Simulation of the behaviour of a silicon strip sensor used in particle physics

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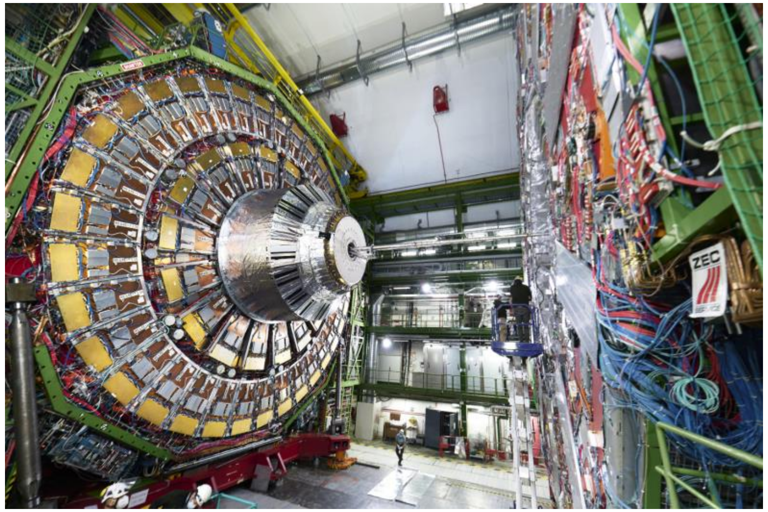
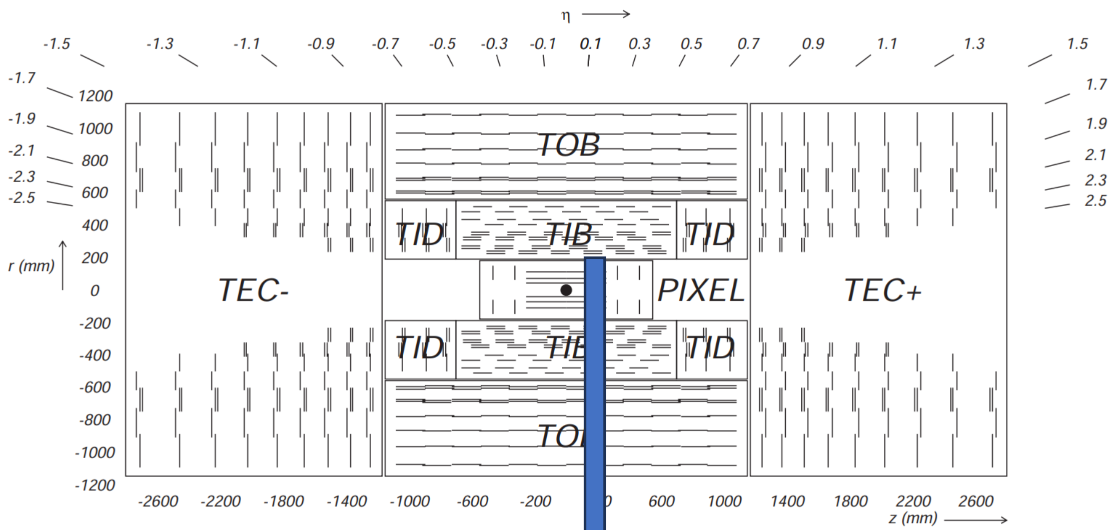
CMS Experiment

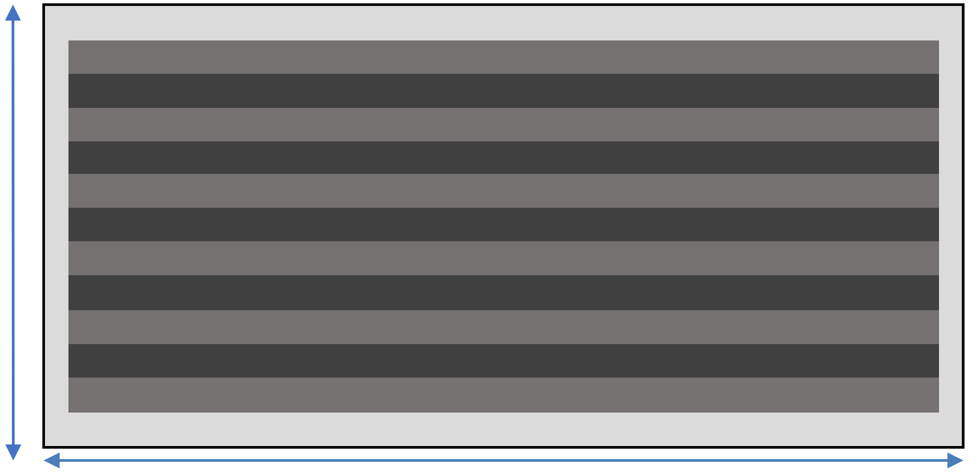
- Stands for Compact Muon Solenoid
- LHC experiment
- Detector : 21x15x15 m³
- International collaboration:
  - 240+ institutes
  - 50+ countries
  - 5500+ physicists, engineers, students
- Studying Standard Model, hypothetic particles of Dark matter, contributed to the discovery of the Higgs boson



