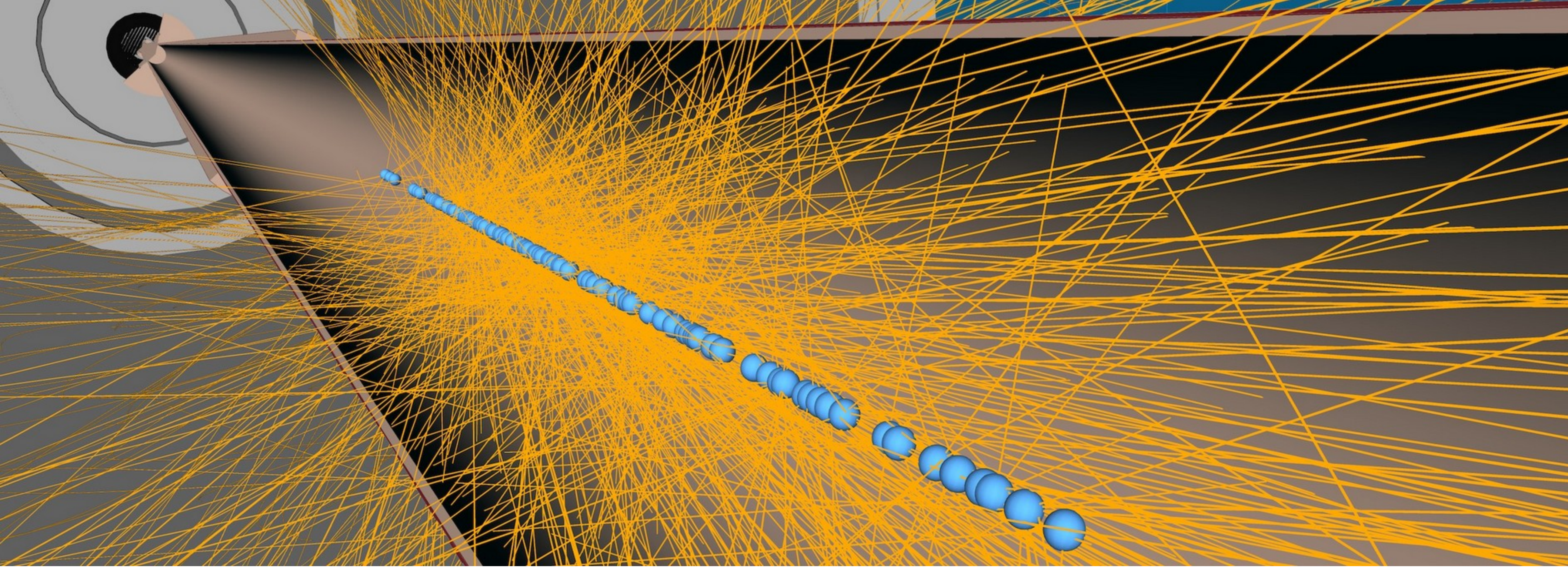


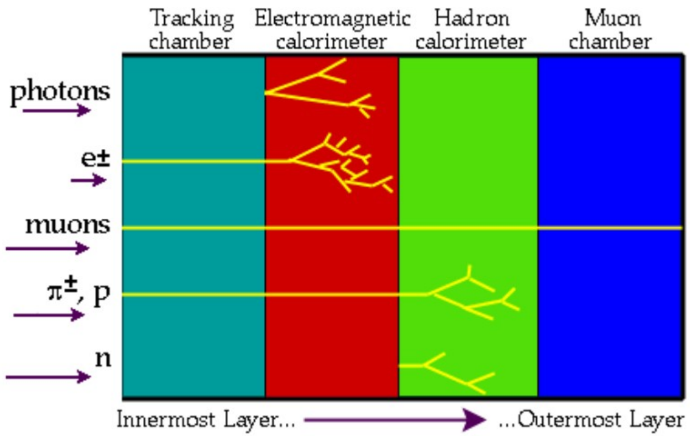
Recap on track reconstruction in HEP

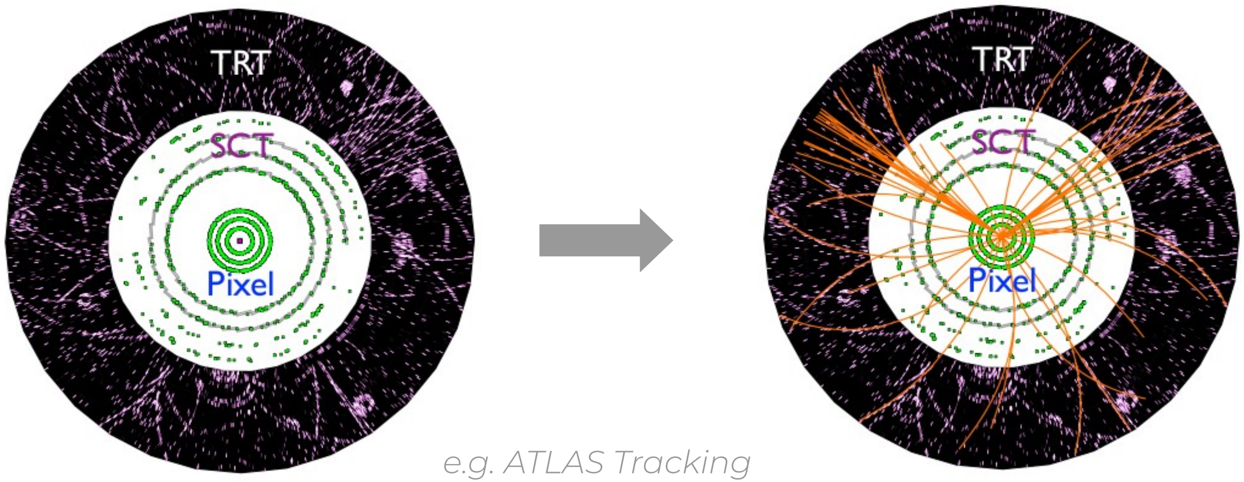
Xiaocong Ai (Zhengzhou University)

