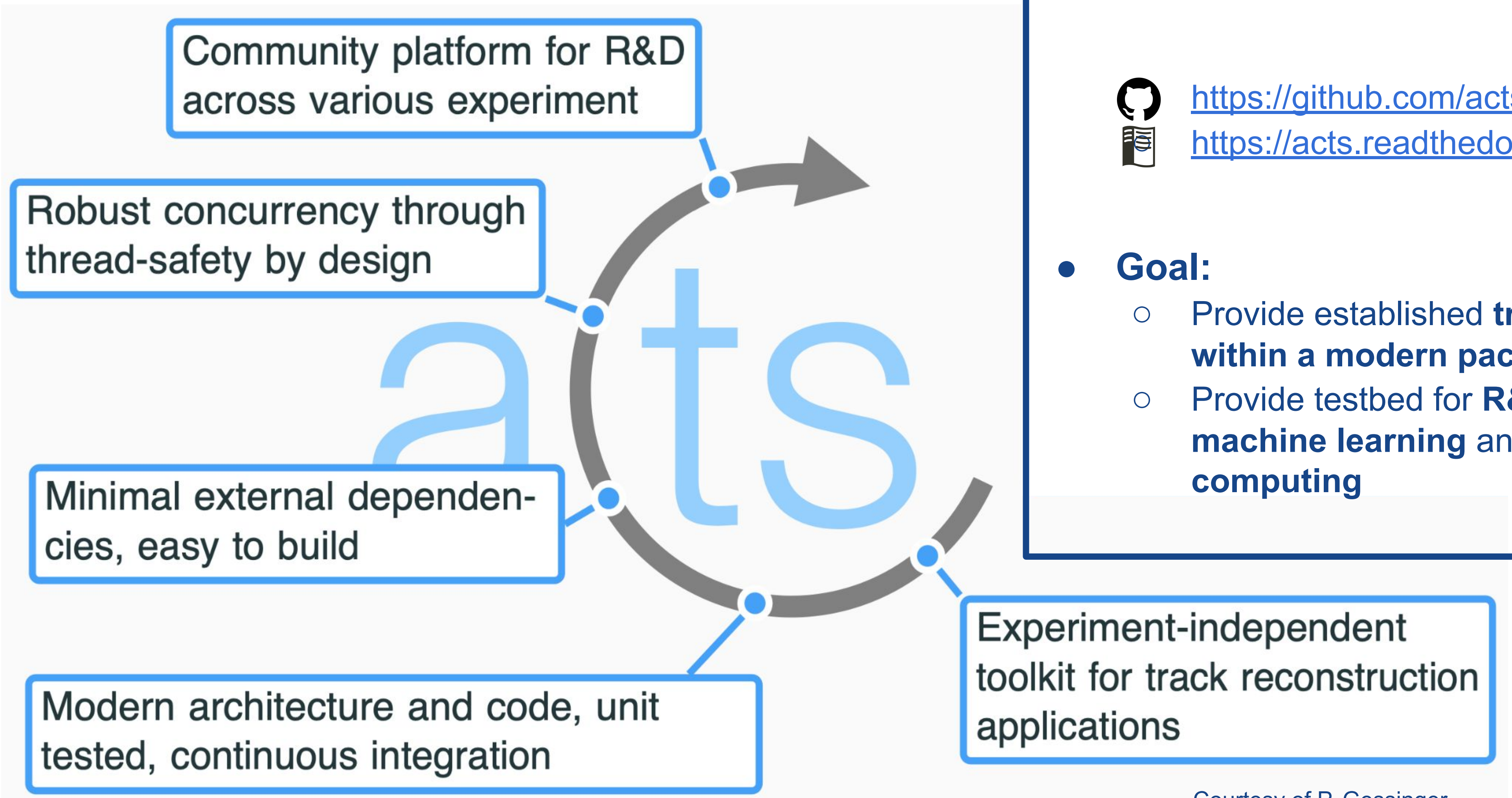
4D Tracking and Vertexing with ACTS

PF,
in collaboration with
V. Cairo, A. Swartzman, L. Santi, A. Stefl, P. Gessinger

CERN | NexTGen Next Generation Triggers | ATLAS EXPERIMENT

COMETA workshop
21 February 2025

What is ACTS?



Courtesy of P. Gessinger

- **A Common Tracking Software (ACTS) is**
  - An open-source library written in modern C++

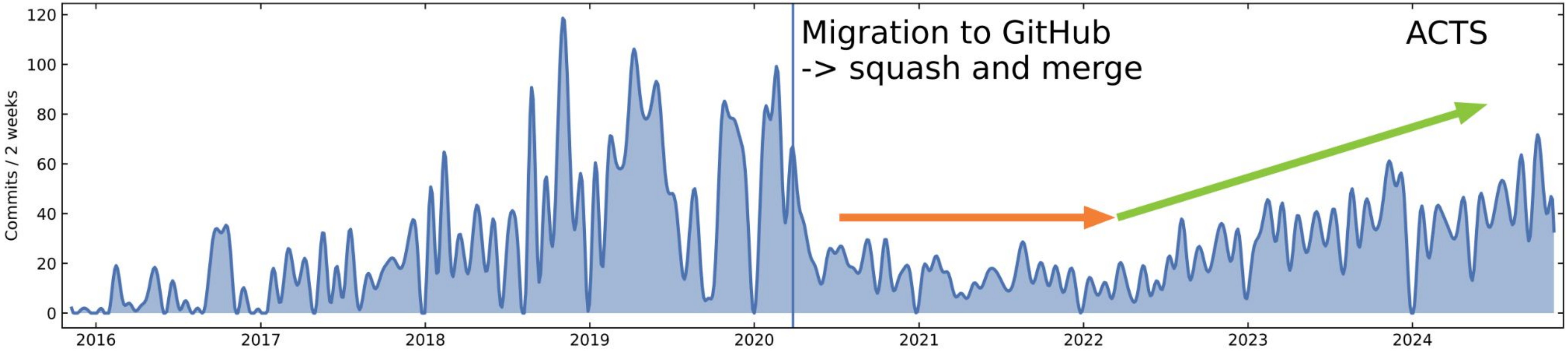
https://github.com/acts-project/acts
https://acts.readthedocs.io/en/

- **Goal:**
  - Provide established **tracking algorithms within a modern package**
  - Provide testbed for **R&D activities**, **machine learning** and **heterogeneous computing**

ACTS, Ai et al '22

ACTS current activity

Courtesy of P. Gessinger

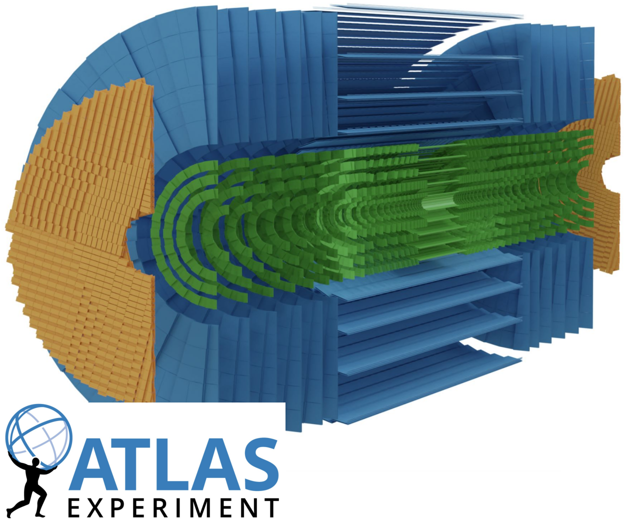


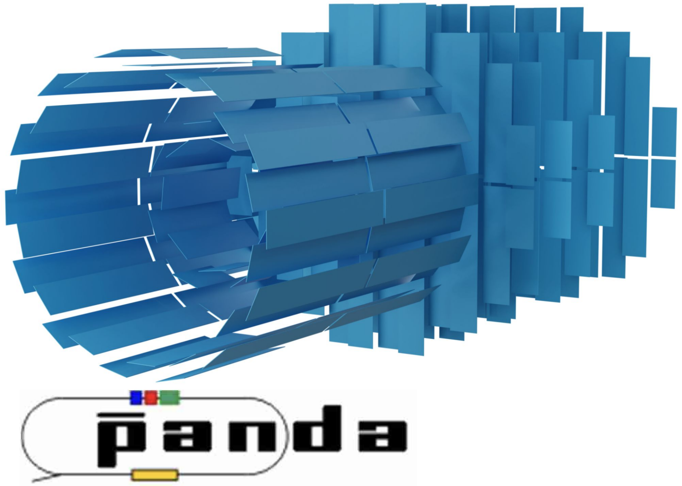
ACTS Workshop '24

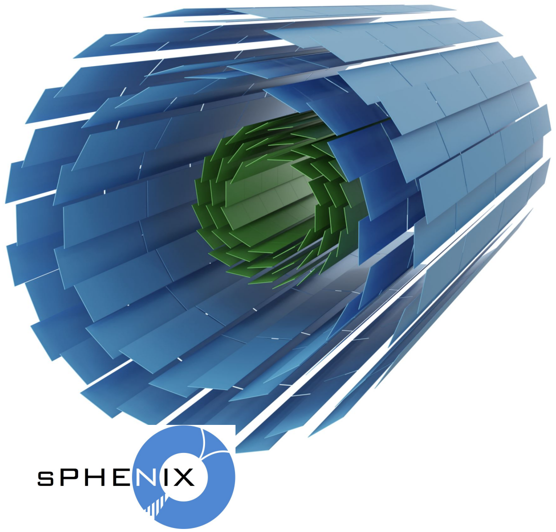
- Project is approaching **10 years of lifetime**
- **Very active and growing community** of developers
- 39 releases, 40+ contributors from multiple experiments

