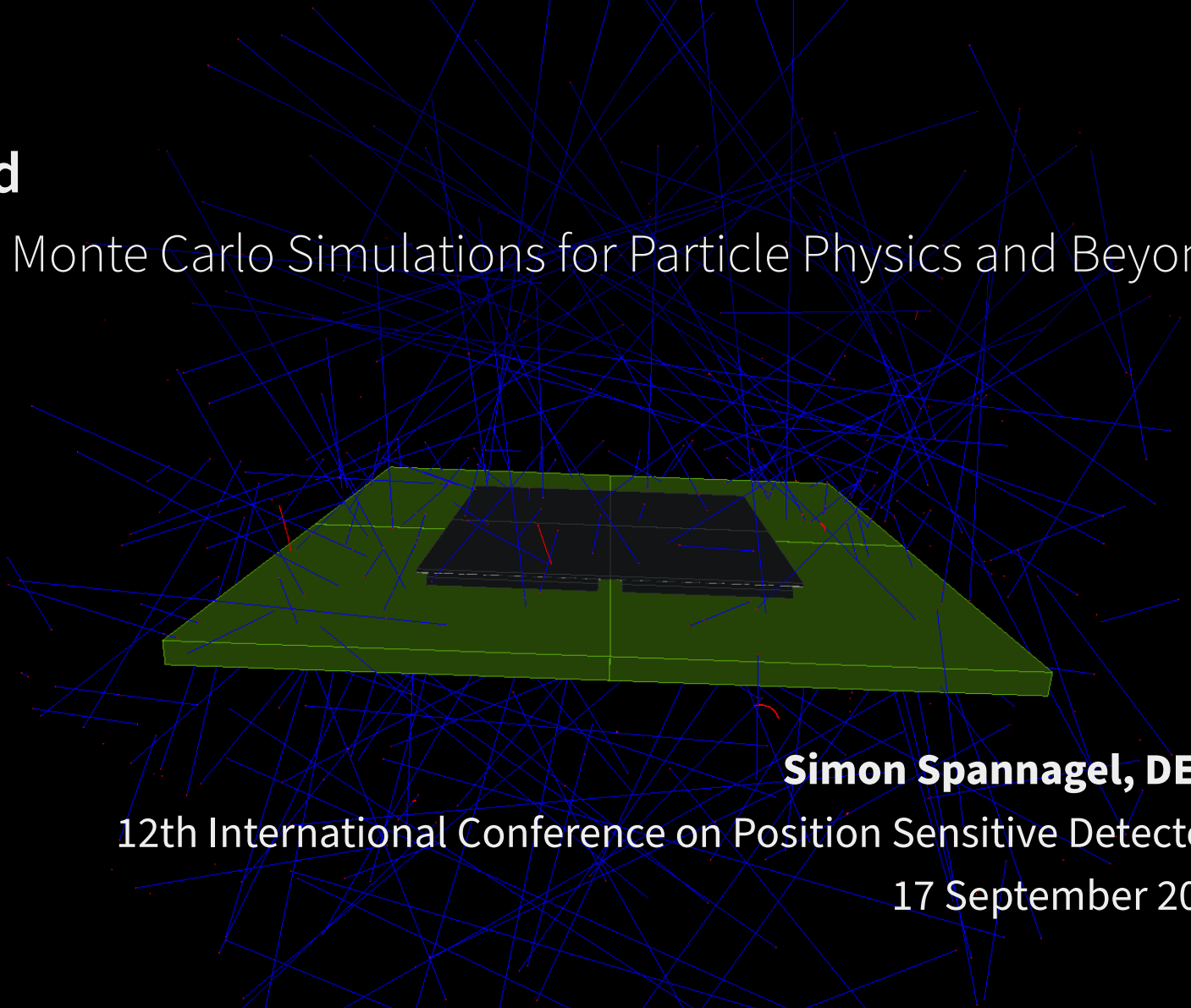
cern.ch/allpix-squared

Allpix Squared

Silicon Detector Monte Carlo Simulations for Particle Physics and Beyond



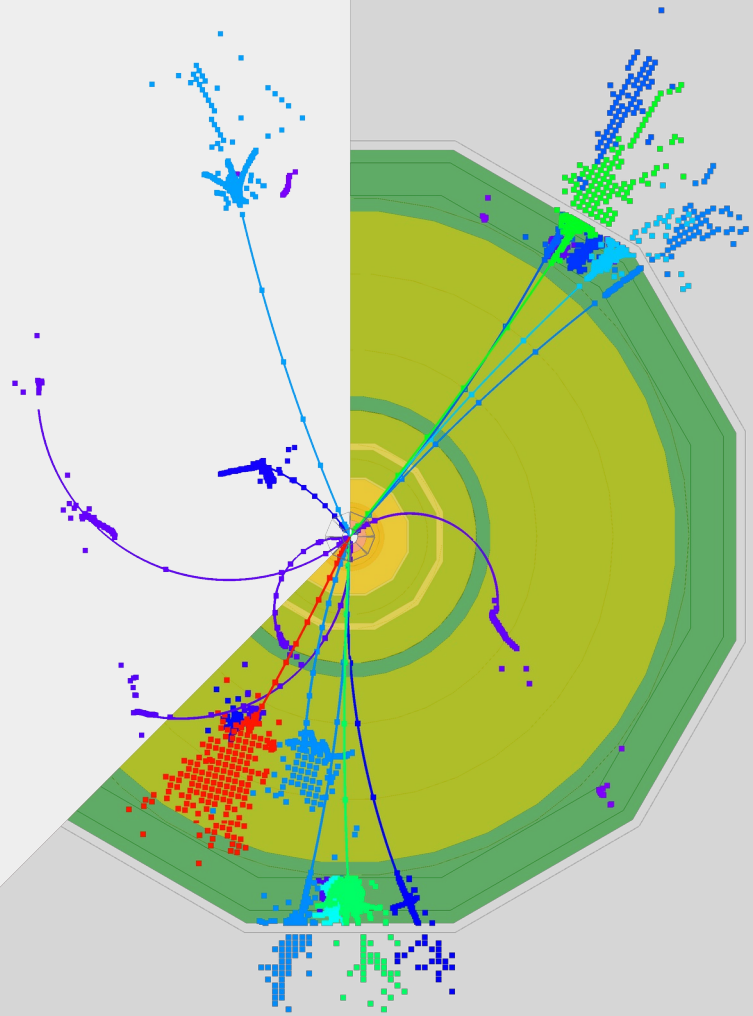
Simon Spannagel, DESY

12th International Conference on Position Sensitive Detectors

17 September 2021

Silicon Detectors

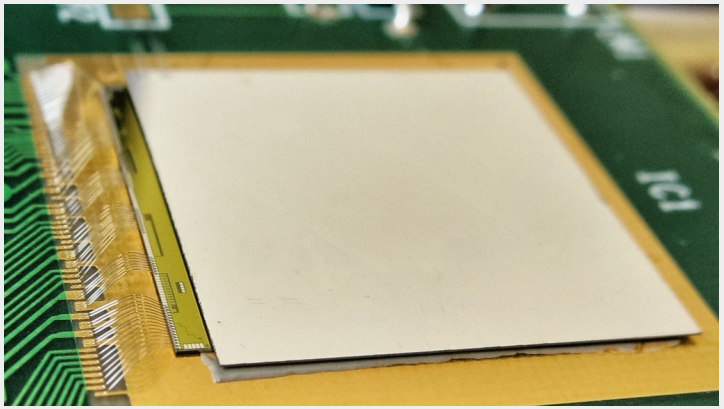
in Particle Physics



Silicon Detectors in Particle Physics

Demands on detectors are high:

- Very high particle flux, tens of MHz / cm^2
- Maximum resolution, minimum (scattering-) mass
- Very high granularity for high particle rates,
  fast readout, minimal dead time (few ns)
- “Smart” detectors
  (zero suppression, clustering, on-chip processing, fast data links)

