TCAD+APSQ SIMULATIONS FOR CLICTD

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Vertex and Tracker Meeting

18/01/2021

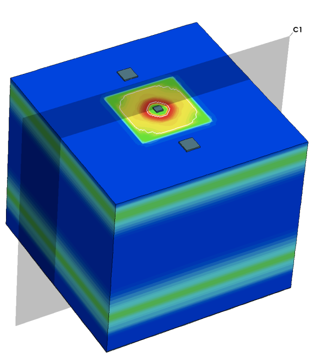
MONTE CARLO + TCAD SIMULATIONS

- Simulation studies for monolithic CMOS sensors are crucial to optimise sensor design in view of e.g.:
  - Small capacitance
  - Fast charge collection

See previous talk by Magdalena

- Optimised sensors can be evaluated by combining electrostatic TCAD and transient Monte Carlo simulations
  - Less computing intensive than transient TCAD
  - Can save time/costs compared to fabricating prototypes and evaluating them in beam tests

➡ Complementary approaches that can give a full picture of a sensor when combined



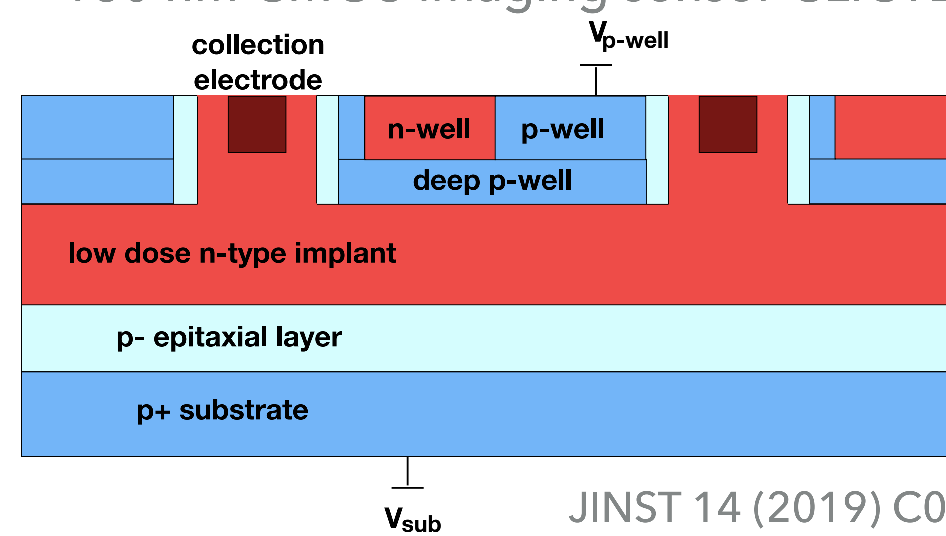
+

ap² allpix squared

Simulating monolithic CMOS sensors with small collection diode

- Complex non-uniform electric field in the small collection diode design
- Knowledge from standard planar sensors does not necessarily hold -> simulations needed to design and evaluate new sensor concepts
- In this talk:

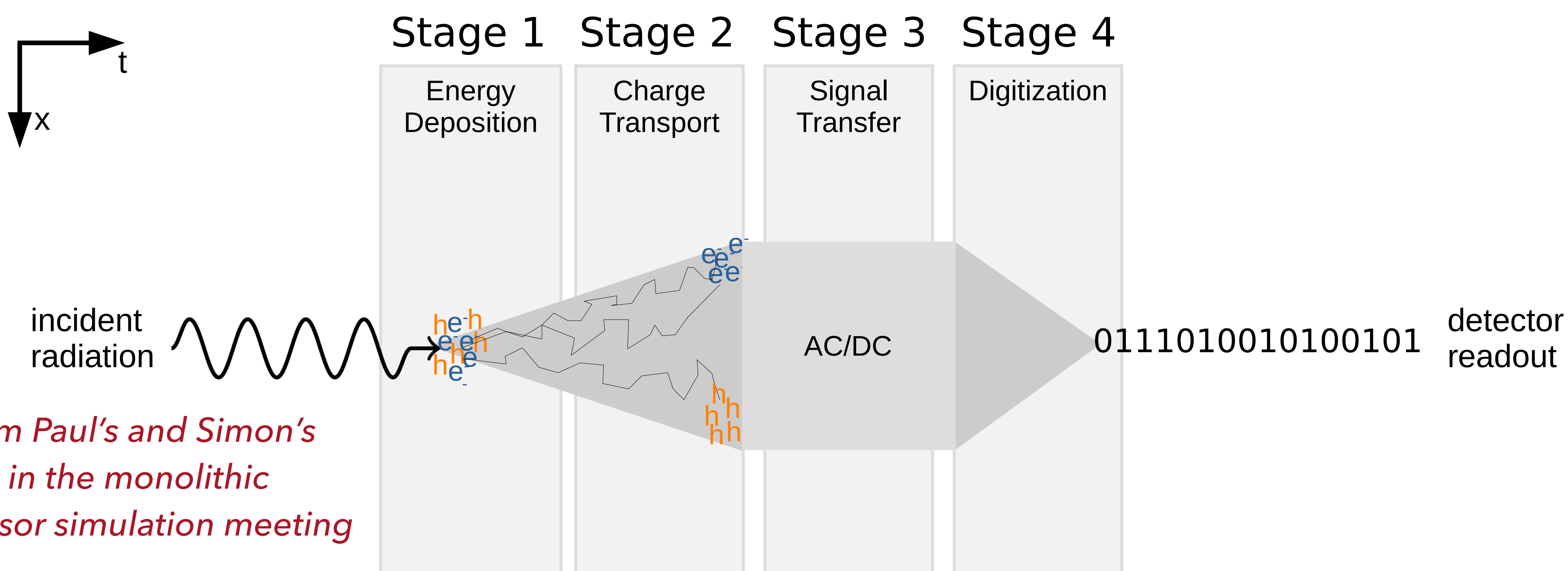
  180 nm CMOS imaging sensor CLICTD



JINST 14 (2019) C05013

ALLPIX SQUARED + TCAD SIMULATIONS

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN



From Paul's and Simon's talk in the monolithic sensor simulation meeting

https://cern.ch/allpix-squared/

NIM A 901 (2018) 164-172

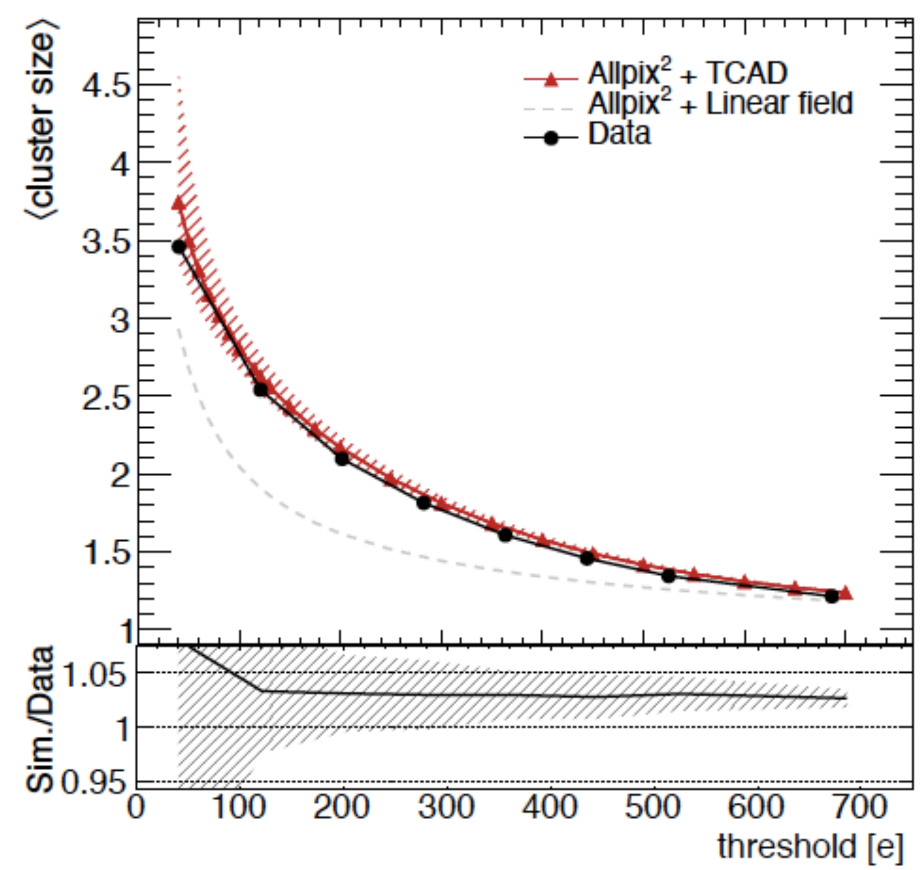
Please see e.g. https://indico.cern.ch/event/984049/

- Allpix Squared handles all simulation steps from charge deposition in sensor to digitisation of signal
- Static fields are imported from 3D TCAD simulations to ensure precise field modelling

  All 3D TCAD simulations in this talk were performed by M. Munker

- Validation of simulation with Investigator test-chip (developed within ALICE ITS upgrade)