Workshop of Computing Software and Technologies in HEP Experiments, Qingdao, June 10, 2023

Tracking what for?

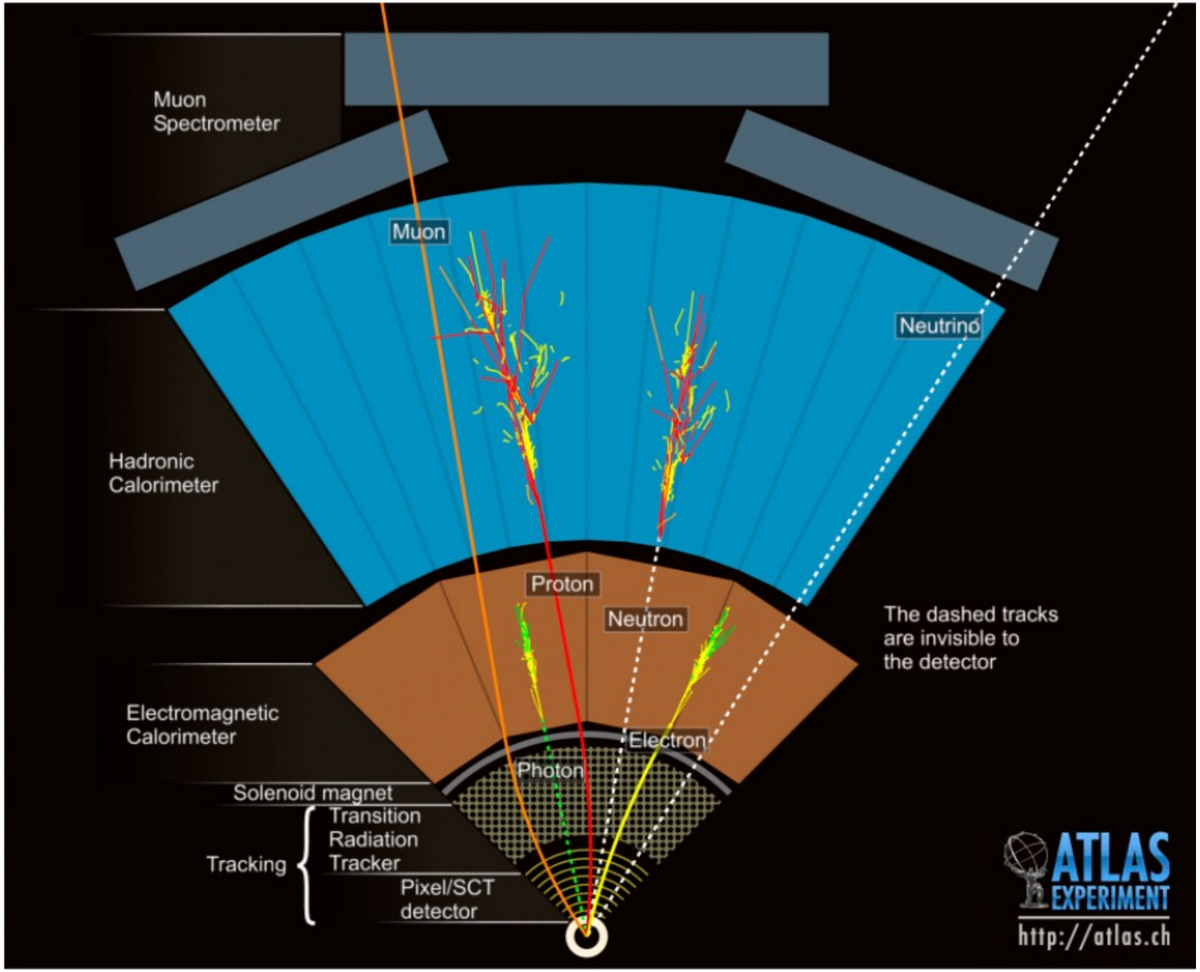
- **Track finding**: associate discrete measurements (a.k.a. hits) to individual tracks
- **Track fitting**: estimate properties of tracks at target (reference) position
  - Position, momentum (with magnetic field), charge, possibly dE/dx (and velocity)





e.g. ATLAS Tracking

Tracking is crucial to success of physics programs



- Tracking is about vertex reconstruction, jet reconstruction and flavor tagging, pileup mitigation, particle identification…

