STCF Hough Tracking and Fitting

Jin Zhang

On behalf of the STCF software group

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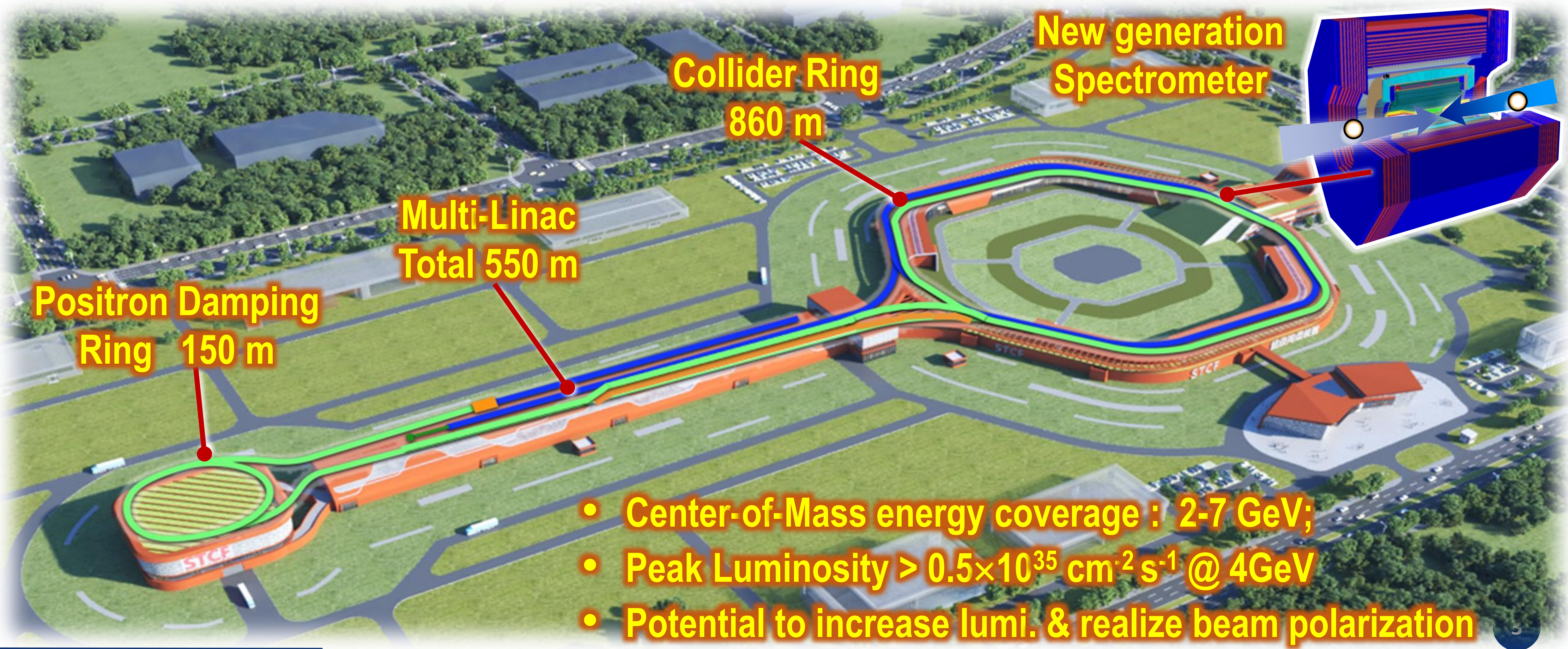
Outline

- Introduction to STCF and the tracking system
- The baseline tracking with Hough transform and GenFit2
- Displaced track optimization with Hough transform
- Tracking performance evaluation for tracker layout optimization
- Summary

Super Tau-Charm Facility

A factory produced massive tau lepton and hadrons, to unravel the mystery of how quarks form matter and the symmetries of fundamental interactions



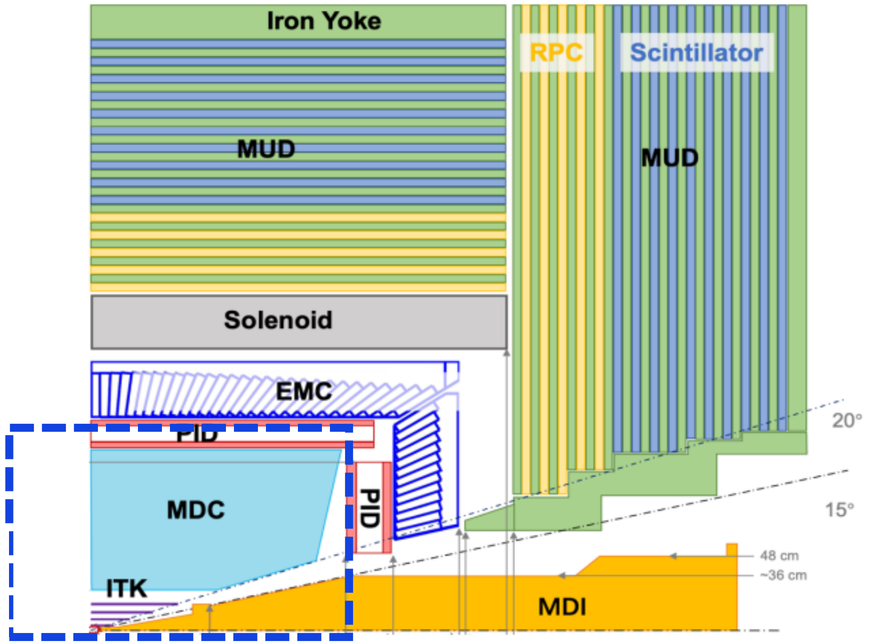
- Center-of-Mass energy coverage : 2-7 GeV;
- Peak Luminosity > 0.5×10^{35} $cm^{-2}s^{-1}$ @ 4GeV
- Potential to increase lumi. & realize beam polarization

Tracking System: MDC + ITK

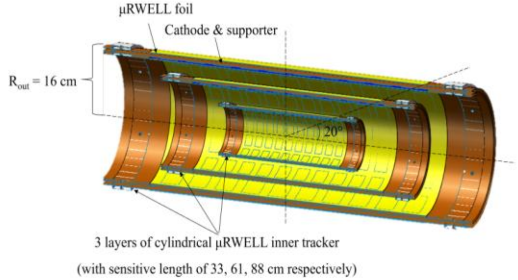
Works in a **1T magnetic field**

CDR:

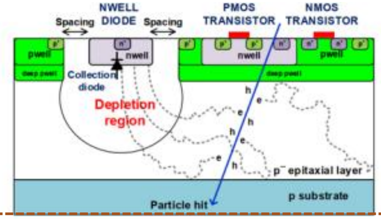
- **MDC**: main drift tracker with large detection volume range
  - 48 layers, 4 stereo super – layers, 4 axial super layers
- **ITK**: 3 layers of detectors with high counting rate capability
  - Placed in the area close to the beam pipe $(3 - 20 \text{ cm})$
  - Two options: MPGD / MAPS

