Track Reconstruction in STCF

Zhang Jin, Sun Yat-sen University (Shenzhen Campus)

On behalf of the STCF software group

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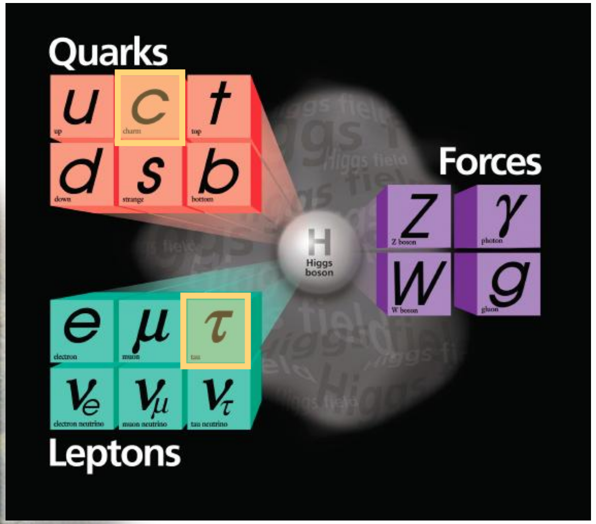
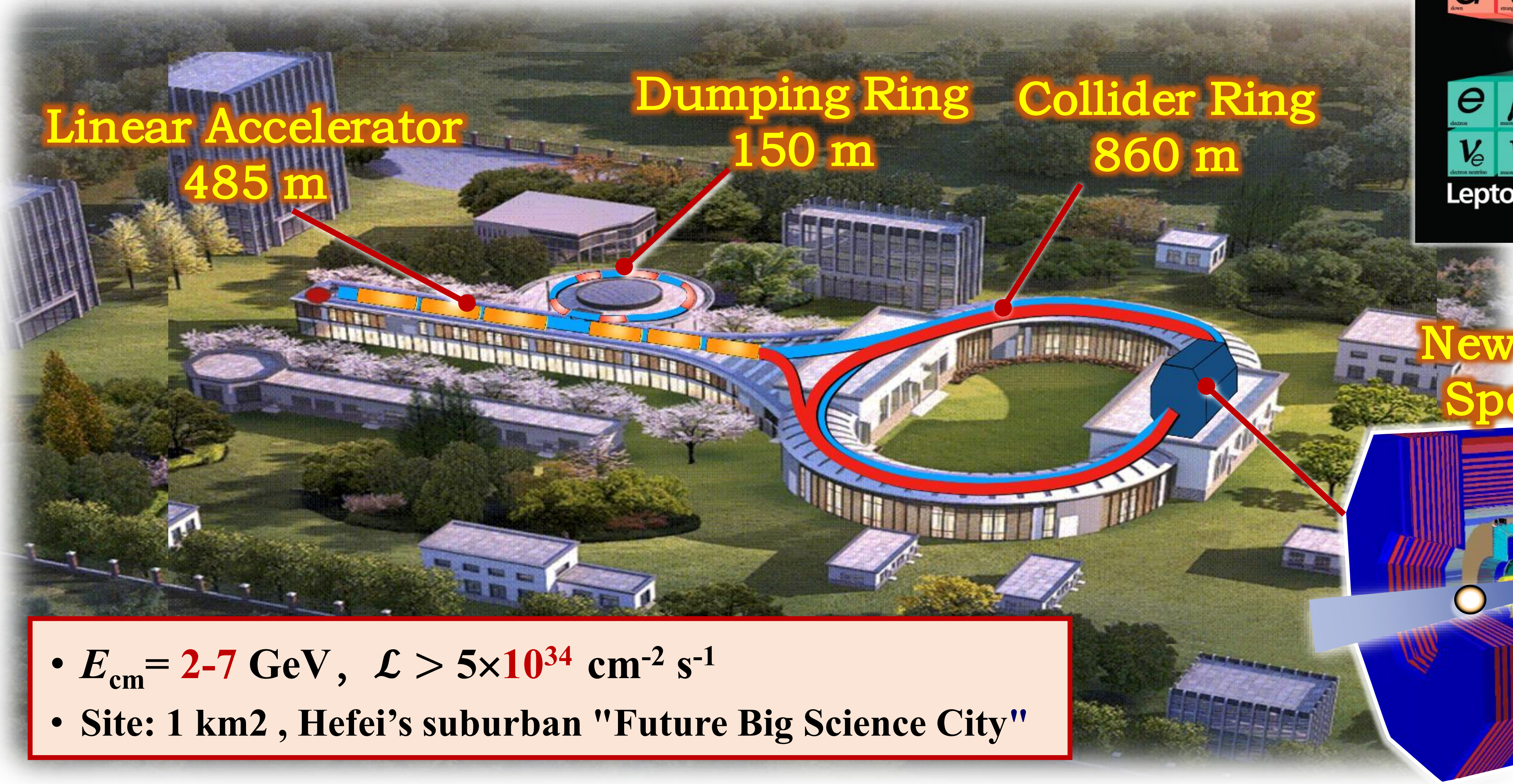
Outline

