Carlo VARNI On behalf of the ATLAS Collaboration

# Integration of the ACTS track reconstruction toolkit in the ATLAS software for HL-LHC operations

**CHEP 2024**

**Conference on Computing in High Energy and Nuclear Physics**

**Krakow (PL)**

19-25 October 2024

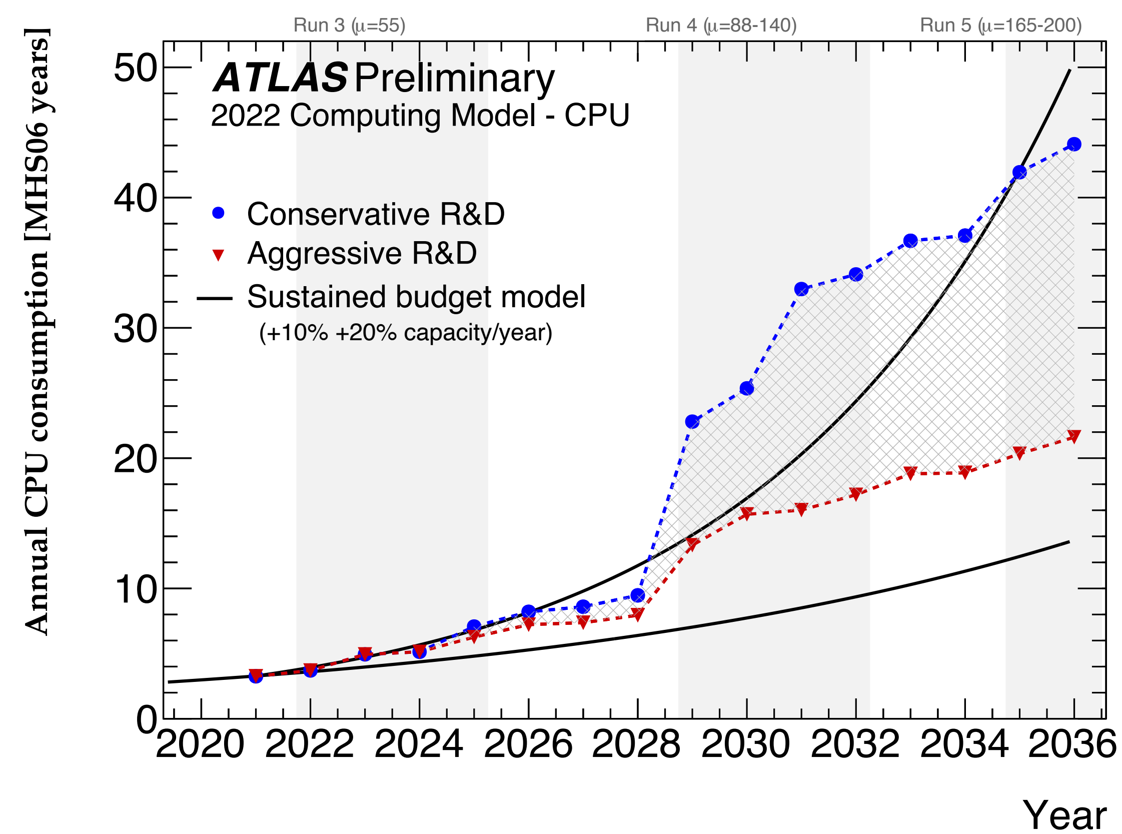
**UC Berkeley (US)**
**Lawrence Berkeley National Laboratory (US)**

# Tracking Challenges at HL-LHC

- **Tracking is extremely CPU consuming**
  - In Run 3 tracking: ~40% of the reconstruction time
  - Tracking complexity scales with the **number of interactions** (μ)

CERN-LHCC-2022-005

| Run 2 | Run 3 | HL-LHC |
|---|---|---|
| ⟨μ⟩~25 | ⟨μ⟩~50 | ⟨μ⟩~140-200 |




- **Stringent demands on computing & software:**
  - CPU budget can prove to be quite a constraint
  - Tracking algorithms are also used at trigger level → even stronger constraints

- **We need modern and maintainable software**
  - Tracking algorithms in ATLAS were developed ~20 years ago
    - Originally designed to deal with an order of magnitude less pile-up
    - Code modified many times to adapt to new running conditions → hard to maintain

# A Common Tracking Software

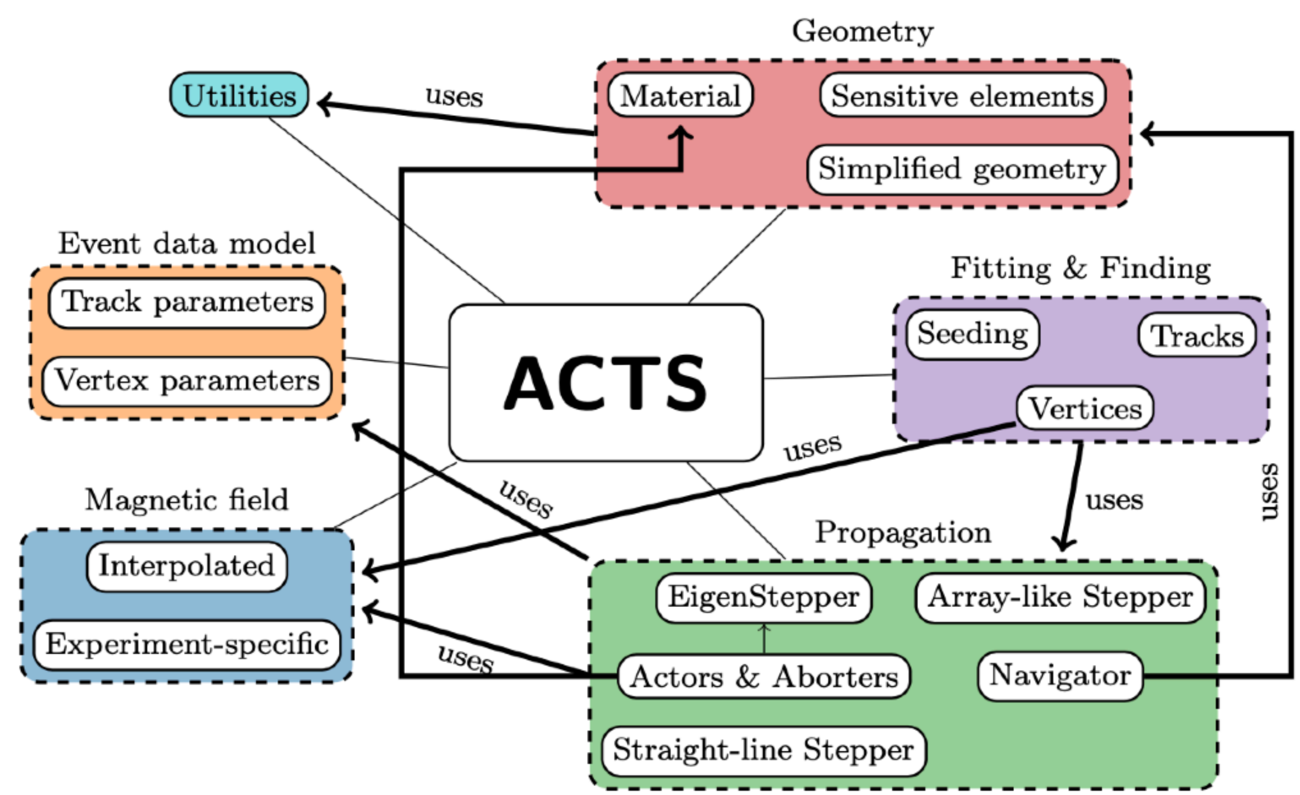
# The ACTS Toolkit

- **A Common Tracking Software**
  - An experiment-independent toolkit for charged particle trajectory reconstruction in HEP experiments, written in modern C++20
  - Goals of the project:
    - Provide production-ready implementations of state-of-the-art tracking methods
    - Serve as algorithmic testbed, including ML methods and computing accelerators
  - Design principles:
    - Provide experiment-independent algorithms
    - Allow efficient experiment-specific usage
    - Thread-safe and maintainable code across the board

- Also include R&D subproject, for tracking on accelerated hardware (GPU, FPGA)

  See Beomki Yeo's presentation for more details on GPU R&D line: traccc

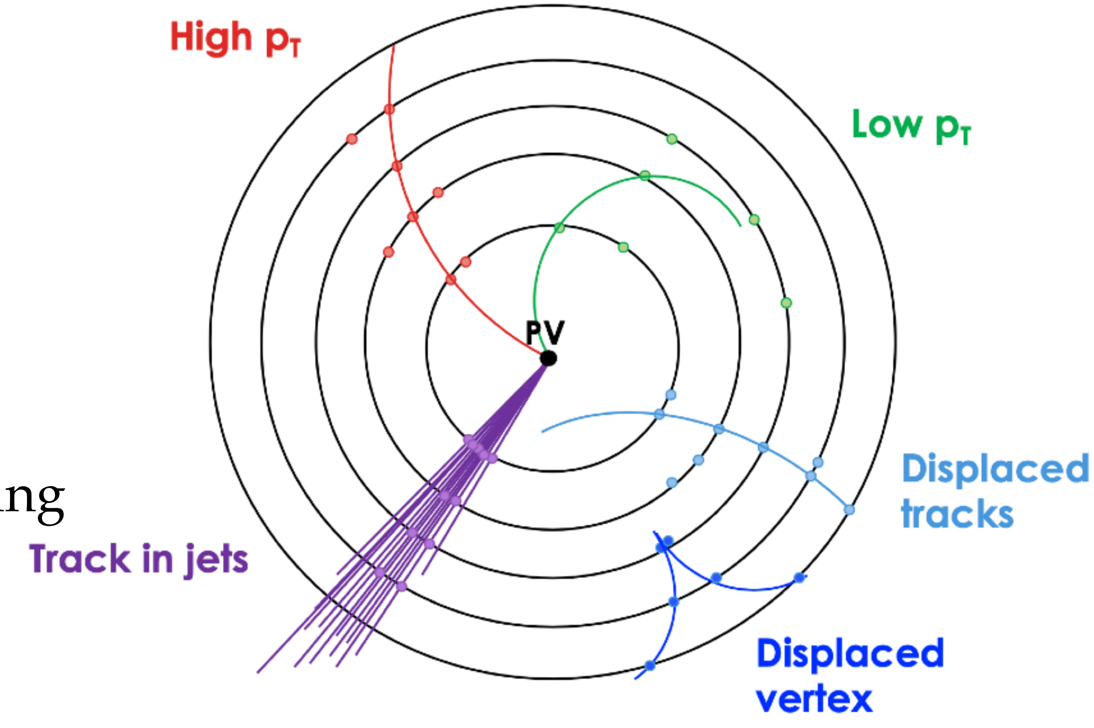
- **Documentation**
  - "A Common Tracking Software Project"
  - ACTS website
  - Code on GitHub



