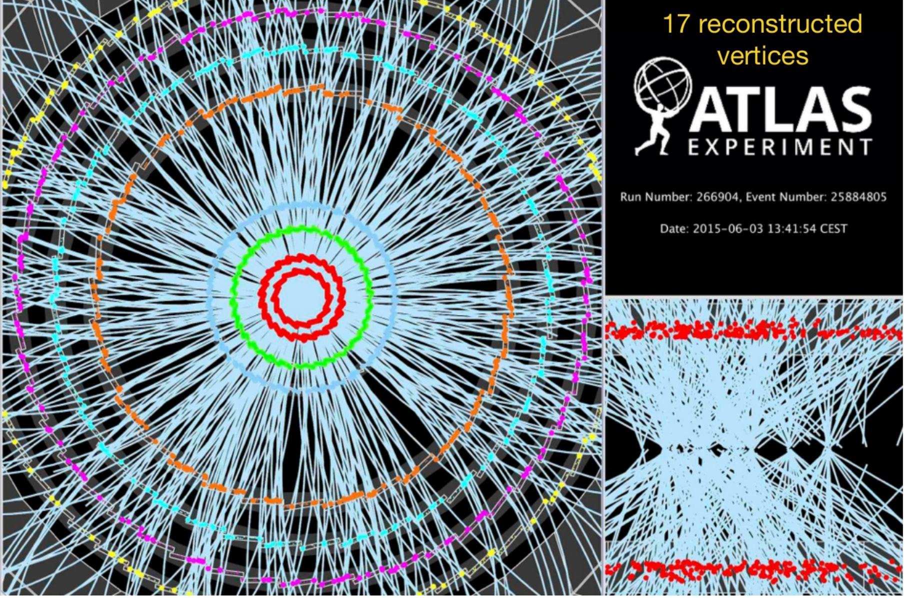


Tracking with A Common Tracking Software

Xiaocong Ai for the ACTS team

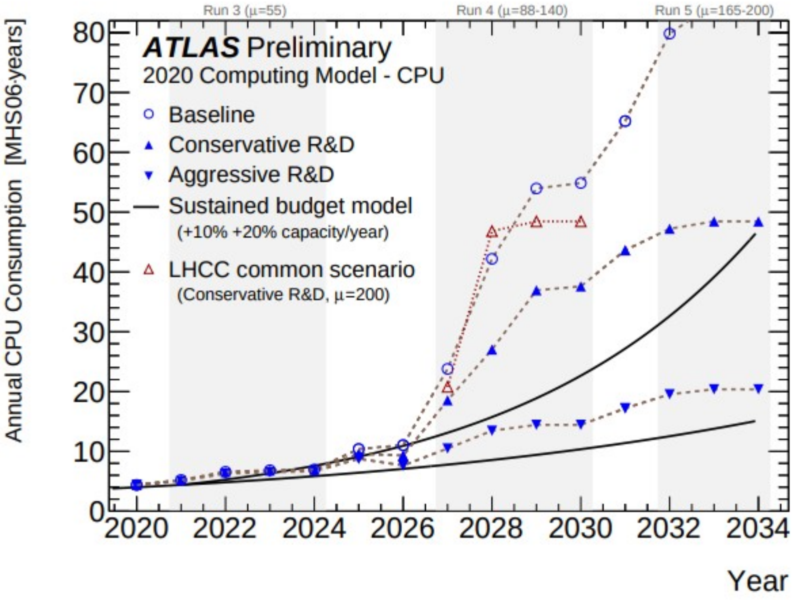
March 1, 2022

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

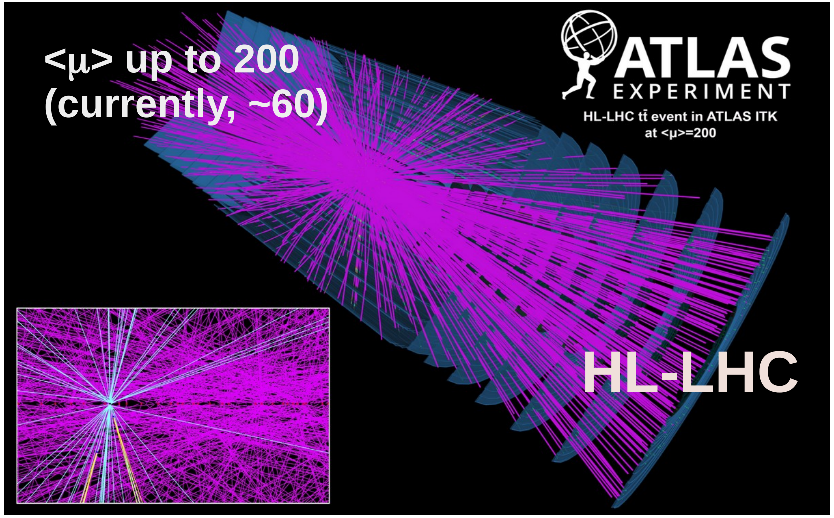
The tracking challenge

- Much increased combinatorics with high pileup at future hadron colliders, e.g.
  - ~7k particles/event with <μ> = 200 at High Luminosity LHC (HL-LHC)
  - <μ> = 1000 at FCC-hh
- Much increased CPU needs



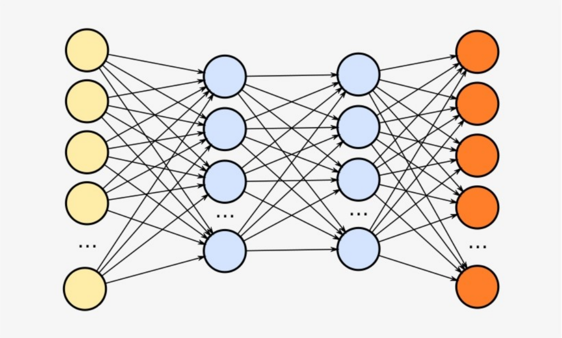
Estimated CPU resources needed for event processing at ATLAS

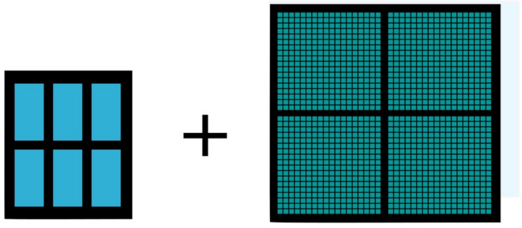
More sensitive to rare phyics, and far more combinatorics!



The A Common Tracking Software project

- To prepare a modern open-source **experiment-independent tracking toolkit** for **current** and **future** detectors based on LHC tracking experience
  - Targeting at HL-LHC, but also for sPHENIX, ALICIE, EIC, Belle-II, FASER, MUC …
- To provide an open-source R&D platform to explore **new techniques, parallelization and acceleration**





About

Experiment-independent toolkit for (charged) particle track reconstruction in (high energy) physics experiments implemented in modern C++

acts.readthedocs.io

simulation · reconstruction · particle-track-reconstruction · physics-experiment

Readme

MPL-2.0 License

Code of conduct

Cite this repository

64 stars

10 watching

82 forks

Releases 94

v17.1.0 Latest

7 days ago

+ 93 releases

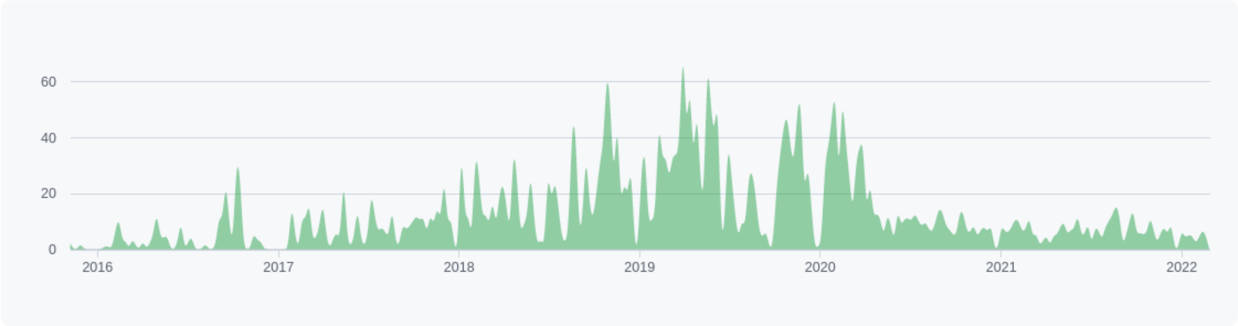
The ACTS developers team

- 10~15 active developers on Core project
  - ATLAS heavy with increasing external contribution

Nov 8, 2015 – Mar 1, 2022

Contributions: Commits

Contributions to main, excluding merge commits and bot accounts



Contributors 40

+ 29 contributors

supported by

EP-R&D

Programme on Technologies for Future Experiments

iris hep

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TUM

cnrs

DESY.

BERKELEY LAB

cooperations

HSF

HEP Software Foundation

intel

CERN openlab

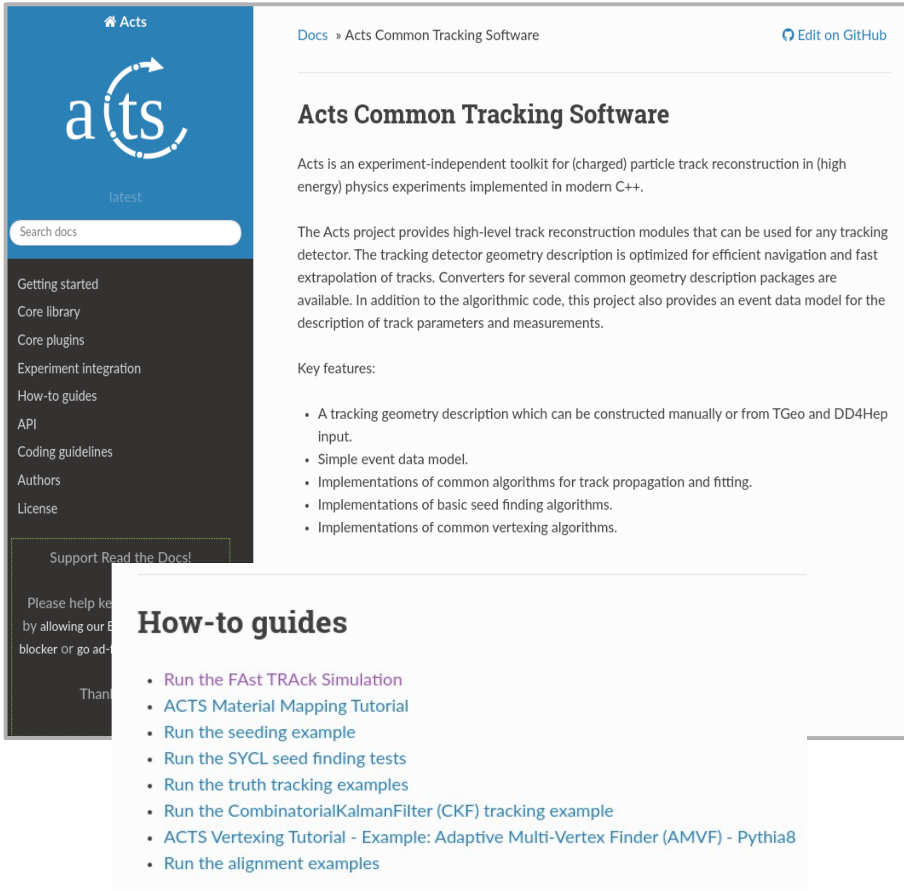
ACTS fosters collaboration

- World-wide users from particle and nuclear physics, collider and non-collider experiments
  - **>10 experiments**
    - ATLAS, Belle-II, ALICE, sPHENIX, FASER, EIC, CEPC, LUXE, PANDA, Muon Collider ...
  - **>15 institutes**
    - CERN, LBNL, ORNL, UC Berkeley, Stanford University, DESY, Universite at Bonn…
  - **~45 forks** of the acts repository
- Regular/irregular discussion between developers and experiment users
  - ATLAS, FASER, sPHENIX, ALICE, EIC...

