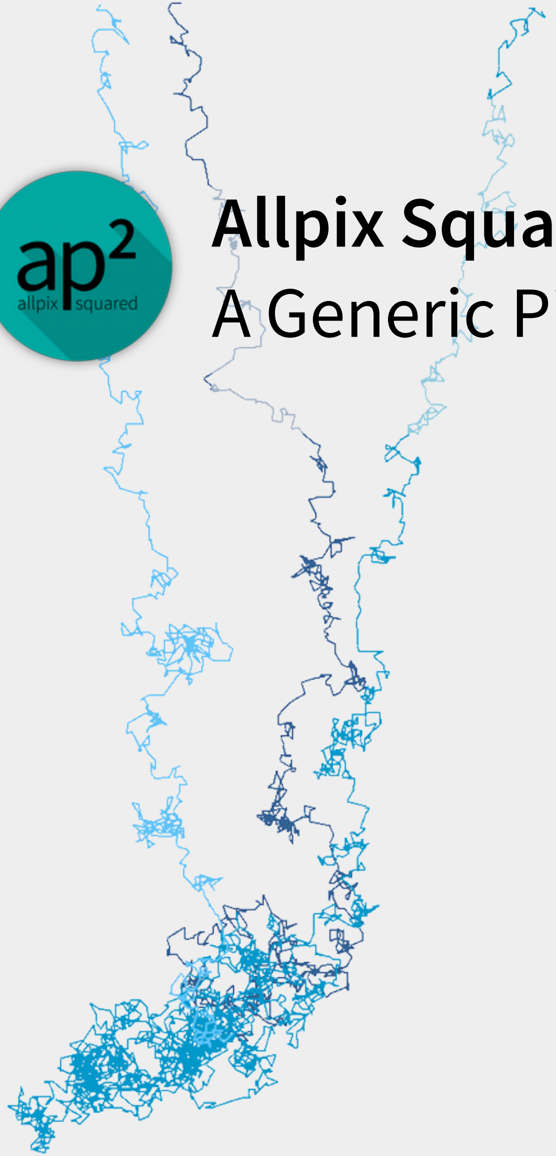
cern.ch/allpix-squared



Allpix Squared

A Generic Pixel Detector Simulation Framework

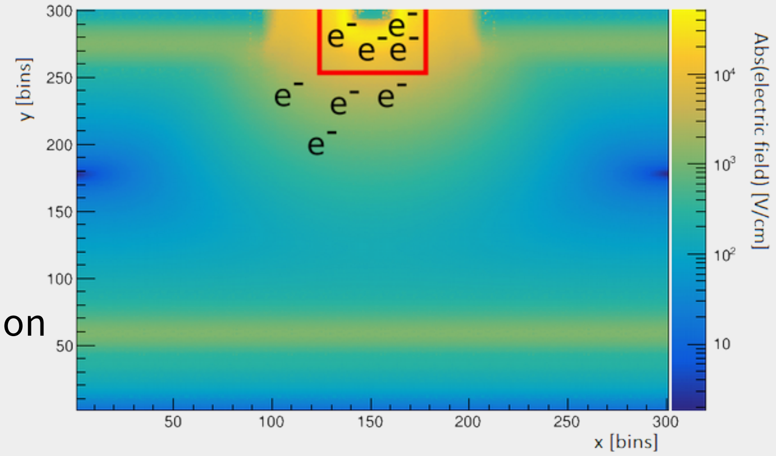
Simon Spannagel, CERN

EP-SFT Group Meeting

CERN, 08 April 2019

The Challenge

- Silicon detectors widely used in HEP – vertex & tracking, timing detectors, calorimeters
- New commercial CMOS technologies entering the market
  - Strong drive towards monolithic detectors
  - Entails complex sensor layouts and charge collection



- **Wanted**: flexible simulation software, that

  ...allowed to **test different** simulation **models for** signal formation

  ...allow parametrized detector models

  ...would facilitate usage of **precise electric fields**

- Developed new framework within **CLICdp collaboration**, based on established ideas:
  - **AllPix** – Geant4 user classes for digitizer development of large simulations: parametrized detector models
  - **PixelAV** – Charge propagation with Runge-Kutta-Fehlberg

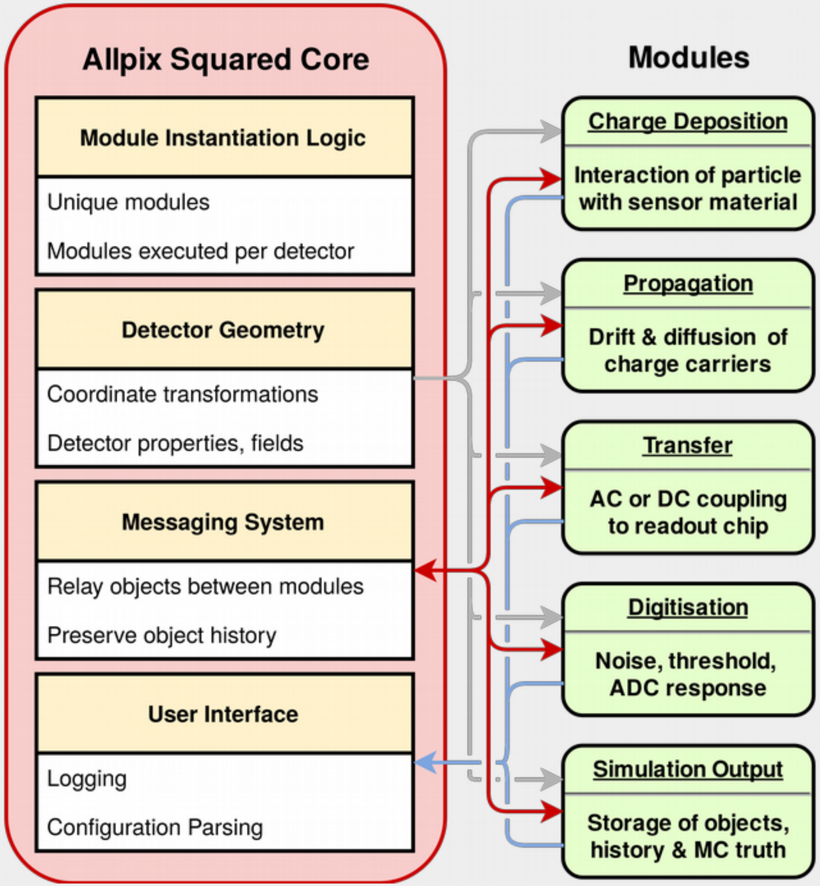
Two-Sentence-Summary

"Allpix² is a generic, open-source software framework for the simulation of silicon pixel detectors. Its goal is to ease the implementation of detailed simulations for both single detectors and more complex setups such as beam telescopes from incident radiation to the digitised detector response."

Nucl. Instr. Meth. A 901 (2018) 164 – 172
doi:10.1016/j.nima.2018.06.020

Basic Design Principle

- Separate infrastructure (core) from the physics (modules)
- Make life easy for the user
  - Allow plugging together the simulation chain from individual modules
  - Auto-generate Geant4 models
  - Convenient configuration, with units
  - Provide Monte Carlo truth information
- Implement physics in independent modules
  - Plug & play concept
  - Offer a selection of different algorithms



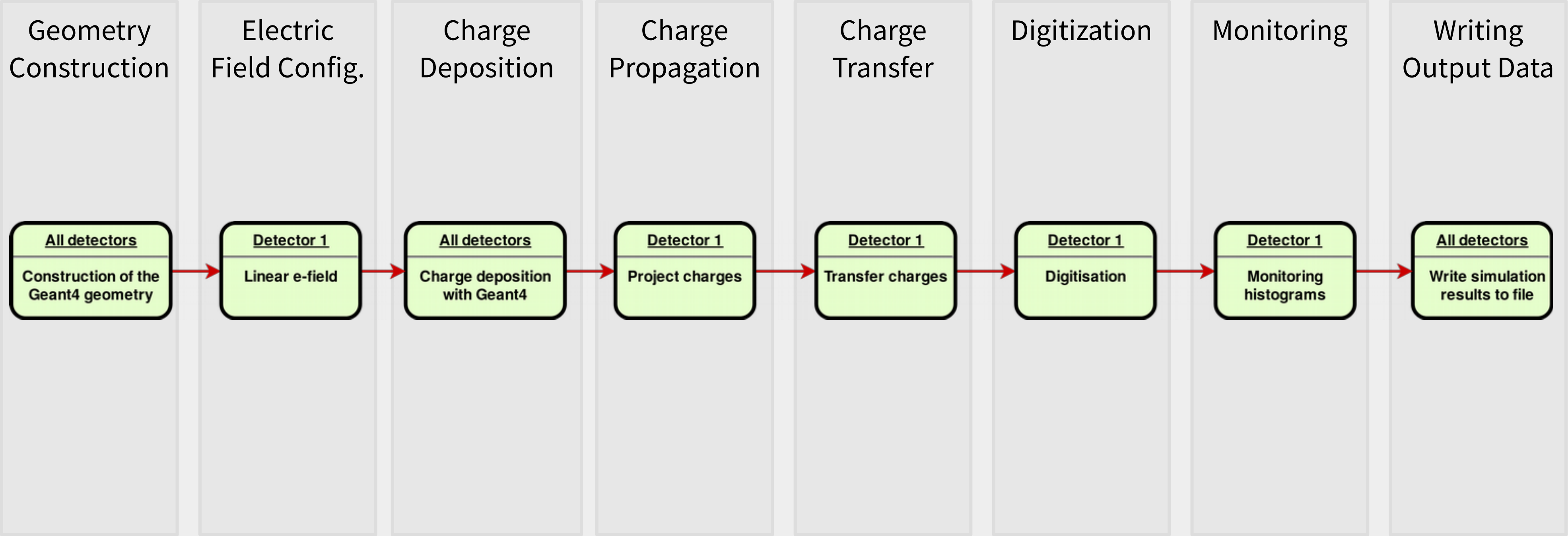
Framework Configuration

- Framework configured by one file
  - All desired modules listed in order of execution
  - Key-value pairs in TOML-style (extended)
    - Human readable
    - Little overhead (e.g. compared to XML)
- Support for physical units
  - Never ask what units are used – type them out!
  - Automatic conversion to internal units
  - No need for manual conversions in C++

```
[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]
```

