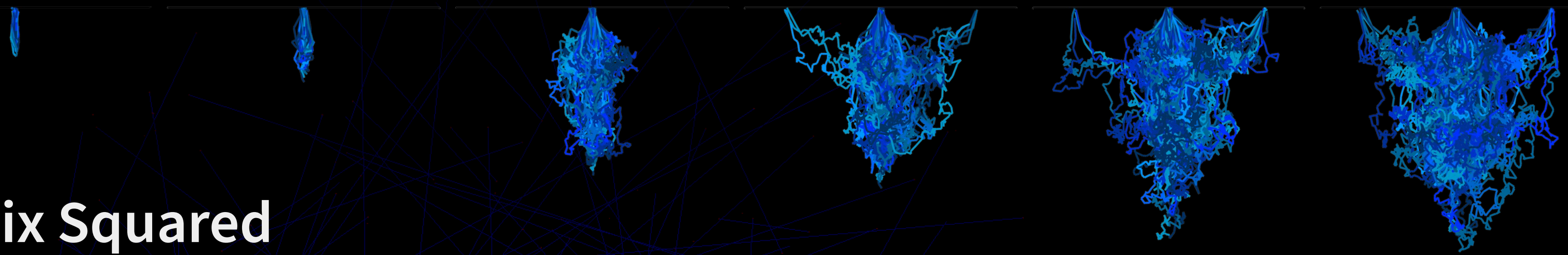
ap²

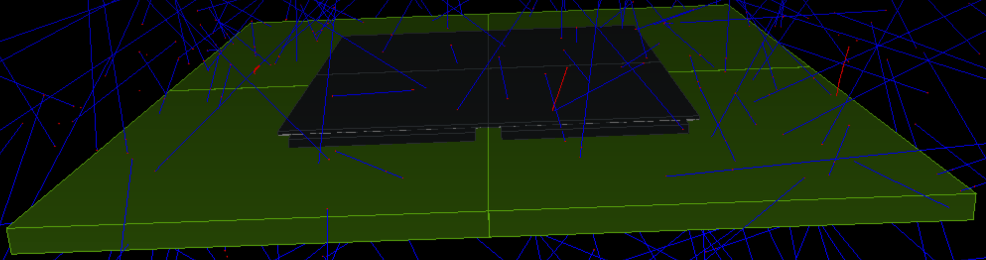
allpix squared

cern.ch/allpix-squared



Allpix Squared

Silicon Detector Monte Carlo Simulations for Particle Physics and Beyond



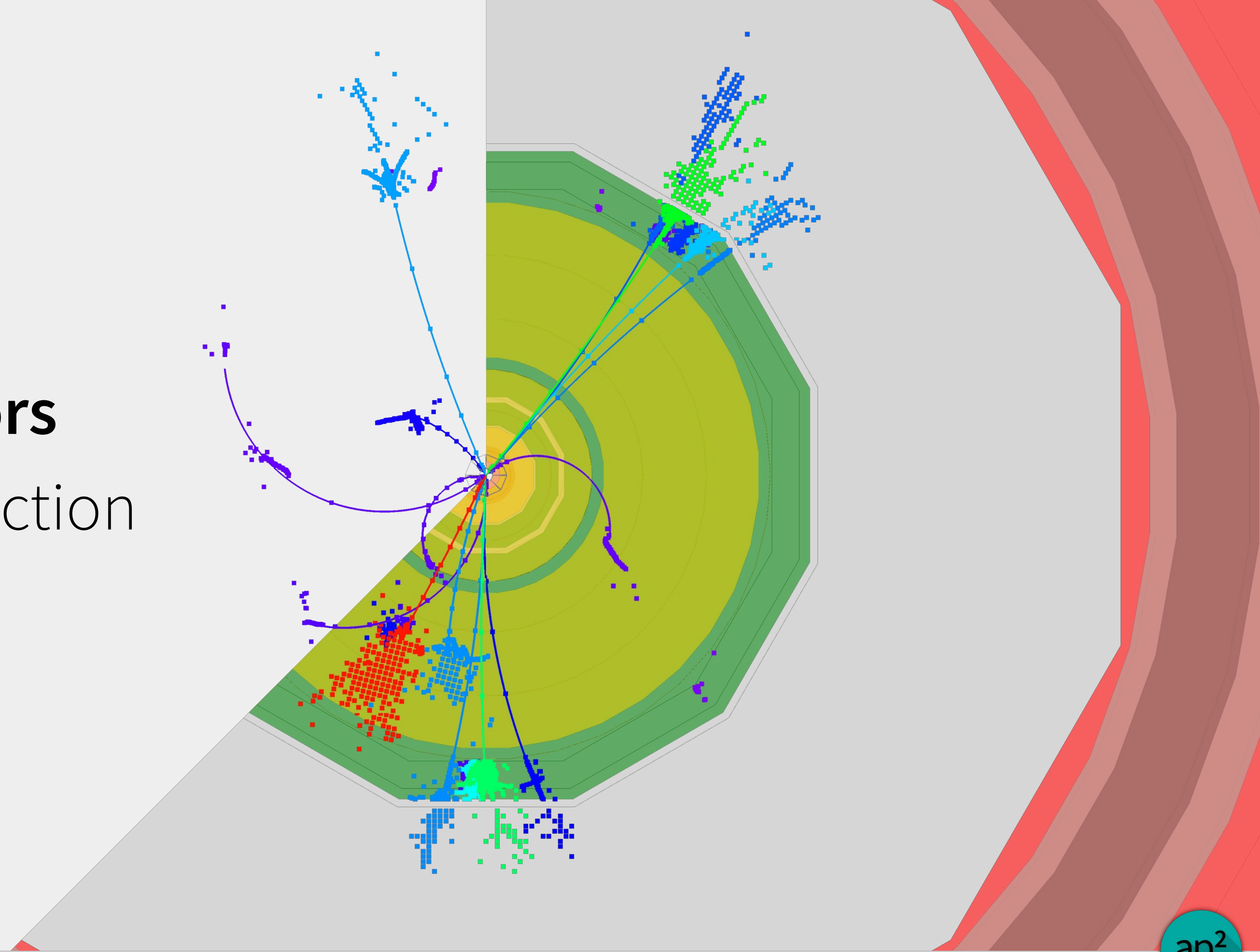
Simon Spannagel, DESY

Université de Genève DPNC Seminar

27 October 2021

Silicon Detectors

for Particle Detection



Silicon Detectors in Particle Physics

Vital for many measurements due to

- Fine segmentation, fast readout: high track multiplicities
- Precise position measurement

Demands are high:

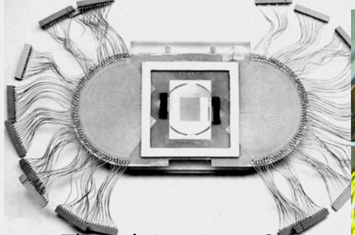
- Very high particle flux, tens of MHz / cm^2
- Maximum resolution, minimum (scattering-) mass
- High granularity, fast readout, minimal dead time
- “Smart” detectors (zero suppression, on-chip processing, …)

Many different technologies used for different applications:
hybrid (sensor + mixed-mode CMOS), monolithic CMOS, LGADs, 3D sensors, …

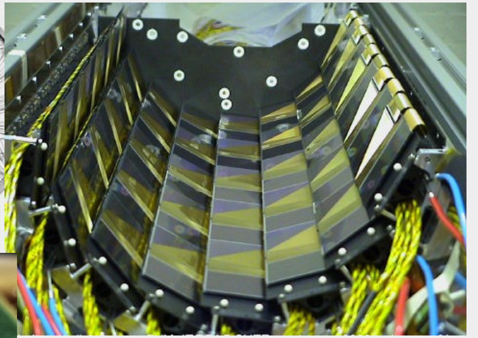
→ Wide range of available detector technologies

→ Thorough understanding of performance in realistic conditions

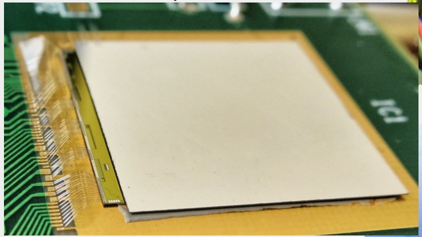
1983: NA11 / CERN



2000: ZEUS MVD / DESY

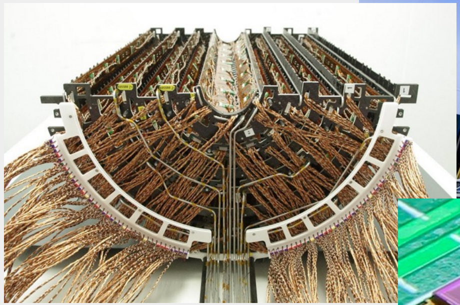


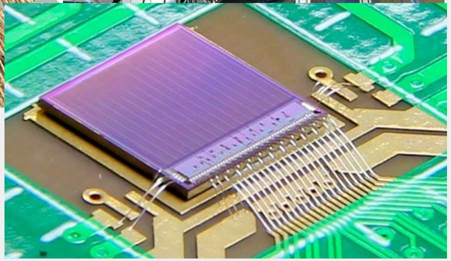
2013: Timepix3 + 50 µm Sensor



2007: CMS Tracker / CERN

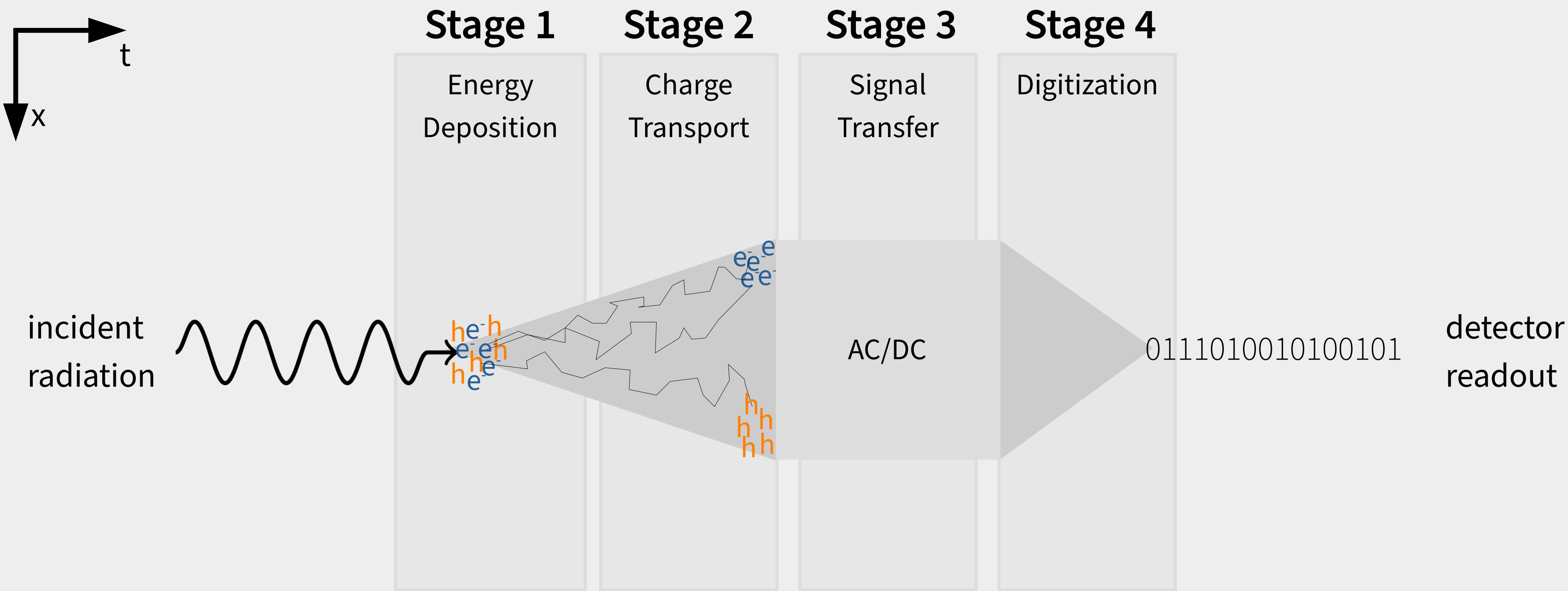
2017: CMS Phase 1 Pixel / CERN





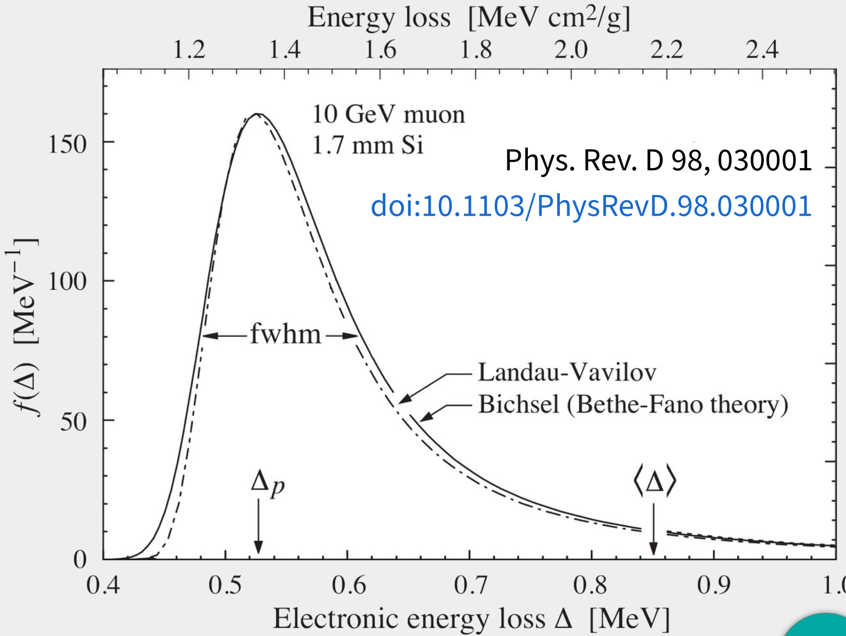
2019: CLICTD MAPS

Particle Detection with Silicon Detectors



Stage 1 – Energy Deposition

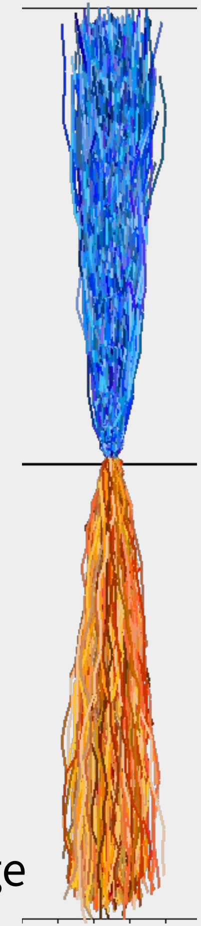
- (heavy) charged particles:
  Mean energy loss described by **Bethe Bloch** formula
- Strong fluctuations of energy loss: **Landau-Vavilov** distribution / **Bichsel** model
  - Varying number interactions, energy transfer
  - Secondary particles (e.g. delta rays)
  - Most probable value < Mean
- Photons:
  Photo effect, Compton effect, pair production
- Creation of e/h pairs: 3.64 eV / pair
  Fluctuations: **Fano** Factor $\sigma_{e/h} = \sqrt{N_{e/h}}\sqrt{F}$



