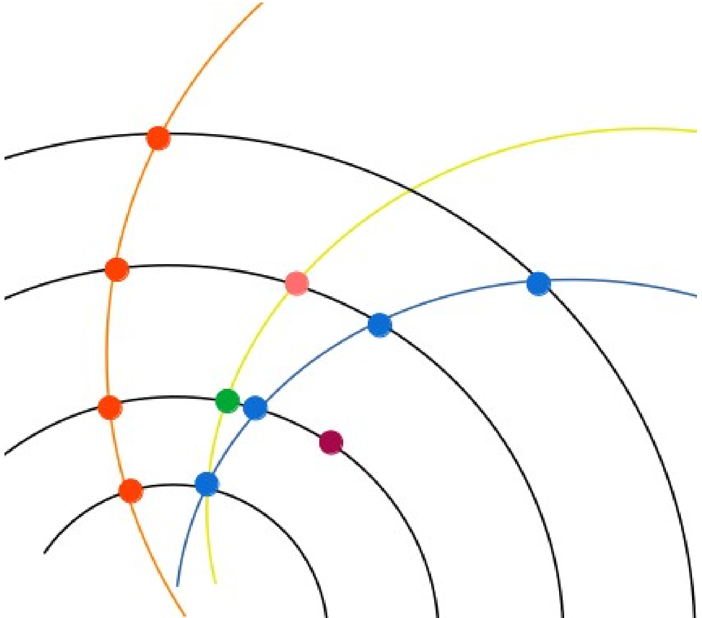
STCF track reconstruction

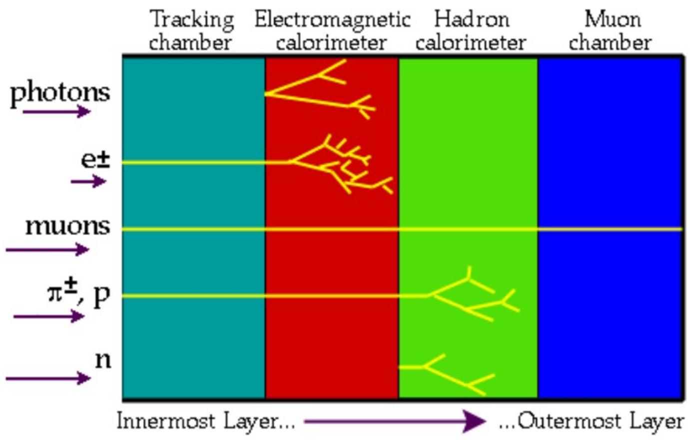
Xiaocong Ai for the STCF Tracking team

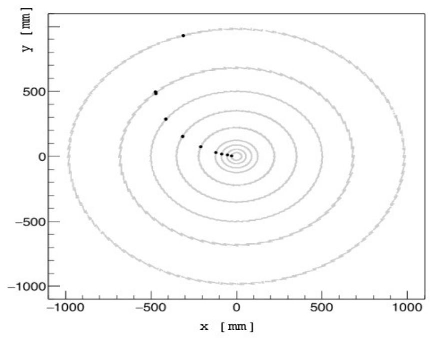
超级陶粲装置研究进展研讨会 , Dec 5, 2022



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)
- Playing the pivotal role in HEP event reconstruction
  - Direct impact on vertex reconstruction, physics object identfication, background mitigation, detector alignment...





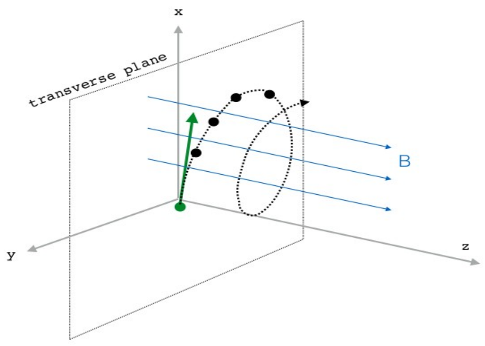
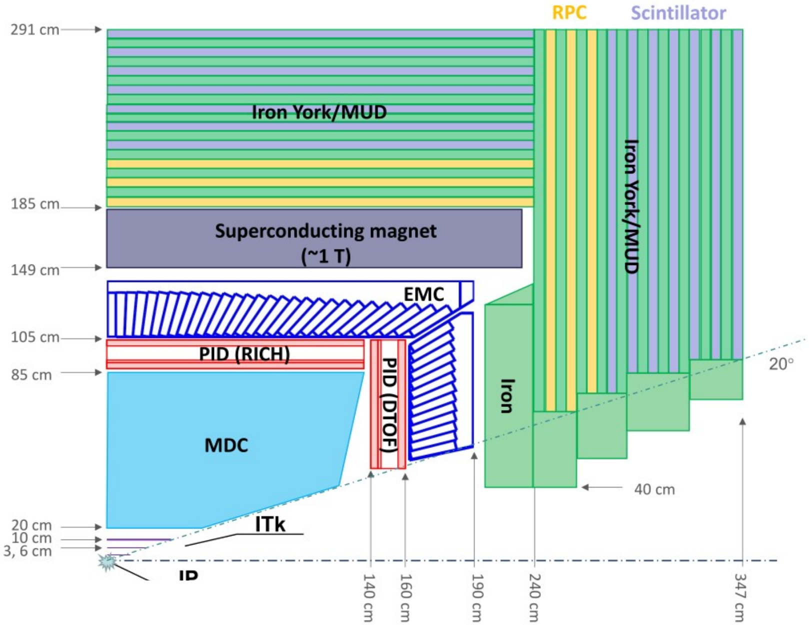


Figure from arxiv:1904.06778

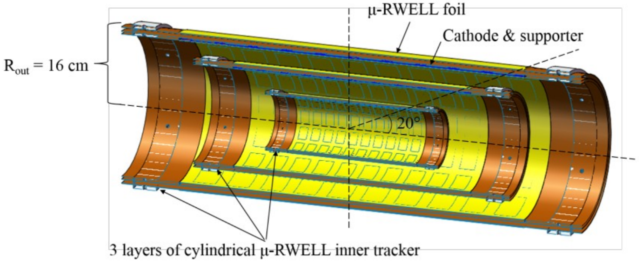
STCF tracking system

- The baseline tracking system includes uRWELL-based Inner Tracker (ITK) and Main Drift Chamber (MDC)
  - ITK: 3 layers, $\sigma_{r\text{-}\phi} \times \sigma_z \approx 100$ um x 400 um
  - MDC: 48 layers, $\sigma_{\text{drift dist}} \approx 120\sim130$ um

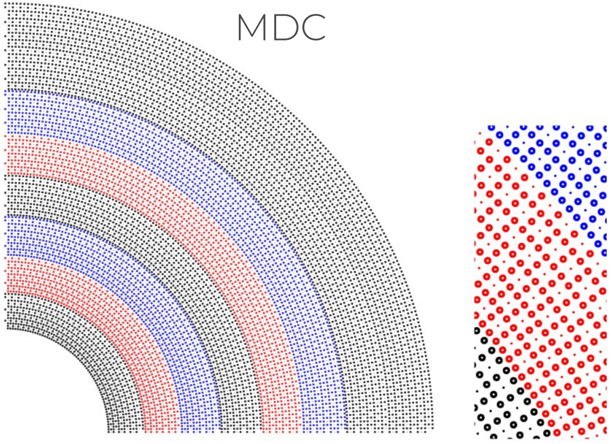


Figures from STCF CDR

uRWELL-based ITK



MDC



(a) (b)