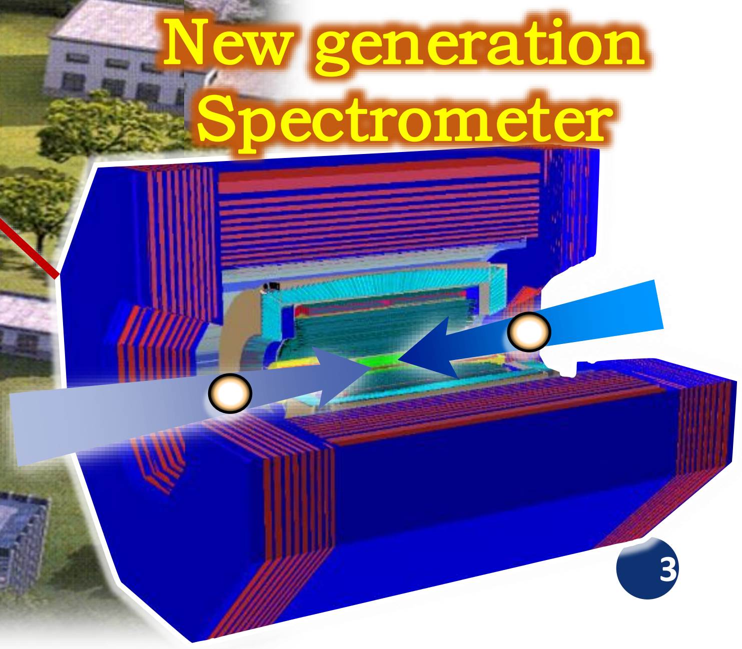
- Introduction to STCF and the tracking system
- Tracking algorithm: task and design approach
- The baseline tracking with Hough transform and GenFit2
- STCF tracking with ACTS
- MDC backgroud filter using GNN
- Summary and outlook

Super Tau Charm Factory(STCF)

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





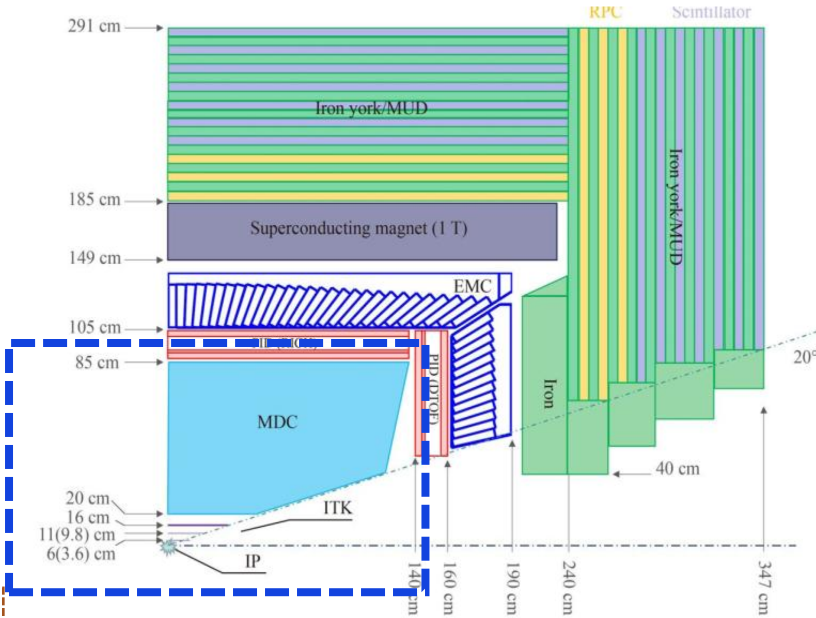


- E_{cm}= 2-7 GeV，$\mathcal{L} > 5\times10^{34}$ cm^{-2} s^{-1}
- Site: 1 km2 , Hefei's suburban "Future Big Science City"

