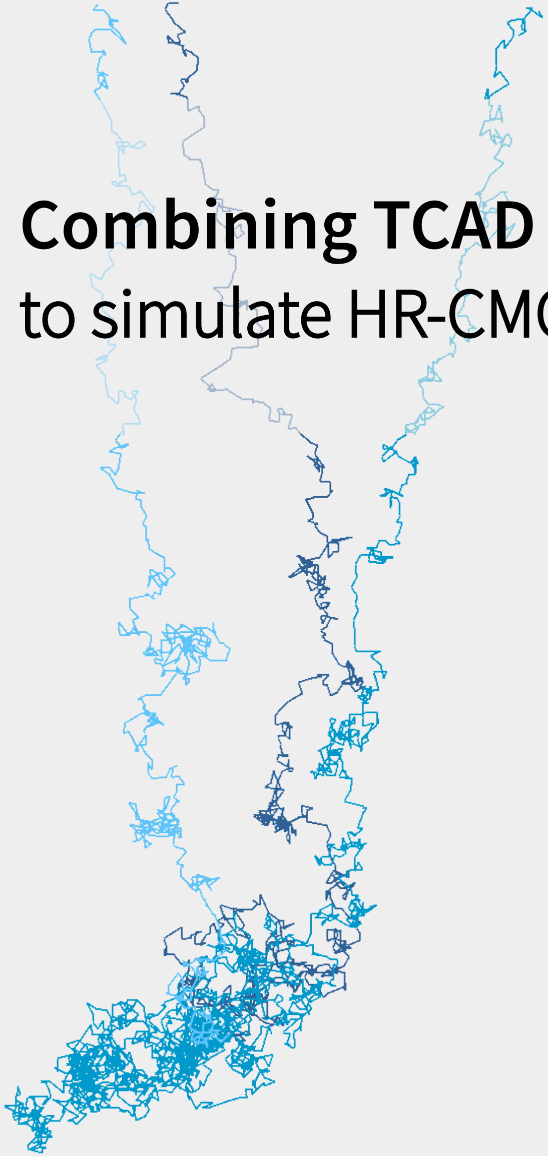
http://clicdp.cern.ch



Combining TCAD and Monte Carlo methods

to simulate HR-CMOS pixel detectors using the Allpix² framework

Katharina Dort, CERN
Magdalena Munker, CERN
Simon Spannagel, CERN

CLICdp Collaboration Meeting
29 August 2018

The Challenge

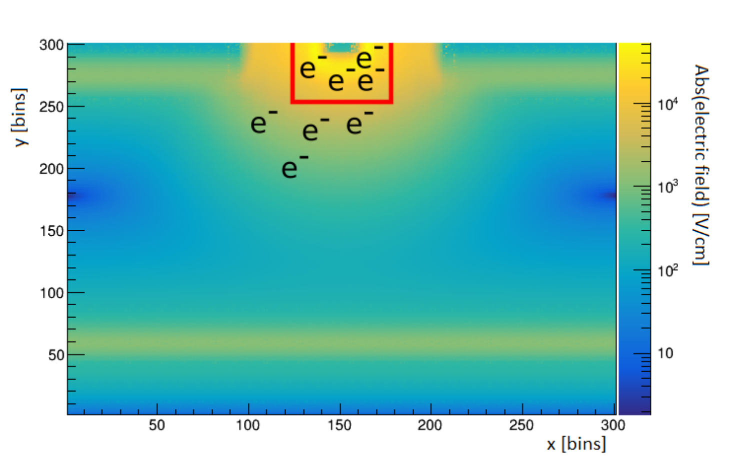
- Goal: assess detector performance parameters
- Issue: complex sensor, require precise microscopic description

- Full transient simulation of a single MIP incidence in TCAD takes **O(3h)**
  - 3D performance of pixel cell requires at least O(200k) events → not feasible
  - Use simplified models to reduce simulation time to **O(ms)** per event

- Validated simulation allows optimization of new sensor designs
- CLICdp: **CLICTD tracker chip** to be submitted in this technology (see Iraklis' talk)

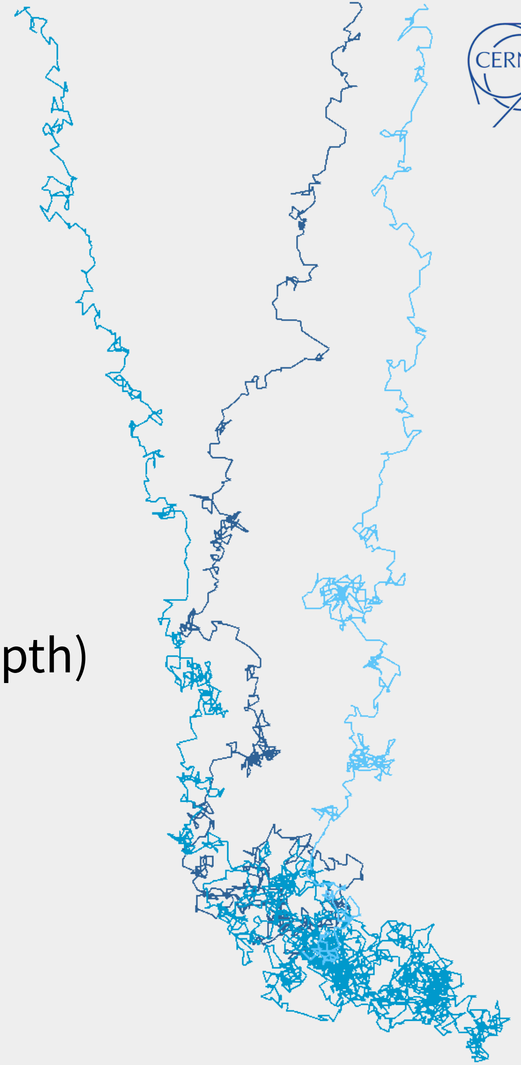
Simulation - Concept

- Use **TCAD for electrostatic simulation** of the field with bias voltage applied
- Export field, convert into regular grid (barycentric interpolation)
- Use Allpix Squared **to simulate particle passage** (see Paul's talk)
  - Geant4 models initial energy deposition & secondary particle creation
  - Charge carriers are propagated using drift-diffusion model (RKF5)
- Simulation model based on "collected charges"
  - With small collection diode, impact from induction during drift should be small
  - Define region of collection implant for collection of charges



Allpix² Drift Visualization

- Allpix² allows to record drift/diffusion path of individual charge carriers
  - 3D positions filled in ROOT TH3D
- On the following pages:
  - One particle, perpendicular incidence in pixel center
  - Projection of drift paths onto X-Z plane (pitch vs. sensor depth)
  - Only draw charges which have reached the sensor implant
- Stop the propagation after different integration times
  - Allows to see where charge carriers are collected from
  - And how they reach the implant



epitaxial

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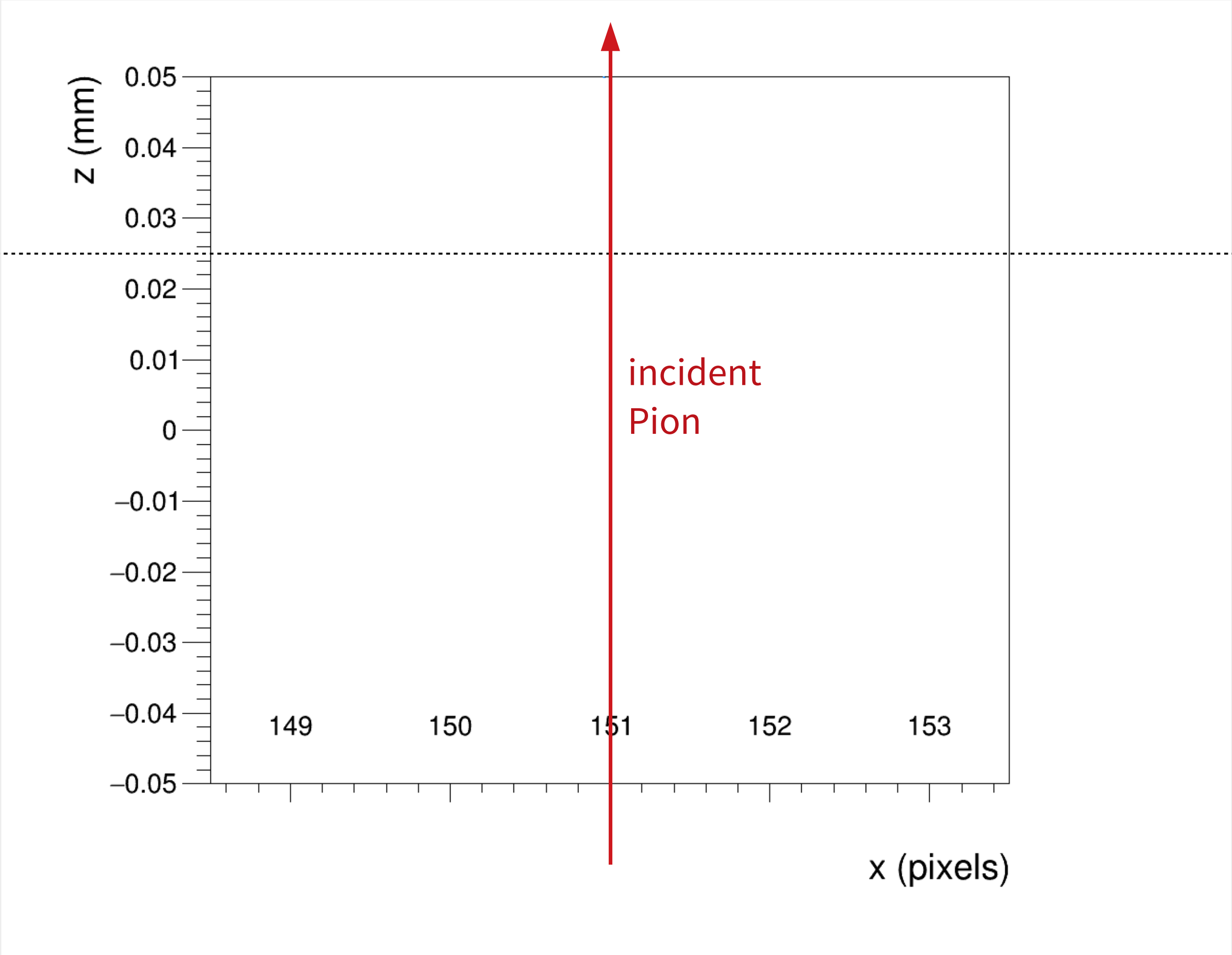

