Transient Studies using a TCAD and Allpix Squared combination approach

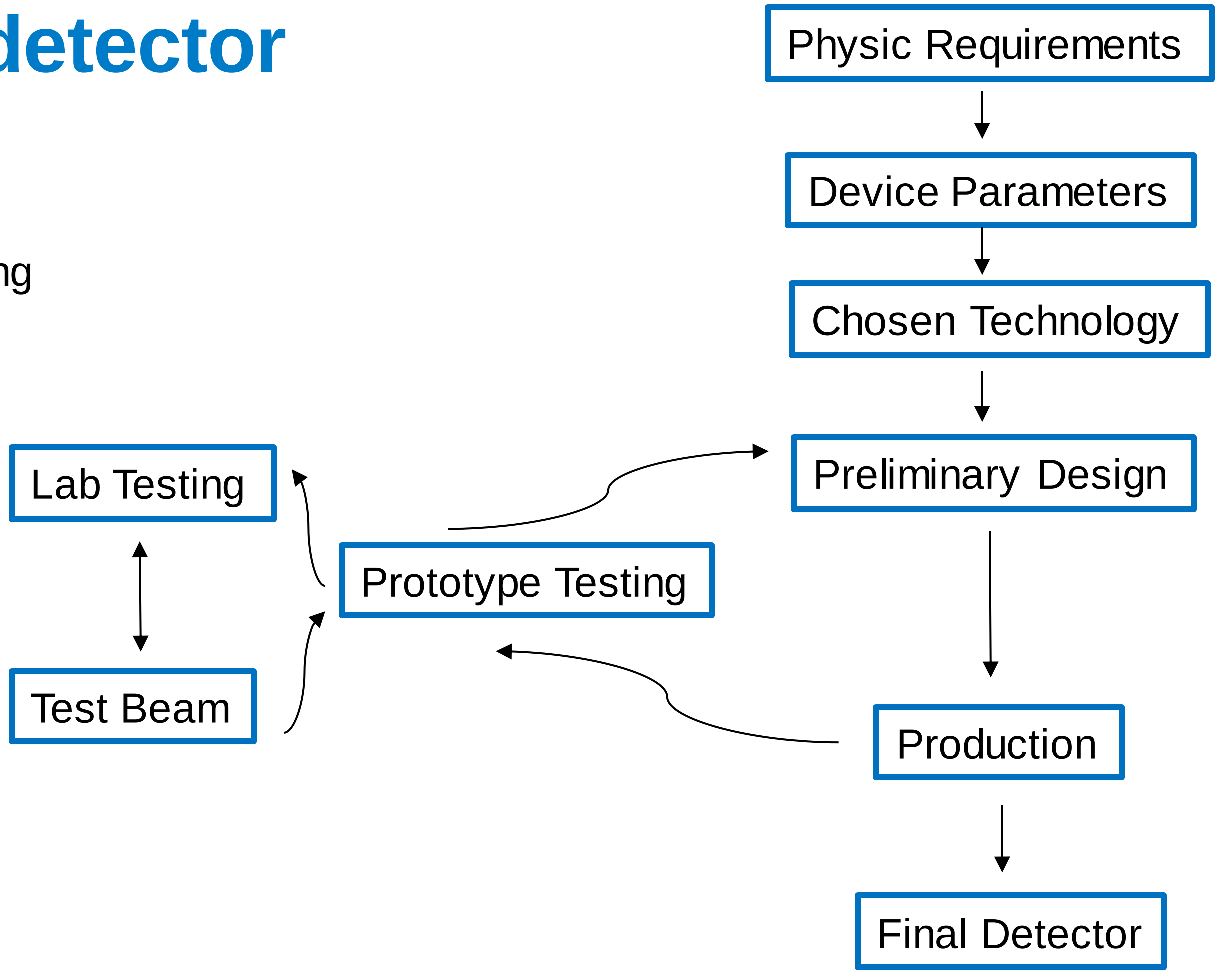
Manuel Alejandro Del Rio Viera on behalf of the Tangerine Project

Technology and Instrumentation in Particle Physics

September 7th 2023

Development cycle of a detector

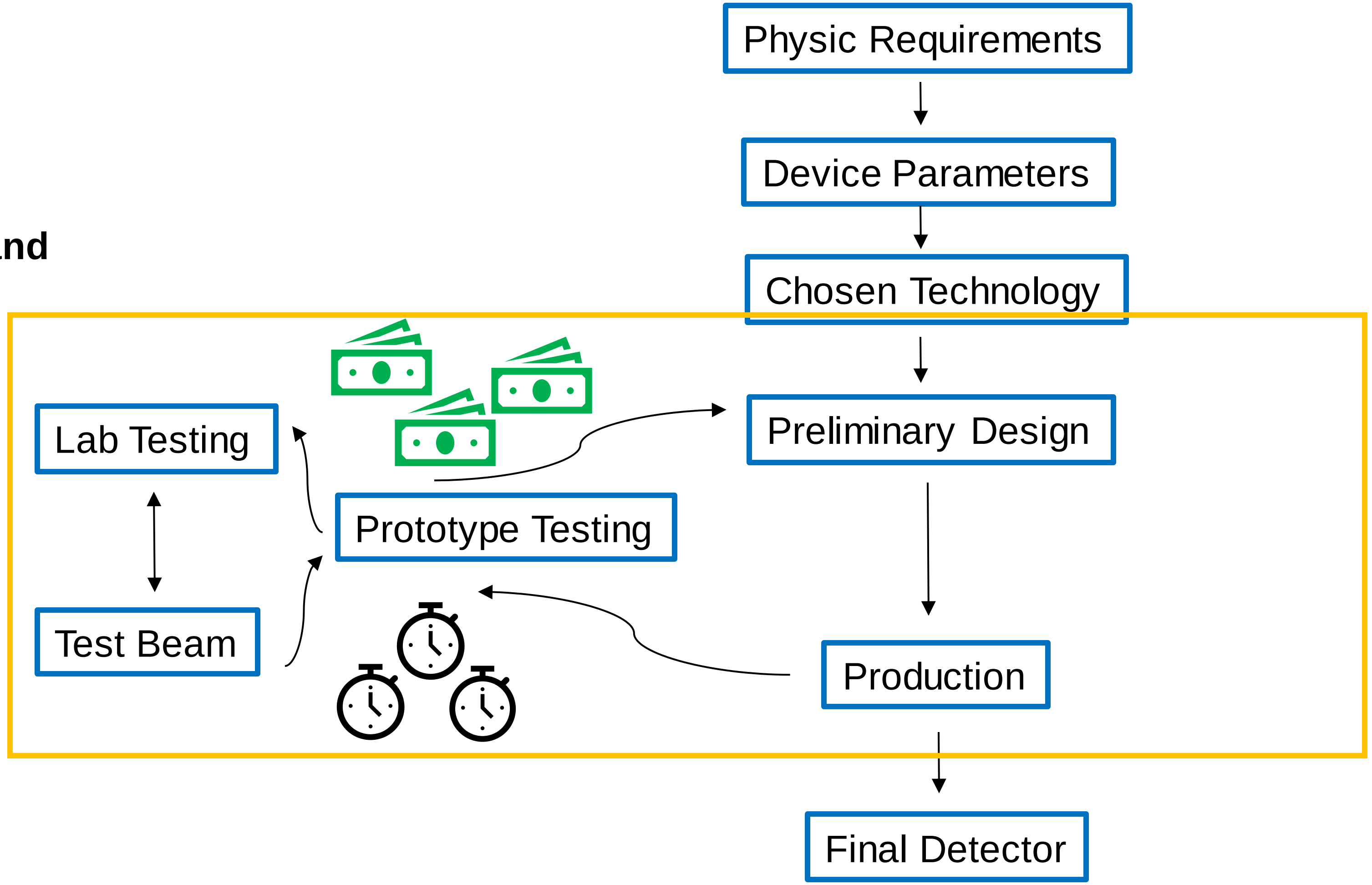
- The development of a detector involves planning and performing many different phases.
- Each phase may take several iterations until a final version of the planned detector is achieved.



Simplified development cycle of a detector

R&D Cycle

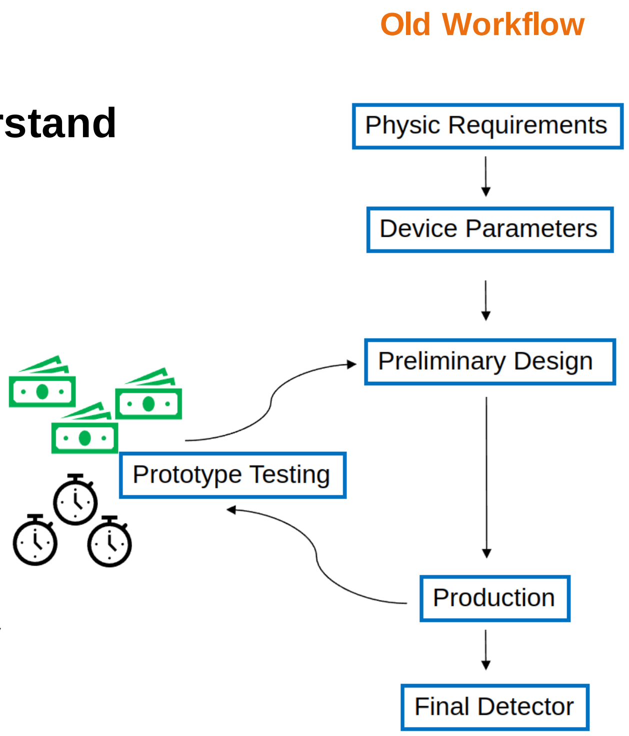
- This is especially true during the **Research and Development Cycle**.
- Each prototype iteration increments the cost due to production cycles and extensive testing.

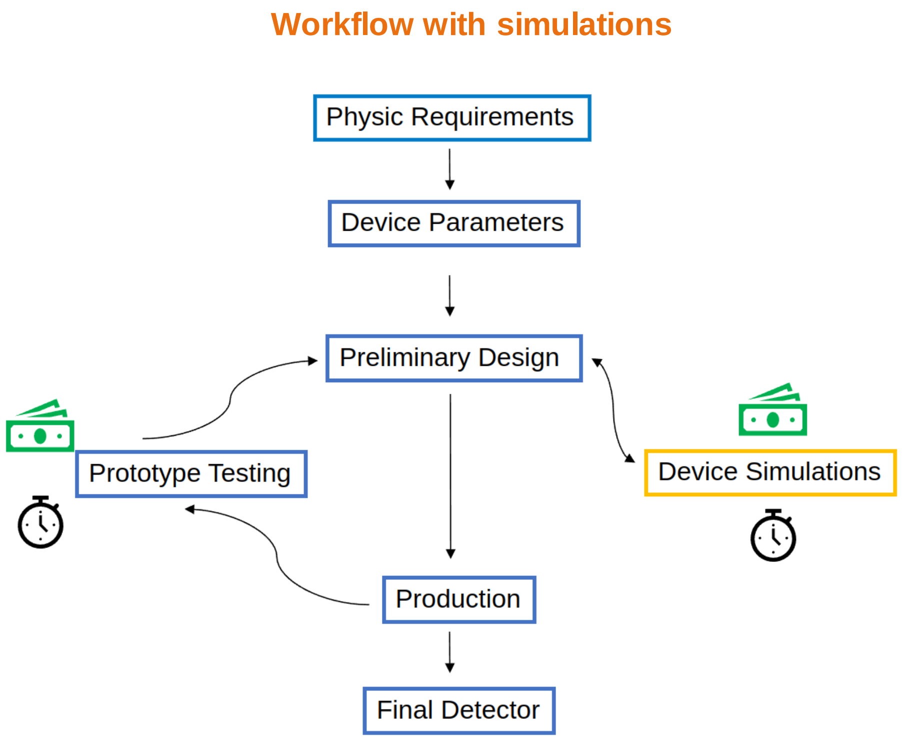


Simplified development cycle of a detector. Focusing on the research and development phase

The advantages of simulations

- Simulations allow us to **predict** and **understand** the **behavior** of our detectors.
- This can reduce **time**, **cost** and **iterations** during the **prototype** phase.
- Simulations are cheaper and faster than prototype production
- A combination of detailed simulations and prototype testing can be used to efficiently guide the way in sensor developments



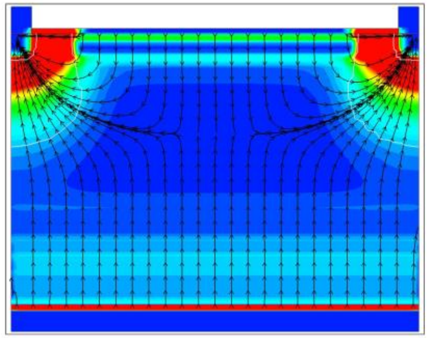


Tools that we use in simulations

Technology Computer-Aided Deisgn

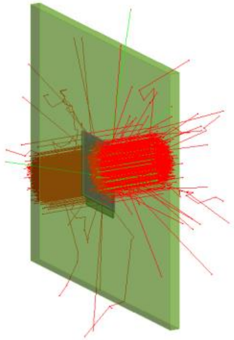
Allpix Squared: a Monte Carlo simulation framework for semiconductor detectors

- Model semiconductor devices using finite element methods
- Calculate highly accurate electric fields, potentials and doping concentration



Example electric field in TCAD

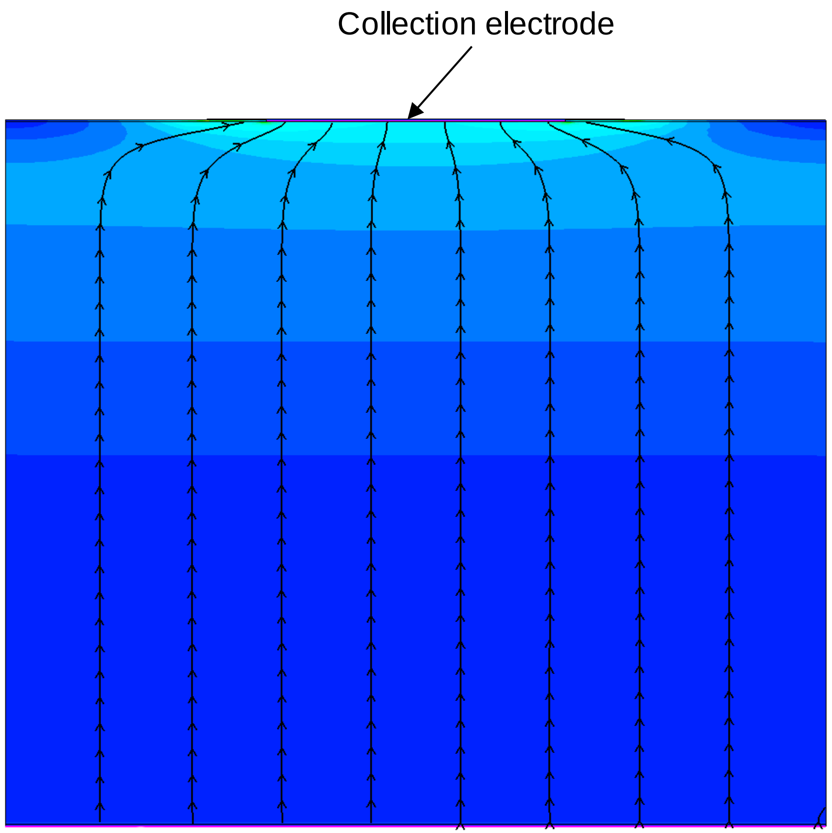
- High statistics Monte Carlo simulations of semiconductor detectors
- Full detector simulation chain, from energy deposition and charge carrier propagation to signal digitization
- Integration with GEANT4 and TCAD.



Particle beam passing through a single sensor in Allpix²

Electric field in planar sensors

- After an ionization event, the charge carriers will drift following the **electric field** lines towards the collection electrode.
- A **simple** and **mostly linear** electric field is able to represent adequately planar sensors.

