Simulating sapphire detectors with Geant4+Allpix^2

Tools overview and Allpix^2 validation against DESY-II test-beam

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Introduction

Objective:

build a precise MC template to model the response of the detector to incident radiation (Compton's gamma at LUXE)

MC Tools:

1. Geant4
2. Allpix2

Strategy:

setup an Allpix^2 simulation of the charge generation, transport, collection and digitization *from the incident radiation to the signal waveform.*

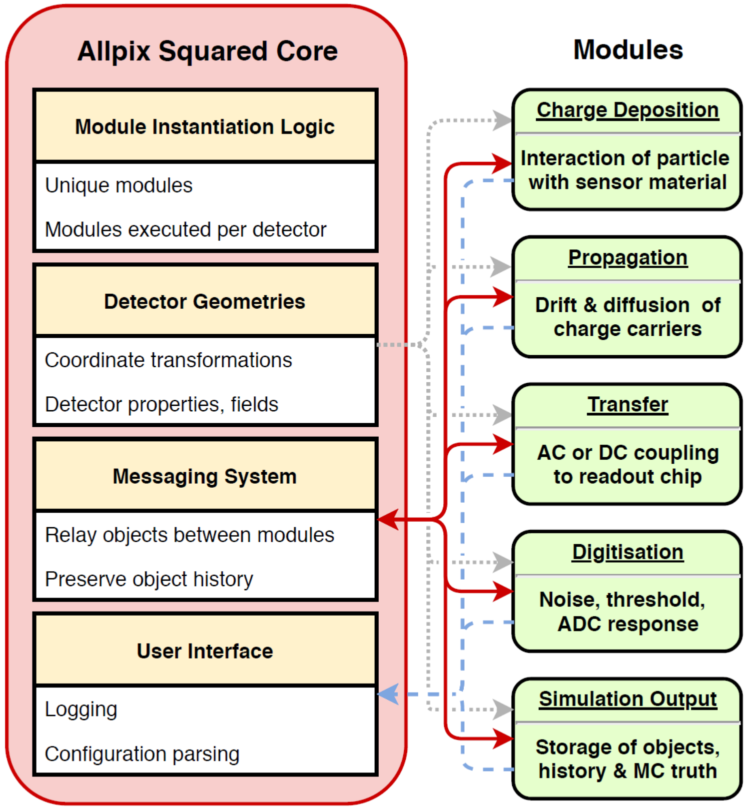
Flowchart:

a) Model transport of charge carriers in sapphire
b) Implementation using Geant4 + Allpix^2
c) Validation of the MC simulator against experimental data (e.g. Desy-2, Padova, Frascati)