Phys. Rev. D 98, 030001
doi:10.1103/PhysRevD.98.030001

Stage 2 – Signal Formation

- Si sensor operated as diode in reverse bias → depleted volume
- Signal formed by motion of e/h pairs in electric field
- Contribution to motion:
  - **Diffusion** – Temperature-driven random motion, mean free path ~ 0.1 µm, mean 0
  - **Drift** – Directed motion, depending on electric field and charge carrier mobility, different parametrizations for mobility available, depending on temperature, silicon, ...
- Motion stops, when...
  - Charge carriers reach readout electrode (conductor)
  - Charge carriers recombine/get trapped (depends on purity, doping, lattice defects, …)
- When carriers reach electrodes, total induced charge is equivalent to collected charge



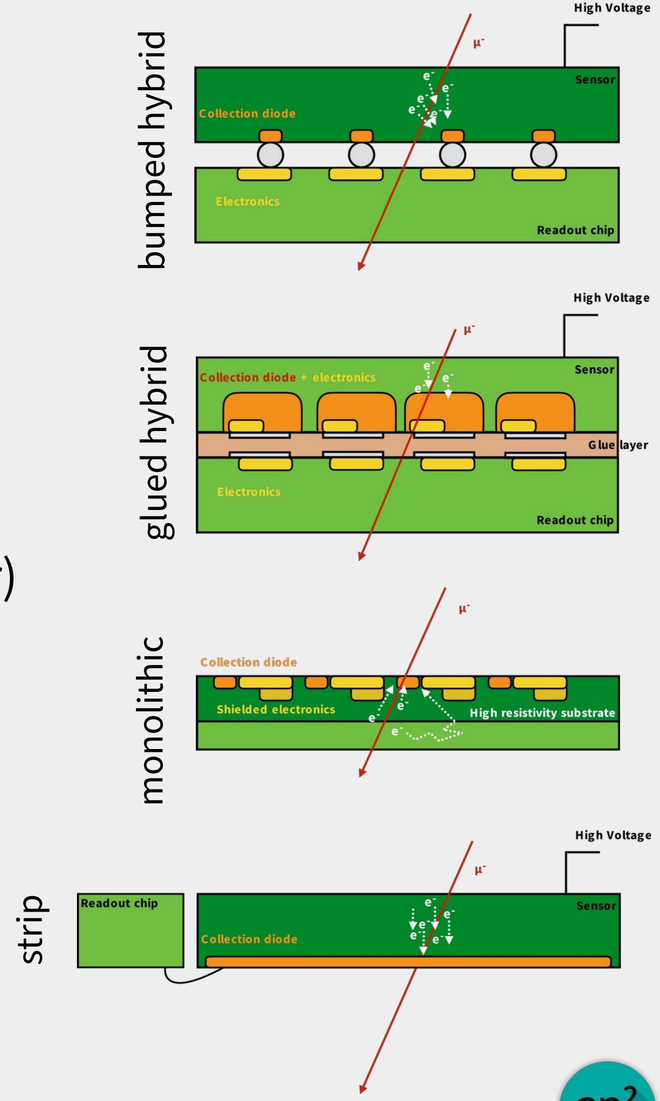
Stage 3 – Signal Transfer

Coupling between sensor & front-end can be

- DC: bump bonds (hybrid pixel), direct (monolithic pixel), …
- AC: glue layers (hybrid pixel), SiO_2 (strip detectors), …

Stage 4 – Digitization

- Signal is amplified, shaped, zero-suppression (discriminator)
- Digitization of the signal via
  - Full ADC
  - Time-over -threshold
  - Threshold crossing (binary hit information)
- Buffering, encoding, data transmission...



Why Detector Monte Carlo Simulations?

Simulate full chain: energy deposition → readout

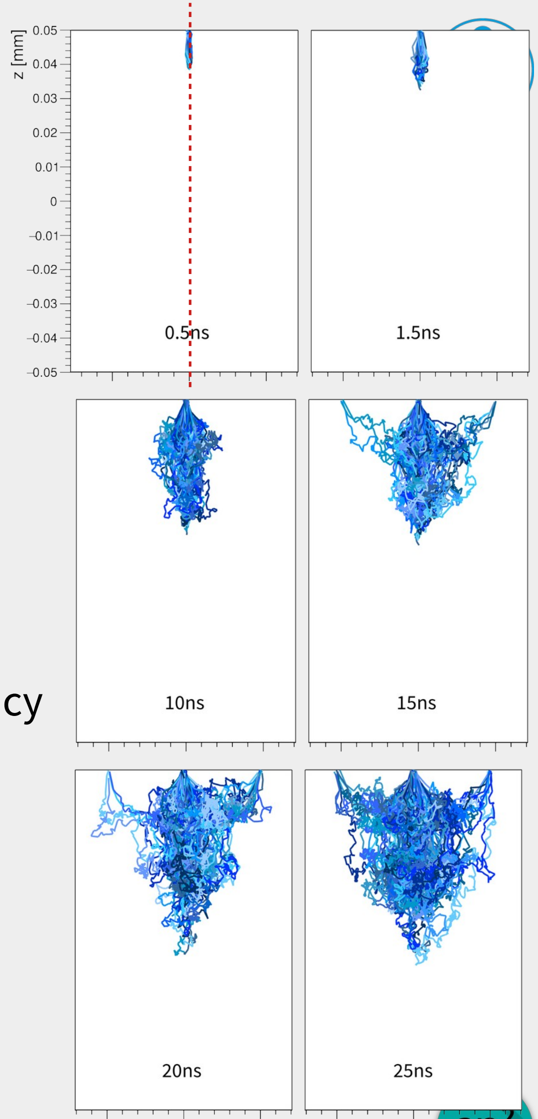
- Detailed modeling of microscopic processes in sensor & front-end
- Include **stochastic effects, fluctuations, secondaries**

Allows to derive **performance parameters**

- Position resolution, timing, efficiency
- Combine with (TCAD / SPICE / …) device simulations results to increase accuracy
- Provides detailed insight into characteristics not accessible in measurements

Requires **simplifications**:

- No self-interaction, static electric field, …
- Empirical models for different stages of detection process



The Allpix² Framework

for Silicon Detector Monte Carlo Simulations

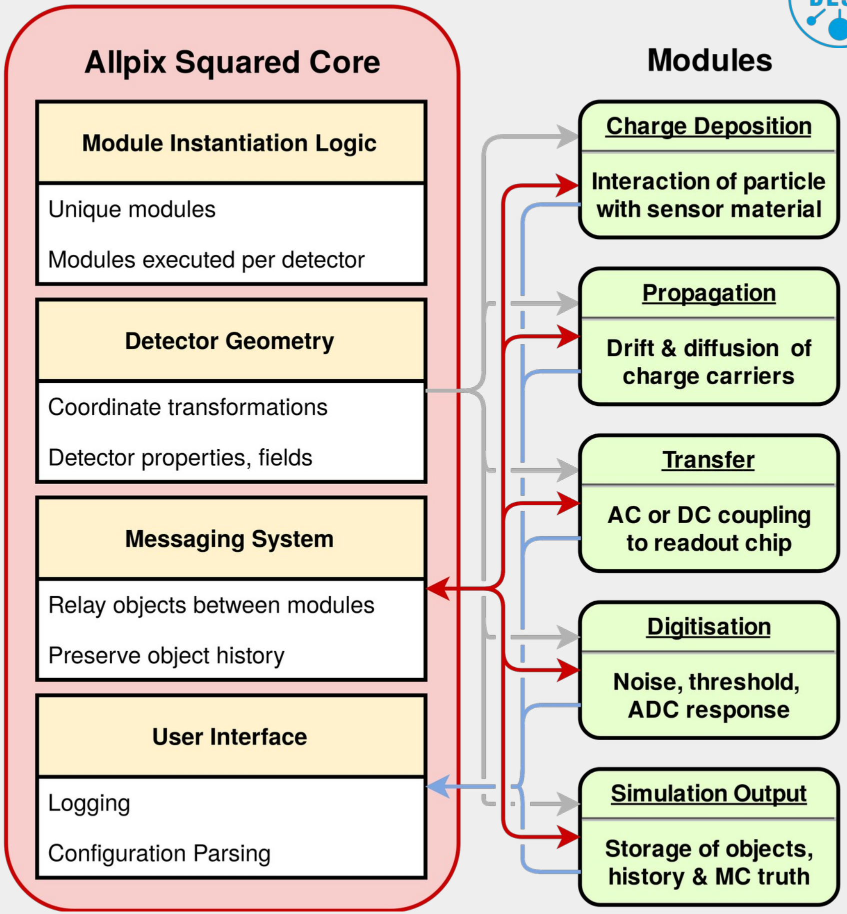
The Allpix² Framework

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

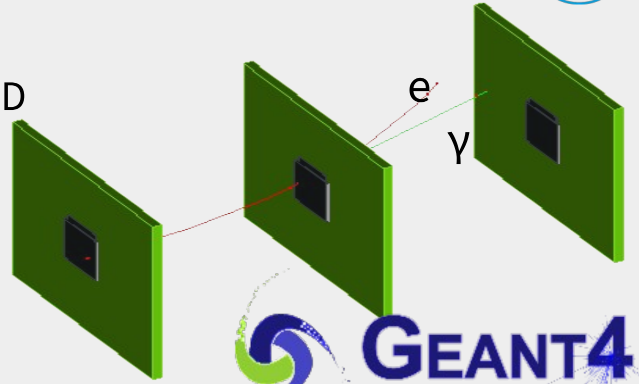


→ **Allpix²:** microscopic end-to-end MC simulations

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

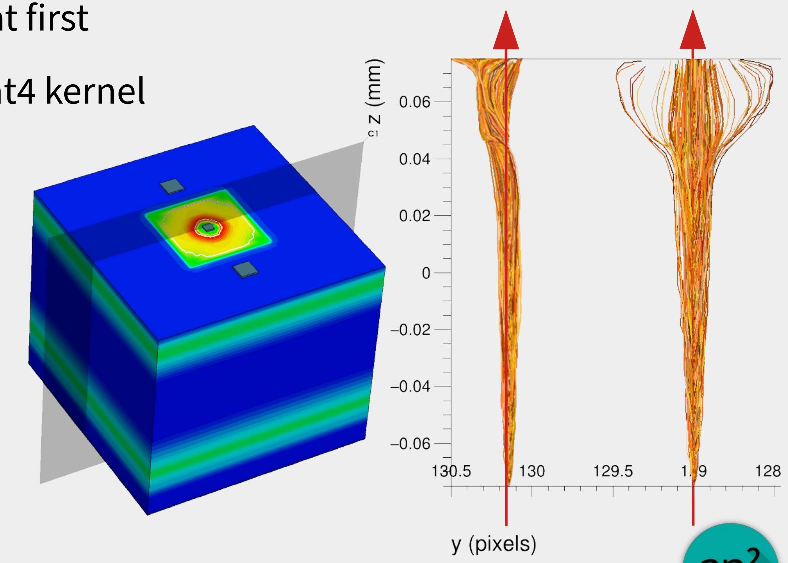


Geant4 – simulating energy deposition of particles passing through matter

- 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 **Allpix²**, we strive for:

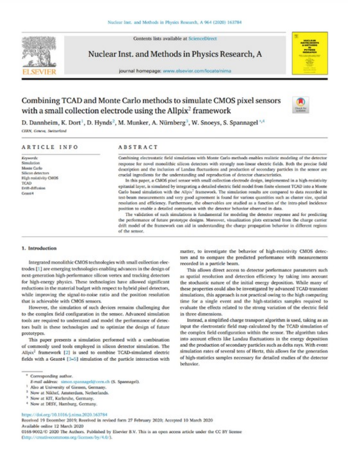
- Validating as much as possible against known data
- Publishing reference studies including full simulation configuration used
- Providing automated tests for every new feature

Organizing User workshops for exchange with 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

In collaboration review

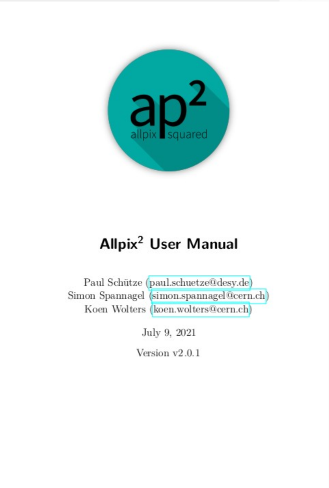
III. Low Entry Barrier for New Users

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

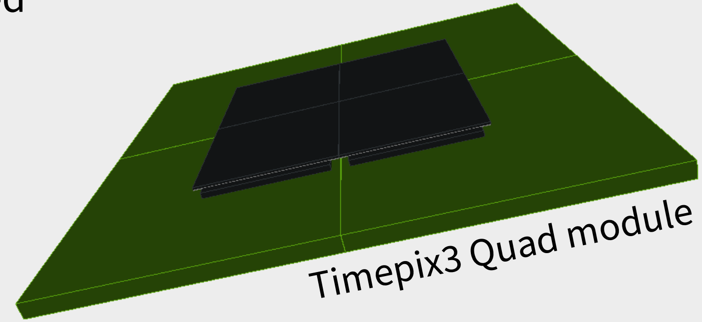
Allpix² attempts to facilitate quick starts:

- 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]
```



Timepix3 Quad module

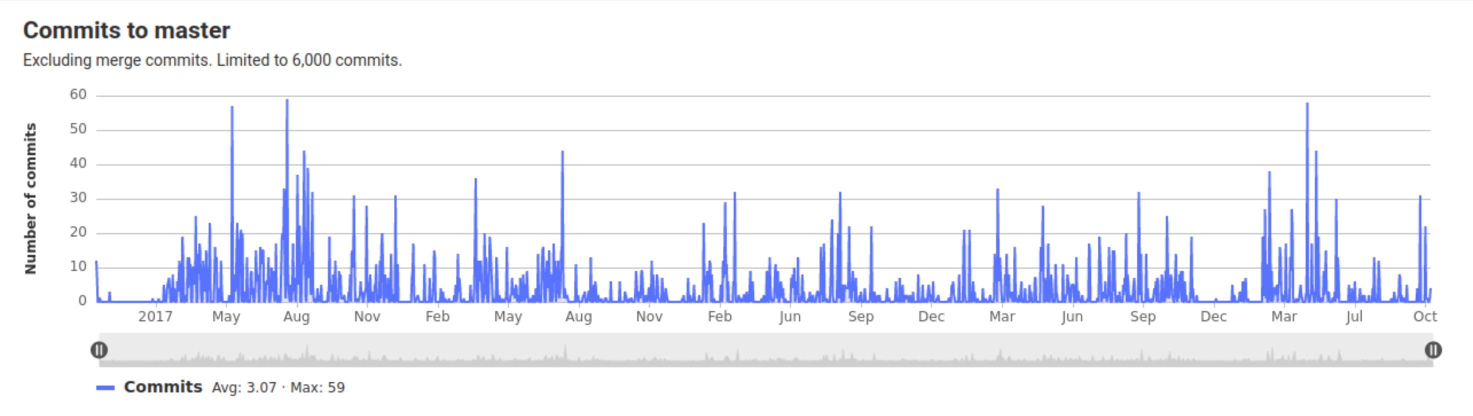
IV. Clean & Maintainable Code

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

- **Allpix^2** implements *best practices* for software development
- Permissive open-source license: MIT

Efforts bear fruit: continuous development since 2017

By now > 40 contributors, many **applications in different fields in research & industry**



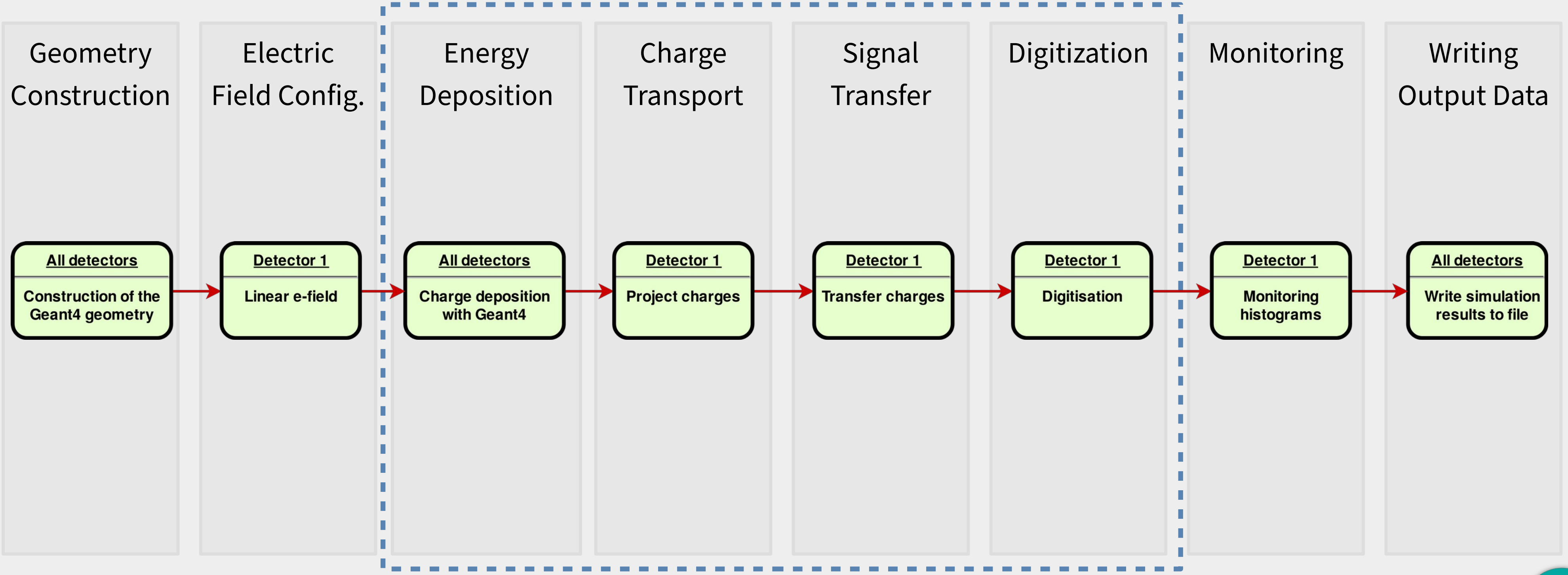
v2.0.2	2021-09-23
v2.0.1	2021-07-09
v2.0	2021-06-10
v1.6.2	2021-04-01
v1.6.1	2021-01-28
v1.6	2020-10-29
v1.5.2	2020-09-14
v1.5.1	2020-07-26
v1.5	2020-04-14
v1.4.4	2020-03-10
v1.4.3	2020-01-10
v1.4.2	2019-11-26
v1.4.1	2019-09-13
V1.4	2019-07-09
v1.3.4	2019-06-07
v1.3.3	2019-04-13
v1.3.2	2019-02-21
v1.3.1	2018-12-17
v1.3	2018-11-21
v1.2.3	2018-11-13
v1.2.2	2018-09-07
v1.2.1	2018-08-02
v1.2	2018-06-13
v1.1.2	2018-04-25
v1.1.1	2018-03-08
v1.1	2018-01-11
v1.0	2017-08-29

The Simulation Chain

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

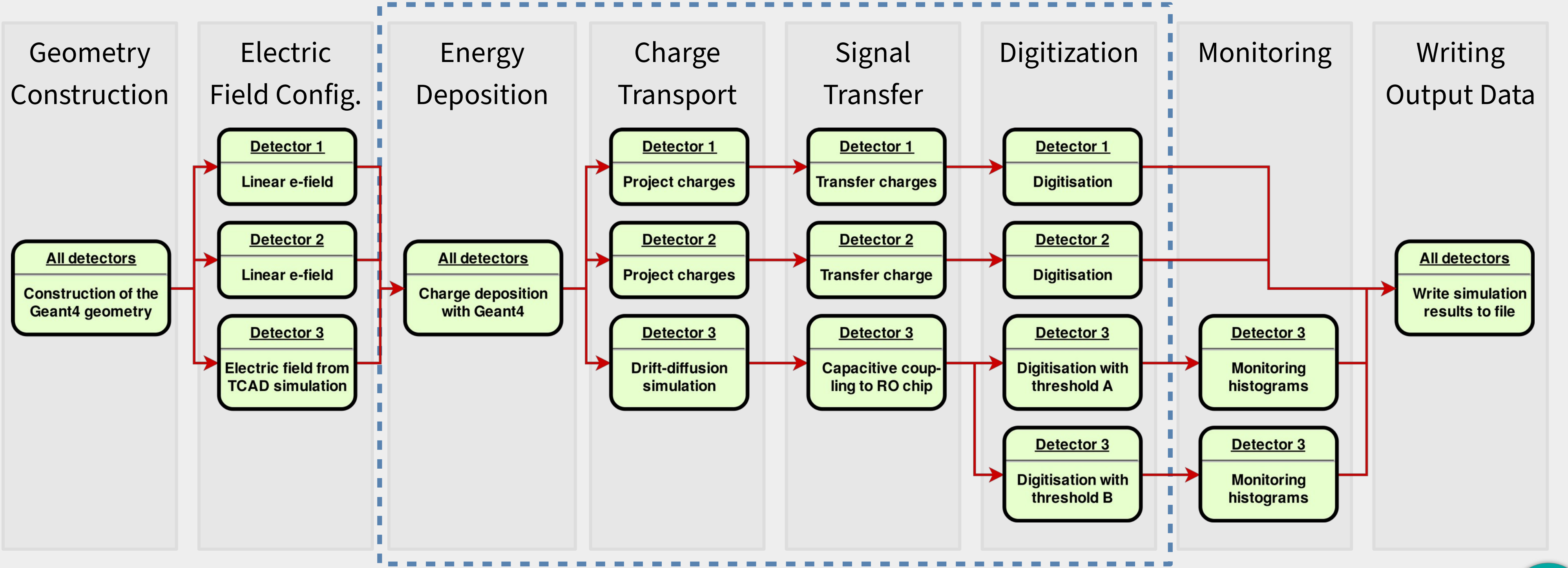
The Simulation Chain

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



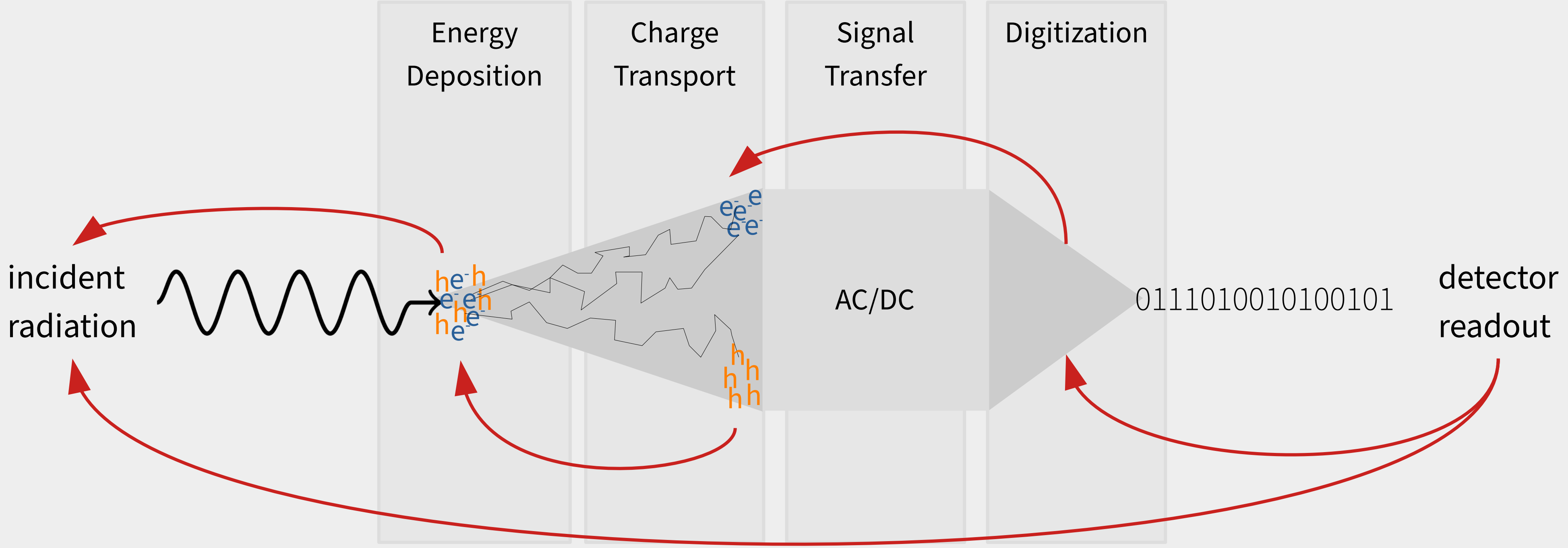
The Simulation Chain

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



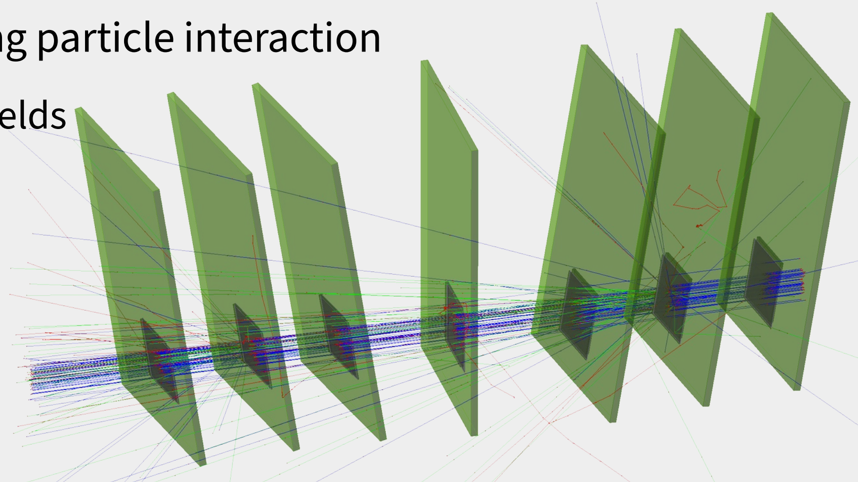
The Monte Carlo Truth

- Allpix^2 keeps history for all simulated objects, every simulation step can be stored
- Cross-references available for convenient access & 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



- **DepositionCosmics:** Using cosmic ray simulation code to generate primaries & Geant4 for tracking

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

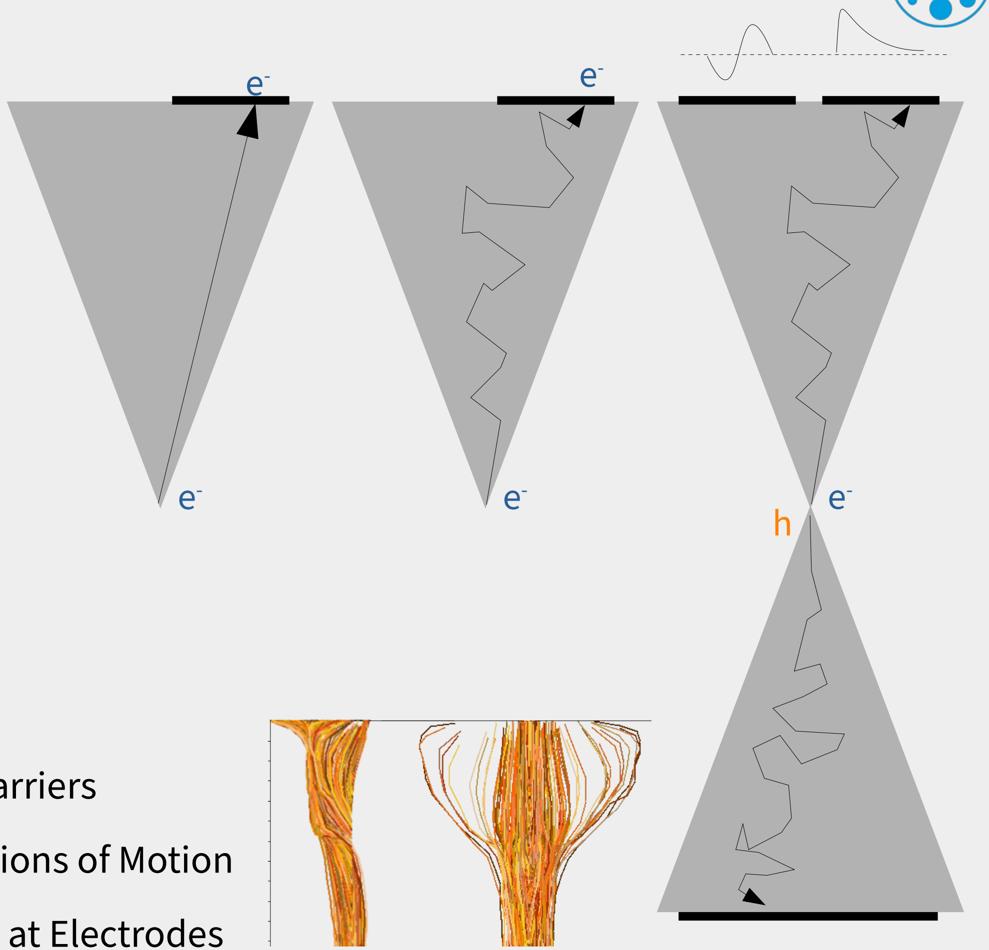
- **DepositionReader:** Read in simulation results from external tools in different formats

Modules for Charge Transport

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

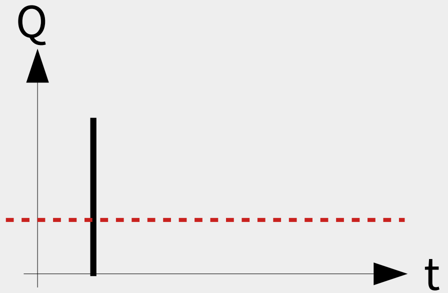
- Multiple charge carriers can be propagated together
  - Depending on initial statistics and required accuracy
  - Some models allow to ignore electrons or holes

- 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

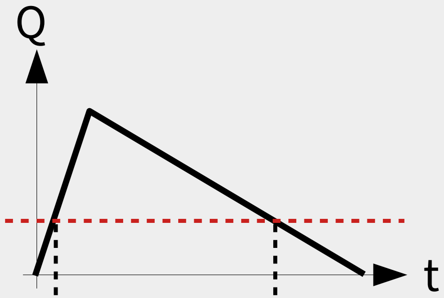


Modules for Digitization

- 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



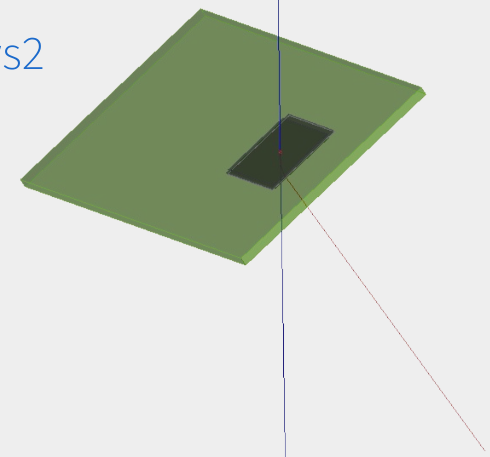
- **CSADigitizer:** Front-end with timing capabilities
  - Requires current pulse
  - Threshold crossings for time-of-arrival and time-over-threshold
  - Possibility to define custom transfer functions



Application Examples

CMOS Sensors, Timing, Calorimetry, Neutron Detection

picked from the 2nd Allpix² User Workshop – https://indico.cern.ch/e/apsqws2

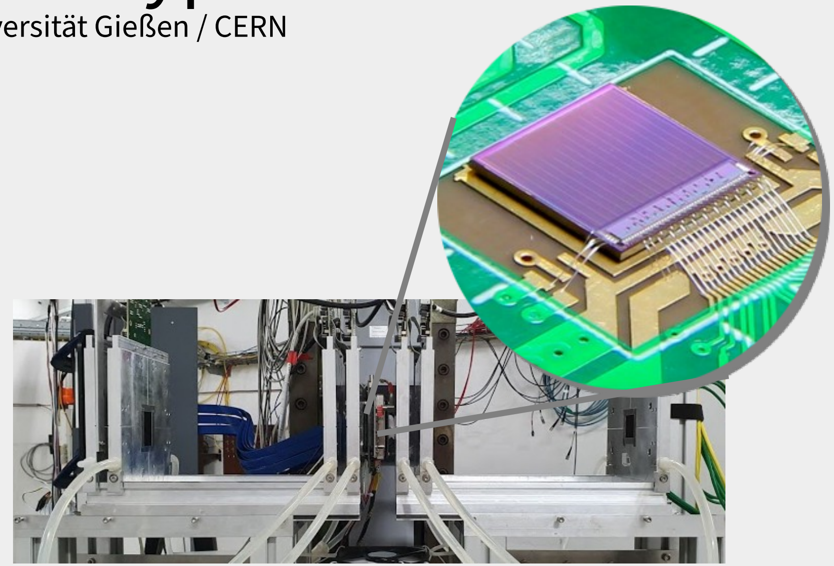


IEEE TNS, vol. 67, no. 10 (2020), 2263
doi:10.1109/TNS.2020.3019887

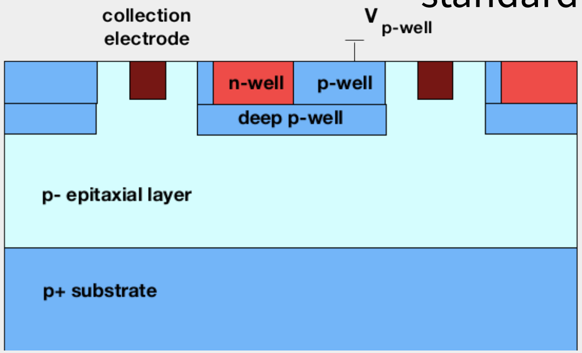
Signal formation in CLICTD MAPS Prototypes

K. Dort, Universität Gießen / CERN

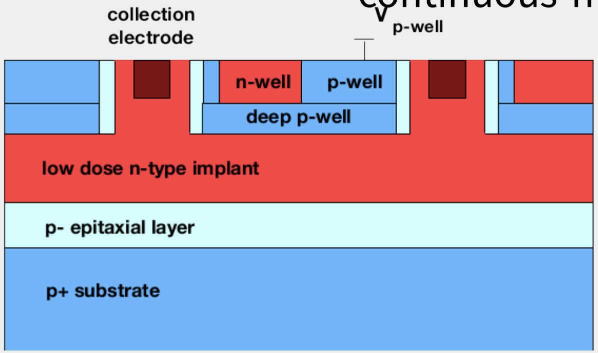