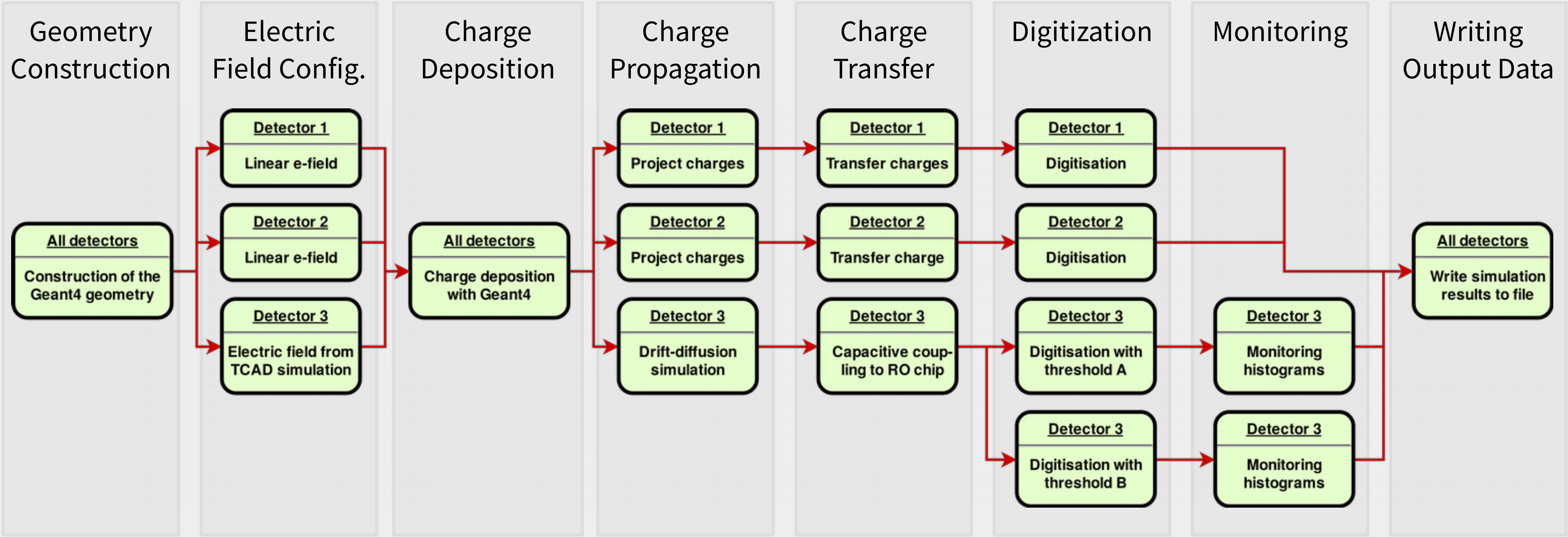
Plugging together the Simulation Chain

- Allows to quickly plug together simple simulations...
  (start from examples shipped in the repository)

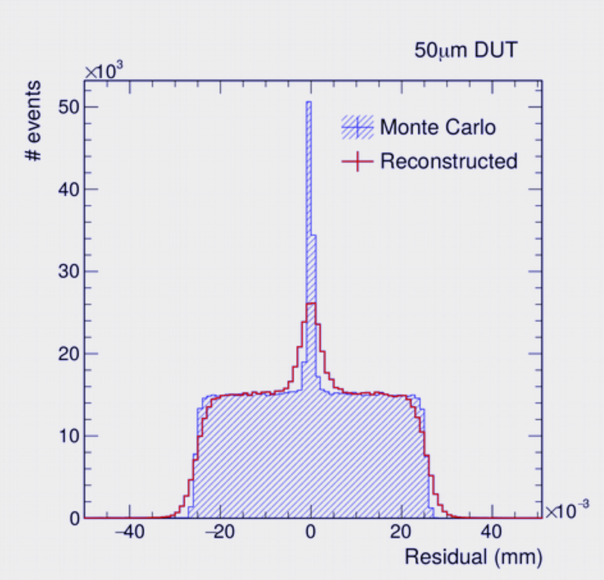


Plugging together the Simulation Chain

- ...as well as more involved simulations



Messages & Object History



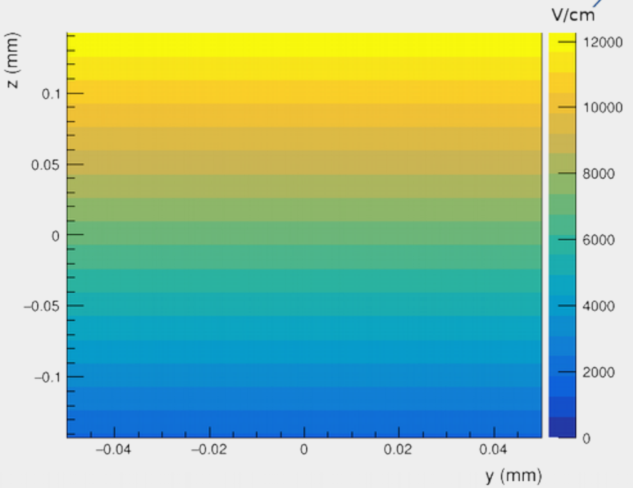
- Data exchanged between modules by means of messages
  - Message holds specific data type and has an origin (detector name, stream name…)
  - Modules bind to specific message (or message type) via central messenger
- Object history
  - For each object the full provenance is recorded using TRef objects

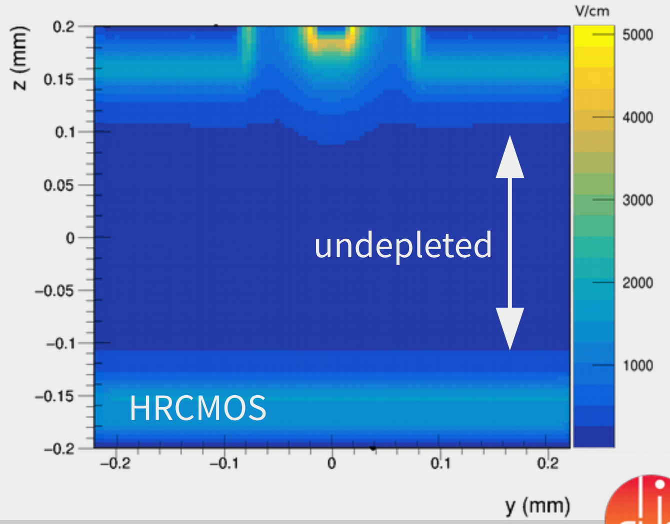
PixelHit ← PixelCharge ← PropagatedCharge(s) ← DepositedCharge(s) ← MCParticle(s) ← MCTrack

  - Allows direct relation of each pixel hit from front-end to initial particle(s)
  - Relation between MCParticles enables sorting between primaries (entered sensor from outside) and secondaries (produced within sensor)
  - Answers questions like “where in the detector did the charge carriers of this hit originate from?”