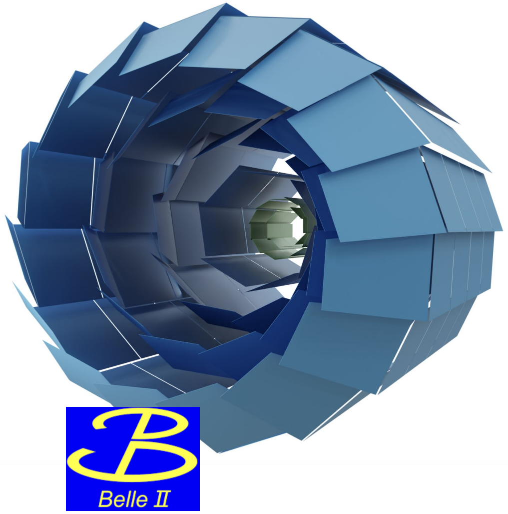
ACTS, Ai et al '22

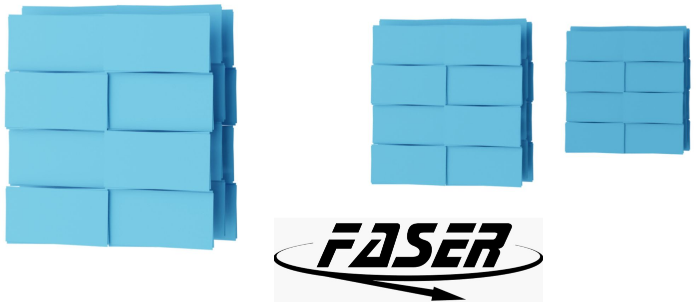
Deployment on experiments

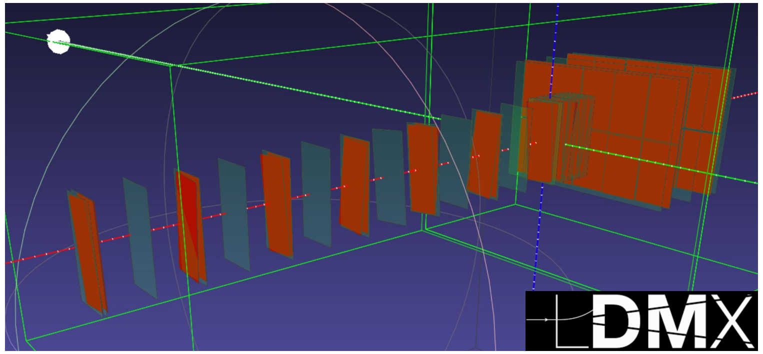


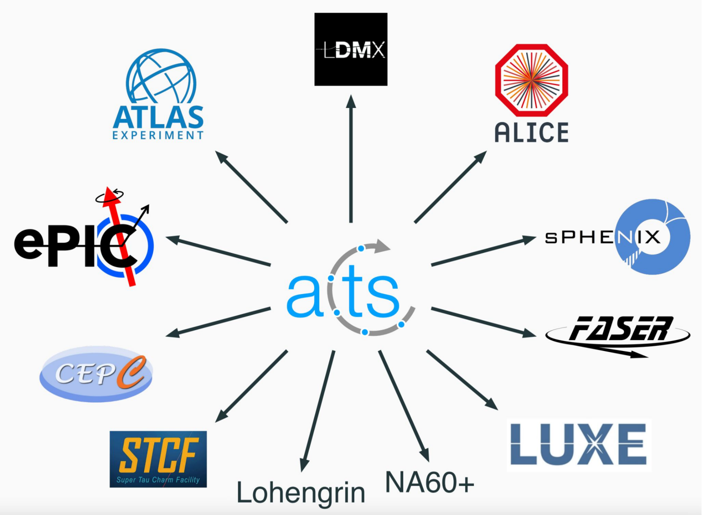








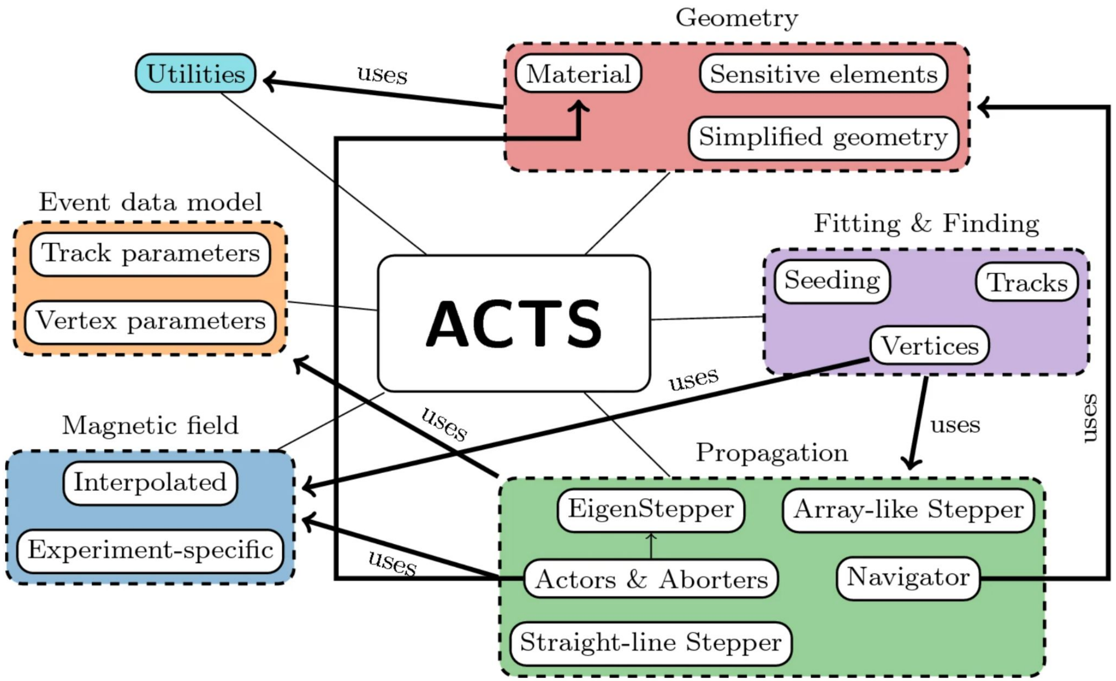


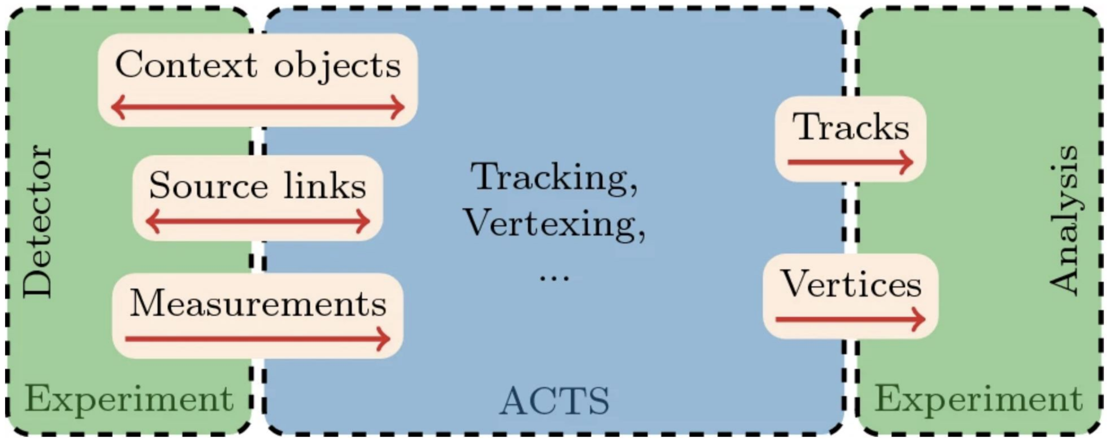


The ACTS Library

- **The ACTS library is made of two main packages**
  - **Core**: collection of algorithms and components to build a tracking algorithm to be exported and used in a specific experiment reconstruction framework
  - **Examples**: standalone event generation, simplified detector interaction and track reconstruction
    - Not intended to be used directly by experiments for reconstruction

- **The library can be extended via dedicated Plugins:**
  - **Machine Learning** algorithms support (ONNX, ExaTrk, ..)
  - **Detector Description** packages (DD4Hep, GeoModel, …)
  - **Heterogeneous computing** (CUDA, Detray, …)

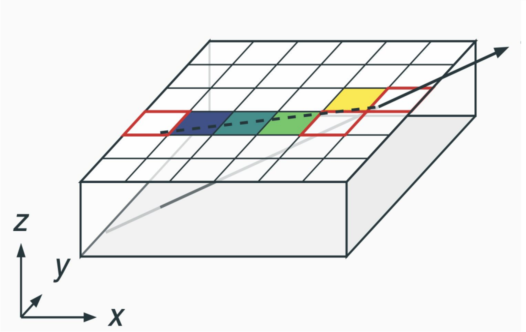


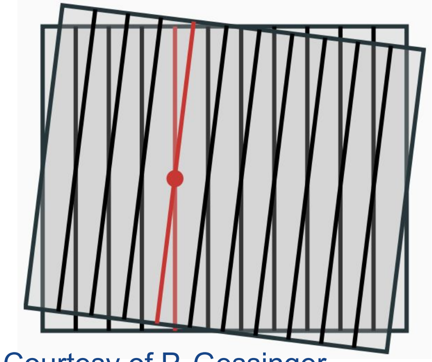


ACTS, Ai et al '22

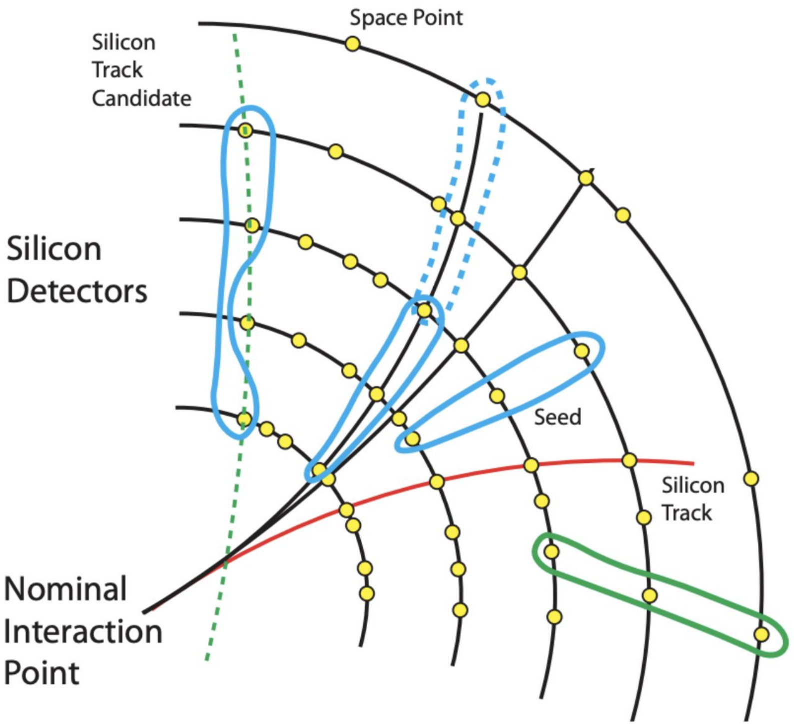
Tracking in a nutshell

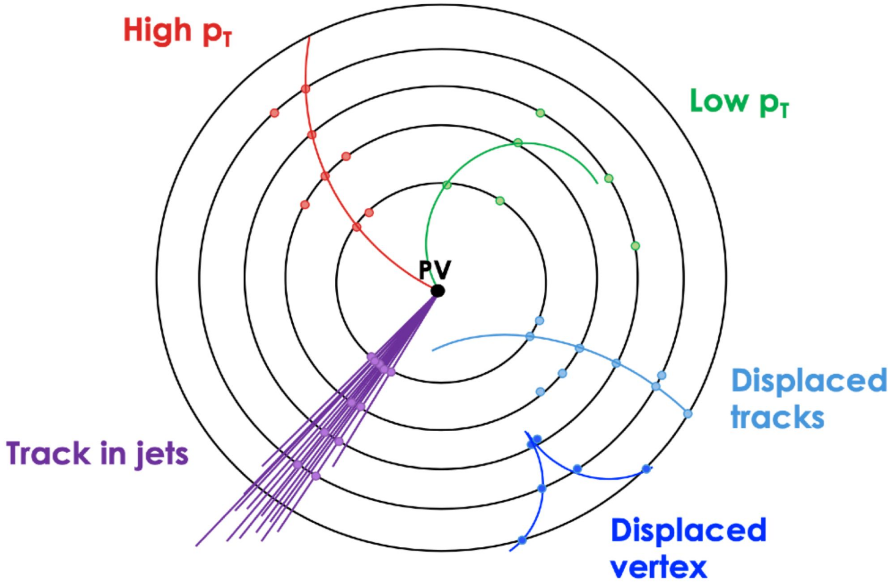
Measurements | **Track Seeds** | **CKF(*) Track Candidates** | **Ambiguity Resolution** | **Dedicated tracking passes**





