[Detector of TrackML challenge]

Experiences & findings in developing common software

The acts project

A. Salzburger (CERN) for the ACTS project

@SaltyBurger

supported by

EP-R&D Programme on Technologies for Future Experiments

iris hep

Bundesministerium für Bildung und Forschung

cooperations

HSF

intel

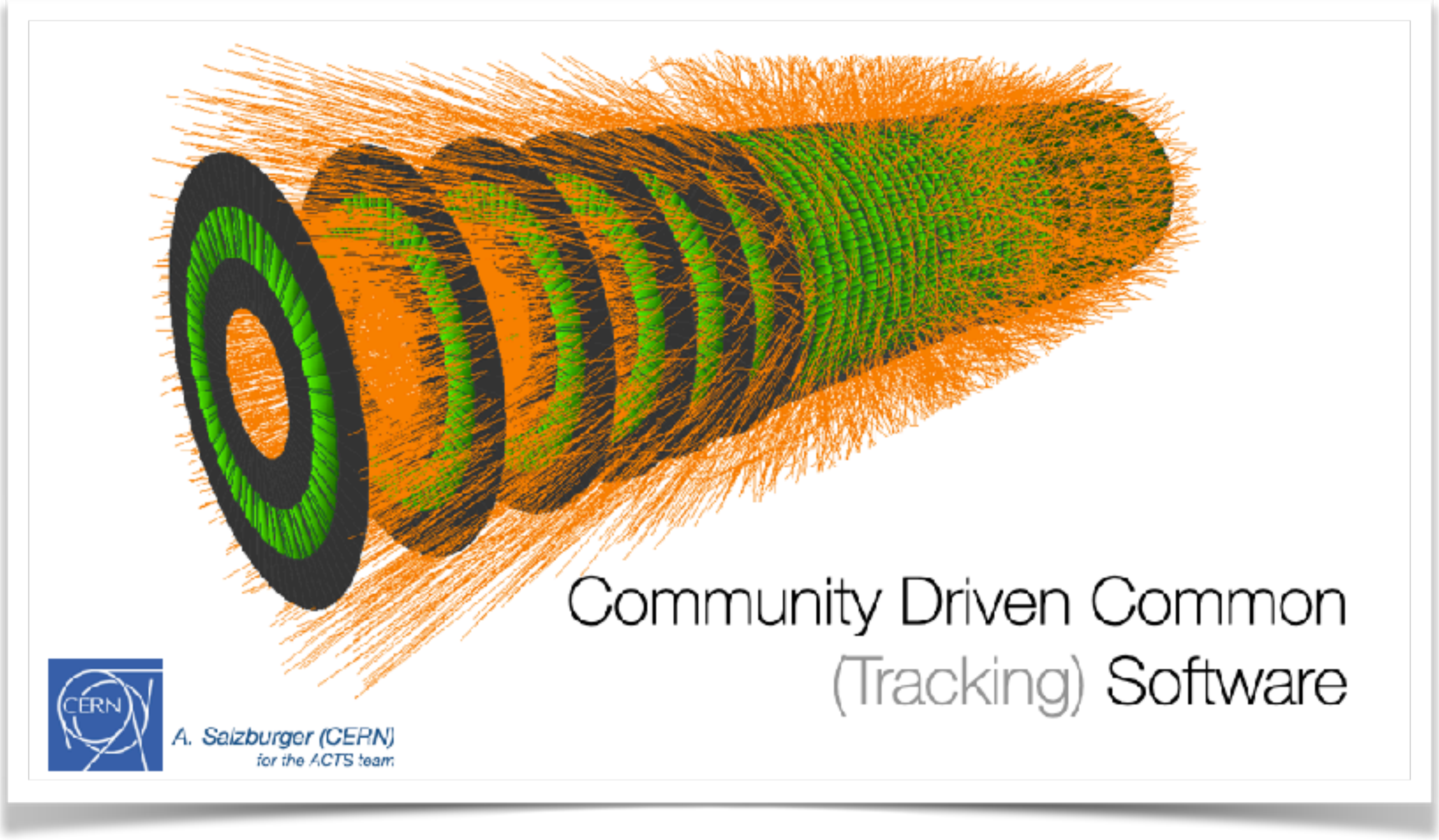
CERN openlab

acts project - Mission statement

- **Preserve & advance** LHC state of the art track reconstruction software

- Develop & deploy **production ready software** for HL-LHC and beyond

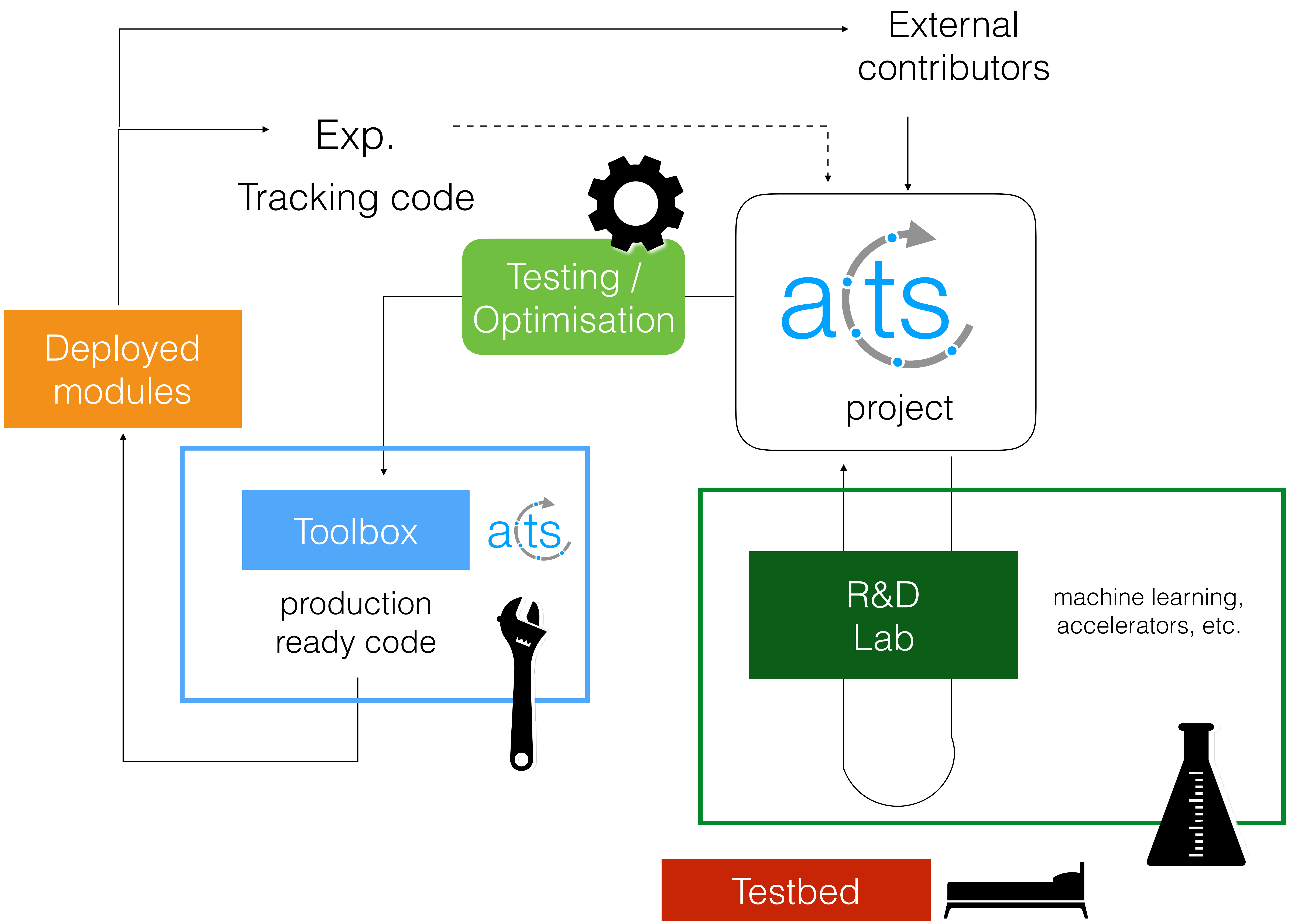
- Establish **R&D testbed** for algorithms, technology advance (e.g. ML, GPU, detectors)



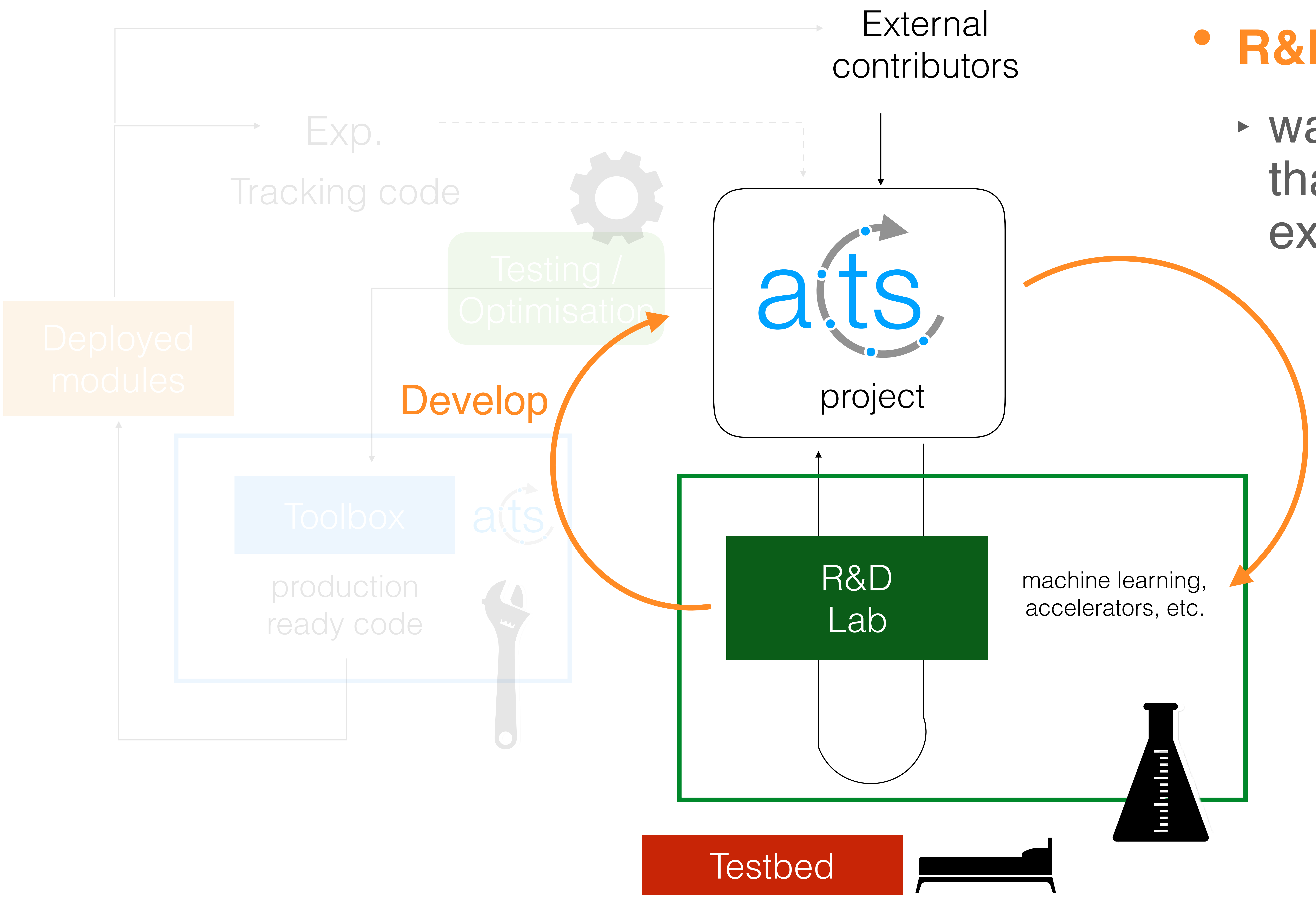
AS, Community Driven Common Tracking Software, Plenary, CHEP2018