Tracking requirements

Momentum distributions of charged particles

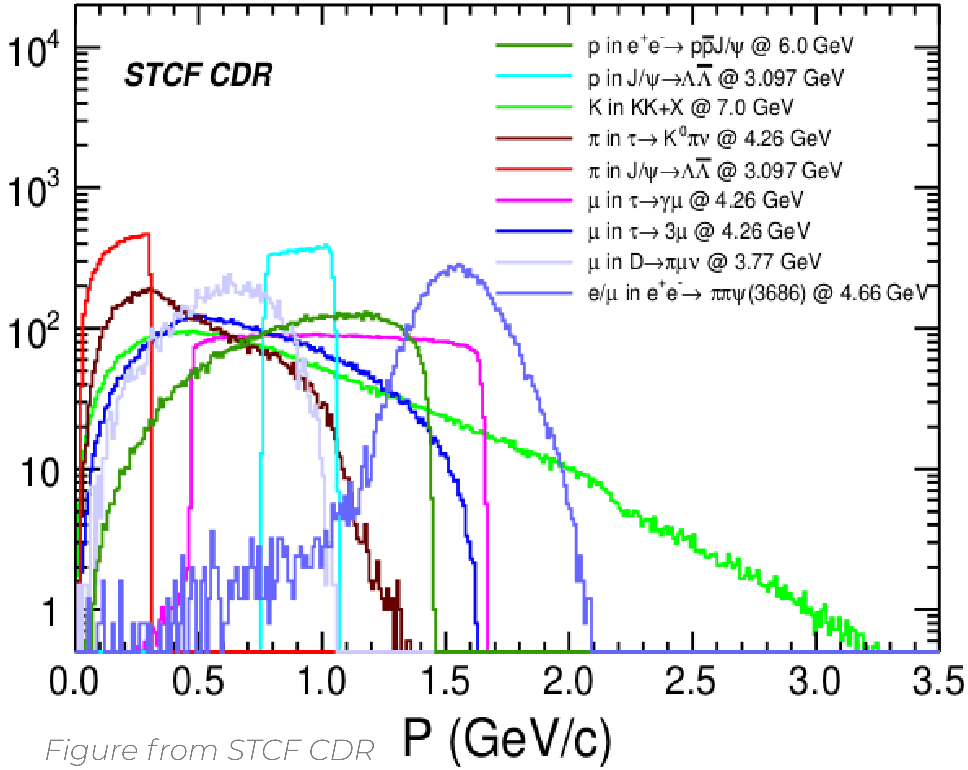
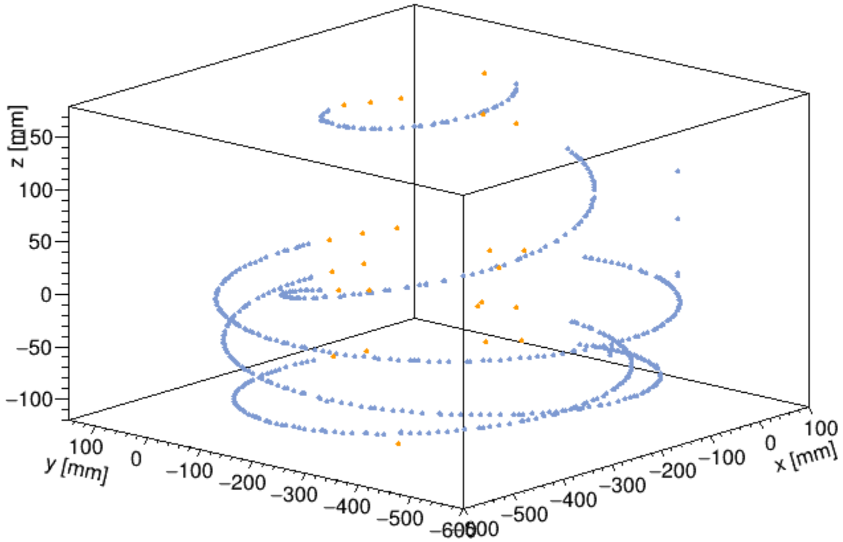


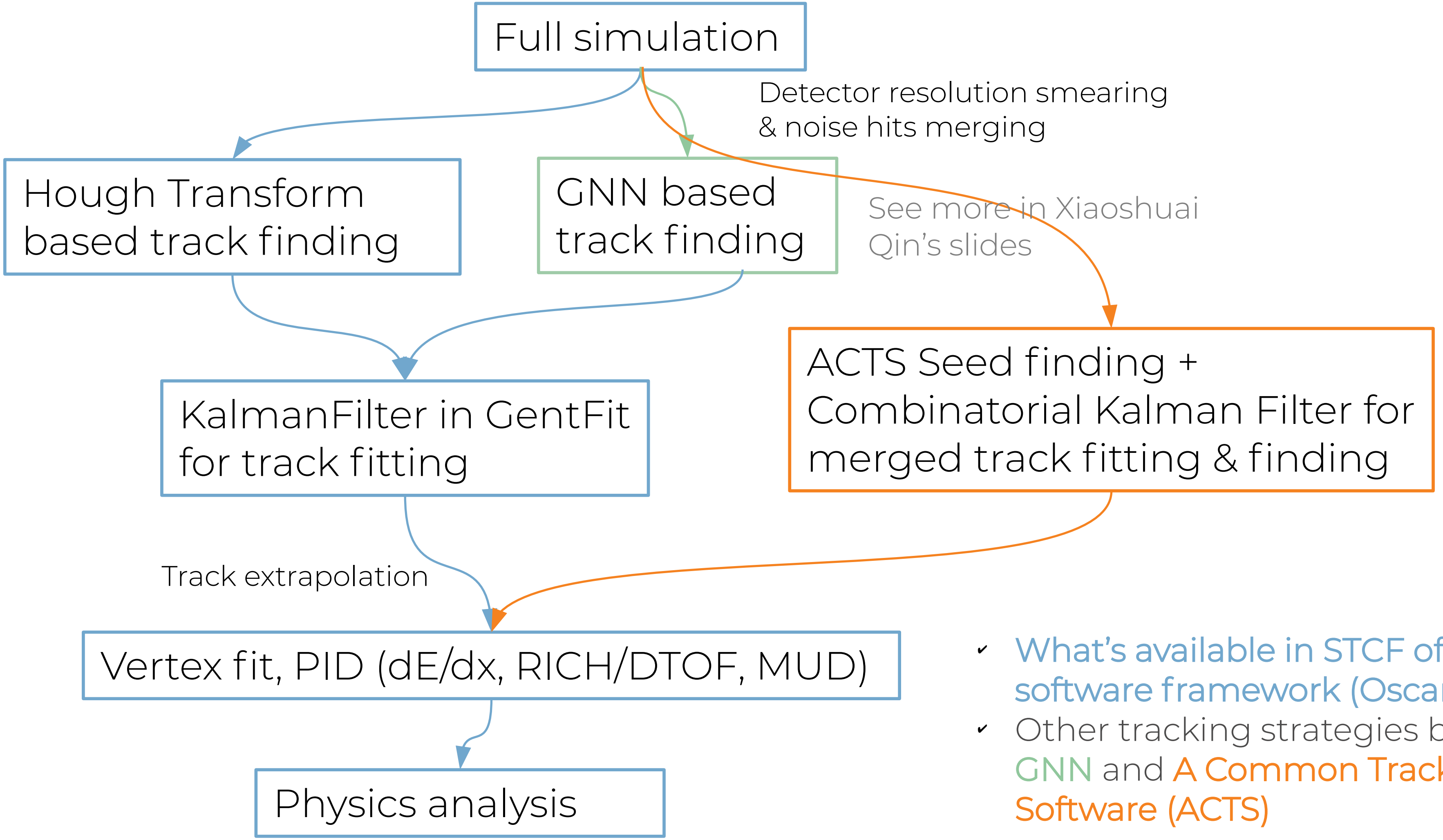
Figure from STCF CDR

- **σ**(p)/p = 0.5% with p = 1 GeV
- Tracking eff. > 50/90/99 % with pt > 50/100/300 MeV
- dE/dx resolution: < 6%