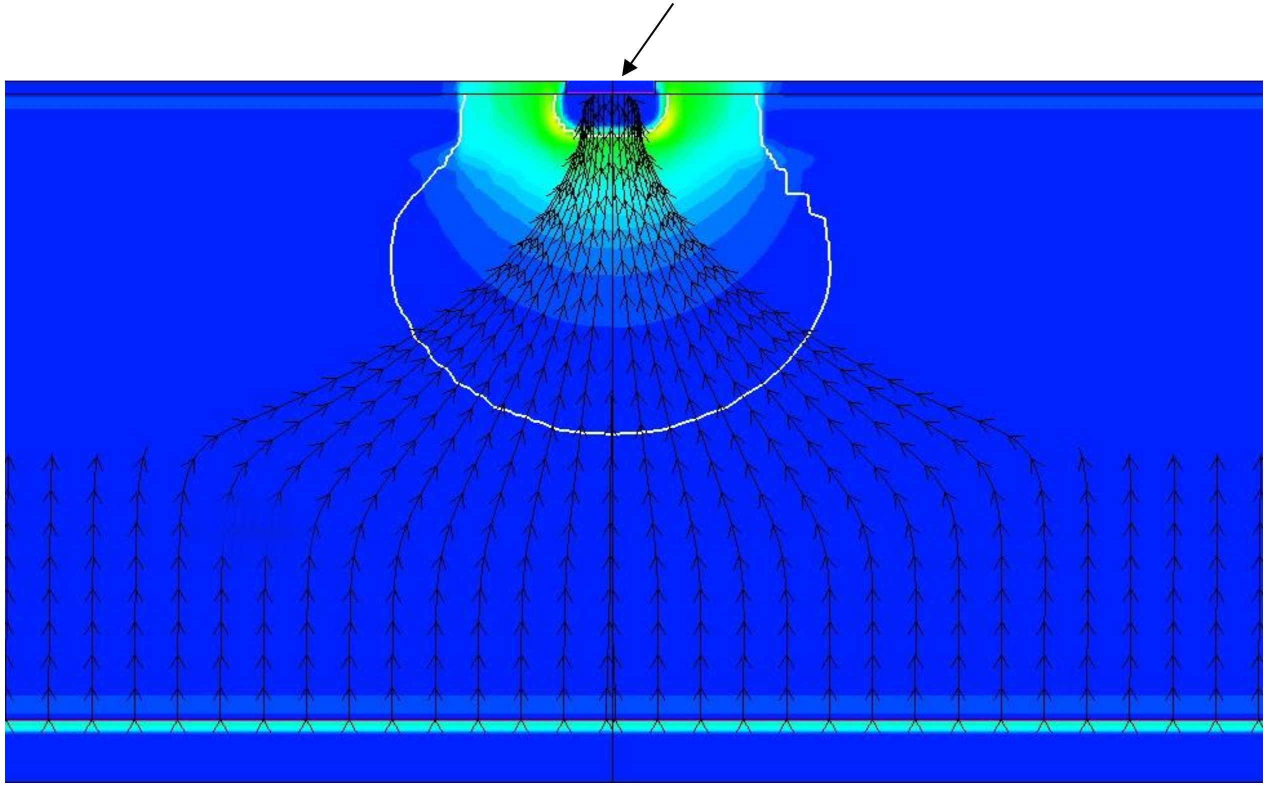


Electric field lines of a 300 µm planar sensor

Electric field in thin silicon sensors

- However, the electric field becomes specially **complicated** in thin sensors.
- Having an **accurate** electric field assures more **precise simulations** that would be able to represent our sensors.

Collection electrode



Electric field lines of a 10 µm sensor and a small collection electrode

The Tangerine Project TowArds Next GEneRation SIlicoN DEtectors

As example of the use of TCAD + Monte Carlo Simulations

Goal: Develop the next generation of monolithic silicon pixel detectors using a 65 nm CMOS imaging process

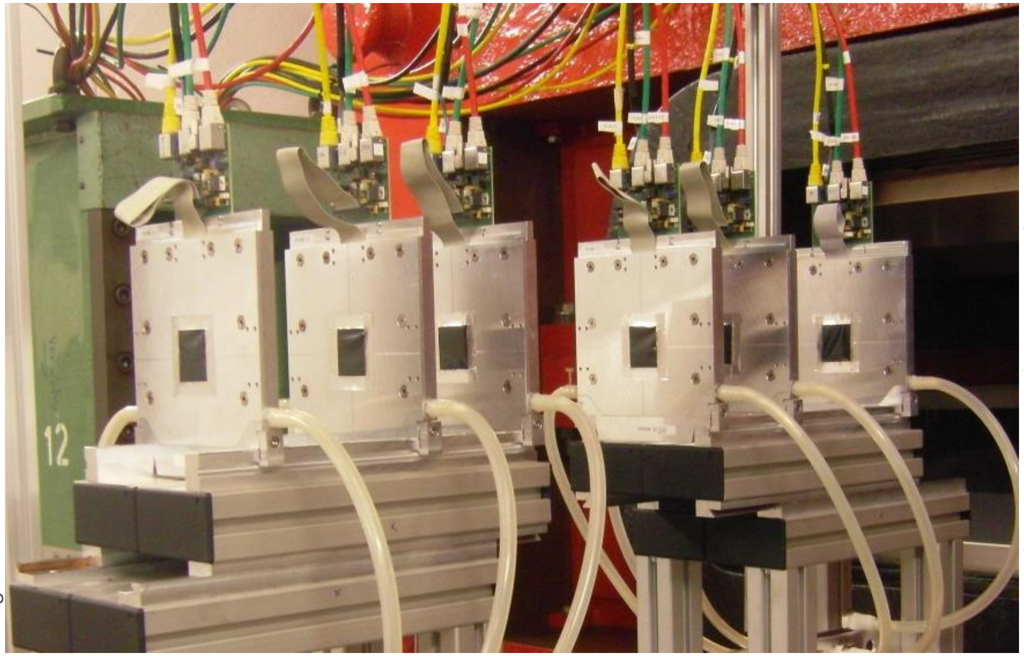
We investigate the potential for the following applications:

- **Trackers for future e^+e^- Colliders**
- **Reference detector at DESY-II test beam upgrade**

Requirements

- Spatial Resolution ~ 3 µm
- Time Resolution ~ 1 -10 ns
- Low material budget ~ 50 µm silicon (compared to hybrid sensors)

Image:DESY



https://newsline.linearcollider.org/2011/08/18/the-impact-of-ilc-detector-rd/desy-beam-telescope/

MIMOSA Telescope at the DESY II Facility

Electric field in thin silicon sensors

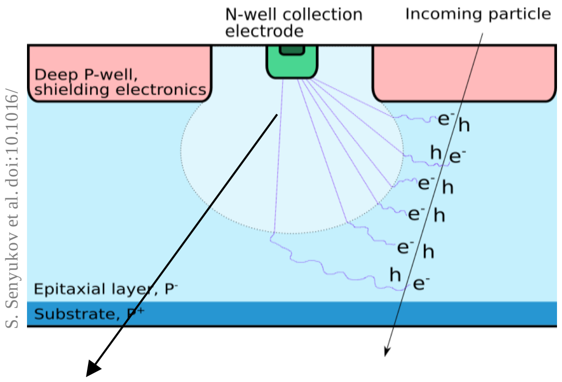
Adriana Simancas

Monolithic Active Pixel Sensors (MAPS)

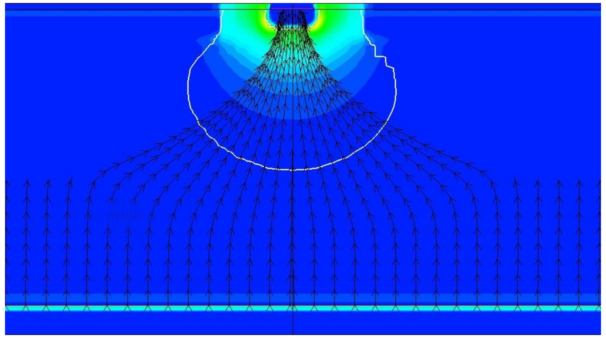
Layout geometry

Electric Field lines

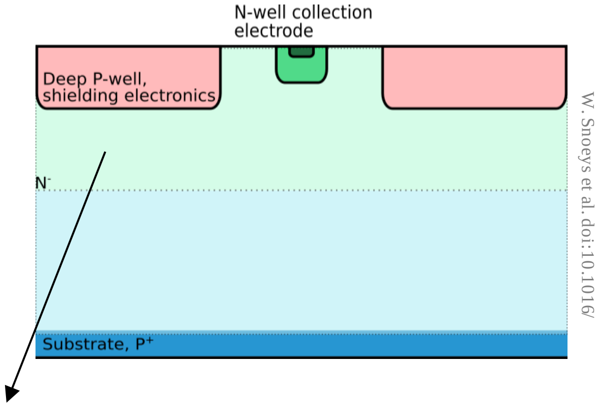
Standard



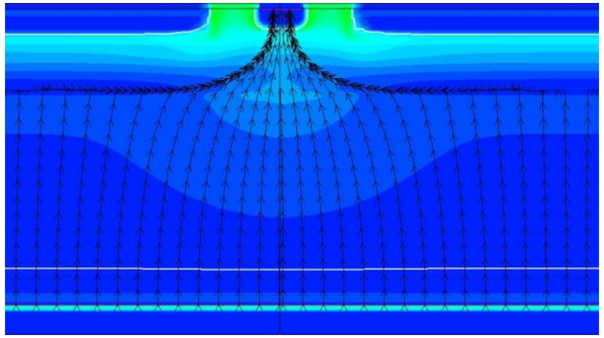
Drift predominates inside depleted region and **diffusion** outside



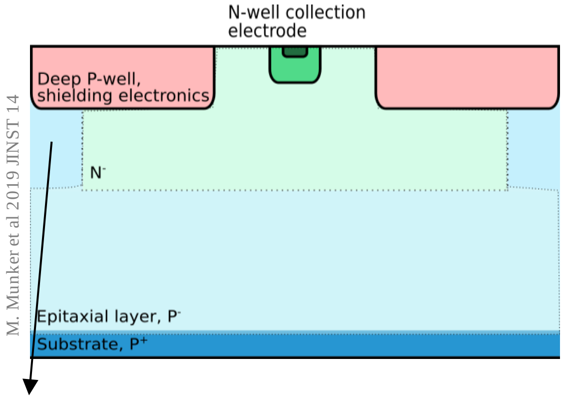
N-Blanket



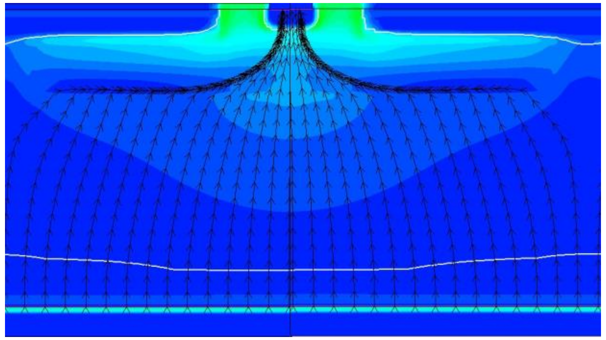
Continuous N-type Implant
Increases the depleted region



N-Gap



Gap in Continuous N-type Implant
Speed up charge collection



Static Monte Carlo Simulations of thin silicon sensors

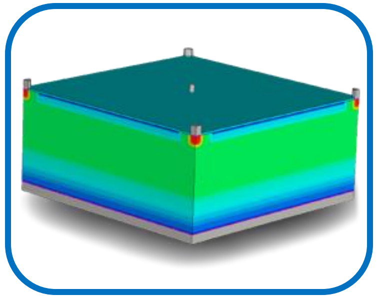
- The **static** Electric Field and Doping Concentration are converted and imported into **Allpix Squared:**
  - ➞ Combining the best of both: High **statistics** and **accurate field modeling**

Static simulations allow us to study the performance of a sensor, e.g. Efficiency, Cluster Size...

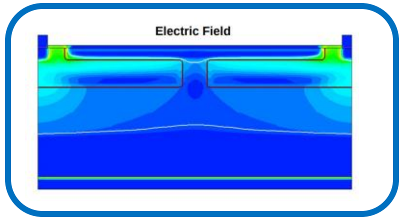
TCAD

SYNOPSYS Silicon to Software

Generic Doping Concentration

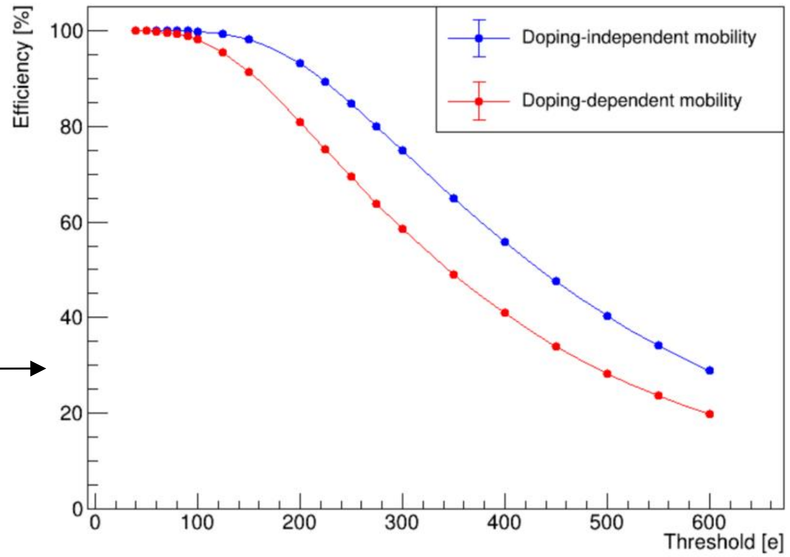


Electric Field



Monte Carlo

ap² allpix squared



Sensor efficiency vs threshold for two different mobility models

Validation with Test Beam data

- “Analog Pixel Test Structure” (**APTS**) provided and designed by **CERN ALICE**

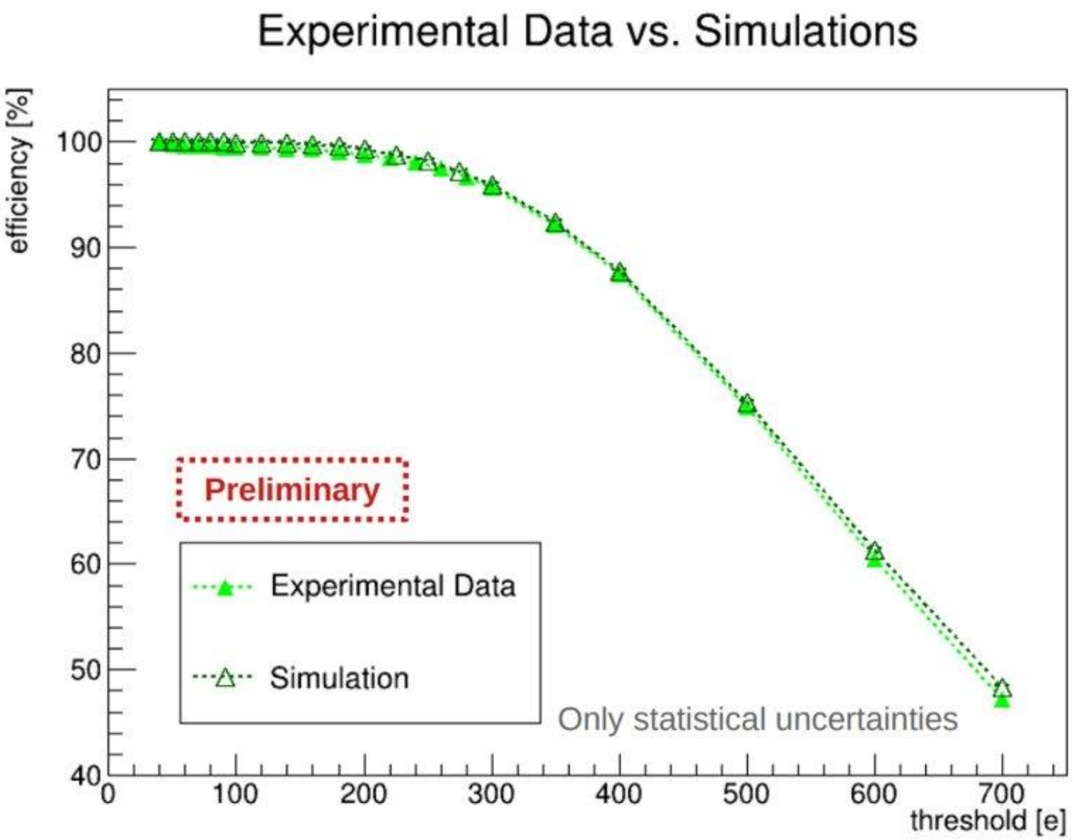
- DAQ and chipboard designed and developed together with **CERN EP R&D**

- Test beams have been carried out at **DESY**, and first comparisons made to simulations

- Results from the APTS
  - N-gap layout
  - 25x25 μm^2 pixel size
  - 4x4 pixel matrix
  - 4.8 V bias voltage

- The trend between simulations and data **matches well**

Motivation: We would like to also study the **time evolution response** of our sensors, i.e. the **signal**