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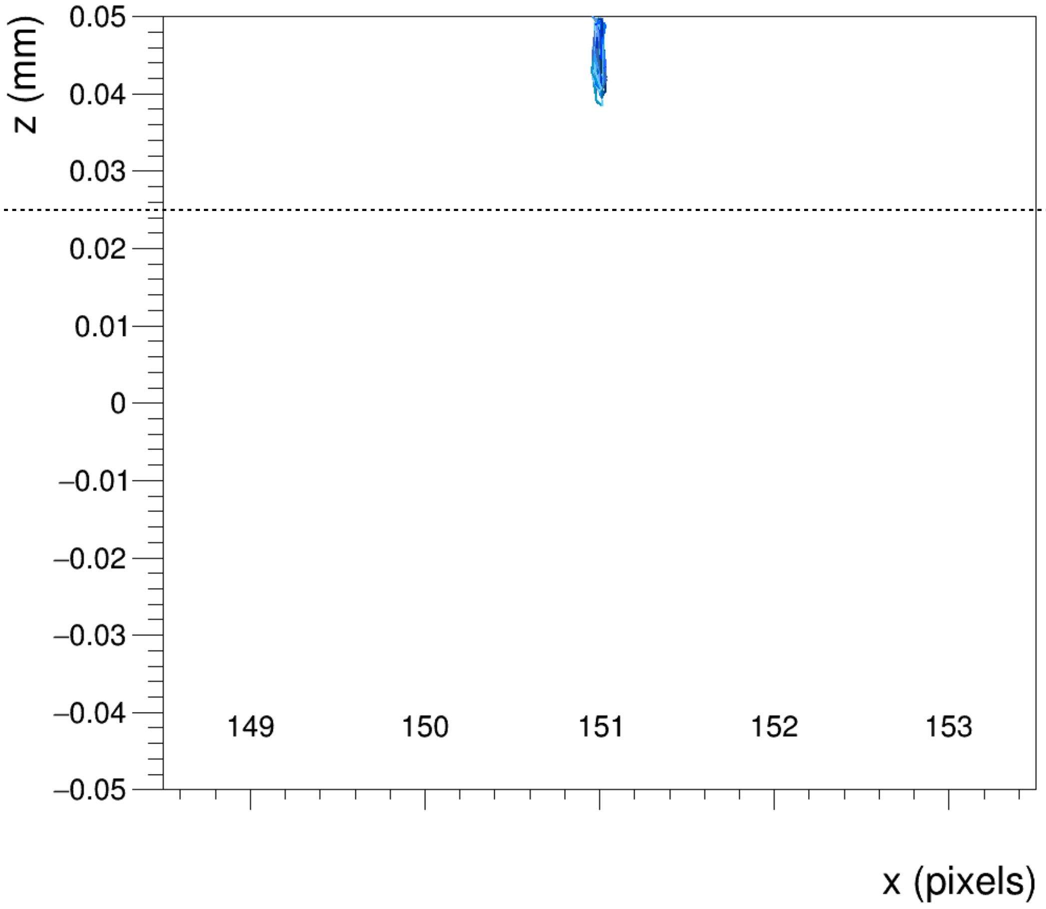

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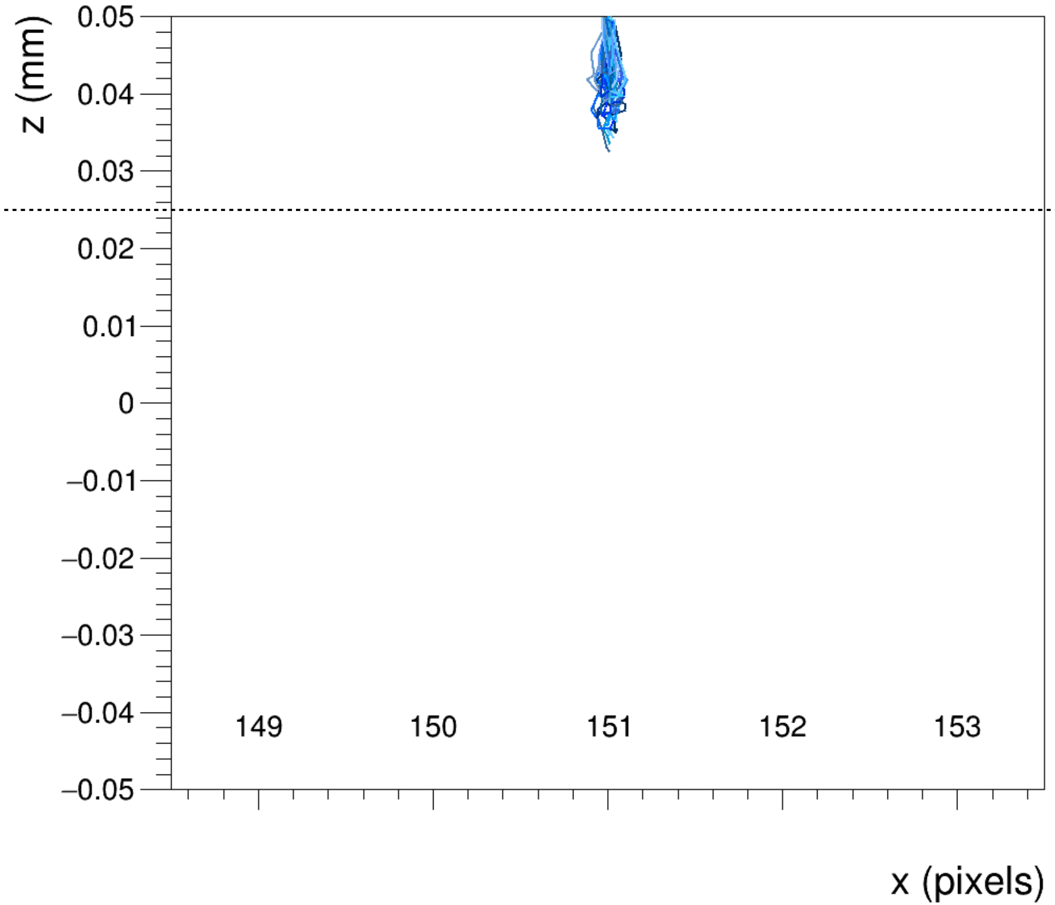