- CLICTD prototype for CLICdet tracking detector
- Using **Allpix²** for high-statistics Monte Carlo studies
  - Electrostatic sensor simulation from **TCAD**
  - End-to-end simulation with induced currents
  - Intra-pixel studies of time & position resolution
- Validation with data recorded at DESY II Testbeam



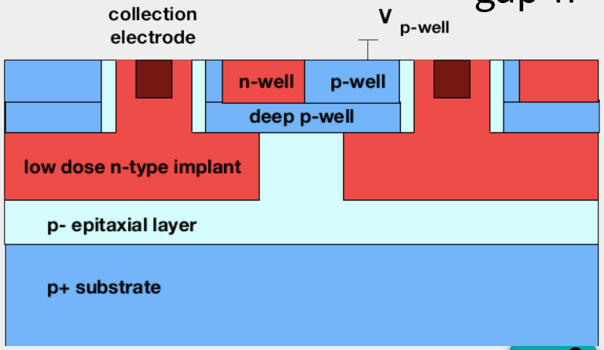
standard



continuous-n

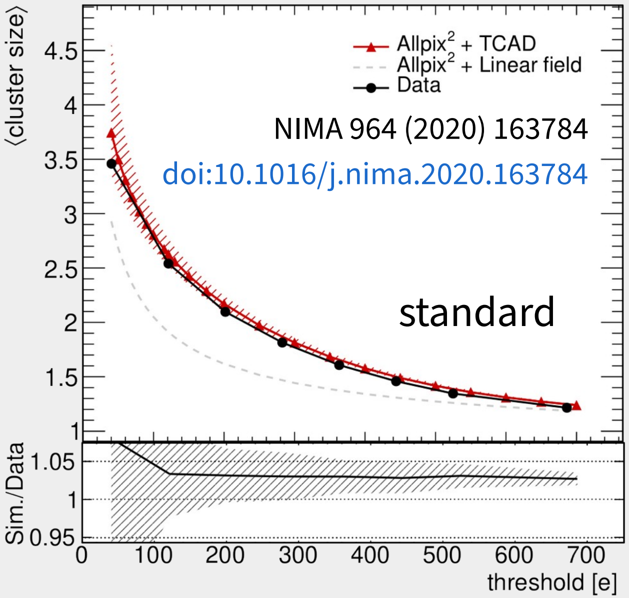


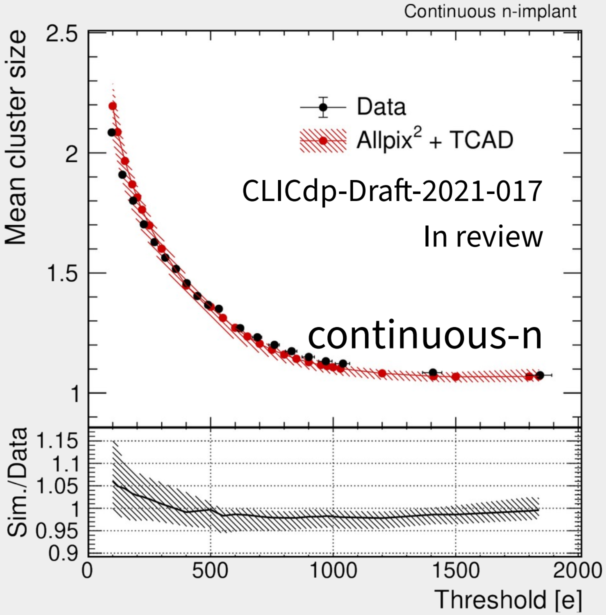
gap-n

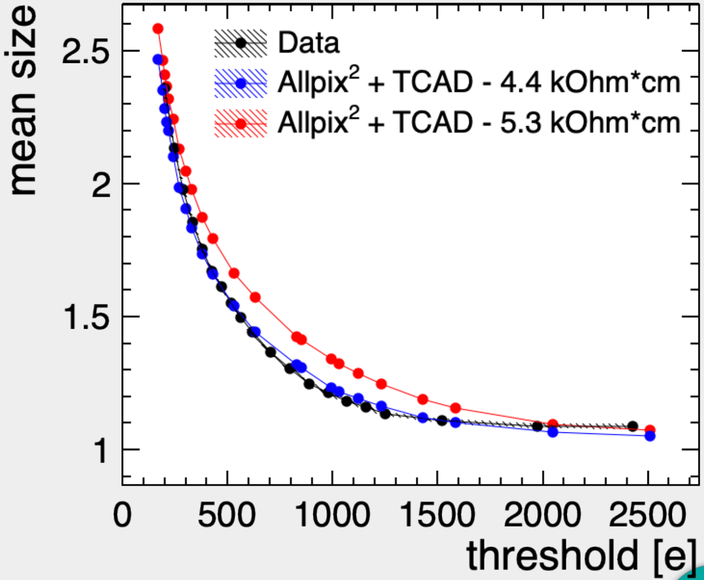


CLICTD: Allpix² Simulation Results

- Comparison of different sensor designs to data – cluster size, resolution
- Validated simulation allows for predictions of current performance & future designs
- Some samples produced on high-resistivity Czochralski substrate,
  Resistivity of sensor material not precisely known – using simulation to confirm





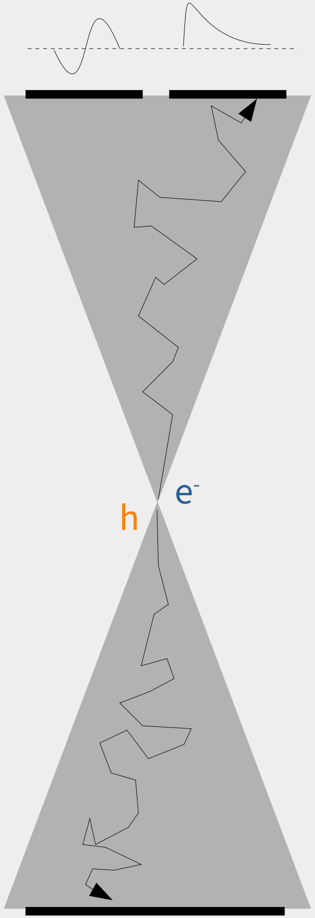


Transient Signal Formation

- Successive integration of motion, calculating induced charge per step via **Shockley-Ramo theorem**:

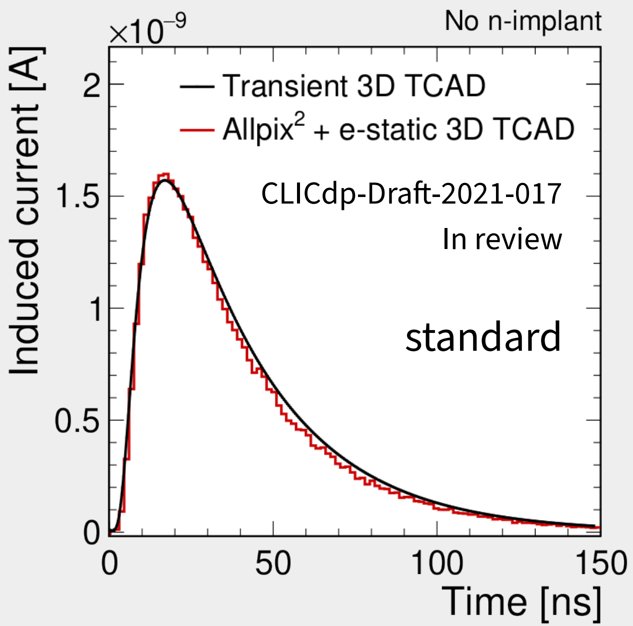
$$Q_n^{\text{ind.}} = \int_{t_{n-1}}^{t_n} I_n^{\text{ind.}} \, \mathrm{d}t = q[\phi(x_n) - \phi(x_{n-1})]$$

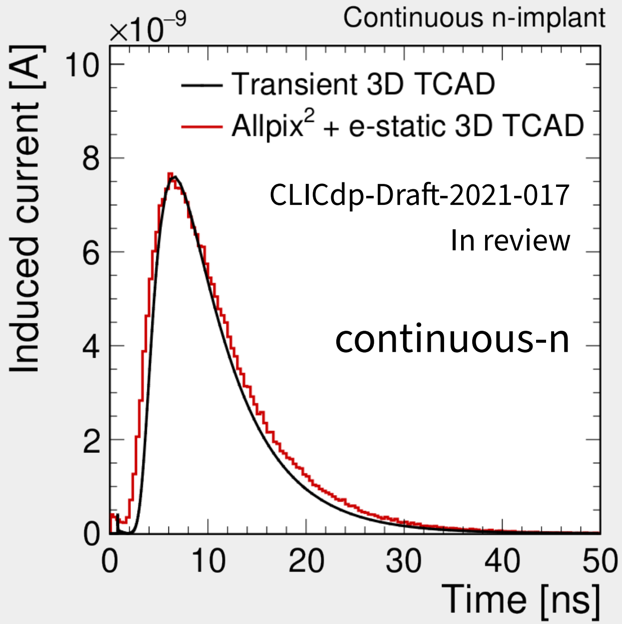
- Take each (group of) charge carrier
  - Calculate mobility & velocity from local fields
  - Make step, add diffusion offset from Gaussian distribution
  - Get induced charge from weighting potential difference for pixel & neighbors
- Requires **static TCAD simulation as input** (e-field, weighting potential)
- Enables time-resolved simulation, much faster than TCAD transient simulation (Allpix^2 < 1 s/event, TCAD ~10 h/event)

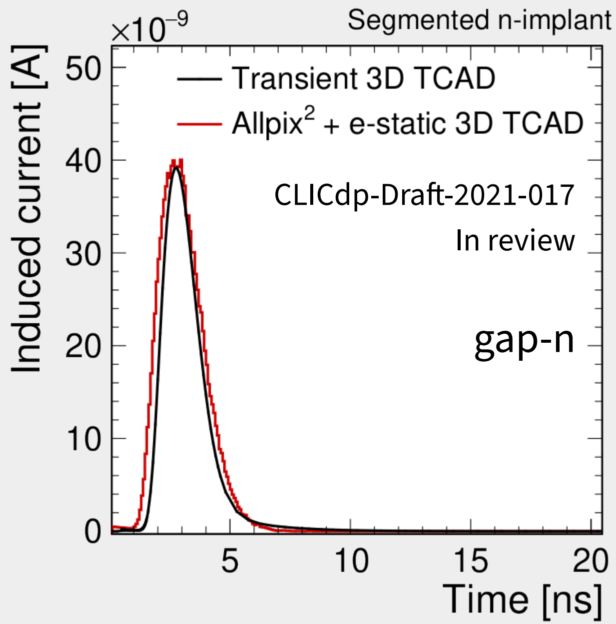


Time Response Studies – Comparison with TCAD

- Simulate linear energy transfer in Allpix² – replicate TCAD situation
- Import electrostatic field & weighting potential from TCAD
- Comparison of current pulse for different CMOS sensor designs:





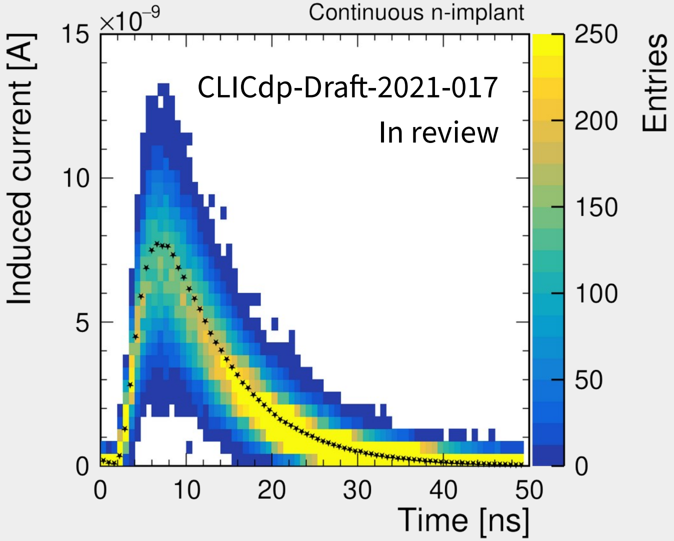


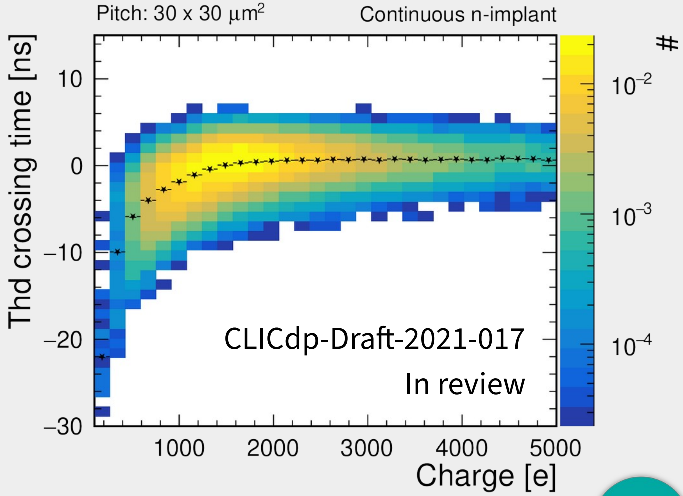
Wield the Power of MC Simulations

- Initial particle with Geant4: Landau, secondaries
- Resulting current pulse exhibits expected fluctuations

- Adding next step: Detector front-end simulation:
  - Analysis of pulse shape in FE electronics, folding with circuit response function
  - Detection of threshold crossings

- Here: time of threshold crossing at rising edge (ToA), expected timewalk behavior observed





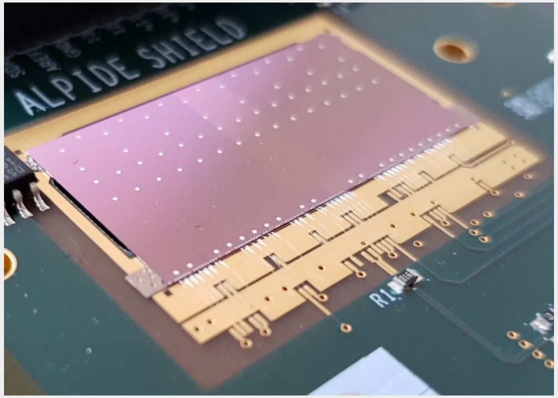
Sensor-level Simulation of MAPS ECAL Test-Beam Data

T. Rogoschinski, Universität Frankfurt

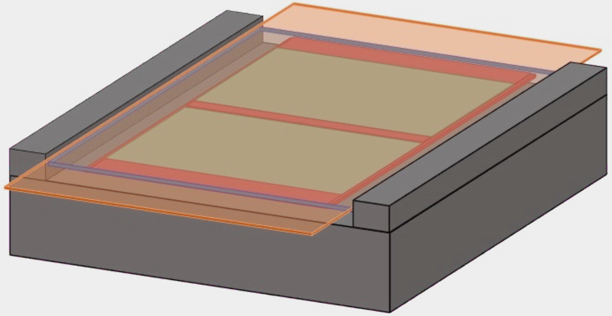
EPICAL-2: MAPS prototype for FoCal

Forward EM calorimeter for ALICE experiment

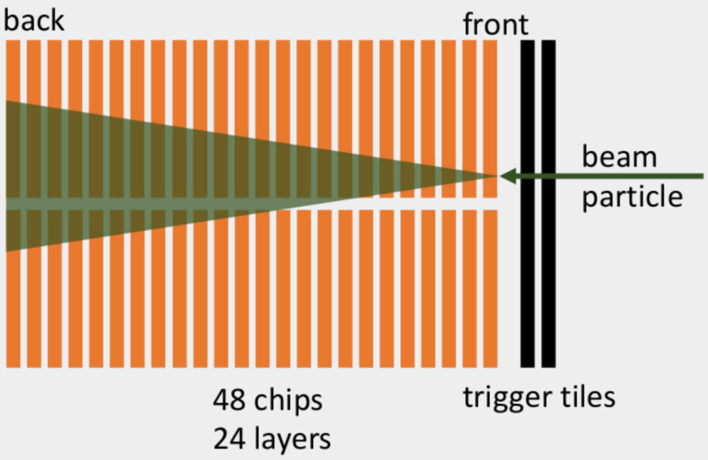
- Fully digital calorimeter prototype
- 24 layers with two ALPIDE chips each + 3mm Tungsten
- 512 x 1024 pixels per chip

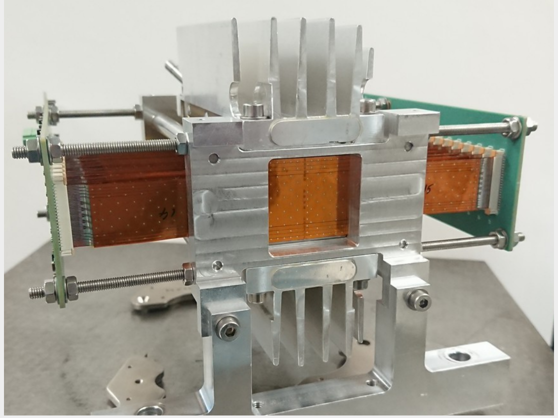


Simulation utilizing Allpix² with precise geometry implementation



layer geometry implemented in Allpix²