The TIB IB1 Sensor

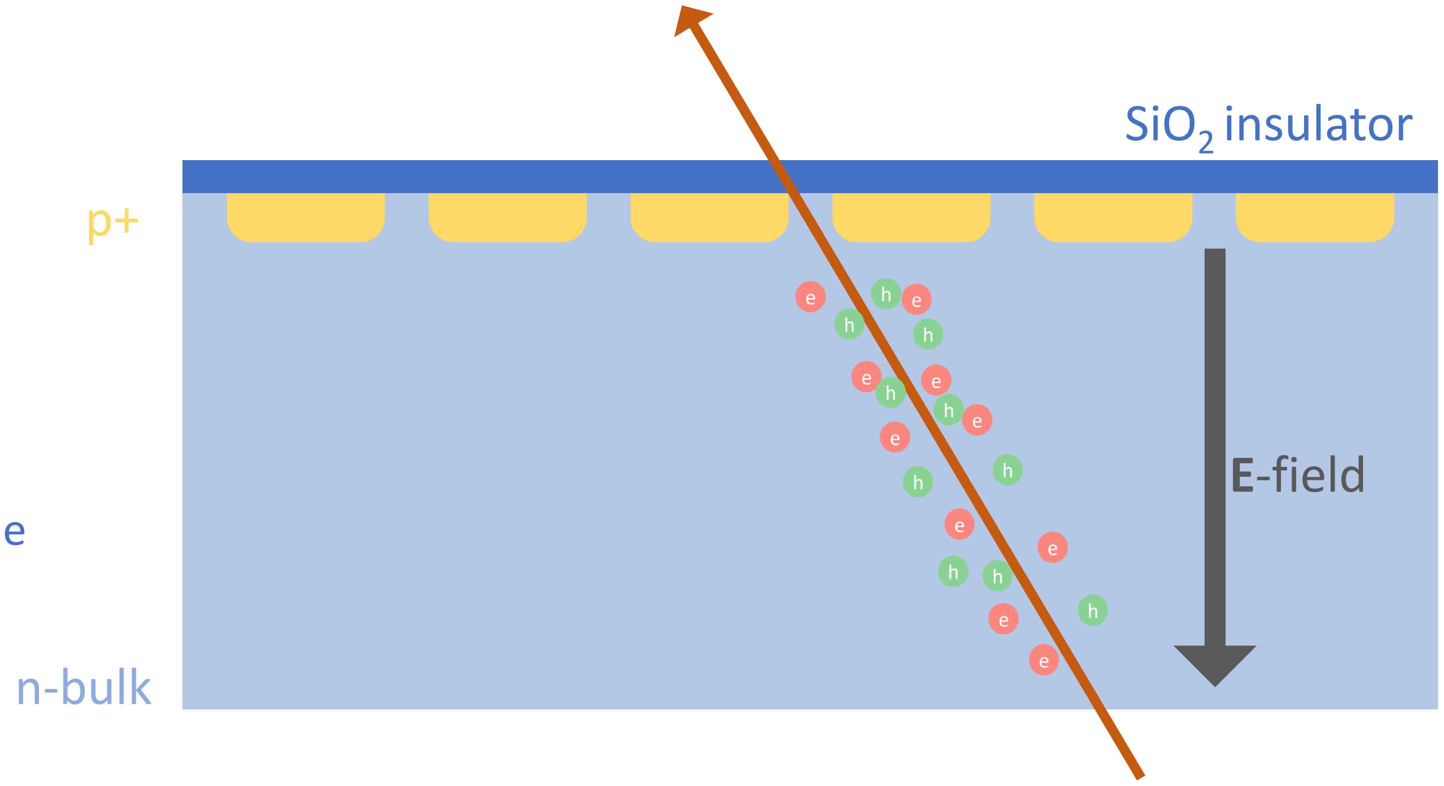
- Tracker Inner Barrel
- Semiconductor sensor
- Dimensions:
  - Width : 63.3mm
  - Length : 119.0mm
  - Thickness : 320µm
- 768 strips parallel to the length with:
  - Pitch : 80µm
  - Length : 118.07mm





Semiconductor sensor

- Silicon sensor
- p-n junctions
- Electric field generate a depleted zone
- Creation e/h pairs by the ionizing particle
- Displacement of charge carriers:
  - electrons follow the E-field
  - holes go against it



AllPix² Presentation

AllPix² logo

Allpix

- Developed by CERN
- Written in C++
- Simulation of semiconductor sensor
- Uses Geant4
- Writes data on ROOT format

Geant4

- Interaction matter/particle
- Large choice of particle
- Visualisation of the sensor

ROOT

- Data arrangement
- Histogram and Graph tracer

AllPix² Modules Setup

AllPix

- Base module
- Load the detector
- Number of events

ElectricField Reader

- Depletion:
  - Voltage
  - Depth
- Bias Voltage

Deposition Geant4

- Particle amount, type, energy
- Beam size and shape
- Source position

Other modules:

- GeometryBuilderGeant4
- DetectorHistogrammer / ROOTObjectWriter
- VisualisationGeant4

AllPix² Modules Setup

- *Charge Propagation*

- Deposition of electron/hole in the semiconductor
- 3D displacement inside the sensor
- Impact of the temperature on the displacement
- Choose the integration time, LHC's default value is 25ns.

Projection Propagation

- Random deposition inside the sensor:
  - 2D gaussian diffusion
  - Simplified calculation
  - Doesn't know what a hole is

Generic Propagation

- Calculate the propagation of electron/hole with integration of the motion:
  - Increased precision
  - Supports hole propagation
  - Long time computation

AllPix²
Modules Setup

- *Charge Transfer*

- Propagate charges between neighboring strips
  - Collect charges propagated inside a strip

SimpleTransfer

- Ignore propagation charge in strips
- Collect only charge inside the strips

InducedTransfer

- Calculate the propagation of charges in the whole sensor
- Requires a mapping of the electric potential in the sensor
- Accurate calculations for every charge

CapacitiveTransfer

- Similar to SimpleTransfer
- But add a coupling matrix to the probability of strip take account a charge inside the neighbor strip

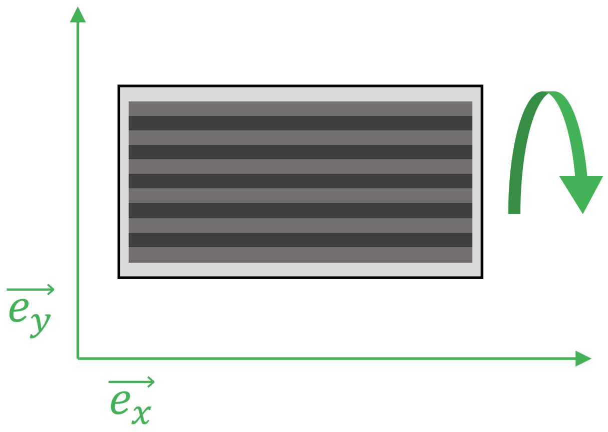
AllPix^2
Recap Setup

Default Digitizer

- Add noise
- Set threshold

- 1000 event per run
- Flat beam 500µm composed of one e^- at 5GeV
- Source at 60mm of the sensor
- GenericPropagation with 250K and 25ns of integration time
- CapacitiveTransfer with (0.01, 0.08, 1, 0.08, 0.01) coupling matrix
- Depletion voltage of 250V and Bias voltage of 300V
- Noise of 900e and Threshold of 1800e

