Transient Simulations: Weighting Potentials through Technology Computer-Aided Design

Manuel Alejandro Del Rio Viera

Allpix Squared 4th Workshop

May 23rd 2023

HELMHOLTZ UNIVERSITÄT BONN

allpix squared

DESY.

The Tangerine Project

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

Requirements

- Spatial Resolution ~ **3 µm**
- Time Resolution ~ **1 -10 ns**
- Low material budget ~ **50 µm silicon**

Application: e^+e^- Colliders

Reference detector at DESY-II test beam

- Funded by Helmholtz Innovation Pool and DESY

Part of the **Work Package 1 (WP1):** Monolithic pixel detectors in novel CMOS imaging technology

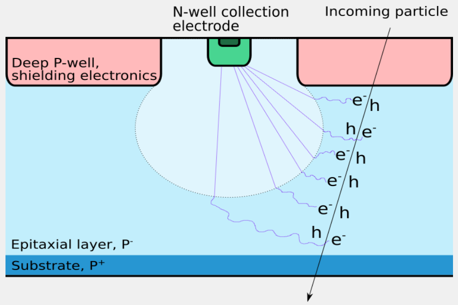
HELMHOLTZ

TowArds Next GEneRation SIlicoN DEtectors

Monolithic Active Pixel Sensors (MAPS)

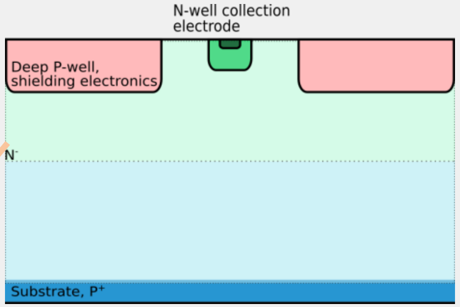
Standard

S. Senyukov et al. doi:10.1016/



Small Collection Electrode

N-Blanket



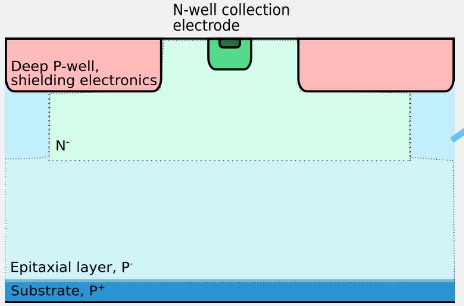
W. Snoeys et al. doi:10.1016/

Continuous N-type Implant

Increase the depleted region

N-Gap

M. Münker et al 2019 JINST 14



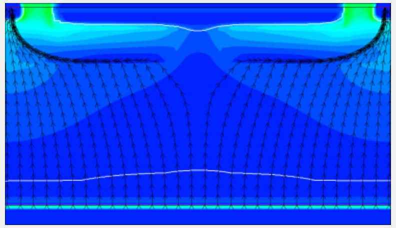
Gap in Continuous N-type Implant

Speed up charge collection

Simulation's Workflow

Why do we need Transient Simulations?

Device Simulations (TCAD)



Allow to optimize the layouts that characterize a sensor

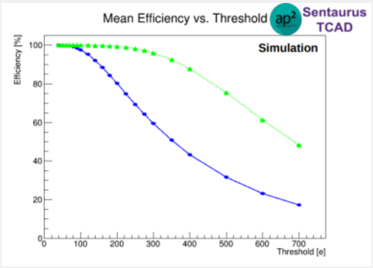
- Electric Fields
- Process Simulations
- Capacitance
- Weighting Potentials

Monte Carlo Simulations

Allow for greater statistics and to analyze detector performance

- Efficiency
- Cluster Size and Resolution
- Pulses

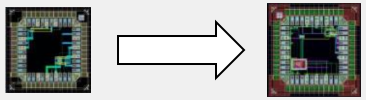
Compare data with simulations



See Adriana's presentation On Simulations and Test Beam Characterization

Motivation of Transient Simualtions

- **Produce accurate pulses in more realistic simulations**
- **Predict sensor and precise FE response**
- **Optimize our sensors.**



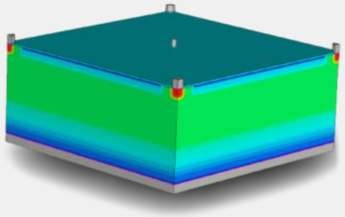
Allpix Squared + TCAD

Transient Simulations - Full Detector Response

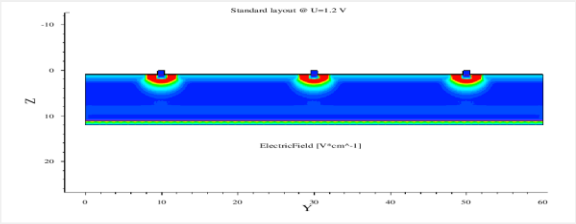
The **static** Electric Field, Doping Concentration and Electrostatic Potential Profiles are converted and imported into **Allpix Squared (APSQ):**

➞ **Combining the best of both : High statistics** and **accurate field modeling**

Generic Doping Profiles



Electric Field



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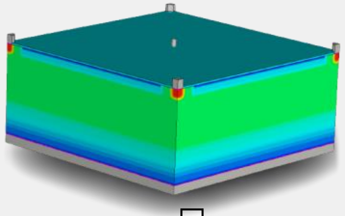
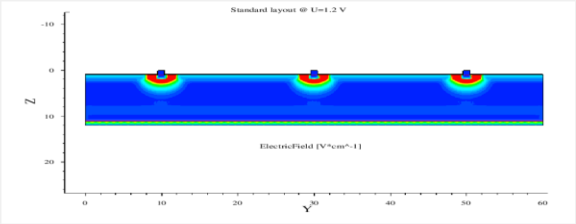
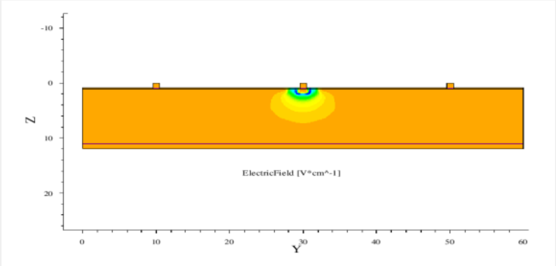
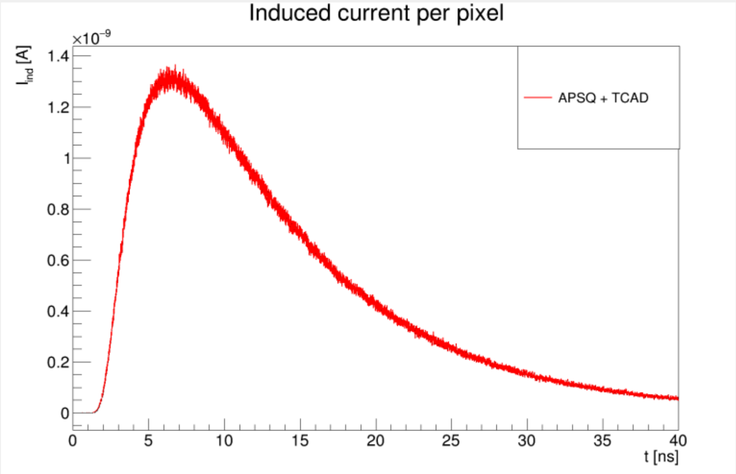


Electric Field



Weighting Potential

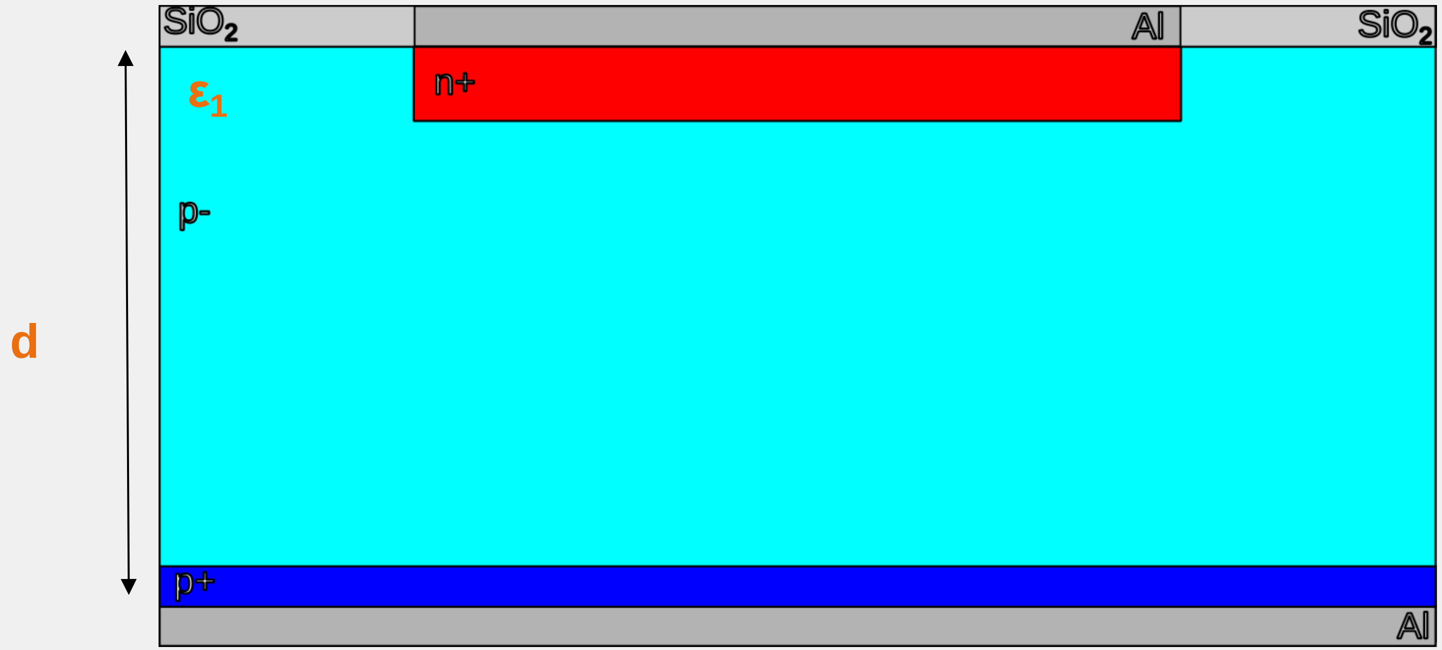




Produce accurate pulses, and thus predict sensor and FE behavior!

Shockley-Ramo's Theorem

Signal Formation on Silicon Sensors



Shockley-Ramo's Theorem

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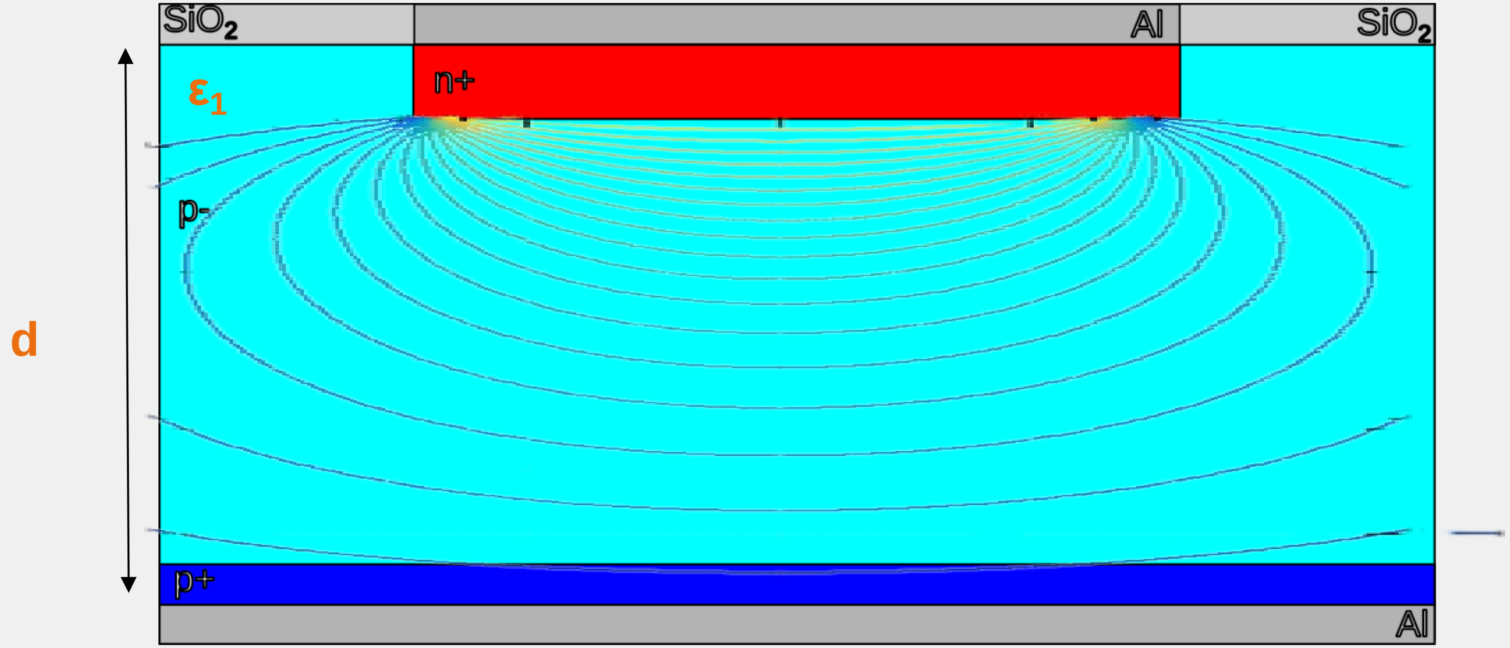
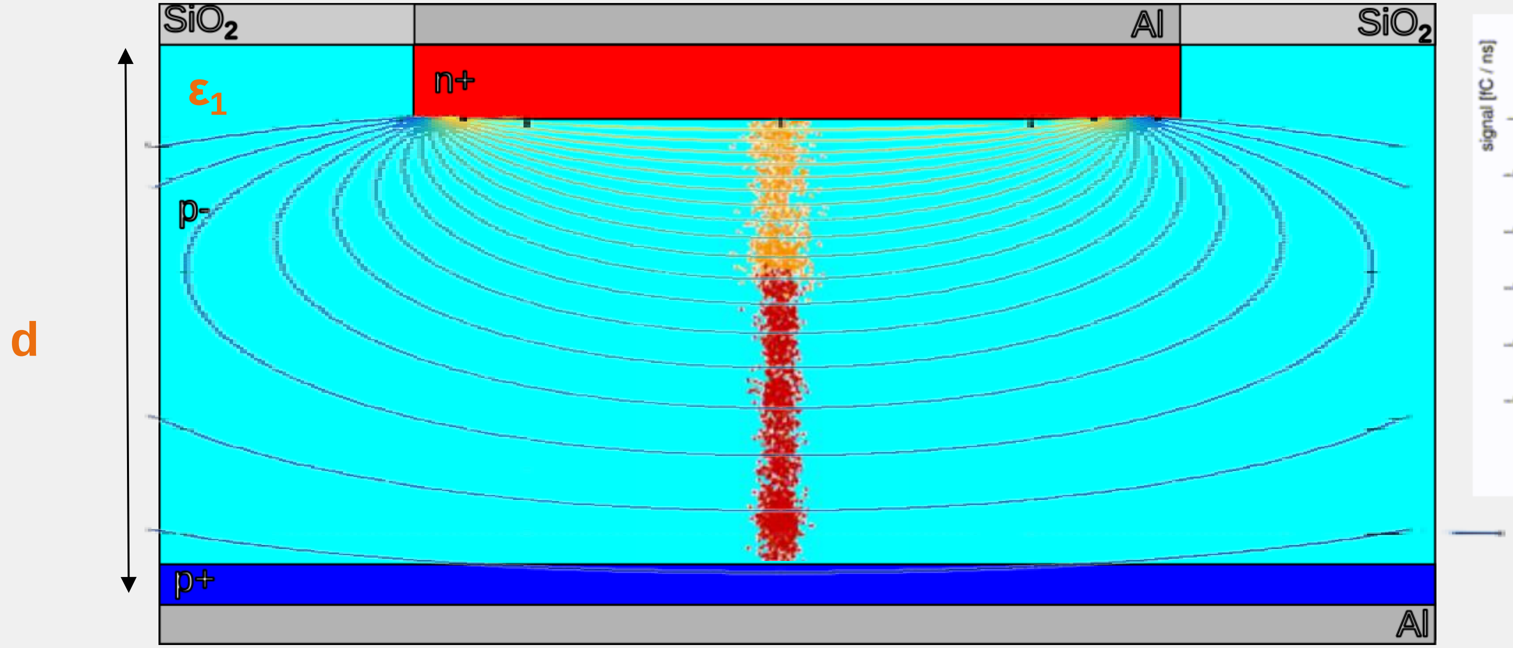


$$\varphi_w = \frac{\varphi_0}{U}\ ;\ \overrightarrow{E_w} = -\vec{\nabla}\varphi_w$$