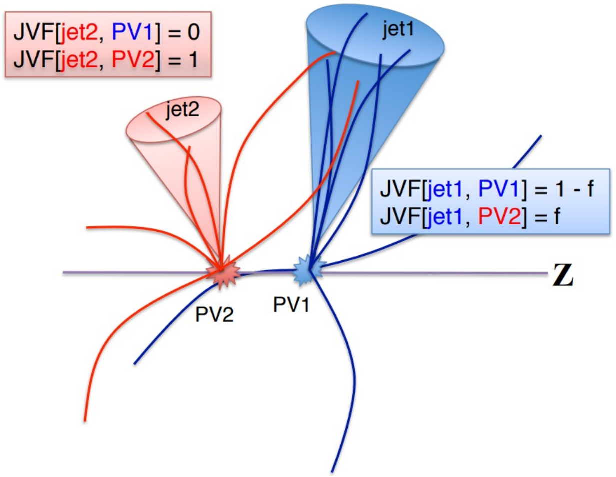
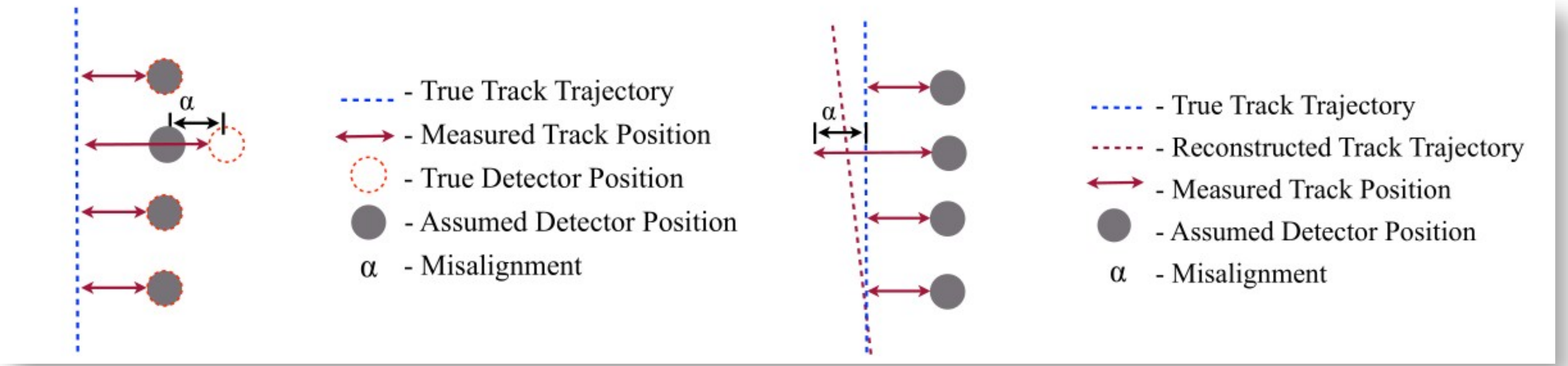


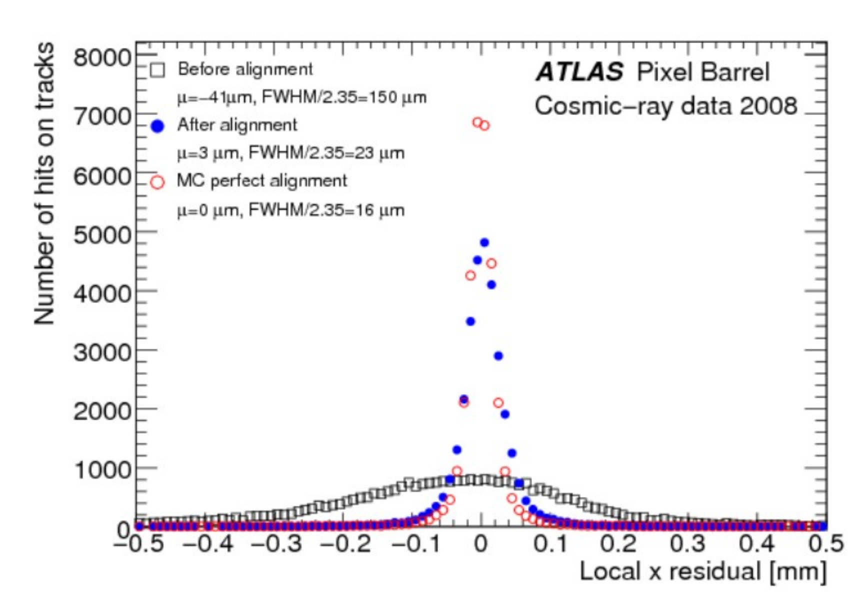
Figure from Eur. Phys. J. C 76, 581

Tracking drives the precision of detector alignment



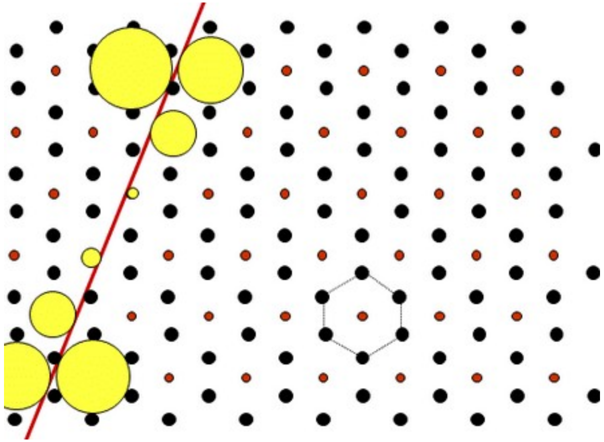
Track-based alignment:
Simultaneous optimization of local track parameters and global alignment parameters:

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

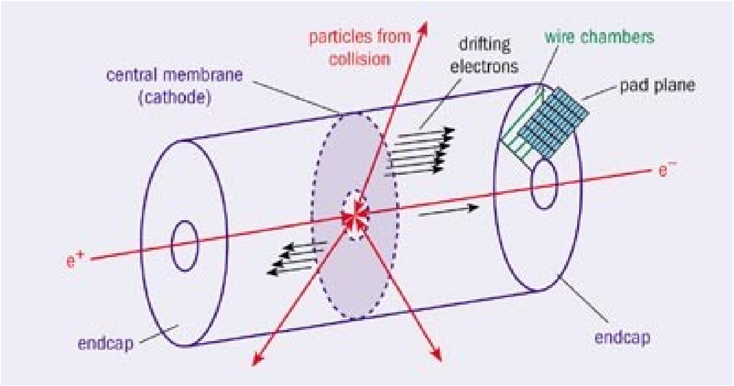


Tracking detectors

- Tracking is possible due to interaction of charged tracks with detector material
  - Energy loss by ionization (and bremsstrahlung for electron)
- Ionization detector:
  - Continuous: e.g. gaseous detectors (drift chamber, Time Projection Chamber)
  - Discrete: e.g. silicon planar detector



Figures from here



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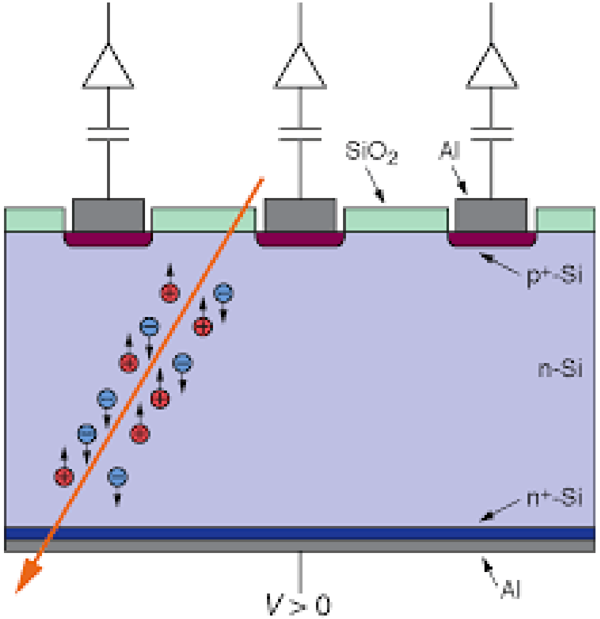