- **Work & educate** in state of the art technology/workflows

acts roject - Roadmap

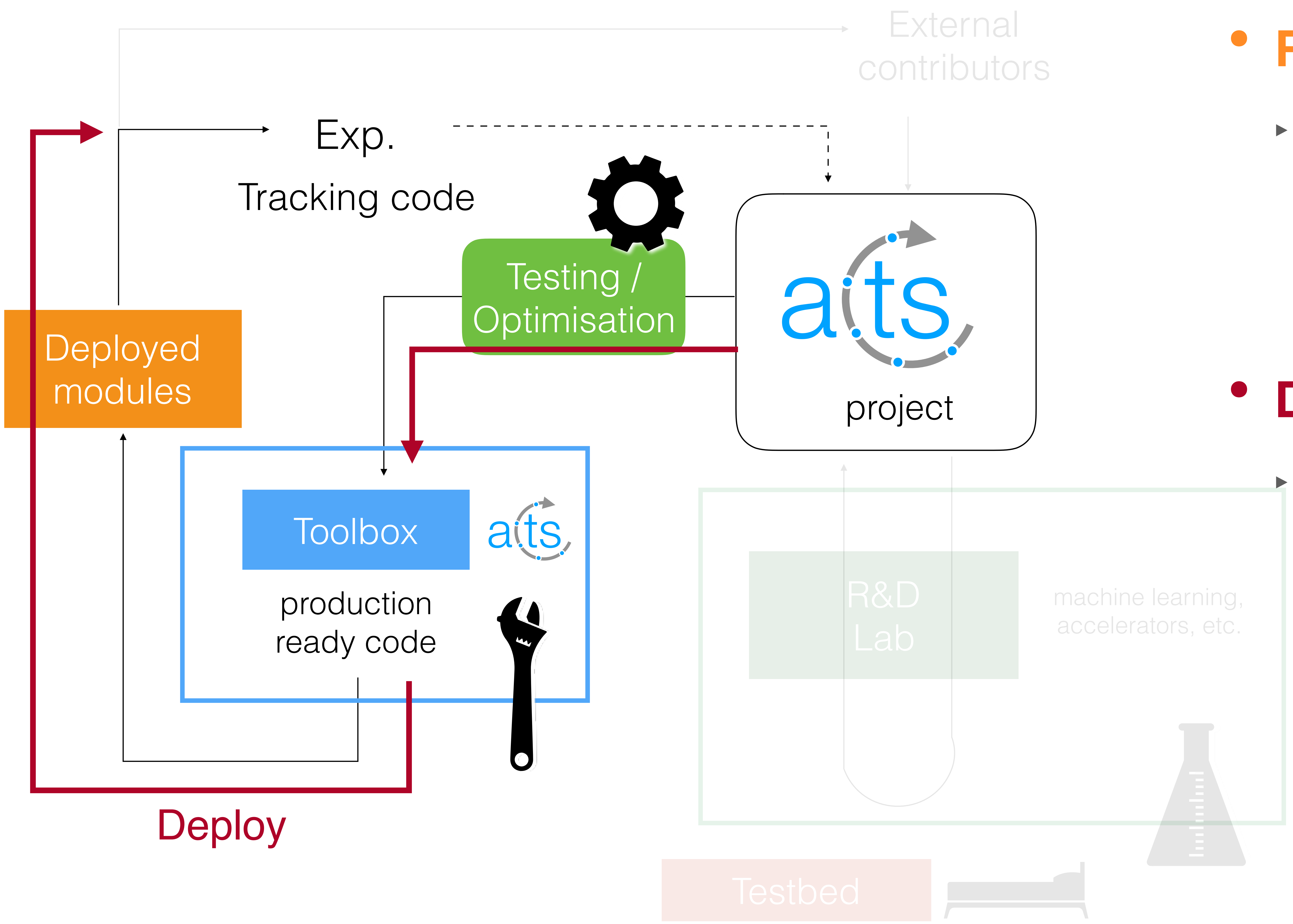


acts project - Roadmap



- **R&D loop**
  - way faster/easier than in one experiment's context

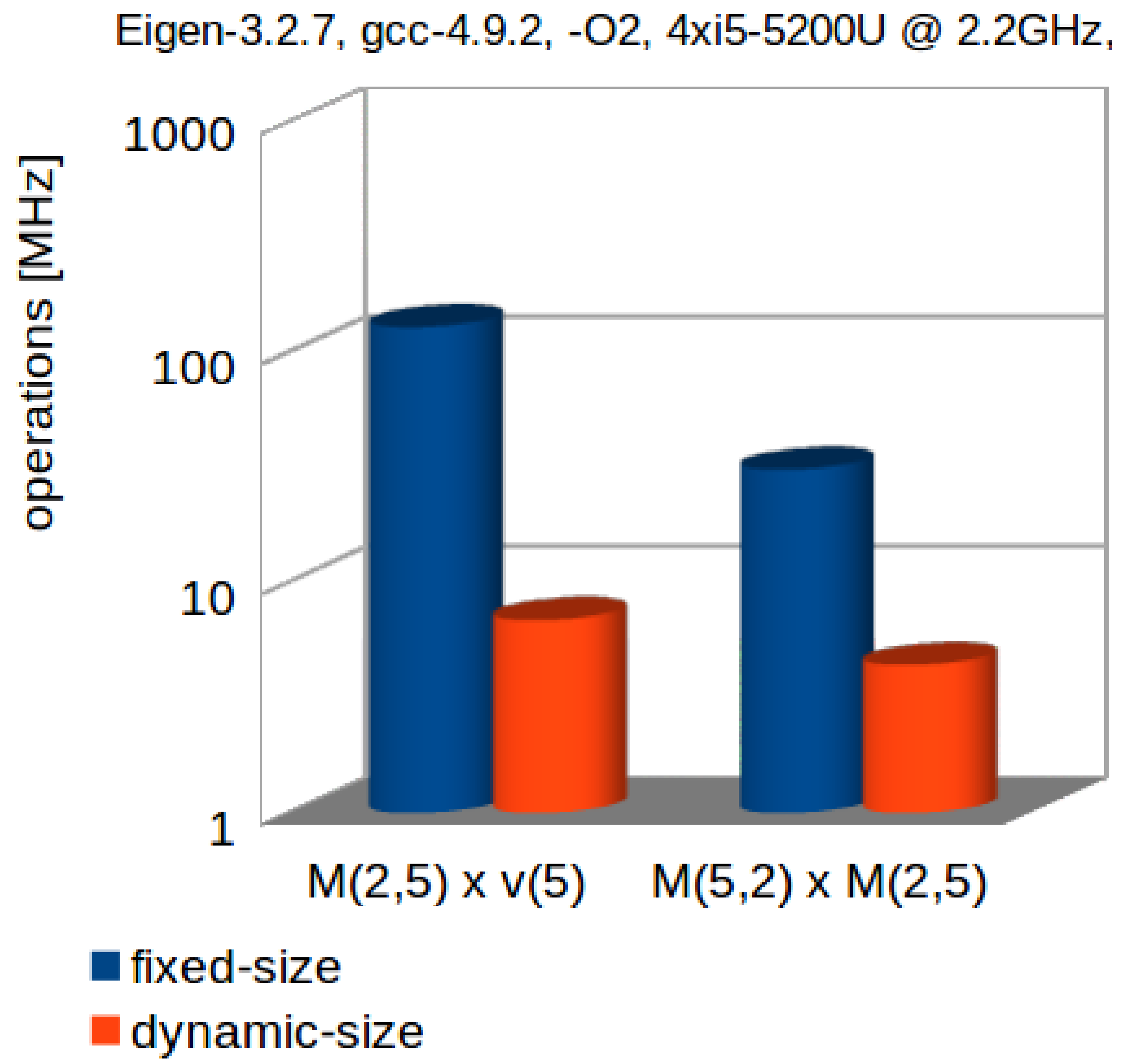
acts project - Roadmap



- **R&D loop**
  - way faster/easier than in one experiment's context
- **Deployment**
  - Significantly slower/ more involved than in one experiments' context

acts project - Preserve & advance

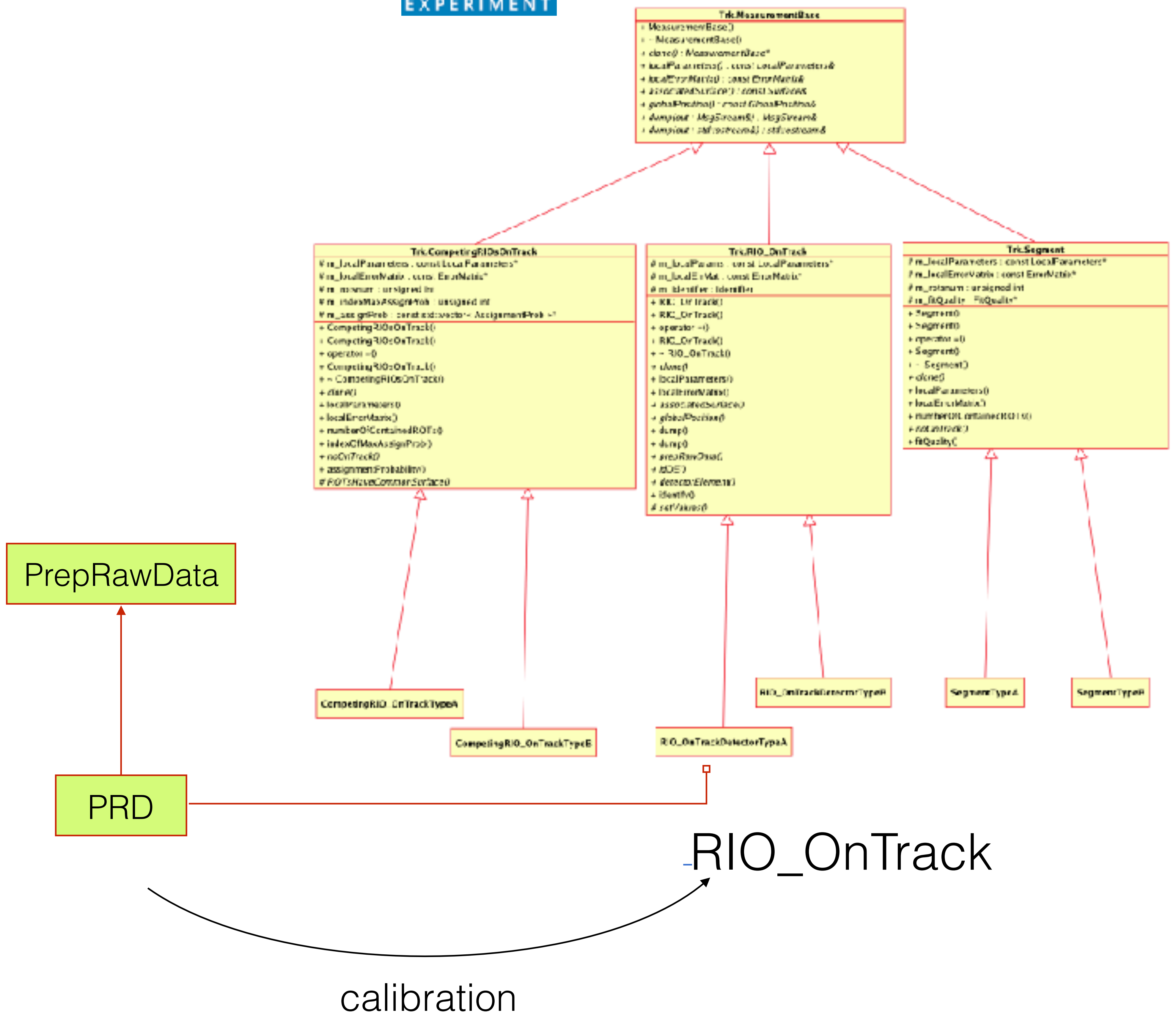
- **Extensive review of existing code**
  - Don’t be shy, **take what’s good**!
  - **Technical paradigm shift:**
    - Flatten data structures
    - Fixed size matrix multiplications
    - Lift runtime polymorphism to compile-time (C++ concepts replacing interfaces)
  - Modernize, simplify & streamline



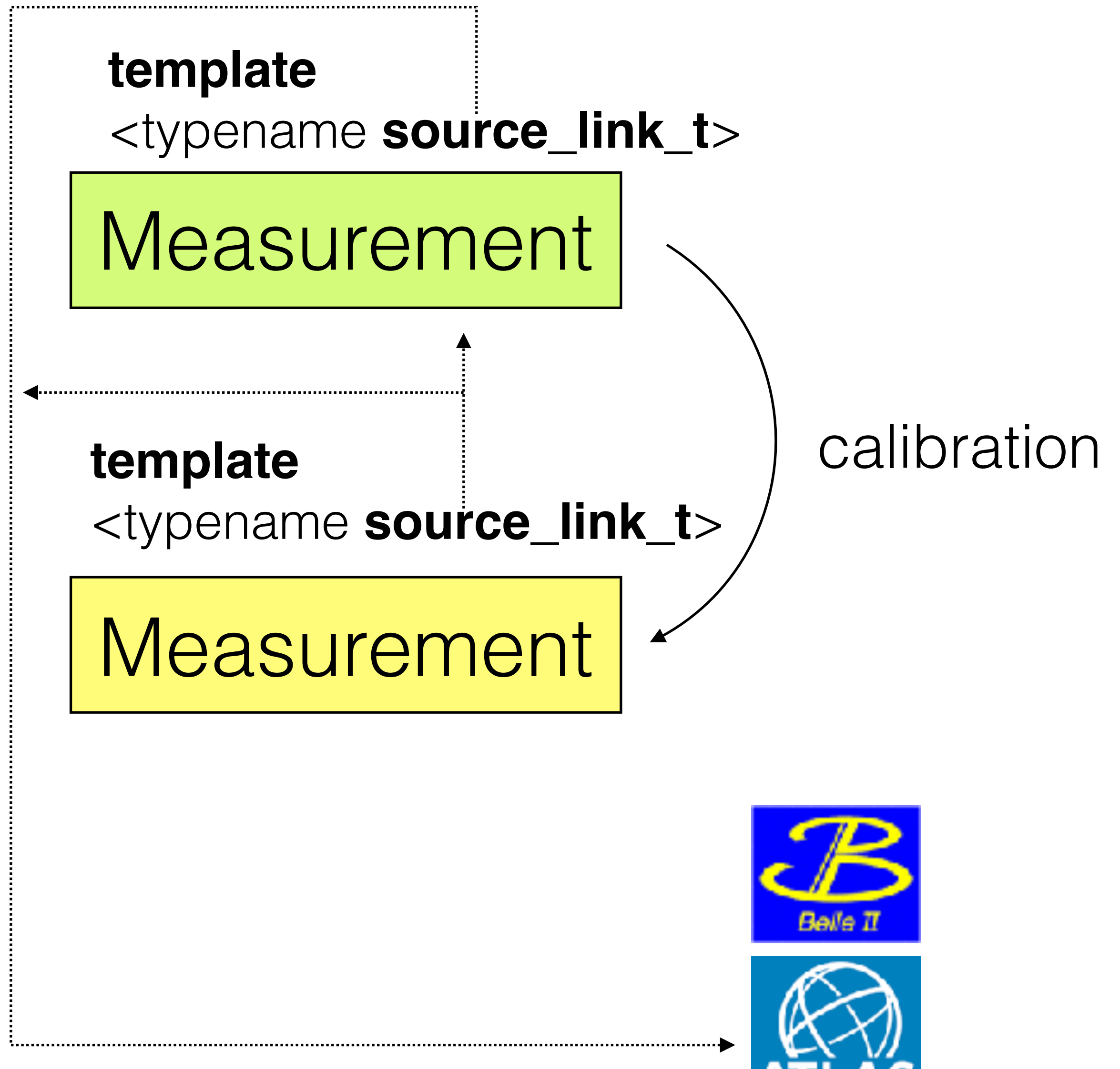
http://eigen.tuxfamily.org/

acts project - Simplify & Streamline

MeasurementBase



Measurement



acts project - Simplify & Streamline

ATLAS Extrapolator

~ 360 lines interface in IExtrapolator.h
~ 4700 lines of code in Extrapolator.cxx

acts Propagator

document the code!

```
/// @brief Propagate track parameters - User method
///
/// This function performs the propagation of the track parameters according
/// to the internal implementation object until at least one abort condition
/// is fulfilled, the destination surface is hit or the maximum number of
/// steps/path length as given in the propagation options is reached.
///
/// @tparam parameters_t Type of initial track parameters to propagate
/// @tparam surface_t Type of target surface
/// @tparam action_list_t Type list of actions
/// @tparam aborter_list_t Type list of abort conditions
/// @tparam propagator_options_t Type of the propagator options
///
/// @param [in] start Initial track parameters to propagate
/// @param [in] target Target surface of to propagate to
/// @param [in] options Propagation options
///
/// @return Propagation result containing the propagation status, final
///         track parameters, and output of actions (if they produce any)
template <typename parameters_t, typename propagator_options_t,
          typename target_aborter_t = SurfaceReached,
          typename path_aborter_t = PathLimitReached>
Result<action_list_t_result_t<
    BoundTrackParameters, typename propagator_options_t::action_list_type>>
propagate(const parameters_t& start, const Surface& target,
          const propagator_options_t& options) const;
```