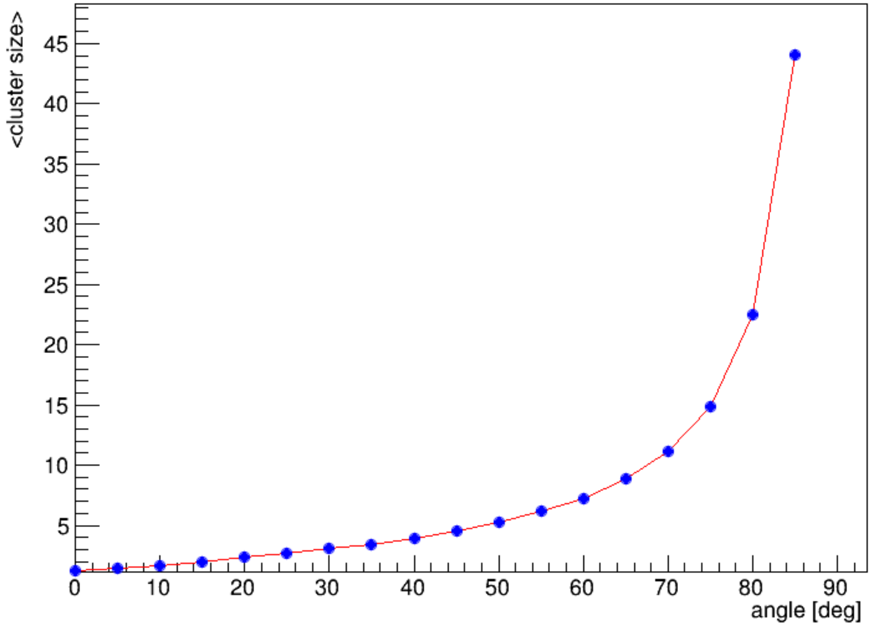
Angle Variation



- Rotation around the Ox axis.
  (both Oy and Oz are irrelevant)

- Invalid behavior at 90°

- Measurement looks like a tan(x)



Cluster: grouping of strips giving a signal

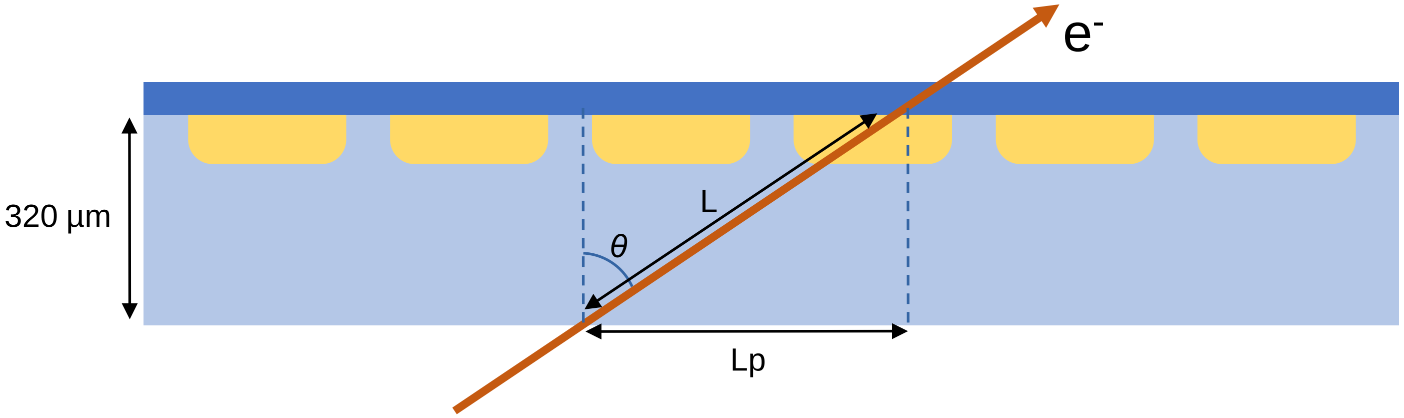
Particle path in the detector

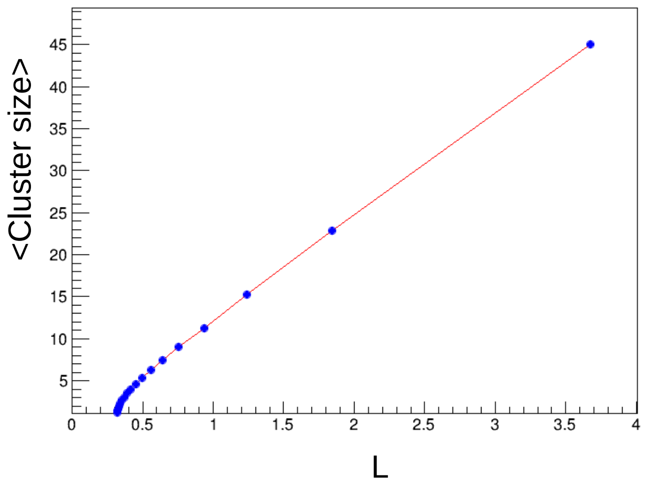
- Rotation around the Ox axis.
  (both Oy and Oz are irrelevant)

