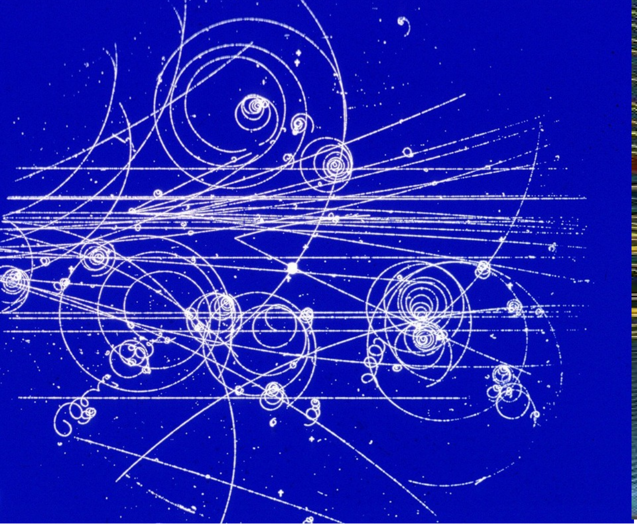
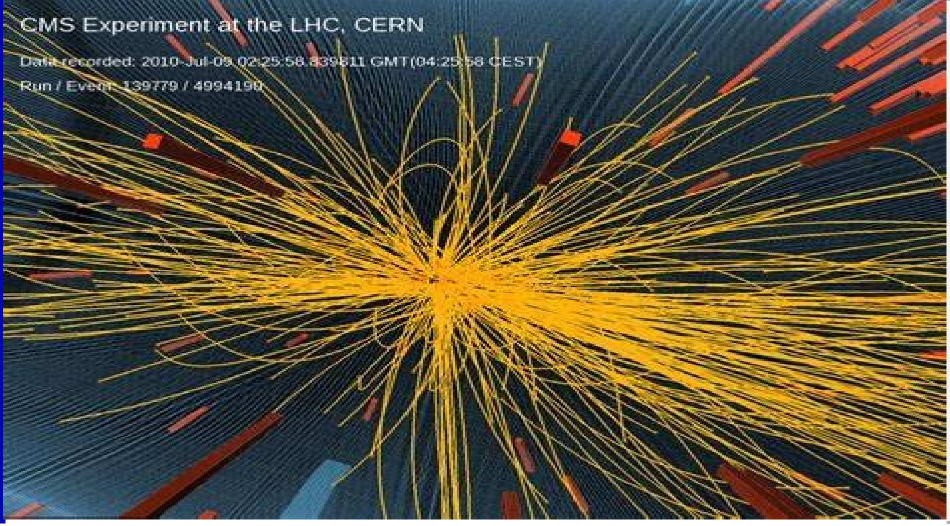
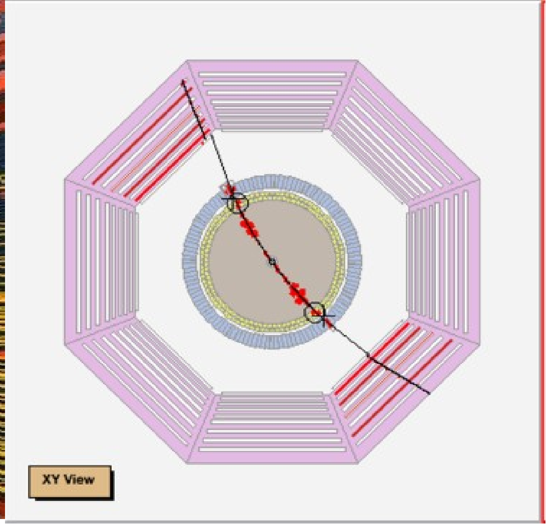





A Common Tracking Software for particle and nuclear physics experiments and GPU-accelerated tracking

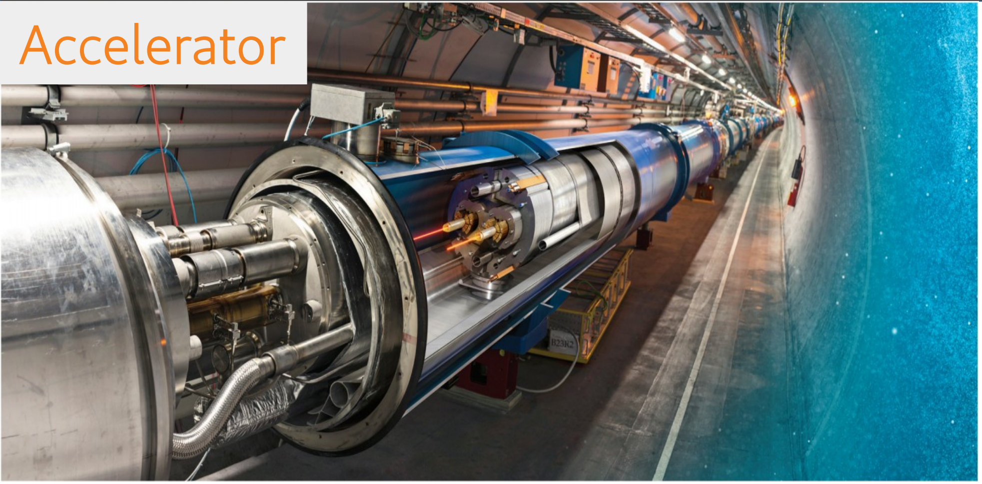
艾小聪 (xiaocongai@zzu.edu.cn), Zhengzhou University

May 26, 2023, USTC Seminar

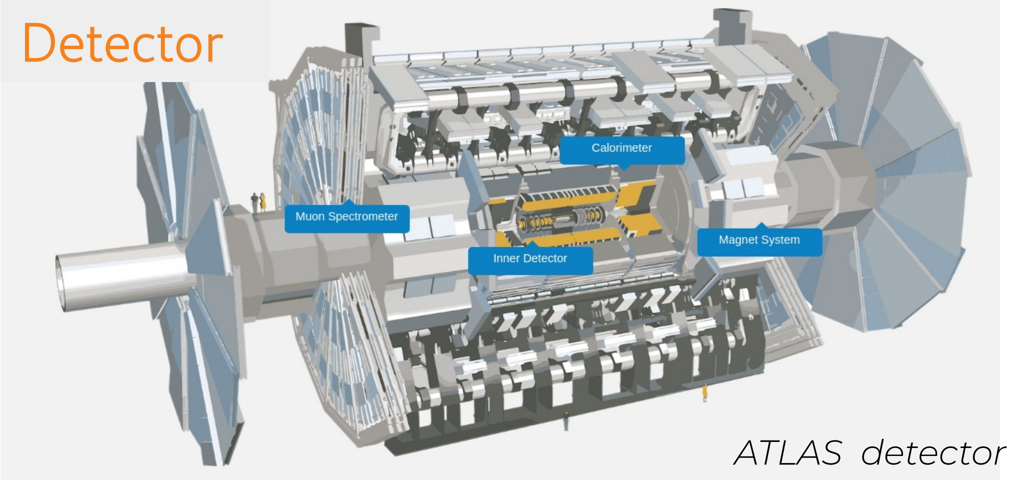
What is tracking?

What makes a particle and nuclear experiment?

Accelerator

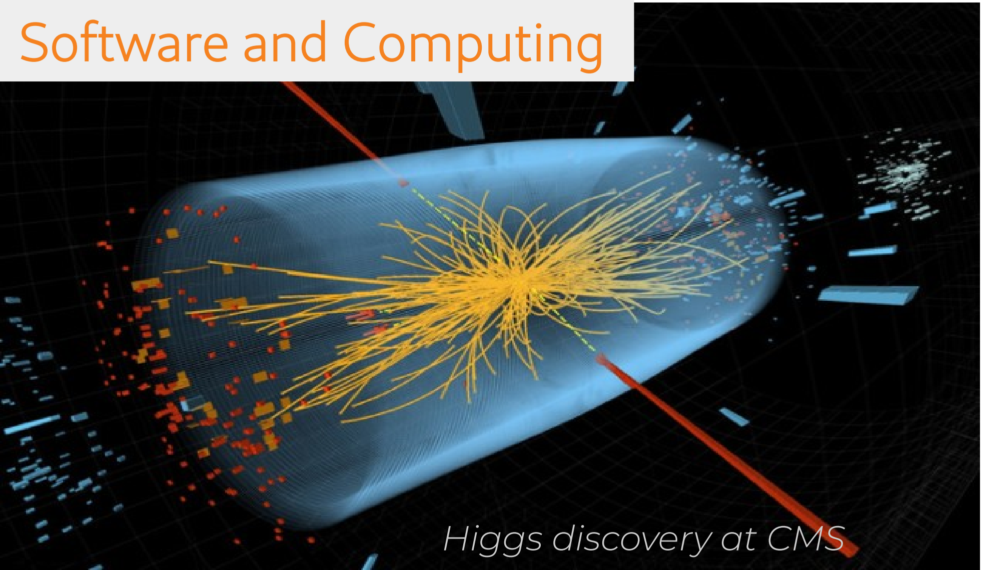


Detector



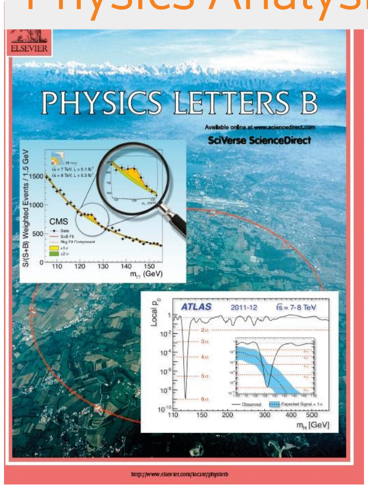
ATLAS detector

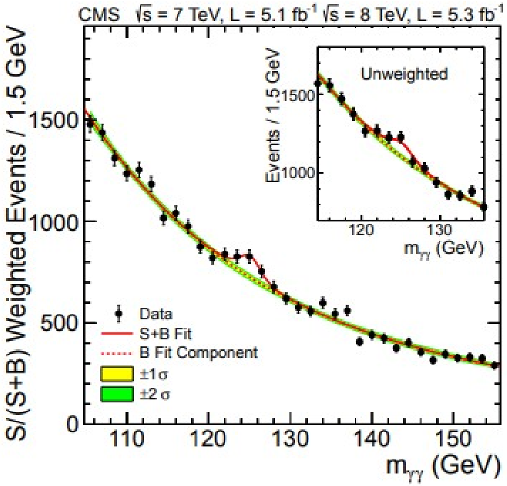
Software and Computing



Higgs discovery at CMS

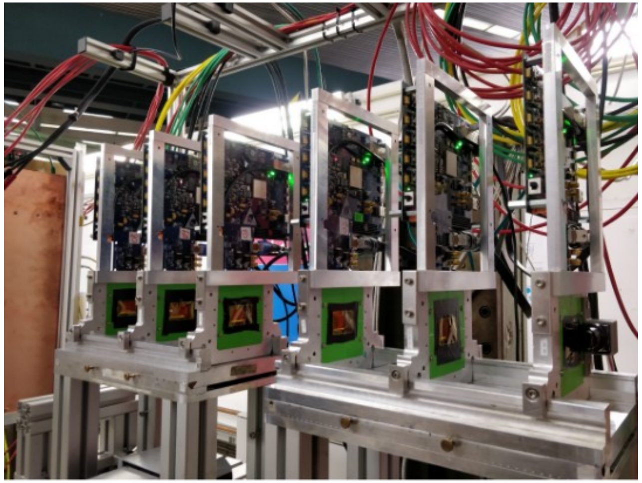
Physics Analysis





What is the role of software and computing in HEP&NP?