Courtesy of P. Gessinger



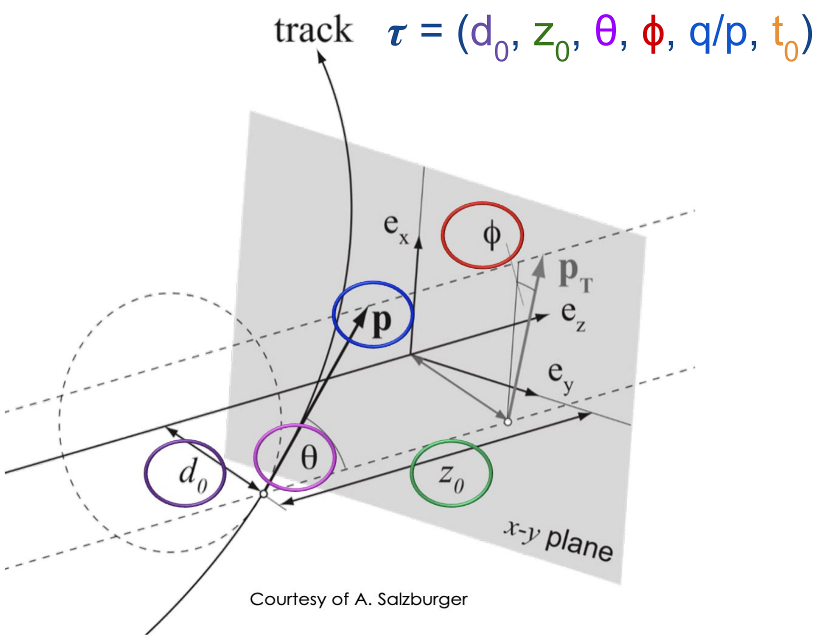


Courtesy of V.Cairo

Track parameterization in ACTS

- **Tracks in ACTS are parameterized by a 6 dimensional vector with respect a reference surface, line or point**
  - 2 impact parameters d_0, z_0
  - 2 angles θ, ϕ
  - charge over momentum magnitude q/p
  - **track time t_0**

- **This parameterization allows:**
  - Seamless **computation of track time of arrival on sensitive devices**
  - Kalman Filter step with time measurements



Courtesy of A. Salzburger

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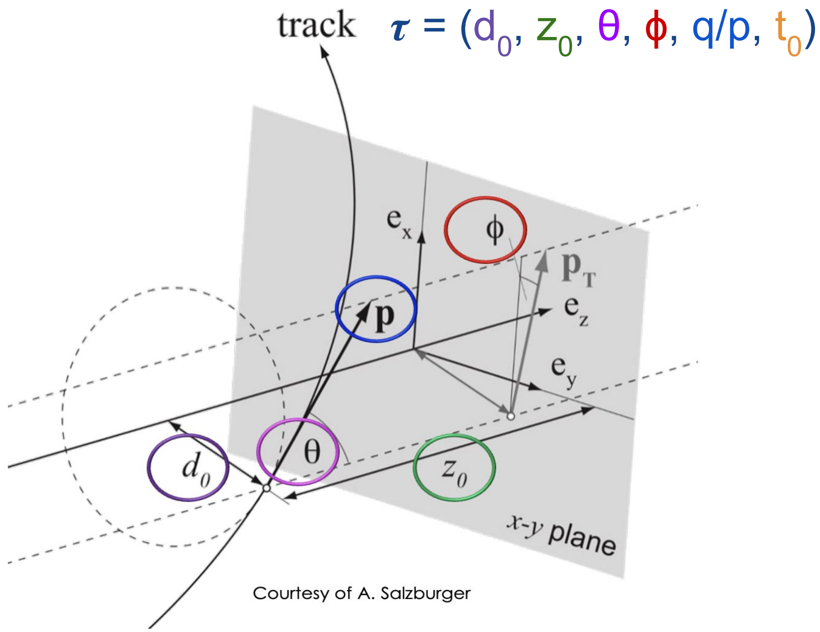
- **Possibility to easily add time measurement on devices**
  - From truth smearing, no digitization



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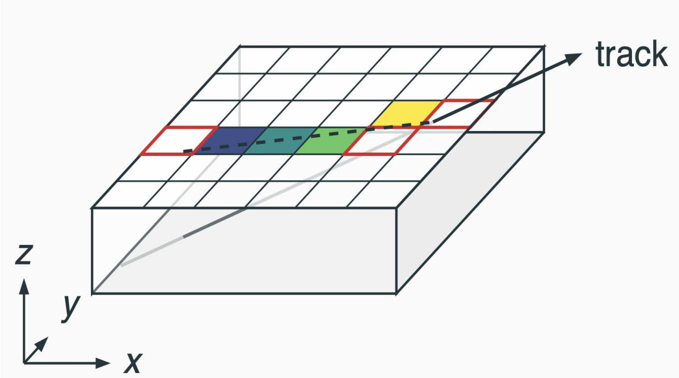
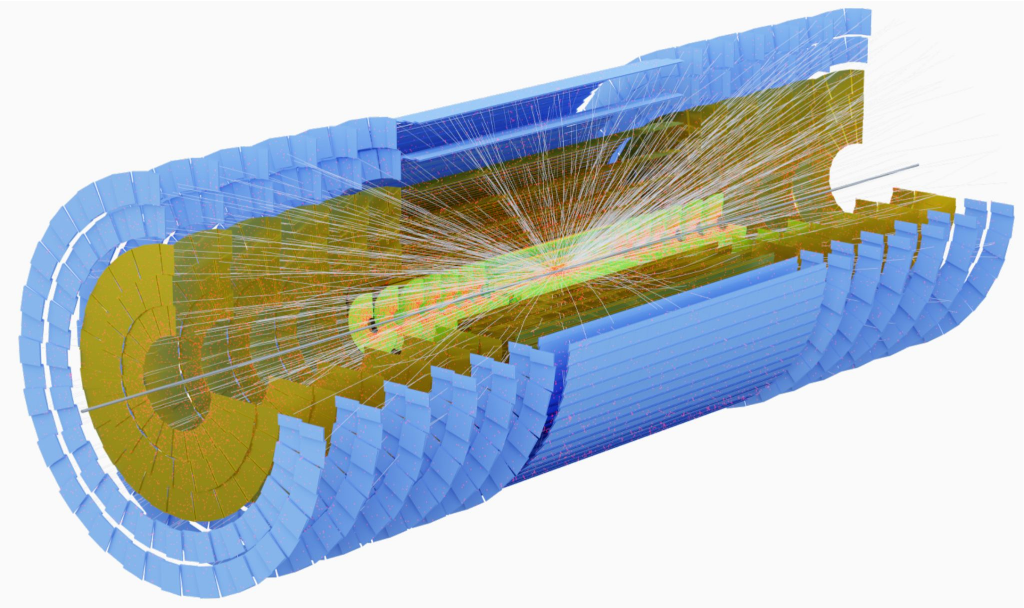


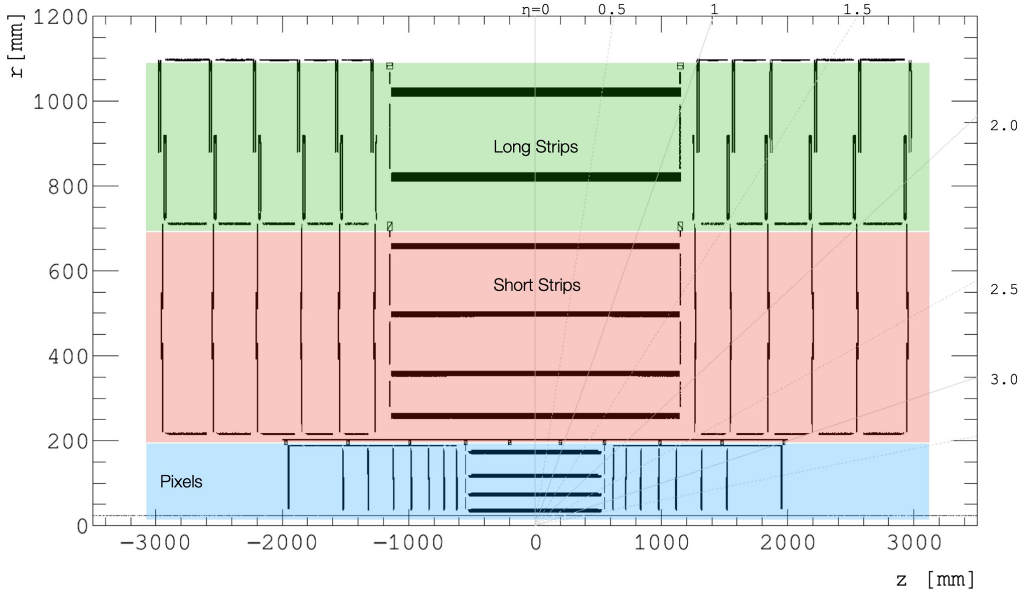
m = (X, Y) 2D

m = (X, Y, T) 3D

The Open Data Detector (ODD)

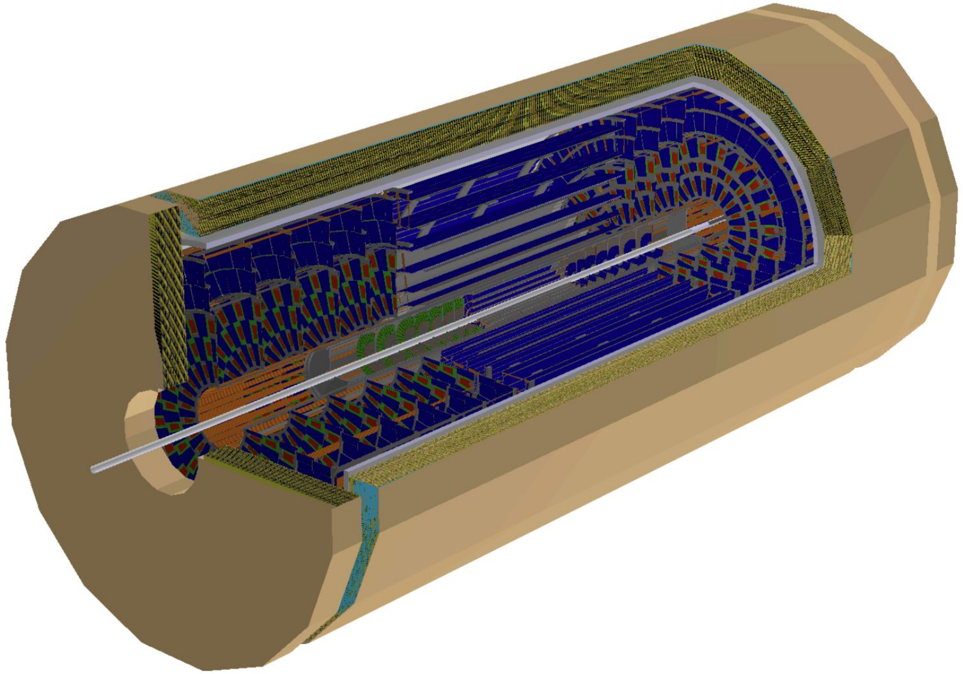


- The **Example** framework comes with a generic silicon (HL-)LHC based on **DD4Hep**
- Heavily in use in the **development of the ACTS track reconstruction toolkit**
- Basis of performance and regression monitoring of ACTS
- Plan **to produce a large Open Access Dataset to supersede the TrackML** one for tracking algorithm R&D in a more realistic environment
- No digitization support, only **hit-smearing with user-defined resolutions**