~ 2 public interface methods, same functionality

acts project - Preserve & advance

- **Example: modernize**

```
// projection of direction onto normal vector of reference frame
double PC = pVector[4] * C[0] + pVector[5] * C[1] + pVector[6] *
double Bn = 1. / PC;

double Bx2 = -A[2] * pVector[29];
double Bx3 = A[1] * pVector[38] - A[2] * pVector[37];

double By2 = A[2] * pVector[28];
double By3 = A[2] * pVector[36] - A[0] * pVector[38];

double Bz2 = A[0] * pVector[29] - A[1] * pVector[28];
double Bz3 = A[0] * pVector[37] - A[1] * pVector[36];

double B2 = B[0] * Bx2 + B[1] * By2 + B[2] * Bz2;
double B3 = B[0] * Bx3 + B[1] * By3 + B[2] * Bz3;
```

AtlasStepper, transcript in ACTS project

```
void covarianceTransport(Covariance& covarianceMatrix, Jacobian& jacobian,
                         FreeMatrix& transportJacobian, FreeVector& derivatives,
                         BoundToFreeMatrix& jacobianLocalToGlobal,
                         const Vector3D& direction) {
  // Build the full jacobian
  jacobianLocalToGlobal = transportJacobian * jacobianLocalToGlobal;
  const FreeToBoundMatrix jacToLocal =
      surfaceDerivative(direction, jacobianLocalToGlobal, derivatives);
  const Jacobian jacFull = jacToLocal * jacobianLocalToGlobal;

  // Apply the actual covariance transport
  covarianceMatrix = jacFull * covarianceMatrix * jacFull.transpose();

  // Reinitialize jacobian components
  reinitializeJacobians(transportJacobian, derivatives, jacobianLocalToGlobal,
                        direction);

  // Store The global and bound jacobian (duplication for the moment)
  jacobian = jacFull;
}
```

EigenStepper, covariance transport

acts project - Production ready toolbox

Hosted on github.com

https://github.com/acts-project/acts

Synchronised gitlab read-only repository (former repo): https://gitlab.cern.ch/acts

Repository Structure:

- **Core:** Toolbox with production-ready code
- **Fatras**: Fast simulation extension
- **Tests:** Unit & Integration tests for
- **Plugins:** third party dependent plugins, e.g. Geant4, DD4Hep, ROOT, …
- **Examples:** Test framework with examples (FCC-hh, ITk, sPhenix, …)

Dependencies

- **Core:** Eigen, BOOST (for unit testing only)

Standards

- **C++17**

CERN officially recommends using an **outside provider** for development including non-CERN contributors …

Licence

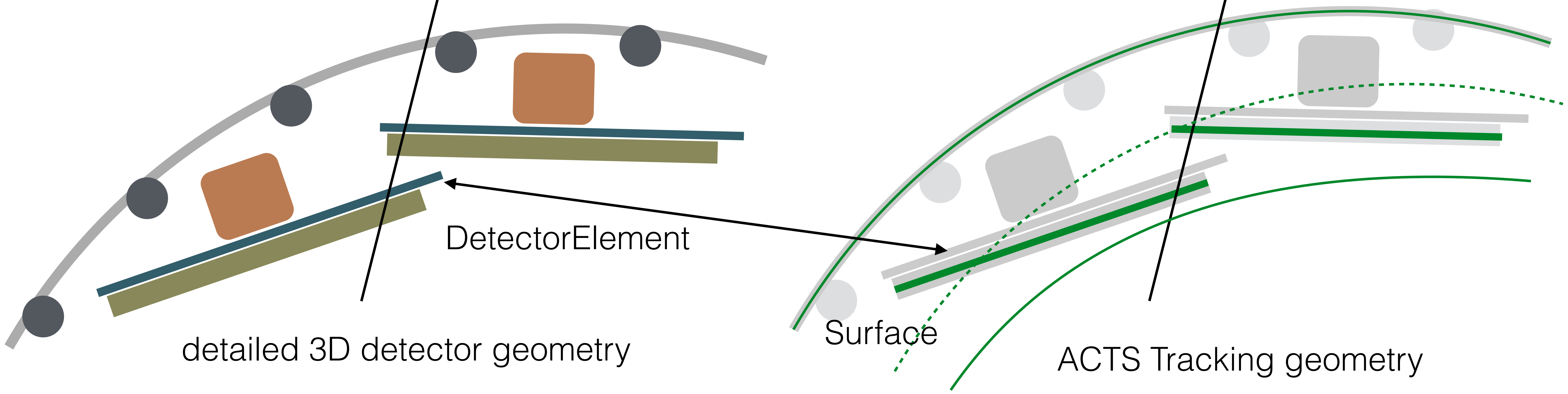
Mozilla Public Licence 2.0

acts project - The toolbox

- Flexibility to interface with detector **SW & Plugin** mechanism

```
namespace Acts {
  /// doxygen documentation
  class DetectorElementBase {
   /// the according represented surface
    virtual const Surface& associatedSurface() const = 0;
  };
}
```

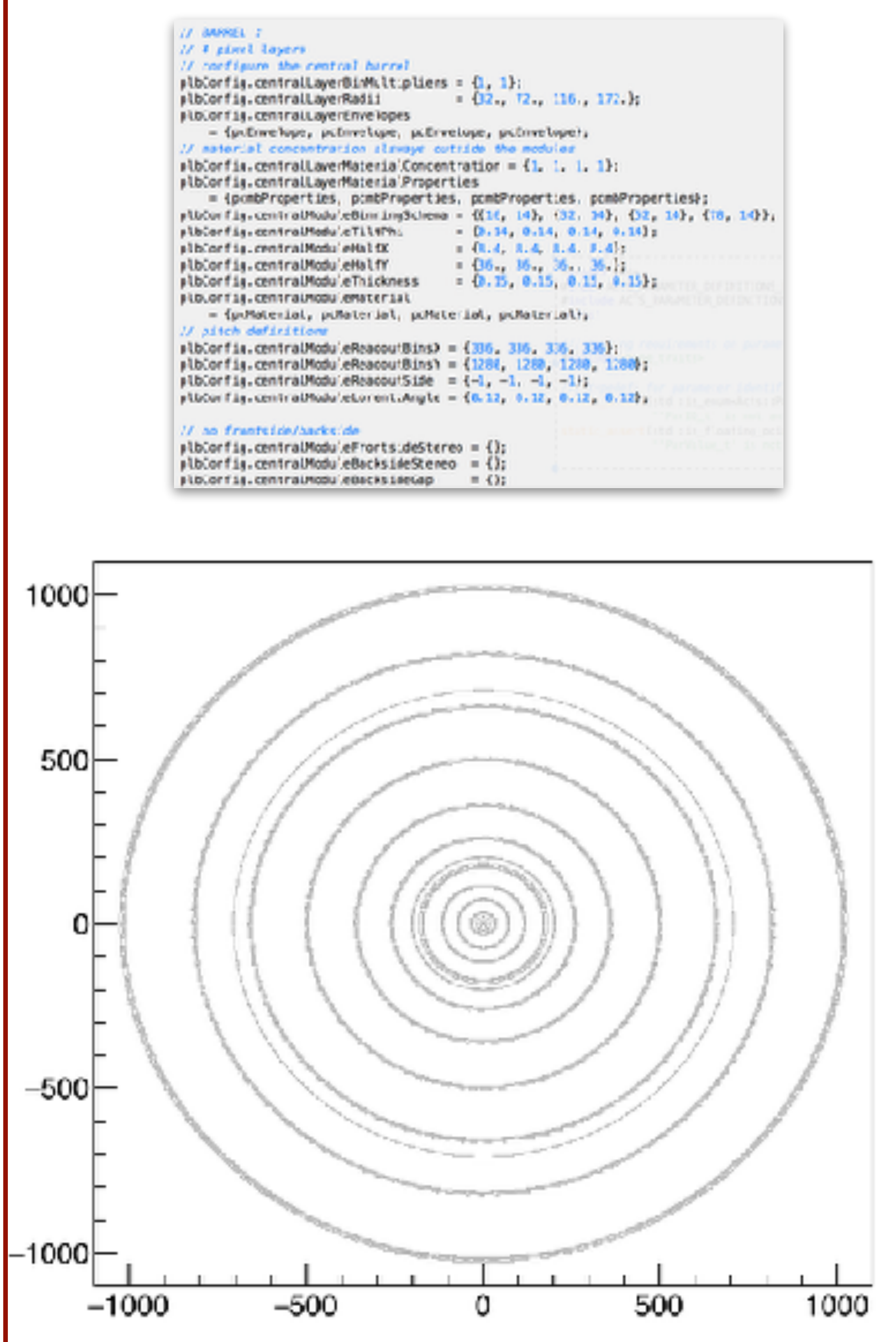
```
class MyDetectorElement {
   /// @copydoc DetectorElementBase::asscociatedSurface
    const PlaneSurface& associatedSurface() const;
 };
```



acts project - The toolbox

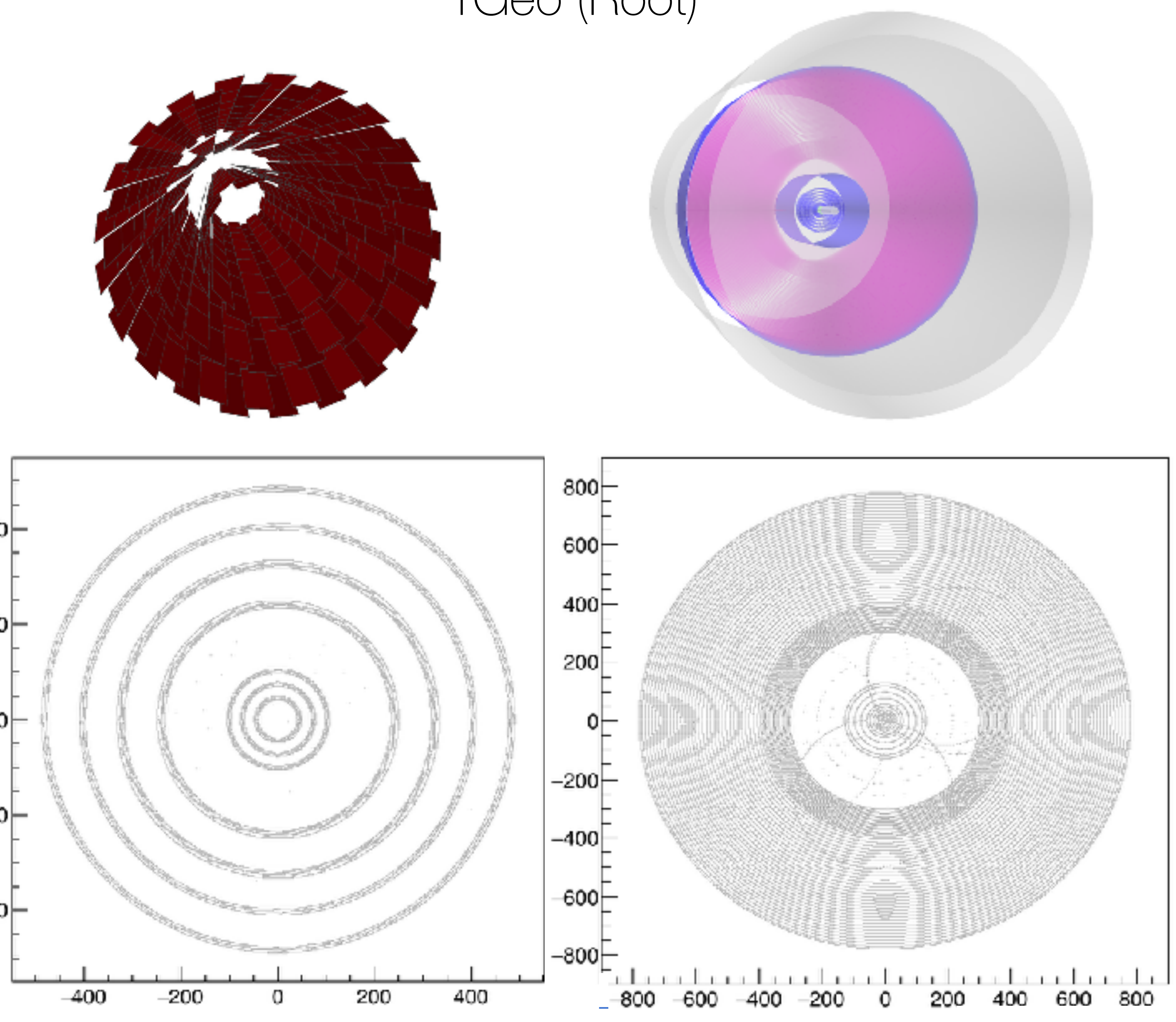
- Flexibility to interface with detector **SW & Plugin** mechanism