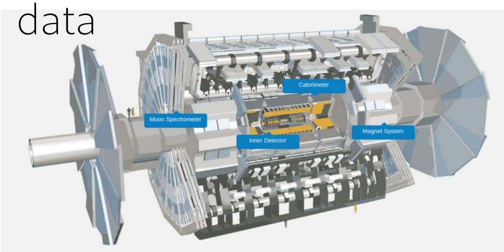
- Guide and support the **design, characterization and construction** of detector through **detector simulation**
- **Turns the recorded data by detectors into physics objects** for ultimate extraction of physics signals
  - Reconstruction, identification, calibration

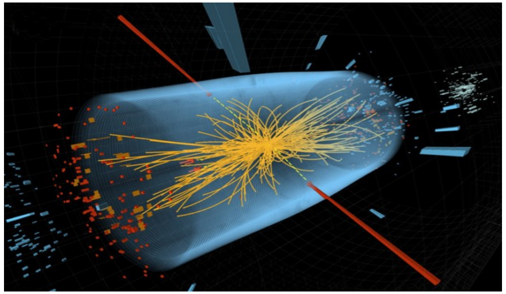


ALPIDE Addenium telescope at DESY

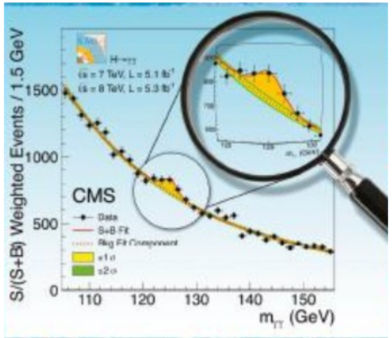
MC: event generation + simulation + digitization

data





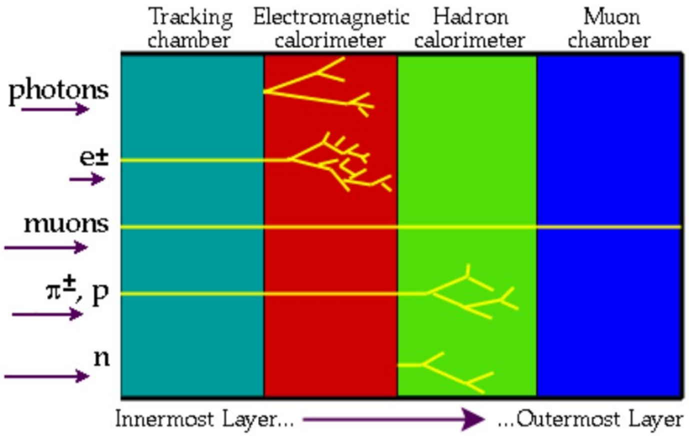
Particle position, drift time, flight time, deposited energy…

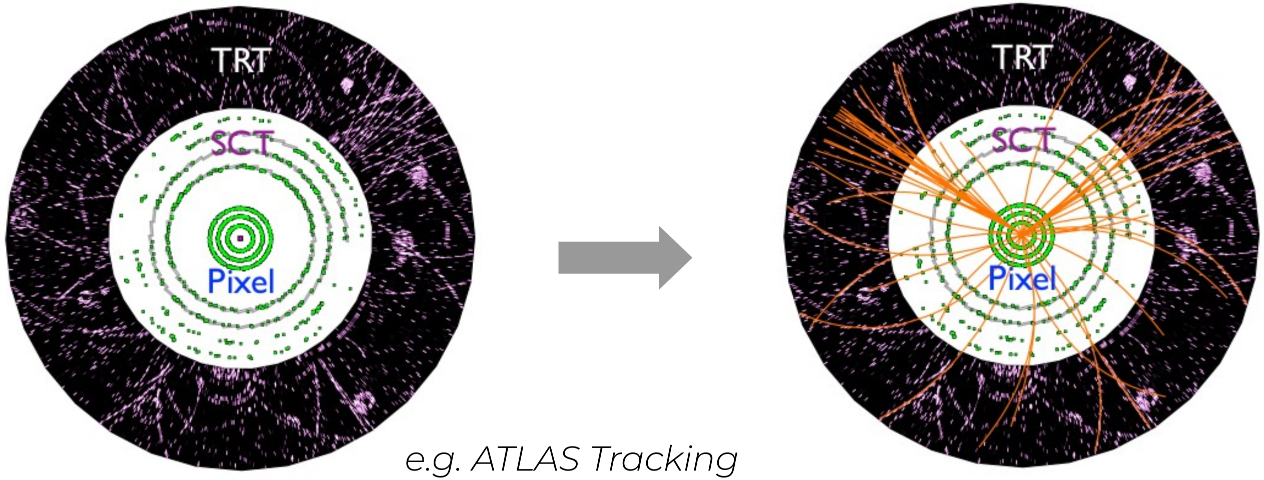


Tracks, vertexs, e, μ, τ, b/c/light-flavor jet, charged hadrons, neutron, K_L, missing energy

What is track reconstruction (a.k.a. tracking)?

- **Reconstruction** (i.e. track finding) of charged tracks and **measurement** (i.e. track fitting) of their quantities, using the signals of trackers (usually in magnetic field)
  - Position
  - Momentum
  - Charge
  - Vertex
  - Velocity (dE/dx)



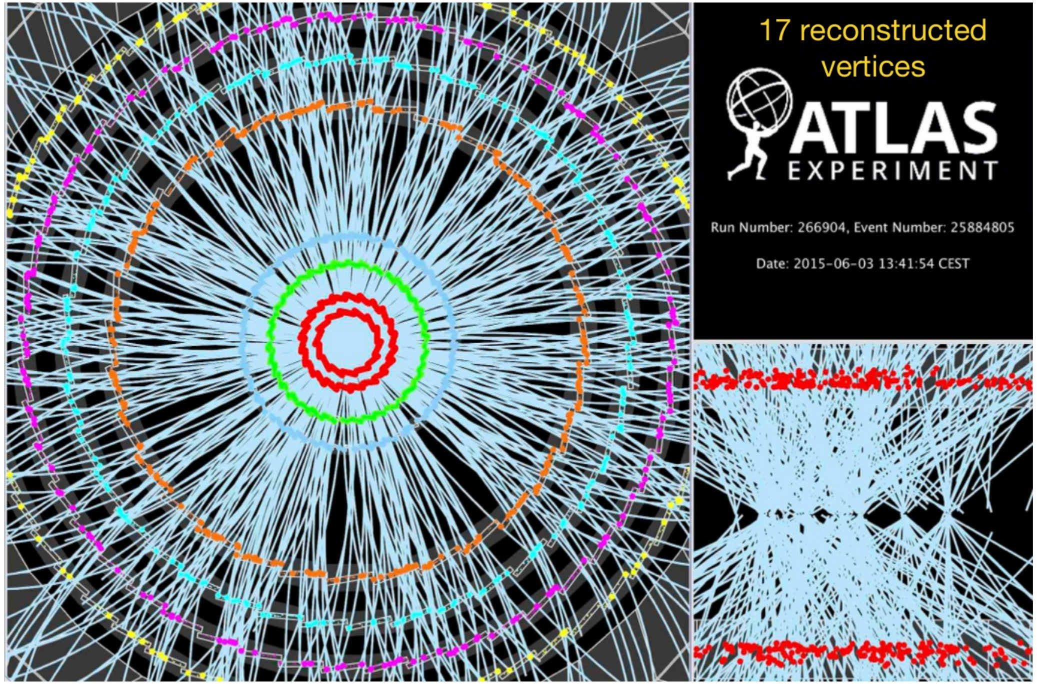


e.g. ATLAS Tracking

Why tracking matters?

Tracking is about vertex reconstruction

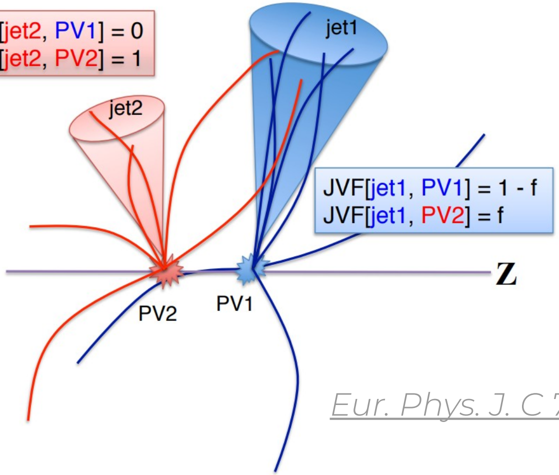
- Primary vertex reconstruction uses estimated track parameters of charged particles as inputs
  - Vertex finding
    - Associate tracks to vertices
  - Vertex fitting
    - Estimate vertex position



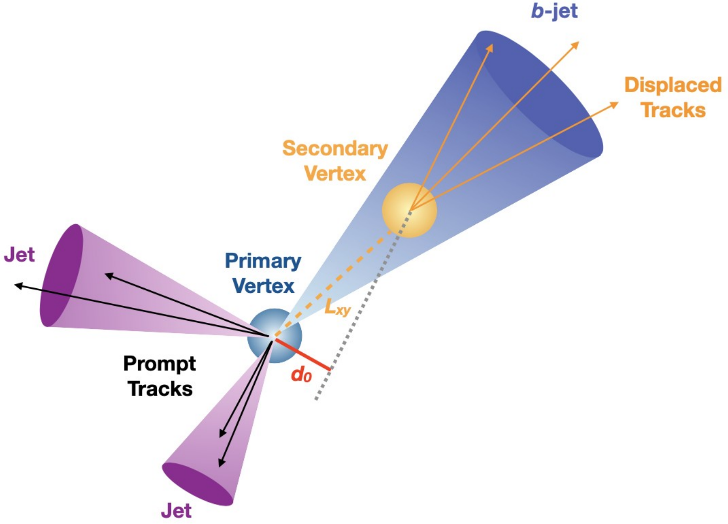
Tens to hundreds of additional proton–proton collisions accompanying the hard-scatter interaction, i.e. pile-up (μ)

Tracks/vertices are not just about charged particles

- Jets and missing energy reconstruction
  - Better p_T resolution for low p_T tracks and angular resolution provided by tracker
  - Tracks/vertices are crucial for pile-up mitigation (needs precise jet-vertex association)
- Jet flavor-tagging (b, c or light-flavor jet)
  - Impact parameters, secondary vertices and length of flight
- Reconstruction of photon conversion vertex
  - Important input for e/γ discrimination



Eur. Phys. J. C 76, 581



Tracking is about detector alignment

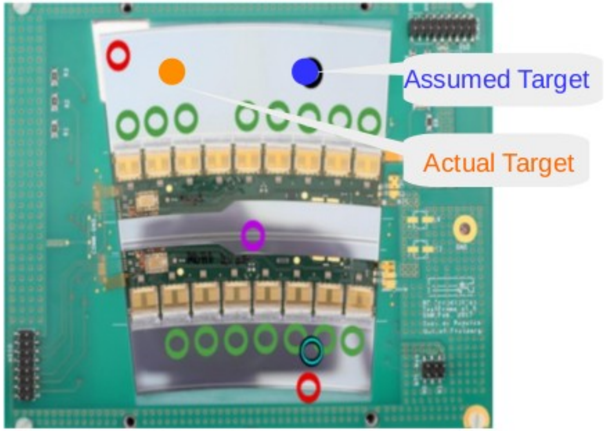
- Misalignment will deteriorate the track resolution, but tracking can notice and correct the misalignment
  - Track-based alignment is a common practice

Local track parameters and global alignment parameters

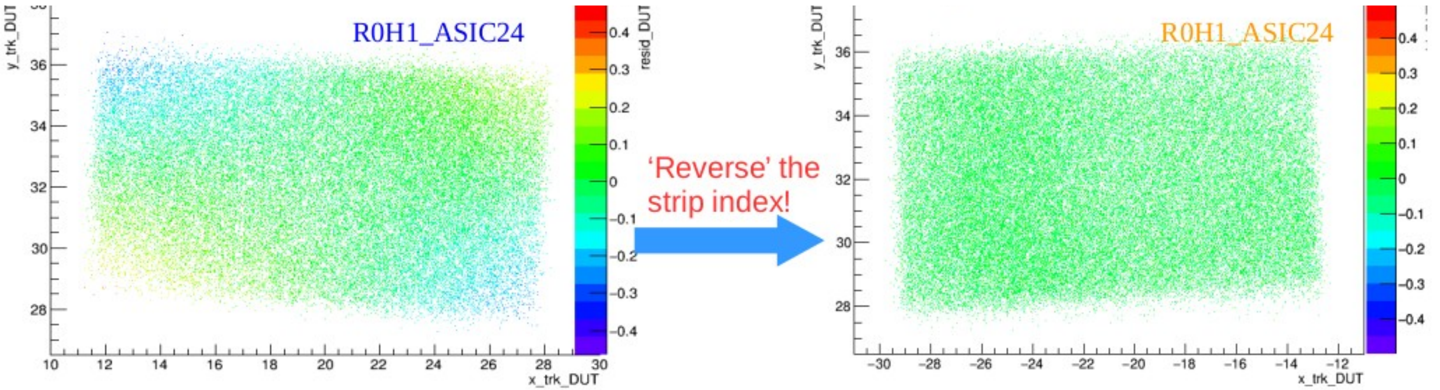
$$\chi^2 = \sum_i {\chi_i}^2 = \sum_i [\vec{m}_i - \vec{h}_i(\vec{x}_i(\vec{\alpha}), \vec{\alpha})]^T V^{-1} [\vec{m}_i - \vec{h}_i(\vec{x}_i(\vec{\alpha}), \vec{\alpha})]$$

$$\frac{d^2\chi^2}{d^2\vec{\alpha}} |_{\vec{\alpha_0}} \Delta\vec{\alpha} = -\frac{d\chi^2}{d\vec{\alpha}} |_{\vec{\alpha_0}}$$