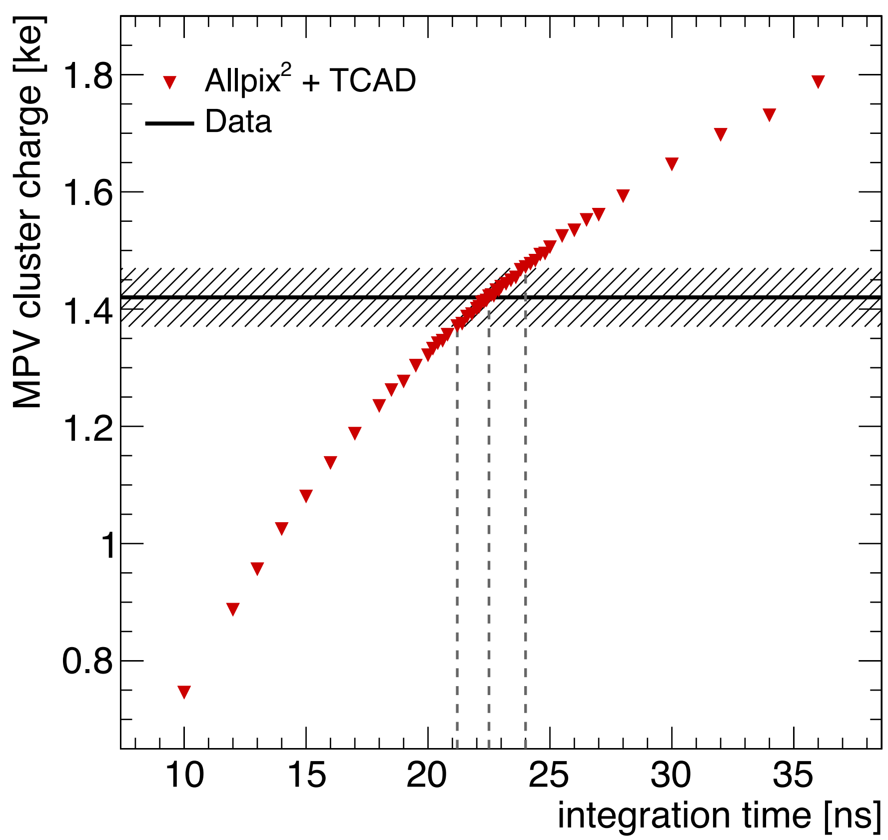
NIM A 964 (2020) 163784

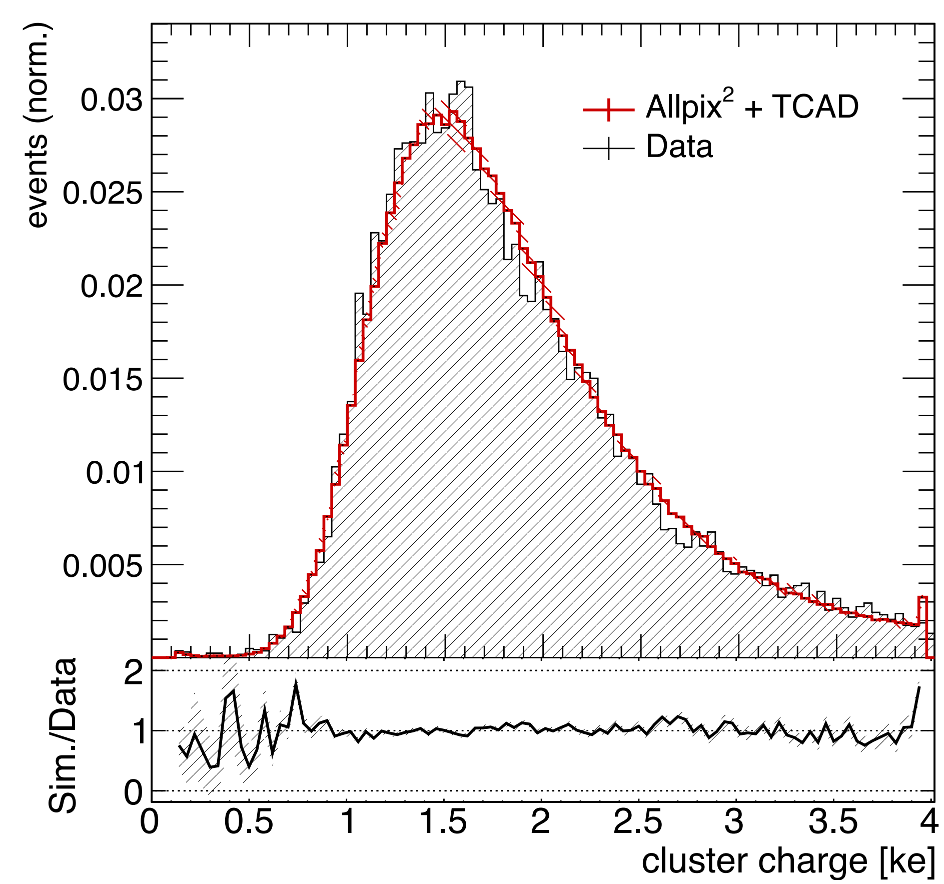


ALLPIX SQUARED + TCAD SIMULATIONS

Simulation of Investigator test-chip

- Integration time = time within which charge carriers are propagated in the sensor
- Integration time is linked to sensor design -> emulates effective recombination time of charge carriers
- Chosen such that most probable cluster charge value matches with data
- Implementation of charge carrier lifetime model would avoid the tuning procedure for the integration time parameter





CHARGE CARRIER RECOMBINATION

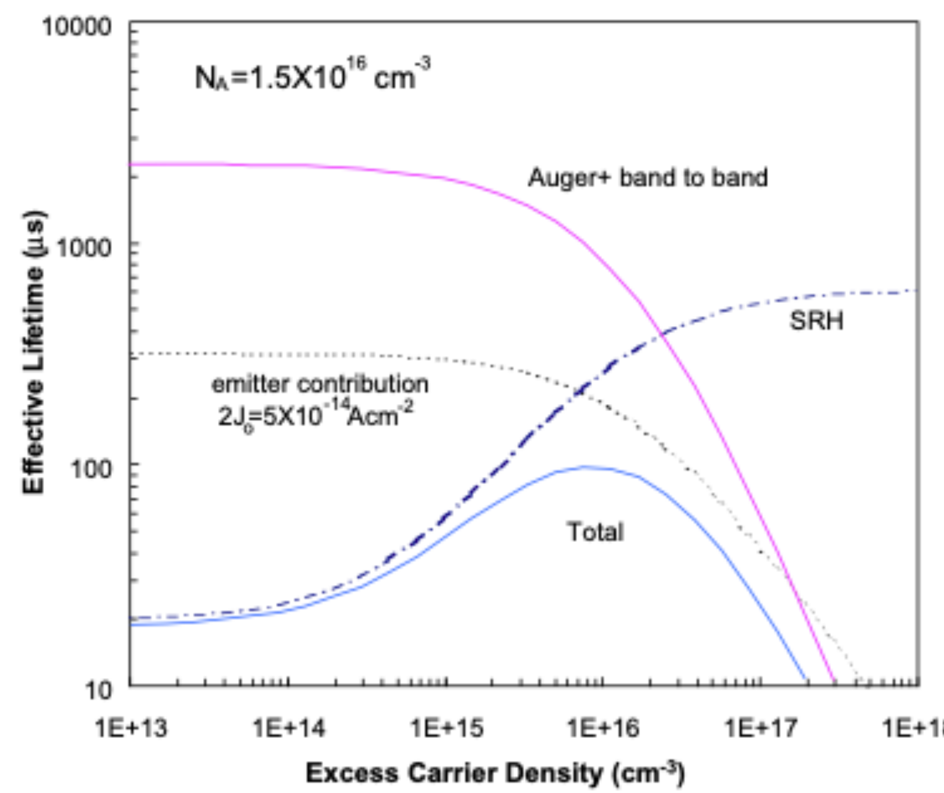
- Charge carrier recombination was implemented based on the following models:
  - Shockley-Read-Hall (SRH) recombination (doping-dependent)
  - Auger recombination (doping-dependent)

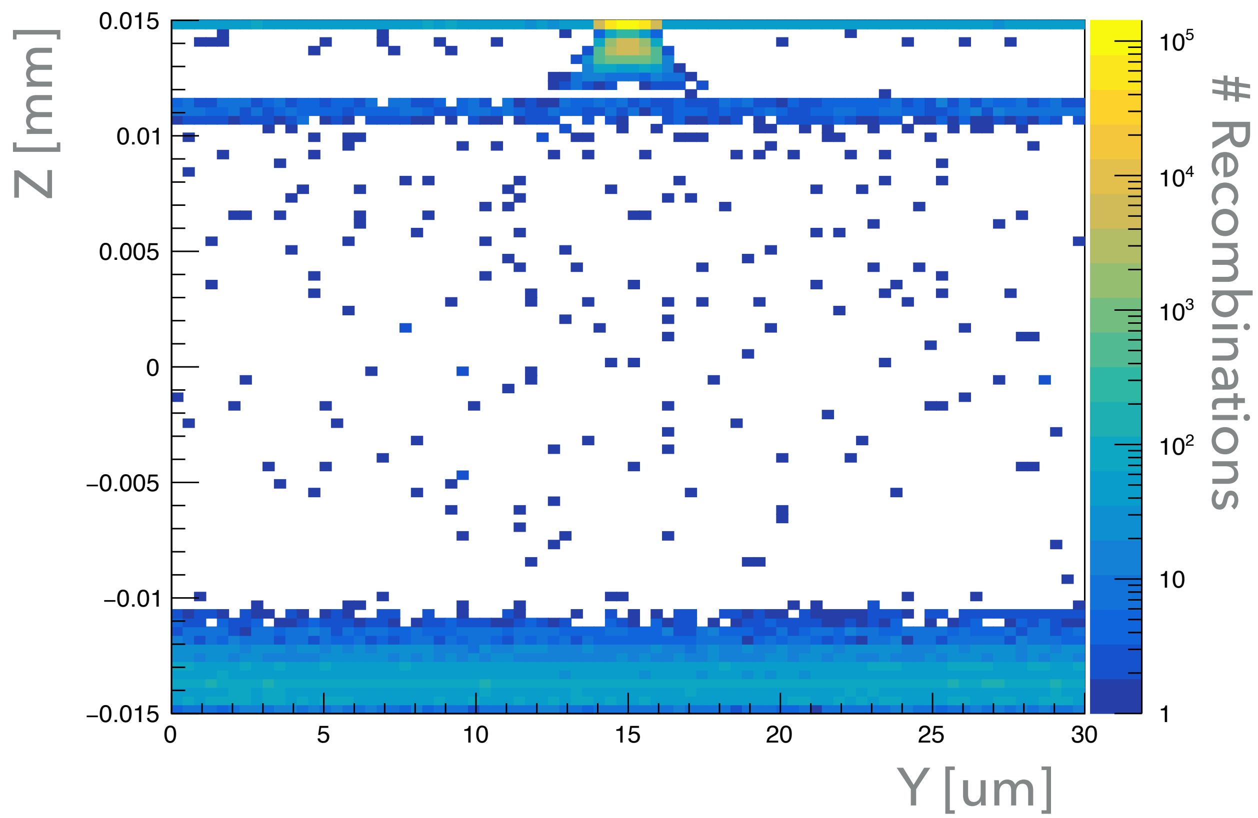
- Effective charge carrier lifetime:

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_{SRH}} + \frac{1}{\tau_{Auger}}$$

- Effective lifetime in highly doped bulk : a few nanoseconds

Solar Energy 76 (2004) 255–262





INTEGRATION TIME

CLICTD simulations

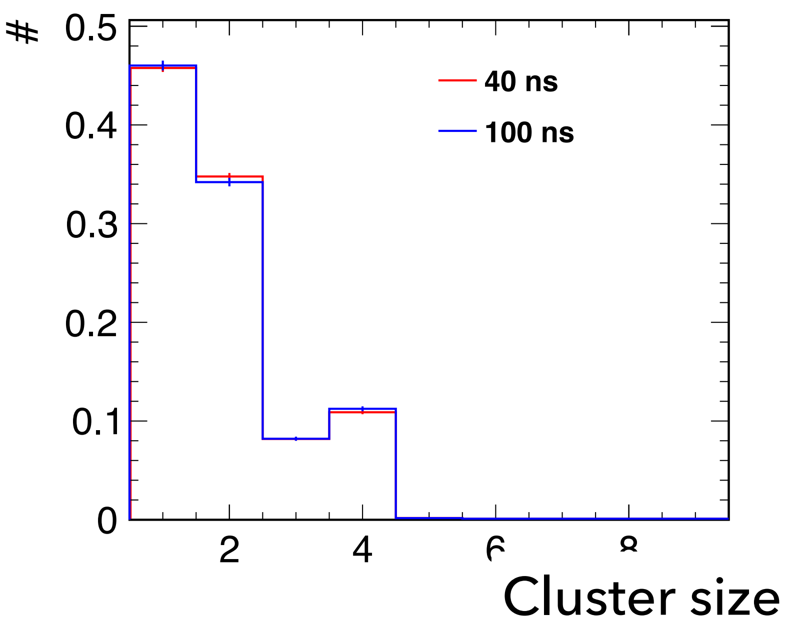
Simulation set-up

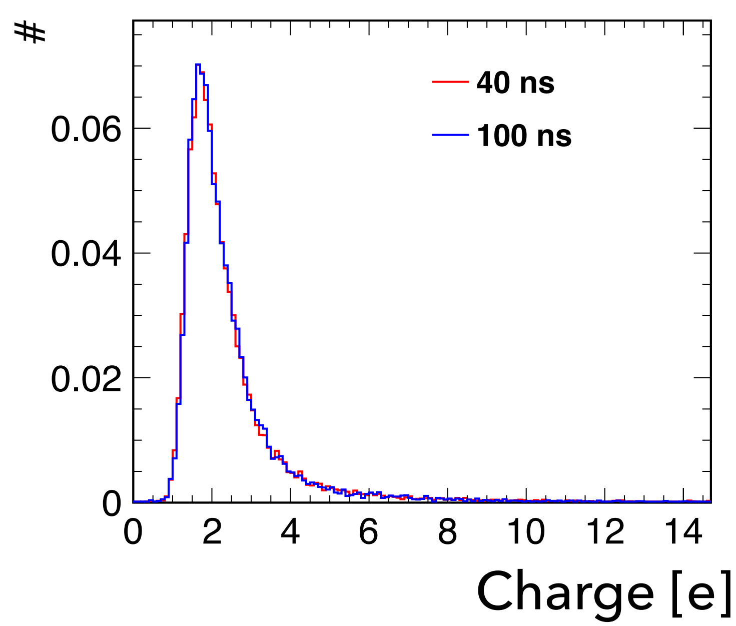
- 5.4 GeV electron beam incident on simulated CLICTD sensor (30 um epitaxial layer + 20 um substrate)
- No simulation of full telescope set-up
- Doping profile, weighting potential and electrostatic field maps are imported from 3D TCAD simulation
- Simulations only for -6V/-6V bias voltage at p-wells/substrate
- Simulations only for pixel flavour with continuous n-implant