ACTS design

https://acts.readthedocs.io/en/latest/

- Modern **C++ 17** concepts
- Highly **templated design** to avoid virtual lookup
- **Abstraction of Event Data Model, geometry description, tracking algorithms** from specific experiment details (geometry, B field,…)
- **Strict thread-safety** to facilitate concurrency
- Supports for **contextual condition data**
  - Calibration, alignment and Magnetic field data
- Minimal dependency (Eigen) to facilitate integration
- Highly configurable for usability
- Well-documented

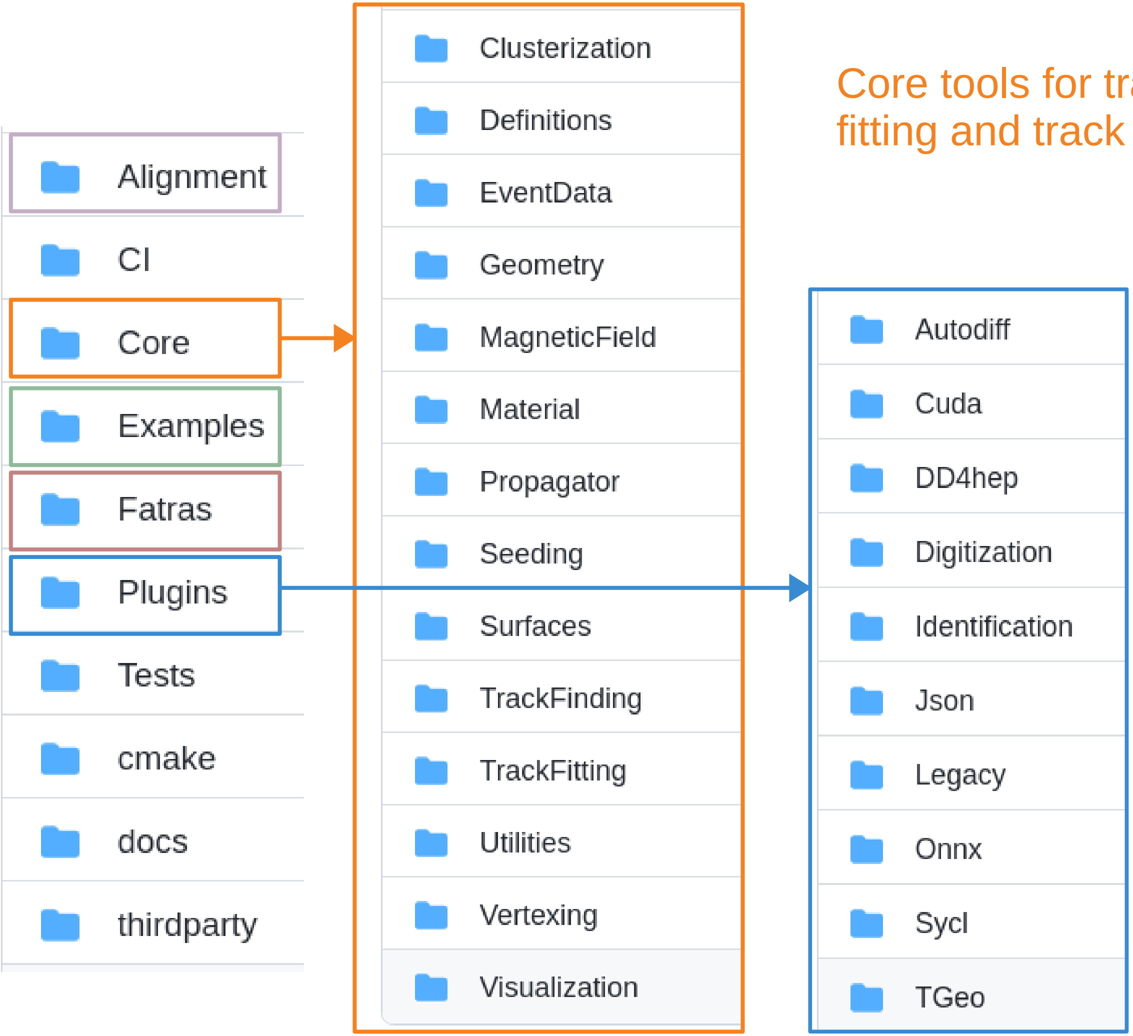


The tracking tools in ACTS

An alignment prototype

A light-weight test framework with application examples

A fast simulation engine

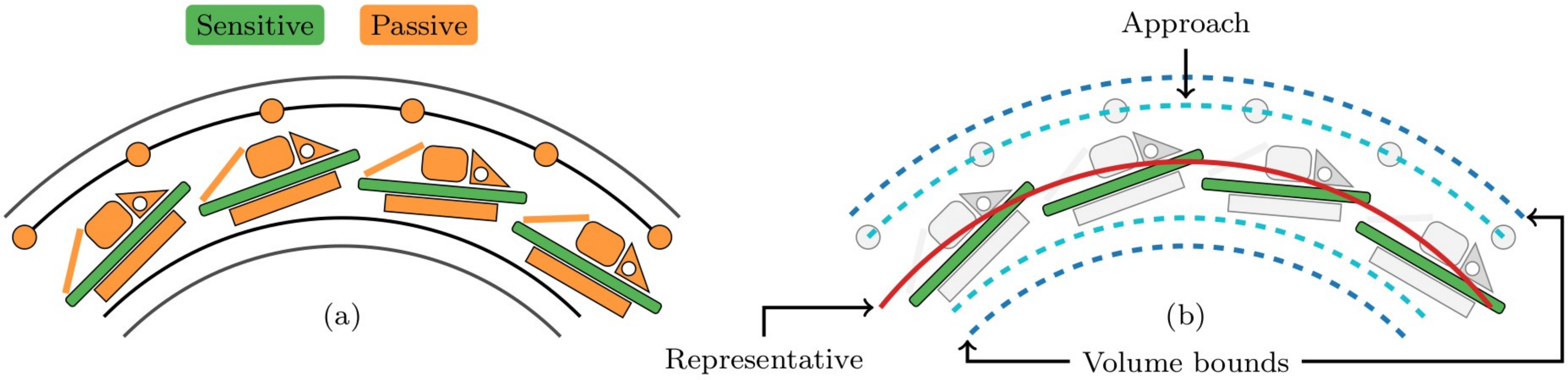


Core tools for track propagation, track fitting and track finding, vertexing...

Plugins to support R&D on new techniques!

ACTS tracking geometry

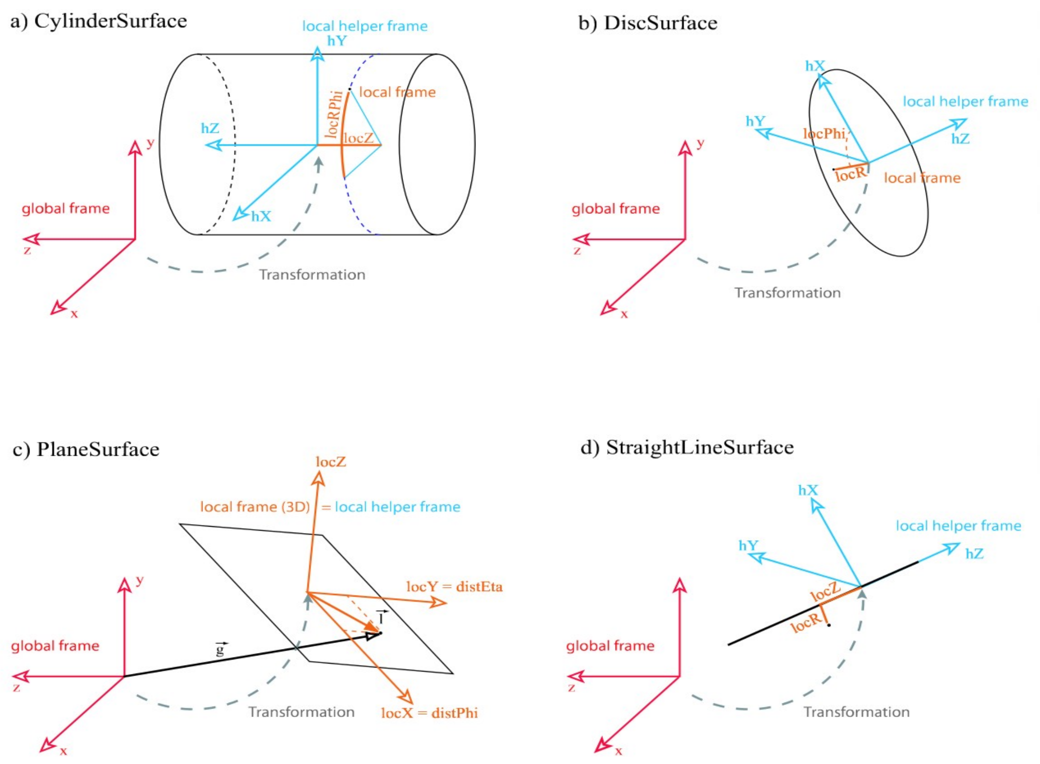
- Geometry used for track reconstruction is simplified from full simulation geometry to reduce CPU consumption and speed up geometry navigation
- Material mapping tools allows to map (averaged) Gean4-based full detector material (recorded using Geantino scan) onto either surfaces or volumes



ACTS Surface concept

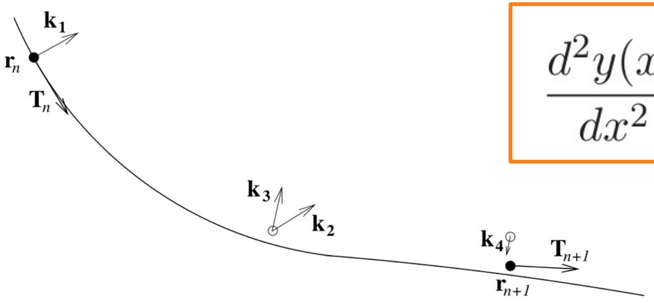
- Surface is the key component of tracking geometry
  - Concepts are largely transcribed from ATLAS SW
- Various concrete surfaces to support description of measurement with different detectors (silicon, wire-chamber, drift tube…)
  - Different local coordinate definitions, shapes and boundaries