First ATLAS ITk Endcap strip R0 module at testbeam in 2017



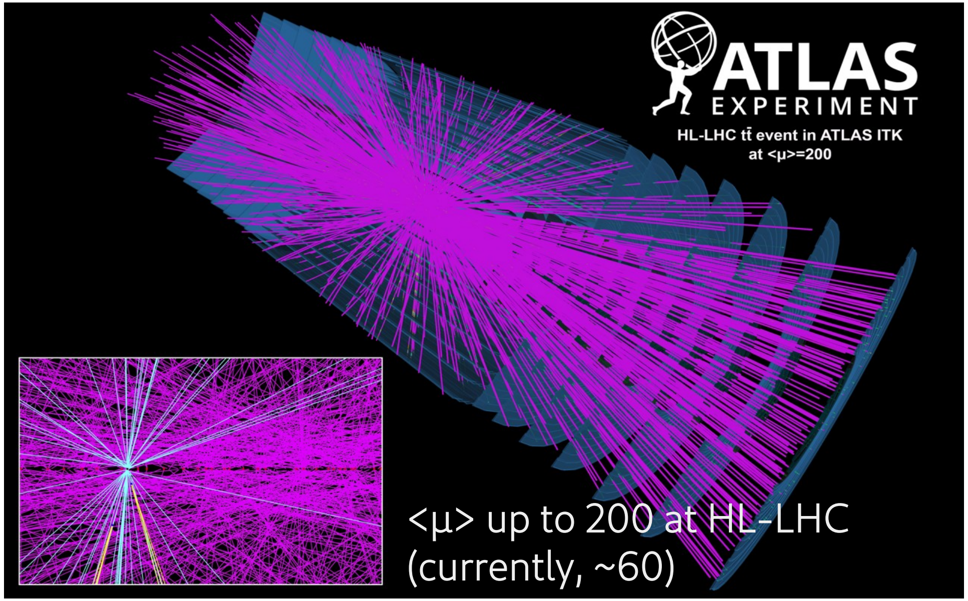
A mistake of moving DUT to wrong target is detected by alignment!

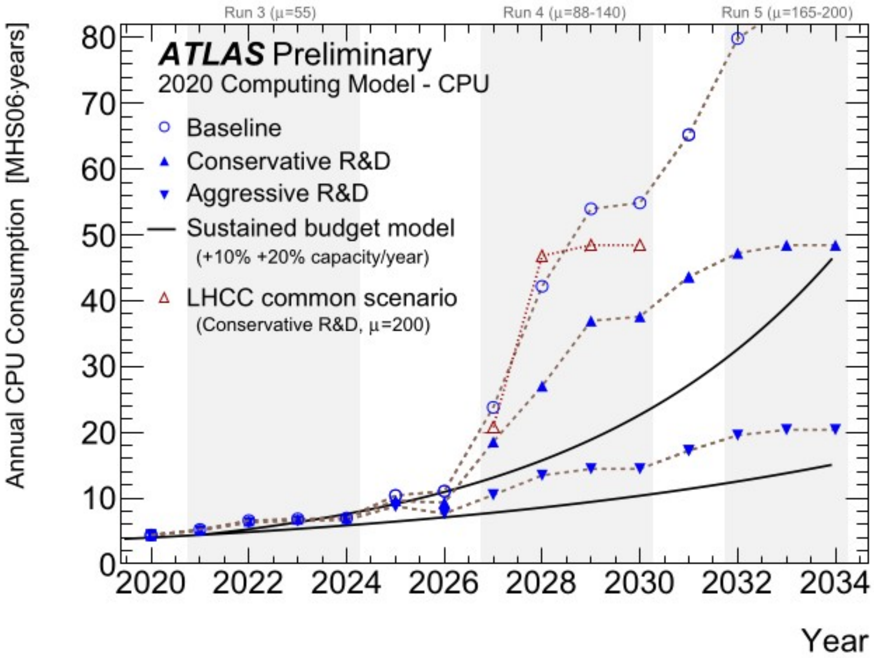


Tracking is challenging

Much more dense environment

- Future colliders tend to have much increased luminosity => higher pileup, e.g.
  - <μ> = 200 at HL-LHC, <μ> = 1000 at FCC-hh
- Much **increased combinatorics, data rate and CPU needs**
  - ~7k particles/event at HL-LHC

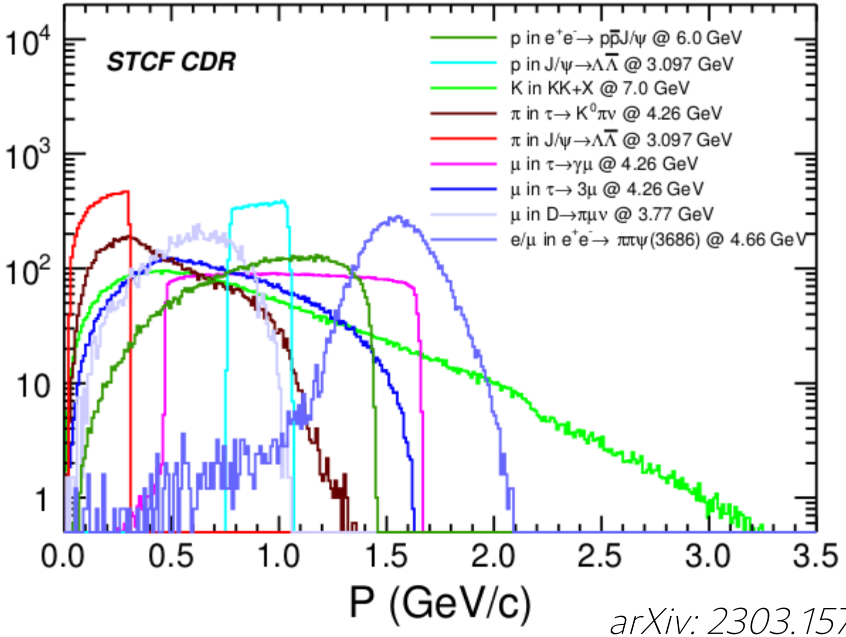




More strict tracking requirements

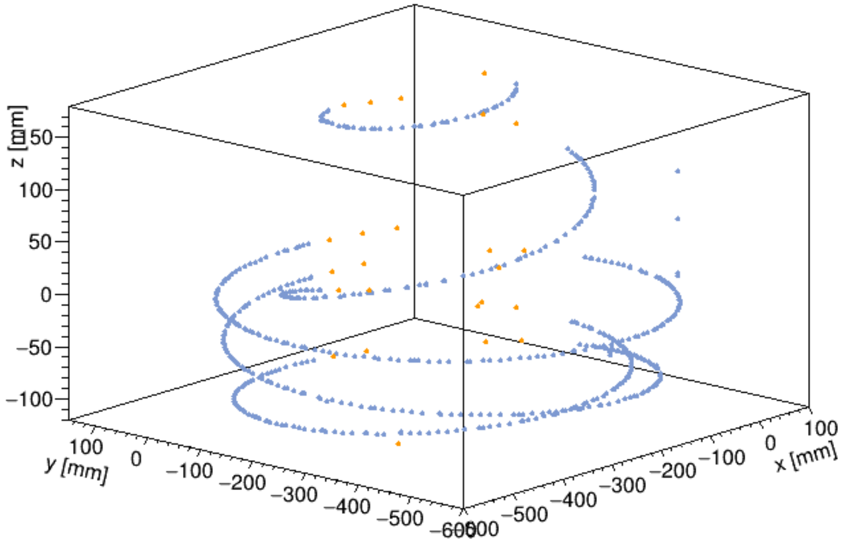
- Tracking of **low p_T tracks** is very important at future flavor factories
  - e.g. tracking eff. > 50/90/99 % with pt > 50/100/300 MeV at STCF (important to probe CPV in $\tau \to K_S \pi \nu_\tau$ and $J/\psi \to \Lambda\bar{\Lambda}$)

Momentum distributions of charged particles



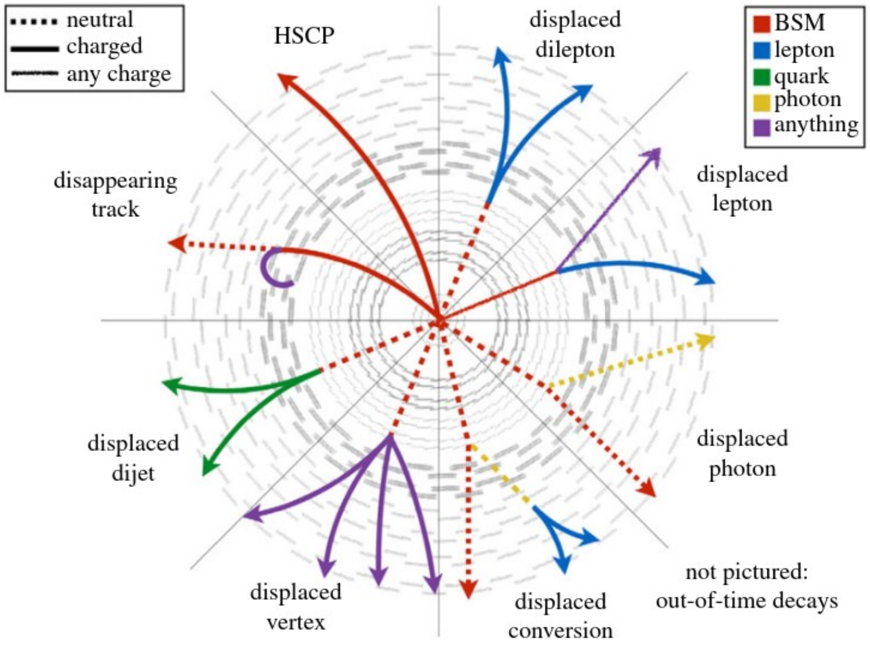
arXiv: 2303.15790

An example of muon trajectory (pT = 100 MeV, theta = 90) at STCF



More complex tracking signatures

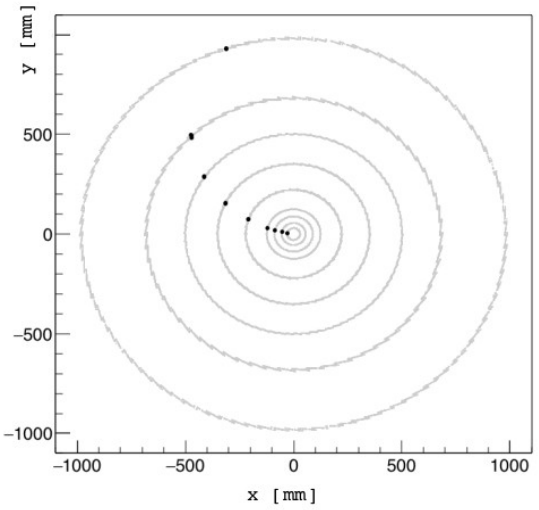
- Tracking of **long-lived particle (LLP) signatures** is import for New Physics search:
  - Displaced tracks
  - Disappearing tracks
  - Anomalous Ionization
  - Magnetic monopole
  - Fractional/multiple Electric Charge



