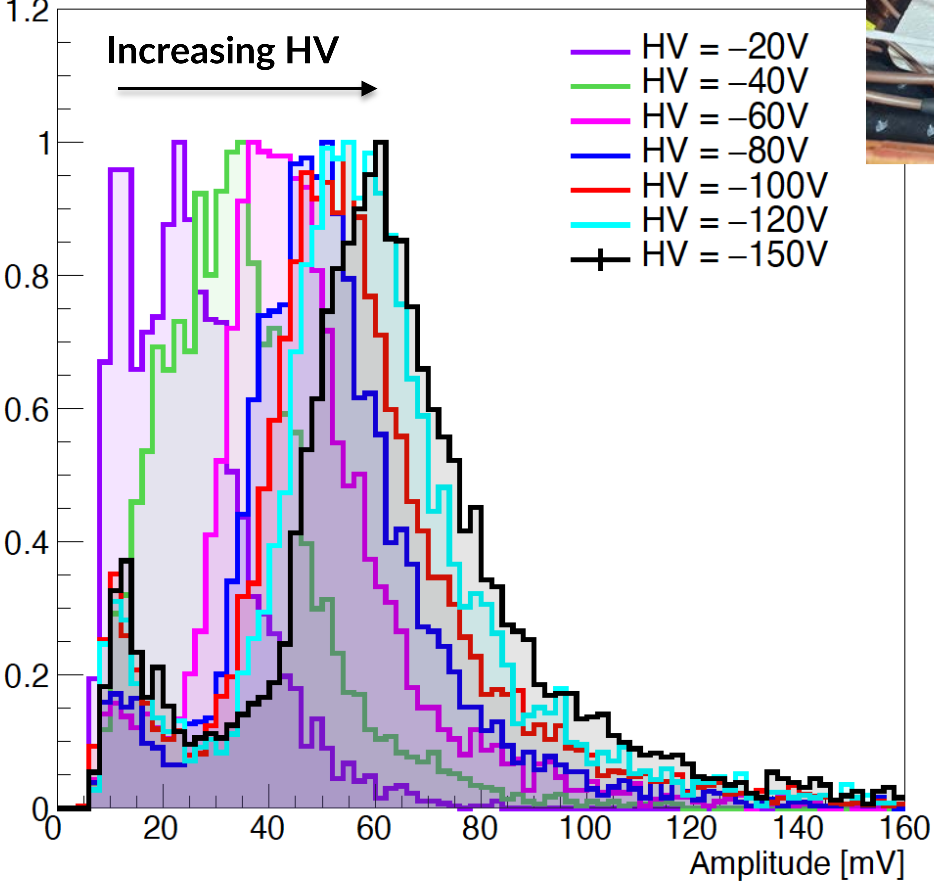
*Single pixel, **irradiated***



Not IRRADIATED, $\alpha_{tilt} = 0^\circ$

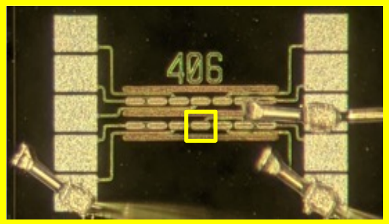


Irradiated @ 2.5 10^{16} n_{eq}/cm^2 , $\alpha_{tilt} = 0^\circ$

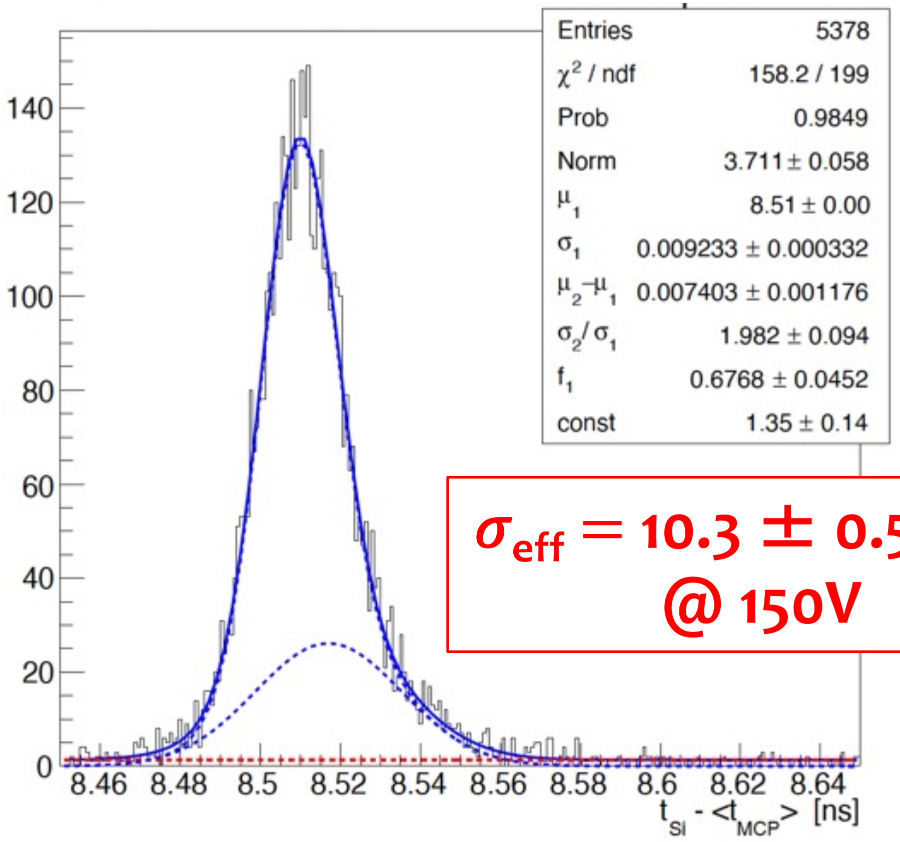


The effect of fluence is evident from the ΔV_{bias} needed to reach the same Amplitude

