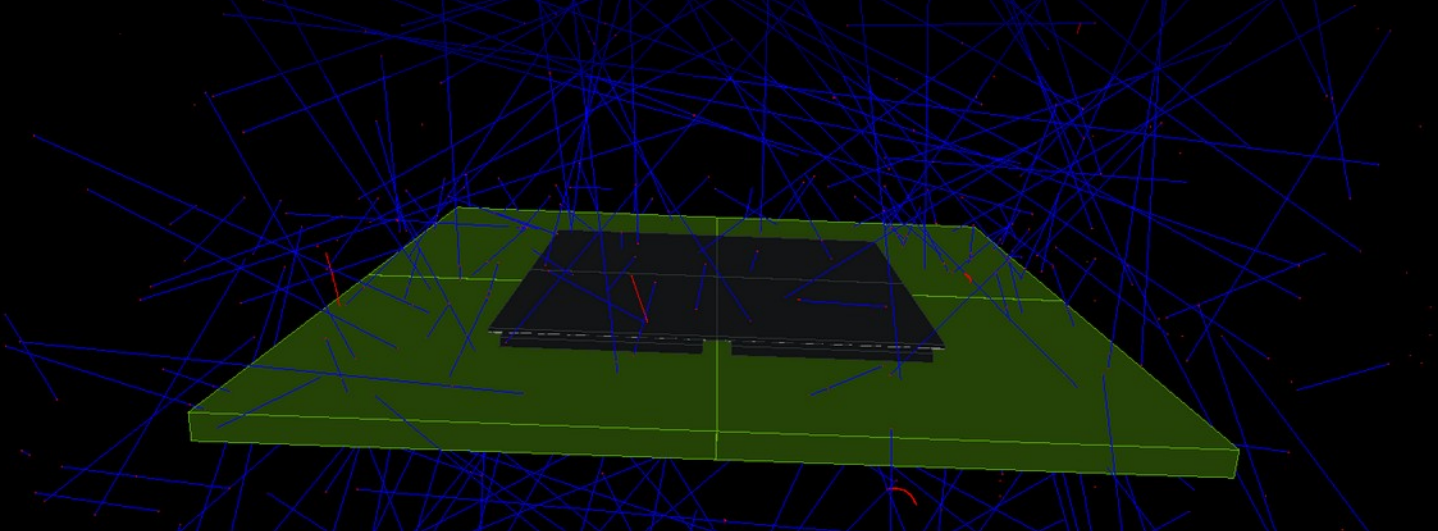
cern.ch/allpix-squared

The Allpix Squared Framework

Silicon Detector Monte Carlo Simulations for Particle Physics and Beyond

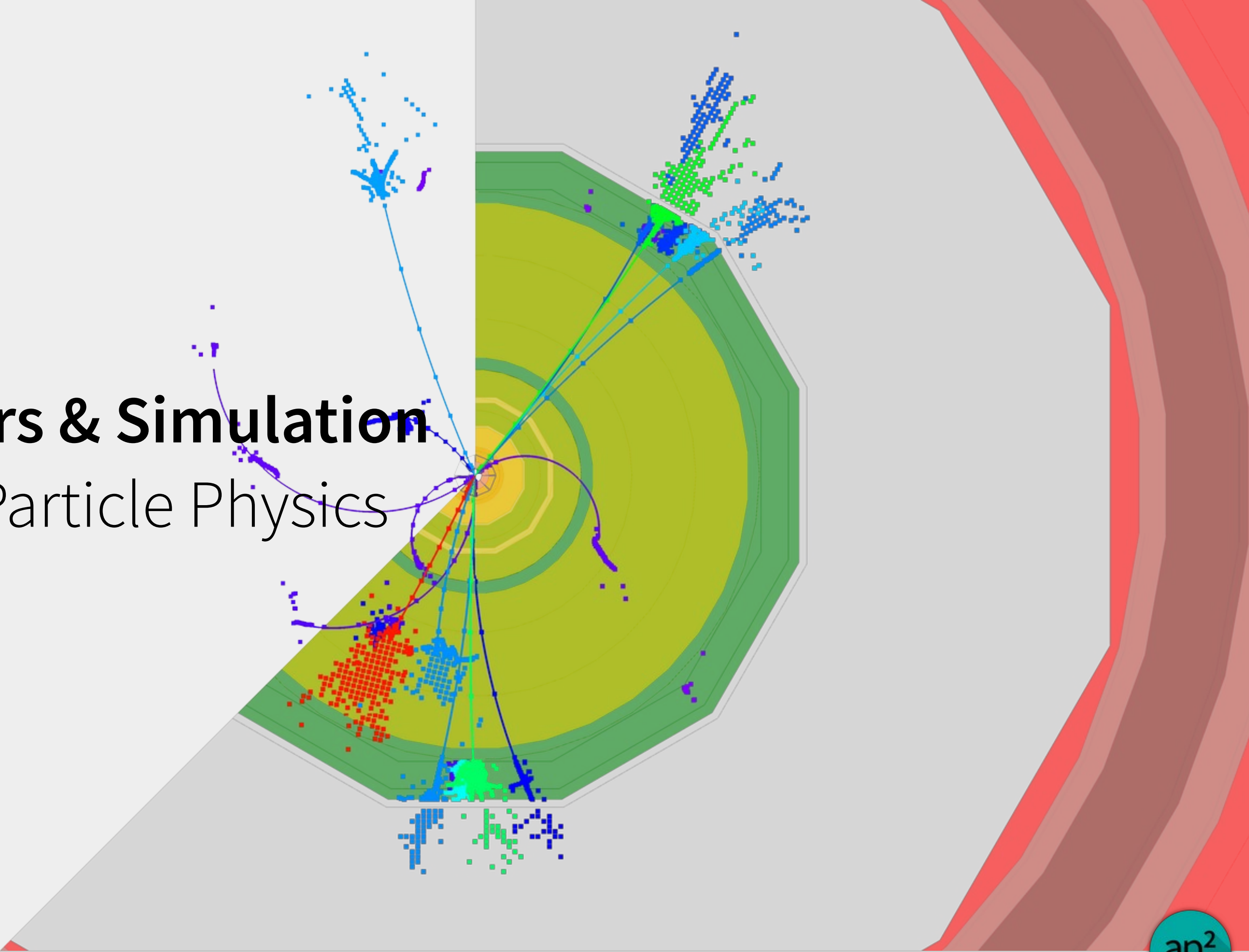


Simon Spannagel, Paul Schütze – DESY

ESA / ESO Detector Modelling Workshop

16 June 2021

Silicon Detectors & Simulation
in High-Energy Particle Physics

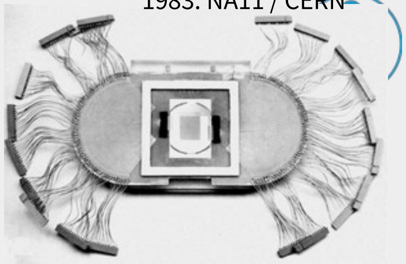


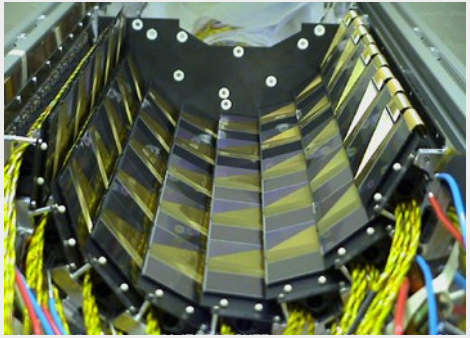
Silicon Detectors in Particle Physics

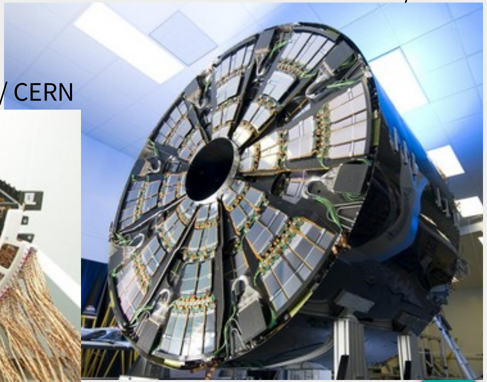
- Silicon detectors vital for many measurements
  - Fine segmentation, fast readout: high track multiplicities
  - Precise position measurement: momentum determination
collision point (vertexing)
particle identification (flavor tagging)

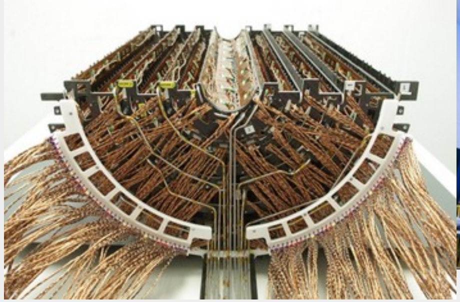
- Instrumental in discovery of Higgs boson at LHC
  - Tracking detectors: strips, 200 m^2 silicon, 70M channels
  - Vertex detectors: pixels, 1 m^2 silicon, 140M channels

- Detector R&D underway for
  - Upgrade of HL-LHC: more radiation damage resilience
  - Future colliders: *faster, higher, better*