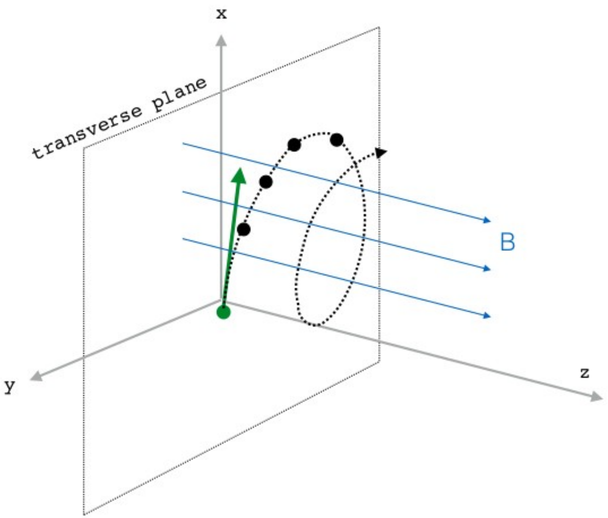
Phil. Trans. R. Soc. A 377, 20190047

Tracking strategies

A helix trajectory in homogeneous magnetic field



arxiv:1904.06778



$$\frac{d^2\mathbf{r}}{ds^2} = \frac{q}{p}\left[\frac{d\mathbf{r}}{ds} \times \mathbf{B}(\mathbf{r})\right]$$

Track propagation is solved numerically using fourth-order Runge-Kutta-Nyström method

Track parameterization

- Described by five parameters (three for transverse + two for longitudinal)

ATLAS parameterization (no assumption of helix):

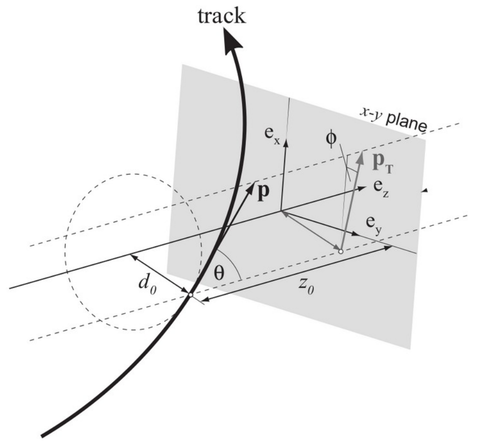
(loc0, loc1, ϕ, θ, q/p)

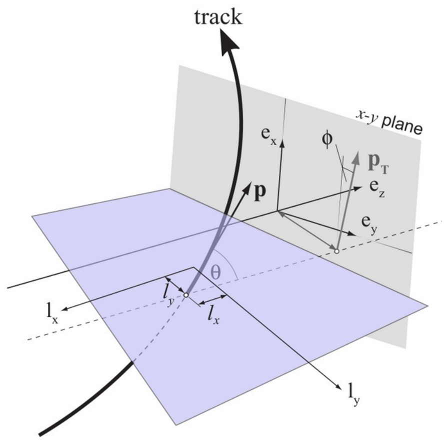
loc0, loc1: track position

ϕ, θ: track direction

q: charge

p: momentum





From E. Moyse

BESIII, Belle II... parameterization:

(d_0, ϕ, κ, d_z, $\tan\lambda$)

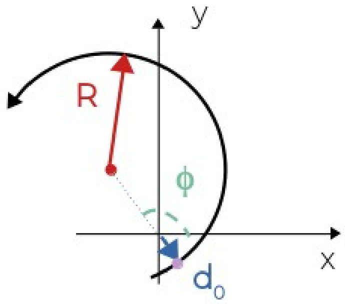
d_0 : distance between reference point to track on xy plane

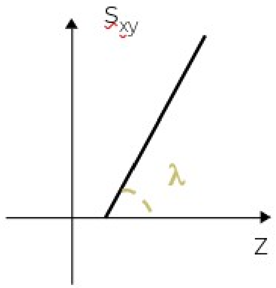
ϕ (ϕ_0) : azimuthal angle of line connecting reference point and circle center on xy plane

$\kappa(\omega)$: (signed) circle curvature

d_z : z coordinate of POA

$\tan\lambda$: ratio of path length on xy (s_{xy}) and along z

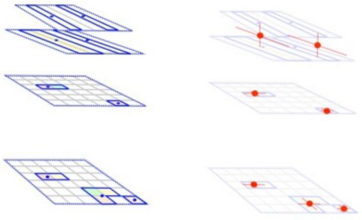




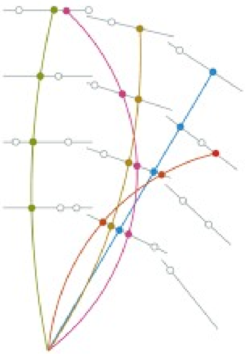
How to find & fit tracks ?

Input preparation → Track finding → Track fitting → Physics object reconstruction

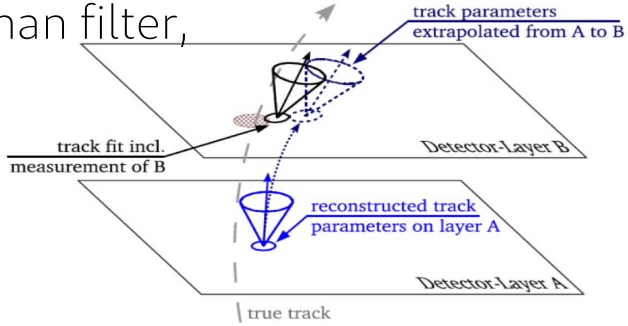
- Raw data converted to cluster/drift circle
- Formation of 3D space point



- Identify measurements to individual tracks
  - Global approach: Hough transform, Graph Neural Networks
  - Local approach: Cellular automaton, Combinatorial Kalman Filter (CKF)

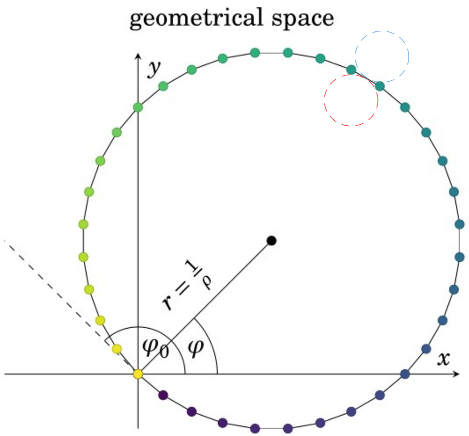


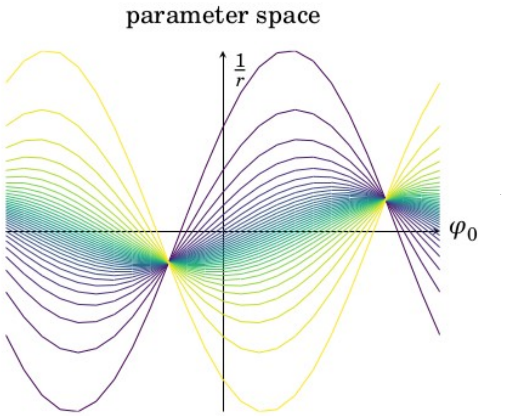
- Estimate the track parameters
  - Least-square fitter (superceded by Kalman filter, can resolve left/right ambiguity)
  - Kalman-filter



Hough Transform

- Each point (x, y) or a drift circle in geometrical space is transformed to a curve (described by two circle parameters) in parameter space
- Track finding becomes finding crossing points of curves in parameter space





e.g. a point (x,y) on the helix circle:

$$0 = x^2 + y^2 - 2r \cdot (x \cdot \cos\varphi + y \cdot \sin\varphi)$$

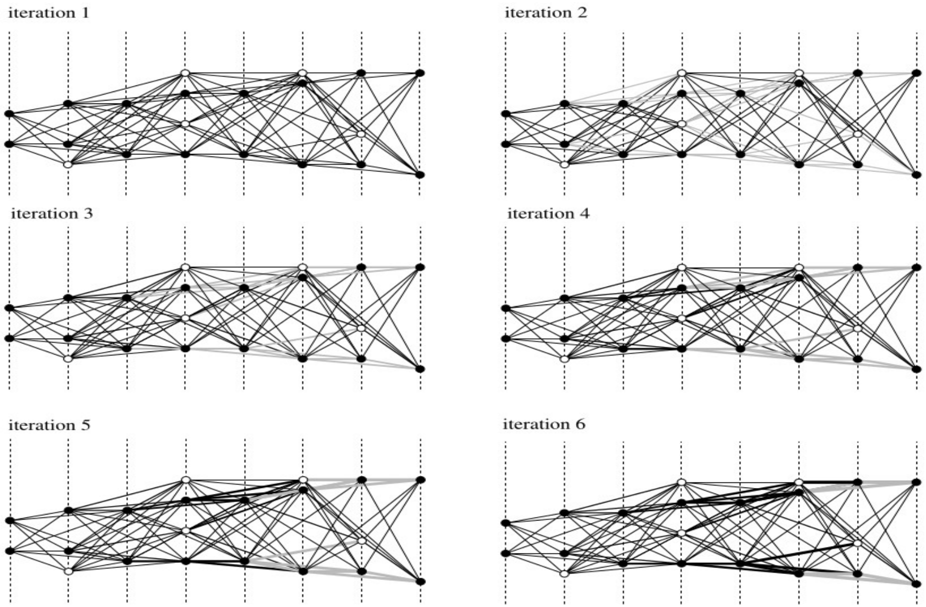
$$\frac{1}{r} = \frac{2}{r_P} sin(\varphi_0 - \varphi_P)$$

$$r_P = \sqrt{X^2 + Y^2}, \alpha_P = arctan(Y/X)$$

Figures from Sara Pohl's thesis

Cellular Automaton

- A cell is a duplet (two hits) with state (describing the "depth" of the cell in a track)
- Evolution of depth of cells following certain "game life"
  - In one evolution, simultaneous revisiting of all cells (increment of the cell depth by one if there is compatible left-sided/inner neighbor and its depth is the same as the neighbor)



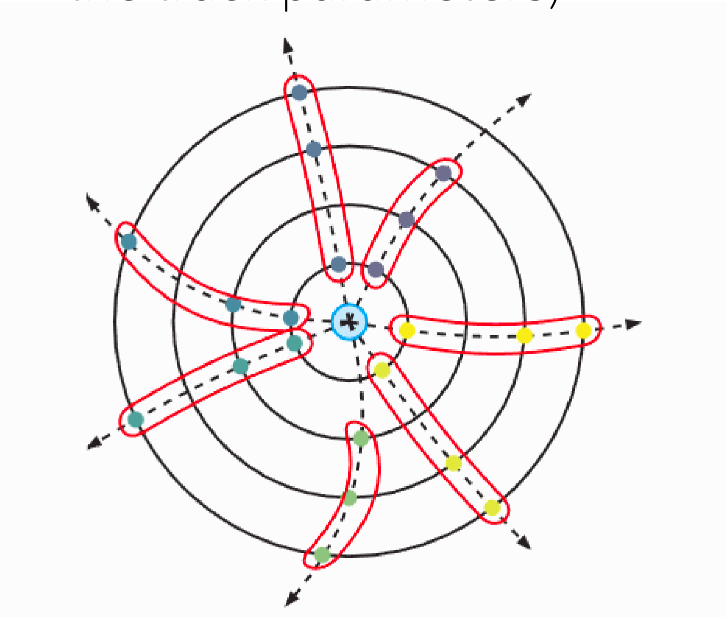
NIMA 489, 389

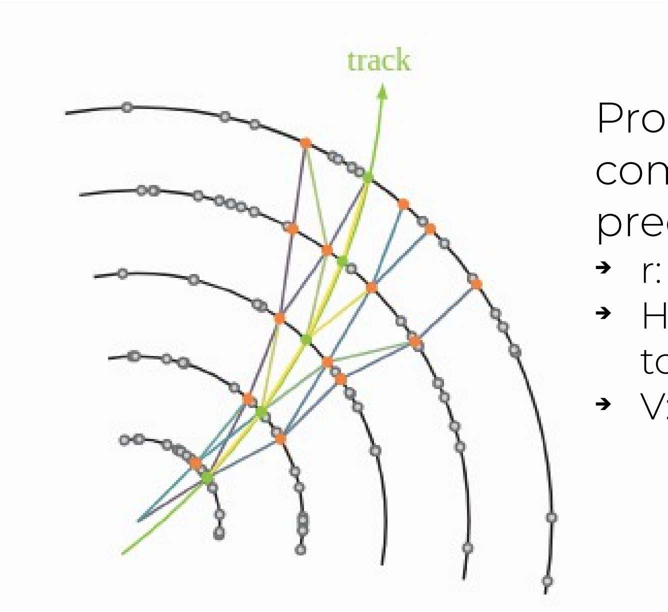
Combinatorial Kalman Filter

Seeding
(provides initial estimate of the track parameters)

→

Combinatorial Kalman Filter
(track finding through KF fitting)





Progressingly associate compatible hits to tracks based on prediction $\chi^2 = r^T (HCH^T + V)^{-1} r$

- r: residual
- H: projection from track parameters to measurement
- V: measurement covariance

Figures from ACTS readthedocs

Towards a modern, efficient, accurate and fast common tracking software

Why a common tracking software?