C++



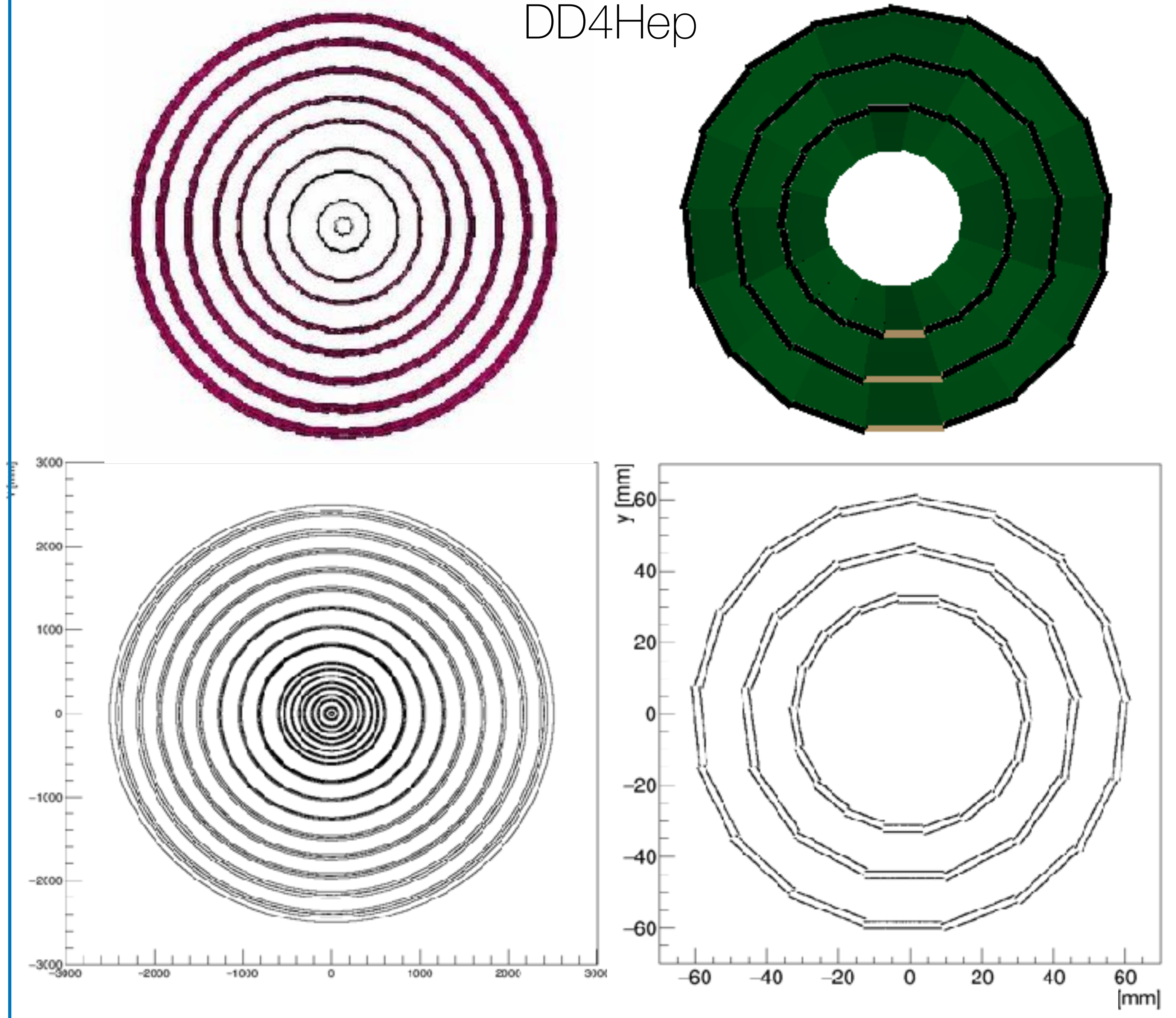
TrackML Detector

TGeo (Root)



CMS Pixel & SVX   sPhenix

DD4Hep



FCC-hh   CLIC Vertex

acts project - The toolbox & integration

- **Plumbing & where it usually gets dirty:** integration into experiment code base
  - **Keep it simple**, e.g. configuration done with nested Config structs

```
namespace Acts {
  /// doxygen documentation
  class WorkHorse {
   /// @struct Config for To
    struct Config {
        float coatColor; ///< configure the coat color
        float maxPath;    ///< set the max path this horse can run
    };
  };
}
```

  - Possible binding to **Gaudi(Hive):**

```
/// feed from Framework into ACTS configuration
declareProperty(“CoatColor”, m_cfg.coatColor);
declareProperty(“MaxPath”,   m_cfg.maxPath);
```

acts project - The toolbox & integration

- **Plumbing & where it usually gets dirty:** integration into experiment code base
  - Any external code **needs to tie in** with experiment code base
    - may sound trivial, but e.g. log messaging needs to work

```
///
/// This macro allows to use a locally defined logging object with the ACTS_*
/// logging macros. The envisaged usage is the following:
///
```

- **General guideline** (“fire brigade design”)
  - You **call us,** we never call you.
  - If you need something from your house, we **will bring** it to you.

acts project - infrastructure & workflows

- HEP SW has/had sometimes a bad reputation in being "aged"
  - Same for workflows & technology
  - Some of it is rooted in the long lifetime & necessity of coherent data processing

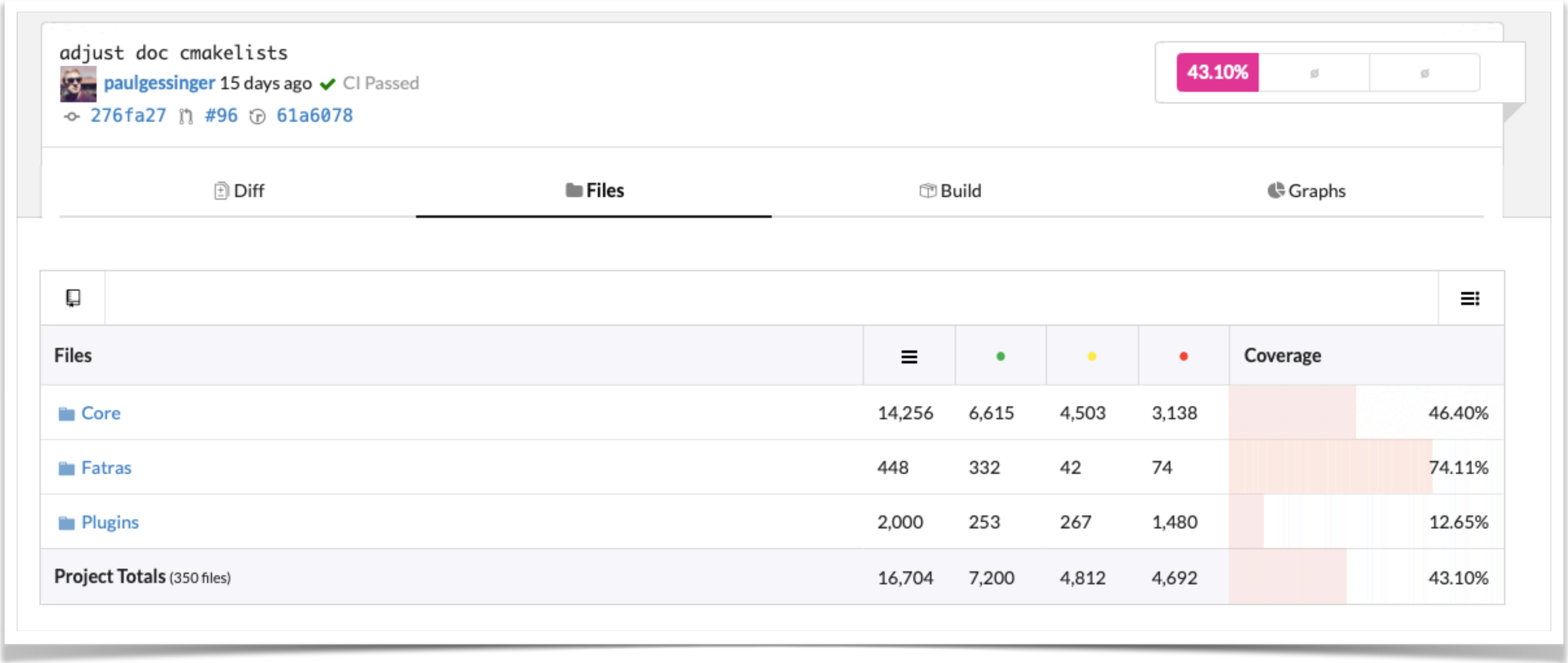
- We need to stay attractive to the best technical students
  - Deploy **modern development workflows**
  - Be **open to move with technology**, new standards
  - A path to **publish the work**

→ **OpenDataDetector** project (backup)

ats project - workflow ecosystem

aits project - testing, code review & CI

- High level of **unit testing & CI** (coverage steadily increasing)



Files	≡	● (green)	● (yellow)	● (red)	Coverage
Core	14,256	6,615	4,503	3,138	46.40%
Fatras	448	332	42	74	74.11%
Plugins	2,000	253	267	1,480	12.65%
Project Totals (350 files)	16,704	7,200	4,812	4,692	43.10%

acts project - testing, code review & CI

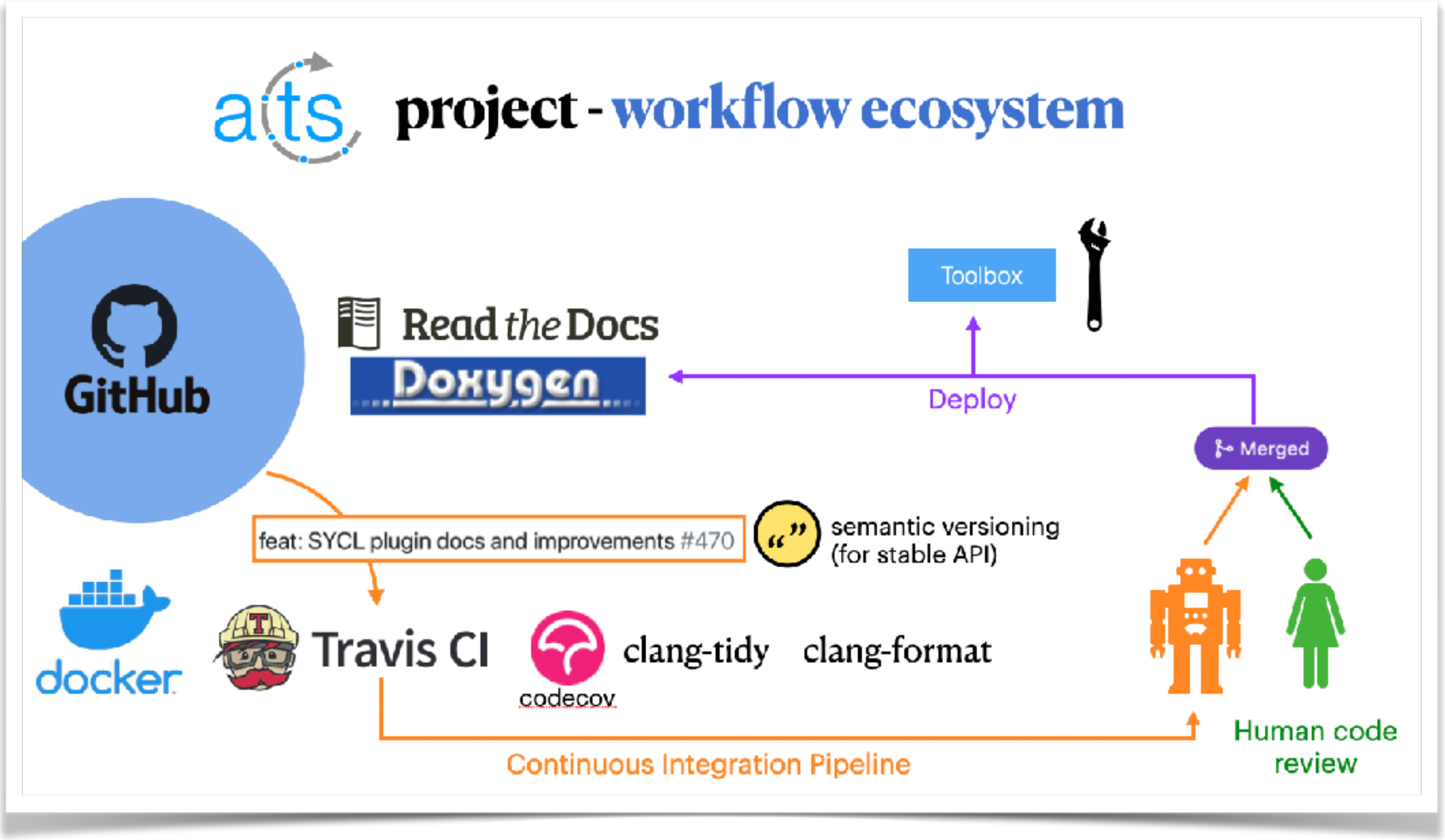
- Directly benefits to involved experiments
  - **Highly tested code** deployed
  - **Experienced developers** that eventually co-authored the deployed code

- **ATLAS** example:
  - Migration to git/CI setup **pioneered** by ACTS developers
  - Vertexing speed-up by 40% being re-deployed to AthenaMT
  - ATLAS phase-2 ITK reconstruction planned with ACTS implementation

-

acts project - experienced workforce

- Modern programming, language, conceptual skills & experience in industry standard workflows
  - Facilitates **change between experiments**
  - Facilitates careers outside the field
    - **open source access** make contribution **traceable**