Figures from here

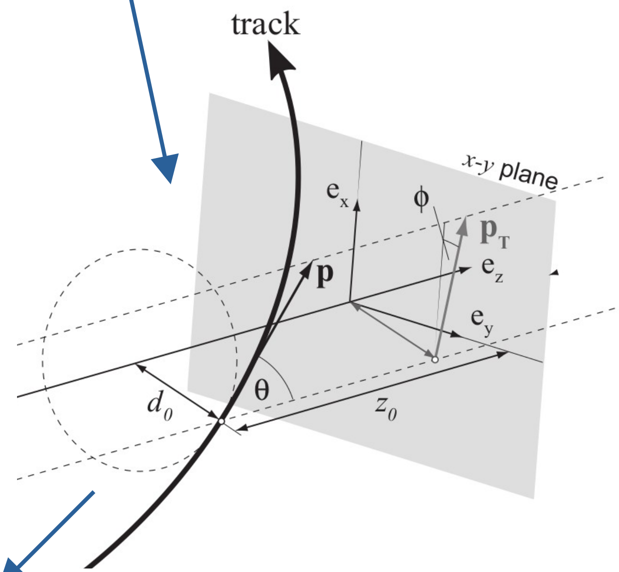
A view of a track

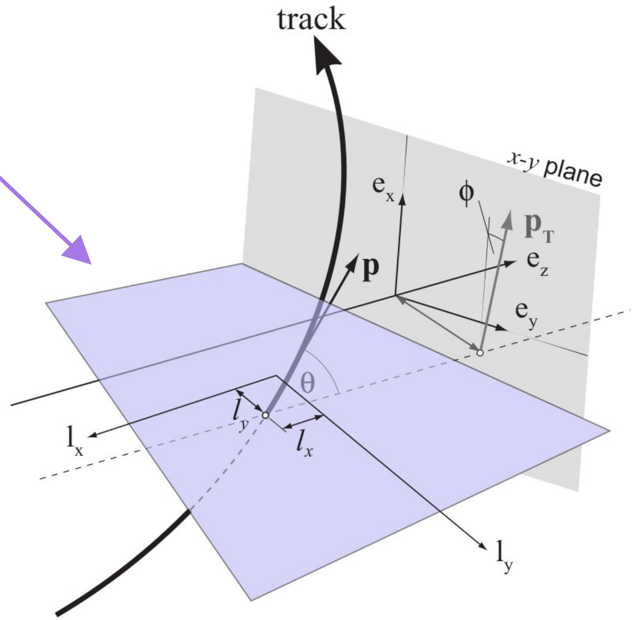
- What we want to know:
  - **How far** is a track from a reference point, or more accurately, a reference line (e.g. the beam line or drift wire), usually described by impact track parameters d0, z0 (or dz)?
  - What is the **intersection** of a track with a planar detector?
  - The **momenta** and **track direction** at a particular point
  - The **charge** of the track
  - Possibly the **time** of the track upon reaching a point

Track parameterization

e.g. ATLAS parameterization: (l_x, l_y, ϕ, θ, q/p)

- l_x, l_y: track position, either d0, z0 or l_x, l_y on a real planar detector (the same parameterization with different reference surfaces)
- ϕ, θ: track direction
- q: charge
- p: momentum





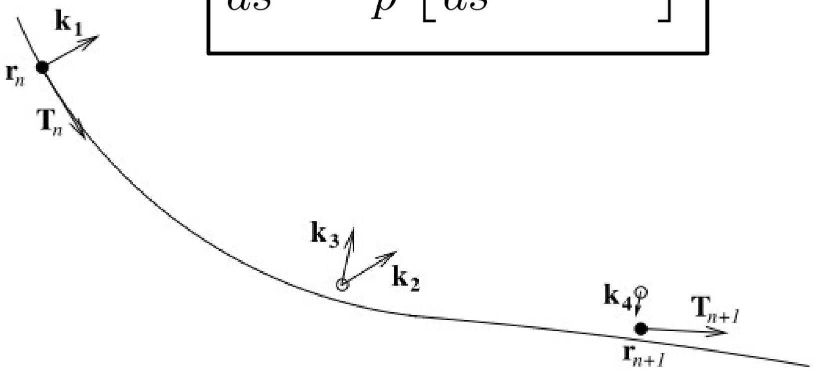
Corresponding parameterization at BESIII, BELLE II
(d_0, ϕ, κ, d_z, $\tan\lambda$) or (d_0, ϕ_0, ω, d_z, $\tan\lambda$)

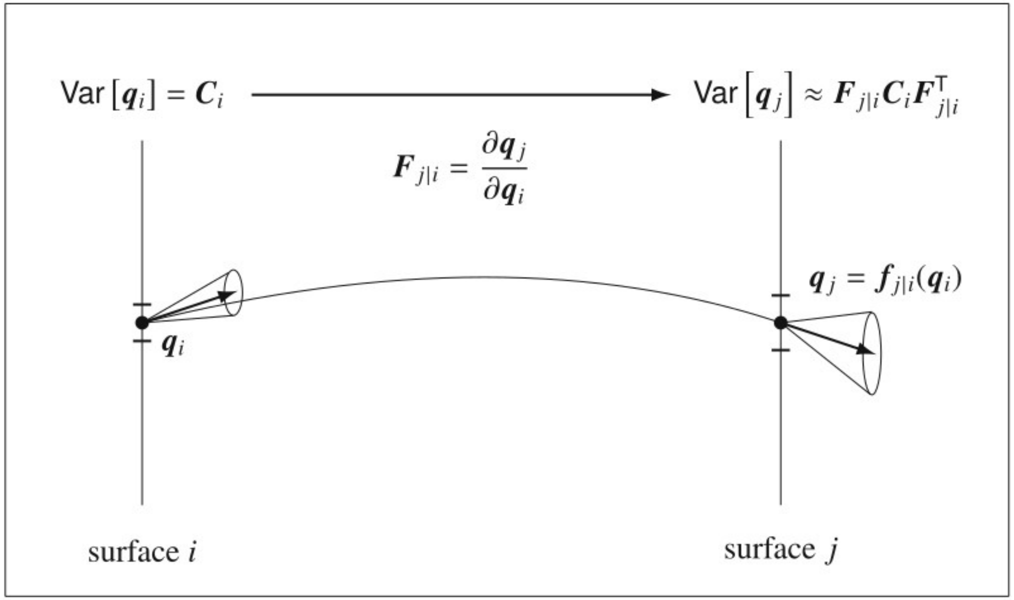
From E. Moyse

Track propagation

- Track propagation is solved numerically using fourth-order **Runge-Kutta-Nyström** method in (**inhomogeneous**) magnetic field
- Propagation of both the track parameters vector and their covariance taking into account **material effects** (both energy loss and multiple scattering)

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





Track finding

- **Global approach**: e.g. Hough transform, Graph Neural Networks
- **Local approach**: e.g. Cellular automaton, Combinatorial Kalman Filter (CKF)