- Tracking is a necessity at particle and nuclear physics experiments
- Tracking experience can be shared with different experiments
- Common software can save manpower from duplicated development and facilitate the long-term maintenance
  - e.g. great success of GEANT4, ROOT, DD4hep…!
- Understanding and optimizing old tracking software which is usually >20 years old is never easy!

A Common Tracking Software (ACTS) project

- A modern open-source **detector-independent tracking toolkit** for current&future HEP experiments (ATLAS, ALICE, sPHENIX, FASER, MUC, CEPC, STCF…) based on LHC tracking experience
- A **R&D platform** for innovative tracking techniques (ML) & computing architectures (GPU)

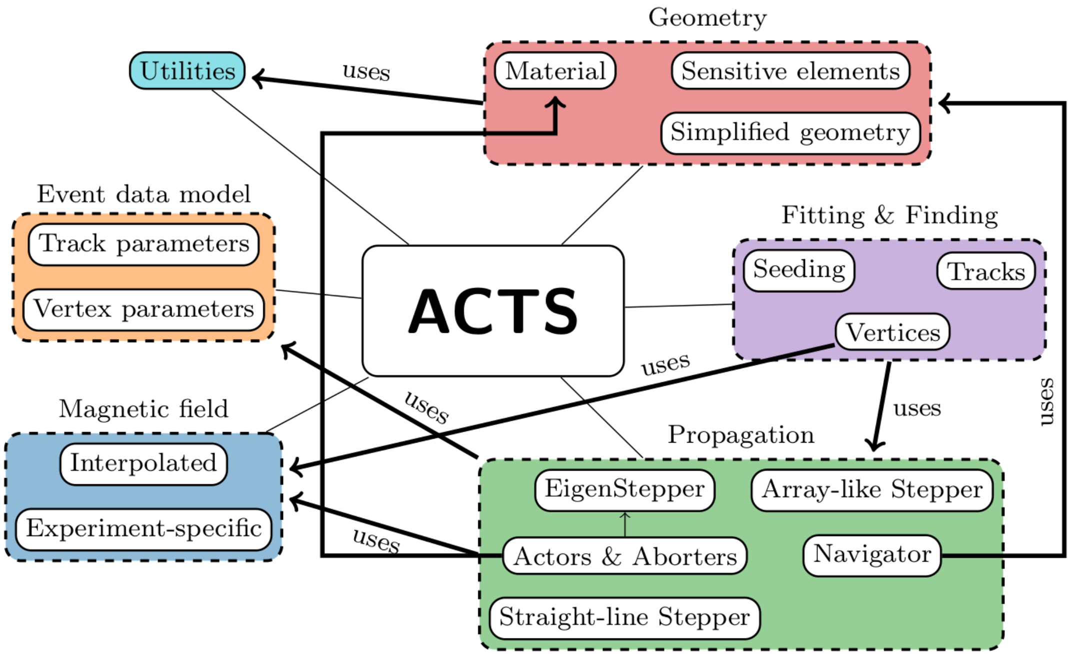
- **Modern C++ 17 (→ 20)** concepts
- **Detector and magnetic field agnostic**
- Strict **thread-safety** to facilitate concurrency
- Supports for **contextual** condition
- Minimal dependency (only Eigen as algebra library)
- Highly configurable for **usability**
- Well documented and maintained
- Flight time in track parameterization (facilitate time measurement):

$$\vec{x} = (l_0, l_1, \phi, \theta, q/p, t)^T$$

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

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

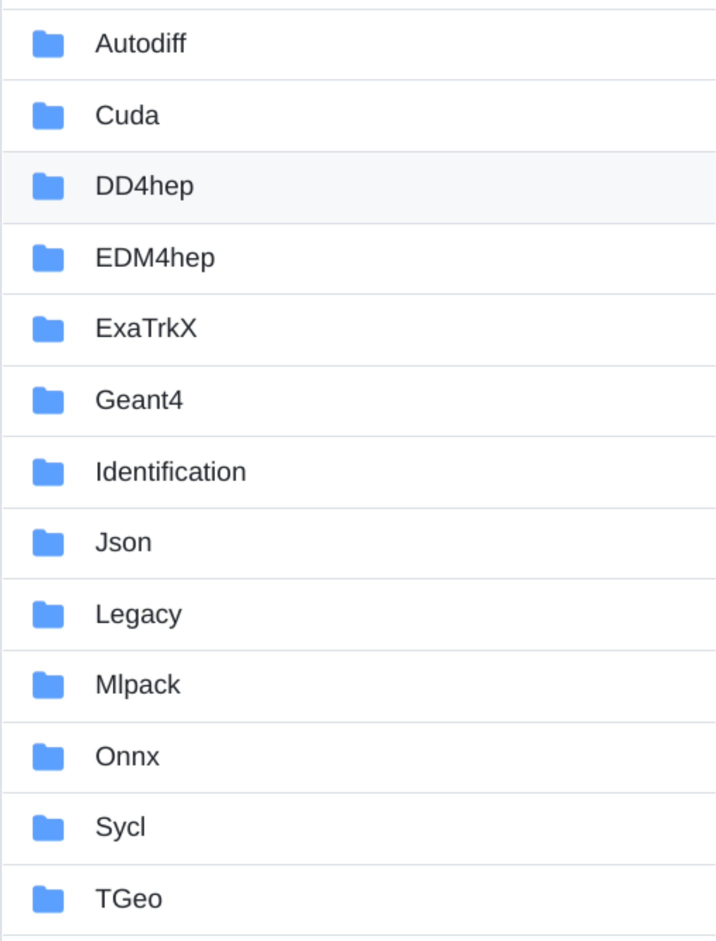
The core tracking&vertexing&alignment tools in ACTS



https://link.springer.com/article/10.1007/s41781-021-00078-8

- Track fitting:
  - ✔ (Extended) KF well, Gaussian Sum Filter, Non-linear KF
  - ◆ Global chisq fitter in WIP
- Track finding
  - ✔ Seeding, CKF, Graph Neural Networks
  - ◆ Hough Transform in WIP
- Vertex finding&fitting
  - ✔ Primary vertex: AMVF, IVF
- KF-based Alignment in WIP

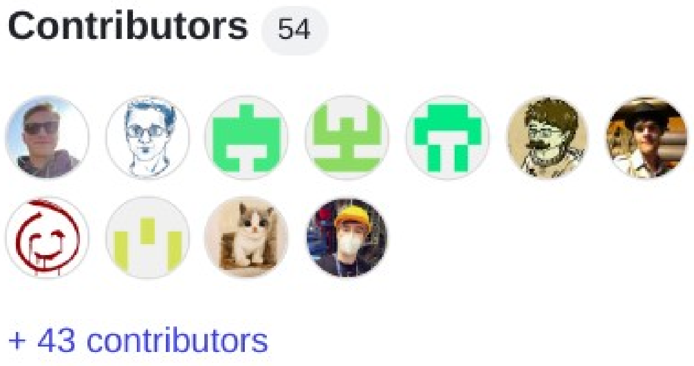
The third-party plugins



- Supports experiment applications, R&D on ML and GPU...
  - Geometry: Geant4, DD4hep, TGeo
  - GPU: Cuda, Sycl
  - ML: Onnx, Mlpack, ExaTrkX
  - Configration: Json
  - EDM: EDM4hep
  - Math tool: Autodiff

World-wide contribution

- 10~15 active developers on Core project



supported by

cooperations

ACTS is one of the four projects in IRIS-HEP **(Institute for Research and Innovation in Software for High Energy Physics)**

➔ $25M, i.e. **~0.17 B CNY**, funded by National Science Foundation

https://iris-hep.org

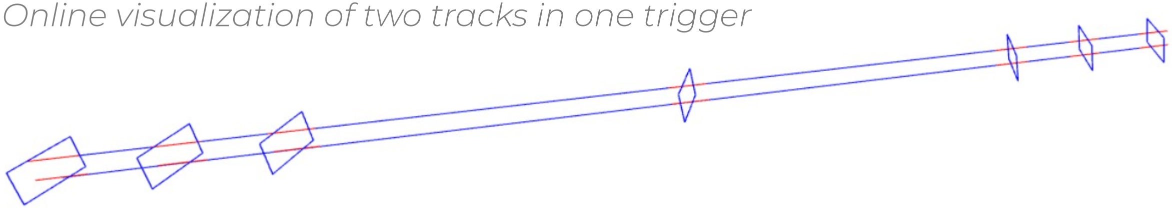
World-wide applications

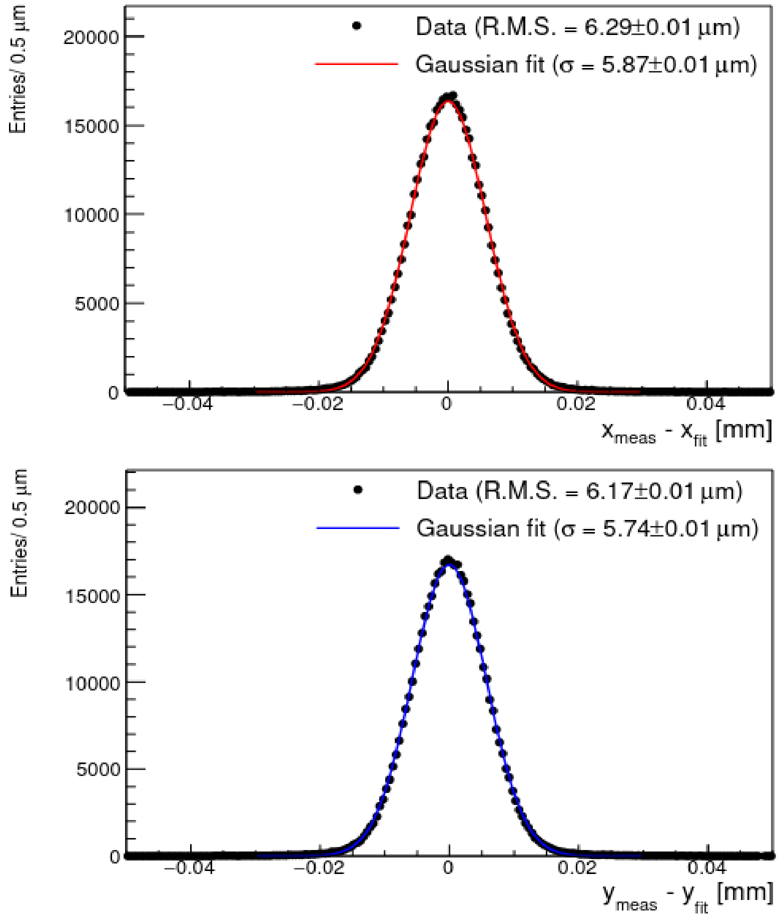
- World-wide users from particle and nuclear physics, collider and non-collider experiments
  - >10 experiments
  - >15 institutes : CERN, LBNL, ORNL, UC Berkeley, Stanford University, DESY, ZZU, …
  - 119 Forks
- Regular/irregular discussion between developers and experiment users
  - ATLAS, FASER, sPHENIX, ALICE, EIC…

ACTS application example: ADENIUM beam telescope

- Beam telescope is a key instrumental tool for particle detector prototyping
- Combined tracking fitting and finding with CKF much ease the tracking process
- Good time performance allows **online track reconstruction and visualization**
  - Event processing rate up to 20 kHz in a single thread!
- First application of ACTS for real data processing!