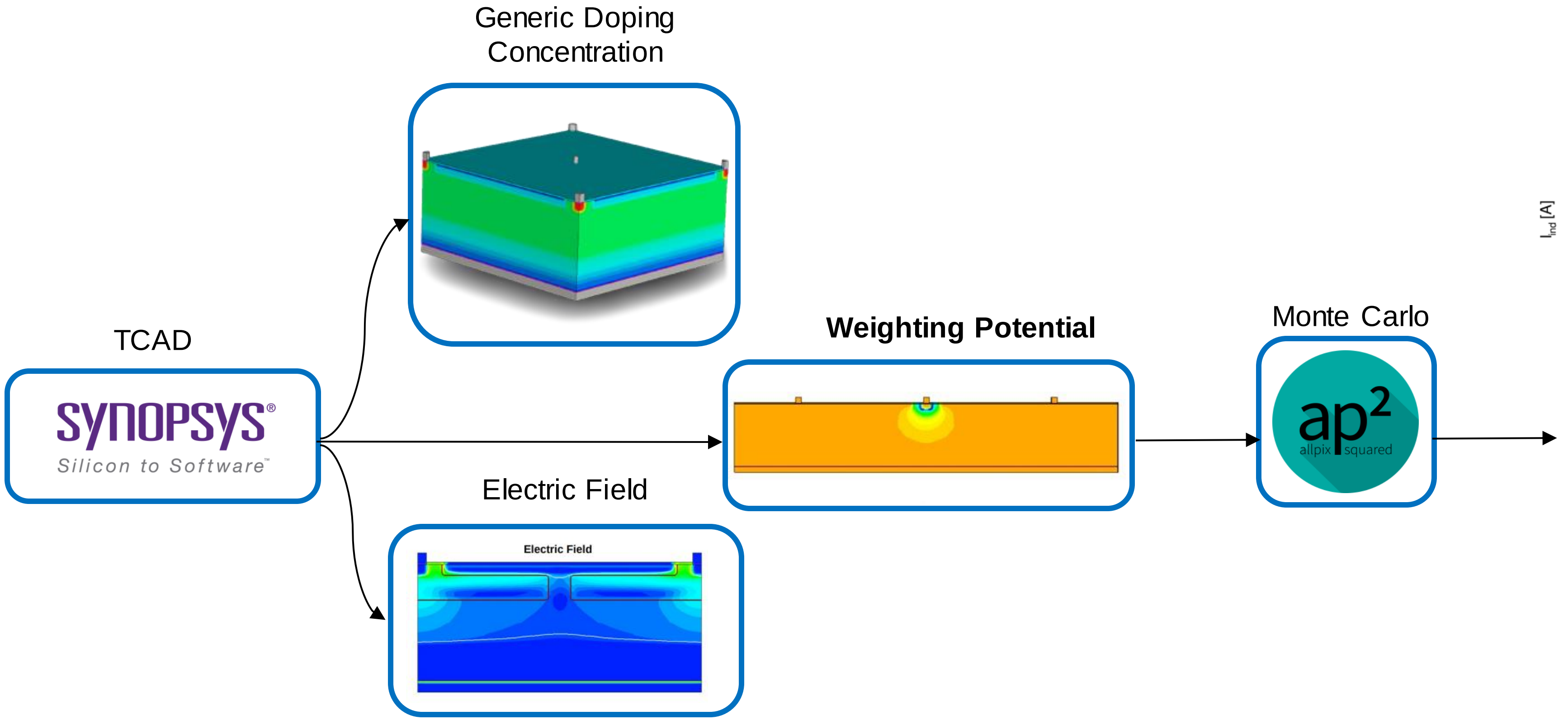


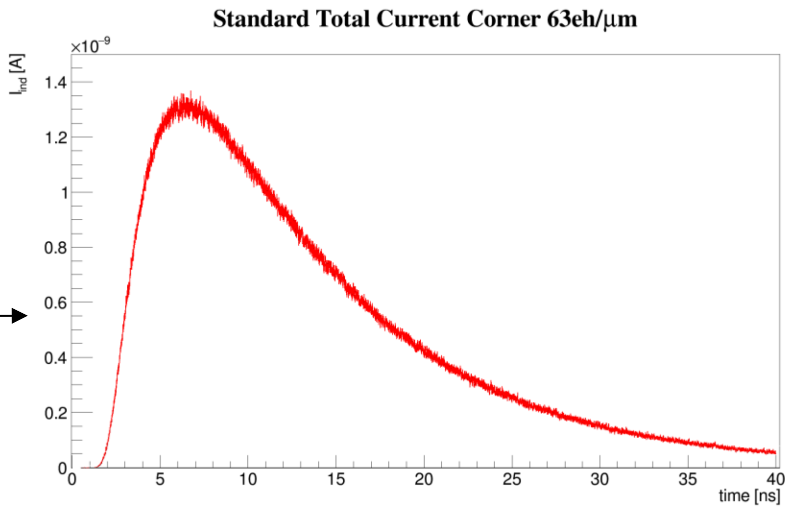
This and more preliminary results presented at **BTTB11**

Transient Simulations

- Transient simulations allow us to study the **time evolution** of the response of a sensor, i.e. the **signal** evolution which is exactly what we want to achieve for our sensors.

- By adding a **Weighting Potential** we can calculate the Induced signal (charge or current) in our sensor.





Example of induced current

Weighting Field: Shockley-Ramo Theorem

Basic Principle of Induced Signal in an electrode

- After an ionization event, the charge carriers will drift following the **electric field** lines towards the collection electrode.

- This will induce a current (**signal**) as the charge carriers move.

- The induced current can be expressed by the **propagation of the charge in the weighting field** :

$$\boxed{I_{ind} = qE_w v}$$

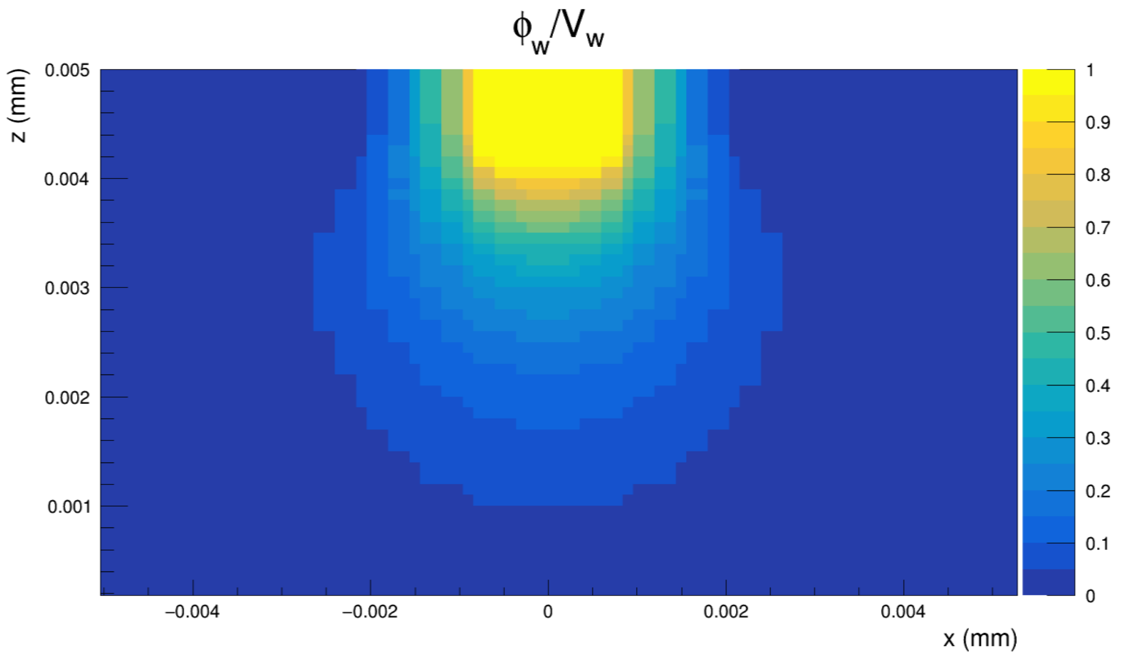
- The weighting field E_w describes the **electromagnetic coupling of a charge** to an arrangement of conducting electrodes.

Weighting Potential: Shockley-Ramo Theorem

Basic Principle of Induced Signal in an electrode

- Often easier to use, the **weighting potential** φ appears as a solution to the Laplace equation**:**

$$\boxed{Q_{ind} = -q(\varphi(x_1) - \varphi(x_0))}$$



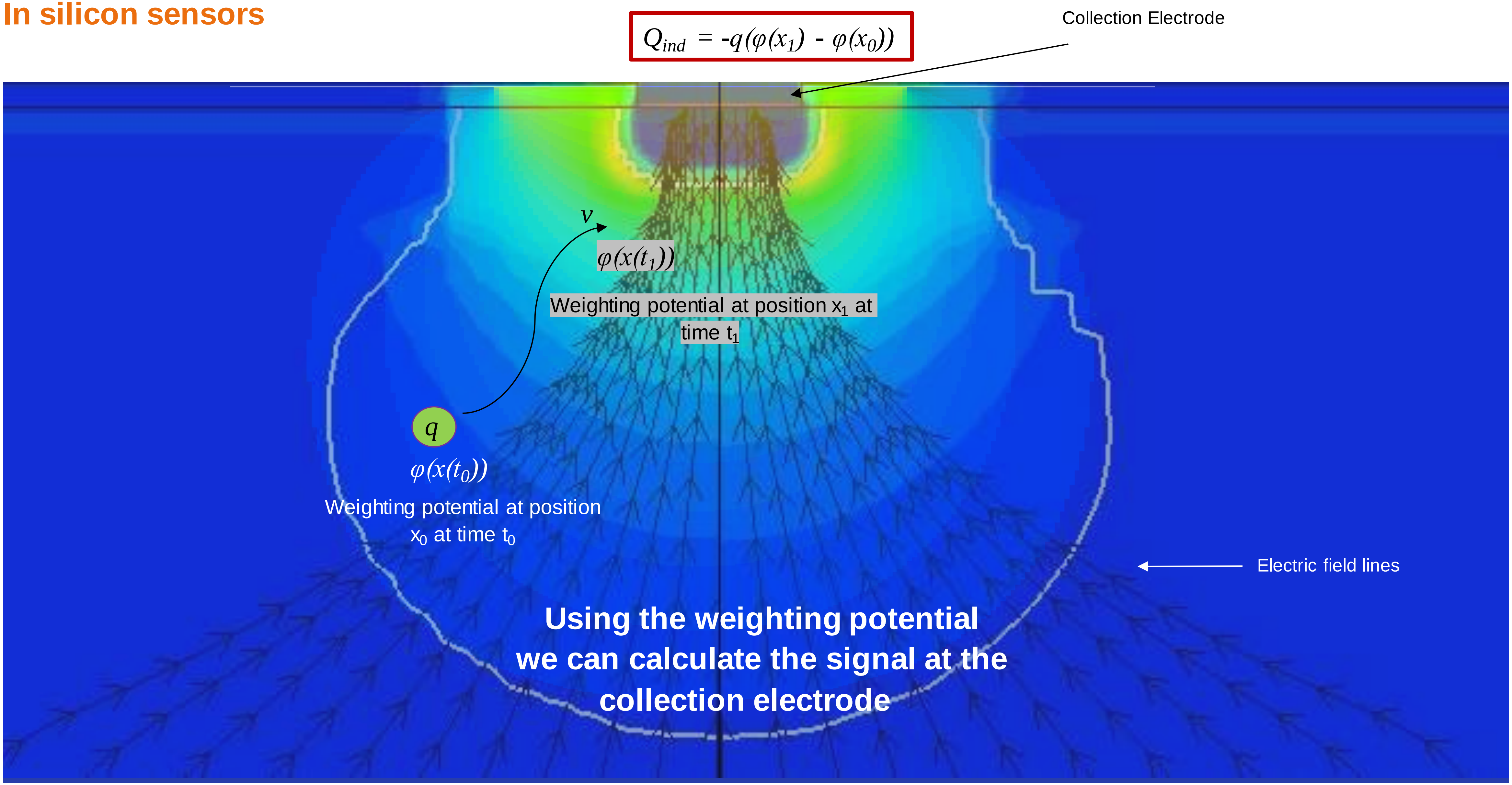
Example of Weighting Potential. Higher values are closer to the collection electrode

Signal Formation

In silicon sensors

Induced charge at collection electrode

$$\boxed{Q_{ind} = -q(\varphi(x_1) - \varphi(x_0))}$$

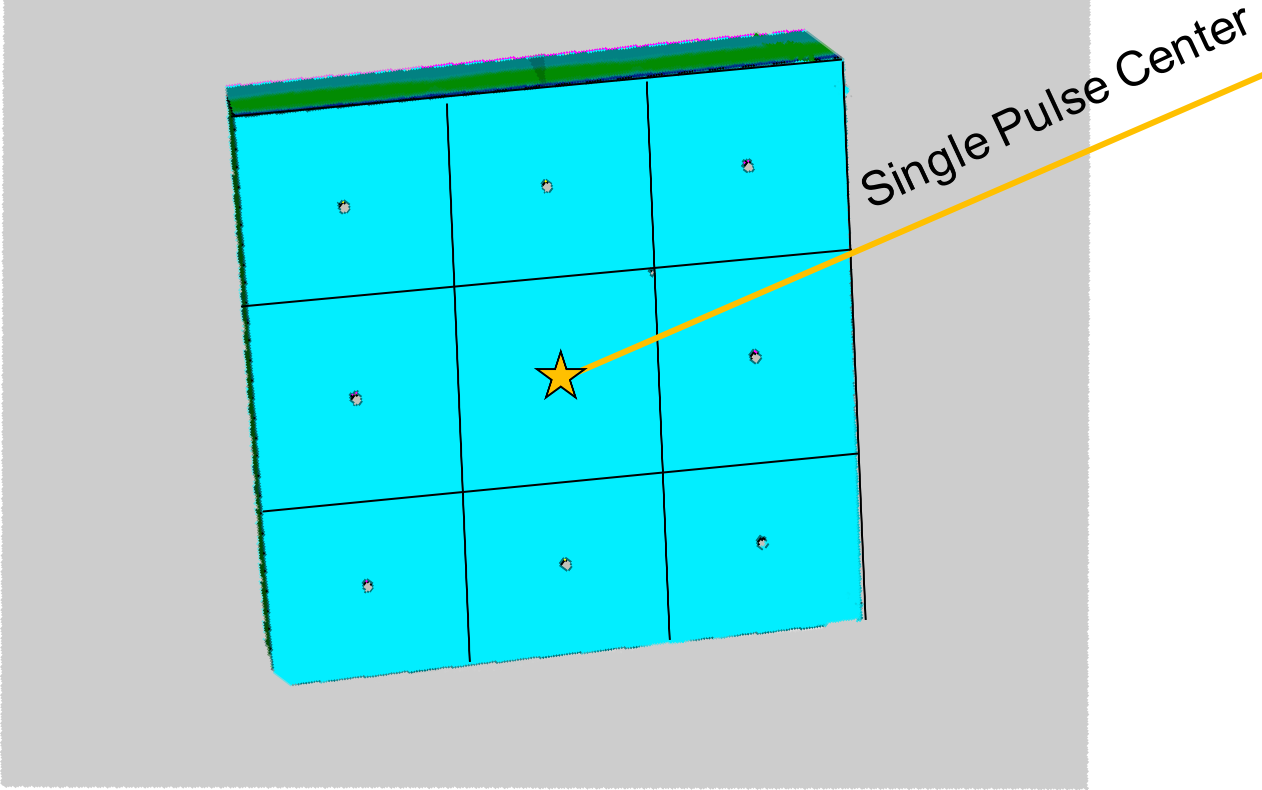


Using the weighting potential we can calculate the signal at the collection electrode

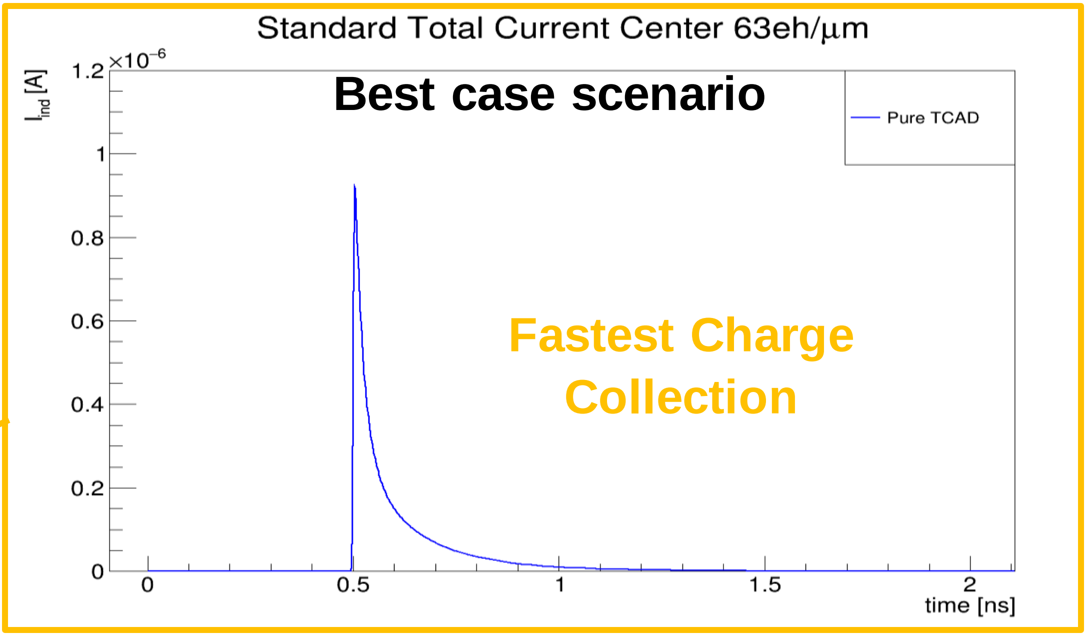
TCAD Simulations

Two extreme cases under study

- Charge carriers injected alongside the pixel **corner** or **center**
- Fixed amount of charge carriers **63 eh/µm**
- Average of pixels over threshold calculated (One for center and four for the corner)