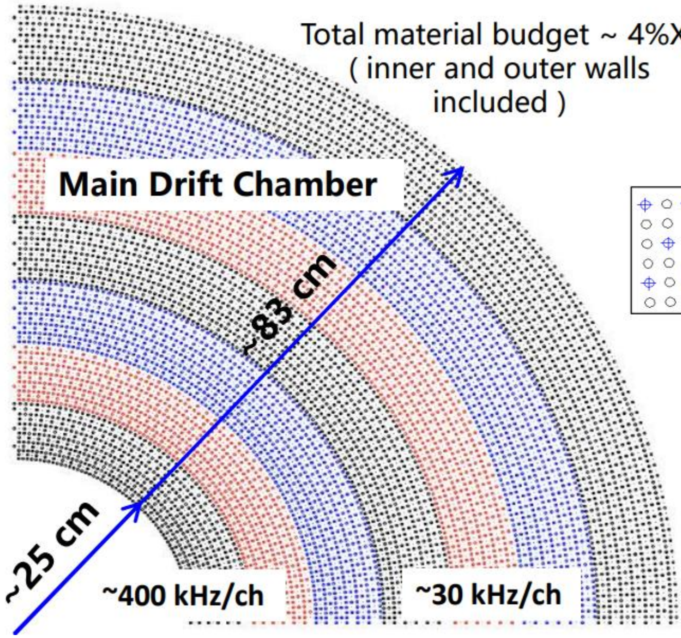


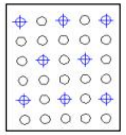
ITK Gaseous option : MPGD



ITK Silicon option: CMOS MAPS







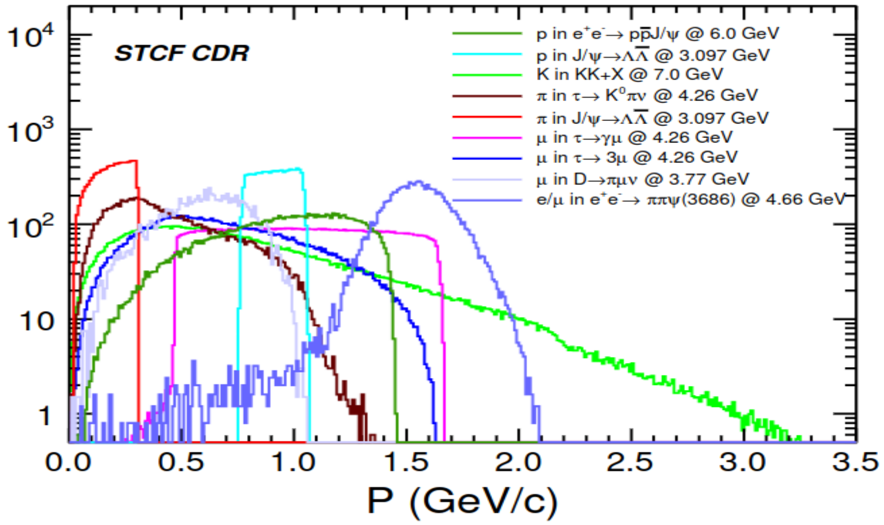
Superlayer	Radius (mm)	Num. of Layers	Stereo angle (mrad)	Num. of Cells	Cell size (mm)
A	200.0	6	0	128	9.8 to 12.5
U	271.6	6	39.3 to 47.6	160	10.7 to 12.9
V	342.2	6	-41.2 to -48.4	192	11.2 to 13.2
A	419.2	6	0	224	11.7 to 13.5
U	499.8	6	50.0 to 56.4	256	12.3 to 13.8
V	578.1	6	-51.3 to -57.2	288	12.6 to 14.0
A	662.0	6	0	320	13.0 to 14.3
A	744.0	6	0	352	13.3 to 14.5
total	200 to 827.3	48		11520	

Task of Tracking and The Landscape in STCF

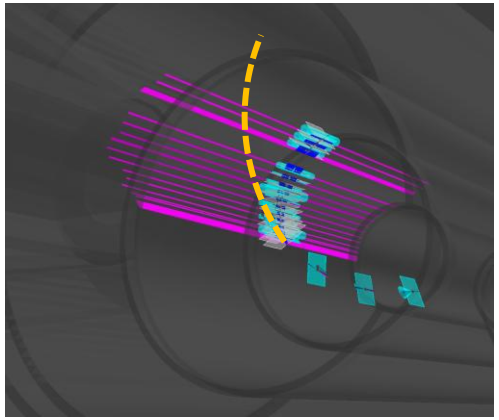
Crucial task for Tracking algorithm : reconstruct particles with **high tracking efficiency and resolution, in a large momentum region(p: 50 MeV~3.5 GeV)**

- **High background** : negatively impact on resolution and efficiency
- Most physics channel have number of particles with **p < 0.4 GeV**
  - **Obvious Material effect** from multiple scattering, ionization energy loss especially for inner wall, ITK, beam pipe
  - **Looping < 125MeV, multi-turn tracks**
- **Long-live particles: displace tracks, sometimes with low pT**

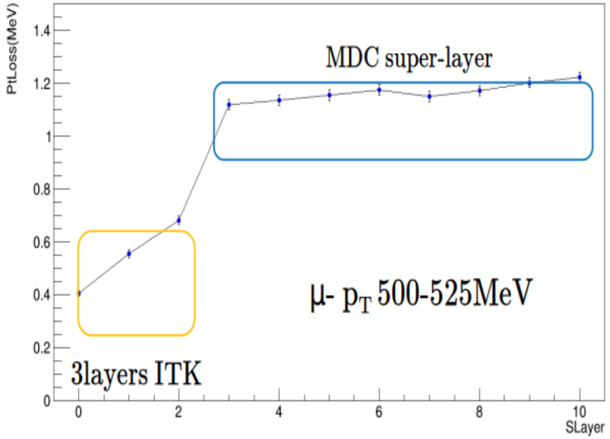
Momentum distributions of charged particles



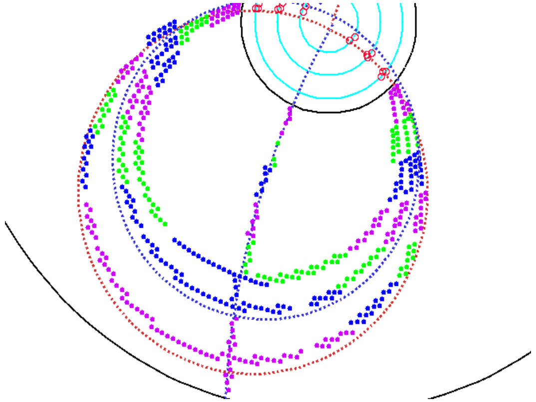
a low p_T track occurs large scattering



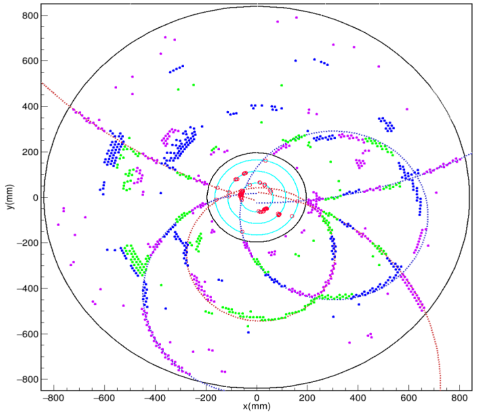
reduction in p_T upon entering MDC



a track with multi-turn loops



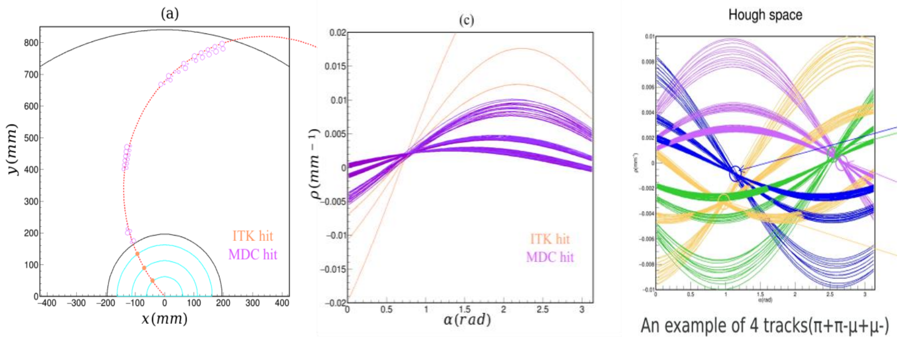
Displaced tracks from long-live particles



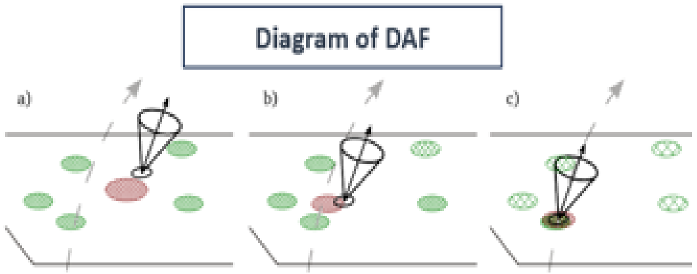
A stable track reconstruction algorithm is essential for studies of physics potential and detector optimization

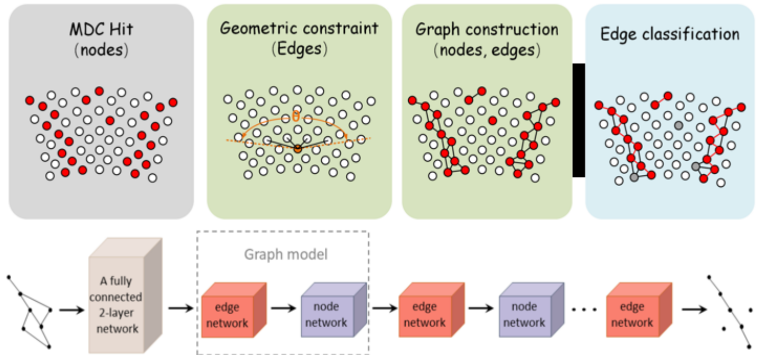
Baseline Tracking Algorithm using Hough Trans and GenFit

Hough + GENFIT2 + GNN(pre-noise filtering)

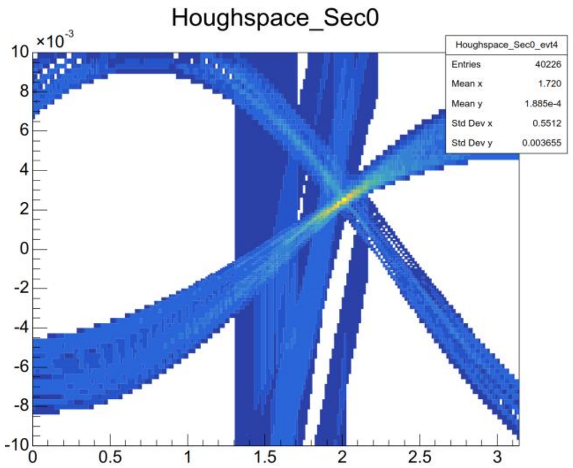


An example of 4 tracks(π+π-μ+μ-)