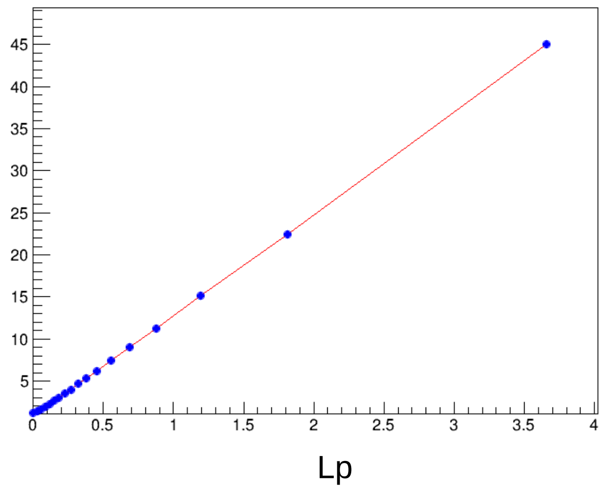
- Particle path length :
  L = 0.320 / cos(θ) [mm]

- Projected length :
  Lp = 0.320 * tan(θ) [mm]

- Linear correspondance between Cluster size and Lp !



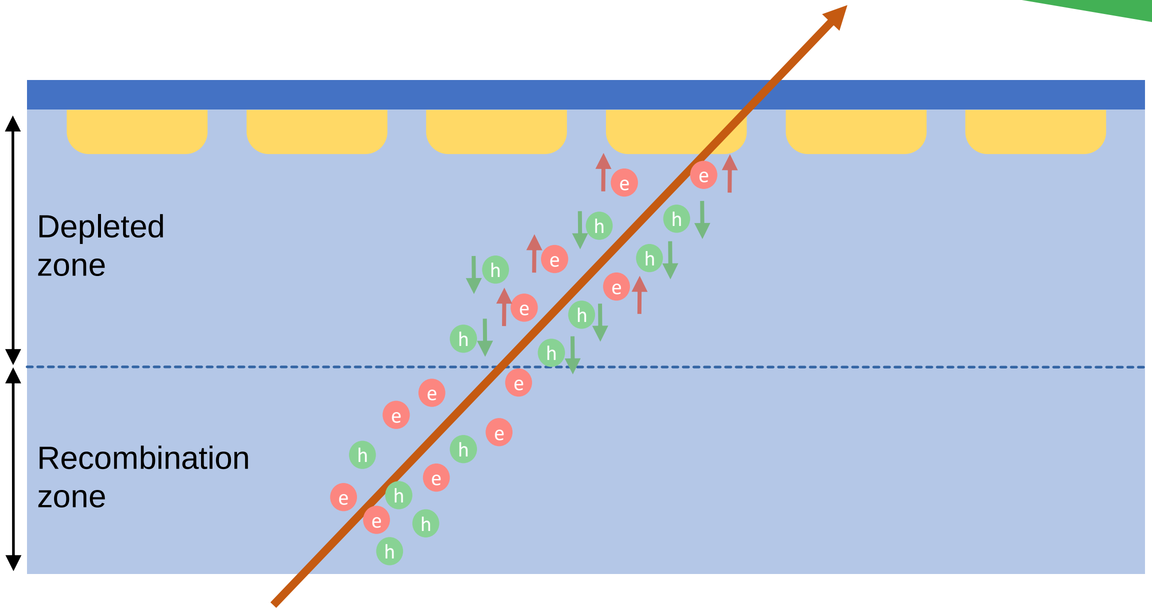


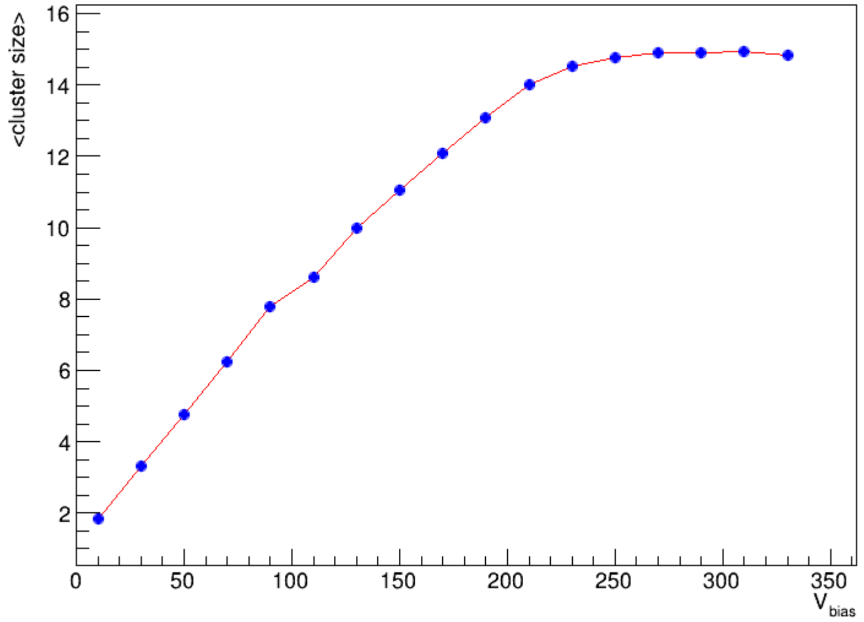


From now on we place our detector at 75°

V_{bias} Variation

- Applying a bias voltage V_{bias} changes the size of the depleted zone
- V_{bias} must be a backward bias
- To maximize the strength of the signal, the detector must be fully depleted (i.e. $V_{bias} > V_{FD}$)

