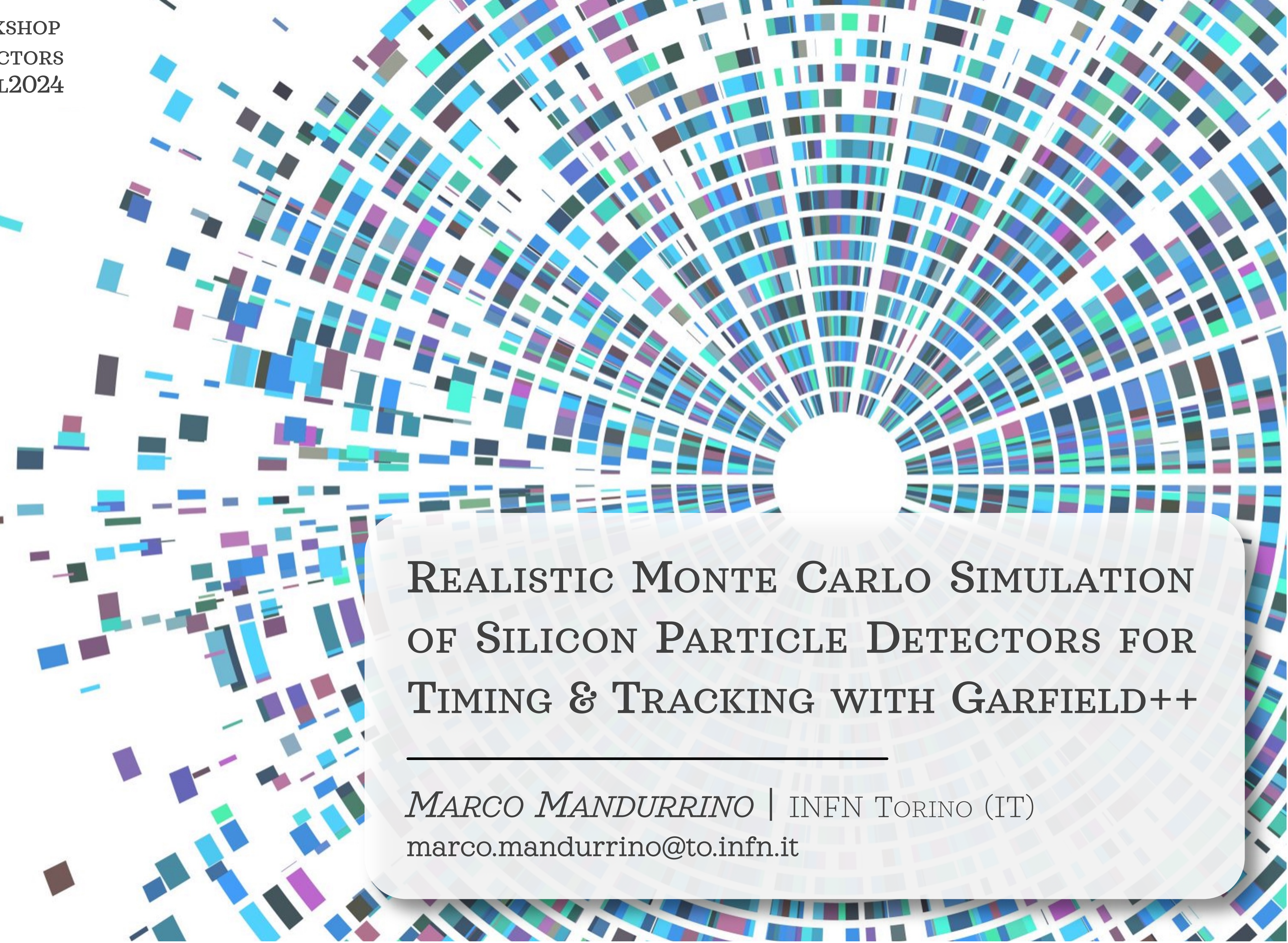
ELEVENTH INTERNATIONAL WORKSHOP
ON SEMICONDUCTOR PIXEL DETECTORS
FOR PARTICLES AND IMAGING, PIXEL2024

UNIVERSITY OF STRASBOURG,
18-22 NOVEMBER 2024



REALISTIC MONTE CARLO SIMULATION OF SILICON PARTICLE DETECTORS FOR TIMING & TRACKING WITH GARFIELD++

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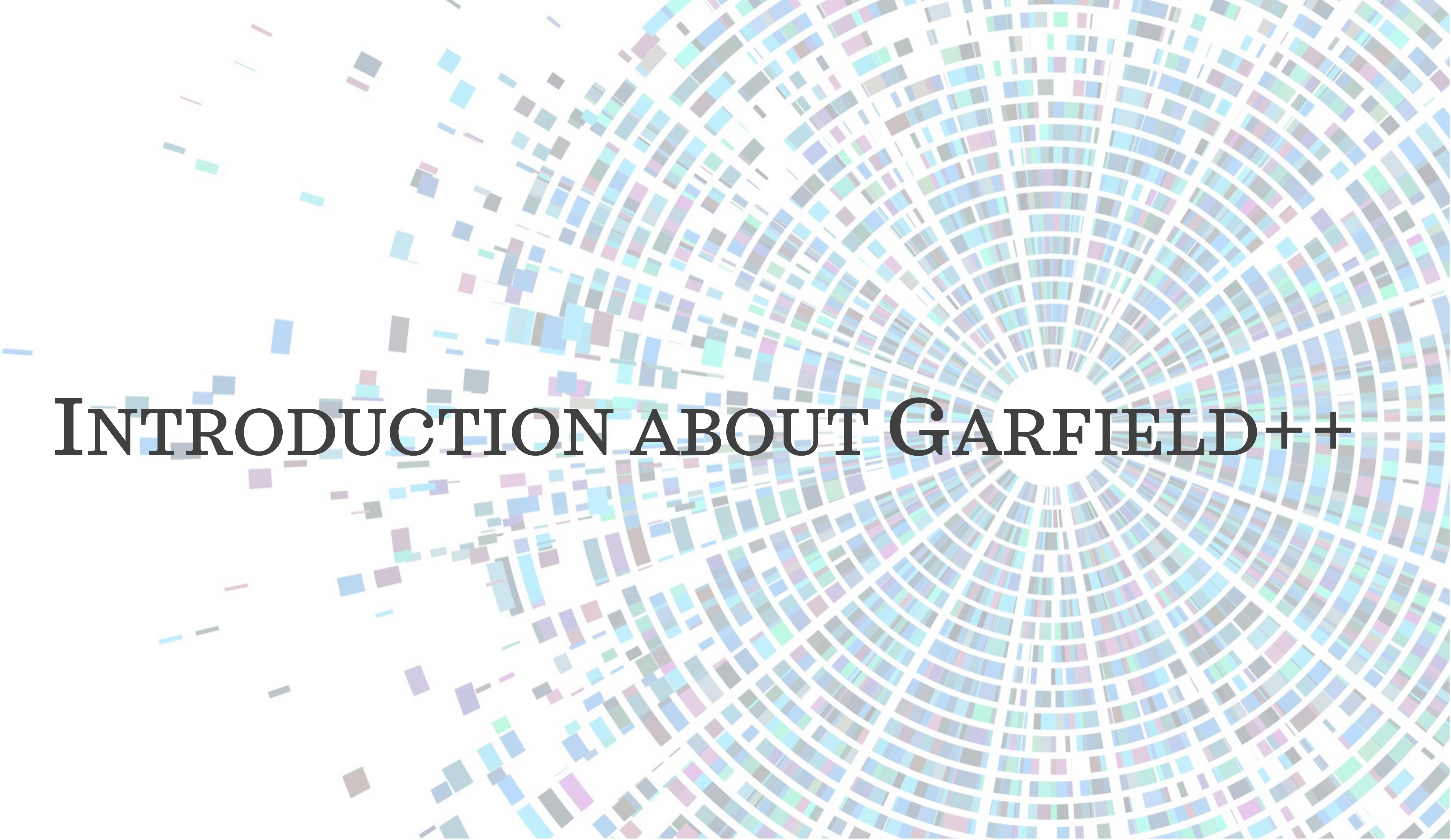
OUTLINE

- Introduction about Garfield++
- Simulation of solid-state detectors
    - electric field setup
    - signal formation
    - charge multiplication
    - read-out electronics
- Case-study I: monolithic CMOS detectors for timing
- Case-study II: monolithic CMOS detectors for 4D particle tracking
- Final Comments & Acknowledgments



Introduction about Garfield++

INTRODUCTION ABOUT GARFIELD++

> "**Garfield++** is an object-oriented toolkit for the detailed simulation of particle detectors based on **ionization** measurement in **gases** or **semiconductors**"

- **Garfield++** is an evolution of the previous Garfield tool (*Rob Veenhof*, 1984) with which shares functionality, and from which differentiates by some point:
  - treatment of charge carrier transport
  - user interface (ROOT-based)
- Its main elements are:
  - **ionization** pattern: *relativistic particles*, *X-ray* absorption, (low-energy) *ions* or others
  - **transport** properties: transport and avalanche in *gas mixtures* or *semiconductors*
  - **electric field** calculation: different options available …

INTRODUCTION ABOUT GARFIELD++

➛ Primary Ionization

- relativistic particles: HEED (High-Energy ElectroDynamics) program, extension of the PAI (Photo-Absorption Ionization) model
- X-ray photoabsorption: interface with HEED
- Ion tracks: imported results from SRIM† or TRIM‡. The first simulates the energy loss of ions in matter, the latter is a Monte Carlo extension that, in addition, accounts for individual ion trajectories
- Other: ionization/avalanche in gases (Magboltz), interface with GEANT4, …

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† Stopping Range of Ions in Matter; ‡ TRansport of Ions in Matter

INTRODUCTION ABOUT GARFIELD++

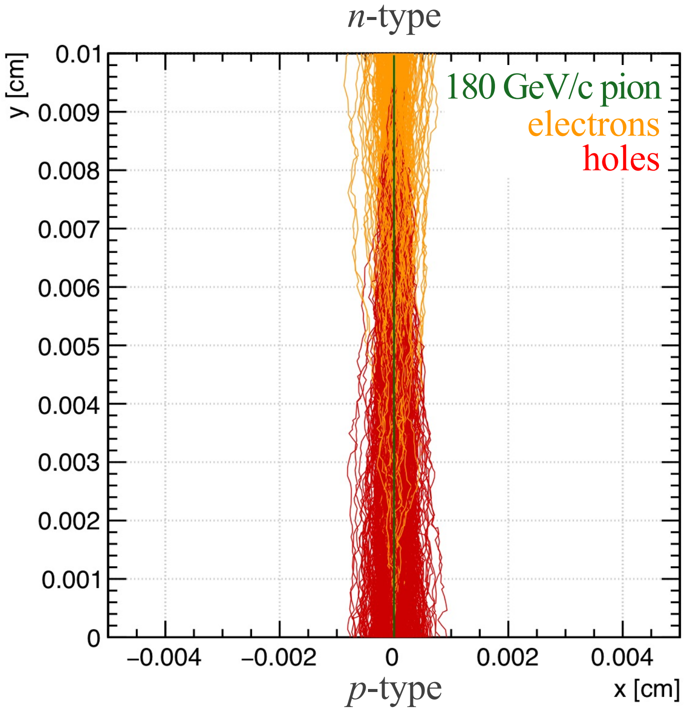
➛ Charge Transport

To find the **drift lines** of **individual electrons** and **holes**, the first-order equation of motion has to be solved.

Garfield++ offers (at least) two different strategies:

- Runge-Kutta-Fehlberg (RKF) integration, proceeding by **iteratively estimating** the **charge position**, **drift velocity** and **time step**
- Monte Carlo (MC) integration, based on **macroscopic transport parameters**

…plus even more accurate methods: see few slides ahead



Source: garfieldpp.web.cern.ch/garfieldpp/

INTRODUCTION ABOUT GARFIELD++

➢ **Charge Transport**: the *Monte Carlo* integration

- a **step** of length $\Delta s = v_d \Delta t$ in the direction of the drift velocity v_d, relative to the local electric and magnetic field, is calculated. Time-step Δt or distance-step Δs must be specified by the user
- a **random diffusion step** is sampled from three uncorrelated Gaussian distributions: one with standard deviation $\sigma_{//} = D_{//}\sqrt{\Delta s}$ for the component parallel to the drift velocity and two with standard deviations $\sigma_T = D_T\sqrt{\Delta s}$ for the transverse components
- the **location** is updated by vectorially adding the two steps

INTRODUCTION ABOUT GARFIELD++

➢ **Electric field**

The field maps can be **imported** from text files or external FEM tools like

- Ansys
- Synopsys® Sentaurus TCAD
- Elmer
- CST Studio
- COMSOL Multiphysics

as well as **defined analytically** (only simple structures) or **directly computed***