3x3-cell model in TCAD

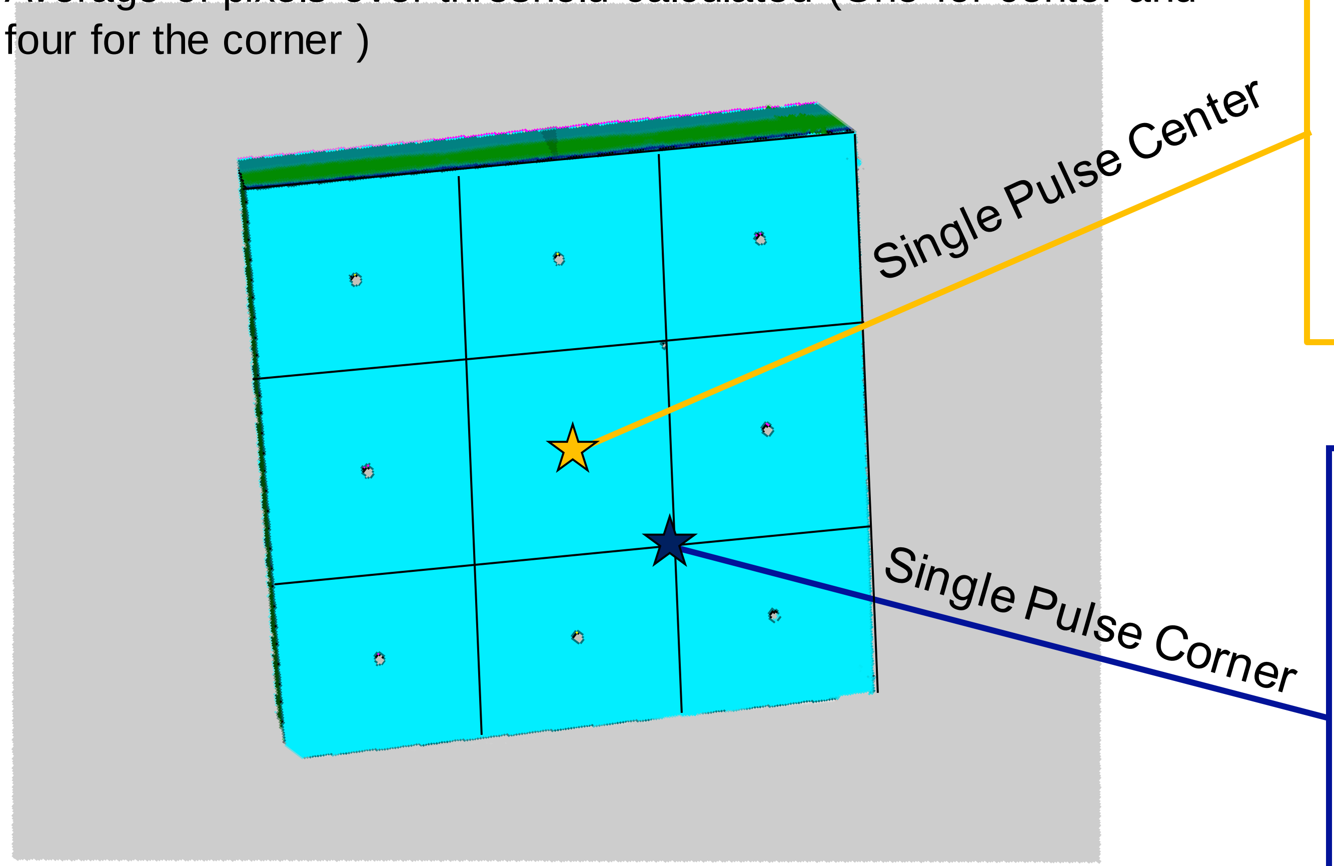


Anastasiia Velyka

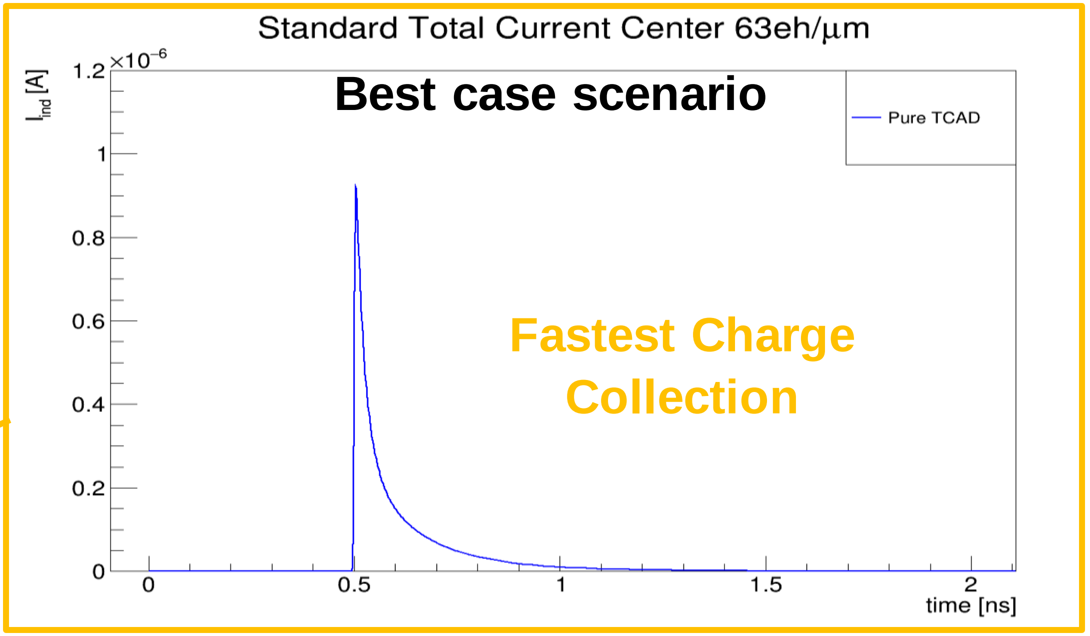
TCAD Simulations

Two extreme cases under study

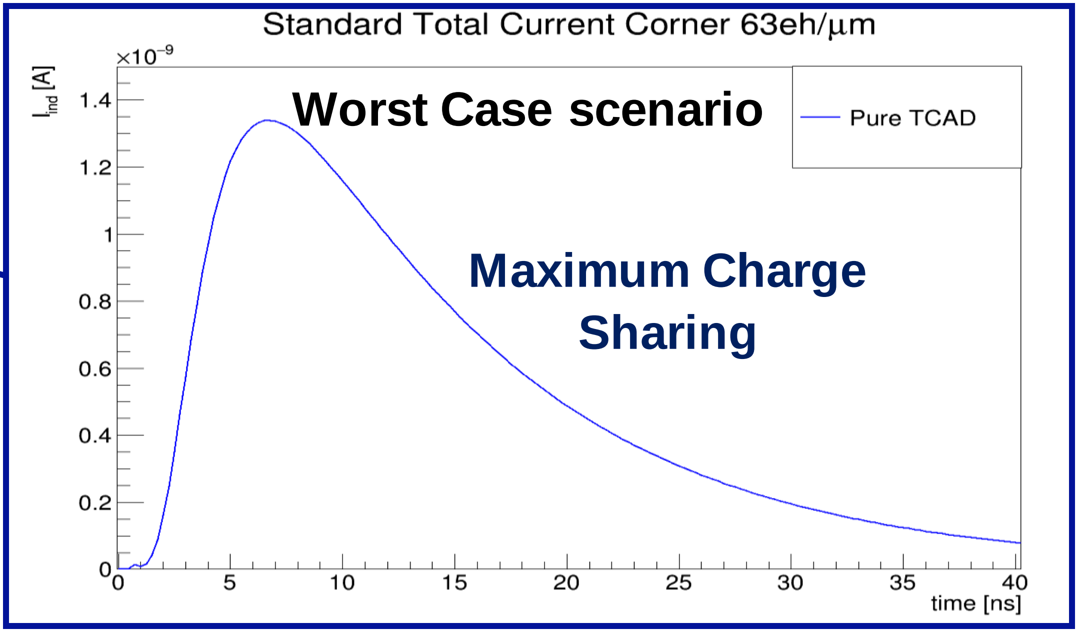
- Charge carriers injected alongside the pixel **corner** or **center**
- Fixed amount of charge carriers **63 eh/µm**
- Average of pixels over threshold calculated (One for center and four for the corner)



3x3-cell model in TCAD



Not same time scale!



Anastasiia Velyka

Validating TCAD + APSQ

With TCAD

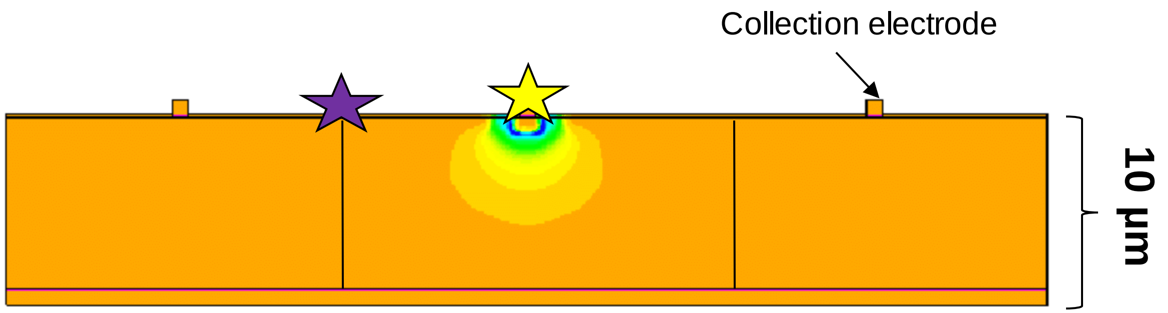
Motivation of TCAD+APSQ

High statistics and Geant4 enable the inclusion of Landau fluctuations, which offers a **more realistic simulation** scenario

But first we have to validate it!

Charge injection at the **center**

Charge injection at the **corner**



3x3 pixel matrix
20x20 µm^2 pitch

To **validate TCAD+APSQ simulations**, same simulation conditions as in transient TCAD are replicated:

- Fixed amount of charge carriers: **63 eh/µm**
- Only the epitaxial layer is simulated: **10 µm**
- Monte Carlo simulation repeated **10000x** times and the average pulse is calculated

Simulation Time

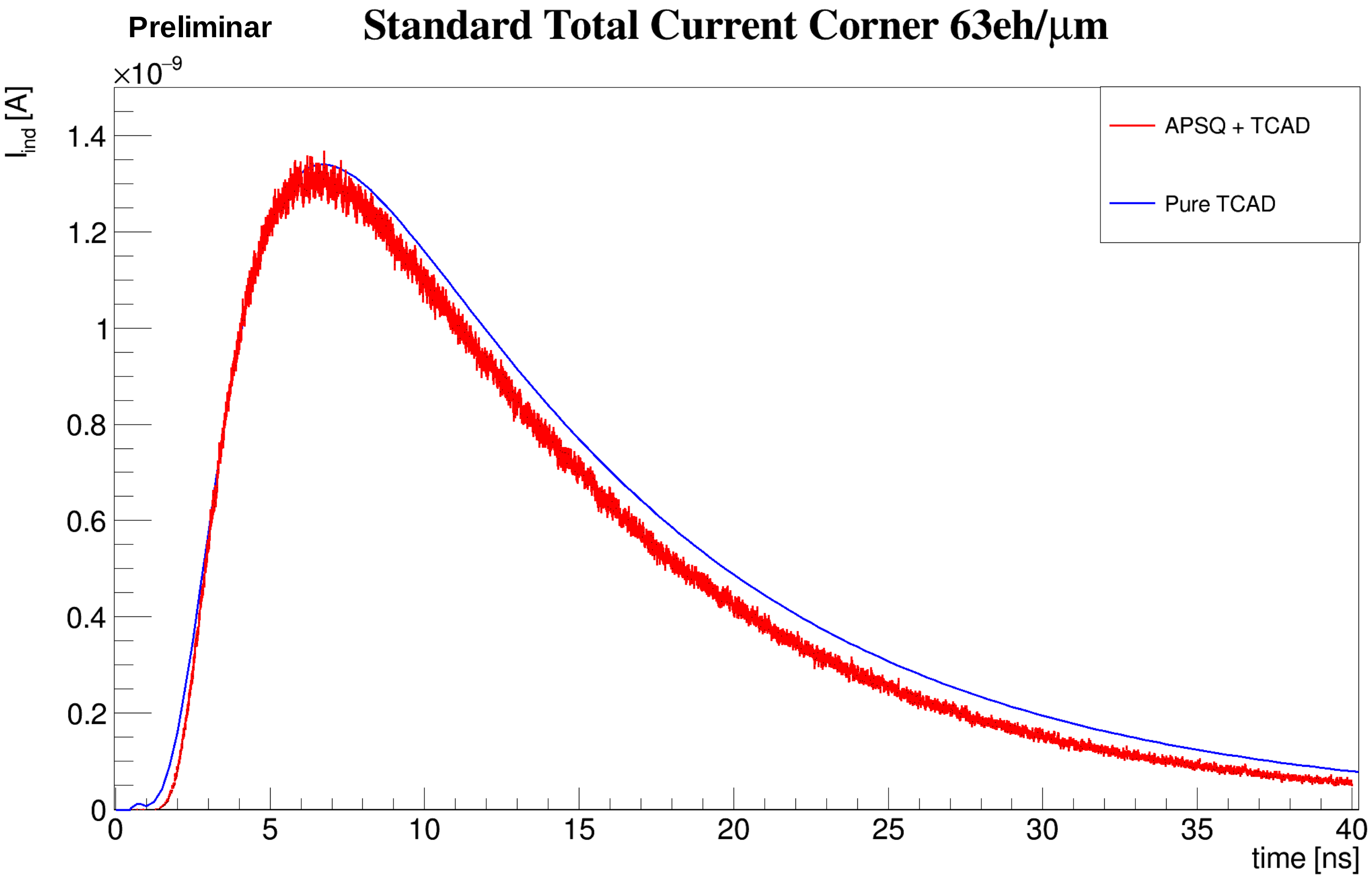
TCAD ~ days (Single Pulse)
TCAD + APSQ ~ seconds (Single Pulse)

Validation – Corner Injection

Average Pulse Comparison

- Same pulse shape, meaning that both undergo the **same physic processes**
- **Good agreement** between both approaches
- Similar values of **collected charge** (obtained by integration)