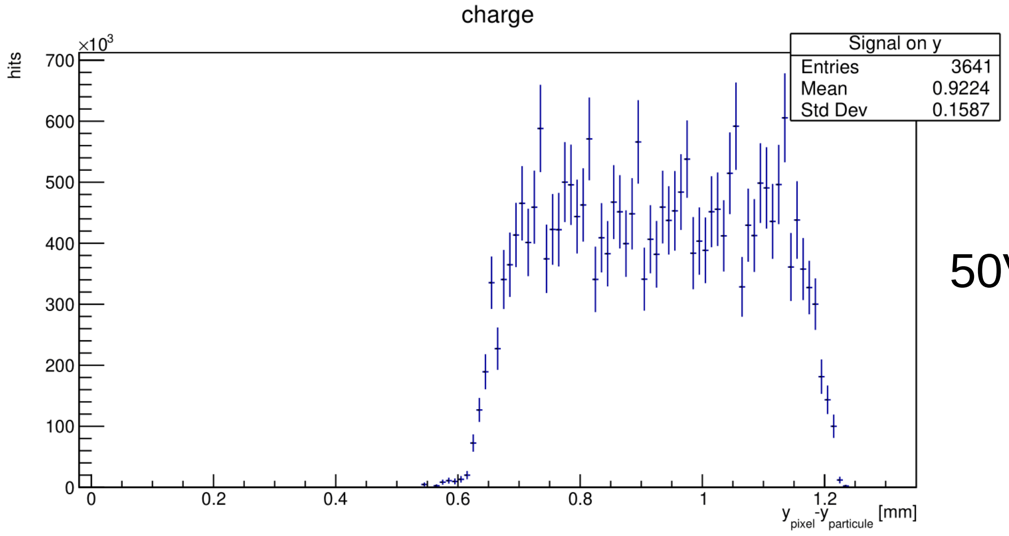




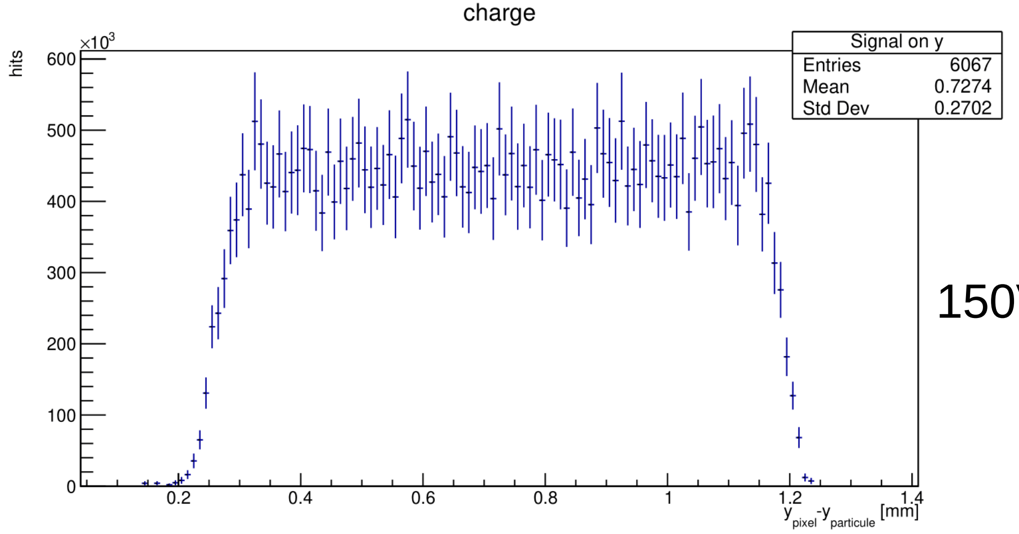
V_{bias} Variation

- Deposited charge in function of relative position

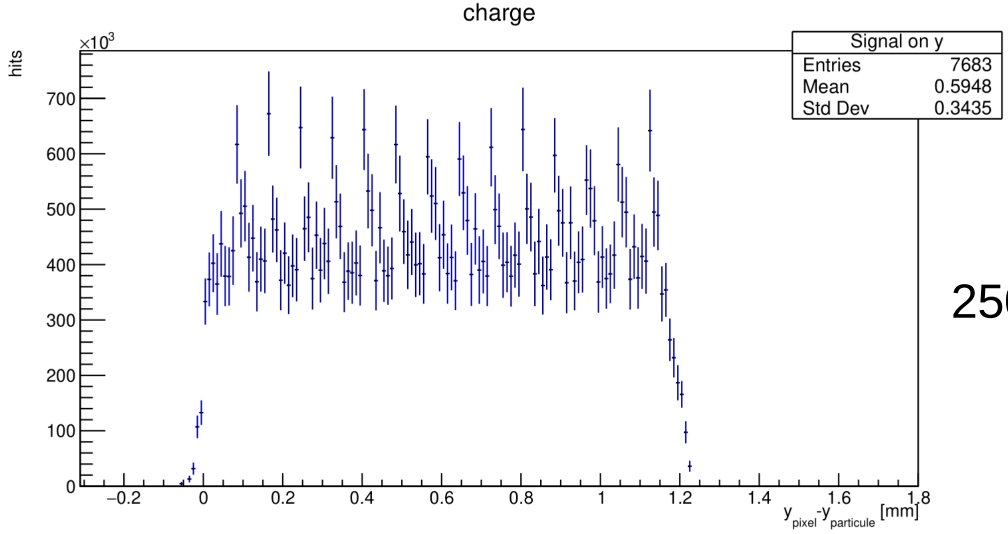
- Particle crossing the recombination zone for V_{bias} < 250V



50V



150V



250V

Irradiation, Fluence, Annealing

- *Introduction*

- What is fluence? (noted Φ $[m^{-2}]$)
  Number of particles that irradiated a material per unit surface.
  (and indirectly, a measure of damage dealt to the detector over time)

- What is annealing?
  Rearrangement of atoms in a material due to thermal agitation.