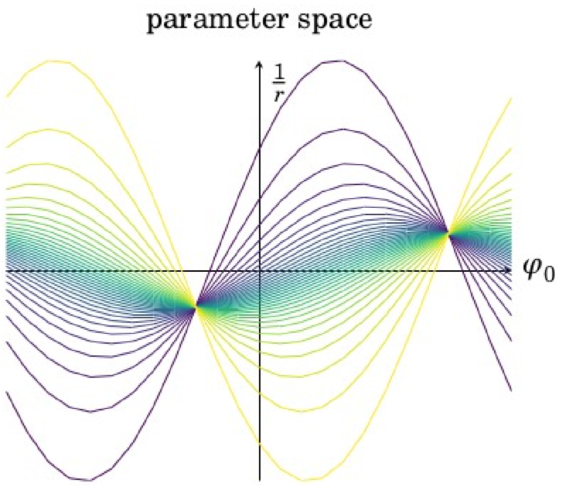
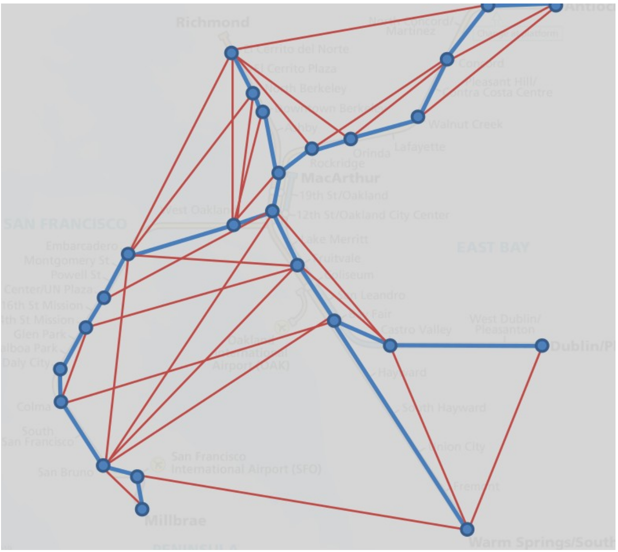
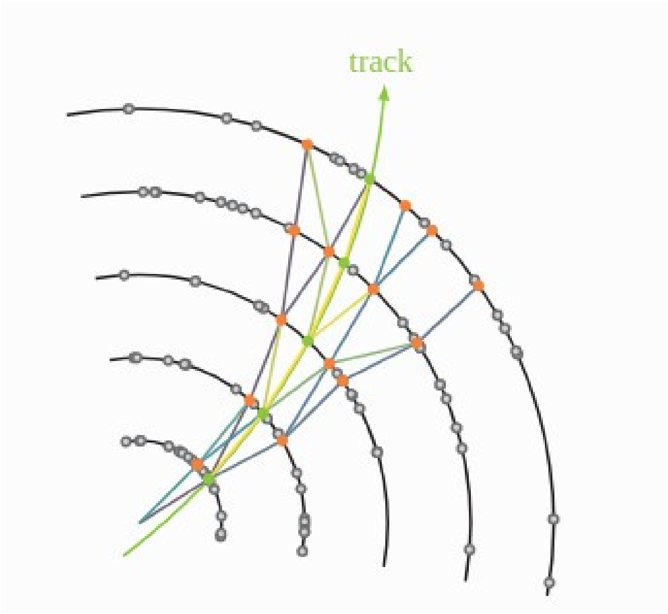


Figure from Sara Pohl's thesis





Figures from ACTS readthedocs

Track fitting

- Least-square fitter:
  - Difficulty with material effects, but can resolve drift distance left/right ambiguity
- Kalman-filter (being used more):
  - More elegant handling of material effects, more extension-friendly