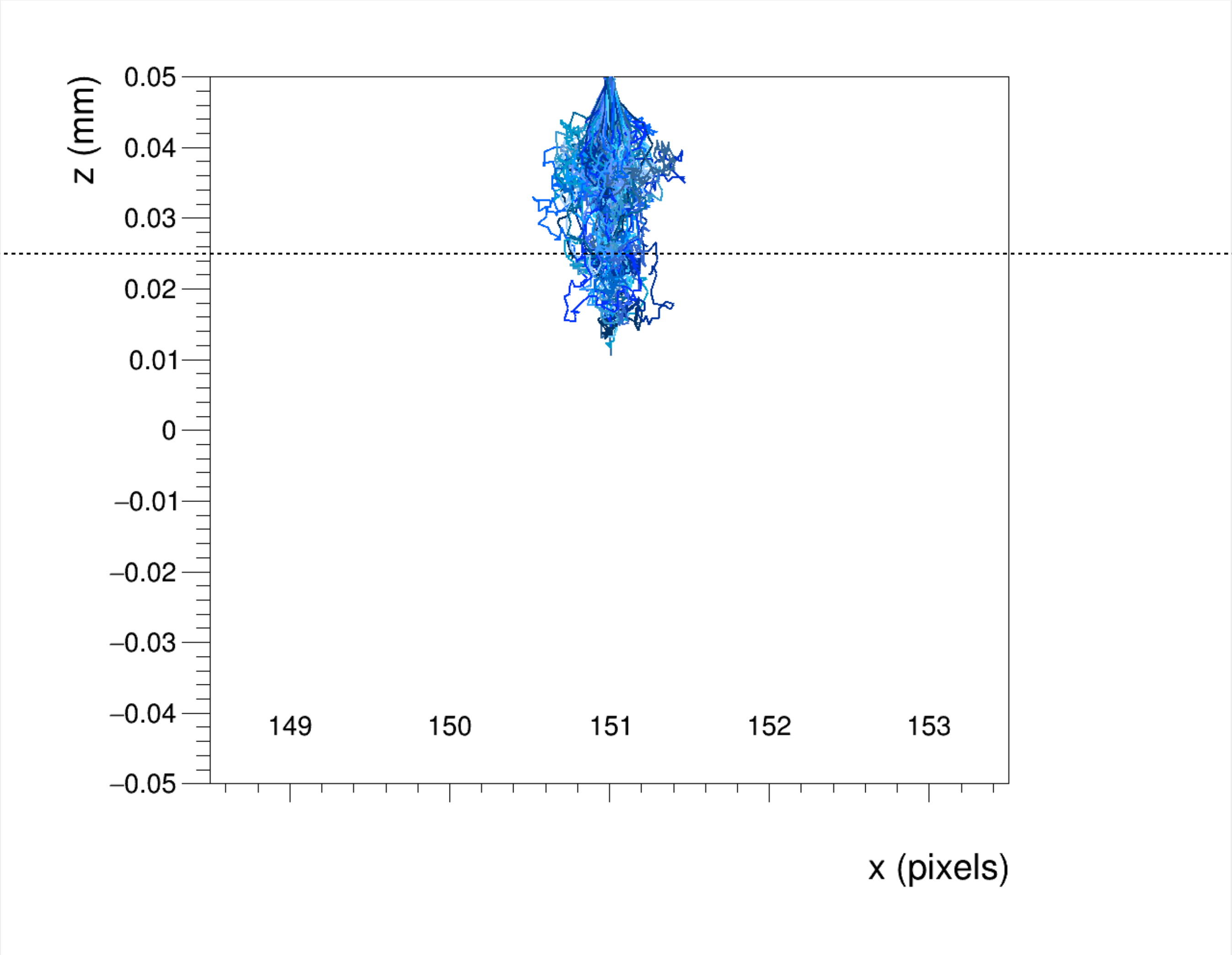

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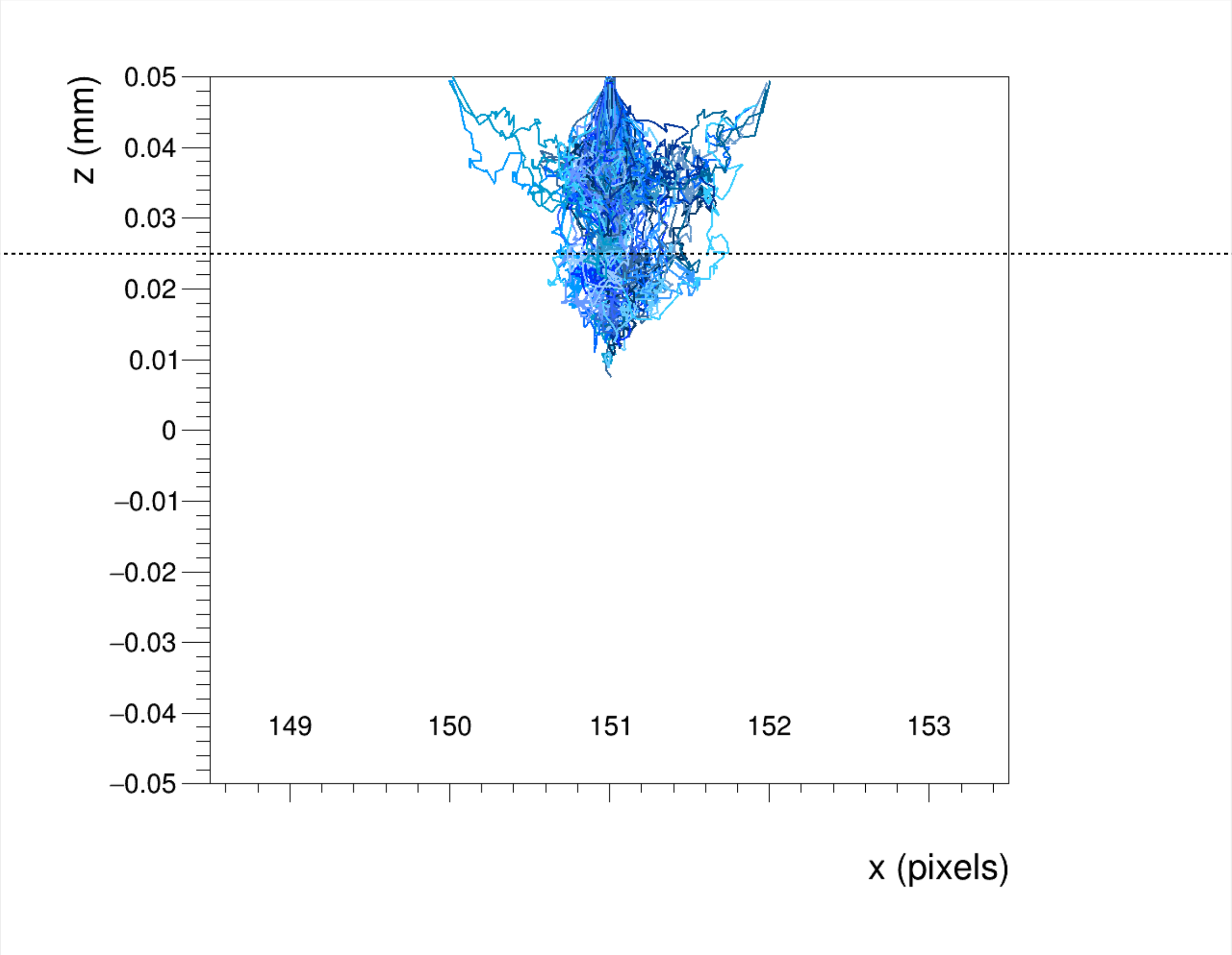

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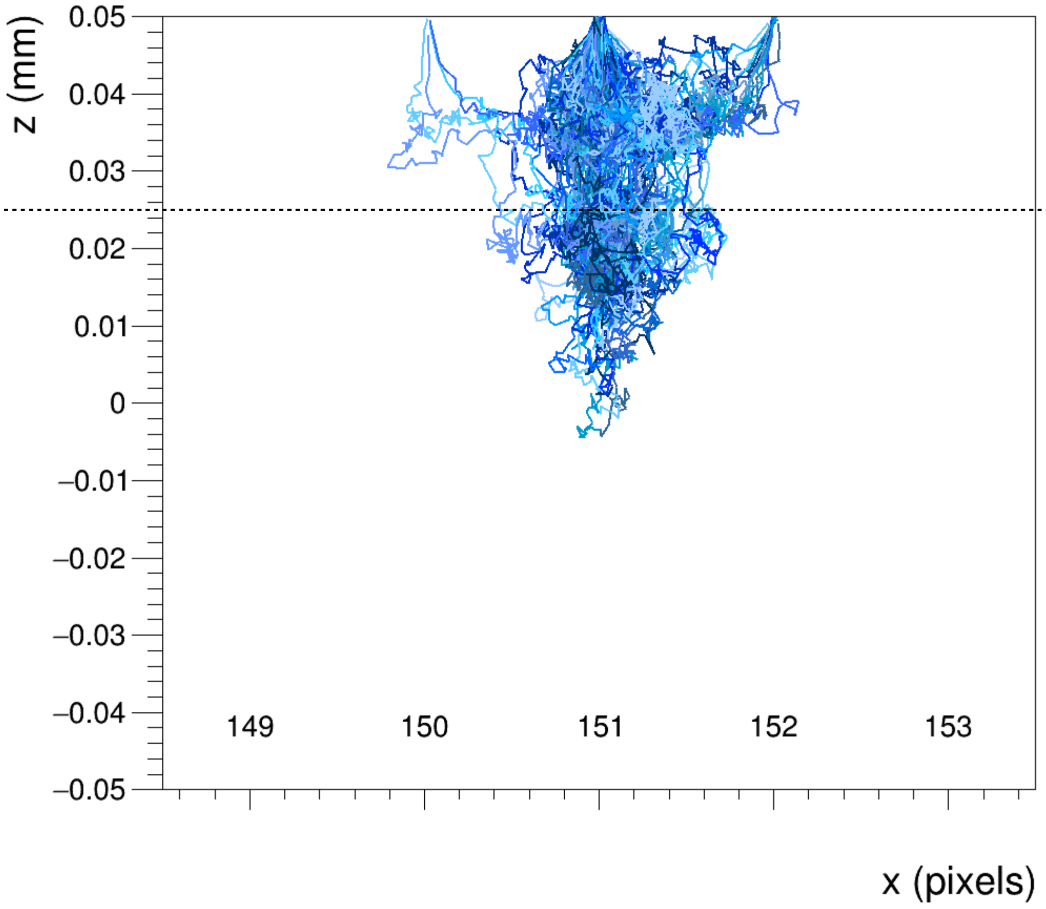

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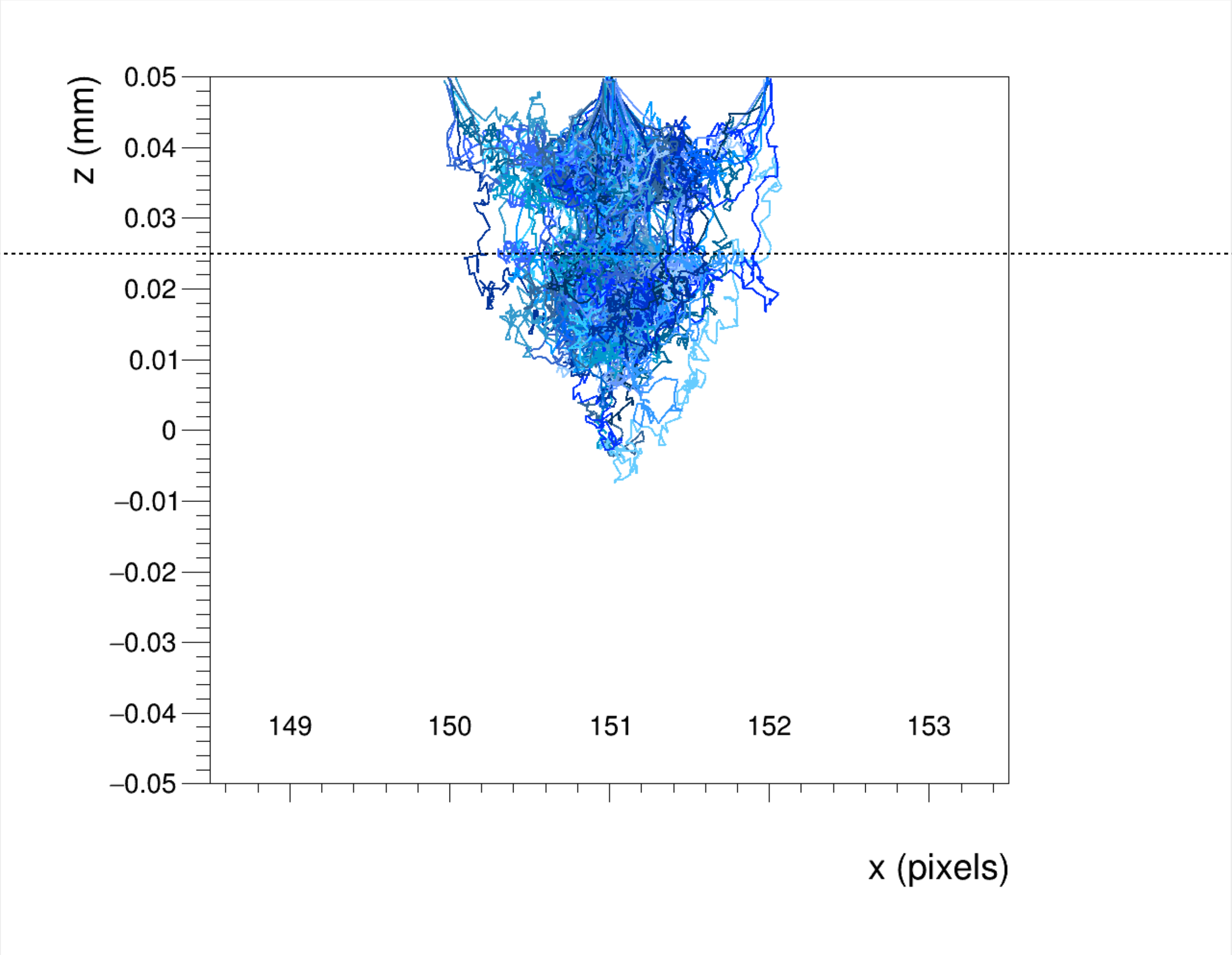