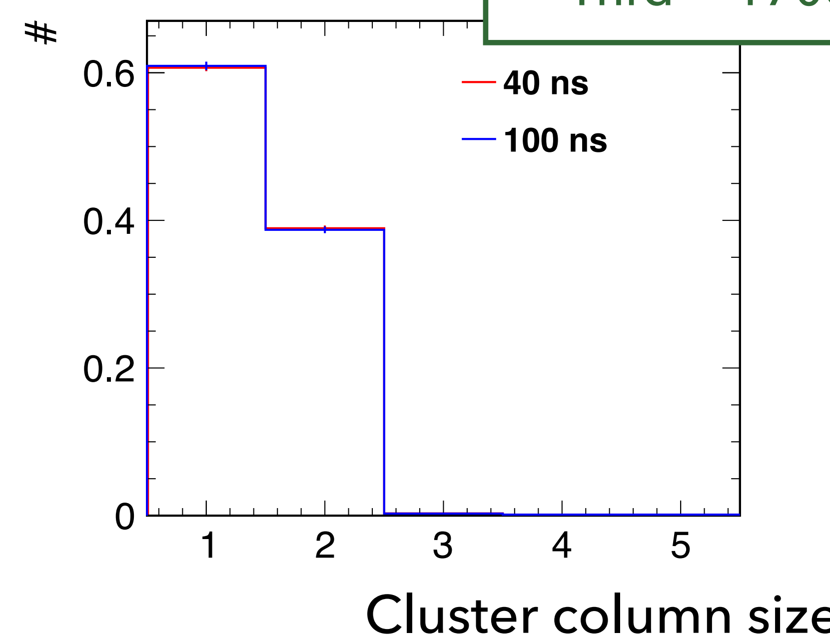
- Cluster observables not sensitive to changes of integration time within reasonable range

$C_a = 2 \times 10^{-30} \text{cm}^6/\text{s}$

Thrd = 170e







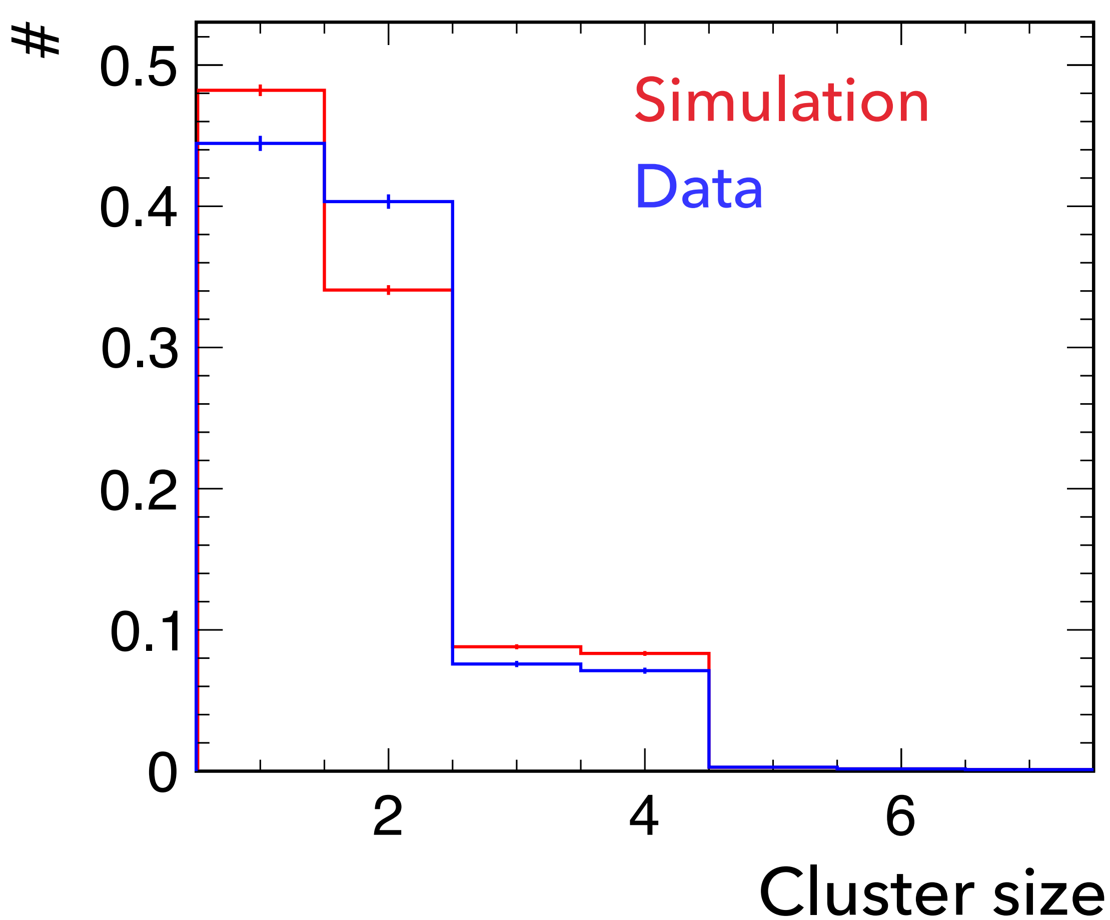
AUGER RECOMBINATION MODEL

How sensitive are cluster observables to variations of the parameters in the lifetime models?

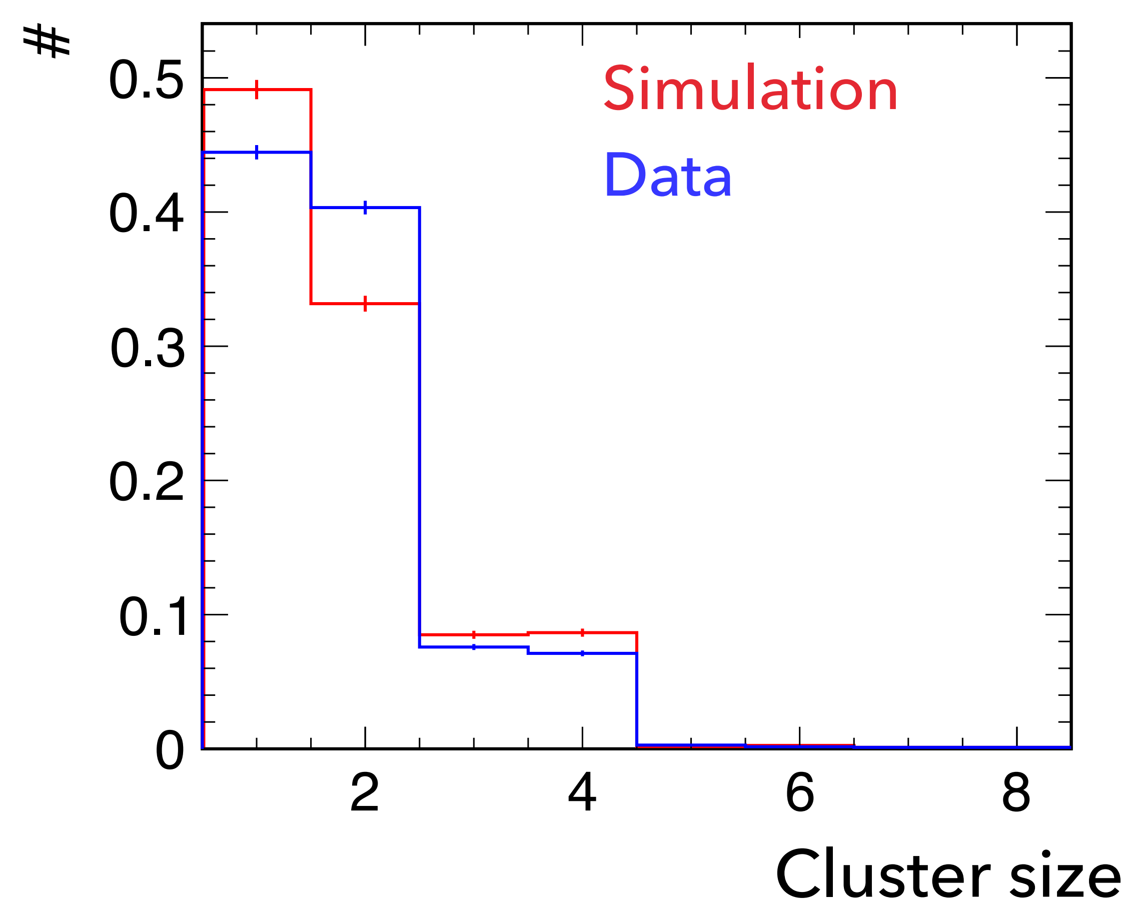
Thrd = 170e

- Lifetime for Auger recombination: $\tau_{Auger} = \frac{1}{C_a \cdot n^2}$
- Increasing Auger coefficient is expected to lead to a lower effective lifetime and therefore a decrease in cluster size
- Minor impact on cluster size at a threshold of 170e

$C_a = 2 \times 10^{-30} \mathrm{cm}^6/\mathrm{s}$



$C_a = 4 \times 10^{-30} \mathrm{cm}^6/\mathrm{s}$



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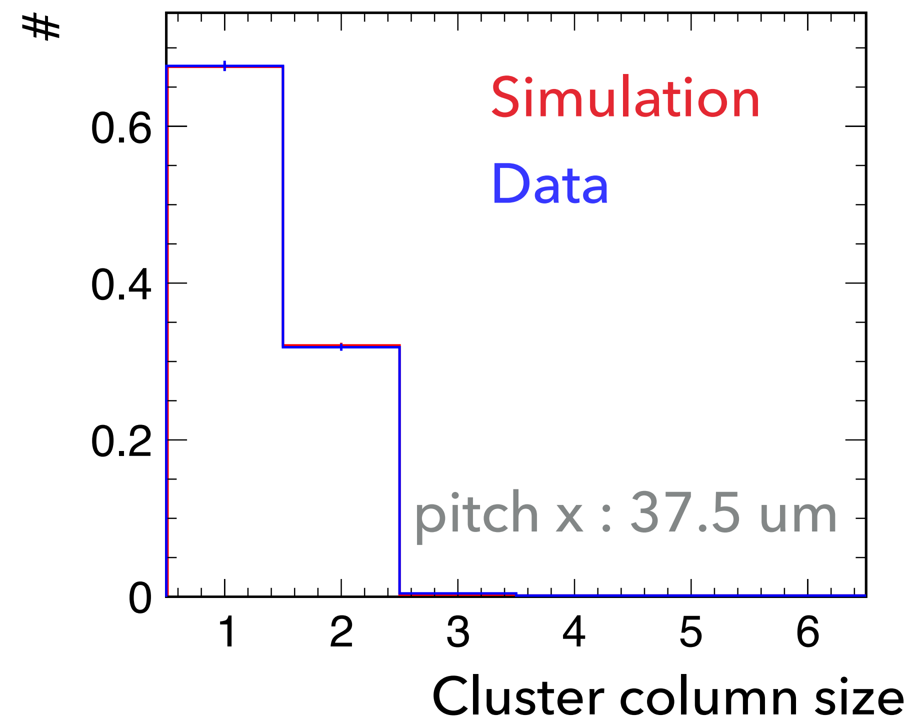
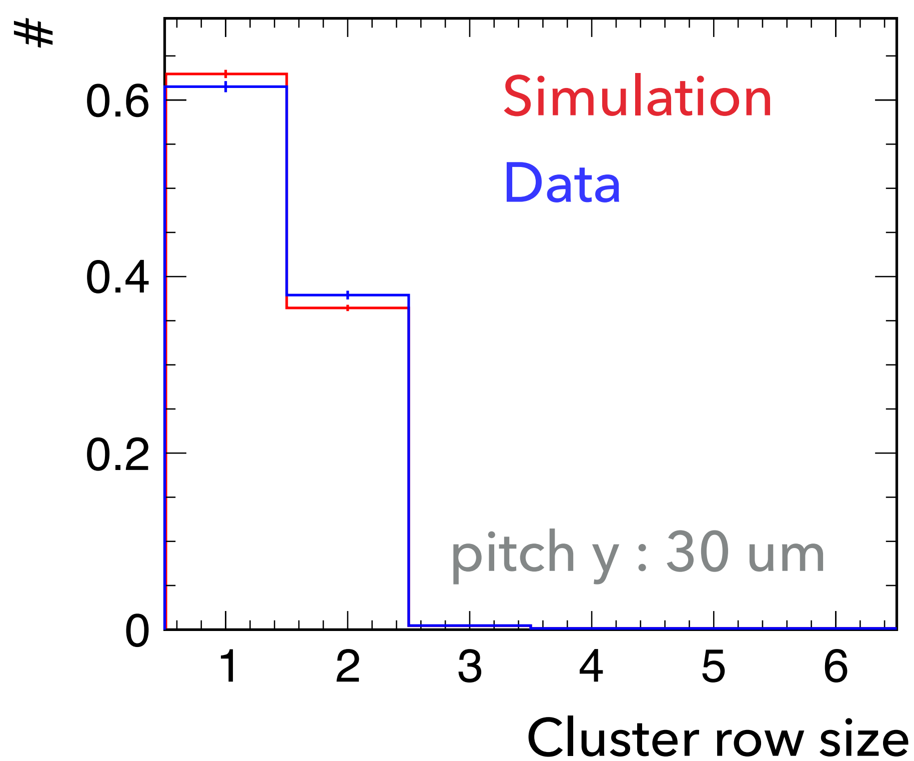
AUGER RECOMBINATION MODEL