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



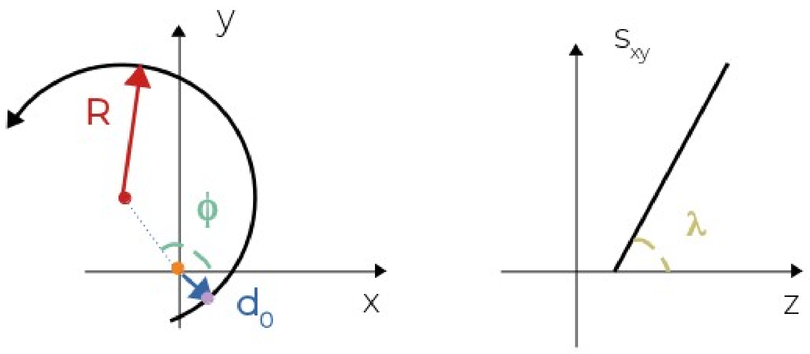
STCF tracking landscape



- ✓ What's available in STCF offline software framework (Oscar)
- ✓ Other tracking strategies based on GNN and A Common Tracking Software (ACTS)

Track parametrization in Oscar

- 5 parameters for describing a helix trajectory
  - d_0 : distance from reference point to track on xy plane
  - ϕ : azimuthal angle of line connecting reference point and circle center on xy plane
  - $\kappa(1/R)$: circle radius parameter
  - d_z : z coordinate of POA
  - $\tan\lambda$: ratio of path length on xy (s_{xy}) and along z

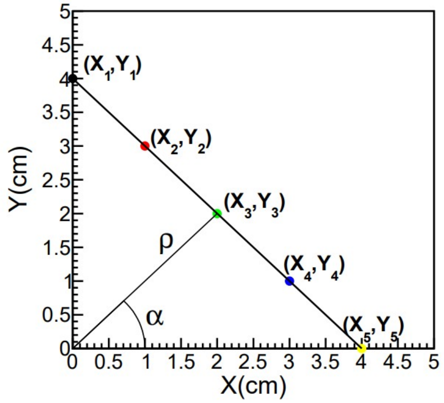


Track finding with Hough Transform

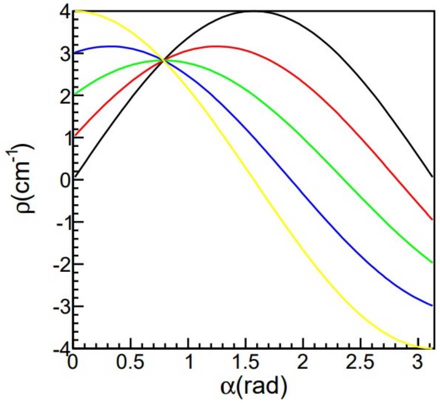
Track finding with Hough Transform

- Each point (x, y) in geometrical space is transformed to a line (described by two parameters) in parameter space
- Track finding becomes finding crossing points of lines in parameter space

A straightline



(a) X-Y plane



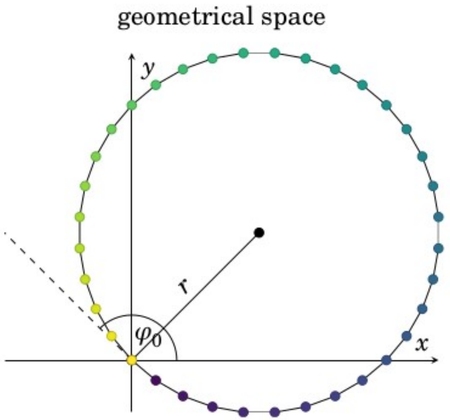
(b) parameter space

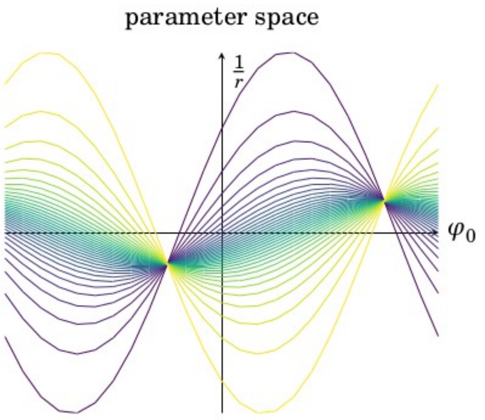
$$Y = -cot(\alpha)X + \frac{\rho}{sin(\alpha)}$$

$$\rho = r_P sin(\alpha + \alpha_P),$$

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

A circle passing (0,0)





Figures from Sara Pohl's thesis

$$X^2 + Y^2 - 2r(cos\phi_0 X - sin\phi_0 Y) = 0$$

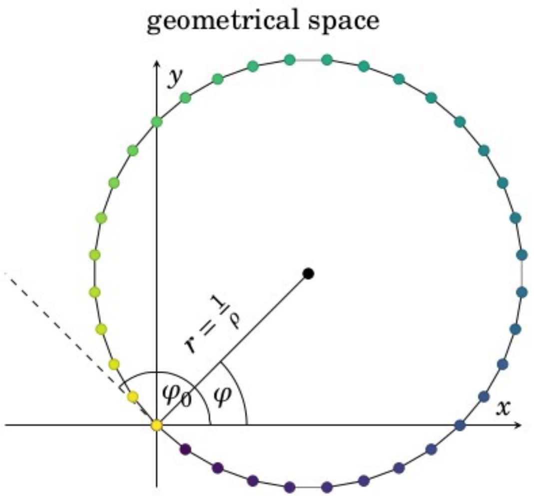
$$\frac{1}{r} = \frac{2}{r_P} sin(\alpha_0 - \alpha_P)$$

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

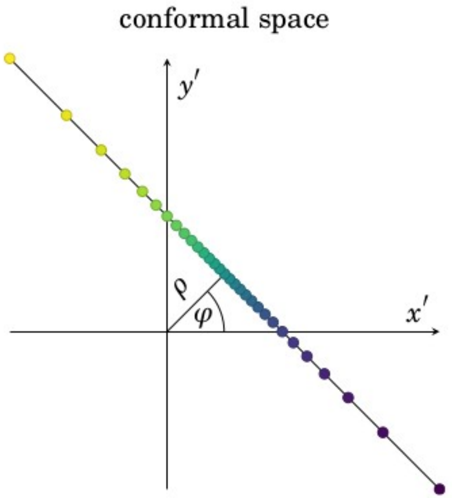
Hough Transform for STCF

Transform (X, Y) of hits on ITK and MDC Axial wires to Conformal space → parameter (hough) space