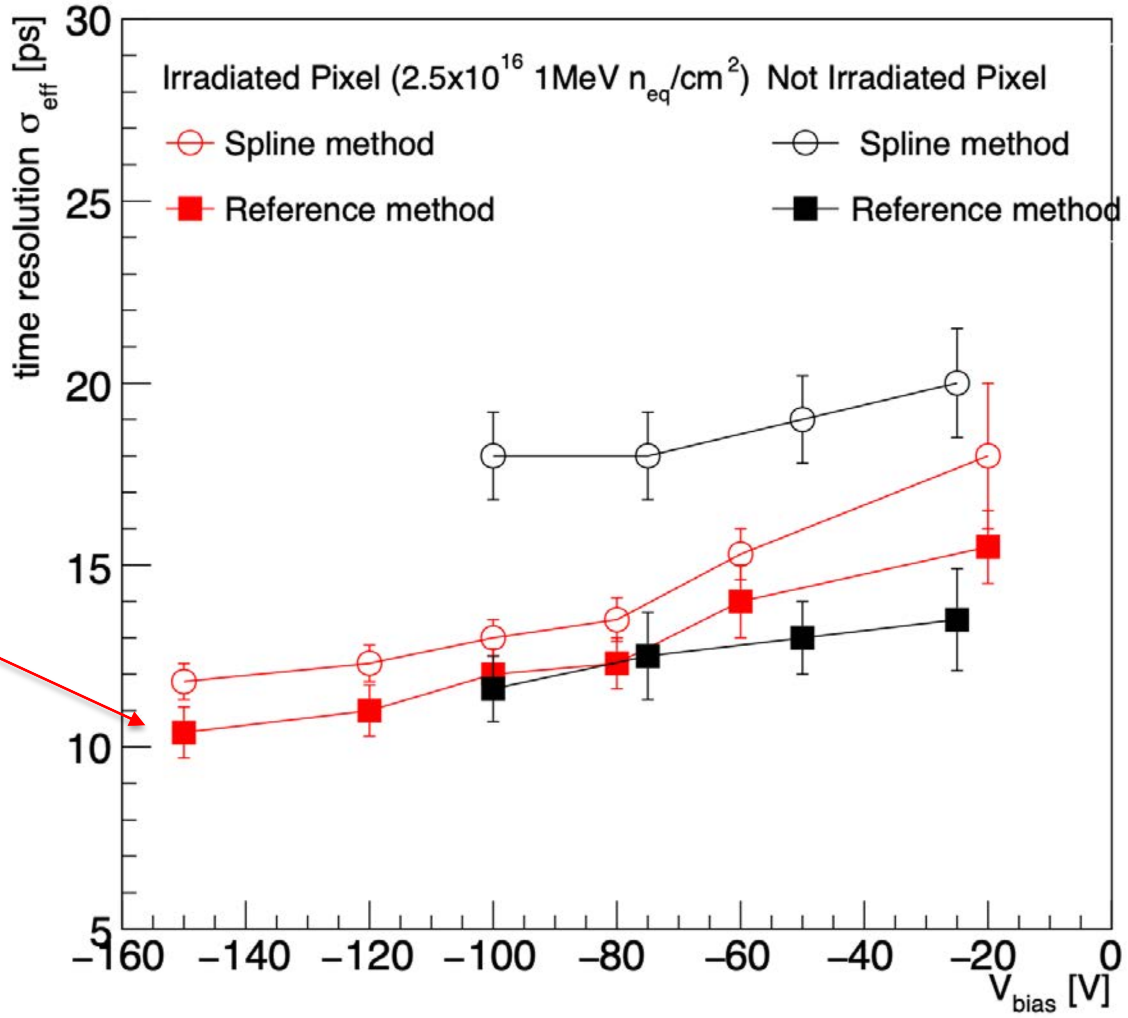
Irradiated sensors: timing performance



Irradiated @ 2.5 10^{16} n_{eq}/cm^2 , α_{tilt} = 0°

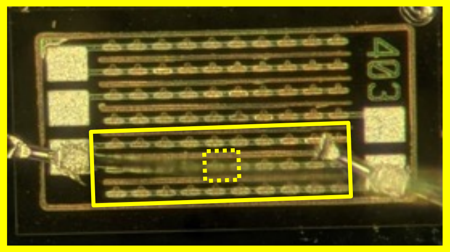


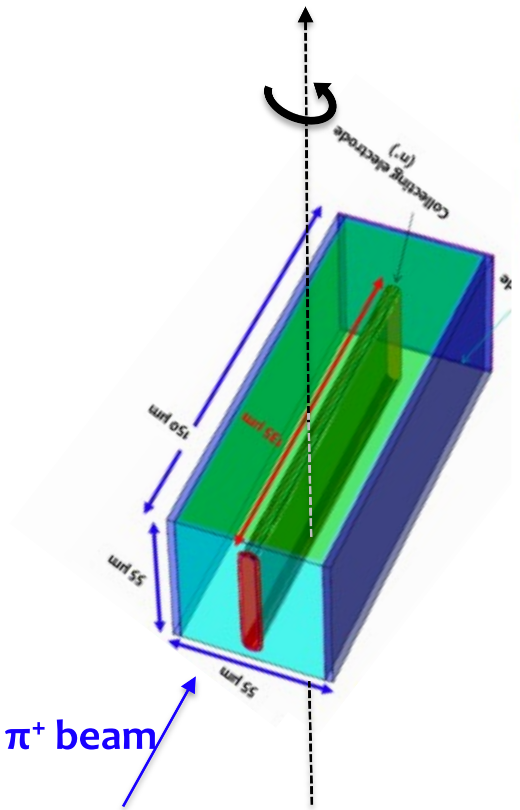
σ_{eff} = 10.3 ± 0.5 ps
@ 150V

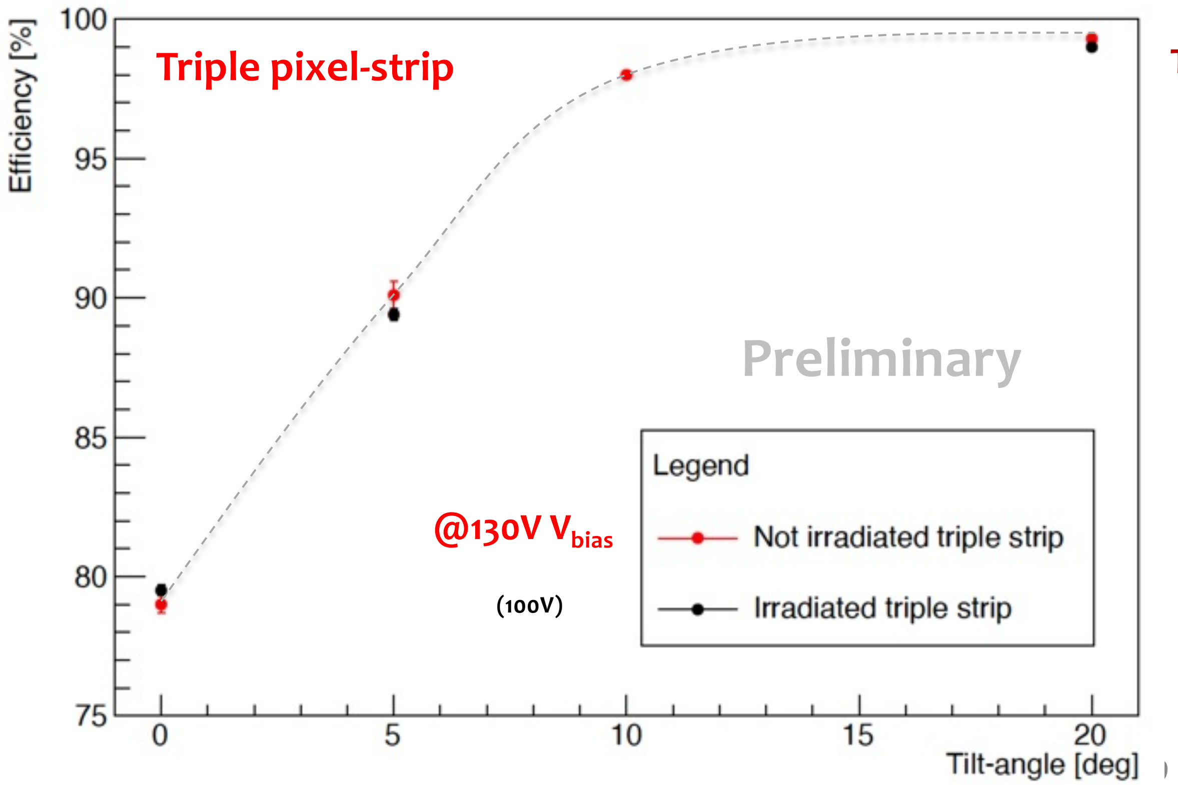


To be compared with 11 ps @ 100 V
of the not-irradiated case

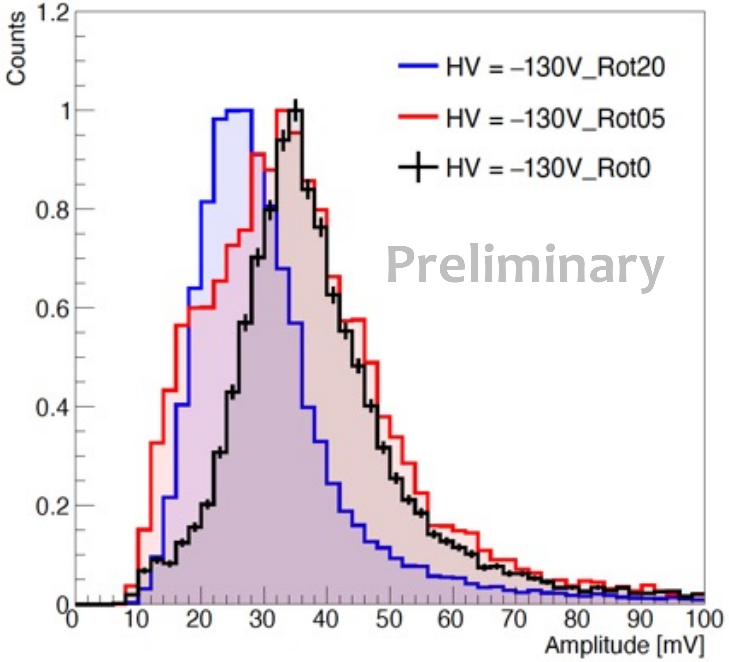
Irradiated sensors: geometrical efficiency







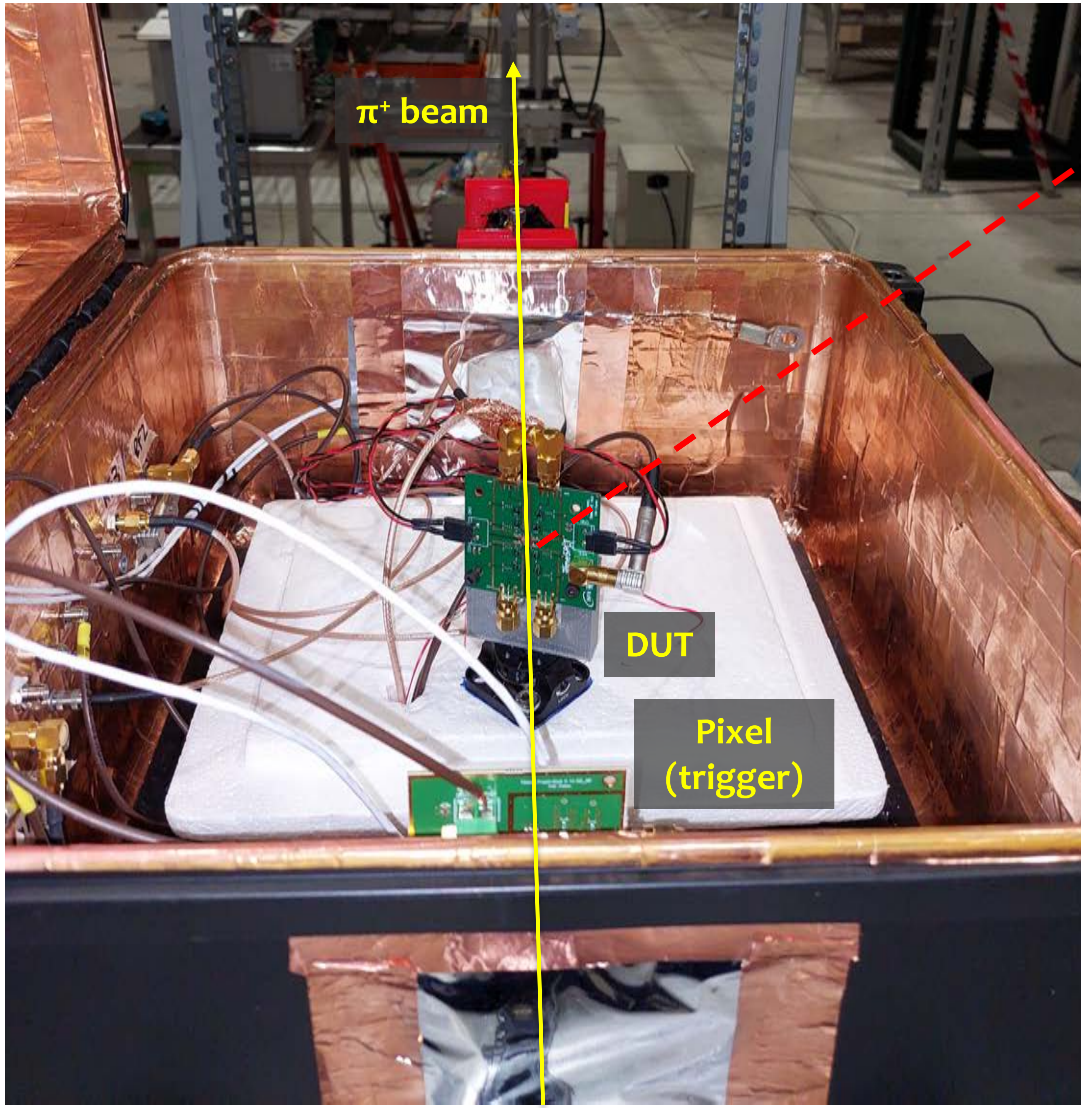
Triple strip @ 2.5 10^{16} n_{eq}/cm^2, α_{tilt} = 0°, 5°, 20°



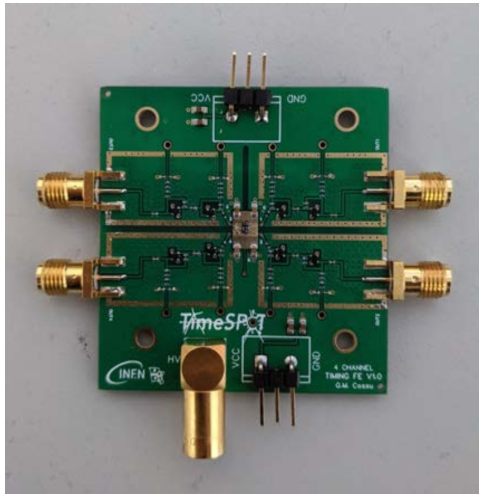
The inefficiency (at normal incidence) due to the dead-area of the trenches is fully recovered by tilting the sensors around the trench axis

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

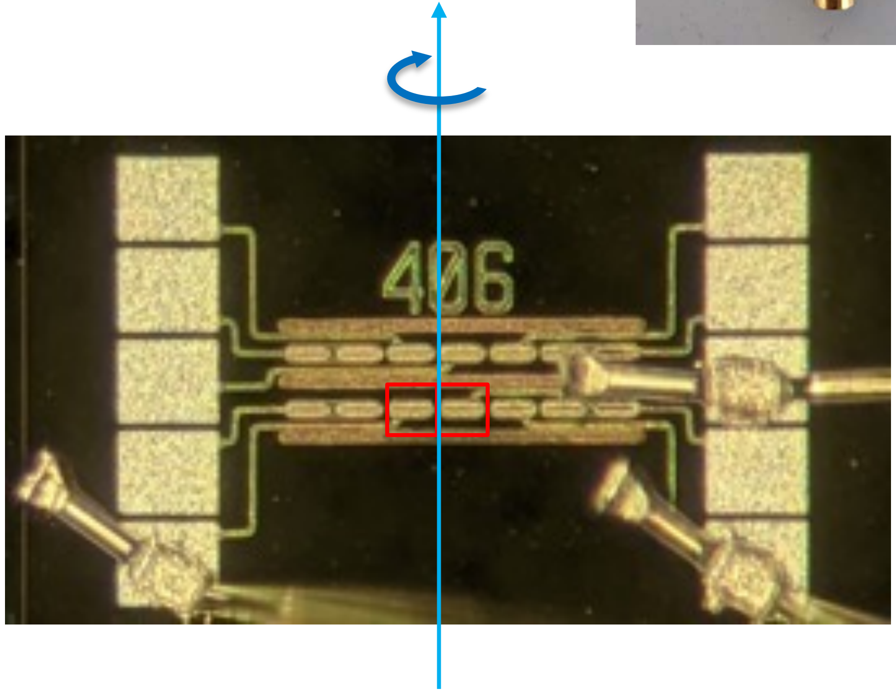
Charge sharing studies: setup



4-channel FEE board

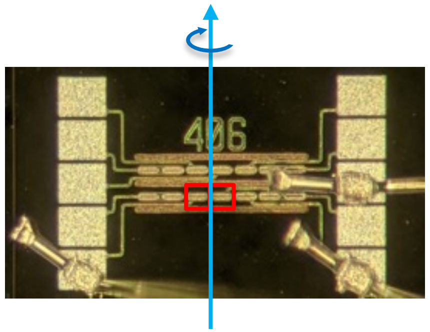


2 adjacent pixels – each one read-out by one FEE channel



Tilting the sensor it is possible to study the behaviour of two pixels when a charged particle crosses both of them

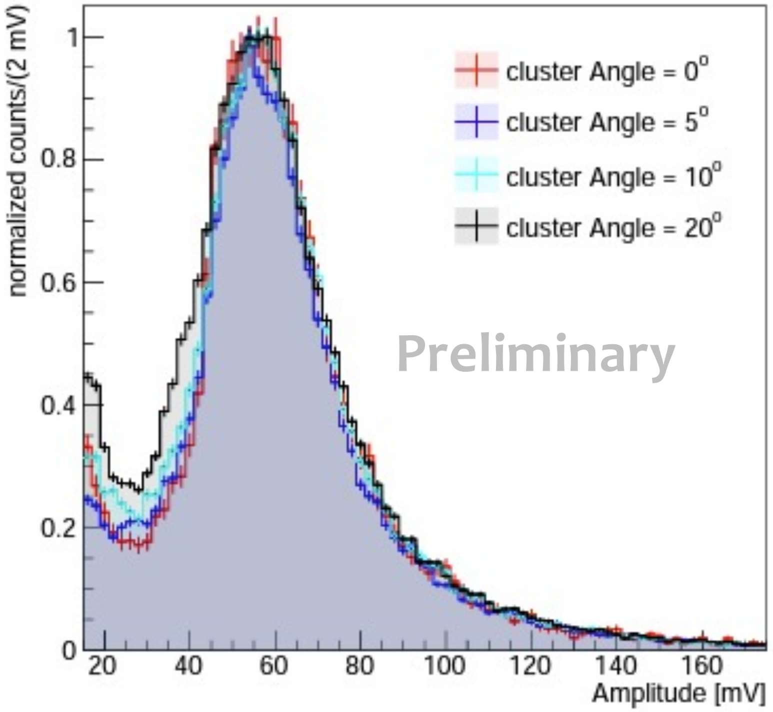
Charge sharing studies: results



When a particle crosses two pixels:

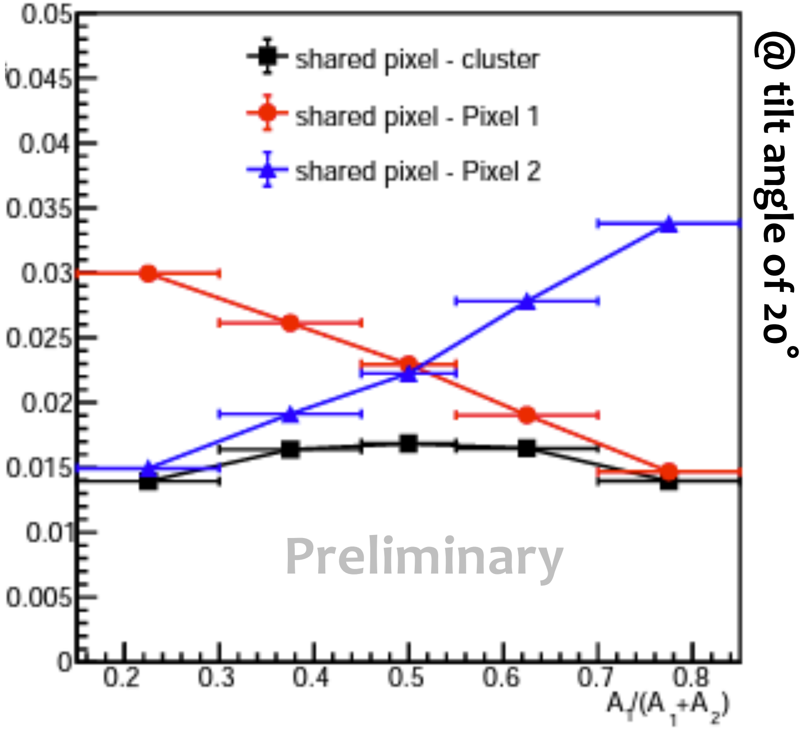
1. Amplitude = sum of the amplitudes of the two signals
2. Time of Arrival = weighted sum on amplitudes of the ToA in the two pixels

Amplitude distributions at different angles



Combining the two pixels information, it is possible to recover the amplitude distribution expected at normal incidence angle

Time resolution as a function of the fraction of sharing



*time resolution from histogram RMS

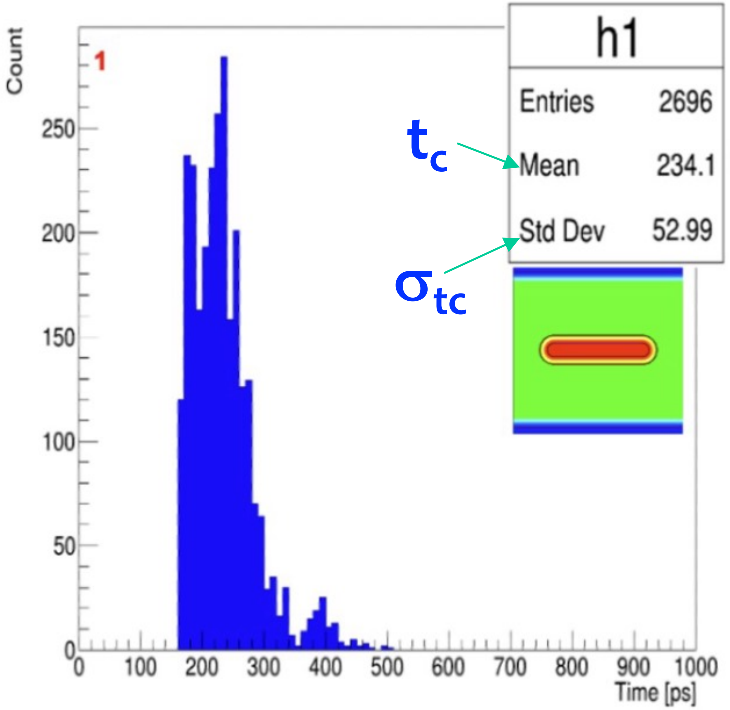
Using the information of both pixels, timing performance improves

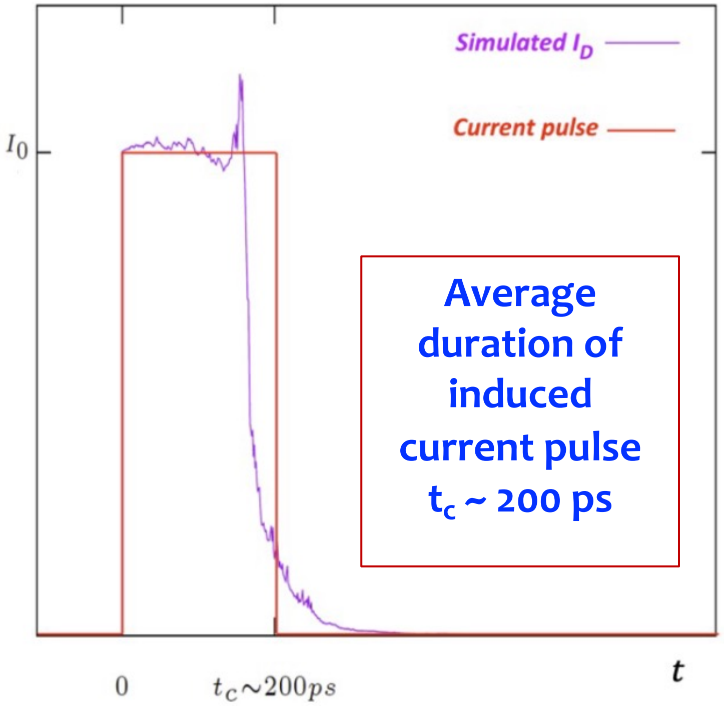
Electronics: the decisive stage. TimeSPOT developments (fast item)

The ≈ ideal Front-End

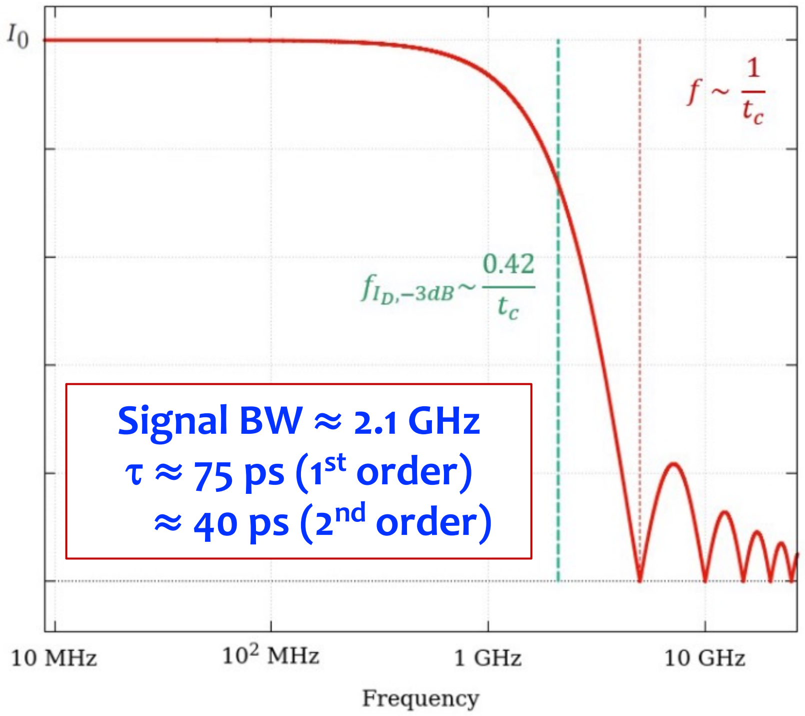
for 3D-trench sensors

Charge Collection Time distribution



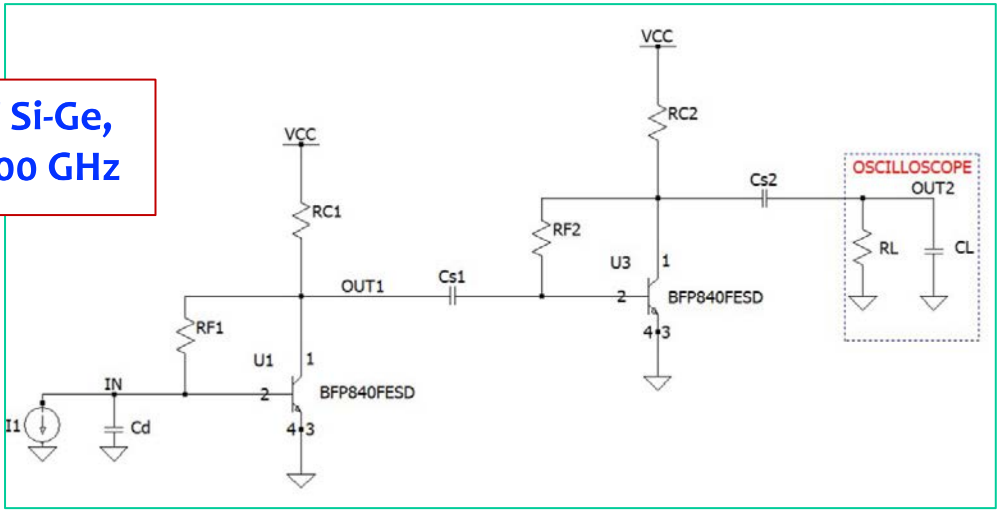


Average duration of induced current pulse t_c ~ 200 ps



Signal BW ≈ 2.1 GHz
τ ≈ 75 ps (1st order)
≈ 40 ps (2nd order)

HBJT Si-Ge,
f_T ~ 100 GHz



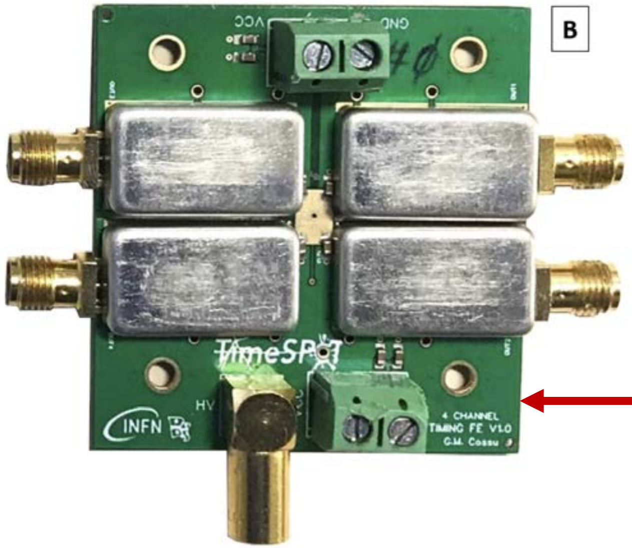
A «quasi» current sensitive amplifier (Trans-Impedance-Amp) stage, with Z_{in} ≈ 50 Ω can sustain C_D ≤ 1 pF

G. M. Cossu and A. Lai, “ *Front-end Electronics for Timing with pico-seconds precision using Solid State Sensors*”, in preparation

A. Lai and G. M. Cossu, “*High-resolution timing electronics for fast pixel sensors*”, arXiv2008.09867, 2020

CMOS 28-nm for pixels with timing capabilities

When system constraints come into play



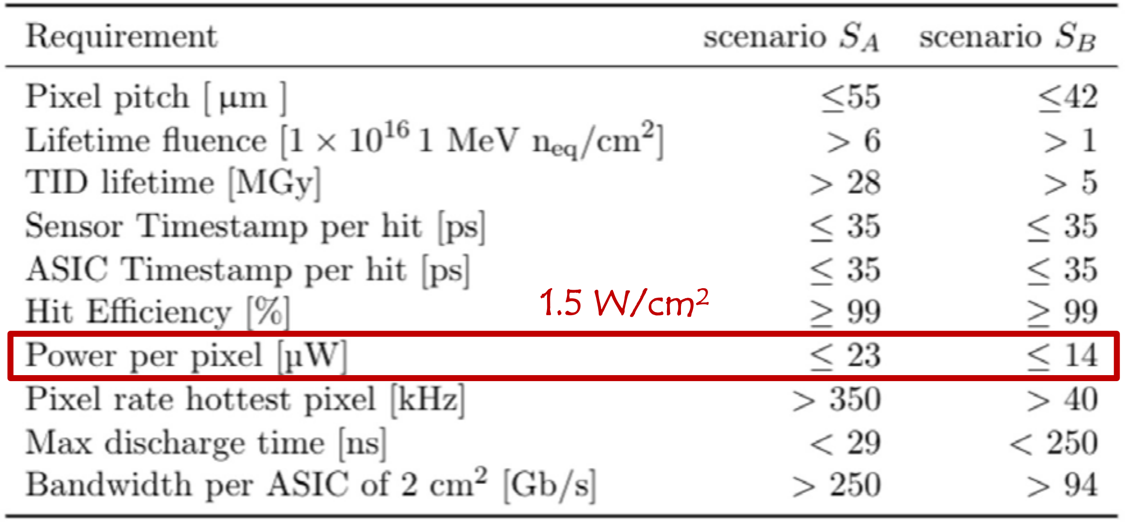
Si-Ge input stages $t_r \approx 100$ ps

Measured $\sigma_{ej} \approx 7$ ps @ 2 fC (1 MIP), 900 fs @ 20 fC

BUT:

Rate constraints
Area constraints
Data BW constraints
Power constraints

A first complete set of «balanced HEP requirements»



Requirement	scenario S_A	scenario S_B
Pixel pitch [µm]	≤55	≤42
Lifetime fluence [1×10^{16} 1 MeV n_{eq}/cm^2]	> 6	> 1
TID lifetime [MGy]	> 28	> 5
Sensor Timestamp per hit [ps]	≤ 35	≤ 35
ASIC Timestamp per hit [ps]	≤ 35	≤ 35
Hit Efficiency [%]	≥ 99	≥ 99
Power per pixel [µW]	≤ 23	≤ 14
Pixel rate hottest pixel [kHz]	> 350	> 40
Max discharge time [ns]	< 29	< 250
Bandwidth per ASIC of 2 cm² [Gb/s]	> 250	> 94

1.5 W/cm²

LHCb-U2 specs from physics needs. VELO support document for FTDR

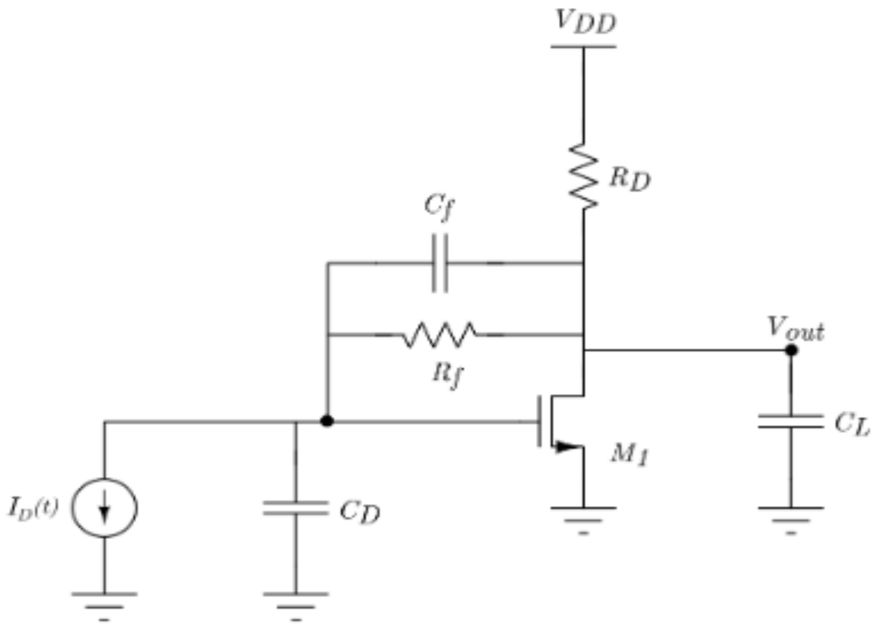
Why CMOS 28-nm? (last "bulk" CMOS node)

1. **It optimizes performance vs radiation hardness, costs, and design techniques**
2. **It appears to be more rad-hard than subsequent (still very expensive) finFET technologies (es. 16 nm)**
3. **Most groups in HEP (CERN included) have chosen (for the reasons above) to adopt it for the next 5-10 years of developments**

The toughest constraint against speed is power budget, originating from the (un)capabilities of our best cooling system techniques at present (micro-channelling)

“Alternative” roads to front-end solutions

Trans-Impedance-Amplifier with shunt-shunt feedback (FB–TIA).



Simplified schematic of the FB–TIA amplification stage

According to the FB parameters used, this scheme can range from an integrator (Charge Sensitive Amplifier) to a fast Current-Sensitive front-end. The role of the specific transistor tecnology used is also decisive, especially when very high speed is pursued (Si-Ge vs CMOS).

We can consider two extreme cases as examples(1):

A) CSA-TIA, when the amplifier peaking time $\tau >> t_c$

It can be demonstrated(1) that in this case

$$\sigma_t = \frac{\partial t_{thr}}{\partial t_c}\sigma_{tc} = \boxed{\frac{1}{2}\sigma_{tc}}$$

B) Fast-TIA, when the amplifier peaking time $\tau \approx t_c$

It can be demonstrated (1) that in this case

$$\sigma_t = \frac{\partial t_{thr}}{\partial t_c}\sigma_{tc} \approx \frac{\tau}{2}\sqrt{\frac{V_{th}}{I_0 R_m}}\frac{\sigma_{tc}}{t_c} \approx \boxed{\left(\frac{1}{2}\frac{\tau}{t_c}\sqrt{\frac{N}{S}}\right)\sigma_{tc}}$$

---

(1) A. Lai and G.M. Cossu, *High-resolution timing electronics for fast pixel sensors*, arXiv:2008.09867

Front-end solutions: theoretical limits

Timing propagation coefficient $\mathcal{P}$

(σ_t/σ_{tc} ratio)

or

fraction of CCT standard deviation propagated to σ_t

$$\frac{\partial t_{thr}}{\partial t_c}$$

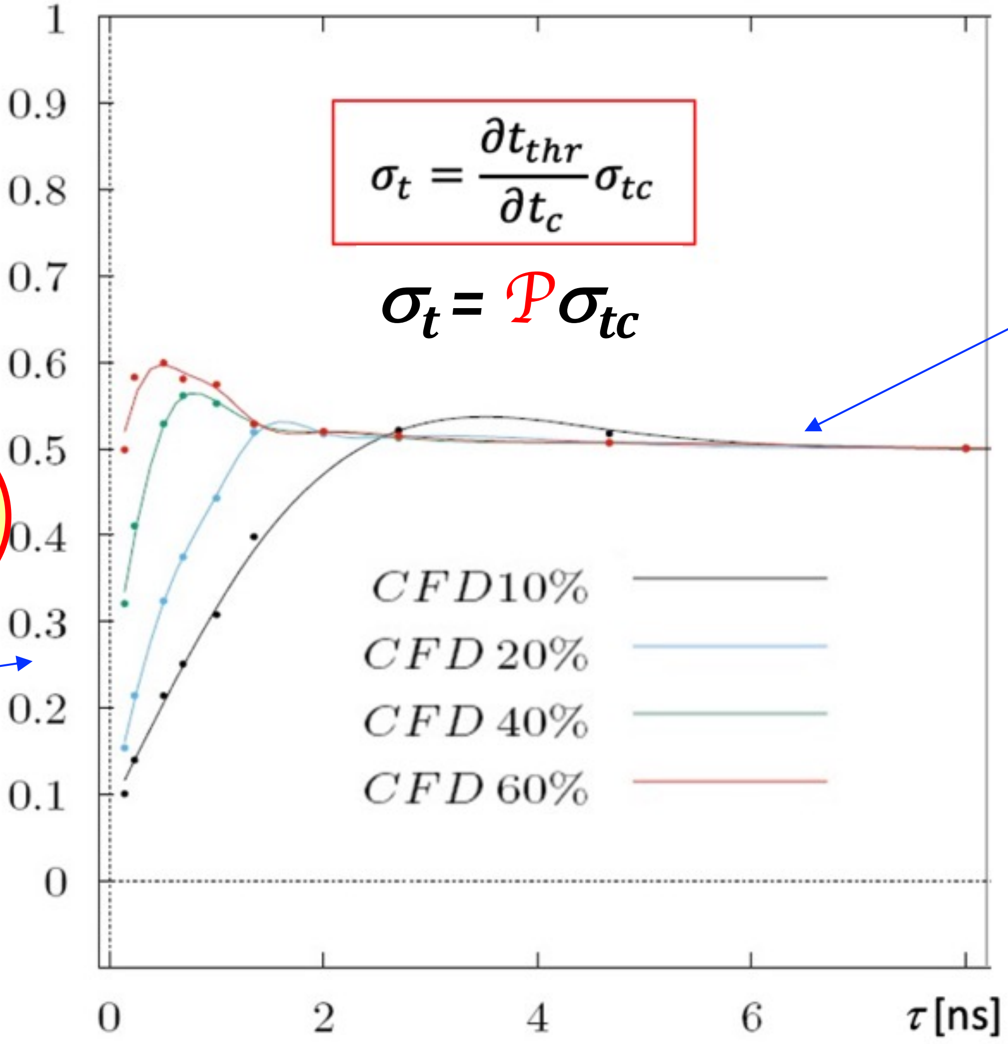
Fast–TIA

For $\tau << t_c$

$\mathcal{P}$

can be considerably less than 1

Resolutions below 10ps can be theoretically reached (1)



$$\sigma_t = \frac{\partial t_{thr}}{\partial t_c}\sigma_{tc}$$

$$\sigma_t = \mathcal{P}\sigma_{tc}$$

$\mathcal{P}$ (= Derivative of time at threshold t_{thr} with respect to average CCT t_c, aka time centroid) vs the amplifier peaking time τ, at t_c = 250 ps for various CFD fractions.

CSA–TIA

For $\tau >> t_c$

$\mathcal{P}$

Approximates ½.

In the case of a 3D-trench pixel, this corresponds to

≈ 20-25 ps

(with a 55 μm pitch)

To reach $\tau \approx$ **100 ps**, the choice of feedback parameters is not sufficient. High performance transistor stages and high power are mandatory as well

(1) A. Lai and G.M. Cossu, *High-resolution timing electronics for fast pixel sensors*, arXiv:2008.09867

Timespot1: Analog Front End

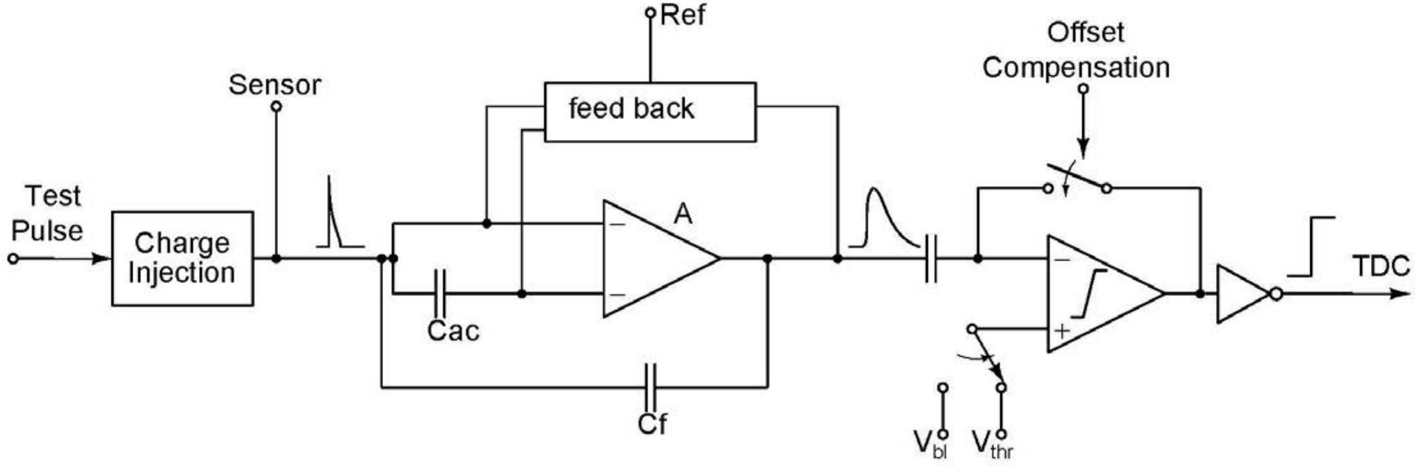
Inverter core amplifier with double Krummenacher FB

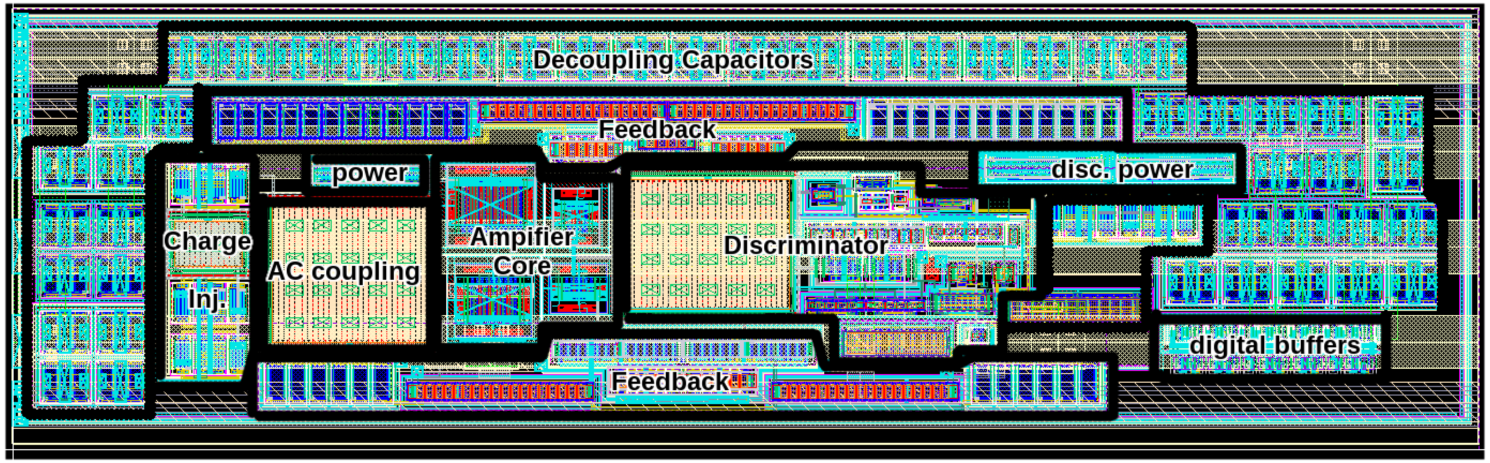
Inverter-based Charge Sensitive Amplifier (CSA) with DC current compensation.