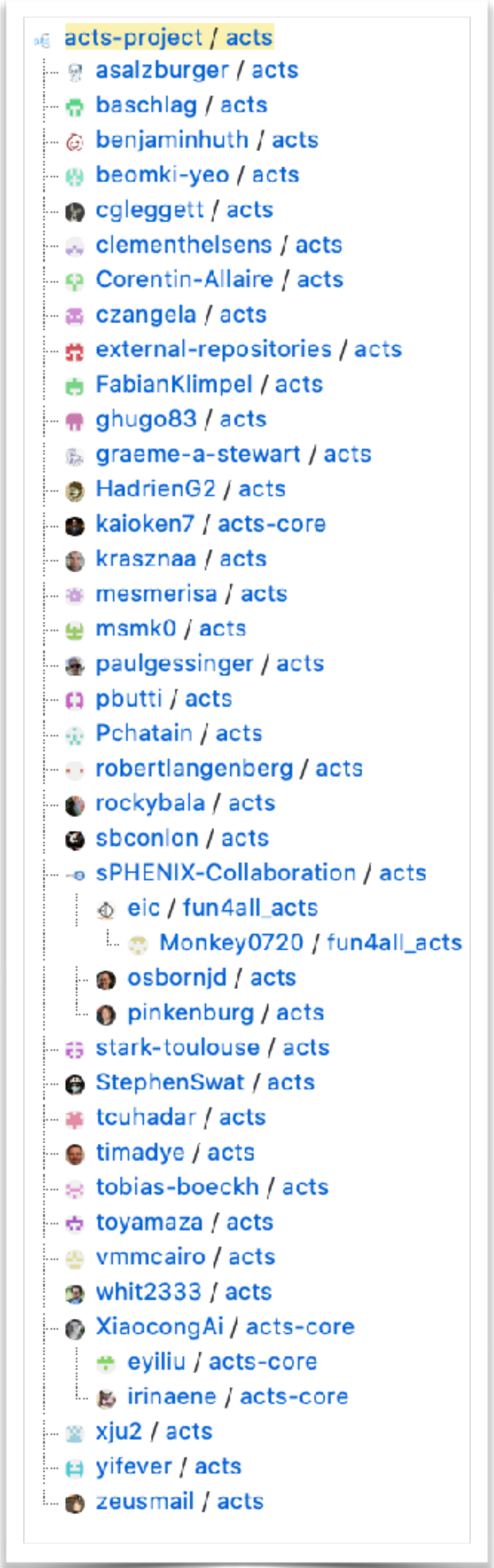


That is an impressive skillset even/particularly outside HEP.

acts project - foster collaboration

- Currently **42** forks of the acts-project
  - Individuals (in HEP, students) or experiment forks (e.g. sPhenix)

- **10-15 active developers** on Core project
  - Still quite ATLAS heavy, though increasing contribution from **sPHENIX, Belle-2** or **non-associated individuals**



acts project - community, friend & family

- ACTS as one project in a new ecosystem of community driven SW
  - We **walk** and **we learn** together
    - interaction between SW projects **under the umbrella of HSF** is key
    - Example: ACTS **report** on Eigen compilation restrictions/issues in HSF WG#2
      similar issues seen by other Eigen clients (CMS), follow up by HSF
  - We should **play** together
    - Encouragement to put modules together, build systems
    - Example: can ACTS run within on top of PataTrack, within ALLEN, etc…
  - Finally, we should **work** together

Summary

- **ACTS project** quite matured in the last 4 years
  - version v01.00.00 released in Sep 2020 with particle frozen API

- Encapsulation from experiment SW stack comes with a price tag
  - however, it did what we strived for: **enabled R&D in many areas**
  - starting to pay off (e.g. vertex reconstruction in ATLAS)

GitHub Mattermost acts Read the Docs

acts-developers@cern.ch
acts-users@cern.ch
acts-parallelization@cern.ch

acts project - The toolbox

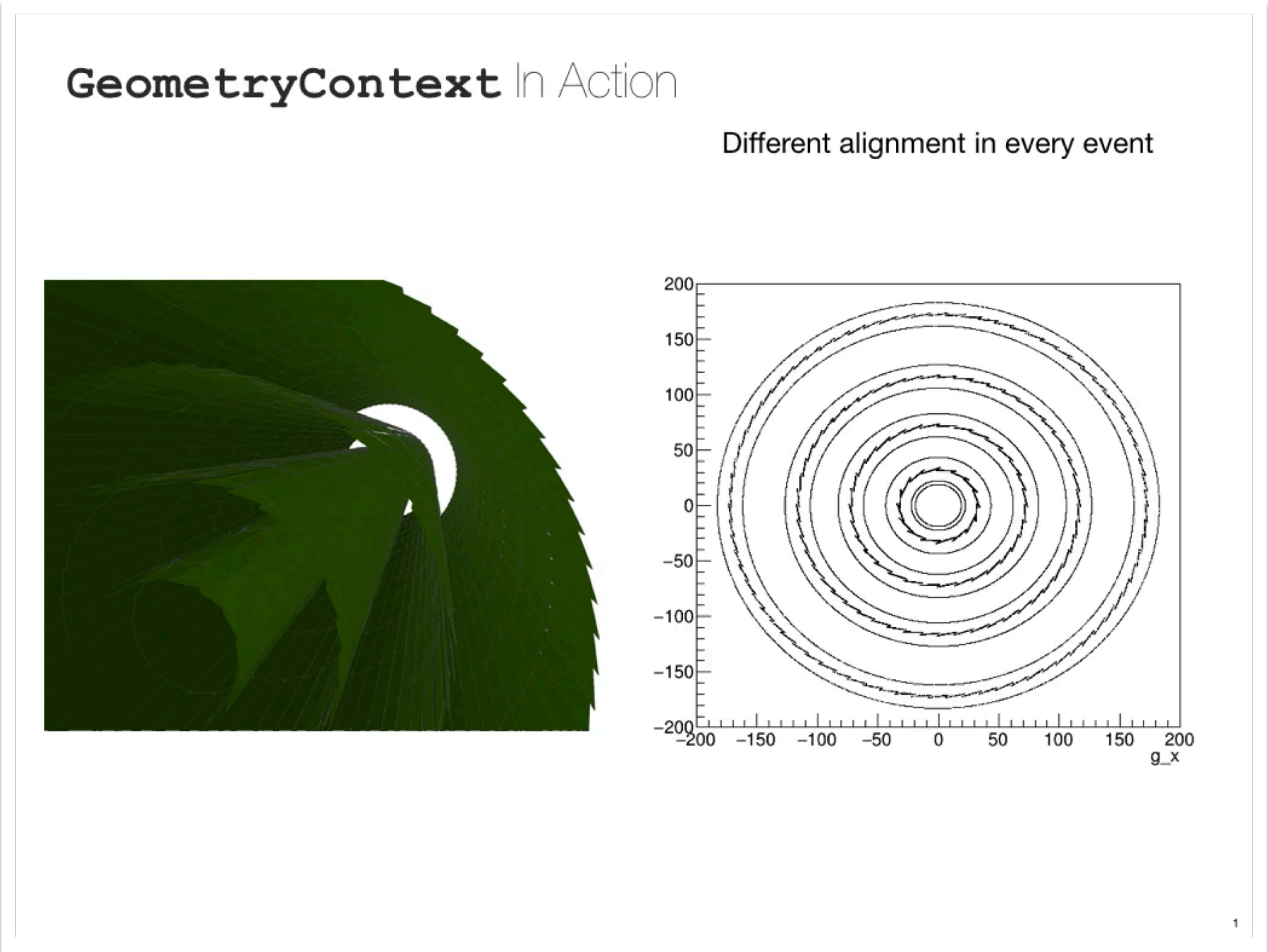
- **Contextual data** processing
  with **parallel** code execution:
  - GeometryContext
  - MagneticFieldContext
  - CalibrationContext

```
everyGeometryCall(…)
        everyMagFieldCall(…)
                everyCalibrationCall(…)
```

Quasi-free condition/contextual data handling.

acts project - The toolbox

- **Contextual data** processing with **parallel** code execution:
  - GeometryContext
  - MagneticFieldContext
  - CalibrationContext



[Animiation of contextual data in ACTS in action]

acts project - R&D for algorithm research

- *Classical* algorithm are **not frozen**, there's room for algorithm R&D

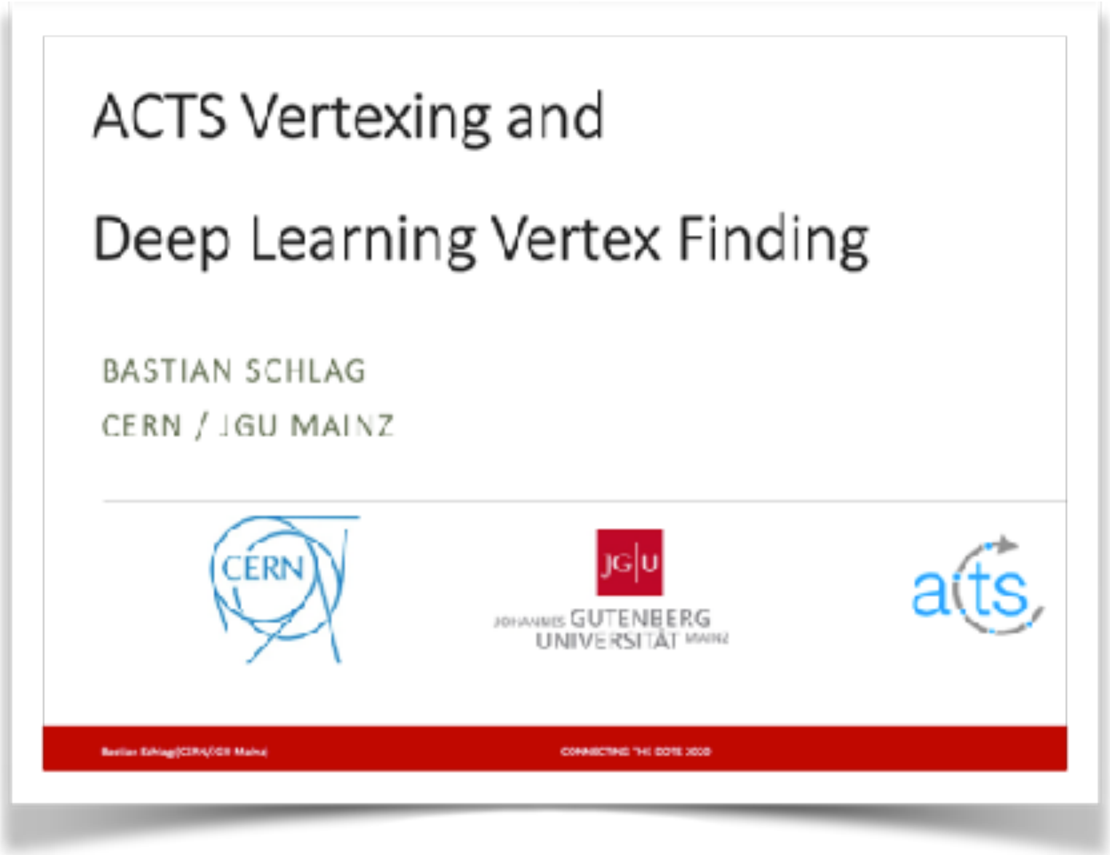
- ACTS aims to provide a testbed for this research:
    - Testbed detectors available for testing
    - Examples (being worked on currently):
      - ray tracing inspired navigation through detector geometry
      - generalised track linearisation in vertex fitting
      - extension of KF into a global measurement formulation

Disclaimer

- **Main focus** of this talk
  - Lessons learnt from/by developing common software
  - **Concepts**, **benefits** & **costs** of doing so

- Recent talks on **ACTS status & performance**

Ai X, Tracking with ACTS, CTD2020



Schlag B, ACTS Vertexing and Deep Learning Vertex Finding, CTD2020

Superficial history of track reconstruction SW

- Many of current algorithms have roots in **LEP era**:
  - Code base usually in FORTRAN
- Move to C++ in early 2000's
  - Common C++ based libraries
  - Era of object oriented design

1987

444 Nuclear Instruments and Methods in Physics Research A262 (1987) 444–450
North-Holland, Amsterdam

APPLICATION OF KALMAN FILTERING TO TRACK AND VERTEX FITTING

R. FRÜHWIRTH

Institut für Hochenergiephysik der Österreichischen Akademie der Wissenschaften, Vienna, Austria

Received 30 June 1987

Recently iterative procedures have been proposed for track and vertex fitting in counter experiments. We show that the proper theoretical framework for these procedures is the theory of linear filtering, in particular the Kalman filter. Using results from filtering theory we confirm and extend the previous results. We also discuss the detection of outliers and of secondary vertices.

R. Früwirth, Applicaiton of Kalman Filtering To Track and Vertex Fitting (1987)

"The Delphi detector was designed for the Kalman Filter"

Superficial history of track reconstruction SW

1991

- Many of current algorithms have roots in LEP era:
  - Code base usually in **FORTRAN**
- Move to C++ in early 2000's
  - Common C++ based libraries
  - Era of object oriented design

"For all its inelegance, and lack of safety features, it seems certain that FORTRAN will remain the main language for HEP code well into the 1990s...."

Computing at CERN in the 1990s

"FORTRAN is probably the only perennial standard which will never be questioned."

Trends in Computing for HEP

"I don't know what the language of the year 2000 will look like but I know it will be called FORTRAN."