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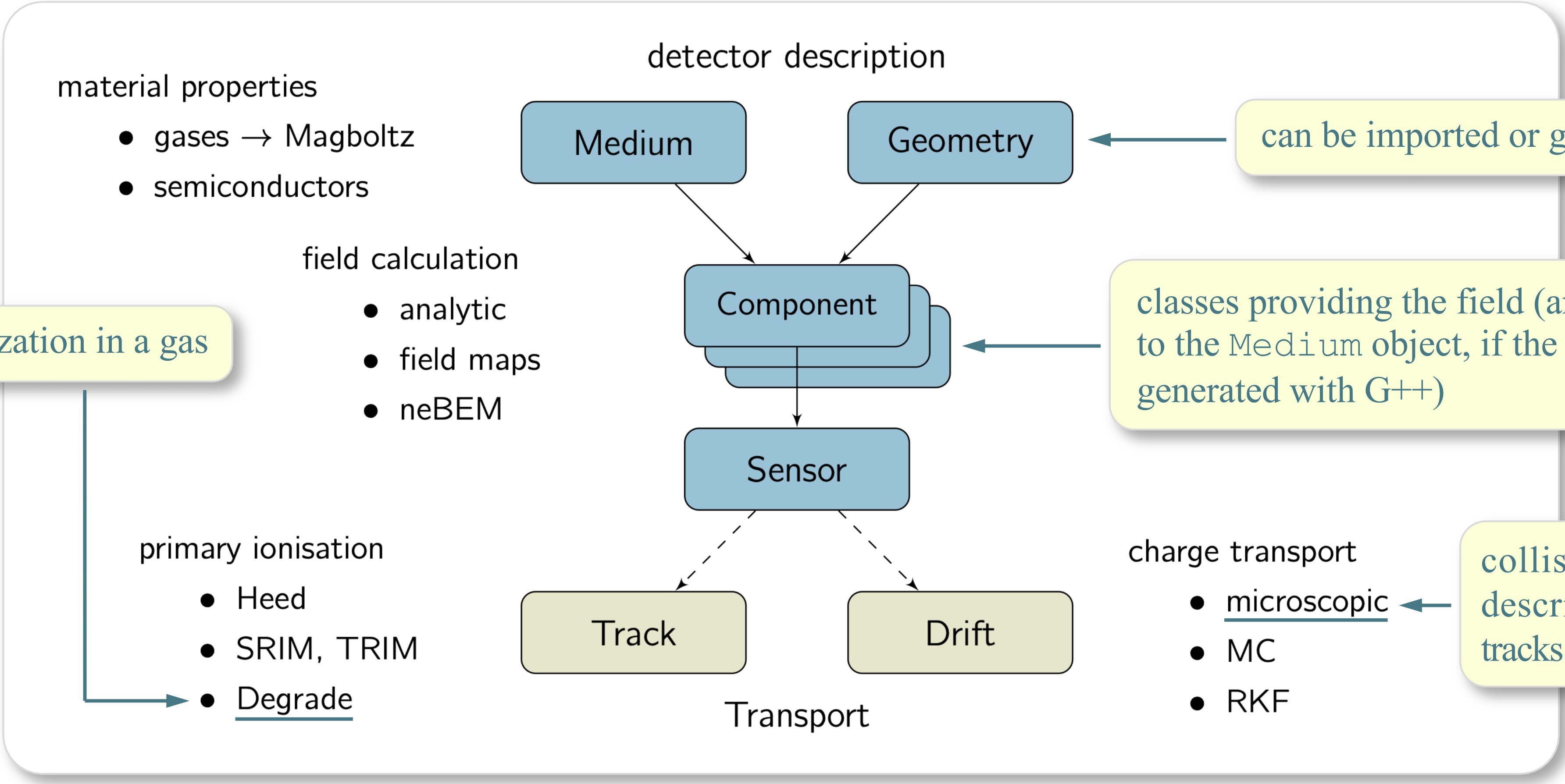
* through an interface with the **neBEM** (nearly exact Boundary Element Method) solver, or applying a **thin–wire limit** solution

INTRODUCTION ABOUT GARFIELD++

Overview of the Simulation Flow



detector description

material properties

- gases → Magboltz
- semiconductors

Medium

Geometry

can be imported or generated

field calculation

- analytic
- field maps
- neBEM

Component

classes providing the field (and a pointer to the `Medium` object, if the geometry is generated with G++)

electrons ionization in a gas

Sensor

primary ionisation

- Heed
- SRIM, TRIM
- Degrade

Track

Drift

Transport

charge transport

- microscopic
- MC
- RKF

collision-by-collision description of particle tracks (microscopic MC)

Source: Garfield++ User Guide

Simulation of Solid-State Detectors

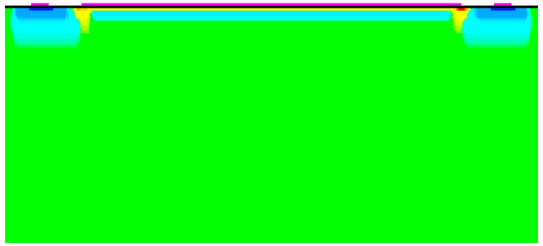
SIMULATION OF SOLID-STATE DETECTORS

Typical simulation-based design process of **silicon detectors** for **HEP applications**:

TCAD

1. **geometry definition** with **TCAD** tools (2D or 3D)[1]
2. definition of **active electrodes**[2] for the signal acquisition
3. **exporting field** and **potential** maps (no need to redefine the mesh in Garfield++)

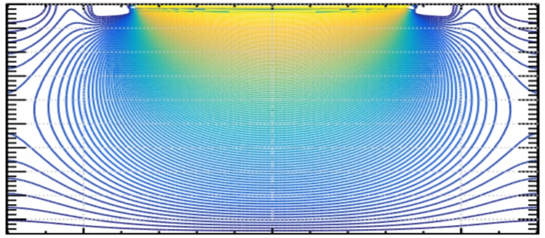
geometry, mesh,
doping ⇒ electric field, potential



G++

4. **calculation** of **weighting field** and **weighting potential**
5. **MC simulation** of **relativistic particles** crossing the detector (HEED model)
6. possible addition of readout **electronic noise**

weighting field,
weighting potential ⇒ signals



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[1] to implement arrays, the user can define a periodicity of the geometry

[2] to generate a weighting field/potential, one has to induce a small perturbation δV ($\sim$1% of V_{bias}) on the collection electrode

SIMULATION OF SOLID-STATE DETECTORS

To generate signals, once the weighting field has been generated, one has to set:

- the incident **charged particle type**: e^-, e^+, μ^-, μ^+, π^-, π^+, K^-, K^+, p, $\bar{p}$, d
- its **momentum**
- the **trajectory**:
  - initial position and time vector `(x0,y0,z0,t0)`
  - direction vector `(dx0,dy0,dz0)`

Besides selecting the **distance-step** Δs (or **time-step** Δt) for the charge transport process, we also need to set the **granularity** of the signal acquisition, through:

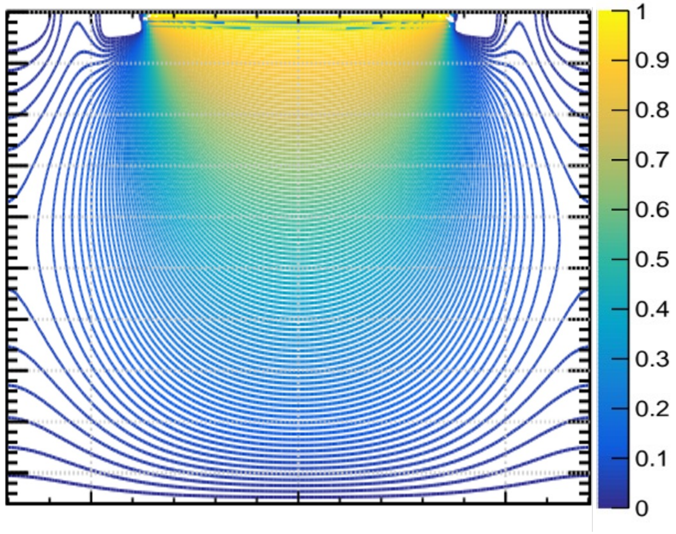
- initial time
- final time
- number of bins

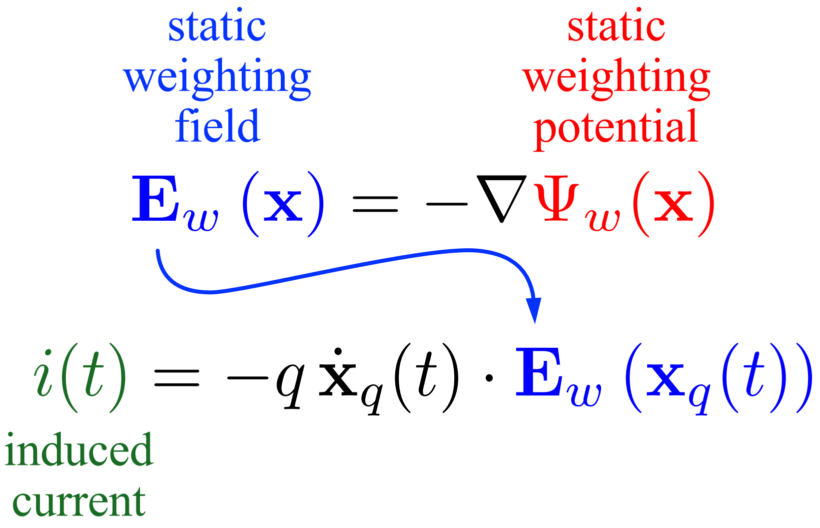
SIMULATION OF SOLID-STATE DETECTORS

Now we are ready to generate a signal

- apply a **potential step δV** to the **readout electrode**: $\Psi_w = \frac{\Psi(V+\delta V)-\Psi(V)}{\delta V}$
- compute the **induced current** through the **Ramo-Shockley theorem**

weighting potential





static weighting field

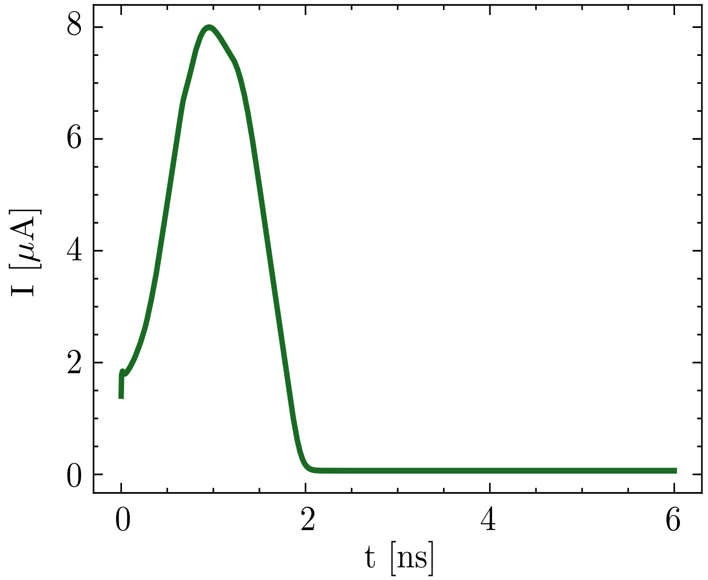
static weighting potential

$$\mathbf{E}_w(\mathbf{x}) = -\nabla \Psi_w(\mathbf{x})$$

$$i(t) = -q\,\dot{\mathbf{x}}_q(t)\cdot\mathbf{E}_w(\mathbf{x}_q(t))$$

induced current

induced current



SIMULATION OF SOLID-STATE DETECTORS

In presence of **internal gain**, there are four options for the **ionization coefficients**

- **Grant**: $\alpha_{\mathrm{Gra}}(E) = A_{\mathrm{Gra}} \exp\left(-\frac{B_{\mathrm{Gra}}}{E}\right)$
- **Massey**: $\alpha_{\mathrm{Mas}}(E) = A_{\mathrm{Mas}} \exp\left(-\frac{B_{\mathrm{Mas}}(T)}{E}\right)$, with $B_{\mathrm{Mas}}(T) = C_{\mathrm{Mas}} + D_{\mathrm{Mas}} \cdot T$
- **van Overstraeten – de Man**: $\alpha_{\mathrm{vOv}}(E) = \gamma A_{\mathrm{vOv}} \exp\left(-\gamma \frac{B_{\mathrm{vOv}}}{E}\right)$
- **Okuto – Crowell**: $\alpha_{\mathrm{Oku}}(E) = A_{\mathrm{Oku}} \left(1 + (T - 300)\, C_{\mathrm{Oku}}\right)\, E \exp\left(-\left(\frac{B_{\mathrm{Oku}} \left(1 + (T - 300)\, D_{\mathrm{Oku}}\right)}{E}\right)^2\right)$

The default model is van Overstraeten – de Man, with coefficients

$$A_{\mathrm{vOv},n} = 7.030 \cdot 10^5\,\mathrm{cm}^{-1} \qquad B_{\mathrm{vOv},n} = 1.231 \cdot 10^6\,\mathrm{V/cm}$$

$$A_{\mathrm{vOv},p} = 1.582 \cdot 10^6\,\mathrm{cm}^{-1}\ (E < 400\,\mathrm{kV/cm}) \qquad B_{\mathrm{vOv},p} = 2.036 \cdot 10^6\,\mathrm{V/cm}\ (E < 400\,\mathrm{kV/cm})$$

$$A_{\mathrm{vOv},p} = 6.710 \cdot 10^5\,\mathrm{cm}^{-1}\ (E > 400\,\mathrm{kV/cm}) \qquad B_{\mathrm{vOv},p} = 1.693 \cdot 10^6\,\mathrm{V/cm}\ (E > 400\,\mathrm{kV/cm})$$

$$\gamma = \frac{\tanh\left(\frac{\hbar\omega_{\mathrm{op}}}{2k_{\mathrm{B}}300\mathrm{K}}\right)}{\tanh\left(\frac{\hbar\omega_{\mathrm{op}}}{2k_{\mathrm{B}}T}\right)}$$

SIMULATION OF SOLID-STATE DETECTORS

Garfield++ allows the modeling of the **front-end electronics** by convoluting the induced current signal with a **transfer function** (delta response function)

The transfer function can be:

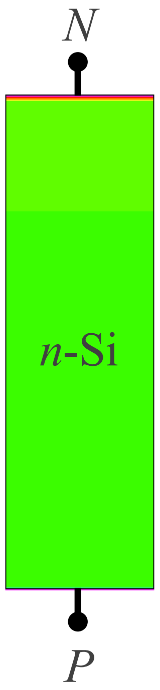
- a user-specific function
- a table
- a pre-implemented analytic model, like the following *n*-stage shaper

$$f(t) = g \exp(n) \left(\frac{t}{t_p}\right)^n \exp(-t/\tau), \;\; \text{with } t_p = n\tau$$

Furthermore, also the **noise** can be added, reproducing a given equivalent-noise charge at the amplifier output