Simulation tool: Allpix²

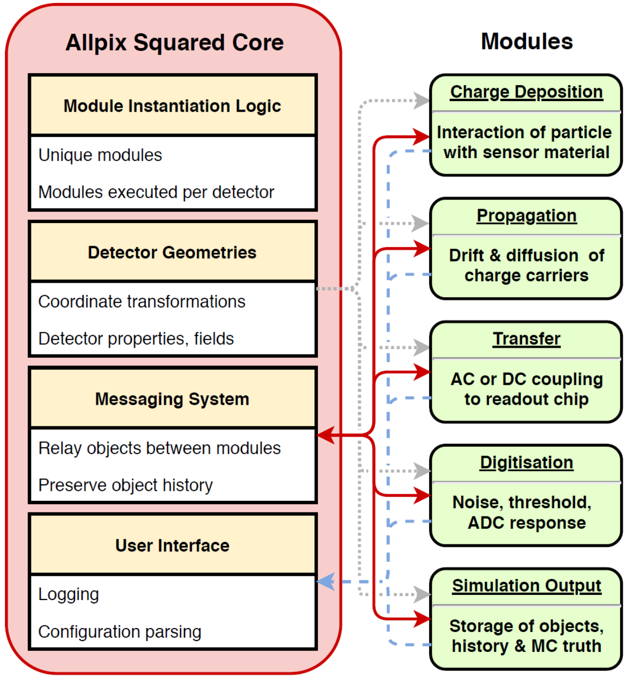
Allpix2 main features

- Charge deposition simulated with Geant4 or external
  - Fano fluctuations
- Propagation
  - Built-in models (Jacoboni-Canali, Hamburg, Masetti, Arora) or custom (carrier mobility **μ** as function of x,E)
  - Drift-diffusion kinetics **σ**
  - Trap-assisted recombination (no de-trapping) **τ**
  - Electric/weighting fields from first principles or externals **E**
  - No self/carrier-carrier interactions
- Transfer
  - Time resolved current pulse at each pixel
  - Capacitive cross-coupling between neighbouring pixels C_{cross}
- Digitization
  - Linear response of a TDC (time-to-digital converter)
  - or QDC (charge-to-digital converter)
  - Electronic RMS noise and threshold



An example: validating Allpix² with literature

Validating Allpix2 with the investigation of a direction sensitive sapphire detector at the 5GeV electron beam at DESY-II



Flowchart:

a. **Get transport model** *from DESY-II* (Hecht eq. in parabolic E-field)
    a. \mu\tau product assigned
    b. Electric field shape assigned
b. **Implementation** in Allpix2
c. **Comparison** with datapoints

Simulation pipeline with DESY-II example:

GeometryBuilderGeant4 + DepositionGeant4 → ElectricFieldReader **(electric field)** → DopingConcentrationReader **(chg. Carriers lifetime)** → WeightingPotentialReader **(weighting field for the Shockley-Ramo th.)** → TransientPropagation **(carriers propagation with custom model)** → Output

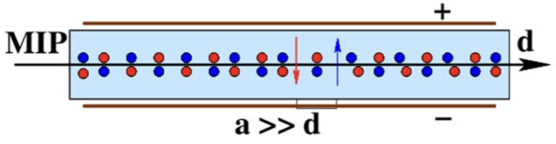
Validating the MC template against Desy-II investigation [1]

[1] **Investigation of a direction sensitive sapphire detector stack at the $5\ GeV$ electron beam at DESY-II**

O. Karacheban[ab], K. Afanaciev[c], M. Hempel[ab], H. Henschel[a], W. Lange[a], J.L. Leonard[a], I. Levy[e], W. Lohmann[bf] and S. Schuwalow[d]

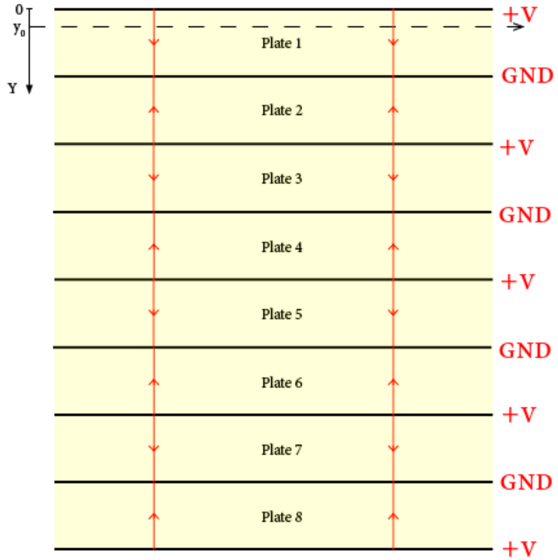
Overview of the experiment

- Device under test (DUT) is a stack of 8 sapphire plates of dimensions 10mm x 10mm x 525um each.



Experimental details

A 5GeV electron beam enters the DUT parallel to the metallization.
Incoming/outcoming particle tracks are reconstructed using a telescope array.
There are 4 readout channels attached to the plates.
Charge collection efficiency (CCE) is measured as a function of the bias voltage and of the carrier generation position y_0 (see drawing)



Deposited charges

Average $\#_{e/h}$ = 22 um^{-1}, therefore 220k pairs are deposited over the 10mm travelled by a 5GeV MIP electron.