1983: NA11 / CERN


2000: ZEUS MVD / DESY

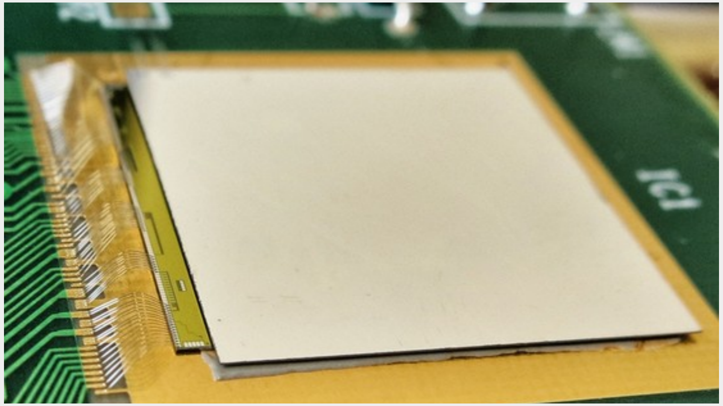

2007: CMS Tracker / CERN


2017: CMS Phase 1 Pixel / CERN

Silicon Detectors in Particle Physics

Demands on detectors are high:

- Very high particle flux, 10s 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)

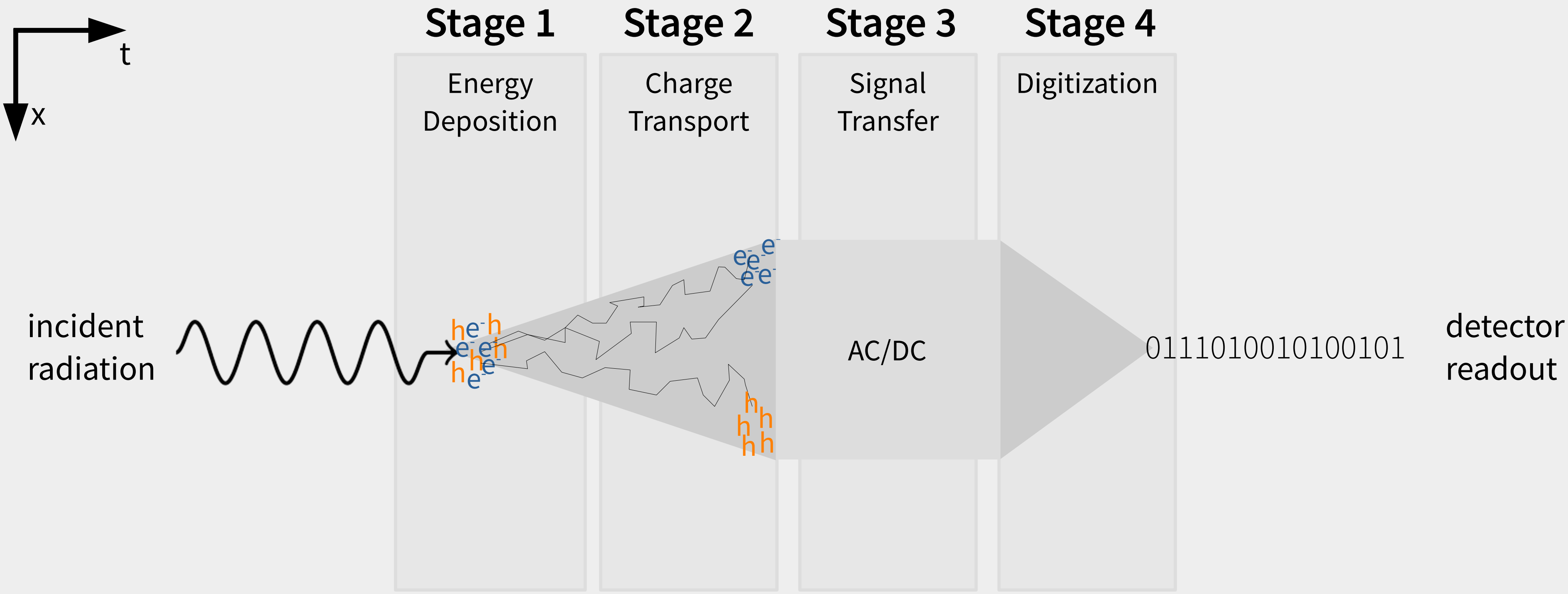


100 µm Timepix with 100 µm Sensor

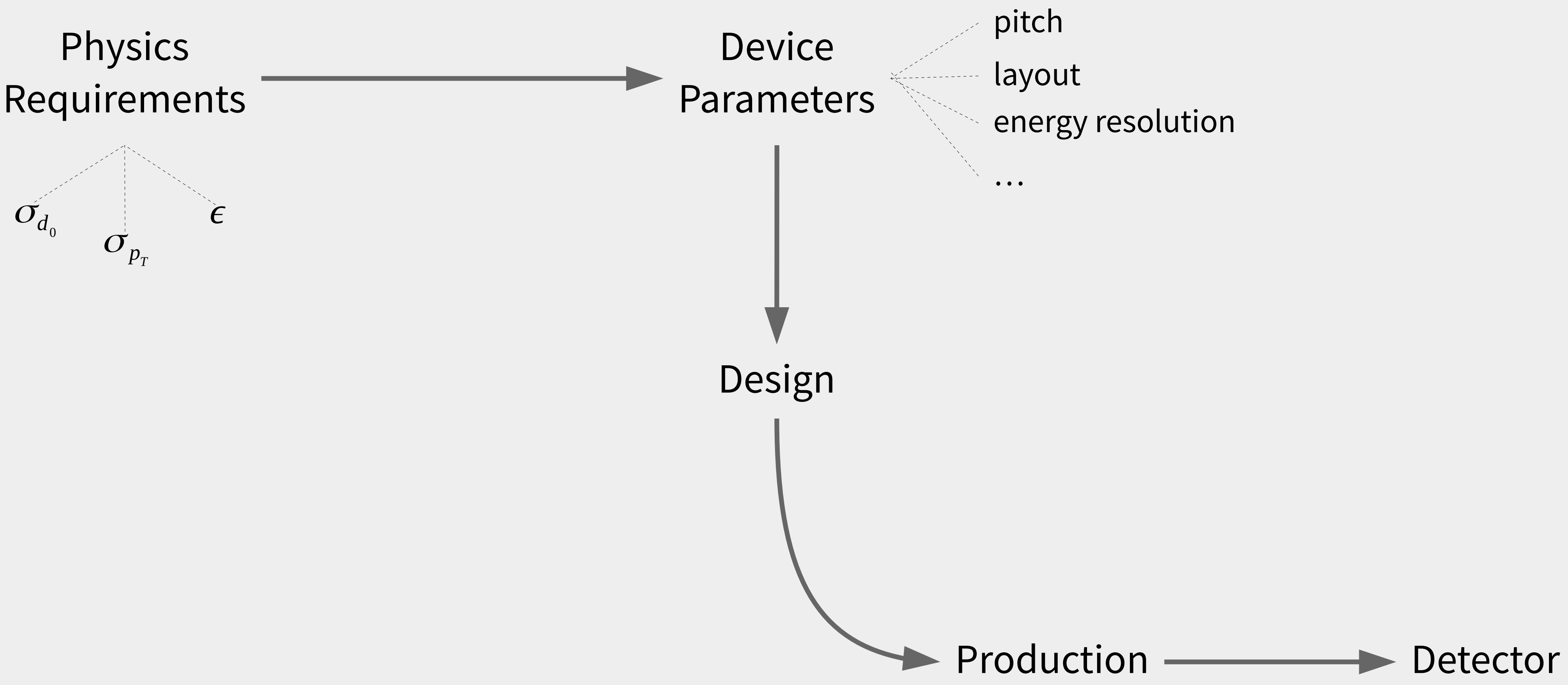
Many different technologies used for different purposes:
hybrid – dedicated sensor + mixed-mode CMOS, monolithic CMOS imaging, LGADs, 3D sensors, …

Simulations for thoroughly understanding detector performance in realistic conditions