Adjusting the Levels of Detail

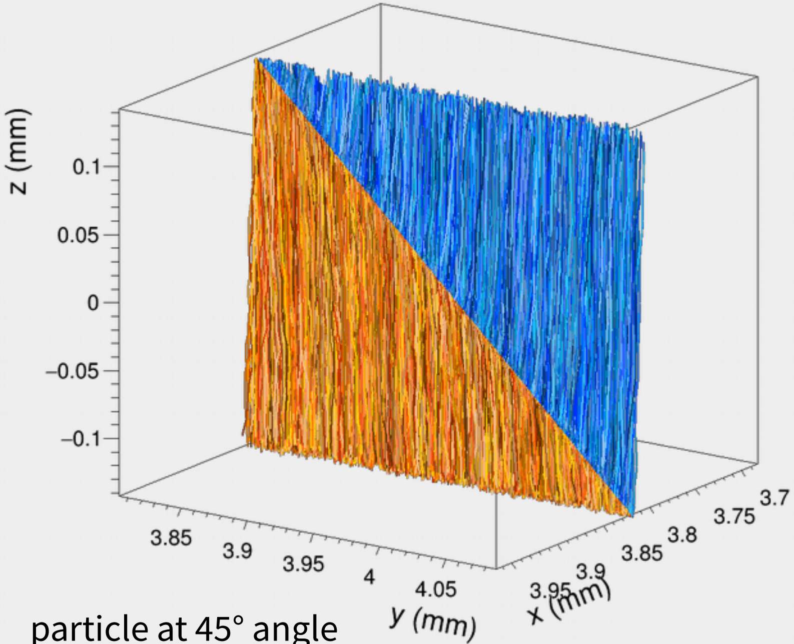
- Modular design allows to choose algorithms. Examples:
  - Energy deposition:
    - Geant4 particle tracking
    - Point charge at defined position
  - Electric field:
    - built-in linear approximation
    - loading finite-element field maps (TCAD)
  - Charge transport:
    - calculate total drift time, project onto surface
    - RKF integration, stepping through field
    - Shockley-Ramo calculation: full current pulse (validation ongoing, to be merged)
- Can be adjusted for each detector individually



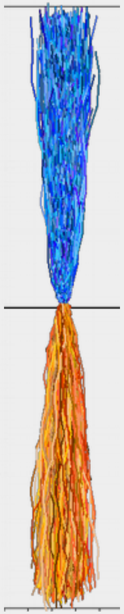


Visualizations of Charge Transport

- Propagation modules can produce line graphs of charge carriers
- Helpful to understand detector behavior

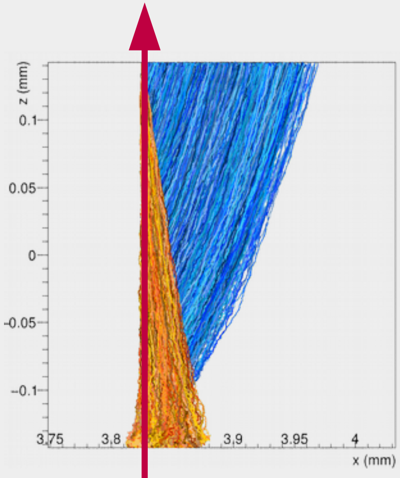


particle at 45° angle
drift paths of electrons & holes

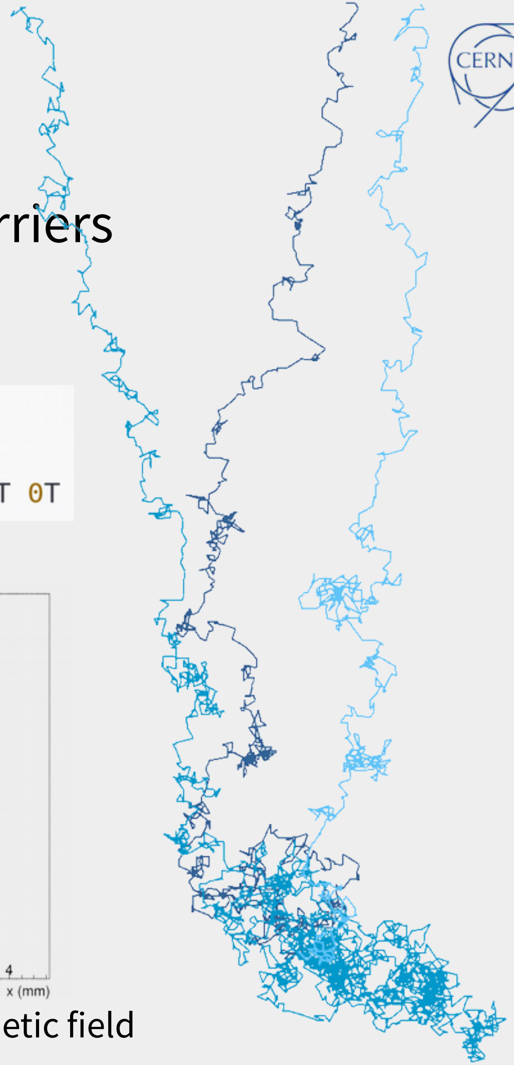


projection along trajectory

```
[MagneticFieldReader]
model = "const"
magnetic_field = 0mT 3.8T 0T
```

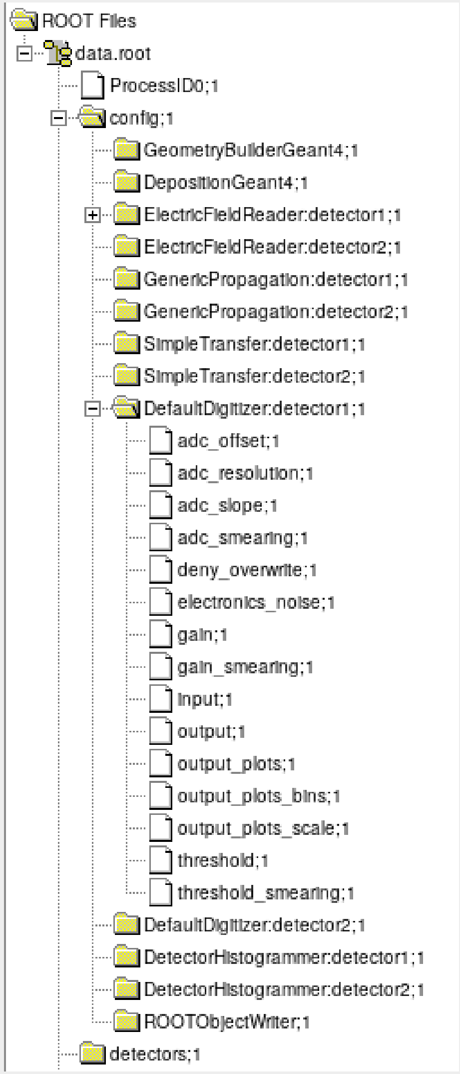


Lorentz drift in magnetic field



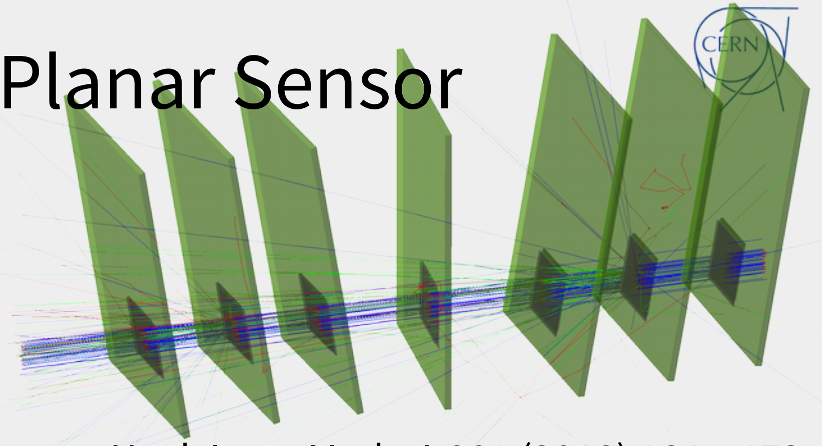
I/O

- Different output writers available
- Native format: ROOT files with all objects
  - Also contains detectors & sim. parameters
  - Full framework **configuration** can be **reconstructed from** single **data file**
- ROOTObject reader replays data from file
  - Simulate deposition & propagation once
  - Read data from file and **quickly repeat** final digitization **step** with different parameters



Simulation of a Timepix3 with 50um Planar Sensor

- Full telescope: 6 planes Timepix3 + DUT
- Linear electric fields
- Full reco: clustering, eta correction, tracking
- Matches very well with data



