Simulation of hybrid pixels using precise TCAD simulations

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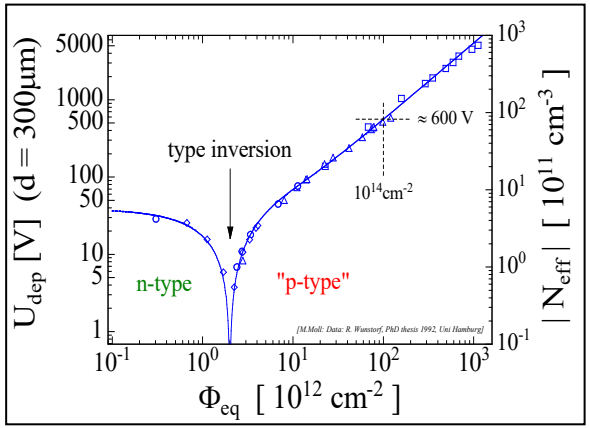
Outline

- Radiation damage to silicon sensor bulk
- Modeling radiation damage: ATLAS approach
- A new strategy for High Luminosity LHC phase
- Allpix Squared for radiation damage digitizer
- New developments:
  - Electric field and potential maps from Silvaco TCAD
  - 3D sensors simulation
  - Trapping model
- Conclusion and Outlook

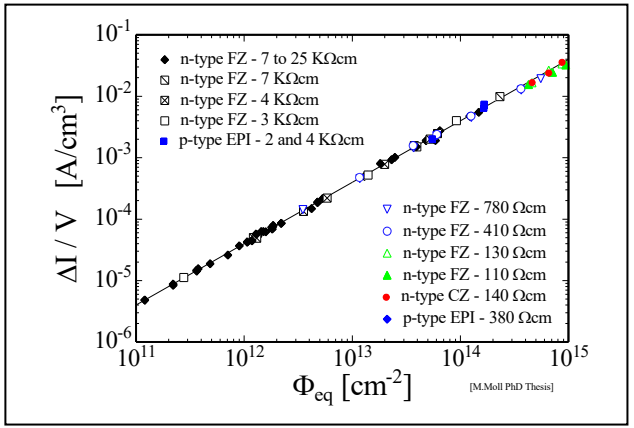
Radiation damage to silicon sensor bulk

- At high energy hadronic colliders detectors made of silicon sensor suffer from radiation damage effects
- Some of these effects impact the operations (depletion voltage increase, and leakage current)
- Other are more important to signal identification, like the reduced charge collection efficiency due to trapping

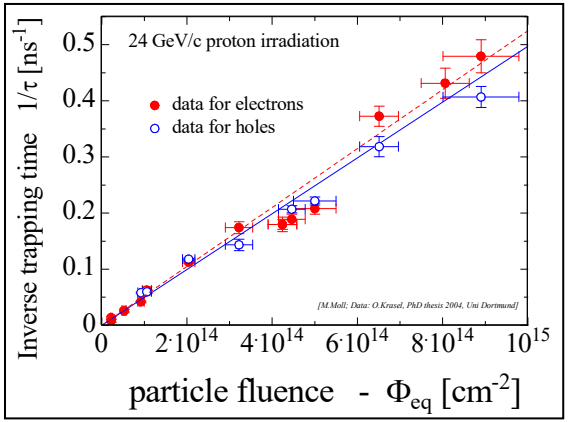
M. Moll, SIMDET 2018



Depletion Voltage (N_{eff})



Leakage Current

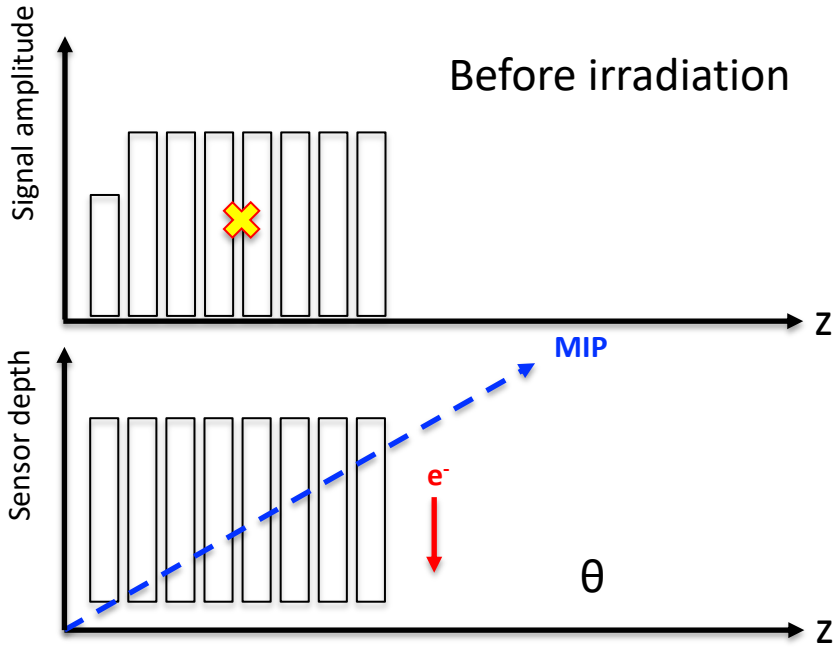


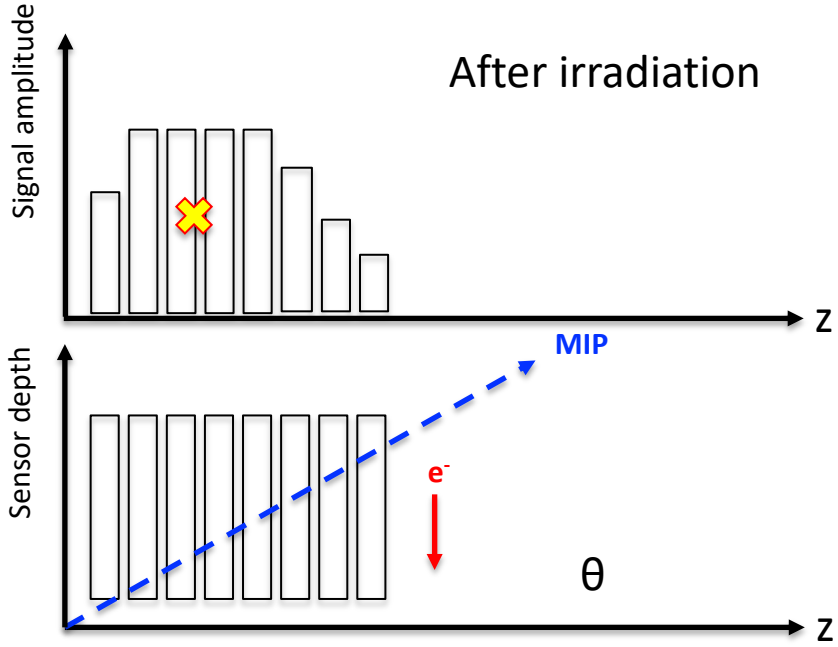
Charge Trapping

Radiation damage to silicon sensor bulk

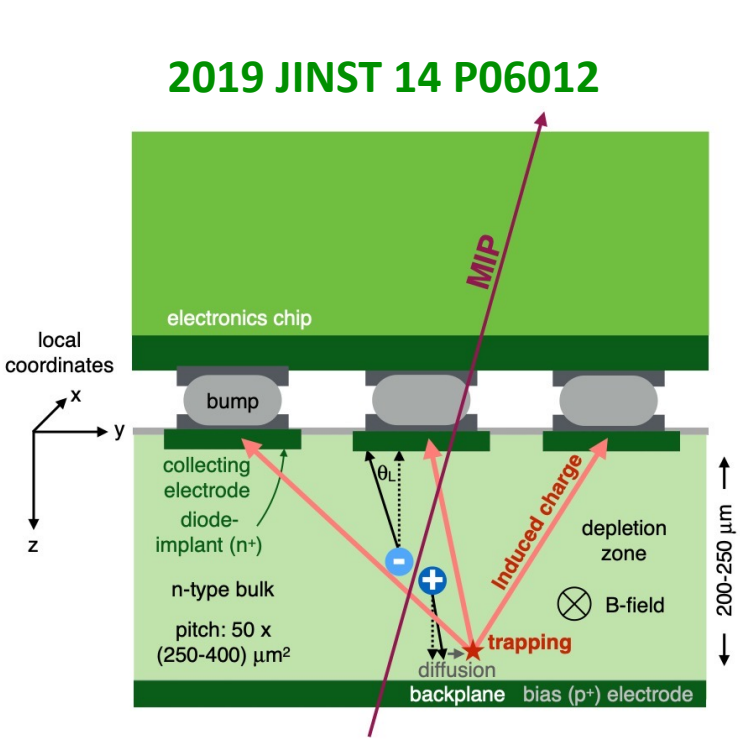
- Signal loss reduces the signal-to-noise ratio
- And biases signal position reconstruction