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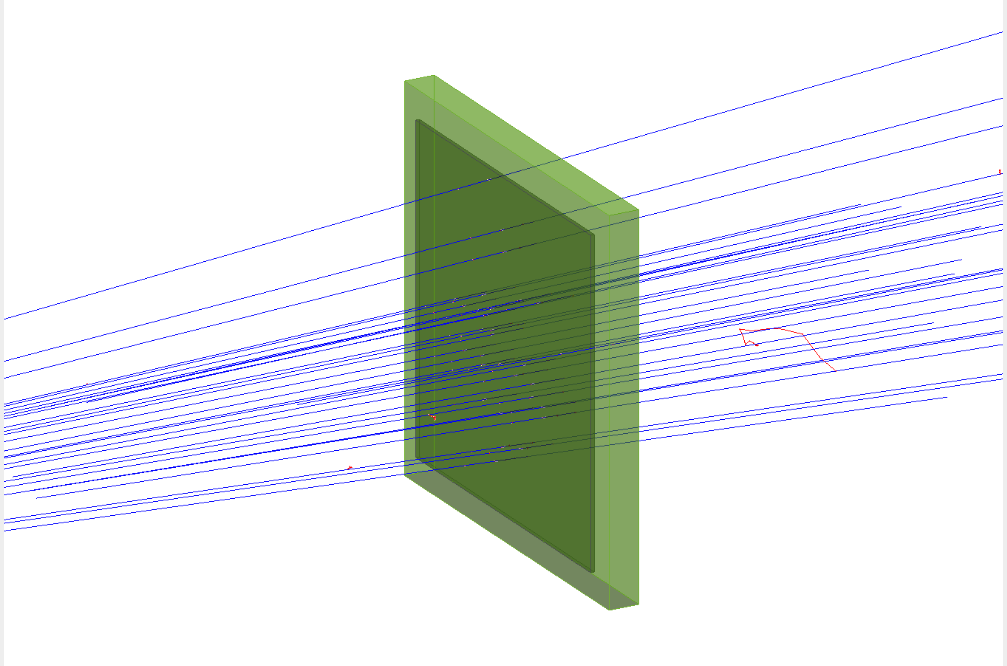
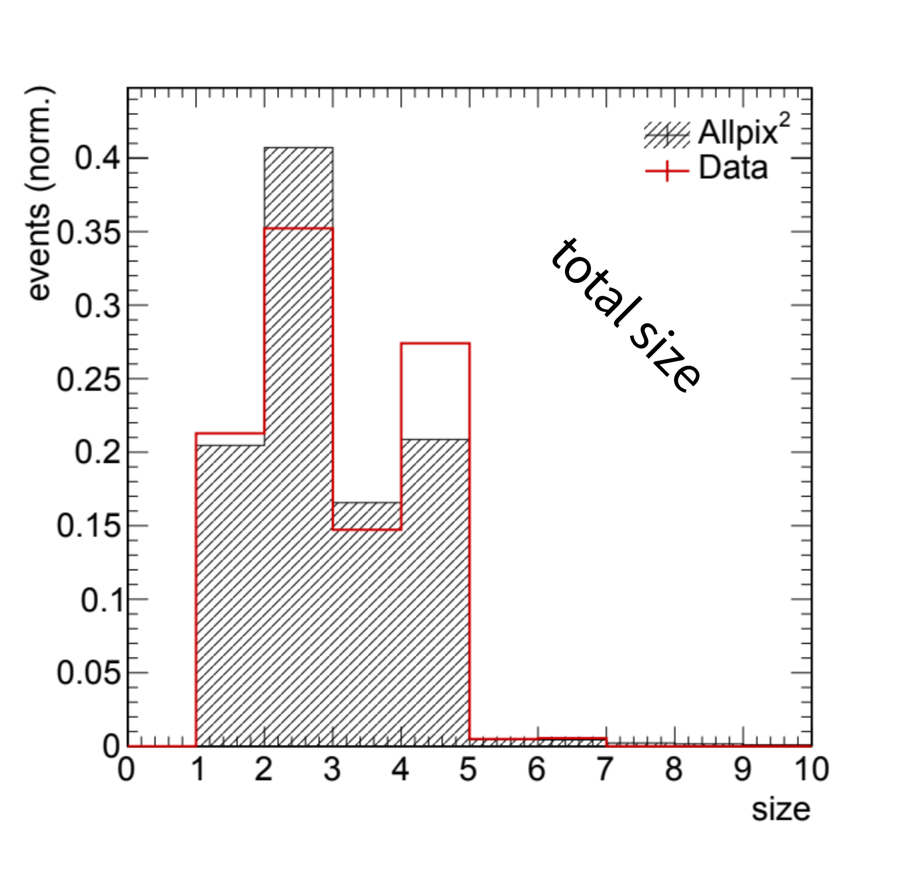
Simulation - Detector

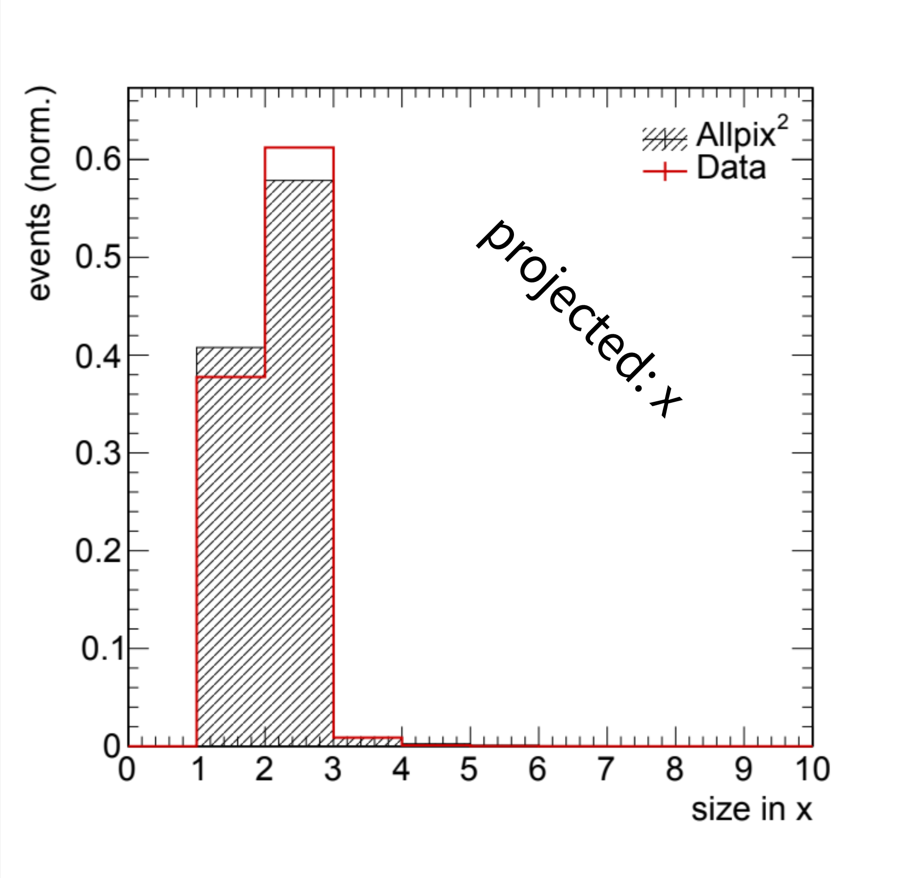
- ALICE Investigator-like detector
  - 28x28 um pixel pitch
  - 2x2 um charge collection implant
- See Magdalena's talk for e-field
- SPS Beam: 120 GeV Pions
- Simulate detector only, no telescope
  - Monte Carlo truth used as tracks



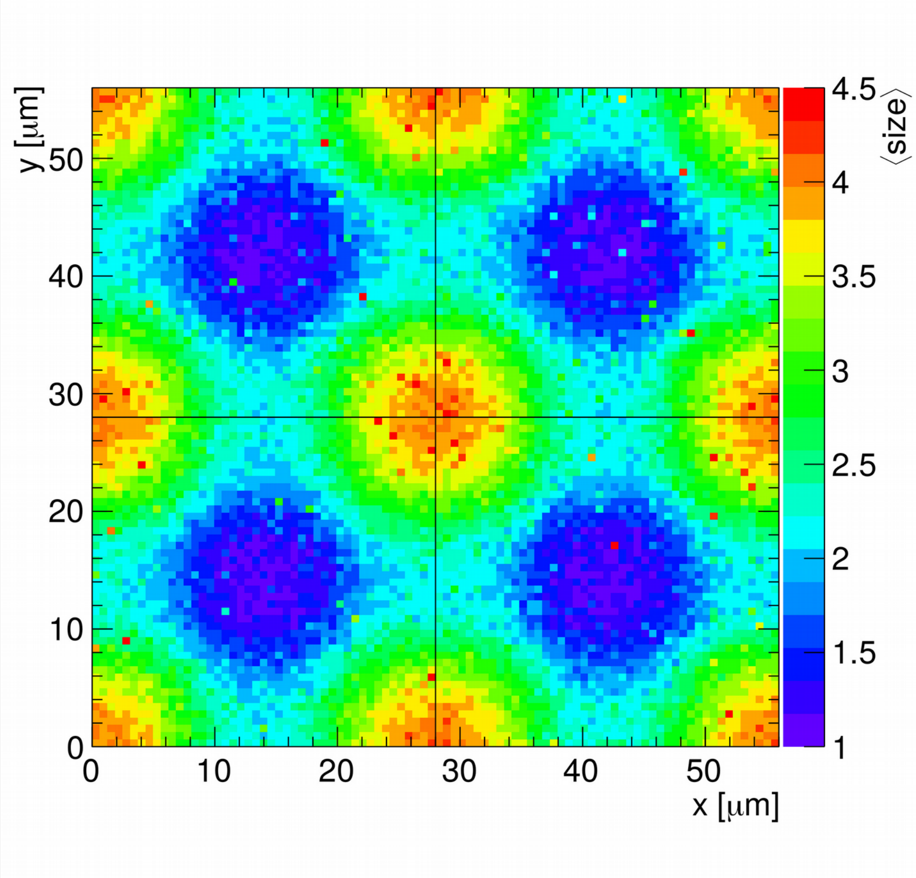
- Comparison with test beam data from Magdalena's PhD thesis
- Using CLICdp Timepix3 telescope, ca 25k events recorded