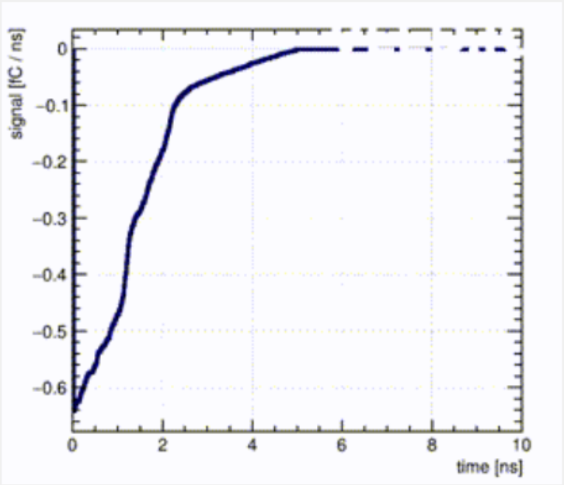
Shockley-Ramo's Theorem

Signal Formation on Silicon Sensors

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



http://garfieldpp.web.cern.ch/garfieldpp/



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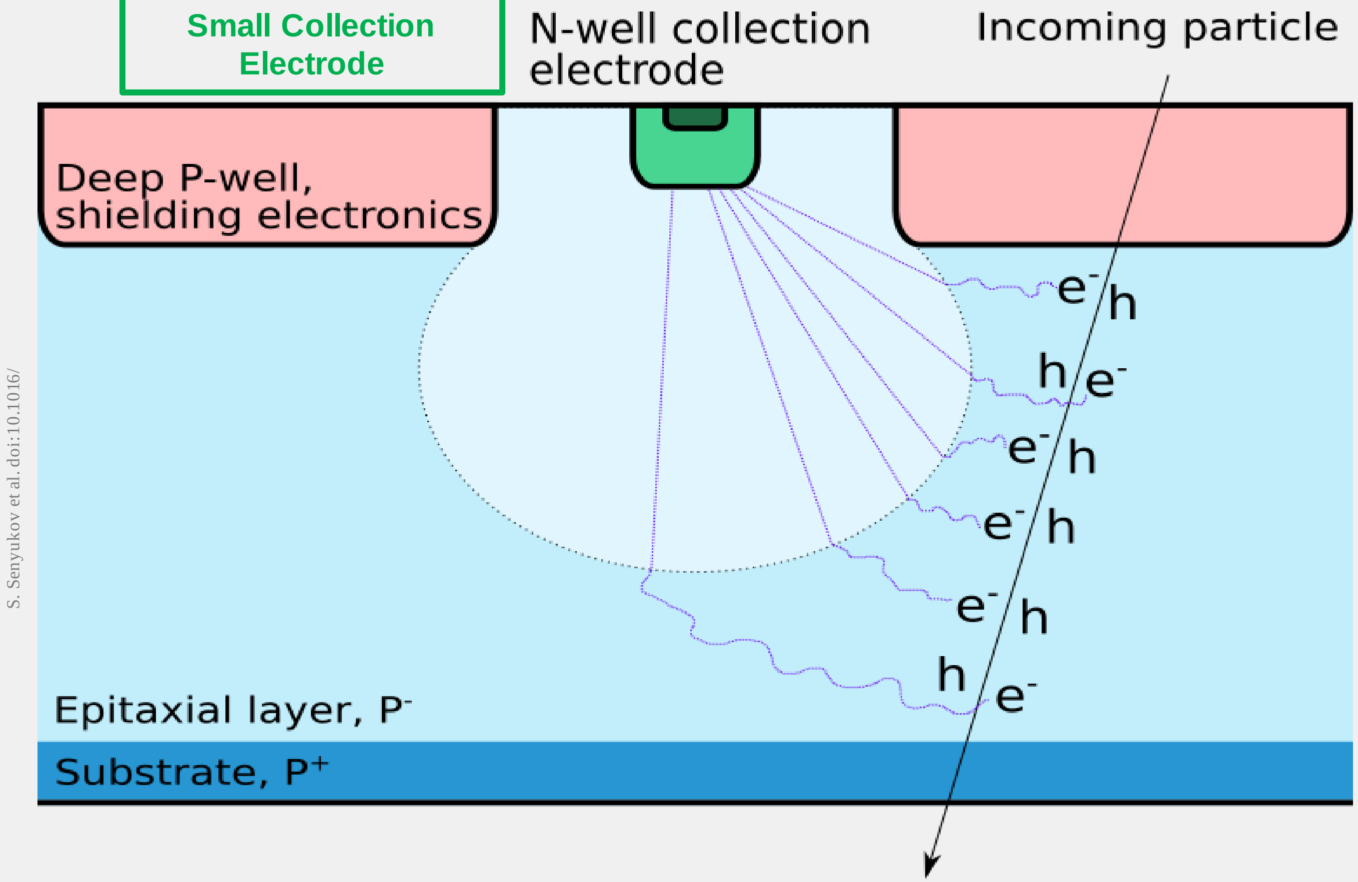
Monolithic Active Pixel Sensors (MAPS)

Thanks to Anastasiia Velyka and Adriana Simancas for providing all the fields!

Standard

Small Collection Electrode



[WeightingPotentialReader]

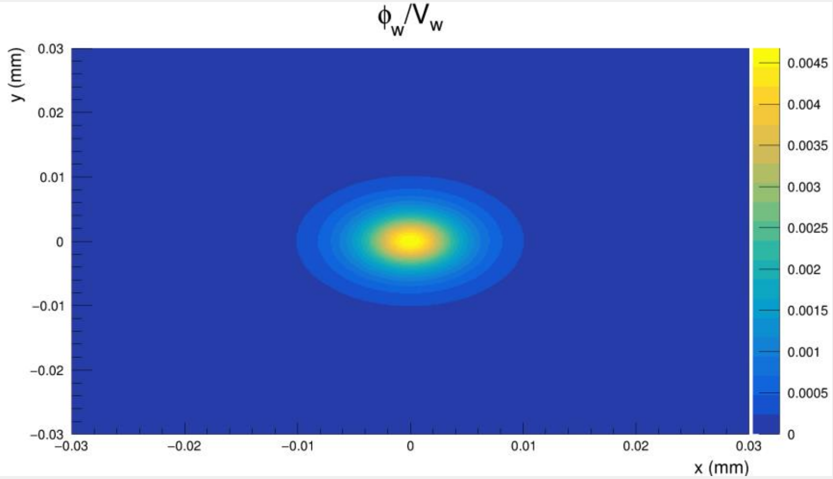
Adds a weighting potential (Ramo potential) to the detector from one of the supported sources. This module support **two types of weighting potentials.**

```
[WeightingPotentialReader]
model = "pad"
output_plots=true
field_scale= 3 3 #Odd number
```

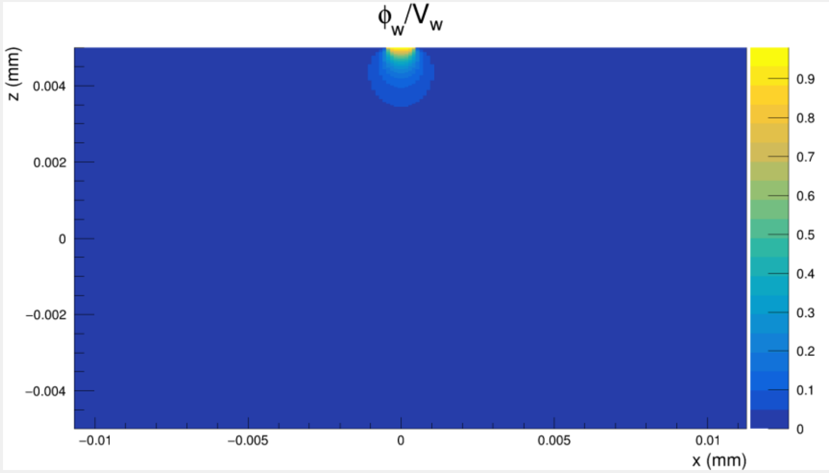
Simulation time consuming!

Models

"Pad"



Upper view of WP (of a 20x20um^2 pitch pixel and 10um thickness)



Transversal cut of WP (of a 20x20um^2 pitch pixel and 10um thickness)

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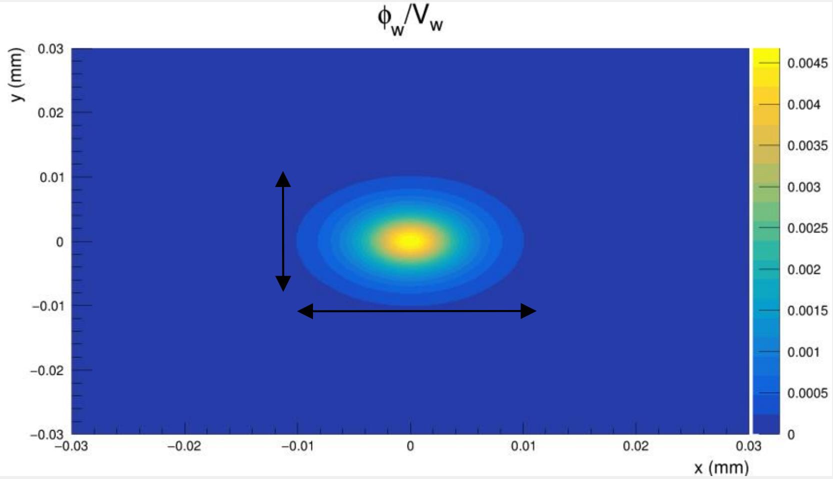

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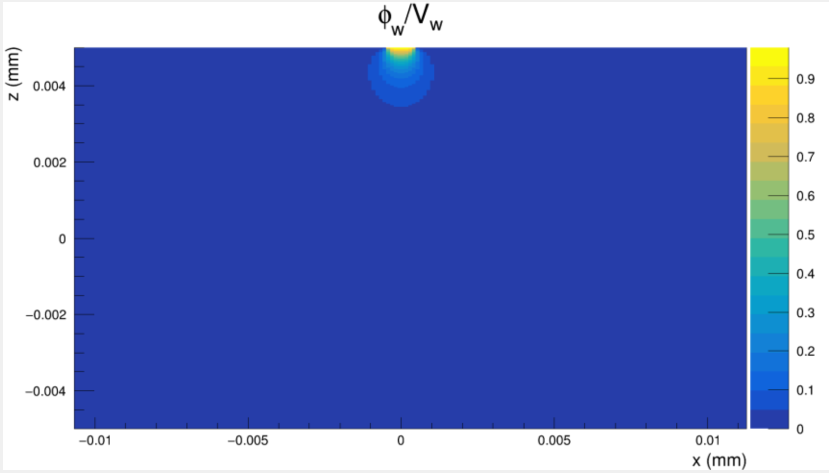

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ap2
allpix squared

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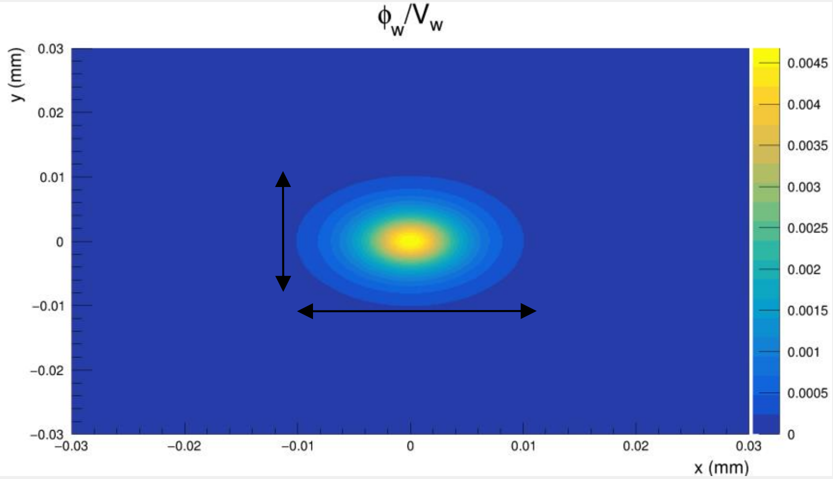

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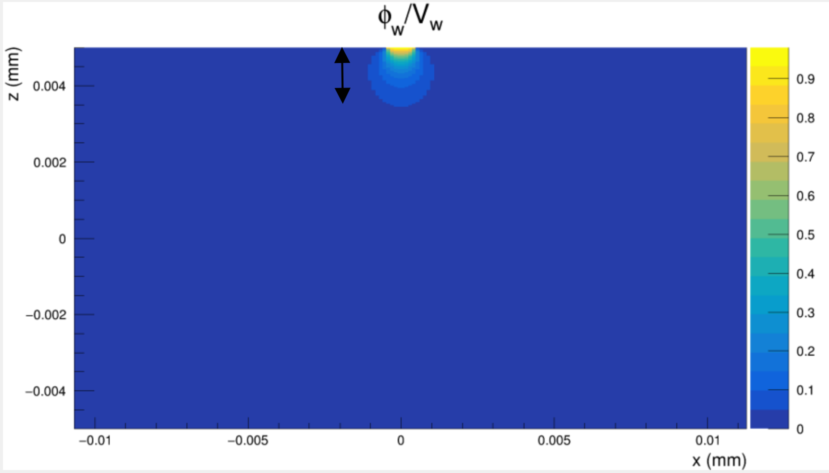

Transversal cut of WP (of a 20x20um^2 pitch pixel and 10um thickness)

[WeightingPotentialReader]

```
[WeightingPotentialReader]
model = "mesh"
file_name = "WP.apf" or "WP.init"
field_scale= 3 3  #Odd number
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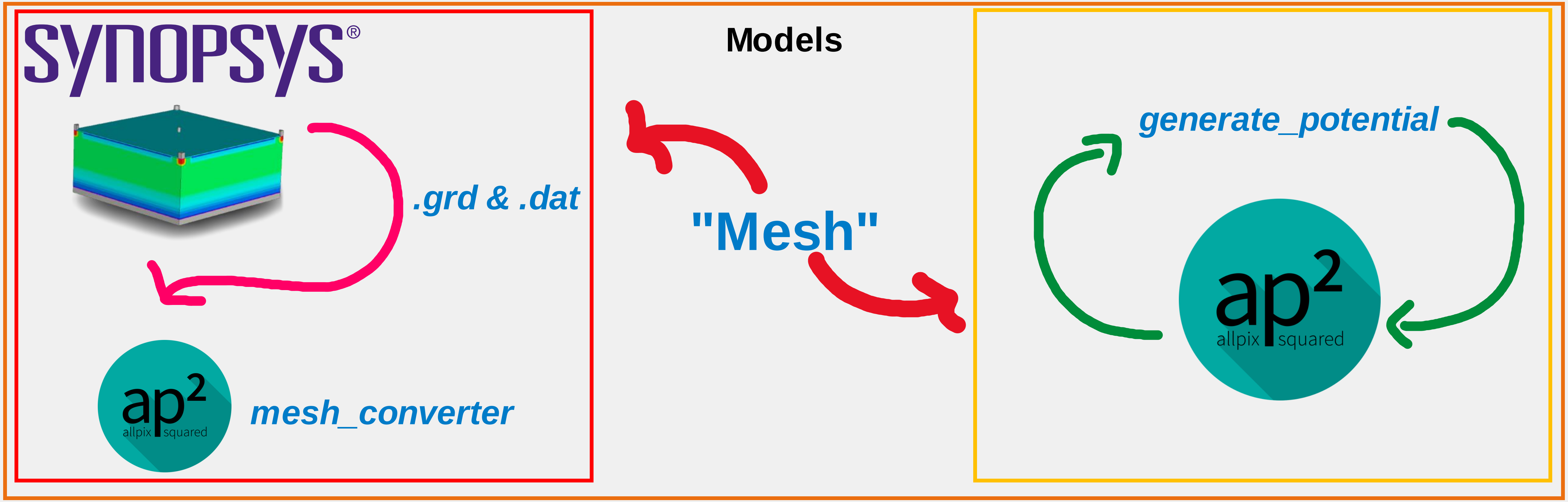

generate_potential Tool

This tool allows to generate simple Weighting Potential based on a **sensor model file**

```
generate_potential --model Sensor.conf --binning 300,300,100 --matrix 3,3 --output WP --init
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```

```
type = "monolithic"

number_of_pixels = 3 3
pixel_size = 20um 20um
implant_size= .9um .9um
sensor_thickness = 10um
```

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```

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pixel_size = 20um 20um
implant_size= .9um .9um
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```

```
Allpix Squared v2.3.2 Weighting Potential Generator
internal ##EVENTS##
##TURN## ##TILT## 1.0
0.0 0.0 0.0
10 60 60 0.0 0.0 0.0 0.0 300 300 100 0.0
1 1 1 1.59266e-05
1 1 2 1.61061e-05
1 1 3 1.6285e-05
1 1 4 1.64629e-05
1 1 5 1.66394e-05
1 1 6 1.68143e-05
```

[WeightingPotentialReader]