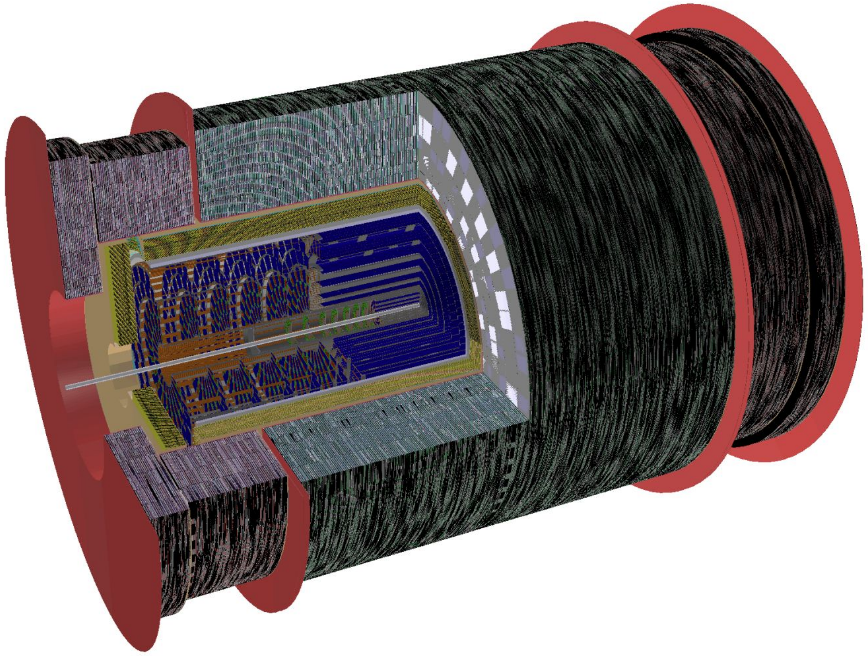


OpenDataDetector CHEP '23 ODD @ CTD '23 ODD @ ACAT 21

The ODD Extensions



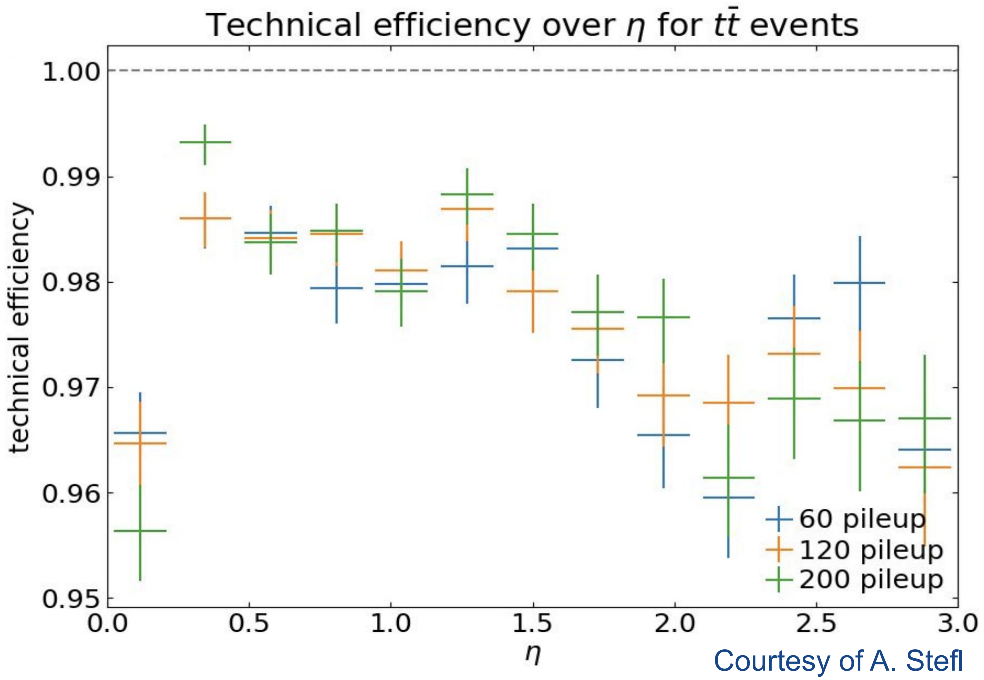
- Recently added an ODD Electromagnetic Calorimeter
  - High granularity SiW sampling calorimeter
- CALICE type, proposed for CLIC, CLD and ILD - inspired CMS HGCal



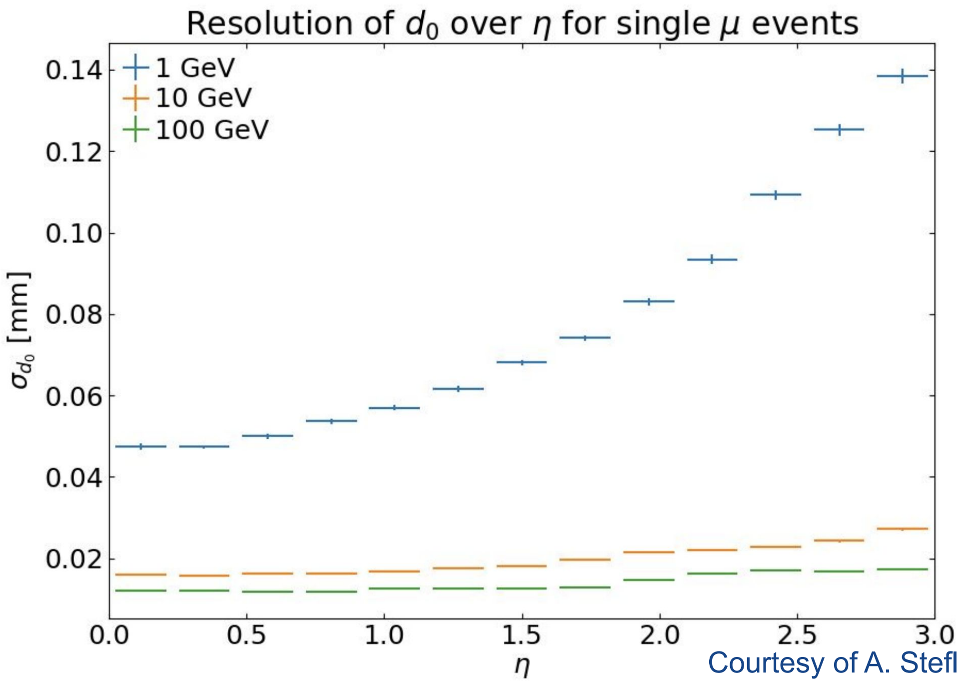
- Possible expansion with the FCC-hh Tile Calorimeter
  - derivate of ATLAS Tile Calorimeter
- Another option could be Silicon Based HCAL

OpenDataDetector   CHEP '23   ODD @ CTD '23   ODD @ ACAT 21

The ODD Tracking Performance



Courtesy of A. Stefl



Courtesy of A. Stefl

- Tracking efficiency defined as **Reconstructible Particles / Reconstructed Tracks**
- Evaluated on ttbar samples at different PU conditions as well as single particle samples
- Track parameter resolutions approach intrinsic layout resolution at high PU
- **Viable R&D platform for tracking algorithm research**

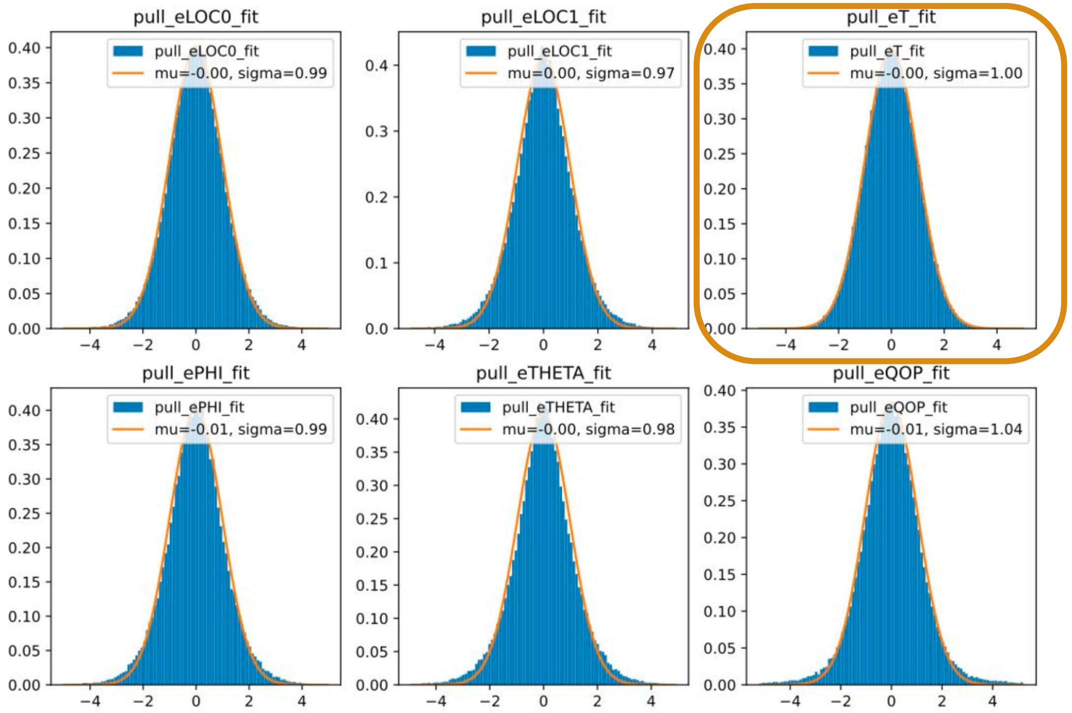
OpenDataDetector CHEP '23 ODD @ CTD '23 ODD @ ACAT 21