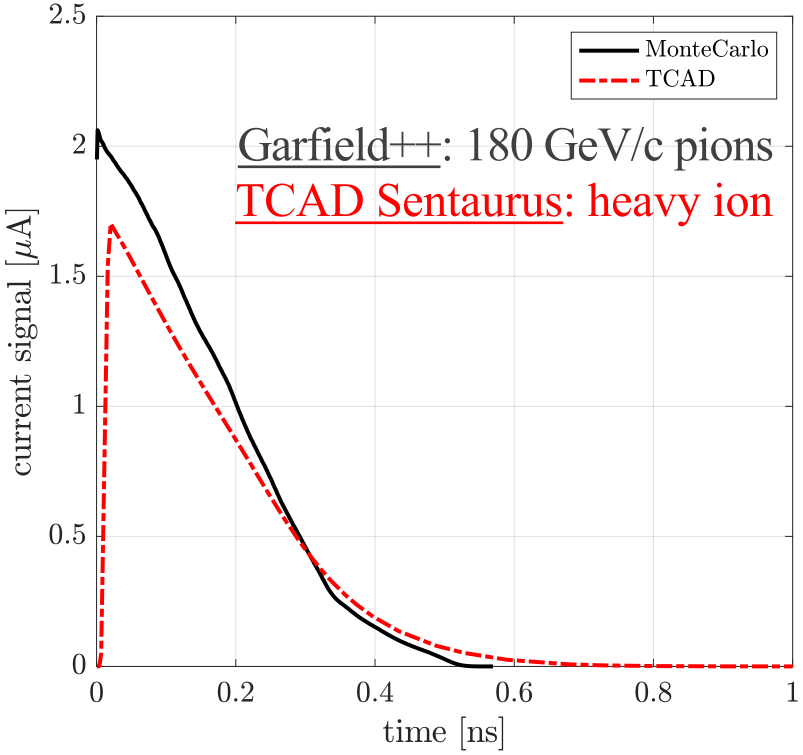
SIMULATION OF SOLID-STATE DETECTORS

Example n.1: the *p-i-n* diode



TCAD implementation
IN: geometry, grid, doping, physics
OUT: field, potential

Signals simulated with **default** physics **models** and **parameters**

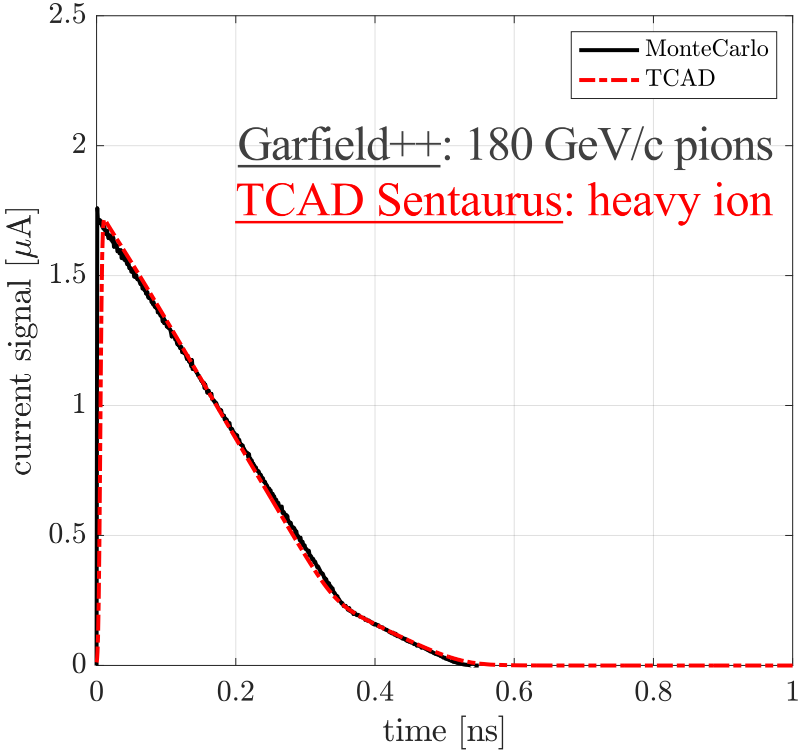


SIMULATION OF SOLID-STATE DETECTORS

Example n.1: the *p-i-n* diode

TCAD implementation
IN: geometry, grid, doping, physics
OUT: field, potential

Signals simulated with **optimized** physics **models** and **parameters**



Parameters involved in the **optimization**

Garfield++:

- mobility: **Masetti** model (default)
- saturation velocity: **Canali** model (def.)
- dimension along the 3rd axis: **10 µm**
- charge transport **time-step**: **1 ps**

TCAD:

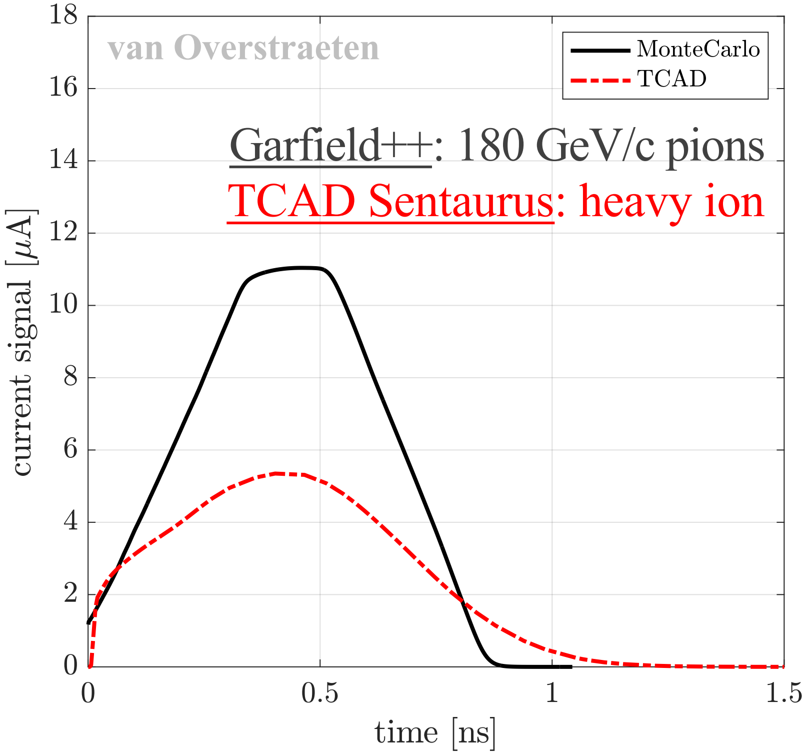
- mobility/v_{sat}: **Extended-Canali** model
- **track width**: **3 µm**
- transient **MaxStep**: **1 ps**
- number of **pairs/µm**: **~70**

SIMULATION OF SOLID-STATE DETECTORS

Example n.2: the LGAD

TCAD implementation
IN: geometry, grid, doping, physics
OUT: field, potential

Signals simulated with **default** physics **models** and **parameters**

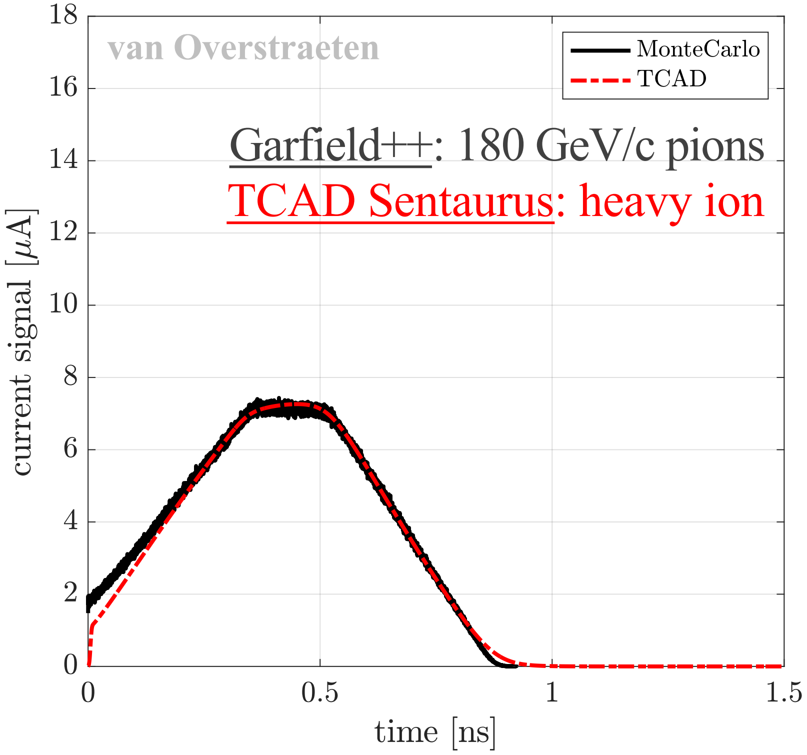


SIMULATION OF SOLID-STATE DETECTORS

Example n.2: the LGAD

TCAD implementation
IN: geometry, grid, doping, physics
OUT: field, potential

Signals simulated with **optimized** physics **models** and **parameters**



Parameters involved in the **optimization**

Garfield++:

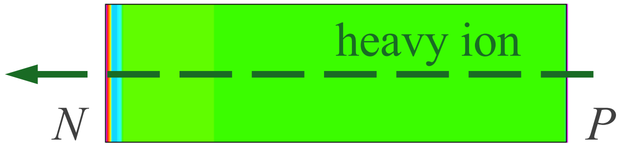
- mobility: **Masetti** model (default)
- saturation velocity: **Canali** model (def.)
- dimension along the 3rd axis: **10 µm**
- charge transport **time-step**: **0.1 ps**

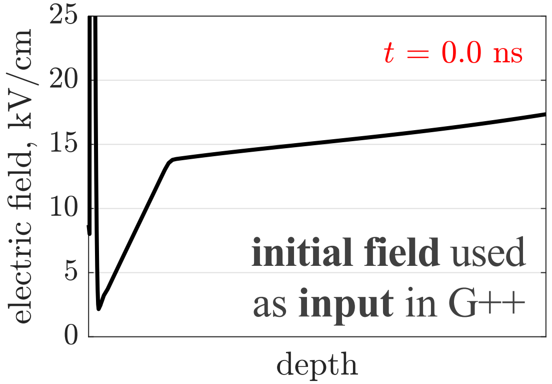
TCAD:

- mobility/v_{sat}: **Extended-Canali** model
- **track width**: 3 µm
- transient **MaxStep**: **0.5 ps**
- number of **pairs/µm**: **reduced** (probably to get rid of *space charge effects*)