It takes adaptative meshes from finite element simulations like TCAD to **regularly space grids** for faster look up of the fields values

```
[WeightingPotentialReader]
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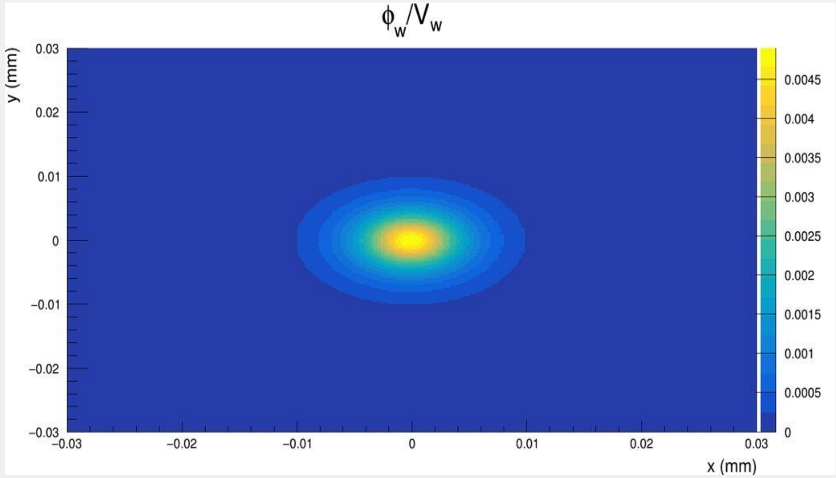
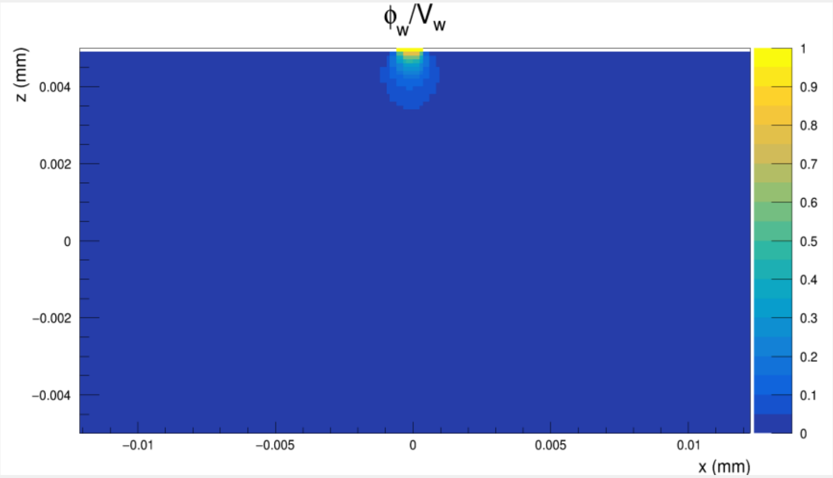
Models



Upper view of WP (of a 20x20um² pitch pixel and 10um thickness)

"Mesh"

generate_potential



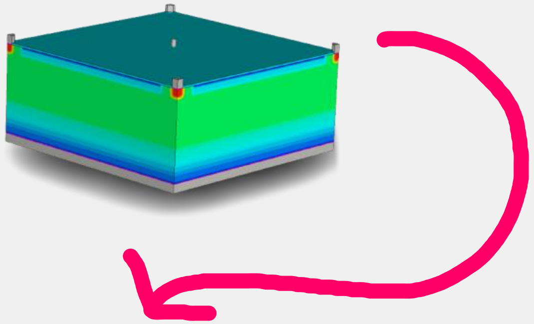
Transversal cut of WP (of a 20x20um² pitch pixel and 10um thickness)

mesh_converter Tool

It takes adaptative meshes from finite element simulations like TCAD to **regularly space grids** for faster look up of the fields values

```
model = "init"
region = "si-bulk"
dimension=3
observable = ElectrostaticPotential
observable_units = ""
divisions = 300 300 100
initial_radius = 0.01
xyz= x y -z
workers = 10
```

SYNOPSYS®



.grd & .dat

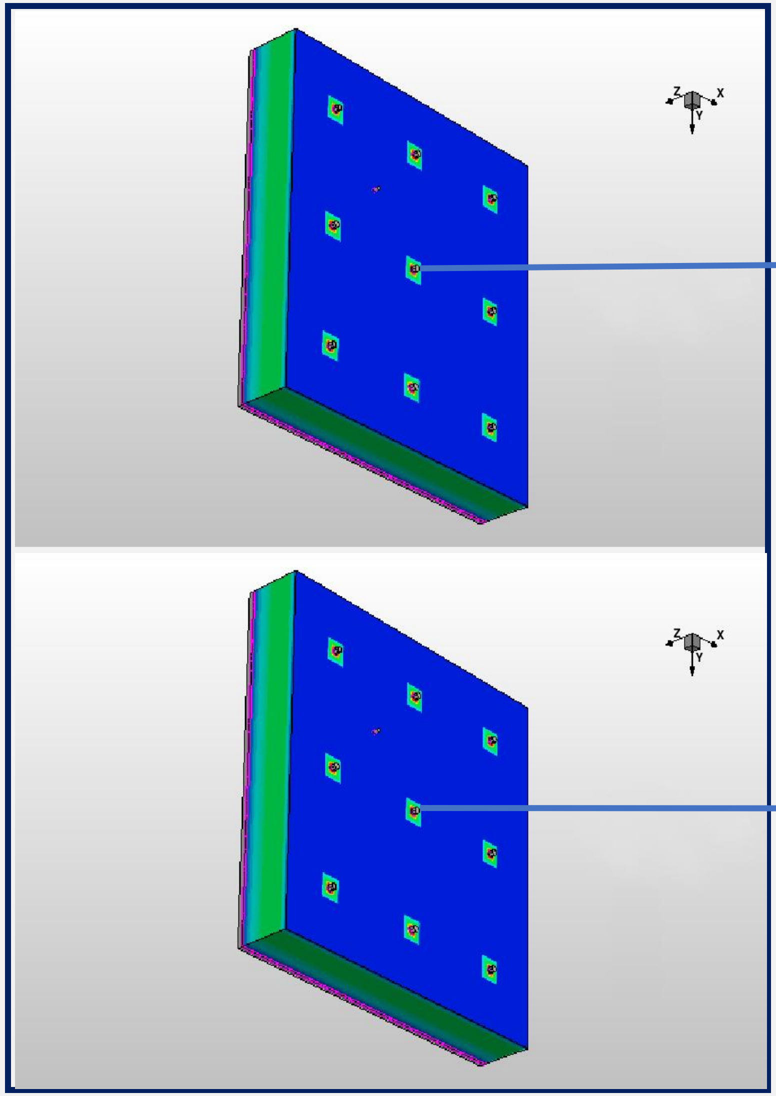
mesh_converter

```
Allpix Squared v2.3.2 Weighting Potential
Generator
internal ##EVENTS##
##TURN## ##TILT## 1.0
0.0 0.0 0.0
10 60 60 0.0 0.0 0.0 0.0 300 300 100 0.0
1 1 1 0
1 1 2 0
1 1 3 0
1 1 4 0
1 1 5 0
1 1 6 0
```

Weighting Potential

How to obtain it?

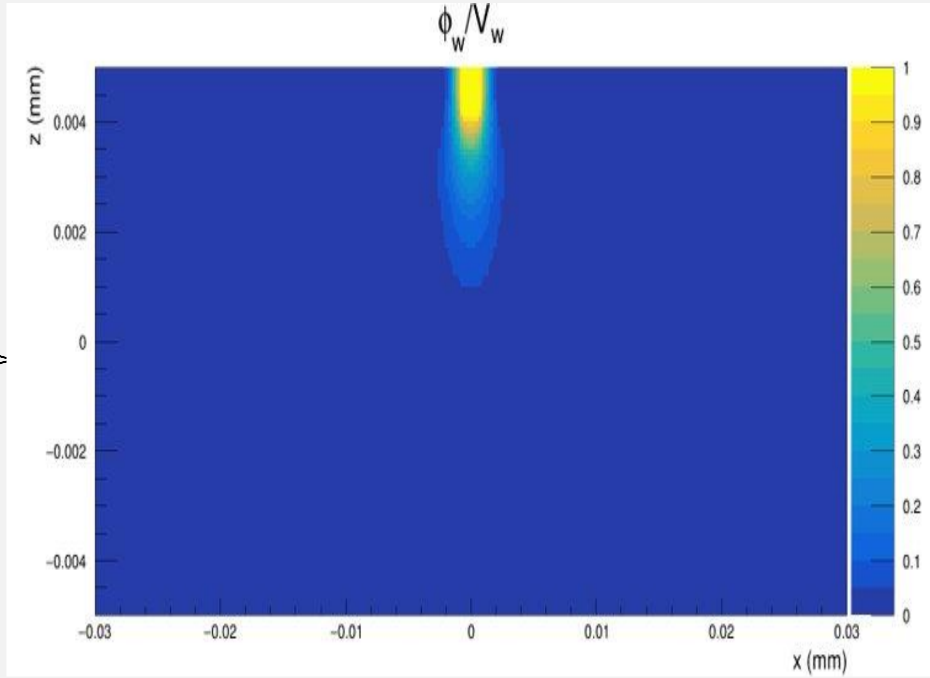
1. Simulate **Electrostatic Potential** with TCAD at the collection electrode for two slightly different voltages
2. Subtract the two electrostatic potentials at every mesh point
3. Divide by the collection electrode voltage difference



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

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Models

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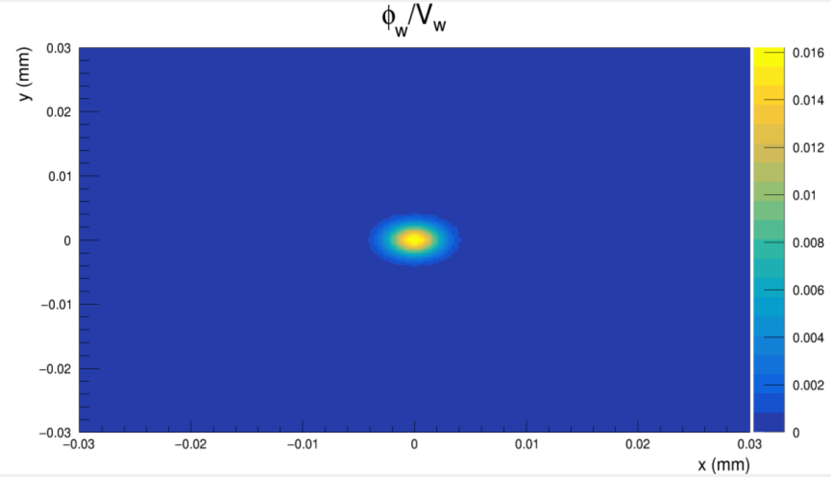

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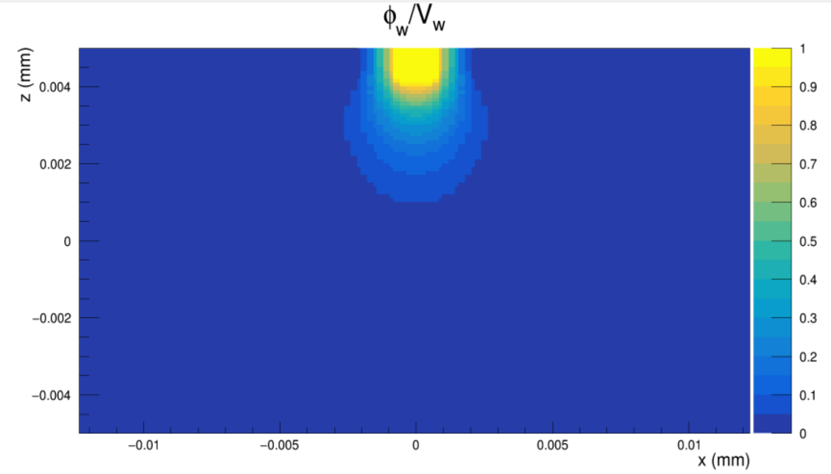

Transversal cut of WP (of a 20x20um^2 pitch pixel and 10um thickness)

[TransientPropagation] Module

Simulates the transport of electrons and holes through the sensitive sensor volume of the detector.

For each step of the simulation, the induced charge on the neighboring pixel implants is calculated via the Shockley-Ramo theorem