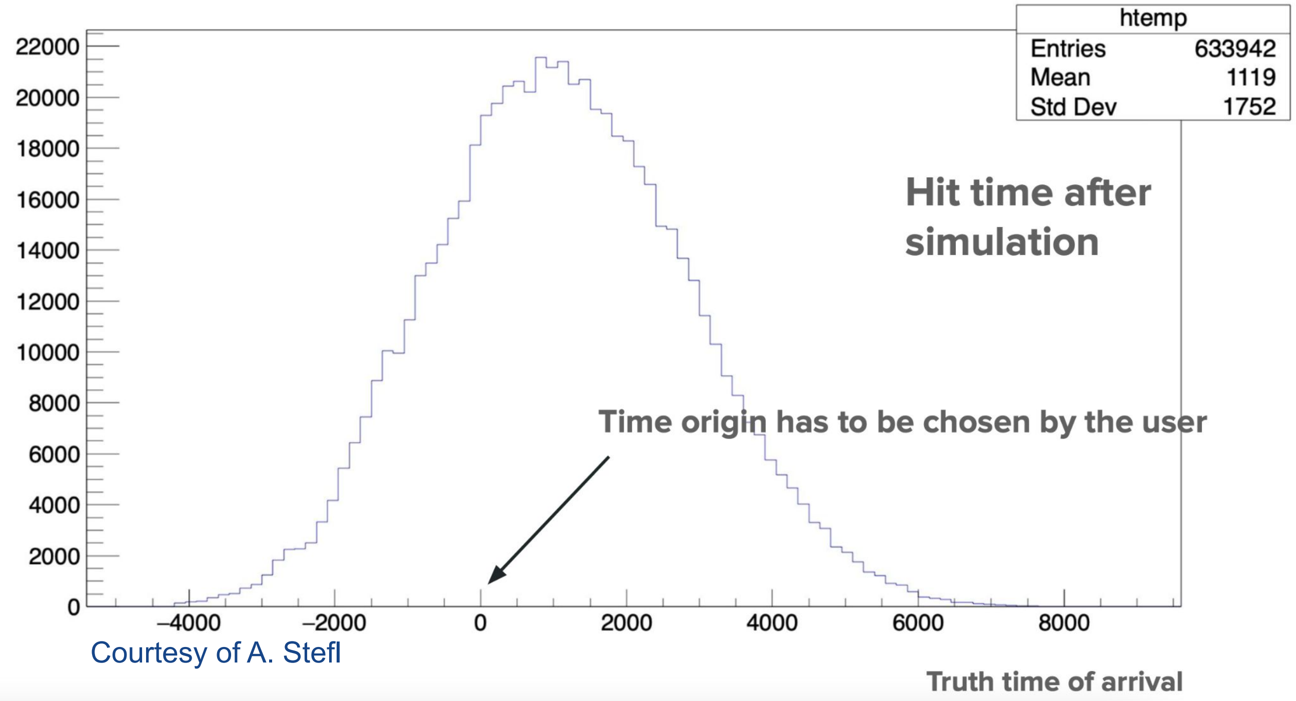
4D Track Fitting and time information in the ODD

- Track finding and fitting **can** use time information
- **Fully integrated in track propagation and filtering formalism**

- Possible to run event simulation with time
- Event Data Model and I/O already supporting time information
- **Algorithms can take time automatically**
  - Or it can be toggled to use it

Courtesy of A. Stefl

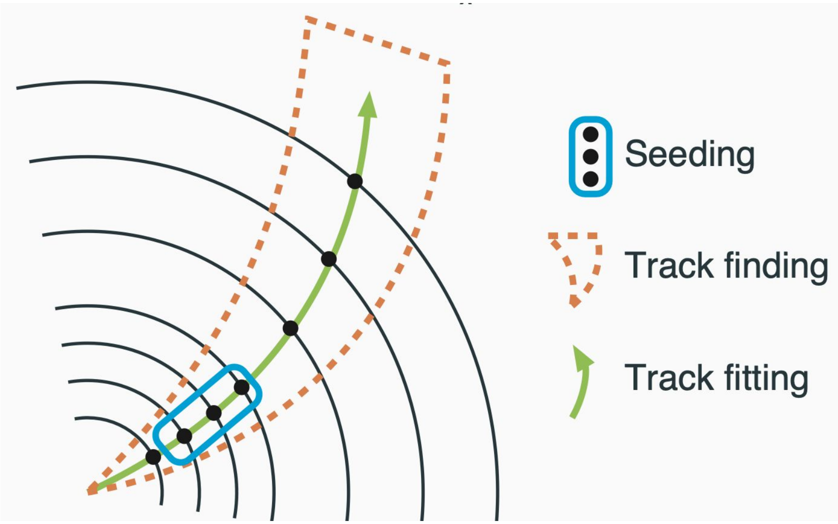


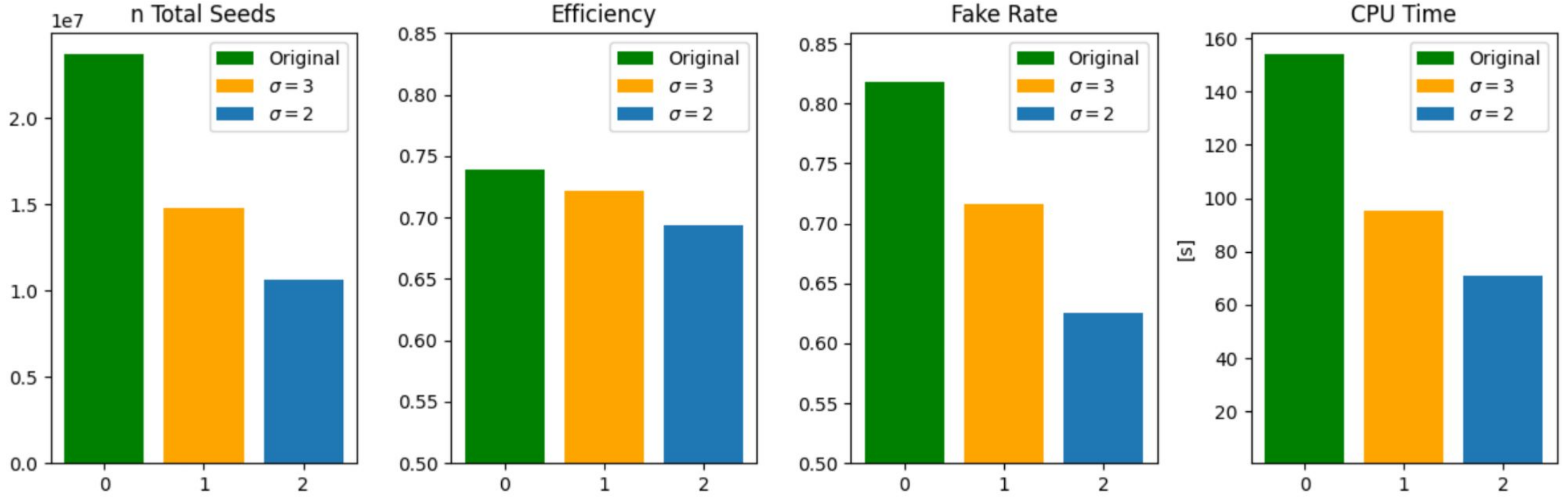


Courtesy of A. Stefl

Track seeding with timing information

- **Hit time information can be used at different stages of track reconstruction**
- **Depending on the experimental environment, seed finding is very computationally expensive**
  - High-efficiency, often low purity
- **Investigated seed finding improvement using σ=30ps time resolution in ODD, ttbar μ=200**
  - Large reduction of Fake Rate and CPU timing (*)





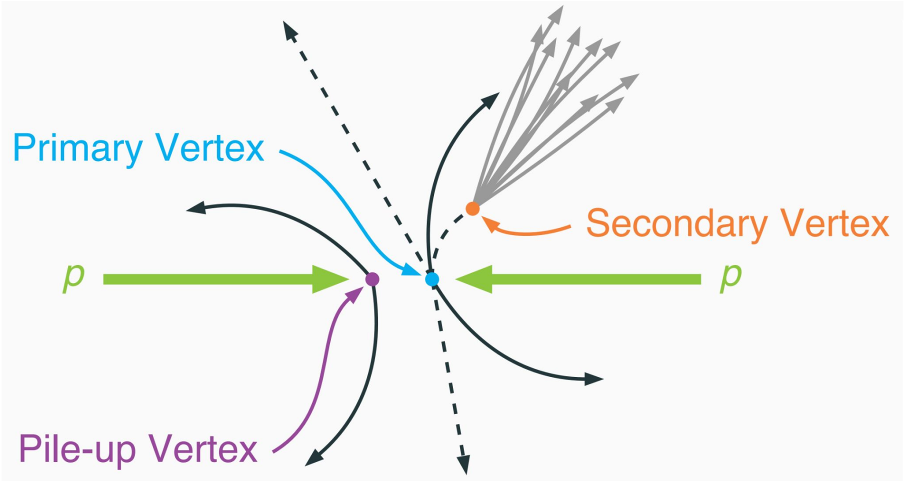
(*) Seeding algorithm not optimized in this test

[Steven's Summer Project]

Vertexing in ACTS

- **Vertexing**: finding the tracks origins / interaction points and estimate their location
- Generally split in two parts: **Finding** and **Fitting**
- We distinguish between **primary** and **secondary** vertexing
  - Depending on the distance from the beamline
- **Secondary vertexing still missing in ACTS line-up**