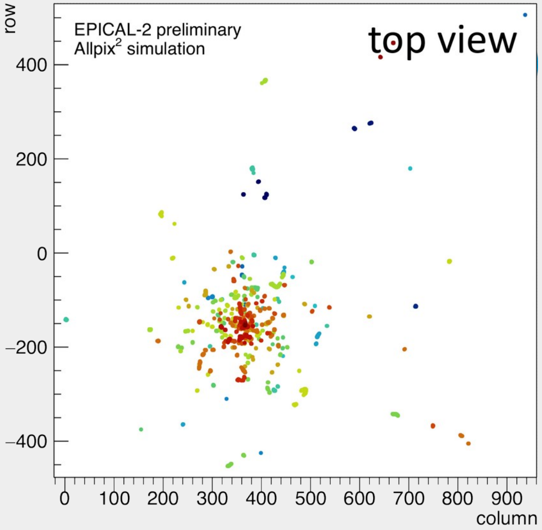


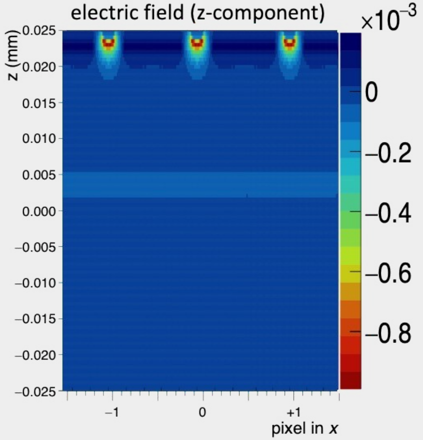


EPICAL-2: Allpix² Simulation Results

T. Rogoschinski, Universität Frankfurt

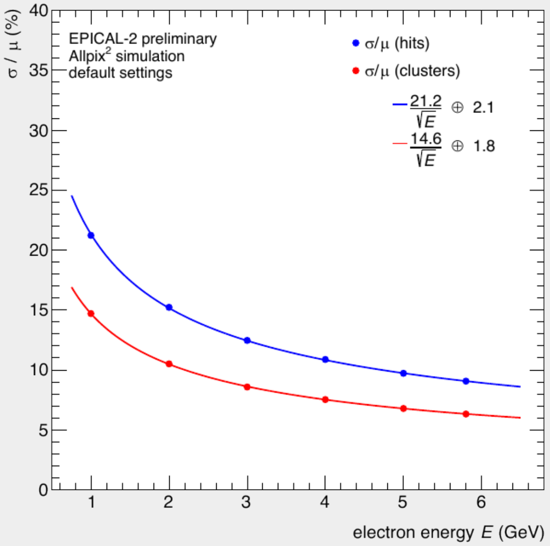
- Using electrostatic field of ALPIDE from TCAD simulations
- Good agreement of simulation and test beam data
- Remaining differences attributed to simplified simulation of beam profile & energy spectrum, adjustments underway



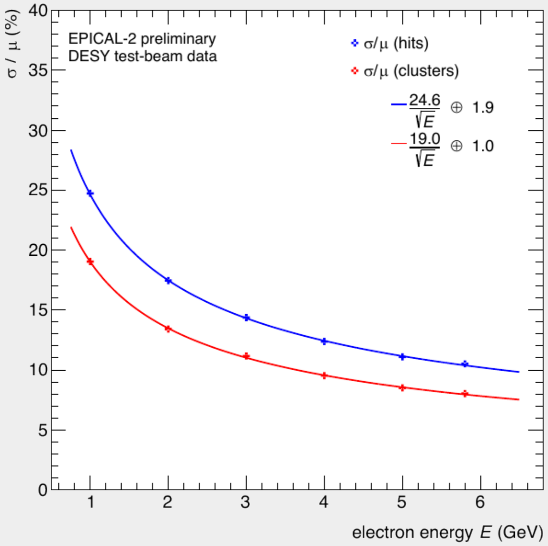


e-static TCAD field

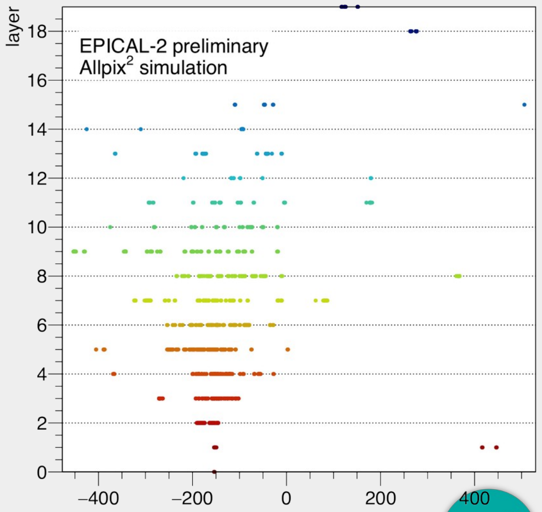
simulation



test-beam data



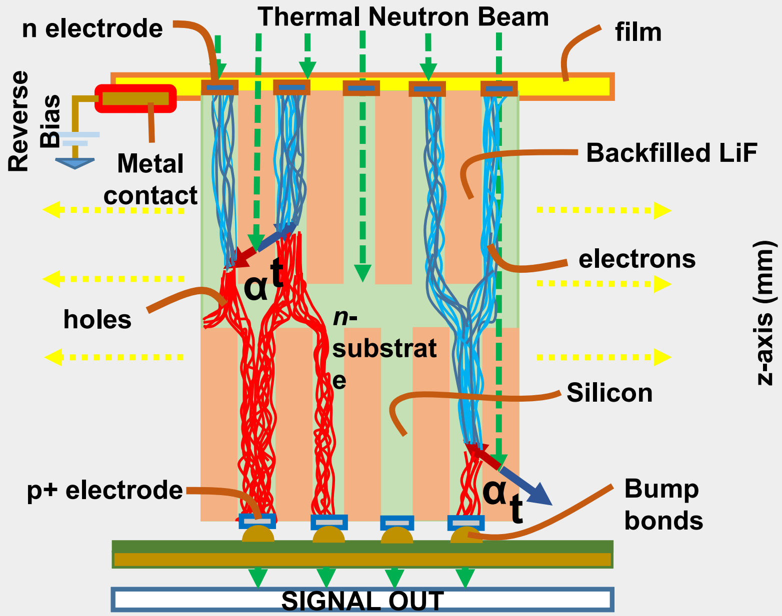
side view: row

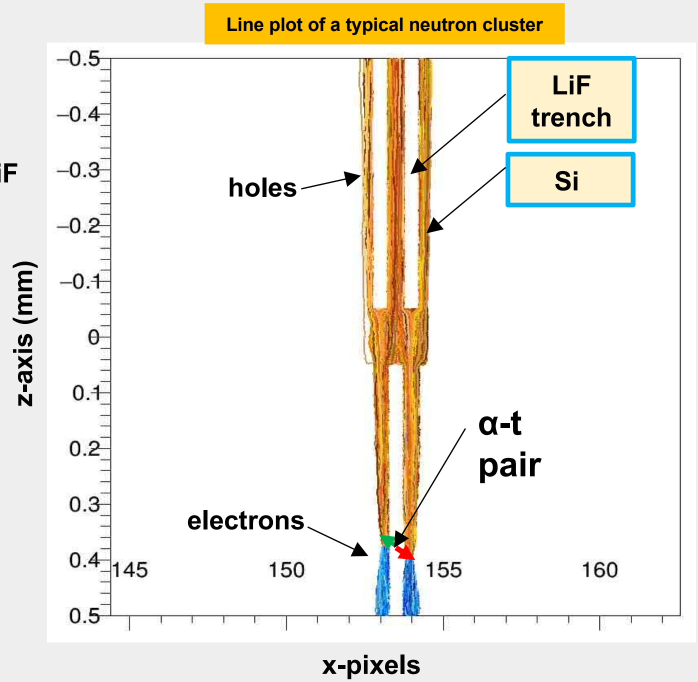


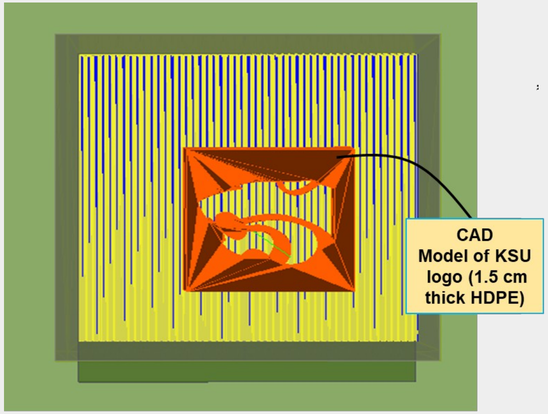
Dual Sided Micro-Structured Neutron Detector

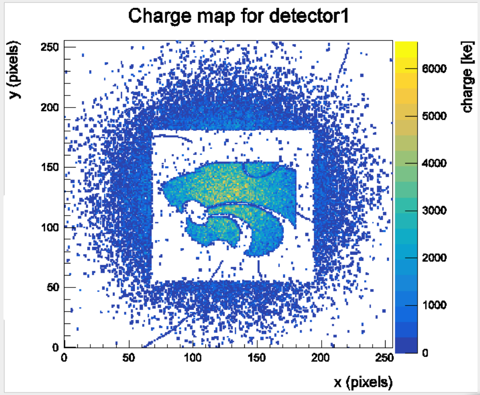
S. Sharma, Kansas State University

- n-type Si sensor with LiF trenches for neutron conversion (n → t + α)
- COMSOL used to generate electric field maps
- End-to-end simulation of entire detection system with Allpix²



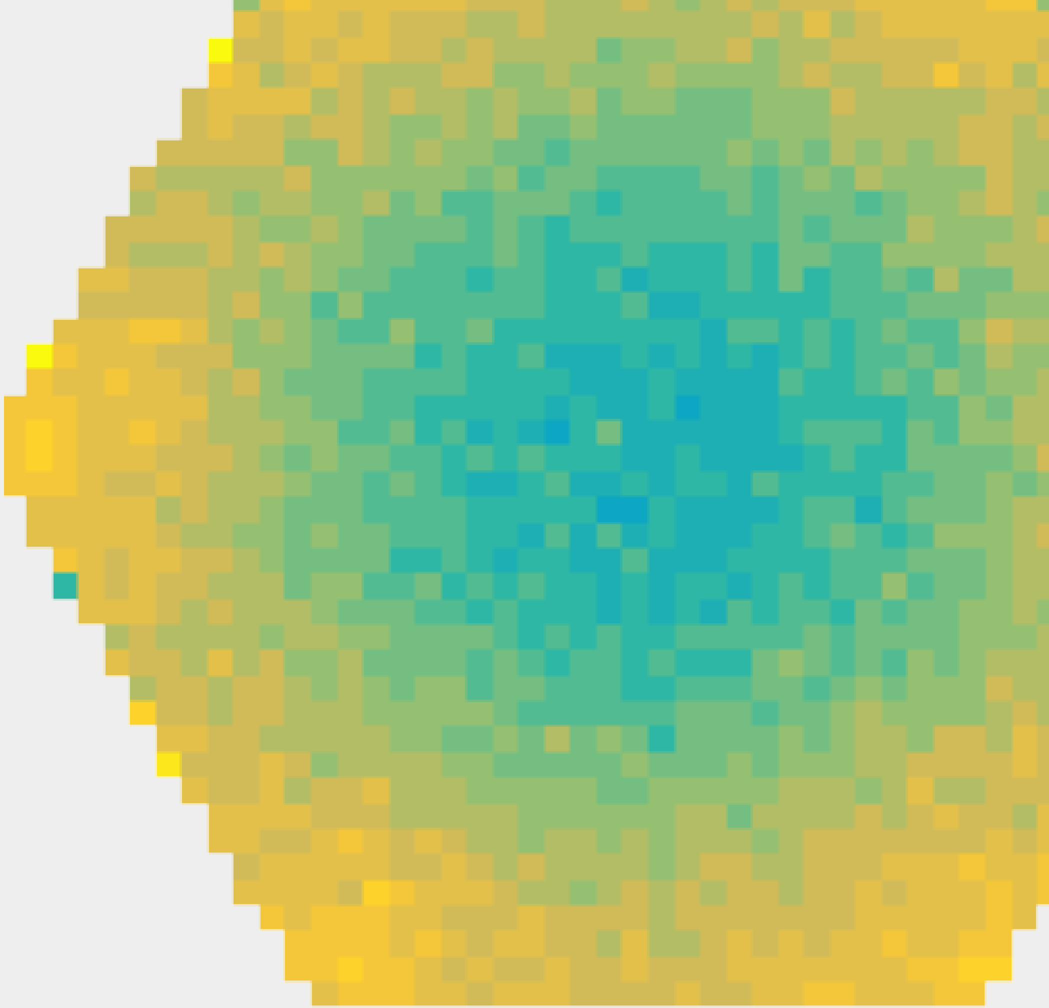






Sneak Peek

New & Upcoming Features

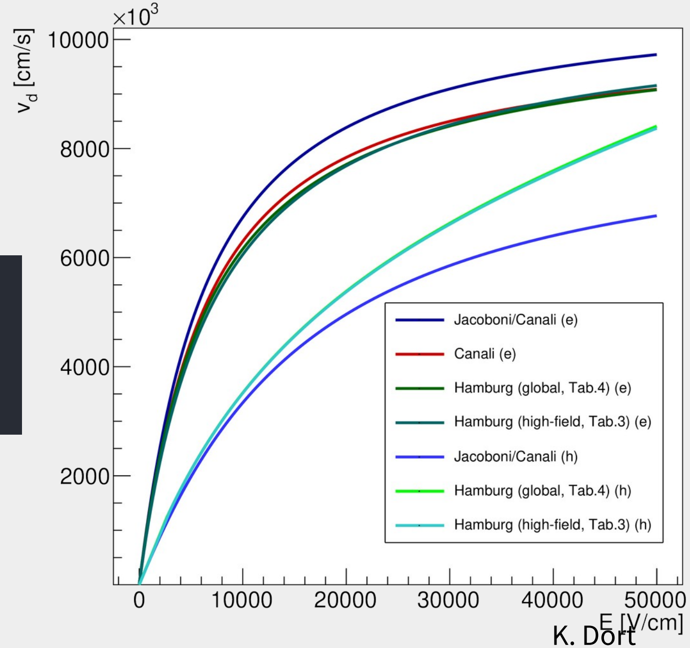


Mobility & Recombination

Introduced possibility to select **charge carrier mobility** model

- Field dependent
- Doping concentration dependent
- Optimized for high-field situations

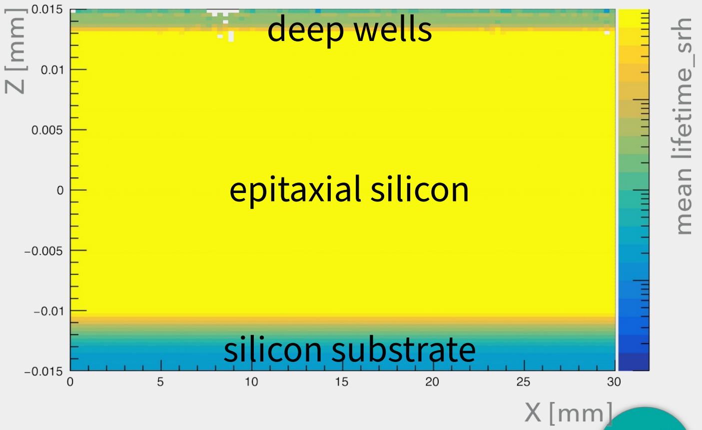
```
[GenericPropagation]
temperature = 293K
mobility_model = "masetti"
```



K. Dort

Support for position-dependent doping maps & **lifetime calculation**

- 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
- Shockley-Read-Hall, Auger models & combination of both



→ **Recently published & available in Allpix^2 2.0**

Impact Ionization

Implementation of charge multiplication through impact ionization underway

- Multiple models available, selection via configuration file:
  - Massey
  - Van Overstraeten-De Man
  - Okuto-Crowell
  - Bologna
- Fully documented in user manual

- **Implementation in Allpix² completed**, undergoing testing, Comparison with Weightfield2 & TCAD simulations

- Looking for interested collaborators for validation of simulation with data

coefficient α and the length of the step l performed in the respective electric field. If the electric field strength stays below a configurable threshold E_{thr}, unity gain is assumed:

$$g(E,T) = \begin{cases} e^{l\cdot\alpha(E,T)} & E > E_{\text{thr}} \\ 1.0 & E < E_{\text{thr}} \end{cases} \tag{6.12}$$

The the following impact ionization models are available:

6.3.1 Massey Model

The Massey model [35] describes impact ionization as a function of the electric field E. The ionization coefficients are parametrized as

$$\alpha(E,T) = Ae^{-\frac{B(T)}{E}}, \tag{6.13}$$

where A and $B(T)$ are phenomenological parameters, defined for electrons and holes respectively. While A is assumed to be temperature-independent, parameter B exhibits a temperature dependence and is defined as

$$B(T) = C + D \cdot T. \tag{6.14}$$