```
[TransientPropagation]
mobility_model="masetti_canali"
recombination_model="srh_auger"
temperature = 293K
charge_per_step = 1
output_plots = true
timestep =7ps
integration_time = 40ns
induction_matrix = 3,3
```

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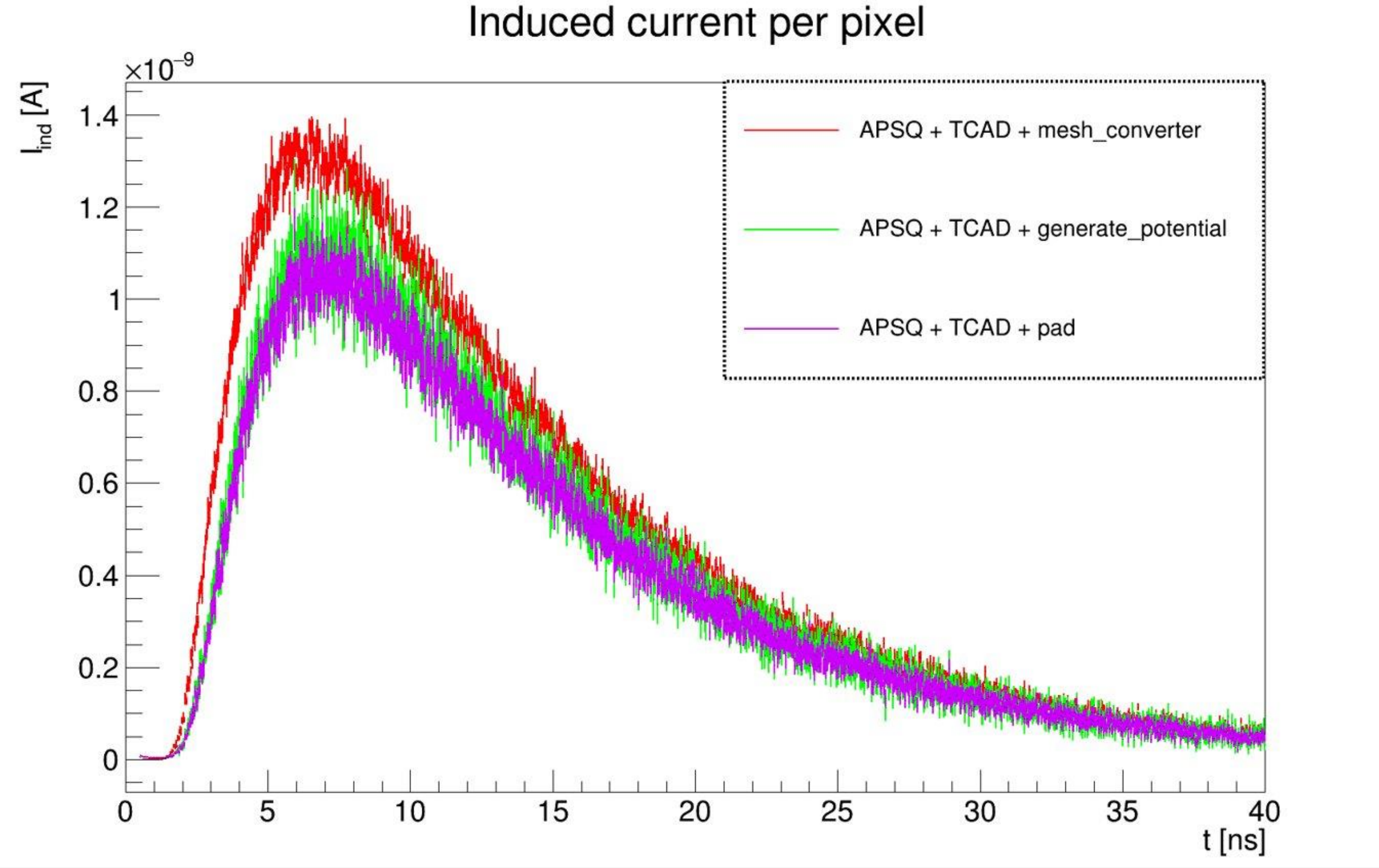
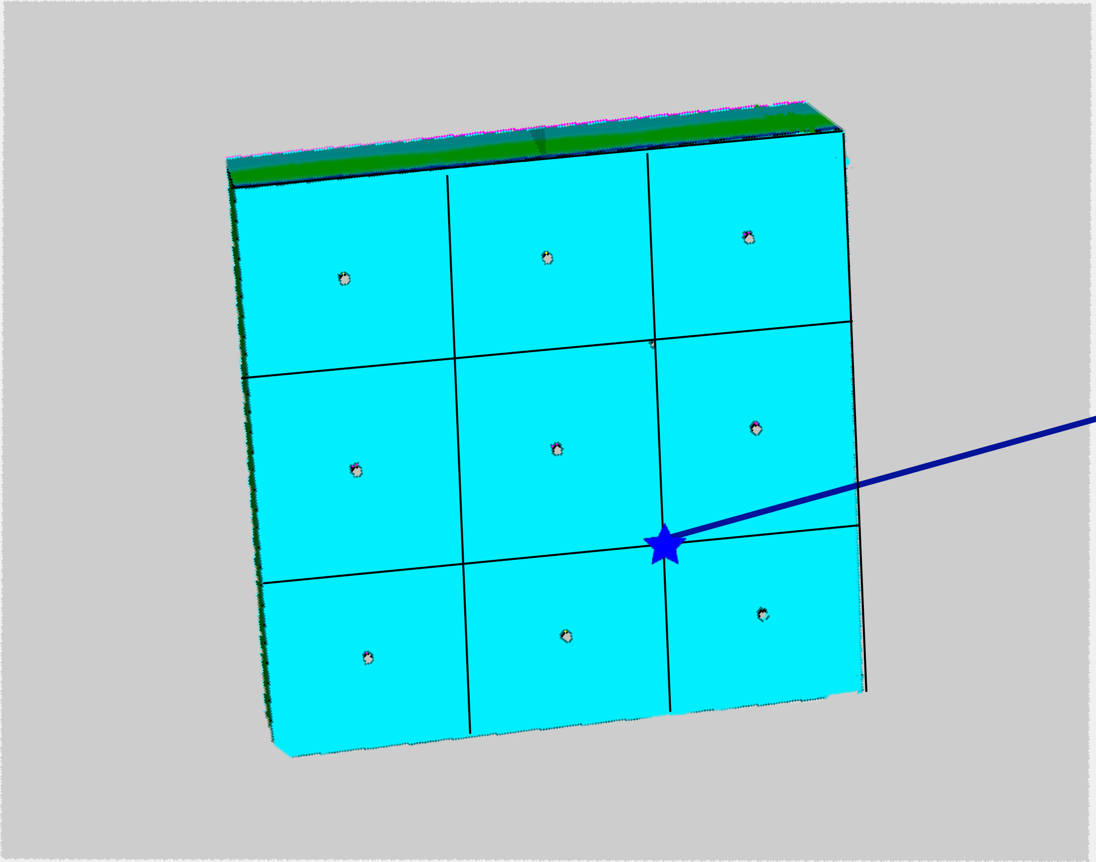
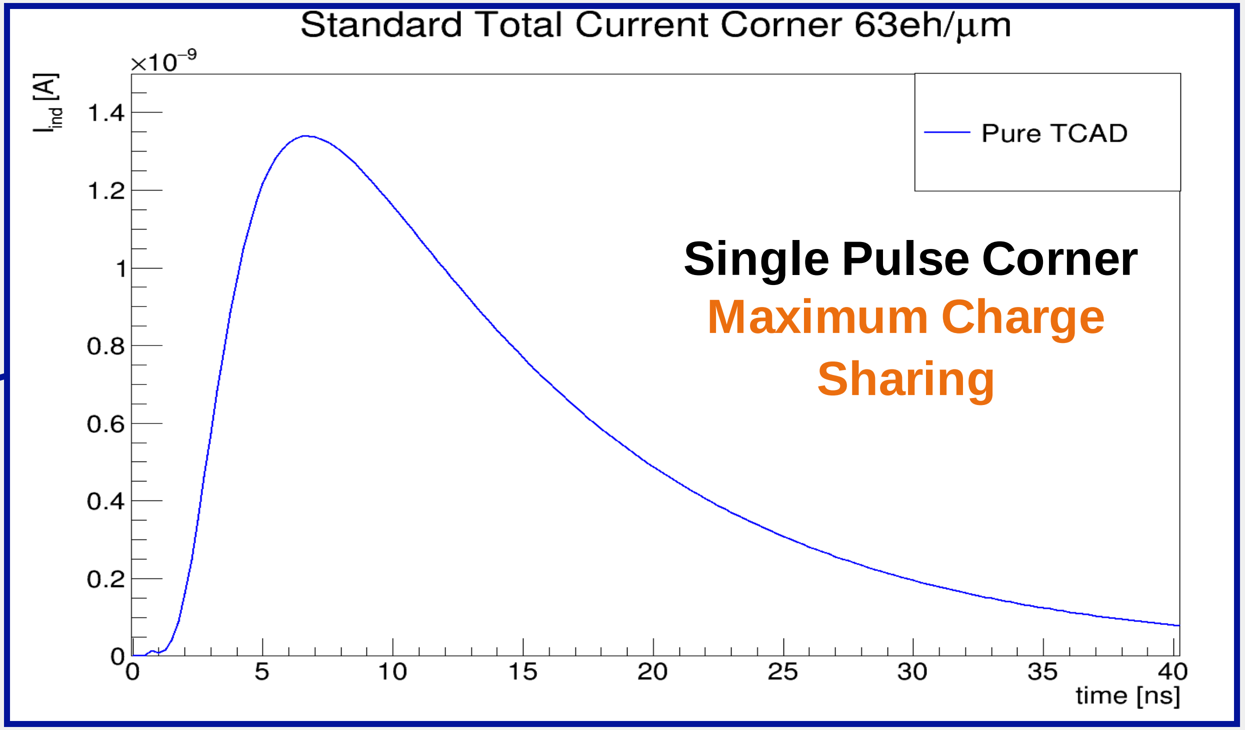


Pure TCAD Simulations

Extreme case under study

- Charge carriers injected alongside the pixel **corner**
- Fixed amount of charge carriers: **Linear Energy Transfer (LET) 63 eh/µm**





3x3-cell model

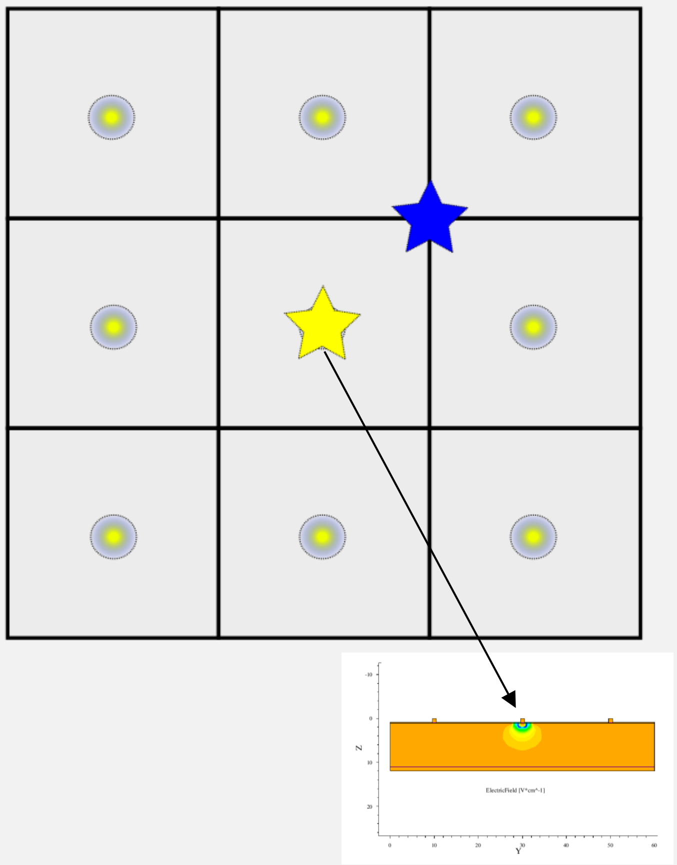
Validation with TCAD

TCAD + APSQ

- To **validate TCAD+APSQ simulations**, same simulation conditions as in transient TCAD are replicated:
  - Charge carriers injected alongside the pixel **corner**
  - Fixed amount of charge carriers: **Linear Energy Transfer (LET) 63 eh/µm**
  - Only the epitaxial layer is simulated: **10 µm**
  - Simulation repeated **1000x** times and the average pulse is calculated

Simulation Time

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



Charge injection at the **corner**

Charge injection at the **center**

Collection Electrode at +1.2 V

P-Well and P-Substrate at -1.4 V

3x3 pixel matrix
20x20 µm^2 pitch

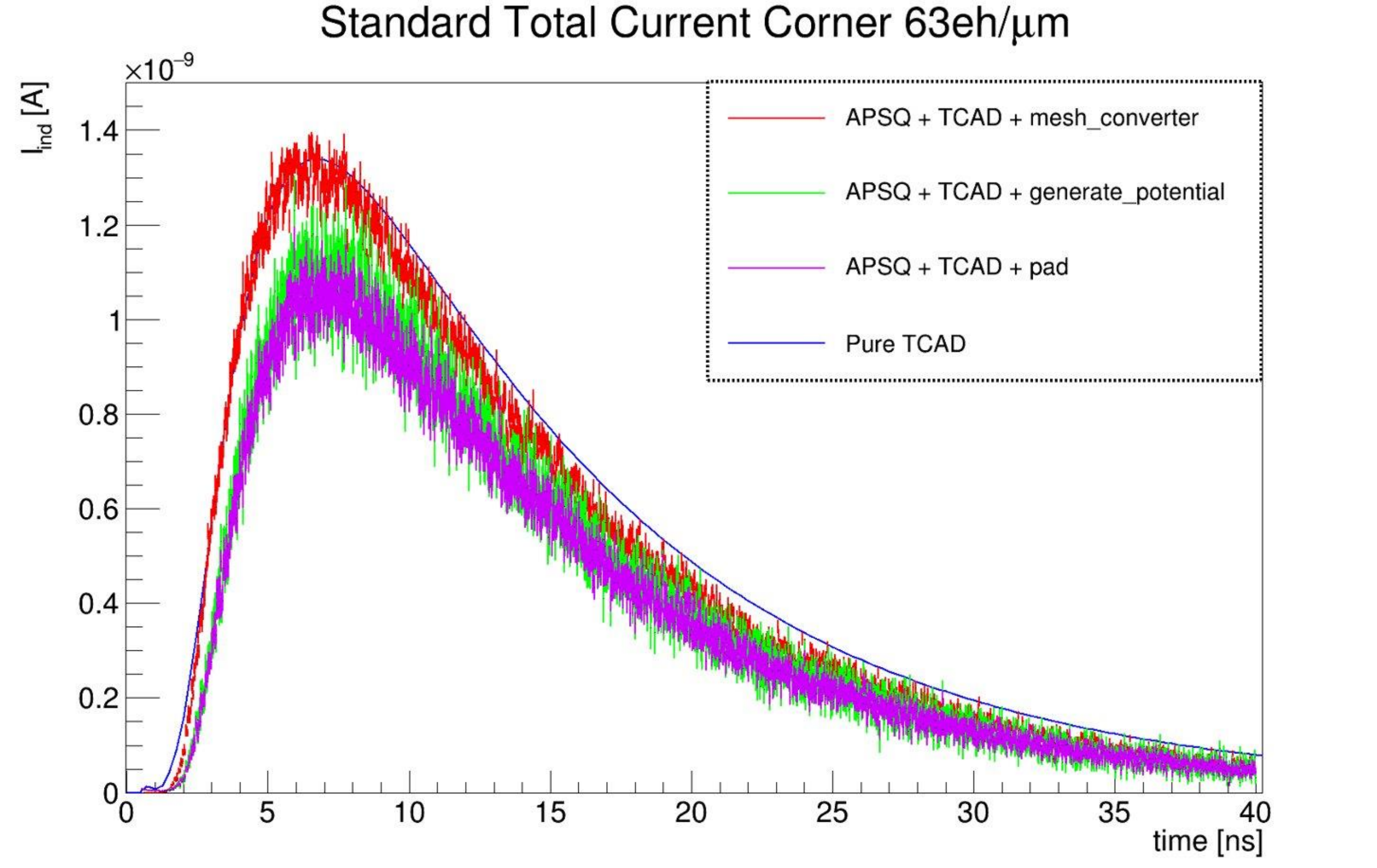
High weighting potential values are concentrated around collection electrode

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!

Comparison with TCAD



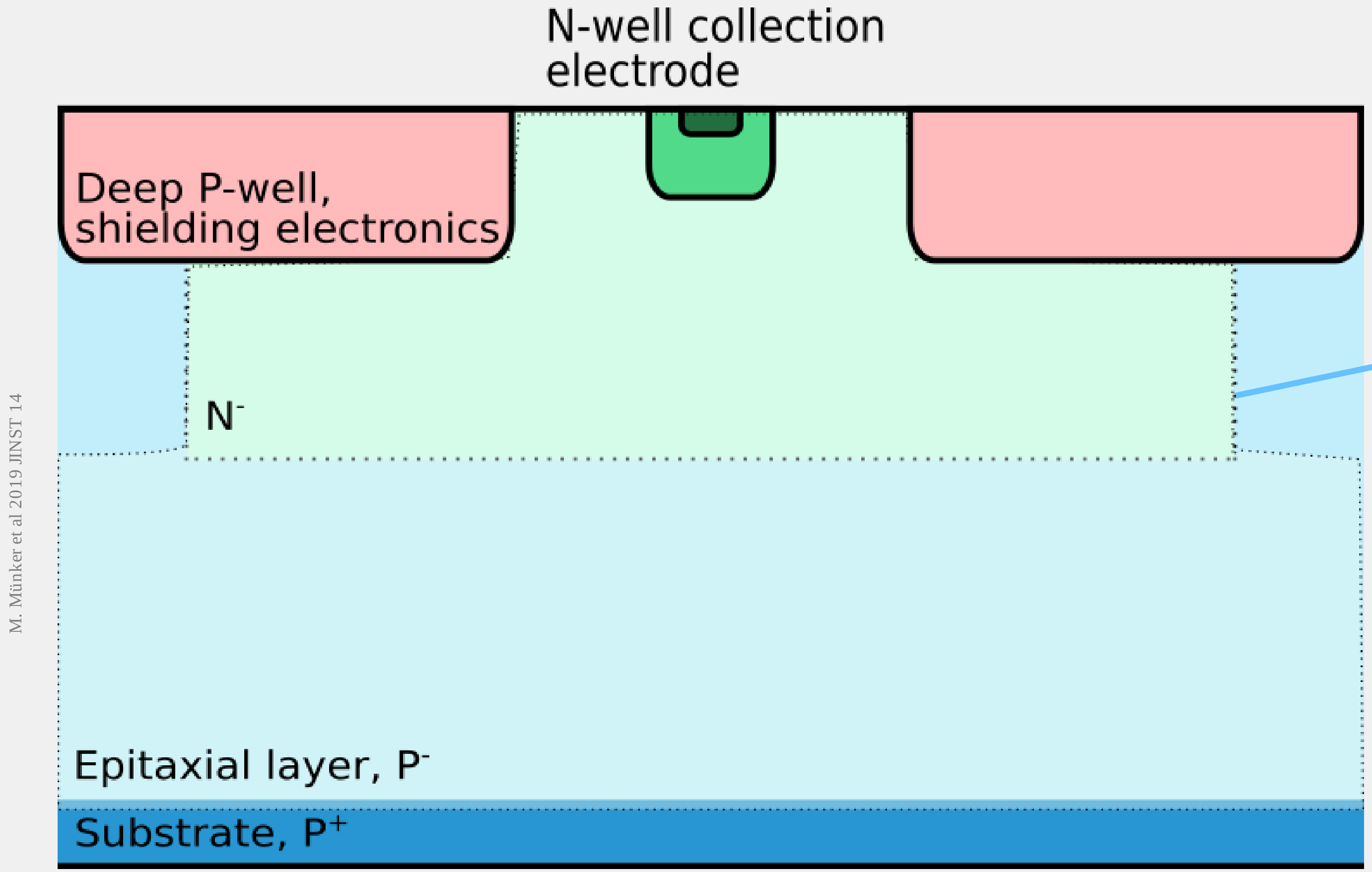
Comparison of the 3 different methods to produce a weighting field to integrate with Allpix Squared

- Similar pulse shape and pulse duration
- Good agreement with TCAD simulation