Online visualization of two tracks in one trigger



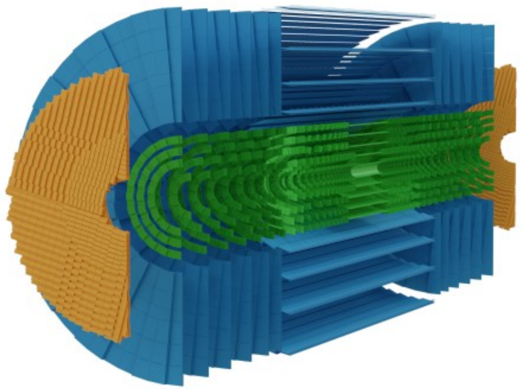


ADENIUM beam telescope

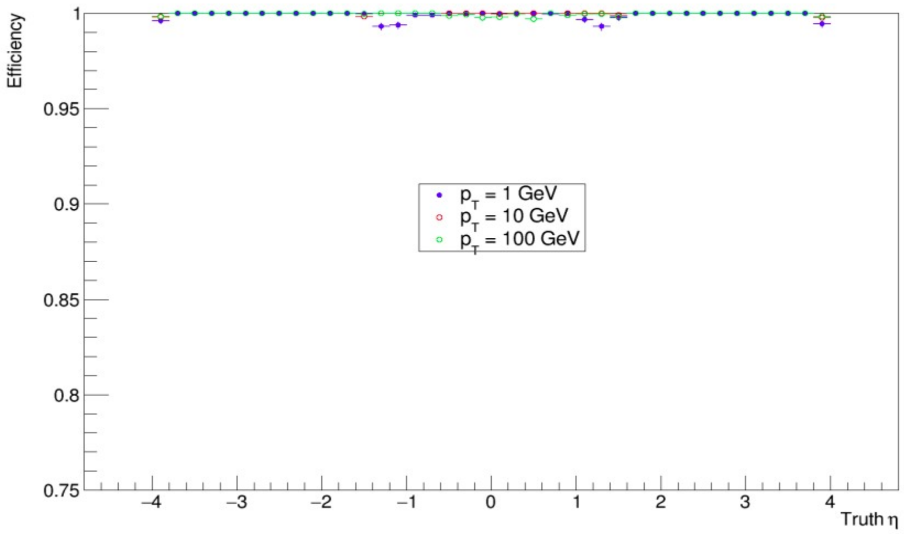
Y. Liu et al. arXiv: 1907.10600

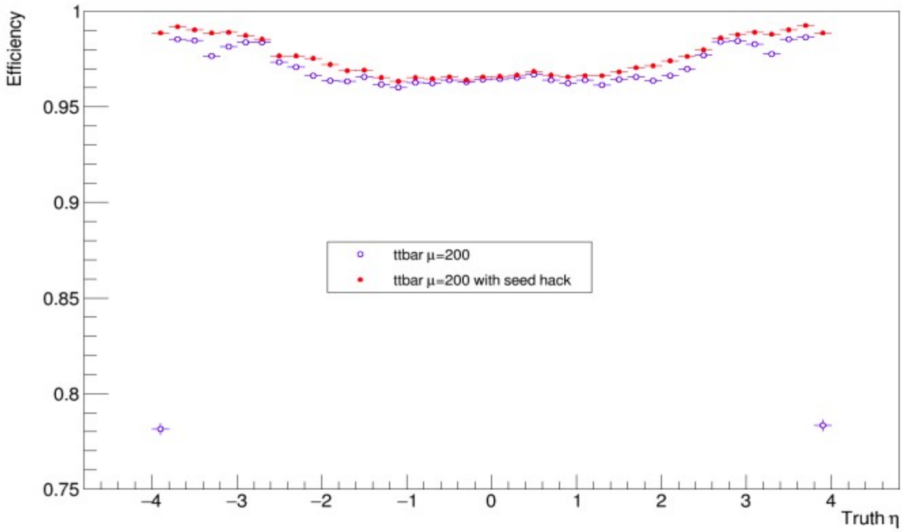
Application for ATLAS ITk

ATLAS ITk (HGTD)



- For example, >95% track finding efficiency for ttbar with μ = 200 for ATLAS ITk

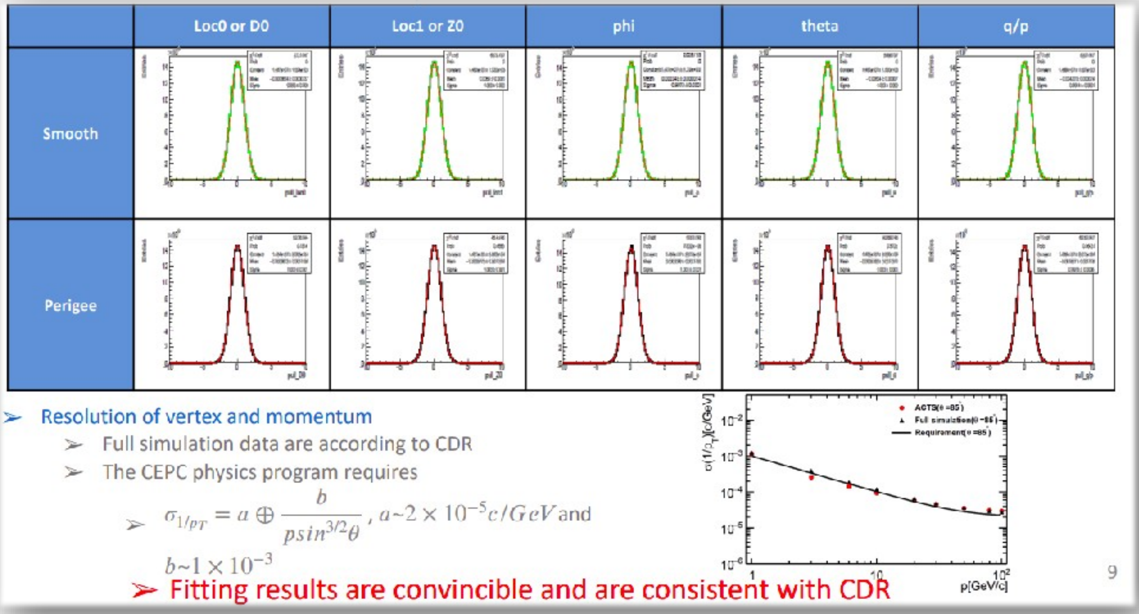


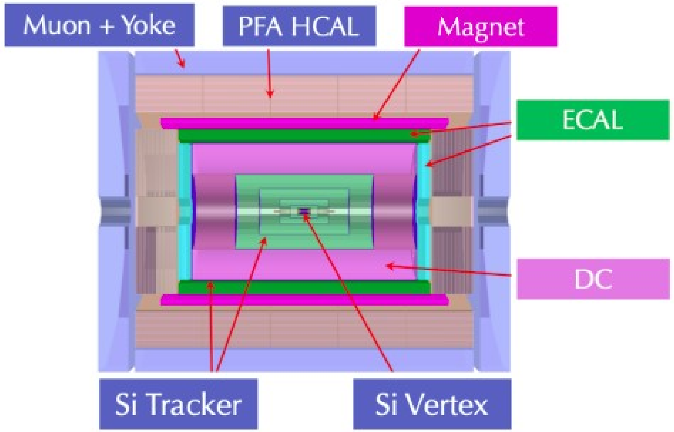


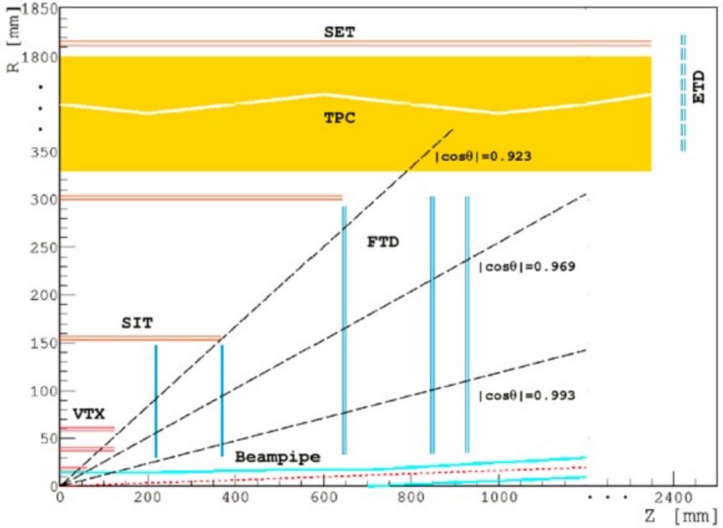
Application for CEPC

- Truth fitting using ACTS KF shows compatible performance with CDR

Figure from J. Zhang's slides at CEPC workshop in 2021

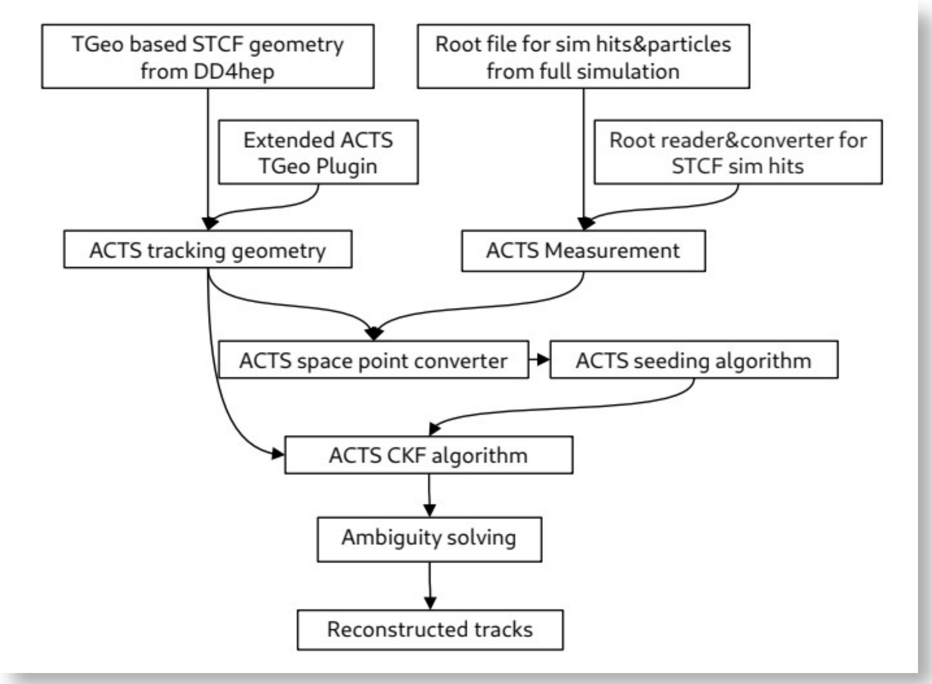




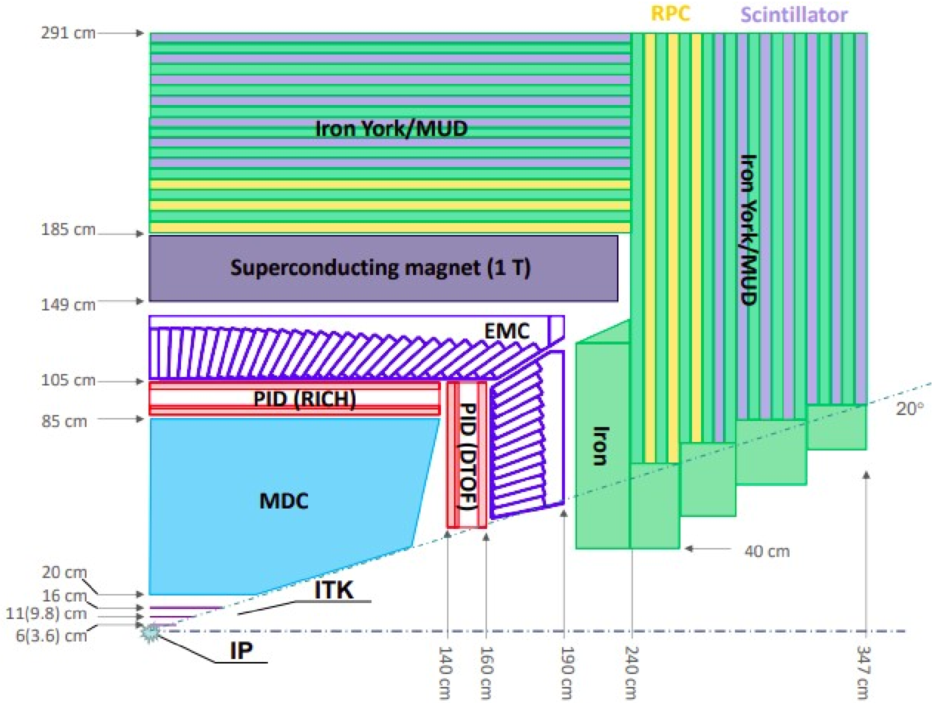


Application for STCF

- First application of ACTS CKF for a drift chamber!