Estimated cluster position





Radiation damage modeling: ATLAS approach



Strategy: evaluate final position and induced signal of a group of carriers in MC

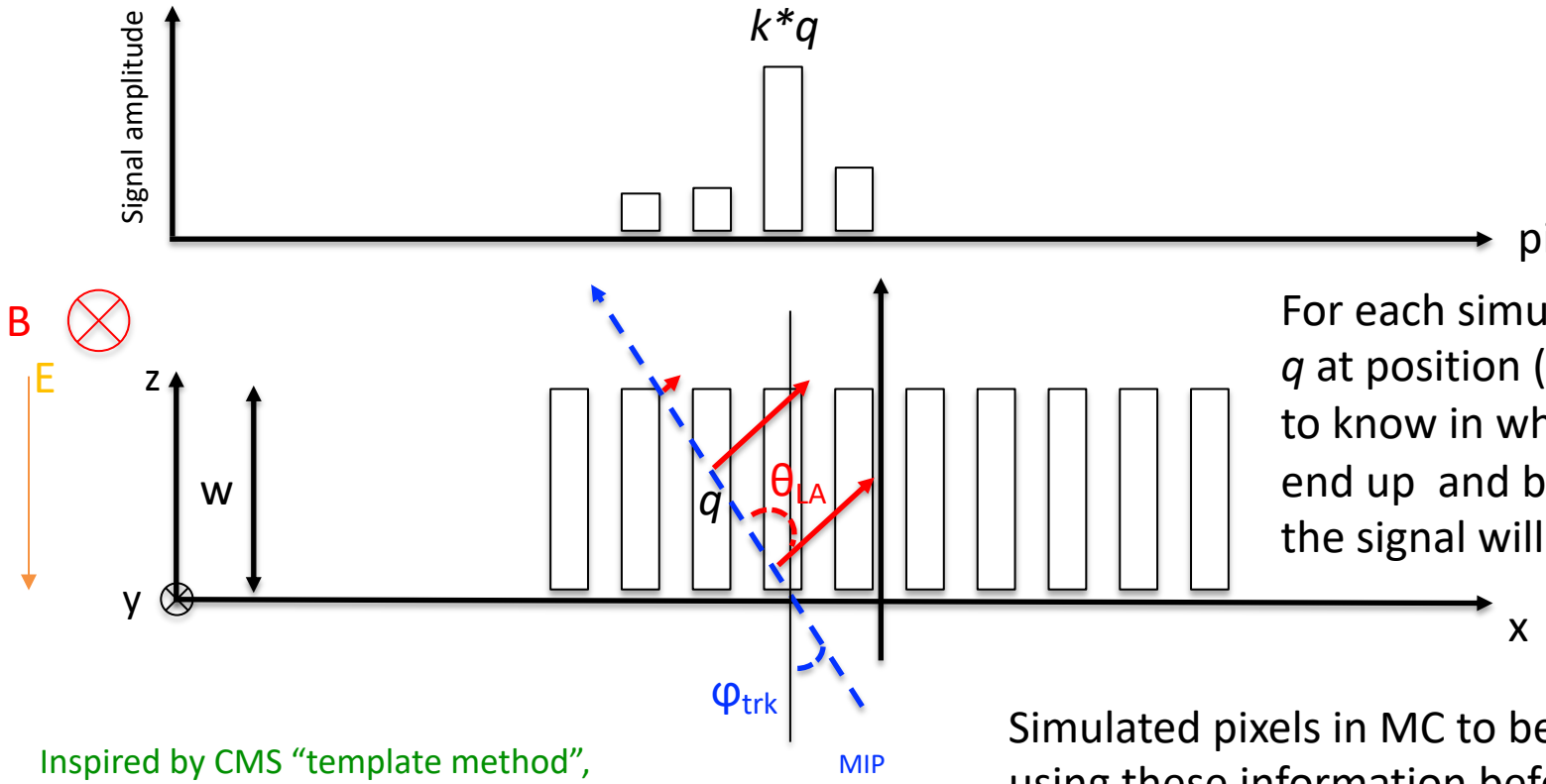
Input:

- precise electric field simulation (TCAD) to take into account radiation damage effects
- weighting potential (TCAD)
- trapping rates (literature)

Due to expected increase of particles density and rates in High Luminosity phase of LHC:

➢ Plans to change approach -> charge reweighting from look-up tables

A new strategy for High Luminosity LHC phase



For each simulated charge *q* at position (x,y,z) we want to know in which pixel it will end up and by how much (*k*) the signal will be reduced

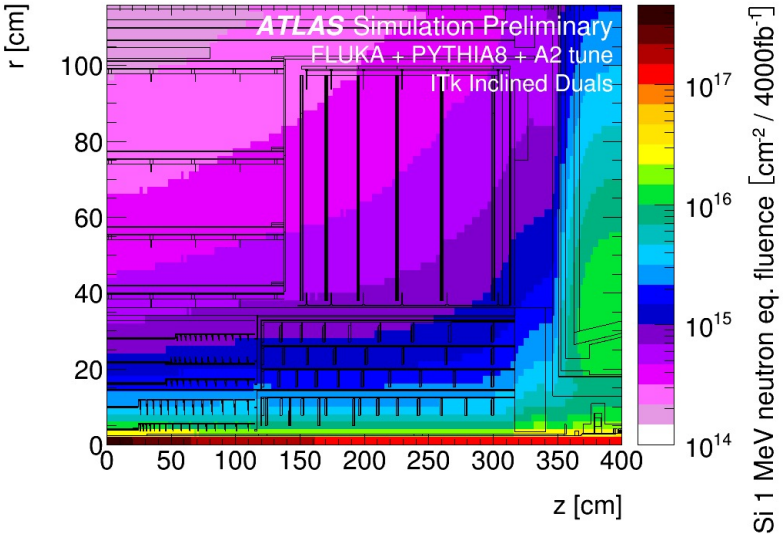
Inspired by CMS "template method", *PoS* VERTEX2007 (2007) 035