Tracking System: MDC + ITK

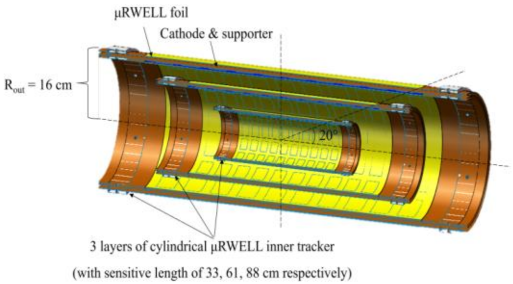
Works in a **1T magnetic field**

- **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 $(3 - 20\ \mathrm{cm})$
  - Two options: MPGD / MAPS

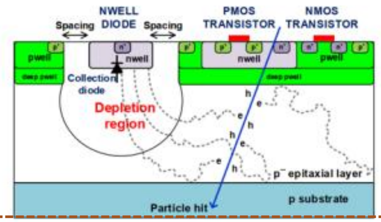


Figures from STCF CDR (arXiv: 2303.15790)

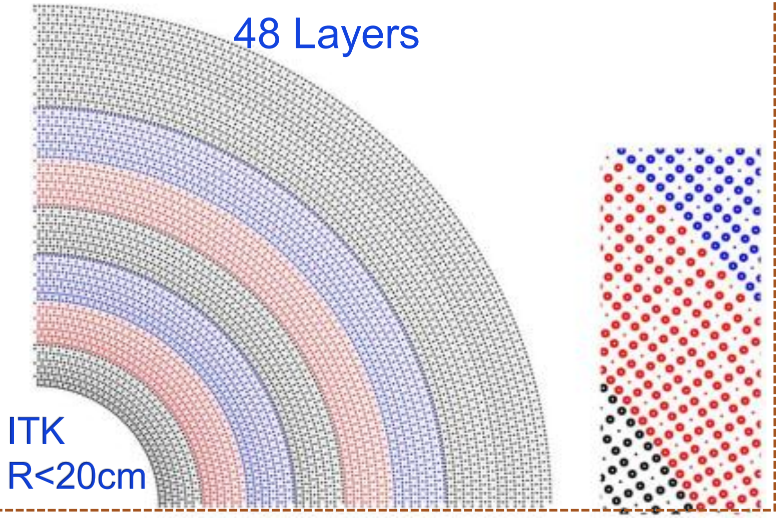
ITK Gaseous option : u-RGroove



ITK Silicon option: CMOS MAPS



MDC(Main Drift Chamber)
R： 20cm-840cm
48 Layers



ITK
R<20cm

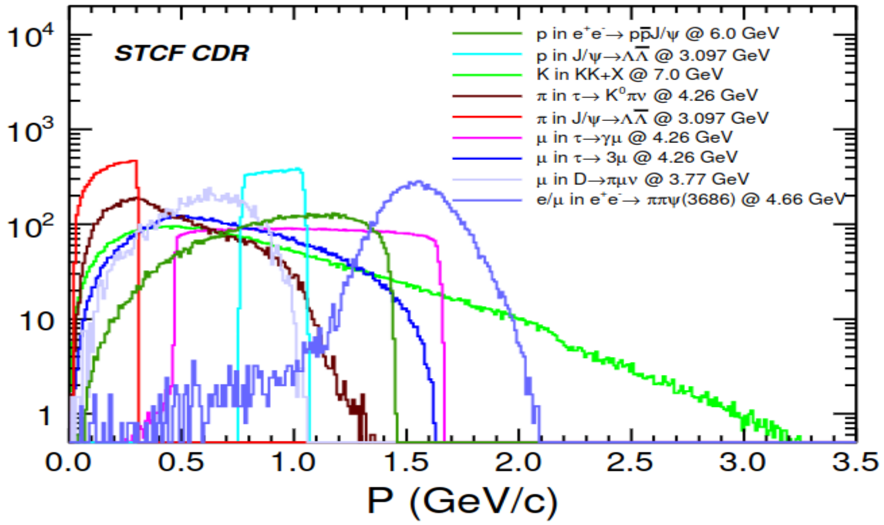
Superlayer	Radius (mm)	Num. of Layers	Stereo angle (mrad)	Num. of Cells	Cell size (mm)
A	200.0	6	0	128	9.8 to 12.5
U	271.6	6	39.3 to 47.6	160	10.7 to 12.9
V	342.2	6	-41.2 to -48.4	192	11.2 to 13.2
A	419.2	6	0	224	11.7 to 13.5
U	499.8	6	50.0 to 56.4	256	12.3 to 13.8
V	578.1	6	-51.3 to -57.2	288	12.6 to 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