X. Ai, X. Huang, Y. Liu, arXiv:2301.04306

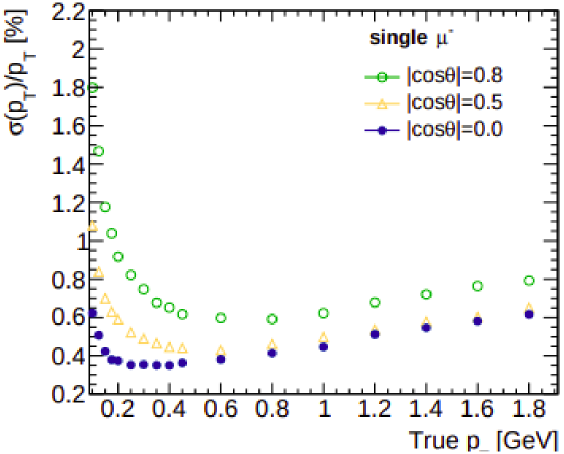


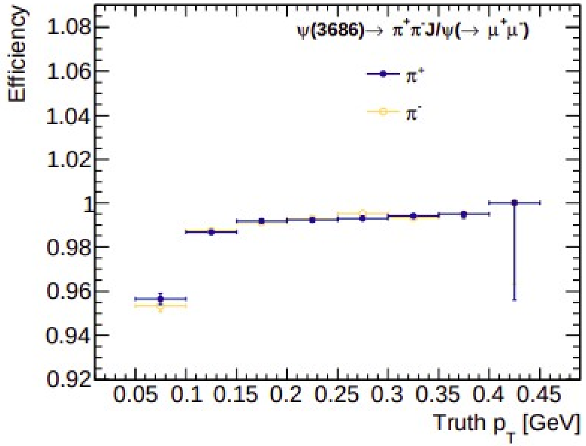
ITK: 3 layers, $\sigma_{r\text{-}\phi} \times \sigma_z \approx$ 100 um x 400 um

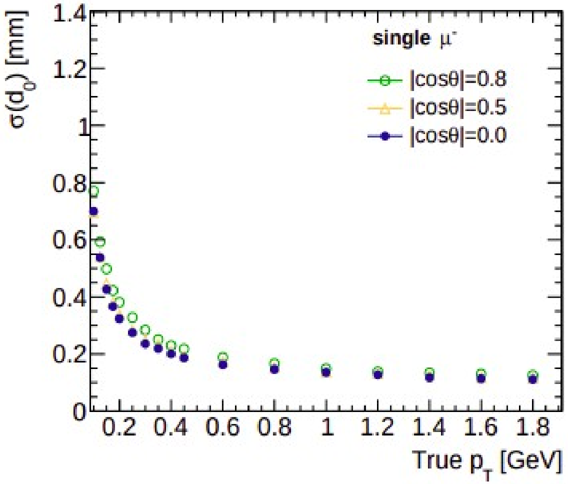
MDC: 48 layers, $\sigma_{\text{drift dist}} \approx$ 120~130 um

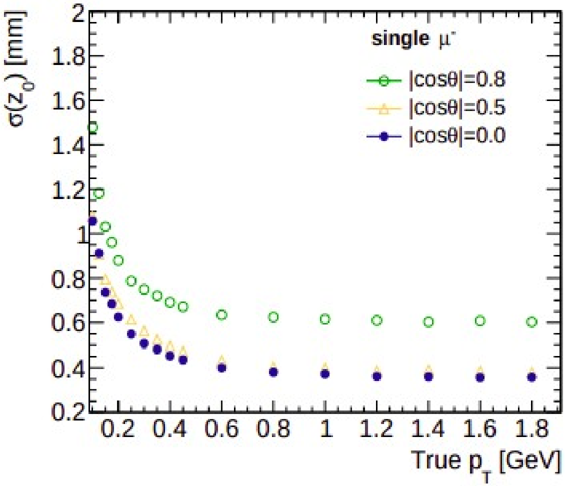
Tracking performance for STCF

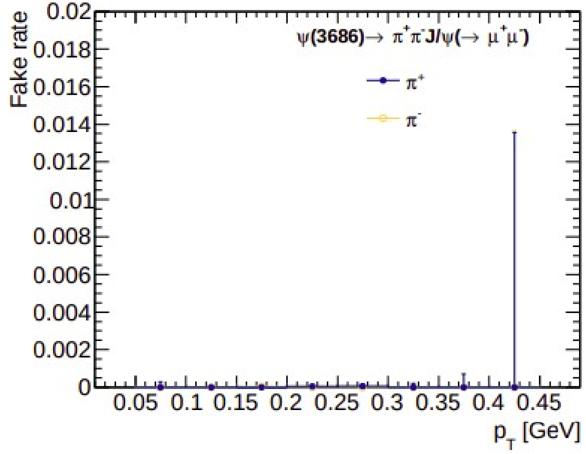
- ✔ For $p_T = 1$ GeV, $\theta = 90$ deg:
  - $\sigma(p_T)/p_T < 0.5\%$, $\sigma(d_0) \sim 150$ μm, $\sigma(z_0) \sim 400$ μm
- ✔ >95% track eff. for p_T in [50, 100] MeV in $\pi^+\pi^- J/\psi$







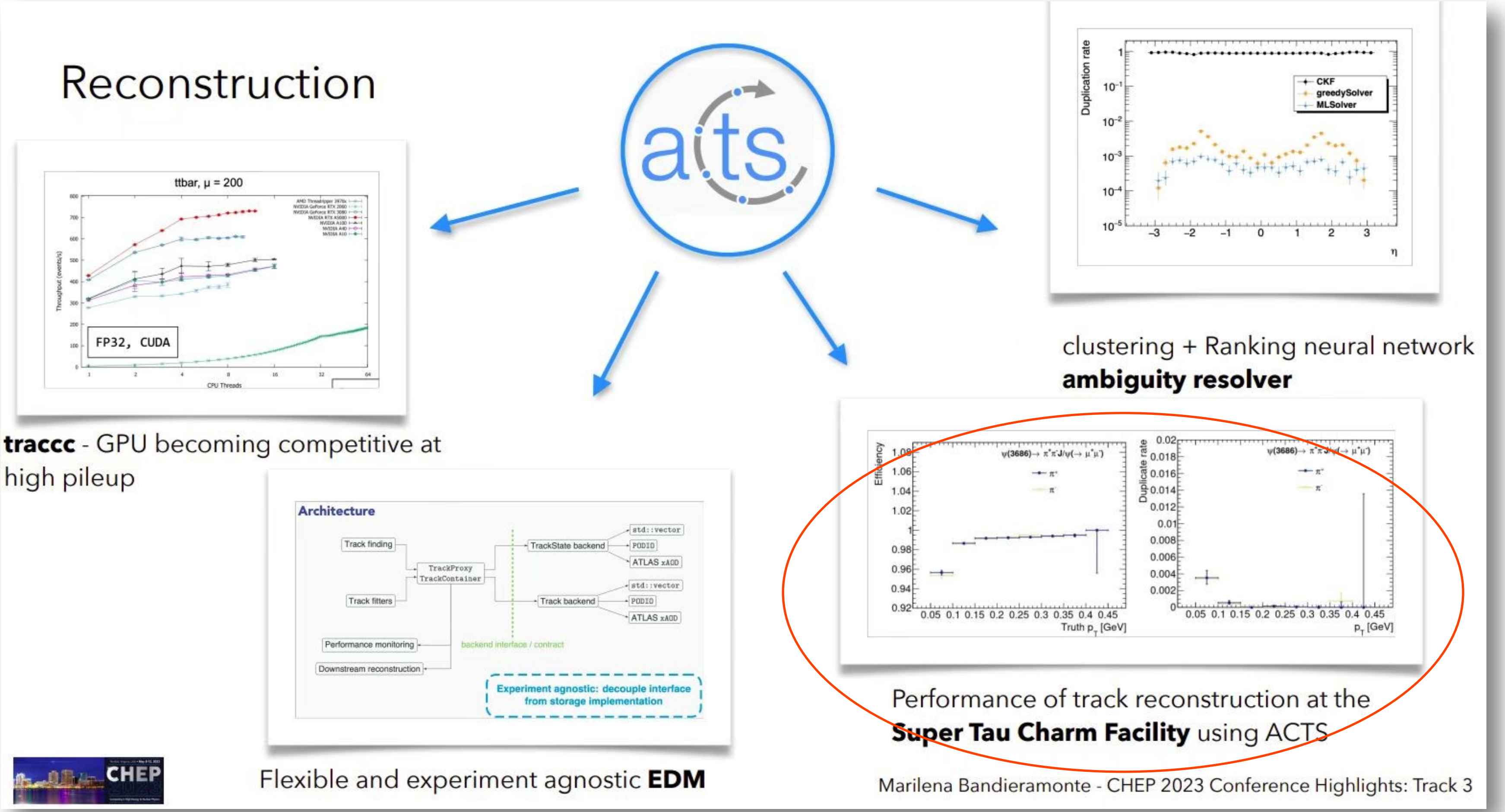




X. Ai, X. Huang, Y. Liu, arXiv:2301.04306

Highlight of Track 3 - Offline Computing of CHEP2023

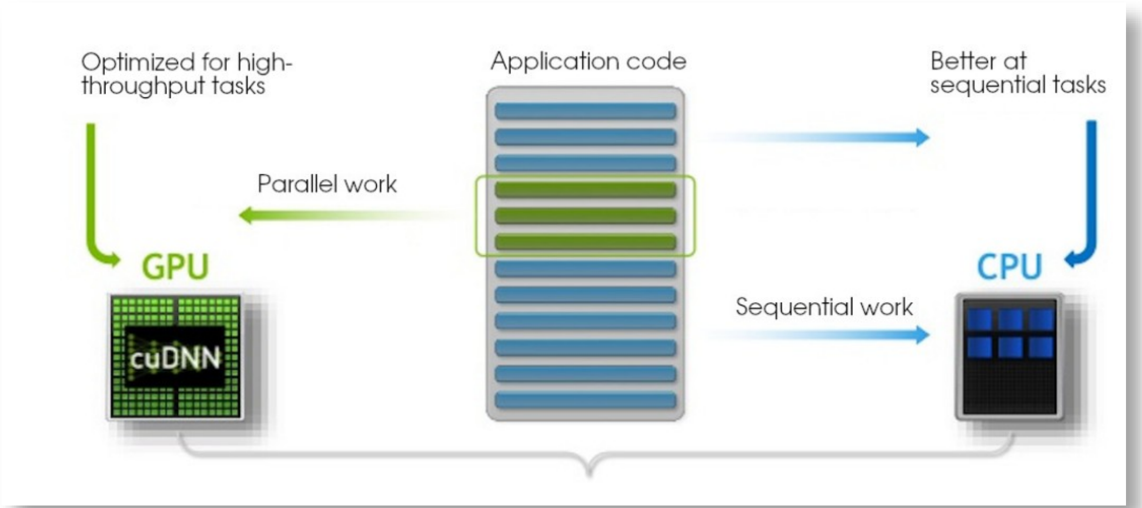
Slides of M. Bandieramonte at CHEP2023

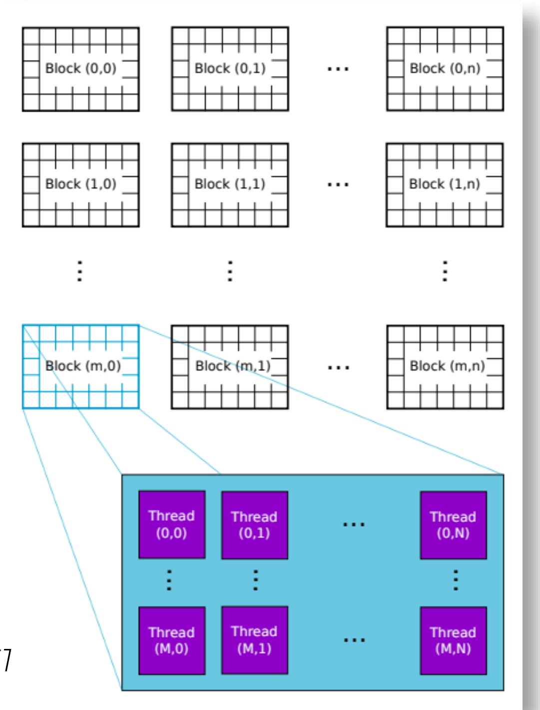


GPU-accelerated tracking

GPU accelerator

- CPU needs increase rapidly while CPU budget is limited in future HEP&NP experiments
- Heterogeneous computing is modern computing paradigm for speedup
  - Host processor: steers the computing
  - Device processor: accelerator with many cores specialized for parallel processing
  - Additional overhead from data transfer between host and device
  - API: CUDA, SYCL, Kokko…