Surface types in ATLAS SW



ACTS track propagation

- Integration of the fourth-order Runge-Kutta-Nyström method for particle transport in magnetic field
- Allows for transport in dense volumes, e.g. calorimeter
- Support custom actions at each propagation step
  - Material effects handling
  - Material recording
  - Kalman filtering



$$\boxed{\frac{d^2y(x)}{dx^2} = f(x, y, y')}$$

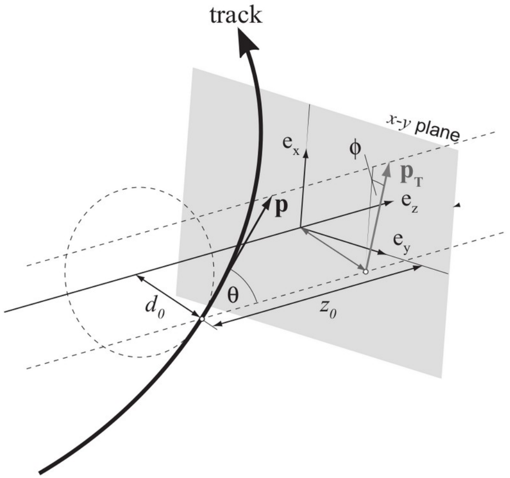
```
// Pre-Stepping: target setting
navigator.target(state);

// Propagation loop: stepping
while (/* step */){
    // Perform a step & check the result
    stepper.step(state);
    navigator.status(state);
    // Apply the actors
    actionList(state, result);
    // Check for abort condition
    if (abortList(result, state)) break;
    // Target after stepping
    navigator.target(state);
}
```

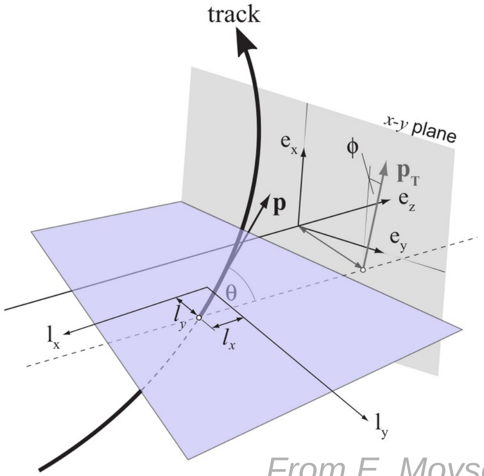
ACTS track and measurement parameterization

- Track parameterization
  - Global: $\mathbf{f} = (x, y, z, d_x, d_y, d_z, \frac{q}{p}, t)$
  - Local (bound): $\mathbf{b} = (d_0, z_0, \phi, \theta, \frac{q}{p}, t)$

New feature of time parameter integration



Local track parameter represented at the perigee w.r.t. beam line



From E. Moyse

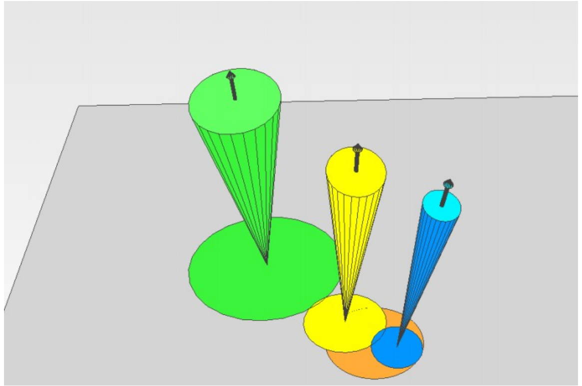
Local track parameter represented at detector local surface

- Measurement is a vector in subspace of the bound track parameters
  - Easy projection from the track parameters to measurement

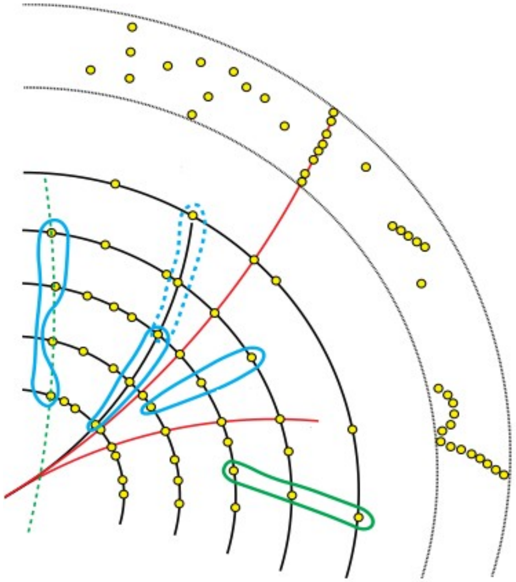
$$\mathbf{r}_i = \mathbf{m}_i - \mathbf{H}_i \mathbf{b}_i$$

- Calibration of experiment-specific “source measurement” to ACTS measurement is possible during tracking time

ACTS track finding/fitting



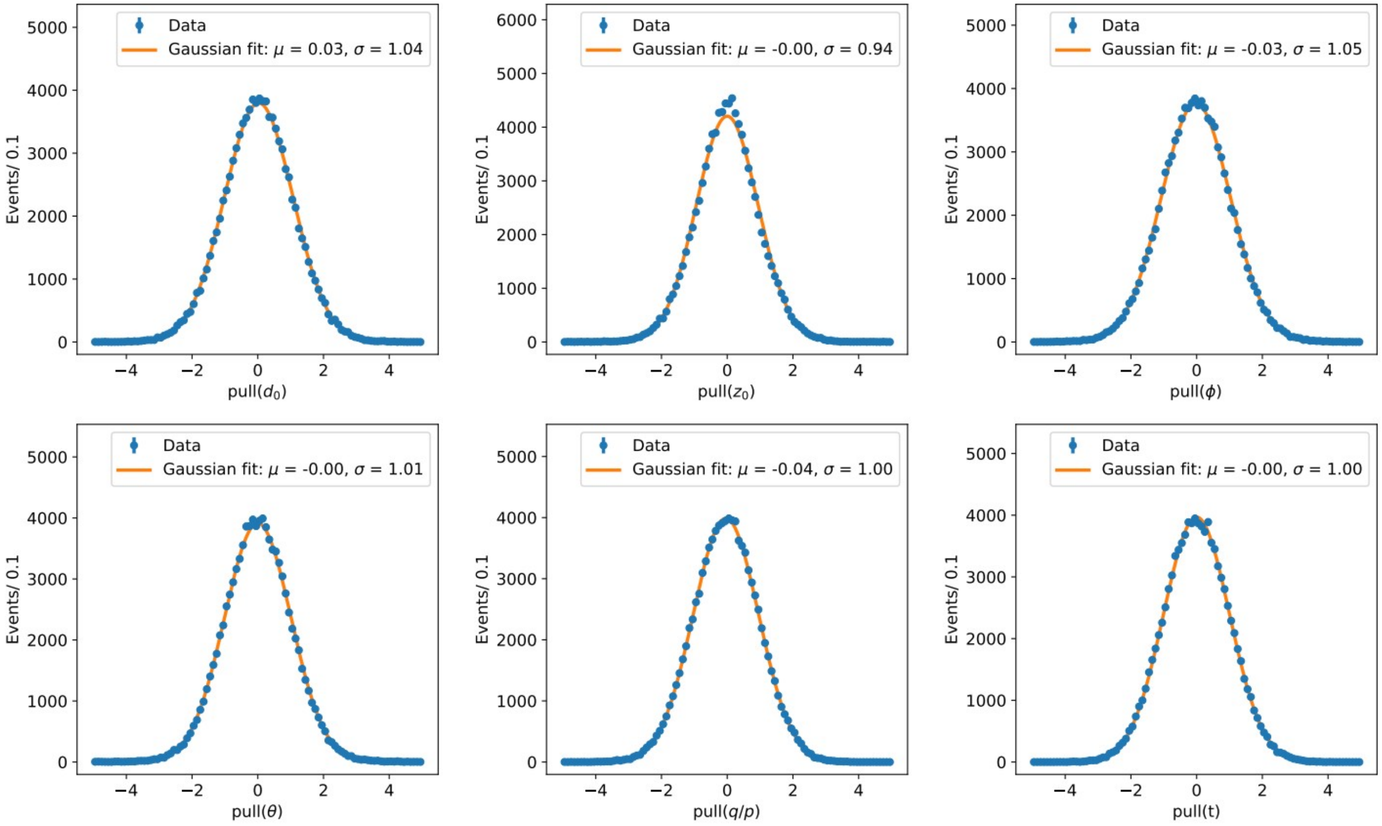
- Based on Kalman-filter (KF) algorithm
  - Straightforward handling of material effects
  - Allows for simulataneous track fitting and finding
  - Supports hole search and outlier rejection during fitting
- Track finding follows seeding + combinatorial Kalman filter (CKF)
- Implementation of Gaussian Sum Filter for non-Gaussian extension is on-going
- Non-linear extension of Kalman filter is in place
  - The commonly used (extended) KF in HEP is optimal for linear system



ACTS tracking performance: track parameters estimation

Pull of track parameters represented at the perigee

arXiv:2106.13593v1

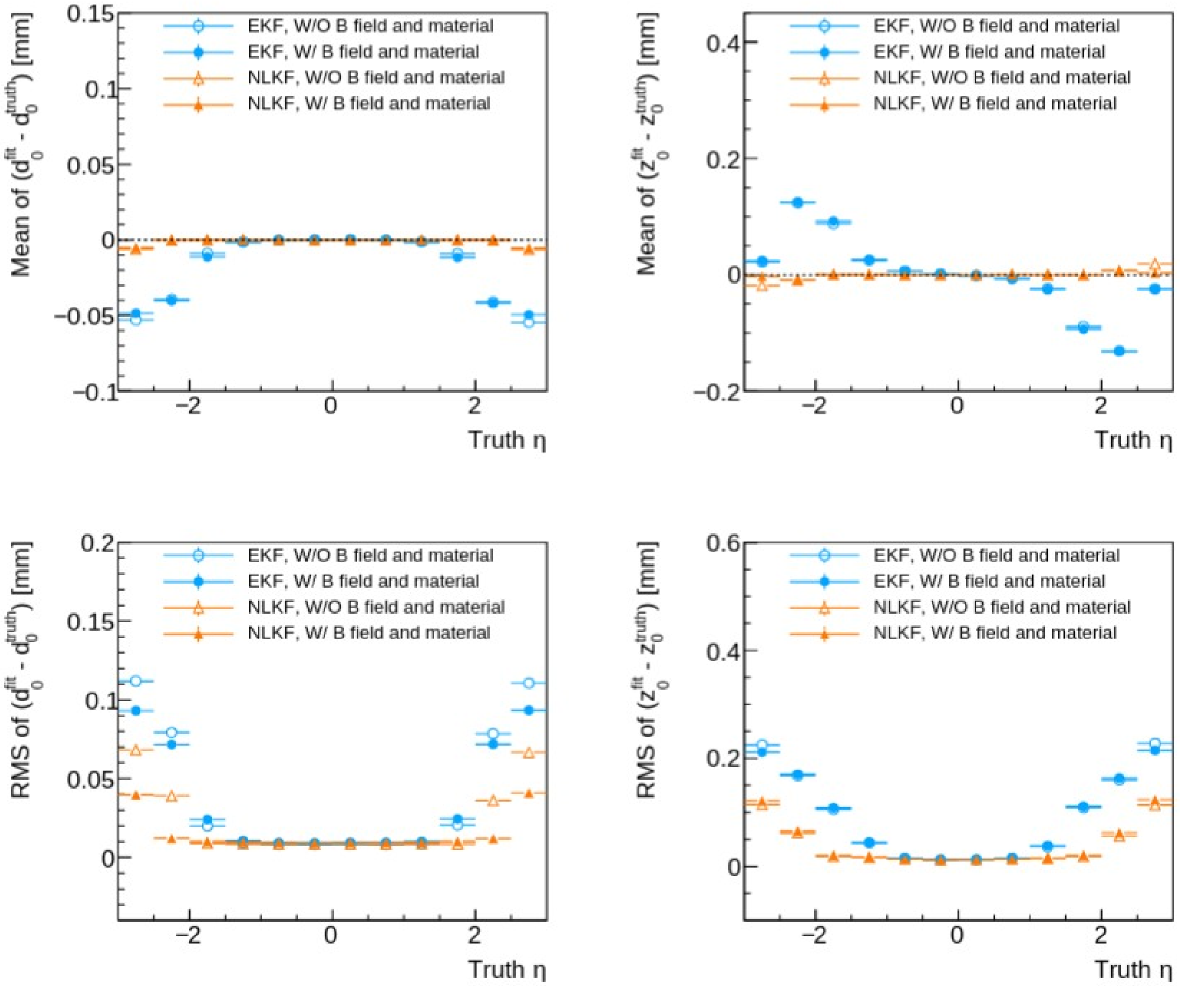


$$v_{\text{pull}} = \frac{v_{\text{fit}} - v_{\text{truth}}}{\sigma_{\text{v}}},$$

Single muon 400 MeV < pT < 100 GeV, |eta|<2.5
TrackML detector, Bz= 2T

Track fitting with non-linearity correction

- The non-linearity correction corrects the bias and improves resolution of track parameters significantly!