Figures from Sara Pohl's thesis

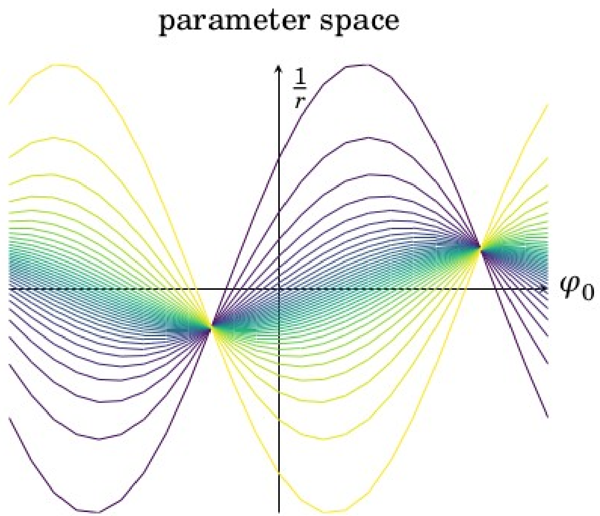


$$X^2 + Y^2 - 2r(cos\phi_0 X - sin\phi_0 Y) = 0$$



$$\frac{1}{r} = cos\phi_0 U - sin\phi_0 V$$

$$U = \frac{2X}{X^2 + Y^2}, V = \frac{2Y}{X^2 + Y^2}$$



$$\frac{1}{r} = \frac{2}{r_P} sin(\alpha_0 - \alpha_P)$$

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

Hough Transform for STCF

Transform (X, Y) of hits on ITK and MDC Axial wires to Conformal space → parameter (hough) space

↓

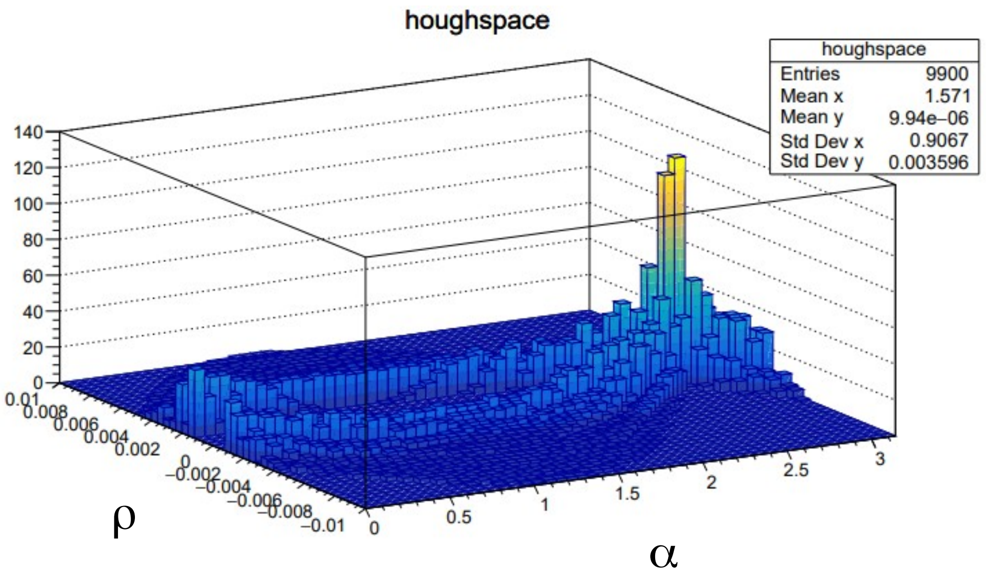
Find bins, i.e. tracks, with entries passing threshold in parameter space

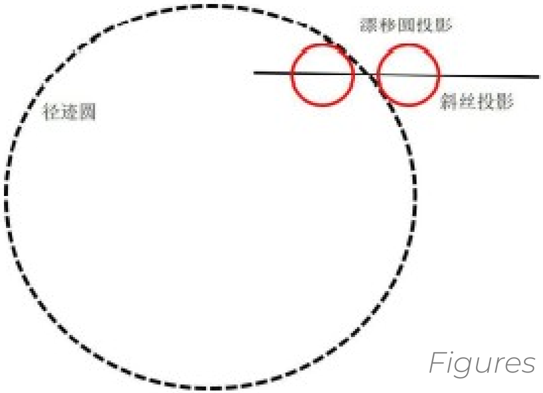
↓

Fit the circle parameters (ρ, α) of the tracks and find potential additional hits from MDC stereo wires

↓

Transform (s_{xy}, Z) of additional hits from MDC Stereo wires to parameter space ($\tan\lambda$), and find compatible hits