arXiv: 1912.09161

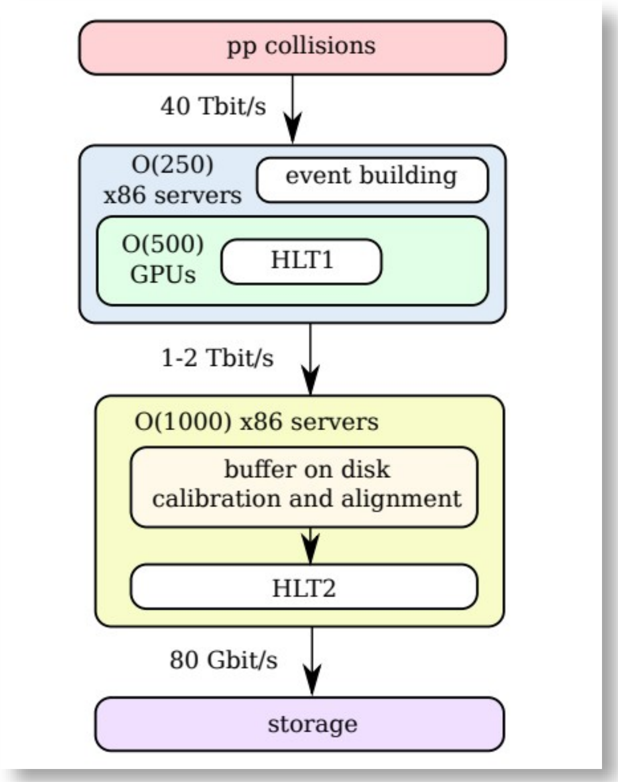
GPU acceleration in HEP&NP experiments

- Event generation
  - e.g. Madgraph4gpu: GPU development for the Madgraph5_aMC@NLO event generator software package
- Simulation
  - e.g. GPU accelerated and parameterized calorimeter simulation at ATLAS with parallelization at event-level, intra-event, or particle-/hit-level parallelization
- Reconstruction
  - e.g. track finding/fitting
- Analysis
  - e.g. GPU Partial Wave Analysis (arXiv:1108.5882.pdf)

GPU accelerated High Level Trigger

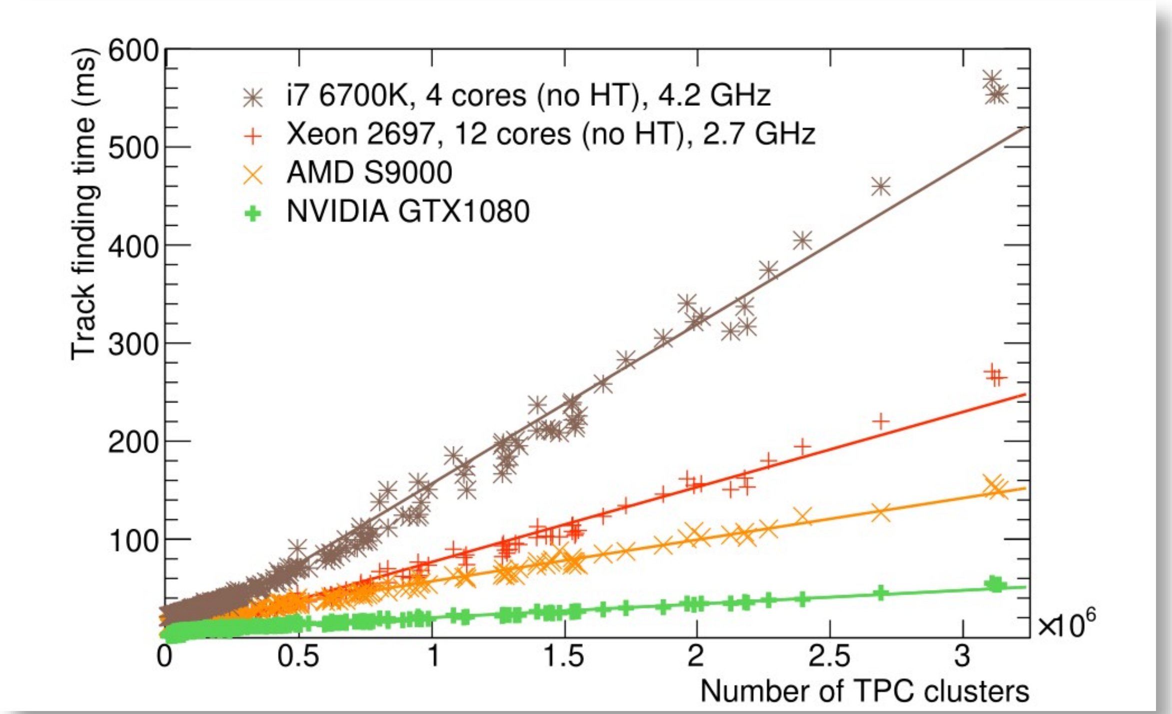
LHCb Allen: facilitates a 'triggerless' trigger strategy by using O(500) GPUs

arXiv: 1912.09161



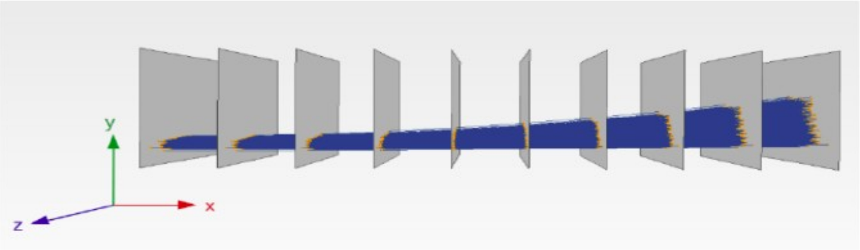
GPU-accelerated track finding with Cellular Automaton for ALICE HLT

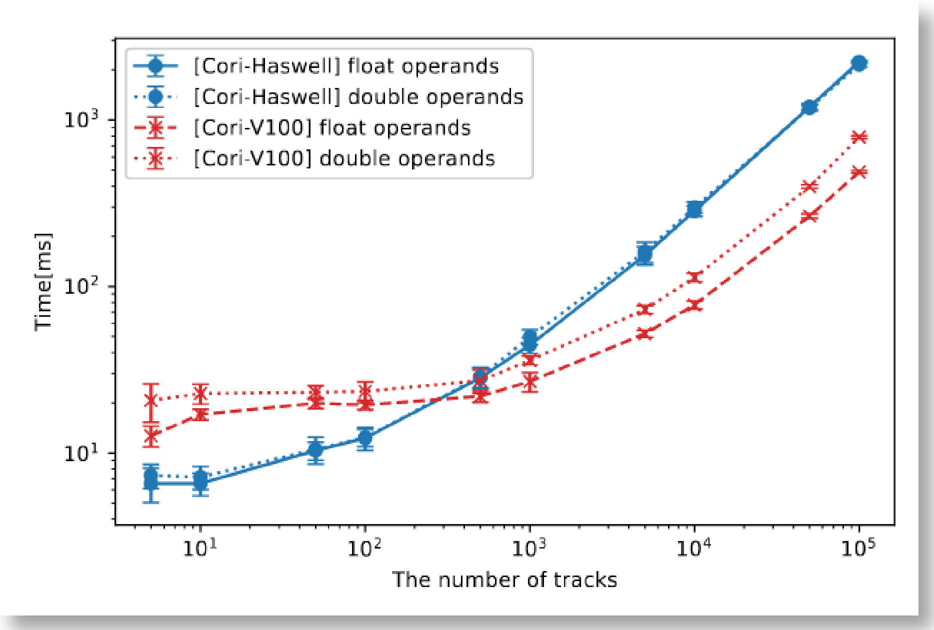
CERN-EP-2018-337



Not every code fits into GPU

- Dynamic polymorphism based on virtual methods are not applicable on GPU Kernel!
- Dynamic memory allocation and deallocation is difficult on GPU
- Branching between different threads is very common in HEP, which slows down the execution on GPU
- Limited resources for each GPU core
- Limited support of external libraries (e.g. Eigen NOT supported on GPU)

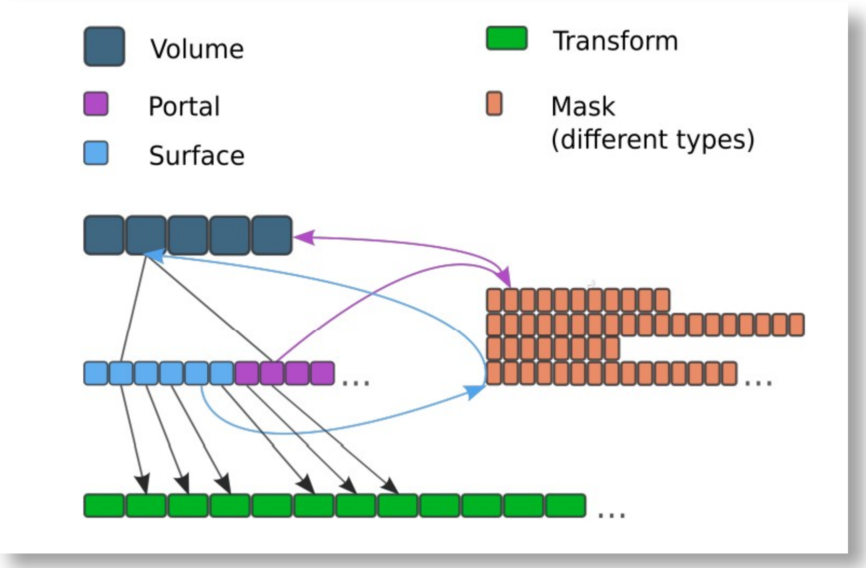




Comput Softw Big Sci 5, 20 (2021)

Towards a common GPU-accelerated tracking strategy

- VecMem: implement a vectorised data model for heterogeneous computing
- Detray: implement geometry without polymorphic inheritance structure
- Traccc: demonstrator tracking chain for accelerators



From J. Niermann

Category	Algorithms	CPU	CUDA	SYCL	Futhark
Clusterization	CCL	✓	✓	✓	✓
	Measurement creation	✓	✓	✓	✓
	Spacepoint formation	✓	✓	✓	⚪
Track finding	Spacepoint binning	✓	✓	✓	⚪
	Seed finding	✓	✓	✓	⚪
	Track param estimation	✓	✓	✓	⚪
	Combinatorial KF	🟡	🟡	⚪	⚪
Track fitting	KF	✓	✓	✓	⚪

✓: exists, 🟡: work started, ⚪: work not started yet

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

Summary&Outlook

Summary

- Tracking is pivotal to event reconstruction in HEP&NP
- Tracking is very complicated and will become much more challenging in the future
- ACTS is an international project to develop an open source and highly performant tracking software
  - Becomes very popular in recent years and interest keeps growing
  - Still a lot remain to be developed and optimized
  - Application of ACTS for more real data experiments is foreseen
    - Already used at FASER and ALPIDE telescope at DESY
- GPU-accelerated tracking is a trend (though challenging) for future high luminosity HEP&NP experiments