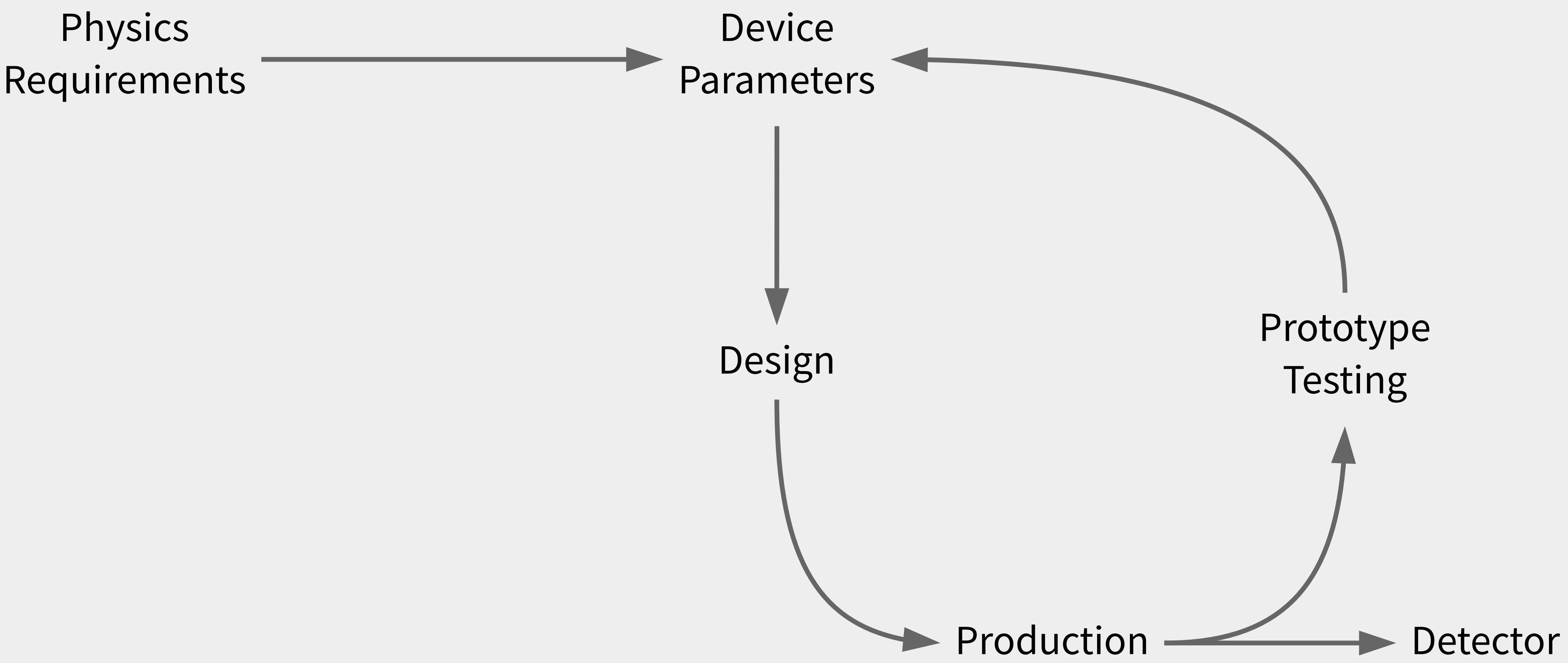
Minimum Ionizing Particle Detector – Broken Down