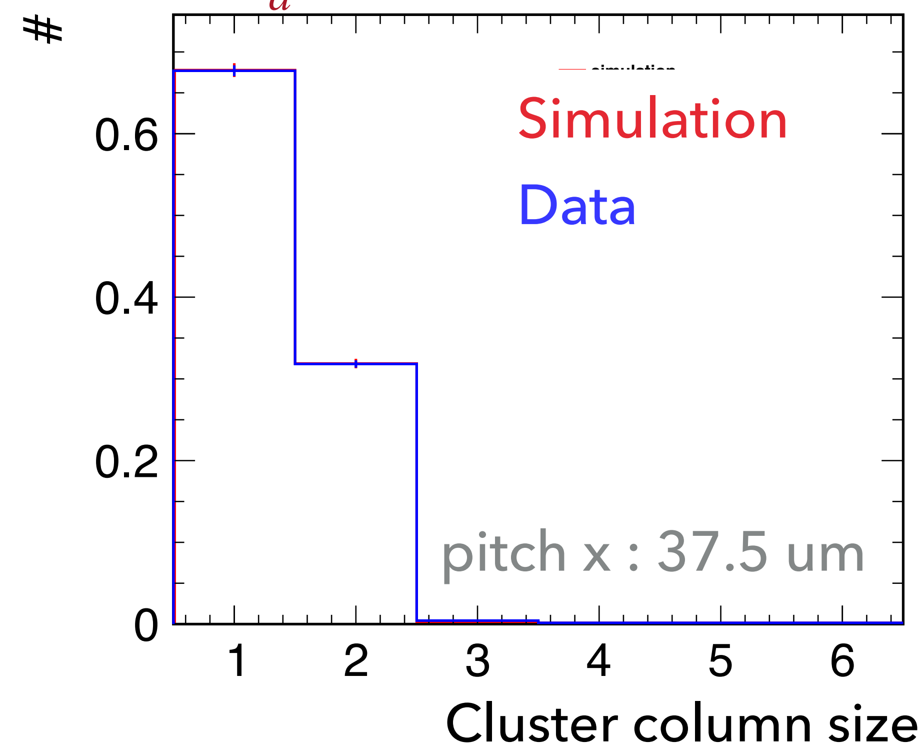
CERN EP R&D

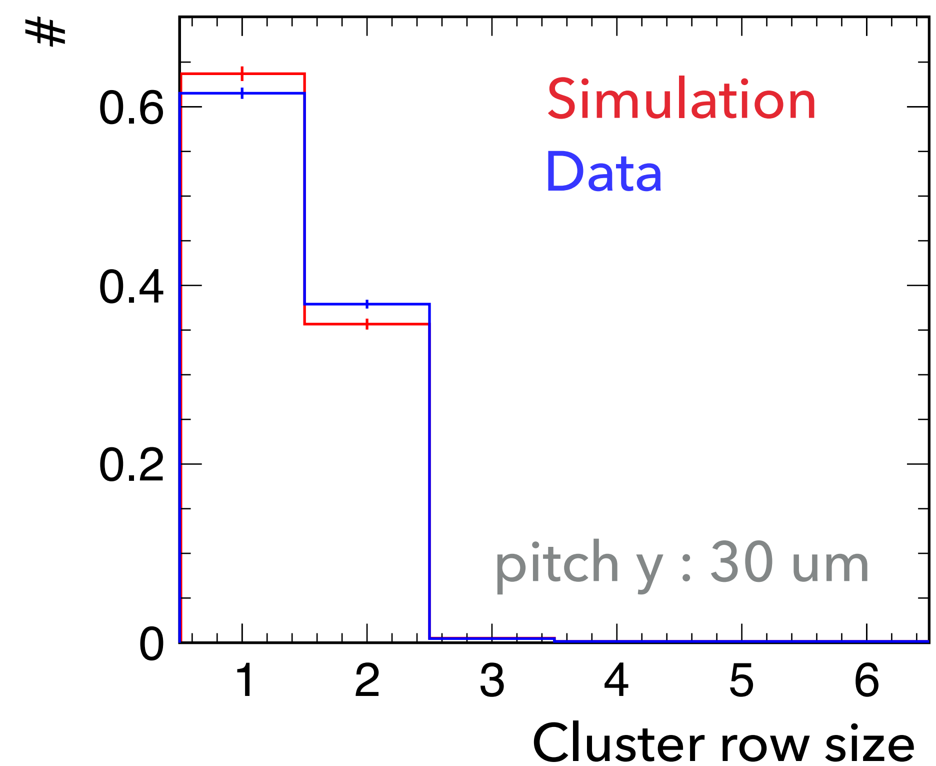
$C_a = 2 \times 10^{-30} \mathrm{cm}^6/\mathrm{s}$





$C_a = 4 \times 10^{-30} \mathrm{cm}^6/\mathrm{s}$





- Cluster size in row direction more sensitive to variations in Auger coefficient due to smaller pixel pitch

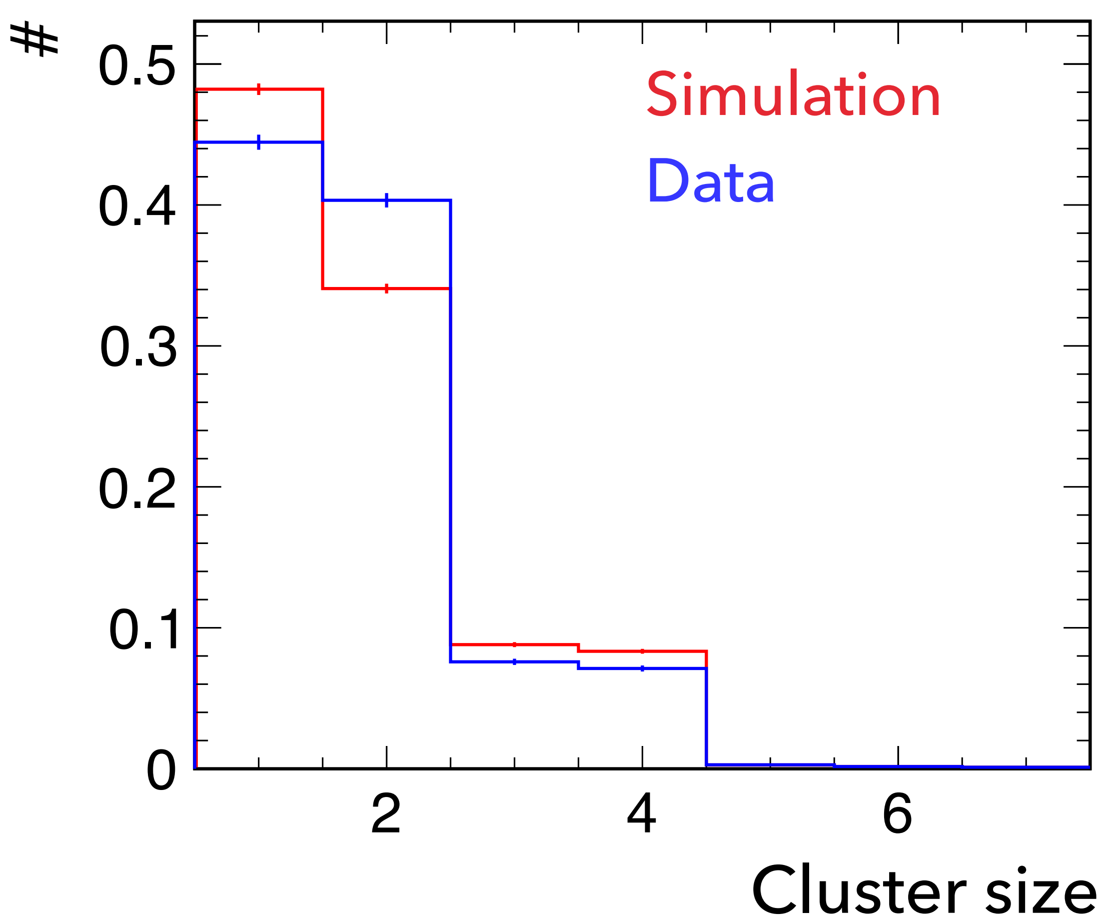
DETECTION THRESHOLD

$C_a = 2 \times 10^{-30} \mathrm{cm}^6/\mathrm{s}$

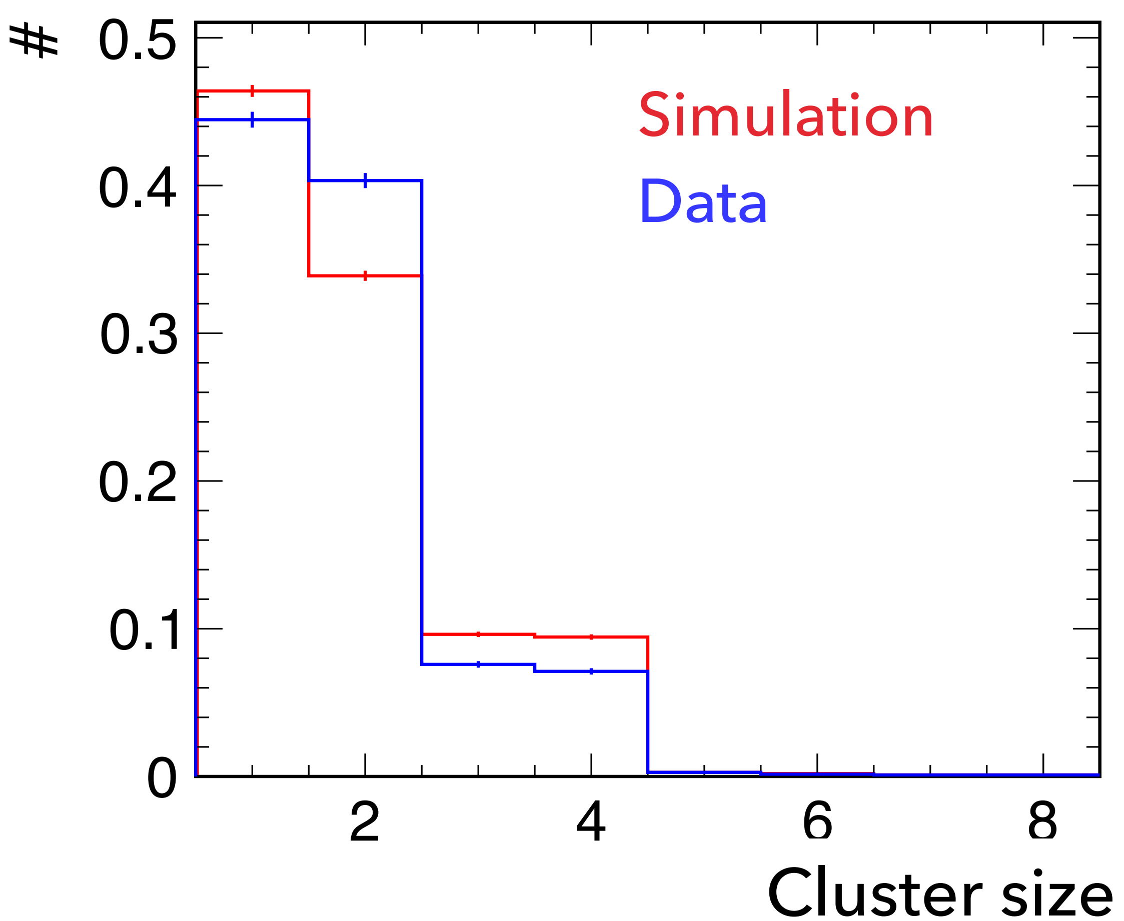
Could uncertainty in threshold calibration account for differences between data and simulation?