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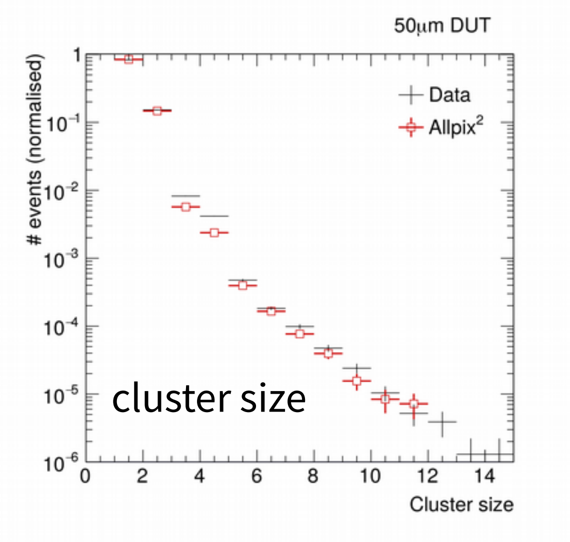
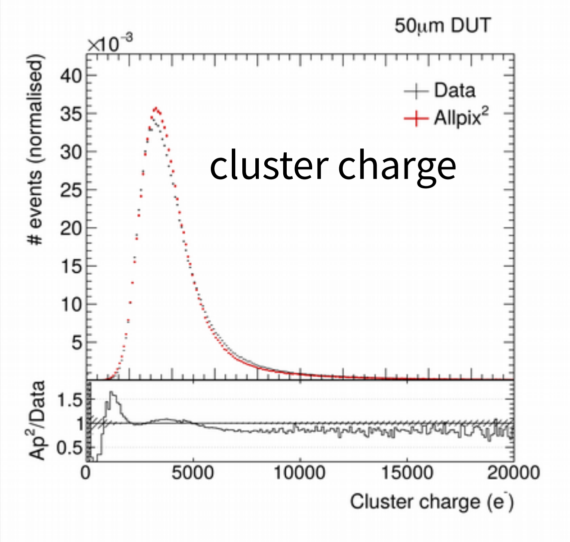
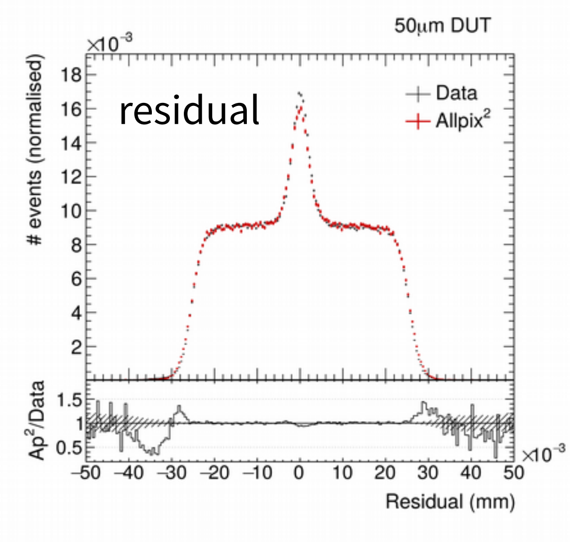
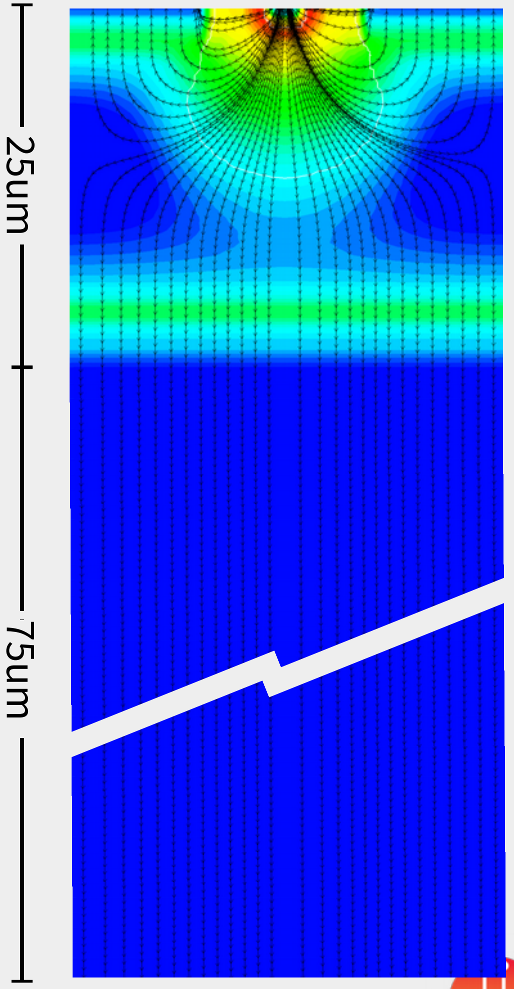






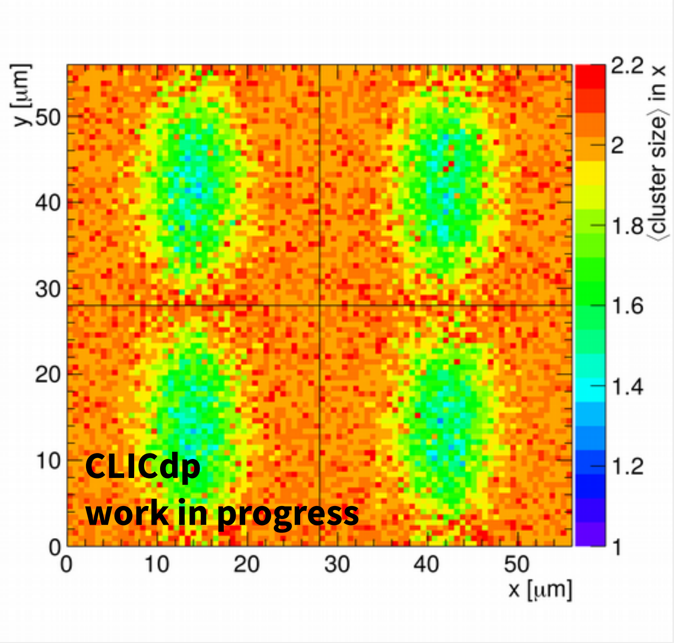
Monolithic CMOS in High-Resistivity Silicon

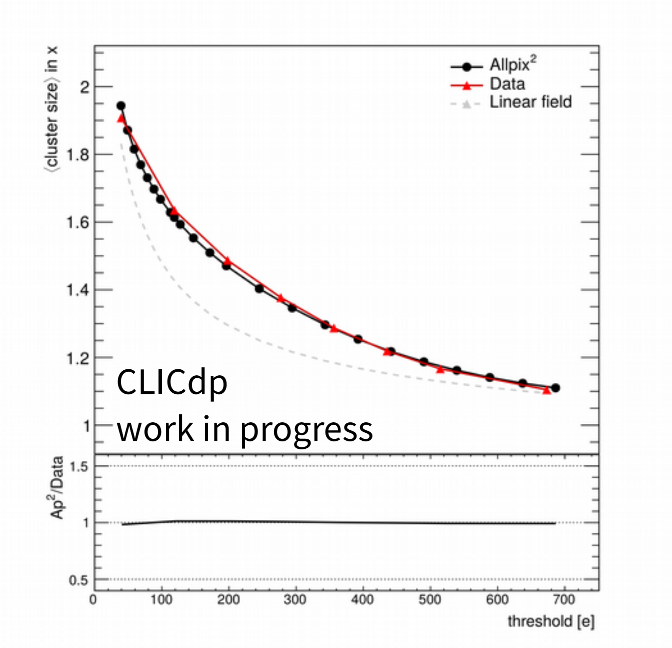
- Simulation of ALICE Investigator-like chip, 28x28um pitch
  - Field in top 25um (high-resistivity) silicon
  - Undepleted in 75um silicon substrate
- SPS beam: 120 GeV Pions, only one detector simulated
  - Using Monte Carlo truth information as reference
  - Smeared with telescope resolution obtained from data
- Import electric field from TCAD simulations
- Using Geant4's photoabsorption Ionization model (PAI) for thin sensors
- Challenges: life time / recombination, influence of charge cloud on field…
  - Trade-off between accuracy and necessary simplifications

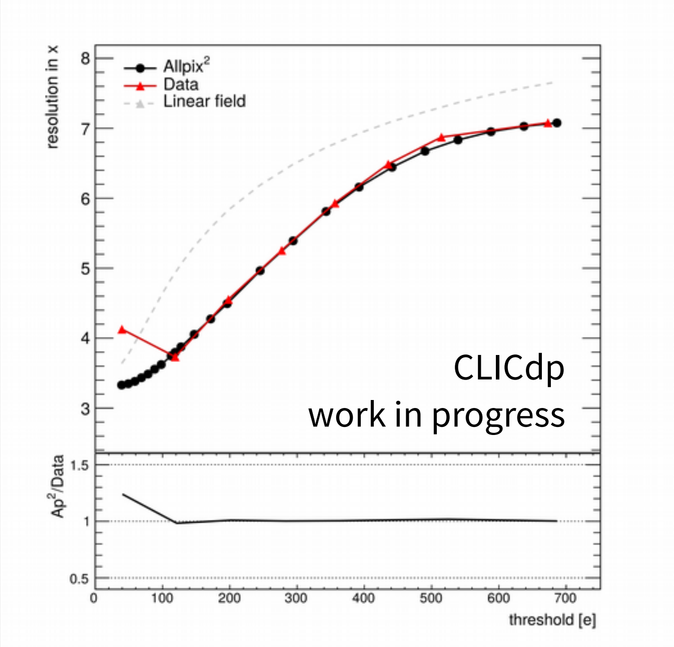


Monolithic CMOS in High-Resistivity Silicon

- Manage to reproduce x-y-correlation features in cluster size
- Data and simulation matches very well: **cluster size & resolution vs. threshold**
- Comparison: linear field simulation does not describe data







Development of Allpix Squared

- Meant as community-driven project
  - Still most contributions from “core team”
  - Increasing number of external contributions
- Fully GitLab-centered development
  - Issue tracking, merge requests, continuous integration
- All development is performed “in the open”
  - Full repository public, including issues
  - Subscribers receive information on all actions
- Semantic versioning:
  Major.Minor.Patch = Framework.Features.Bugfixes