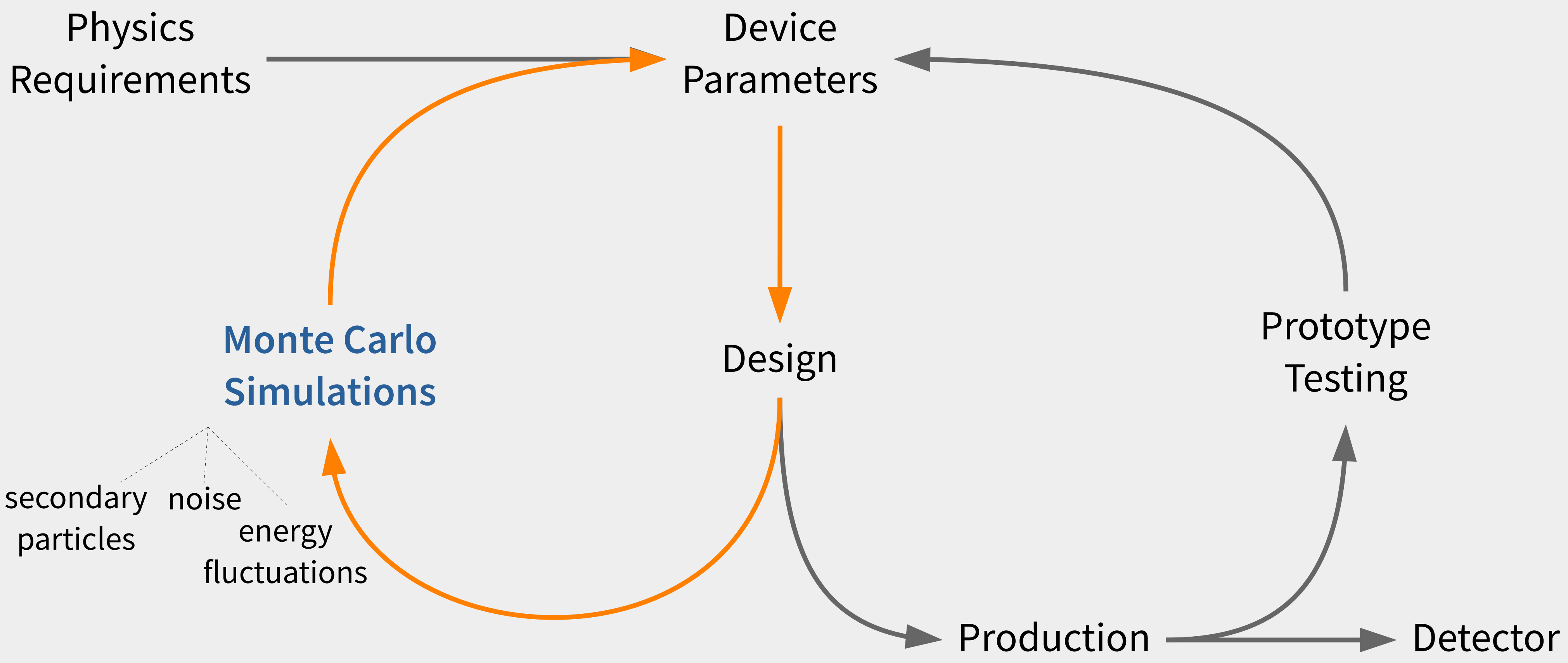
Development Cycle of a Silicon Detector



Development Cycle of a Silicon Detector

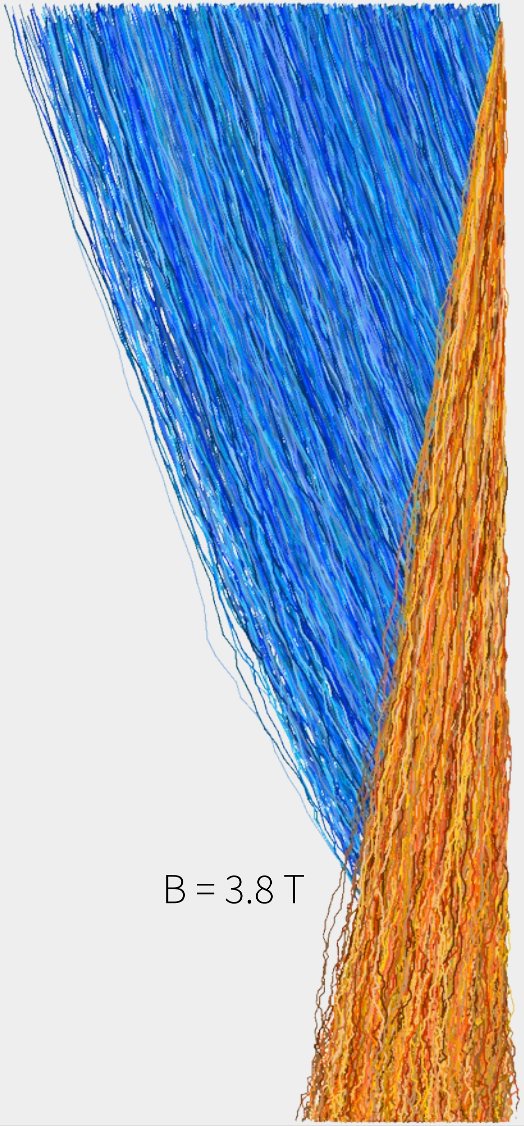


Development Cycle of a Silicon Detector



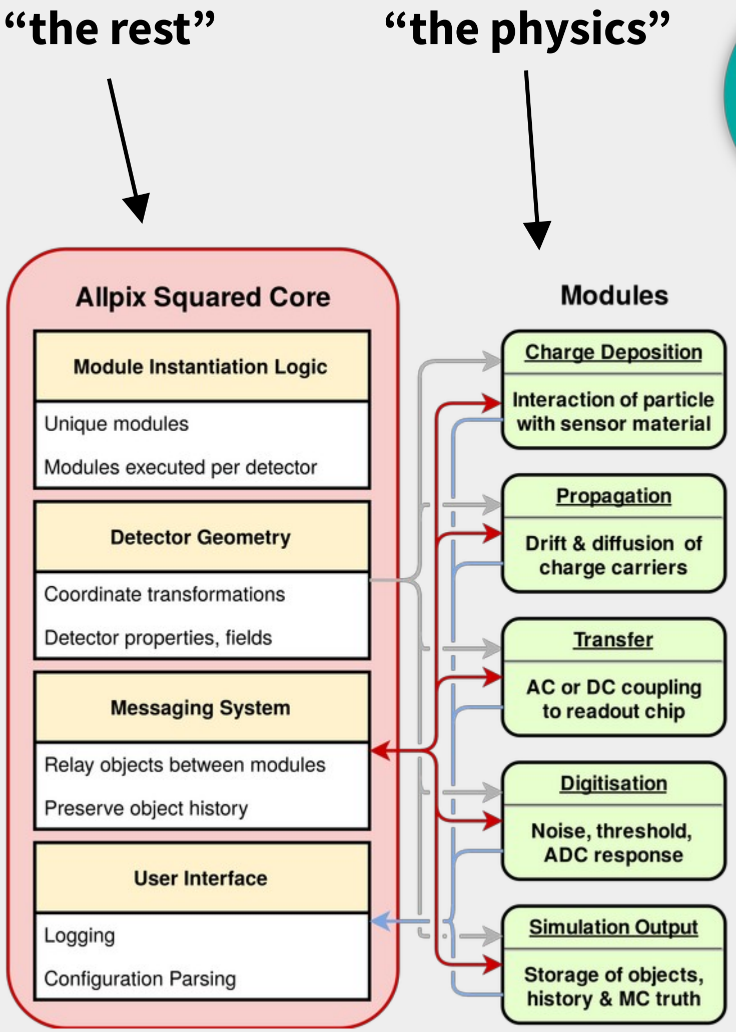
The Allpix Squared Framework

Monte Carlo Simulation



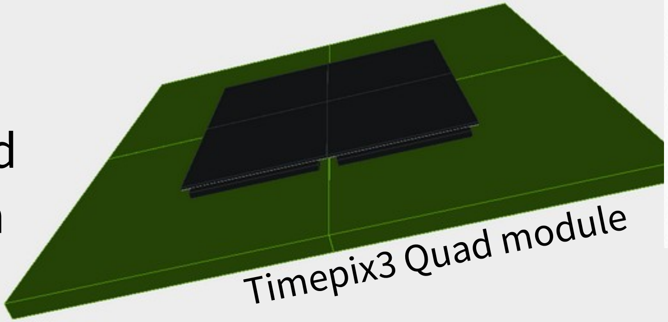
The Allpix² Framework

- **Powerful & flexible**
  - Direct integration with Geant4
  - Many physics models implemented
  - Validated against beam data
- **Easy setup & configuration**
  - Human-readable config files
  - Support for units
  - Fully configurable, no coding required
- Detailed documentation
- **Regular patch & feature releases since 2017**
- **FOSS: MIT-licensed**



Configuration of the Simulation Chain

- **File 1:** Simulation chain with individual modules
  - Configuration file with modules in order of execution
  - Every parameter documented in manual
- **File 2:** Geometry configuration
  - Position/orientation of individual detectors
  - Model files define detector geometries
  - Geant4 solids generated from model description



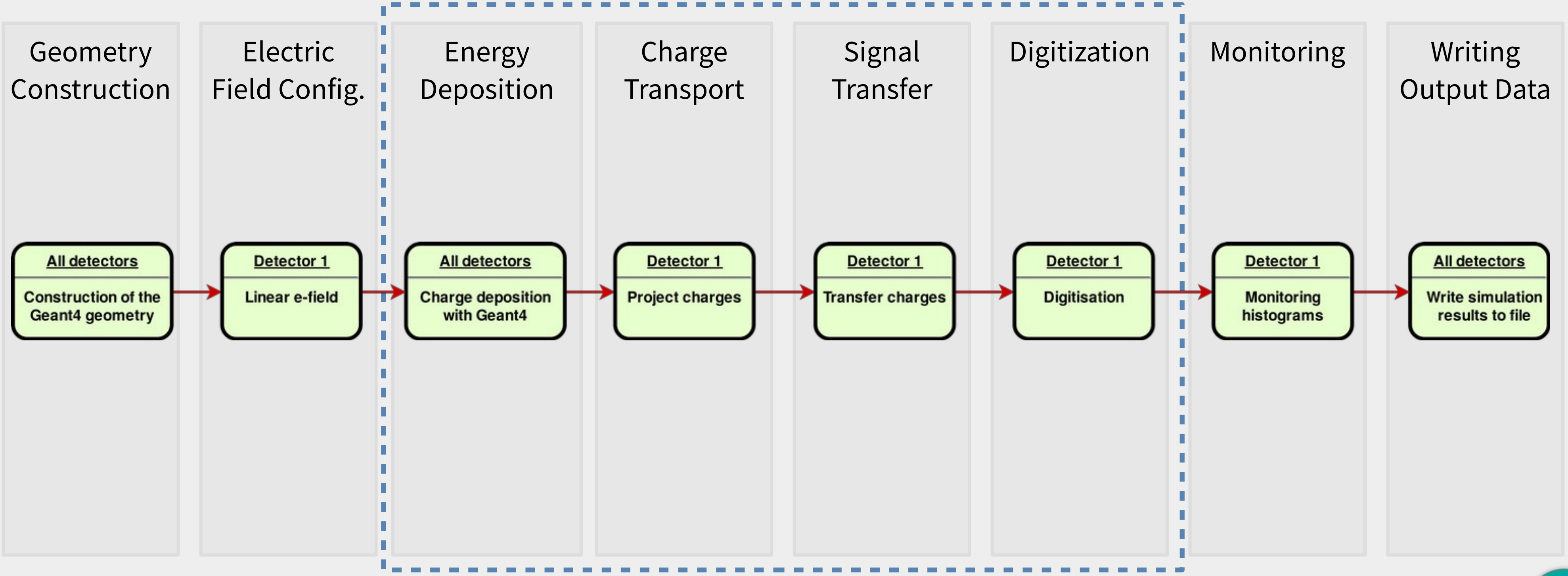

```
[AllPix]
log_level = "INFO"
number_of_events = 500000
detectors_file = "telescope.conf"

[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]
```

The Simulation Chain

- Geometry Construction
- Electric Field Config.
- Energy Deposition
- Charge Transport
- Signal Transfer
- Digitization
- Monitoring
- Writing Output Data