Leading Edge Discriminator with Discrete-time Offset-Compensation for threshold uniformity
OC procedure: 250 ns every ≤800 µs

Pwr regime	nominal	high
Pwr/channel [µW]	18.6	32.9
Slew rate [mV/ns]	250	360
Z_{in} [Ω] in BW	23k	23k
Gain [dB]	93	93
RMS noise [mV]	3.9	3.8
BW [MHz]	311	455
Jitter [ps]	15.6	10.5

Expected performance @ 2 fC
(post-layout simulation)





50x15 µm²

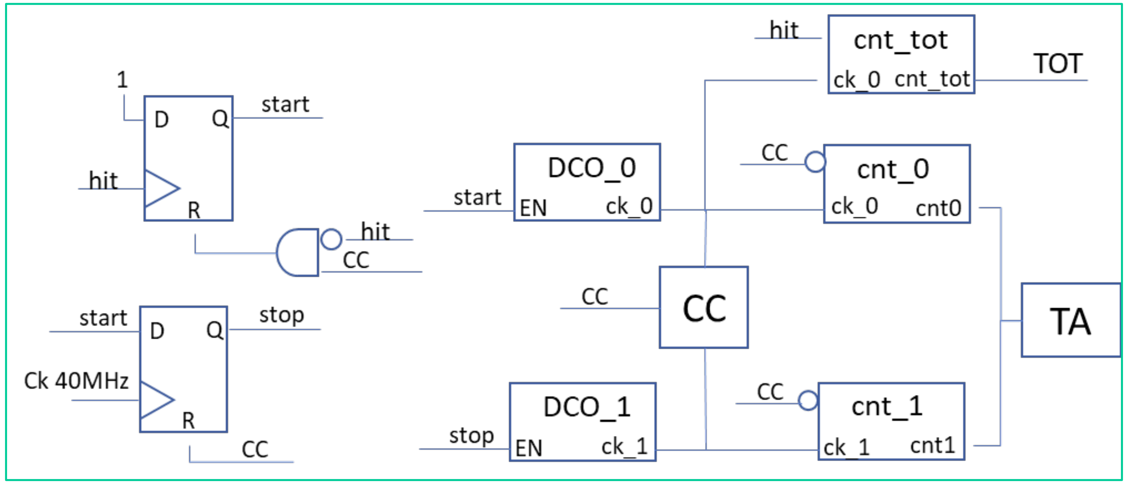
Timespot1: TDC

Fully digital design, standard-cell based

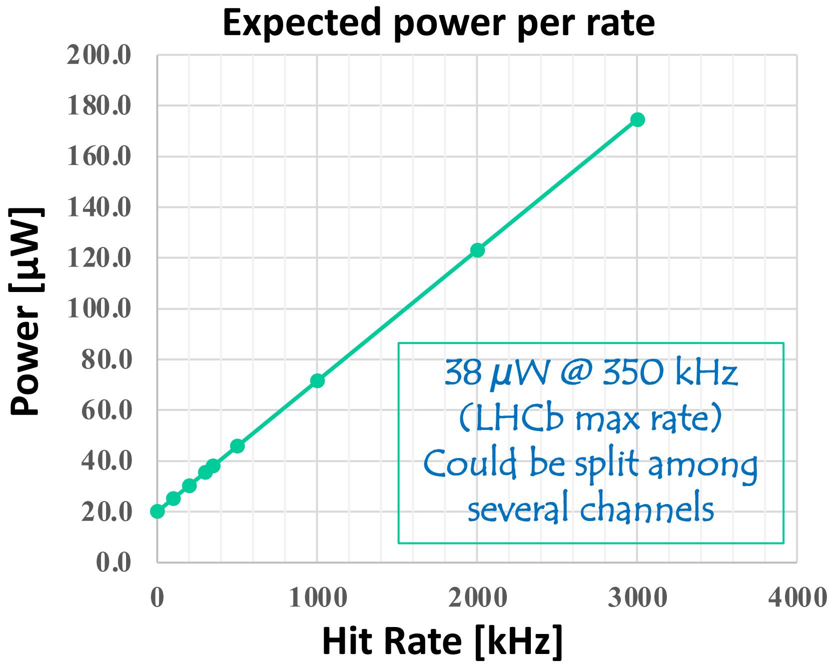
To maximize sustainable rate, 1 TDC per pixel channel has been integrated

Max input rate = 3 MHz
23 bits output word (ToA + ToT)
ToT resolution ≈ 1 ns

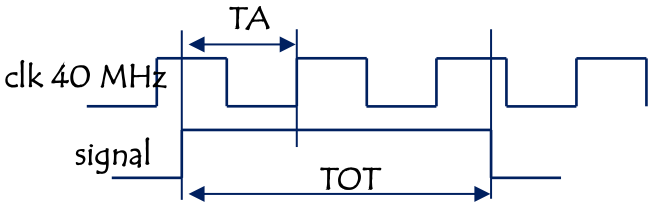
High resolution, "low" consumption TDC based on 2 DCOs and a Vernier architecture



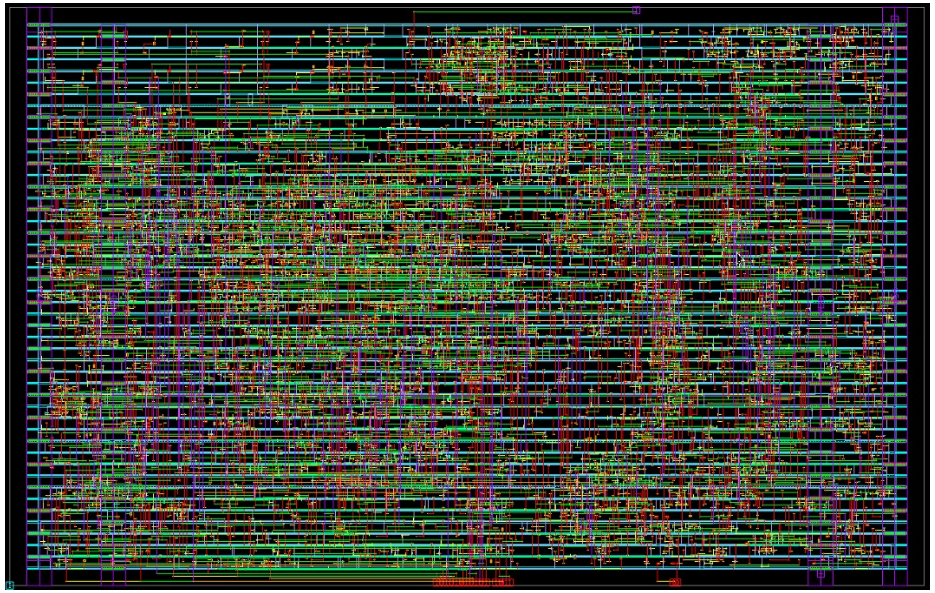
Expected power per rate



38 µW @ 350 kHz
(LHCb max rate)
Could be split among several channels



The TDC gives the phase of the signal wrt the 40MHz BX clock
The TDC and the counter use the same DCO-generated Clk (~1 GHz)
4 levels of Vernier precision (Δ*f* in DCOs) can be programmed.
Typical LSB 12 ps

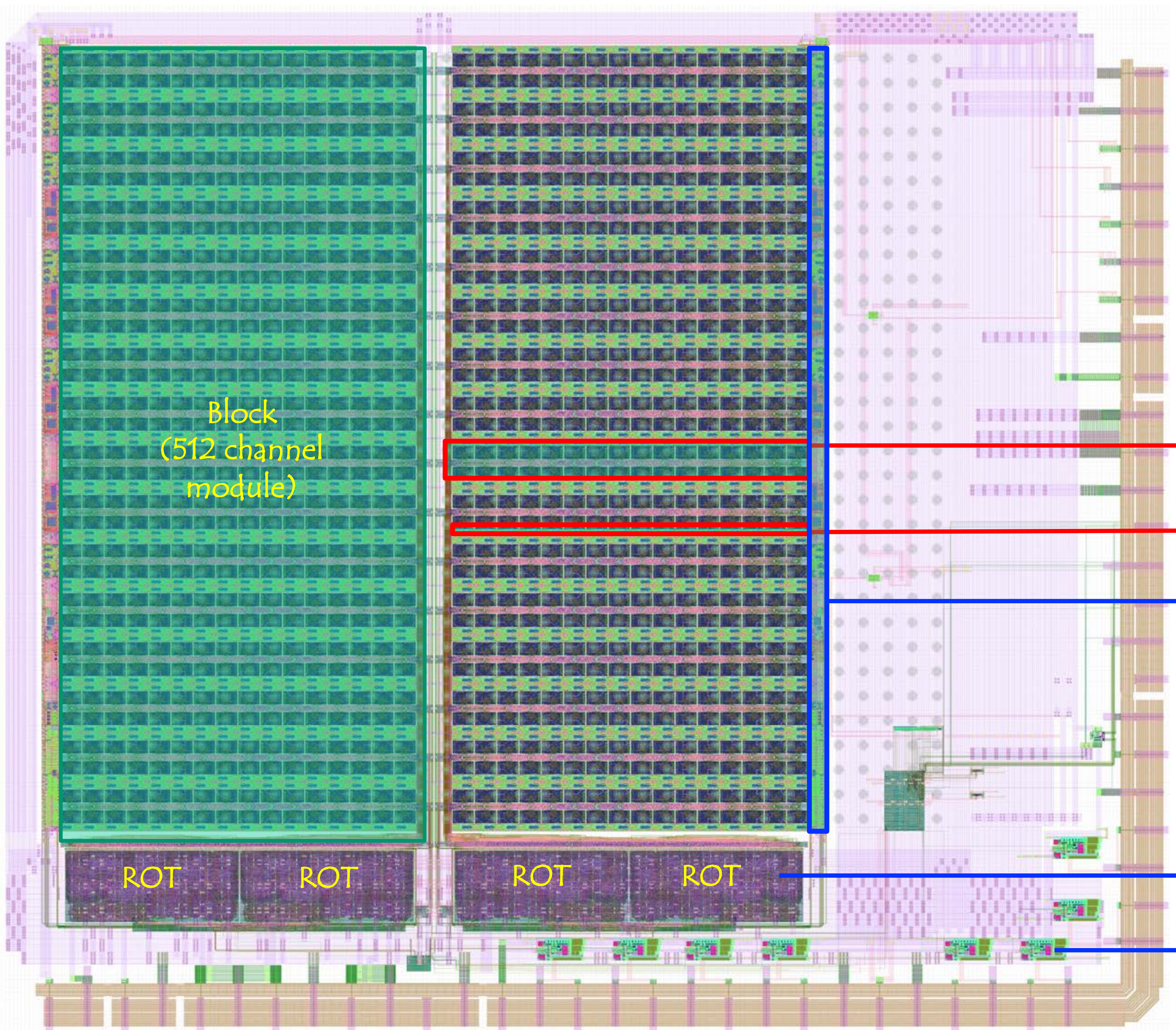


50x32 µm²

Timespot1 ASIC

28-nm CMOS

- Reduced size (1024 pixels, 6 mm²)
- HPC flavour
- Complete set of functionalities for pixel readout
- Slow read-out (demo-test purpose)