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

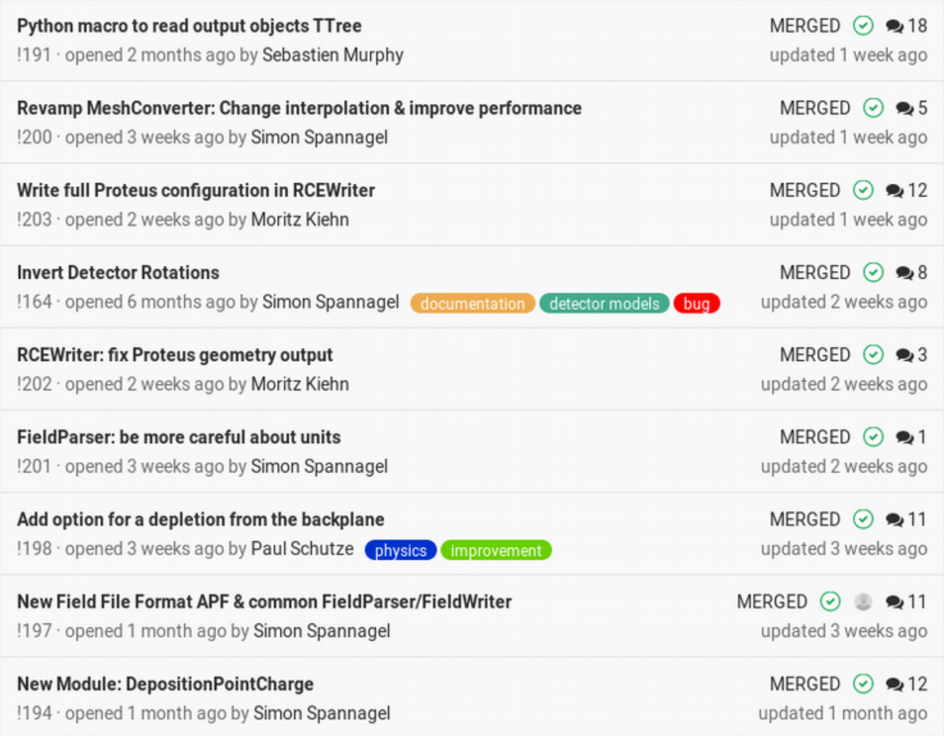
Warnings, Strict Formatting & Code Linting

- In order to maintain a high code quality, we
  - Enabled many compiler warnings, with **-Werror**
  - Require strict adherence to code formatting (indentation, brace positions…)
  - Clang-tidy is used to spot e.g. missing &, std::move() or NamingConventionViolations
- A bit painful for newcomers
  - CI fails many times, users need to be taught how to read failed job logs
- Particularly useful: /etc/git-hooks
  - **pre-commit-clang-format-hook** – checks formatting before committing
  - **pre-push-tag-version-hook** – check for pre-release things (update version)
- CMake suggests installing hooks (suggests update on changes)

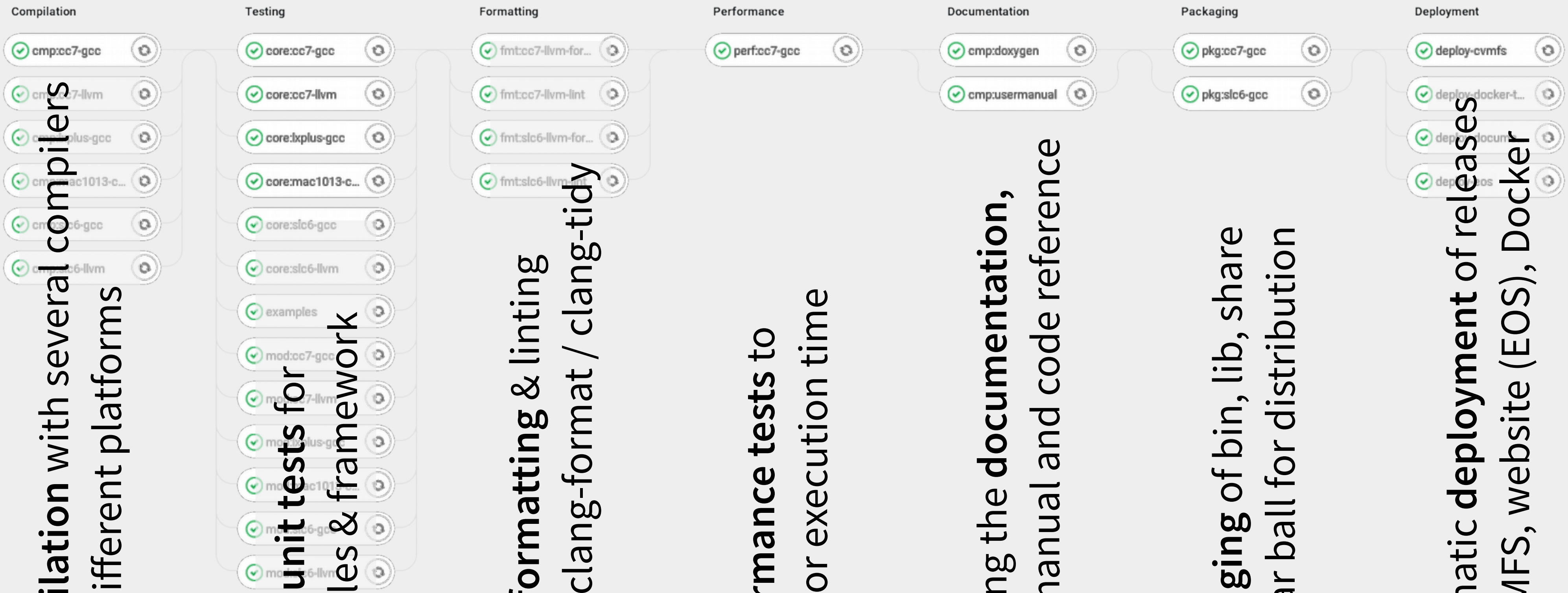
Code Review via Merge Requests

- No new code lands in master without review by another party
  - Using GitLab's approval feature
  - 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**
  - Read (and understanding) every change
  - Always be supportive, positive

...just some of them



Continuous Integration & Testing



compilation with several compilers on 3 different platforms

many **unit tests** for modules & framework

code formatting & linting using clang-format / clang-tidy

performance tests to monitor execution time

building the **documentation**, user manual and code reference

packaging of bin, lib, share into tar ball for distribution

automatic **deployment** of releases to 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)
#PASSOSX (DEBUG)  misaligned: (9.04007deg,170.886deg,178.731deg)
```

```
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
```

- No real “unit testing” up till now, more of a “system test”
- Framework & module tests
- Prepare a plethora of configuration files
  - Run single event with fixed seed
  - Reproduces same output
  - Matching regular expressions
- Single change (1e difference) fails CI
- Invaluable for monitoring framework → catching issues before merging code

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 in LaTeX
  - Automatically compiled by CI
  - Module documentation as Markdown
    - Document module parameters, algorithms
    - Included in manual via Pandoc

```
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;
```

Automated Deployment of Tagged Versions

- Using CERN GitLab CI Tools
  https://gitlab.cern.ch/ci-tools
- Deployment to website
  - Binary tarball packages placed on EOS
  - Using "**ci-web-deployer**" image
- Deployment as Docker image
  - Using "**docker-image-builder**"
  - DOCKER_FILE specified as variable
  - Build on top of Docker image
    w/ dependencies (Geant4, ROOT6)

```yaml
variables:
    EOS_PATH: "/eos/project/a/allpix-squared/www/"
    DOCKER_FILE: etc/docker/Dockerfile
```

```yaml
deploy-eos:
    stage: deployment
    tags:
      - docker
    variables:
        GIT_STRATEGY: none
    # Only run for new tags:
    only:
        - tags
        - schedules # Only execute this on scheduled "nightly" pipelines
    dependencies:
        - pkg:cc7-gcc
        - pkg:slc6-gcc
    # Docker image with tools to deploy to EOS
    image: gitlab-registry.cern.ch/ci-tools/ci-web-deployer:latest
    script:
        - deploy-eos
```

```yaml
deploy-docker-tag:
    stage: deployment
    tags:
        - docker-image-build
    dependencies: []
    only:
        - tags
    script:
        - "echo" # unused but this line is required by GitLab CI
    variables:
        TO: gitlab-registry.cern.ch/allpix-squared/allpix-squared:${CI_COMMIT_TAG}
```

Automated Deployment: CVMFS

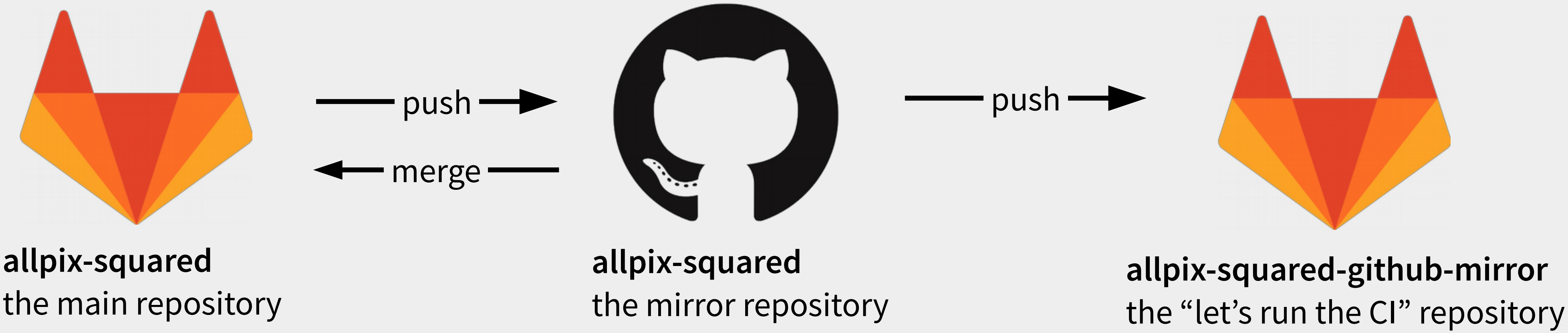
- A bit trickier… (see talk by Marco Petric)
  - Runner (selected via "cvmfs-deploy" tag) opens shell on CVMFS submission server
  - No direct access to artifacts → use script to download & deploy
- Deployed version ready for use on LXPlus or HTCondor submission