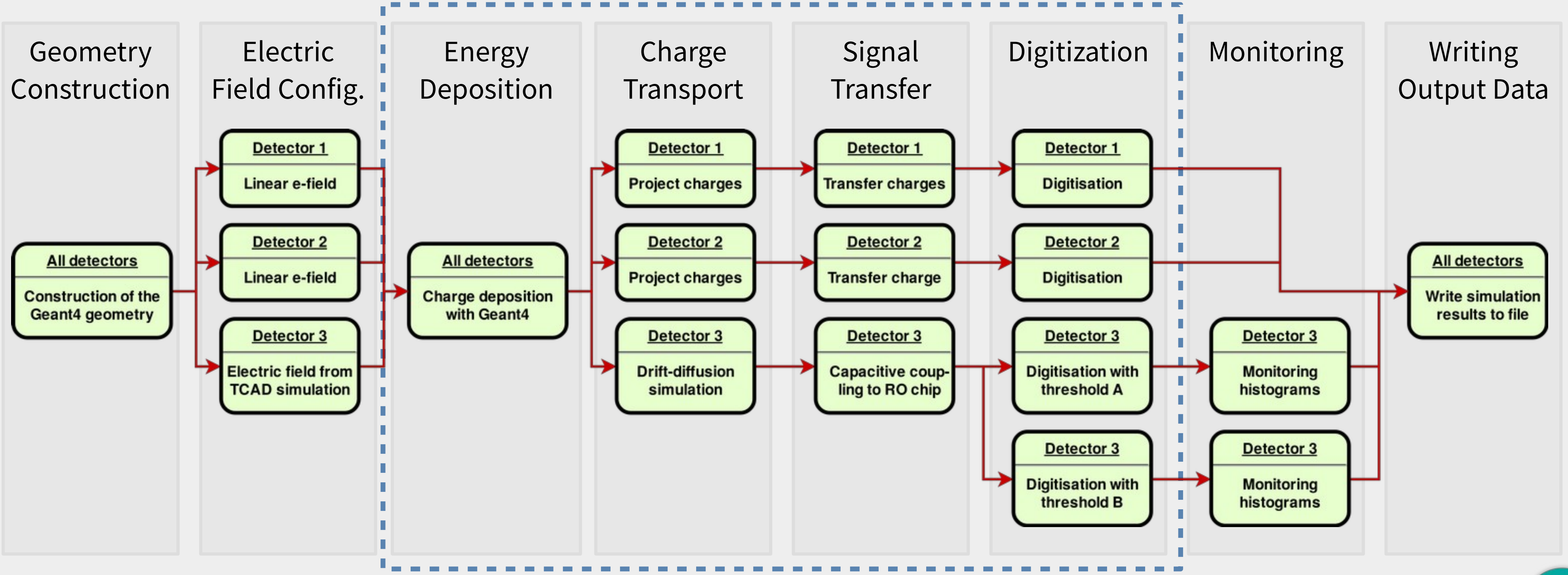
The Simulation Chain

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



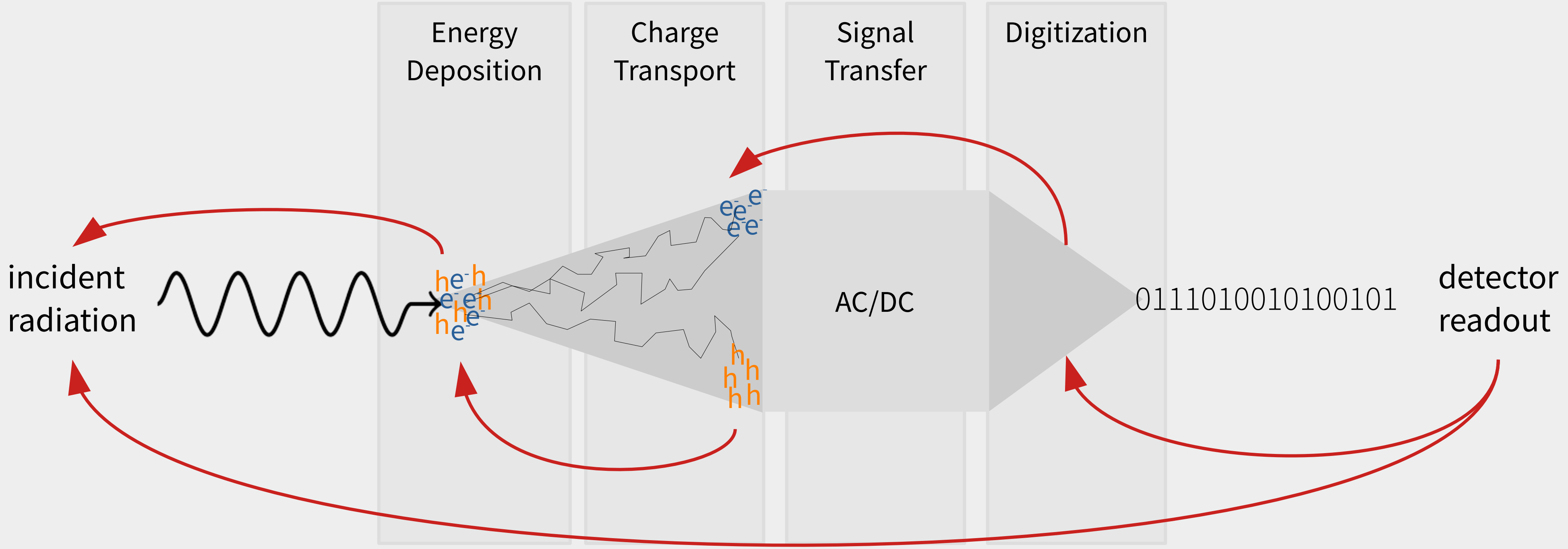
The Simulation Chain

Simulation very flexible: modules configurable on per-detector level
Multiple instances can be run in parallel (simulate different signal formation or front-ends)



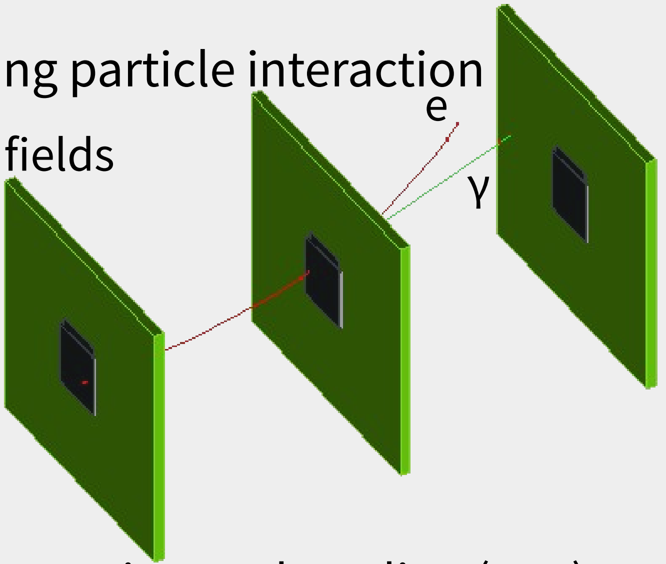
The Monte Carlo Truth

Allpix^2 keeps history for all simulated objects – available for detailed analysis:



Modules for Energy Deposition

- **DepositionGeant4:** Using established software for simulating particle interaction
  - Tracking of particles through entire setup, including magn. fields
  - Production and tracking of secondary particles
  - Provides MC truth information on all particles
  - Allows visualization of setup



- **DepositionPointCharge:** Simple model, depositing charge at point or along line (LET)
  - Convenient for comparison with e.g. TCAD device simulations

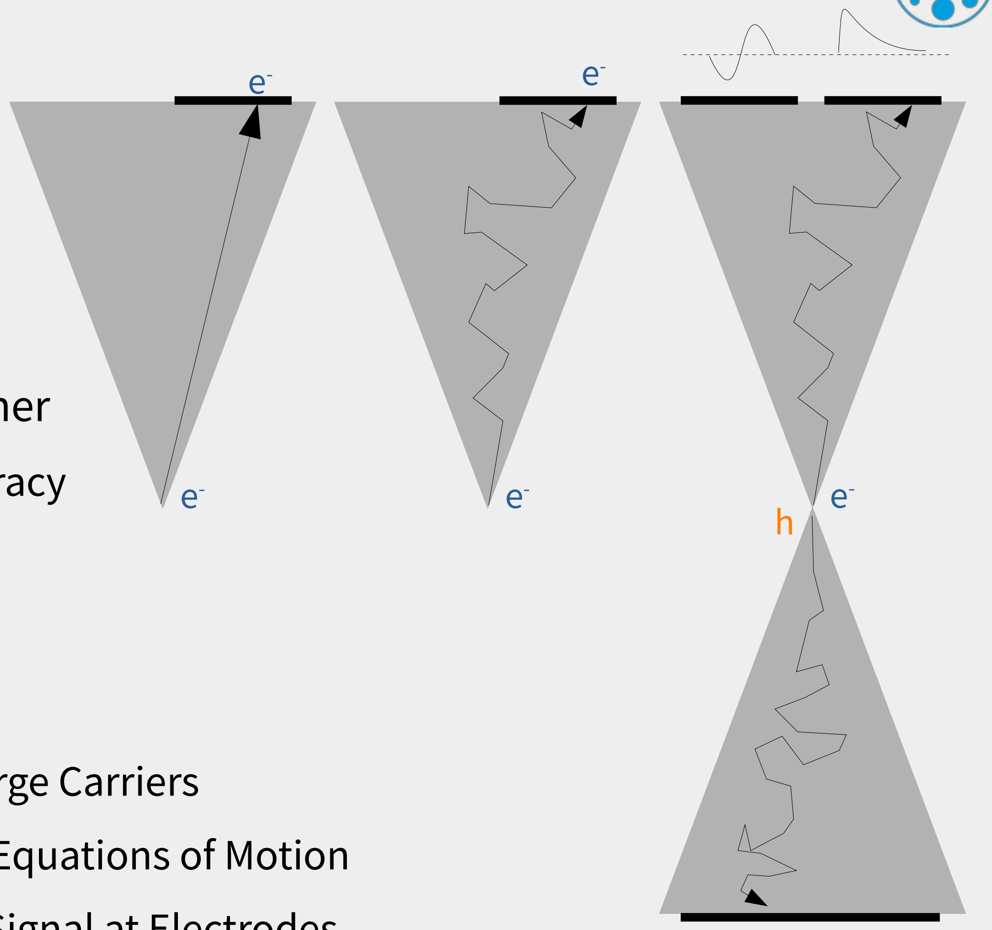
- **DepositionReader:** Read in simulation results from external tools in different formats

Modules for Charge Transport

- Most crucial (and time consuming) component in simulation chain

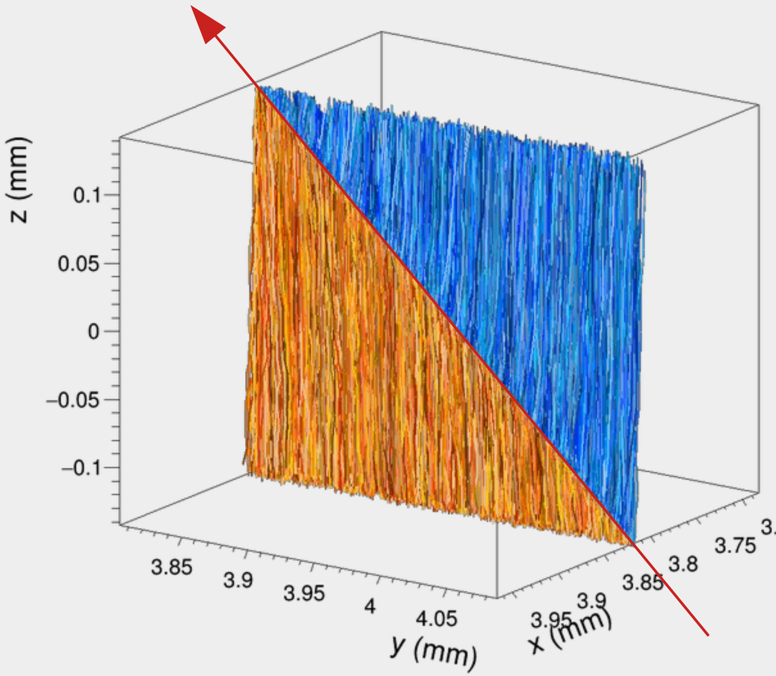
- Multiple charge carriers can be propagated together
  - Depending on initial statistics and required accuracy
  - Some models allow to ignore electrons or holes