Cluster Size Distributions



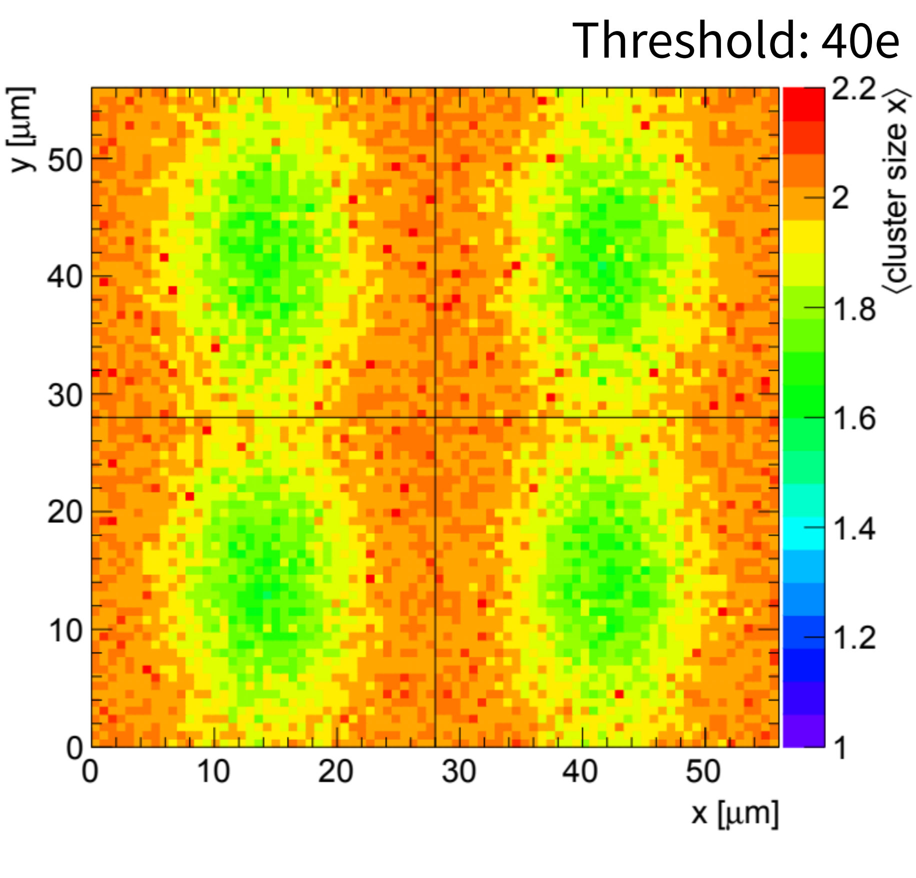


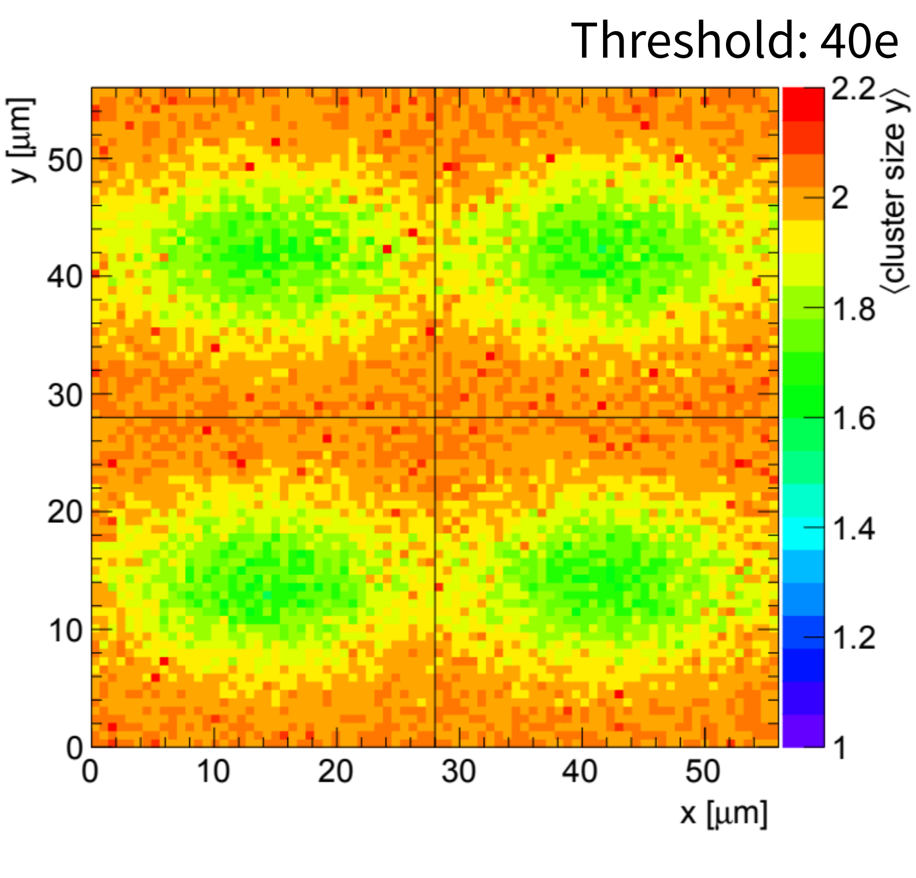
In-Pixel Distribution of Cluster Size



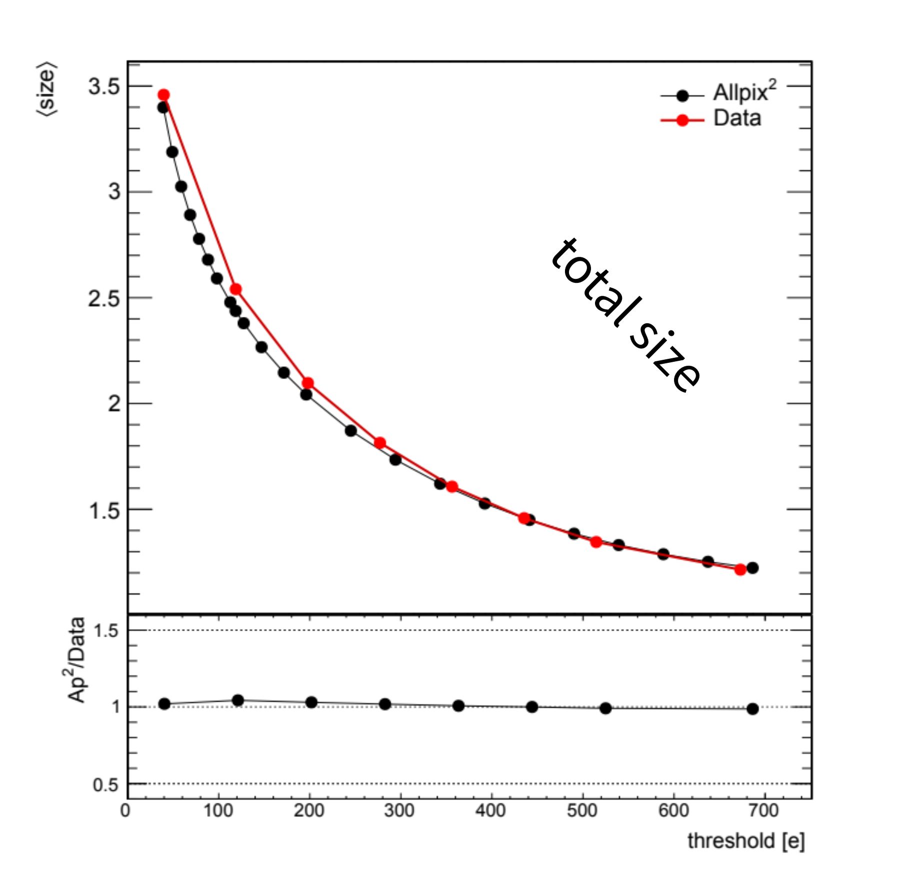
- Using Monte Carlo truth to calculate position within pixel
- Fold statistics from full sensor into four pixel cells
- Mean size behaves as expected:
  - 1-px cluster in pixel center,
  - Charge sharing towards neighbors
    - In edges
    - In corners

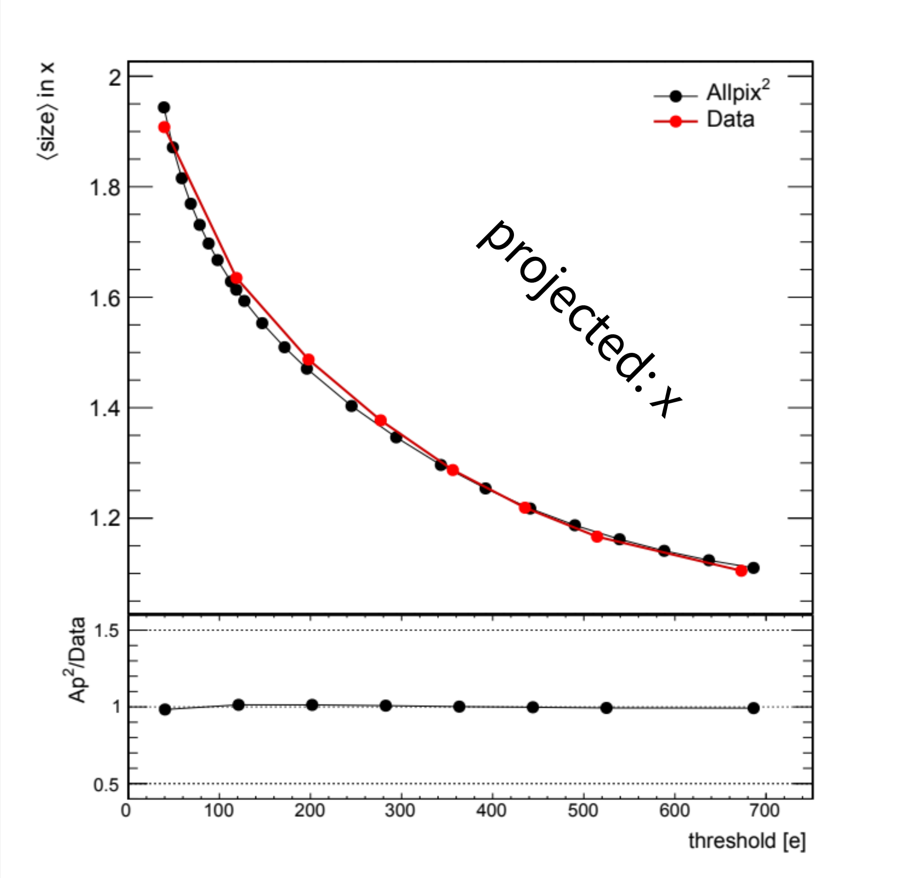
Projected Cluster Sizes – Correlation





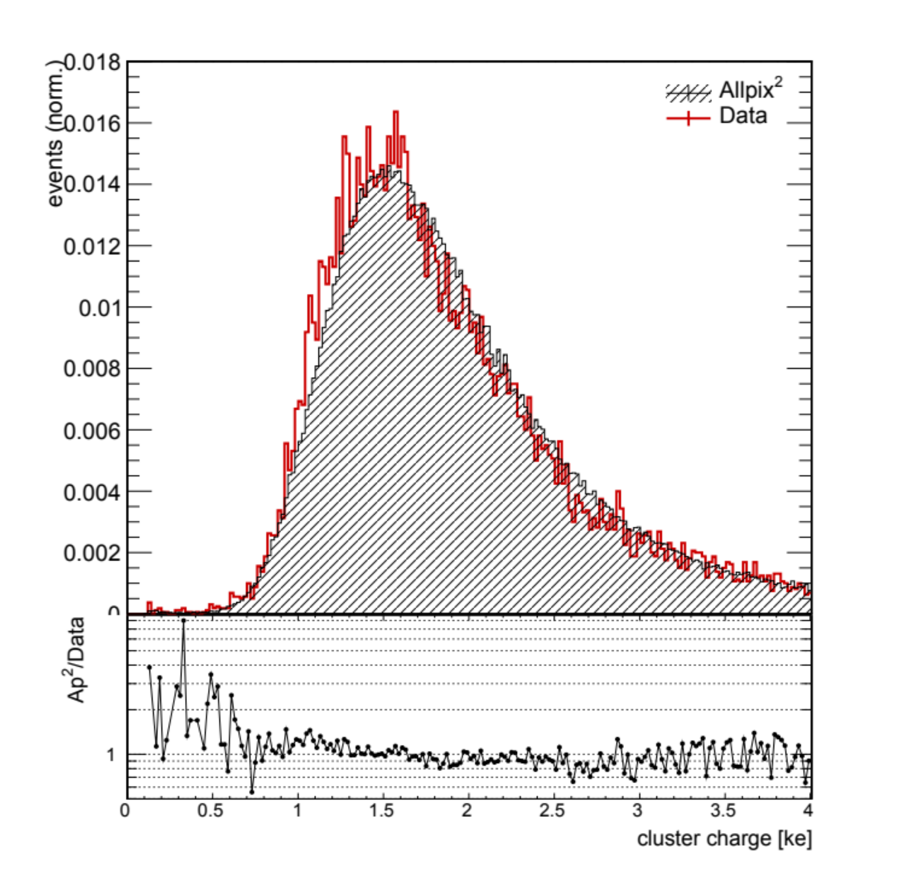
Mean Cluster Size





Cluster Charge Distribution

- Charge distribution matches well
- Simulation includes
  - Landau fluctuations,
  - Delta rays, …
- Using Geant4's photoabsorption Ionization model (PAI)
  - Improve description of energy deposition
  - Relevant since charge is collected from upper ~40um only