APSQ + TCAD – Average 10000 pulses
Pure TCAD – 1 pulse



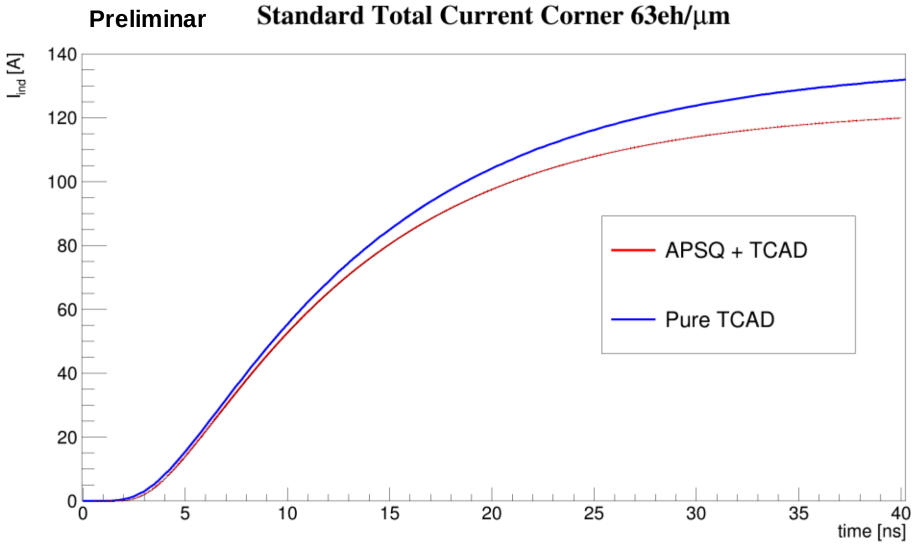
Induced signal due to charge injection

Validation – Corner Injection

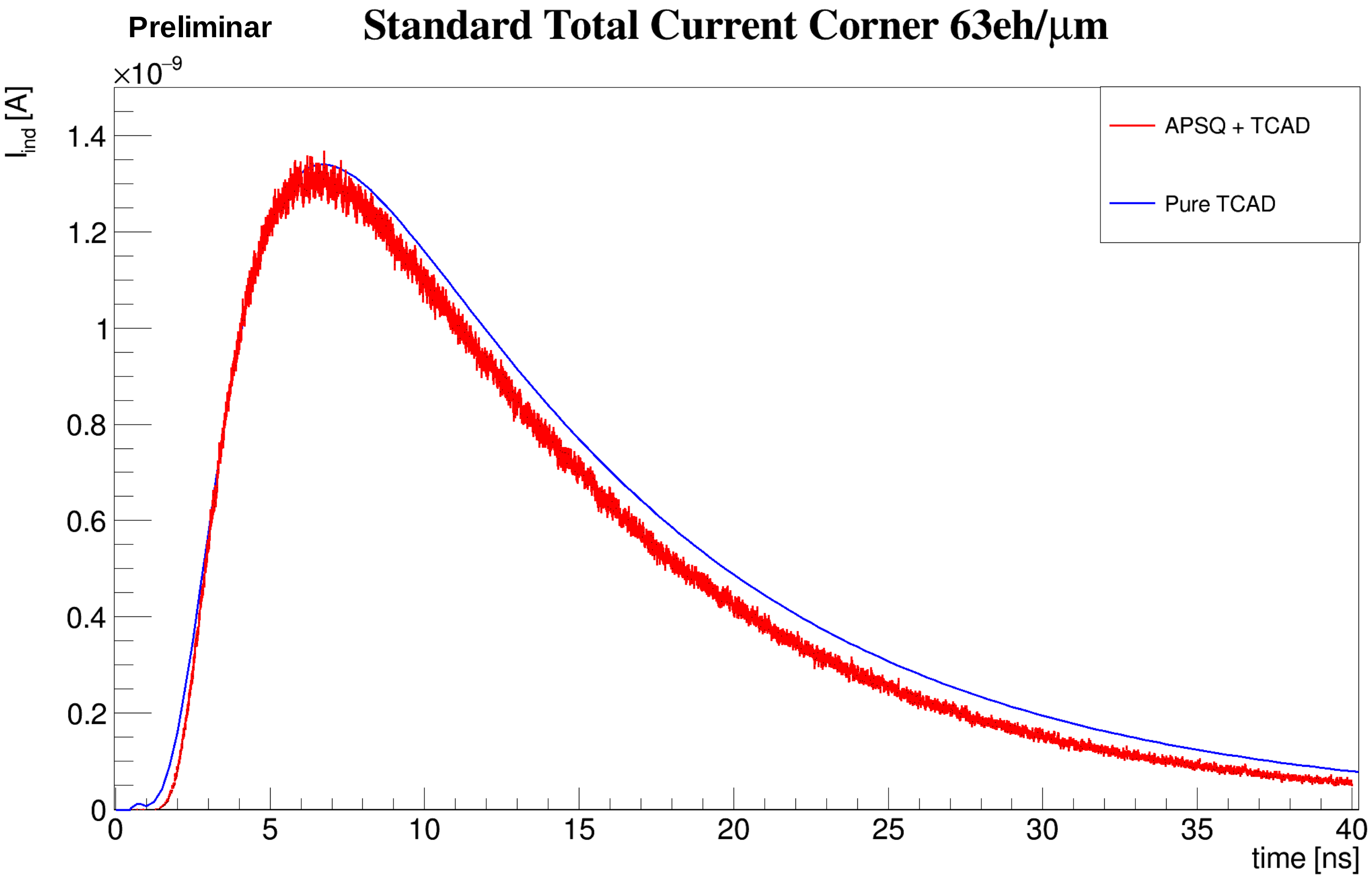
Average Pulse Comparison

- Same pulse shape, meaning that both undergo the **same physic processes**
- **Good agreement** between both approaches
- Similar values of **collected charge** (obtained by integration)

APSQ + TCAD – Average 10000 pulses
Pure TCAD – 1 pulse



Collected charge

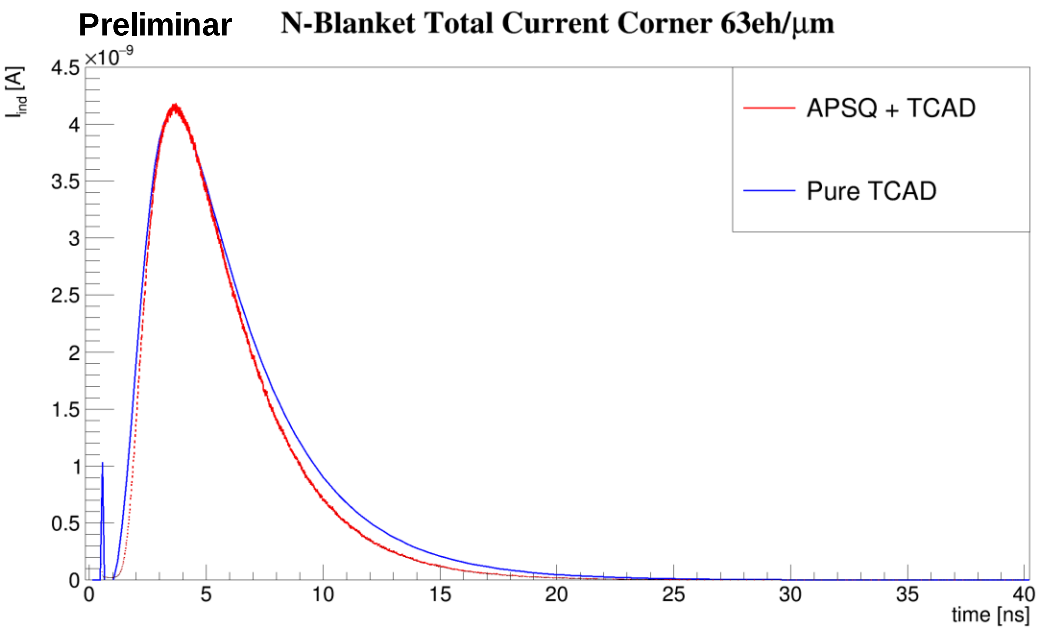


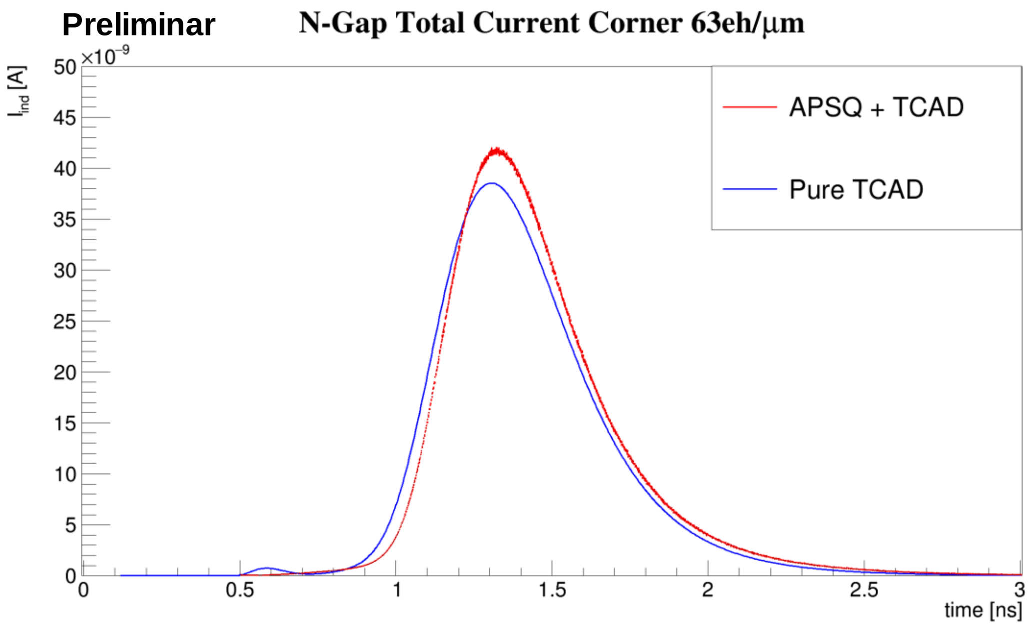
Induced signal due to charge injection

Validation – Different Layouts

Average Pulse Comparison

APSQ + TCAD – Average 10000 pulses
Pure TCAD – 1 pulse





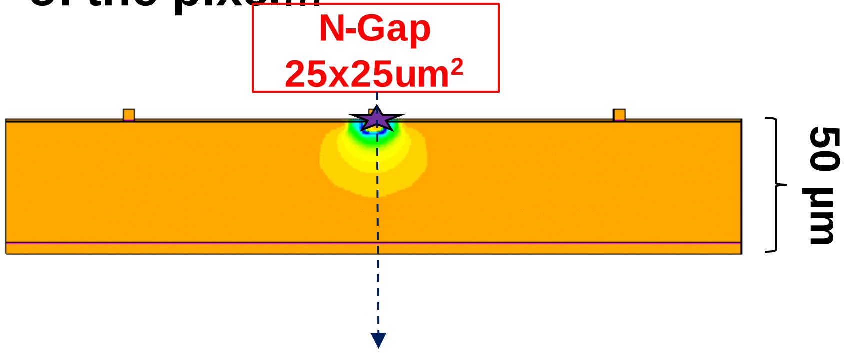
- Same pulse shape, meaning that both undergo the **same physic processes**
- **Good agreement** between both approaches

- Same pulse shape, meaning that both undergo the **same physic processes**
- **Good agreement** between both approaches

Simulation with Minimum Ionizing Particles – Beam at the center

- We can proceed by shooting MIP particles and thus take into account **Landau fluctuations, secondary particle production, Photo Absorbtion Ionization...**

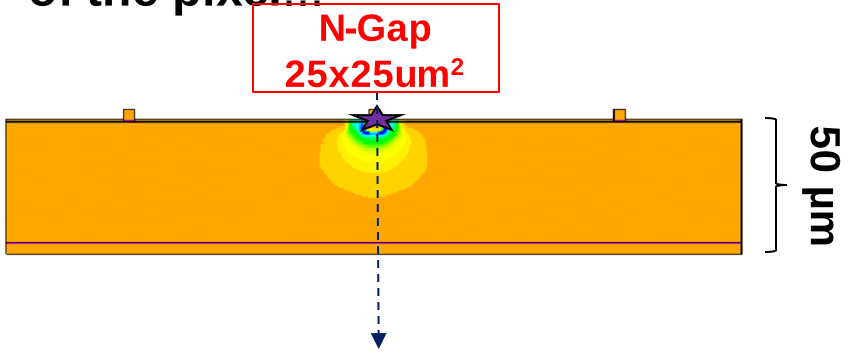
- Not only that but also include contributions from the **substrate** and investigate this further by shooting in **different positions of the pixel...**

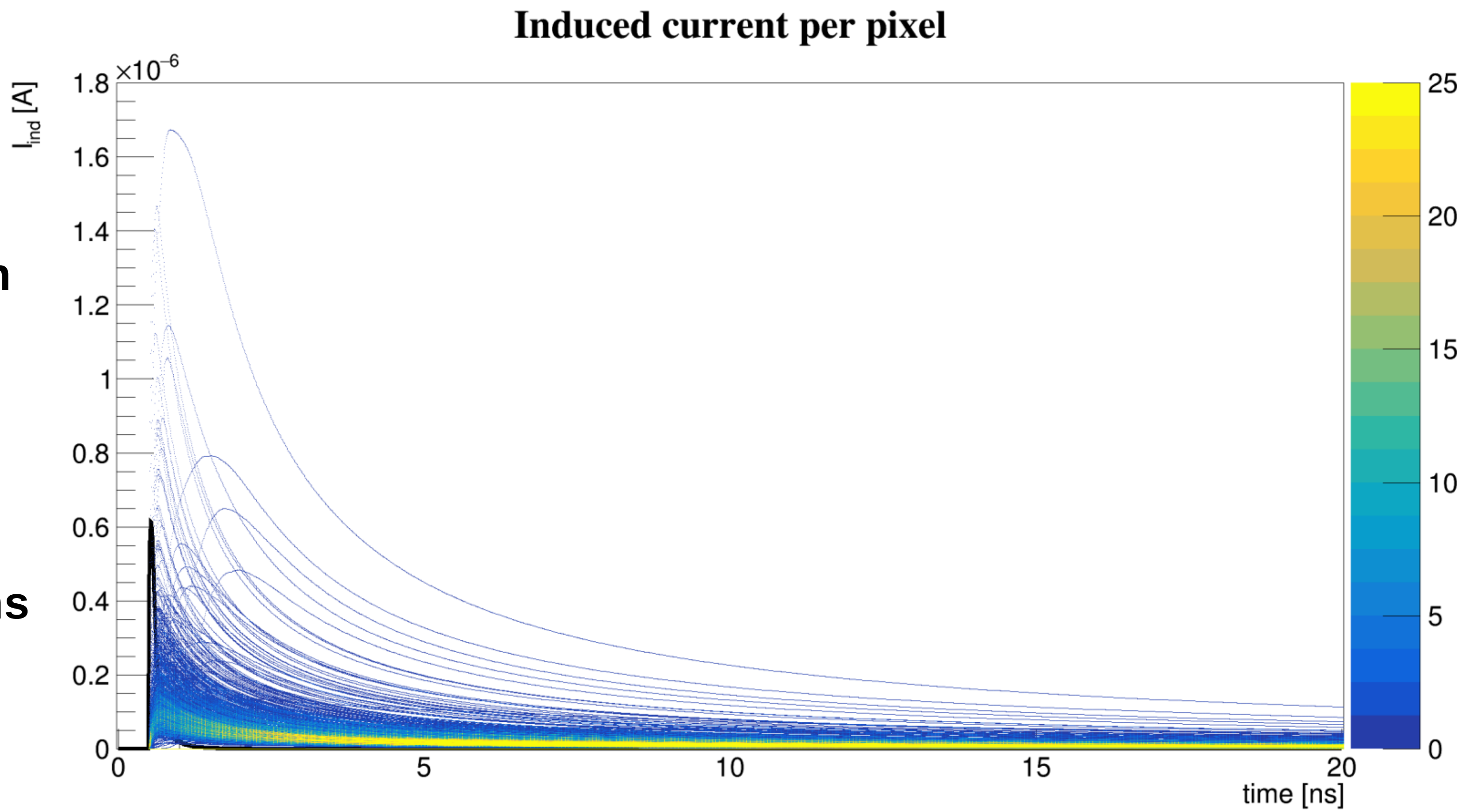


Simulation with Minimum Ionizing Particles – Beam at the center

- We can proceed by shooting MIP particles and thus take into account **Landau fluctuations, secondary particle production, Photo Absorbtion Ionization...**

- Not only that but also include contributions from the **substrate** and investigate this further by shooting in **different positions of the pixel...**





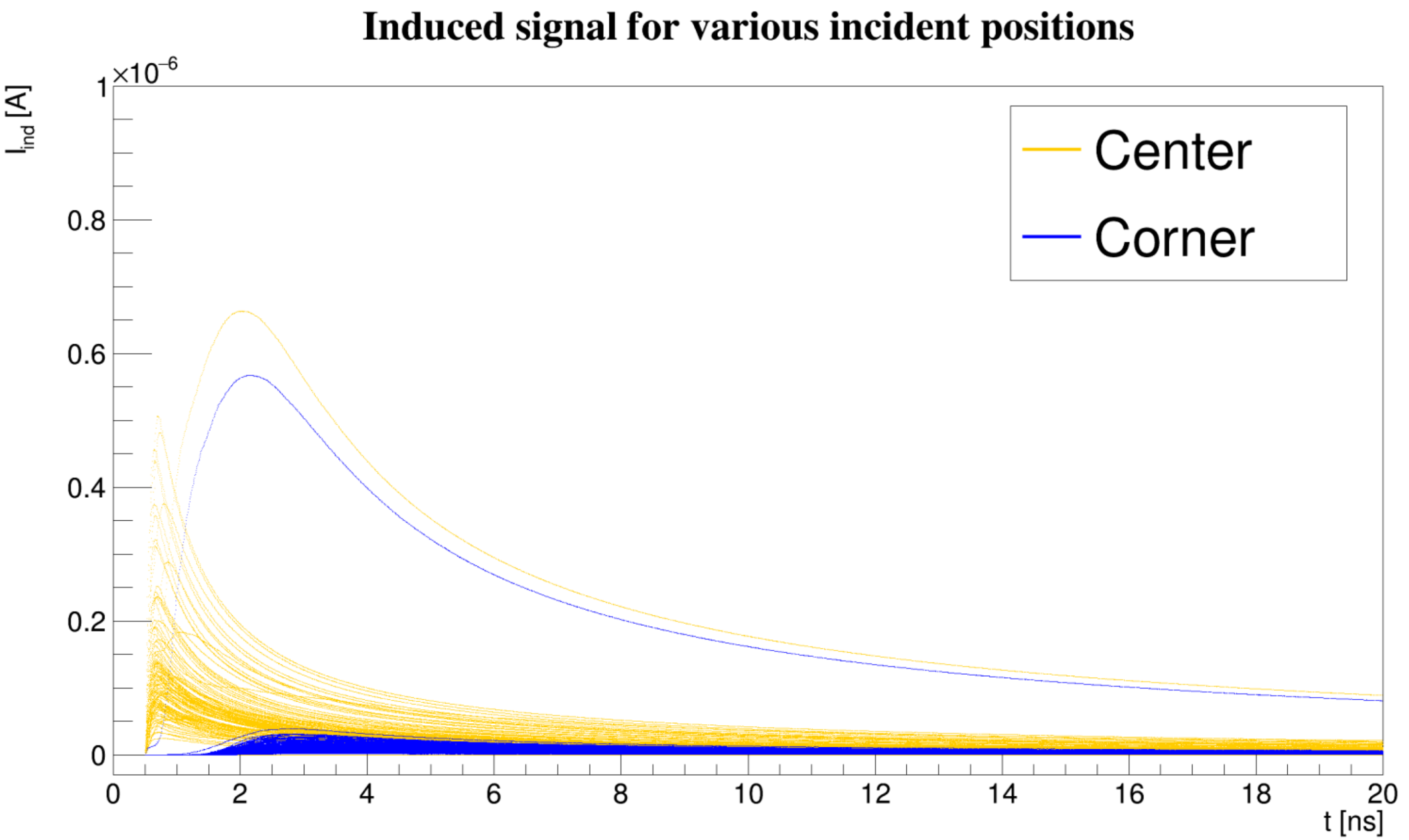
Induced signal due to a 5 GeV electron beam
Stochastic effects are visible
TCAD 63 eh/µm in black for comparison

Simulation with Minimum Ionizing Particles – Beam at various incident positions

- **Fluctuations** between both locations are distinguishable. Center pulses reaching their peak faster compared to corner ones.