- Threshold is varied by 20 e which is significantly higher than the threshold uncertainty in data (< 10 e)

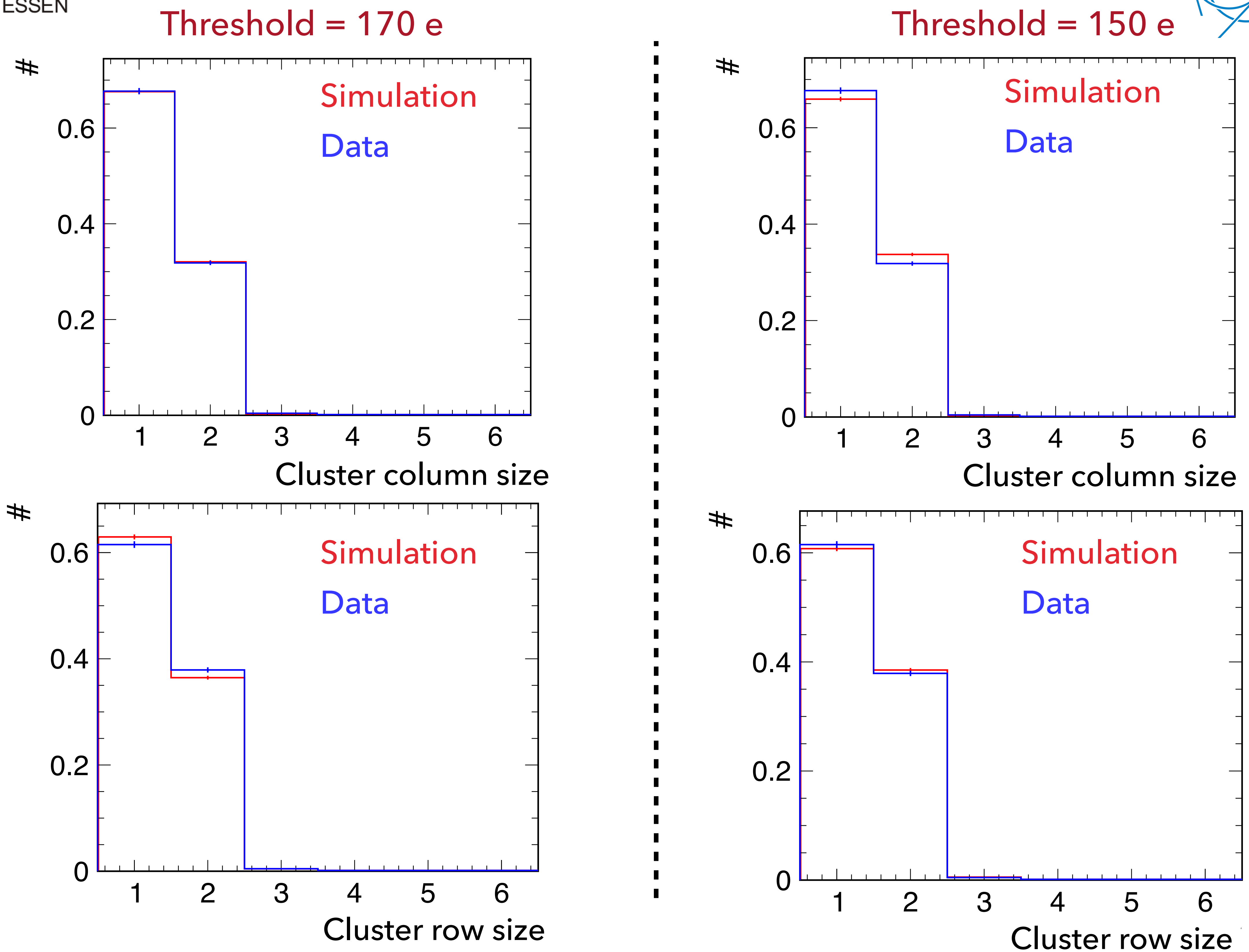
Threshold = 170 e



Threshold = 150 e



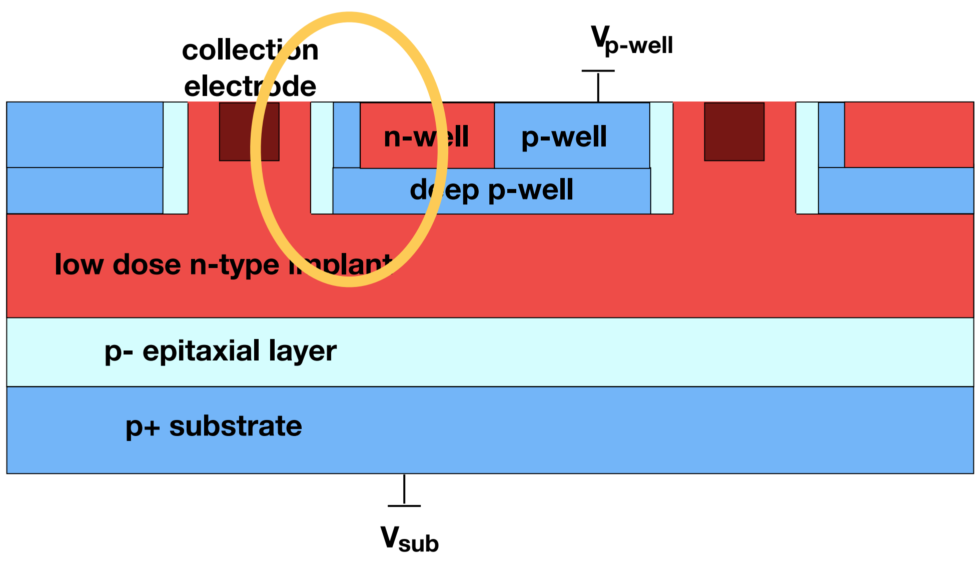
DETECTION THRESHOLD



LATERAL PROFILE SPREAD OF P-WELL IMPLANT

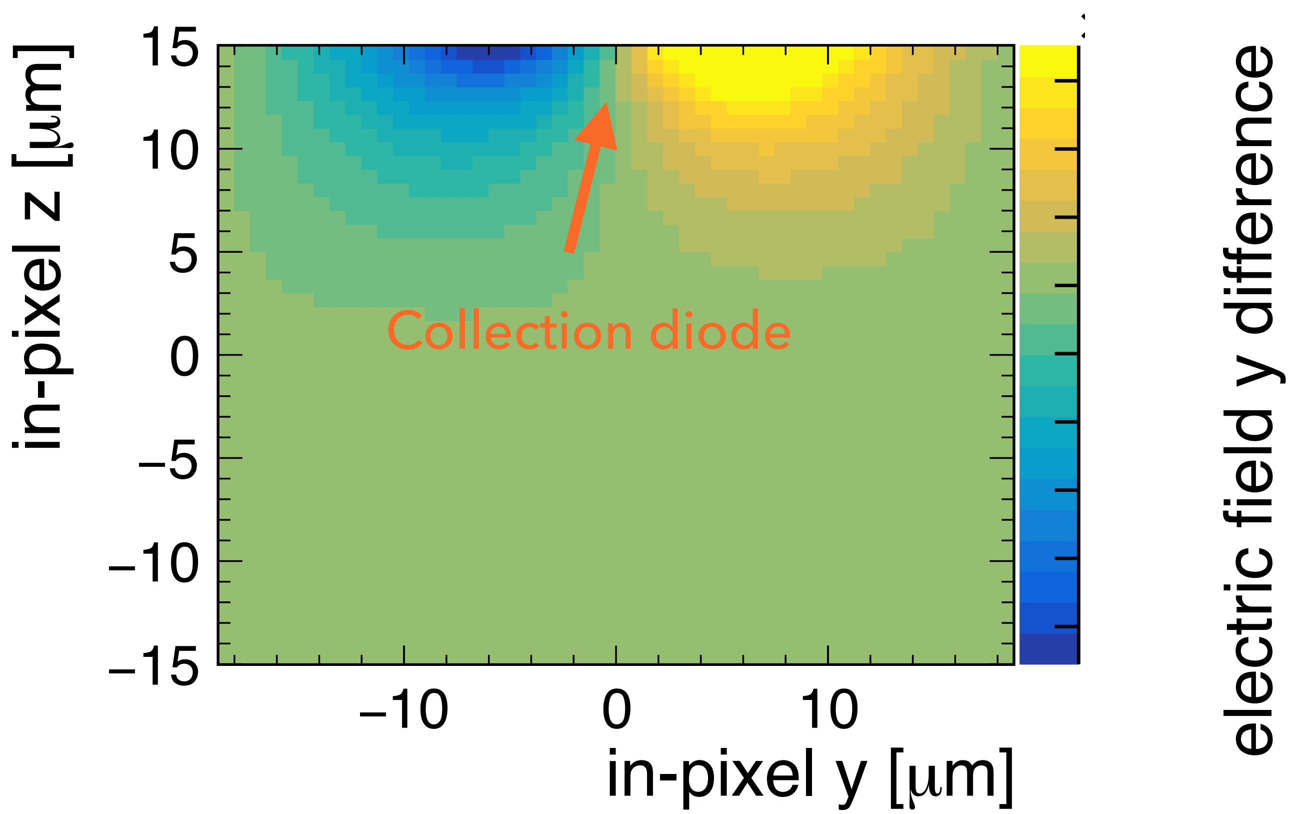
What is the impact of uncertainties in the doping profiles on the charge sharing ?