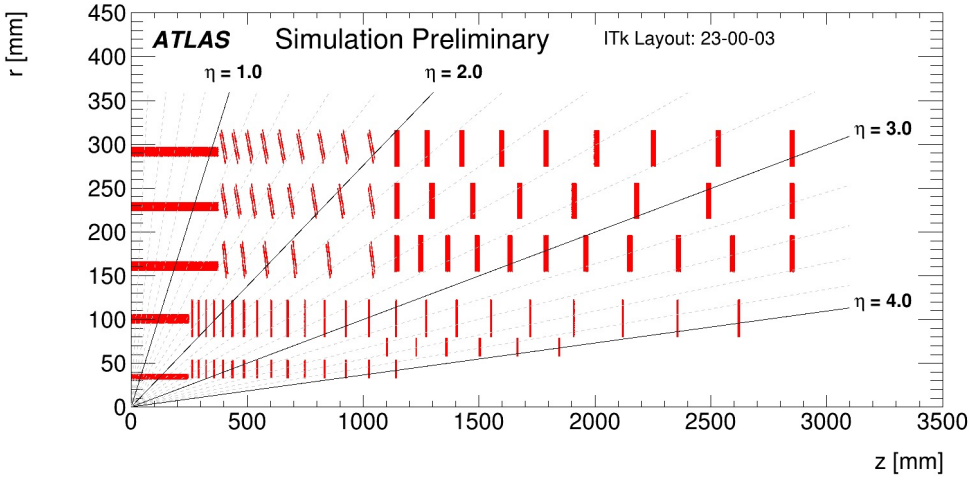
Simulated pixels in MC to be corrected using these information before digitization

Allpix-Squared for radiation damage digitizer

- To implement such a correction scheme we have thought Allpix-Squared is the perfect tool

➢ Simulate sensors before and after irradiation, per geometry and per fluence





Allpix-Squared for radiation damage digitizer

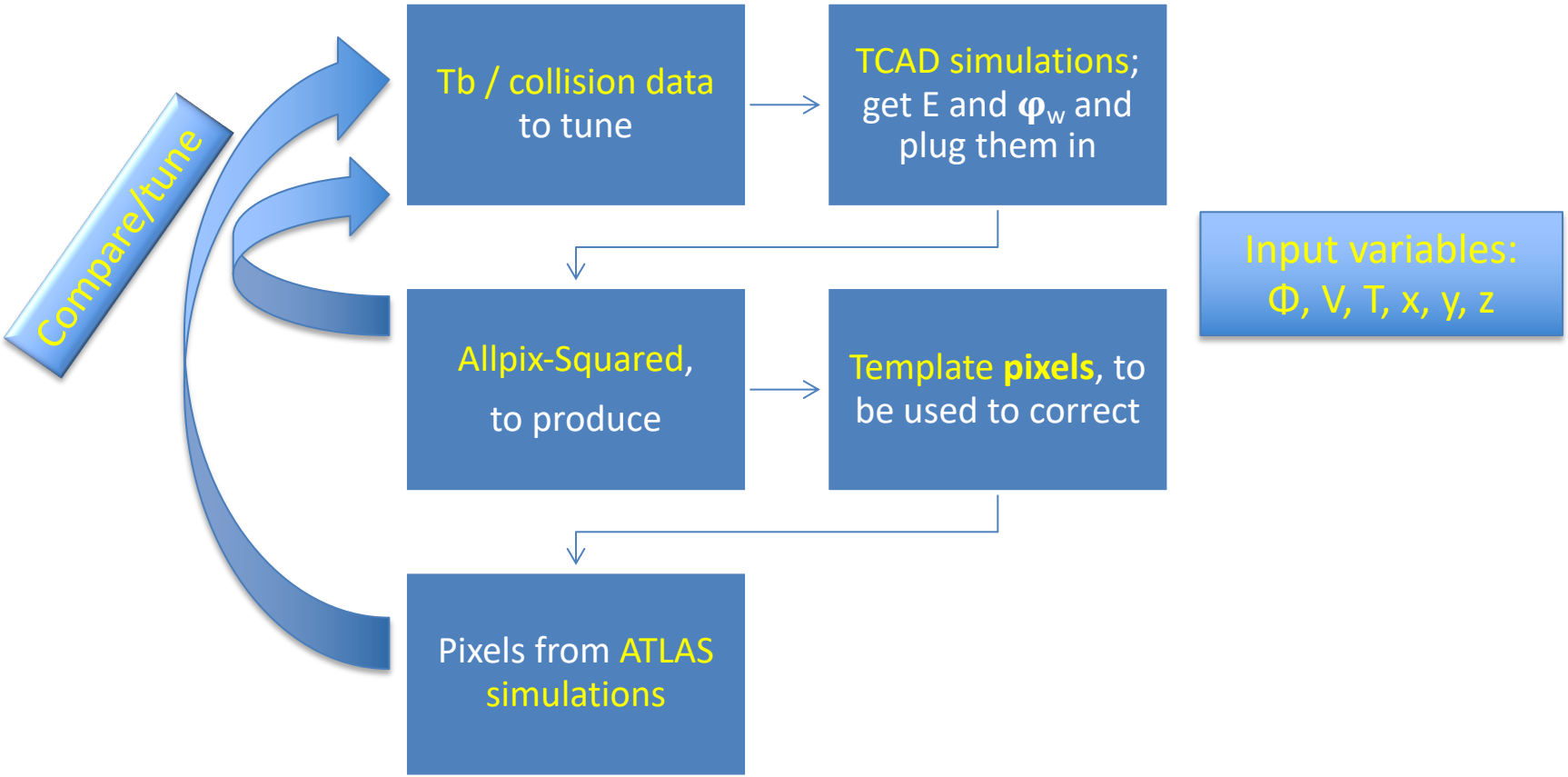
- To implement such a correction scheme we have thought Allpix-Squared is the perfect tool

➢ Simulate sensors before and after irradiation, per geometry and per fluence

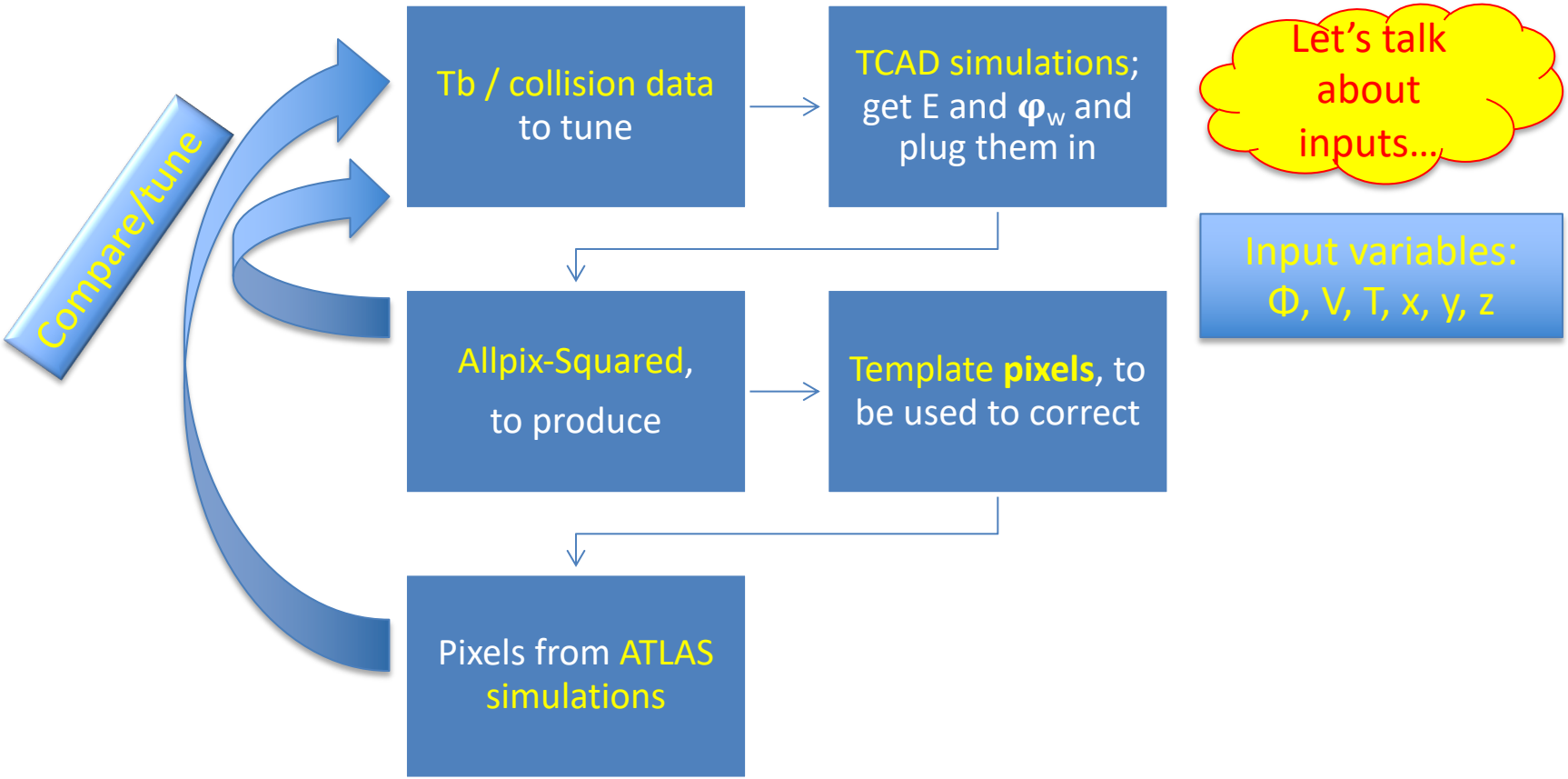
➢ Save the ratio of after-over-before irradiation collected charge for a pixel struck at a certain position (x,y,z)