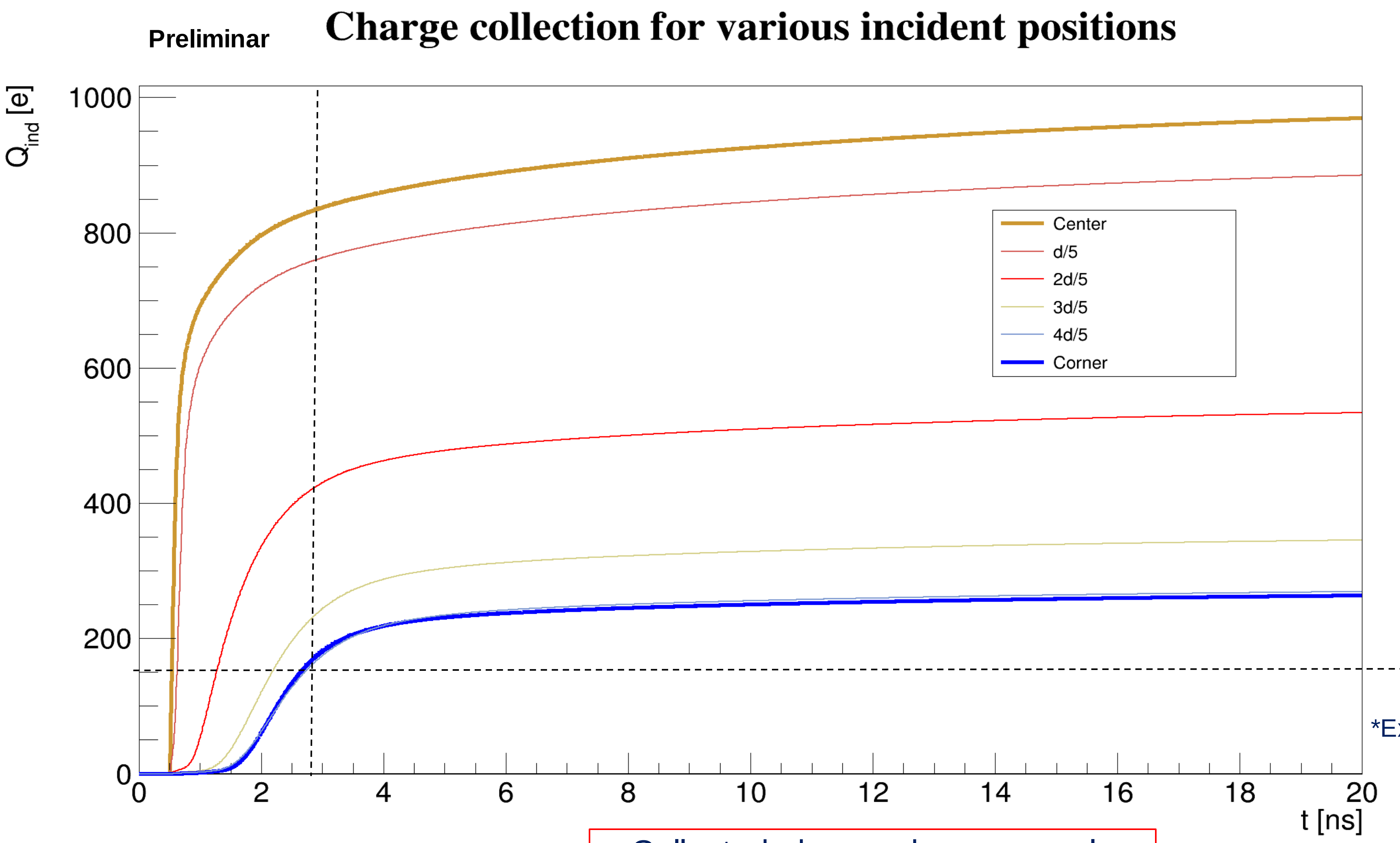
- **Higher average charge collection** from particles hitting the center is expected.

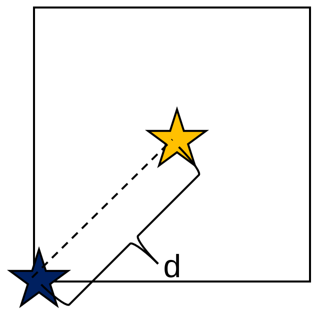
- In the plot a **high energy deposition** event for each incident position are also observed.



Comparison between pulses in center and corner of the pixel

Average Charge Collection



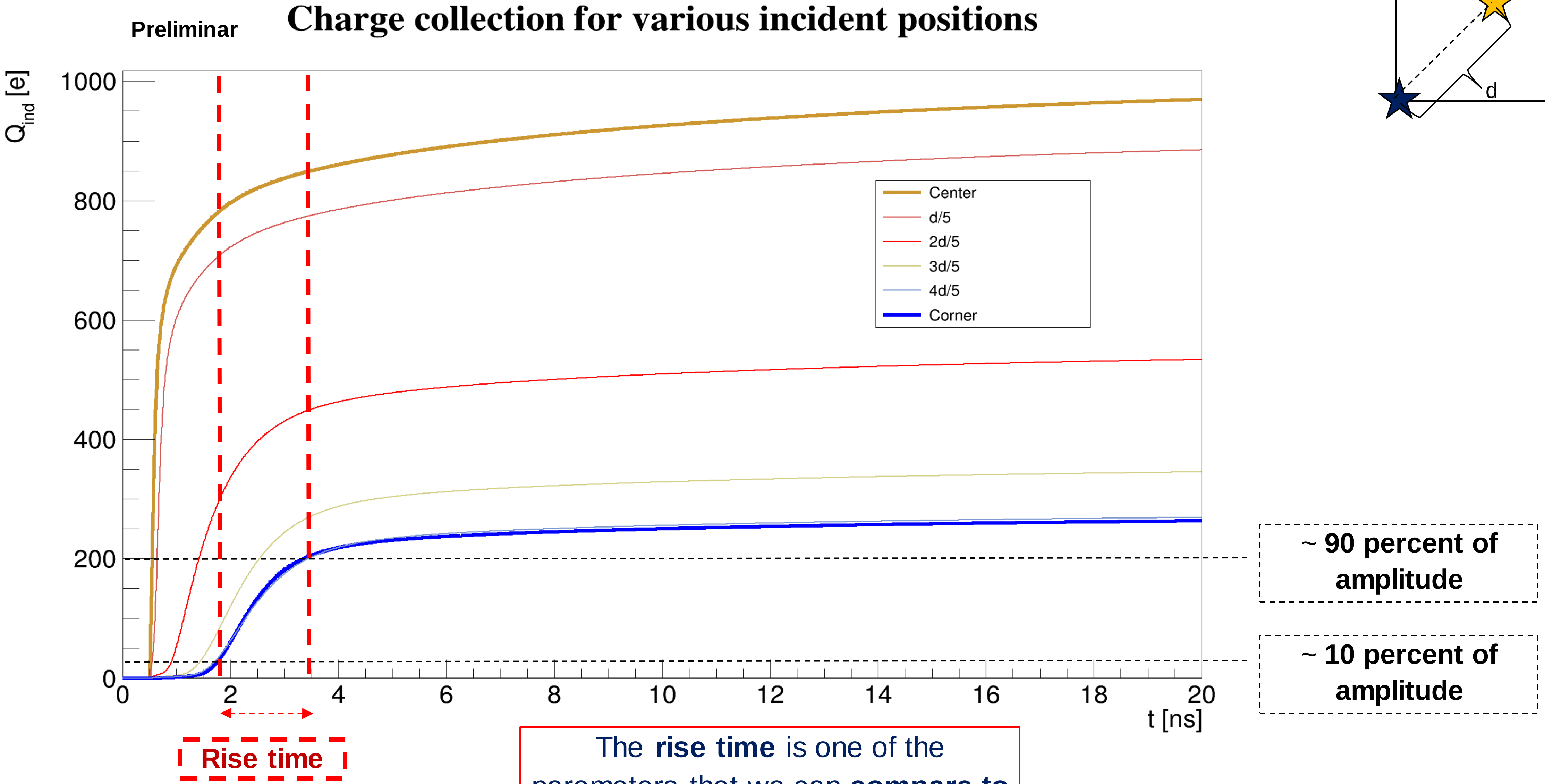


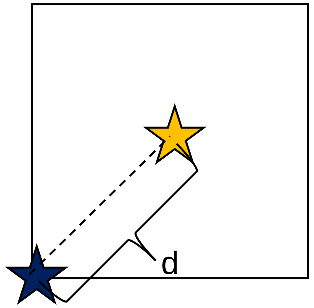
Threshold ~ 160e*

*Expected lowest reference threshold

Collected charge above example threshold within 3 ns **regardless of incident position**

Rise time for average charge collection

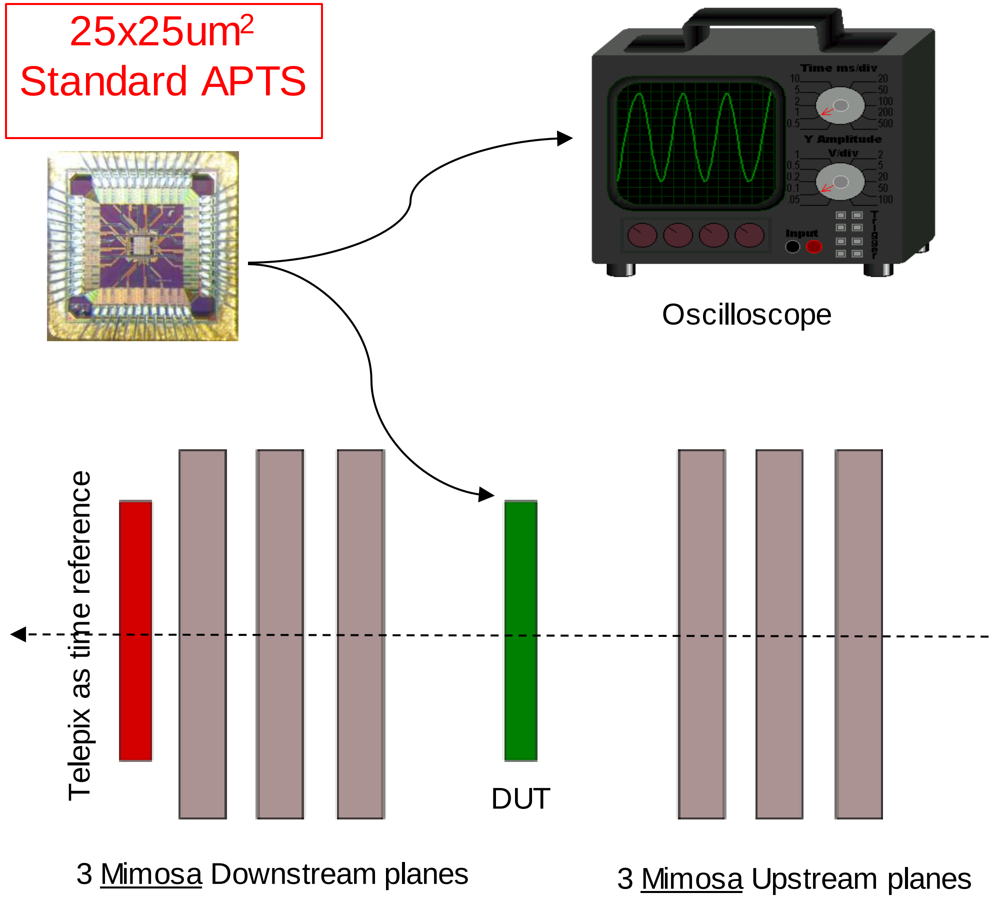




The **rise time** is one of the parameters that we can **compare to data** obtained from test beam

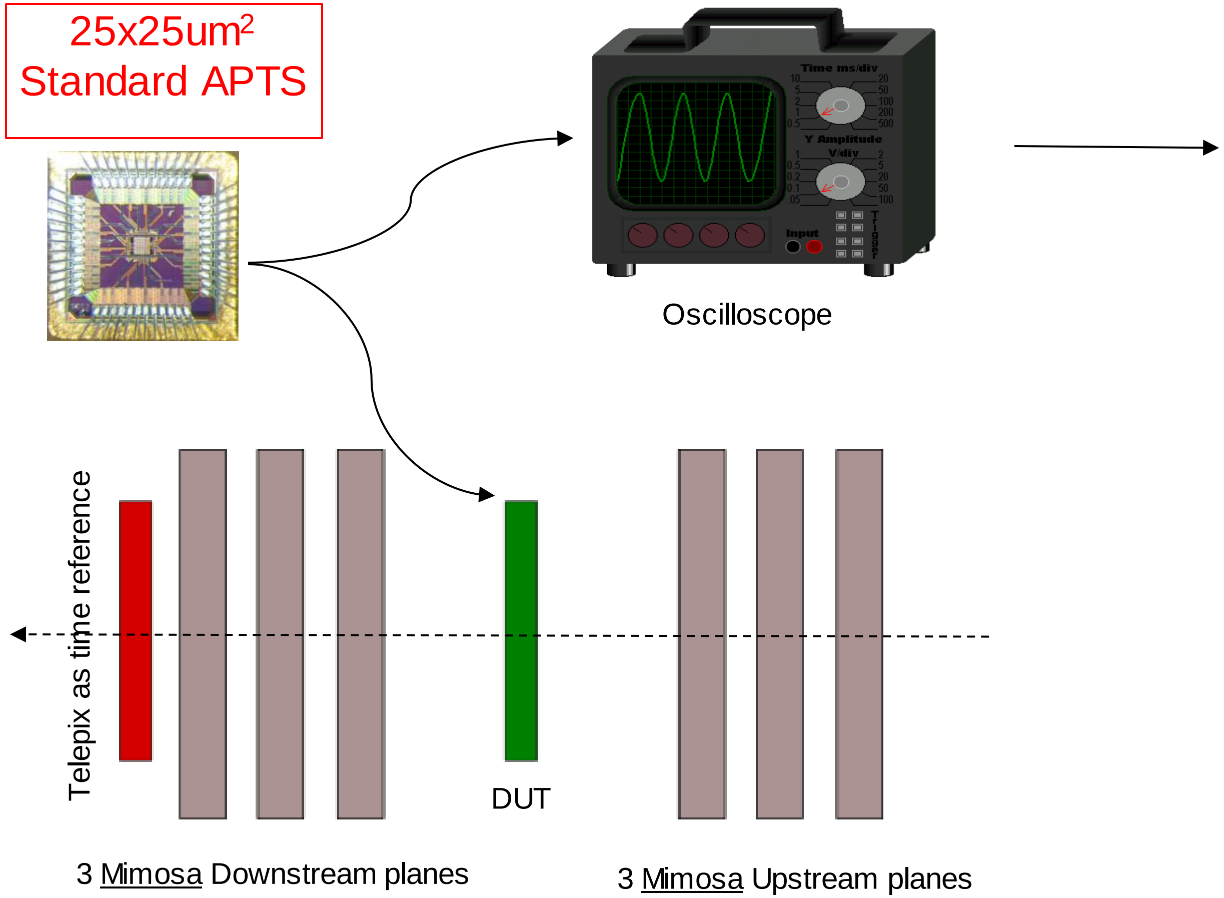
Comparison with Test Beam data

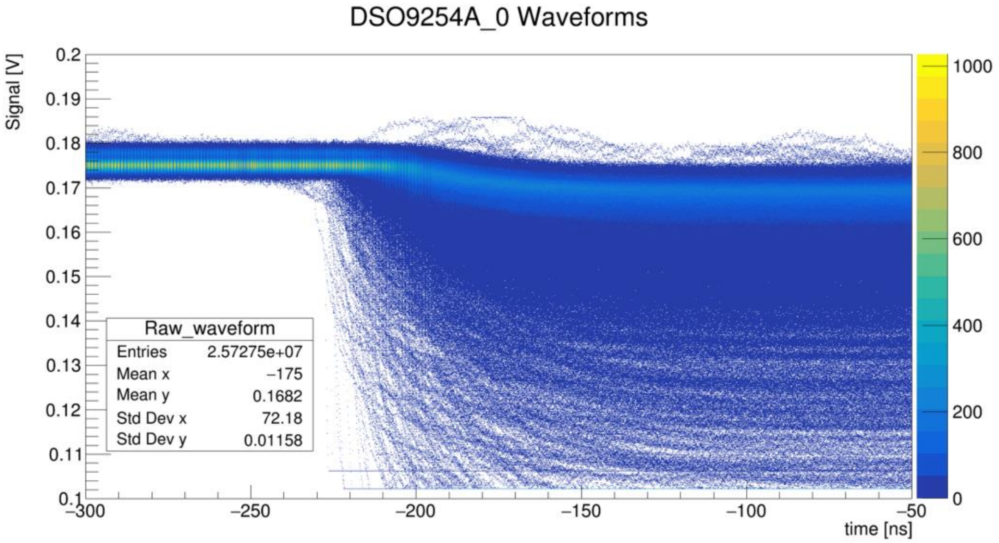
Test Beam at DESY May 2023



Comparison with Test Beam data

Test Beam at DESY May 2023



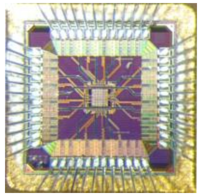


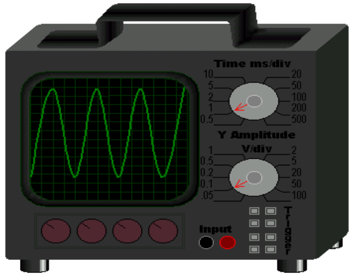
Waveforms over threshold. Stochastic effects are visible