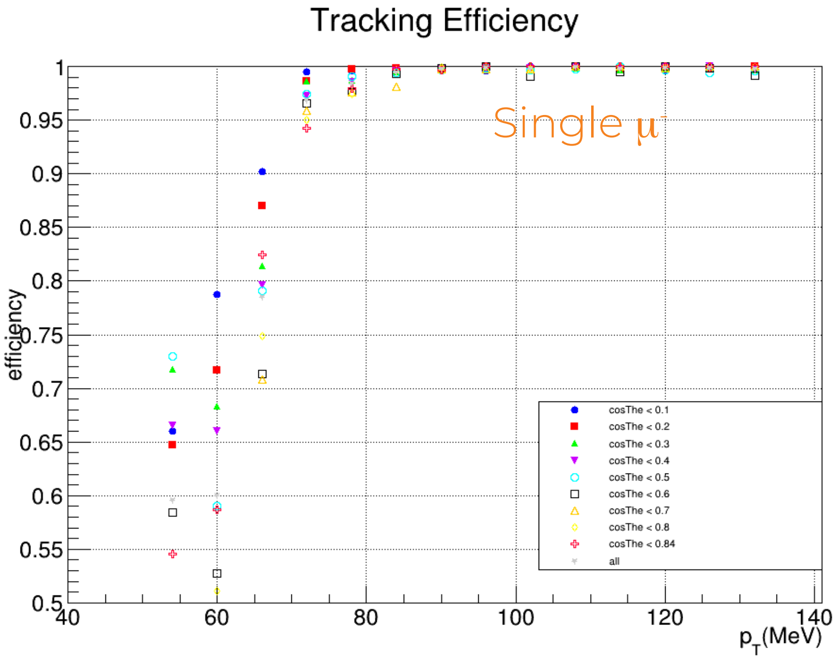


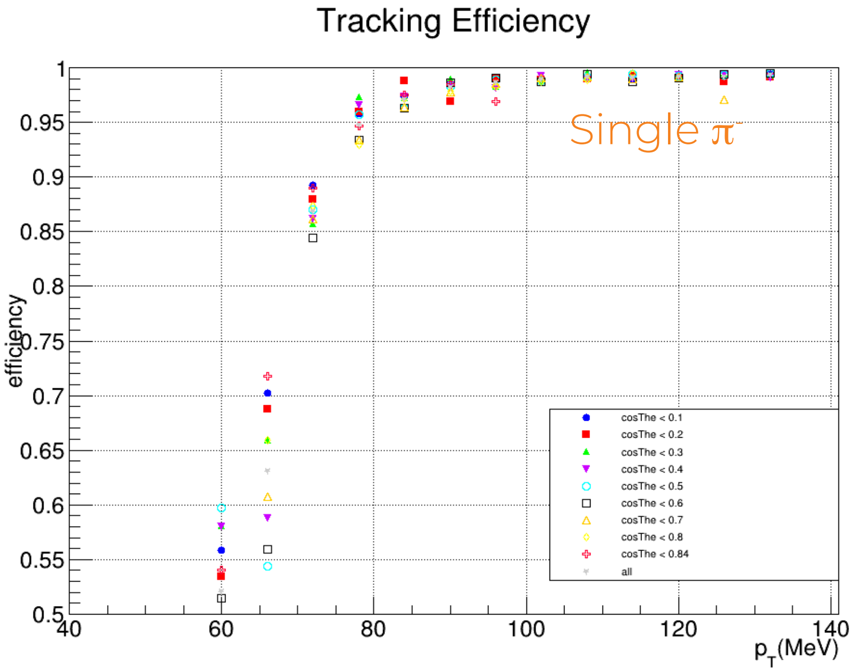


Figures from Hang Zhou

Tracking efficiency with Hough Transform

- Tracking efficency is above 97%/95% for single μ^-/π^- with pT > 80 MeV





Plots from Hang Zhou

Track finding&fitting with ACTS

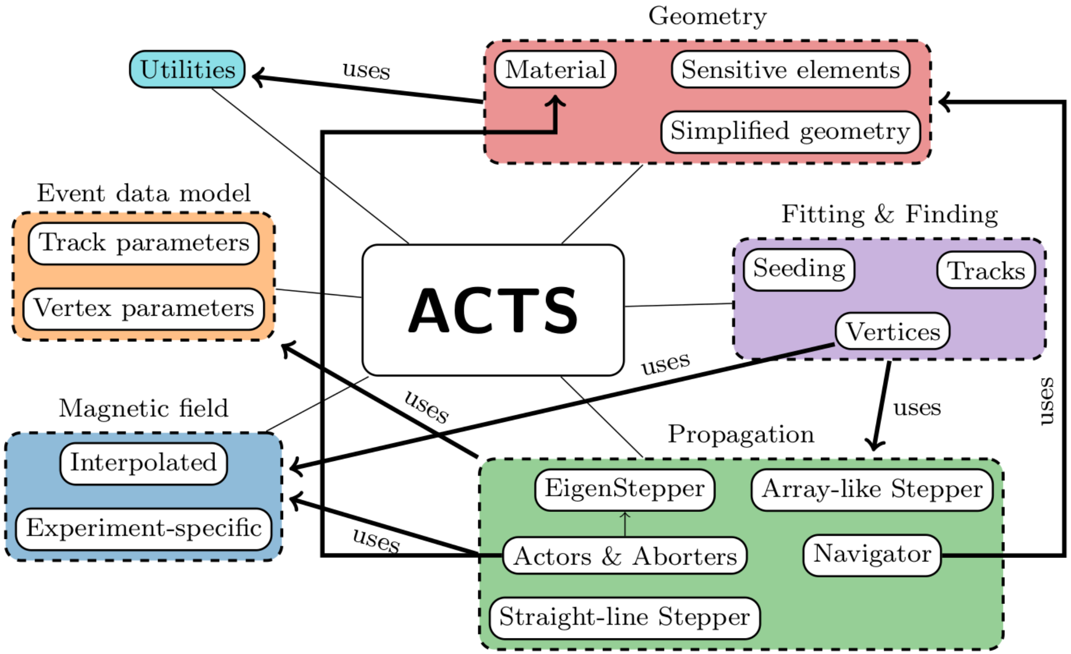
A Common Tracking Software (ACTS)

- 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** concepts
- **Detector and magnetic field agnostic**
- Strict **thread-safety** to facilitate concurrency
- Supports for **contextual** condition
- Minimal dependency (Eigen)
- Highly configurable for **usability**
- Well documented and maintained

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

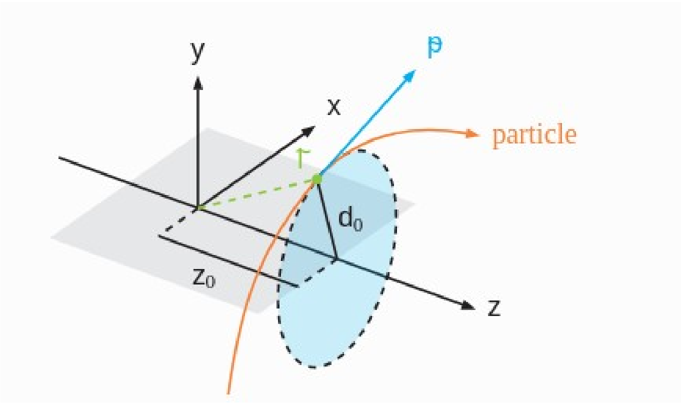
The basic tracking tools in ACTS



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

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

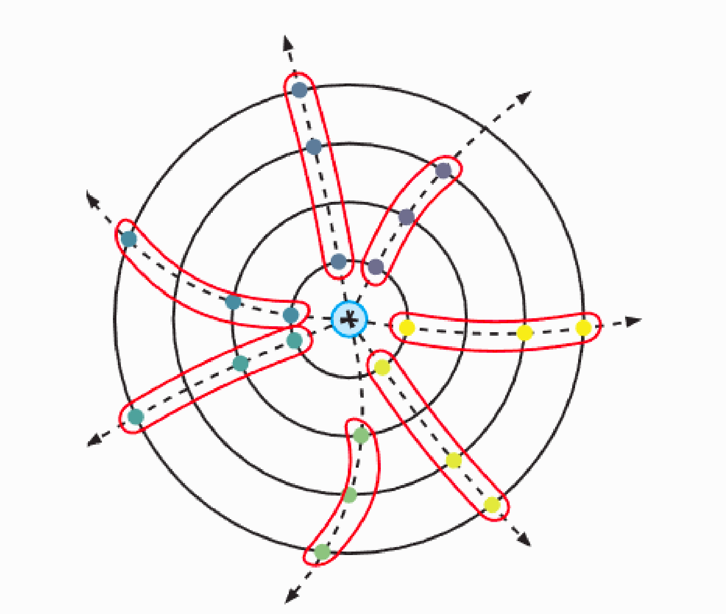
- No assumption of helix track for track parametrization
- Flight time in track parameterization (facilitate time measurement)

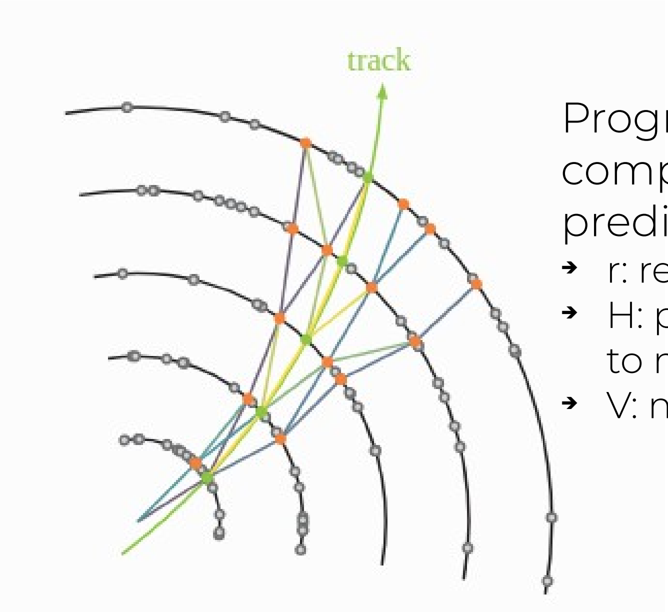


Figures from ACTS readthedocs

Tracking finding&fitting with ACTS

Seeding
(find seeds using hits on ITK layers) → Combinatorial Kalman Filter (CKF)
(track finding through KF fitting)