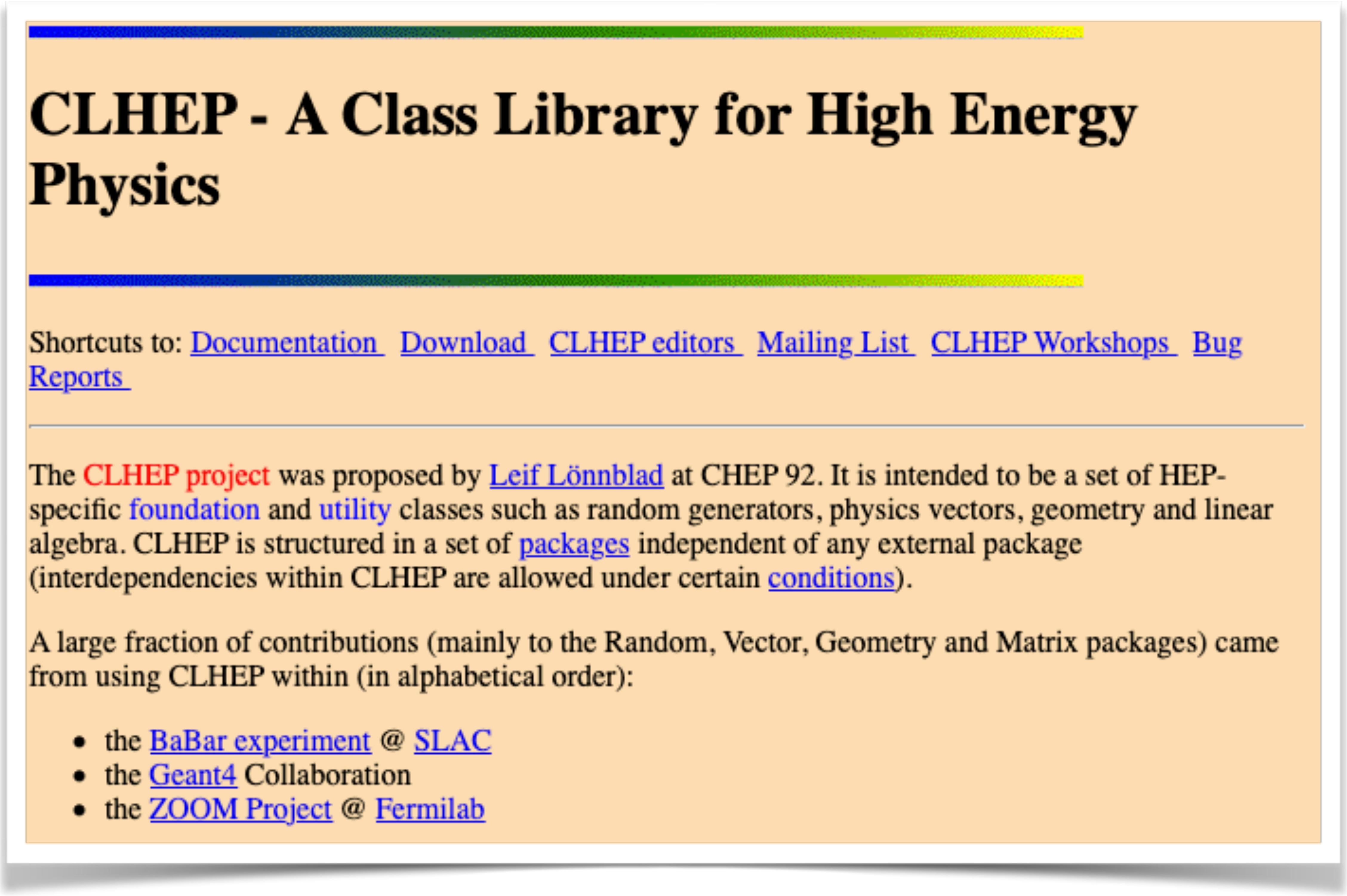
Tony Hoare

White, B. The comparison and selection of programming languages for high energy physics application (1991)

Superficial history of track reconstruction SW

1994

- Many of current algorithms have roots in LEP era:
  - Code base usually in FORTRAN
- Move to C++ in early 2000's
  - Common **C++ based libraries**
  - Era of object oriented design



CLHEP - A Class Library for High Energy Physics

Shortcuts to: Documentation Download CLHEP editors Mailing List CLHEP Workshops Bug Reports

The CLHEP project was proposed by Leif Lönnblad at CHEP 92. It is intended to be a set of HEP-specific foundation and utility classes such as random generators, physics vectors, geometry and linear algebra. CLHEP is structured in a set of packages independent of any external package (interdependencies within CLHEP are allowed under certain conditions).

A large fraction of contributions (mainly to the Random, Vector, Geometry and Matrix packages) came from using CLHEP within (in alphabetical order):

- the BaBar experiment @ SLAC
- the Geant4 Collaboration
- the ZOOM Project @ Fermilab

L. Lönnblad, CLHEP—a project for designing a C++ class library for high energy physics (1994)

Superficial history of track reconstruction SW

2006

- Many of current algorithms have roots in LEP era:
  - Code base usually in FORTRAN
- Move to **C++** in early 2000's
  - Common C++ based libraries
  - Era of **object oriented (OO) design**

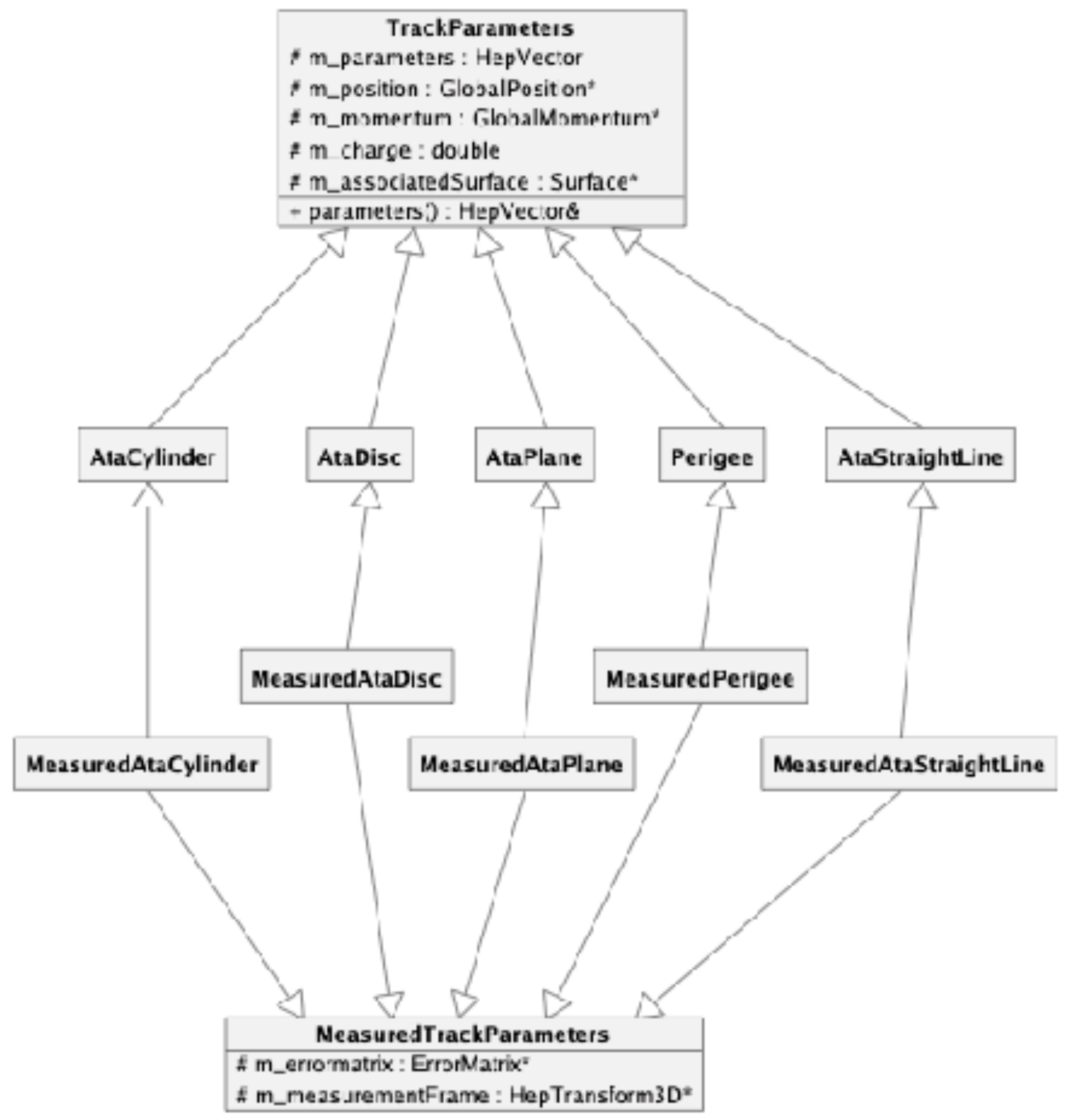


Figure 3: UML diagram showing the inheritance structure of `TrackParameters` *data classes.* `TrackParameters` *exist in both, an unmeasured and a measured flavour. The measured track parameter classes follow a double inheritance structure, inheriting from the unmeasured class they represent and a common base class for measured track parameters, holding the error matrix description and the measurement frame definition.*

[Akeson, P F et al, ATLAS Tracking Event Data Model (2006)]

Now we'd call it over-object oriented (OOO) …

Legacy of the LHC era

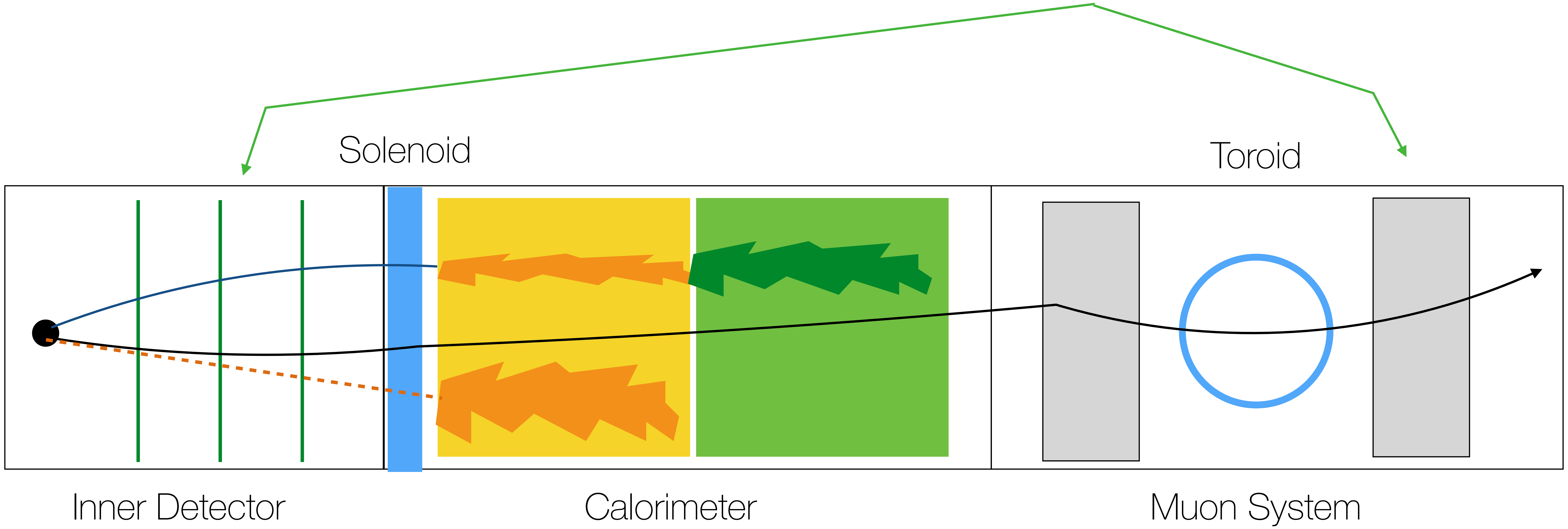
- Extremely ironed-out code
  - Many 10^{10} events processed (numerically validated)
- Extremely well performing track reconstruction algorithms
  - Technical track reconstruction (μ) efficiency ~100 %
- A great starting point!

Future challenges

- HL-LHC / FCC-hh studies
  - Way higher particle multiplicities (combinatorics)
- The rise of new technologies
  - C++20 has little to do with C++98
  - Heterogeneous computing
- Robots/AI want to take our jobs!

A great starting point

- ATLAS Track reconstruction SW
  - Designed/written with common (agnostic) top layer for **two** tracking devices



  - Highly polymorphic Tracking reconstruction SW, with common abstraction layer

[Cornelissen T et al, Concepts, Design and Implementation of the ATLAS New Tracking, 2008]

A great starting point

- ATLAS Track reconstruction SW
  - Designed/written with common (agnostic) top layer for **two** tracking devices
  - Some very fast **algorithms & modules** in place

```
// projection of direction onto normal vector of reference frame
double PC = pVector[4] * C[0] + pVector[5] * C[1] + pVector[6] * C[2];
double Bn = 1. / PC;

double Bx2 = -A[2] * pVector[29];
double Bx3 = A[1] * pVector[38] - A[2] * pVector[37];

double By2 = A[2] * pVector[28];
double By3 = A[2] * pVector[36] - A[0] * pVector[38];

double Bz2 = A[0] * pVector[29] - A[1] * pVector[28];
double Bz3 = A[0] * pVector[37] - A[1] * pVector[36];

double B2 = B[0] * Bx2 + B[1] * By2 + B[2] * Bz2;
double B3 = B[0] * Bx3 + B[1] * By3 + B[2] * Bz3;
```

AtlasStepper, transcript in ACTS project

Some of this great CPU performance still roots in the FORTRAN style writing.