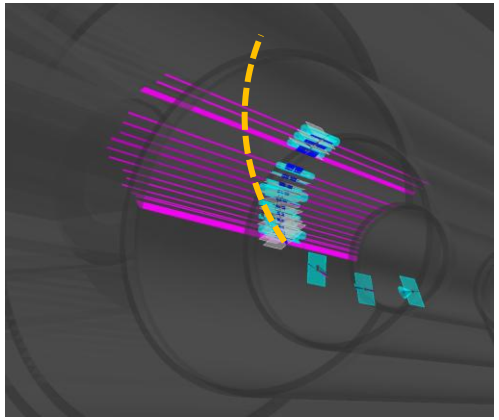
Crucial task for Tracking agorithm : reconstruct particles with **high tracking efficiency and resolution, in a large momentum region(p: 50 MeV~3.5 GeV)**

- **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**
  - Large dip angel : usually with less hits, heavier material effect
- **Long-live particles: displace tracks**, **sometimes with low pT**

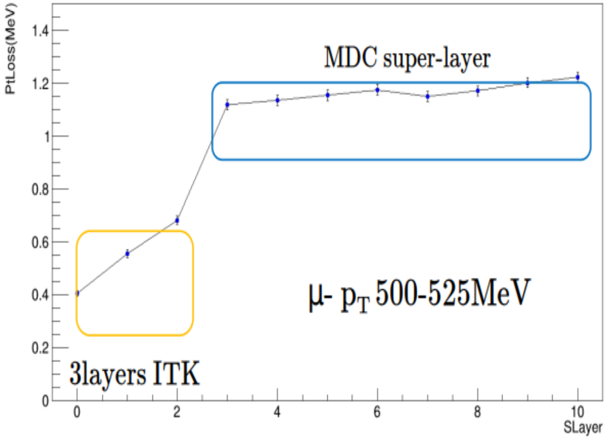
Momentum distributions of charged particles



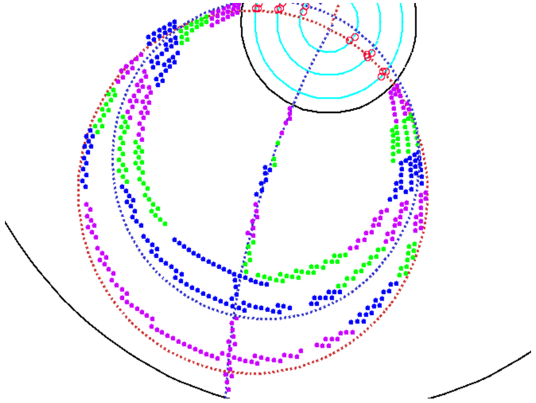
a low $\mathbf{p_T}$ track occurs large scattering



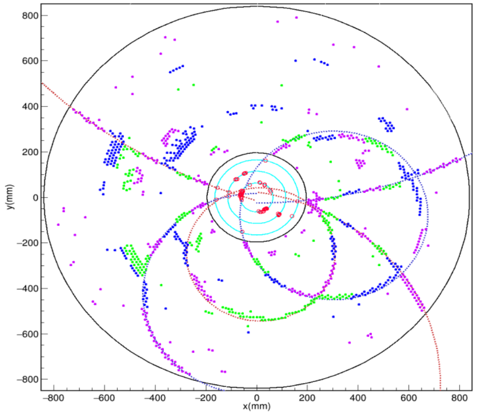
reduction in $\mathbf{p_T}$ upon entering MDC



a track with multi-turn loops



Displaced tracks from long-live particles

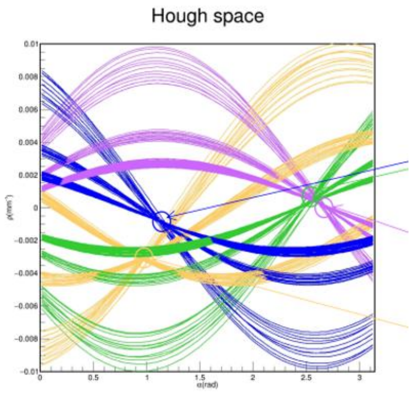


A stable track reconstruction workflow is essential for detector optimization and studies of physics potential