- Lateral spread of the profile at the edge of the p-well implant (*p-well smearing*) was varied
- Low smearing leads to a stronger lateral electric field



Differences in electric field in y

Low p-well smearing - high p-well smearing



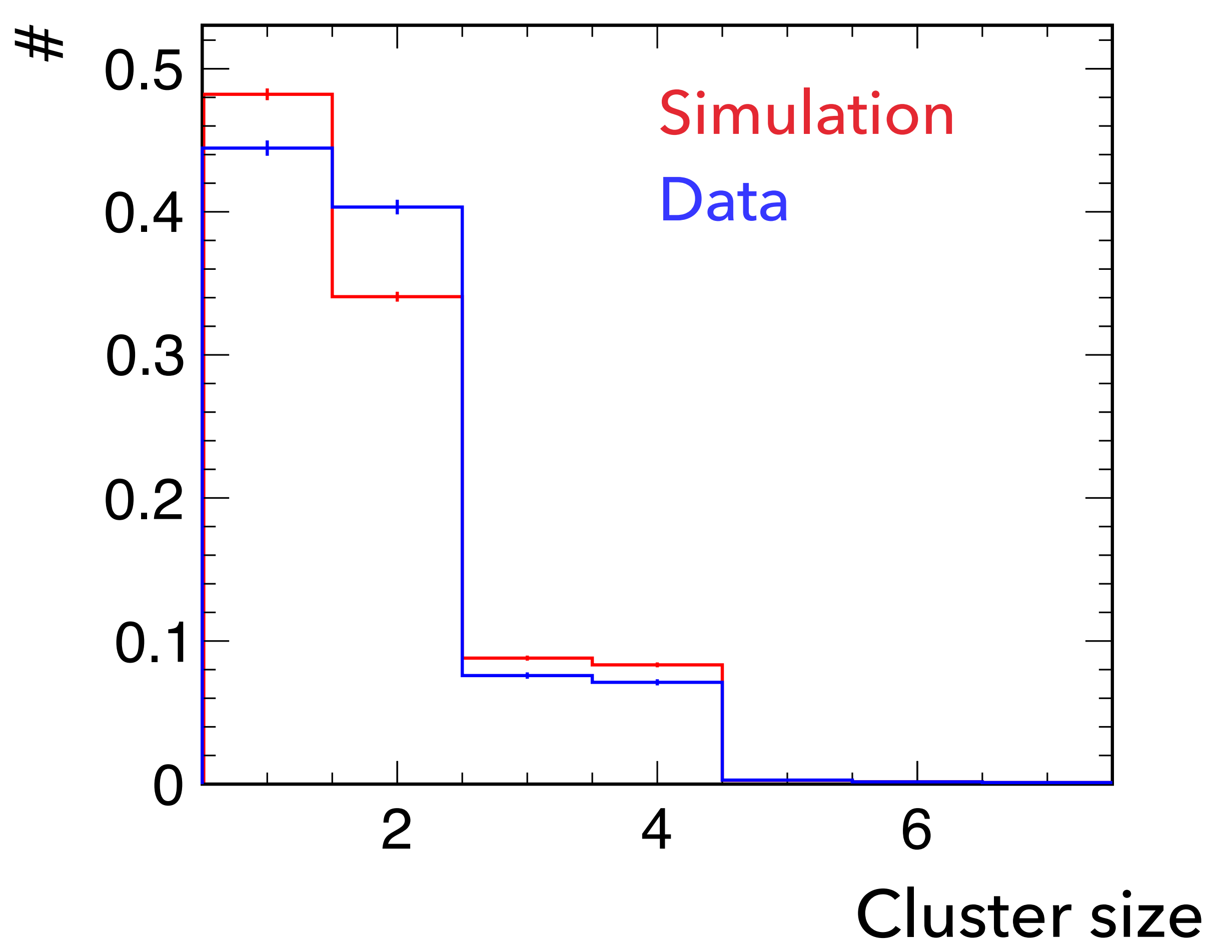
P-WELL SMEARING

- Stronger lateral field leads to less charge sharing and consequently a lower cluster size
- Ignorance of exact doping profiles has considerable impact on cluster observables
- Tuning the doping profiles (within the given uncertainties) to the data is **not** the objective of this study

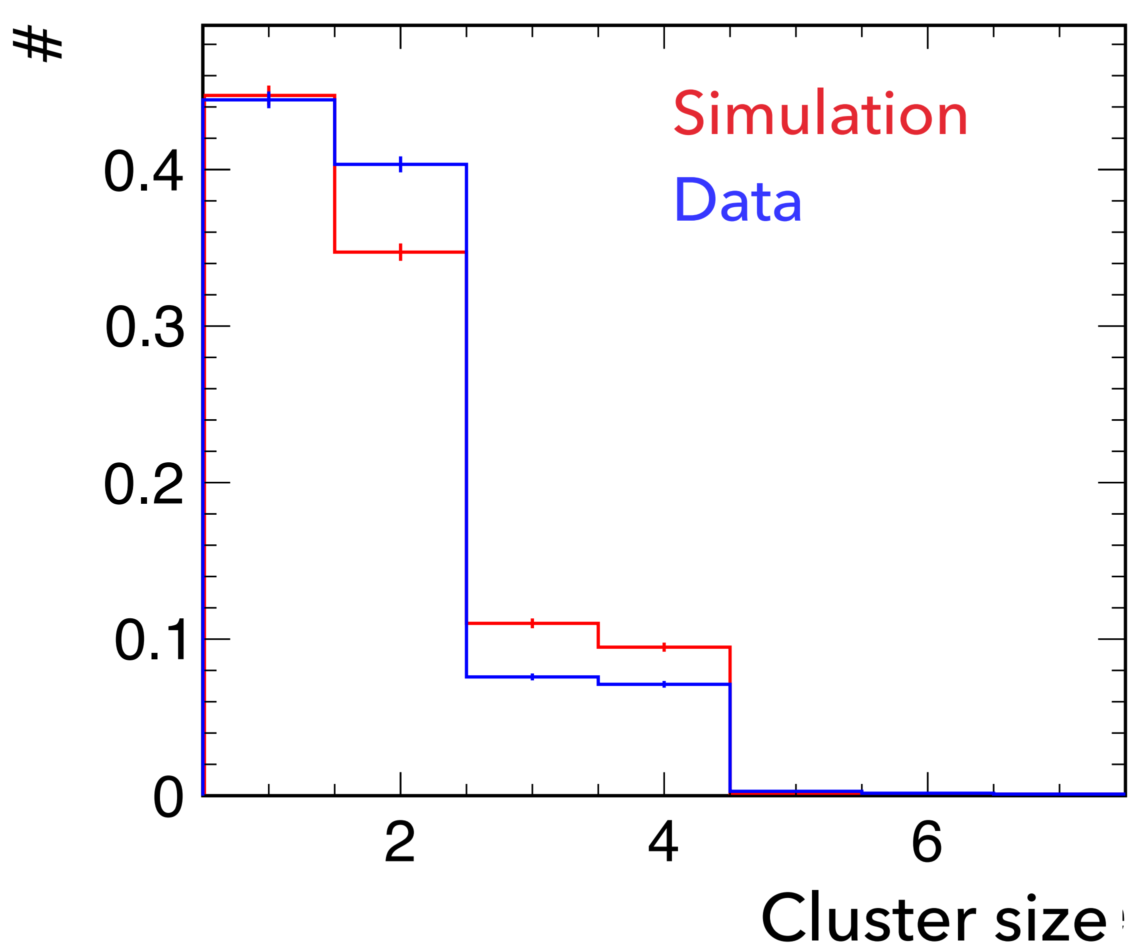
$C_a = 2 \times 10^{-30} \mathrm{cm}^6/\mathrm{s}$