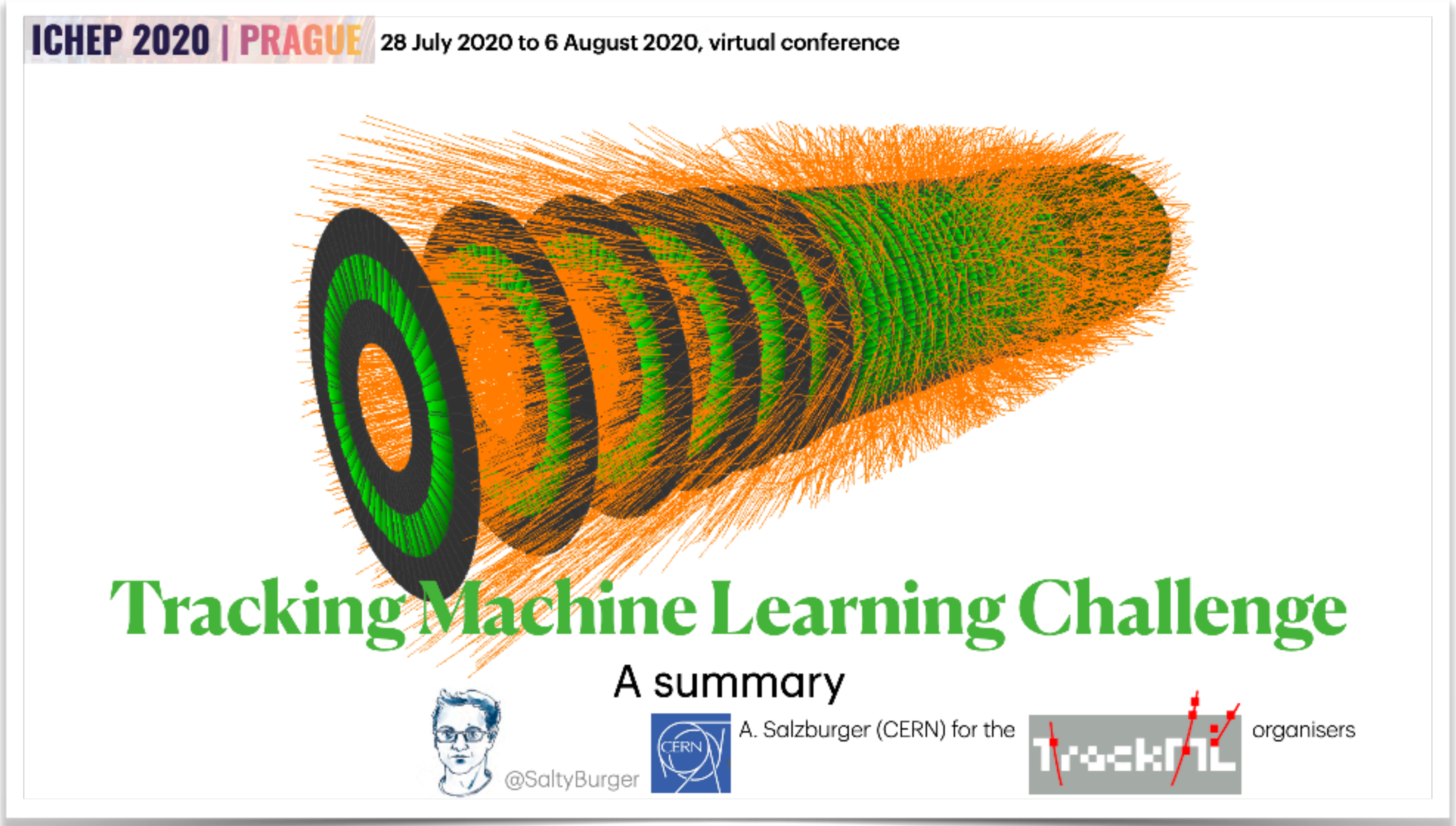
A great starting point

- ATLAS Track reconstruction SW
  - Designed/written with common (agnostic) top layer for **two** tracking devices
  - Some very fast **algorithms & modules** in place
  - Undergone (like other experiment SW) **successful cleanup campaigns**
    - all LHC experiments reduced CPU time significantly since LHC startup

- However, time starts to show its scars
  - Several **developers left** the project/field
  - Some **technology advancements** missed/only profited in a limited manner

acts project - R&D for ML

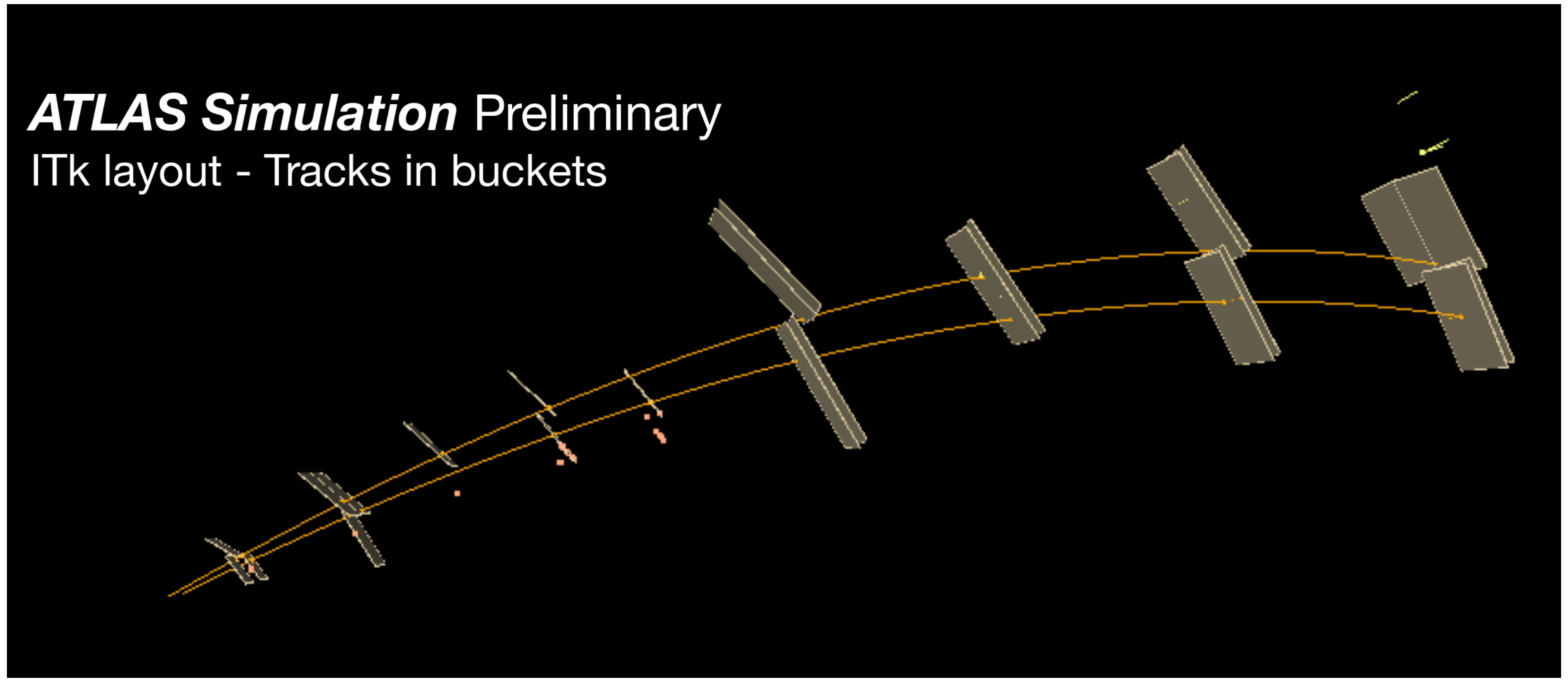
- Fast simulation extension was used for **Tracking Machine Challenge**
  - Very successful **kaggle** & **codalab** challenges
  - Many interesting ideas & solutions
  - Established a reference data set & format
    - still in use for much of current Tracking R&D



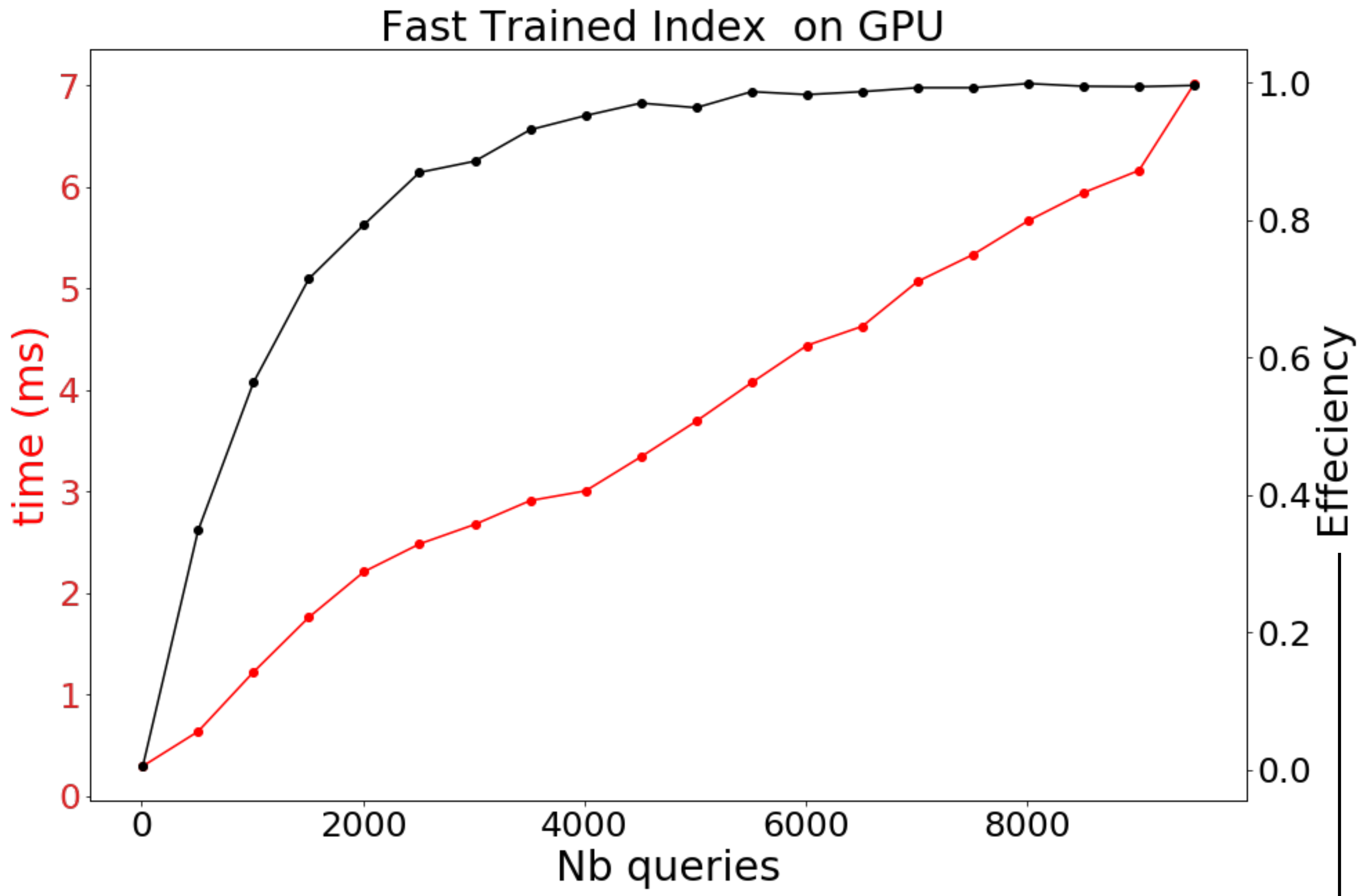
[AS, Conclusion of the TrackML Challenge, ICHEP2020]

acts project - R&D for ML

- Standalone examples allow for novel (ML) algorithm R&D
  - **Example:** track seeding using approximate nearest neighbourhood



These tracks are brought to you by



To find a bucket with at least 4/hits of the track contained (good enough for track seeding)

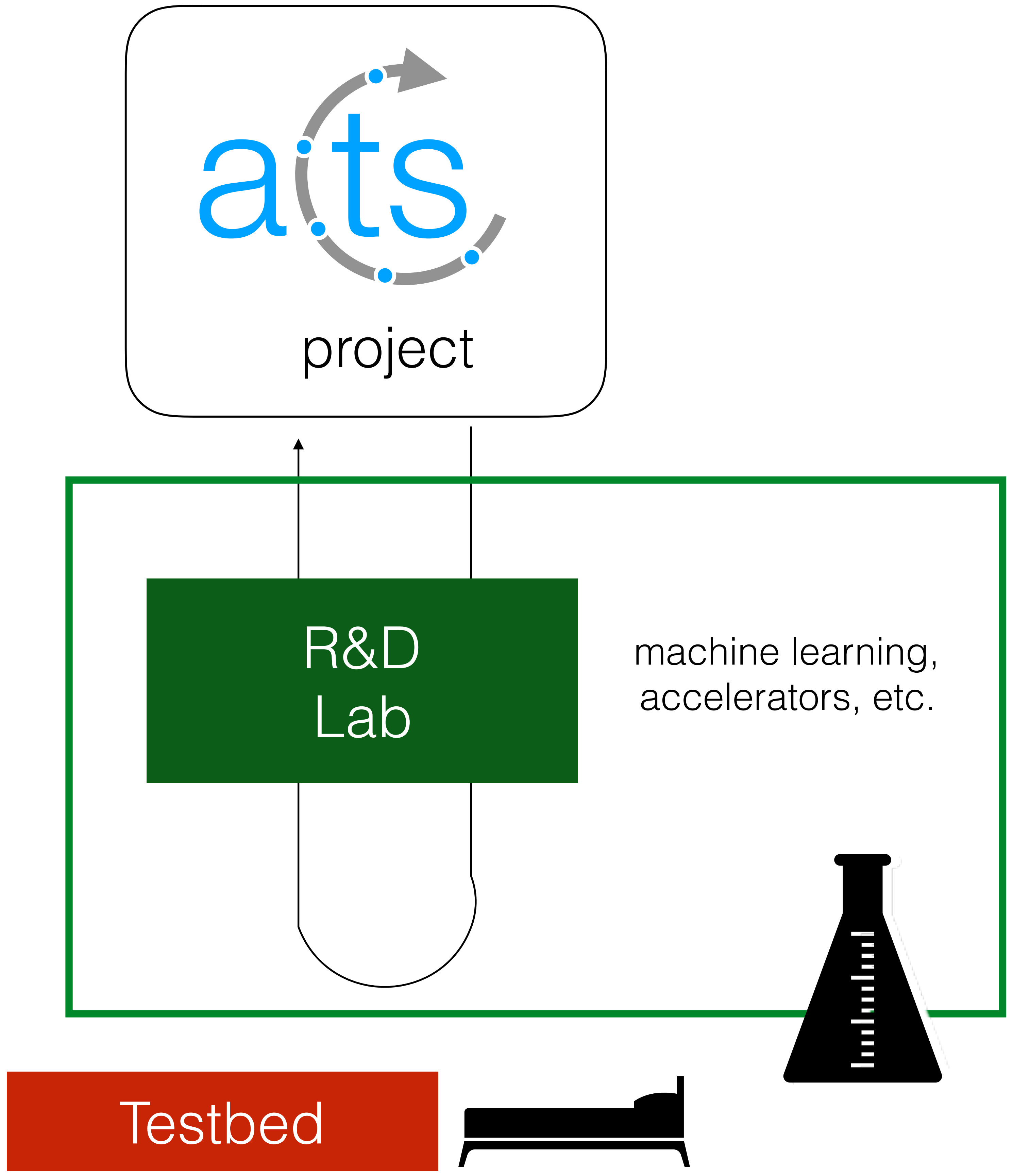
[S. Amrouche, T. Golling, M. Kiehn, AS: Music, Neighbours & Tracking]