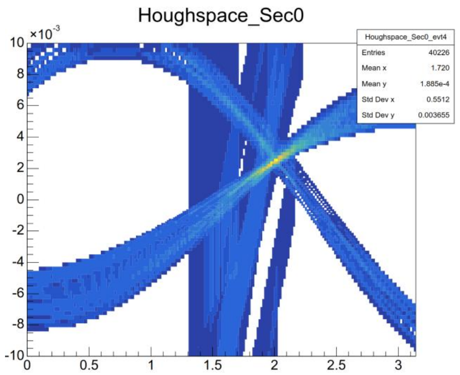
Task of Tracking and The Landscape in STCF

OSCAR : The offline software of STCF

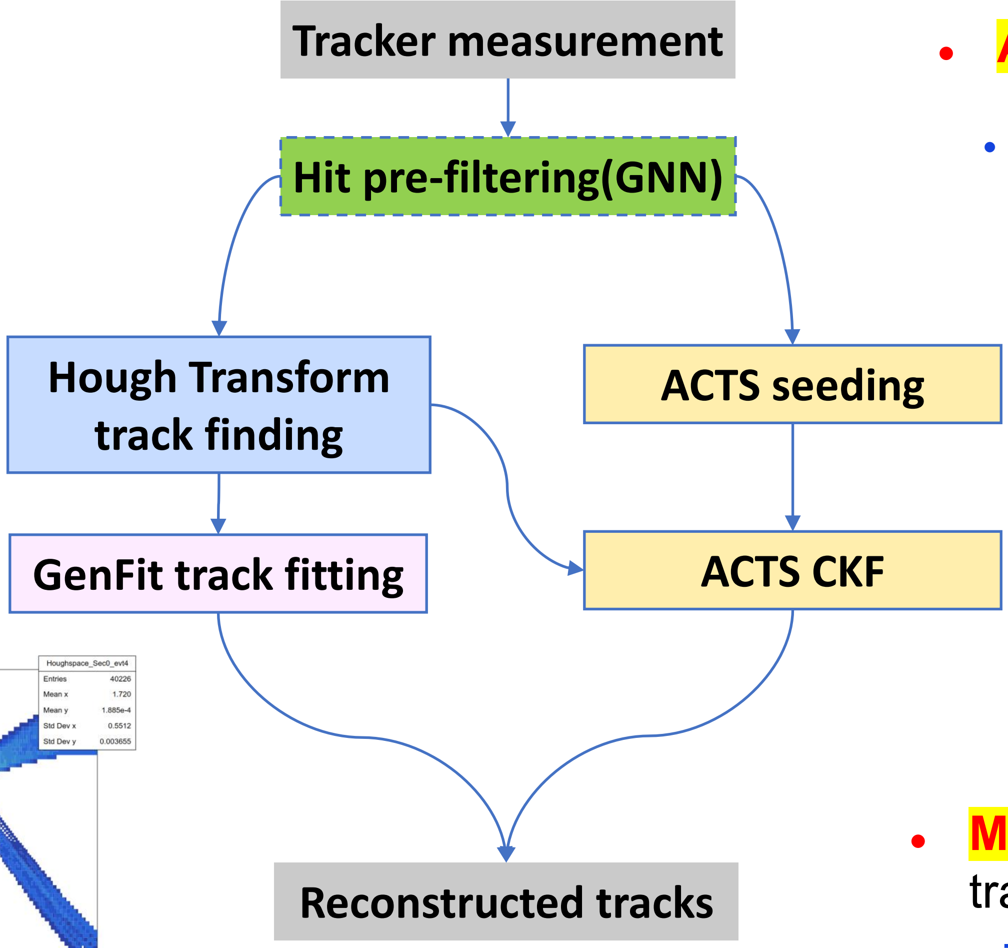
- **Baseline : Hough + GENFIT2**
  - **Global track reconstruction based on Hough transform** and DAF
    - process all hits simultaneously
    - **enhancing the ability to search for displaced tracks**
    - Extended Kalman Filter(**DAF**) using GENFIT2



An example of 4 tracks(π+π-μ+μ-)