The parameter values implemented in Allpix² are taken from Section 3 of [35] as:

$$\begin{aligned} A_e &= 4.43 \times 10^5 \,/\text{cm} & A_h &= 1.13 \times 10^6 \,/\text{cm} \\ C_e &= 9.66 \times 10^5 \,\text{V/cm} & C_h &= 1.71 \times 10^6 \,\text{V/cm} \\ D_e &= 4.99 \times 10^2 \,\text{V/cm/K} & D_h &= 1.09 \times 10^3 \,\text{V/cm/K} \end{aligned}$$

for electrons and holes, respectively.

This model can be selected in the configuration file via the parameter `multiplication_model = "massey"`.

6.3.2 Van Overstraeten-De Man Model

The Van Overstraeten-De Man model [36] describes impact ionization using Chynoweth's law, given by

$$\alpha(E,T) = \gamma(T) \cdot a_{\infty} \cdot e^{-\frac{\gamma(T)\cdot b}{E}}, \tag{6.15}$$

For holes, two sets of impact ionization parameters $p = \{a_{\infty}, b\}$ are used depending on the electric field:

$$p = \begin{cases} p_{\text{low}} & E < E_0 \\ p_{\text{high}} & E > E_0 \end{cases} \tag{6.16}$$

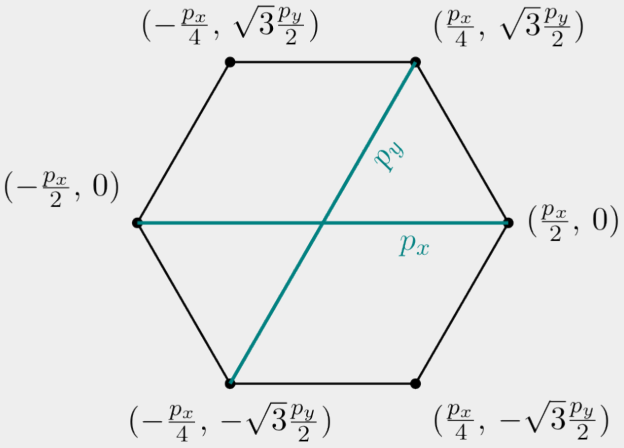
Temperature scaling of the ionization coefficient is performed via the $\gamma(T)$ parameter following the Synposys Sentaurus TCAD user manual as:

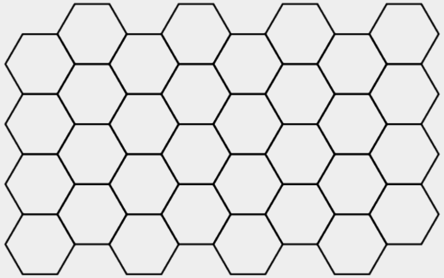
$$\gamma(T) = \tanh\left(\frac{0.063 \times 10^6 \,\text{eV}}{28.6173 \times 10^{-5} \,\text{eV/K} \cdot T_0}\right) \cdot \tanh\left(\frac{0.063 \times 10^6 \,\text{eV}}{28.6173 \times 10^{-5} \,\text{eV/K} \cdot T}\right)^{-1} \tag{6.17}$$

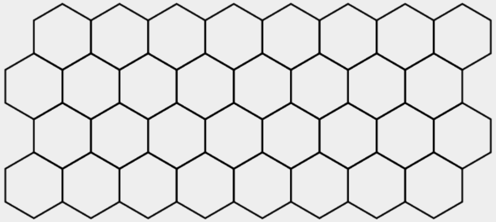
Hexagonal Pixel Geometries

Extension of Allpix² geometry subsystem to enable simulation of different pixel shapes & matrix arrangements

- Hexagonal geometry interesting for many applications
  - Avoid problematic field regions in corners
    (small electrodes: low fields, large electrodes: high fields)
  - Symmetry more close to circle – more uniform response
- **Implementation in Allpix² completed**, undergoing testing:
  - Using **axial coordinate system**
  - Support for "pointy" & "flat" hexagon orientation,
    regular (same-pitch) and distorted (different pitch) hexagons



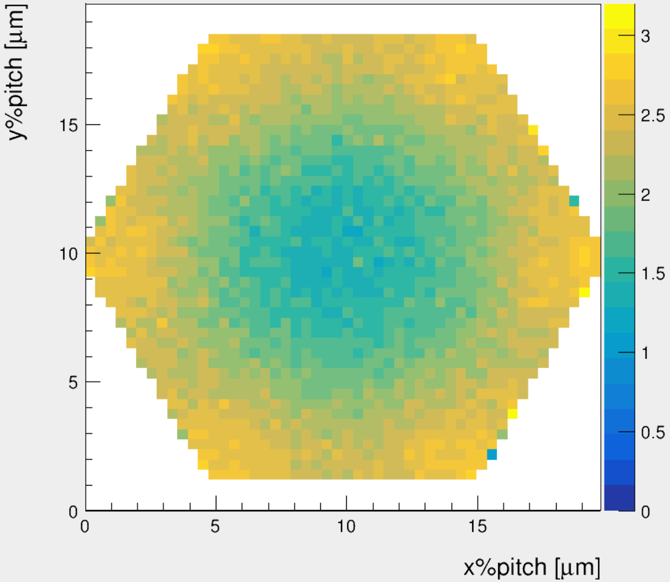


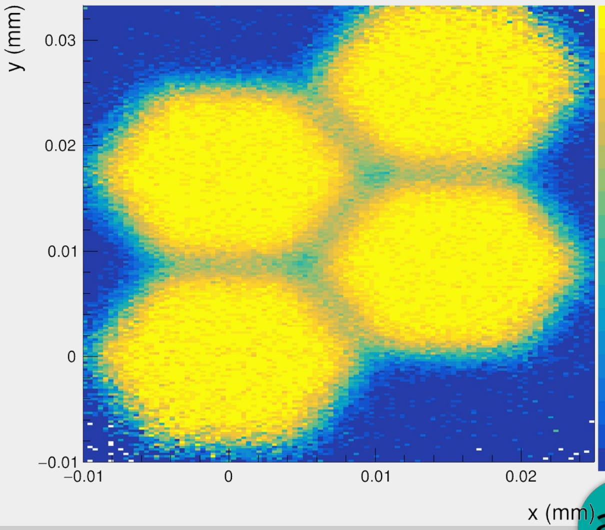


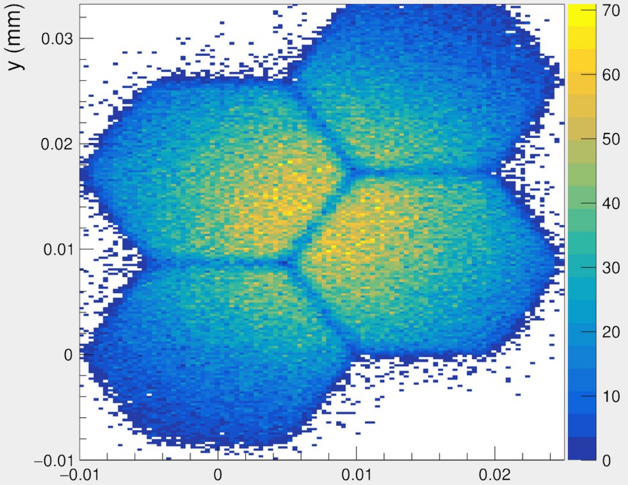
Other geometries also in preparation (e.g. radial strips @ ATLAS ITk)

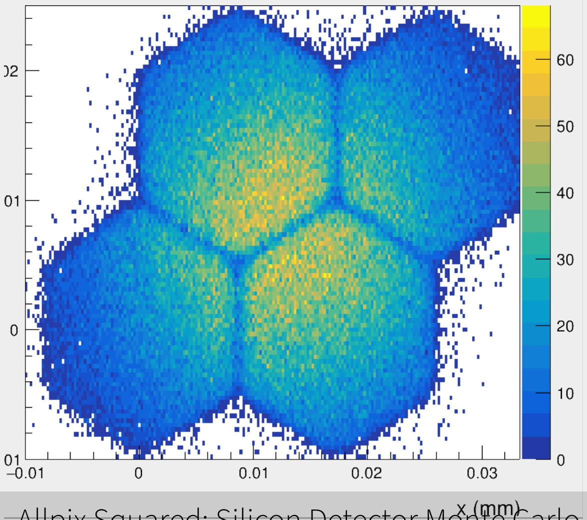
First Simulations with Hexagonal Pixels

- Performed implementation tests with hexagonal pixel detector
  large pixels, linear electric field, high charge threshold
- Analysis of basic properties
  - Recovery of radial beam profile from pixel matrix
  - In-pixel cluster size distribution
  - Efficiency fall-off at hexagon edges



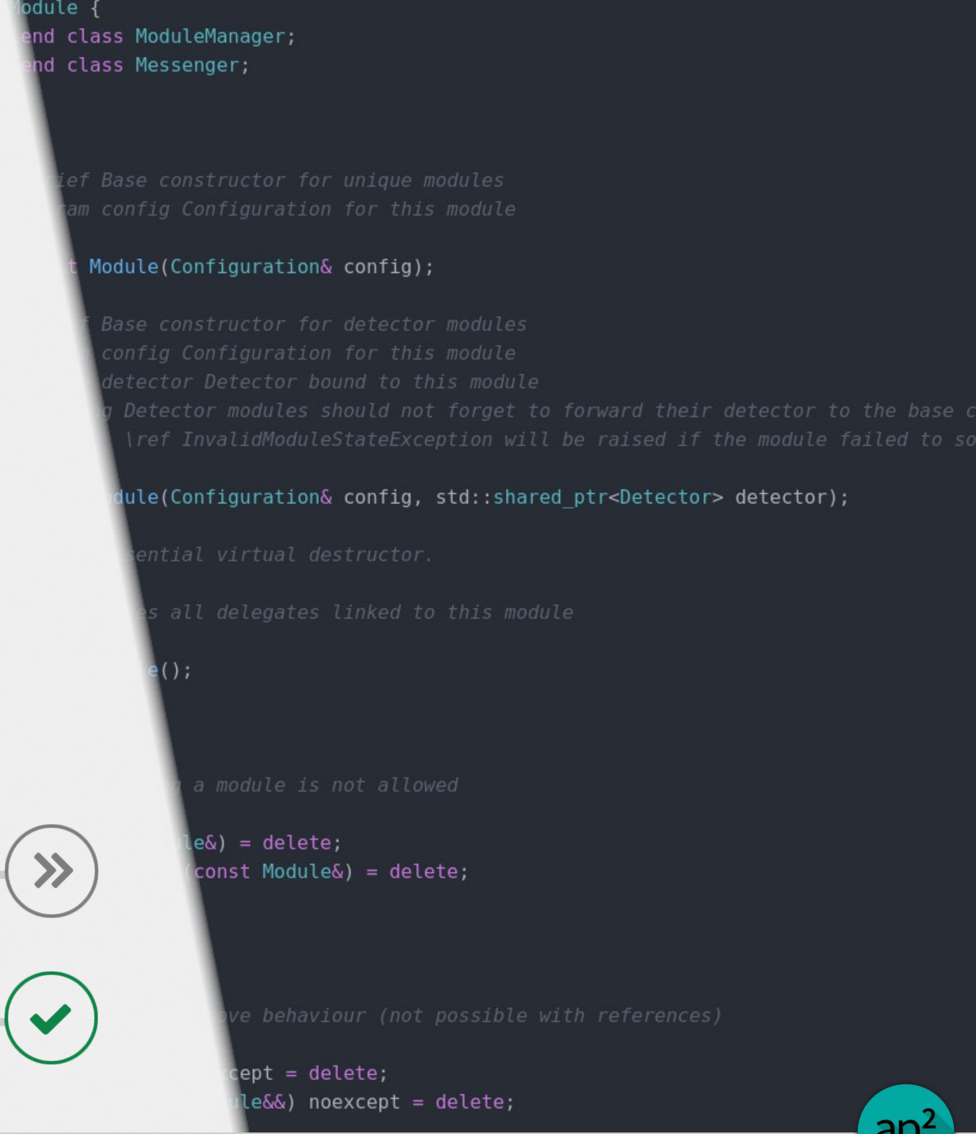






A Word On...

Sustainable Development



Sustainable Development of Common Software Tools

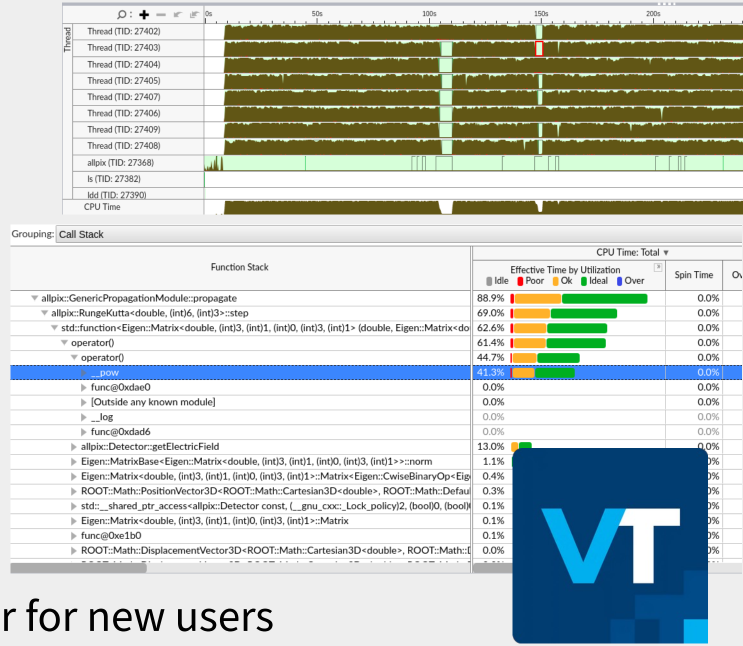
Implementing algorithms such, that they are...

...validated with prototype data & device simulations

...well documented & tested

...making efficient use of computing resources