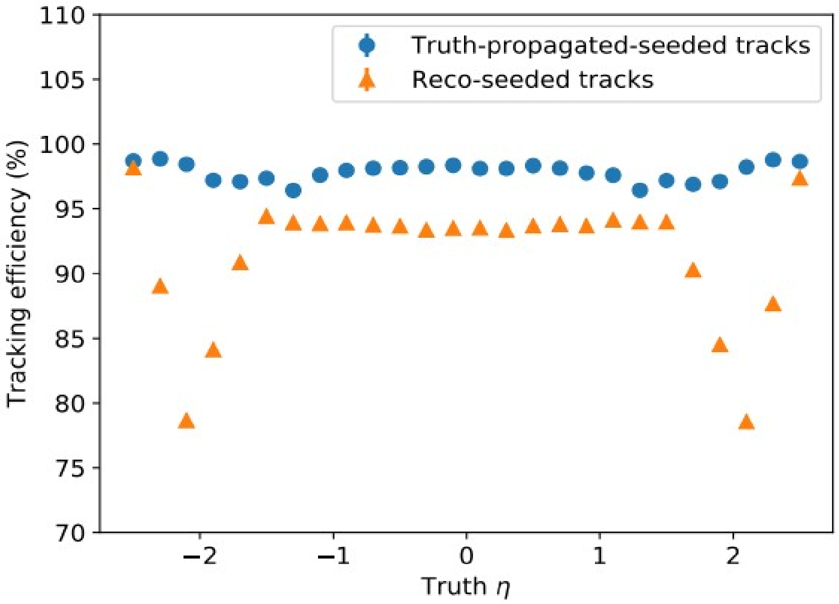
Single muon (20<pT<100 GeV)
Open Data Detector, solenoidal
Bz= 2T (ATLAS-like)

arxiv: 2112.09470. Submitted to NIMA
X. Ai, H. Gray, A. Salzburger, N. Styles

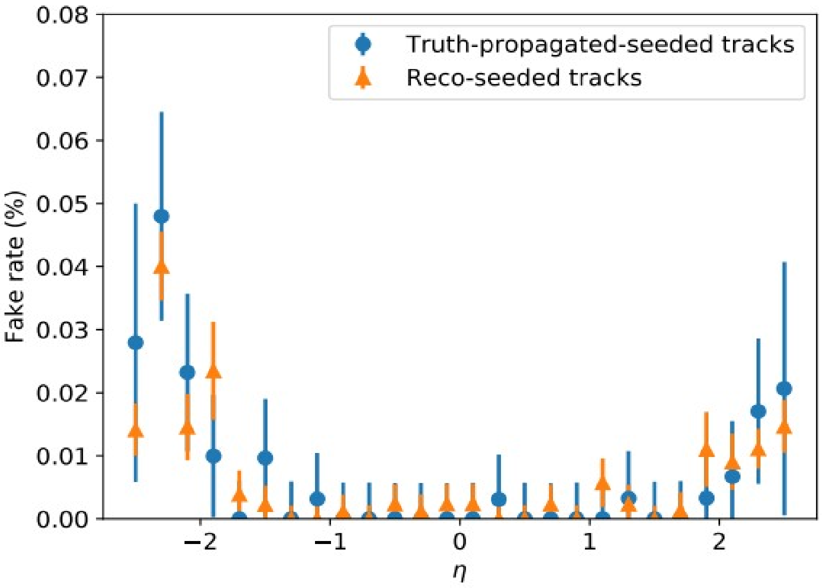
ACTS tracking performance: efficiency and fake rate

- >99% tracking efficiency and <0.01% fake rate for $t\bar{t}$ at <μ>=200 (~3000 charged tracks/event)

Tracking efficiency



Fake rate

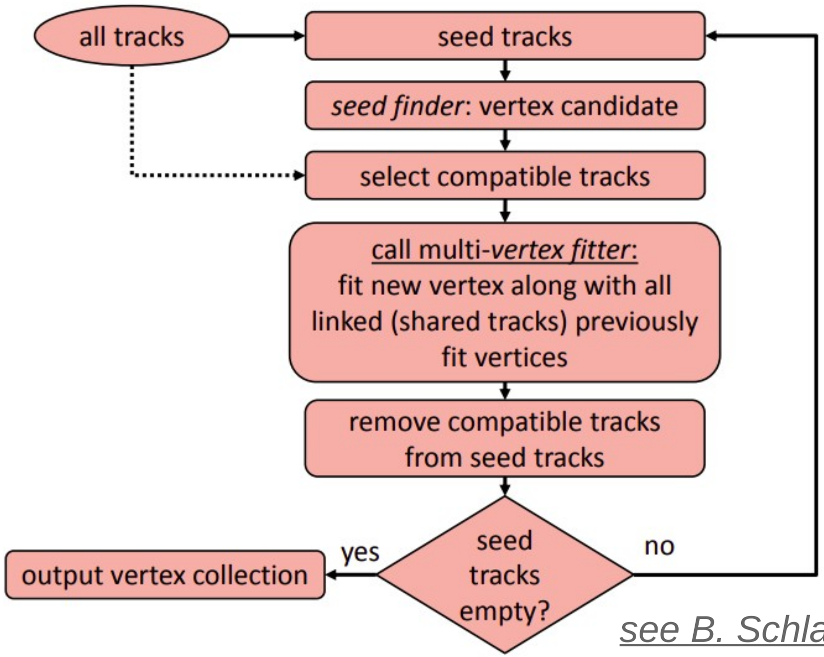


sqrt(s) = 14 TeV, $t\bar{t}$, μ =200
TrackML detector, Bz= 2T

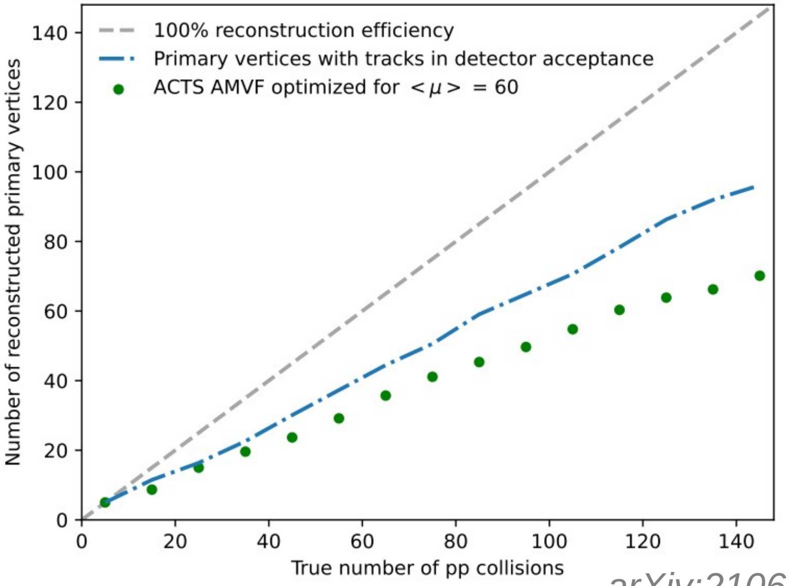
arXiv:2106.13593v1

ACTS vertex finding/fitting

- Various vertexing tools have been transcribed from ATLAS vertexing algorithms (performance well validated against ATLAS SW)
  - Iterative fitting-after-finding: **Iterative Vertex Finder (IVF)** (used at ATLAS Run-2)
  - Finding-through-fitting: **Adaptive Multi-Vertex Finder (AMVF)** (to be used at ATLAS Run-3)



see B. Schlag's slides

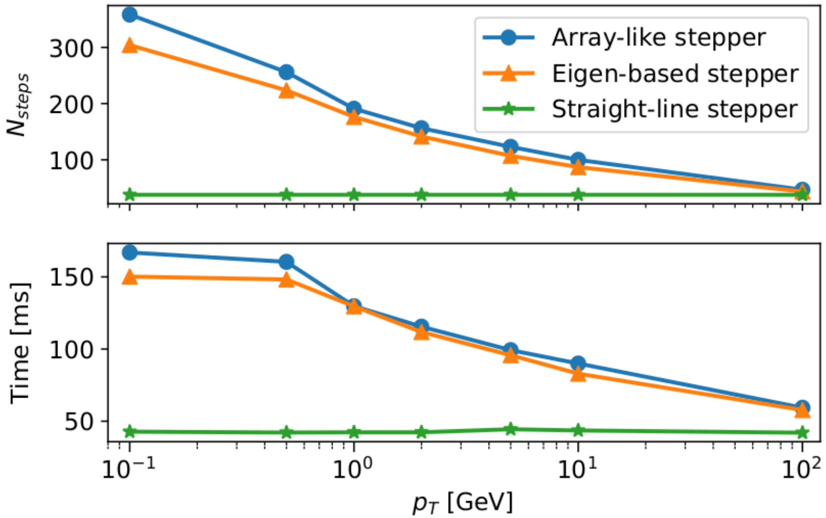


arXiv:2106.13593v1

ACTS time performance

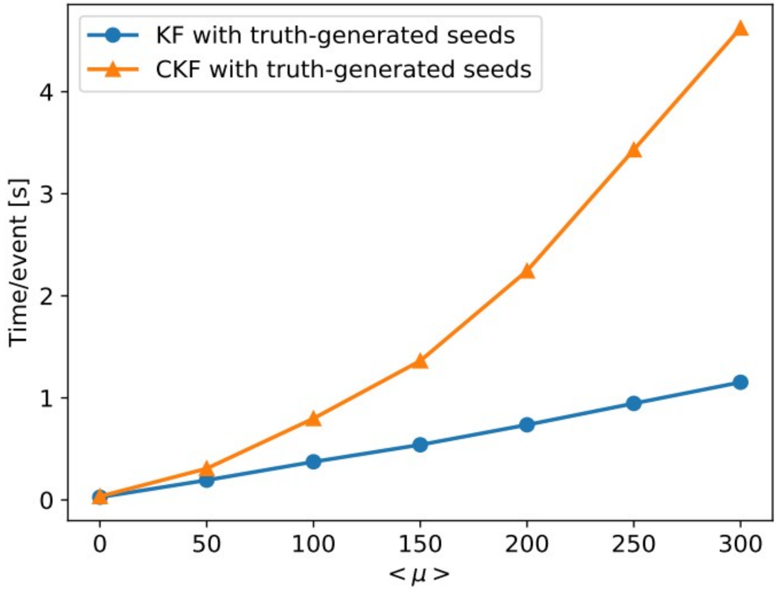
- Pure track fitting time ~ 0.2 ms/ track for ~15 detector layers with a single thread