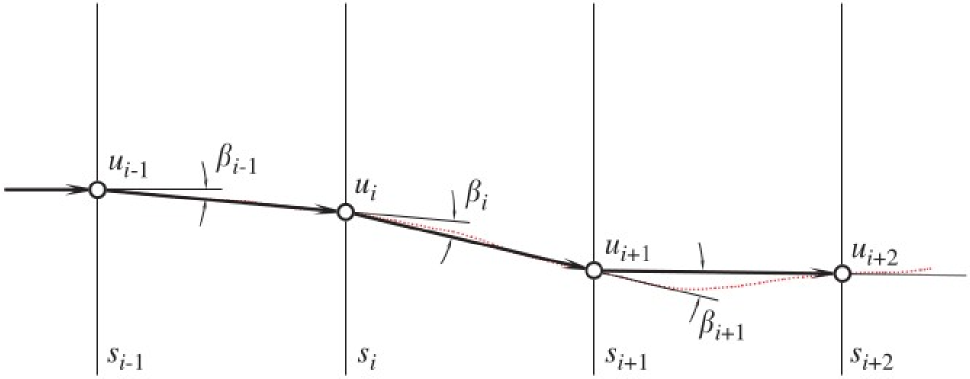
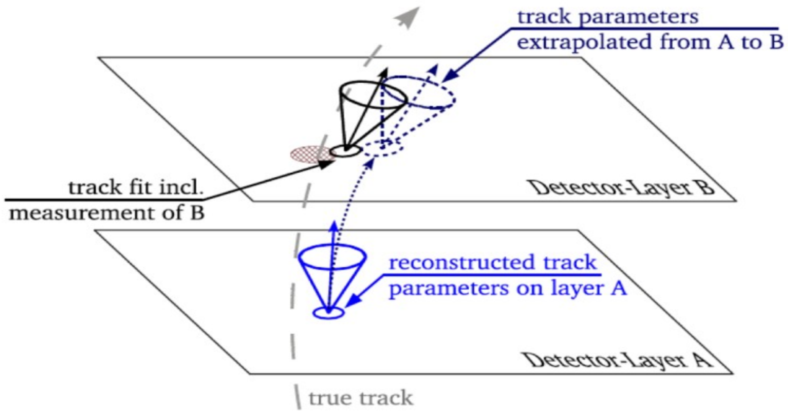
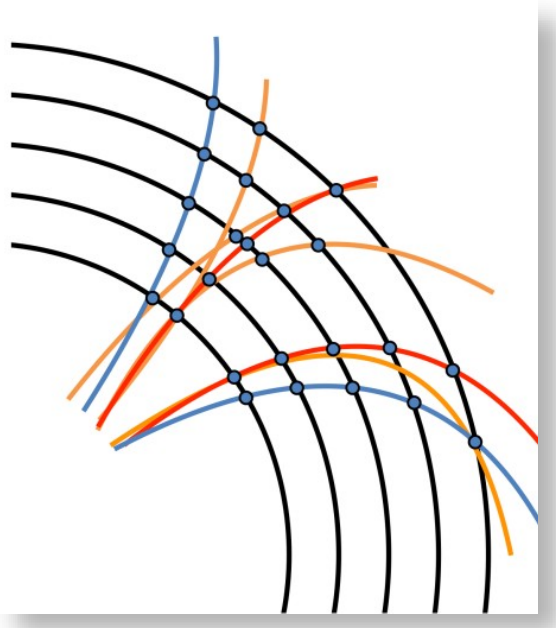


Figure from NIMA 566, 14



Track selection

- Reconstructed raw tracks are often passed to further filtering (might involves scoring)
  - Tracks can be scored based on track parameters, fitting quality, number of (shared) hits...
  - Track with poor qualities are removed



e.g. Ranking Neural Network for separation of good and bad tracks by at least a margin

$$loss_{part} = \frac{1}{N_{tracks}} \sum^{tracks} max(0, x - y + margin)$$

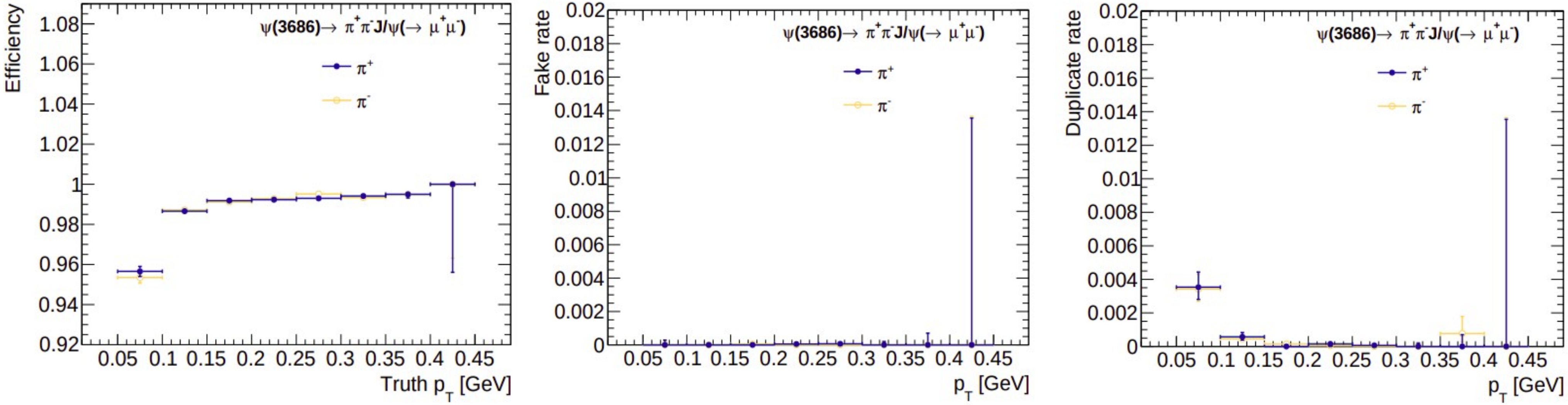
x: track score; y: good track score; margin = 0.05

See slides of Corentin Allaire at CHEP2023

Tracking performance

Tracking efficiency and rate of fake/duplicate tracks

- Fake track: sometimes, the hits left on detector by several particles can be accidentally grouped to make a track
- Duplicate track: two reconstructed tracks can be largely overlapped