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



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

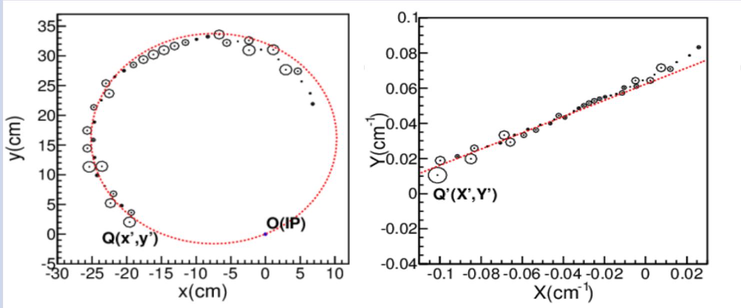
- **Machine learning techniques:** tracking with GNN
  - **GNN for background filter**
  - clustering(track finding) using DBSCAN、RANSAC

Tracking based on Hough Transform and GENFIT

- Implementation and studies of Hough Transform in OSCAR framework
- Tracking for displaced tracks with Hough transform
- Fitting algorithm and the implementations of GENFIT in STCF

Hough Transform / Legendre Transform

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



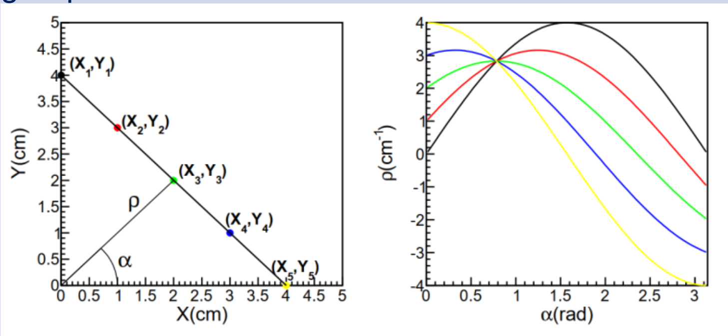
- (Trajectory) Circles *passing the origin point ->* conformal straight lines
- (Drift) Circles *not passing the origin point ->* conformal circles

"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

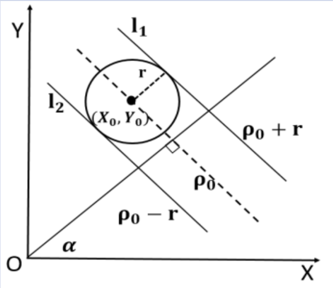


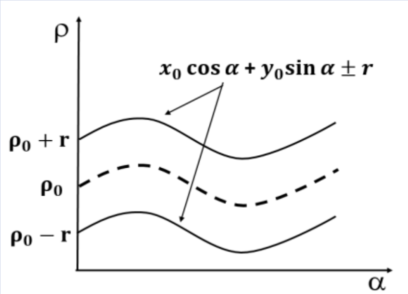
For Drift Chamber： Legendre transform

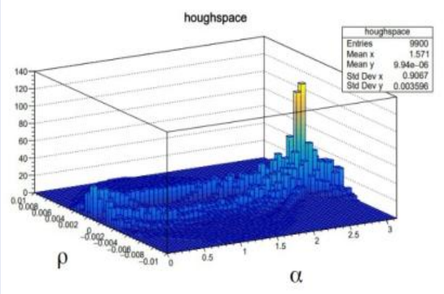
- **One drift circle->two curve lines on Hough space**