640 MHz master clock

Digital row: 16x2 TDC
+ Controls, Conf. registers, I²C I/F

Analog row (16x2 AFE)

Analog (service) column.
Each contains:

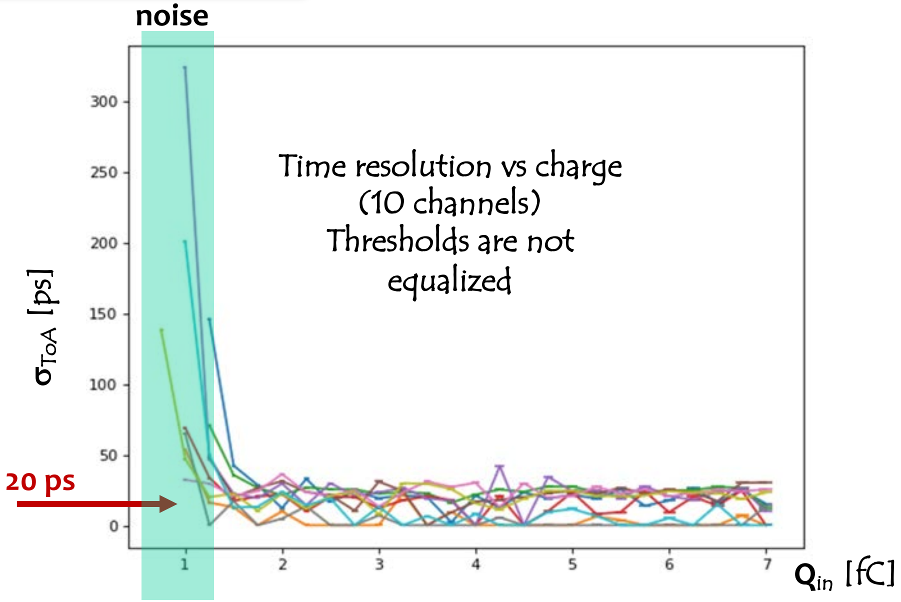
- 1 Band-Gap circuit
- 5x Σ–Δ DACs (producing analog levels used by pixels)
- Programmable bias cell (for power consumption)
- bias replicas with source followers.

4x Read Out Trees

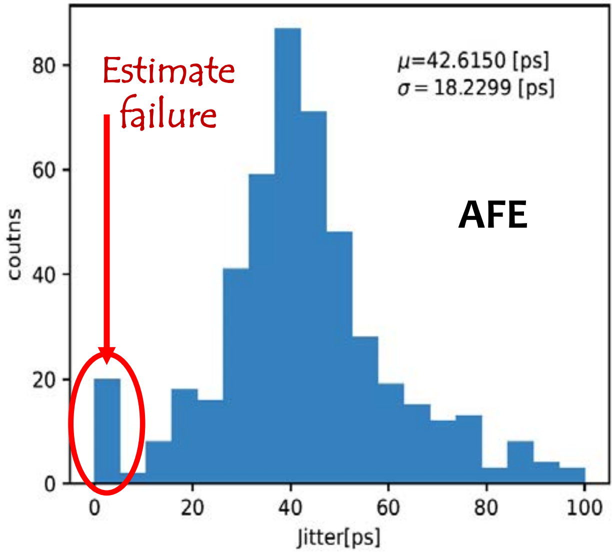
8x LVDS driver
(each @1.28 Gbps)

Timespot1 ASIC operation

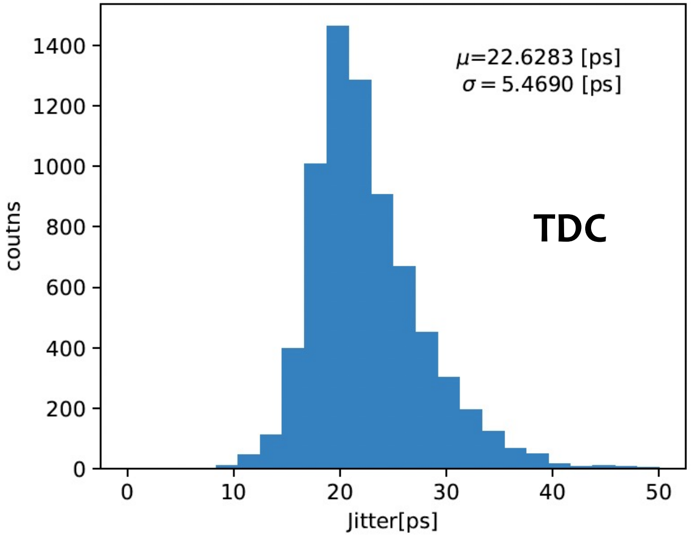
Time of Arrival Resolution



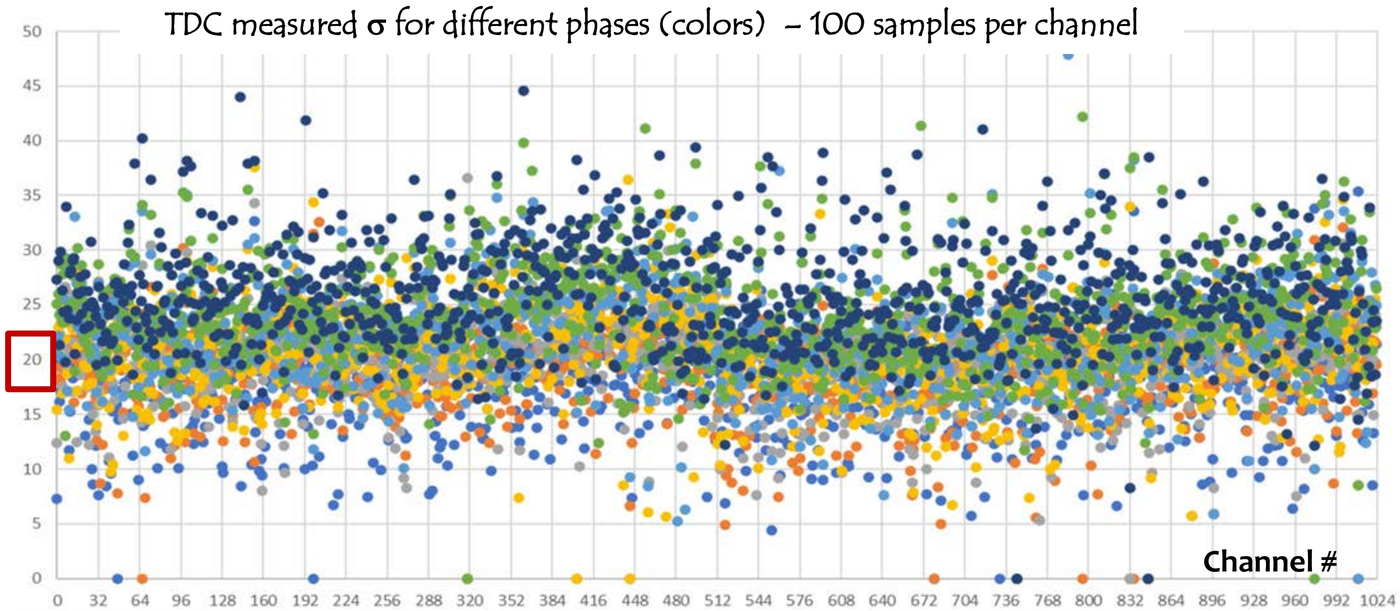
Time resolution vs charge (10 channels)
Thresholds are not equalized



Estimate failure



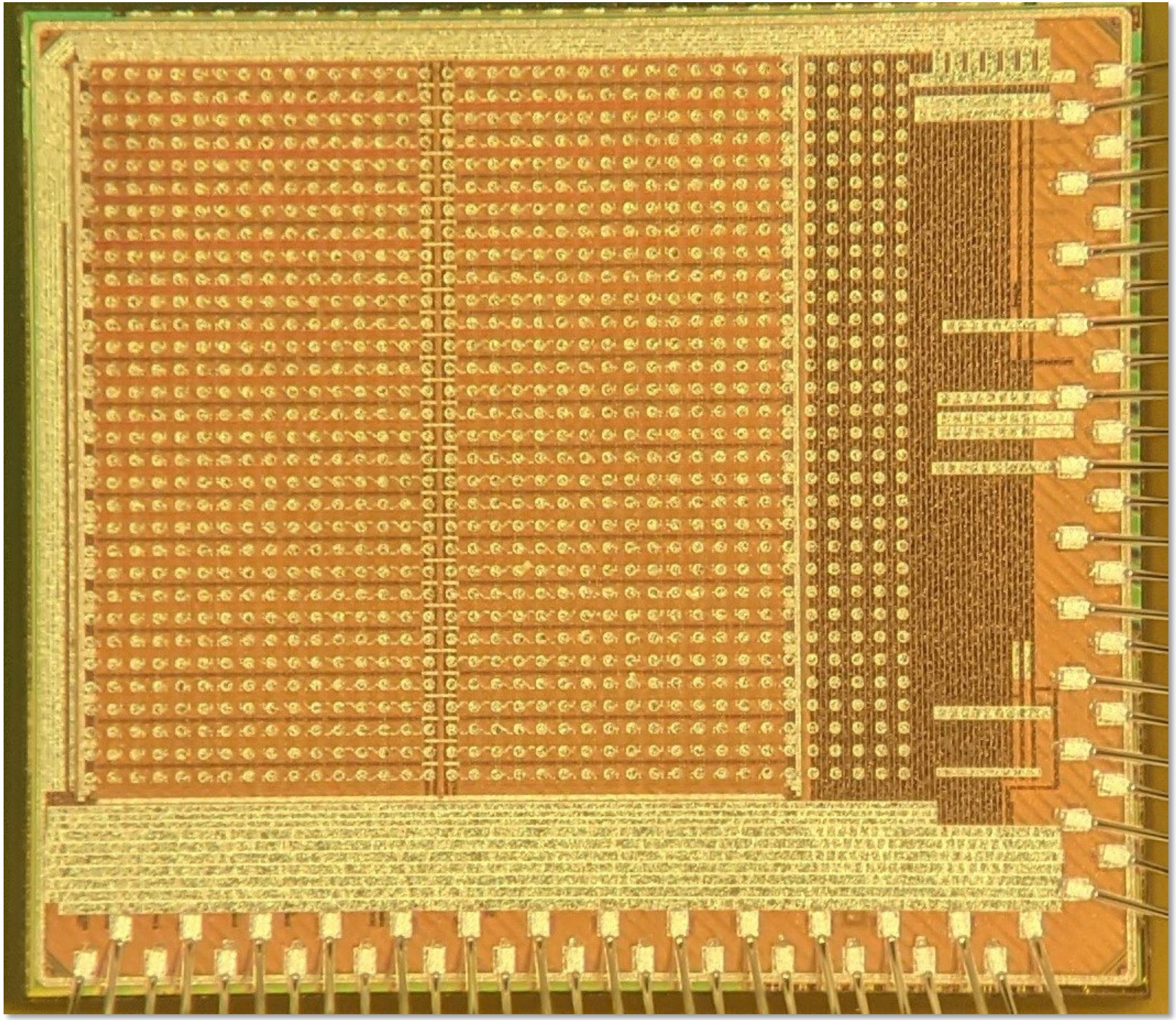
Distribution of the TA standard deviation across 1024 channels and 7 phases. Each point is computed from 100 repeated measurements.