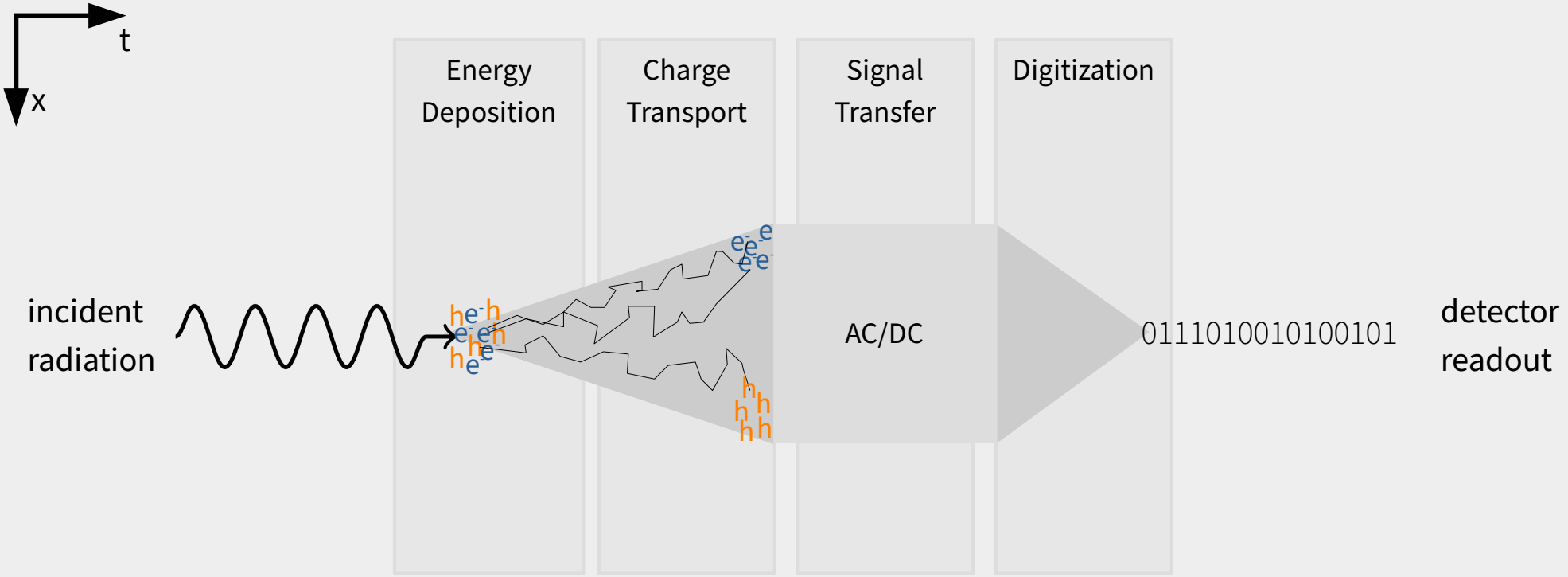


100 µm Timepix with 100 µm Sensor

Many different technologies used for different purposes:
hybrid – dedicated sensor + mixed-mode CMOS, monolithic CMOS imaging, LGADs, 3D sensors, …

- Simulations required for thoroughly understanding detector performance in realistic conditions
- Tools needed to cover wide range of detector technologies

Minimum Ionizing Particle Detector – Broken Down



The Allpix Squared Framework

for Silicon Detector Monte Carlo Simulations

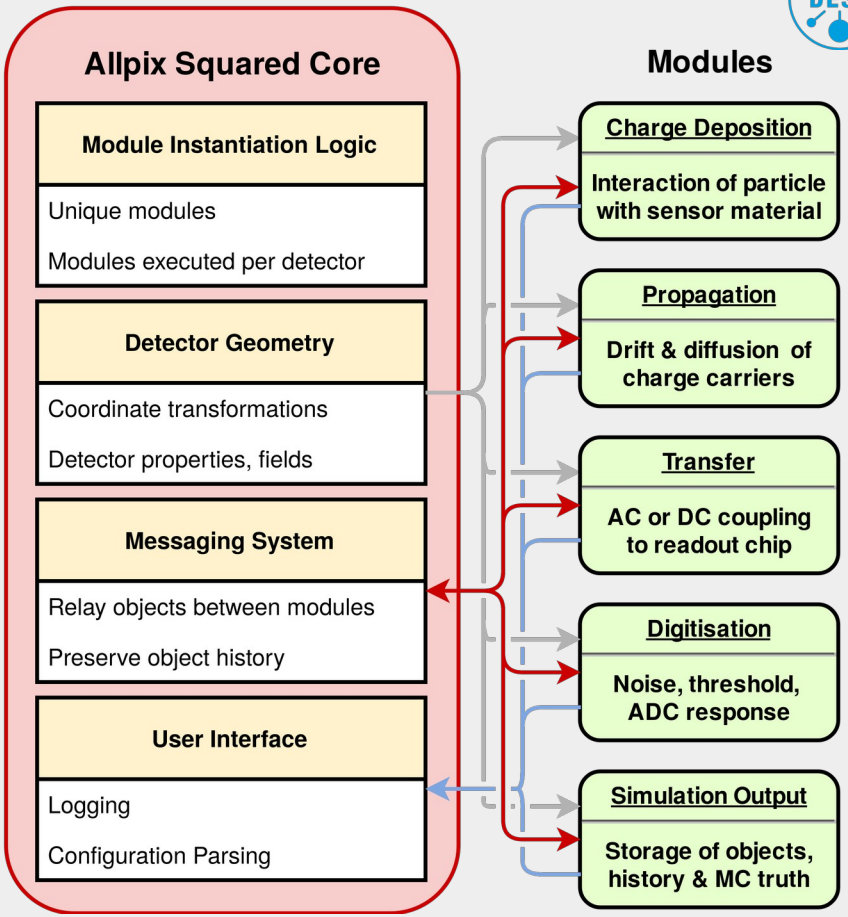
The Allpix² Framework

- Proliferation of many different codes for detector simulation:

  Experiment-specific, specialized on specific detectors, written as part of a PhD thesis, abandoned afterwards

- **Wanted:** flexible MC simulation software with…
  I. Integration of Existing Toolkits
  II. Well-Tested & Validated Algorithms
  III. Low Entry Barrier for New Users
  IV. Clean & Maintainable Code

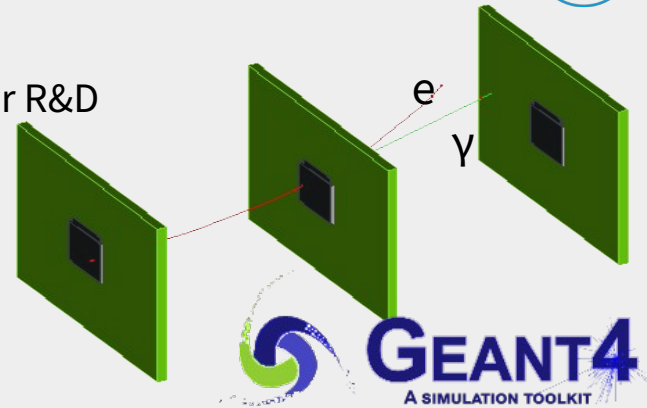
→ **Allpix²:** first release 08/2017, 26 releases since