High Energy irradiation → impurities in the S-C lattice → n+ bulk gradually gains acceptors

Irradiation, Fluence, Annealing

- *Theory*

Irradiation consequences on V_{FD}:

- Change in the effective dopant concentration
- $$\Delta N_{eff}(\Phi, t, T) = N_C(\Phi) + N_A(\Phi, t, T) + N_Y(\Phi, t, T)$$

N_C : describes Donor removal & Acceptor creation
N_A : describes Beneficial annealing
N_Y : describes Reverse annealing

- $$V_{FD} = \frac{qd^2}{2\epsilon_0 \epsilon_{Si}} N_{eff}$$

d : thickness of bulk
q : elementary charge

Irradiation, Fluence, Annealing

- *Theory*

- Ignore N_A and N_Y :

$$\Delta N_{eff} = N_C(\Phi) = |N_0 - N_{eff}|$$

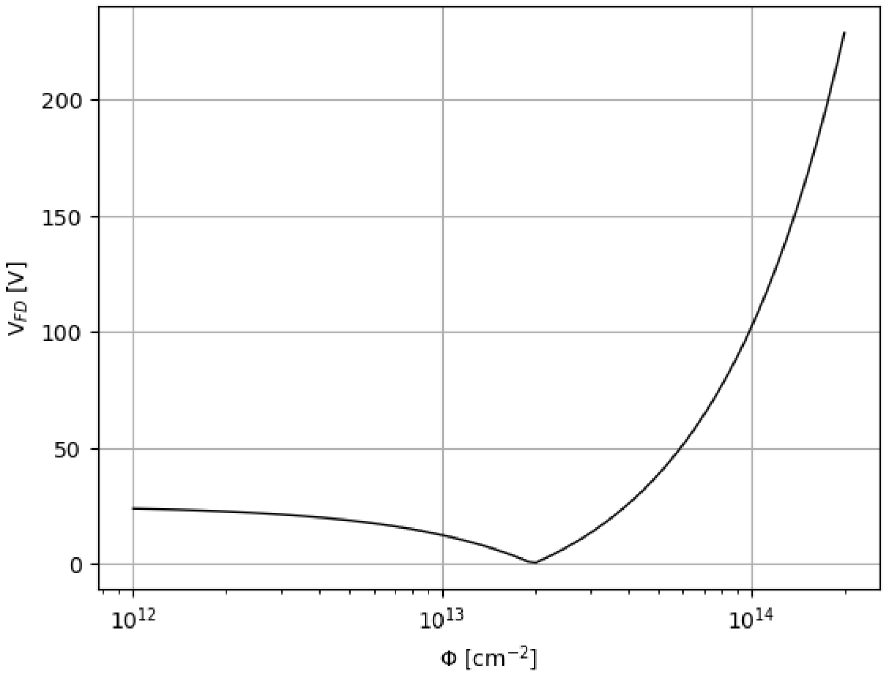
$$\rightarrow N_{eff} = |N_0 - N_C|$$

And $N_C(\Phi) = N_{C,0}(1 - e^{-c\Phi}) + g_c\Phi$

- From N_C, get V_{FD} :

$$V_{FD} = \frac{qd^2}{2\epsilon_0\epsilon_{Si}}|N_0 - N_C|$$

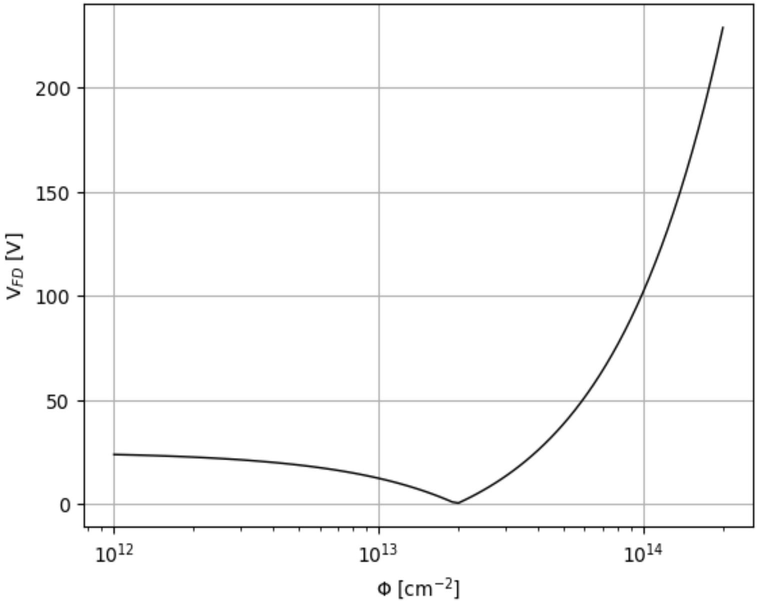
Evolution of V_{FD} in fonction of the fluence