- Models with different complexity:
  - **ProjectionPropagation** – O(1), Projecting Charge Carriers
  - **GenericPropagation** – O(N), Integration of Equations of Motion
  - **TransientPropagation** – O(2xNxM), Induced Signal at Electrodes

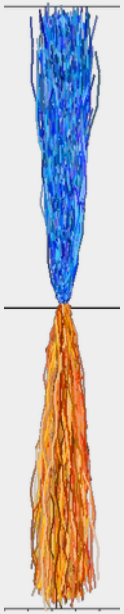


Drift Path Visualizations

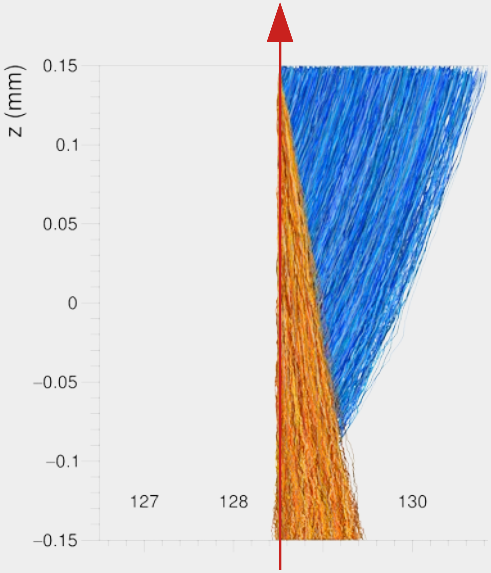
Recording individual steps of the carrier paths enable visualizations



particle at 45° angle
drift paths of electrons & holes

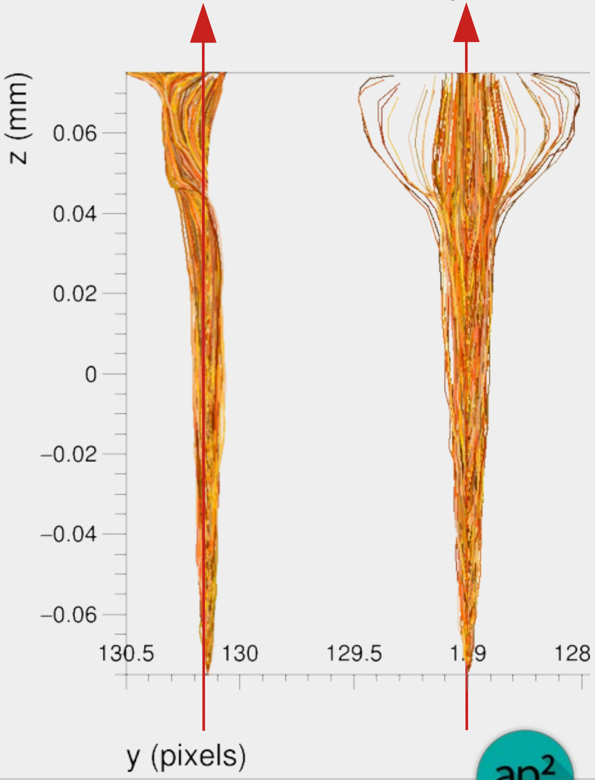


projection along trajectory



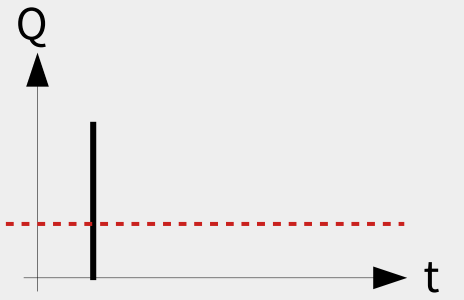
drift in magnetic field:
effect from Lorentz force

drift in non-trivial field
(here: holes only)

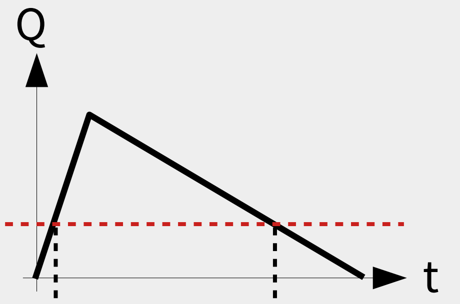


Modules for Digitization

- Methods depend on available information from charge transport
- **DefaultDigitizer:** Simple front-end
  - Compare total charge against configured threshold
  - Add input noise, threshold dispersion, convert to ADC units
  - Possibility to simulate saturation

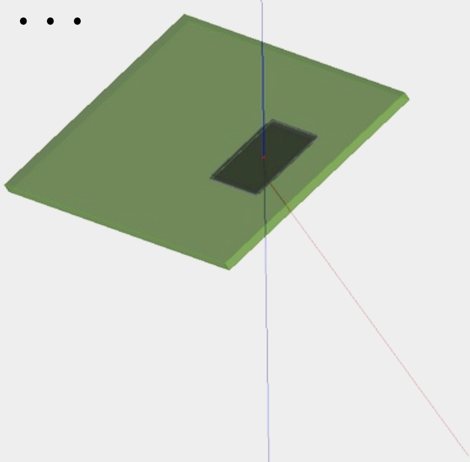


- **CSADigitizer:** Front-end with timing capabilities
  - Requires current pulse
  - Threshold crossings for time-of-arrival and time-over-threshold
  - Possibility to define custom transfer functions



Application Examples

Detector Systems, CMOS Imaging Sensors, . . .



Monolithic CMOS in High-Resistivity Silicon

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

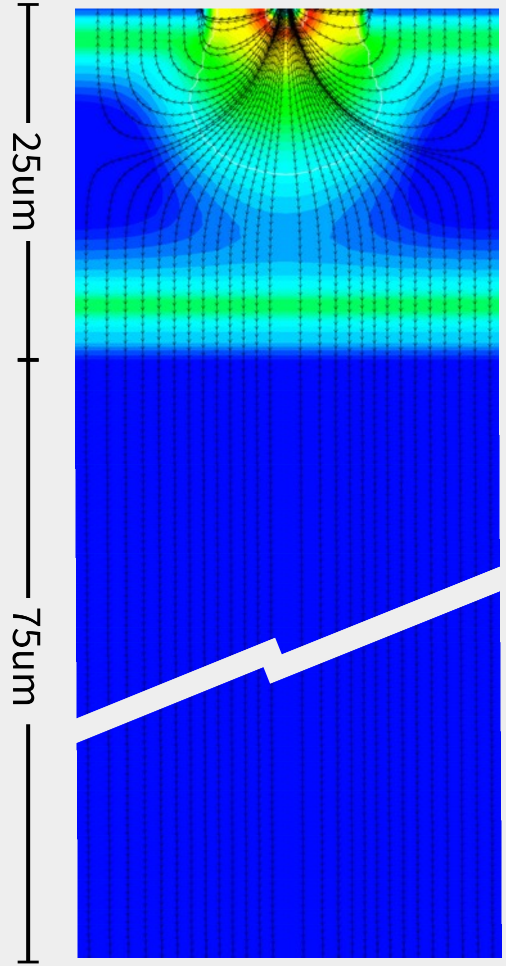
Monolithic sensor in commercial CMOS imaging process

- Pixel pitch 28x28um
- Field in top 25um (high-resistivity) silicon
- Undepleted in 75um silicon substrate

Simulation compared to data taken with 120 GeV π beam

- Simulating only detector under investigation
- Using Monte Carlo truth information as reference

Electrostatic field obtained from TCAD device simulations



Monolithic CMOS in High-Resistivity Silicon

NIMA 964 (2020) 163784
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High statistics of 3D Monte Carlo simulation:

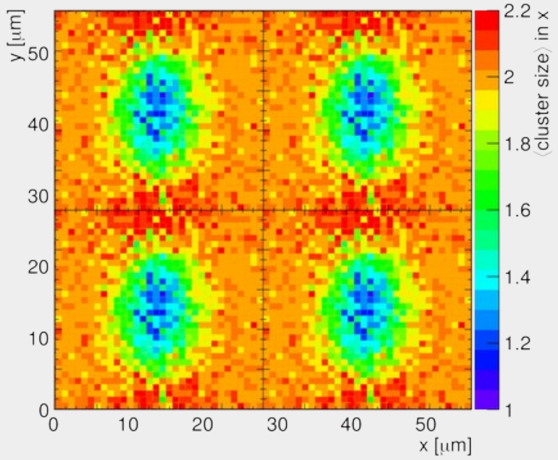
- Sampling of quantities within pixel cells
- Here: cluster size in x

Fully depleted planar sensors:
expecting bands without y-dependence

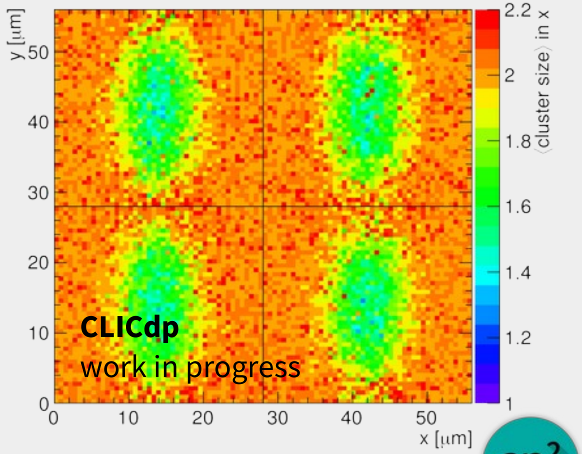
Cluster size exhibits correlation between x/y