Courtesy of P. Gessinger



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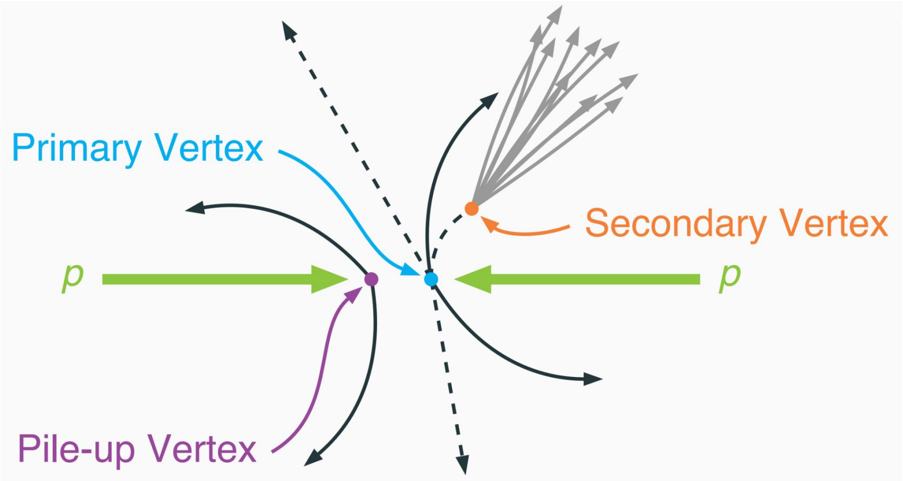
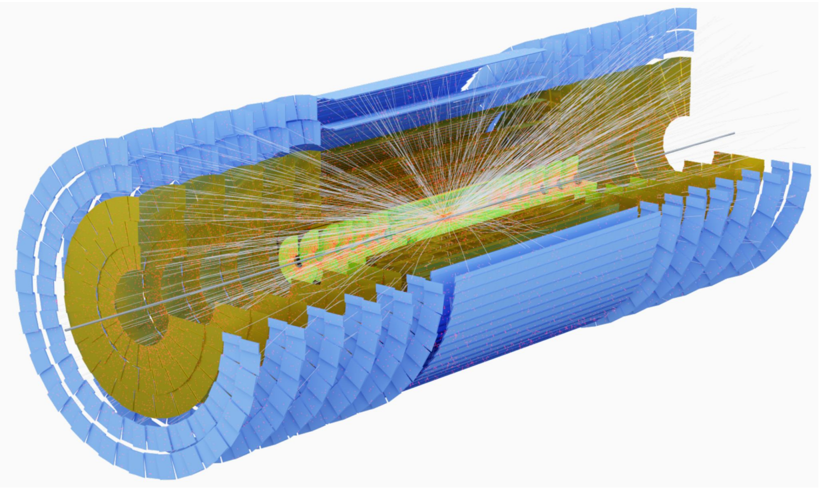
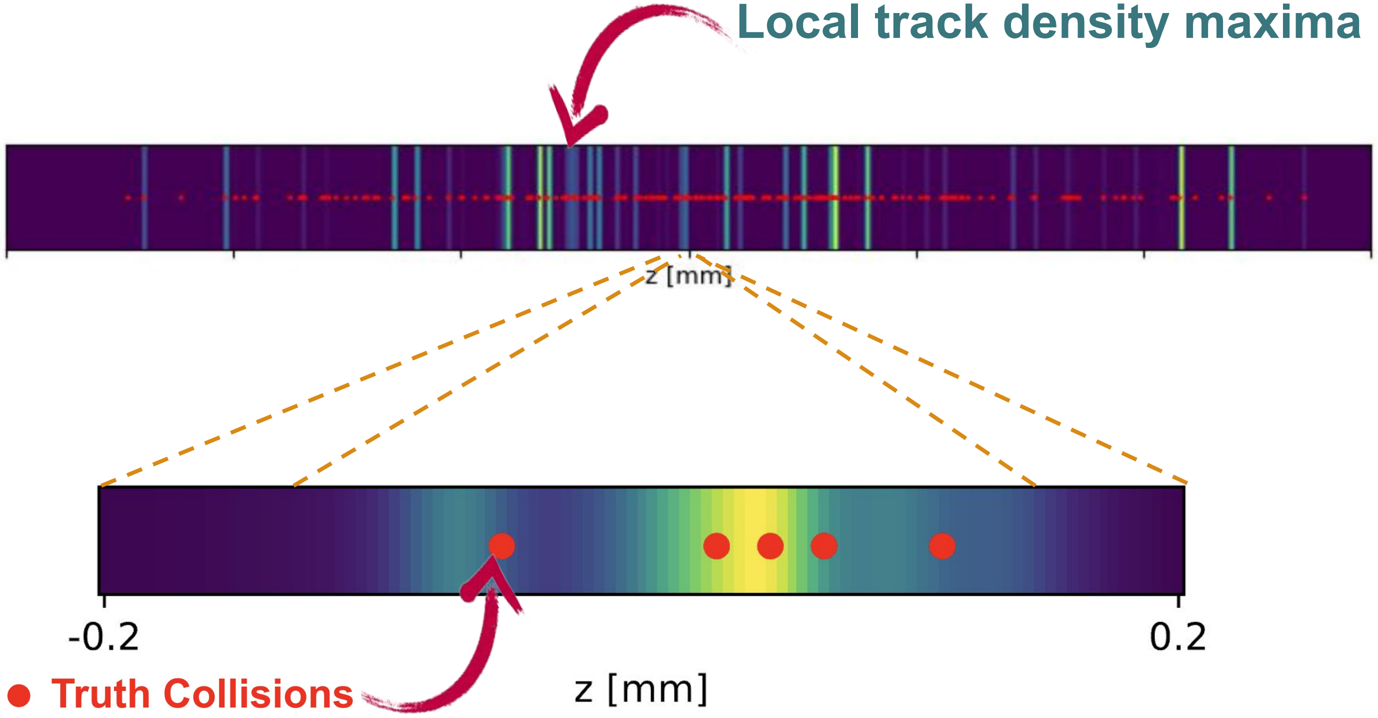


- **Vertexing in ACTS is generally a low person-power area**
  - Great opportunity to step-up and get involved

4D Vertexing in ACTS - Finding

- ACTS provides two finding algorithms:
  - **Iterative Vertex Finder** (IVF)
  - **Adaptive Multi-Vertex Finder** (AMVF) (*)
- Several methods to find local maxima of track agglomerates.
- ***Ex: Adaptive grid density finder***
  - Tracks with large d_0 are dampened away





(*) ATL-PHYS-PUB-2019-015

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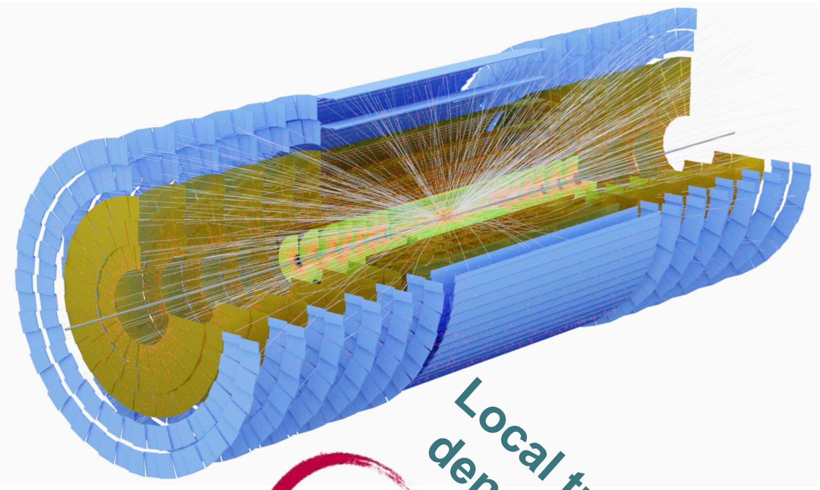
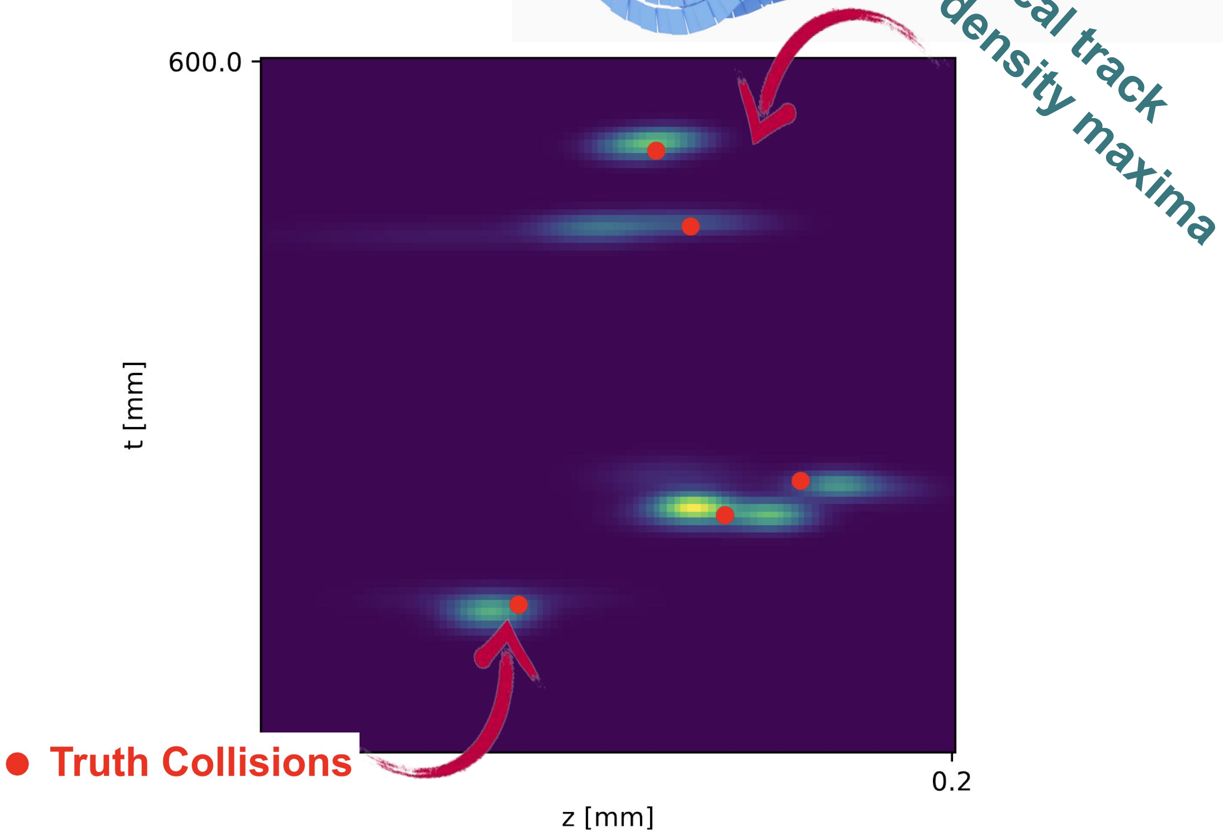
- ***Ex: Adaptive grid density finder***
  - Tracks with large d_0 are dampened away
- **Extended ACTS vertex finding algorithms to include track time information**