Simulation time (using 15 cores):
mesh_converter ~ 8 minutes
generate_potential ~ 8 minutes
pad ~ 6 hours

Monolithic Active Pixel Sensors (MAPS)

N-Gap

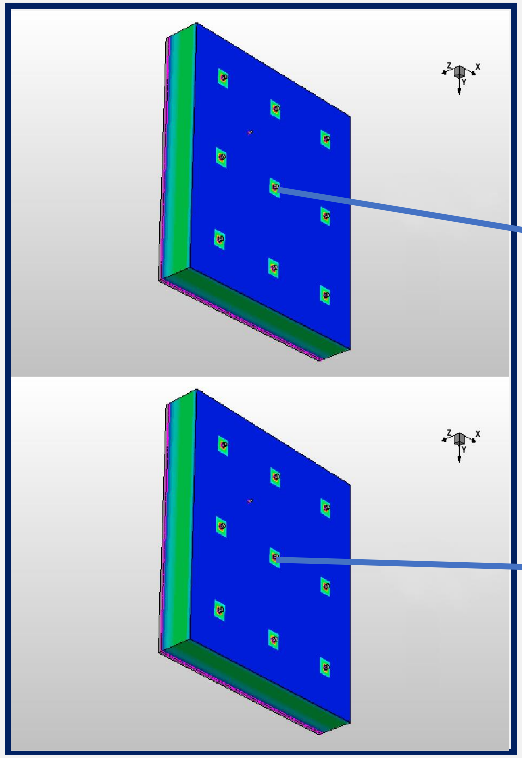


Gap in Continuous N-type Implant

Speed up charge collection

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

How to obtain it?



i.e. Voltage: -1.2 V

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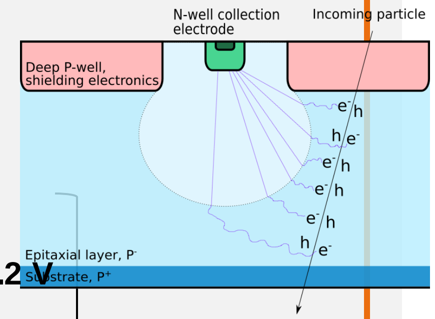
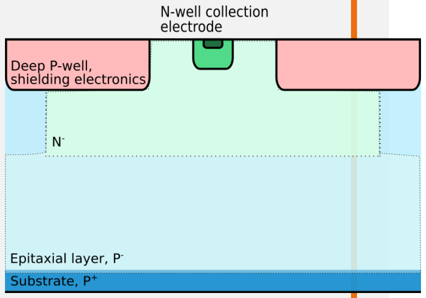
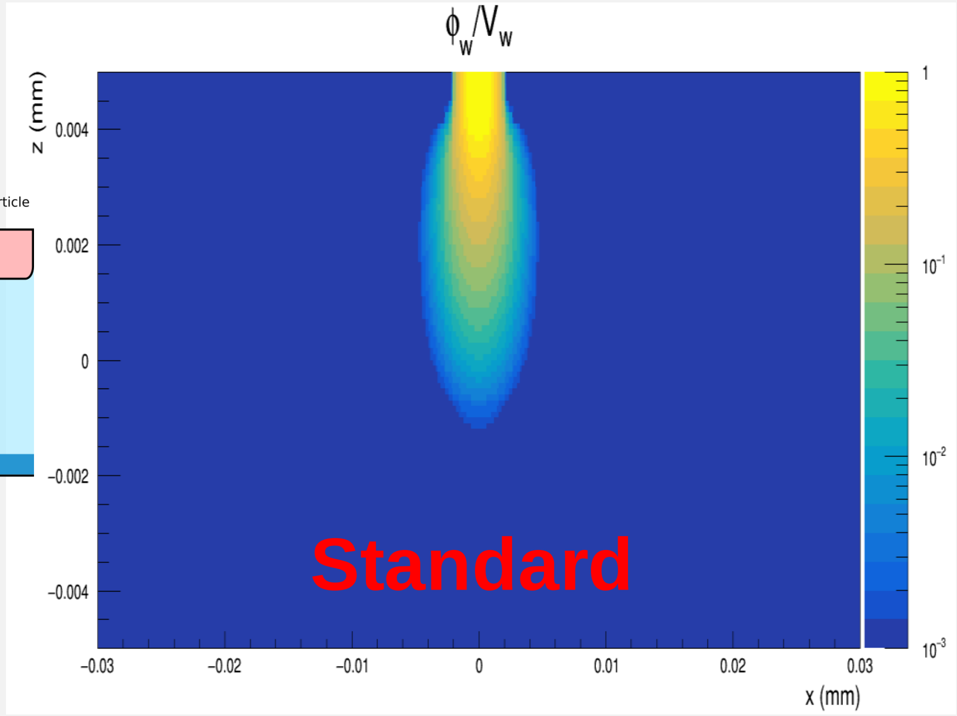
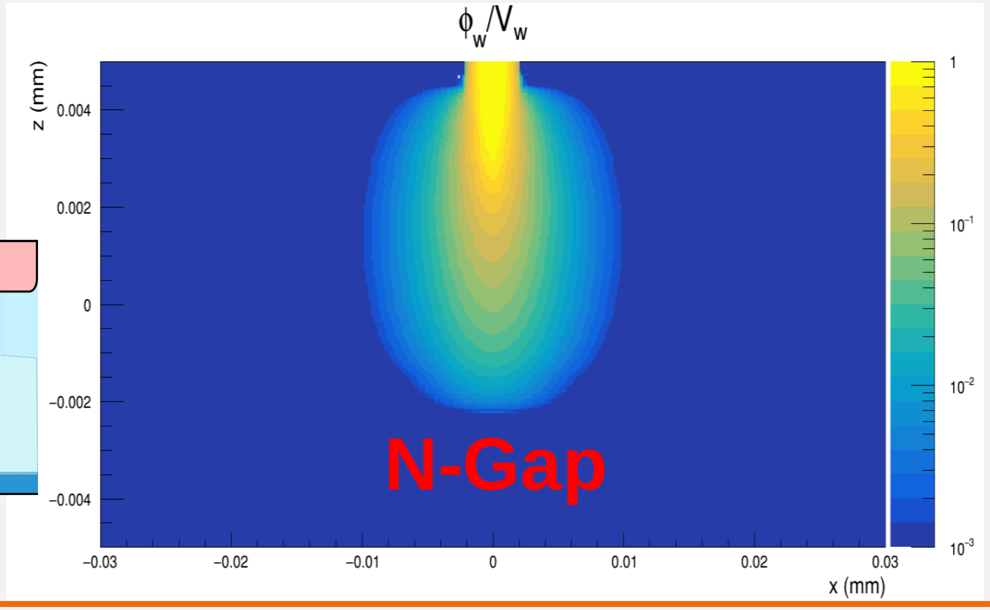




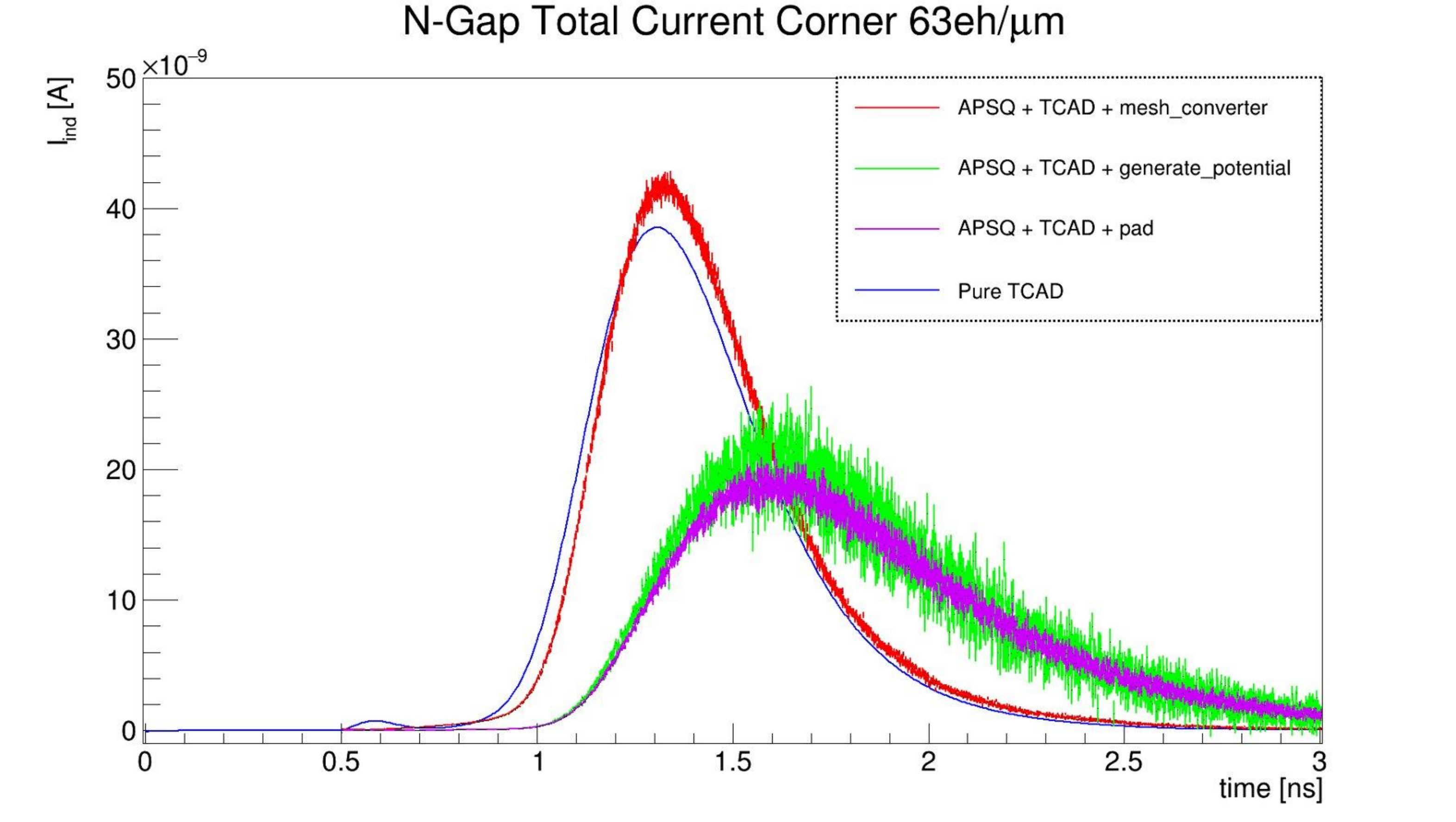
Only Geometry dependent!

So it remains the same for other voltages





Comparison with TCAD



Comparison of the 3 different methods to produce a weighting field to integrate with Allpix Squared

- Good agreement with TCAD simulation (**mesh_converter**)
- Other methods too simplistic to accurate reproduce TCAD results

Simulation time (using 15 cores):
mesh_converter ~ 6 minutes
generate_potential ~ 6 minutes
pad ~ 4 hours

Summary

Simple Geometry Sensors

- Good agreement in pulse shape and duration between approaches
- generate_potential tool simple to use and good for simulation time

More complicated Geometry Sensors

- Both pad and generate_potential too simplistic to produce accurate results
- Tweaks to WP required
- Resort to other methods or just use TCAD profiles

Thank you for your time!

Contact

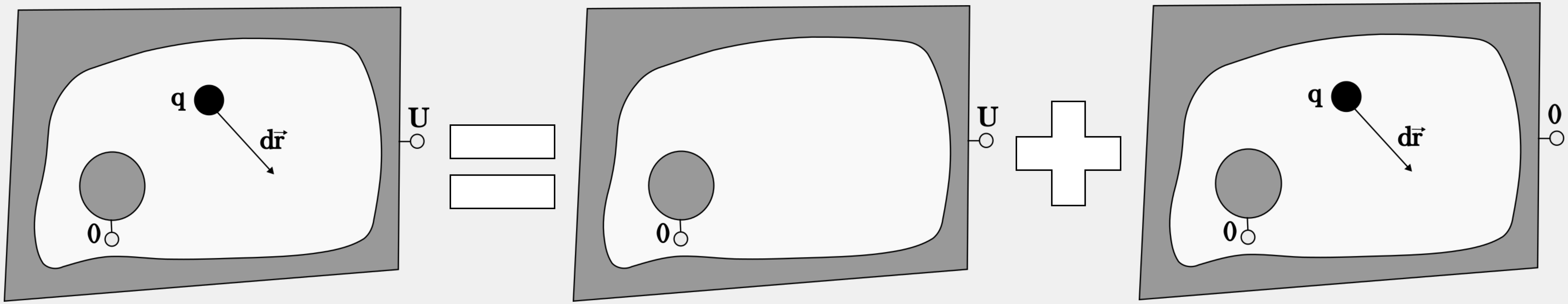
Manuel Alejandro Del Rio Viera
manuel.del.rio.viera@desy.de

Backup

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: $0 = dW_{E_0} + dW_{E_q} = UdQ + q\overrightarrow{E_0} \cdot d\vec{r} \rightarrow dQ = -q\frac{\overrightarrow{E_0}}{U} \cdot d\vec{r}$