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

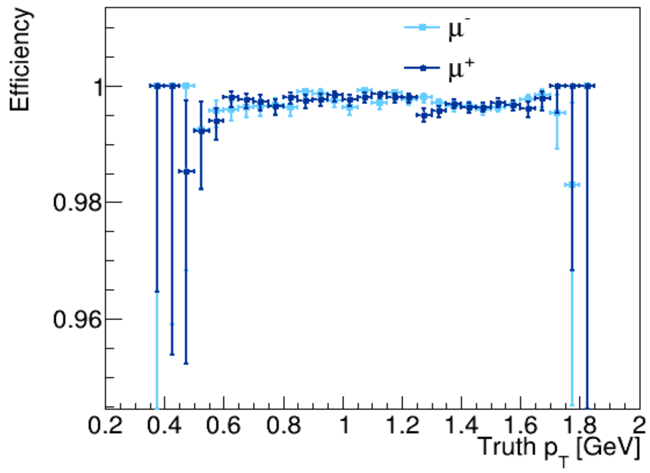
- r: residual
- H: projection from track parameters to measurement
- V: measurement covariance

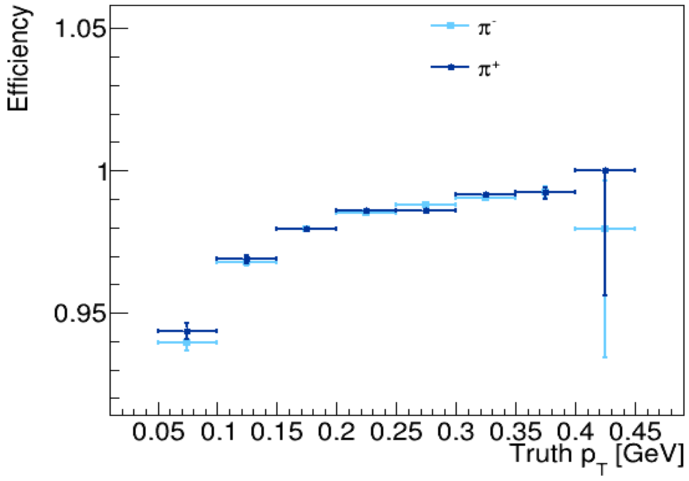
Figures from ACTS readthedocs

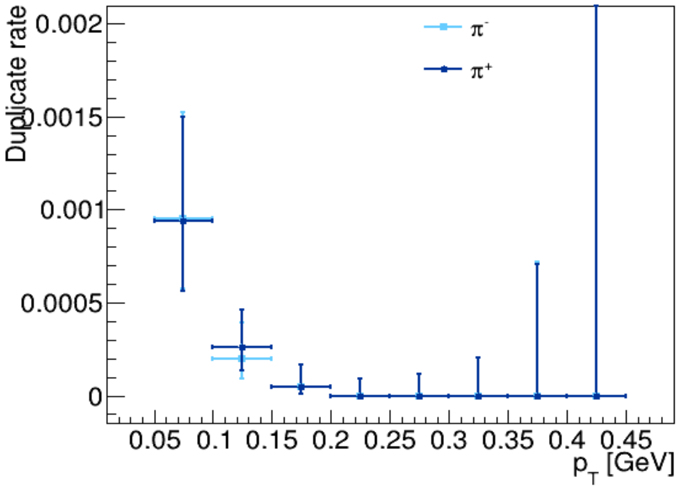
Track finding performance with ACTS

- Above 99% efficiency for pT > 400 MeV
- 94% efficiency for pion with pT in [50, 100] MeV
- <0.1% duplicate tracks for pT < 130 MeV due to duplicate seeds for looping tracks

psi(3686)→ $\pi^+\pi^- J/\psi(\mu^+\mu^-)$







Track parameters resolution with ACTS

- CKF also provides track parameters at specified target surface, e.g. beam line or tracker exit
- When pT = 1 GeV, theta = 90 deg,
  - σ(d0) ≈ 150 um, σ(z0) ≈ 400 um
  - $\sigma(p_T)/p_T$ = 0.45%

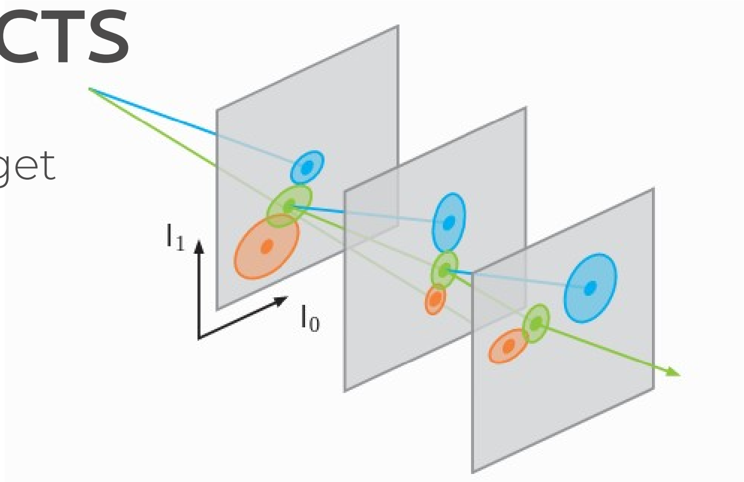
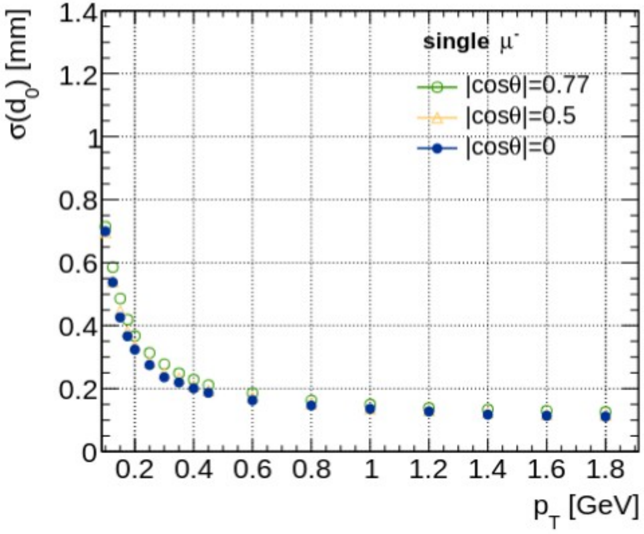
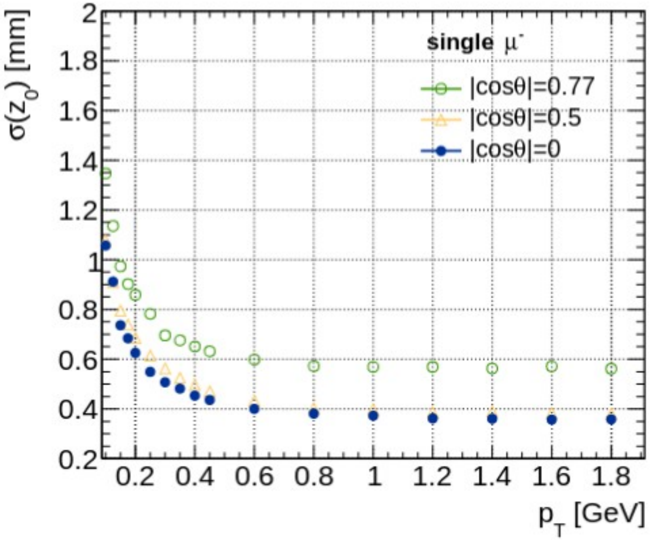
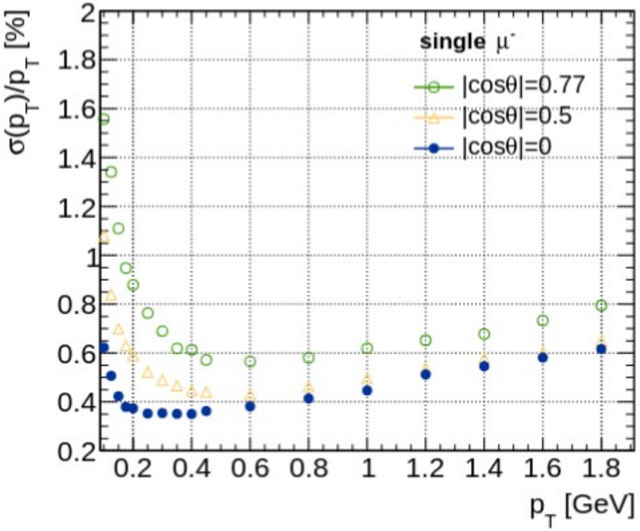