Track propagation time



1000 charged pions per event
TrackML detector, Bz= 2T

(C)KF time

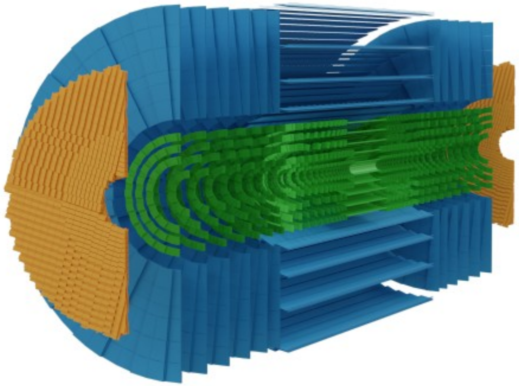


sqrt(s) = 14 TeV, $t\bar{t}$, μ =200
TrackML detector, Bz= 2T

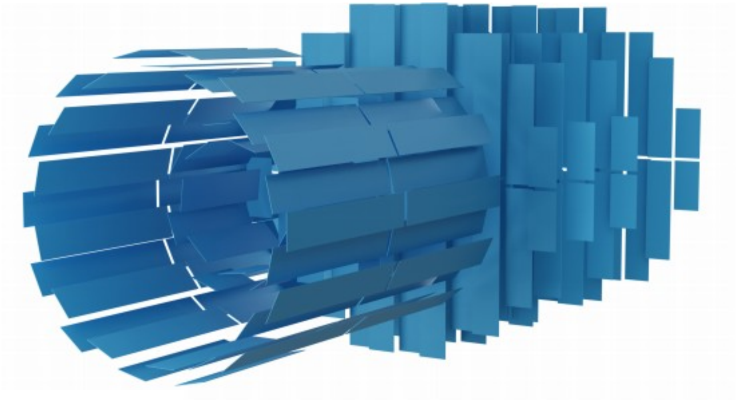
arXiv:2106.13593v1

ACTS application examples

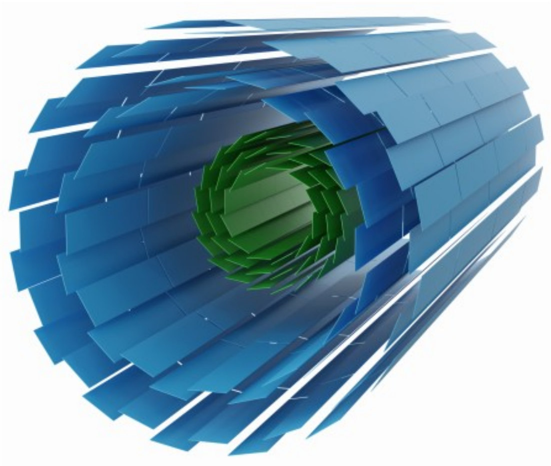
ATLAS ITk (HGTD)

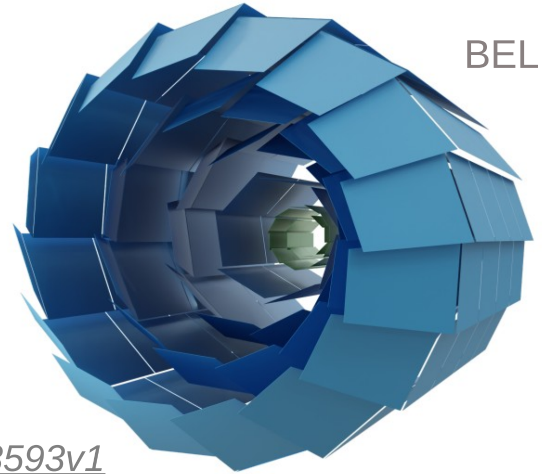


PANDA silicon



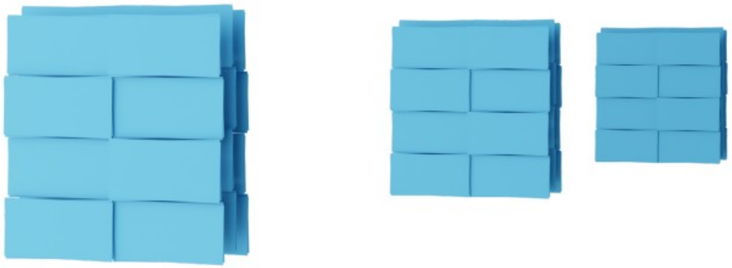
sPHENIX silicon





BELLE II

FASER

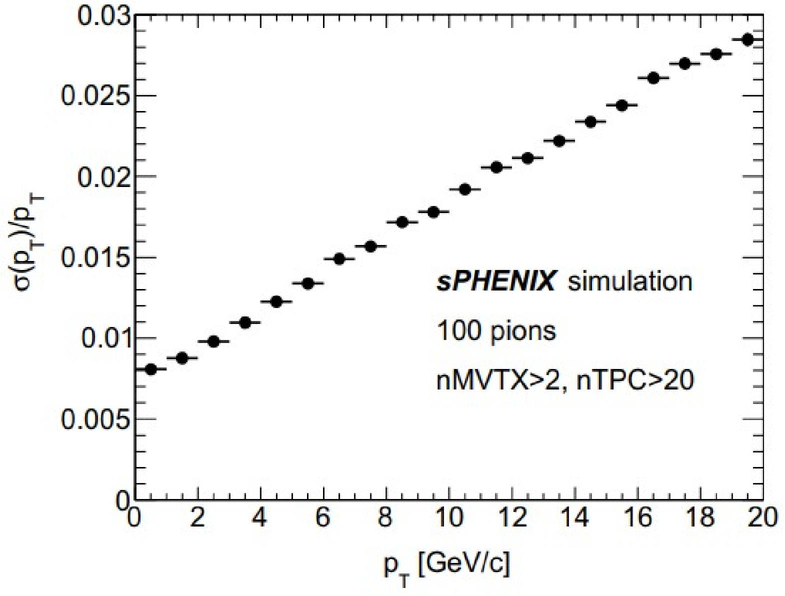


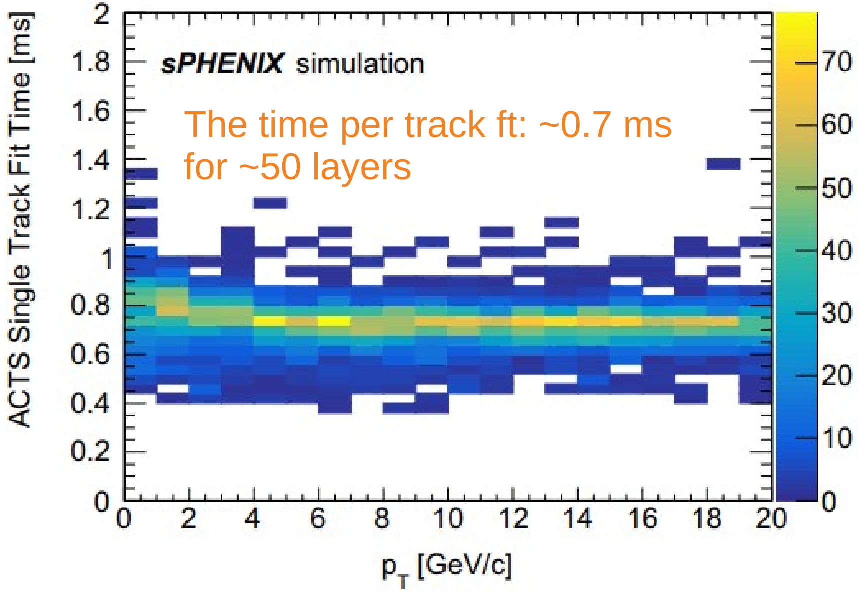
arXiv:2106.13593v1

ACTS application example: sPHENIX

- ~1000 tracks/ event in Au+Au collision at sPHENIX
- ACTS provides necessary tracking resolution to resolve high momentum jets
  - Δp/p ≲ 0.2%·p (GeV) for pT > 10 GeV tracks
- ACTS provides **X8 faster** tracking than GenFit package
  - Total tracking time is 10 s/event (fitting time: ~1 s/event)

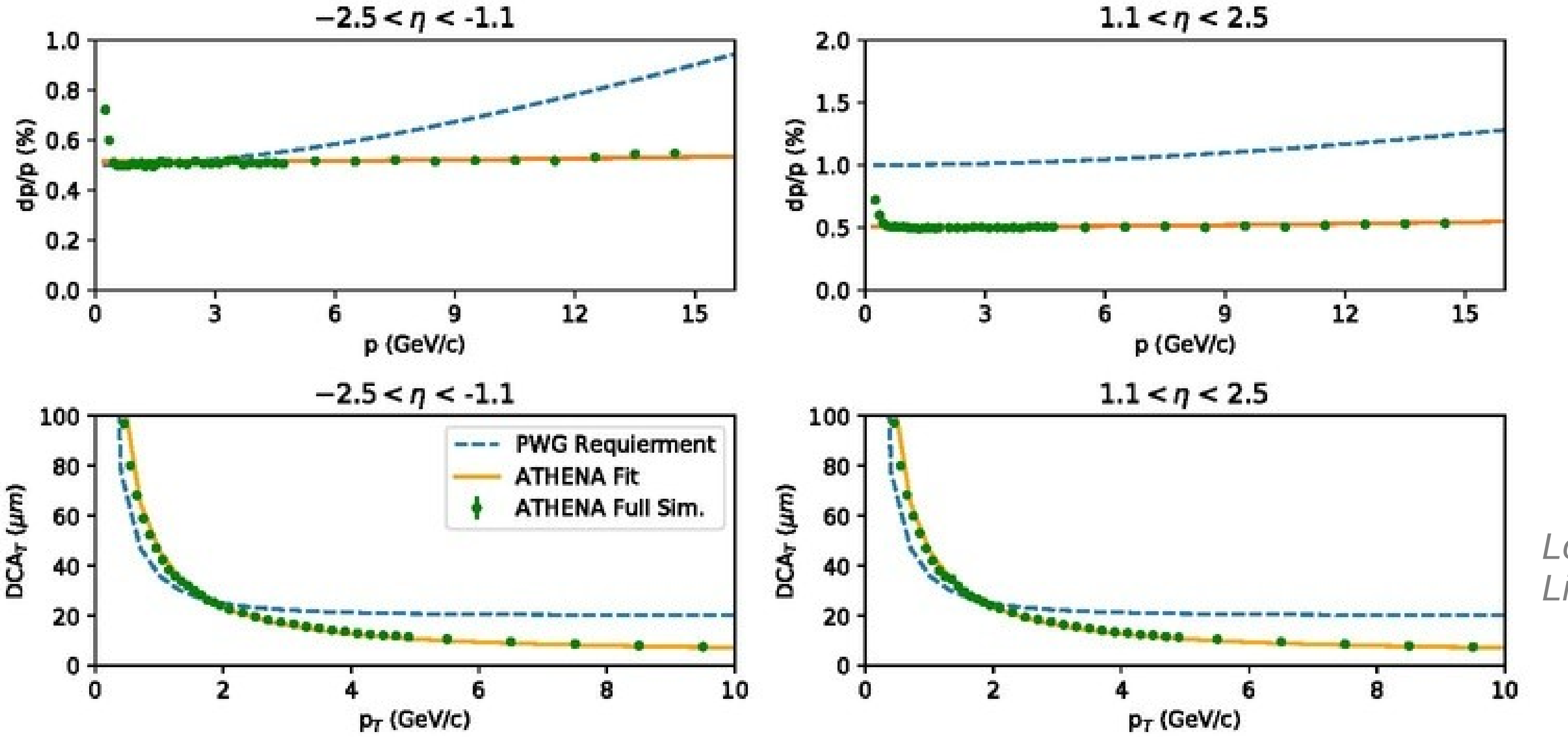
Comput Softw Big Sci 5, 23 (2021)