...maintainable over a period longer than O(1 fellow) / O(1 PhD)

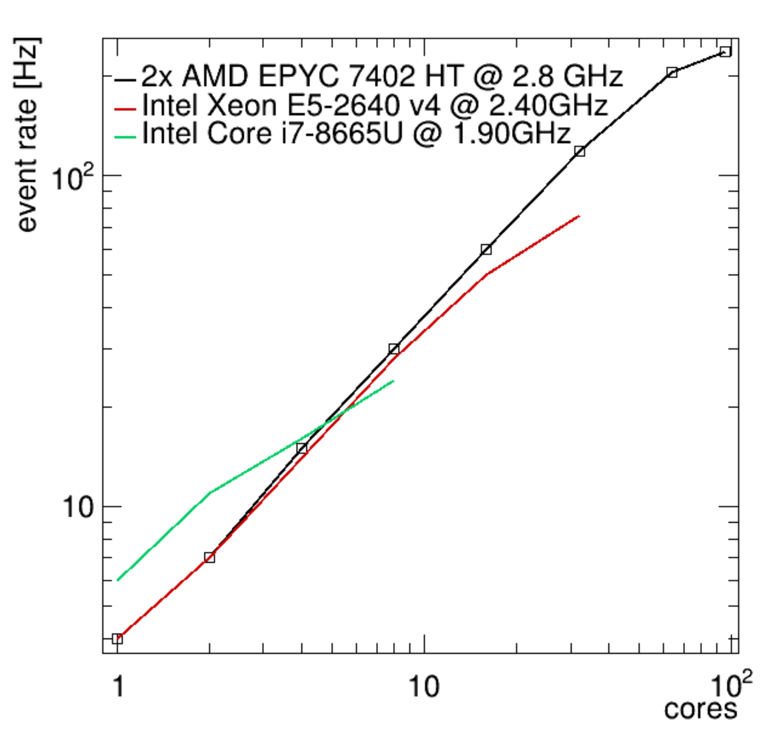


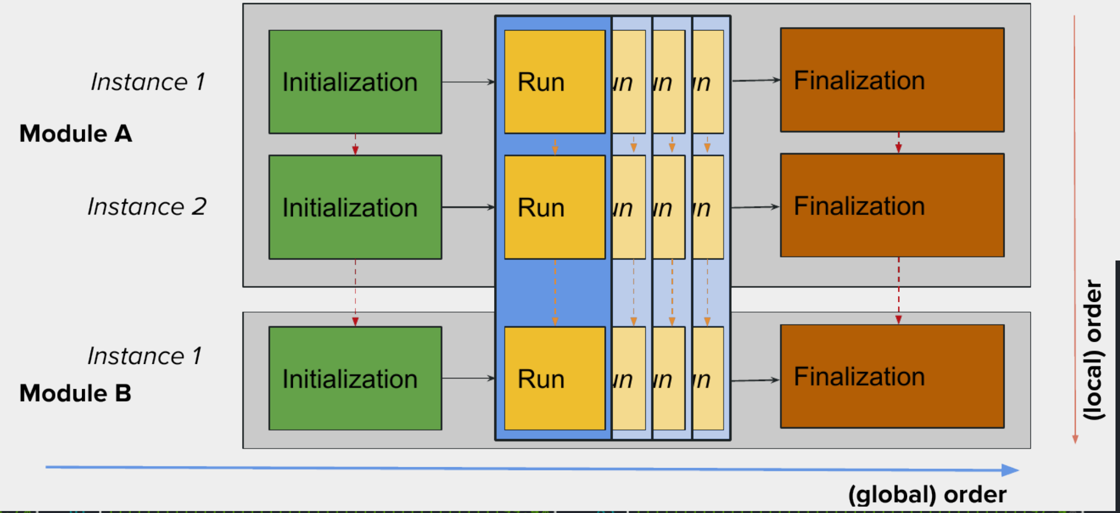
Development of Allpix²: spend considerable time on

- Writing documentation → lower barrier for new users
- Implementing automated testing, compilation → ensure software always works
- Code review for new features → ensure functionality/compatibility
- Benchmarking / optimization → run as efficiently as possible

Multithreading Support

Allpix² supports event-based multithreading while retaining strong reproducibility, exact same result independent of number workers, fully transparent to user / simulation





Tasks: 80, 1073 thr; 96 running
Load average: 32.64 10.39 3.81
Uptime: 180 days(!), 22:26:44

Allpix² fully utilizing 96 cores

Code Review via Merge Requests

No new code lands in Allpix² **without review** by another party

- Using GitLab's code review / approval tools
- Extensive discussions about code, but also style, naming schemes

Proven to be **very effective**

- Several bugs found before the merge
- New users appreciate guidance

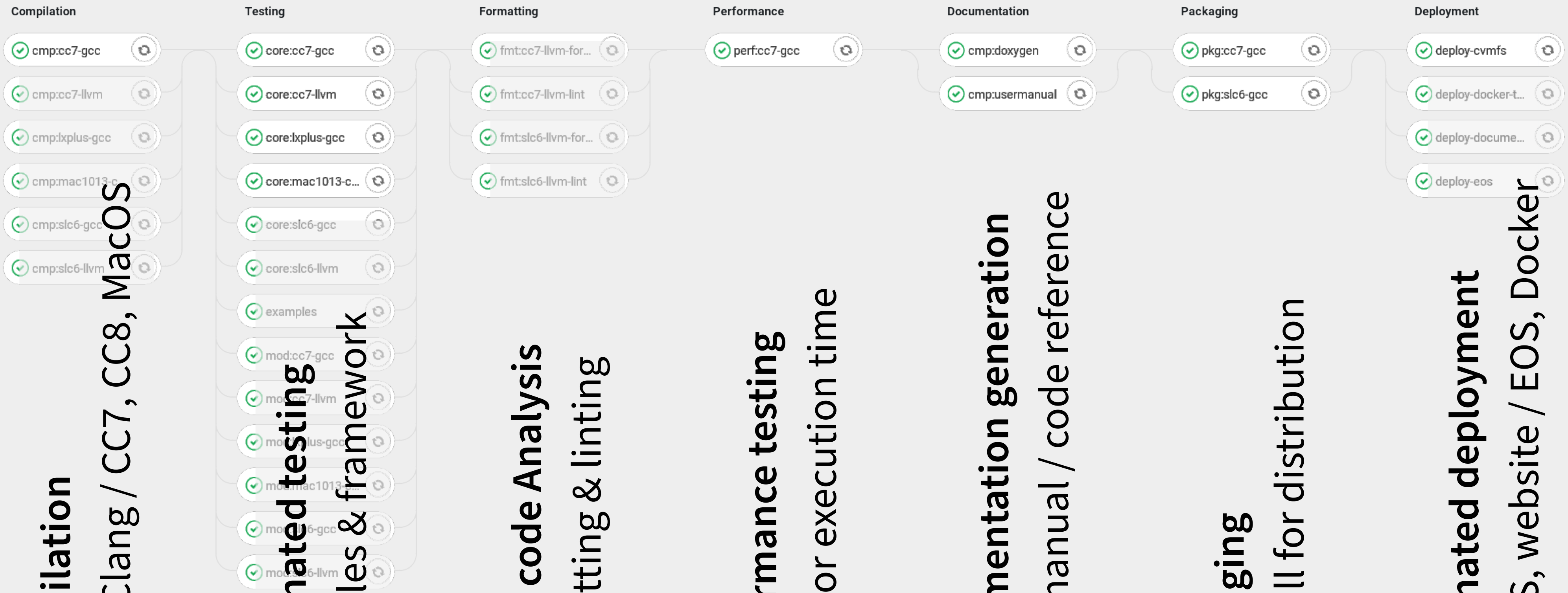
Proven to be **labor-intensive**

- Reading (and understanding) every change
- Always be supportive, positive

...just some of them

Slight alteration to progress percentage calculation, to avoid integer overflow. !554 · created 3 weeks ago by Haakan Wennloef	MERGED Approved 9 updated 3 weeks ago
Prepare Patch Release v2.0.2 !534 · created 1 month ago by Simon Spannagel Patch v2.0.2	MERGED Approved 0 updated 4 weeks ago
DetectorModel: fix calculation of pixel center !540 · created 1 month ago by Simon Spannagel bug detector models	MERGED Approved 0 updated 1 month ago
Moving model-specific methods to DetectorModel !515 · created 3 months ago by Radek Privara	MERGED Approved 24 updated 1 month ago
DepositionGeant4: check for possible nullptr dereference !536 · created 1 month ago by Simon Spannagel Patch v2.0.2 bug	MERGED Approved 1 updated 1 month ago
Hit transform matrix !532 · created 1 month ago by Radek Privara	MERGED Approved 11 updated 1 month ago
Enhance Github CI !533 · created 1 month ago by Paul Jean Schutze continuous integration	MERGED Approved 1 updated 1 month ago
DepositionGeant4: add debug output when using ions as source !530 · created 1 month ago by Simon Spannagel	MERGED Approved 0 updated 1 month ago
modified chip thickness and support material !480 · created 5 months ago by Reem Hani M Taibah	MERGED 1 left 1 updated 1 month ago
Minor fixes and changes to eudet rd53a example !529 · created 1 month ago by Paul Jean Schutze	MERGED Approved 5 updated 1 month ago

Continuous Integration & Deployment Pipeline



Compilation
GCC, Clang / CC7, CC8, MacOS

Automated testing
modules & framework

Static code Analysis
formatting & linting

Performance testing
monitor execution time

Documentation generation
user manual / code reference

Packaging
Tar ball for distribution

Automated deployment
CVMFS, website / EOS, Docker

Automated Testing