```
deploy-cvmfs:
    stage: deployment
    dependencies:
        - pkg:cc7-gcc
        - pkg:slc6-gcc
    tags:
        - cvmfs-deploy
    only:
        - tags
        - schedules # Only execute this on scheduled "nightly" pipelines
    script:
        - ./.gitlab/ci/download_artifacts.py $API_TOKEN $CI_PROJECT_ID $CI_PIPELINE_ID
        - export RUNNER_LOCATION=$(pwd)
        - if [ -z ${CI_COMMIT_TAG} ]; then export BUILD_PATH='latest'; else export BUILD_PATH=${CI_COMMIT_TAG}; fi
        - sudo -u cvclicdp -i $RUNNER_LOCATION/.gitlab/ci/gitlab_deploy.sh $RUNNER_LOCATION $BUILD_PATH
        - rm -f allpix-squared-*.tar.gz
    retry: 1
```

```
$ source /cvmfs/clicdp.cern.ch/software/allpix-squared/1.3.2/x86_64-centos7-gcc7-opt/setup.sh
$ allpix --version
Allpix Squared version v1.3.2
                    built on 2019-02-21, 19:43:54 UTC
```

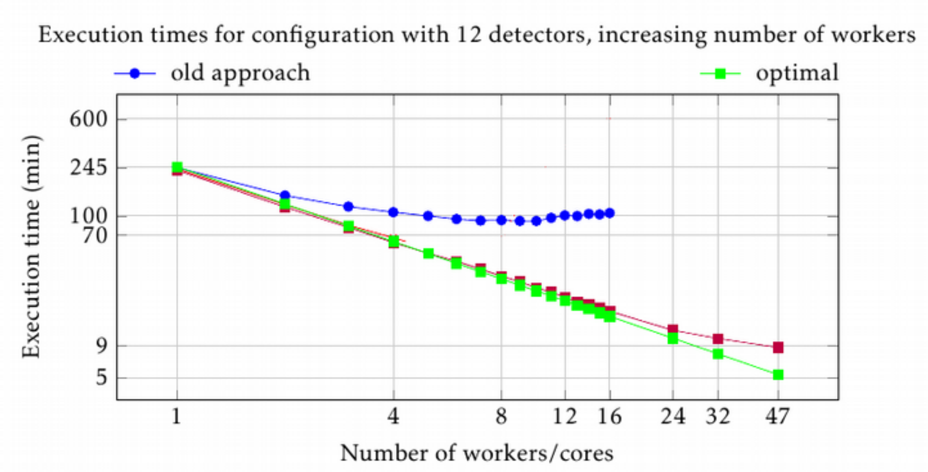
External Contributions via GitHub

- We rely on CERN's GitLab CI (and our own runners)
  - Allows us to run extensive CI and adjust to our needs
  - Requires full CERN account for write acces
- Our solution: ping-pong mirror to GitHub



Google Summer of Code

- Participated for the first time in GSoC last year through HSF/CERN
  - Proposed project: Event-based Multi-Threading for Allpix Squared
  - Quite intricate due to seeding of PRNGs & potential race conditions
- Student was very active and motivated
  - Restructured parts of core framework, implemented first working version
  - Some road blocks encountered (interfaces with dependencies)
- Interesting observation:
  - Student was expecting direct instructions, we expected scientific collaboration → worked out well after discussing!



Summary

- Allpix Squared is a framework for MC simulation of silicon pixel detectors
  - Flexible framework combining Geant4, electrostatic TCAD simulations and charge transport algorithms
  - Continuously developed and extended