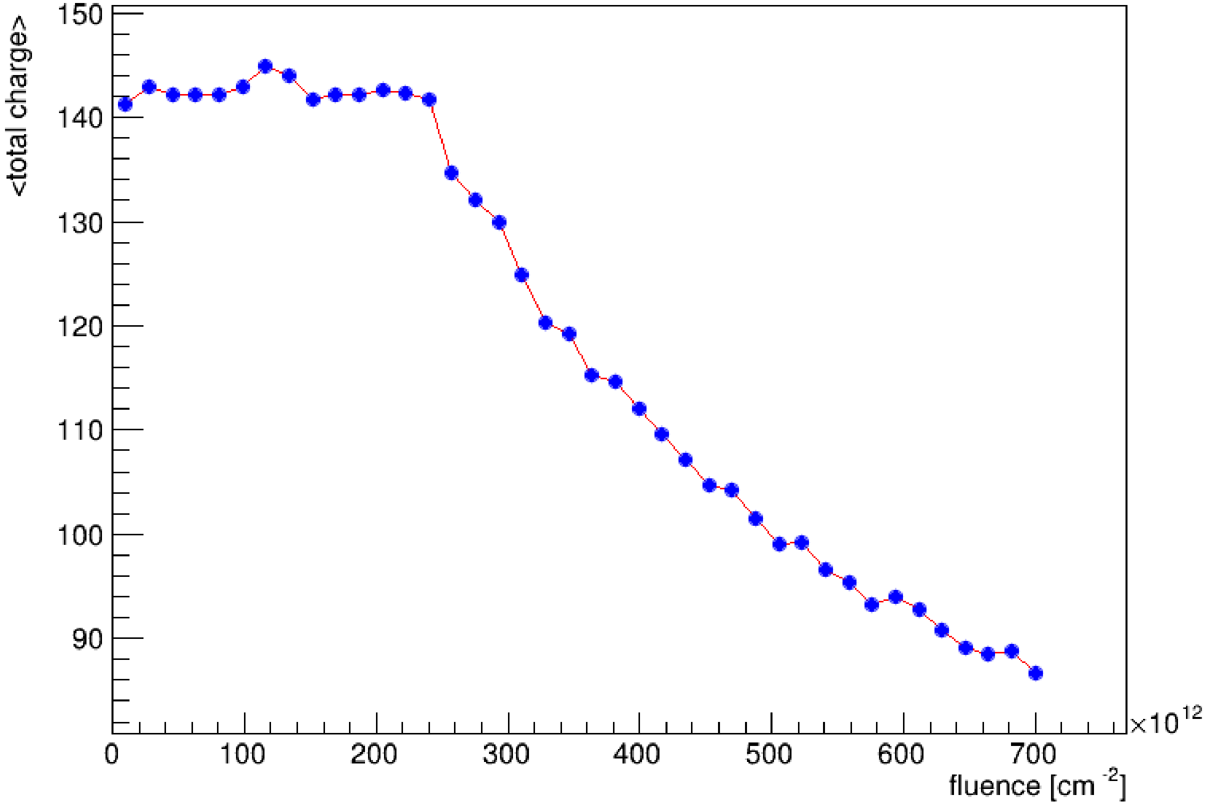
Irradiation, Fluence, Annealing

- *Measurements*

- Mean total charge in the sensor
- Start at 10e12 finish at 700e12
- Decrease the charge collection of the sensor



Evolution of the mean total charge in function of the fluence, with V_{bias} = 300V



Recap and Conclusion

- Discovery and first simulations with AllPix²
- Study of the general behavior of the TIB IB1
- Mostly observations

Bibliography

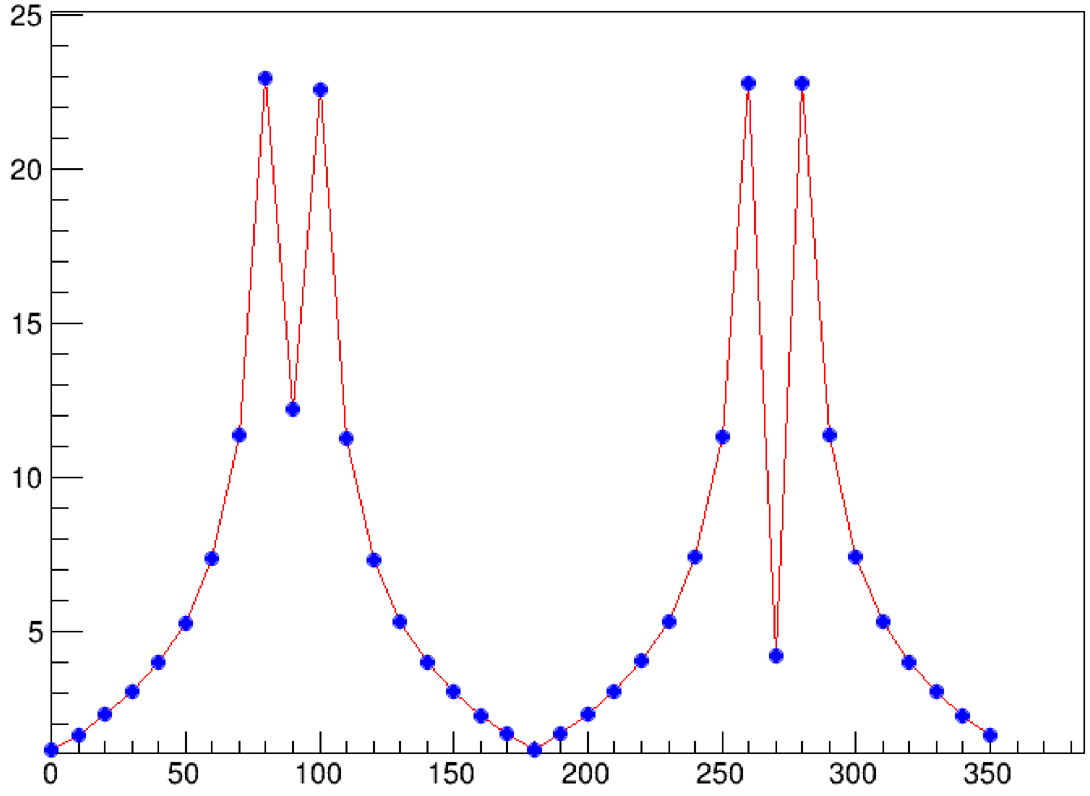
- Allpix Squared documentation : https://allpix-squared.docs.cern.ch
- Tonon Nicolas Thesis
- The silicon sensors for the Compact Muon Solenoid tracker—design and qualification procedure (CMS)
- Simulation of Heavily Irradiated Silicon Pixel Sensors and Comparison with Test Beam Measurements : https://arxiv.org/abs/physics/0411143v2
- Barth Christian Thesis