- Reason is field configuration & signal contributions from diffusion
- Simulation with TCAD field reproduces correlation

Data



Allpix²

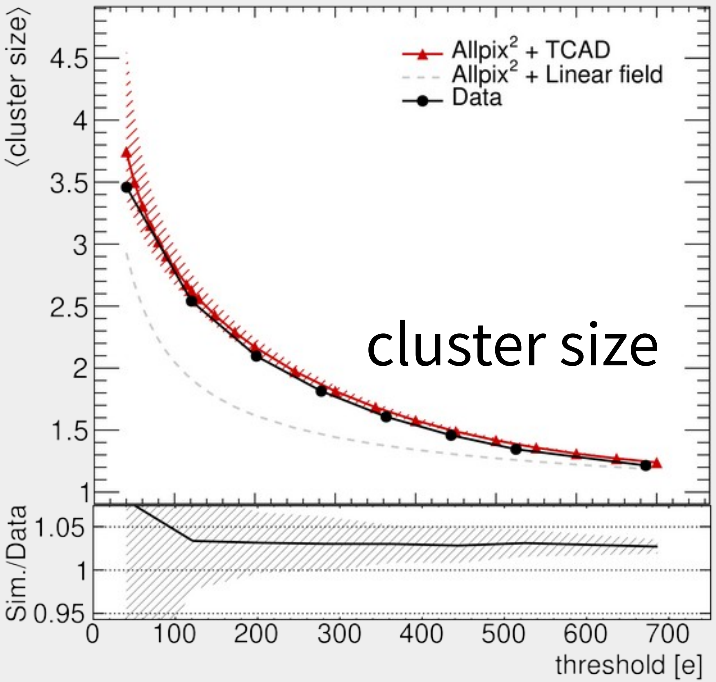


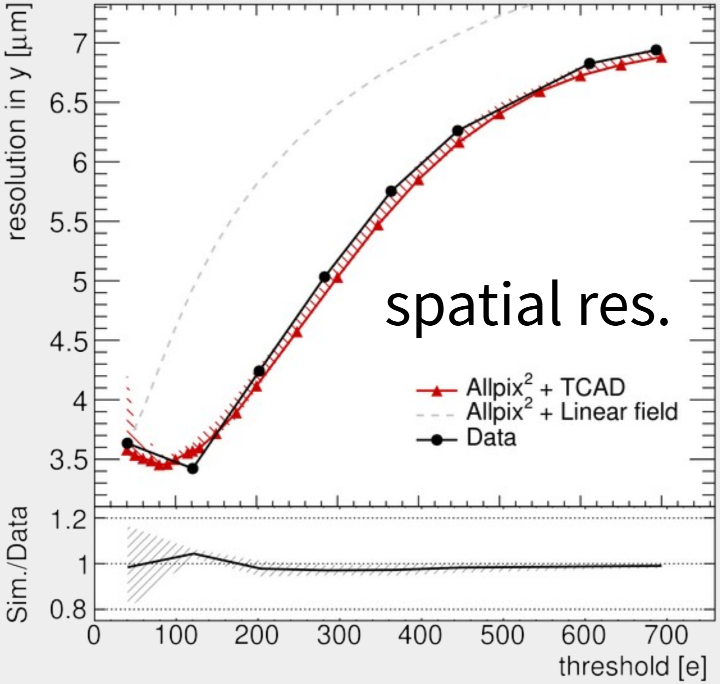
Threshold Dependence of Resolution

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

Data and simulation match well, e.g. for **cluster size & resolution vs. threshold**

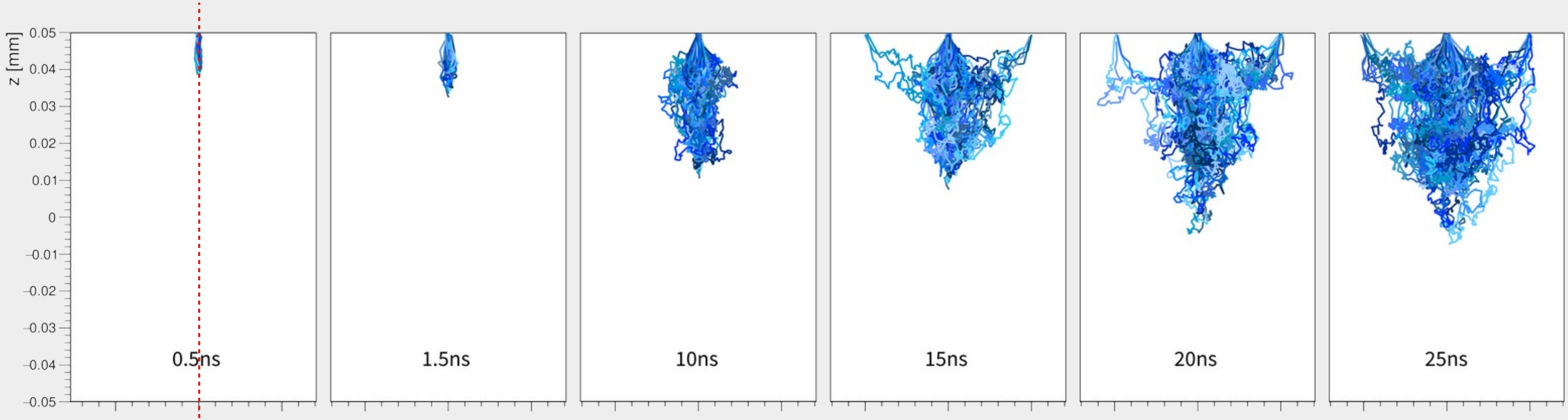
Simulation with linear electric field does not describe data





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

Visualizing Charge Carrier Motion



Charge carrier movements at different times after the deposition

- Only electrons shown which reach the electrodes, holes & other electrons omitted
- Contributions form the substrate silicon after ~10ns
- Charge sharing visible after ~15ns

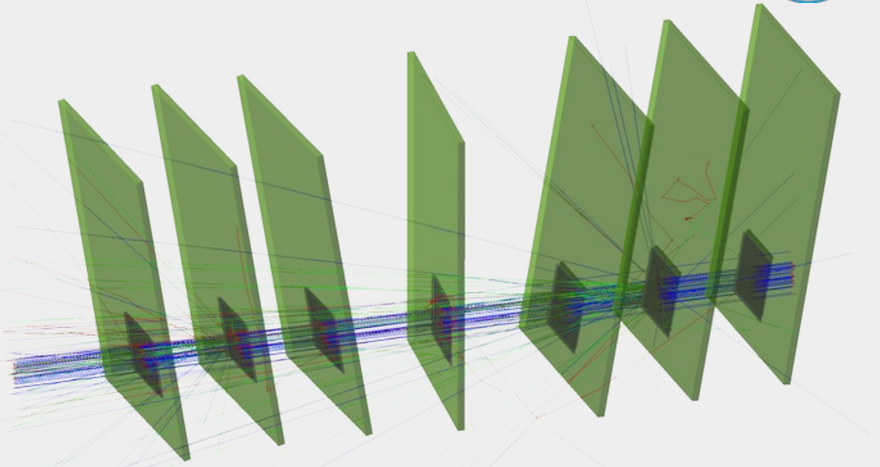
NIMA 901 (2018) 164 – 172
doi:10.1016/j.nima.2018.06.020

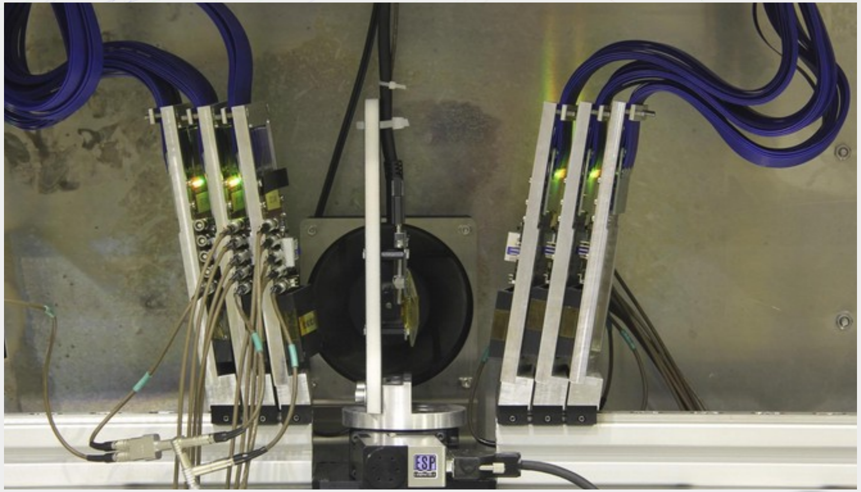
Simulation of a Detector System

- Simulation of a beam telescope setup:
  - Telescope: 6x Timepix3 w/ 300 μm sensors
  - DUT: 1x Timepix3 w/ 50 μm sensor

- Different algorithms used:
  - Telescope: projection
    DUT: successive integration