NIMA 901 (2018) 164 – 172
doi:10.1016/j.nima.2018.06.020

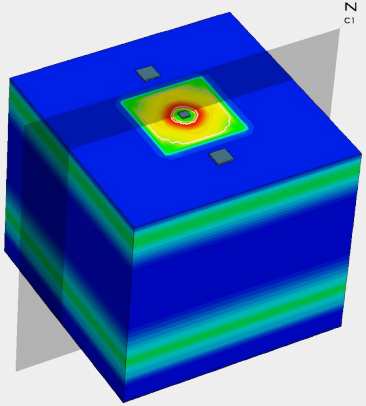
I. Integration of Existing Toolkits

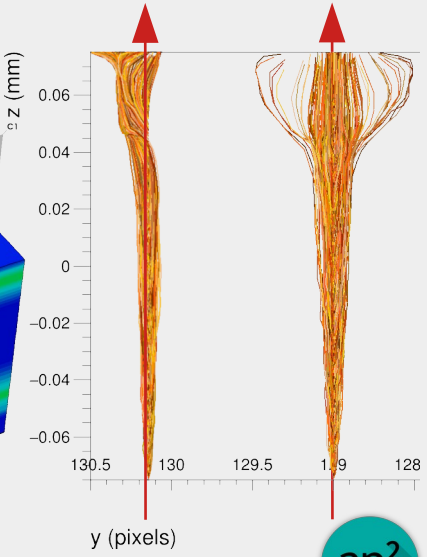
- Many very powerful tools developed and employed over decades of detector R&D
  Leverage their capabilities by providing interfaces for their integration



- **Geant4** – simulating energy deposition of particles passing through matter
  - Extensive toolkit, detailed simulation of many interactions & processes
  - Cumbersome to use for beginners, complexity often overwhelming at first
  - Provide abstraction layer that auto-generates models and calls Geant4 kernel

- **TCAD** – solving Poisson's equation using doping information
  - Detailed understanding of field configuration, sensor behavior
  - Tools & knowledge widely spread in community
  - Provide possibility to import results to complement MC simulations





II. Well-Tested & Validated Algorithms

- Simulations provide insights into physical processes – but only if they model them correctly!
  Validation of algorithms is a crucial and time-consuming process

- With Allpix Squared, we strive for
  - Validating as much as possible against known data
  - Publishing reference studies including full simulation configuration used
  - Providing automated tests for every new feature

- User workshops for exchange of the community, discussions, planning…


Nuclear Inst. and Methods in Physics Research, A

Allpix²: A modular simulation framework for silicon detectors

NIMA 901 (2018) 164 – 172
doi:10.1016/j.nima.2018.06.020


Nuclear Inst. and Methods in Physics Research, A

Combining TCAD and Monte Carlo methods to simulate CMOS pixel sensors with a small collection electrode using the Allpix² framework

NIMA 964 (2020) 163784
doi:10.1016/j.nima.2020.163784


Combining Electrostatic Finite-Element and Transient Monte Carlo Simulations for the Optimization and Characterization of Silicon Sensors

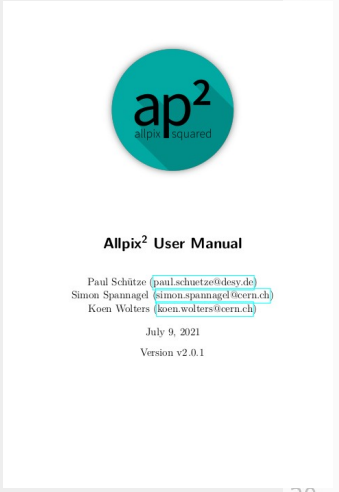
In preparation…

III. Low Entry Barrier for New Users

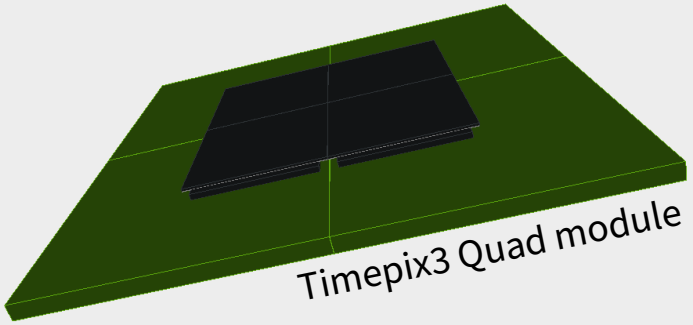
- Simulation frameworks often very complex:
  code complexity, lack of documentation, physics

- Allpix Squared attempts to facilitate quick starts:
  - Extensive documentation / user manual / help forum
  - Human-readable configuration files
  - Support for physical units
  - No coding or code-reading required

- Successfully used e.g. in university education, summer schools, …

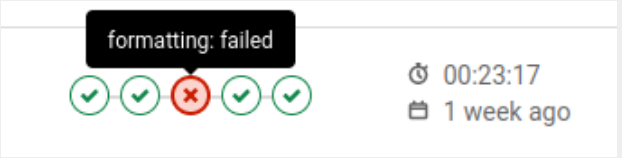



```
[AllPix]
log_level = "INFO"
number_of_events = 500000
detectors_file = "telescope.conf"

[GeometryBuilderGeant4]
world_material = "air"

[DepositionGeant4]
physics_list = FTFP_BERT_LIV
particle_type = "Pi+"
number_of_particles = 1
beam_energy = 120GeV
# ...

[ElectricFieldReader]
model="linear"
bias_voltage=150V
depletion_voltage=50V

[GenericPropagation]
temperature = 293K
charge_per_step = 10
spatial_precision = 0.0025um
timestep_max = 0.5ns

[SimpleTransfer]
```