ACTS application example: EIC ATHENA

- ACTS is used as the tracking tool for ATHENA proposal at EIC
- Achieved tracking resolution reaches the physics working group requirement



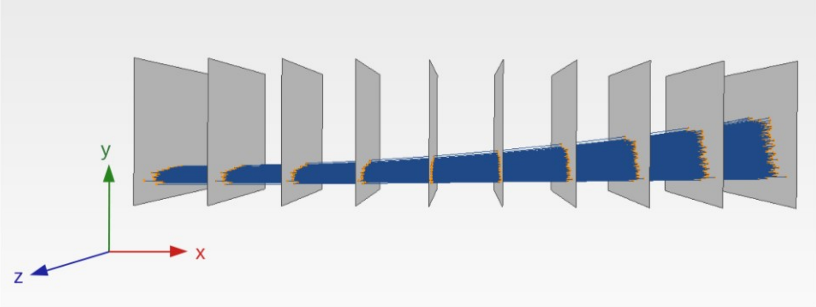
Lots of thanks to Shujie Li and Wenqing Fan

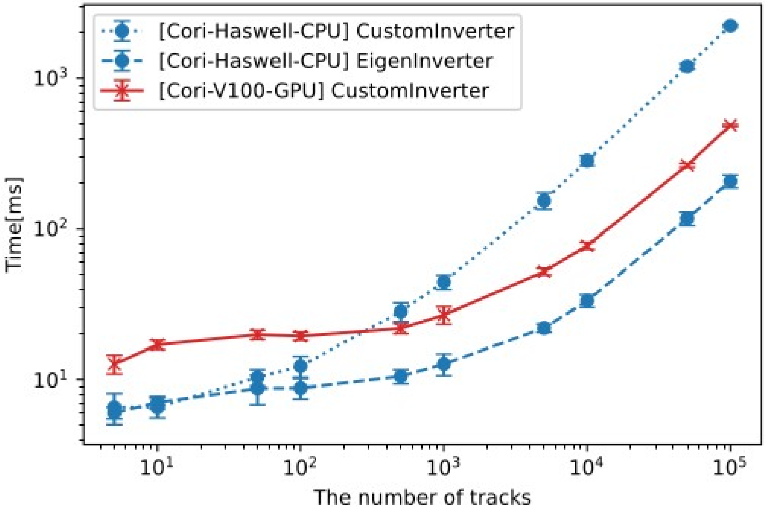
ACTS R&D: GPU-accelerated track fitting

- ALICE, LHCb. CMS are exploring GPU for HLT trigger
- The first look at heterogeneous computing in ACTS was porting a full KF to GPU
  - **~ 4.5X speed gain for >1000 tracks!**
  - But not detector agnostic yet

[Comput Softw Big Sci 5, 20](#)

X. Ai, G. Mania, H. Gray, M. Kuhn, N. Styles





CPU

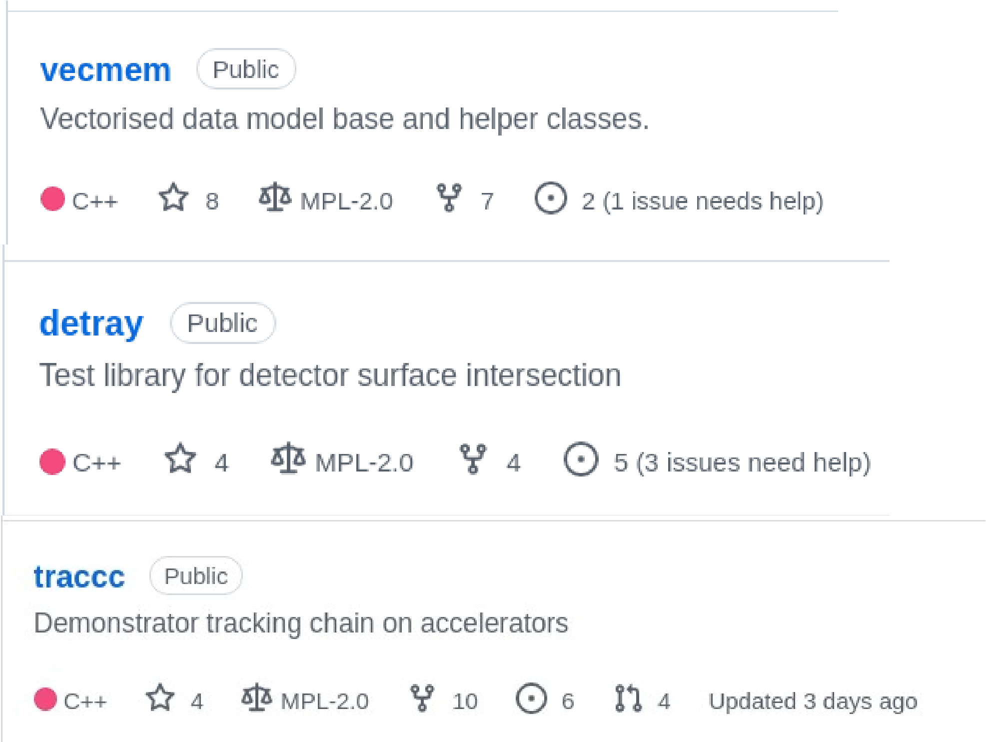
Sys.		S×C×T	Clock rate (GHz)	Mem. (GB)
1	Intel Xeon E5-2698 v3 (Cori-Haswell-CPU)	2×16×2	2.30	128
1	Intel Xeon Phi 7250 (Cori-KNL-CPU)	1×68×4	1.40	96
2	Intel Xeon Gold 5115 (NAF-SL-CPU)	2×10×2	2.40	376

GPU

Sys.		FP32 cores	FP64 cores	Clock rate (GHz)	Mem. (GB)
1	GV100-SXM2 (Cori-V100-GPU)	5120	2560	1.53	16
2	GP100-PCIe (NAF-P100-GPU)	3584	1792	1.48	16
2	GV100-SXM2 (NAF-V100-GPU)	5120	2560	1.53	32

ACTS R&D: accelerating the full tracking chain

- On-going development **towards a full tracking chain on GPU** in ACTS community
  - Needs general solutions for difficulties with GPU: C++ STL containers and algorithms not usable, polymorphism not supported ...



Designing **STL-like containers** and memory manager for both CPU and GPU

See S. Swatman's talk at ACAT21

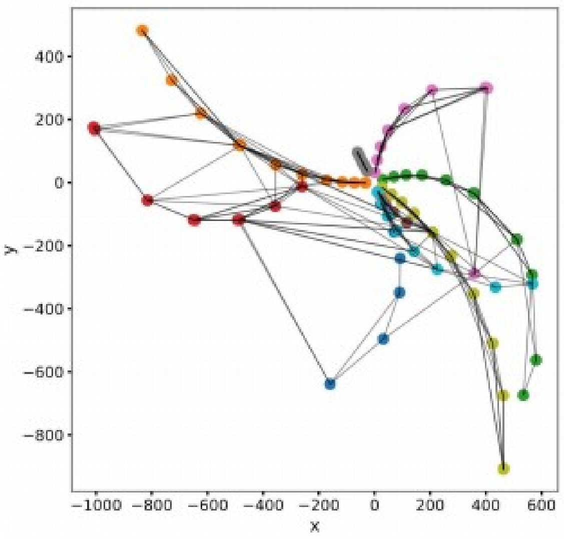
Geometry navigation **without runtime polymorphism** based on indiced surfaces (boundaries, transformations, material...)

See J. Niermann's talk at ACAT21

DESY is actively invovled:
G. Mania, N. Styles

ACTS R&D: Machine Learning-based tracking

- ML is widely deployed in tracking domain
  - GNN for track finding (e.g. Exa.TrkX)
  - Evolutionary algorithm for parameters tuning
  - DNN based track classification
  - KNN for surface prediction
- The microsoft ONNX plugin was implemented in ACTS to allow deployment of ML solutions
  - Implementation of GNN in ACTS is being discussed



See poster at ACAT21

Summary

- Tracking will be more challenging at the HL-LHC era and other future particle and nuclear physics experiments
- ACTS is preparing a modern performant generic tracking software for this
- Growing interest from nuclear and particle experiments (utilized by >10 experiments)
- Active R&D lines within ACTS to accommodate the new computing landscape
- Outlook
  - There are still tools to develop and optimize in ACTS
  - Interplay with experiment frameworks is the key to make a real generic toolkit

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

Mattermost https://mattermost.web.cern.ch/acts/channels/town-square

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

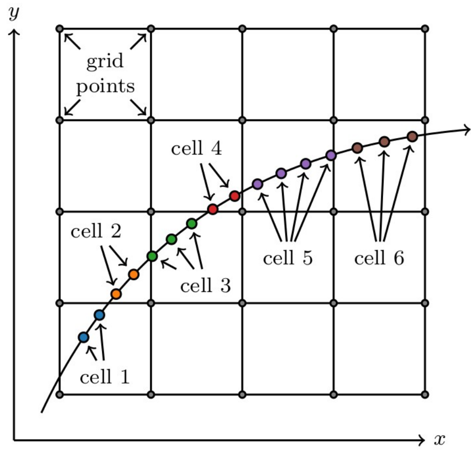
Q&A

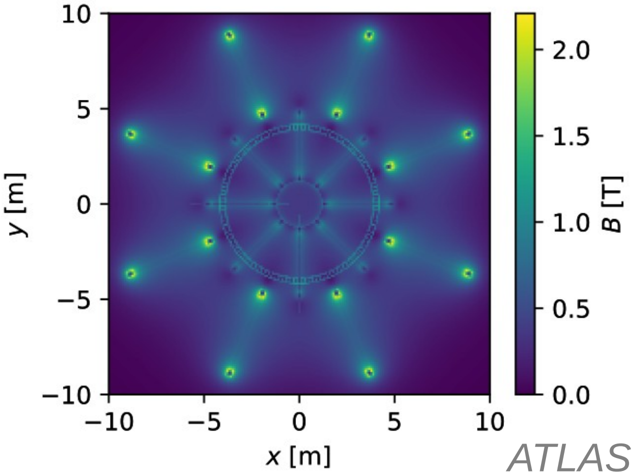
Backup

ACTS magnetic field

- Magnetic field interfaces:
  - Constant magnetic field
  - Interpolated magnetic field
    - Calculates an interpolated B field value from a grid of known field values
  - Analytical solenoid magnetic field
    - Calculates field vectors analytically

Interpolated magnetic field





ATLAS Magnetic field in ACTS

- Magnetic field access:
  - Cache of field value make the access less expensive
  - To ensure thread-safety, the field cell is cached by client and passed between client and magnetic field service via client function argument