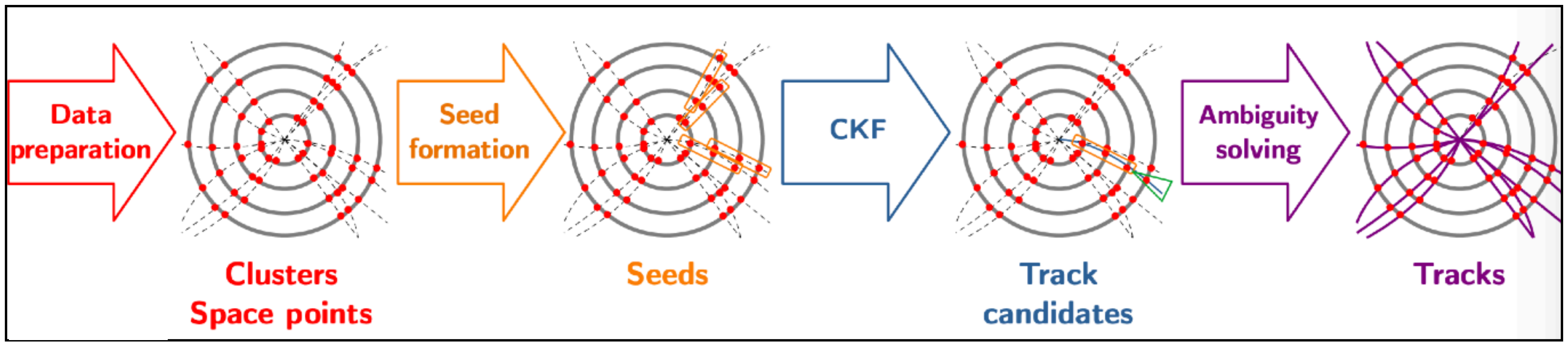
# ATLAS Track Reconstruction

# ATLAS Track Reconstruction

- **High-precision Tracks pivotal for event reconstruction**
  - Different topologies of tracks, which may require different reconstruction strategies
- **Track reconstruction sequence**
  - Pre-processing step: clustering and space point (3D representations of clusters) formation
  - Identification of seeds, e.g. triplets of space points compatible with a helix trajectory
  - Iterative Combinatorial Kalman Filter (CKF) extending track seeds into tracks candidates using all clusters compatible with the estimated trajectory
  - Ambiguity solver to resolve overlaps among track candidates




- ACTS provides reconstruction algorithms flexible enough to be tuned for all the topologies

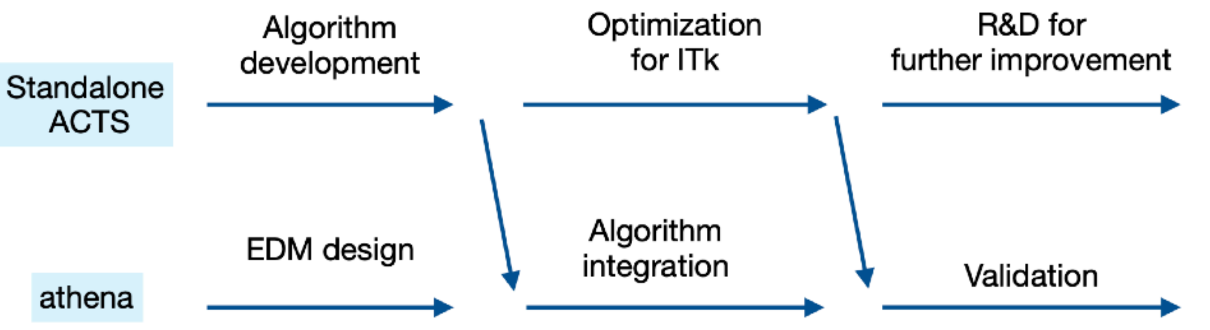


ATLAS software is called Athena

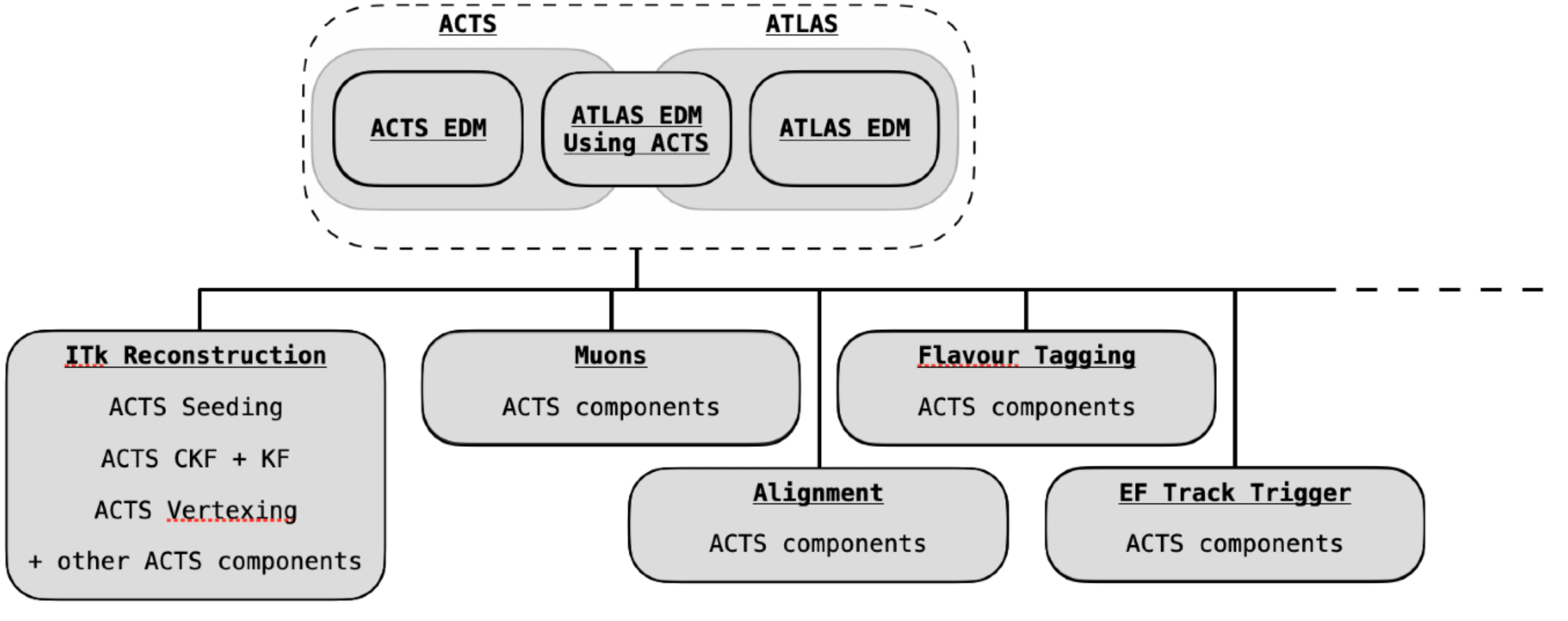
# ACTS Integration into Athena

# ACTS Integration in Athena

- **ACTS as a sandbox for R&D**
  - Developments, optimizations and improvements made in ACTS standalone
  - Periodic releases and deployment to experiments




- **Integration into an experiment implies**
  - Definition of an Event Data Model, connecting experiment and ACTS' representation of the core objects
  - Integration of the ACTS components into the reconstruction chain
  - Possible adaptation of downstream objects reconstruction to the above changes



# Event Data Model

See Scott Snyder's presentation for more details on ATLAS EDM

## Internal ACTS EDM

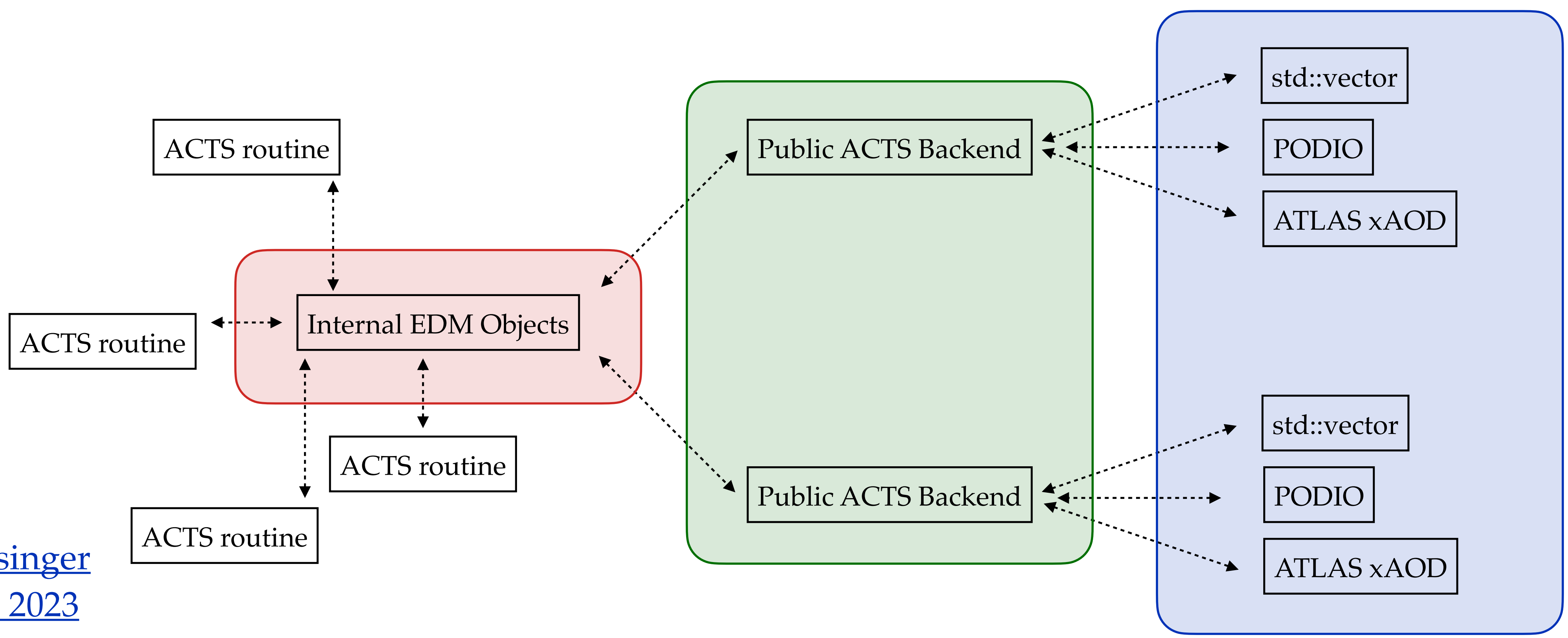
- Data objects to pass around between different parts of the ACTS library
- Library-specific, tightly coupled to the algorithm

## Public ACTS EDM

- Data objects clients directly interact with
- Should be experiment agnostic
- Extensible by experiment, easy integration

## Experiment EDM

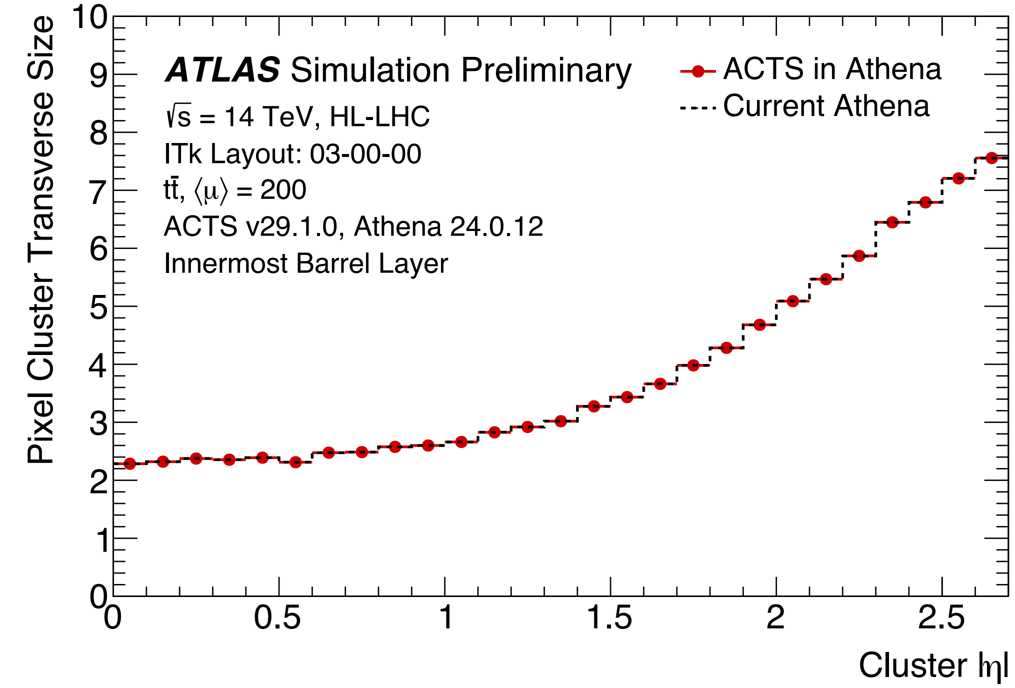
- Data objects experiments use, can save to file