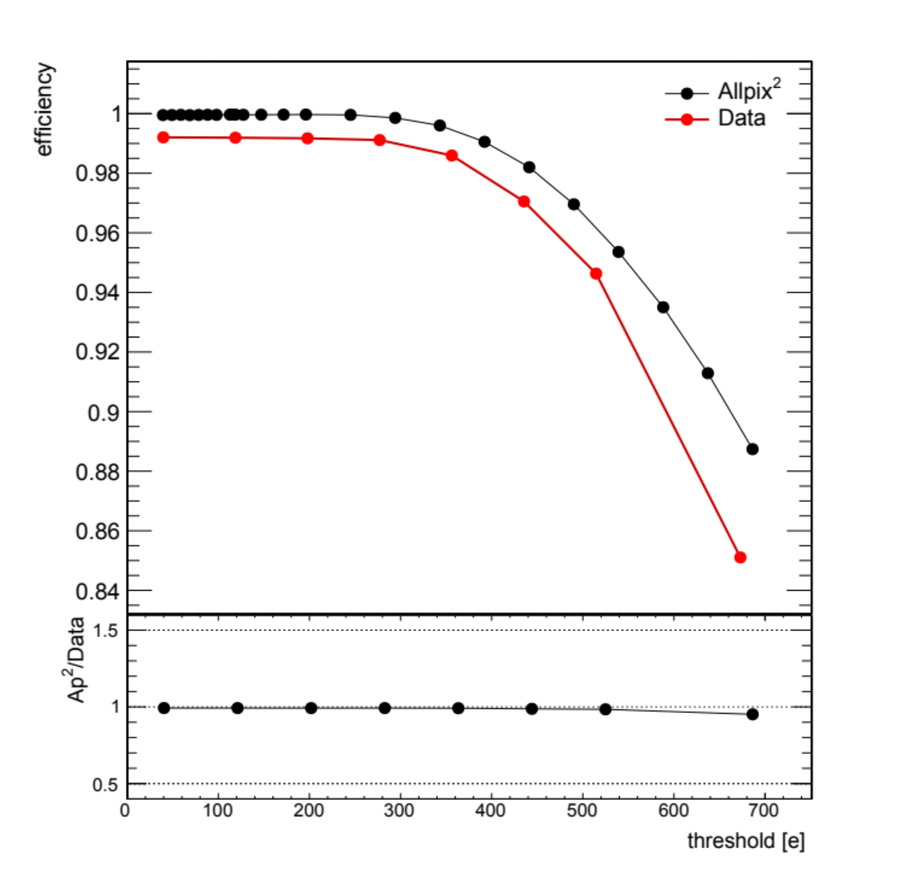
A Comment On “Tuning”

- Several parameters found with strong influence on simulation:
  - Electric field – small changes yield strong changes
  - Integration time – needs to be adapted to be “equivalent” to actual measurement
- Interesting observation: these parameters are not “free”, only one value produces sensible results in all observables together (global minimum)

- Negligible influence from variations of
  - Threshold dispersion, input noise, additional noise hits
  - Stepping size of the charge transport algorithm
  - Number of charge carriers propagated together (5 → 1)

Efficiency

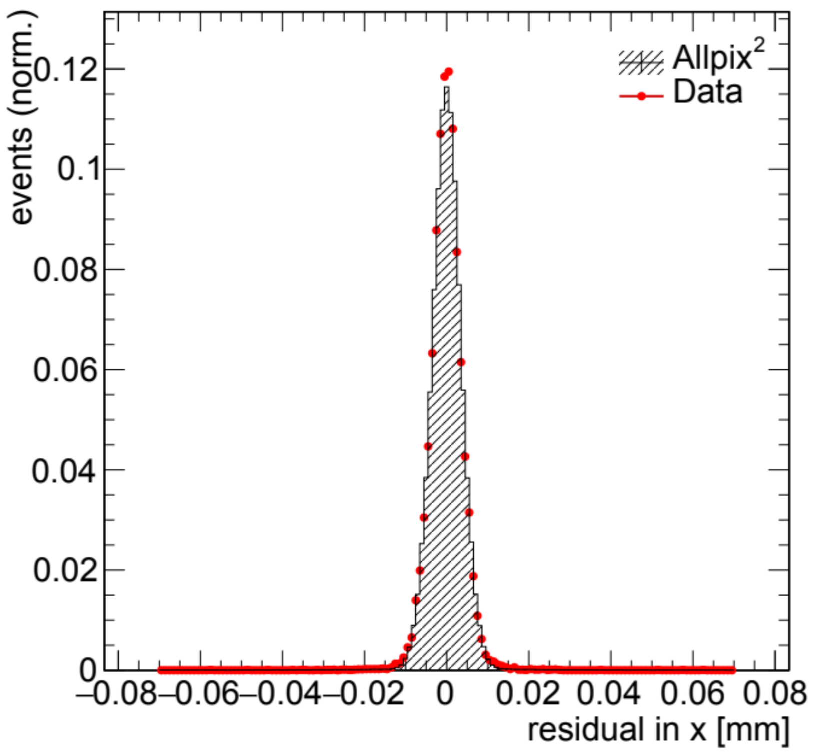
- Detection efficiency as function of charge threshold
- Good reproduction of shape
- Absolute value of data expected to be lower
    - Complex test beam setup
    - Effects of readout system
- ALPIDE chip in same technology reaches similar efficiencies as simulation



Detector Resolution

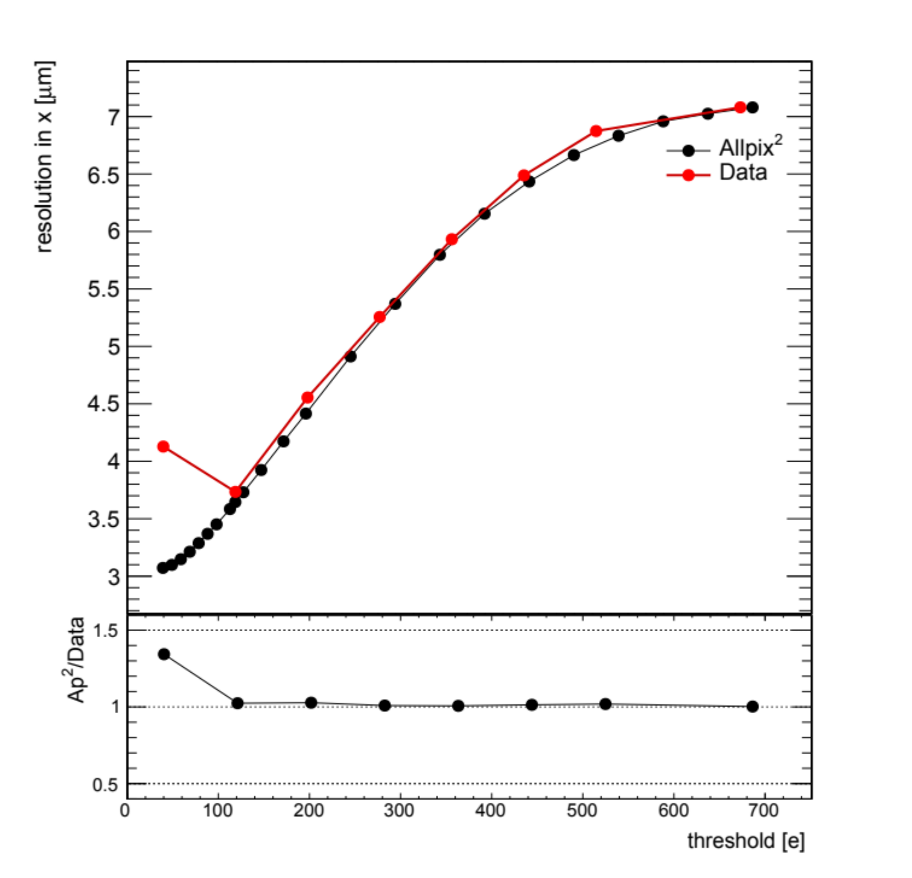
- Compare particle impact with reconstructed cluster position
- Using Monte Carlo truth information
  - Smeared with measured telescope resolution: ~2um
- Residual width (distribution RMS):
  - Data: 3.7um
  - Simulation: 3.6um

Threshold: 120e



Detector Resolution

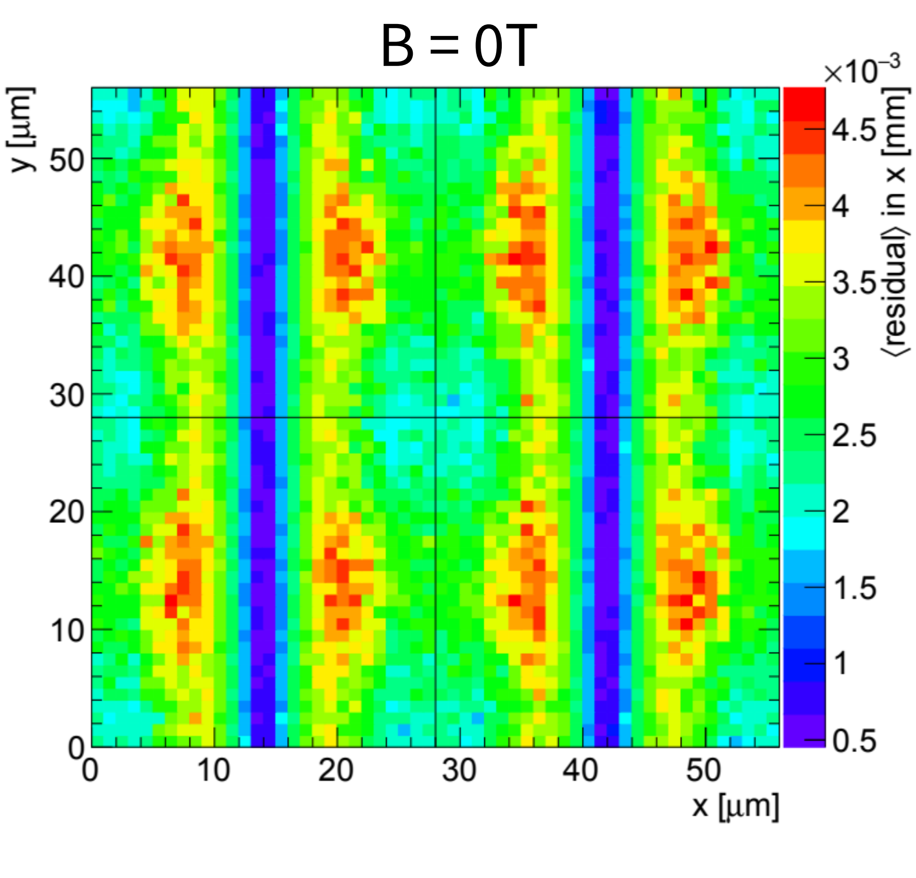
- Threshold scan 40 – 700e
  - No telescope resolution subtracted
- Very good agreement
- Deviations only at lowest threshold
  - Chip designers: “to be expected”
  - Cross-talk/effects in test chip
  - Various, only partially understood noise sources (non-gaussian)
- Relevant range for future chips:
  - 150 – 300e