Comparison with Test Beam data

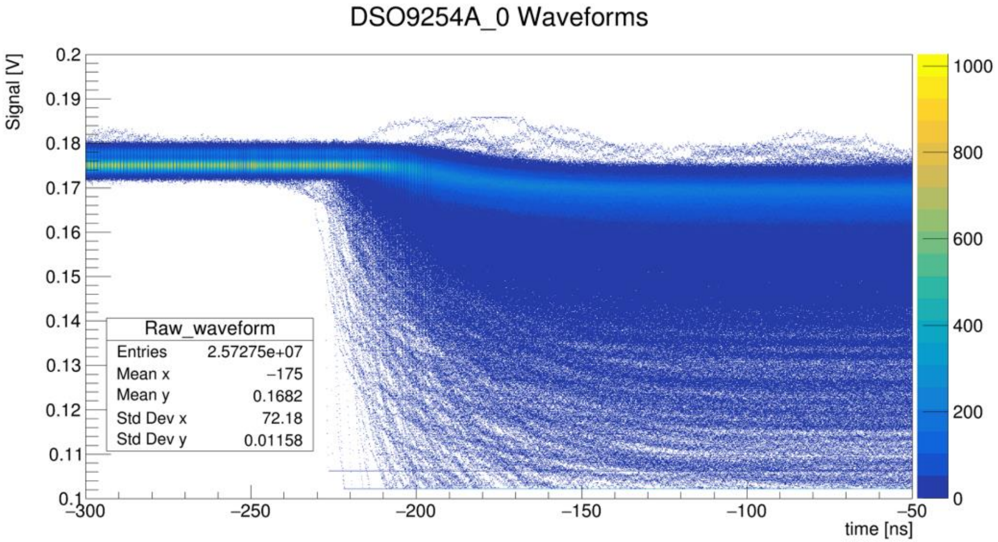
Test Beam at DESY May 2023

25x25um^2
Standard APTS

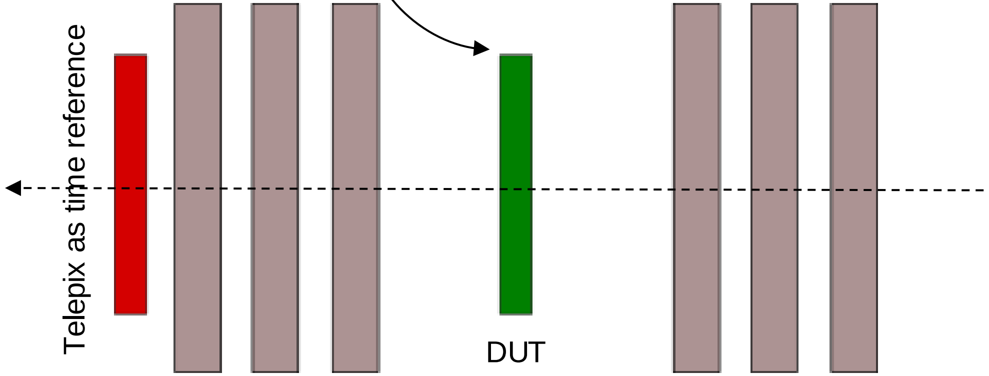




Oscilloscope



Waveforms over threshold. Stochastic effects are visible



3 Mimosa Downstream planes

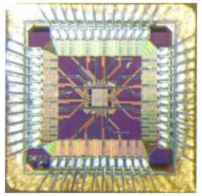
3 Mimosa Upstream planes

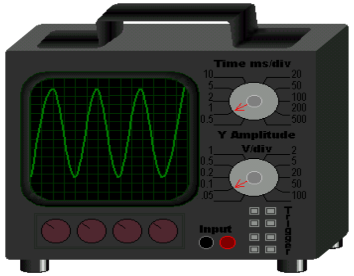
Corryvreckan 4D track reconstruction and analysis software for test beam data

Comparison with Test Beam data

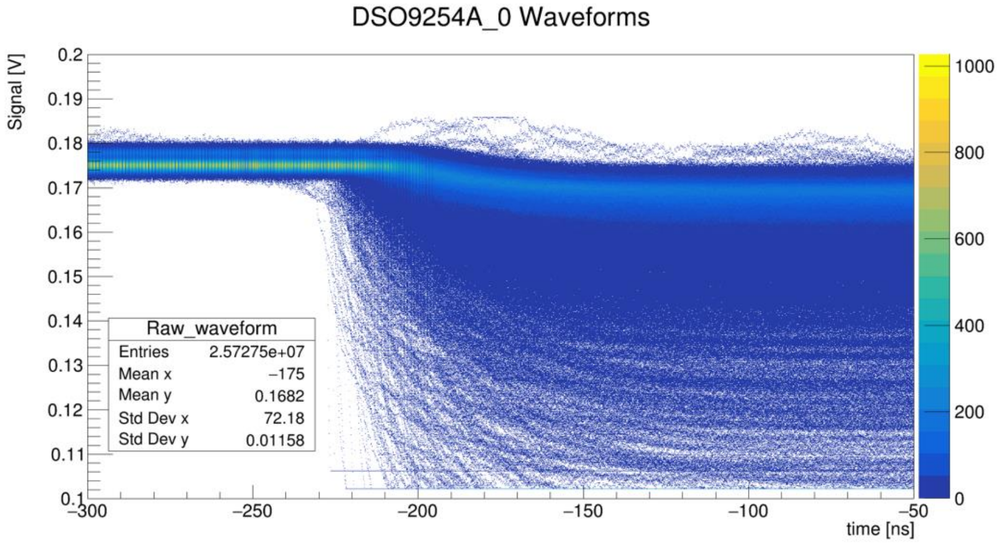
Test Beam at DESY May 2023

25x25um^2
Standard APTS

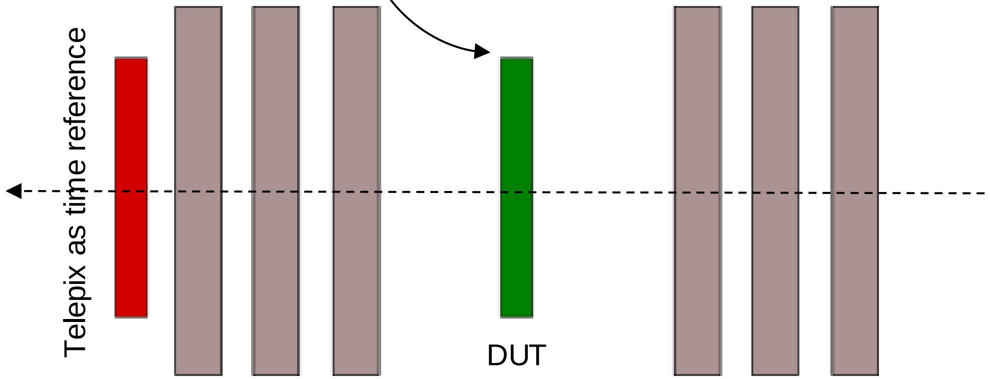




Oscilloscope



Waveforms over threshold. Stochastic effects are visible



3 Mimosa Downstream planes

3 Mimosa Upstream planes

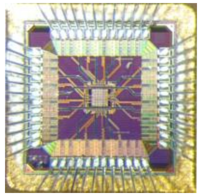
Waveform information is imported into the track reconstruction framework

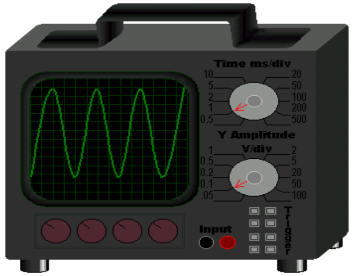
Corryvreckan 4D track reconstruction and analysis software for test beam data

Comparison with Test Beam data

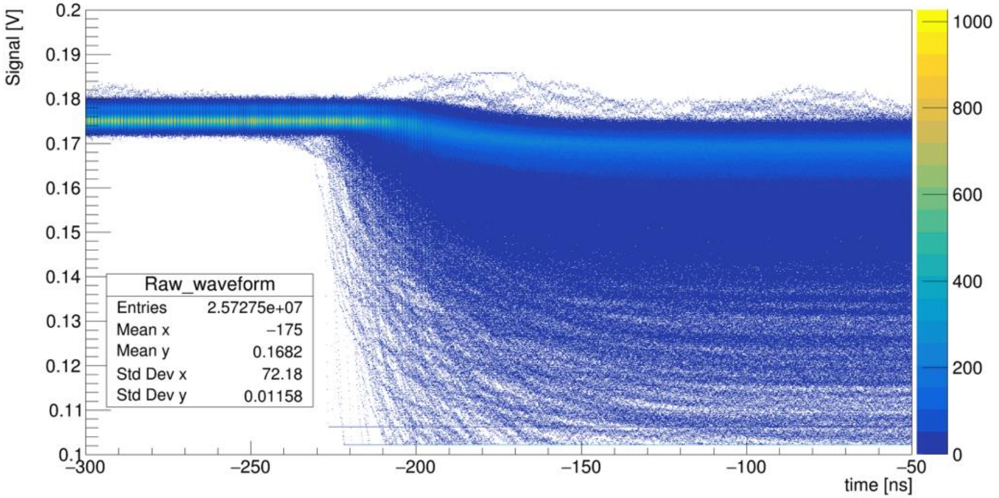
Test Beam at DESY May 2023

25x25um^2
Standard APTS

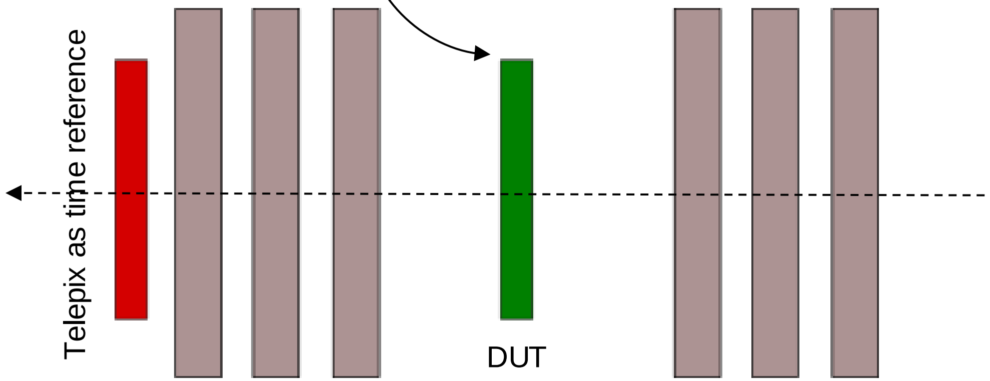




Oscilloscope



Waveforms over threshold. Stochastic effects are visible



3 Mimosa Downstream planes

3 Mimosa Upstream planes

Corryvreckan 4D track reconstruction and analysis software for test beam data

Waveform information is imported into the track reconstruction framework

- After the **track reconstruction** using Corryvreckan, each trigger event is assigned a waveform.
- From the waveforms we can obtain information such as the **rise time** and associate it to a track position.

Summary and outlook

Summary

- An APSQ+TCAD approach has been **validated** with pure TCAD simulations.
- This offers the possibility to perform **realistic** simulations.
- We performed a test beam to obtain data to compare with our Transient Simulation studies.

Outlook

- Implementation of **electronic output** in Allpix Squared.
- Feed simulation pulses in Circuit simulations.
- **Analysis** of the test beam data to obtain **parameters** to compare to our simulations.
- A **preliminary validation** of the simulation with data.

Thank you for your time!

Contact

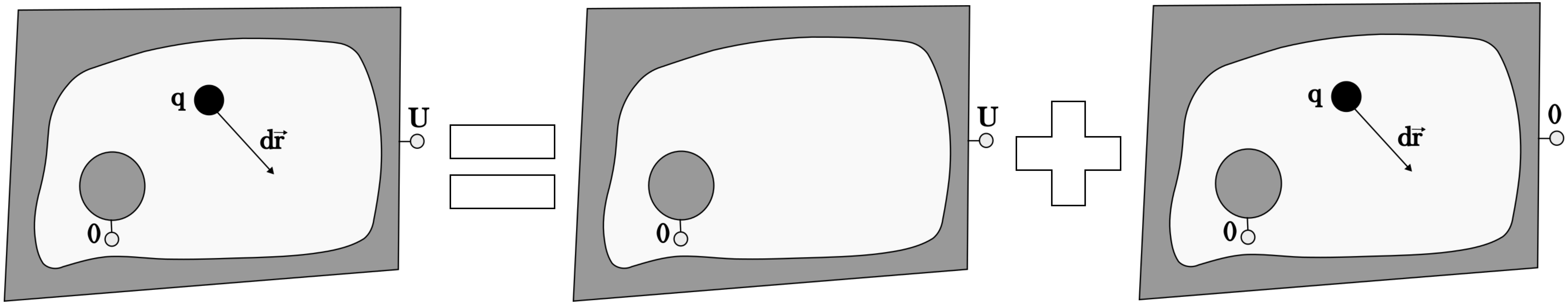
Manuel Alejandro Del Rio Viera
manuel.del.rio.viera@desy.de

Back up

Weighting Field: Shockley-Ramo Theorem

Basic Principle of Induced Signal in an electrode

See academic training lecture by W. Riegler (https://indico.cern.ch/event/843083/)



Total Potential | **Potential without charge** | **Potential of point charge**

For a **static electric field, the energy:** $W_E = W_{E_0} + W_{E_q}$

No change in total field energy when charge is moving: $0 = dW_{E_0} + dW_{E_q} = UdQ + q\vec{E_0} \cdot d\vec{r} \rightarrow dQ = -q\frac{\vec{E_0}}{U} \cdot d\vec{r}$

Solved by a **weighting field and a weighting potential**: $\boxed{\varphi_w = \frac{\varphi_0}{U}\ ;\ \vec{E_w} = -\vec{\nabla}\varphi_w}$

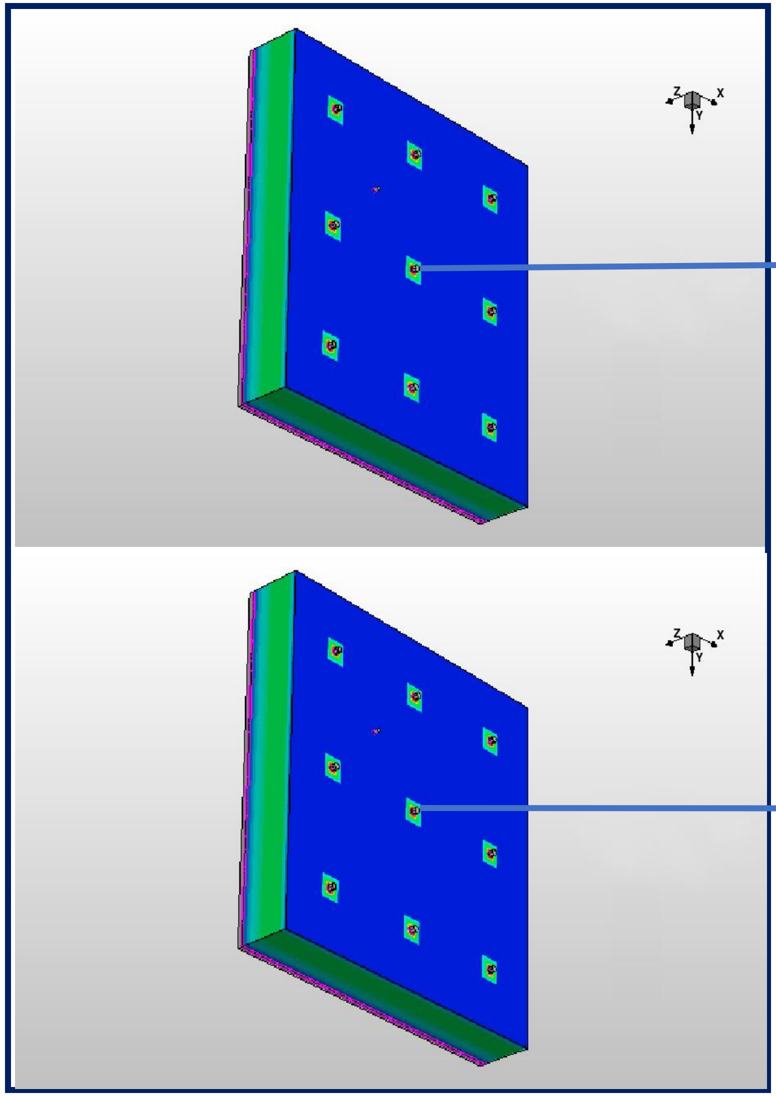
The induced current can be expressed by the **propagation of the charge in the weighting field** :

$$\boxed{\begin{aligned} I_{ind} &= q\vec{E} \cdot \vec{v} \\ Q_{ind} &= q(\varphi_w(\vec{r}_{t_0}) - \varphi_w(\vec{r}_t)) \end{aligned}}$$

Weighting Potential

How to obtain it?