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

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



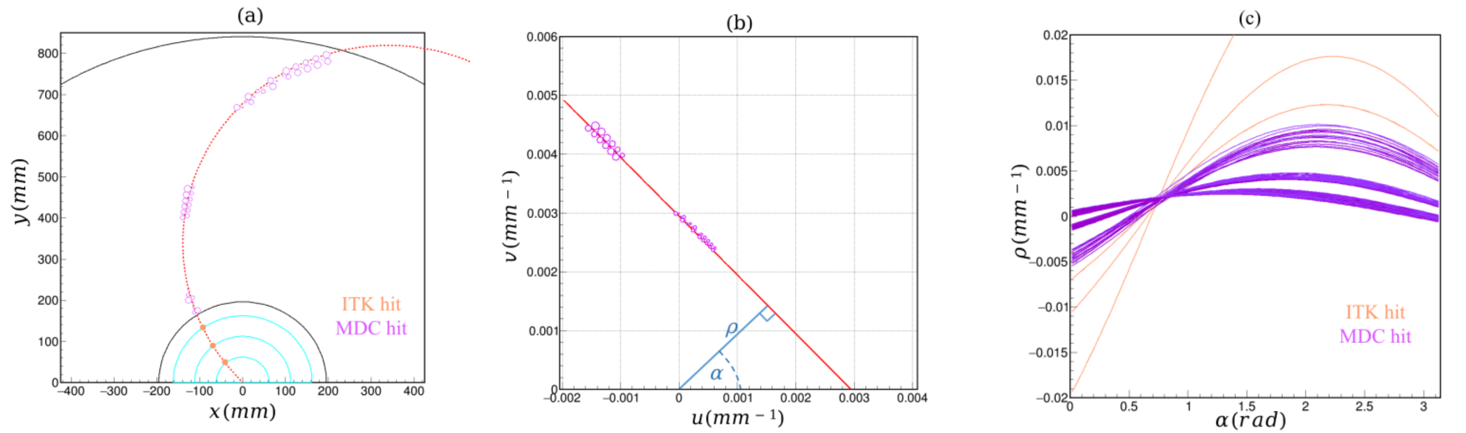




To use the MDC information, Legendre transform is applied in STCF

Implementation of Hough Transform (2D)

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



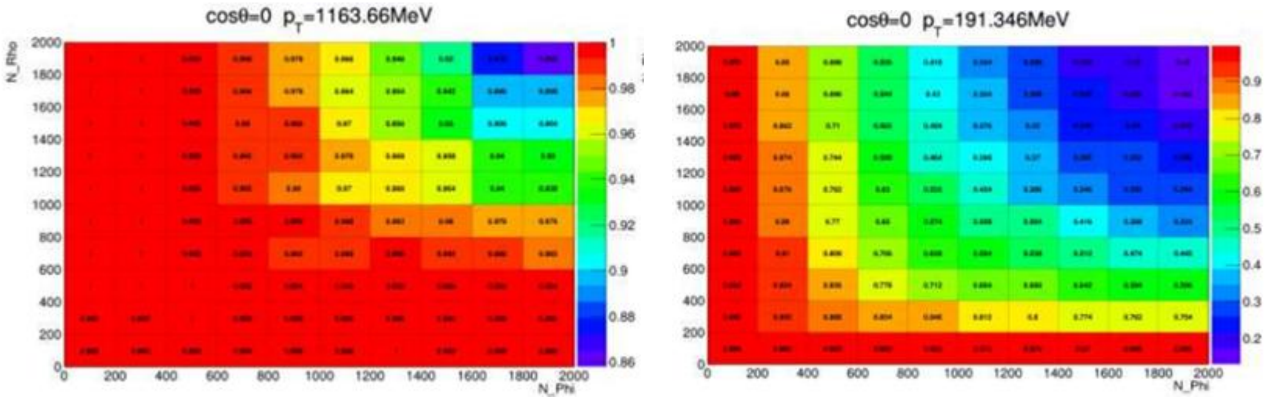
I. Conformal transform: **circular trajectories -> conformal straight lines**
II. **Handling ITK and MDC measurements simultaneously**, populating the Hough Space (2D histogram)
III. Peak finding approach to identify candidate tracks(circles) in Hough Space
IV. Global chi-square fit for circle tracks

Implementation of Hough Transform (2D)

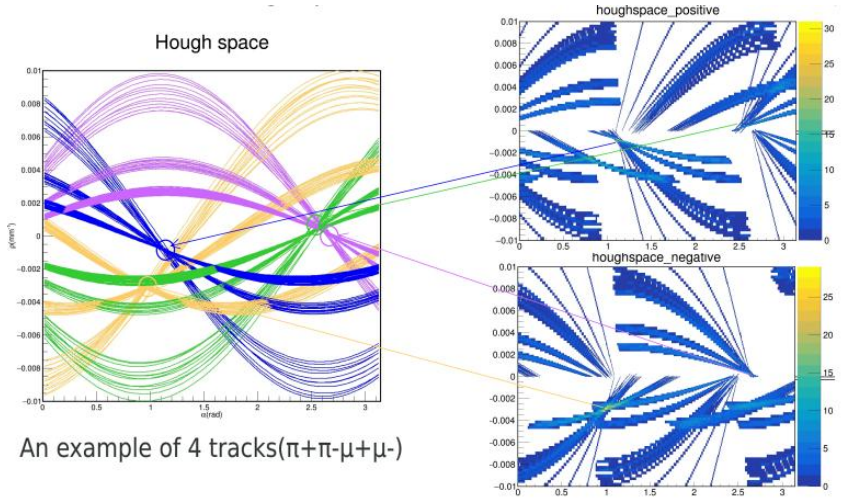
- **Key optimizations in 2D Hough track finding**
  - Optimizations of bin size in Hough Space : **non-uniform** along ρ direction
  - Two histograms are used, filling which histogram is judged by calculating $\rho \mathrm{d}\rho / \mathrm{d}\alpha$