SIMULATION OF SOLID-STATE DETECTORS

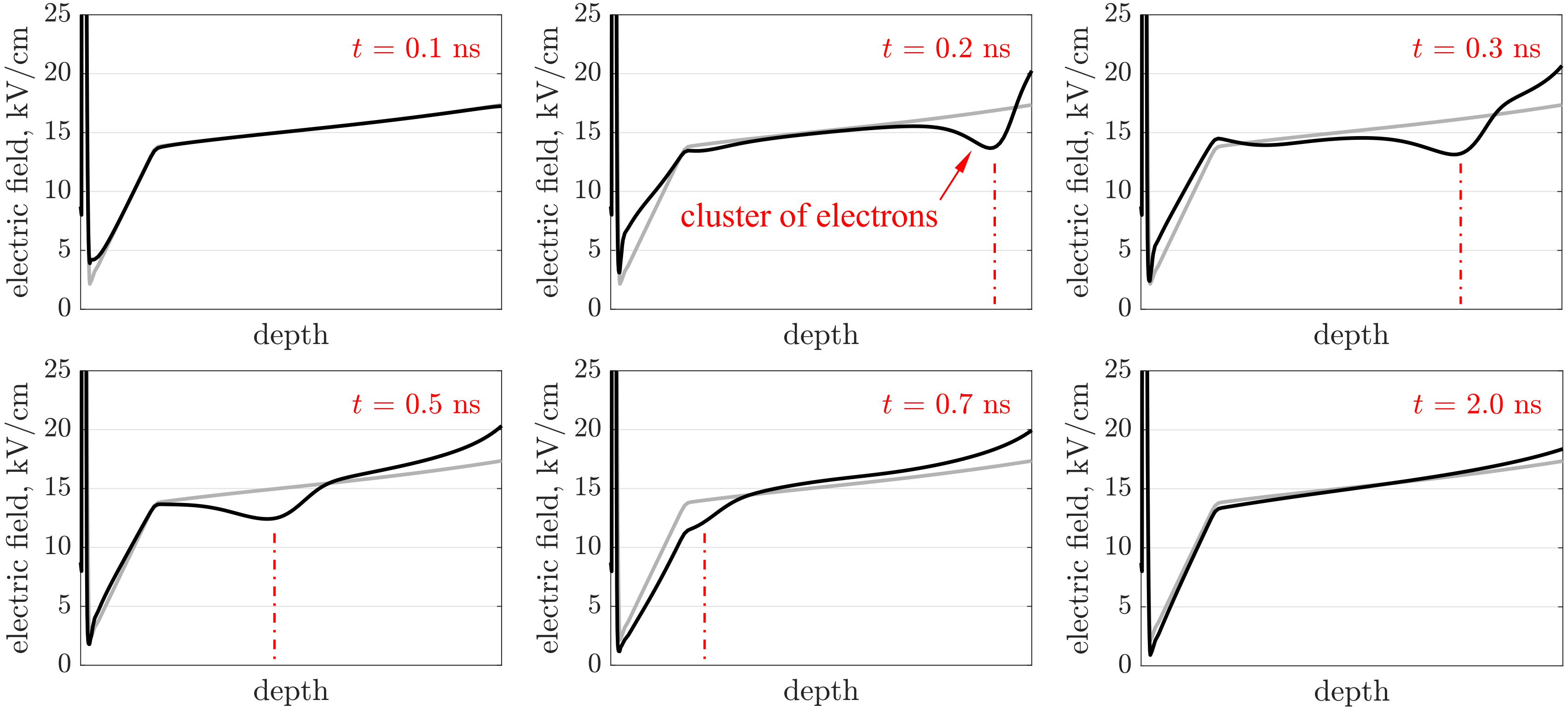
Example n.2: the LGAD





initial field used
as **input** in G++

Initial $t = 0$ (*grey*) versus dynamic (*black*) electric field



cluster of electrons

⇒ **Ongoing efforts** to include the **time-dependent field** in Garfield++

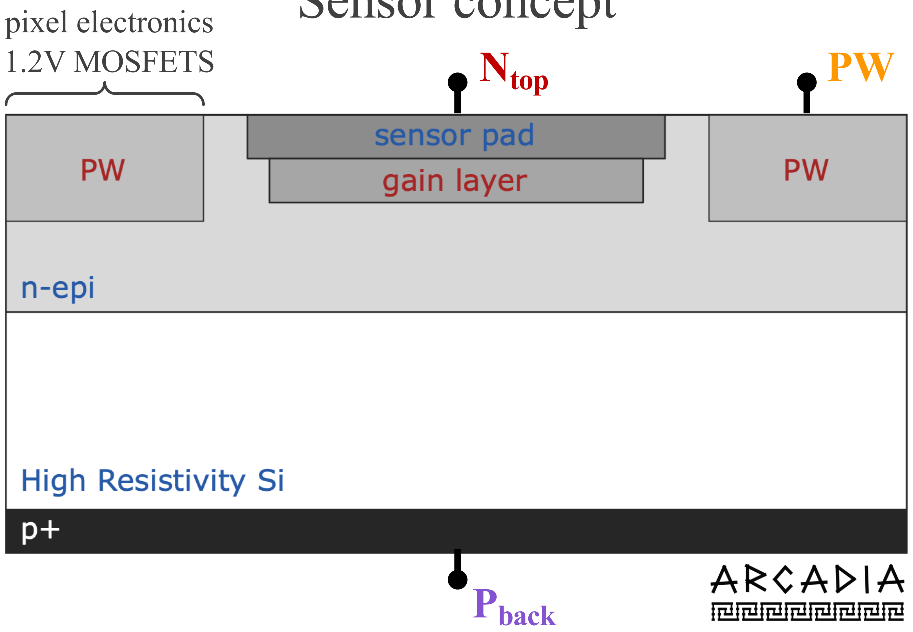
CASE-I

CMOS DETECTORS FOR TIMING

CASE-I: CMOS DETECTORS FOR TIMING

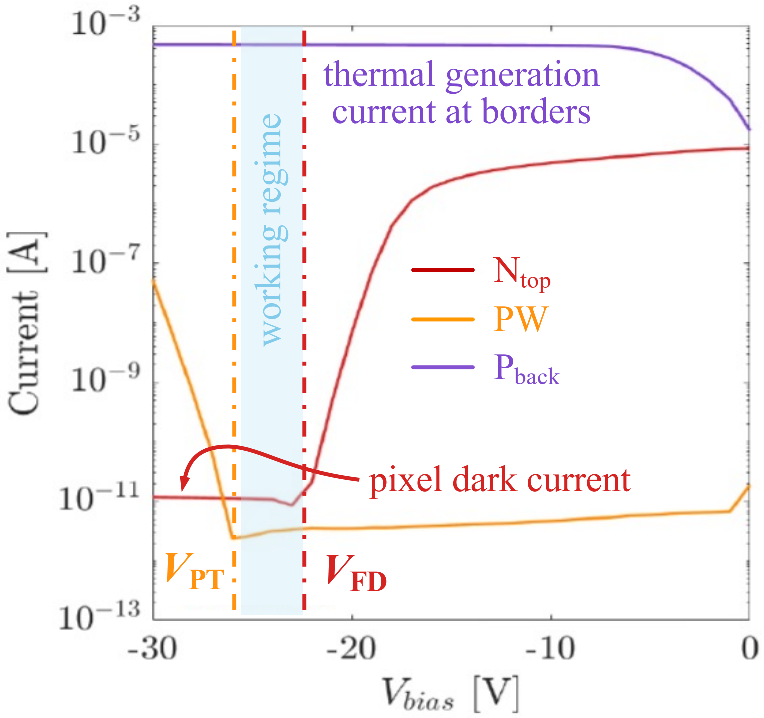
ARCADIA project (INFN) towards the development of **MAPS with gain**

Sensor concept



Standard **110 nm CMOS** process at **LFoundry**
***n*-type high resistivity** substrate
***n*-epi** active layer to **increase V_{PT}**

Operation regime

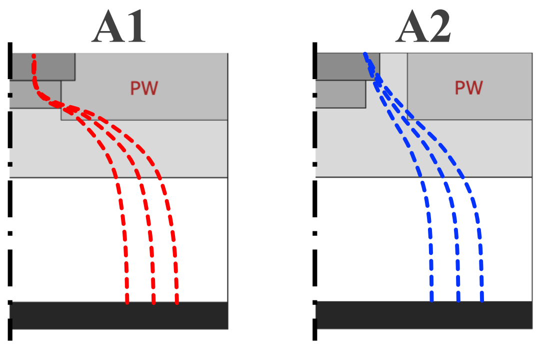


Main constraints

- **full-depletion** condition
- **punch-through** driven by the **backside bias**
- **edge breakdown** (due to gain) induced by the **topside voltage**

Two border layouts

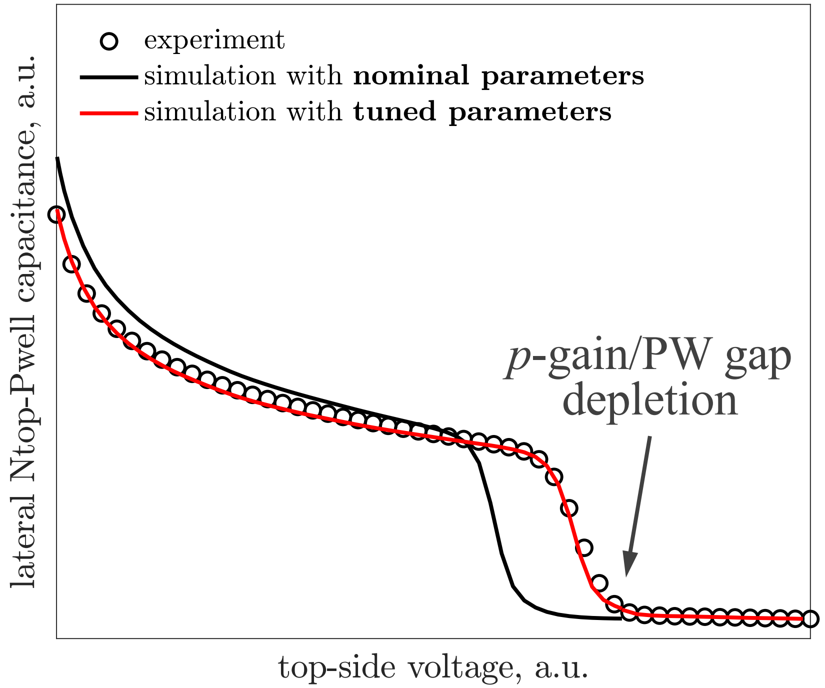
- **A1** – **uniform multiplication**
- **A2** (std.) – **uniform response**



CASE-I: CMOS DETECTORS FOR TIMING

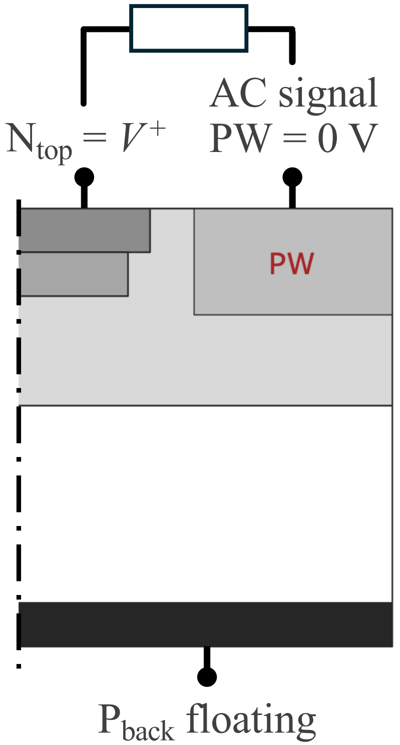
To have **realistic predictions** of the sensor figures-of-merit, the **technology parameters** have been previously tuned on **electrical measurements**

Lateral pad capacitance



Parameters involved in the tuning:

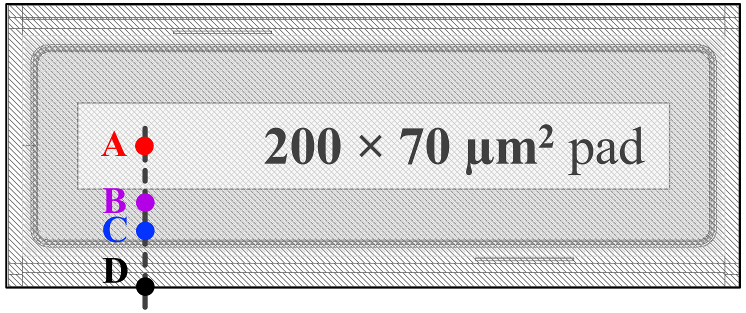
- **implants lateral diffusion** (p-gain, n^+, p-wells)
- p-gain **implantation energy** and **dose**
- n-epi **doping** concentration



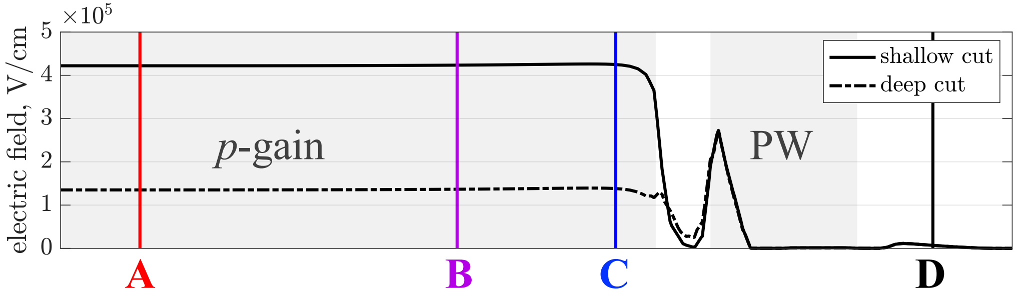
Case-I: CMOS Detectors for Timing

Particle scan to investigate the impact of **borders** on **charge collection**

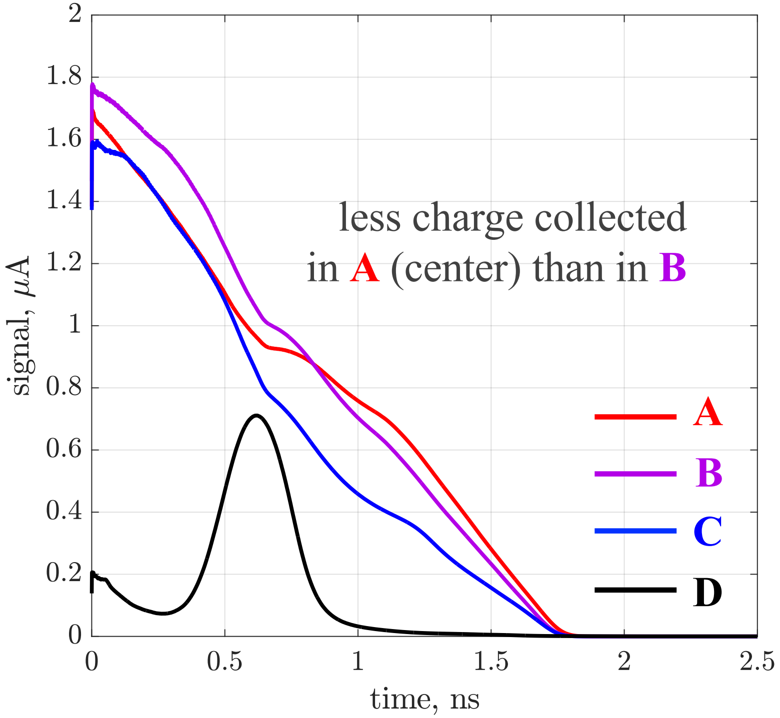
Sensor with **gain** and **front-end**
from **ARCADIA run3** – **layout A2**



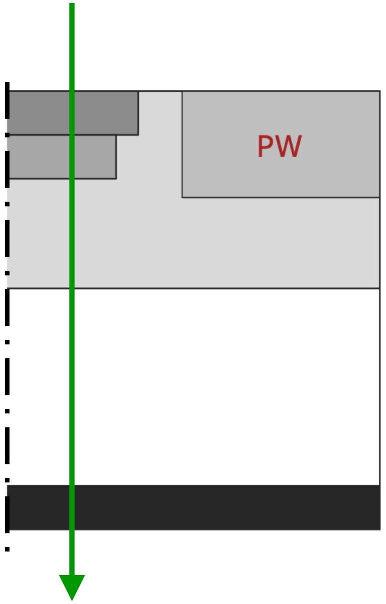
Electric field profile extracted at different depths



Average signals at
different coordinates
simulated with **Garfield++**



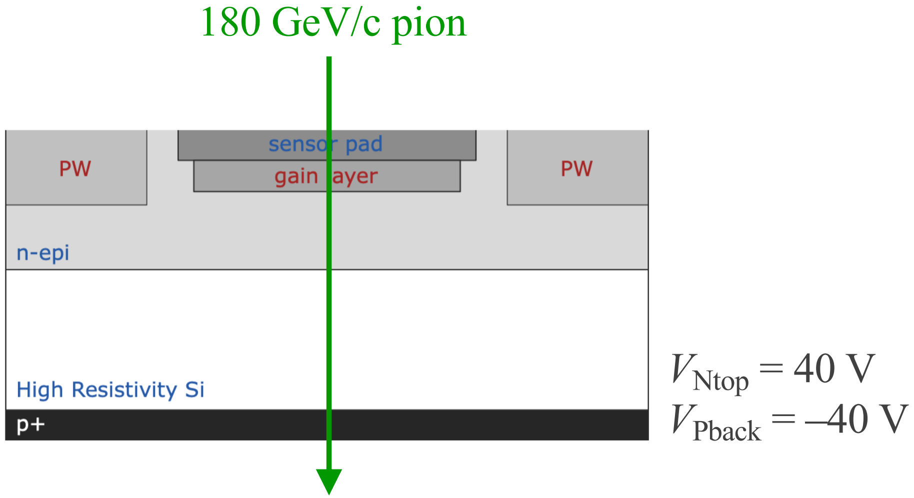
180 GeV/c
pion

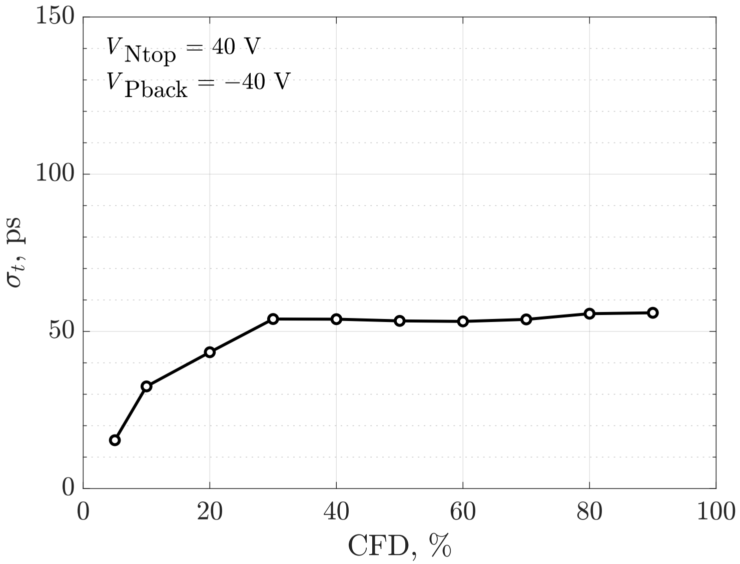


CASE-I: CMOS DETECTORS FOR TIMING

Further **numerical investigations** on the **response uniformity**:

- **Particle injection** in the **center** of the **active area**



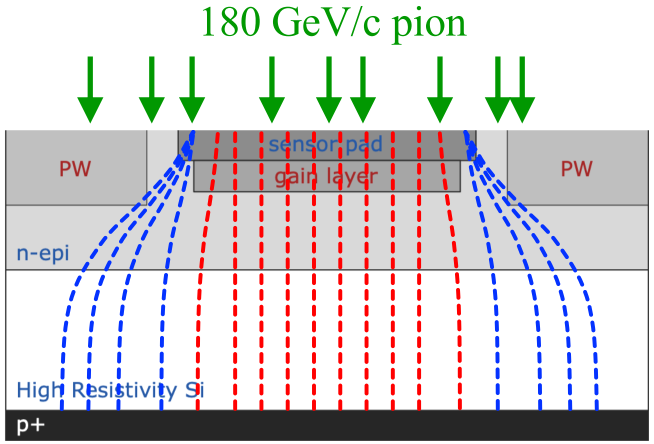


Time resolution estimated of the order of **~50 ps** (without electronics)

CASE-I: CMOS DETECTORS FOR TIMING

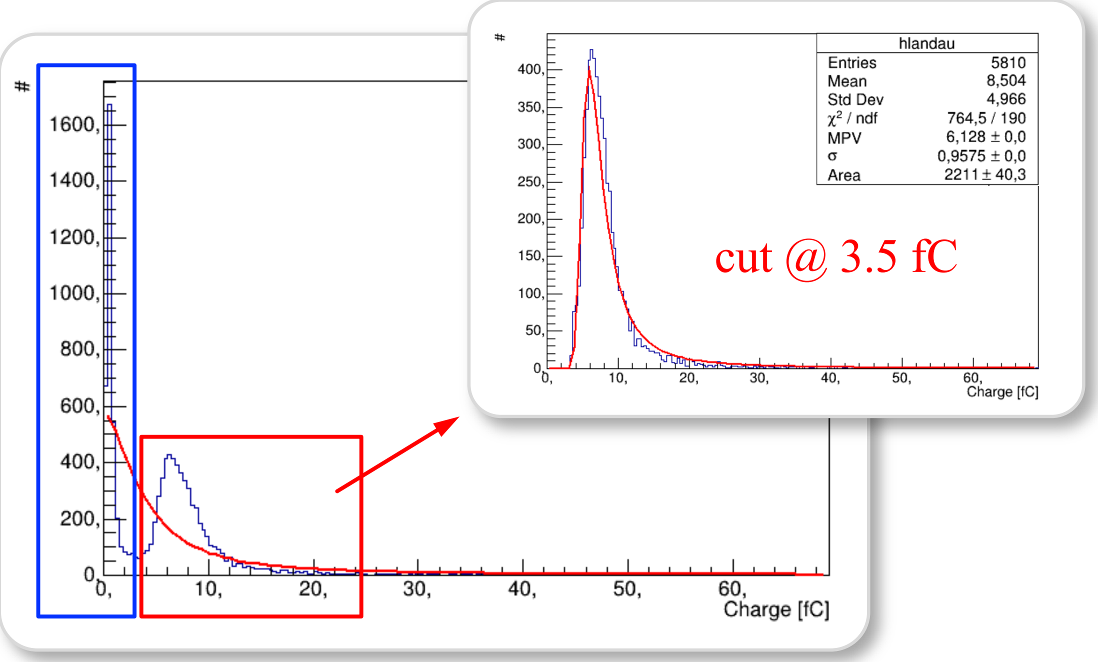
Further **numerical investigations** on the **response uniformity**:

- **Particle injection** according to a **random uniform distribution**



$V_{\mathrm{Ntop}} = 40$ V
$V_{\mathrm{Pback}} = -40$ V

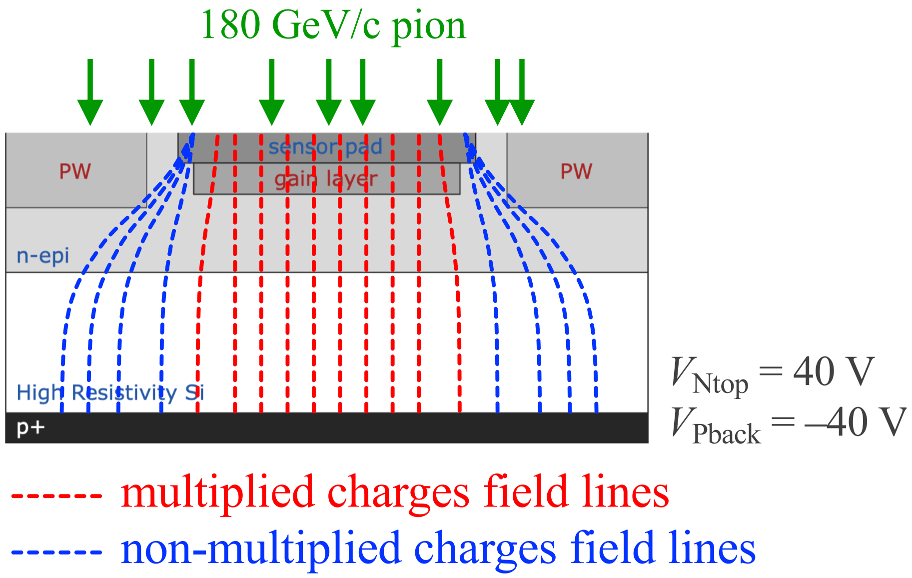
------ multiplied charges field lines
------ non-multiplied charges field lines

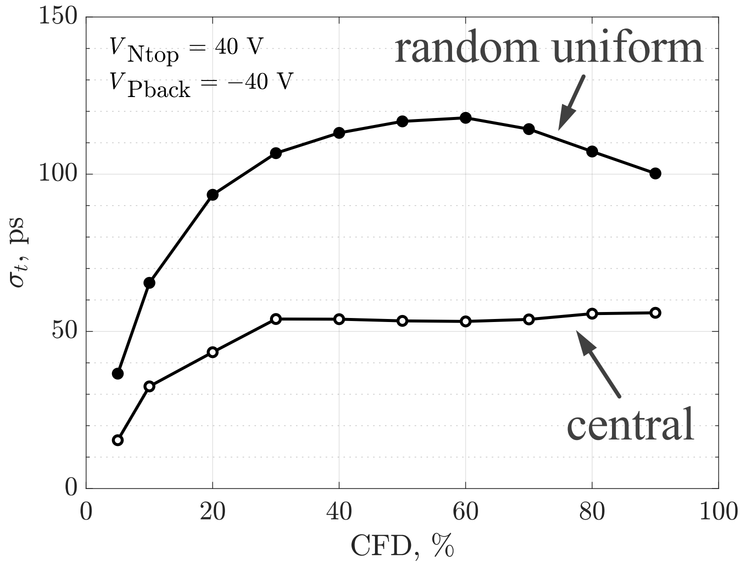


CASE-I: CMOS DETECTORS FOR TIMING

Further **numerical investigations** on the **response uniformity**:

- **Particle injection** according to a **random uniform distribution**





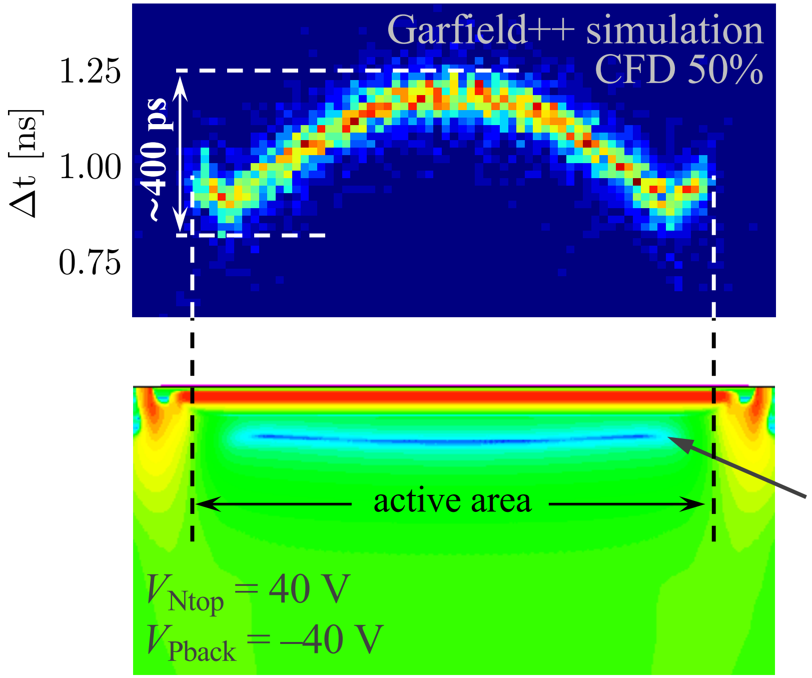
Why the **resolution is high** although **A2** was expected to have **good timing performances**?

CASE-I: CMOS DETECTORS FOR TIMING

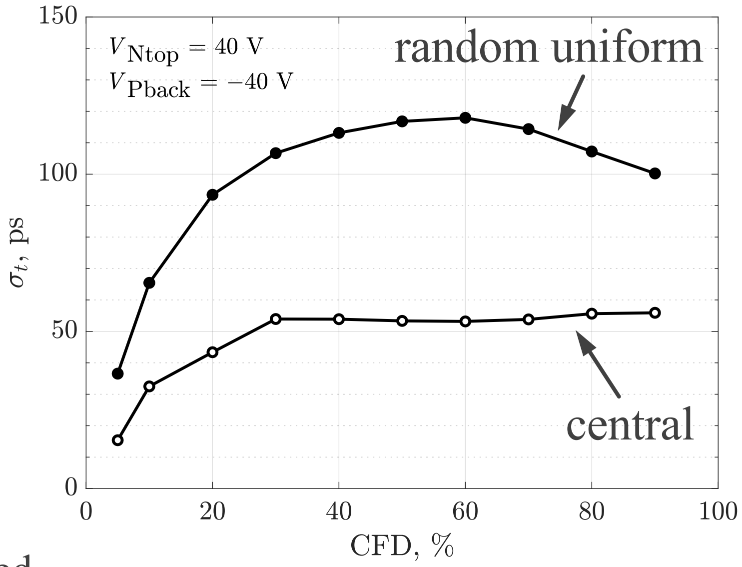
Further **numerical investigations** on the **response uniformity**:

- **Particle injection** according to a **random uniform distribution**

time/position correlation



field sag region (non-optimized substrate)



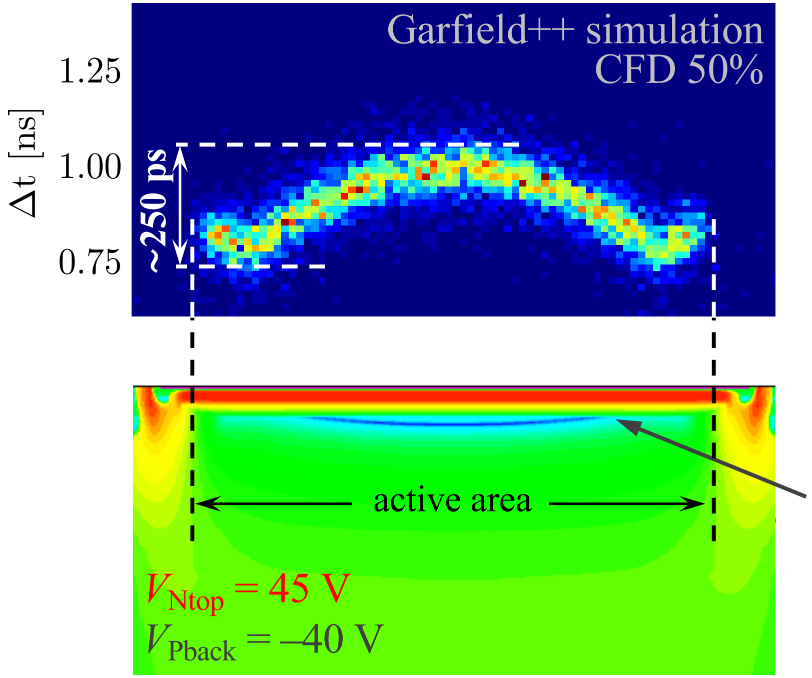
The **field sag** region **slows down** the multiplied **charges**, **deteriorating** the overall sensor **resolution**

Case-I: CMOS Detectors for Timing

Further **numerical investigations** on the **response uniformity**:

- **Particle injection** according to a **random uniform distribution**

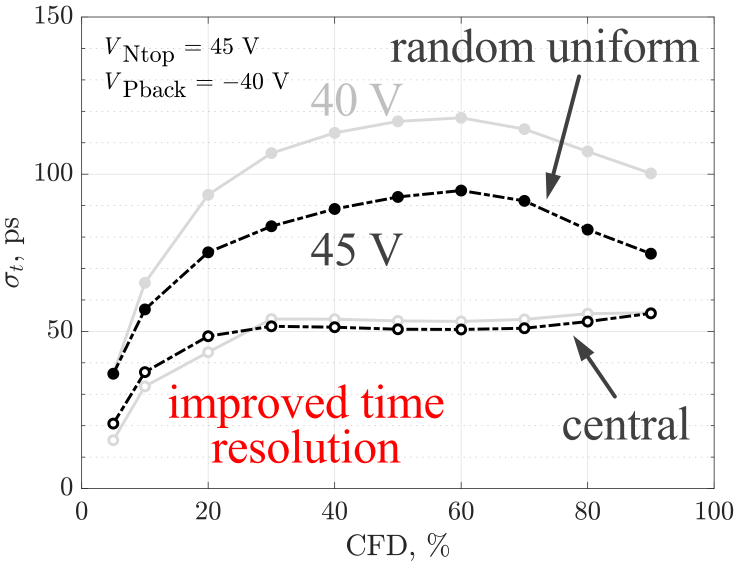
time/position correlation



faster response

reduced delay

reduced field sag



The **field sag** region **slows down** the multiplied **charges**, **deteriorating** the overall sensor **resolution**

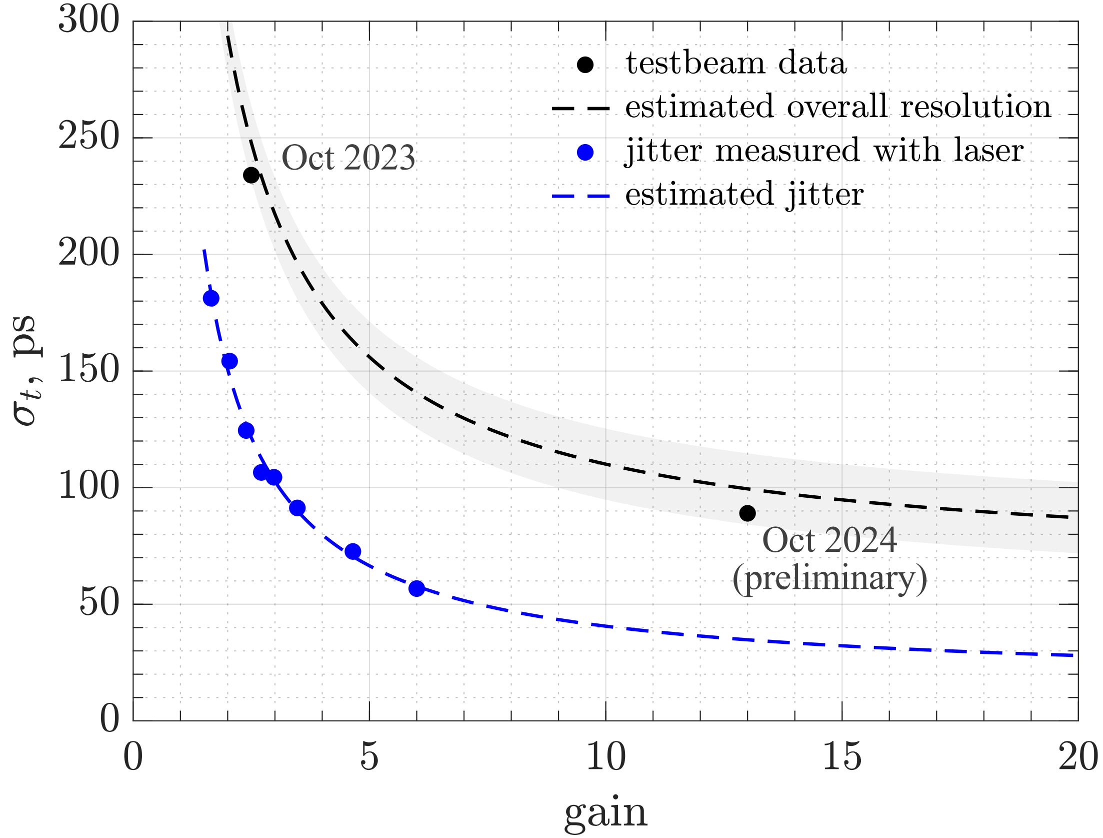
Increasing the **top-side bias** improves the performances (random)

Other studies in the backup:

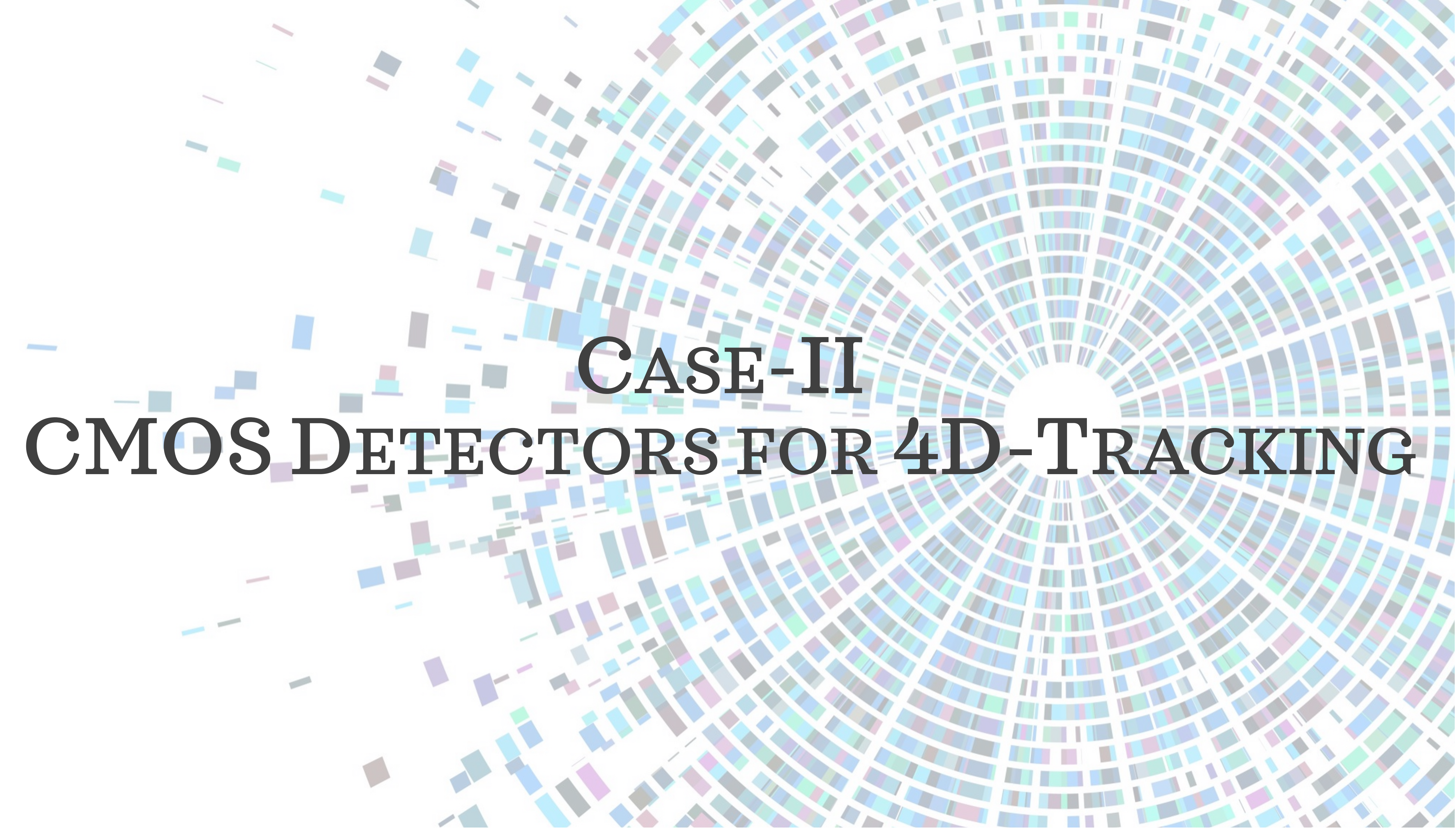
- w/ and w/o *noise*
- different *pad widths*
- different *sensor thicknesses*

CASE-I: CMOS DETECTORS FOR TIMING

Simulated versus **measured** time resolution in a **50-µm-thick CMOS-LGAD**



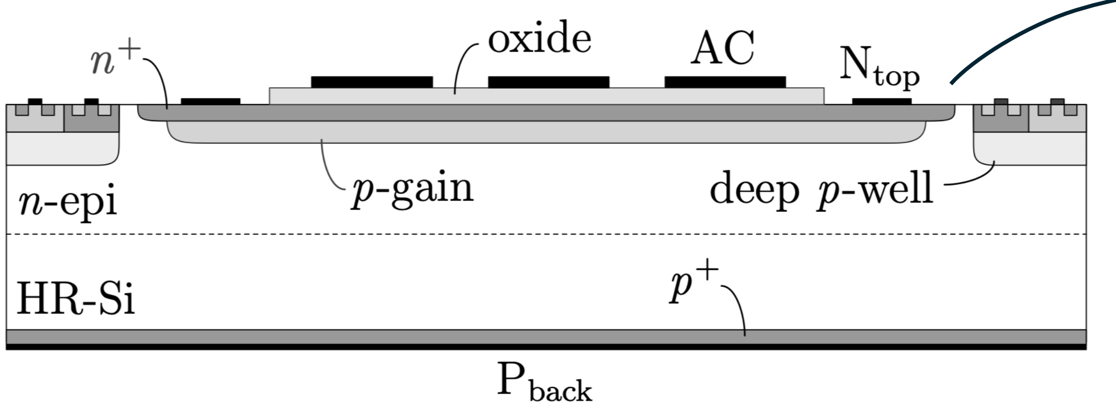
dashed curves are obtained by fitting **Garfield++ simulations** (*black*) in random uniform distribution configuration and **experimental data** (*blue*)

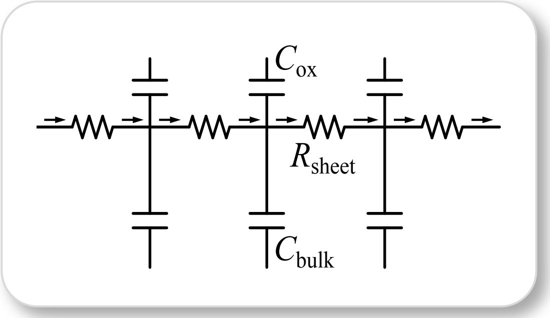


Case-II
CMOS Detectors for 4D-Tracking

Case-II: CMOS Detectors for 4D-Tracking

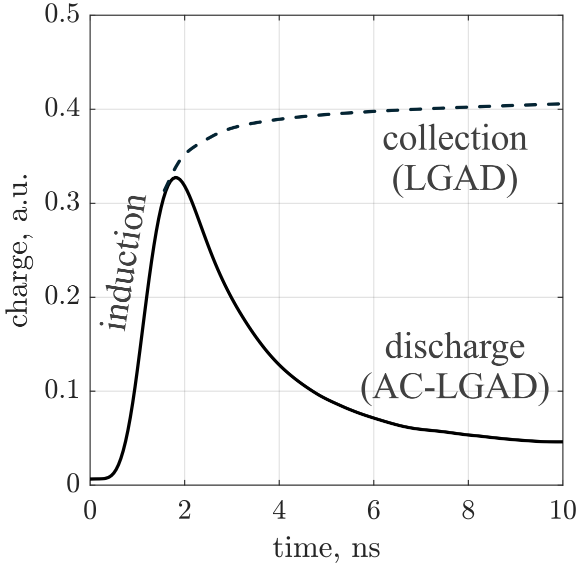
We are about to integrate the **RSD readout** into the monolithic **CMOS technology**

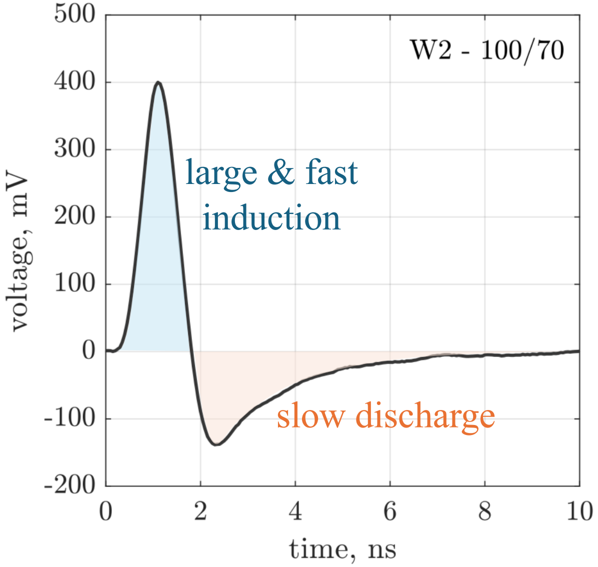




Resistive AC-Coupled Silicon Detectors
(RSD) readout: continuous p-gain
and resistive layer, coupling oxide

Same process and substrates of CMOS-LGADs
(**110 nm CMOS** at **LFoundry**)





CASE-II: CMOS DETECTORS FOR 4D-TRACKING

To calculate induced signals in presence of **finite conductivity** elements we need an **extension*** of the **Ramo-Shockley theorem** based on the fact that signal formation depends on both **charge movement** in the **drift medium** and the **time-dependent reaction** of **resistive materials**

In addition to the usual procedure to extract the potential map, one has to run a **transient simulation** after applying the voltage increment δV, saving the potential at **different points in time**:

$$\begin{cases} V_{\text{bias}} \to \Psi^{p}_{w}(\mathbf{x}) \\ \delta V \to \Psi^{d}_{w}(\mathbf{x},t) \end{cases} \Rightarrow \quad \Psi_{w}(\mathbf{x},t) = \overbrace{\Psi^{p}_{w}(\mathbf{x})}^{\substack{\textit{prompt} \\ \text{component}}} + \overbrace{\Psi^{d}_{w}(\mathbf{x},t)}^{\substack{\textit{delayed} \\ \text{component}}}, \;\; \text{with} \;\; \Psi^{d}_{w}(\mathbf{x},0) = 0$$