Paul Gessinger @ CHEP 2023

# Clusterization

- **ACTS Clusterization**
  - Grouping adjacent energy deposits
  - Reimplementation of pixel and strip clustering
    - Based on prior ATLAS implementation, with some modifications
  - Number of clusters and cluster sizes agree with current ATLAS SW
    - Exact problem: one 1 right solution → 100% agreement
  - Faster execution time compared to current ATLAS SW (~15% for Pixel and ~5% for Strips)

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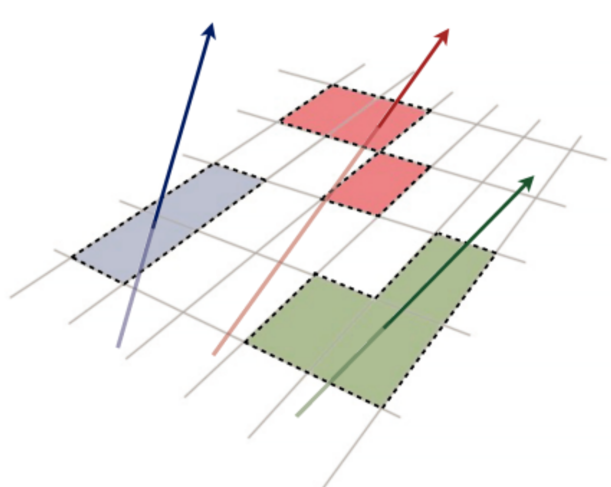

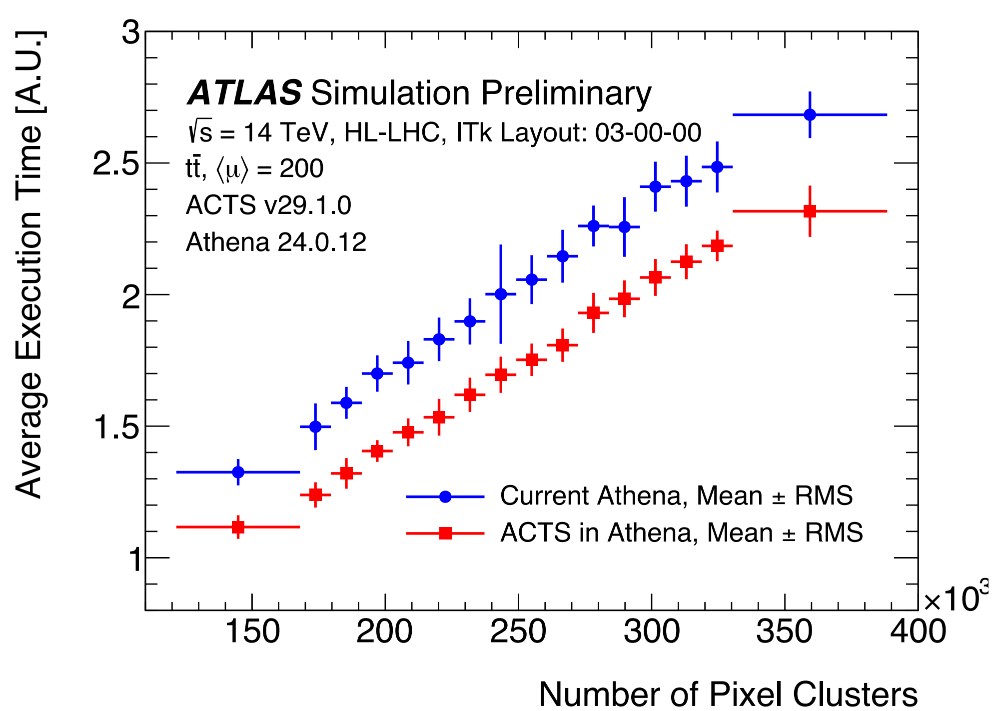


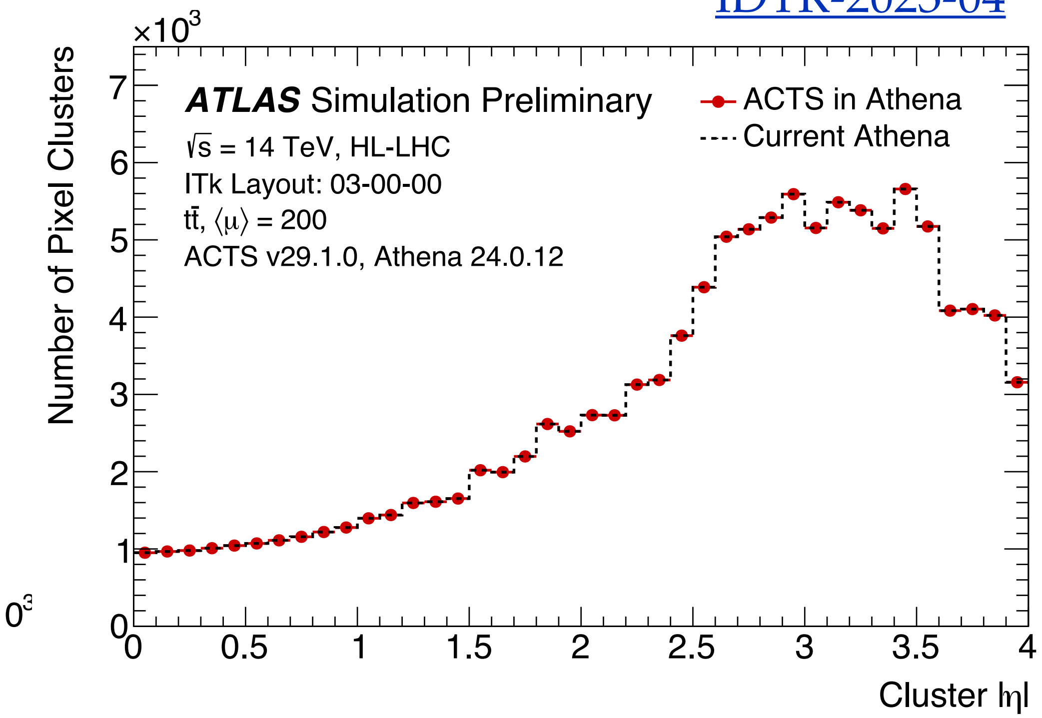

# Seed Finding

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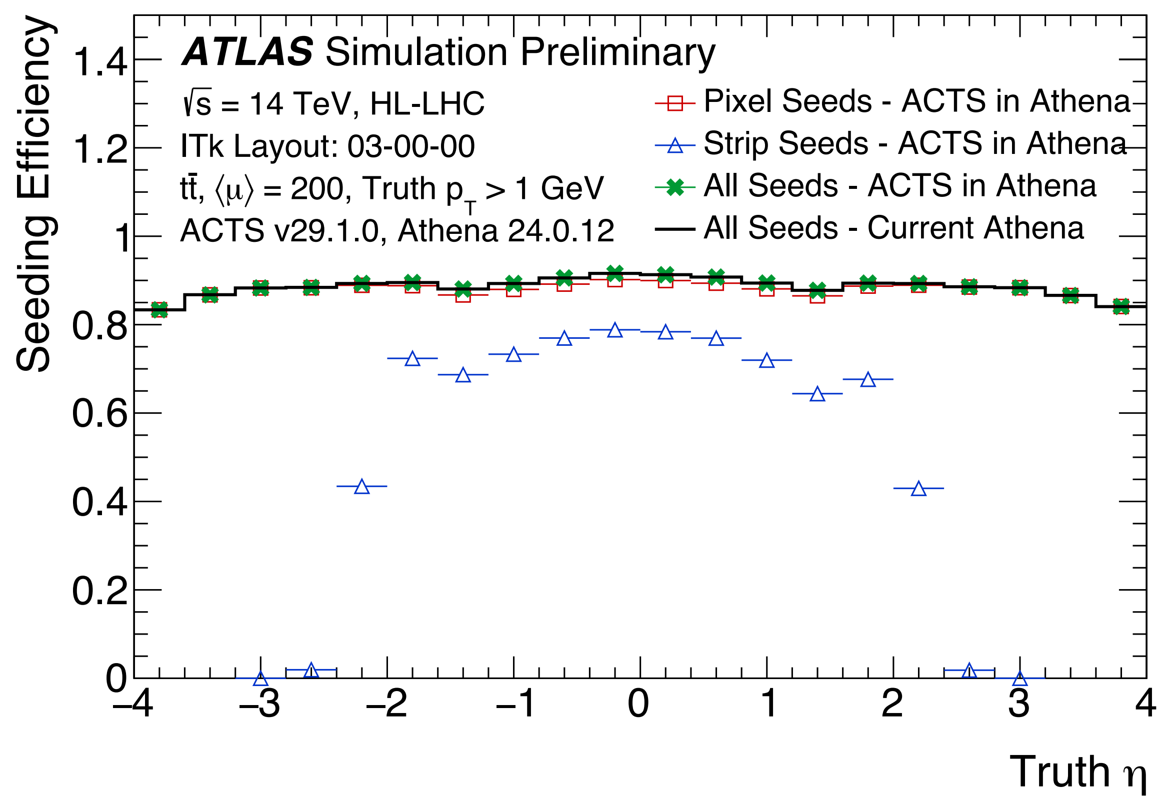
- **ACTS Seed Finding**
  - Search for triplet 3D space-points compatible with helix trajectory
  - Reimplementation of ATLAS seeding strategy
    - Reproduce seeds 1-1
  - Current focus is now CPU optimization
    - Currently, about 15% slower than Athena implementation