Thrd = 170e

Low p-well smearing

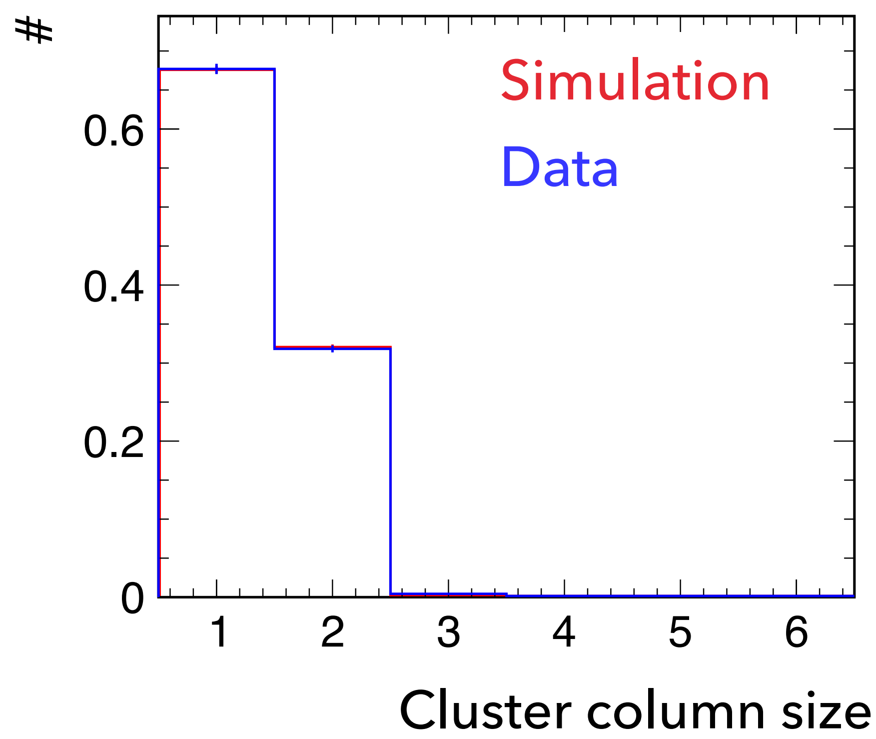


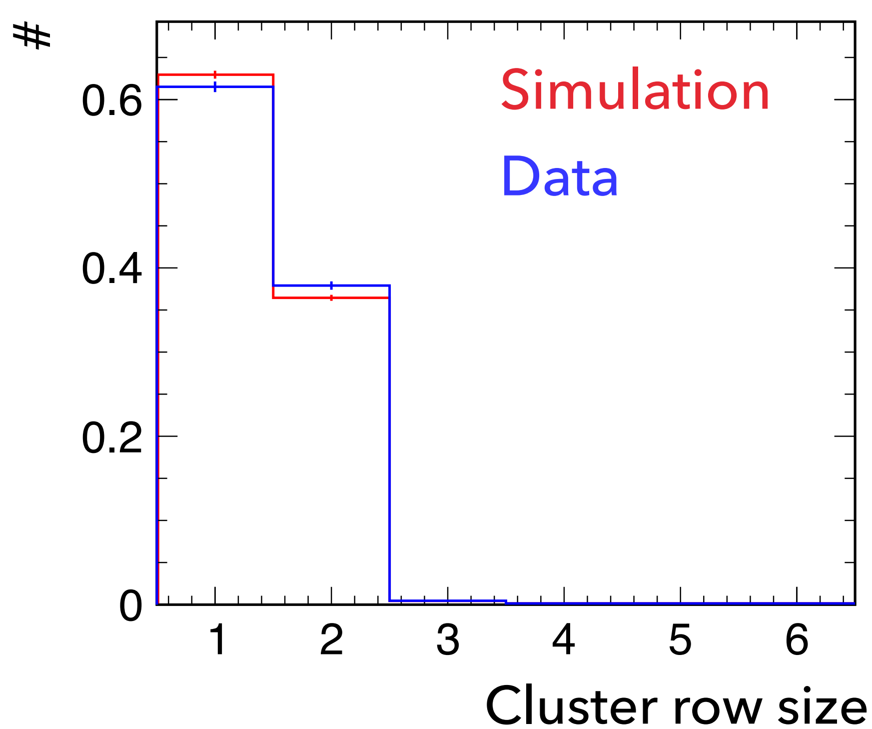
High p-well smearing



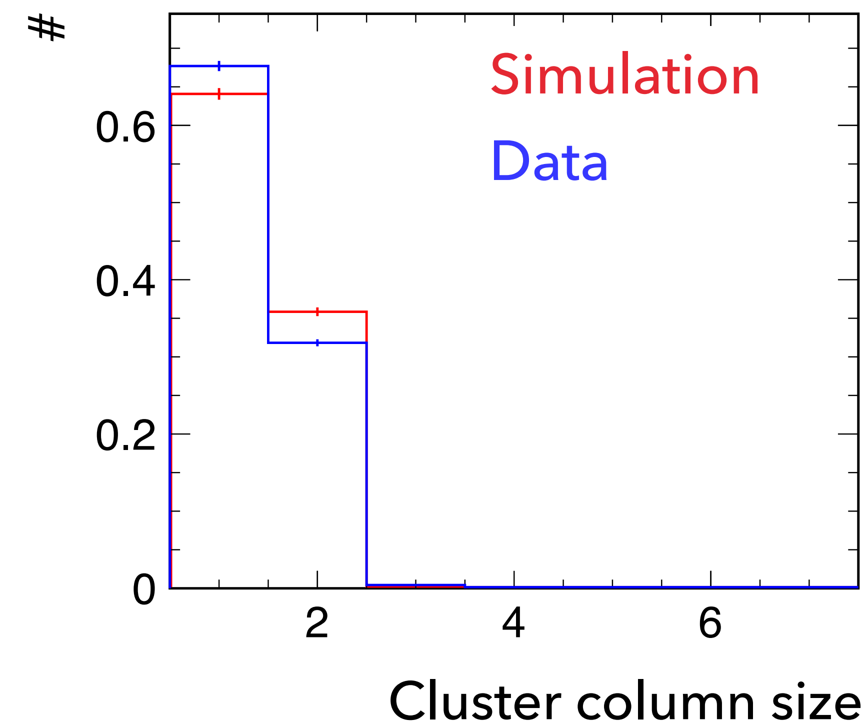
P-WELL SMEARING

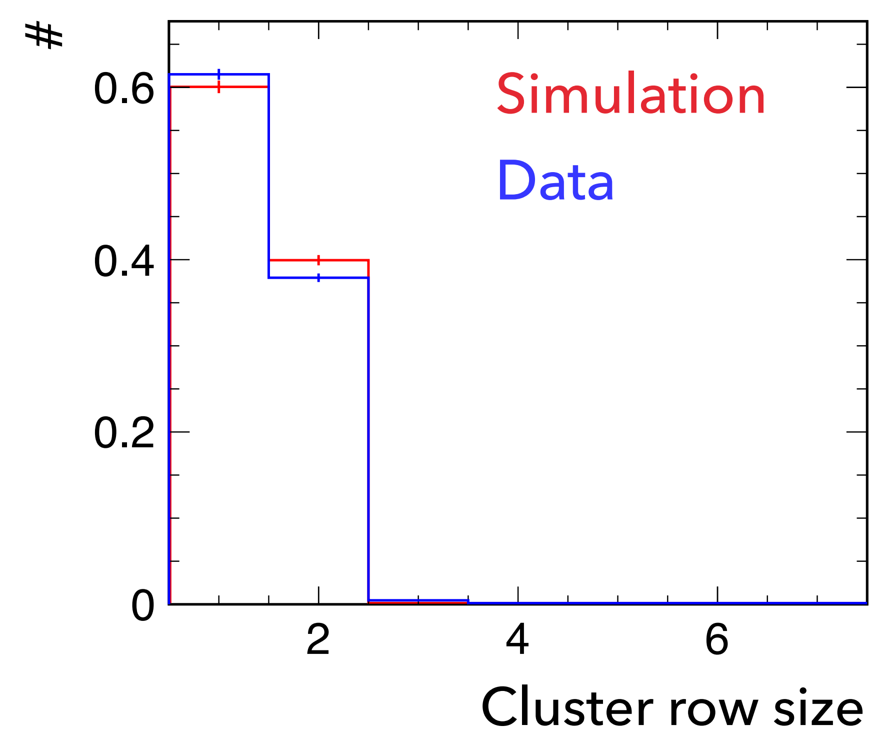
Low p-well smearing





High p-well smearing



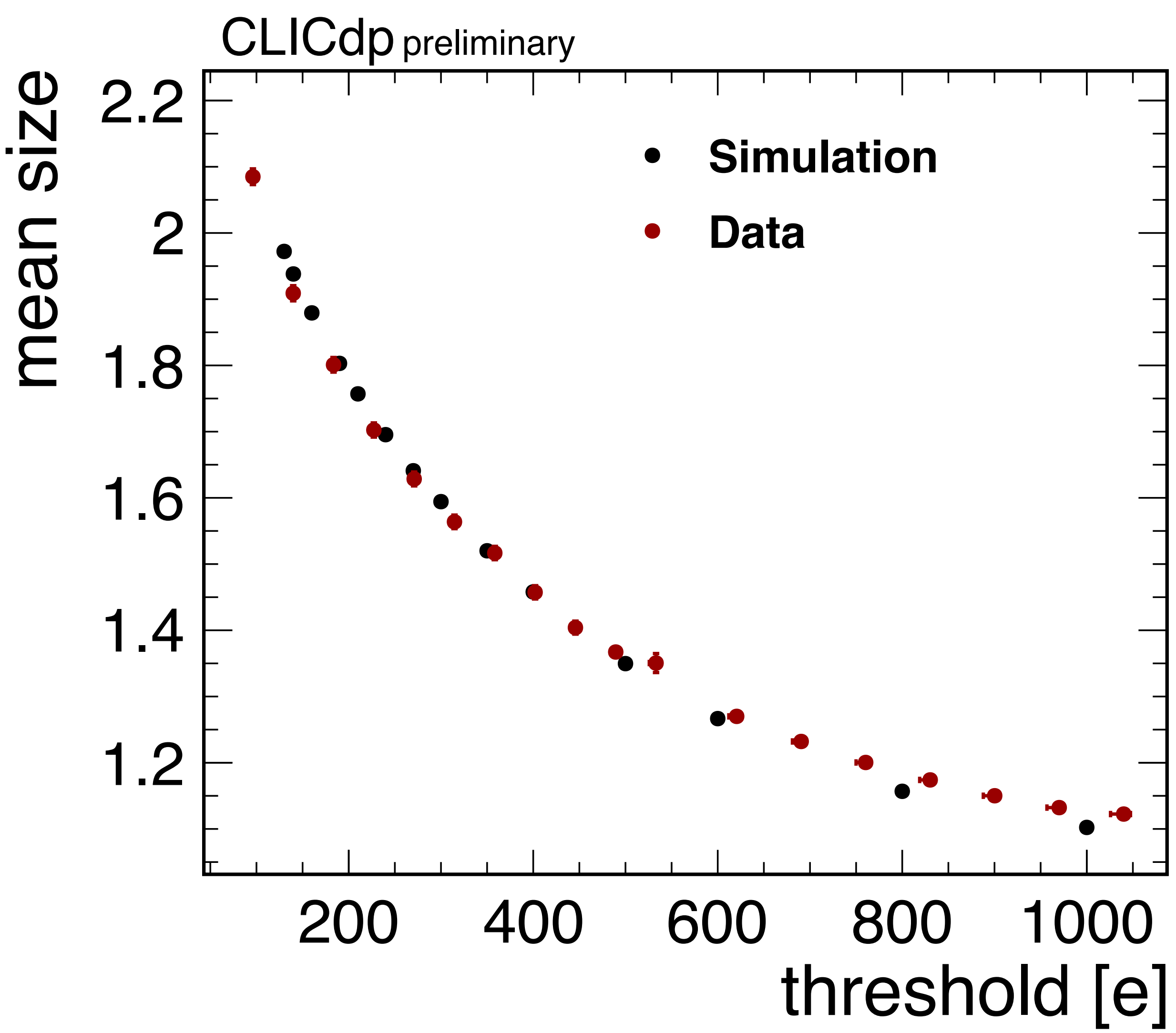


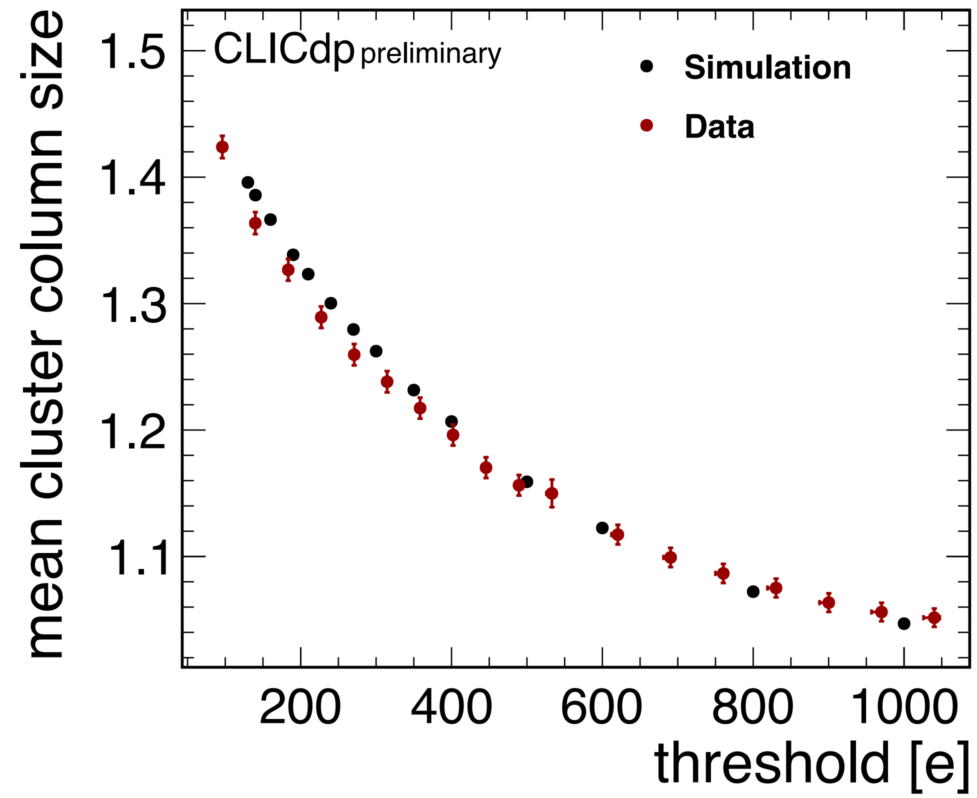
- Effect of p-well smearing is clearly visible in both spatial dimensions

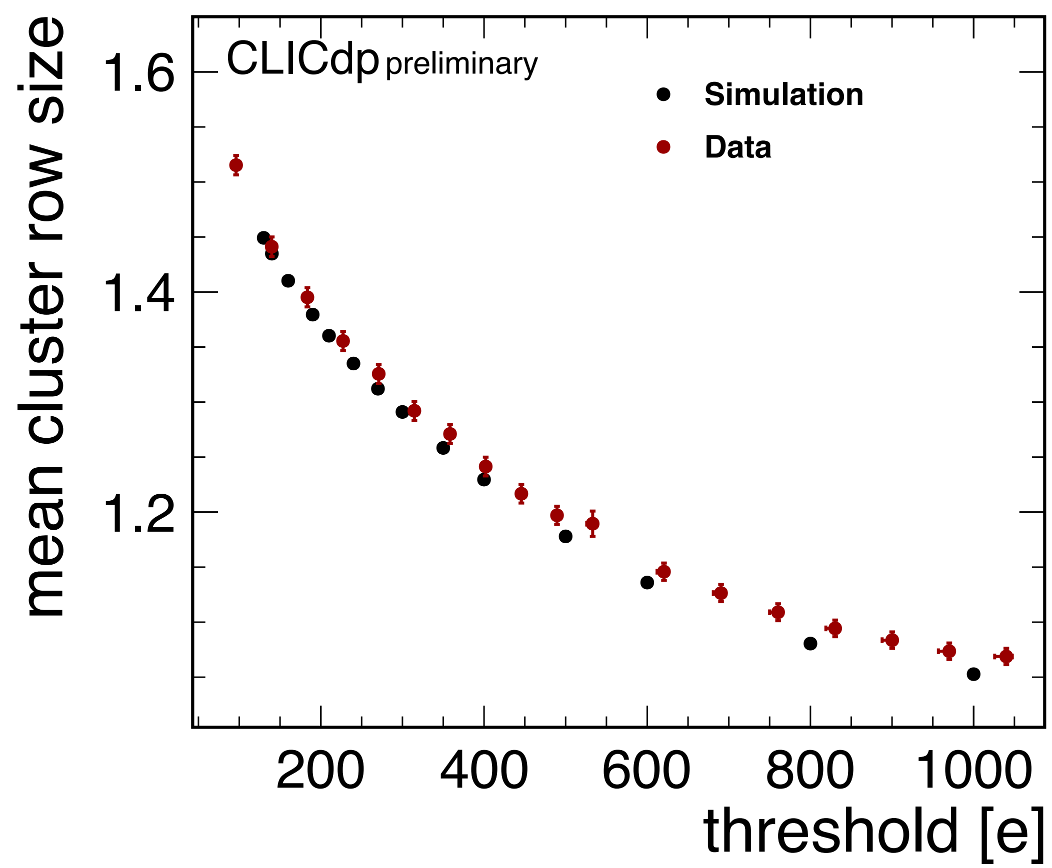
Threshold scan

High smearing
$C_a = 2 \times 10^{-30} \text{cm}^6/\text{s}$

- Agreement between data and simulation does not deteriorate with increasing threshold