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* see Refs. W. Riegler, NIM A 535 (2004) 287, W. Riegler, NIM A 940 (2019) 453 and D. Janssens, Ph.D. thesis (2024)

CASE-II: CMOS DETECTORS FOR 4D-TRACKING

Standard procedure | Modified procedure

$$\Psi_w(\mathbf{x},t) \quad \Rightarrow \quad \Psi_w(\mathbf{x},t) = \overbrace{\Psi_w^p(\mathbf{x})}^{\textit{prompt}\ \text{component}} + \overbrace{\Psi_w^d(\mathbf{x},t)}^{\textit{delayed}\ \text{component}}$$

$$\overset{\text{static weighting field}}{\mathbf{E}_w(\mathbf{x})} = -\nabla \overset{\text{static weighting potential}}{\Psi_w(\mathbf{x})} \quad \Rightarrow \quad \overset{\text{dynamic weighting field}}{\mathbf{H}_w(\mathbf{x},t)} = -\nabla \overset{\text{dynamic weighting potential}}{\frac{\partial \Psi_w(\mathbf{x},t)}{\partial t}}$$

$$i(t) = -q\,\dot{\mathbf{x}}_q(t)\cdot\mathbf{E}_w\left(\mathbf{x}_q(t)\right) \quad \Rightarrow \quad i(t) = \boxed{-q\int_0^t \mathbf{H}_w\left(\mathbf{x}_q(t'),t-t'\right)\cdot\dot{\mathbf{x}}_q(t')\,\mathrm{d}t'}$$

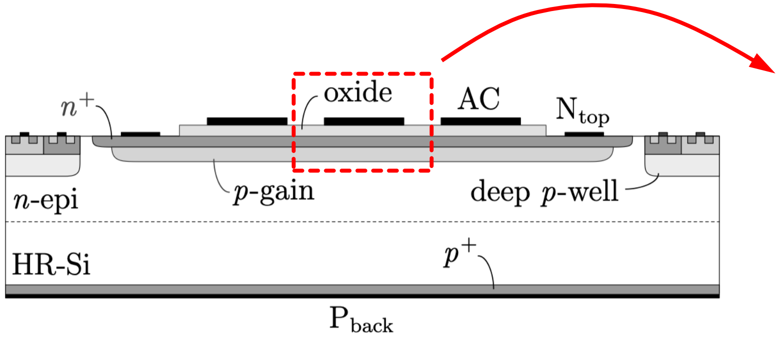
reaction from resistive medium

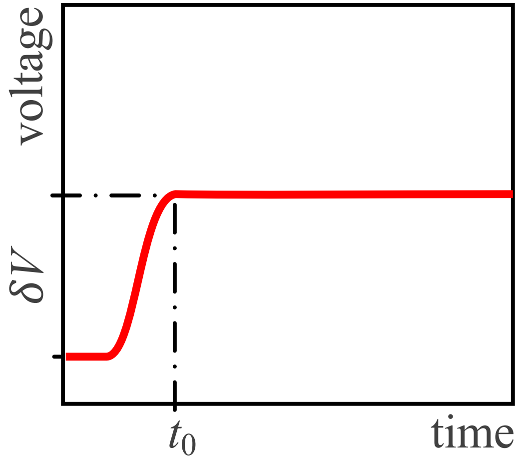
$$\boxed{-q\,\dot{\mathbf{x}}_q(t)\cdot\mathbf{E}_w\left(\mathbf{x}_q(t)\right)}$$

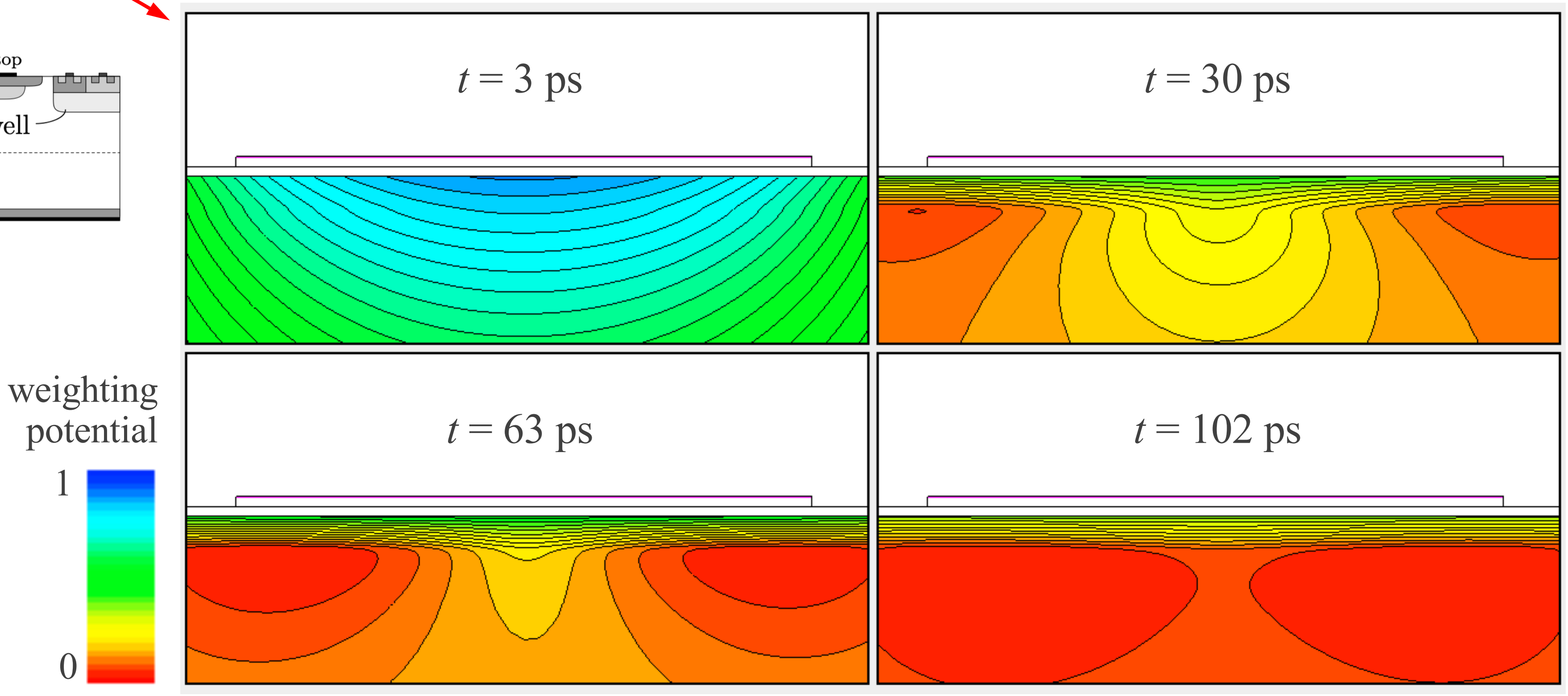
direct induction

Case-II: CMOS Detectors for 4D-Tracking

A real example of **dynamic weighting potential** $\Psi_w(\mathbf{x}, t)$ in an **RSD** at work:







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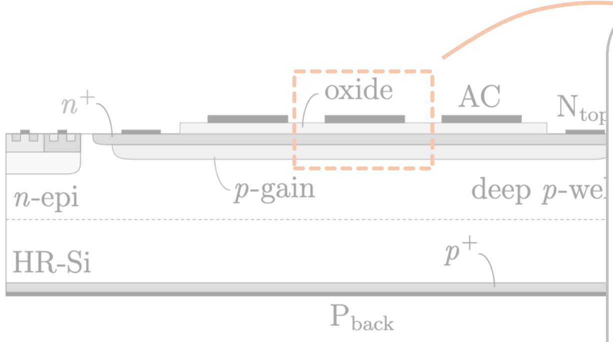
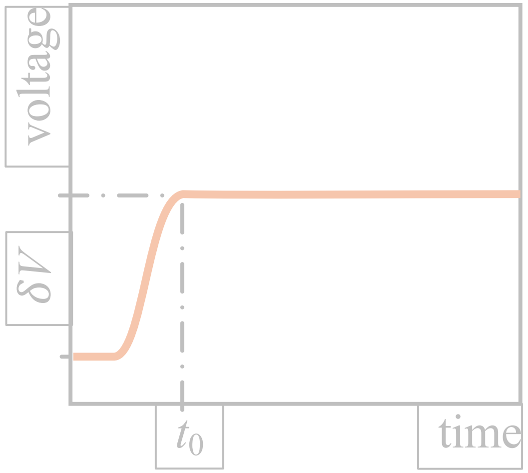
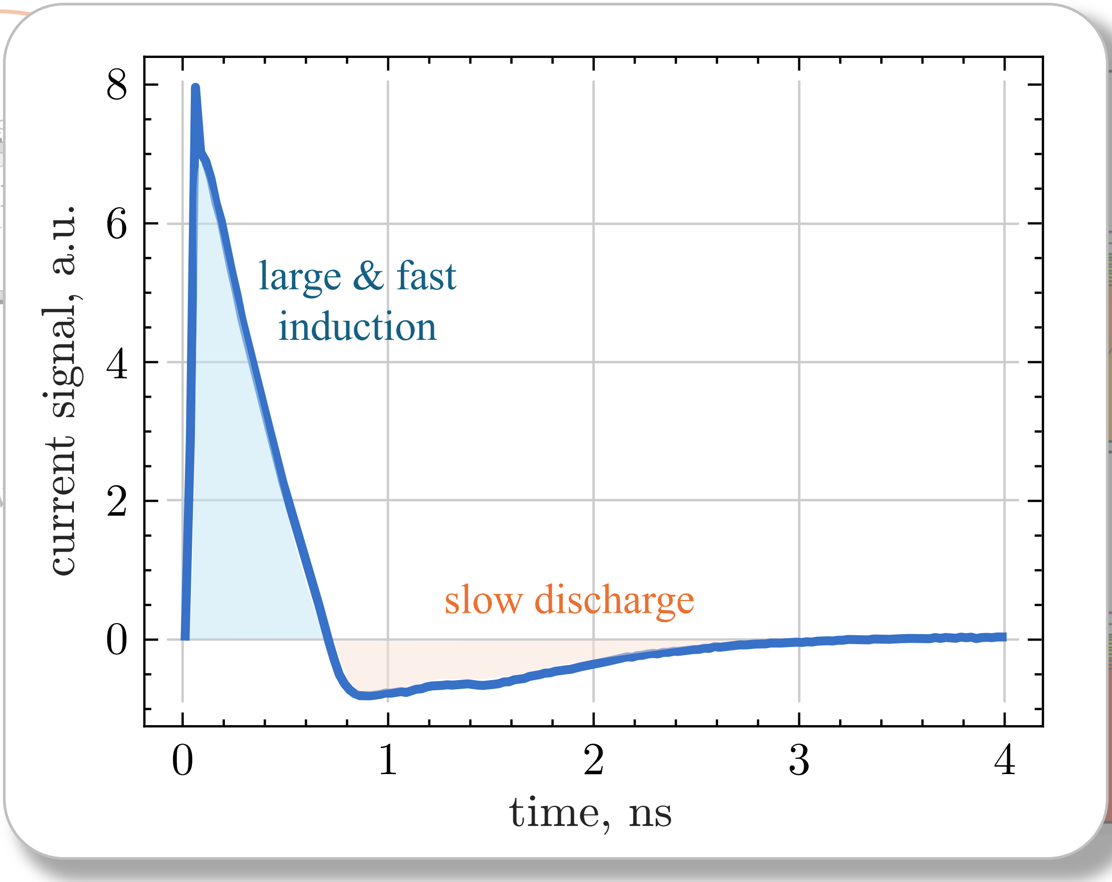
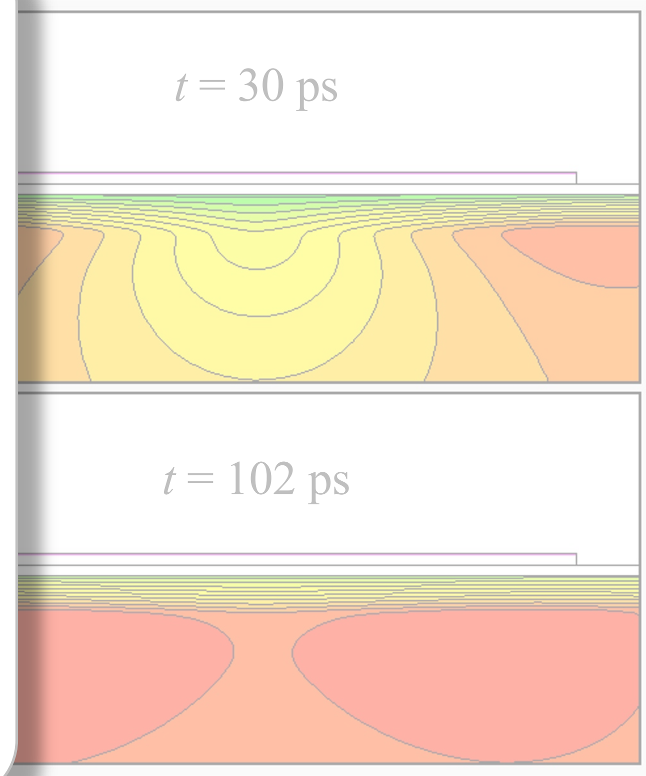
A real example of **dynamic weighting potential** $\Psi_w(\mathbf{x}, t)$ in an **RSD** at work:









FINAL COMMENTS & ACKNOWLEDGMENTS

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- Garfield++ is a **Monte Carlo** toolkit optimized for simulation of **ionization**, **charge transport** and **current induction** in gaseous/semiconductor detectors
- The tool demonstrates **very good capabilities** in reproducing subtle **dynamic effects** within the sensor, while significantly **reducing computational time** with respect to traditional FEM approach
- Garfield++ stands out for some important features like the capability to **import** all the **material parameter libraries** and the **mesh grid** structure from TCAD, as well as to manage the signal induction in structures with **resistive elements**