Solved by a **weighting field and a weighting potential**:

$$\varphi_w = \frac{\varphi_0}{U} \; ; \; \overrightarrow{E_w} = -\vec{\nabla}\varphi_w$$

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

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

The Tangerine Project

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

Requirements

- Spatial Resolution ~ **3 µm**
- Time Resolution ~ **1 -10 ns**
- Low material budget ~ **50 µm silicon**

Application: e^+e^- Colliders

Reference detector at DESY-II test beam

- Funded by Helmholtz Innovation Pool and DESY

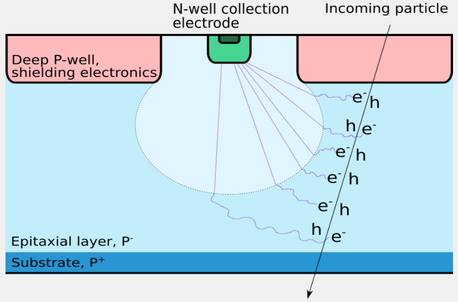
Part of the **Work Package 1 (WP1):** Monolithic pixel detectors in novel CMOS imaging technology

HELMHOLTZ

TowArds Next GEneRation SIlicoN DEtectors

Monolithic Active Pixel Sensors (MAPS)

Standard

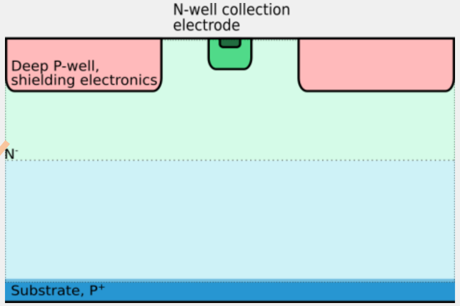


S. Senyukov et al. doi:10.1016/

Small Collection Electrode

N-Blanket

Continuous N-type Implant

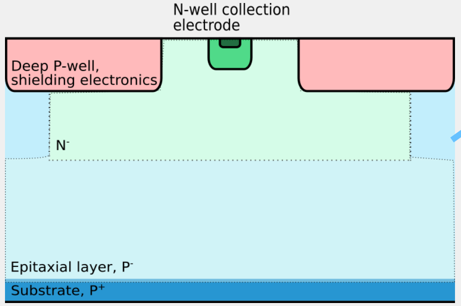


W. Snoeys et al. doi:10.1016/

Increase the depleted region

N-Gap

M. Münker et al 2019 JINST 14



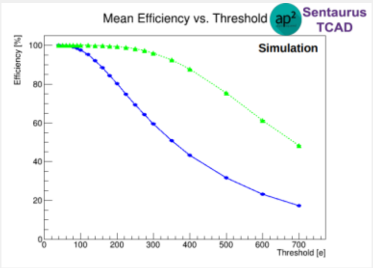
Gap in Continuous N-type Implant

Speed up charge collection

Simulation's Workflow

Why do we need Transient Simulations?

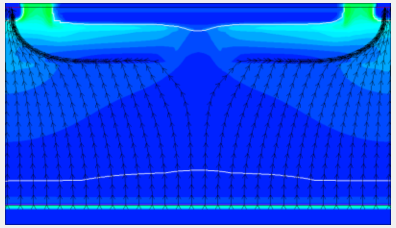
Compare data with simulations



See Adriana's presentation On Simulations and Test Beam Characterization

Device Simulations (TCAD)

SYNOPSYS®



Allow to optimize the layouts that characterize a sensor

- Electric Fields
- Process Simulations
- Capacitance
- Weighting Potentials

Monte Carlo Simulations

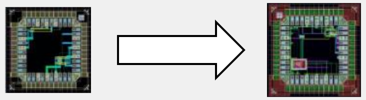