Theoretical model for CCE(y_0)

Model characteristics

1. Fraction f_d of carriers recombine immediately.
2. Drifting charge can be trapped, be τ_e and τ_h carriers lifetime (assumed constant).
3. Space charge density (assumed linear) of trapped charges generate an internal polarization field, with the direction opposite to the external one.
4. The integral of the electric field over full thickness is the bias voltage.

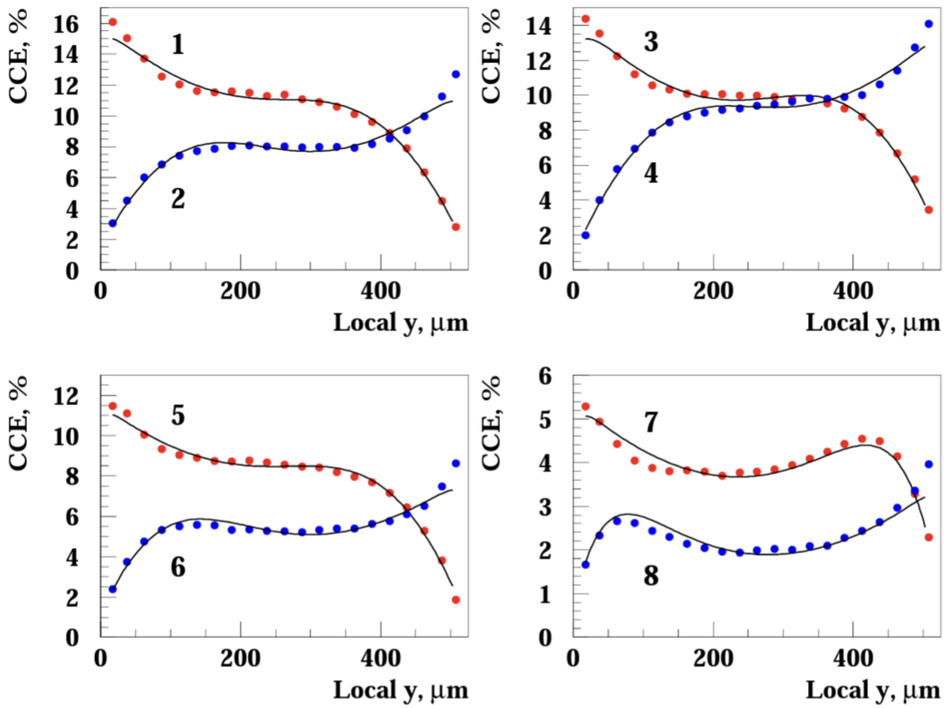


Figure 7: The CCE measured as a function of the local y coordinate inside a plate in slices of 25 μm for all plates of the sapphire stack. Blue dots are for the electric field in the direction of y and red dots for the opposite field direction. The lines are the result of a fit including both electron and hole drift. The fit parameters are given in Table 3.

Validating allpix2

Objective

Reproduce the theoretical model using the MC.