- Linear electric field approximation

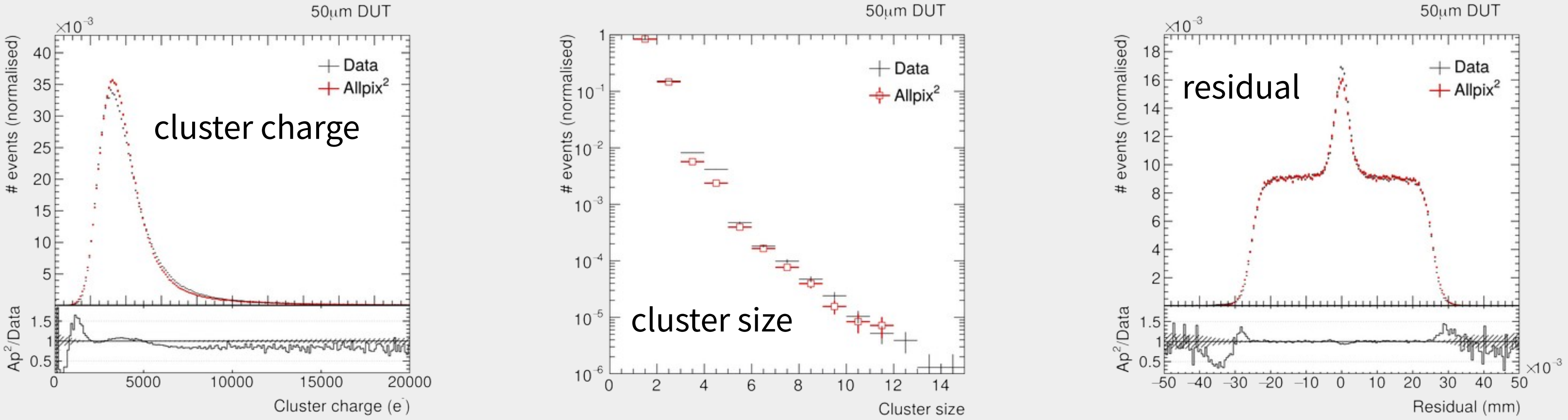




NIMA 901 (2018) 164 – 172
doi:10.1016/j.nima.2018.06.020

Simulation of a Detector System

- Using same reconstruction algorithms as for data: clustering, η correction, tracking
- Very good agreement between data and simulation observed (total charge: **Geant4**; cluster size: both; residual shape: **Allpix^2**)



Allpix Squared 2.0

Recent Developments

Release of Allpix Squared 2.0

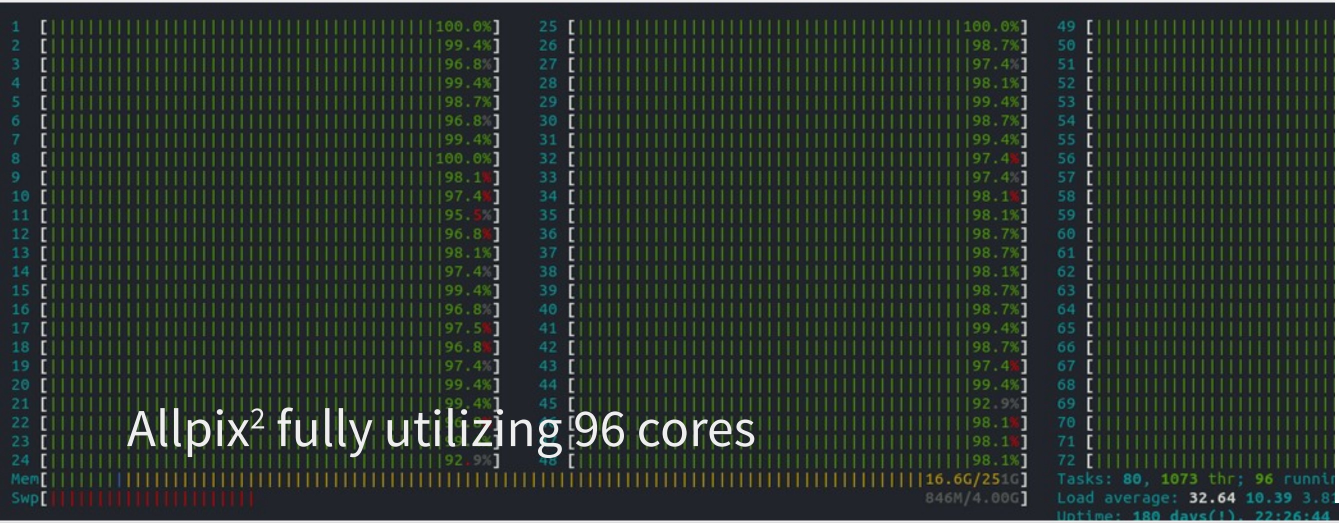
- First major release introducing structural changes to framework since 1.0 (2018)
  - More than 1500 commits over previous feature release 1.6
  - Introduced fully parallel event processing (Started as Google Summer of Code project)

- Further separation between physics models & algorithms,
  Model for mobility, recombination configurable per module instance
  - Mobility: Jacoboni/Canali, Hamburg, Masetti, Arora, ext. Canali/Masetti
  - Recombination: Auger, Shockley-Read-Hall, combined

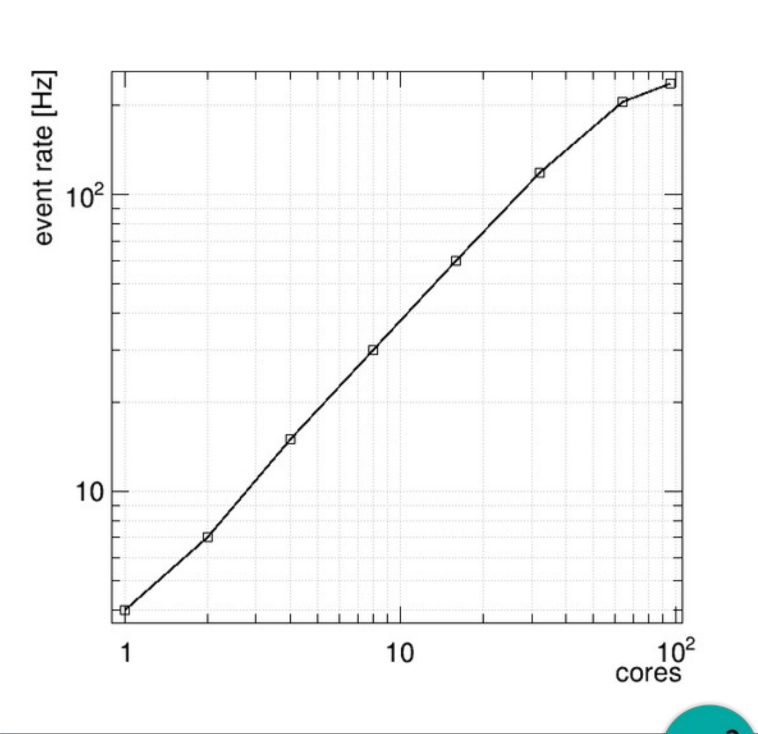
- Tons of small improvements, cleanup, documentation improvements:
  https://cern.ch/allpix-squared/post/2021-06-15-version-2.0.0/

Event-Based Seeding & Multithreading

- Efficient use of system resources / multiple cores
- Retaining strong reproducibility: exact same result, independent of # workers
  Event order in output files is preserved
- Fully transparent to user / simulation



Allpix² fully utilizing 96 cores



User Manual & Code Documentation

- Focus from the very beginning on well-documented framework
- Source code documentation for every class, method
  - Doxygen markup for code reference
  - Deployed to the website for tags
- Extensive User Manual, describing
  - Framework functionality
  - Physics models
  - Modules & parameters

```
namespace allpix {

    /**
     * @brief Instantiation of a detector mode
     *
     * Contains the detector in the world with
     * (like the electric field). All model sp
     * properties are stored in its DetectorMo
     */
    class Detector {
        friend class GeometryManager;

    public:
        /**
         * @brief Constructs a detector in the
         * @param name Unique name of the dete
         * @param model Model of the detector
         * @param position Position in the wor
         * @param orientation Rotation matrix
         */
        Detector(std::string name,
                 std::shared_ptr<DetectorModel
                 ROOT::Math::XYZPoint position
                 const ROOT::Math::Rotation3D&

        /**
         * @brief Get name of the detector
         * @return Detector name
         */
        std::string getName() const;
```

2nd Allpix Squared User Workshop

Workshop: 17 – 19 August 2021
https://indi.to/WhdJn

Abstract submission: 24 July 2021

Registration: 16 August 2021

Contributions welcome!

Summary

- Monte Carlo simulations:
  vital component of understanding & interpreting detector performance
- Allpix^2: comprehensive MC simulation framework for silicon detectors
  - Offers a variety of modules which can be combined to form simulation chain
  - Easy to use and well documented
  - Validation against data recorded in particle beams
- Continuous development and support
  - New major release last week, providing full multithreading capabilities
  - Regular patch releases with bug fixes
- 2nd Allpix Squared User workshop 17 – 19 August 2021

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.