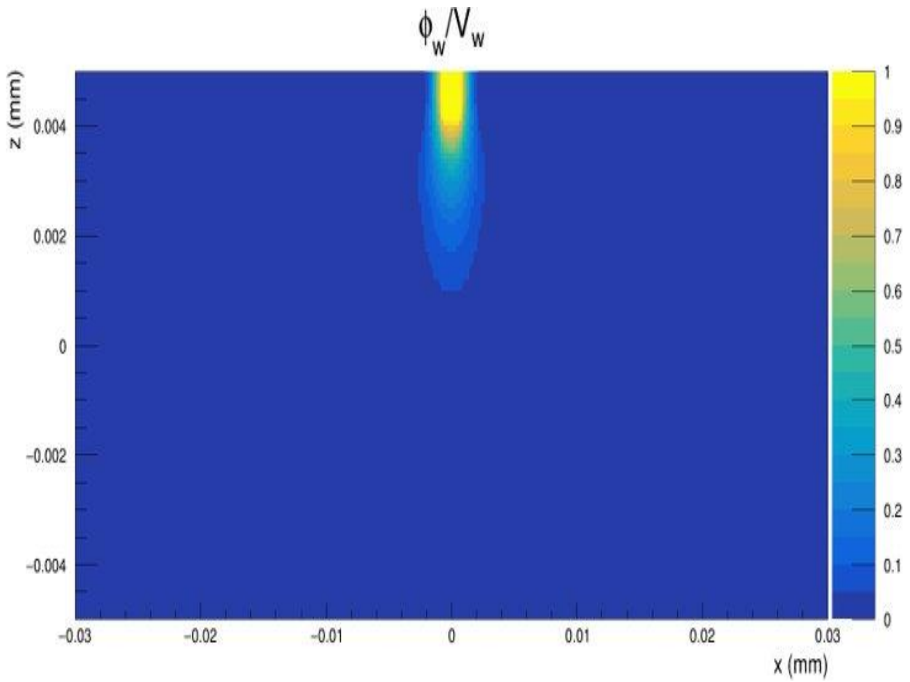
1. Simulate **Electrostatic Potential** with TCAD at the collection electrode for two slightly different voltages
2. Subtract the two electrostatic potentials at every mesh point
3. Divide by the collection electrode voltage difference



i.e. Voltage: -1.2 V

$$(\varphi_1 - \varphi_2)/\Delta U$$

i.e. Voltage: -1.3 V



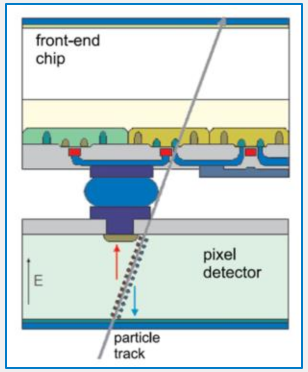
High weighting potential values are concentrated around collection electrode

Anastasiia Velyka

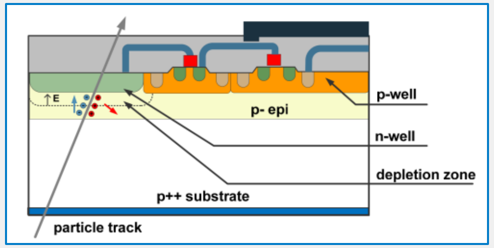
Monolithic Active Pixel Sensors (MAPS)

in a 65 nm CMOS technology

Hybrid

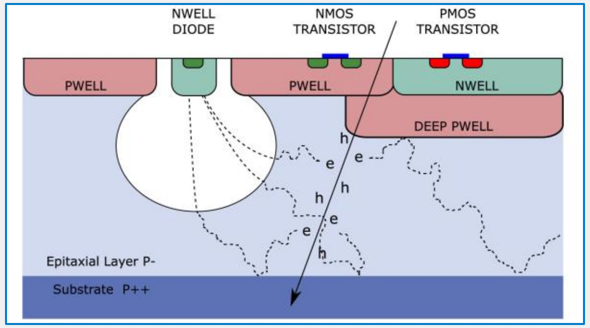


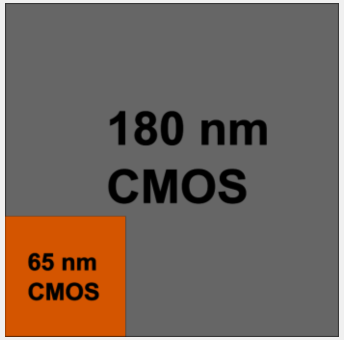
Monolithic



N. Wermers/Univ. of Bonn

ALPIDE ALICE ITS Upgrade





From Hybrid to Monolithic

- ➢ Reduced material budget
- ➢ Reduced complexity
- ➢ Reduced production cost
- ➢ Smaller pixels

Small Collection Electrode

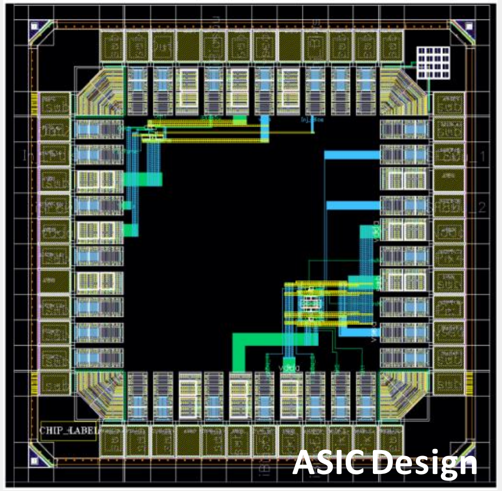
- ➢ Reduce noise and power consumption (~40 mW/cm^2)
- ➢ Better spatial resolution ~ 5 µm

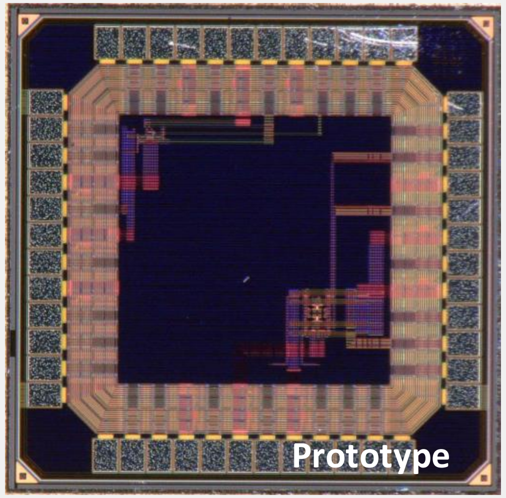
180 nm to 65 nm

- ➢ Higher logic density
  - ✓ Smaller pixels
  - ✓ Better in pixel functionality
- ➢ Further decrease in power consumption

Second sensor under study

Multi-Layer Reticle 1 (MLR1) production

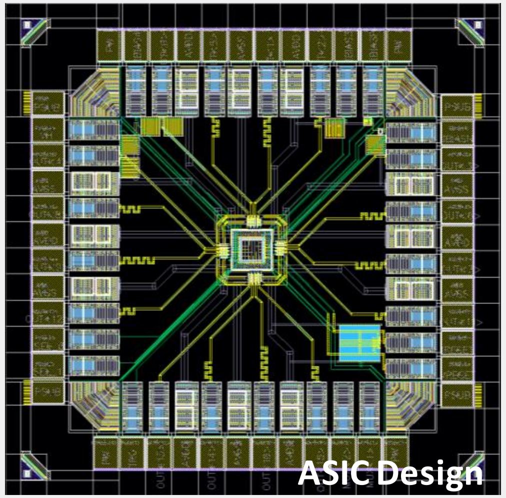


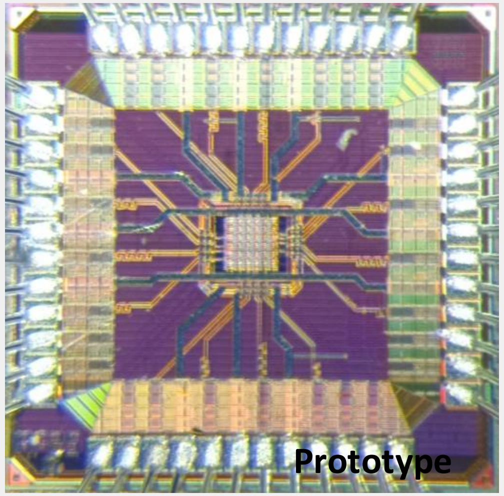


DESY MLR1:

- Entirely developed at DESY
- Test structures for Charge Sensitive Amplifier (CSA) characterization developed at DESY
- Block of 2x2 16 µm pixels with an analogue readout for pixel characterization

Analogue Pixel Test Structures (APTS)





Analogue Pixel Test Structures (APTS):

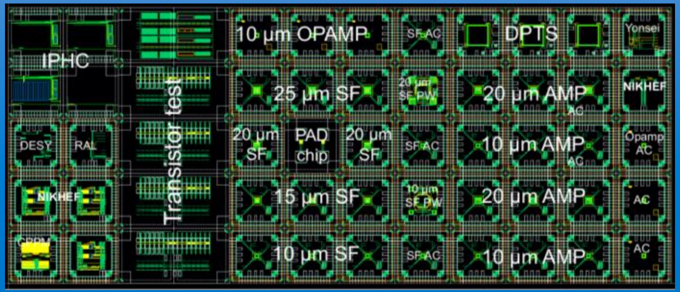
- Designed at CERN (DESY involved in the lab and TB characterization)
- 4x4 pixels structure with analogue output
- Different sensor pitches and layouts

EP R&D

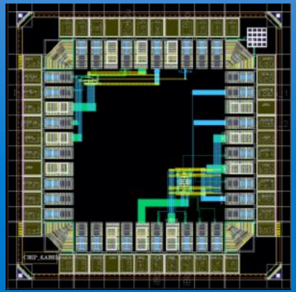
ALICE

Timeline and next to come

From MLR1 to ER1

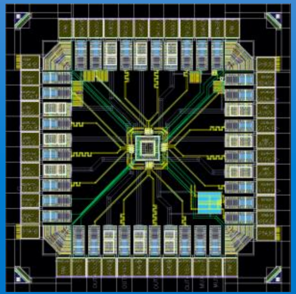


MLR1 reticle



DESY Chip V1

2021

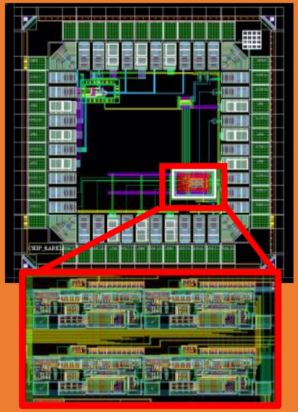


APTS

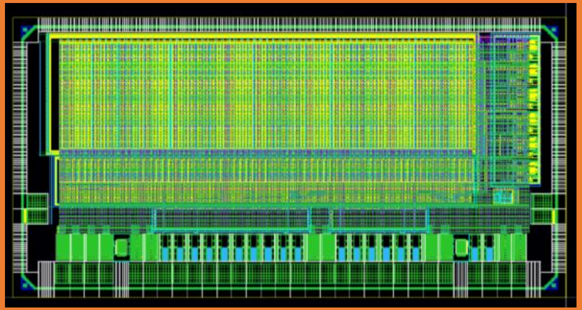
2022

Engineering Run 1 (ER1) in Production

ER1 reticle



DESY Chip V2



H2M Chip

2023

DESY Chip V2

- 2x2 pixel (35x25 µm^2) with all-in-pixel functionality
- External access to CSA and discriminator output
- N-gap layout with 2.5 µm and 4 µm gap
- Single Front-End with charge Injection

H2M (Hybrid-To-Monolithic)

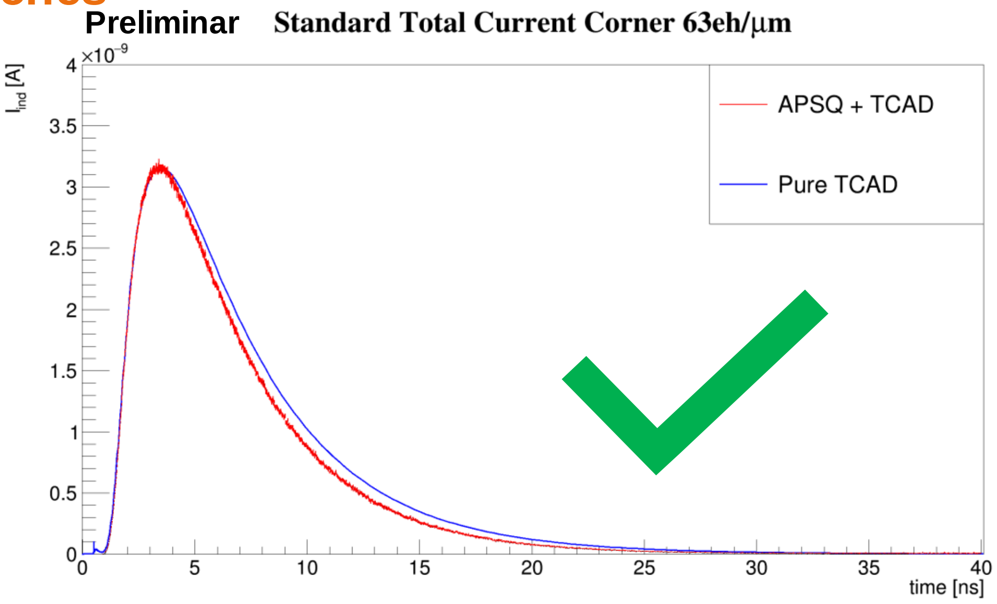
- Collaboration of DESY, CERN and IFAE
- 3 x 1.5 mm^2 , 64 x 16 square pixel, 35 µm pitch
- 8-bit counter per pixel
- 4 acquisition modes (ToA, ToT, counting, binary RO)

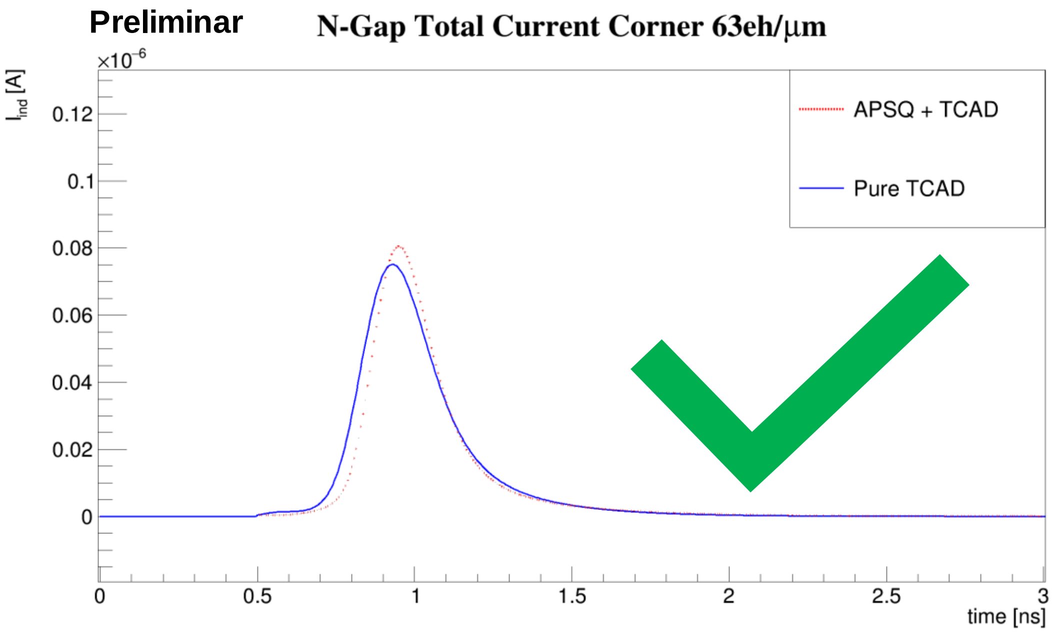
Validation with TCAD

Various Pitches

Standard | **N-Gap**

$15x15um^2$





$25x25um^2$