This work would not have been possible without these **funding** and **projects**: **RSD** and **ARCADIA** INFN CSN5 projects, the European Union's **Horizon 2020** Research and Innovation Programme, and the **AIDAInnova** programme

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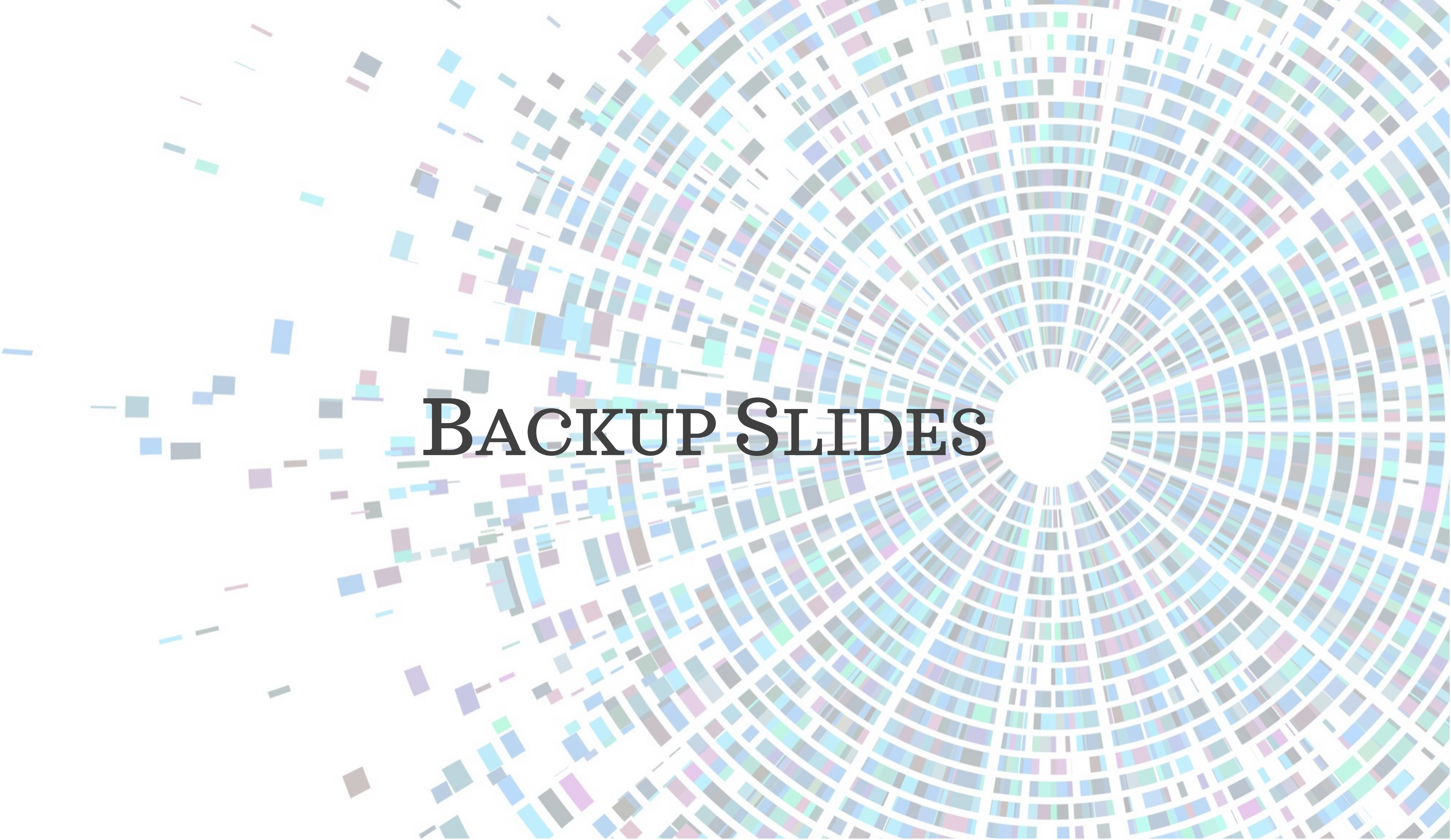
Thank You for Your Attention

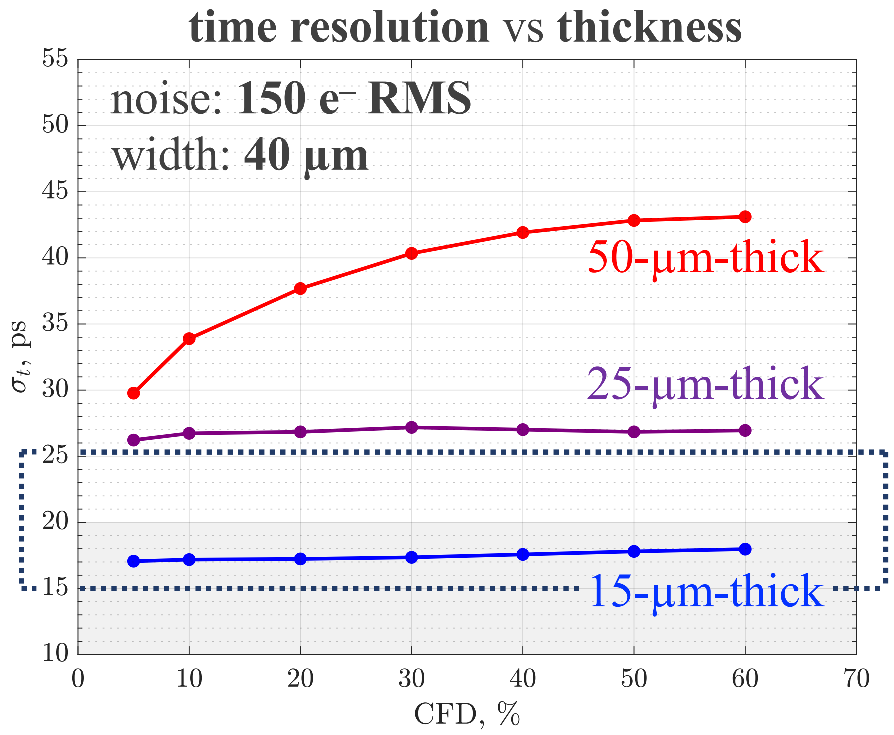
Any Questions..?

BACKUP SLIDES

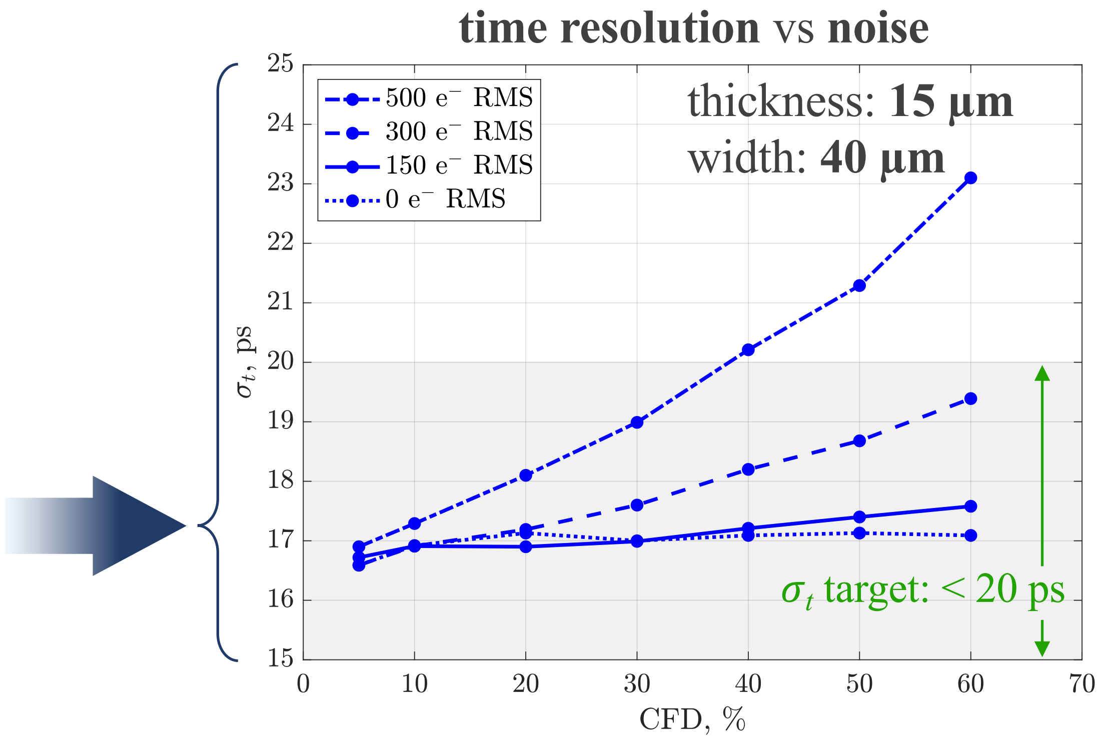


SIMULATIONS OF TIME RESOLUTION

Time resolution vs. **sensor thickness** and **noise**



time resolution vs **thickness**

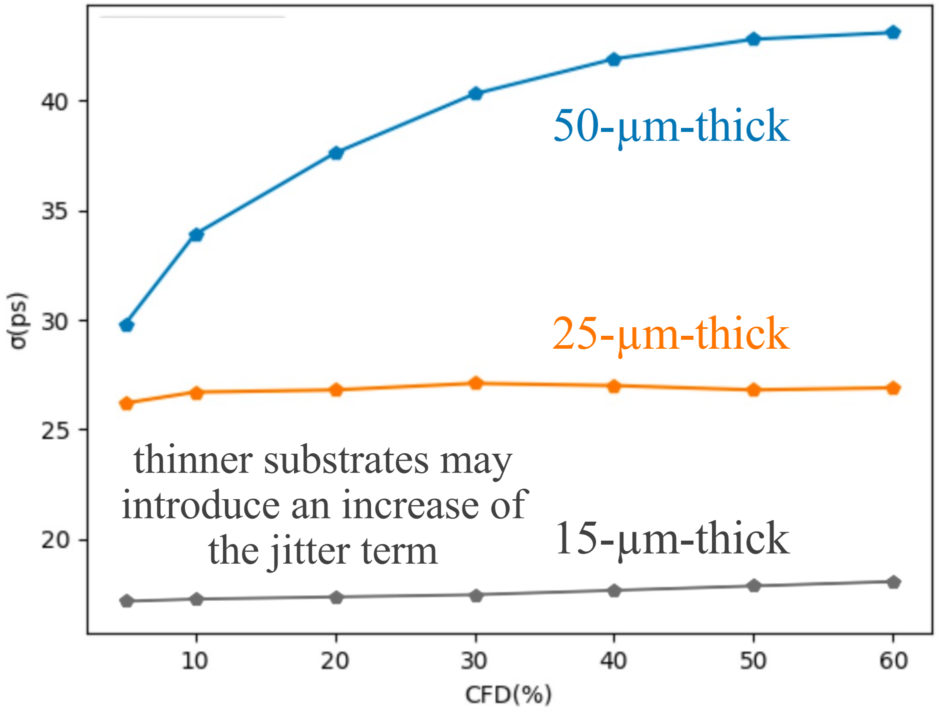


time resolution vs **noise**

SIMULATIONS OF TIME RESOLUTION

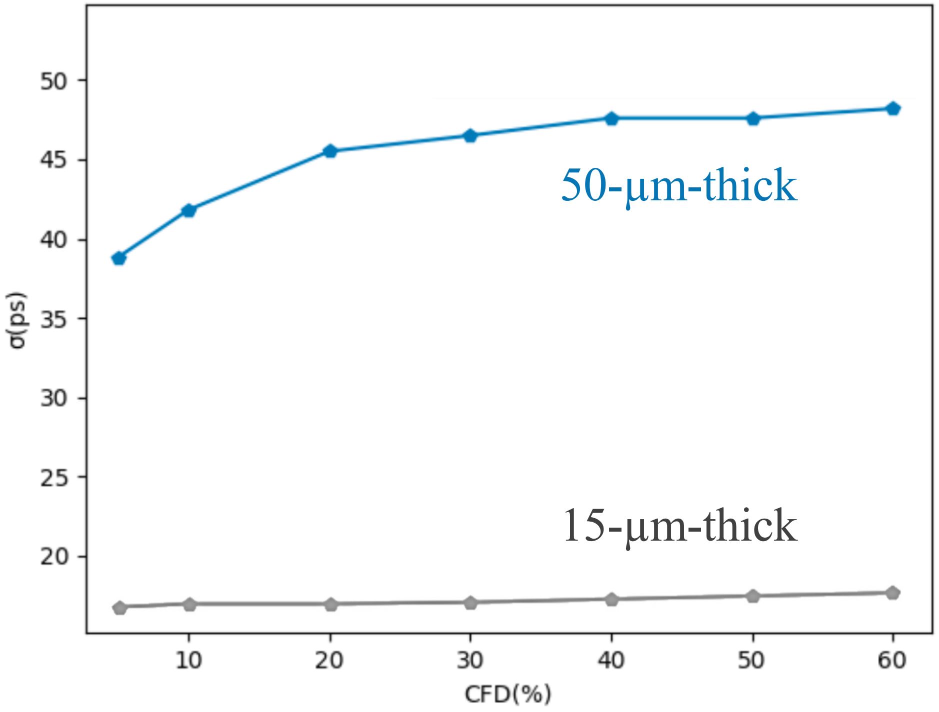
Time resolution vs. **sensor width**

noise: **150 e^- RMS**
width: **40 µm**



thinner substrates may introduce an increase of the jitter term

noise: **150 e^- RMS**
width: **70 µm**



FRONT-END CONTRIBUTION IN GARFIELD++

integrated **pre-amplifier transfer function**

$$f(t) = g \exp(n) \left(\frac{t}{t_p}\right)^n \exp(-t/\tau)$$

$$t_p = n\tau$$