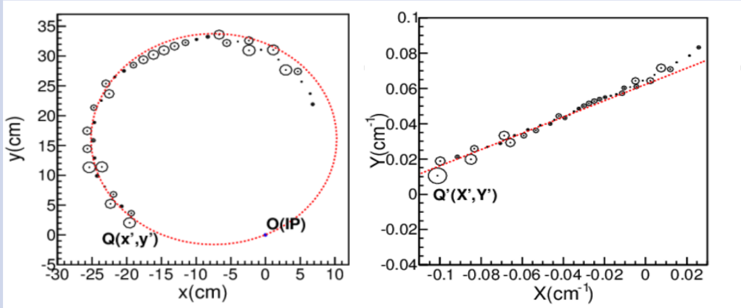
- **Global track reconstruction based on Hough transform and DAF**
  - Global method, robust to local inefficiencies
  - **enhancing the ability to search for displaced tracks**
  - Extended Kalman Filter(**DAF**) using GENFIT2
  - GNN is used as noise filtering, details in previous talk



displaced tracks in $J/\psi \to \Xi^{-}\bar{\Xi}^{+}$, with a Hybrid Hough transform

Hough Transform / Legendre Transform

Conformal Mapping : reliable for prompt tracks, but ineffective for displaced tracks



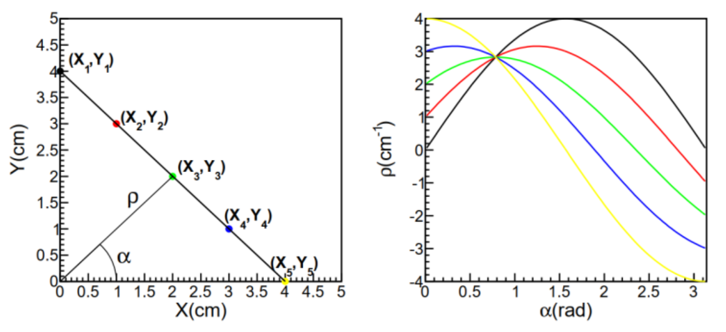
- **(Trajectory) Circles** ***passing the origin point ->*** **conformal straight lines**
- **(Drift) Circles** ***not passing the origin point ->*** **conformal circles**

"conformal circles" are tangent to "conformal straight line"

Negative impact for displaced tracks

Hough transform

- Transform a point in real space to a line or a curve in Hough Space
- Points rest on a line in real space ←→ lines or curves focusing in Hough Space

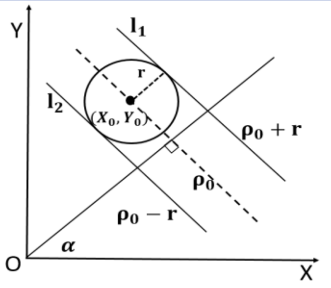


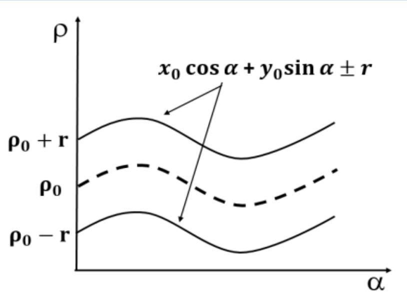
For Drift Chamber： Legendre transform

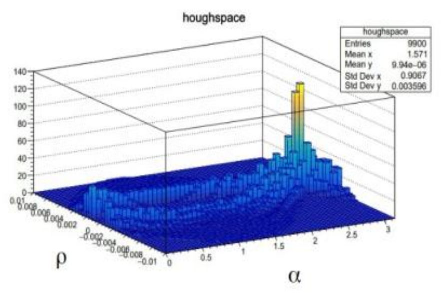
- **One drift circle->two curve lines on Hough space**

$$\rho = X\cos\alpha + Y\sin\alpha + r, (upper\ half\ circle)$$

$$\rho = X\cos\alpha + Y\sin\alpha - r, (lower\ half\ circle)$$



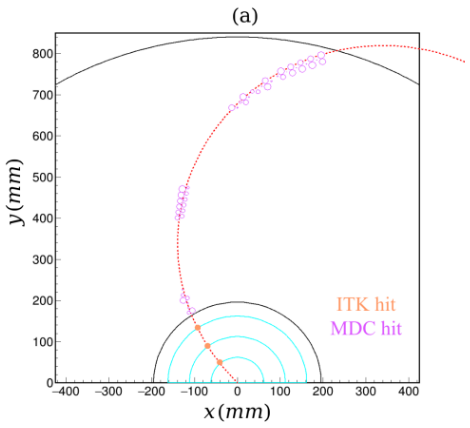


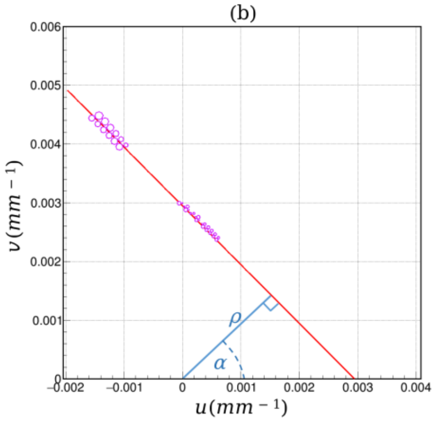


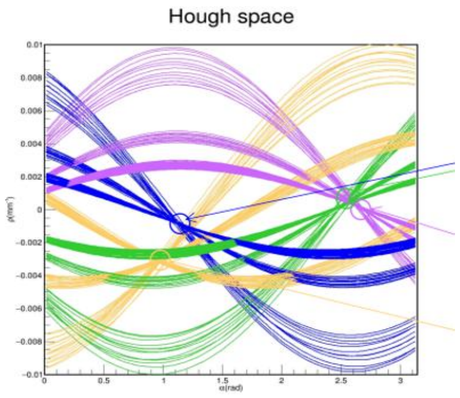
To use the MDC information, Legendre transform is applied in STCF

Implementation of Hough Transform (2D)

Conformal Transform → **Hough Transform(2D)** → **Histogram filling Peak finding** → **Global fitting(circle) Hit selection**







An example of 4 tracks(π+π-μ+μ-)

I. Conformal transform: **circular trajectories -> conformal straight lines**

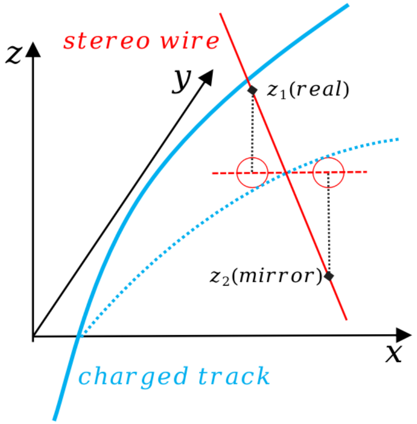
II. **Handling ITK and MDC measurements simultaneously**, populating the Hough Space (2D histogram)

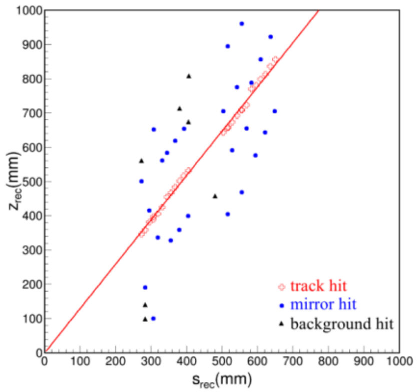
III. Peak finding approach to identify candidate tracks(circles) in Hough Space

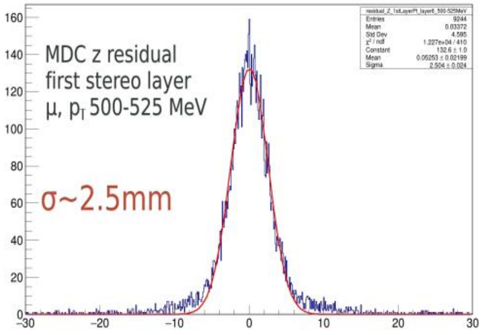
IV. Global chi-square fit for circle tracks

Implementation of Hough Transform (3D)

Stereo hits association → **Hough Transform(SZ)** → **s-z track finding** → **Global fitting(helix)**







I. Match MDC stereo wire hits, and calculate z position, flight path(s) values

II. The trajectory is a straight in the s-z space → similar to the 2-D track finding: **Hough transform on SZ plane**

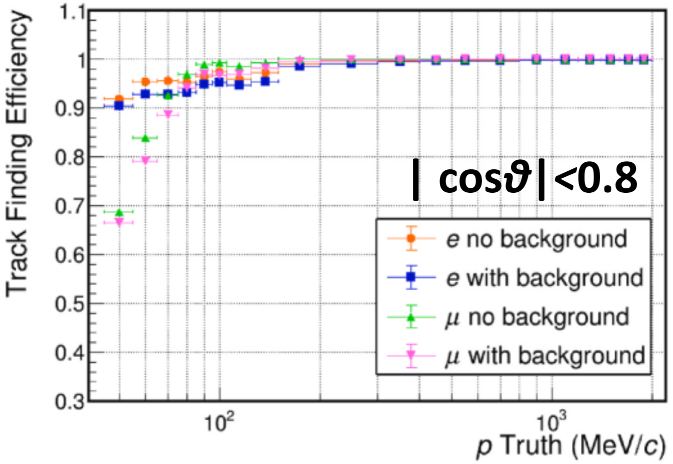
Left/right ambiguity is considered in **Hough(SZ) Space**