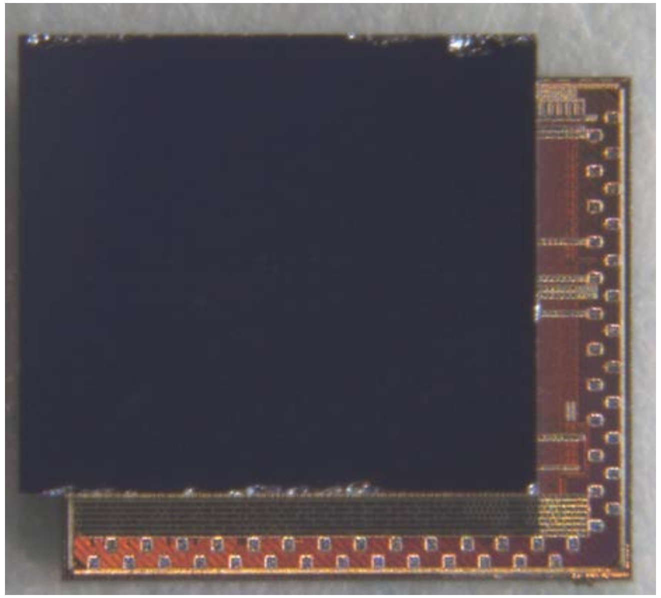
TDC measured σ for different phases (colors) – 100 samples per channel

In brief:

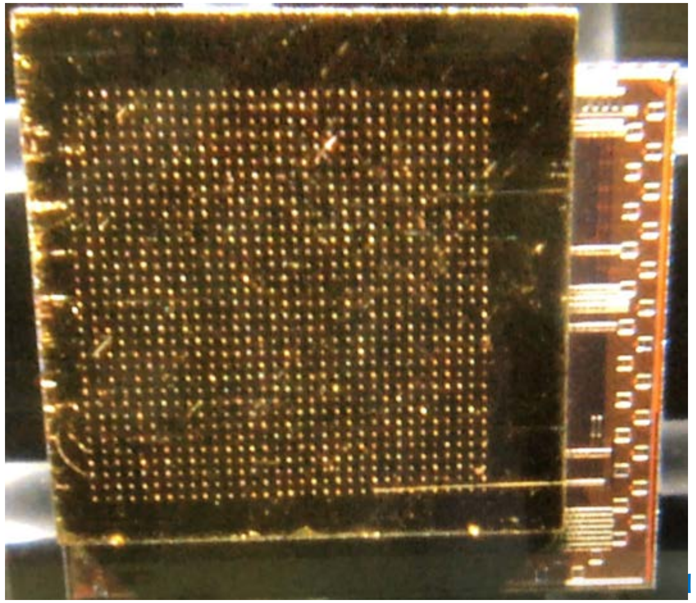
- **The TDC has a typical $\sigma_t \approx$ 20 ps, with relatively wide dispersion (5 ps) and is limited by the system clock jitter**
- **The AFE σ_t is intrinsically below 20 ps but an identified bug in the discriminator spoils σ_t in most of the channels. The bug is easily amendable.**
- **In general, global (digital) clock distribution issues limit the very good resolution at the pixel level.**
- **Maximum care is mandatory in global layout and final verification procedures**



Timespot1 on 3D-trench silicon matrix

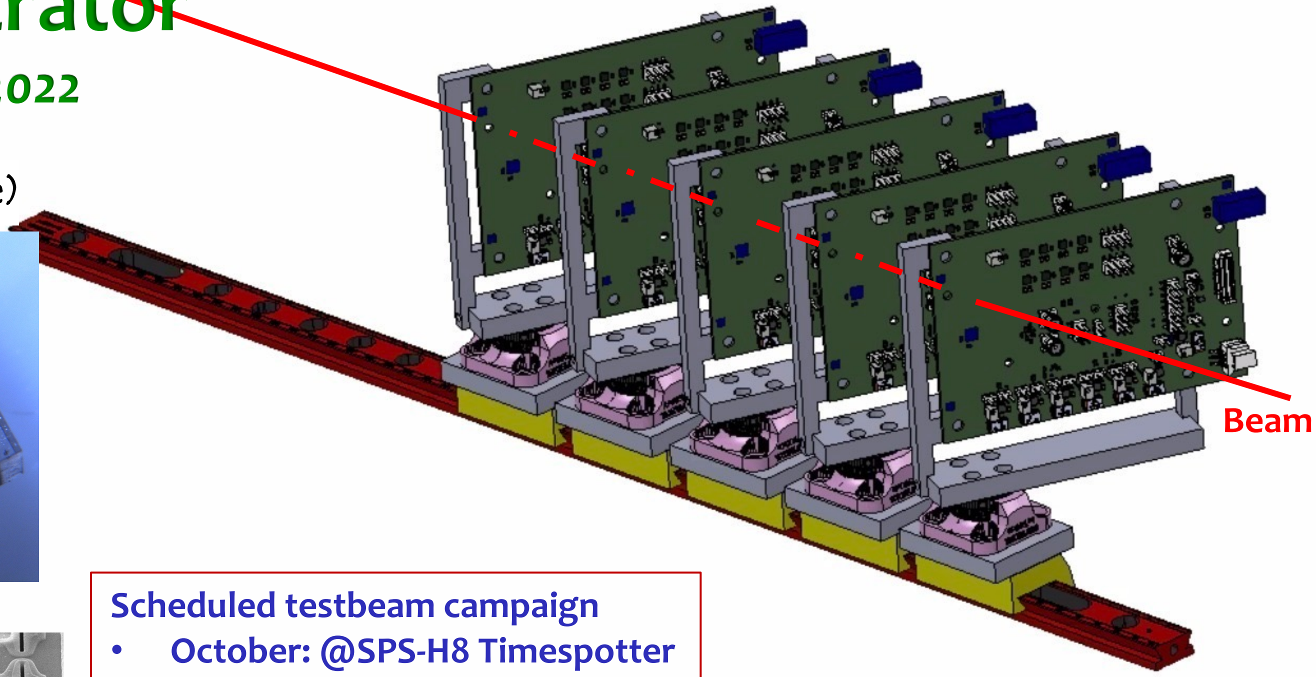


Timespot1 on 3D-column diamond matrix

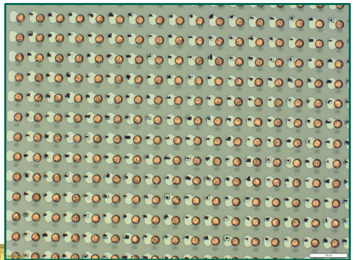


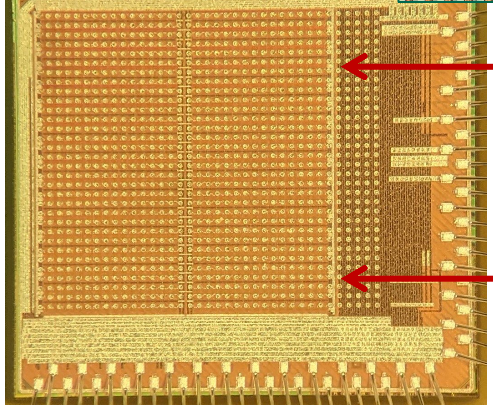
The Timespotter® demonstrator

A mini-tracker, under beam in autumn 2022



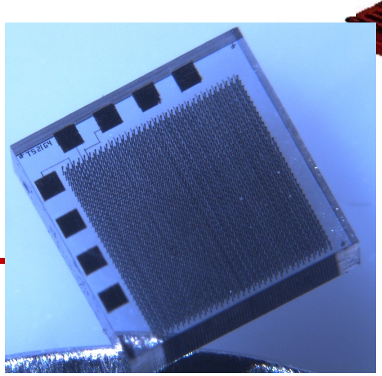
8 samples of each «flavour» are under preparation at IZM



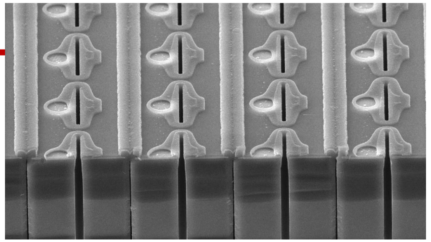


Hybridized @IZM

Diamond (Firenze)



32x32 matrix

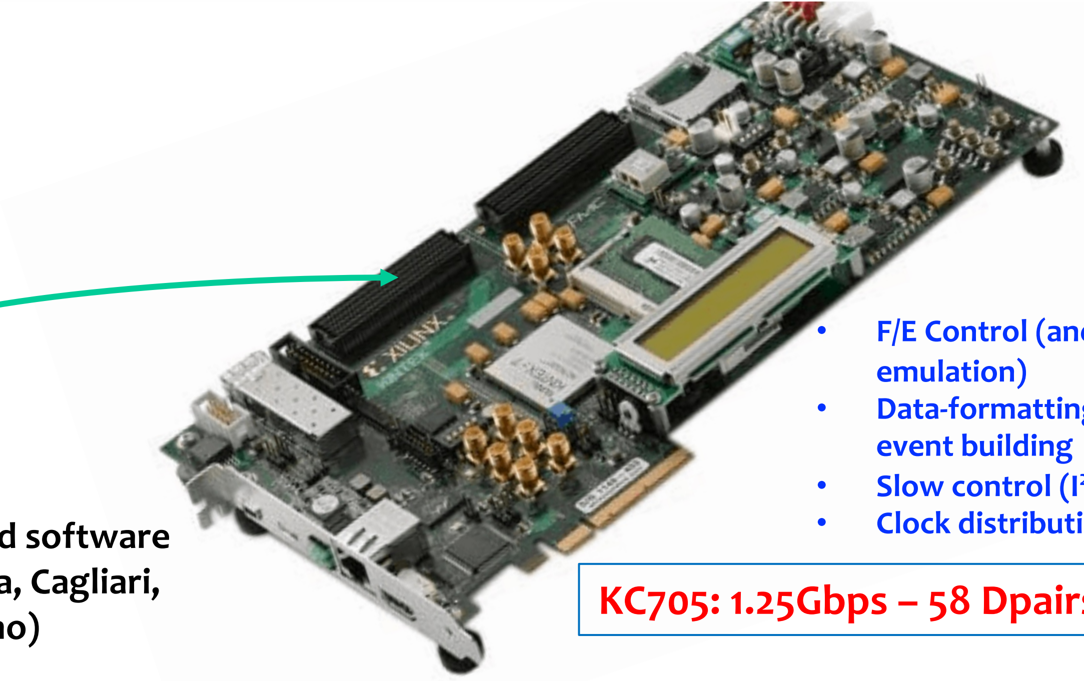


Silicon (FBK)

TS1-PCB 120x80 mm² (Cagliari, Milano, Torino)

Hi-speed, Hi-density Samtec twinax

Scheduled testbeam campaign
- **October: @SPS-H8 Timespotter**



- F/E Control (and emulation)
- Data-formatting, event building
- Slow control (I²C)
- Clock distribution

KC705: 1.25Gbps – 58 Dpairs

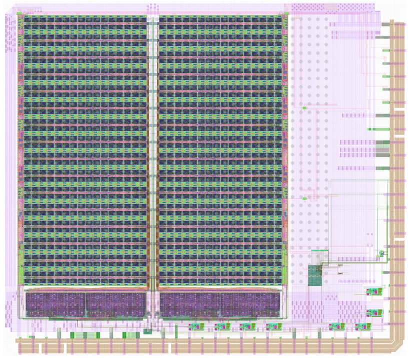
The DAQ firmware and software are finalized (Bologna, Cagliari, Firenze, Milano)

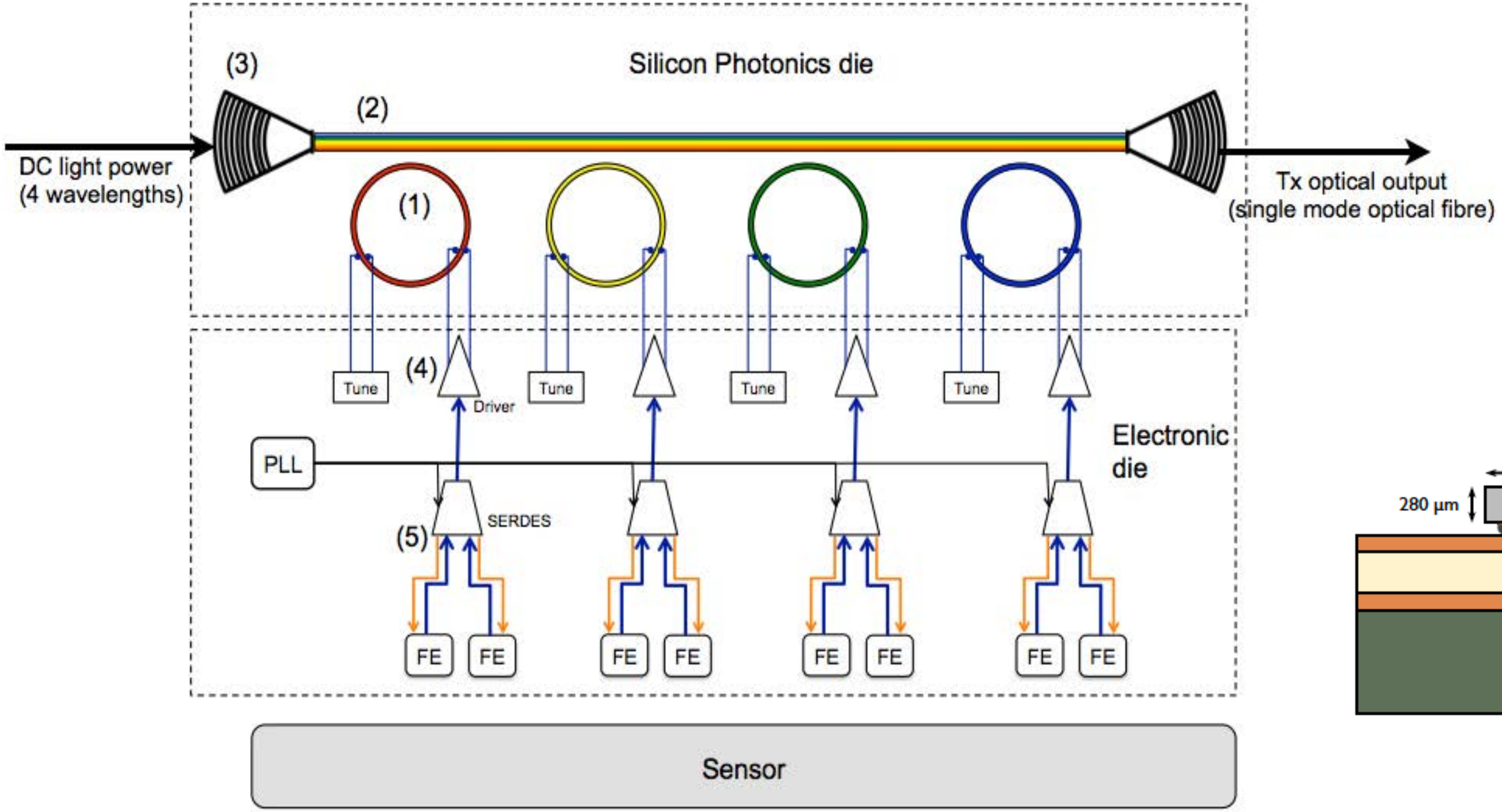
Conclusions

1. 3D-trench (geometric) sensors show excellent performance in timing even at extreme fluences → the limit must still be reached
2. Electronics is by far the weak ring of the chain
3. Reaching ≈20 ps time resolution in 28-nm CMOS can be «easily» achieved as far as the pixel circuit is concerned within a low-moderate power budget
4. 4D timing is mainly not a matter of sensors or single devices, it is a matter of system constraints (power in primis, cooling, stable clock distribution, interconnectivity, data BW, material budget)
5. The timing problem size scales dramatically with the area (and volume) of the system
6. A system-level development has to be launched soon