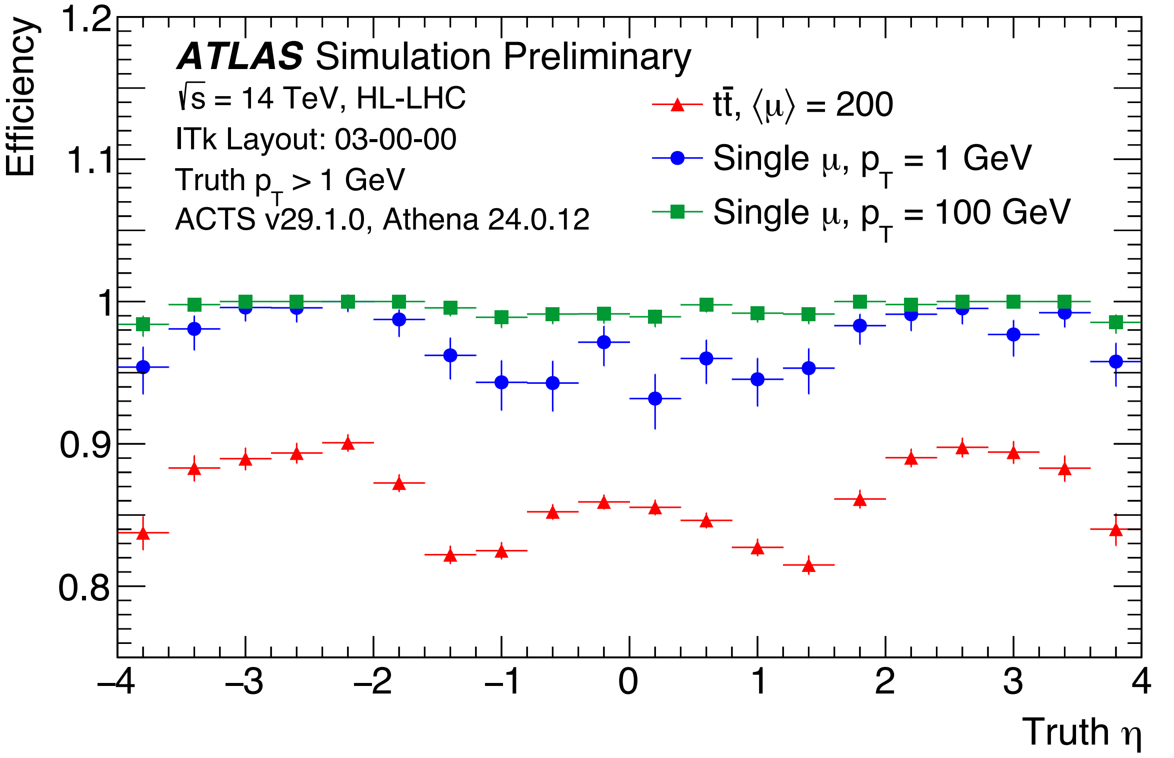



- **Alternative seeding algorithms are available**
  - Orthogonal seeding, using k-d trees
    - Partitions data into a k-dimentional space
  - ML-based seeding algorithms, e.g. GNN-seeding
  - Dedicated implementations for GPUs

# Track Finding

IDTR-2023-04

- **Combinatorial Track Finding**
  - ACTS follow different approach than the current ATLAS strategy
    - Extends seeds into track candidates by using all clusters compatible with the estimated trajectory
    - Branching mechanism available, handles multiple compatible clusters on same sensitive detector element




- **Ambiguity Resolution**
  - Ambiguity resolution step also deployed
    - Resolve overlaps among tracks and reject low-quality candidates
    - Alternative approaches (e.g. ML-based algorithms) available in ACTS and being integrated in ATLAS

# Optimization

- **Plans for the integration into ATLAS**
  - Aiming at a complete demonstrator by the end of this year, i.e. finalize integration of all the required components in the reconstruction chain
  - Already starting tuning and optimization of algorithms:
    - Target: similar or faster execution time than current ATLAS software counterparts, while achieving same or better physics performance
  - Track finding as an example case

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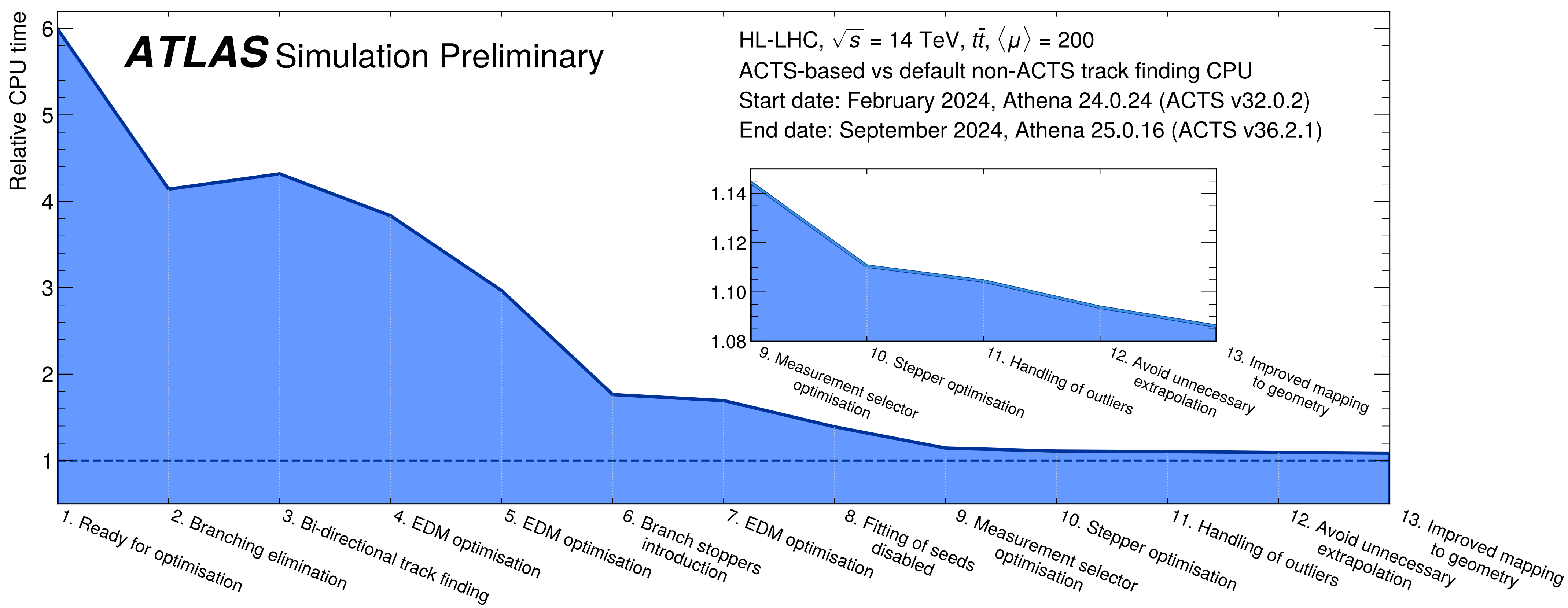


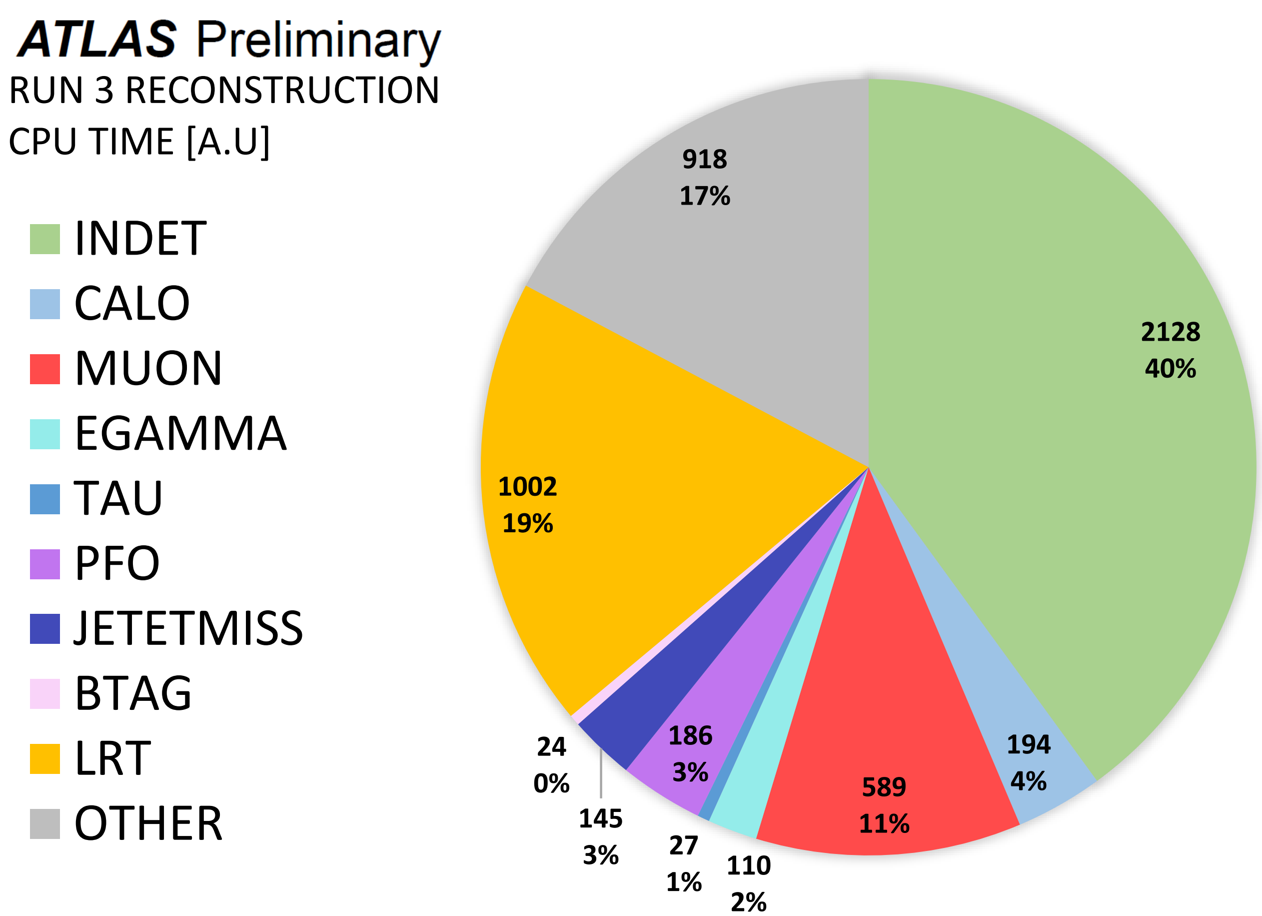
# Conclusions

- **Use ACTS for HL-LHC track reconstruction**
  - Challenging environment due to running conditions
  - New detector will be installed, with extended pseudo rapidity coverage and higher granularity
  - We need modern and maintainable software

- **ATLAS Track reconstruction software for HL-LHC**
  - ACTS as track reconstruction software for Track Reconstruction in HL-LHC
    - Ensures long-term maintainability of the software
    - CPU improvements all across the board
  - Full ACTS-based reconstruction chain now available in ATLAS
    - Now implementing the last remaining components
    - Vertex reconstruction with ACTS already deployed for Run 3 data-taking period
  - Promising performance already
    - The upcoming optimization campaign will improve this further

# Back-Up Slides

# Tracking CPU Time




ATL-PHYS-PUB-2021-012

- Fraction of the total CPU requirement for full ATLAS reconstruction split by domain for Run 3 for one data run at $\langle\mu\rangle = 50$