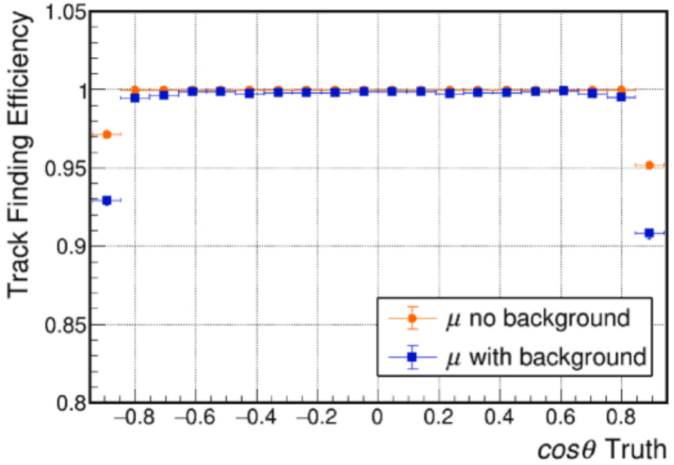
III. A global chi-square fitting is performed to retrieve the parameters of helix track

IV. Track merging and fake-track rejection are performed on the constructed helix candidate tracks

Tracking Performance of Hough Transform

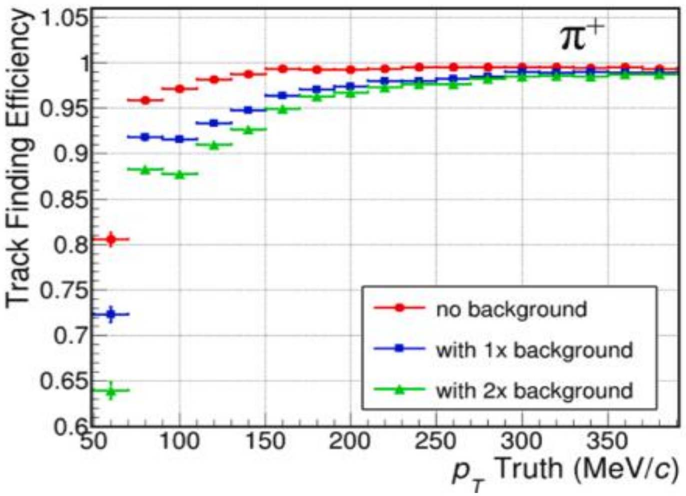
- The track finding efficiency for single e and μ is studied in **full simulation**

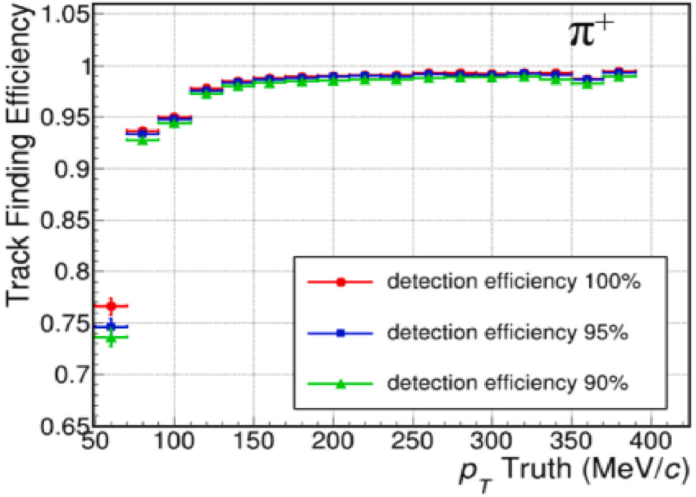




Track finding efficiency : N1 / N2
N1: Number of reconstructed tracks matching with the truth tracks
N2: Number of truth tracks with simulated hits >= 5, within 20°<θ<160°

- ψ(3686) → π+π- J/ψ, J/ψ → μ+μ- is studied in **full simulation**





- Reliable and stable performance for single particle and physics channel
- High track finding efficiency is maintained with reduced detector efficiency
- Track finding efficiency of pion is **above 95%/90% without/with 1X background** at 100MeV

Track Fitting based on GENFIT2

- **GENFIT2 – A Generic Track Fitting toolkit**
  - Experiment-independent, modular track-fitting framework
  - Open-source C++ code, larger user community (e.g., Belle2, PANDA, SHiP, AFIS …)
  - ➢ Providing typical track fitting tools, e.g., **Kalman Filter (KF), Deterministic Annealing Filter (DAF), Reference KF, Reference DAF**

- **GENFIT2 is implemented in OSCAR**
  - Candidate tracks from **Hough track-finding algorithm** are fed into GENFIT2
  - Process with multiple particle hypotheses
  - **Deterministic Annealing Filter (DAF)** is used as the default fitting algorithm
  - **For curling tracks**, hits from **first half** are provided to fitting algorithm

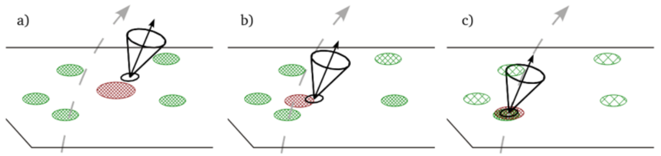
Kalman filter: Iterative bi-directional Kalman filter is applied in GENFIT2

- Forward / backward fitting
- The **iterative process** continues over measurements until convergence is achieved

DAF(Deterministic annealing filter): Iterative Kalman filter with weighting and annealing process

- assignment probabilities for measurement as used as weight
- capable of rejecting noise/outliers and to resolve left/right ambiguities

Diagram of DAF



a) At first, all measurements get similar weights, and all will be considered.

b) After update, measurement with large errors are assigned smaller weight.

c) As the temperature decreases, measurements with large errors are given even less weight.

- the weight drops below the threshold, reject

Track reconstruction in the ATLAS experiment : The deterministic annealing filter

Track Fitting Performances

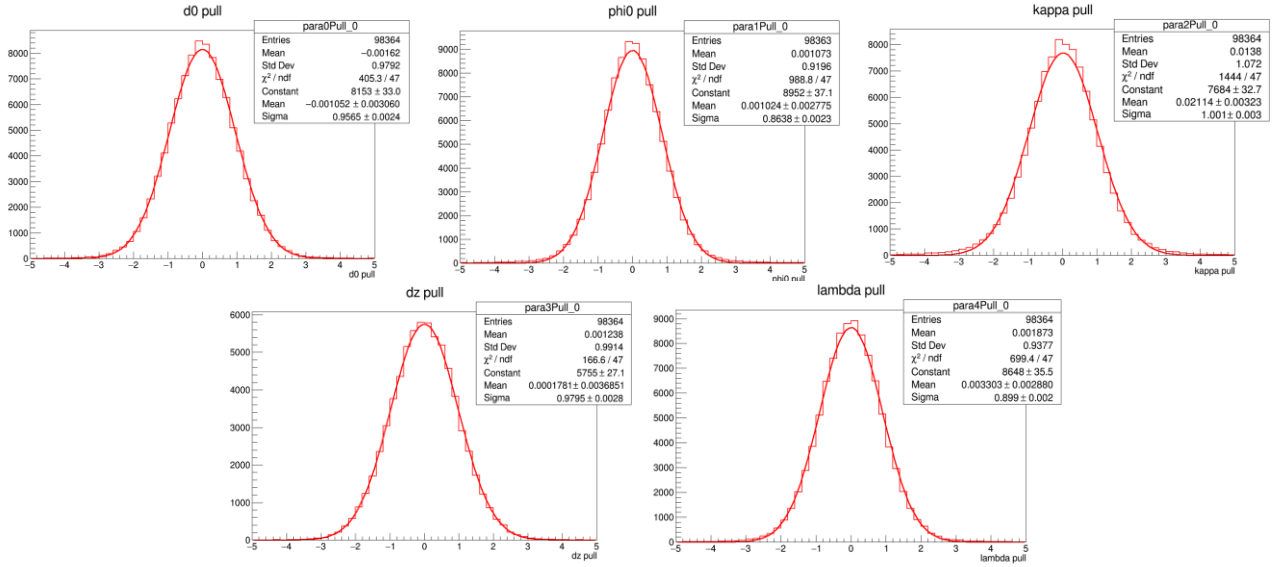
- **The pull distributions are approximately consistent with standard normal distributions**

$$\text{Pull} = \frac{v_{fit} - v_{truth}}{\sigma_v}$$

v_{fit} : the estimated value

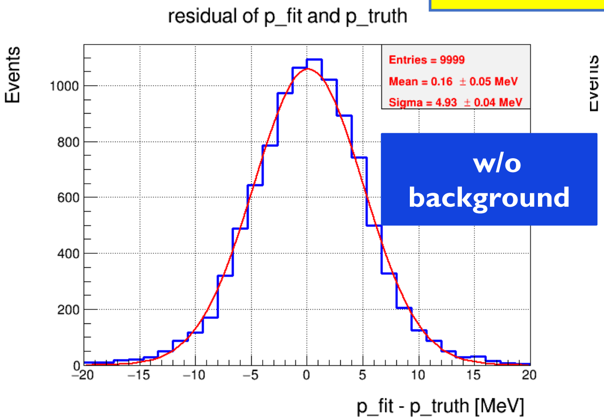
v_{truth} : the true simulated value

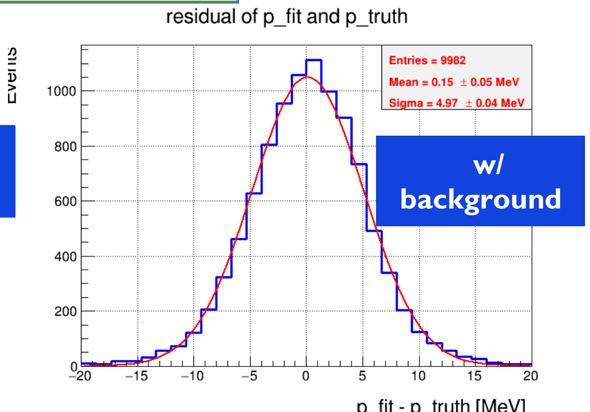
σ_v : the estimated uncertainty parameter