Figure from ACTS readthedocs







Summary and Outlook

- Basic tracking algorithms for track finding (Hough Transform), fitting (GentFit), extrapolation are in place in Oscar
  - Tracking efficency is above 97%/95% for single μ^-/π^- with pT > 80 MeV
- Alternative tracking strategy with ACTS looks promising
  - 94% tracking efficiency with pT in [50, 100] MeV
  - $\sigma(p_T)/p_T < 0.5\%$ with pT = 1 GeV, theta = 90 deg is achieved
- Future focus is to optimize and tune tracking algorithms for vast tracker&MUD design and layout optimization (in more realistic tracking environment)
  - Tracking performance validation tools have been developed

Contribution is very very very welcome!

stcf-reco@lists.ustc.edu.cn

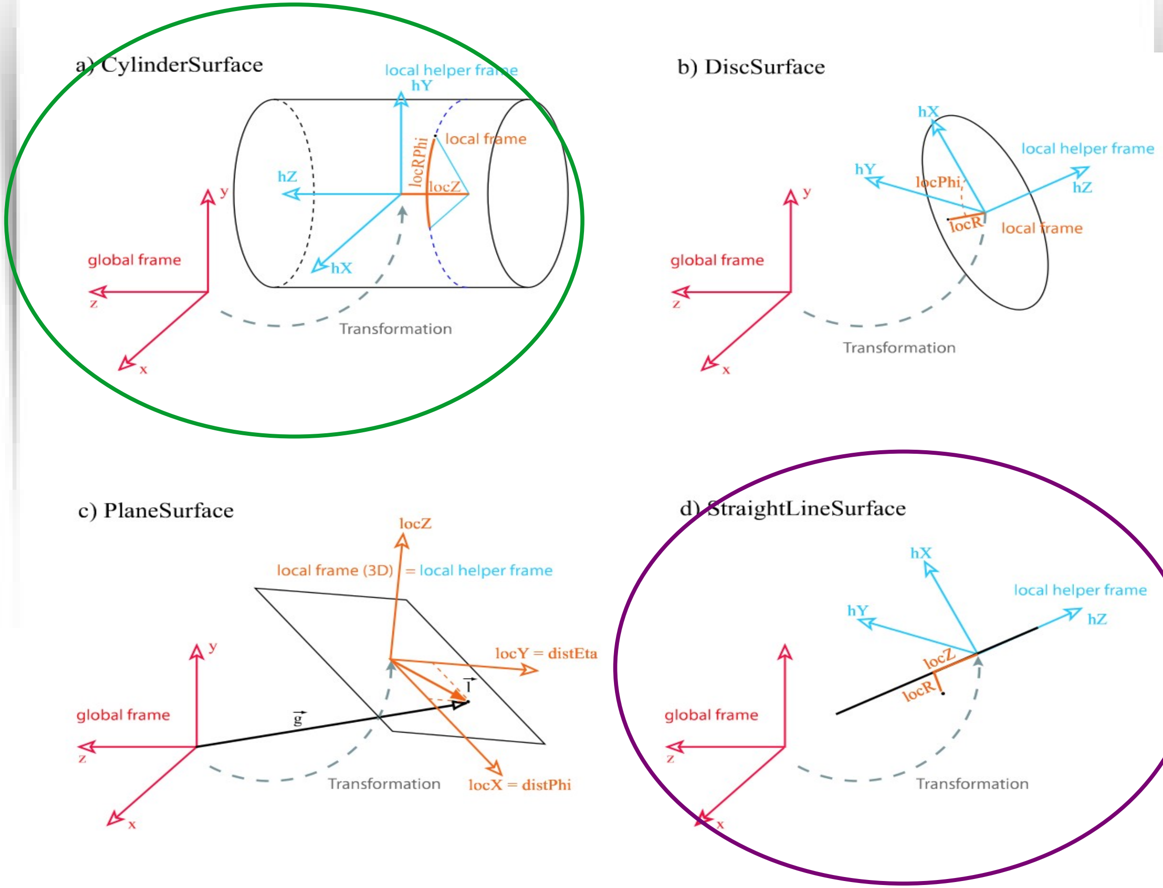
Weekly STCF reconstruction (currently focus on Tracking&MUD reconstruction) at 2 pm each Friday