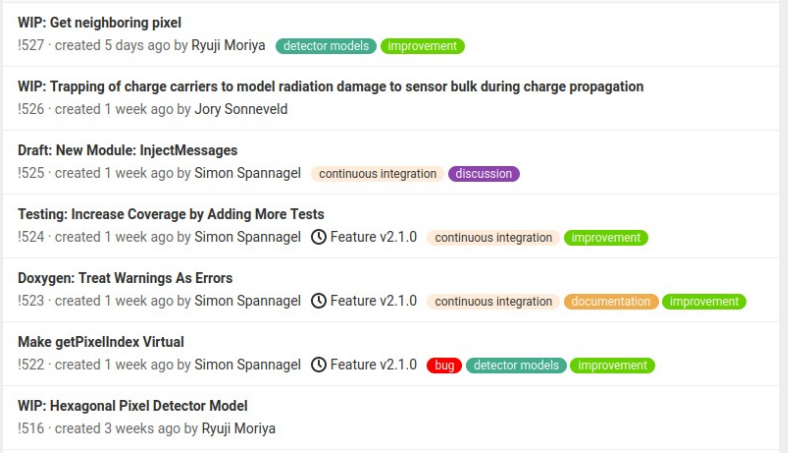


IV. Clean & Maintainable Code

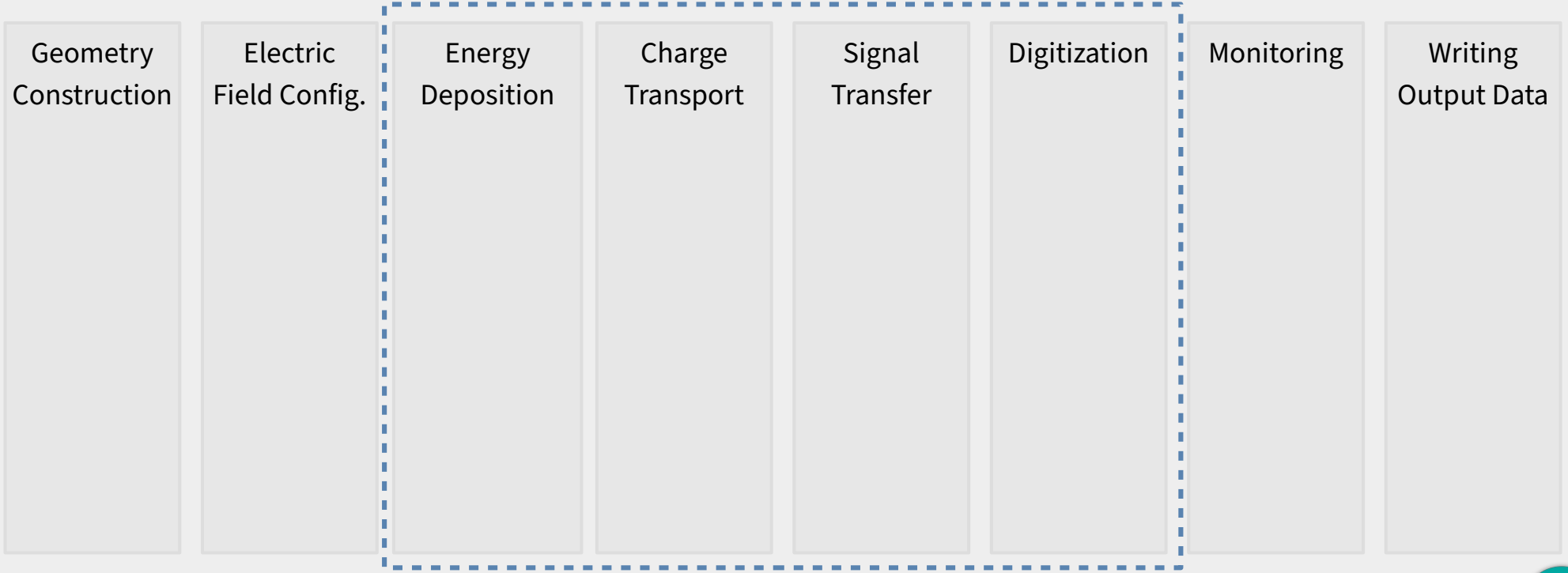
- Collaborative software development requires well-defined procedures – Otherwise quickly becomes unmaintainable



- Allpix Squared implements *best practices* for software development
  - Permissive open-source license: MIT
  - Extensive code reviews via merge requests
  - Strict enforcement of coding conventions & formatting
  - Regular static code analysis

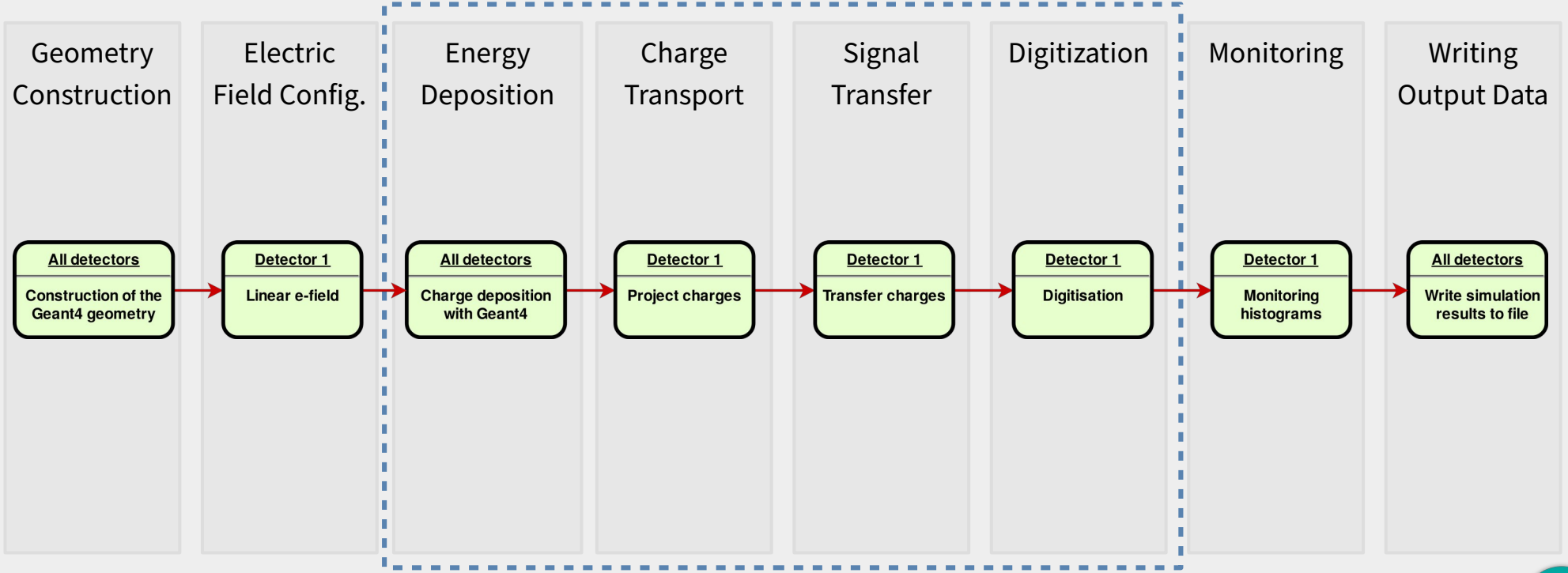


The Simulation Chain



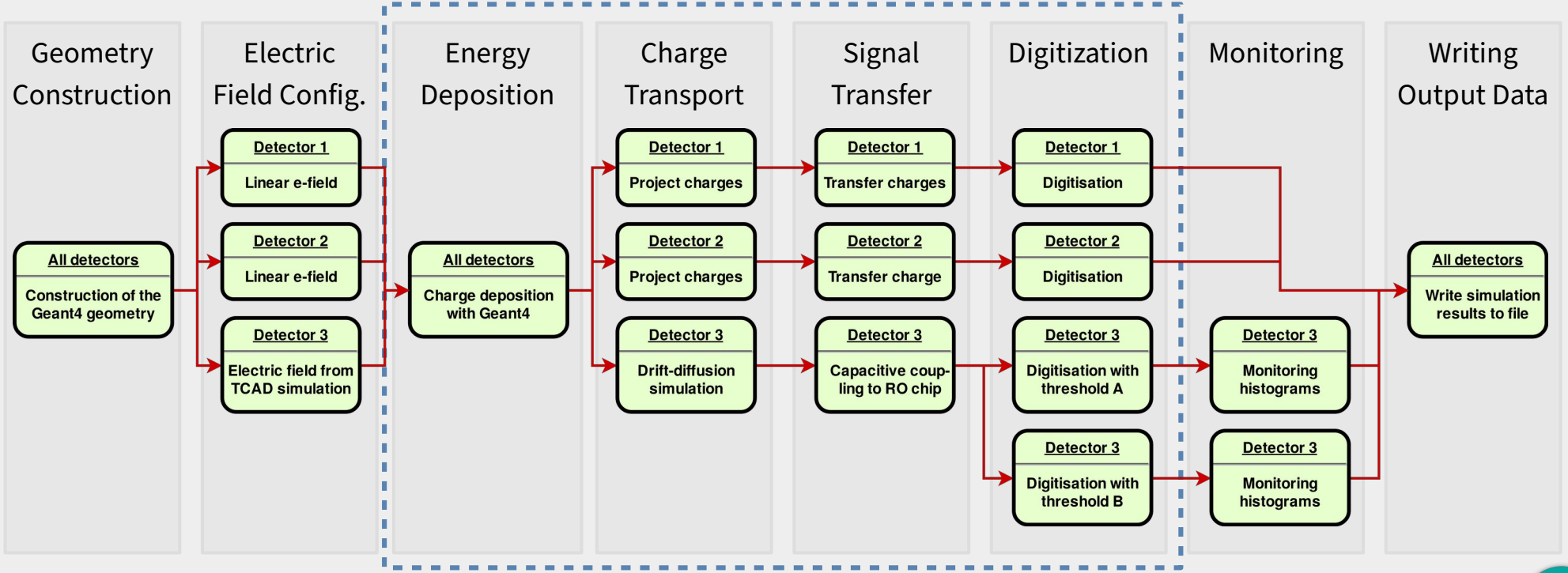
The Simulation Chain

- Building blocks follow individual steps of signal formation in detector
- Algorithms for each step can be chosen independently