# The ACTS Toolkit

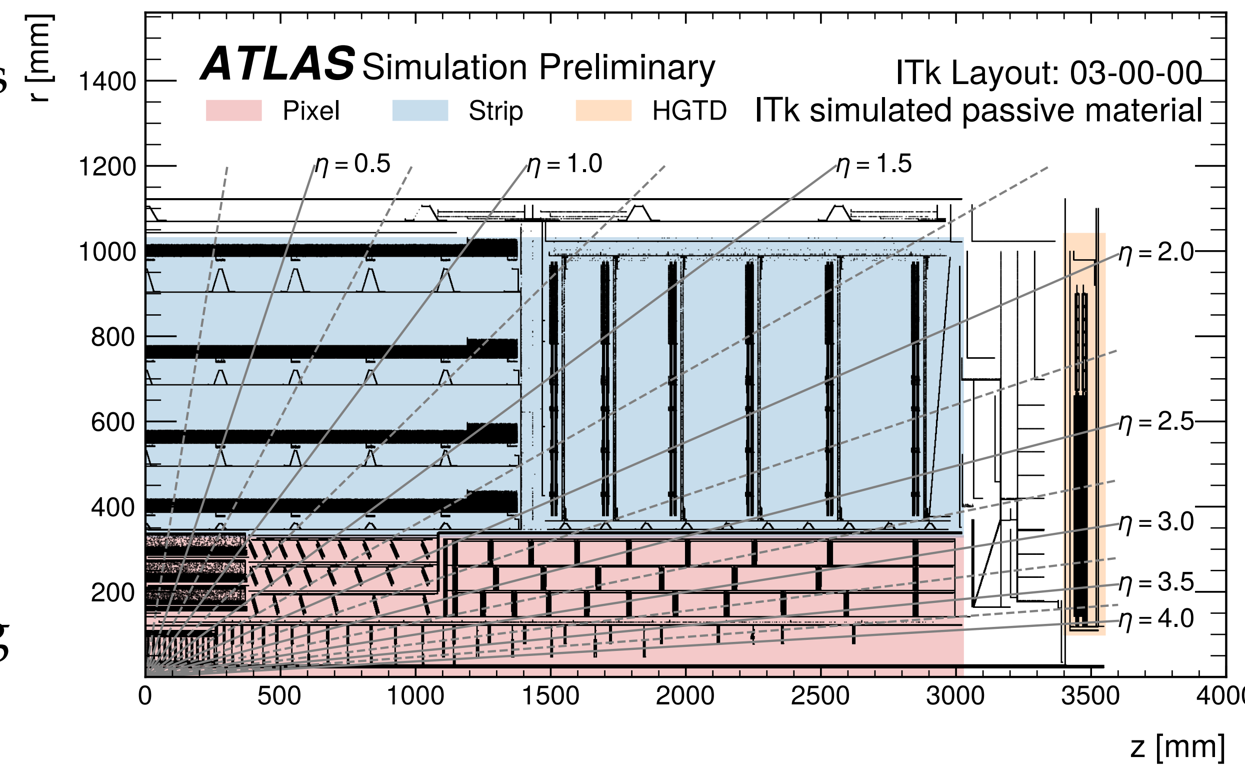
- **Use by experiments**
  - Used in physics data taking by **ATLAS, FASER, sPHENIX**
  - Under consideration by 8 experiments
  - Initial studies from:
    - **FCC**: Need person power for proper key4hep integration
    - **Belle-II**: Had technical issues in past with geometry description, now solved

From A. Salzburger's presentation at ACTS Developer Workshop 2023

# An Upgraded Detector

- **All silicon-based detector: Inner Tracker (ITk)**
  - Strip detector: 4 barrel layers + 12 endcap disks
  - Pixel detector: 5 barrel layers + inclined and vertical rings
- Achieve minimum of 9 precision measurements per track, with an extended pseudo-rapidity coverage ($|\eta| < 4.0$) and higher granularity than current detector

- High Granularity Timing Detector (HGTD), covering $2.6<|\eta|<4.0$, adding timing information to improve vertex resolution for forward tracks

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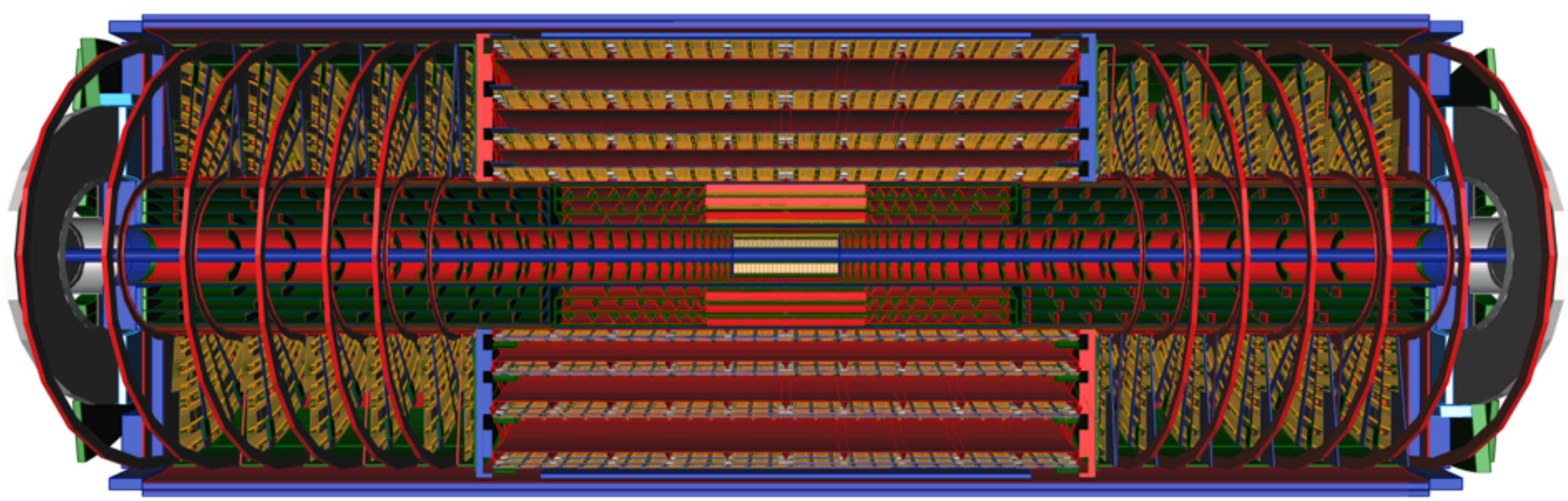
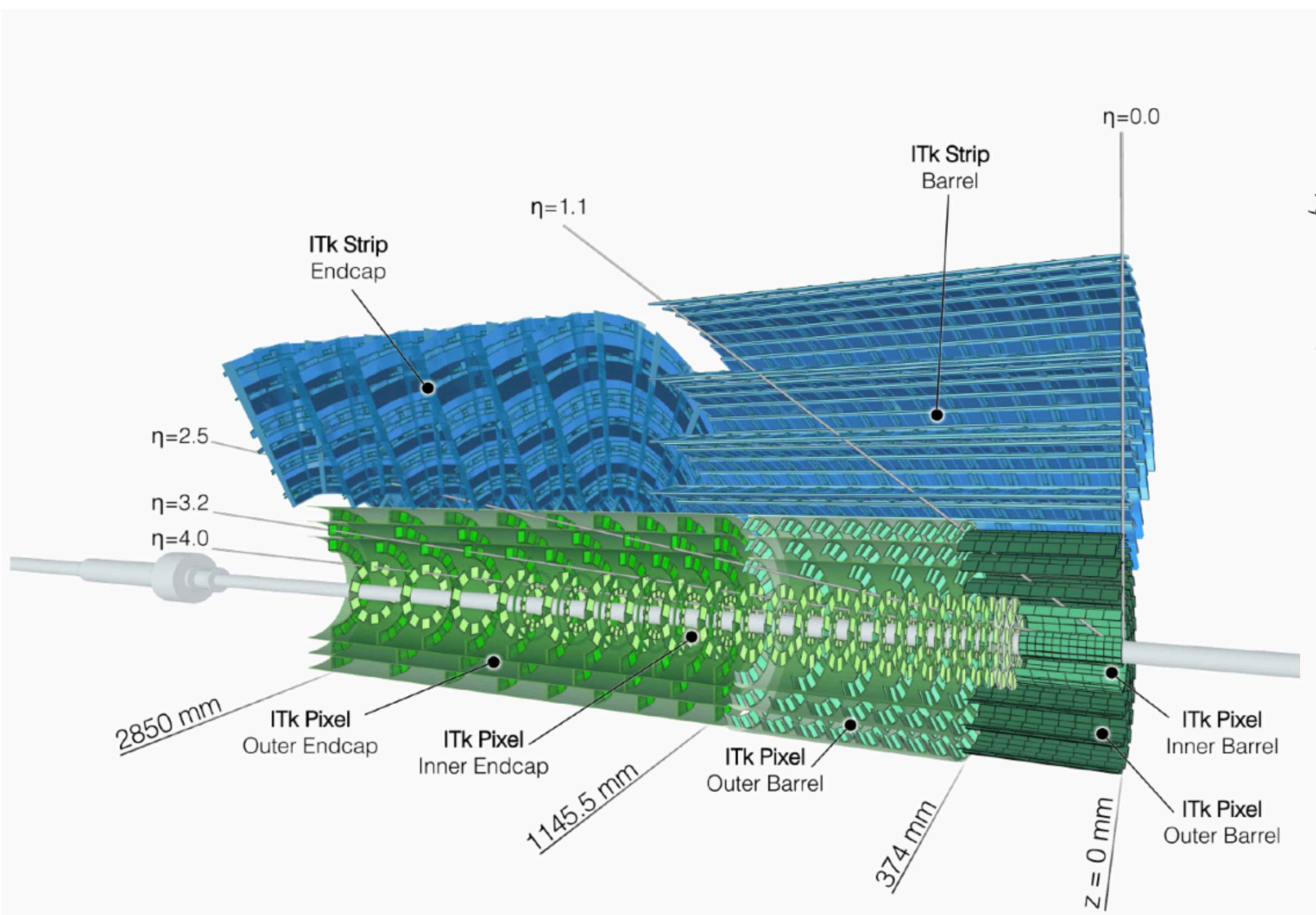
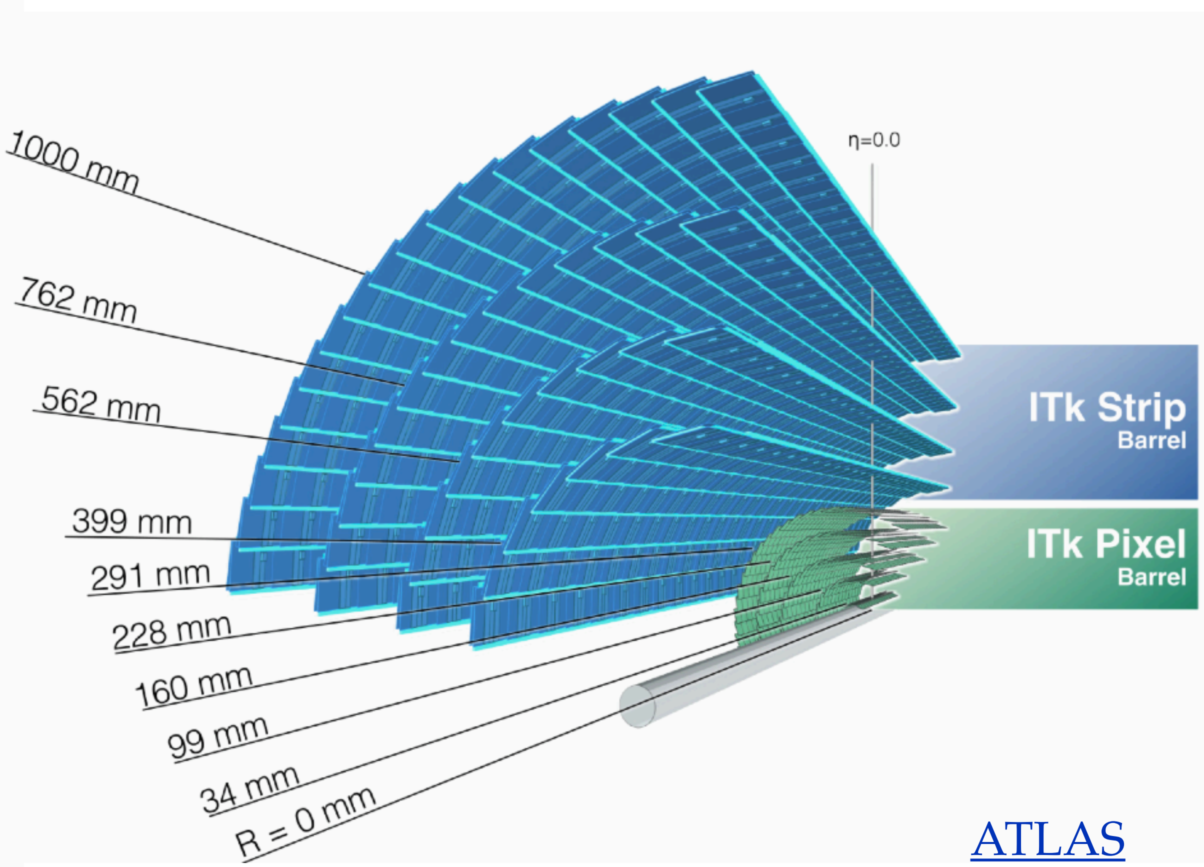