- **The Fitting convergence efficiency is greater than 99%**
- **achieves good momentum resolution (<0.5% @ 1GeV, w/ w/o background)**

single μ^+ @ 1GeV

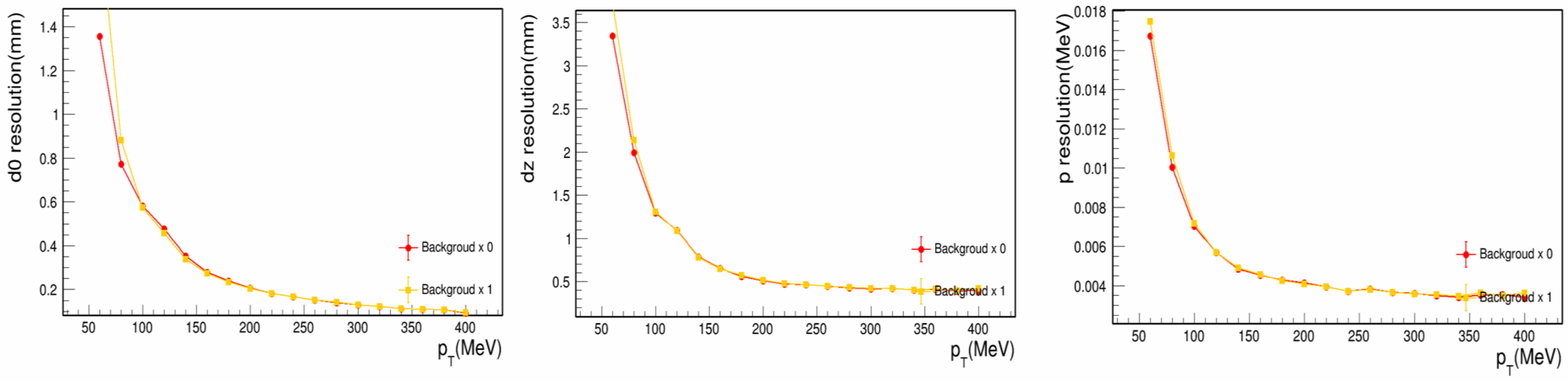




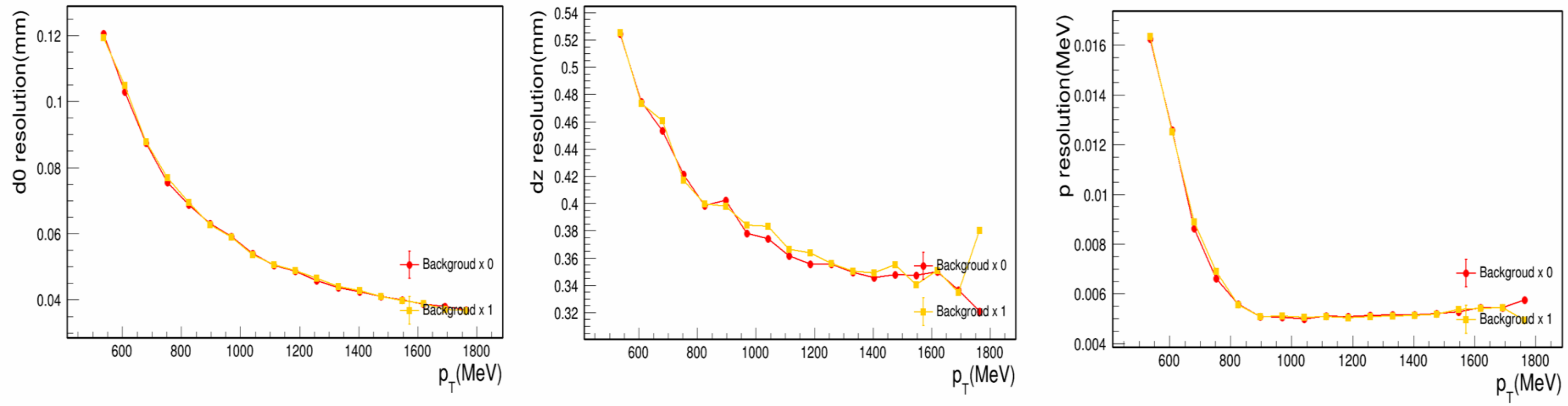
Resolution of Tracking Parameters

Impact parameter and momentum resolution form $\psi(3686) \to \pi^+\pi^- J/\psi, J/\psi \to \mu^+\mu^-$

Pion



Muon



The impact parameter and momentum resolution show stable performance w and w/o noise

Tracking for displaced tracks with Hough Transform

The final-state particles from the decay of long-lived particles may be **produced far from the origin :**

$J/\psi \to \Lambda\bar{\Lambda} \to p\pi^-\bar{p}\pi^+$ **(low momentum pion)**

$J/\psi \to \Xi^-\bar{\Xi}^+ \to \Lambda\pi^-\bar{\Lambda}\pi^+ \to p\pi^-\pi^-\bar{p}\pi^+\pi^+$ **(low momentum pion, multiplicities)**

For Traditional Hough: To reduce complexity, conformal mapping is applied, as input

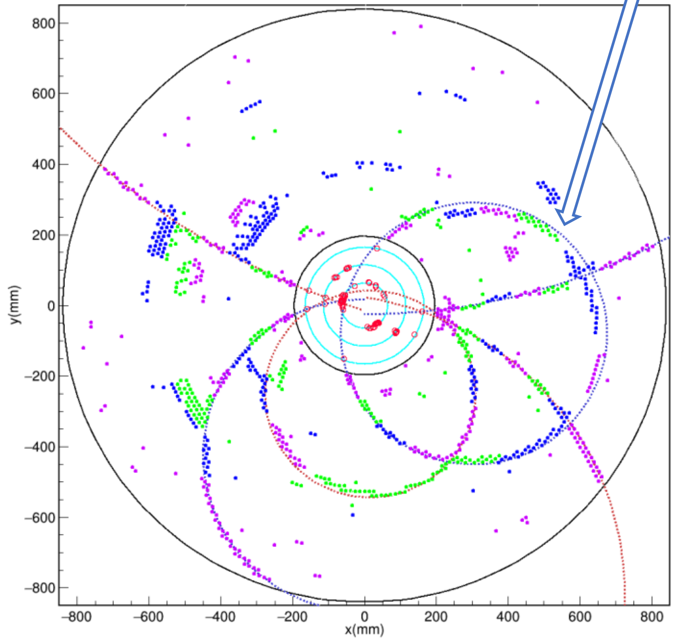
(Trajectory) Circles ***passing the origin point*** **-> conformal straight lines**

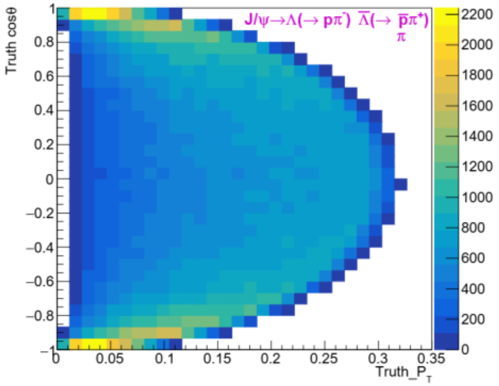
(Drift) Circles ***not passing the origin point*** **-> conformal circles**

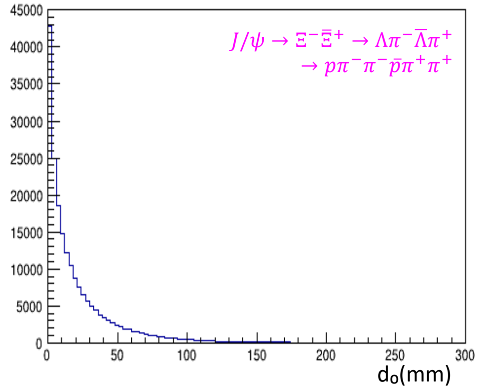
The real factors affecting the traditional conformal-mapping–Hough-transform are:

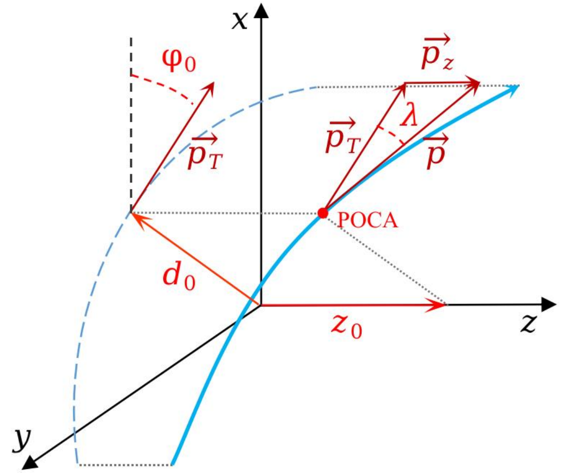
- whether the **2D circle** from the track projection is **geometrically close** to the **origin** **(i.e., whether the d_0 is small enough)**.
- the size of the **2D circular radius** relative to the scale **(i.e., pT)**