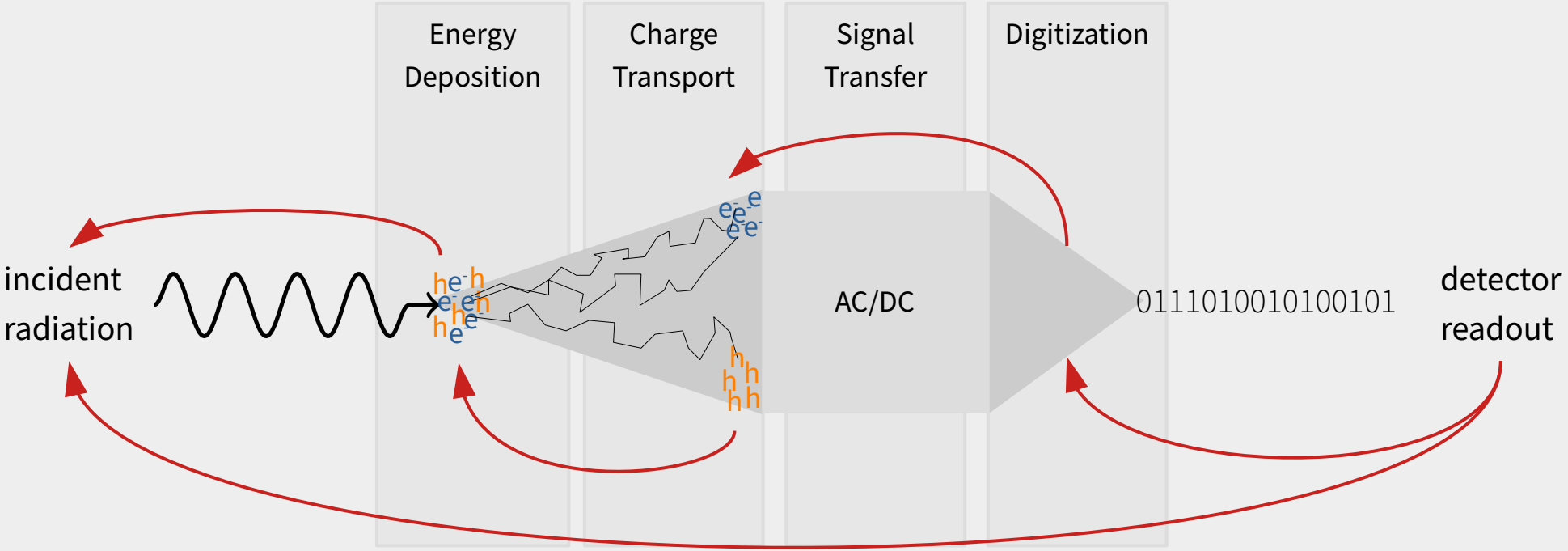
The Simulation Chain

- Simulation very flexible: modules configurable on per-detector level
- Multiple instances can be run in at the same time (e.g. to simulate different front-ends)



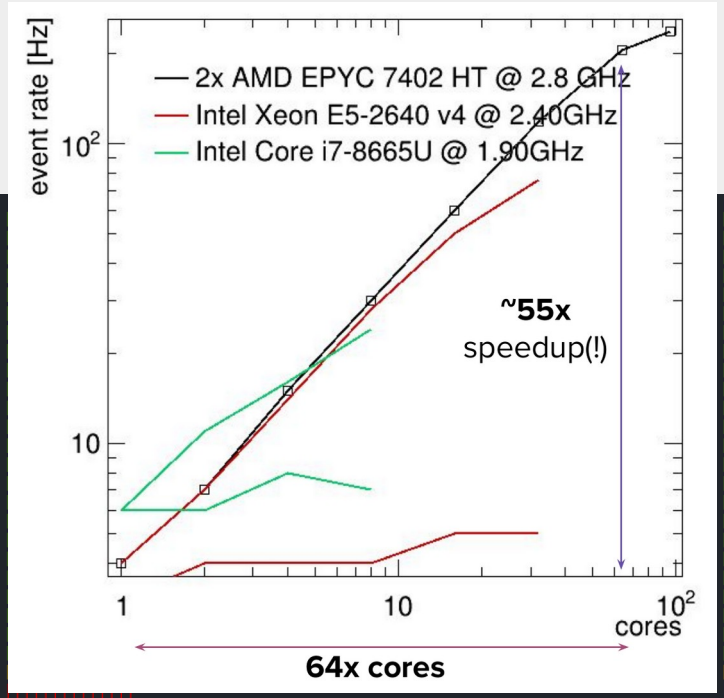
The Monte Carlo Truth

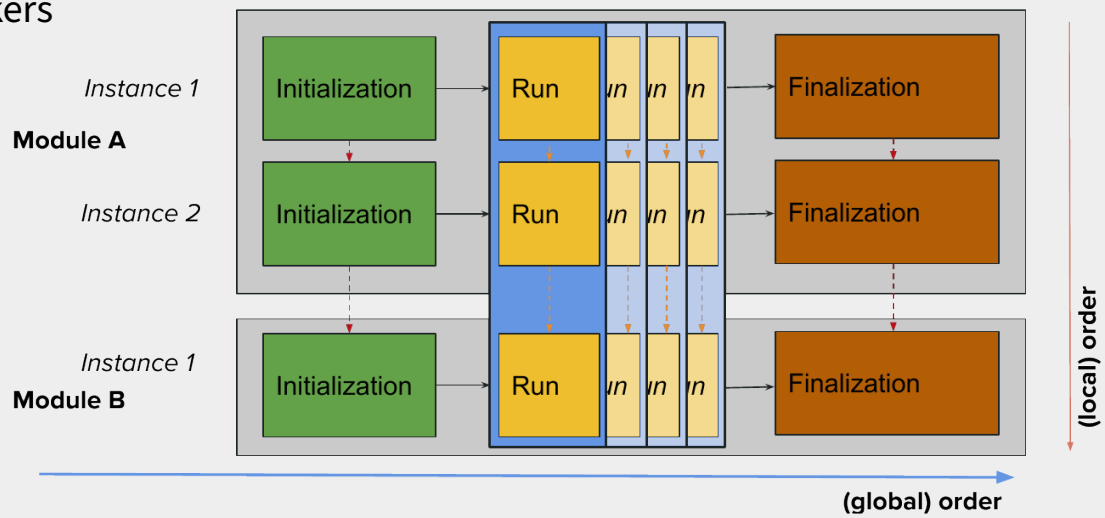
- Allpix^2 keeps history for all simulated objects
- Cross-references available for detailed analysis



Multithreading Support

- Allpix Squared supports event-based multithreading while retaining strong reproducibility:
  - exact same result, independent of number workers
  - fully transparent to user / simulation