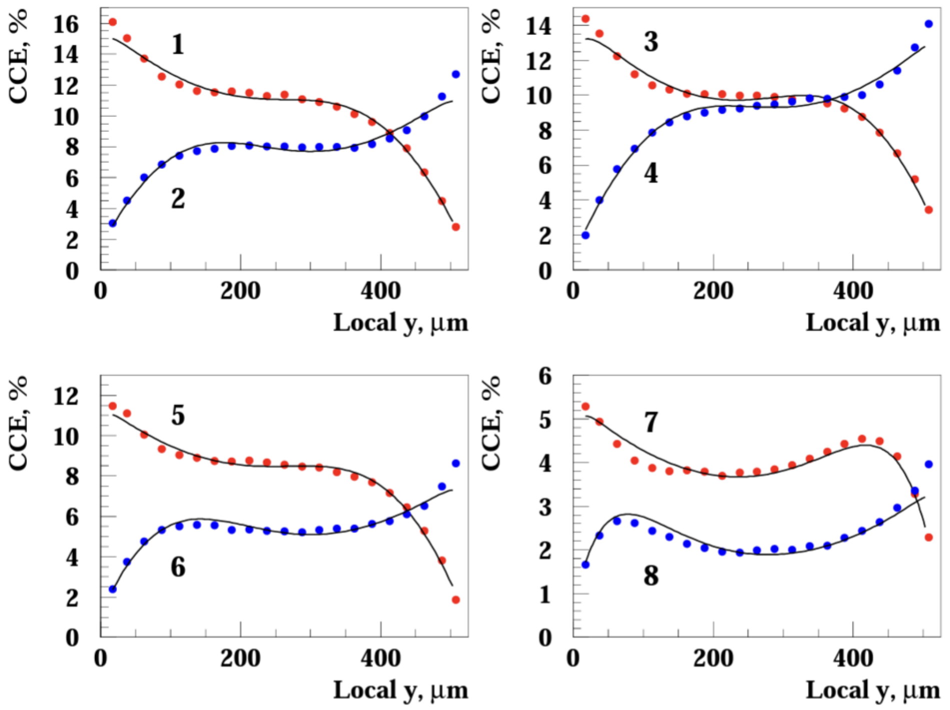
Strategy

Setup a set of simulations with

1. Ad-hoc charge transport model where charge carriers have constant uniform mobilities;
2. Electric field with the par. y-dependence
3. (Mobility x lifetime) fixed

Implementation