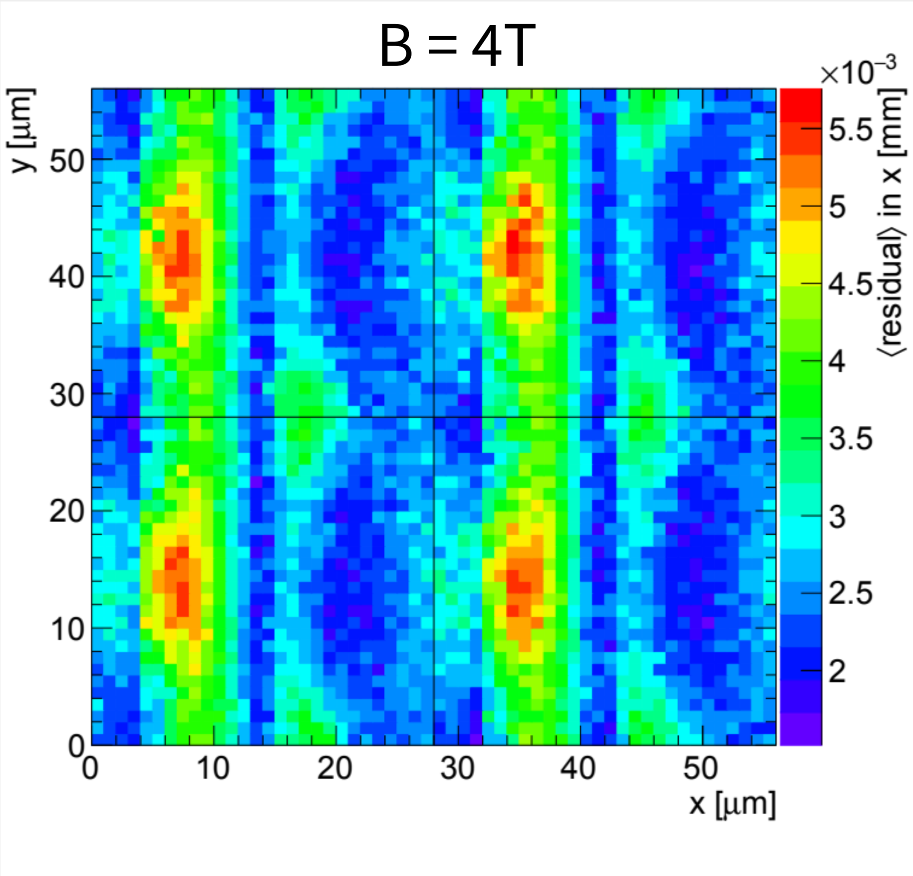


Outlook: Magnetic Fields

- Detectors will be operated in strong magnetic fields
  - Altered charge collection behavior due to additional Lorentz force
  - Performance changes expected
- Test beam measurements in fields very complex
  - Use validated simulation to test performance in magnet
  - Optimize detector geometry (sensor tilt)
- Example:
  - 4T homogeneous magnetic field, parallel to sensor surface
  - Same detector/simulation as before
  - **VMWIP** - Very Much Work In Progress

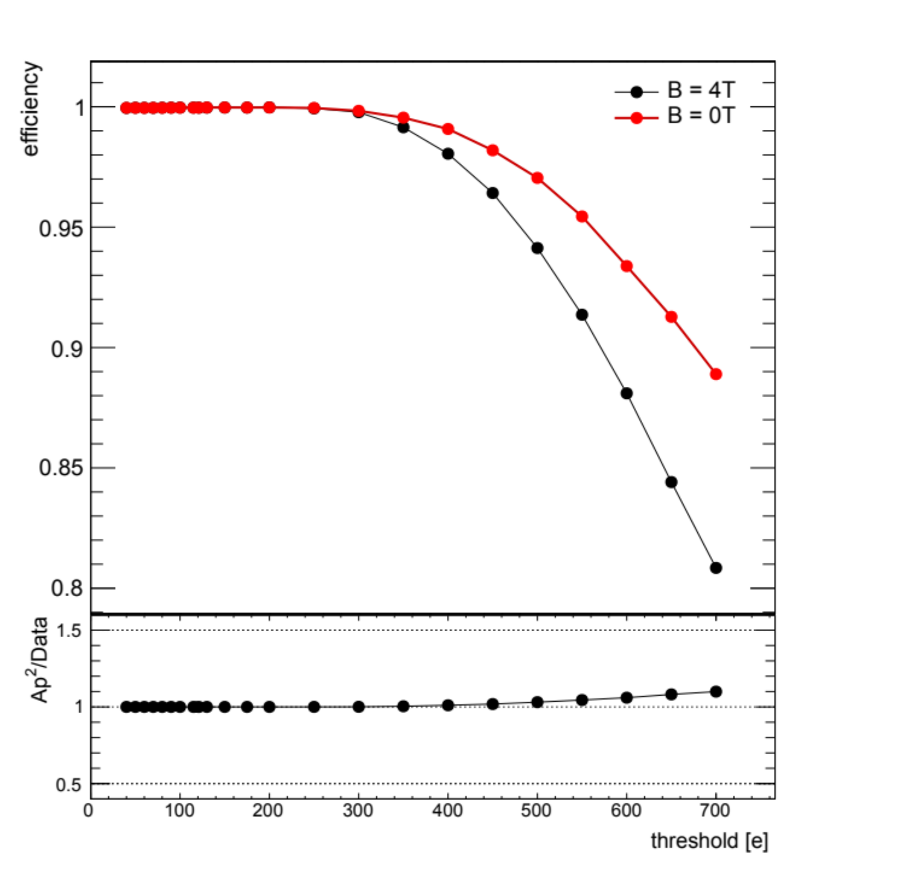
In-Pixel Residual in X – Qualitative Comparison





Efficiency in Magnetic Field

- Efficiency drops earlier
  - Altered charge sharing
  - Earlier drop w/ magnetic field
- Chips expected to be operated at ~< 300e threshold
  - No large impact expected
- Study very preliminary
  - Adapt geometry to CLICTD
  - Validate with test beam data



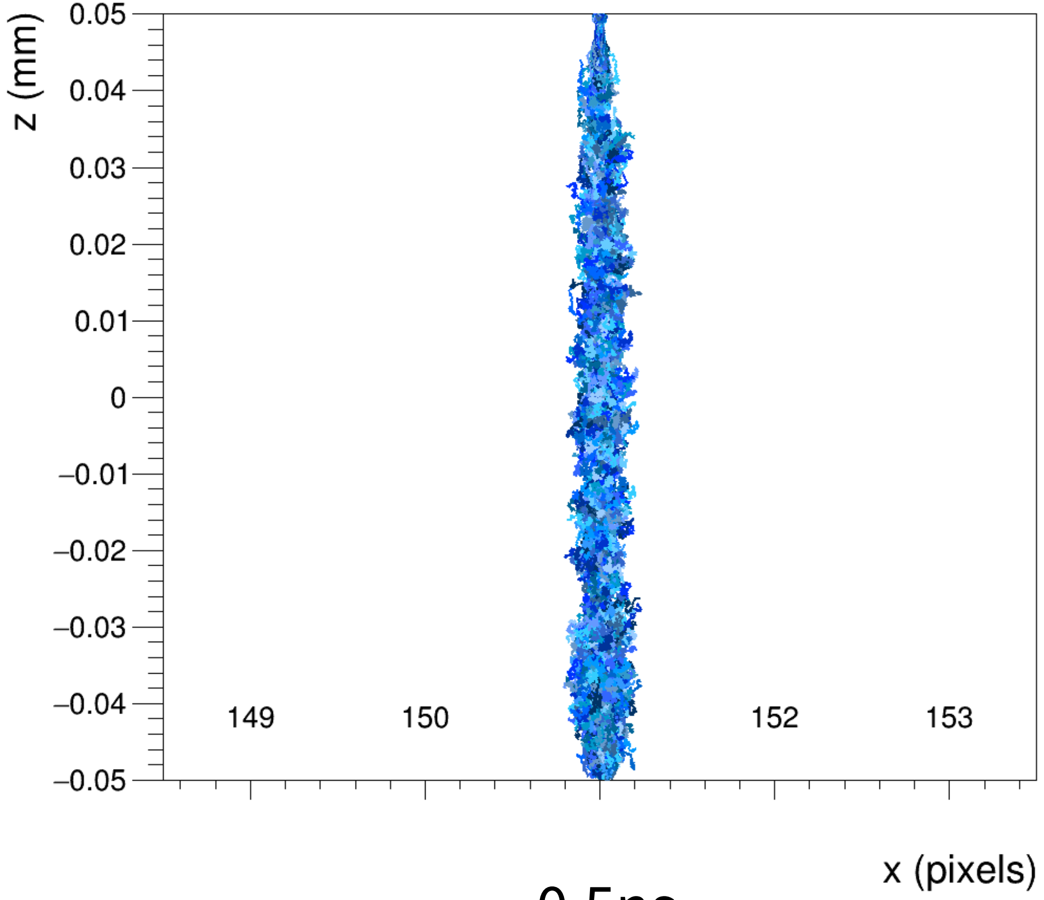
Summary

- **First simulation of HR-CMOS process** combining TCAD & Monte Carlo methods
  - Direct access to performance parameters
  - Allows to gauge HR-CMOS sensor designs
- Simulations **validated with test beam measurements** of ALICE Investigator
  - Very good agreement in most control observables and performance parameters
- Validated simulation can be used to simulate
  - CLICTD chip performance (different geometry, potentially different doping)
  - Behavior under different conditions such as magnetic fields

- > 1.7 kThanks to **Katharina Dort**, CERN Summer Student @ LCD!