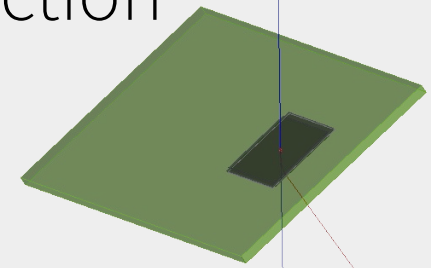




Allpix² fully utilizing 96 cores

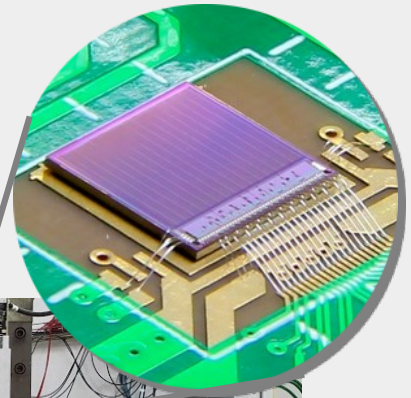
Application Examples

CMOS Sensors, Calorimetry, Neutron Detection

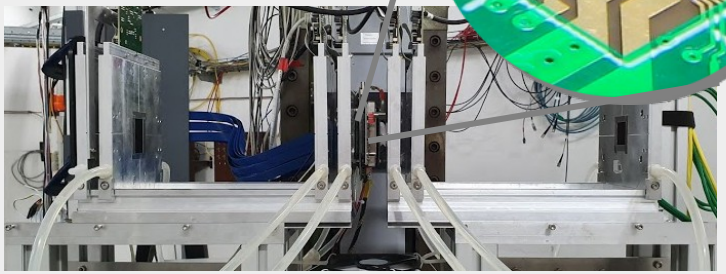


Signal formation in CLICTD MAPS Prototypes

K. Dort, Universität Gießen / CERN

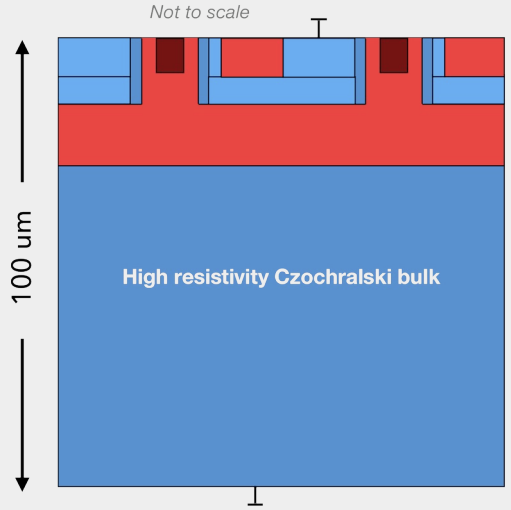


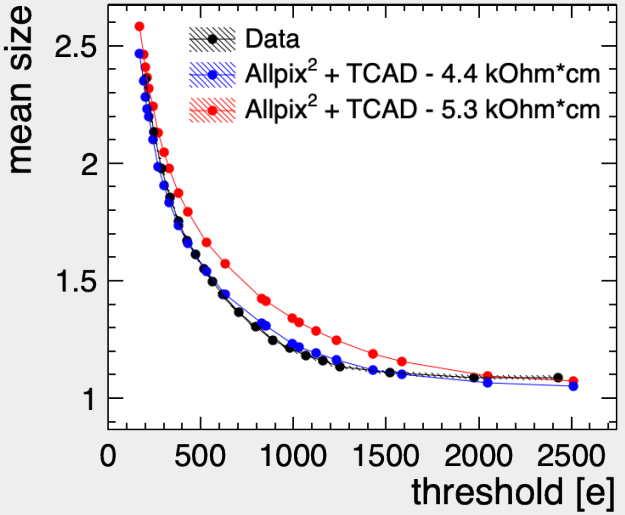
- Combining simulation tools for high-statistics MC studies of CLICTD protoypes
  - Electrostatic sensor simulation from **TCAD**
  - Energy deposition, drift through field, induced current in **Allpix Squared**
  - Comparison to data recorded at DESY II Test Beam Facility



- Samples produced on high-resistivity Czochralski substrate
- Doping not precisely known
- Using simulation to confirm

IEEE TNS, vol. 67, no. 10 (2020), 2263
doi:10.1109/TNS.2020.3019887
NIMA 964 (2020) 163784
doi:10.1016/j.nima.2020.163784

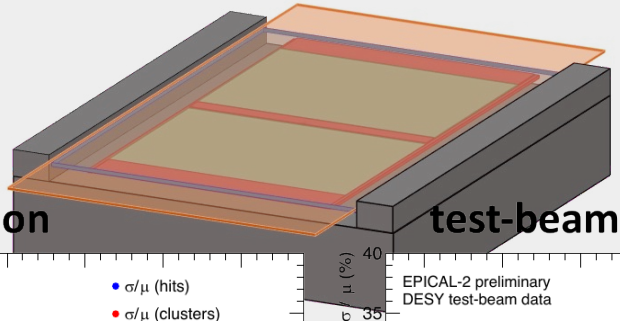


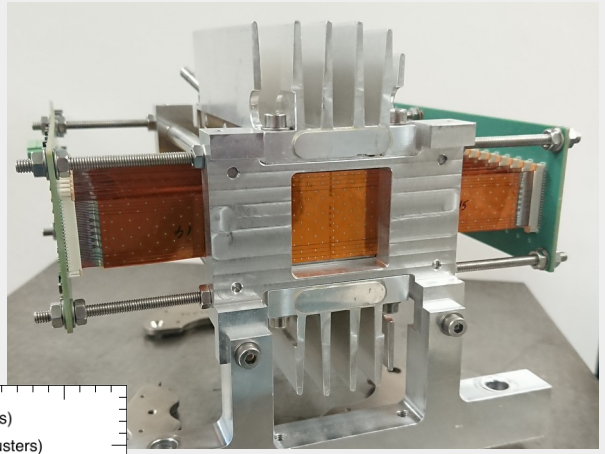


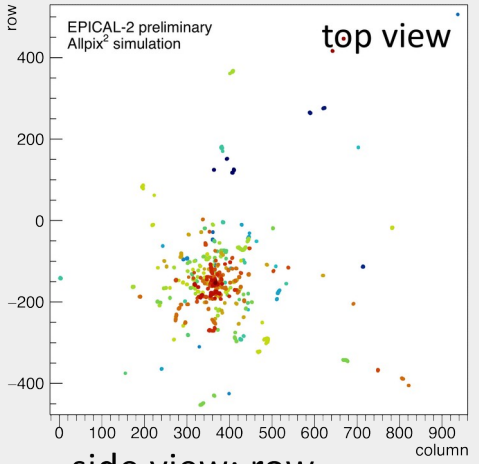
EPICAL-2: Electromagnetic Pixel Calorimeter

T. Rogoschinski, Universität Frankfurt

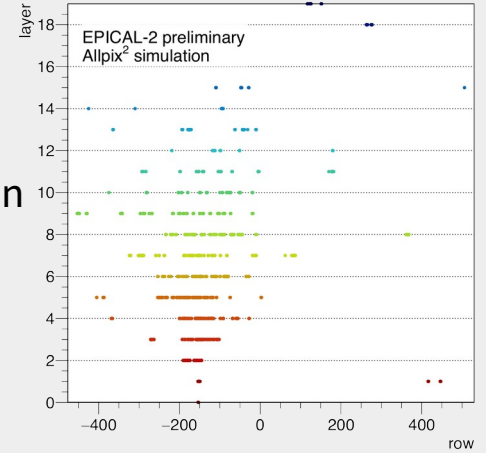
- Forward EM calorimeter for ALICE experiment
- 24 layers ALPIDE, 3mm tungsten absorbers