sensor

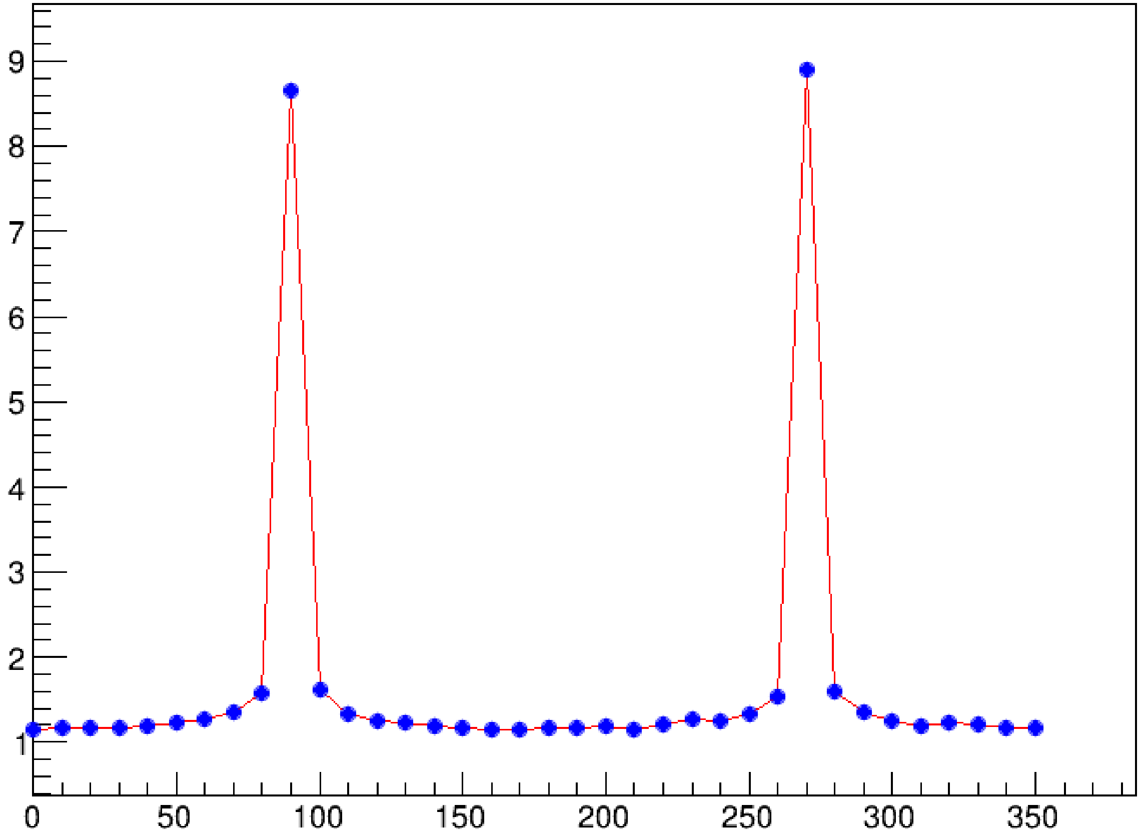
```
type = "monolithic"
geometry = "pixel"

number_of_pixels = 1 768
pixel_size = 118.07mm  80um

sensor_thickness = 320um
sensor_excess= 0.93mm



chip_thickness = 0um
```

```
[detector]
type = "CMS_detector"
position = 0um 0um 0mm
orientation_mode = "xyz"
orientation = 75deg 0deg 0deg
```

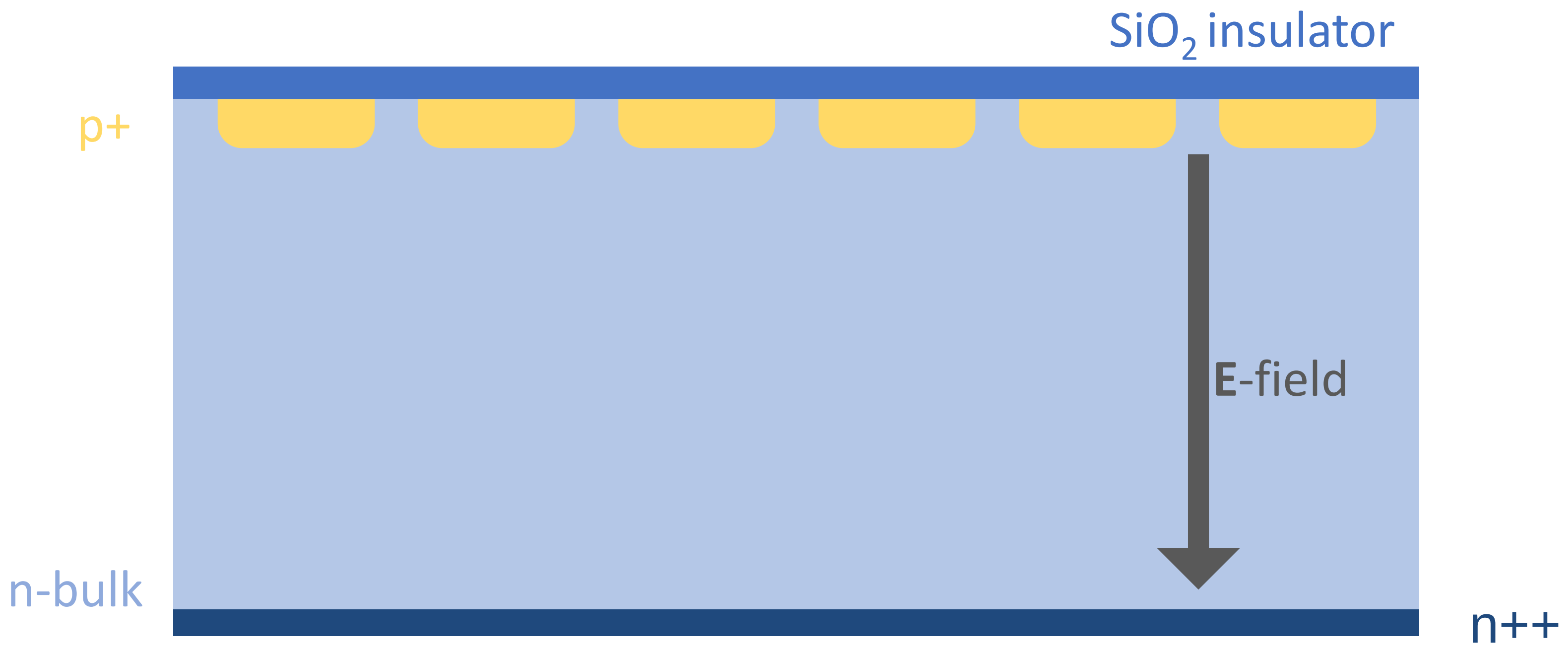
Angle



Angle_2



sensor



Fluence initial condition

- d=320 µm
- c=1,09e^{-1} m²
- $\frac{qd^2}{2\epsilon_0\epsilon_{SI}} N_0 = V_0 = 250V$
- g_c=1,6e^{-2}