$J/\psi \to \Xi^-\bar{\Xi}^+ \to \Lambda\pi^-\bar{\Lambda}\pi^+ \to p\pi^-\pi^-\bar{p}\pi^+\pi^+$







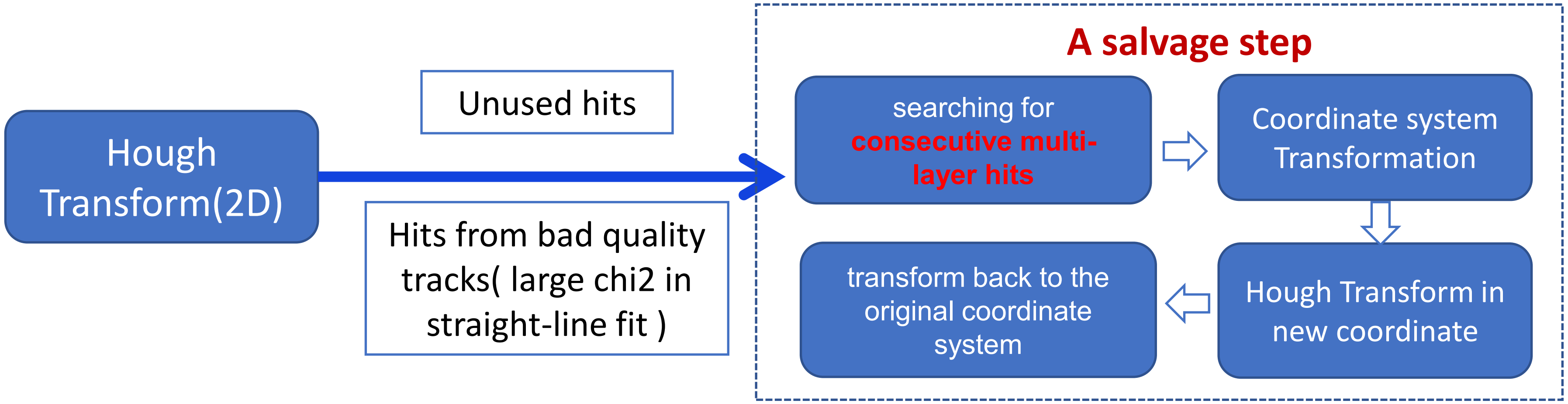


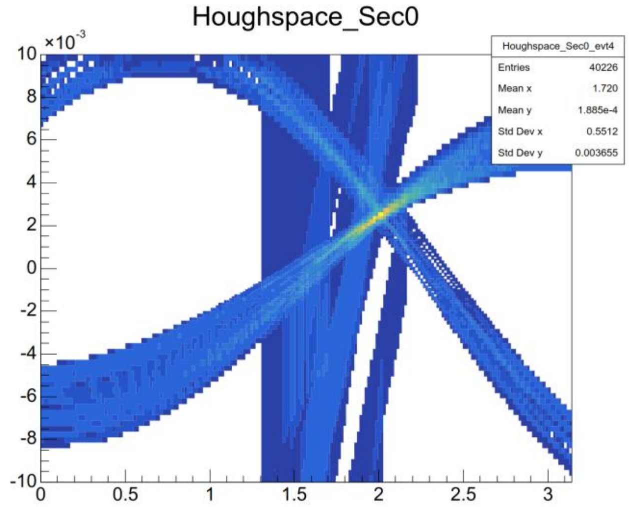
Tracking for Displaced Tracks with Hough Transform

Tracks with a large d_0 and relatively low transverse momentum **deviate from a straight line** after conformal mapping, resulting in lower tracking efficiency.

Lost tracks and bad quality tracks in Conformal space are our TARGET

A Hybrid Hough Transform Incorporating Local Approach

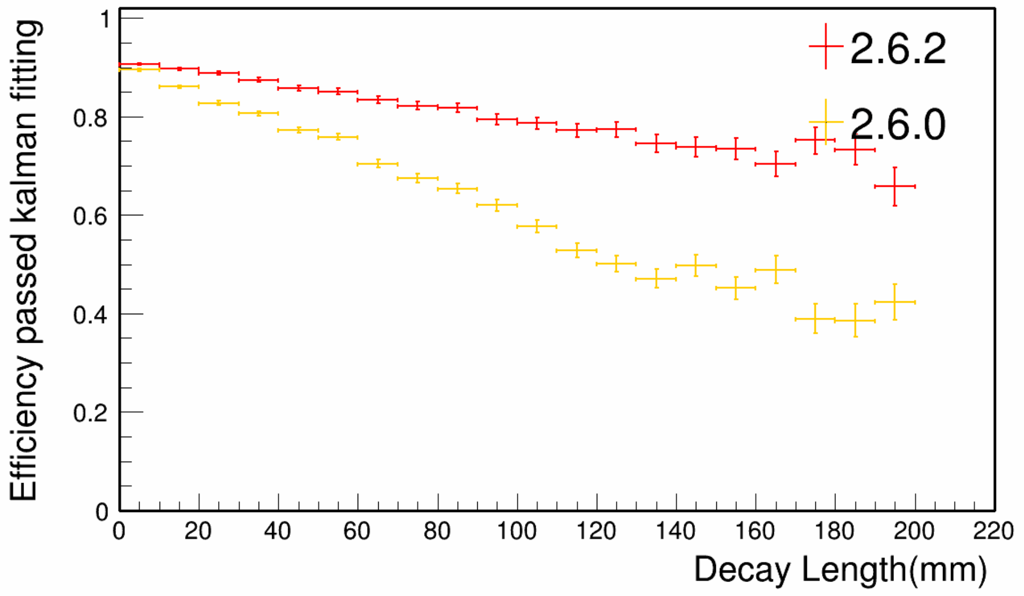


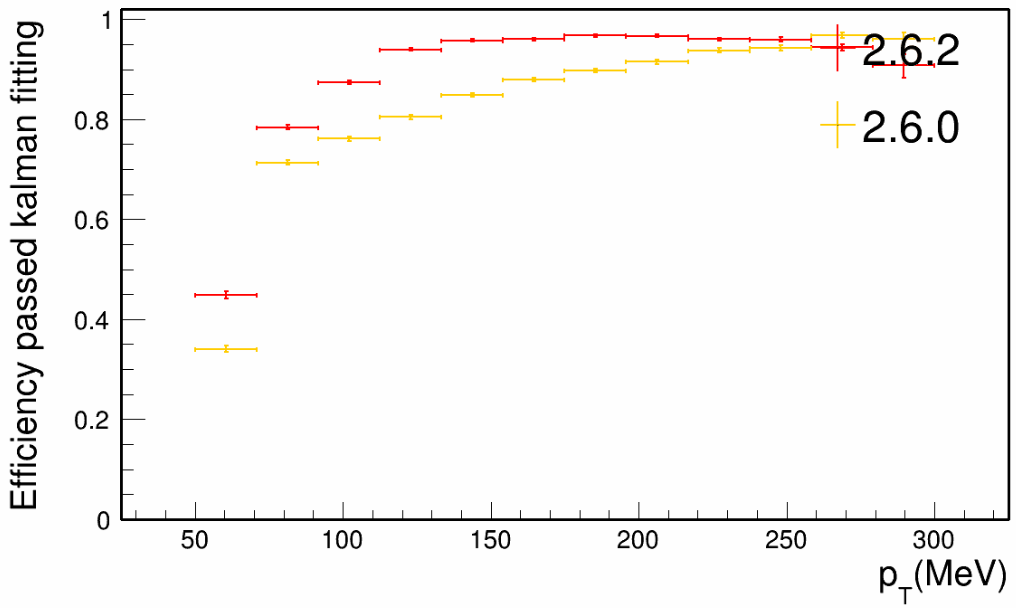


- Salvage step is performed after the initial 2D track finding: **hits on candidate tracks with large fit χ^2 will be reused.**
- A new Hough Map is built with seeds information.
- Many optimizations for very close track candidates and subsequent clone tracks.