➢ Evaluate Lorentz angle deflection too as a function of track impact position

Implementation strategy: reminder

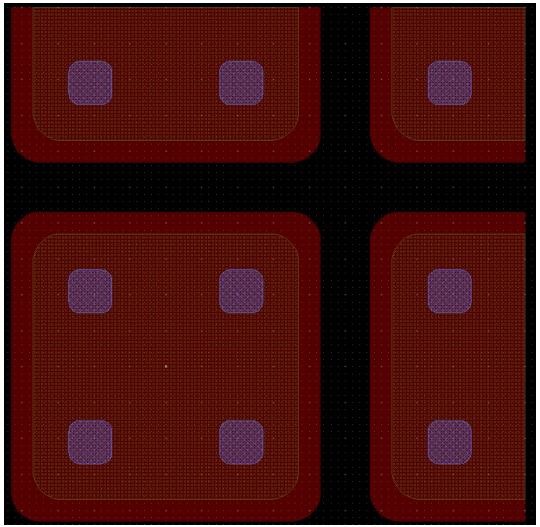


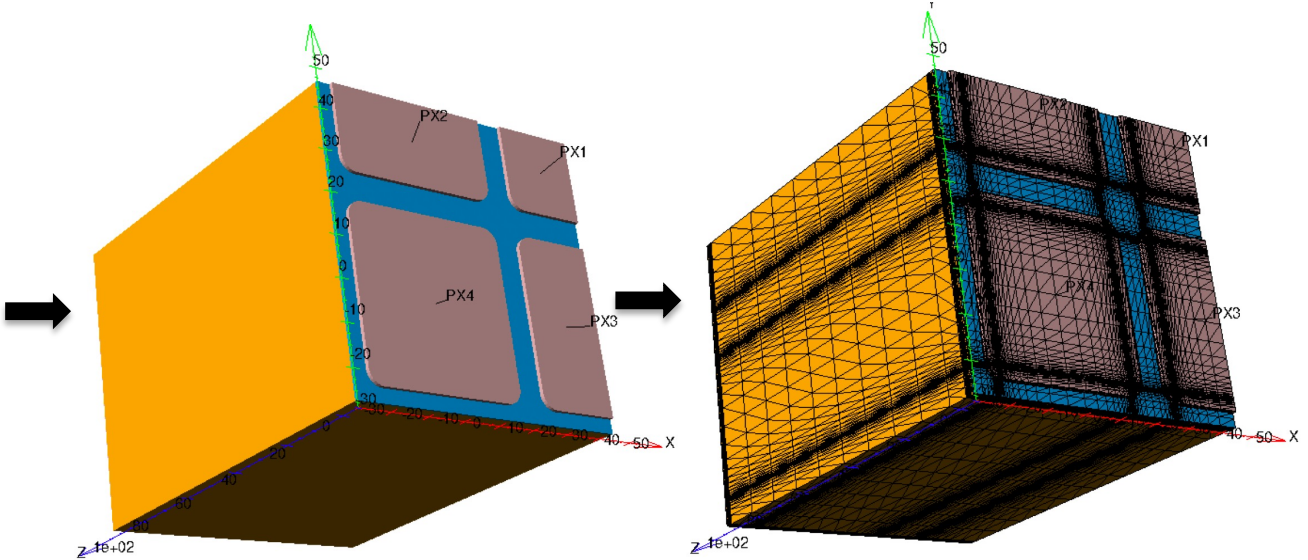
Implementation strategy: reminder



Precise TCAD simulations

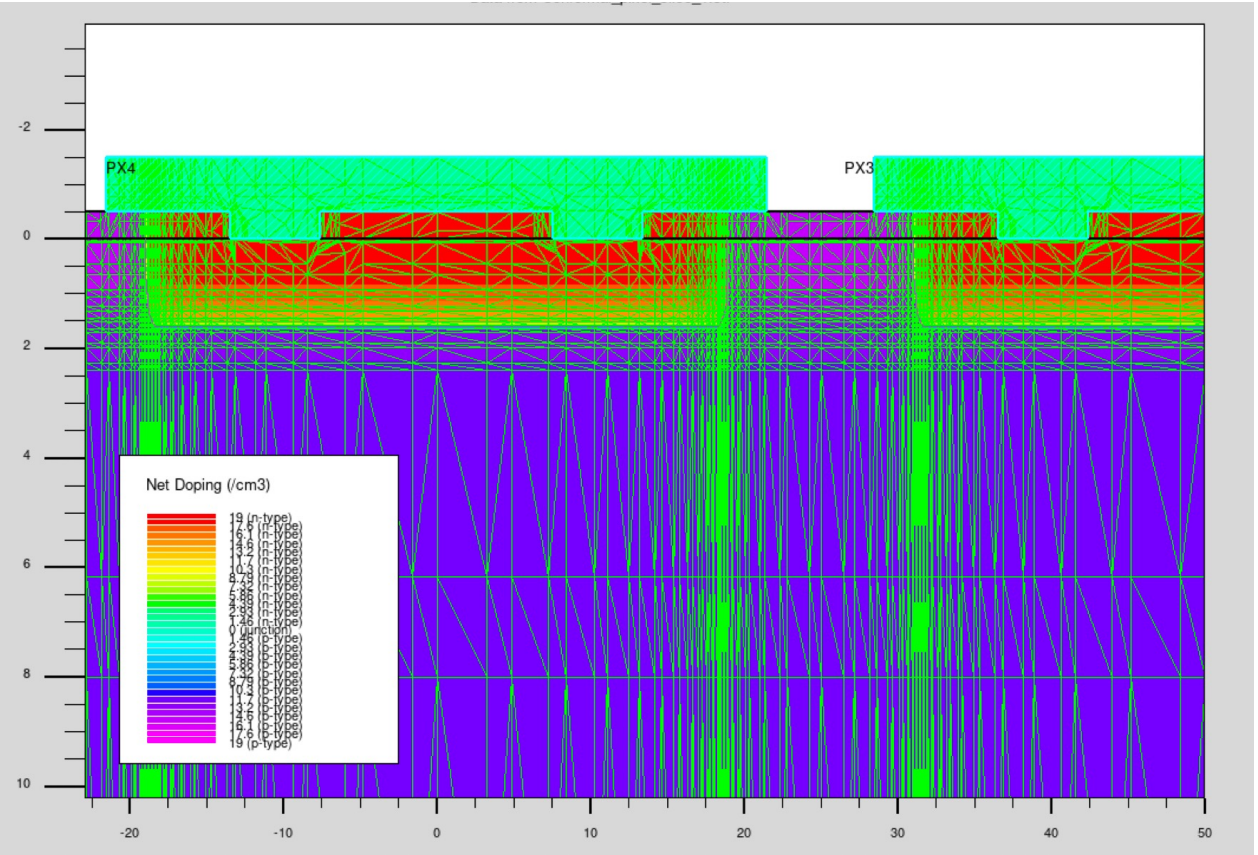
Victory suite by Silvaco