# ACTS description of the ITk detector

- **ACTS description of the ITk detector**
  - ATLAS ITk geometry description has been converted to an ACTS representation (using ACTS objects e.g. surfaces, layers) and fully integrated in Athena
    - Used by ACTS algorithms
  - Both Geometry and material maps are automatically kept in sync with non-ACTS description from ATLAS



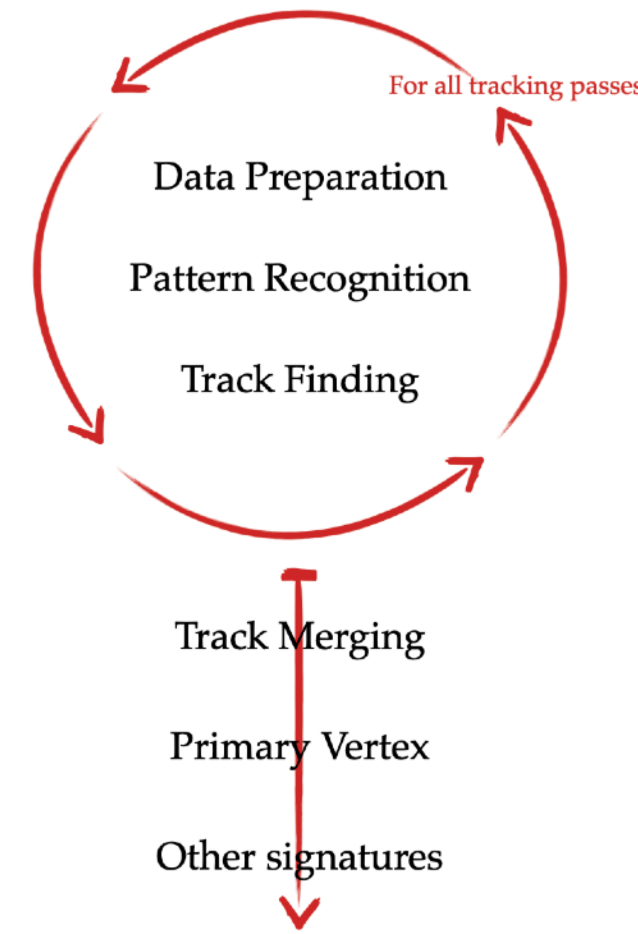



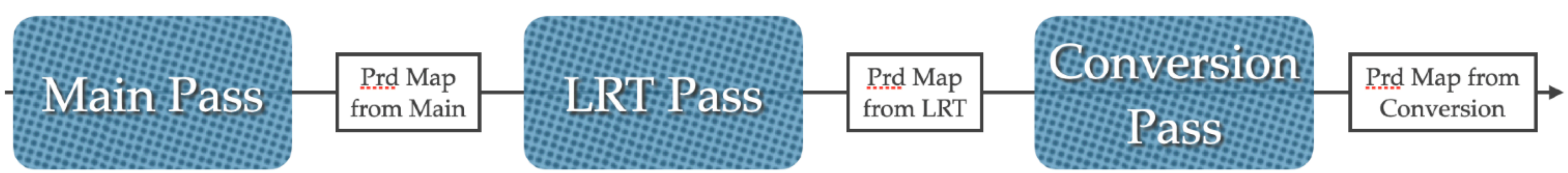

[ATLAS Schematics]

# ATLAS Track Reconstruction

- **Different tracking passes**
  - Tracking sequence is run multiple times with different purposes!
    - Conversion Tracking: tracks from photon conversion
    - Large Radius Tracking: tracks displaced from primary vertex
    - Low pT Tracking: low momentum tracks (< 1 GeV)
  - Each pass removes clusters used by previous passes with a dedicated mechanism

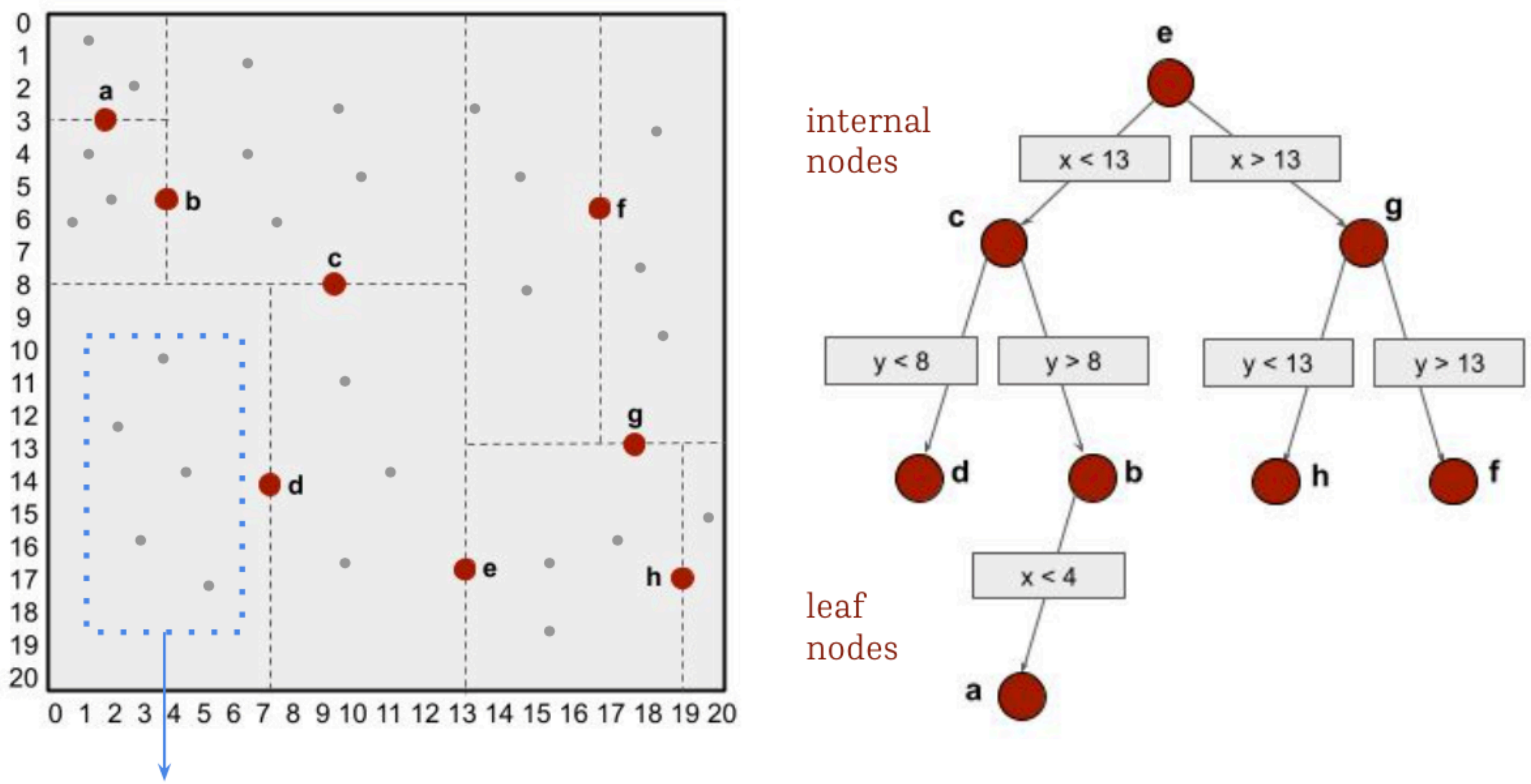
- Resulting tracks may be combined together for downstream processing for reconstruction of other objects



# Seed Finding

[Luis Falda Coelho @ CTD 2023]




Bounding Box: smallest box that contains all points within that node

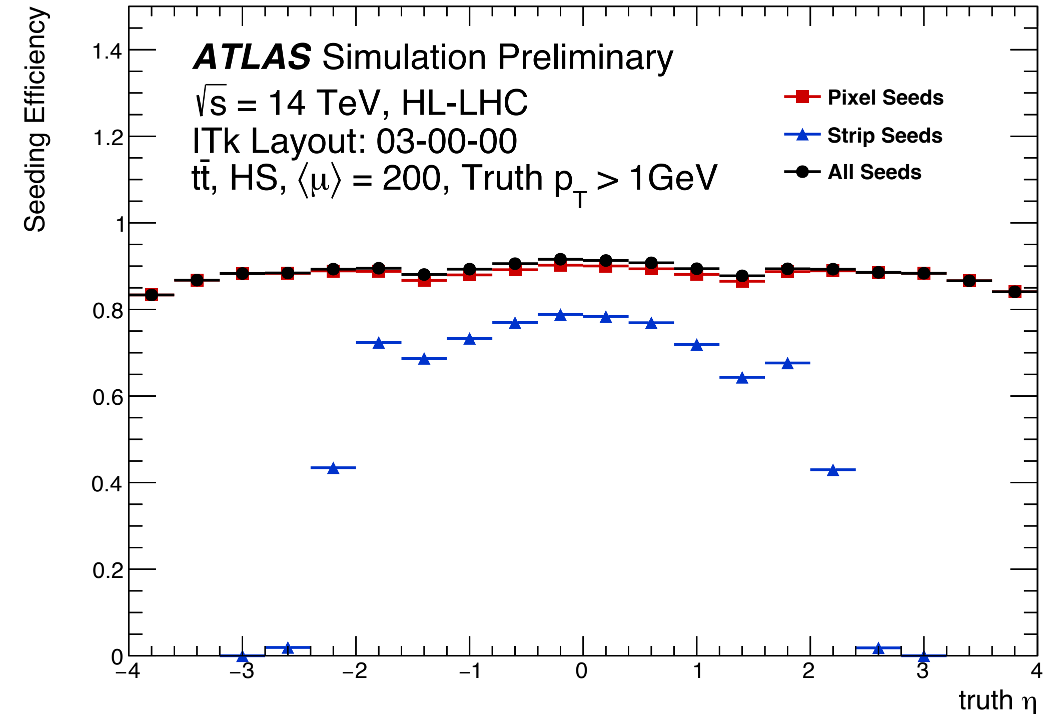
- **Alternative seeding algorithms are available**
  - Orthogonal seeding, using k-d trees
    - Partitions data into a k-dimentional space
  - ML-based seeding algorithms, e.g. GNN-seeding
  - Dedicated implementations for GPUs