Performances of Displaced Tracks

tracking efficiency of π in $J/\psi \to \Xi^-\bar{\Xi}^+ \to \Lambda\pi^-\bar{\Lambda}\pi^+ \to p\pi^-\pi^-\bar{p}\pi^+\pi^+$



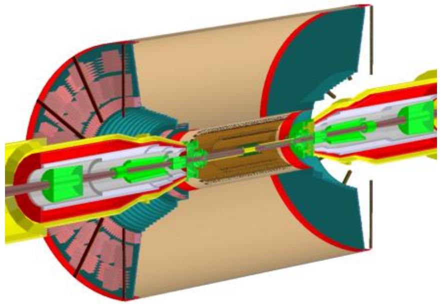


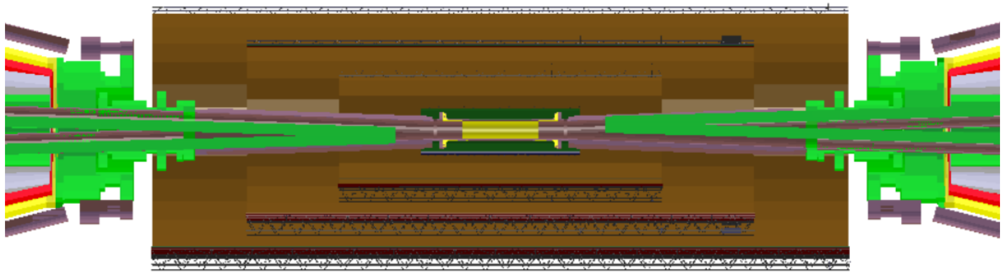
Significantly improvement with Hybrid-Hough-Trans(v2.6.2) comparing to basic Hough-Trans(v.2.6.0)

Performance Evaluations for Tracker Layout optimization

Two major considerations are the tracking performance for low-pT tracks and the ability to cope with high counting rates.

Layout Options	Beam Pipe	ITK	MDC
CDR	high material budget	3 layers, 36~168 mm	48-layers, 20~80 cm
1		3 layers, 36~168 mm	inner chamber with super small cells + 42 regular layers, 20~83 cm
2	low material budget	3 layers, 36~168mm	inner chamber with super small cells + 42 regular layers, 20~83 cm
3		4 layers, 36~168 mm	inner chamber with super small cells + 42 regular layers, 20~83 cm
4		4 layers, 36~210 mm	42 regular layers without inner chamber, starting with stereo layers, 25~83 cm

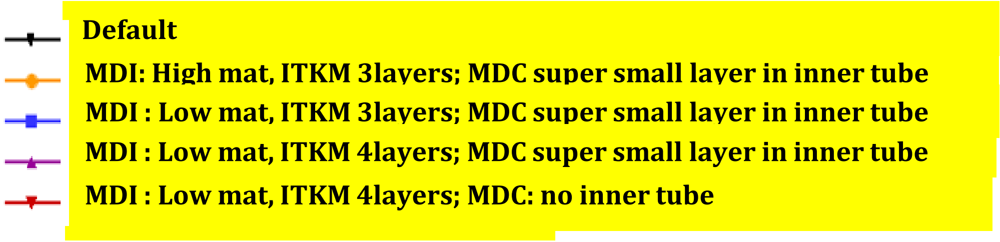


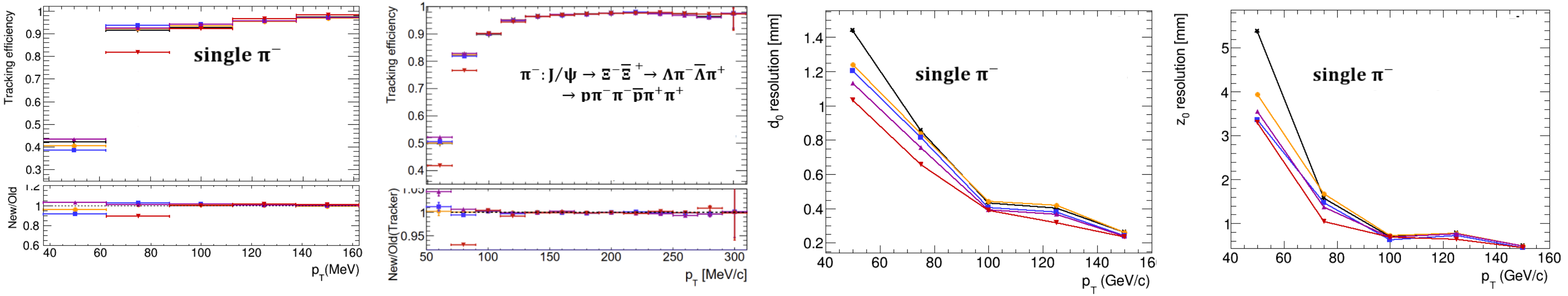


- ✓ All above detector geometries were implemented in OSCAR
- ✓ Hough + GenFit was performed for benchmark physics processes to assess tracking performance

Performance Evaluations for Tracker Layout optimization

- Same tracking efficiency for different layouts when pt >100 MeV/c





- For the last option : 4 ITKM layers with no MDC inner tube
  - Vertex resolution is slightly better
  - Important to have axial layers in the MDC inner part to maintain tracking efficiency for pt < 100 MeV/c
    - Current tracking algorithm has been extensively optimized for axial wires : for prompt/displaced tracks
    - One more ITKM layer provides better flexibility for further optimizations
  - The optimized tracker layout : 4 ITK layers + 42 MDC layers started with 10 axial layers

Detailed performance studies and iteration of algorithm are underway

Summary

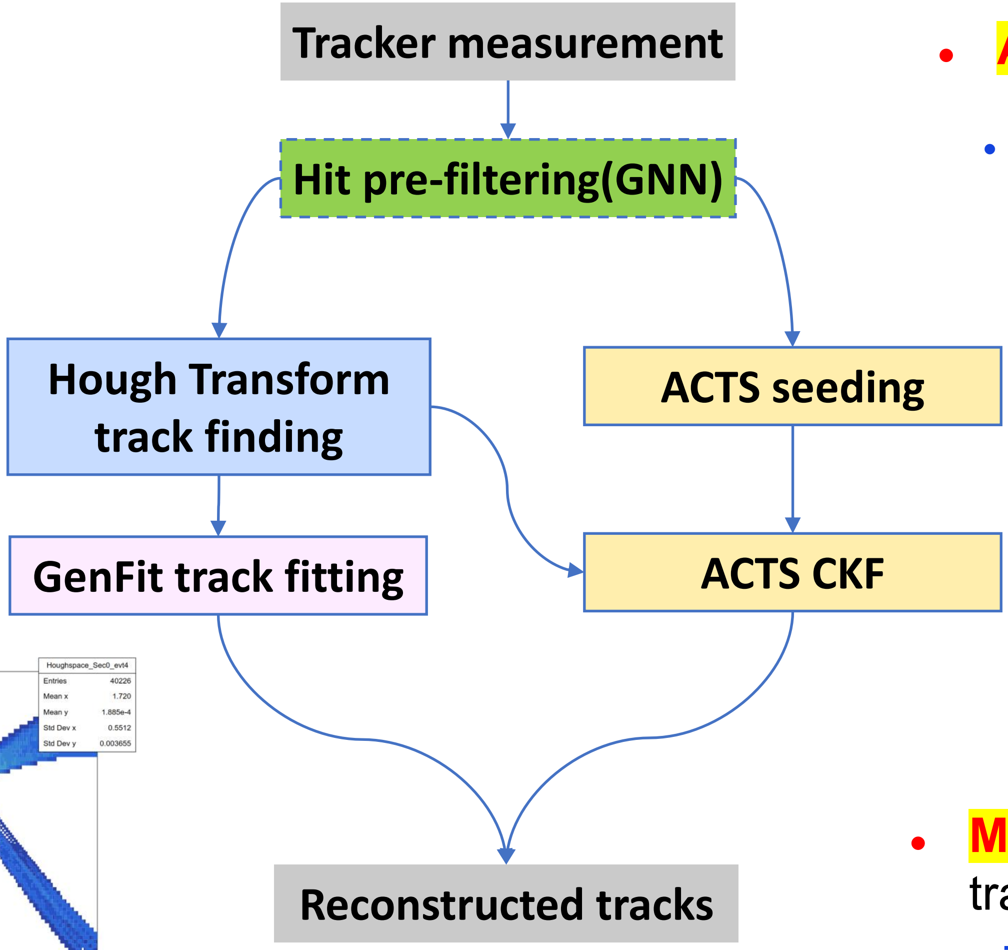
- The baseline track reconstruction algorithm based on Hough transform and GenFit show **reliable and stable performance**
  - With Hough tracking algorithm, high tracking efficiency can be achieved to **meet the requirements of STCF**
  - The DAF algorithm in GENFIT2 shows the stability and robustness
- Over the past year, we carried out extensive algorithm optimizations guided by physics benchmark, including **tracking for both displaced and prompt tracks**
- **Performance evaluation of the tracker layouts** is currently in progress, and optimization of baseline algorithm is underway

Backup

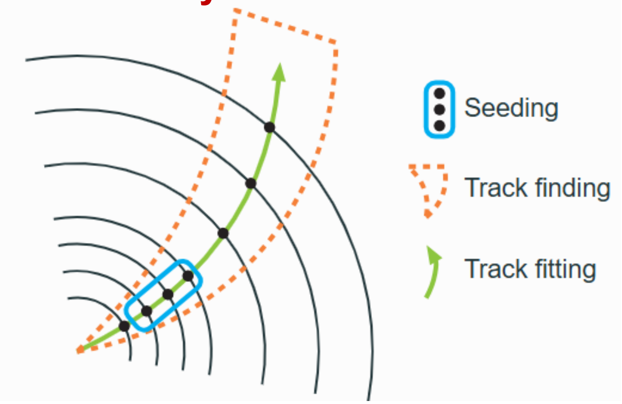
Task of Tracking and The Landscape in STCF