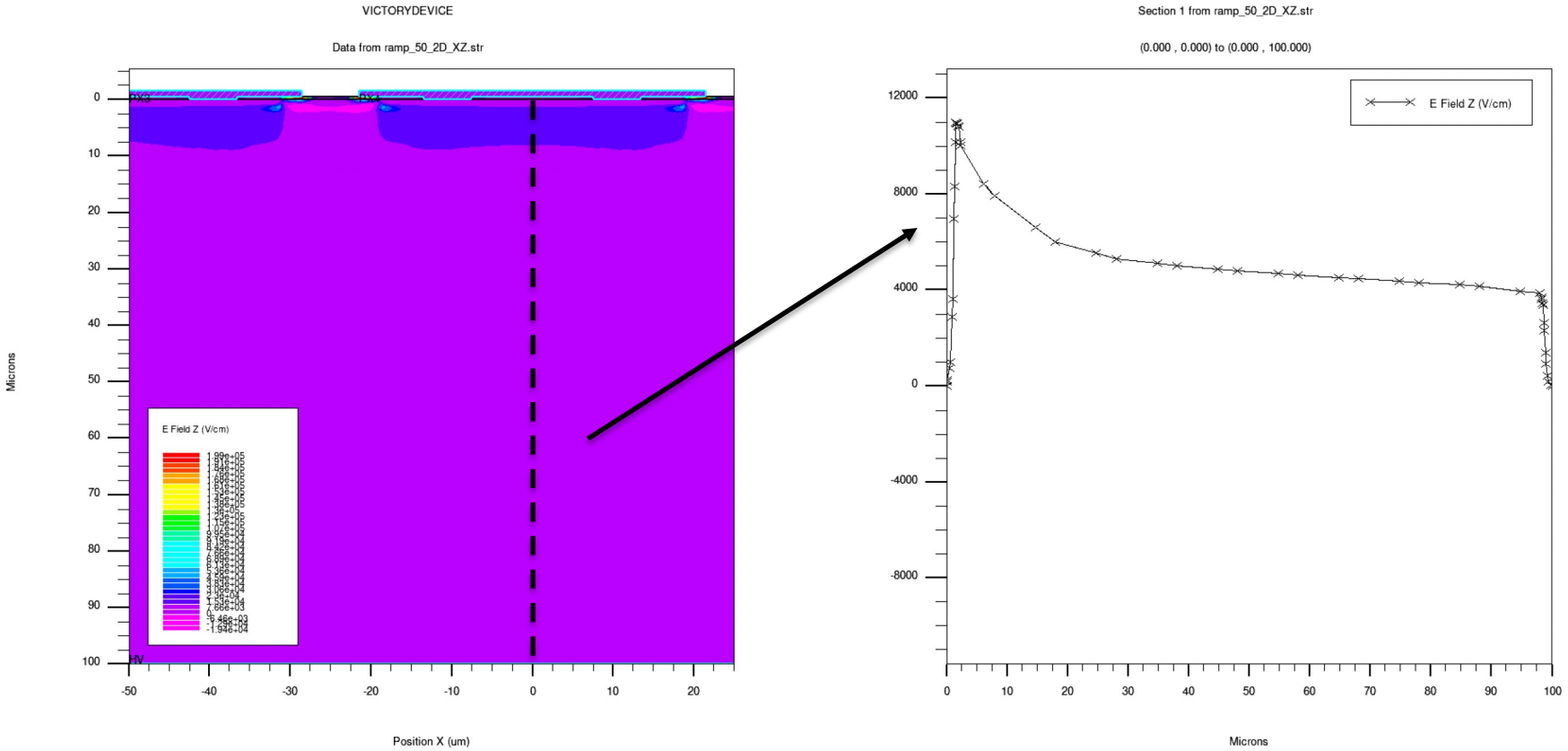


¼ of 3x3 pixels matrix

2D slice of meshed structure (zoom)

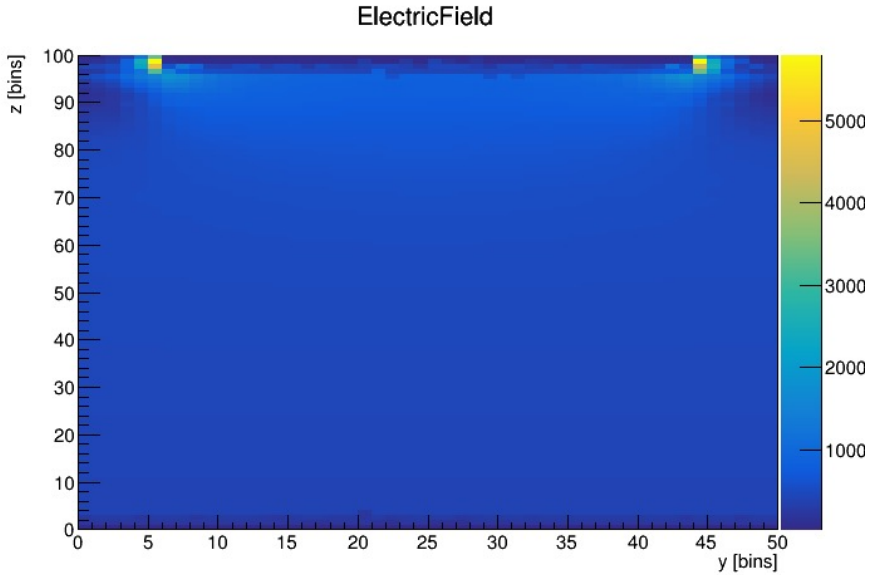


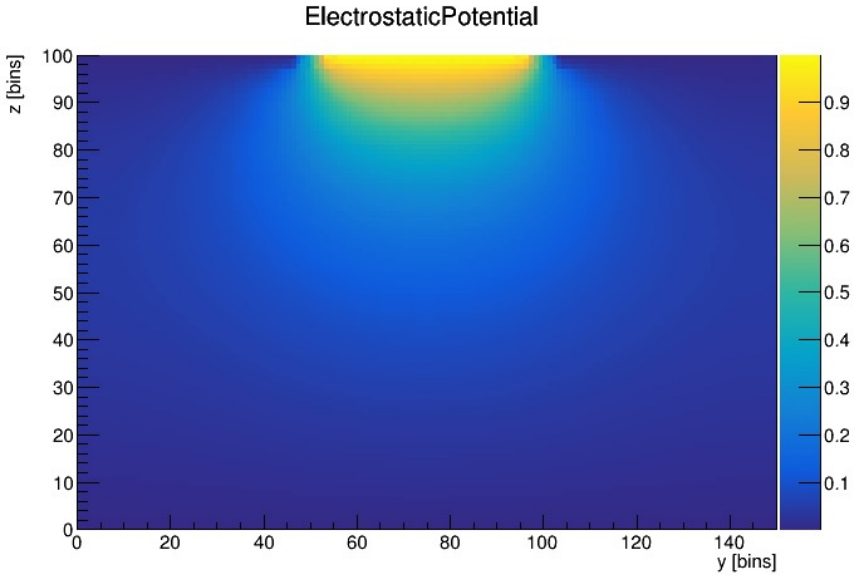
Electric field prediction from TCAD



From TCAD to Allpix-Squared

New module to read field maps from Silvaco!