[S. Amrouche, N. Calace, T. Golling, M. Kiehm. AS : Hashing & similarity learning]

acts project - R&D for ML

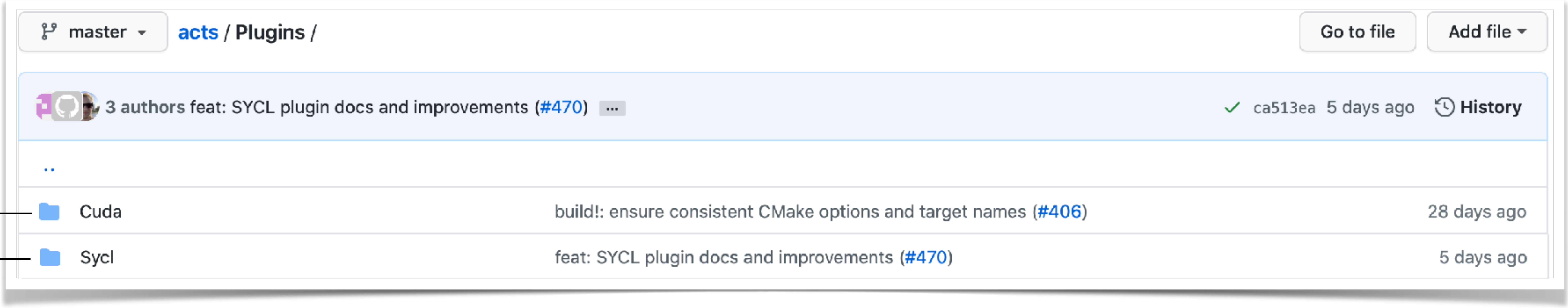
- Standalone examples allow for novel (ML) algorithm R&D
  - **Example:** track seeding using approximate nearest neighbourhood
  - Aim to have a **path** way of these R&D projects **back** into the ACTS code base - **eventually** even production code

- **Learn** how to integrate external non-HEP software into HEP reconstruction code



acts project - R&D for accelerators

- Dedicated sub-group for parallelisation (acts-parallelization@cern.ch)
  - Evolving code to **run on different hardware**

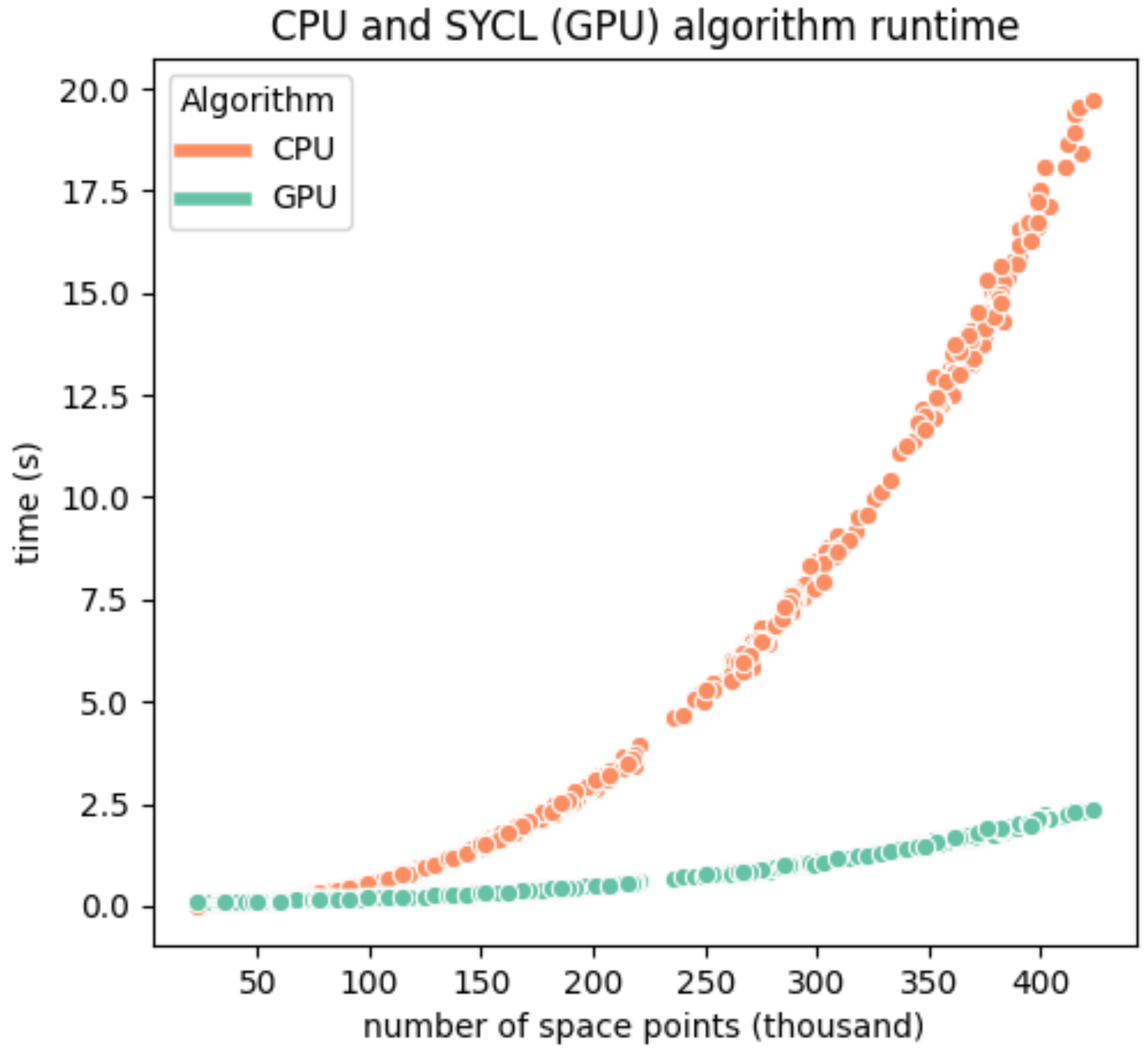


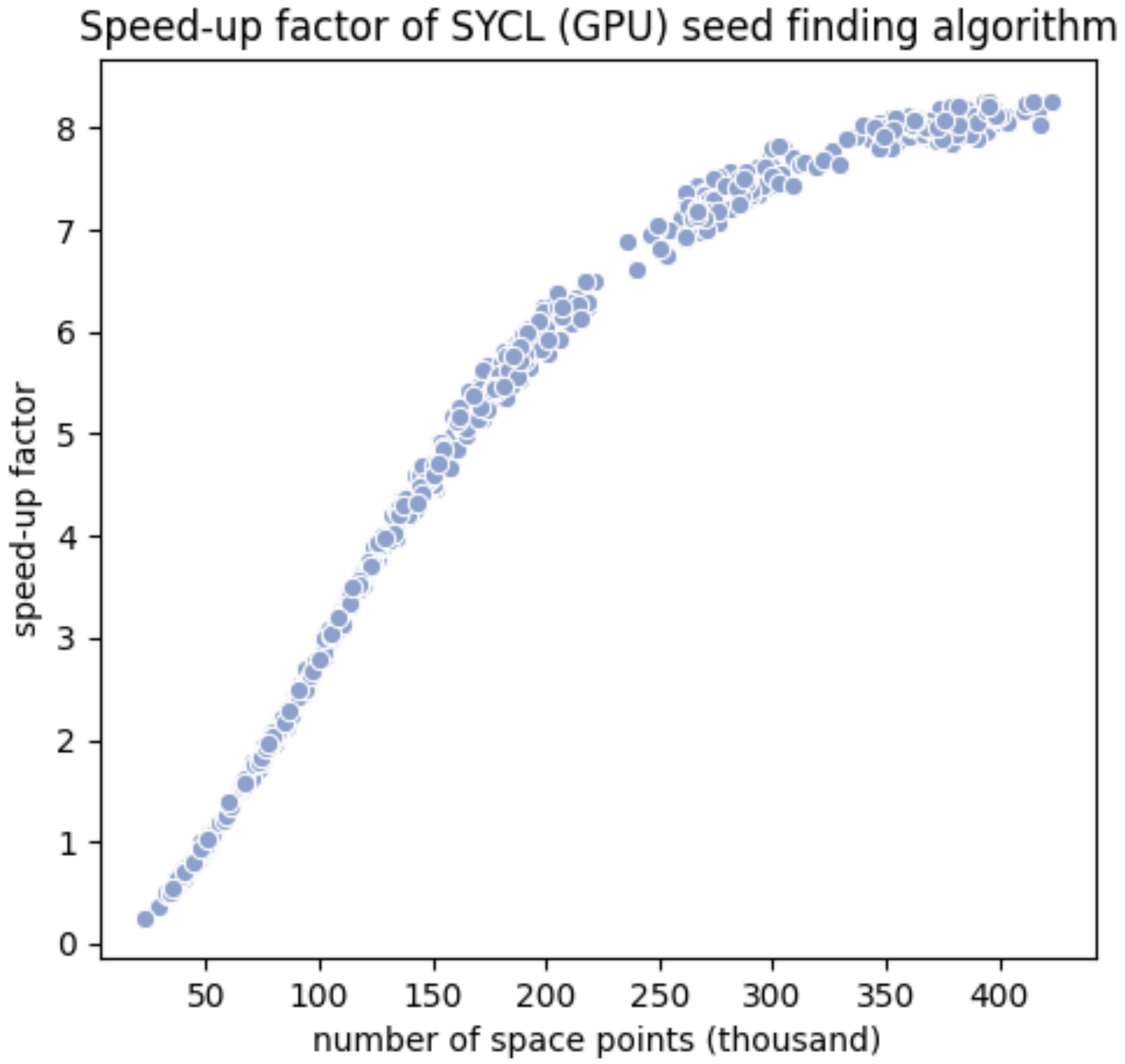
  - Native CUDA modules (Seeding, Propagation, Fitting)
  - SYCL/onAPI module (Seeding)

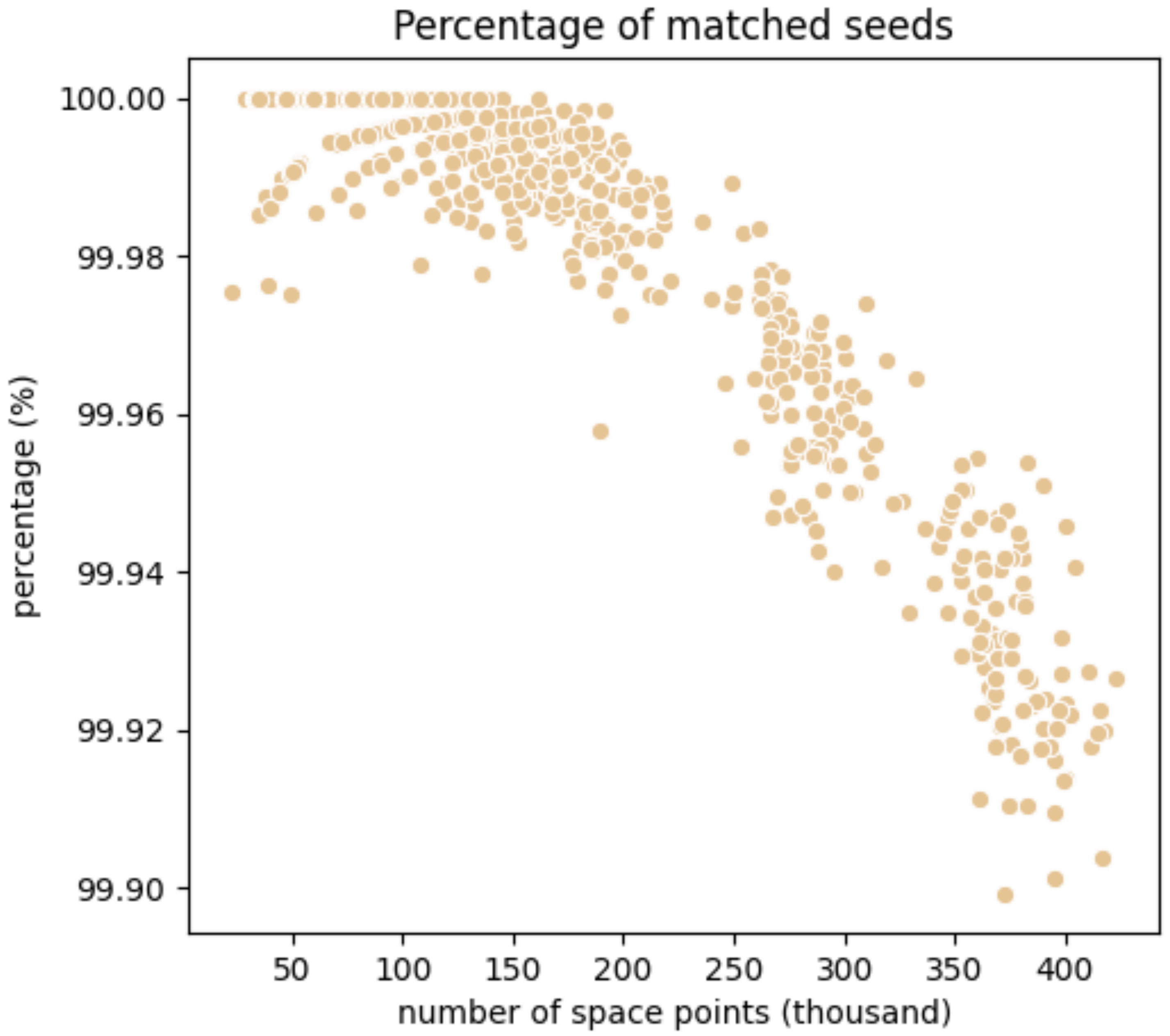
CERN openlab / intel project

acts project - R&D for accelerators

- **Example:** SYCL/oneAPI implementation of track seeding algorithm
  - Reference to CPU implementation (ATLAS implementation)







  - Valuable lessons/feedback to ACTS core project wrt EDM/algorithm design

acts project - R&D for new SW technologies

- Stand-alone character of the repository eases R&D
  - Even larger scale inclusions, tests, expansions are simplified
  - Testbeds allow for rapid feedback on development

- Example: ACTS **auto-diff** within propagation
  - **auto-diff** is a rather recent development coming from the ML sector
    - relies on the fact that machine instructions are per definition differentiable
  - Test implementation in track propagation for derivative/jacobian calculation done