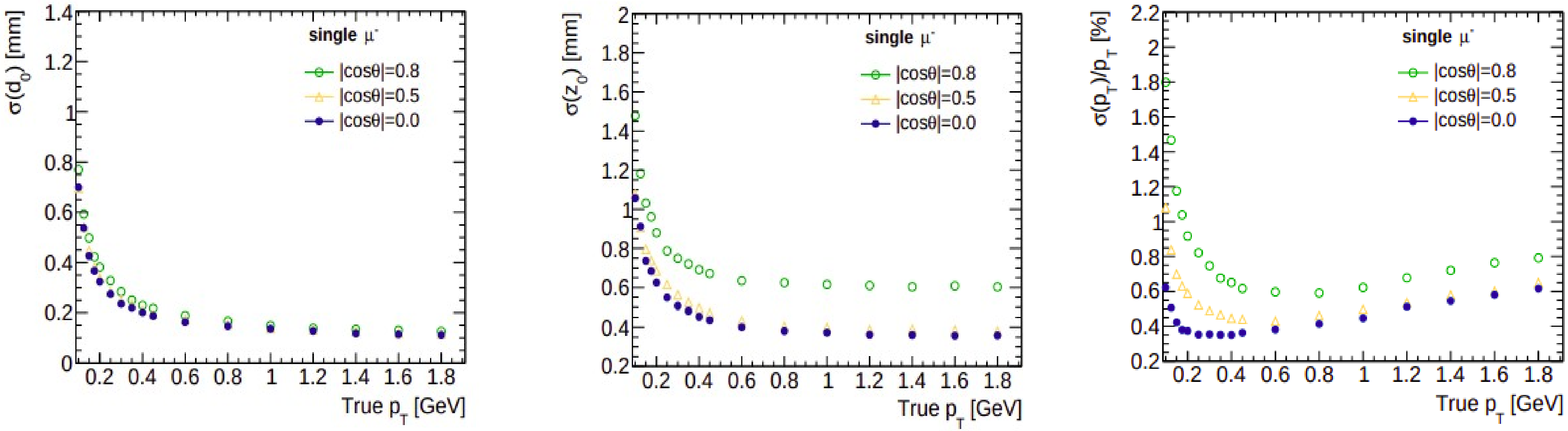


Examples of tracking performance of STCF using ACTS: arXiv:2301.04306

Tracking performance

Tracking resolution

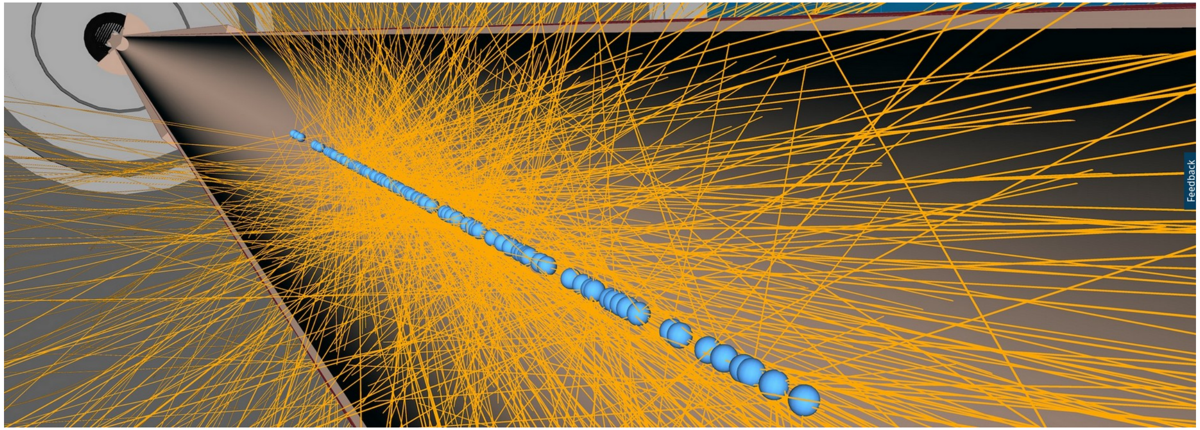
- Characterizing the accuracy of the reconstructed track parameters
- Relevant with the intrinsic resolution, layout and material budget of detectors



Examples of tracking performance of STCF using ACTS: arXiv:2301.04306

Towards the future HEP tracking

- Experiments need high-performance tracking software to not compromise physics goals
  - Preserved efficiency, precision and speed with increased luminosity (e.g. $\langle\mu\rangle = 200$ at HL-LHC, up to 7k particles per event)
  - Capability of handling particles with complicated experimental signatures
  - Easy to extend for new detector technologies
  - Supports parallelization (even with heterogeneous computing)
  - Ease of maintenance



e.g. ATLAS at HL-LHC

How about 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…!

We already started the effort >5 years ago: A Common Tracking Software (ACTS) project!

➔ See A. Salzburger's talk right away

Summary

- Tracking is pivotal to reconstruction, identification and calibration of high-level physics objects
- Resolving individual tracks is a non-trivial task
  - Material effects, bending by magnetic field, possible huge amount of combinatorics…
- Tracking is concerned with efficiency, resolution and CPU needs
- Tracking will become even more challenging in the future
- We need a performant, extendable, maintainable, and even detector agnostic tracking software to achieve our physics goals
  - A common tracking software, i.e. ACTS, keeps growing and maturing (A. Salzburger's talk right away)
  - Stay tuned for talks of J. Zhang (BESIII), H. Zhou (STCF) and M. Liu (CEPC) for experiment-specific tracking strategies

Thank you