A Python script is used to generate configuration macros for Allpix, running standalone simulations where localized charge is spawn at y_0



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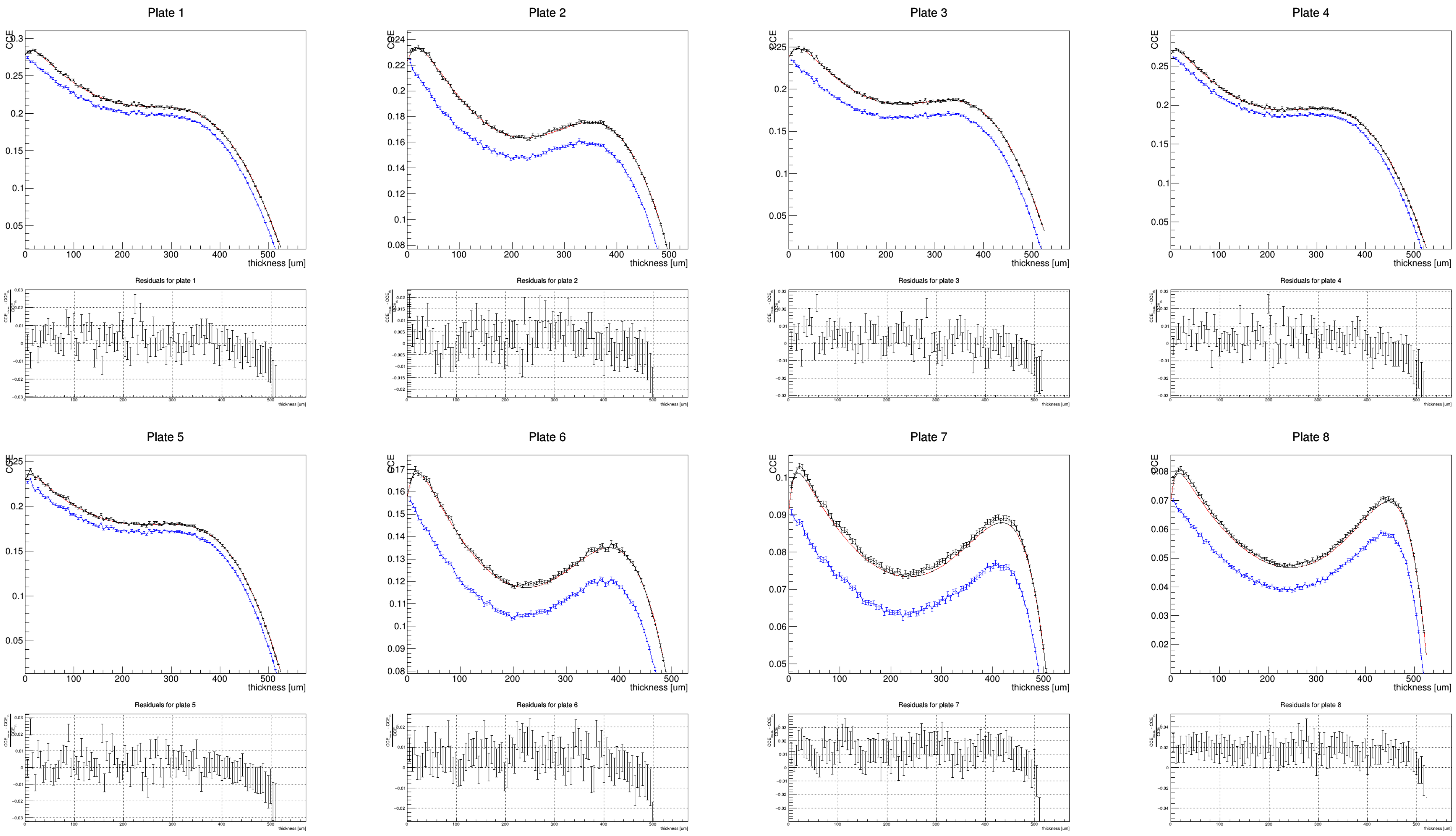
Results. Comparison 1/2