ap² allpix squared

Allow for greater statistics and to analyze detector performance

- Efficiency
- Cluster Size and Resolution
- Pulses

Motivation of Transient Simualtions

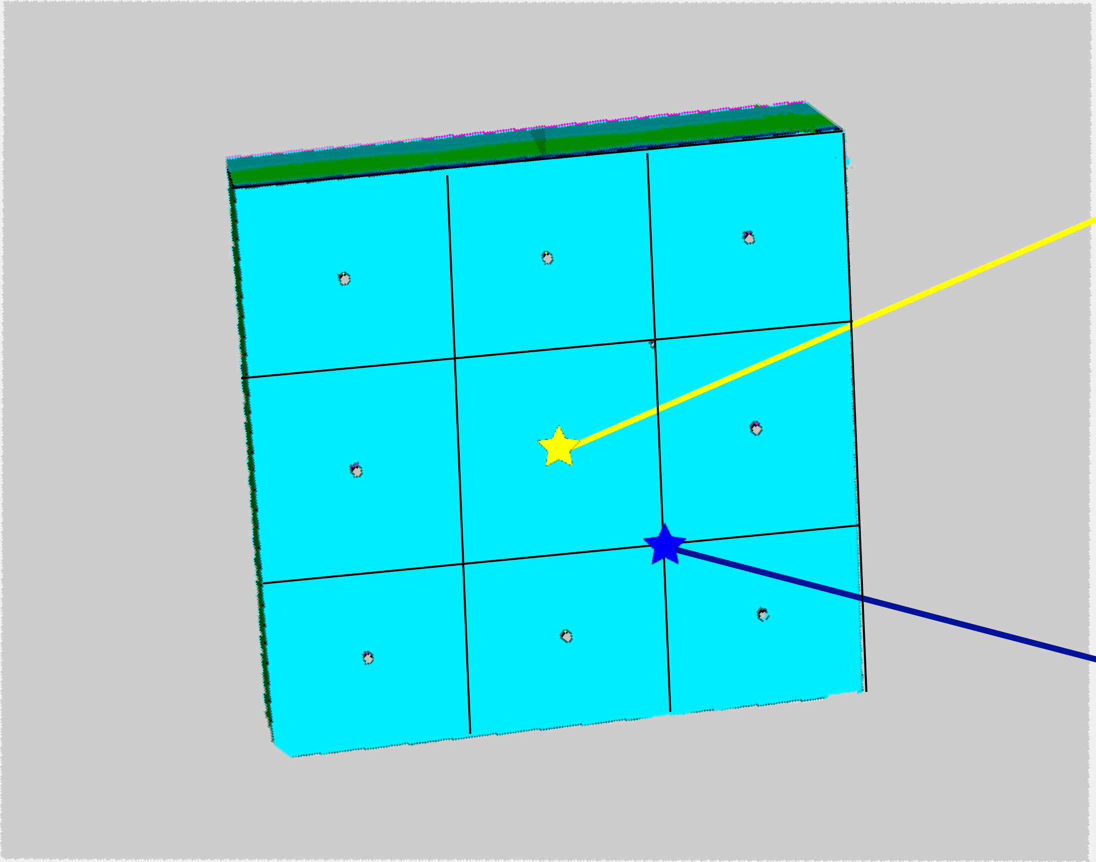
- **Produce accurate pulses in more realistic simulations**
- **Predict sensor and precise FE response**
- **Optimize our sensors.**



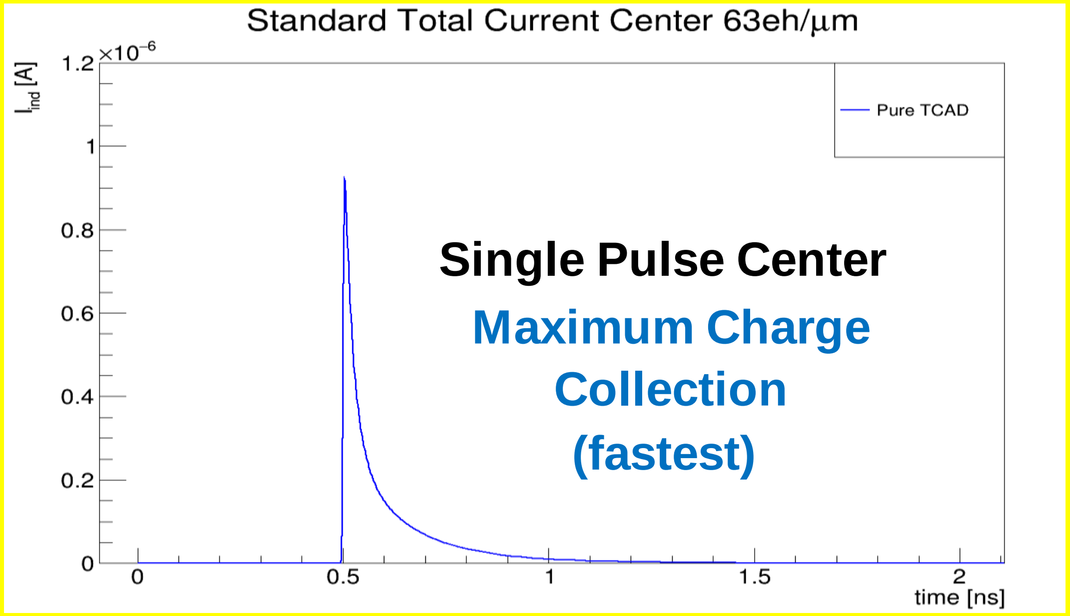
Pure TCAD Simulations

Two extreme cases under study

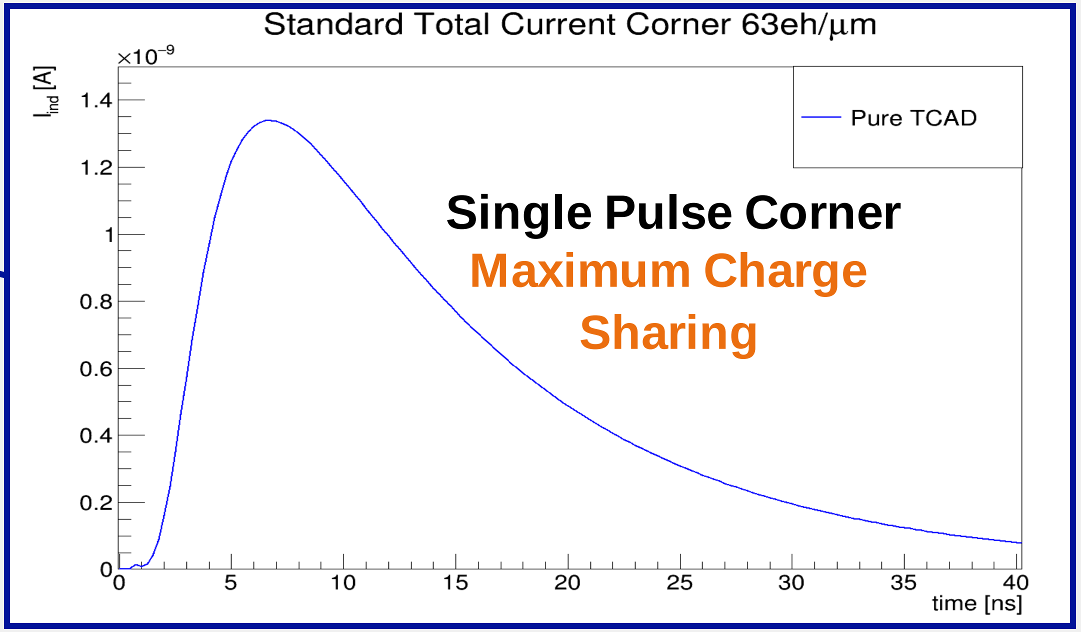
- Charge carriers injected alongside the pixel **corner** **or** **center**
- Fixed amount of charge carriers: **Linear Energy Transfer (LET) 63 eh/µm**



3x3-cell model

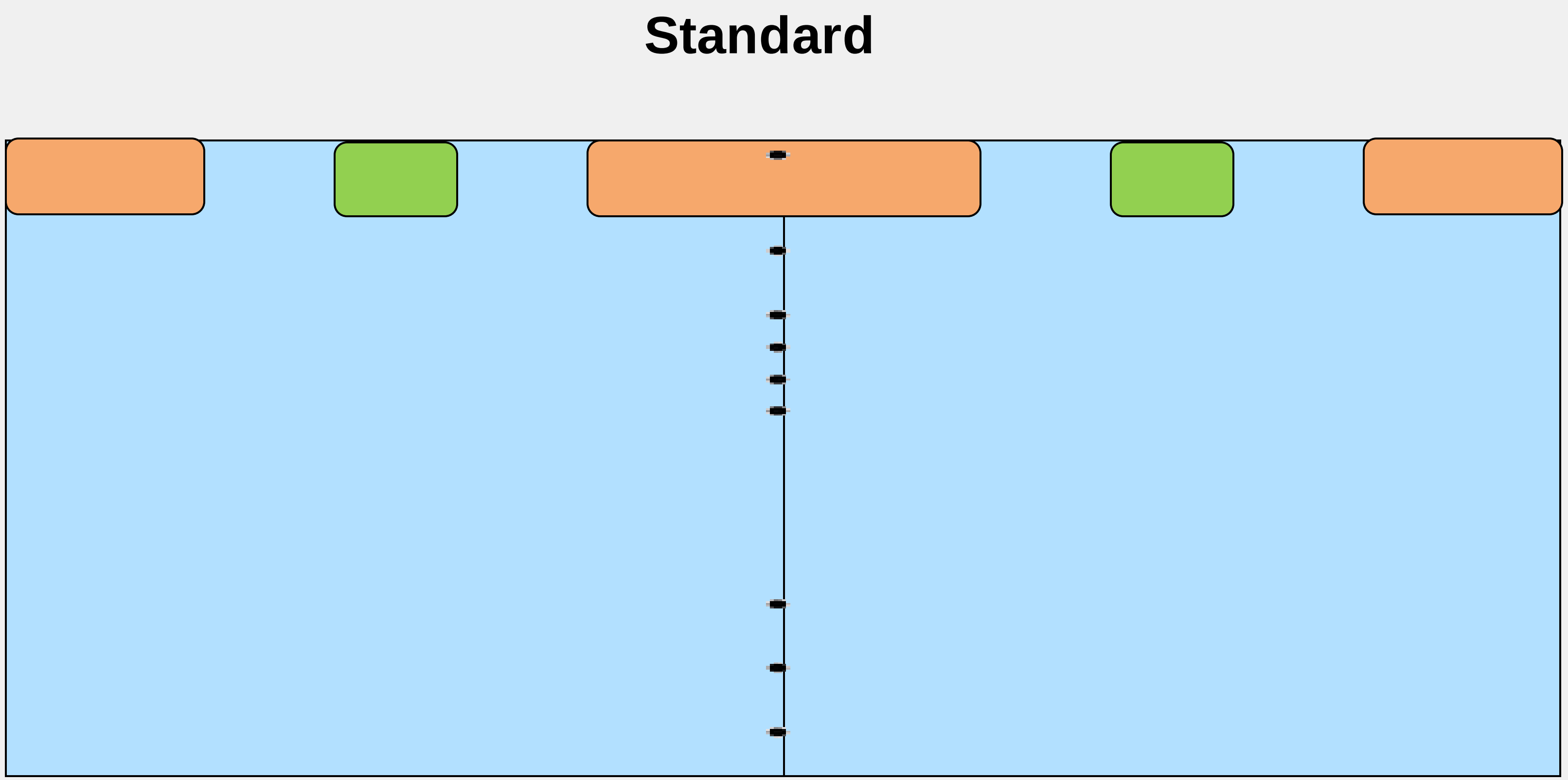


Not same time scale!



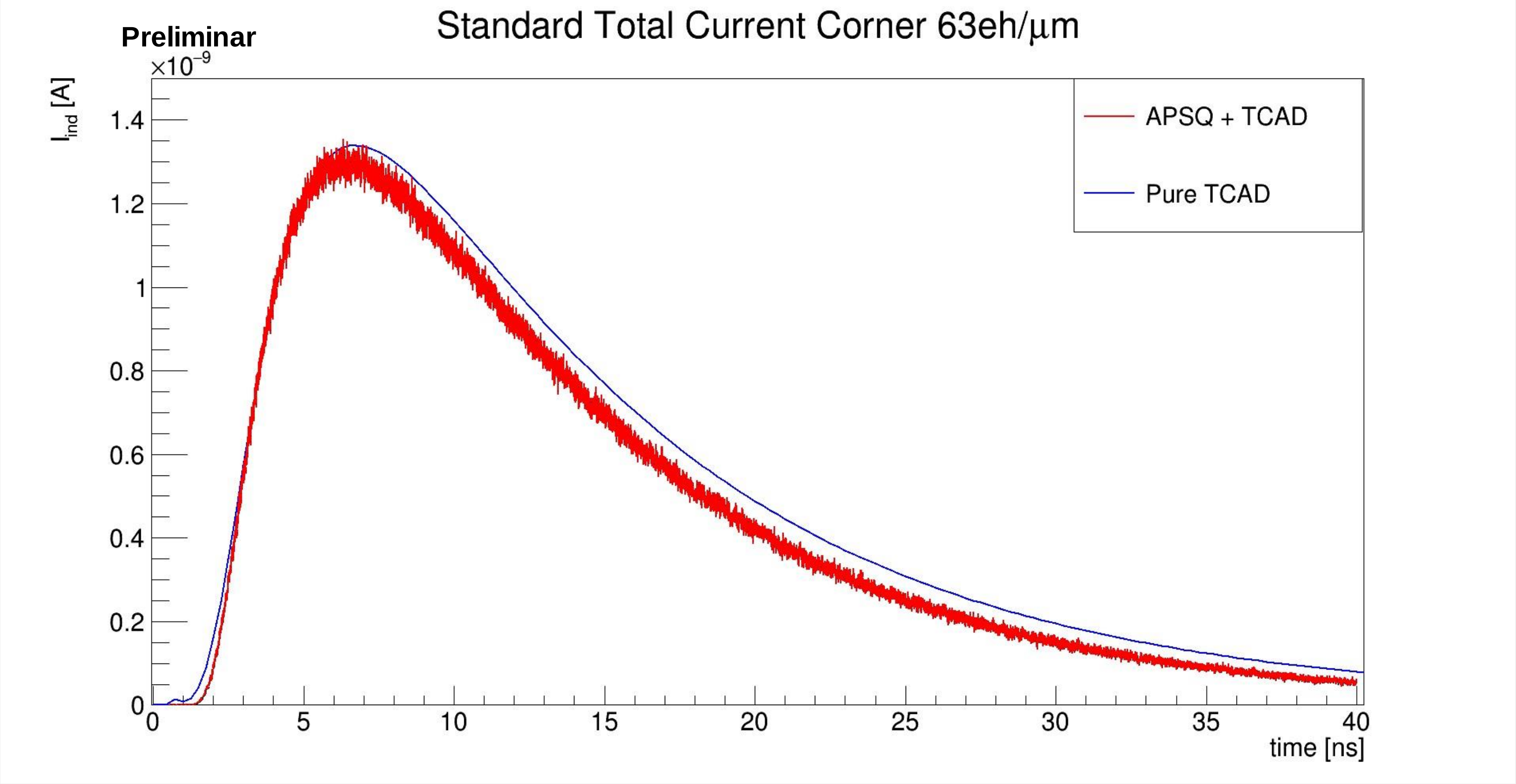
Standard Linear Charge Injection

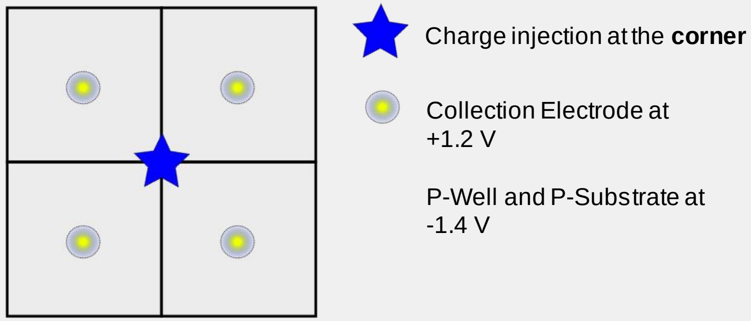
Monolithic Active Pixel Sensors (MAPS)

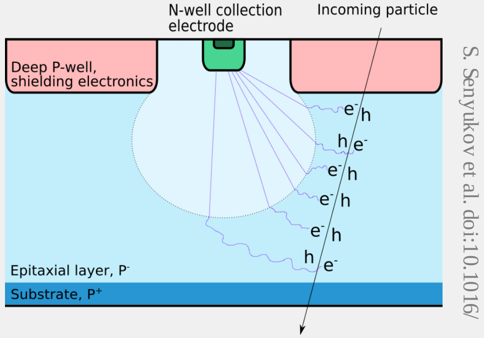


Validation – Corner Injection

Average Pulse Comparison







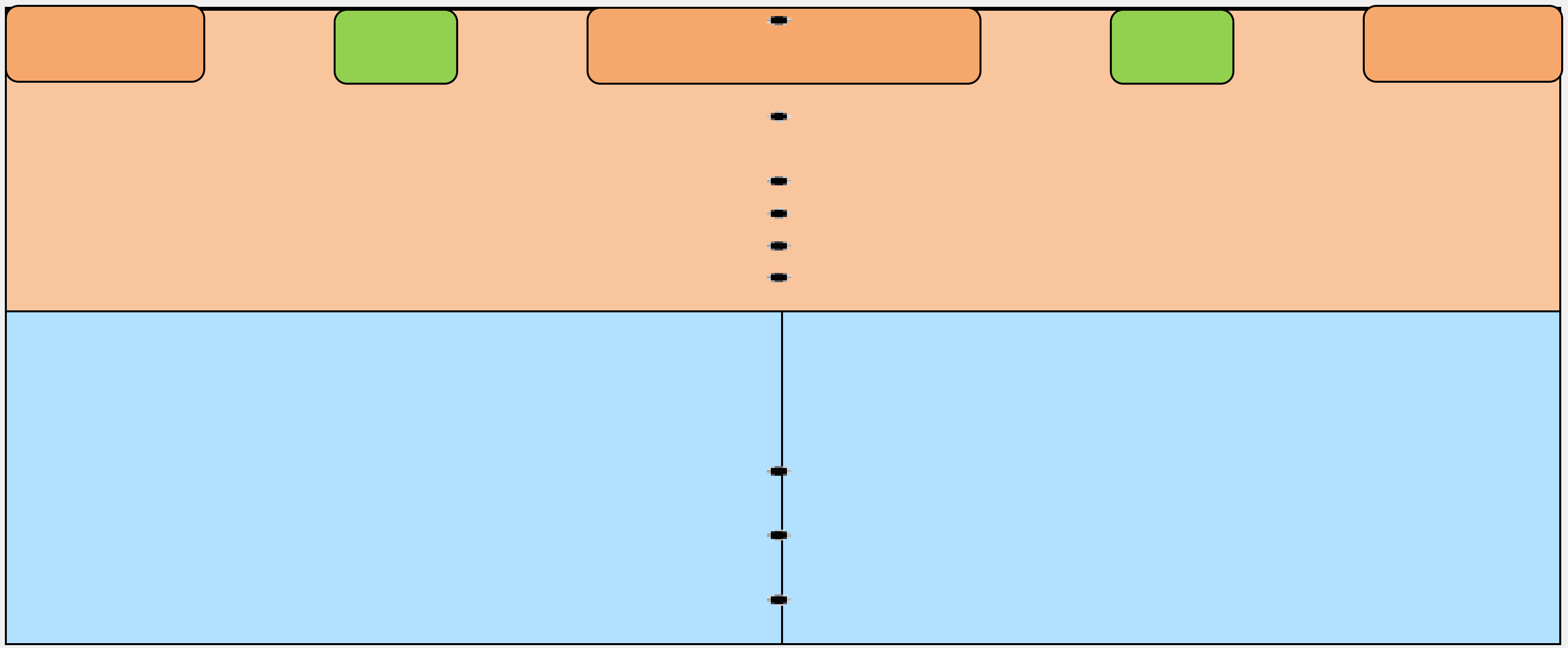
Standard
Pulse duration ~ 40ns

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

N-Blanket Linear Charge Injection

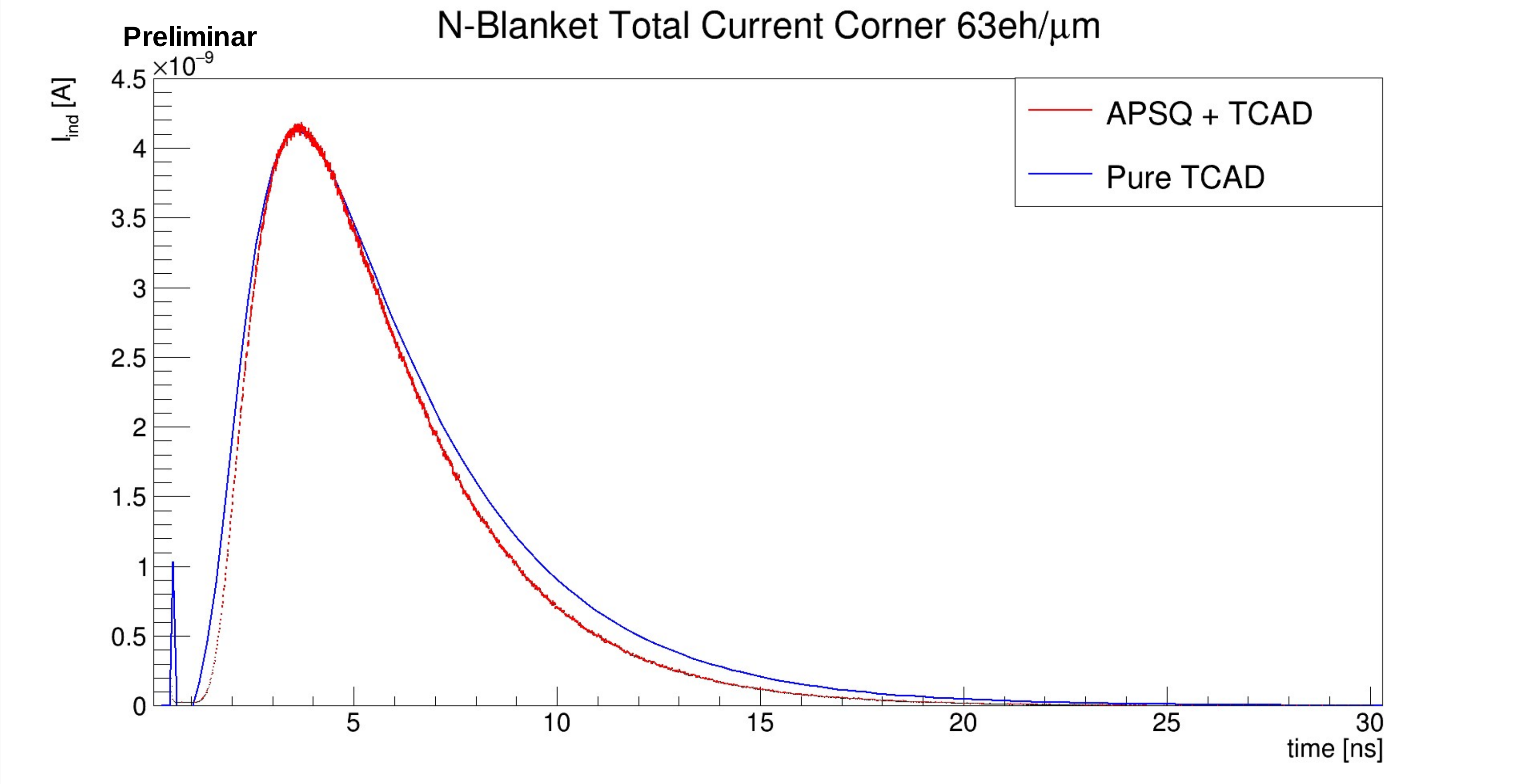
Monolithic Active Pixel Sensors (MAPS)

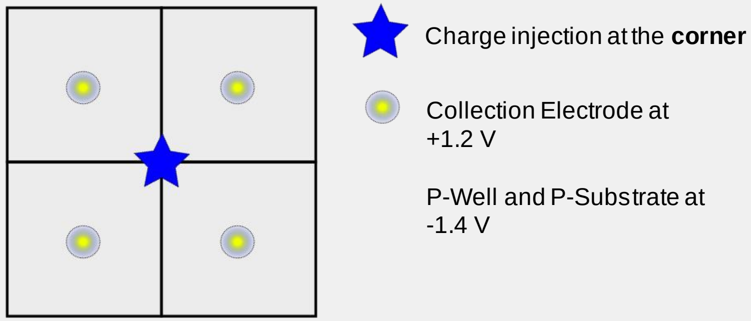
N-Blanket

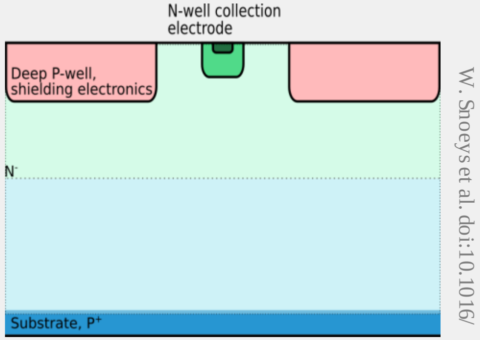


Validation – Corner Injection

Average Pulse Comparison





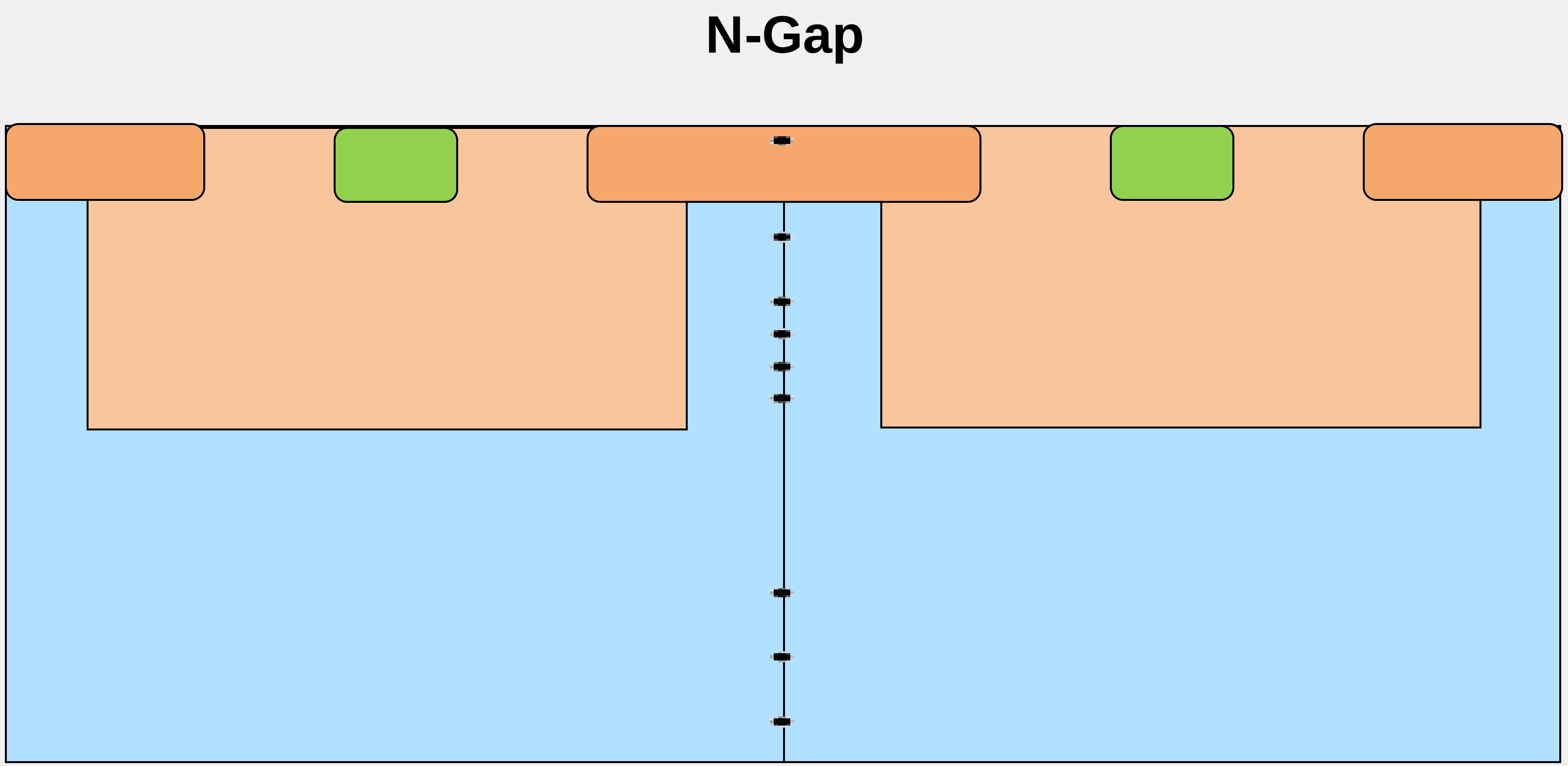


N-Blanket
Pulse duration ~ 25ns

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

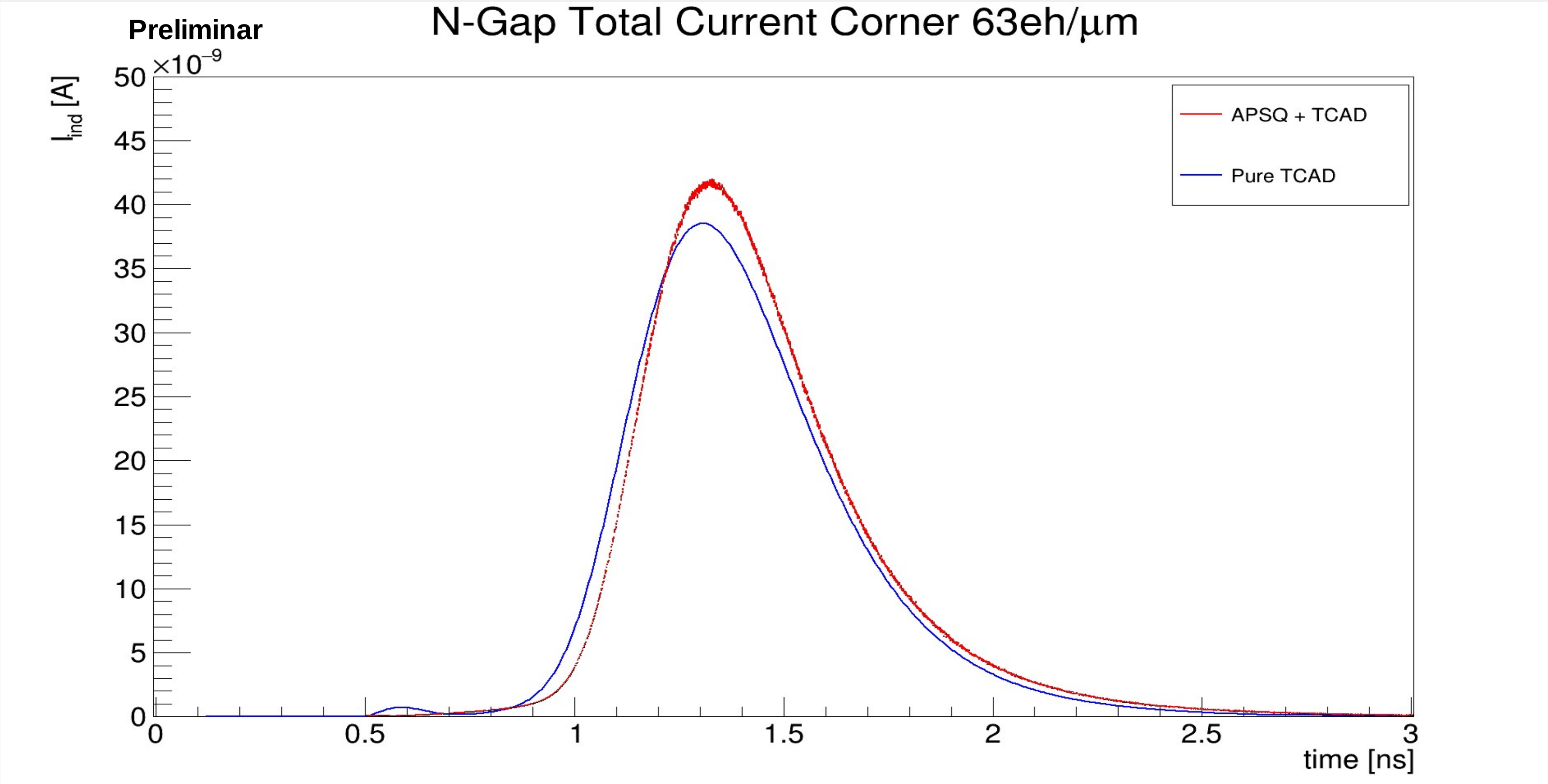
N-Gap Linear Charge Injection

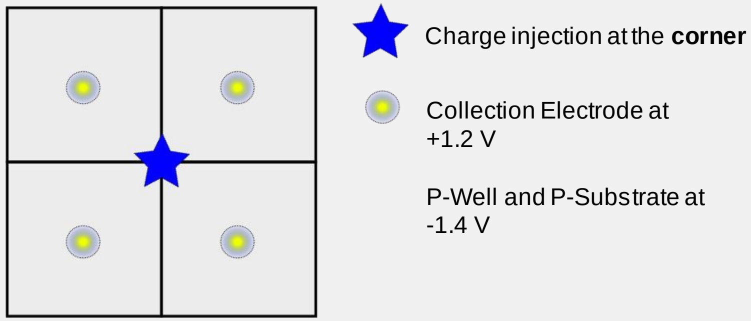
Monolithic Active Pixel Sensors (MAPS)

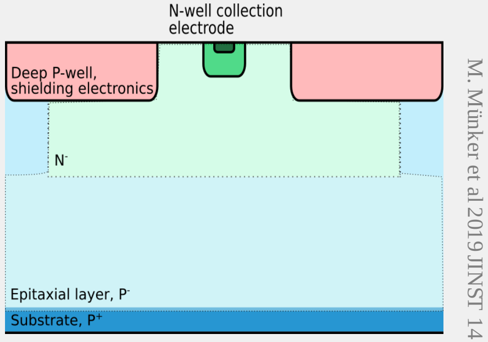