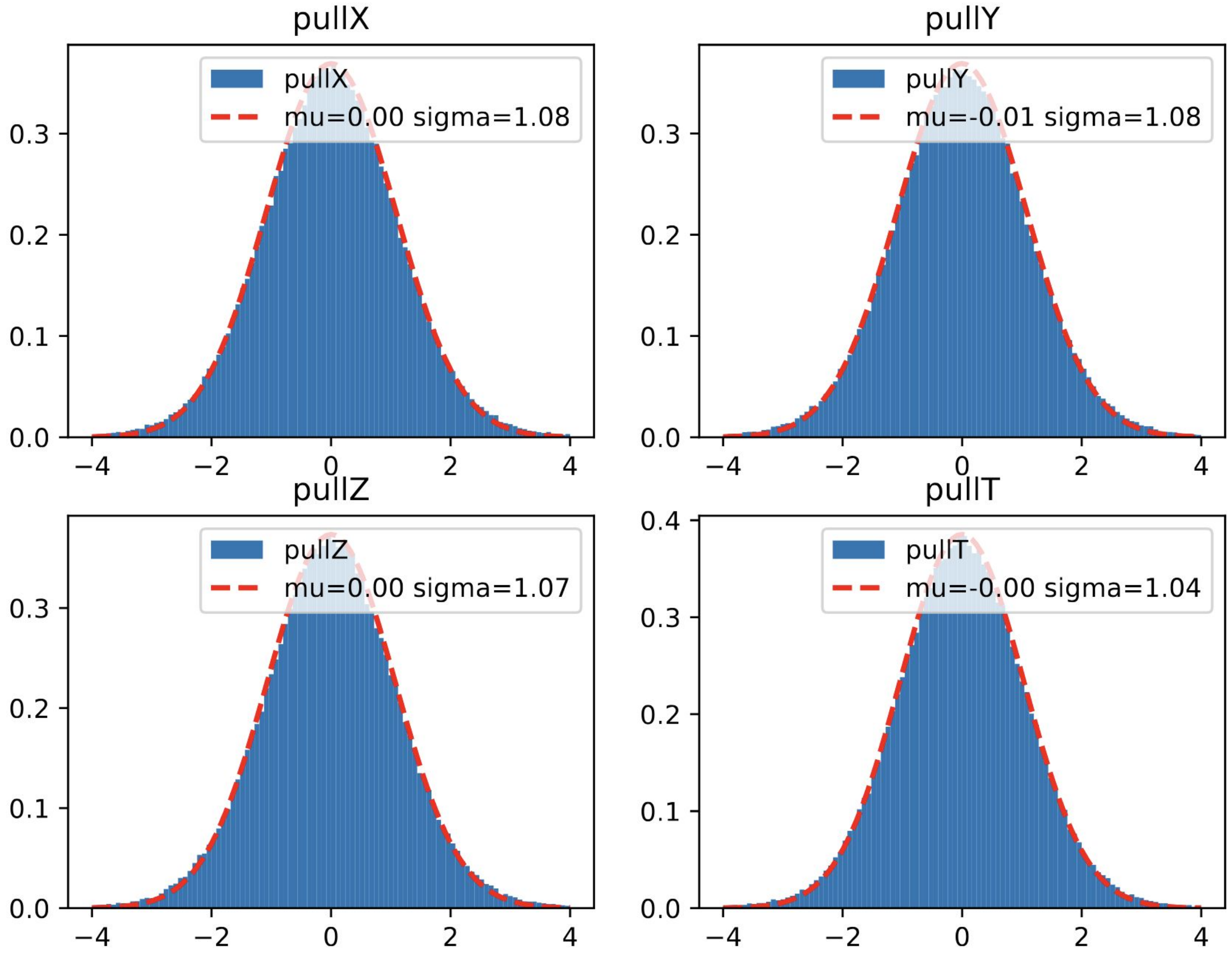




(*) ATL-PHYS-PUB-2019-015

4D Vertexing in ACTS - Fitting

- **ACTS implements a complete 4D vertexing fit**
  - First analytical derivation of the vertexing Jacobians and numerical implementation
- **Very good vertexing fit** performance tested on ttbar and single particle samples
- **Max-Likelihood** approach to correct for vertices composed by tracks with **multiple mass hypothesis**
  - Approach similar to (*)

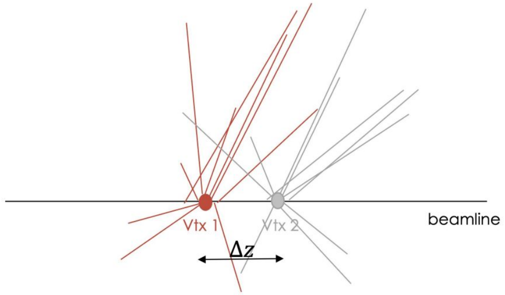


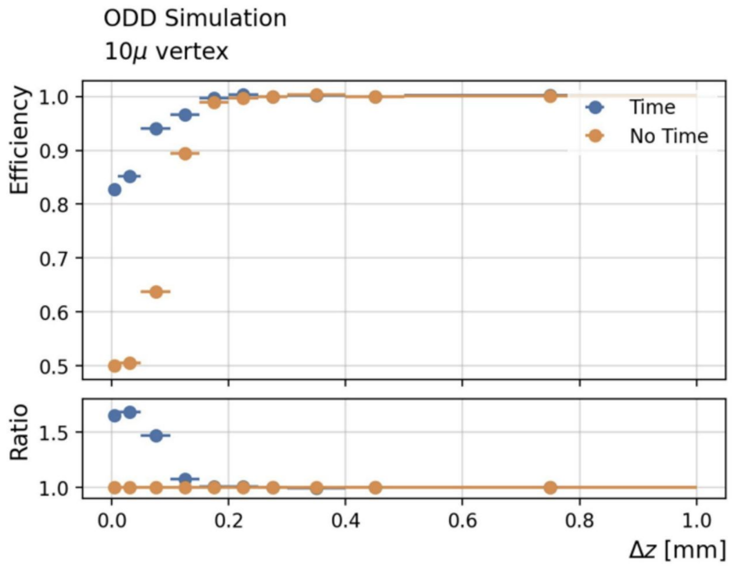
4D Vertexing pulls for 4μ-vertices

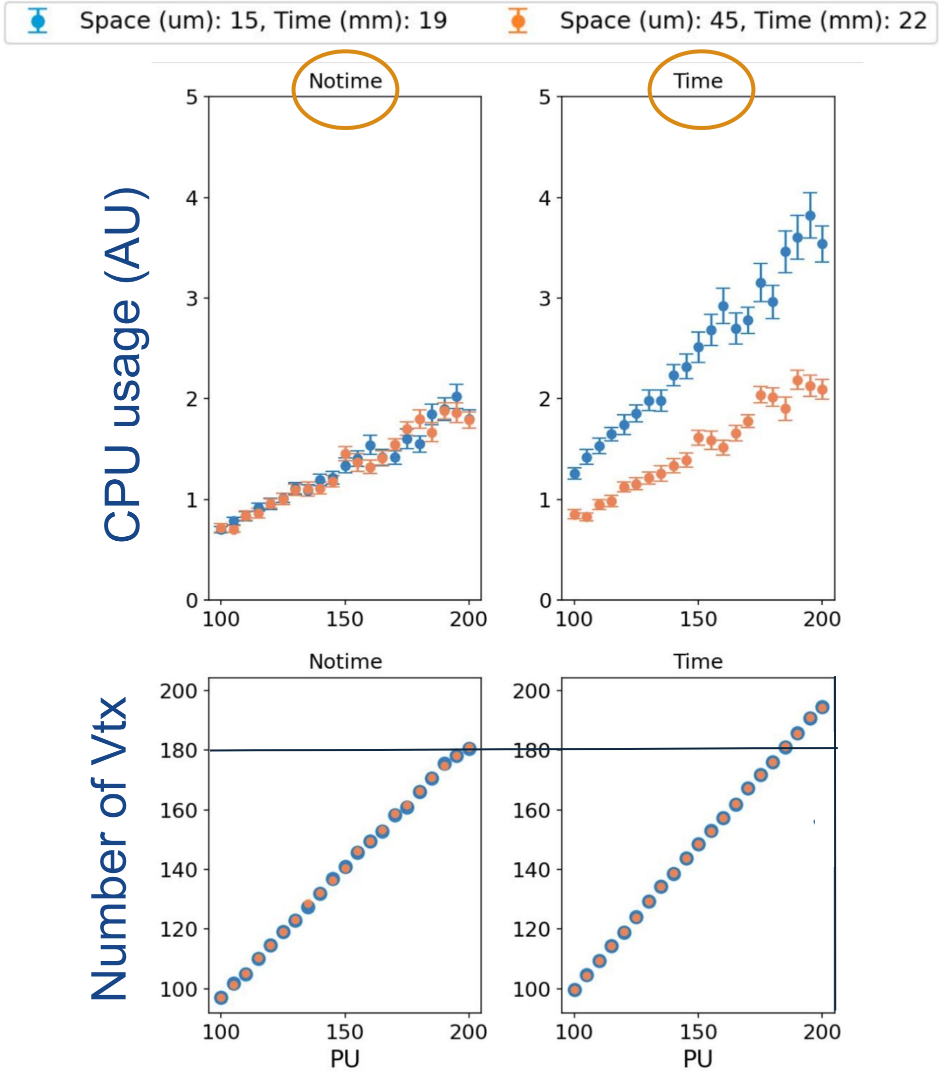
(*)CMS Vertex Timing CHEP24

4D Vertexing in ACTS - Results

- ACTS + ODD showcases the vertexing performance with time
- Clear benefit for dense environments







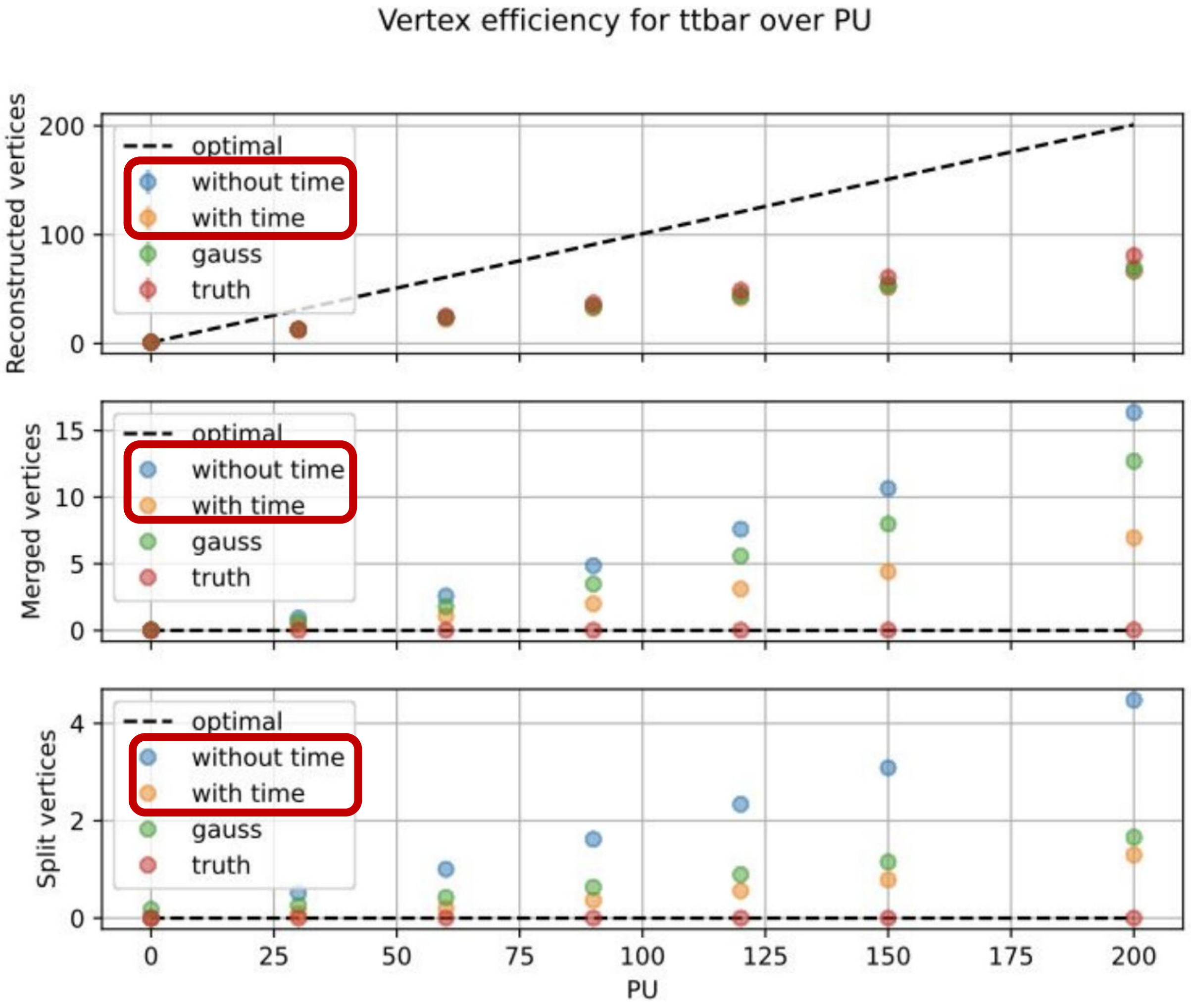
- Tuning of 4D vertexing parameters allows for higher reconstruction efficiency with lower CPU budget (*)