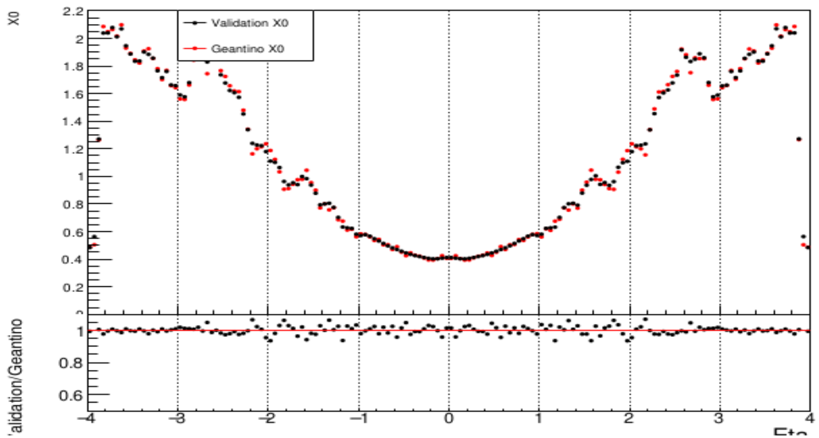
Material description

- Material effects need to be considered in tracking

Surface mapping for e.g. Silicon:

- Mapping material to discrete binned surfaces
- Material is considered when surface is crossed

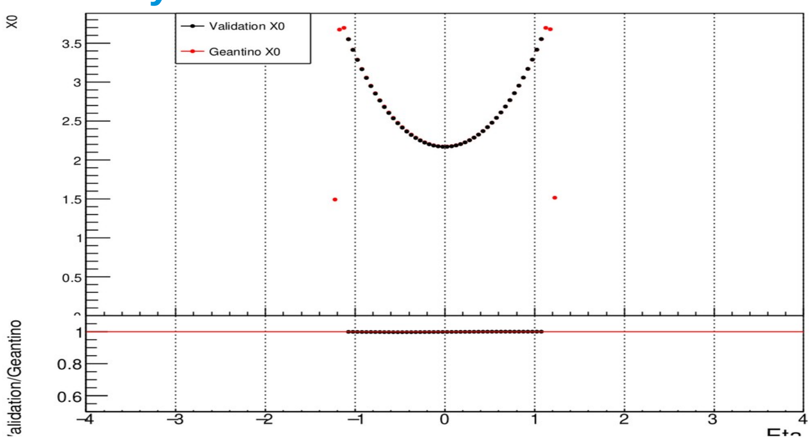
X0 ratio Validation/Geantino vs η for ITk



Volume mapping for e.g. Calorimeter:

- Mapping material to 3D volume grid points
- Material considered at each propagation step

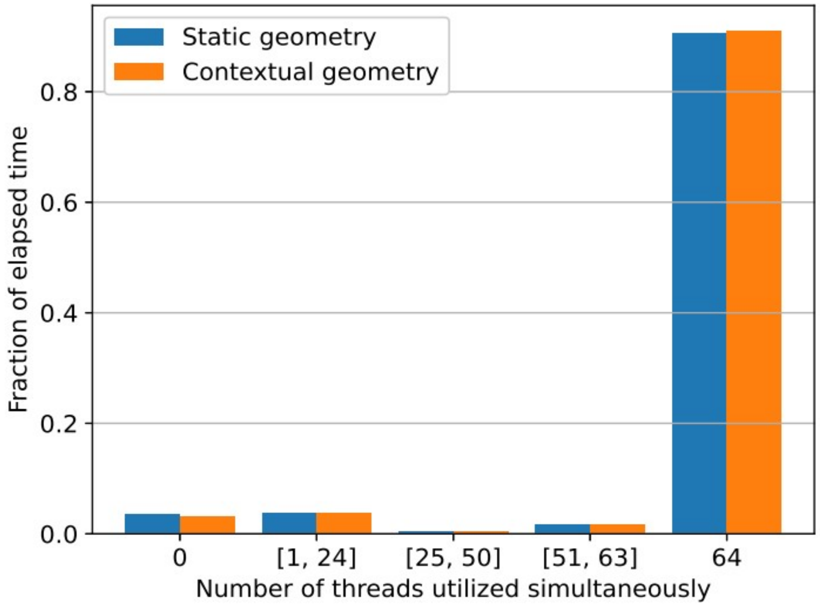
X0 ratio Validation/Geantino vs η for a dummy Calorimeter



Concurrency and parallelization in ACTS

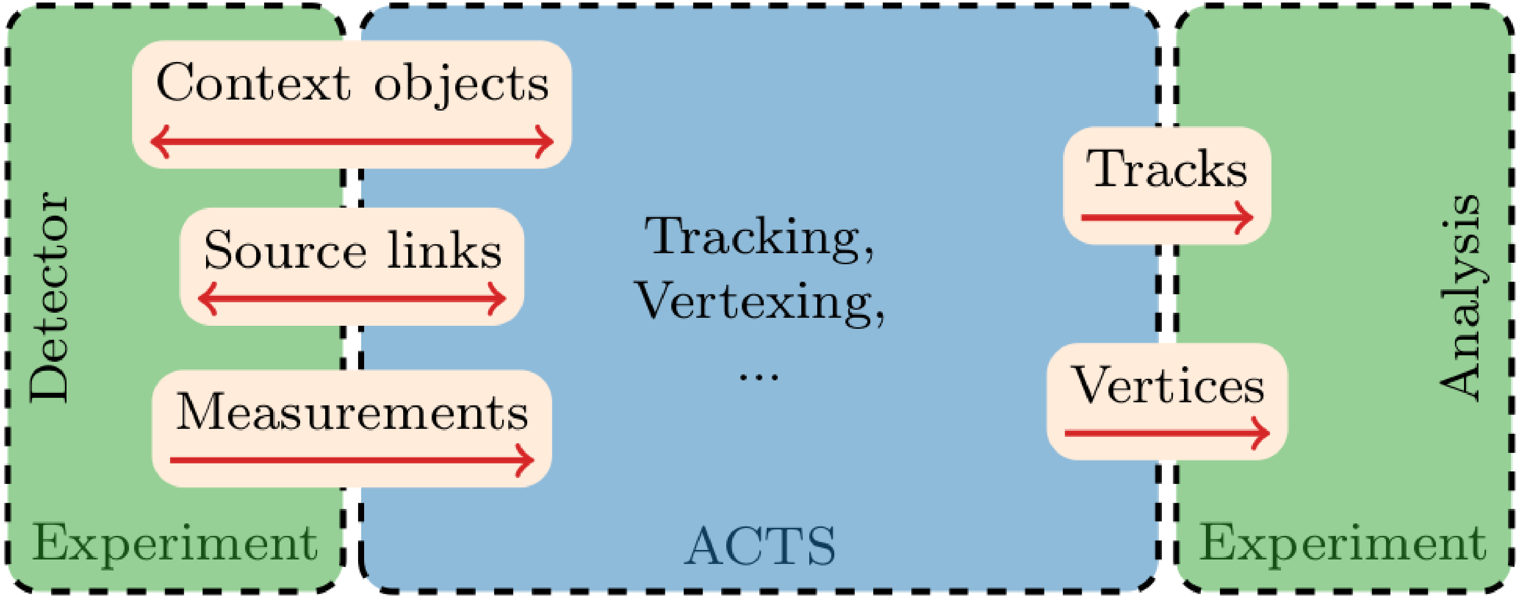
- ACTS is designed to support both inter- and intra-event parallelization
  - Stateless and const-correct tools
  - Contextual data design to support concurrent event execution with multiple conditional data on flight
    - Calibration, alignment and Magnetic field data
  - Concurrent code execution tested within unit and integration test suites

Efficient CPU utilization even with contextual geometry



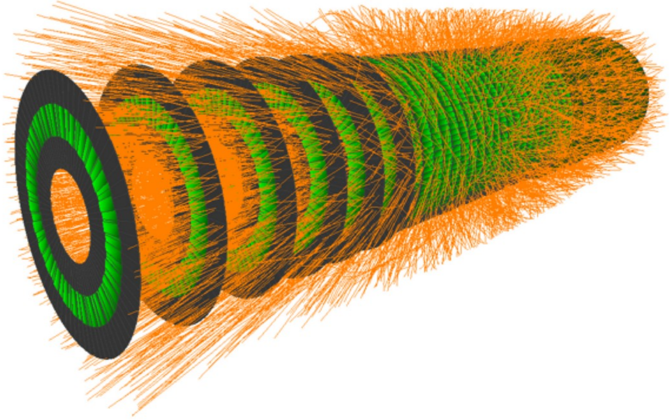
arXiv:2106.13593v1

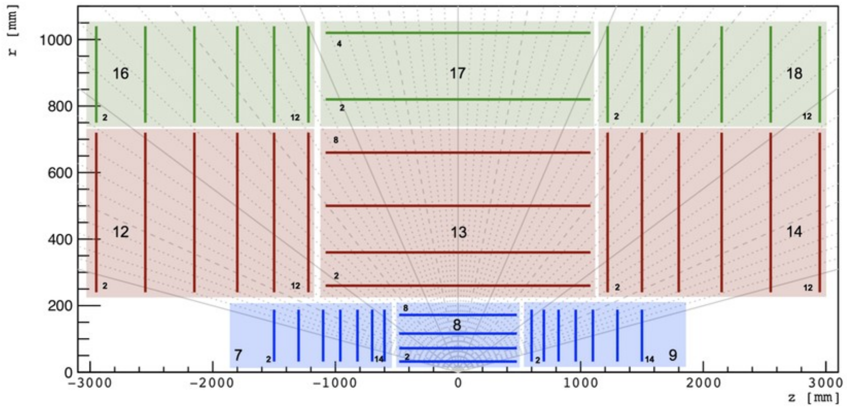
Integration of ACTS into experiment software