CERN

Drift Paths of all Charge Carriers



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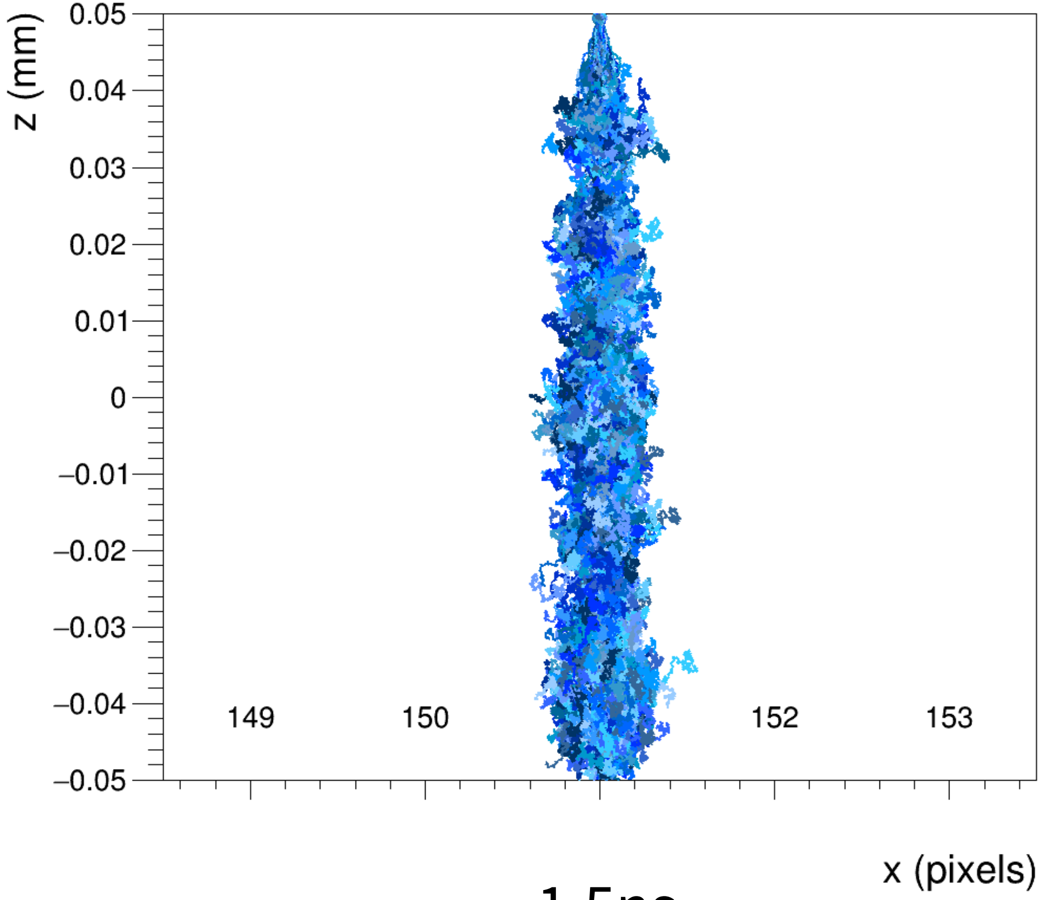
Drift Paths of all Charge Carriers



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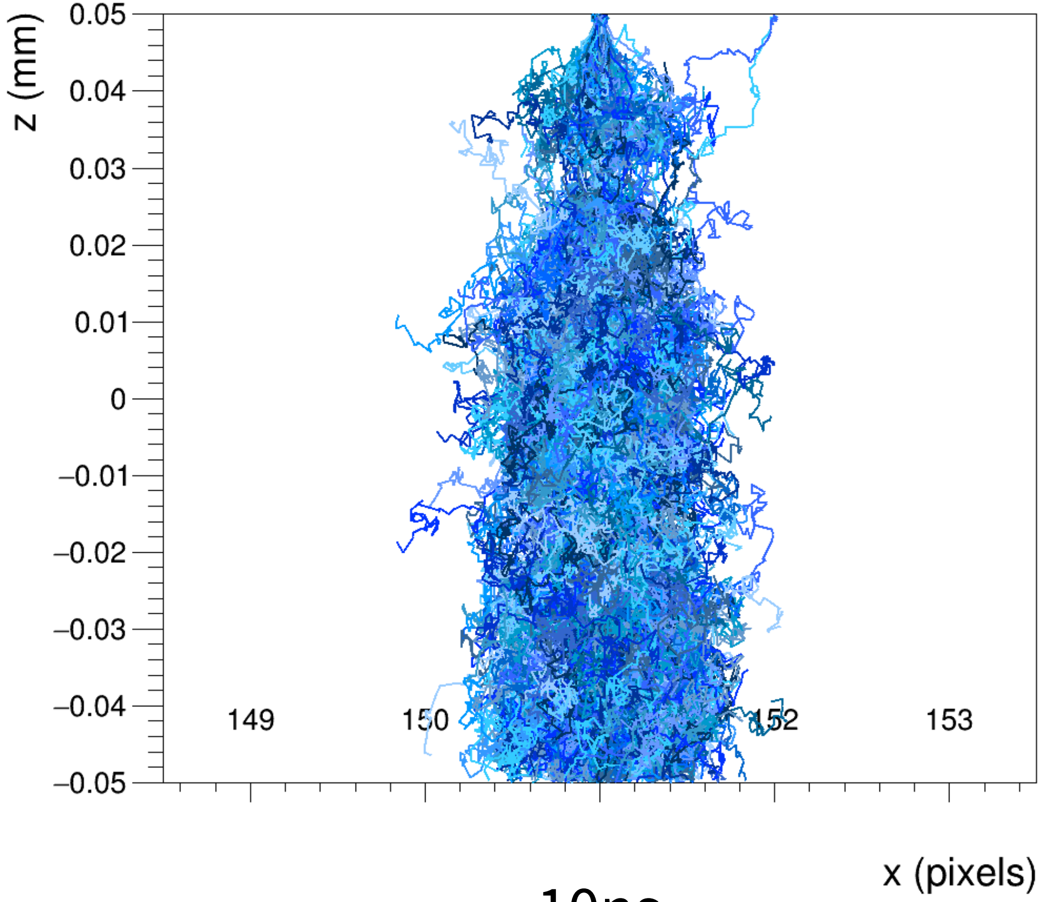
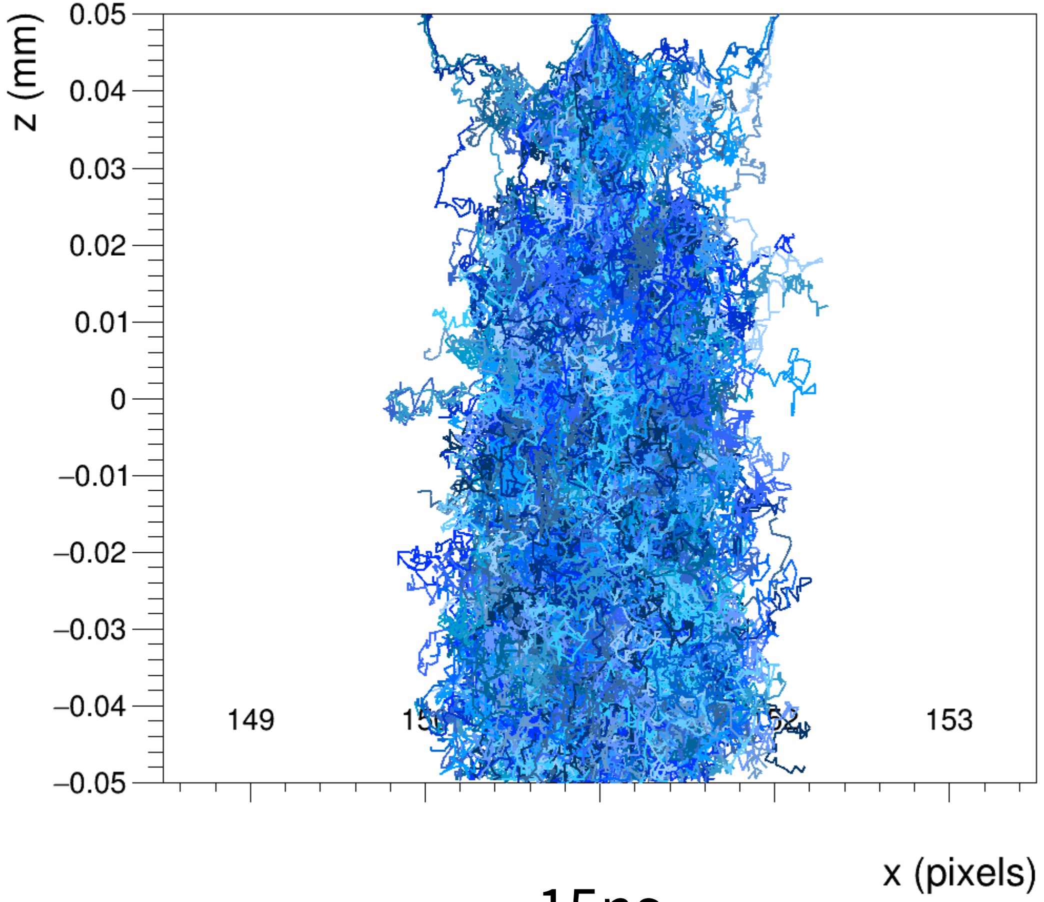
Drift Paths of all Charge Carriers



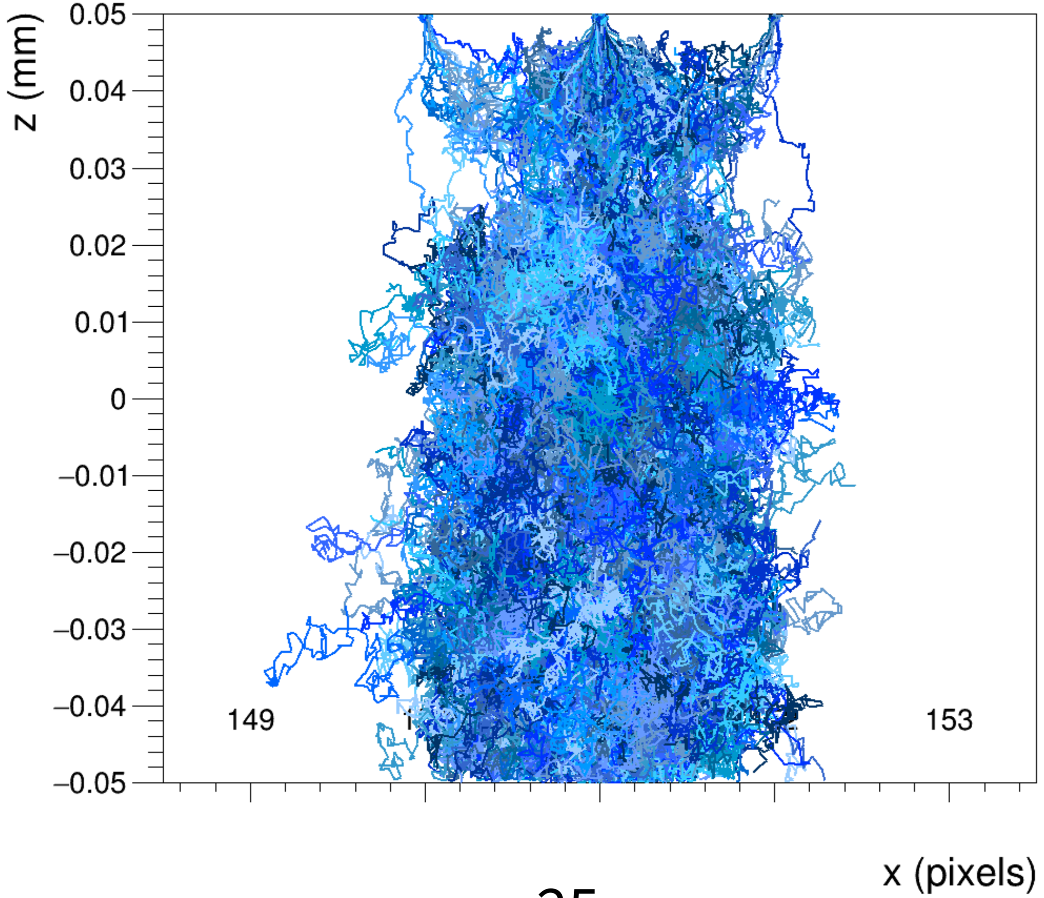
10ns

Drift Paths of all Charge Carriers



15ns

Drift Paths of all Charge Carriers



25ns