BACKUP

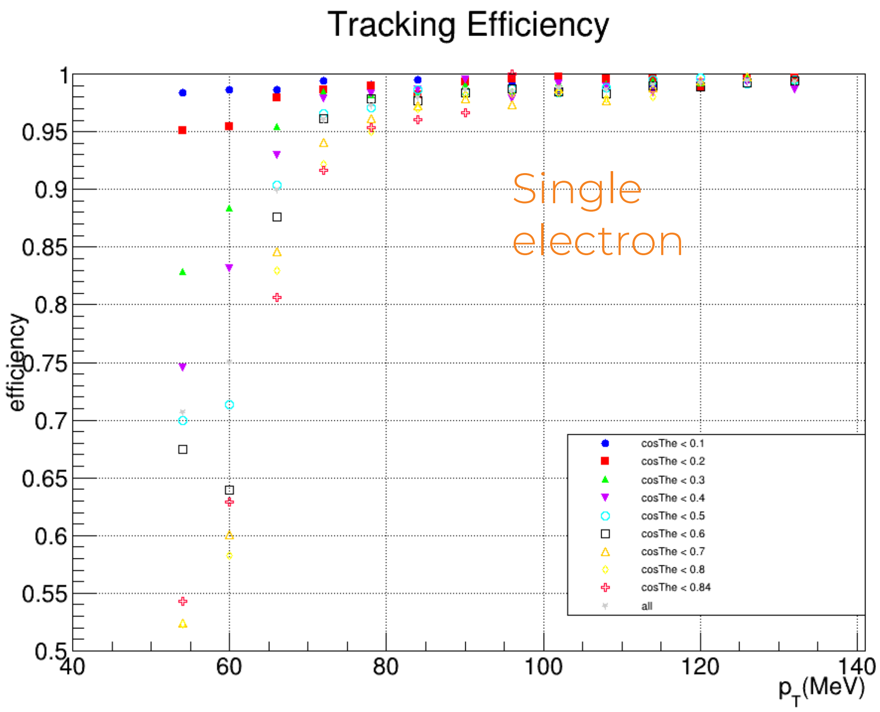
STCF tracking geometry

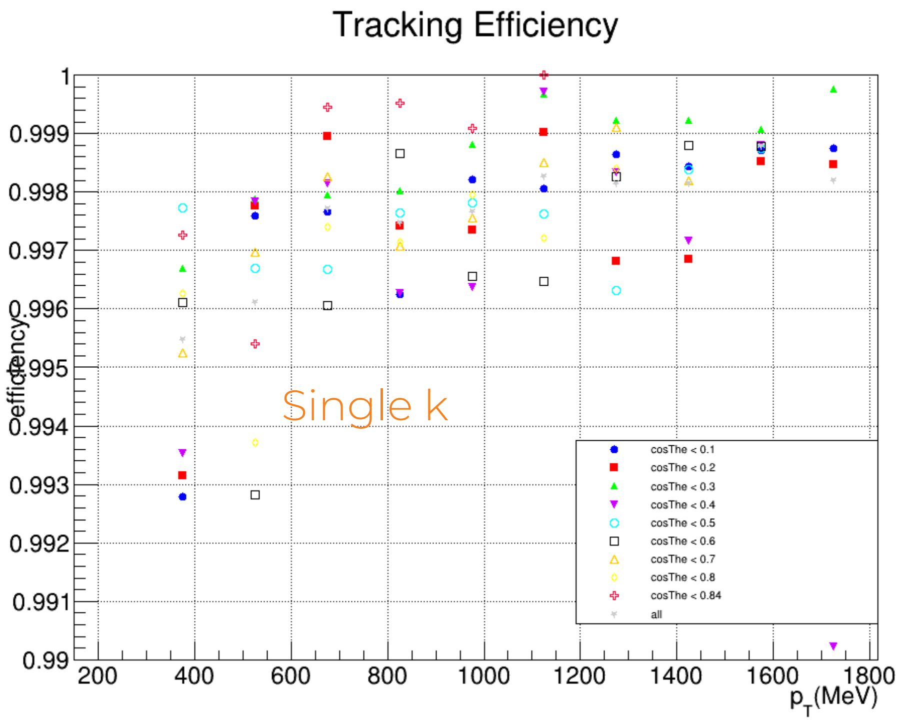
- Full sim geometry of STCF based on DD4hep is exported as TGeo file
- And then converted to ACTS tracking geometry by TGeo Plugi
  - Each layer of ITD is converted to an ACTS Layer with a sensitive CylinderSurface
  - Each layer of MDC containing N cells is converted to an ACTS Laye with N LineSurfaces

Surface types in ATLAS SW & ACTS



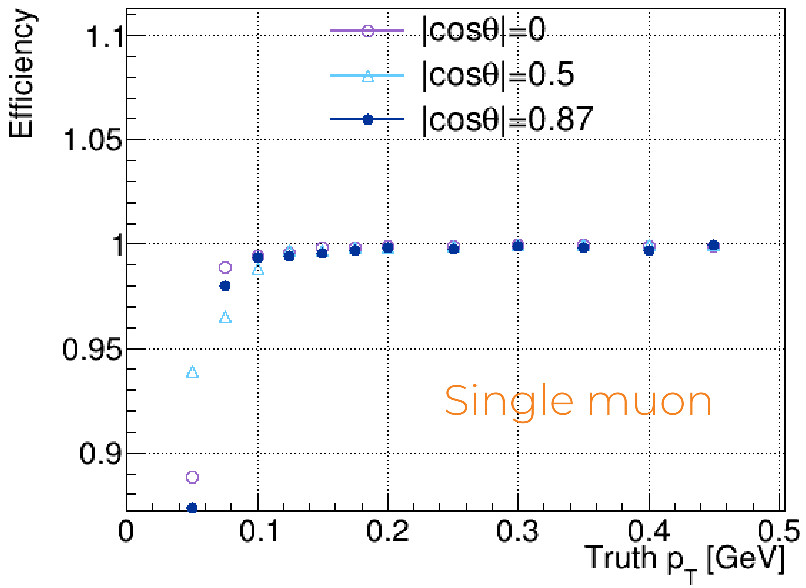
Tracking efficiency with Hough Transform

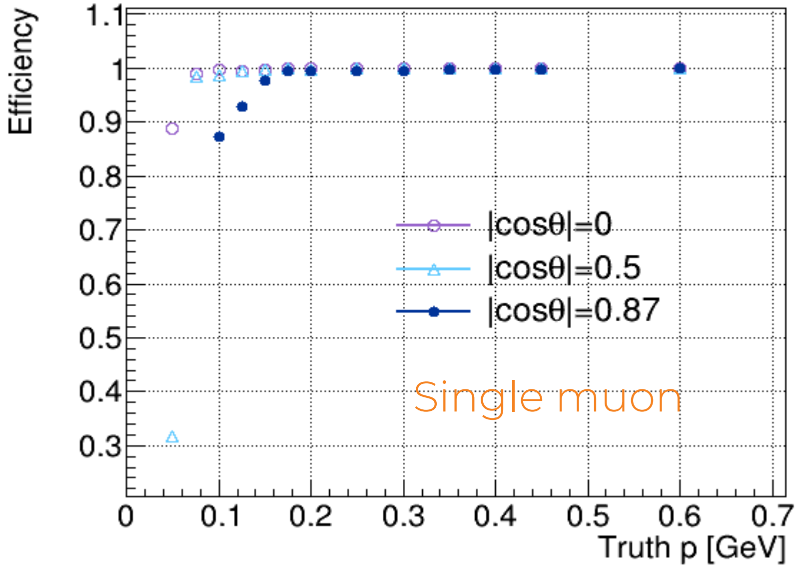




Plots from Hang Zhou

ACTS tracking efficiency





Study of tracking efficiency and its systematic uncertainty from $J/\psi \rightarrow p\bar{p}\pi^+\pi^-$ at BESIII*

Chinese Physics C 40, 026201 (2016)

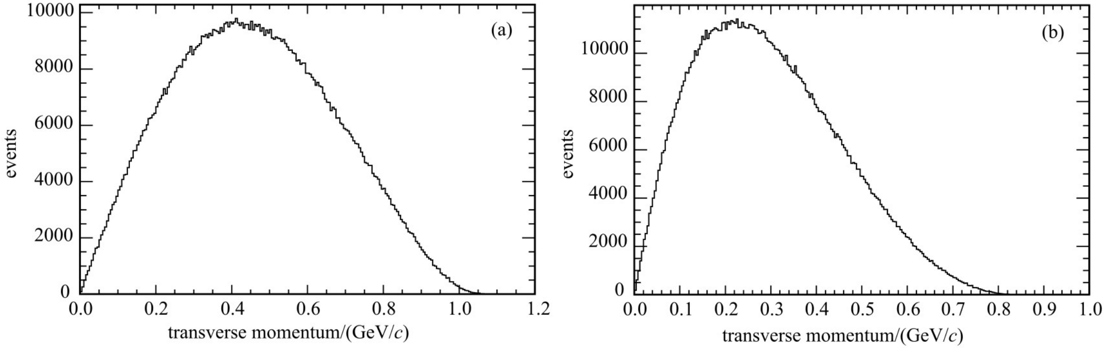


Fig. 1. Typical P_{T} distribution of (a) protons and (b) pions from exclusive MC sample.