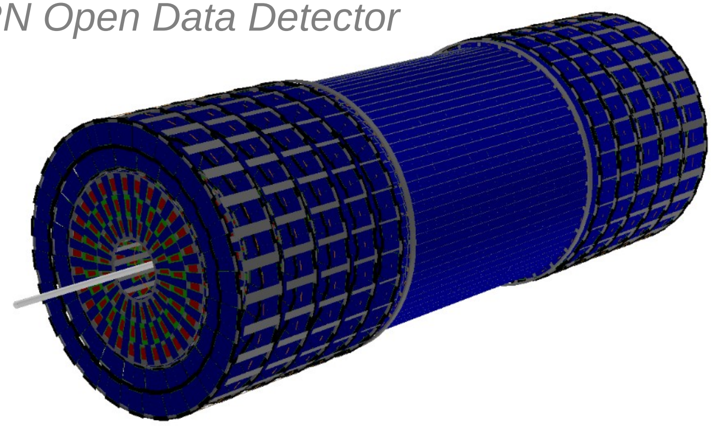
The detectors used for development

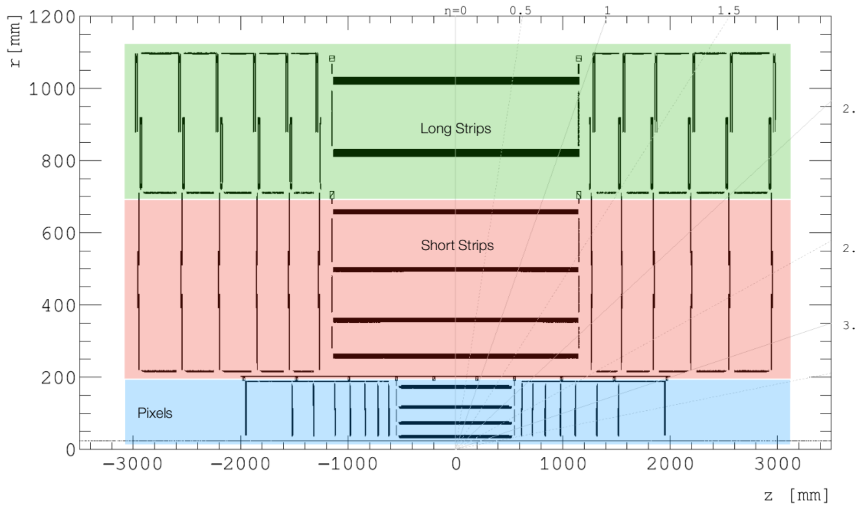
The TrackML detector





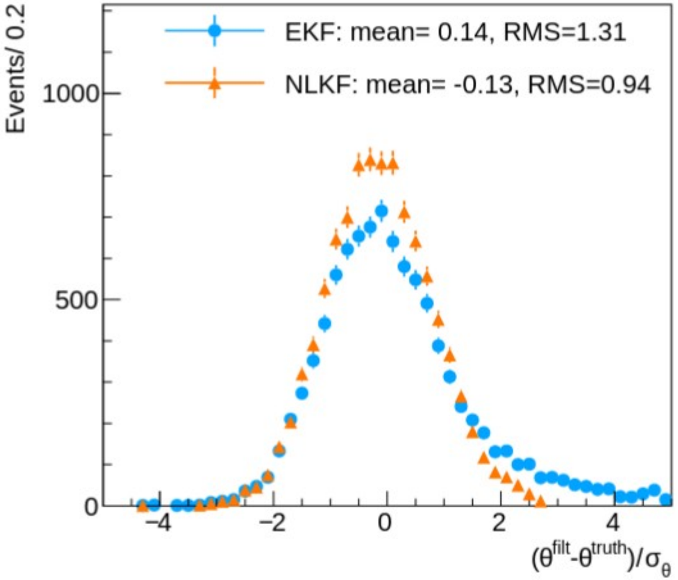
The CERN Open Data Detector

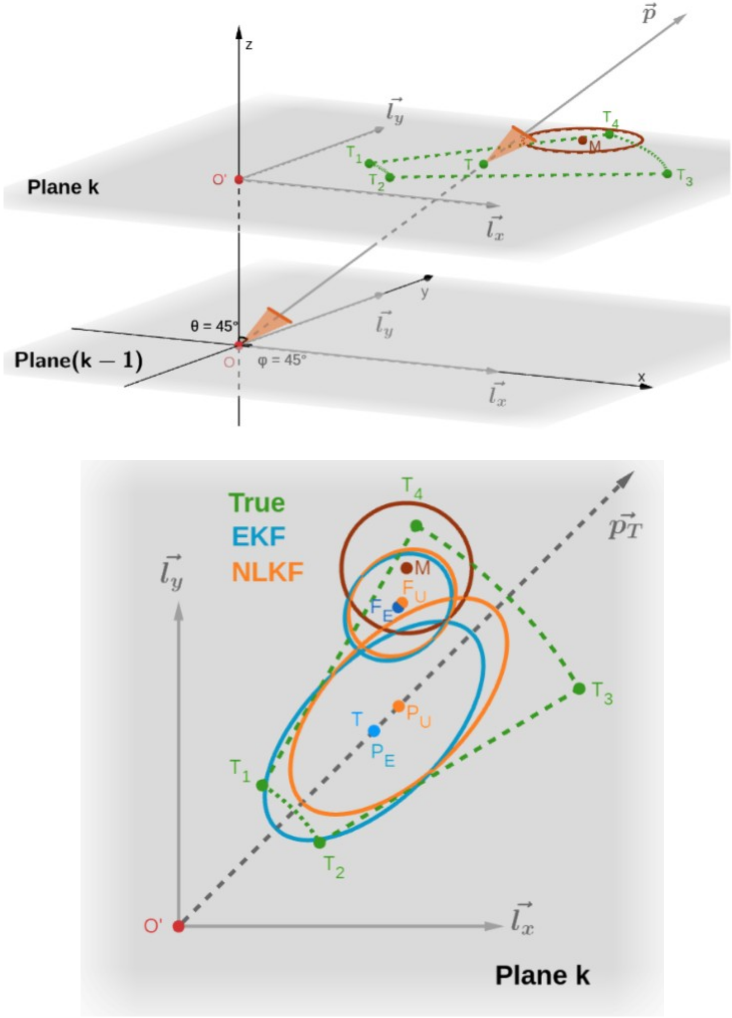




The non-linearity in tracking

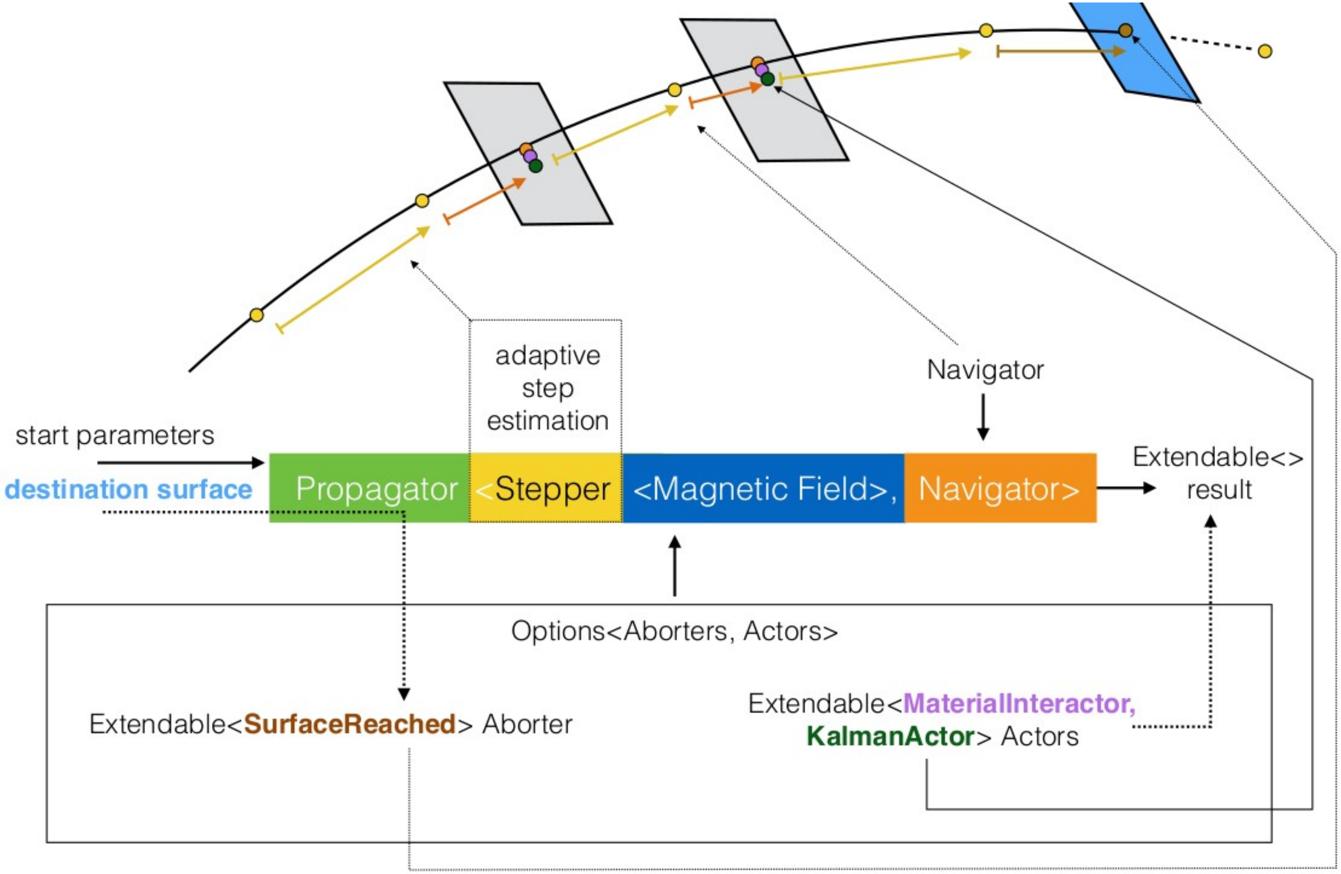
- The (extended) KF used in HEP is optimal for linear system
- Tracking precision is degraded by significant non-linear effects with large incident angle





ACTS Track parameter propagator interface

Integrating particle transport & geometry navigation
Highly-templated design emphasizing on speed and customizability



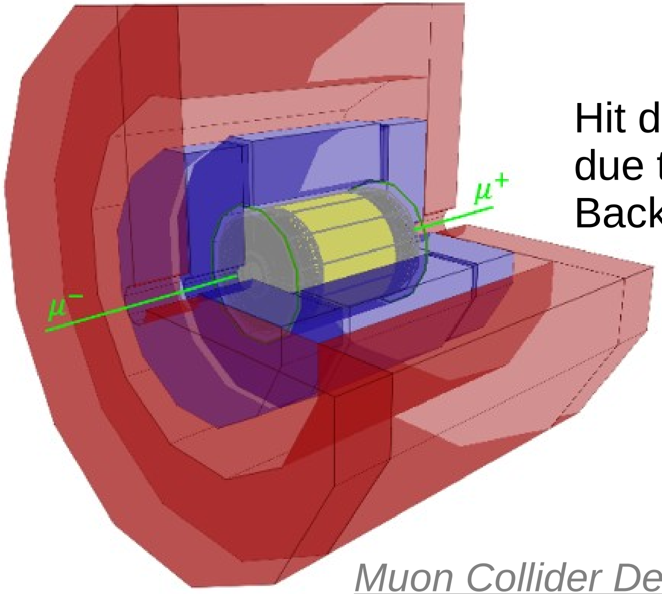
ACTS application example: Muon Collider

International MUON Collider Collaboration

Great potential for discovery in the multi-TeV energy range!

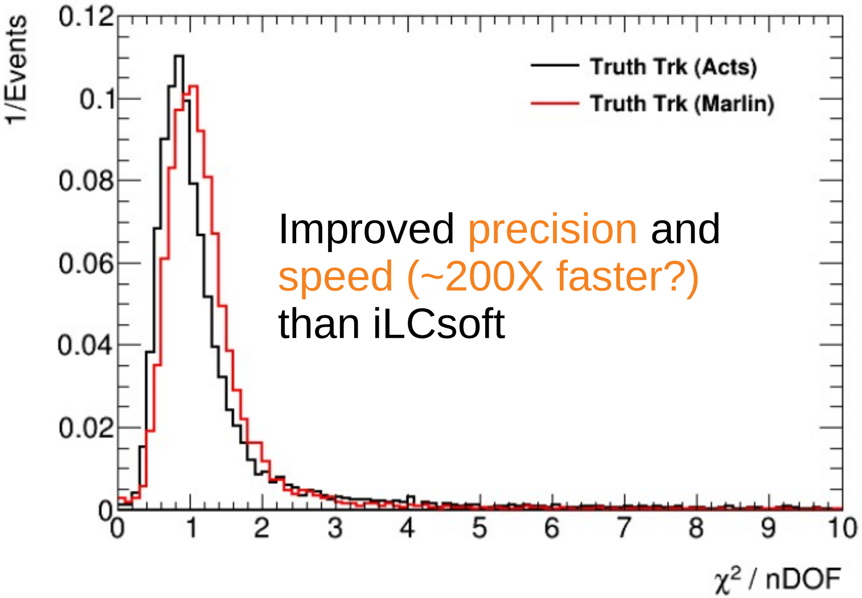
EW measurement, Higgs couplings, new resonances DM search …

Hit density is 10x HL-LHC due to Beam Induced Background (BIB)



Muon Collider Detector

Plots from K. Krizka



Improved precision and speed (~200X faster?) than iLCsoft

Fit Library	Execution Time
ACTS	0.5 ms / evt
iLCsoft	100 ms / evt