  - Modular design, strict coding rules, collaborative workflow
- Continuous integration one of the backbones
  - Automated compilation and testing, ensuring compliance with rules
  - Deployment of compiled versions to CVMFS, Docker, website
- Participation in GSoC 2018 very useful

- Will participate again in GSoC 2019, have very promising candidate already
- Interested in **Google Season of Docs** to further improve documentation, separate coding/physics
- Many ideas for extensions
  (transient current, high-Z materials, multi-threading, charge multiplication, lifetime)

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

CERN

Users & Contributors

Disclaimer: these are just some users we have been in contact with – there probably are some more.

ONERA Aerospace Lab, Toulouse
Georg-August-Universität Göttingen
University of Birmingham
University of California, Berkeley
NIKHEF, Amsterdam
University of Glasgow
Czech Techn. University, Prague
Rutherford Lab, STFC
ETH Zurich
Université de Montréal
Charles University, Prague
IHEP Beijing
CLICdp @ CERN
CMS Pixel @ CERN
ATLAS Strips @ CERN
LHCb VeloPix @ CERN
ATLAS Monolithic @ CERN
Freiburg University
Utrecht University
ATLAS @ DESY
CMS Lorentz Angle @ DESY
ELAD @ DESY
University of Liverpool
ATLAS SCT @ KEK
Dortmund University
Université de Genève
AGH University Krakau

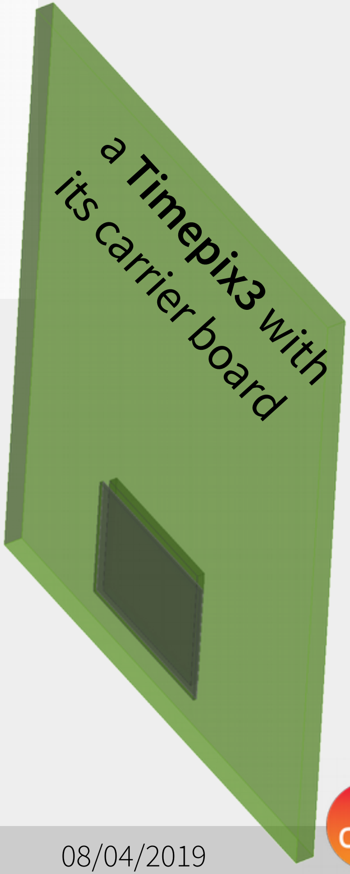
- First **user workshop** held 26-27 November 2018 @ CERN
- Tutorials, discussions, feedback
- Very successful, to be continued

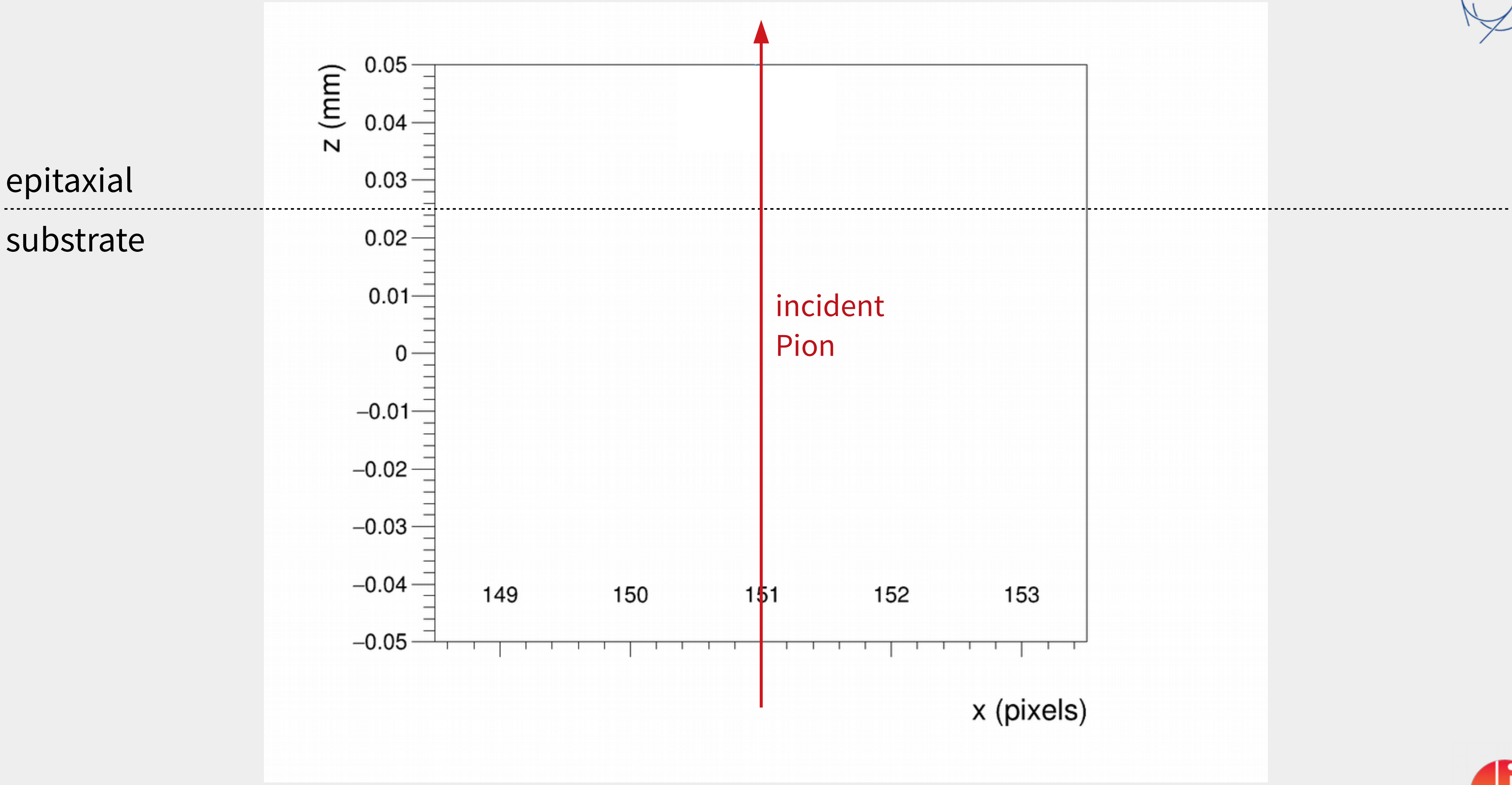
Detector Models

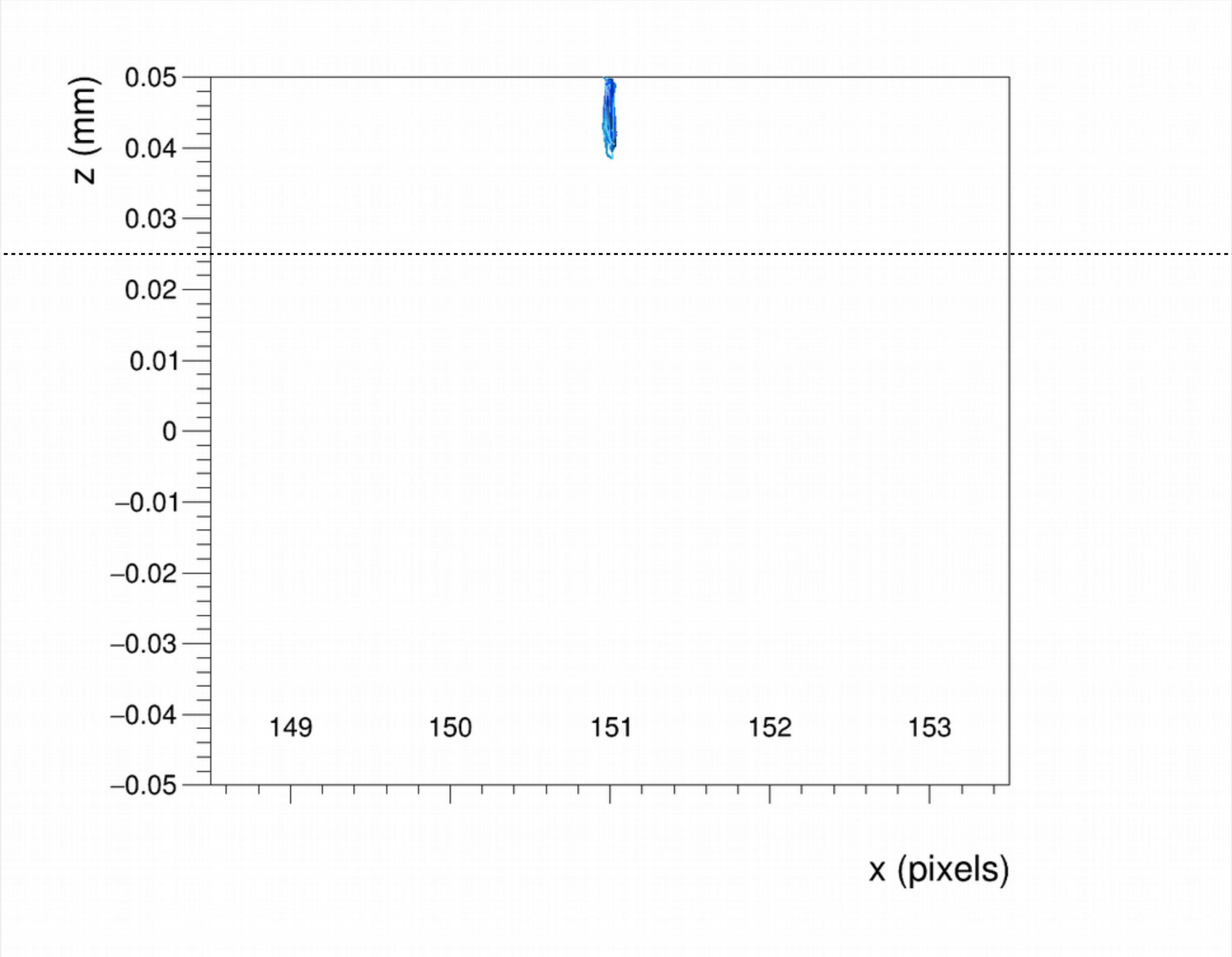
- Different detector types available
  - Monolithic detectors
  - Hybrid detectors w/ bump bonds
- Easy configuration through model files
  - Give it a name, decide on the type
  - Set detector parameters
- Some model files already shipped with the framework, at the moment

  ATLAS FE-I3, FE-I4, CMS PSI46/dig, Medipix3, Timepix3, CLICpix, CLICpix2, Mimosa23, Mimosa26