# Expected Performance

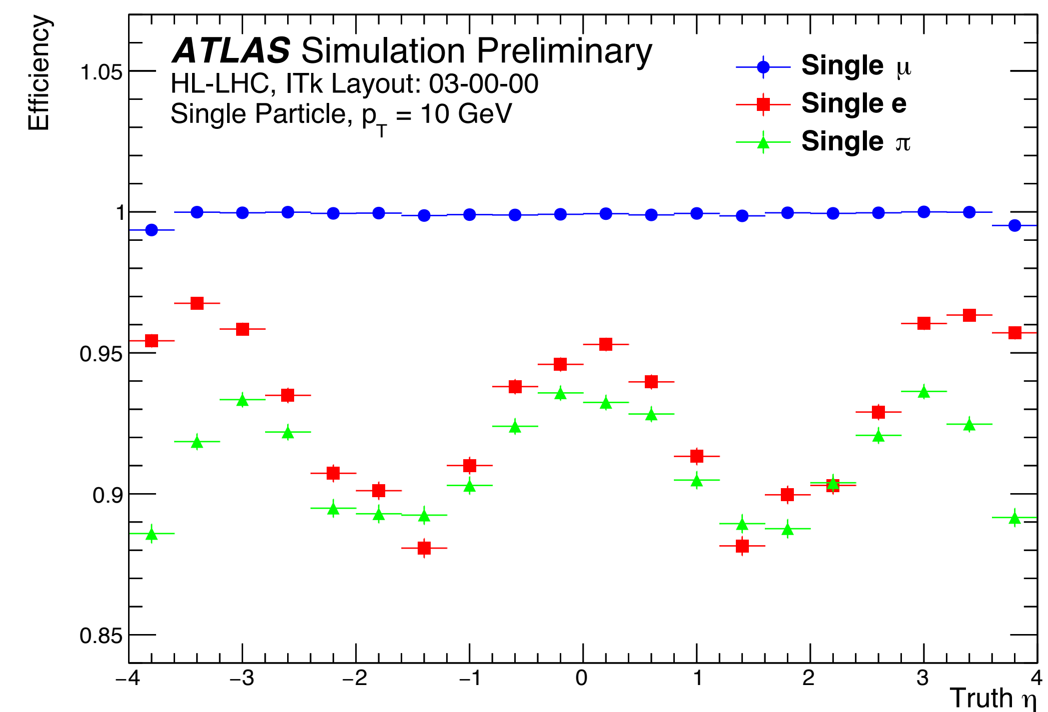
IDTR-2023-05

- Expected performance of ITk track reconstruction (without ACTS)

- **Seed Finding**
  - Seeding efficiency as a function of the pseudo-rapidity. The independent pixel-only and strip-only seeding efficiencies are shown, in addition to the combined seeding efficiency.



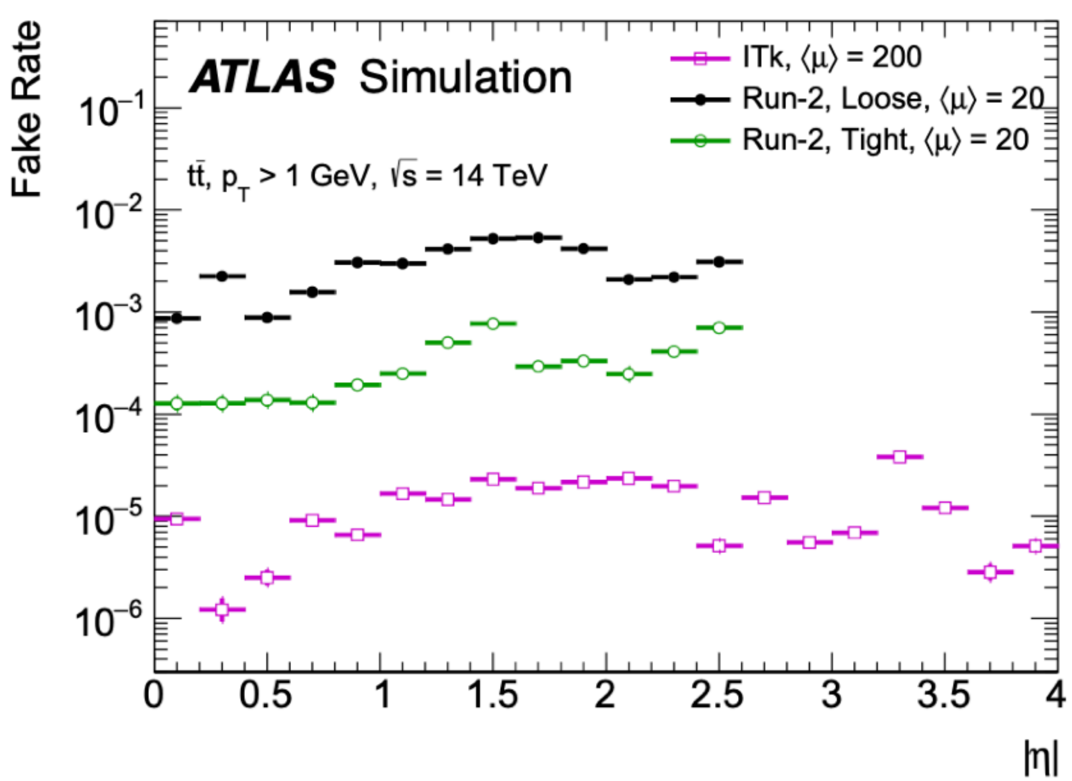

- **Combinatorial Track Finding**
  - Tracking efficiencies for muons, electrons and pions at $p_T = 10$ GeV. The efficiency is defined as the number truth particles with at least one reconstructed track matched to them, divided by the total number of truth particles. A track is considered matched if the matching probability is over 50\% for a truth particle.



# Fake Rate

- We are in the process of re-evaluating fake rate with latest ITk geometry: soon to be public

ATLAS-TDR-030 (ITk TDR 2018)

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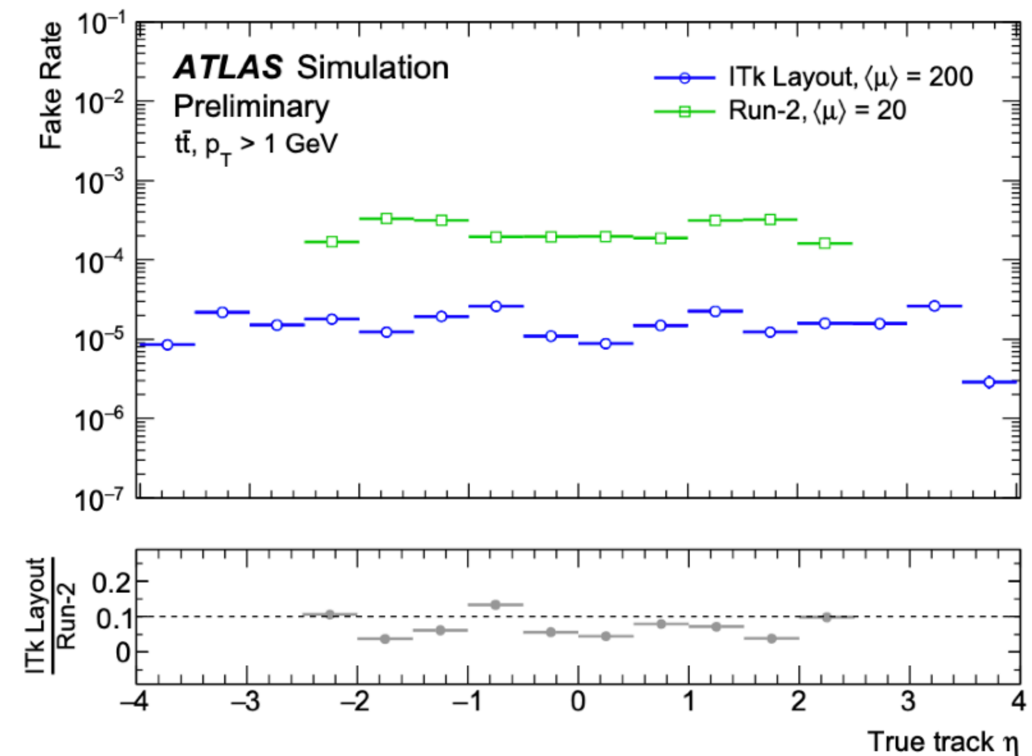

# Vertex Reconstruction

- **Experience with ATLAS already encouraging**
  - ATLAS is already using ACTS right now in Run 3
    - Athena vertex algorithm (AMVF) has been rewritten in ACTS
    - A necessity for high pile-up conditions
    - ACTS vertex finding algorithm is the default implementation for Run-3
  - Comparison with non-ACTS vertex finding algorithm shows 40% improvement in computing time
    - Physics performance unchanged!