1 pixel

3x3 pixels

(Caveat: z-axes are opposite in orientation in TCAD and in Allpix-Squared)

Comparison of diode vs pixel electric field

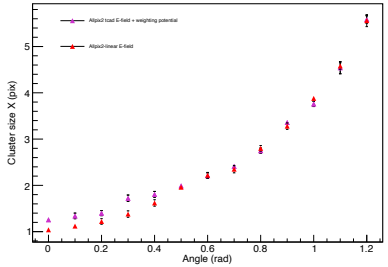
Simulating 100 um thick 50x50 um^2 sensor

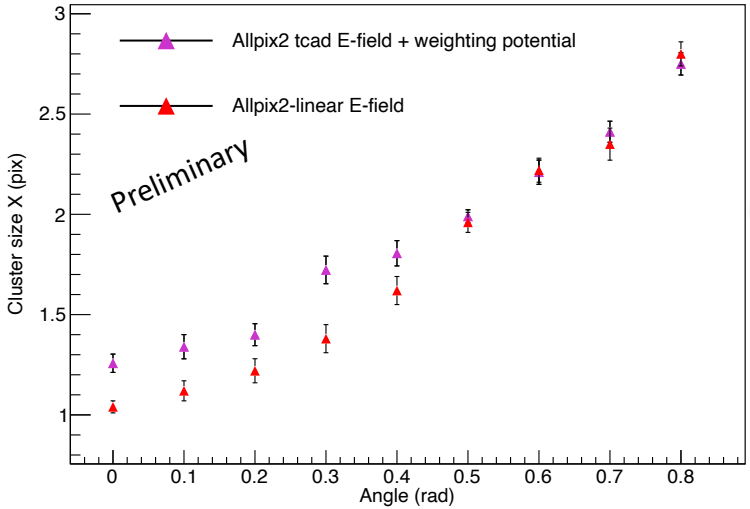
Two electric fields used:

Linear field (50 V bias , 10 V depl. voltage)
Field from TCAD (same conditions)

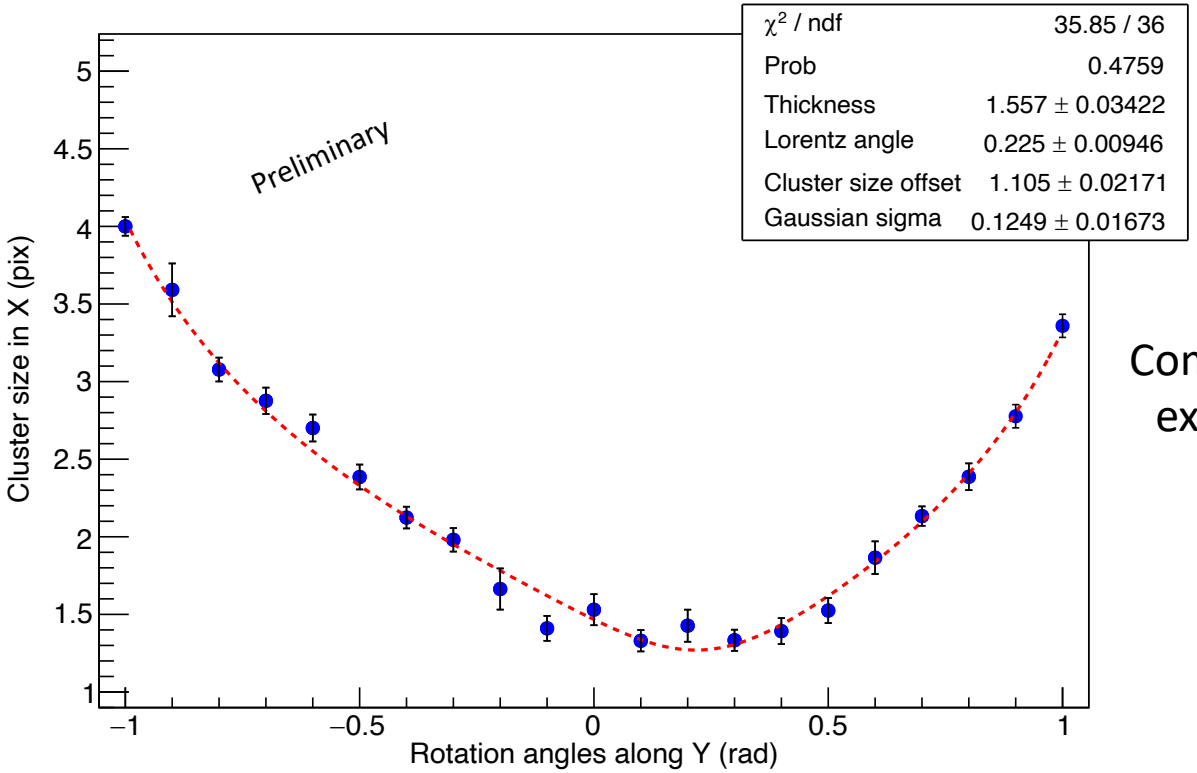
Comparing cluser size as a function of the track impinging angle