```
[Allpix]
detectors_file = "detector_rotate_misaligned.conf"
log_level = "TRACE"
number_of_events = 0
random_seed = 0
random_seed_core = 0

[GeometryBuilderGeant4]

#PASS (DEBUG)  misaligned: (8.72466deg,171.099deg,178.504deg)
```

```
Test project /builds/allpix-squared/allpix-squared/build
      Start 53: test_core/test_01-1_globalconfig_detectors.conf
      Start 54: test_core/test_01-2_globalconfig_modelpaths.conf
      Start 55: test_core/test_01-3_globalconfig_log_format.conf
      Start 56: test_core/test_01-4_globalconfig_log_level.conf
 1/22 Test #53: test_core/test_01-1_globalconfig_detectors.conf .........   Passed    0.81 sec
      Start 57: test_core/test_01-5_globalconfig_log_file.conf
 2/22 Test #56: test_core/test_01-4_globalconfig_log_level.conf .........   Passed    2.11 sec
 3/22 Test #55: test_core/test_01-3_globalconfig_log_format.conf ........   Passed    2.11 sec
      Start 58: test_core/test_01-6_globalconfig_missing_model.conf
      Start 59: test_core/test_01-7_globalconfig_random_seed.conf
 4/22 Test #57: test_core/test_01-5_globalconfig_log_file.conf ..........   Passed    1.11 sec

[...]

100% tests passed, 0 tests failed out of 22
```

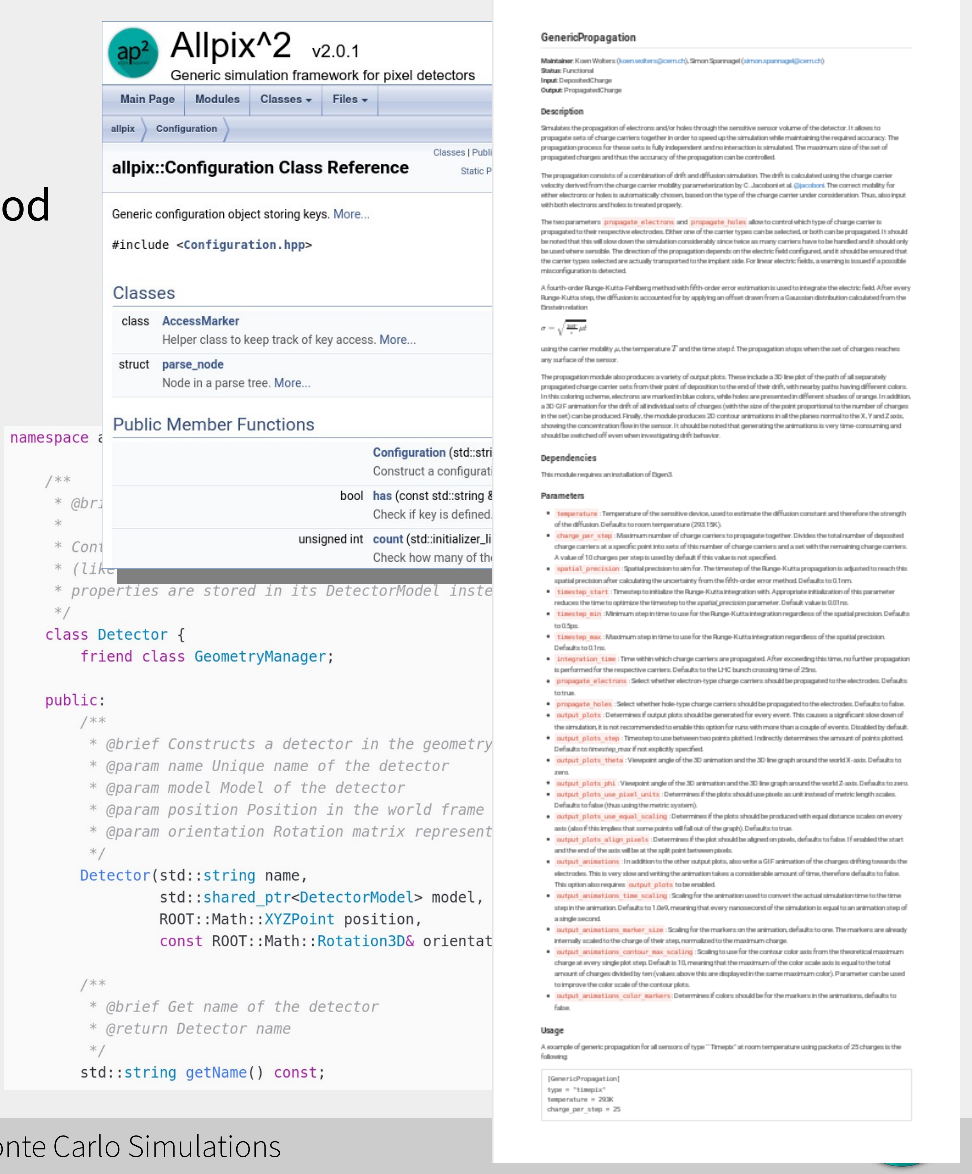
Test framework & modules by automatically running simulation configurations with known outcomes

- Each test is a configuration file:
  - Run single event with fixed seed
  - Reproduces same output
  - Matching regular expressions
- Single change (1e difference) fails test
  → adaptation of test in case of expected change
- Invaluable for monitoring framework
  → catching issues before merging code

User Manual & Code Reference

- Source code documentation for every class & method
  - Doxygen markup for code reference
  - CI checks for complete & correct documentation
  - Deployed to the website for every release

- User Manual (currently) in LaTeX
  - Module documentation as Markdown
    - Document module parameters, algorithms
    - Included in manual via Pandoc
  - Manual automatically compiled by CI
  - Deployed to the website for every release



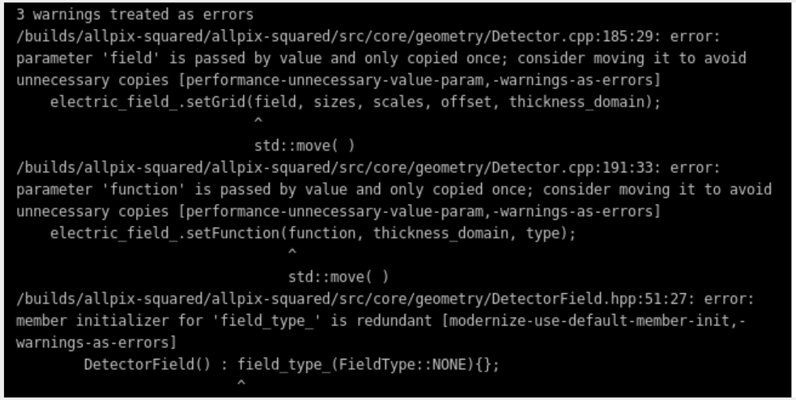
How To Contribute – A Cookbook

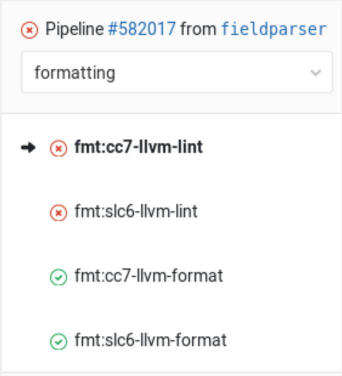
- **Get in touch** – mail, forum, issue tracker, CERN Mattermost…
  Let's discuss the idea, maybe we have input, maybe others are working on it already

- **Fork the repository**
  Creating your own copy of the code with which you can mess as much as you want

- **Start hacking**
  Implement the desired functionality, come back to us when you have doubts or questions

- **Make sure the CI passes**
  Enable the CI in your fork and publish your new code there – check that the CI works!





- **File a Merge Request**
  This provides us a central point to discuss and review all your code changes

- **See your code being merged and published!**

Summary

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.