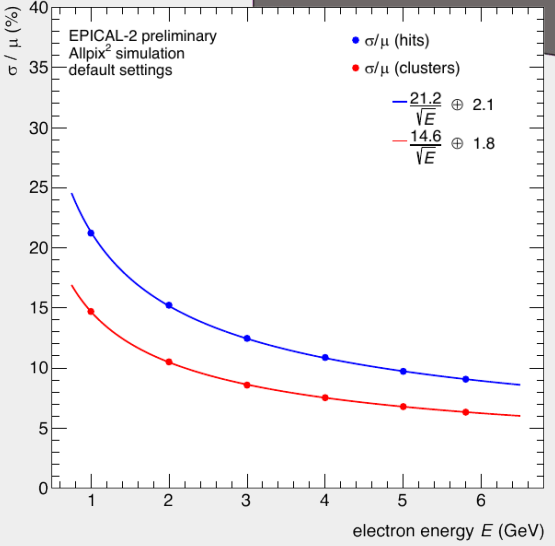




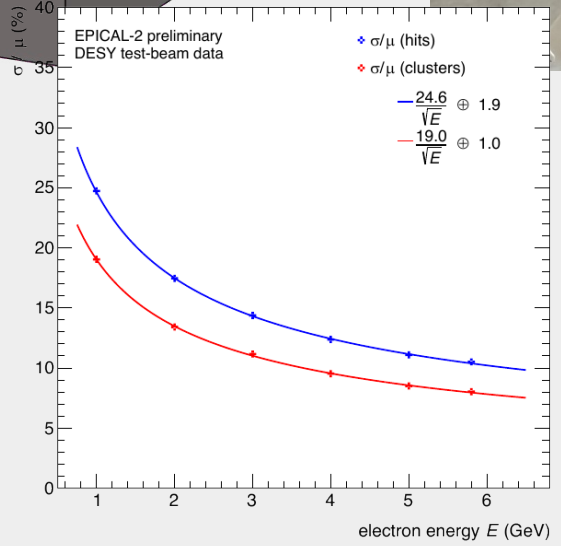
side view: row



simulation



test-beam data

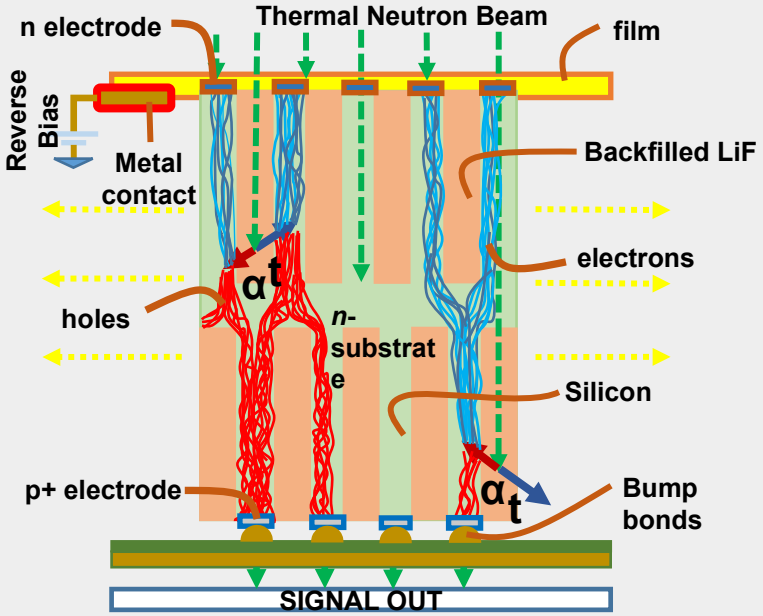


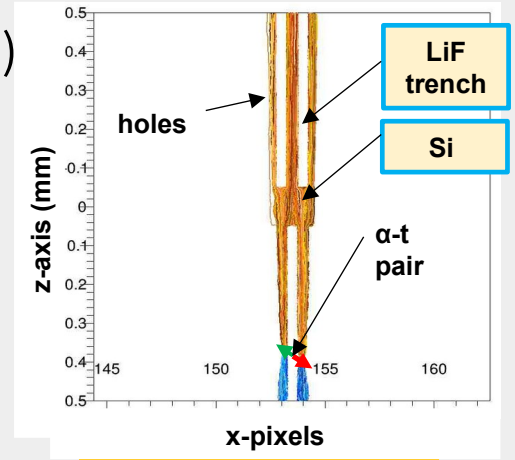
- Calorimeter simulation in Allpix Squared
- Good agreement of simulation and test beam data
- Adjustments of beam profile & energy spectrum underway

Dual Sided Micro-Structured Neutron Detector

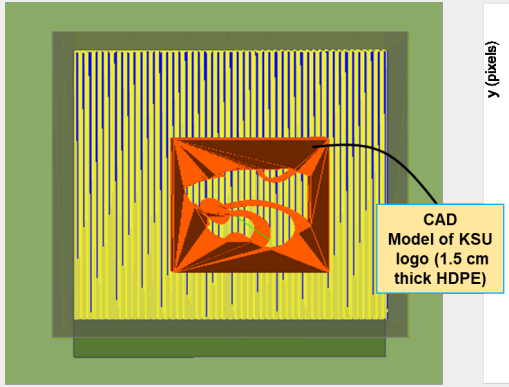
S. Sharma, Kansas State University

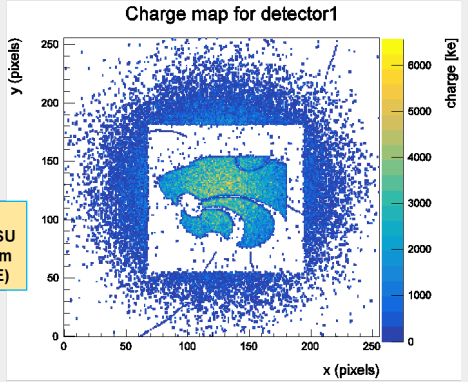
- n-type Si sensor with LiF trenches for neutron conversion ($n \rightarrow t + \alpha$)
- COMSOL used to generate electric field maps
- Allpix Squared used to simulate entire detection system