```
type = "hybrid"

number_of_pixels = 256 256
pixel_size = 55um 55um

sensor_thickness = 300um
chip_thickness = 700um

# ...

[support]
thickness = 1.76mm
```




epitaxial
substrate
z (mm)
0.05
0.04
0.03
0.02
0.01
0
−0.01
−0.02
−0.03
−0.04
−0.05
149
150
151
152
153
x (pixels)
incident
Pion



epitaxial

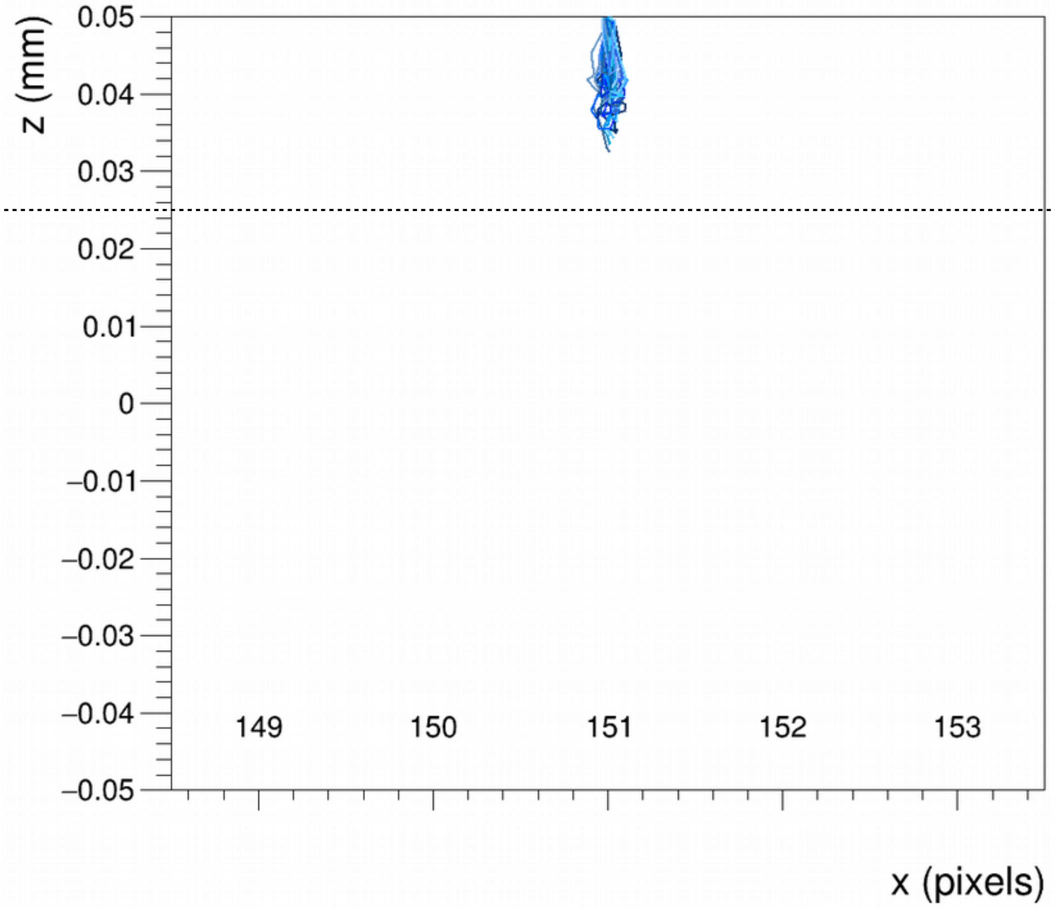
substrate

0.5ns

1.5ns

epitaxial

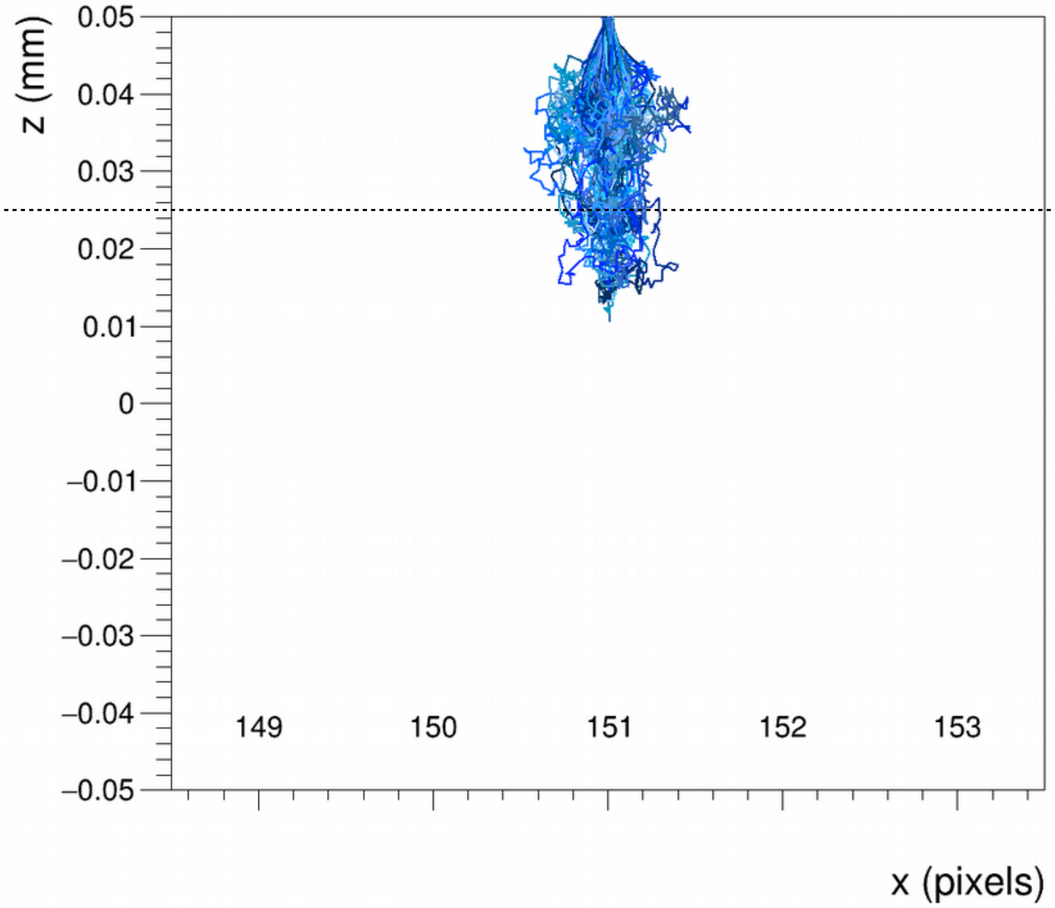
substrate



10ns

epitaxial

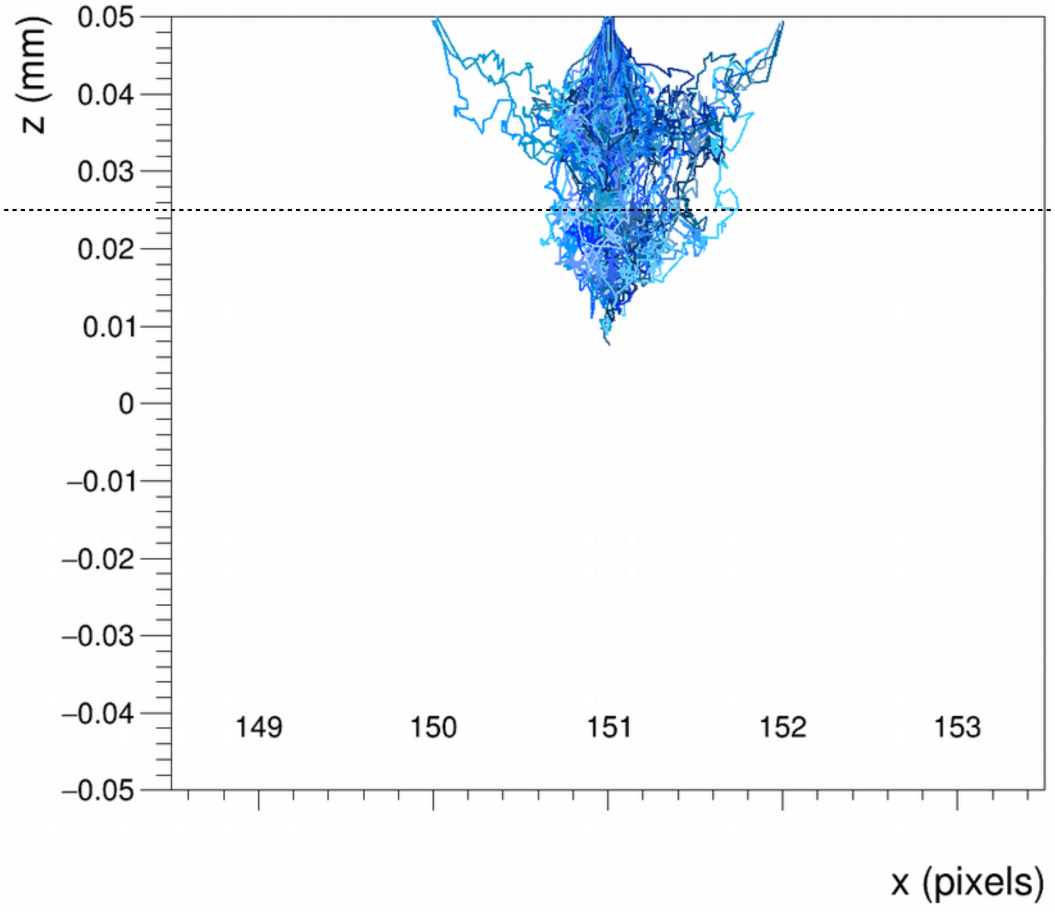
substrate



15ns

epitaxial

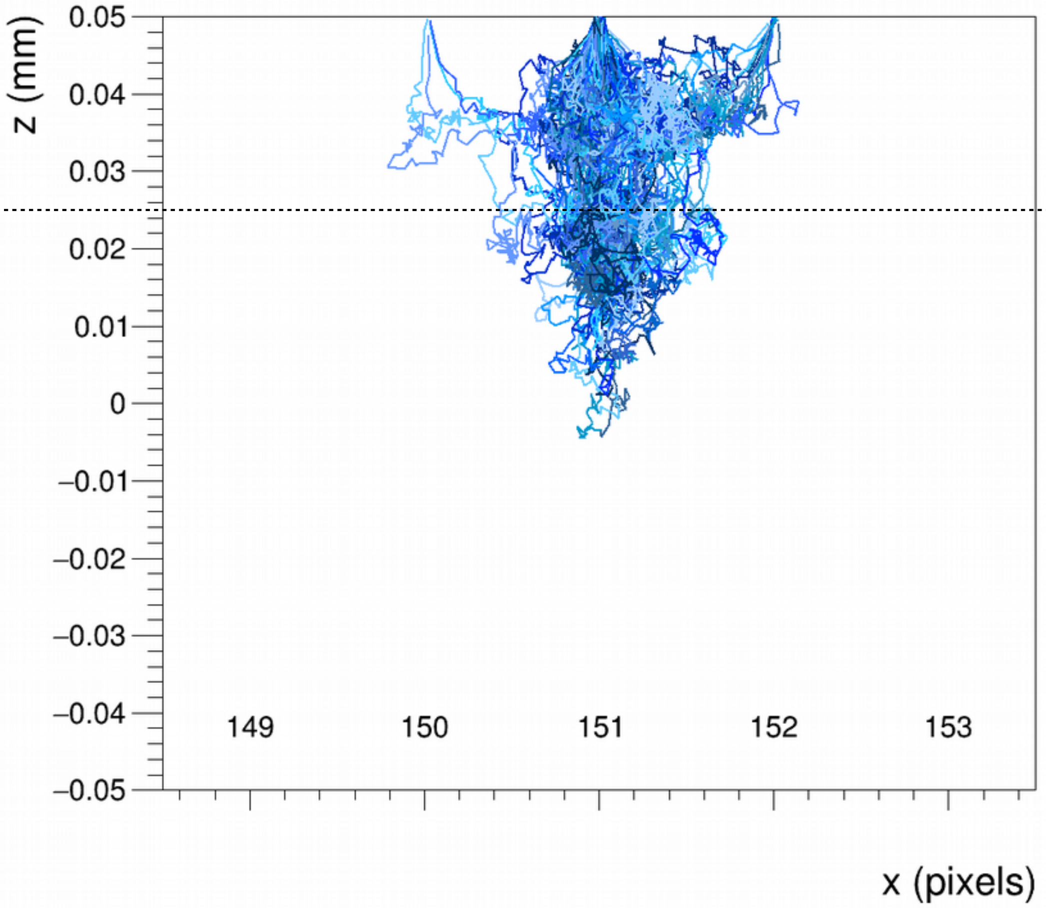
substrate



20ns

epitaxial

substrate



25ns

epitaxial

substrate