Validation – Corner Injection

Average Pulse Comparison





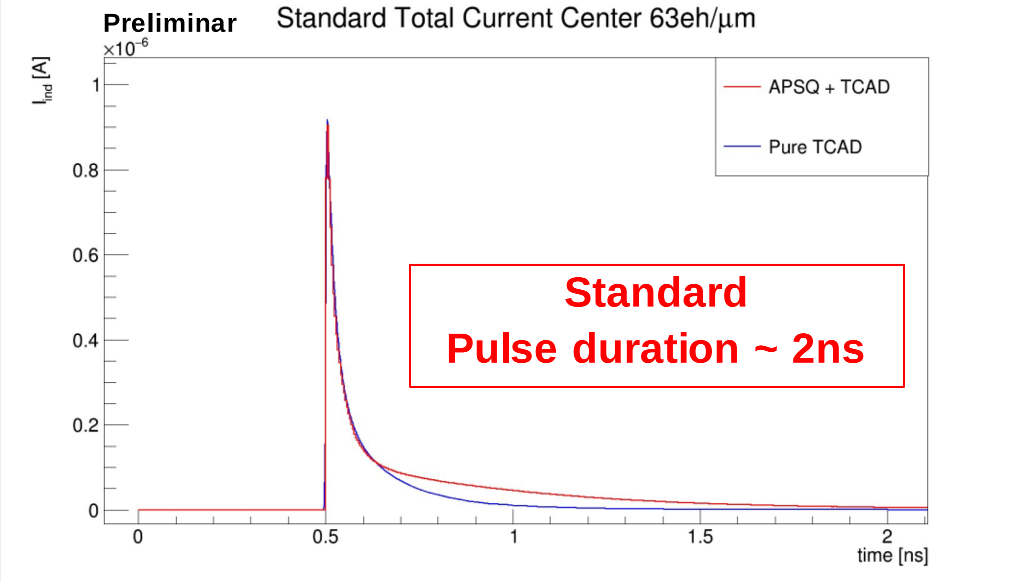


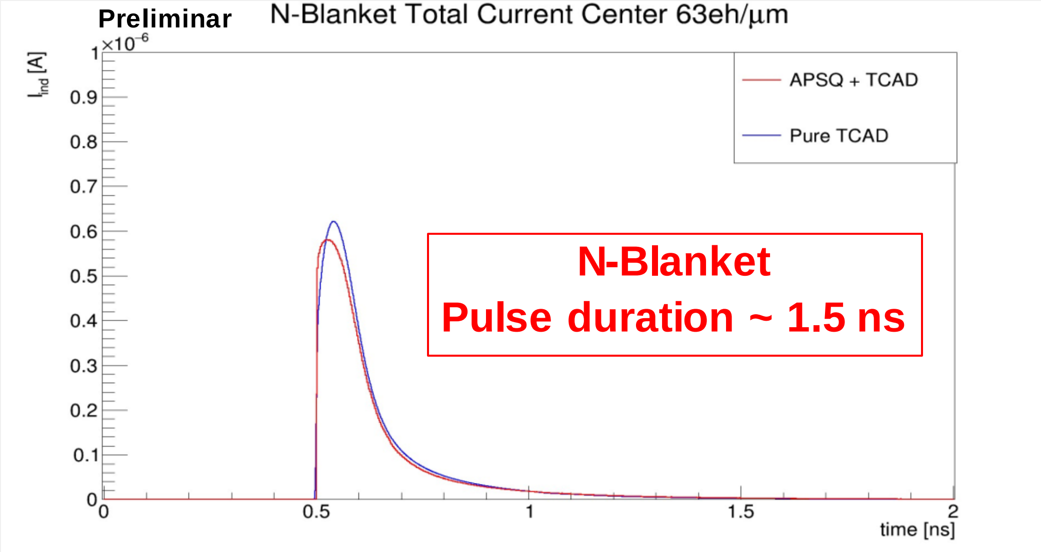
N-Gap
Pulse duration ~ 3 ns

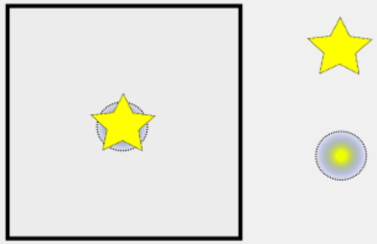
Pure TCAD - 1 pulse
APSQ + TCAD – Average 10000 pulses

Validation – Center Injection

Average Pulse Comparison



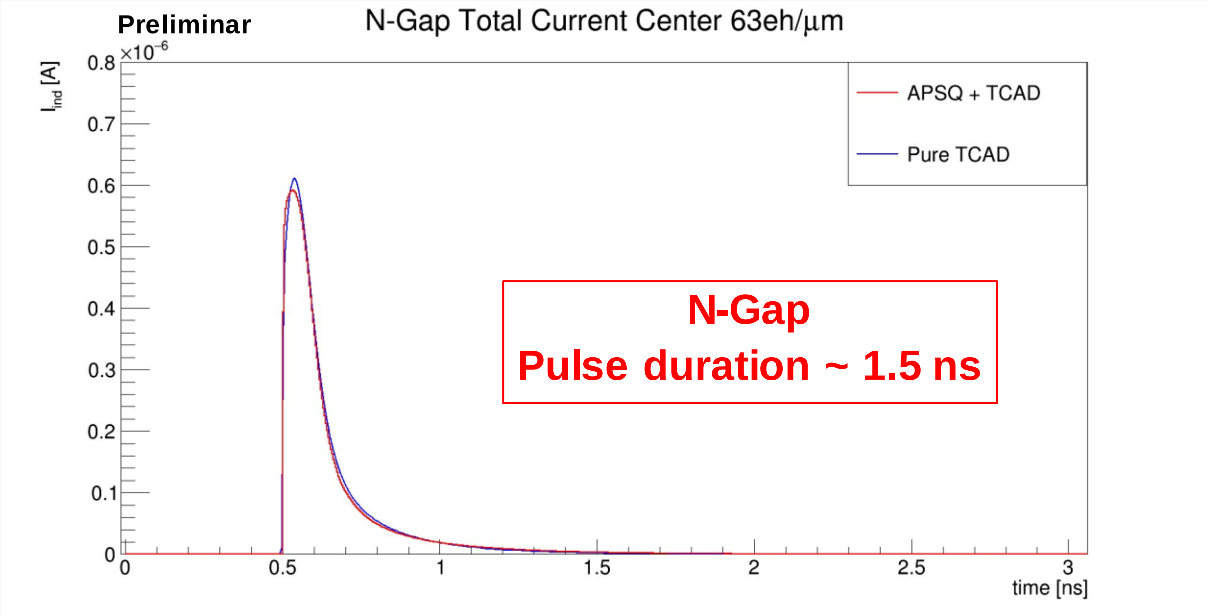




Charge injection at the **center**

Collection Electrode at +1.2 V

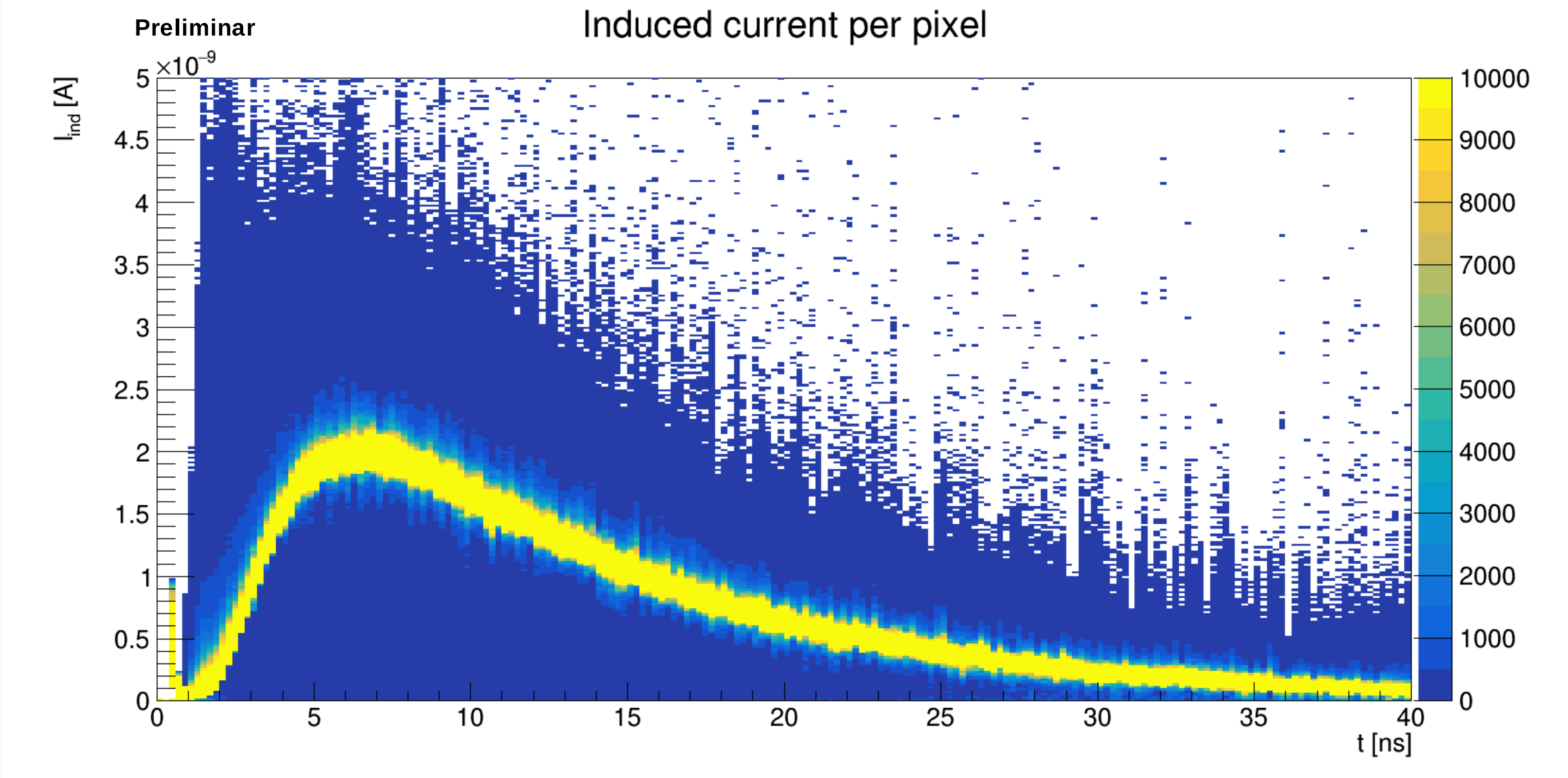
P-Well and P-Substrate at -1.4 V



Pure TCAD - 1 pulse

APSQ + TCAD – Average 10000 pulses

Comparison GEANT4 – Corner Injection



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

→ **Sensor and Layout Scan**

→ **Timing Performance**

Shockley-Ramo's Theorem

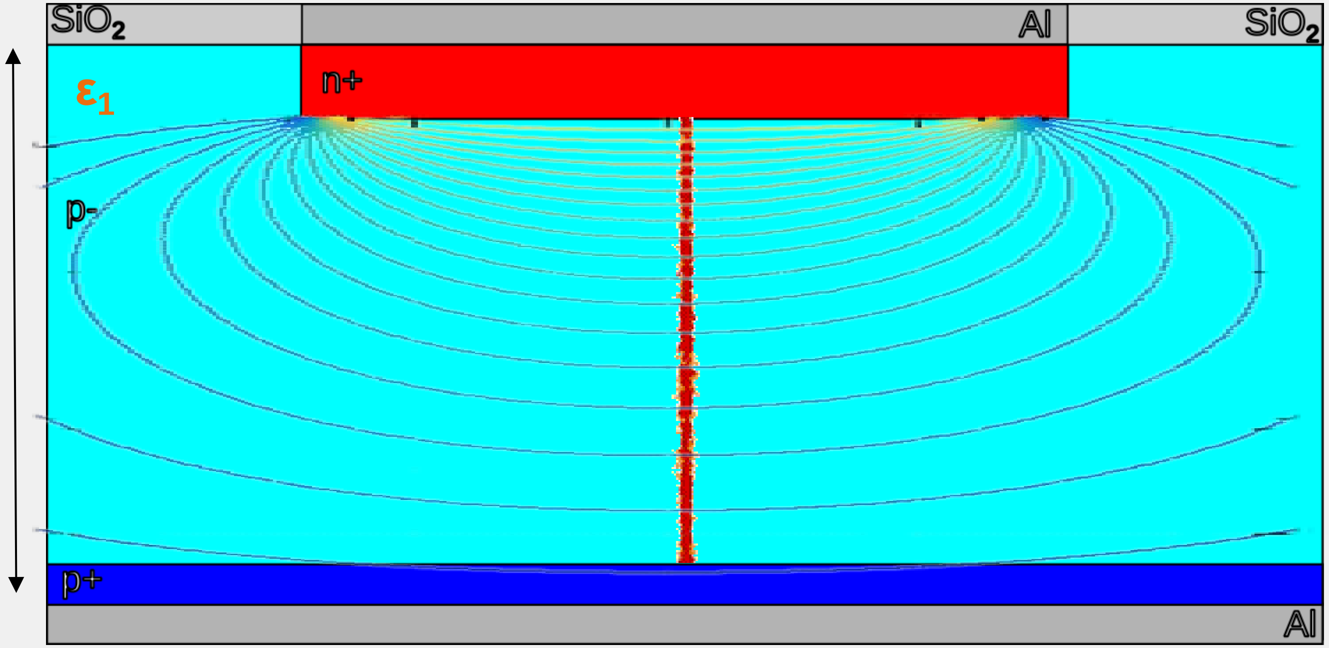
Signal Formation on Silicon Sensors

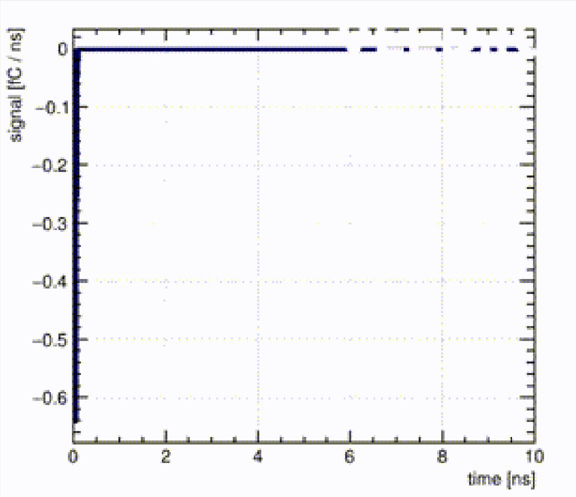
$$I_{ind} = q\vec{E}\cdot\vec{v}$$

$$Q_{ind} = q(\varphi_w(\vec{r}_{t_0}) - \varphi_w(\vec{r}_t))$$

http://garfieldpp.web.cern.ch/garfieldpp/

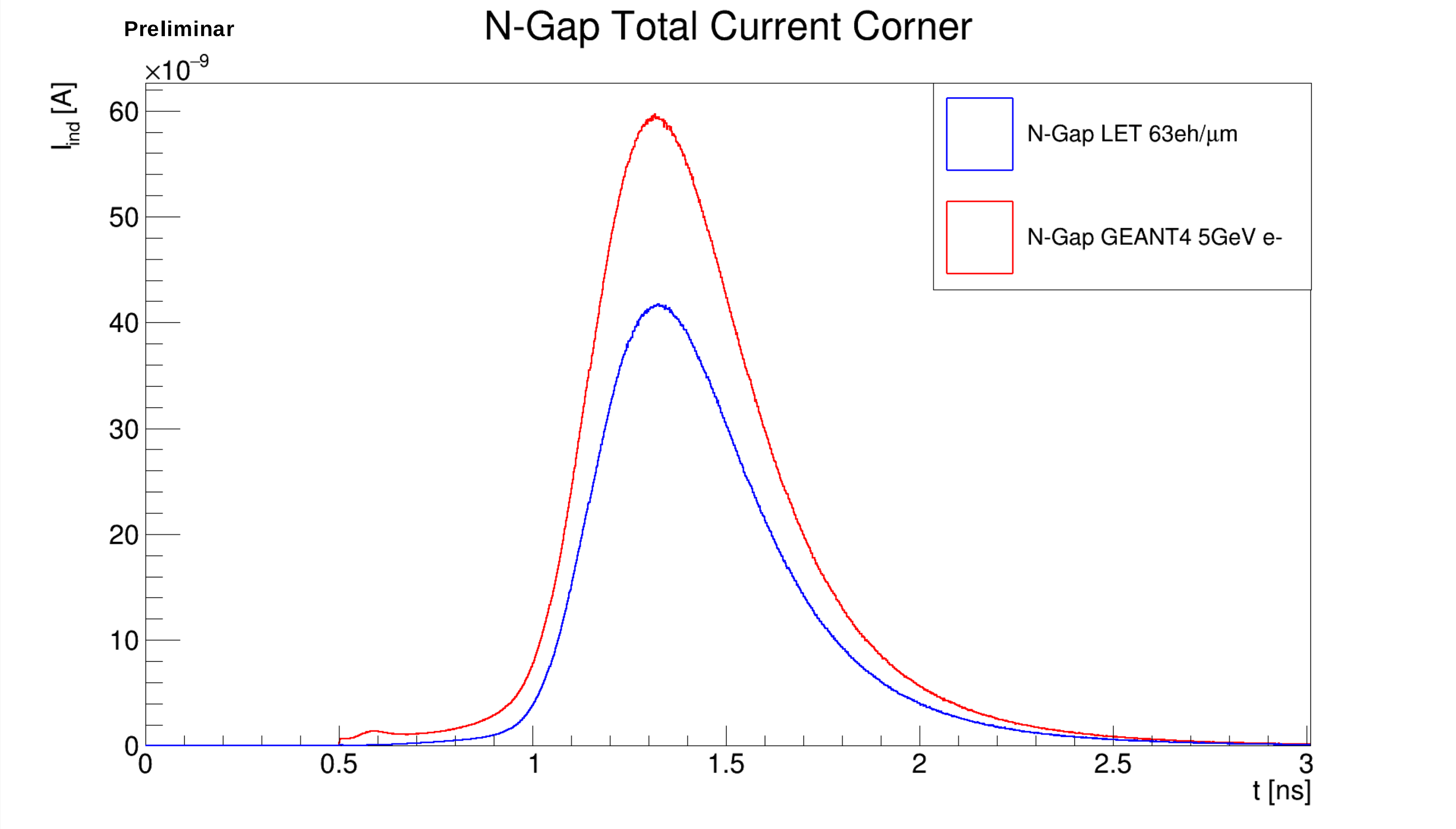
d





$$\varphi_w = \frac{\varphi_0}{U}\ ;\ \overrightarrow{E_w} = -\vec{\nabla}\varphi_w$$

Comparison GEANT4 – Corner Injection



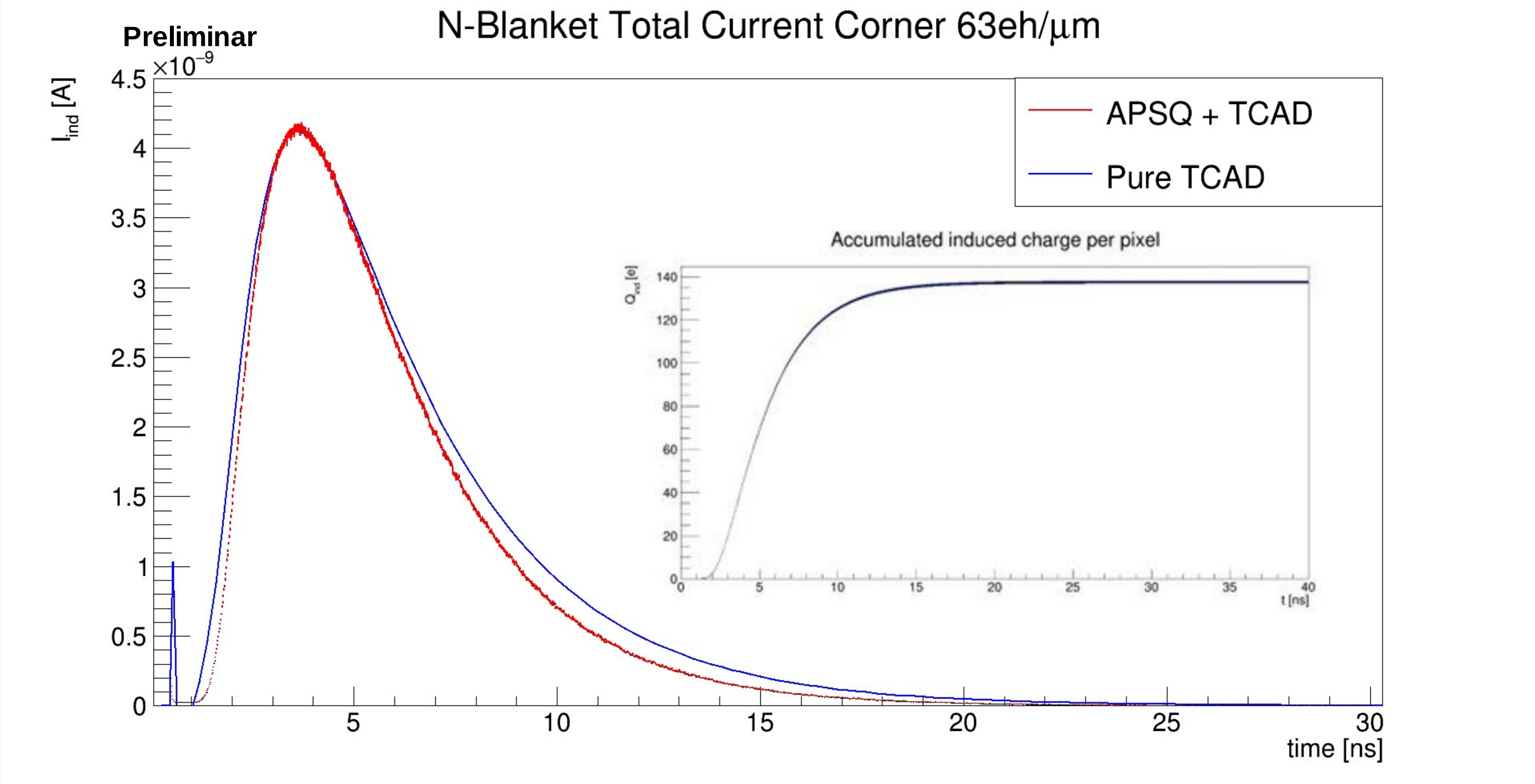
We can proceed by shooting MIP particles and thus take into account **Landau fluctuations, secondary particle production, Photoabsorbtion Ionization...**

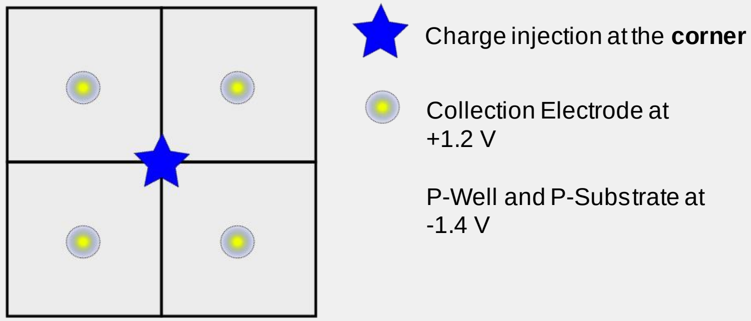
➞ **Sensor and Layout Scan**

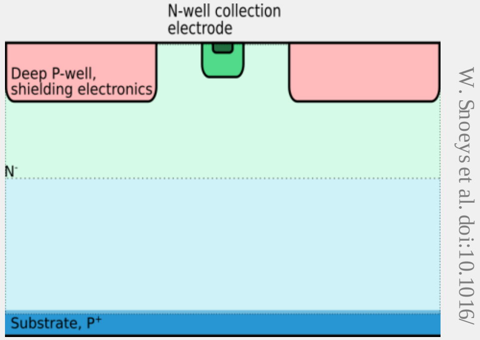
➞ **Timing Performance**

Validation – Corner Injection

Average Pulse Comparison







N-Blanket
Pulse duration ~ 25ns

Pure TCAD - 1 pulse
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