Nice test to make sure all the chain works as expected





Lorentz angle

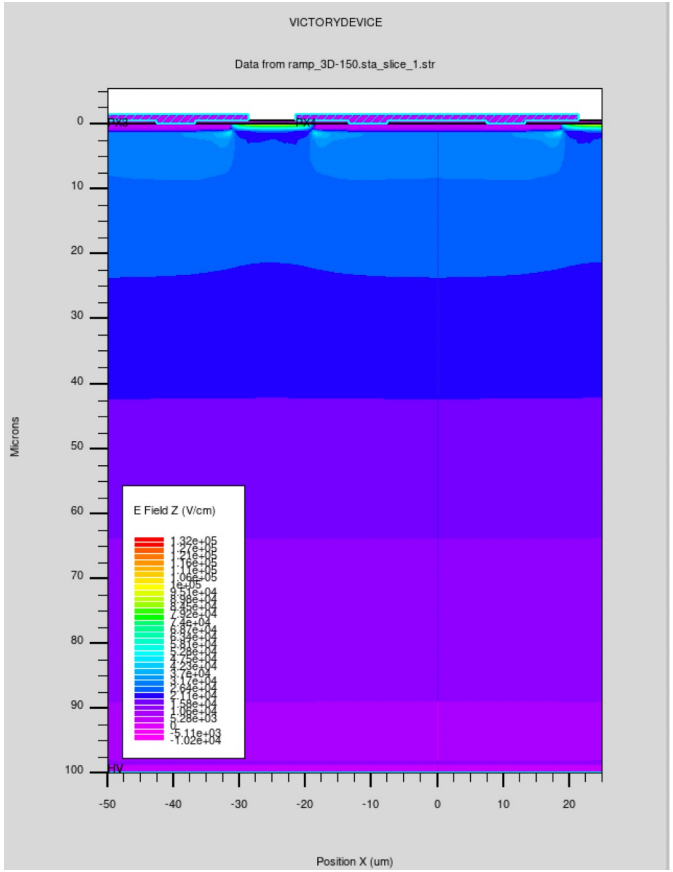


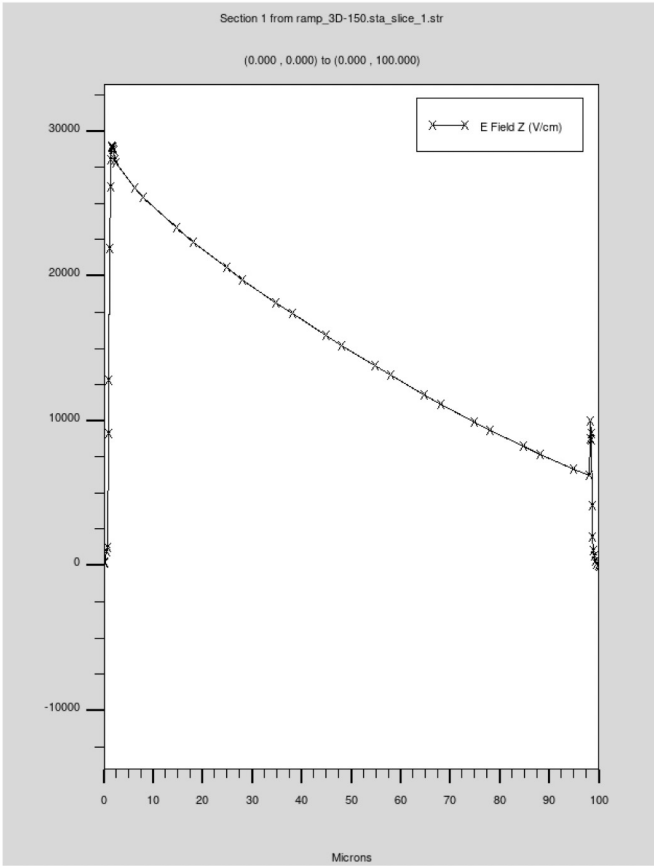
Compatible with expectections

Extra: electric field for irradiated sensor

1e15, 150 V
LHCb model*

*NIMA 874 (2017) 94–102

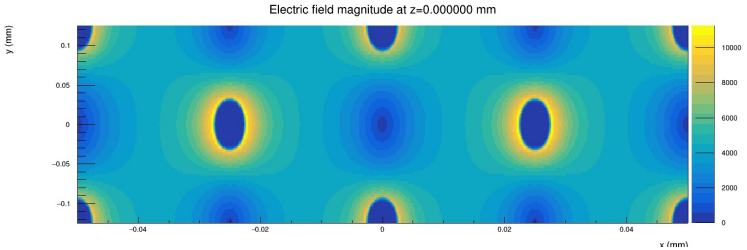


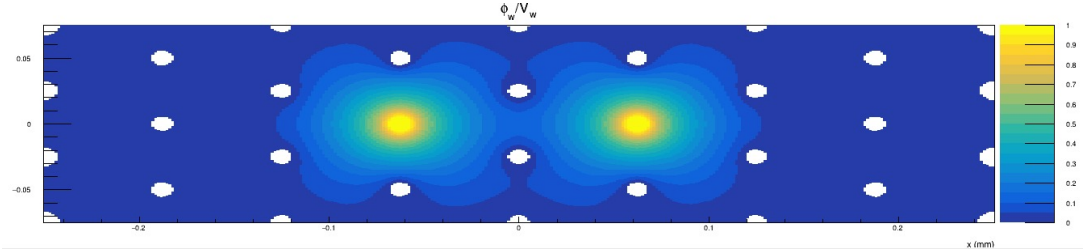


3D sensors in Allpix-Squared

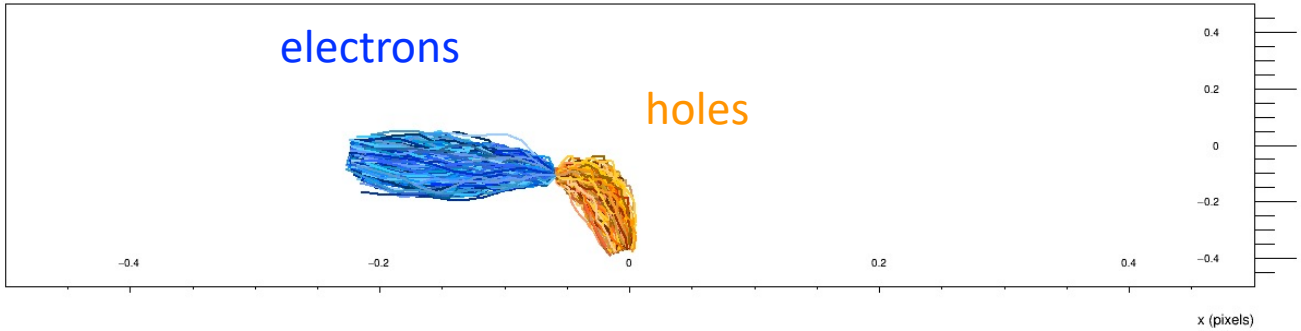
Thanks to Allpix-Squared developers we can simulate 3D sensors too!

Electric field and Ramo potential (thanks to Gilberto Giugliarelli, Uni. Udine)





Carriers drifting



Many thanks to Simon!

Charge trapping in Allpix-Squared

Credits to Jory Sonneveld (Nikhef)

Diode model for 1e15

- Hamamatsu p+-n-n+ silicon sensors
- Pads of 0.25 cm^2 area
- ⟨100⟩float zone silicon
- 200 µm thick
- 90 V bias unirradiated

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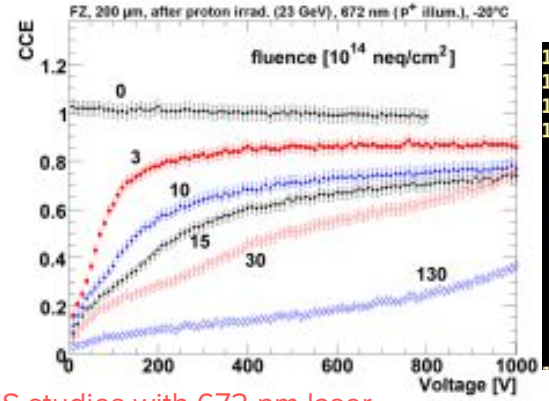
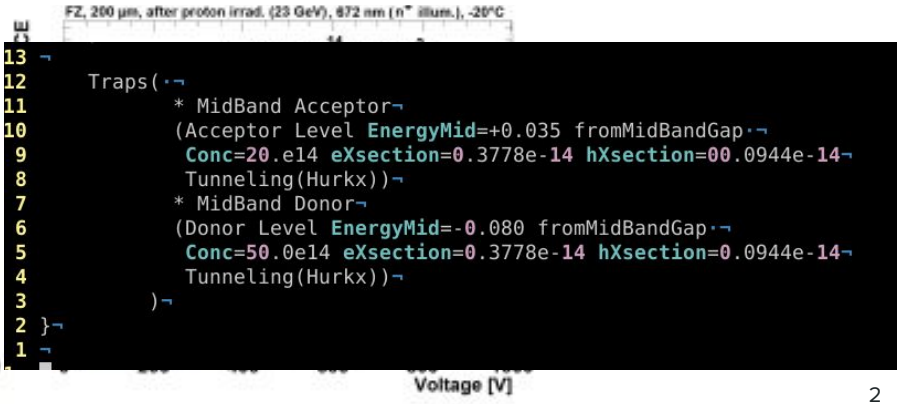
Table 1. The key parameter values used in the Synopsys device simulation. These include: donor and acceptor concentrations, N_D and N_A, and their electron and hole capture cross sections, $\sigma^{e,h}_{D,A}$, for silicon sensors after irradiation with 23 GeV protons (top rows) [11], and for sensors after irradiation with 23 MeV protons (bottom rows) [8].