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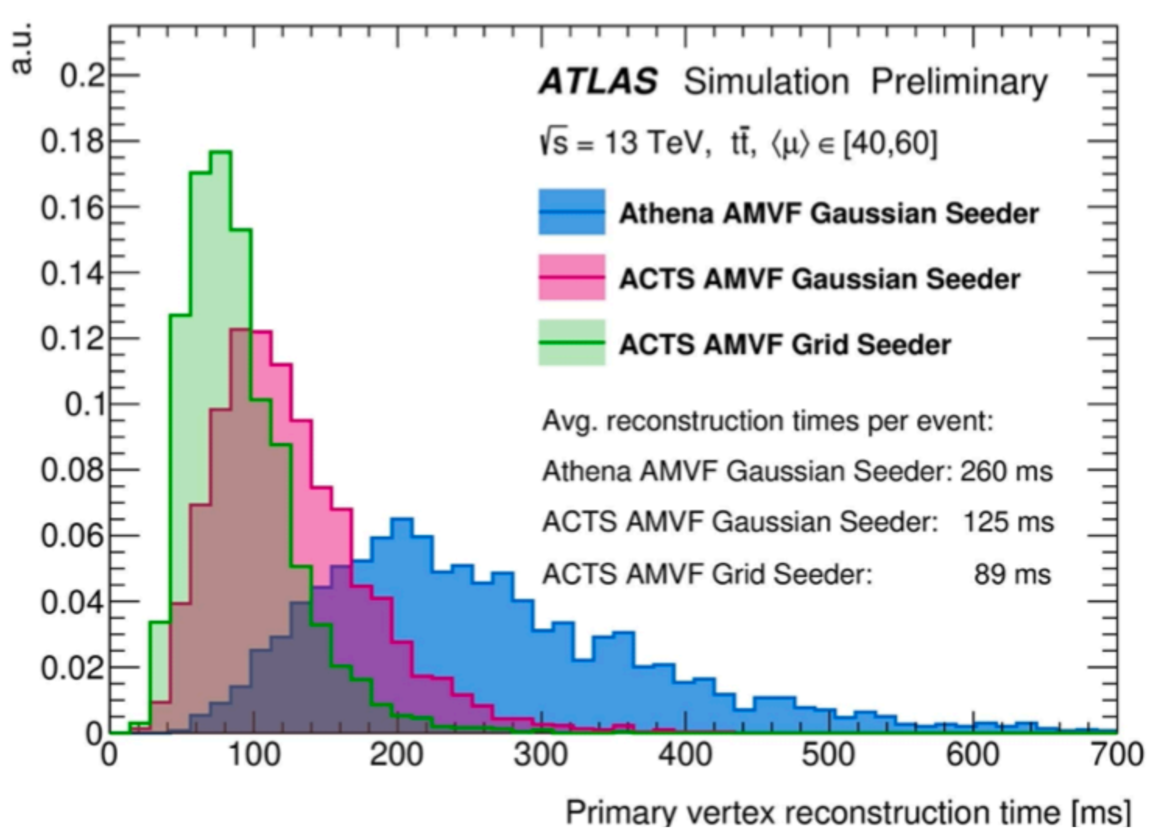
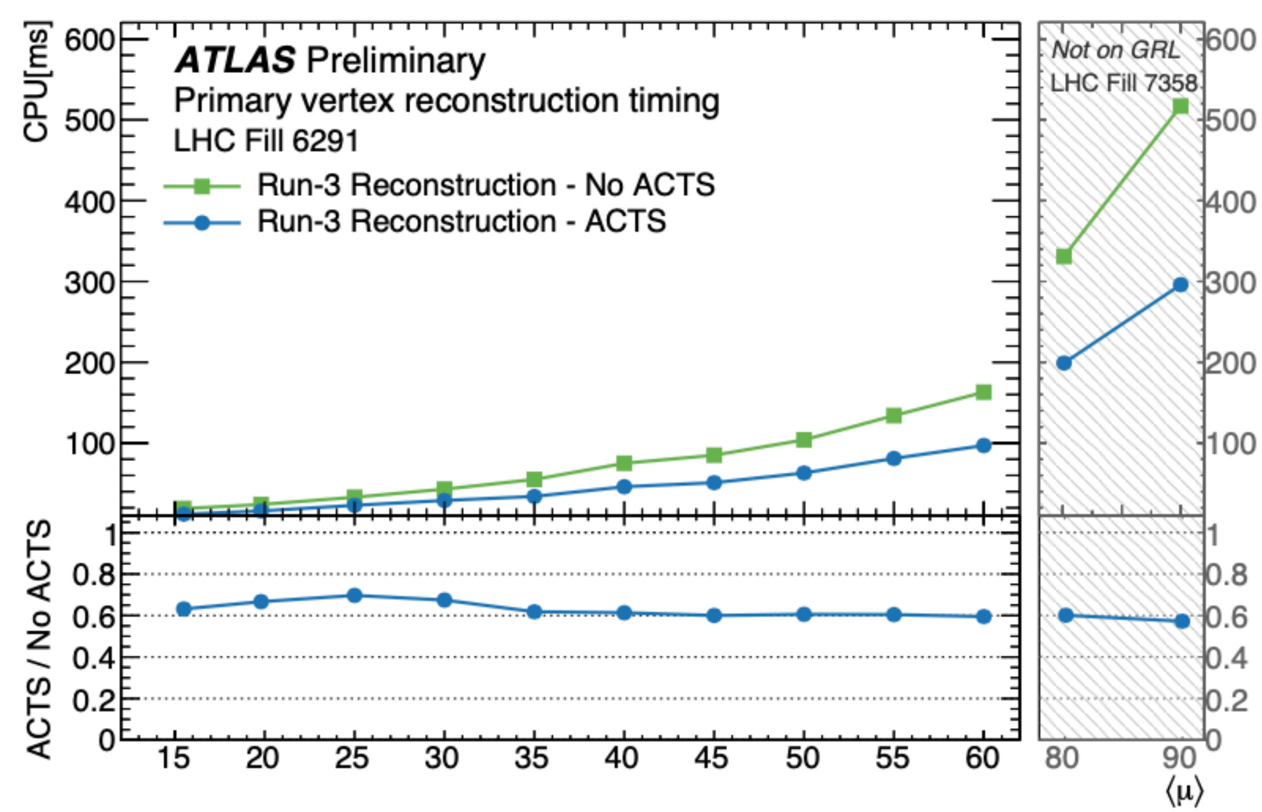
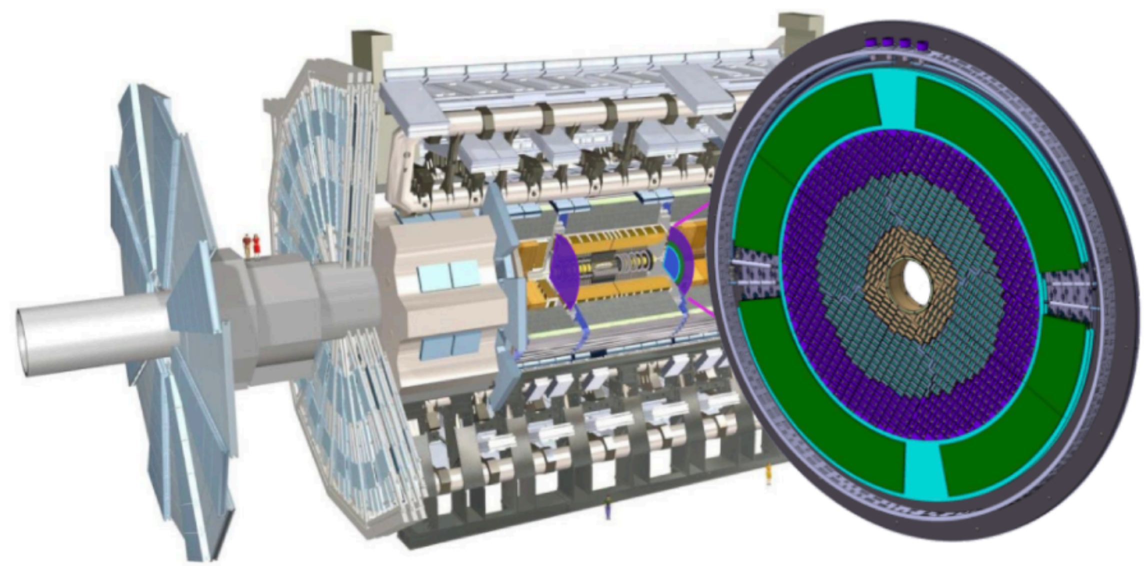
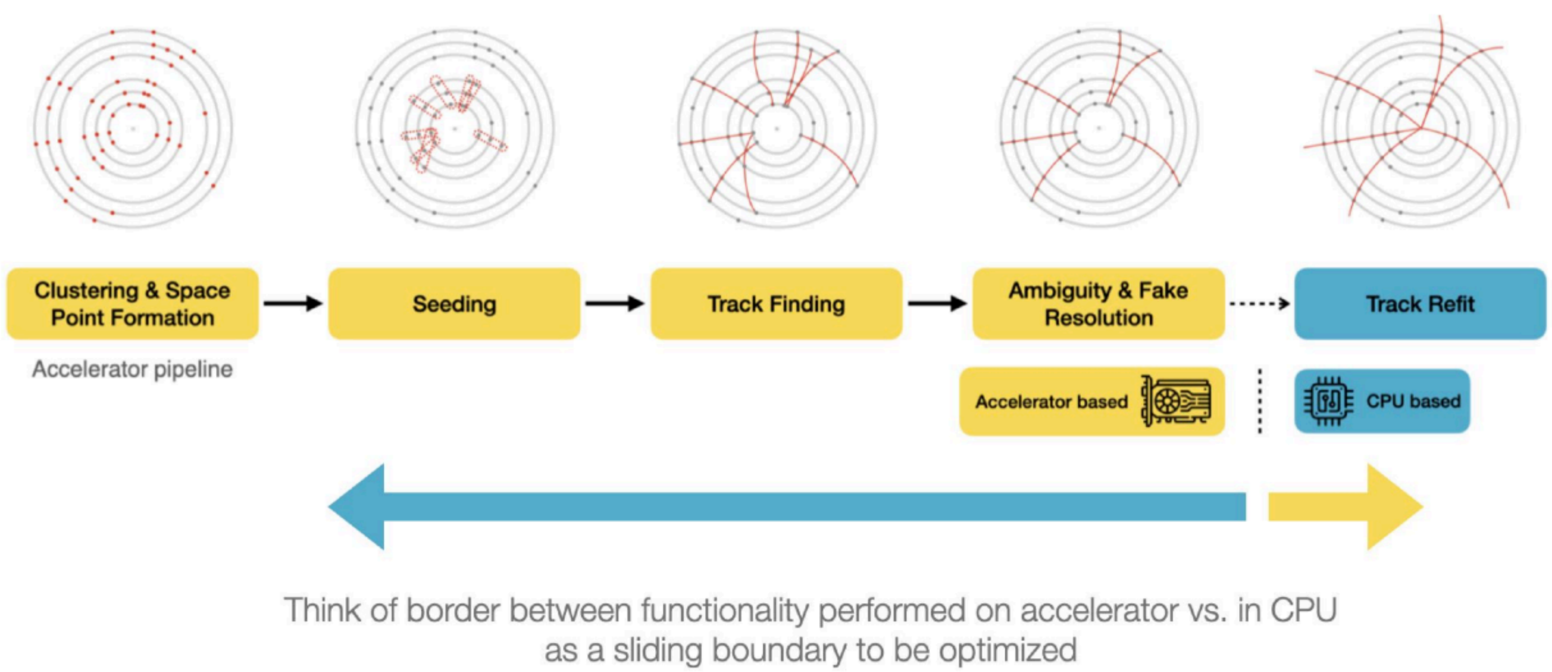


# ACTS Integration in ATLAS

- **ACTS integration also extends to multiple areas**
  - Extension of ACTS framework to HGTD
  - Muon and e-gamma Reconstruction
  - Trigger and Event Filter (EF) Tracking

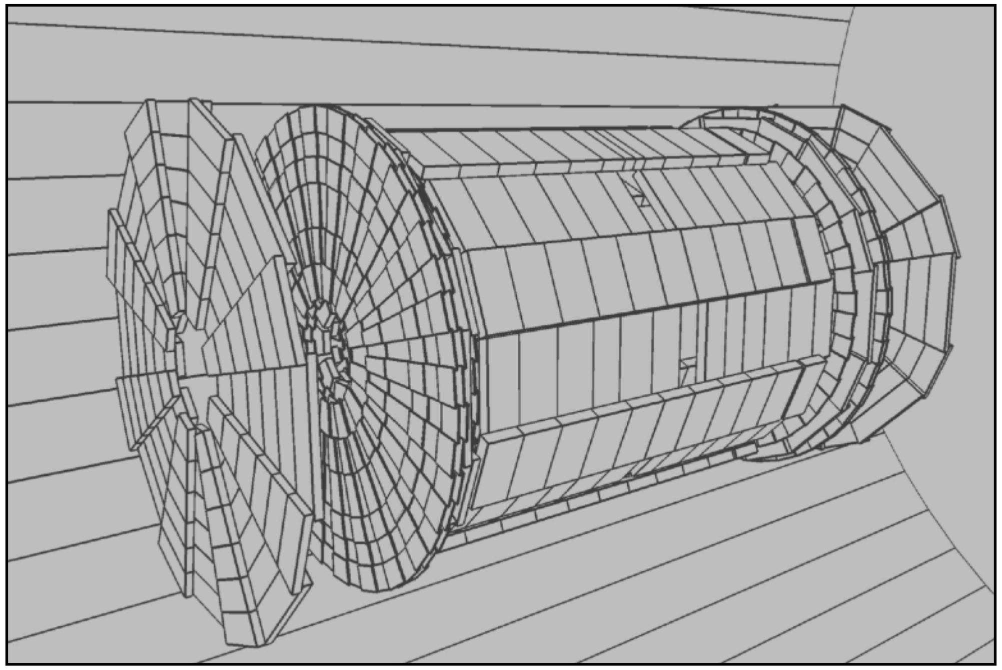





- **ACTS for Track reconstruction with accelerators**
  - Dedicated R&D Line for Track Reconstruction on GPUs: traccc
  - Exploring heterogenous systems

# ACTS in Muon Reconstruction

- **ACTS also deployed for Muon reconstruction**
  - A complete rewrite of the geometry and tracking code for HL-LHC
  - Reimplement the tracking geometry, navigation and redesign of EDM
  - Reconstruction strategy has been revised as well
- Different technologies involved, e.g. drift chambers



- **Pattern recognition with Hough Transform from ACTS**
  - Hit in detector space → one (or multiple) lines in a parameter (sub-)space
  - Fill Hough histogram as a function of track parameters (suitably binned)
  - Seed candidates as maxima in the Hough histogram

$$y_0(\tan\vartheta) = y_{tube} - \tan\vartheta \times z_{tube} \pm r_{Drift}\sqrt{1+\tan(\vartheta)^2}$$