Theory

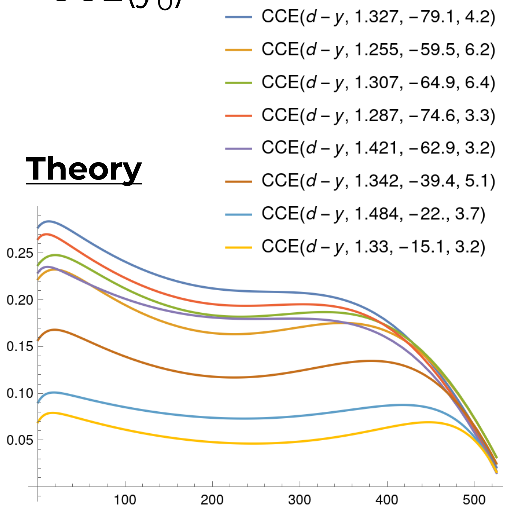
Red solid line:
theoretical prediction for CCE(y_0)

Simulation

Black points:
simulated CCE(y_0)

Blue points:
contribution from e^- only to the simulated CCE(y_0)

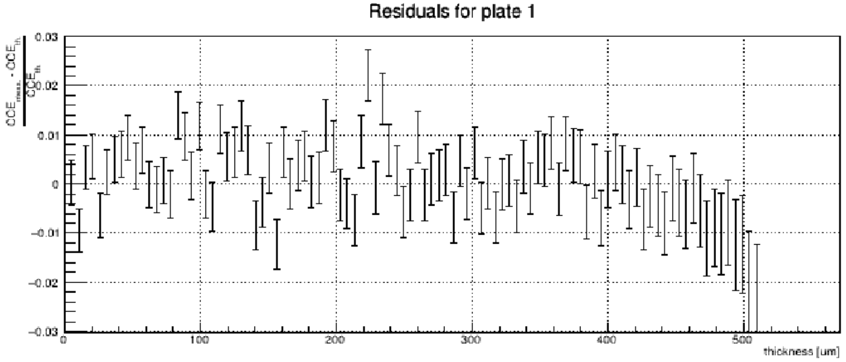
Theory



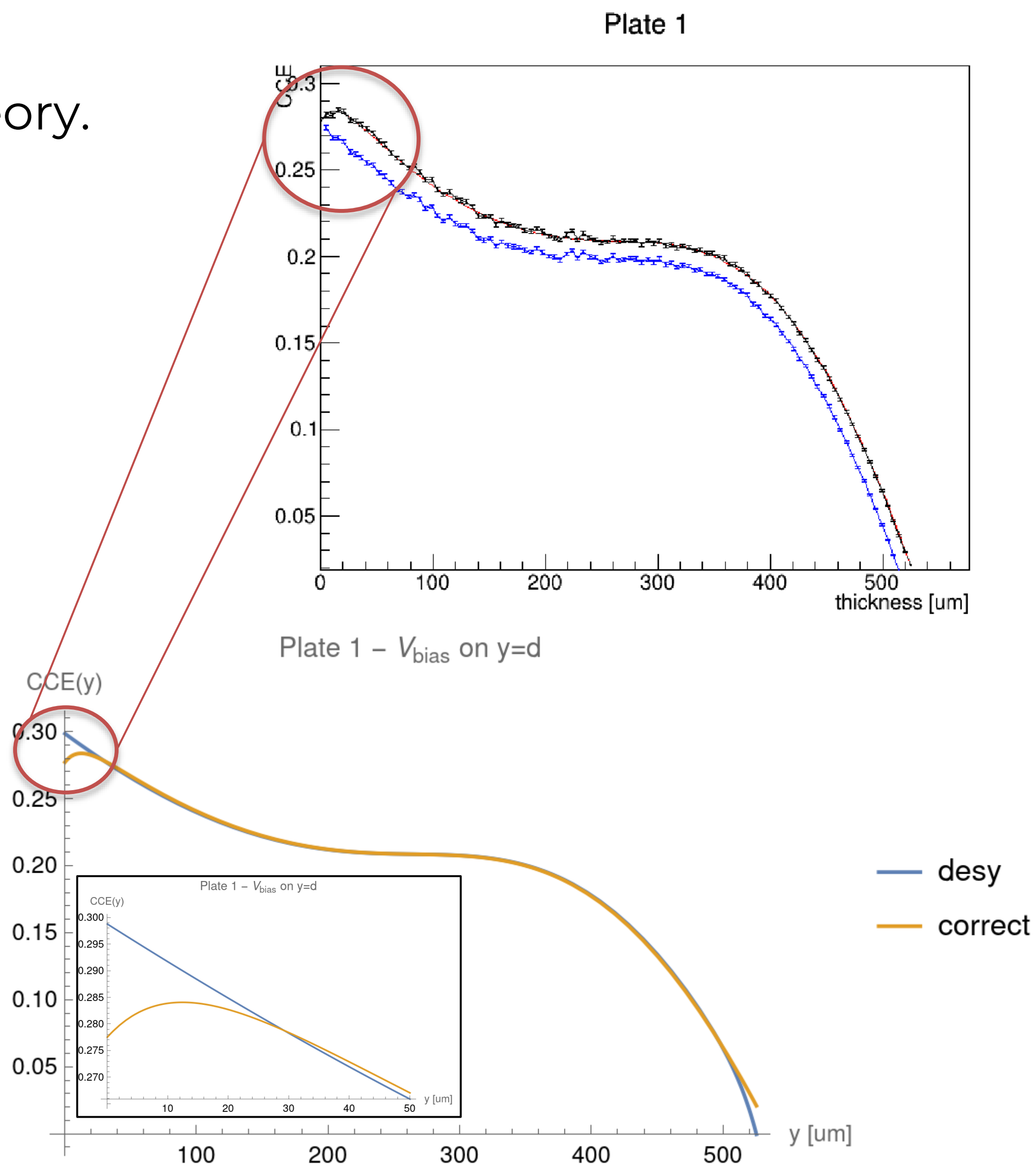
Comparison

- Good agreement (<4%) between simulation and theory.

e.g. plate1



- Simulated the hole-induced behaviour near y=0



Comments

Simulation deviations form theory can be found in

a. finite integration cut-off
b. time integration step
c. electric/weighting-field approximation
d. limited sim. statistics
e. charge-clustering

Bibliography

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