(*)Cleo's Summer Project '24

4D Vertexing in ACTS

Merged Vtx: two truth vertices reconstructed as one vtx
Split Vtx: one truth vertex reconstructed as two vtx

- **ACTS implements a full 4D tracking and vertexing chain**
  - From hit-time associated to the measurements to vertex finding and fitting algorithms
  - Fully tested end-to-end on ODD detector
- Additional algorithms still need to be instrumented with timing information
- Fully portable chain to other experiment layouts (*)

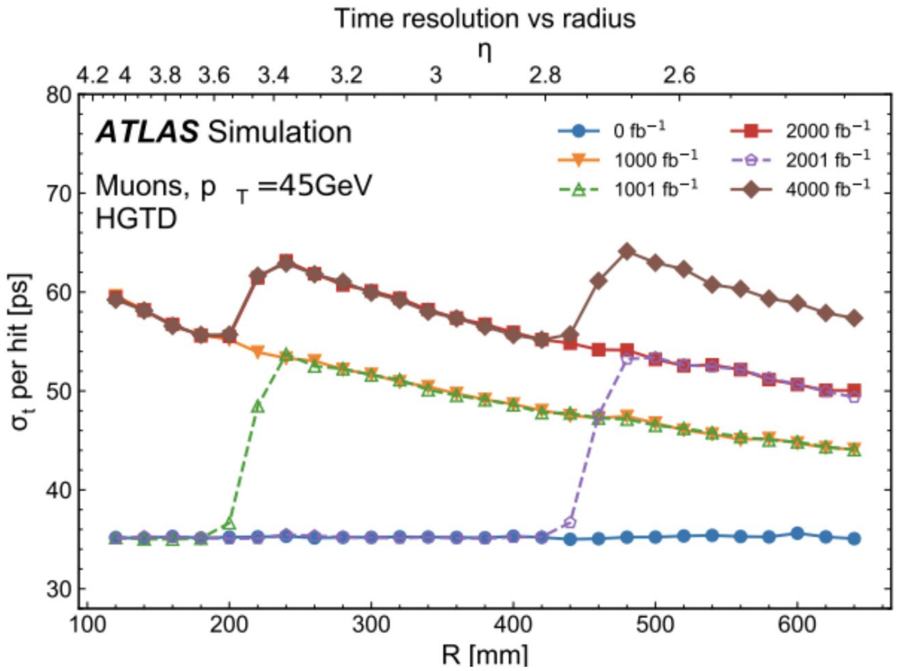


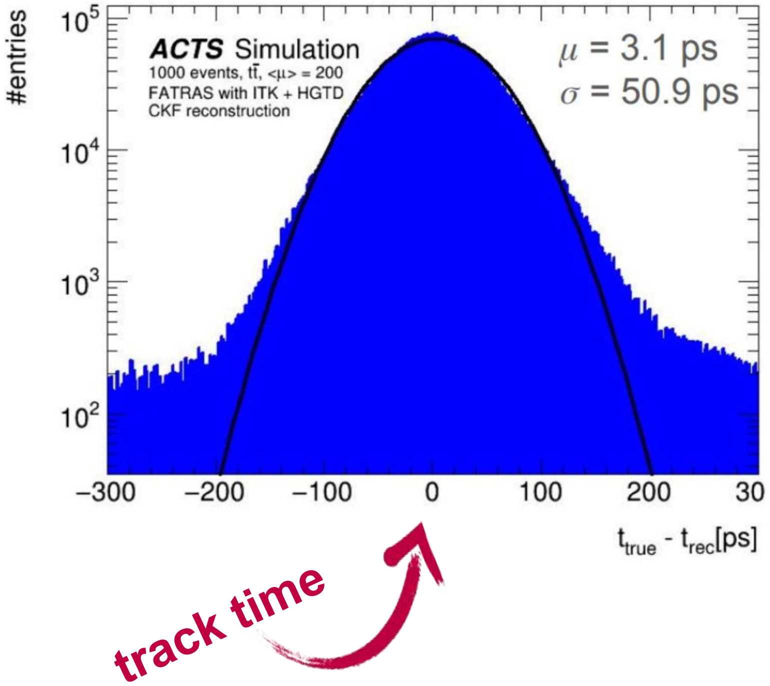
(*) experiment-dependent tuning of the algorithms required

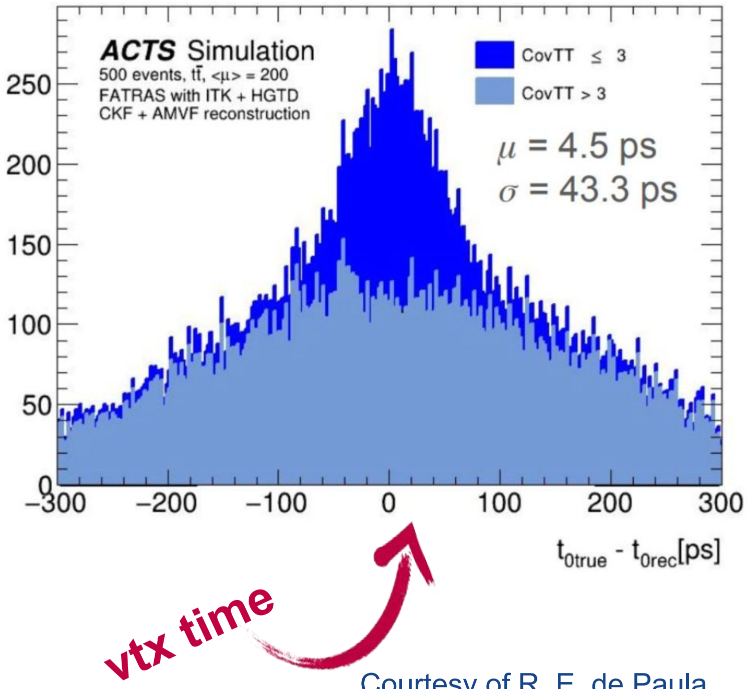
Optimal is just the ideal case. **Reconstructible** vertices are the **truth** points

ACTS 4D tracking and vertexing in ITk - HGTD

- ITk-HGTD ACTS standalone performance for CKF time fitting over radiation exposure
- Propagate track time information to vertex finding and fitting algorithms





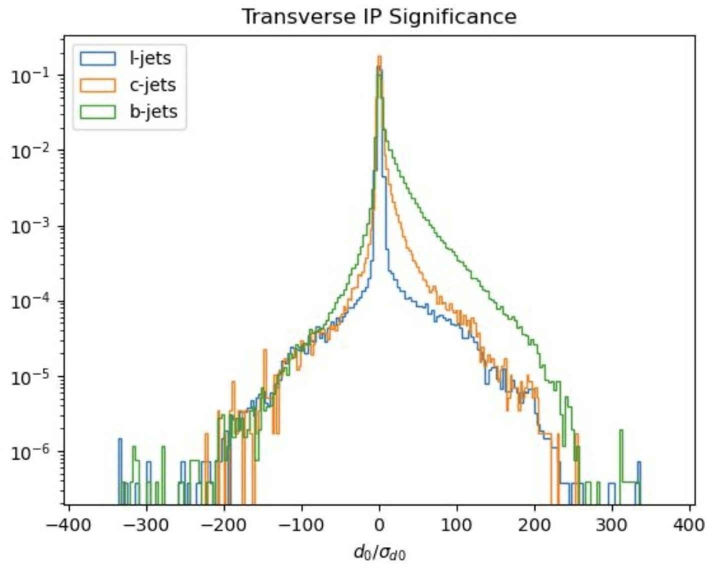


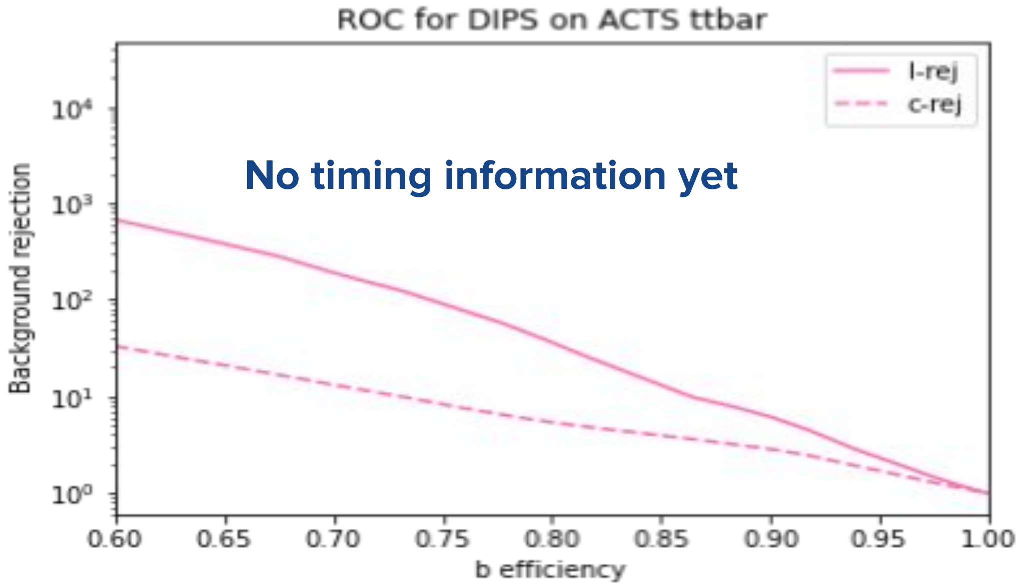
[HGTD ACTS Workshop '24]

Courtesy of R. E. de Paula

A step beyond: flavour tagging with ODD

- **Jet reconstruction algorithms** (e.g. [FastJet](#)) **can and have been interfaced with ACTS** to build particle level jets, which can in turn be used for jet and flavour tagging studies **(*)**
- Jets formed by passing to FastJet Pythia8 stable particles **(truth Jets) (see [ACTS-FastJet-repo](#))** allowing Track-Jet association
  - With new ODD layouts, Calorimeters could be used for same purpose
- ACTS can produce standardized ntuples for Flavour Tagging ML algorithms, i.e. [DIPS](#) or GNT (**)





[(*) C. Mauceri's Project](#) (*) DIPS has also been run on ITk geometry with timing information and confirms gains observed in GNT studies, see A. Tomsic's studies

Conclusions and Summary

- **A Common Tracking Software (ACTS) is an experiment independent toolkit for track reconstruction**
- Embraces **a large community of developers** and its usage is growing across various experiments
- **ACTS** not only natively **supports 4D tracking in its core algorithms**, but also provides a framework to develop, test and deploy 4D tracking algorithms using the Open Data Detector (ODD) as generic layout
- **ACTS can produce inputs to higher level reconstruction algorithms**, e.g. Flavour Tagging, Particle Identification, …
- **ACTS track reconstruction can be applied to different detector layouts and experiments**

CERN

NexTGen

Next Generation Triggers