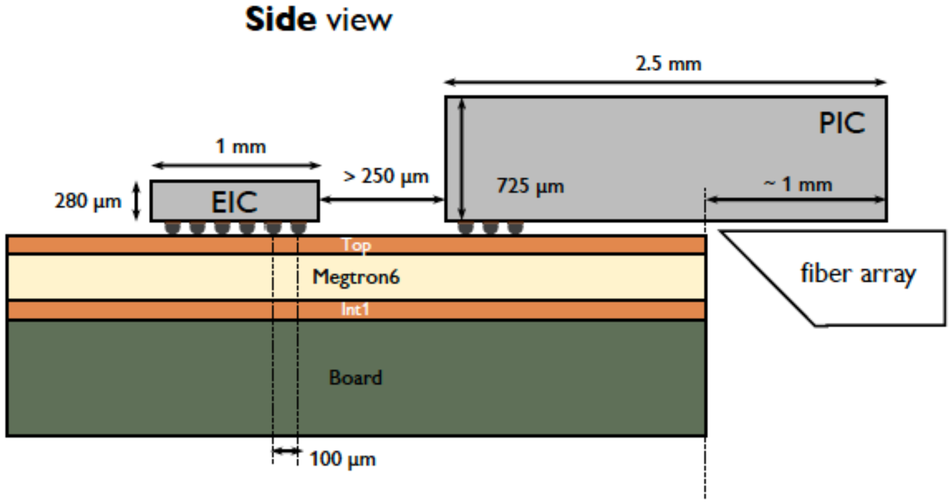
A glimpse into the (immediate) future

TimeSPOT meets Photonics
(Falaphel *project and* **IGNITE**)





Schematics of the PIC and EIC assembly (FALAPHEL demonstrator). Ring resonators (1) with different and tunable resonator wavelengths are located along horizontally drawn bus waveguides (2) which are connected to optical glass fibers by efficient and robust focusing grating.



Interposer-free flip-chip integration using a high-speed PCB

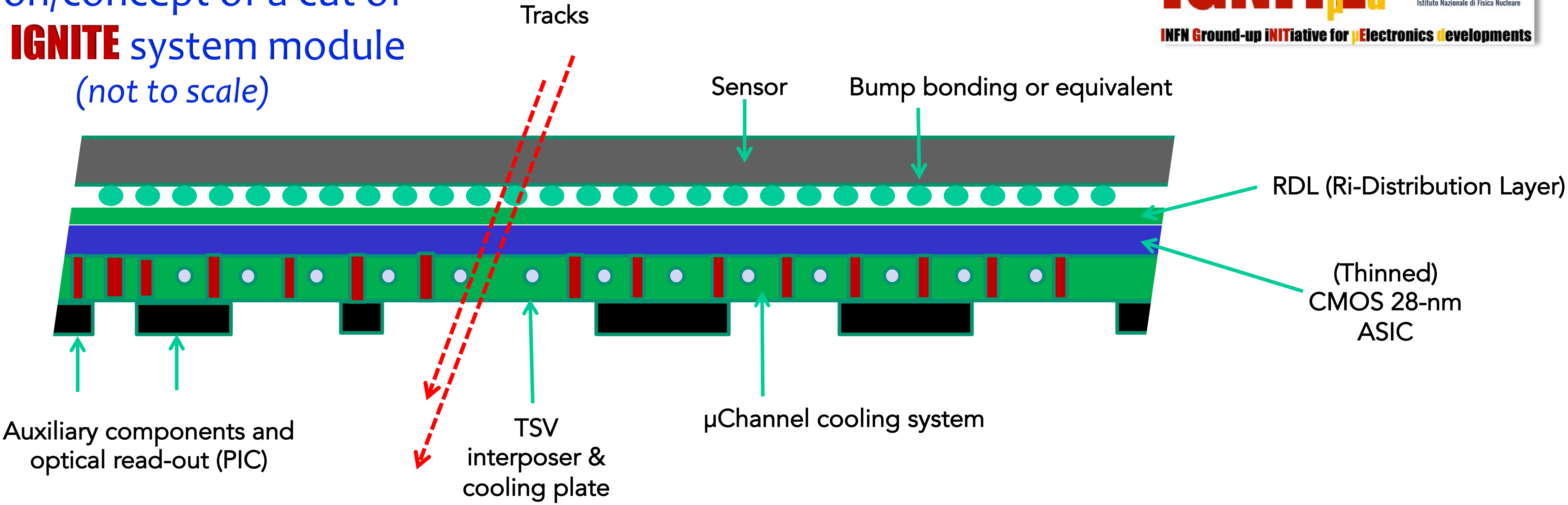
Electronics and Technologies for fast (high density) timing

(in the «hybrid approach»)

INFN Ground-up iNITiative for µElectronics developments

Vision/concept of a cut of the **IGNITE** system module

(not to scale)



Target deliverable of the IGNITE project:

- **A complete module (sensor, read-out ASIC, vertical IC, photonic circuit for data links, cooling system)**
- **The module development as a route to optimize material budget issues and High Density Interconnectivity between the device stages**
- **The whole thing below 0.8 (LHCb) ÷ 0.5 (NA62) % X_0**

INFN Institutes and Organization

IGNITE INFN Ground-up iNITiative for µElectronics developments

INFN Istituto Nazionale di Fisica Nucleare

Bologna
Bari
Cagliari
Genova
Firenze

LNF
Milano
Milano B.
Padova
Pavia

Perugia
Pisa
Torino
TIFPA

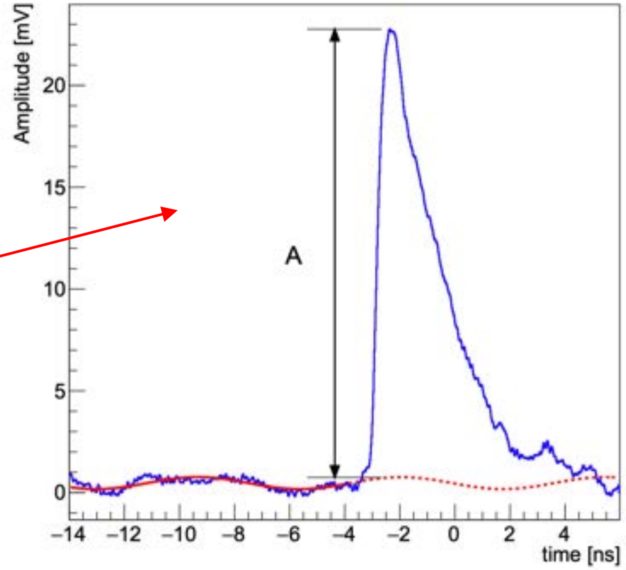
- 14 INFN Institutes
- Involvement of researchers from ATLAS, CMS, LHCb, NA62
- 20 FTE + dedicated Research Contracts on project funds
- 4 year project
- **Funds:** 2.4 M€ for developments and ASIC submissions
- Additional specific budget for HR (amount still under definition)
- Starting 2023

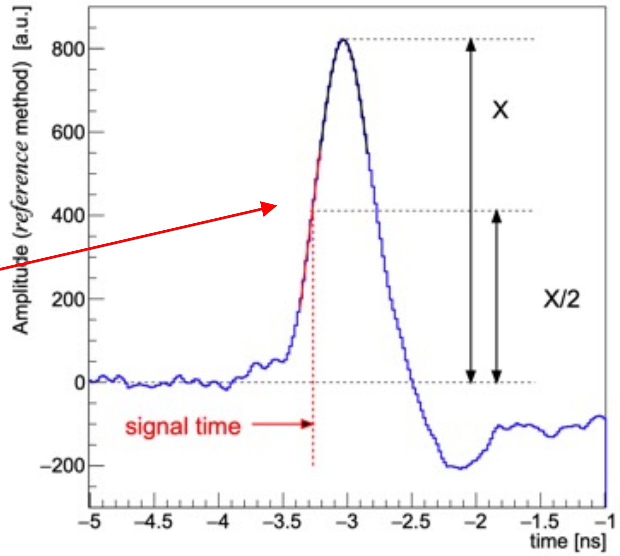
INSIGHTS

Waveform processing

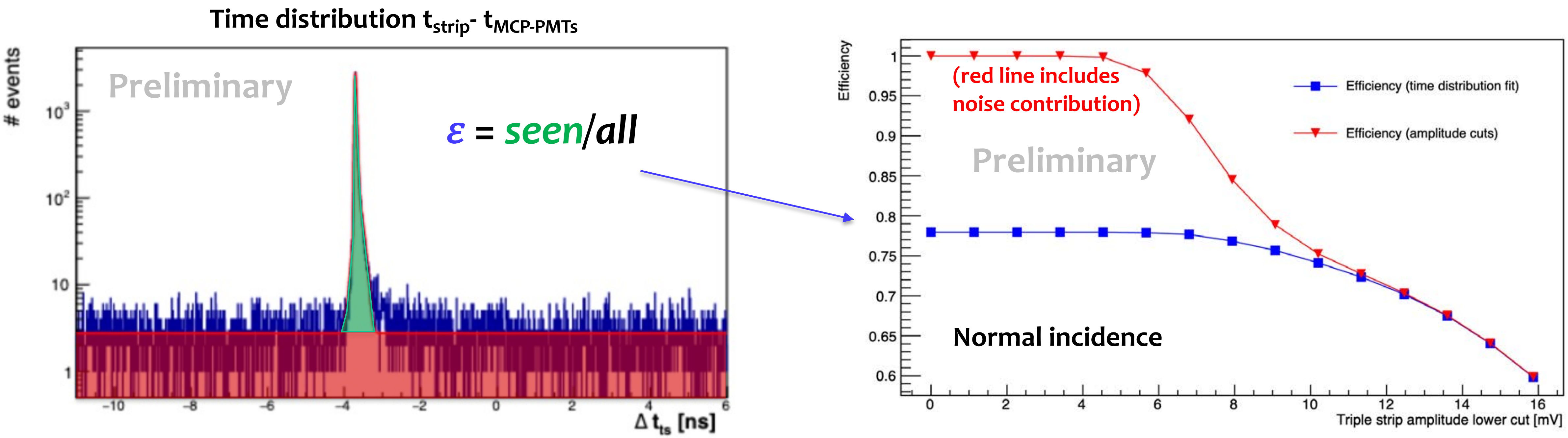
For each sensor's waveform:

- **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 15 mV signal amplitude, linear interpolation around threshold (time-walk effect is present)**
  - **LE corrected for the amplitude to suppress the time-walk effect**
  - **Spline: a classic CFD at 20% with rising edge interpolated with a spline**
  - ***Reference*: 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**





Efficiency: method


Time distribution t_{strip}- $t_{MCP\text{-}PMTs}$

ε = *seen*/*all*

(red line includes noise contribution)

Normal incidence

- Time distribution of **all triple-strip signals** w.r.t. MCP-PMTs and count as 'seen' the ones under the peak (the flat background corresponds to undetected hits)
- 3D pixel detection (geometrical) efficiency at normal incidence is in agreement with calculated fraction of active area (~80%)