Line plot of a typical neutron cluster

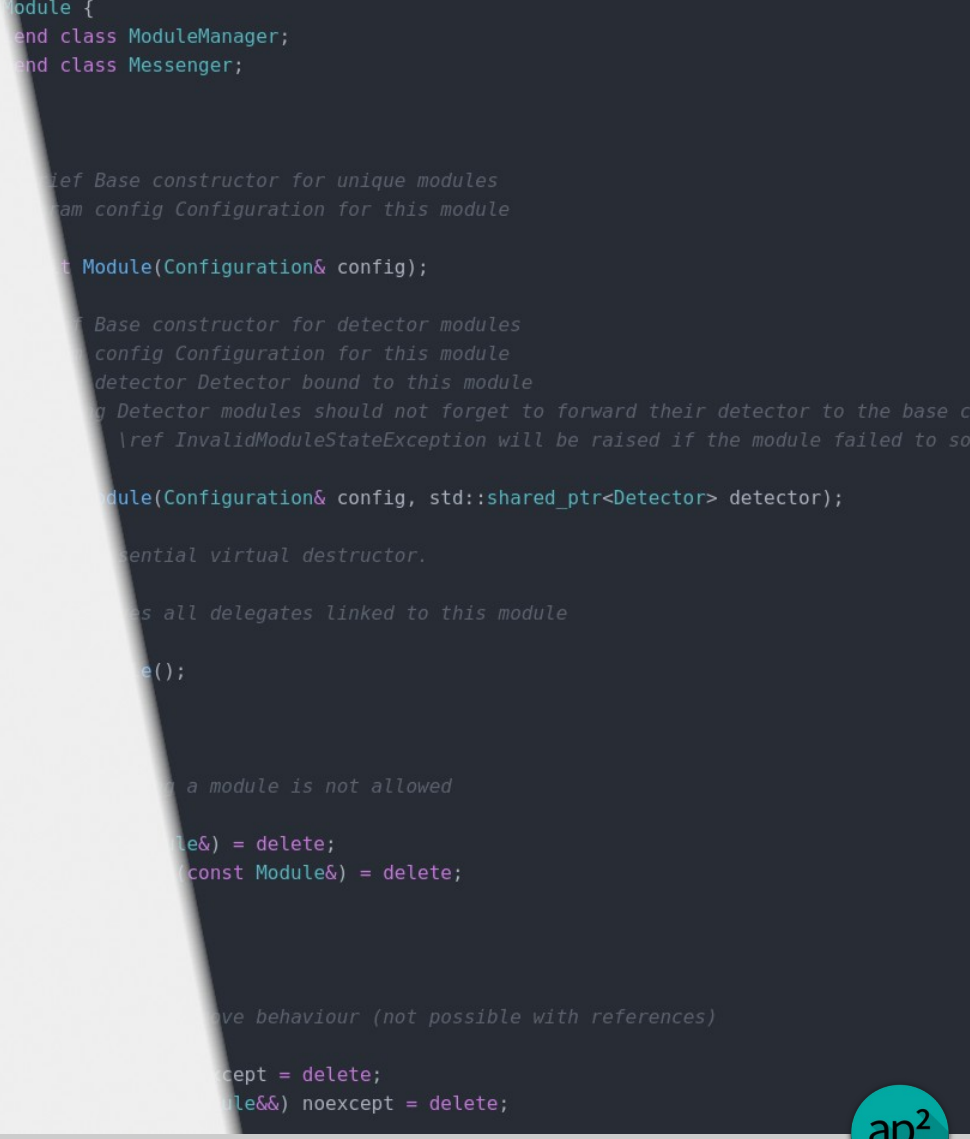




Imaging result from 0.0253 eV Mono-energetic beam of neutrons

Ongoing Projects

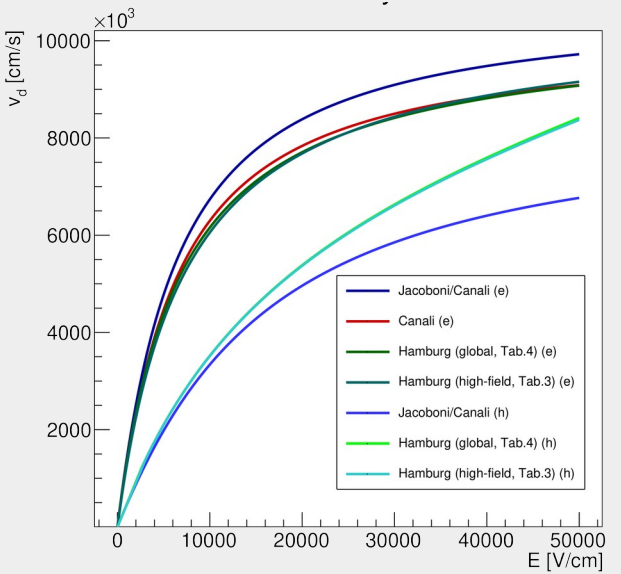
and Developments



Mobility & Recombination

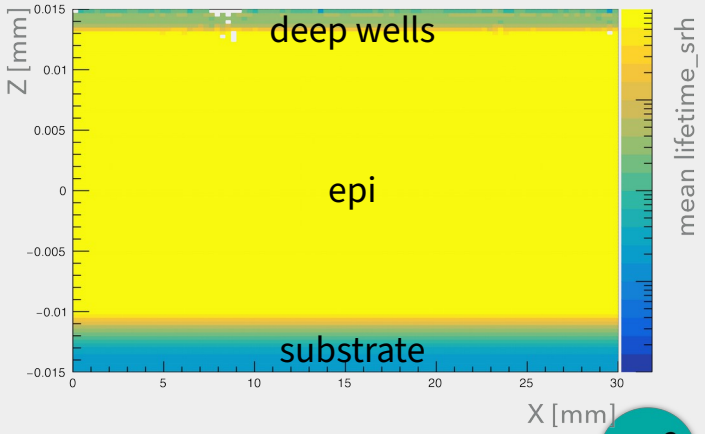
- Introduced possibility to select charge carrier mobility model
  - Field dependent
  - Doping concentration dependent
  - Optimized for high-field situations
  - …

```
[GenericPropagation]
temperature = 293K
mobility_model = "masetti"
```



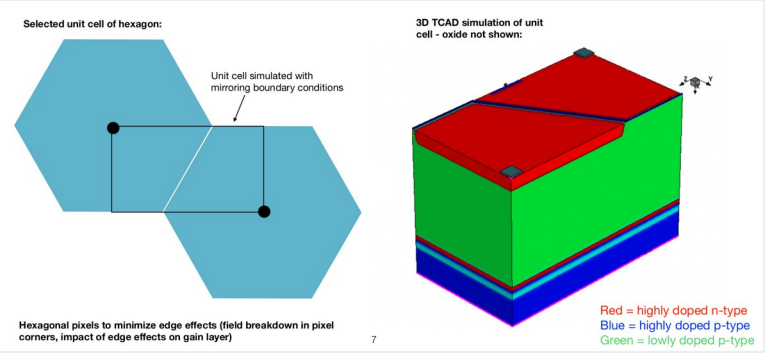
- With fast signal formation: all e/h pairs reach electrodes
- Finite charge carrier lifetime interesting in:
  - High-dopant regions
  - Low electric fields, signal formation via diffusion
- Support for position-dependent doping maps & lifetime calculation
  - Using combined Shockley-Read-Hall & Auger recombination

K. Dort



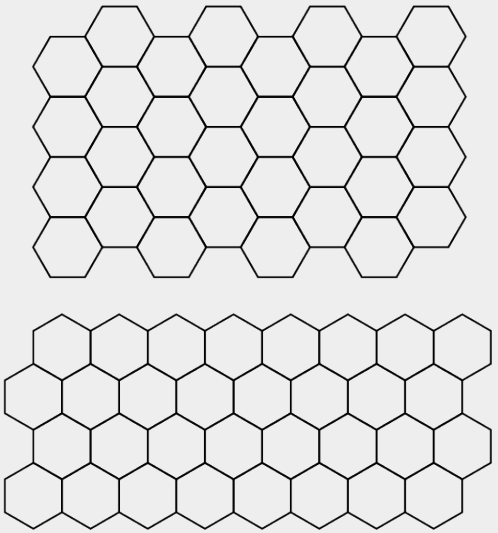
Hexagonal Pixel Geometries

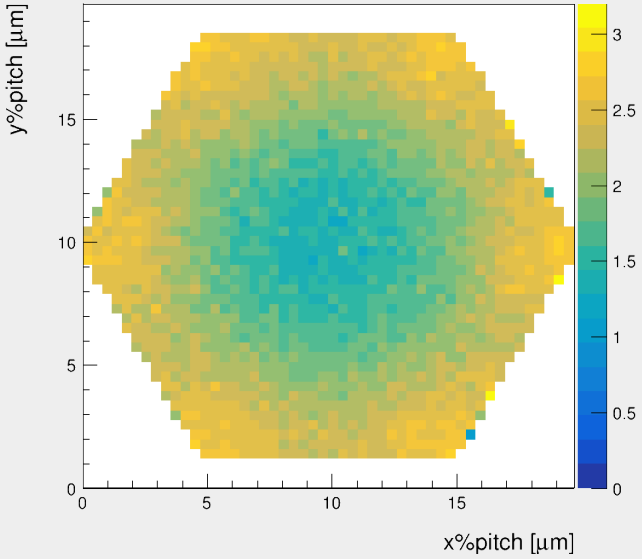
- More flexible geometry to support different pixel shapes
- Hexagonal geometry interesting for many applications
  - Avoid problematic field regions in corners
  - Symmetry more close to circle
    – more uniform response



MONOLITH – M. Munker / Uni Genève

- Other geometries also in preparation
  e.g. radial strips (ATLAS ITk)





Summary

- Silicon Detector Monte Carlo simulations:
  vital component of understanding & interpreting detector performance

- Allpix Squared:
  comprehensive MC simulation framework for silicon detectors
  - integrates existing toolkits
  - provides validated algorithms
  - is easy-to-get-started and well documented
  - has a clean and solid code bases

- Used in many areas: CMOS sensors, calorimetry, DSMS neutron detectors, …
- Continuous development and support, many new features already underway

Allpix Squared Resources

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

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

Docker Images
https://gitlab.cern.ch/allpix-squared/allpix-squared/container_registry

User Forum:
https://cern.ch/allpix-squared-forum/

Mailing Lists:

allpix-squared-users https://e-groups.cern.ch/e-groups/Egroup.do?egroupId=10262858

allpix-squared-developers https://e-groups.cern.ch/e-groups/Egroup.do?egroupId=10273730

User Manual:
https://cern.ch/allpix-squared/usermanual/allpix-manual.pdf


DESY.