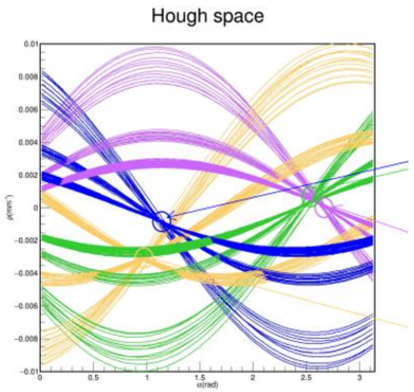
OSCAR : The offline software of STCF

- **Baseline : Hough + GENFIT2**
  - **Global track reconstruction based on Hough transform** and DAF
    - process all hits simultaneously
    - **enhancing the ability to search for displaced tracks**
    - Extended Kalman Filter(**DAF**) using GENFIT2

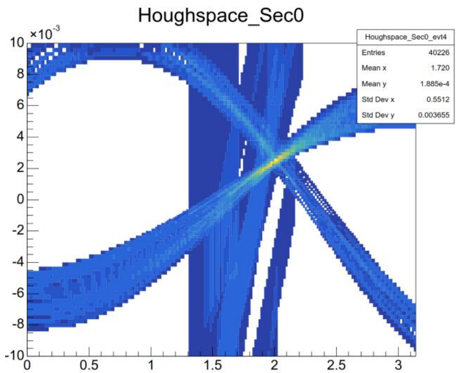


- **Another tracking option : ACTS**
  - **Local approach**
    - **Seeding + Combinatorial Kalman Filter**
    - Material effect in track finding
    - Strongly influenced by the **seeding efficiency**



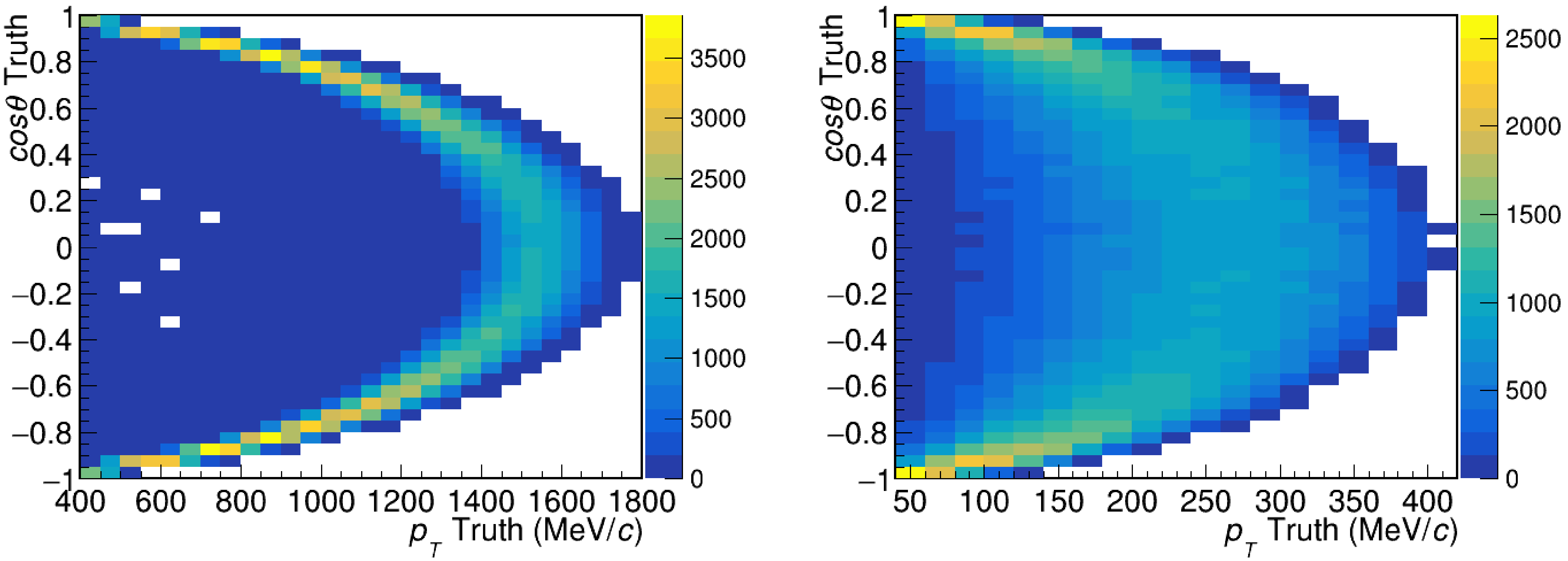


An example of 4 tracks(π+π-μ+μ-)



displaced tracks in $J/\psi \to \Xi^-\bar{\Xi}^+$, with a Hybrid Hough transform

- **Machine learning techniques:** tracking with GNN
  - **GNN for background filter**
  - clustering(track finding) using DBSCAN、RANSAC

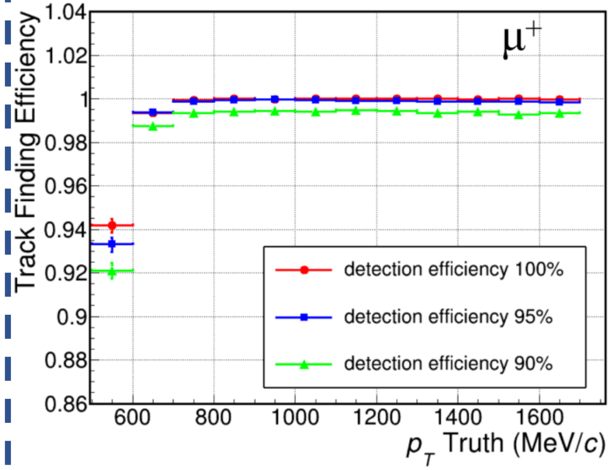


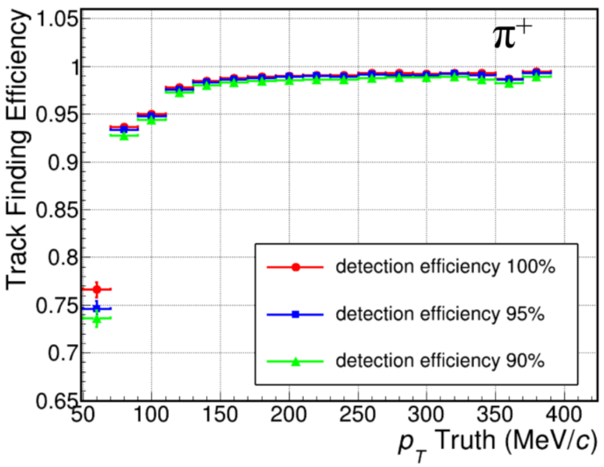
The distributions of p_T versus cosθ for μ (left) and π (right)
in ψ(3686) → π+π- J/ψ, J/ψ → μ+μ- events

Performances of Hough-based Track Finding

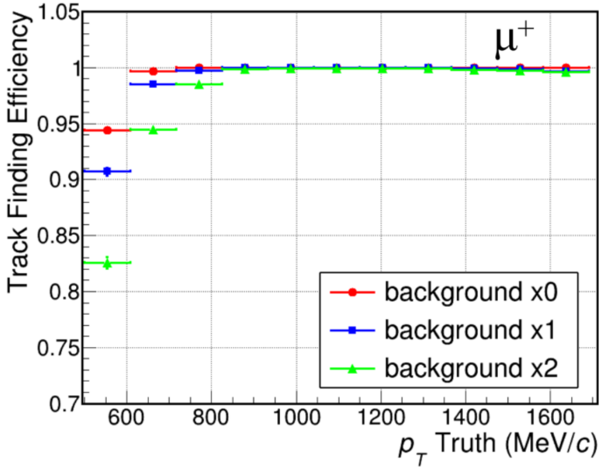
- ψ(3686) → π+π- J/ψ, J/ψ → μ+μ- is studied in **full simulation**

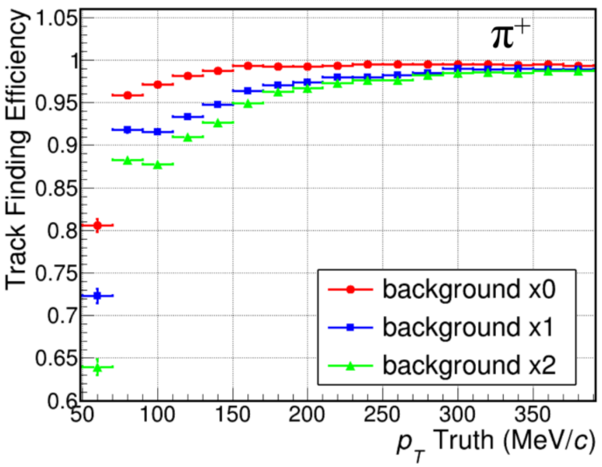
Track finding efficiency : N1 / N2
N1: Number of reconstructed tracks matching with the truth tracks
N2: Number of truth tracks with simulated hits >= 5, within 20°<θ<160°





- The study is performed without background
- Varying detection efficiencies of both ITK and MDC
- High track finding efficiency is maintained with reduced detector efficiency: the global algorithm is robust against local inefficiencies





- The study is performed with detection efficiency at 100%
- Track finding efficiency of pion is **above 95%/90% without/with 1X background** at 100MeV
- The track finding efficiency is more affected by background for tracks with **low pT** and **large dip angle**