ϕ_{neq} [10^{14}neq/cm^2]	N_A [10^{14}cm^{-3}]	N_D [10^{14}cm^{-3}]	σ^e_A [10^{-15}cm^2]	σ^e_D [10^{-15}cm^2]	σ^h_A [10^{-15}cm^2]	σ^h_D [10^{-15}cm^2]
2 (23 GeV) [11]	6.8	10	6.6	6.6	1.65	6.6
6 (23 GeV) [11]	16	40	6.6	6.6	1.65	1.65
12 (23 GeV) [11, 18][4]	30	69	3.8	3.8	0.94	0.94
24 (23 GeV) [11, 18][4]	61	138	3.8	3.8	0.94	0.94
3 (23 MeV) [8]	4.2	13	10	10	10	10
10 (23 MeV) [8]	12.5	52	10	10	10	10

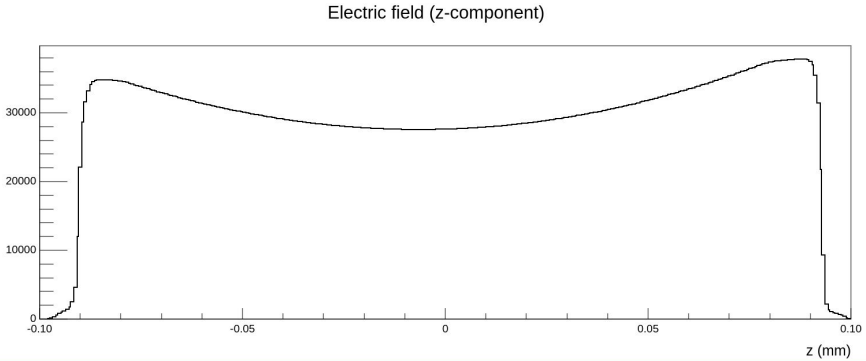





```
Traps(
        * MidBand Acceptor
        (Acceptor Level EnergyMid=+0.035 fromMidBandGap
         Conc=20.e14 eXsection=0.3778e-14 hXsection=00.0944e-14
         Tunneling(Hurkx))
        * MidBand Donor
        (Donor Level EnergyMid=-0.080 fromMidBandGap
         Conc=50.0e14 eXsection=0.3778e-14 hXsection=0.0944e-14
         Tunneling(Hurkx))
      )
}
```

From CMS studies with 672 nm laser

Ingredients



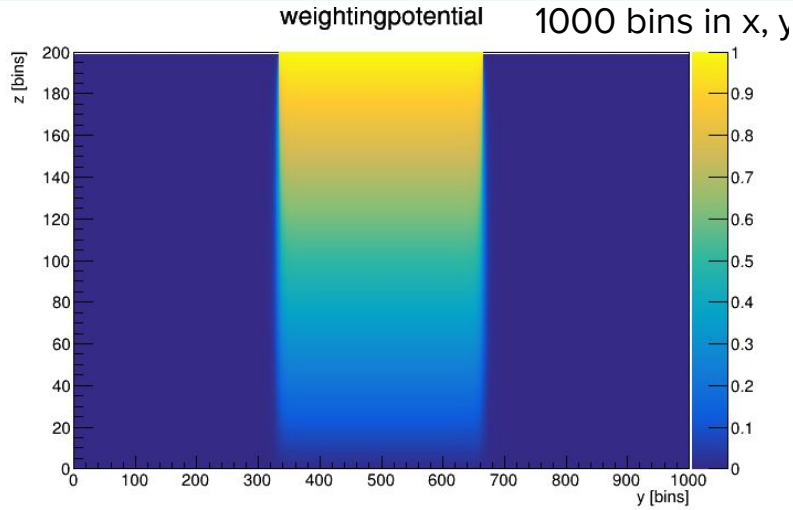
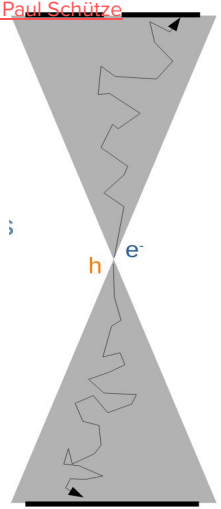
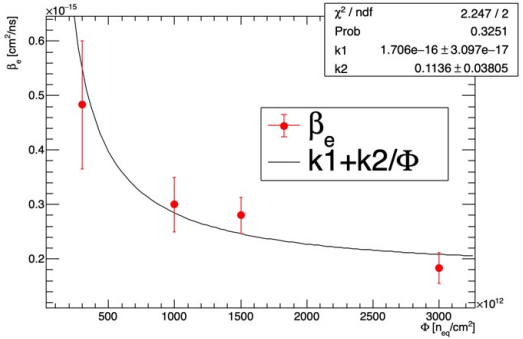
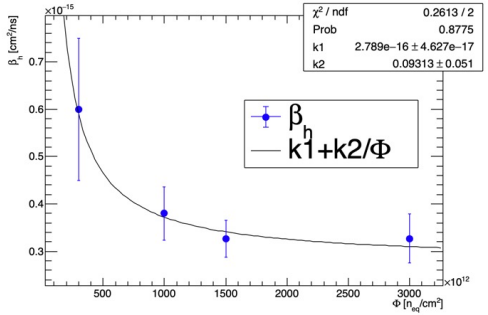


Image from Paul Schütze



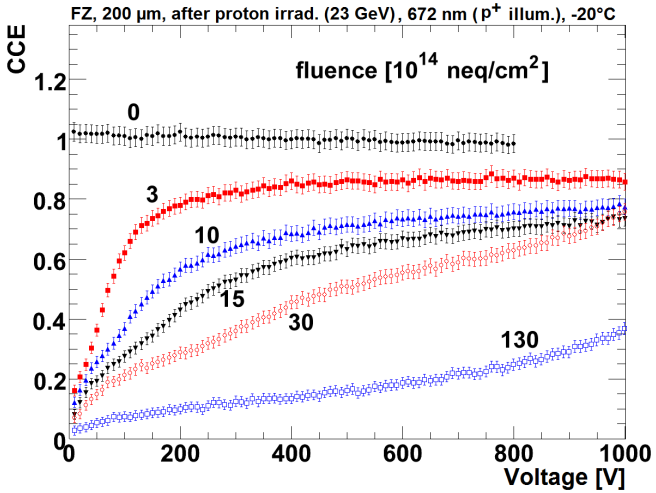
TransientPropagation
Induced charge from **weighting potential** from M neighbors

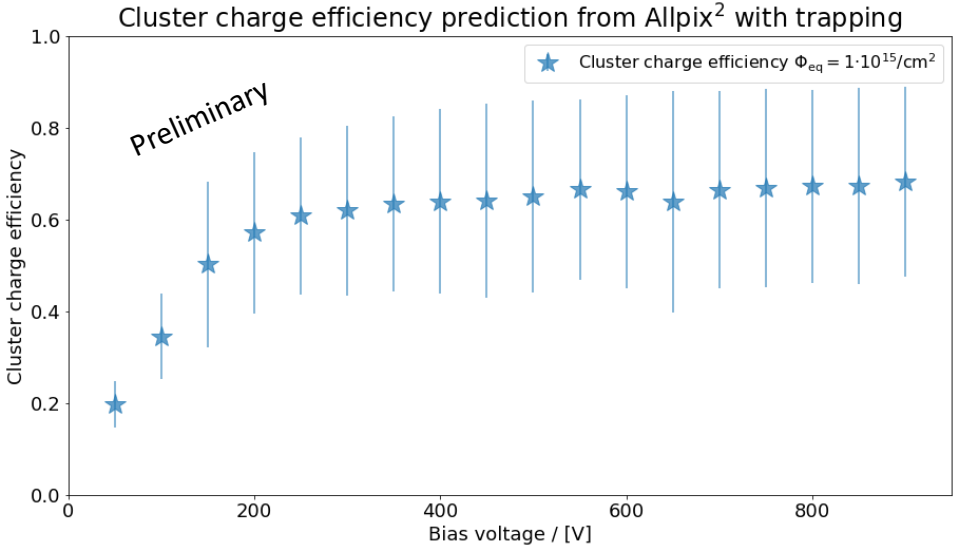




Charge collection efficiency results

Jory Sonneveld (Nikhef)





Getting closer and closer ☺

… and, once more, thanks to Allpix-Squared developers!

Conclusion and outlook

- Silicon detectors at hadronic colliders are exposed to unprecedented levels of radiation damage
- Signal loss is the most important effect for cluster position determination
- Simulation of these effects in ATLAS MC for HL-LHC thanks to pixel reweighting
- Allpix-Squared plus detailed TCAD simulations to make correction to take into account signal reduction and cluster shape changes
- Rapid progress on all aspects thanks to invaluable help from Allpix-Squared developers!
- Next: validate trapping model and run first realistic simulations!

Backup