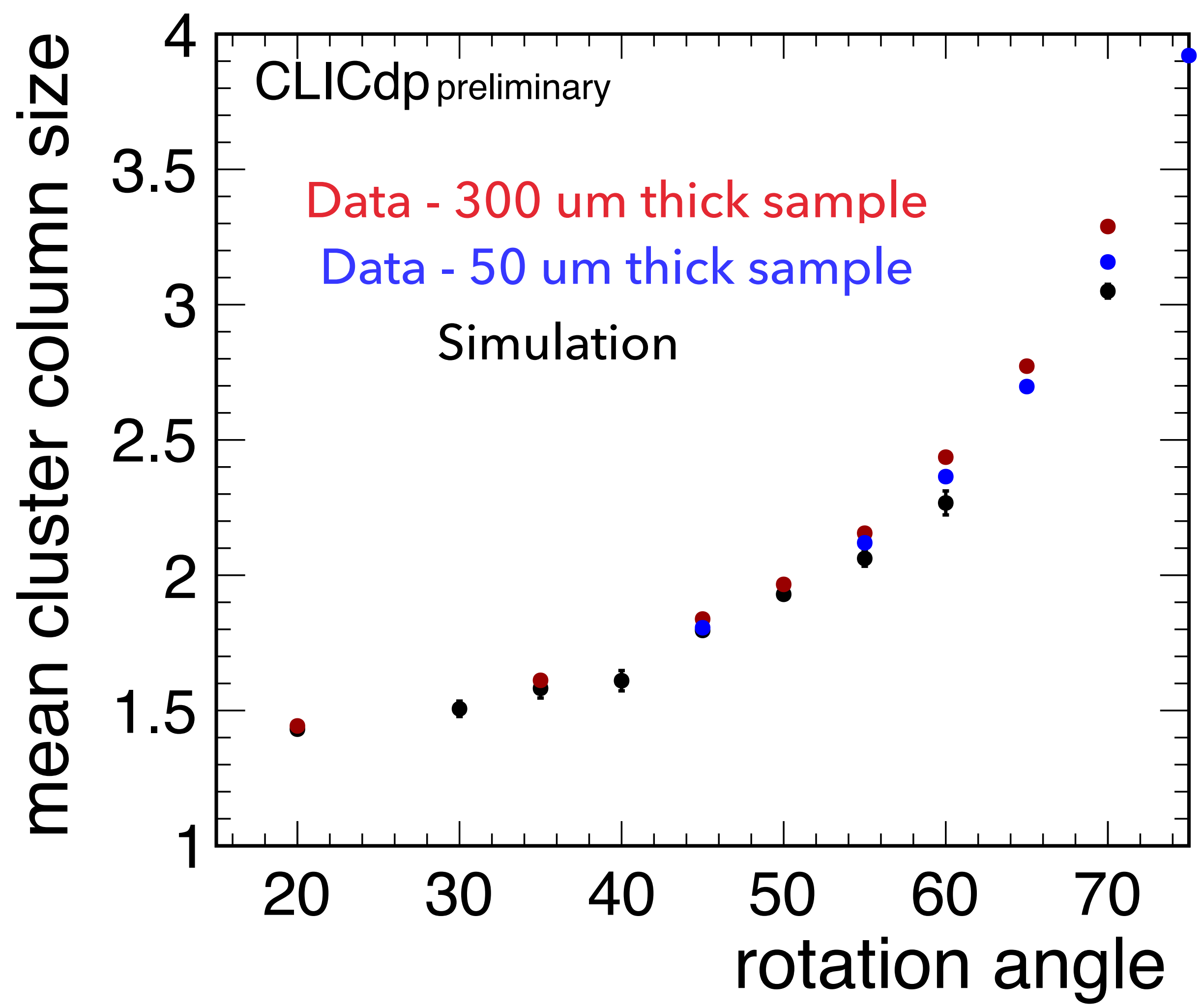
High smearing

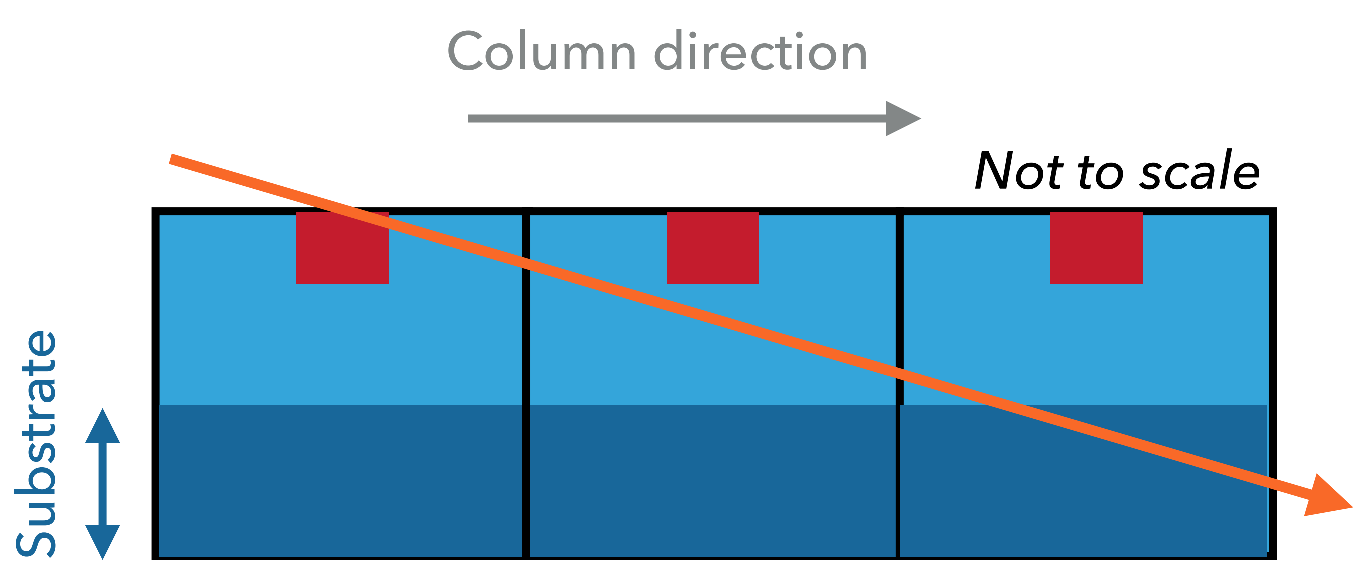
$C_a = 2 \times 10^{-30} \mathrm{cm}^6/\mathrm{s}$

Thrd = 170e

Rotation scan

- Sensor is tilted in column direction
- Charge carriers created in or close to the substrate are expected to have a stronger contribution to the cluster size for increasing rotation angles





SUMMARY AND OUTLOOK

Summary

- Charge carrier recombination models (Shockley-Read-Hall and Auger recombination) have been implemented
  - Effective charge carrier lifetime is determined by these models and not by integration time
- Ignorance of exact doping profiles introduces uncertainties in the simulation

Outlook

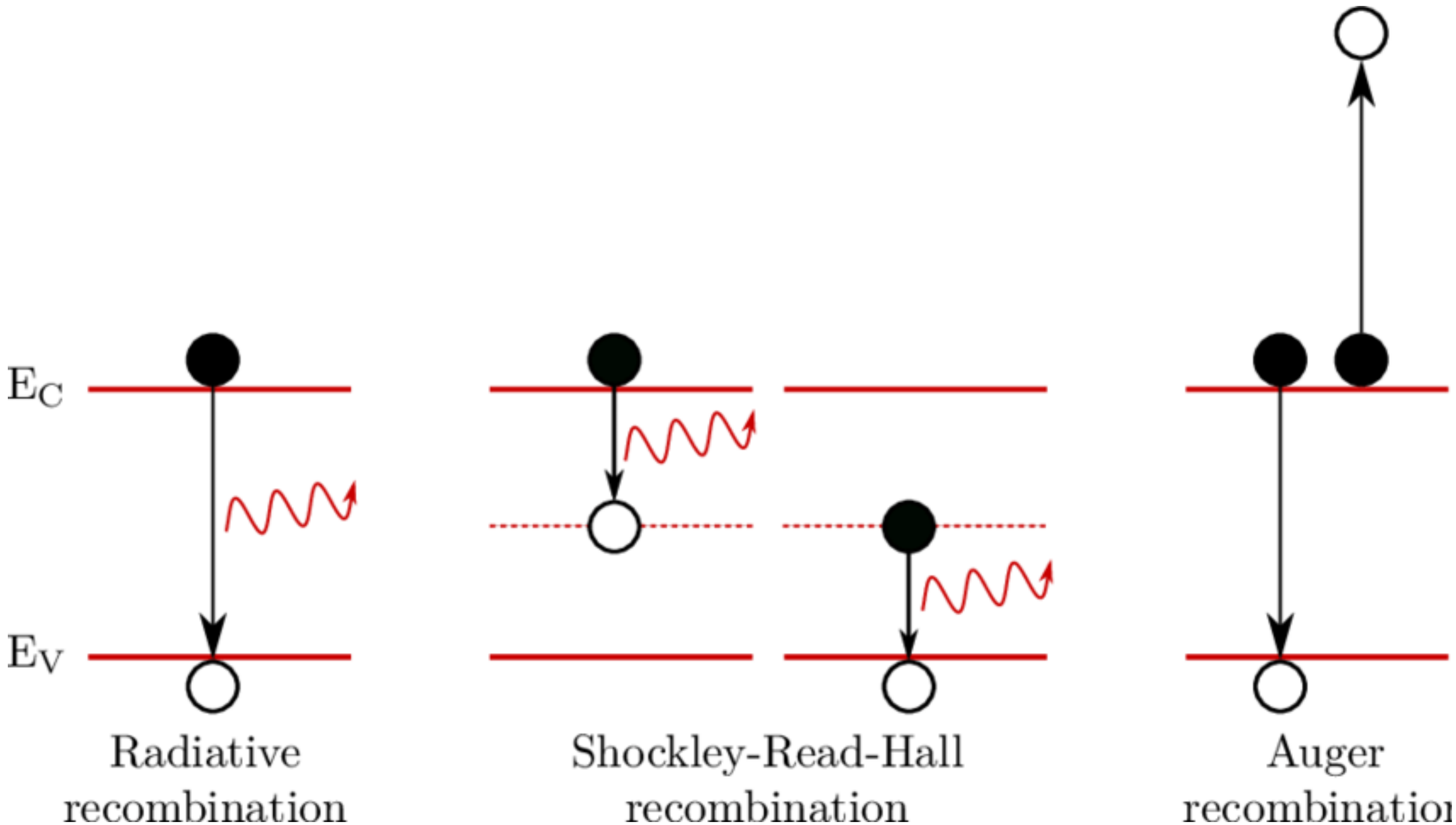
- Studying impact of additional variations in the doping profiles on the cluster observables
- Comparison of simulation against FastPix measurements (analogue information available)
- TCAD+APSQ simulations for 65 nm process

A thousand thanks to Magdalena and Simon for their invaluable support and supervision for this work

Thank you for your attention

Back-up

CHARGE CARRIER RECOMBINATION



Tucher, Nico. (2016). Analysis of photonic structures for silicon solar cells.

In-pixel cluster size difference

High smearing
$C_a = 2 \times 10^{-30}$
Thrd = 170e