    → **hits from different charged particles don't interfere with each other when peak finding**
  - Peak detecting method and merging of duplicate tracks
  - Weighted chi-square fit is applied in the 2D track fitting process

bin width is based on the efficiency of peak hit inclusion



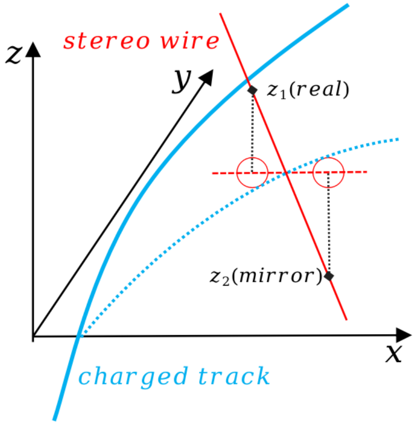
Split the map into 2 different clockwise using slope of the curves

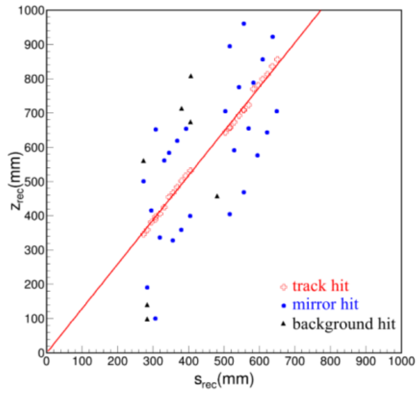


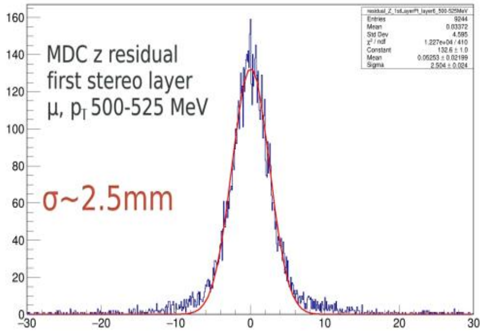
An example of 4 tracks(π+π-μ+μ-)

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**

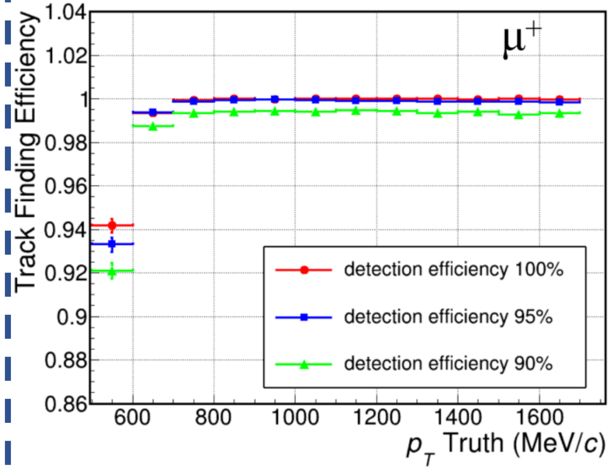
III. A global chi-square fitting is performed to retrieve the parameters of helix track

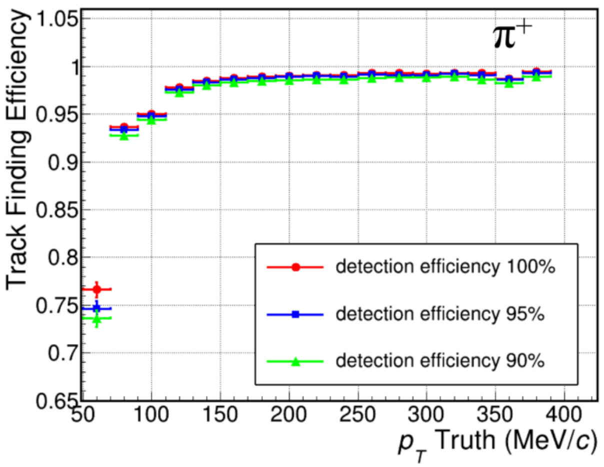
- Track merging in the last step is considered
- Fake tracks will be handled based on track quality

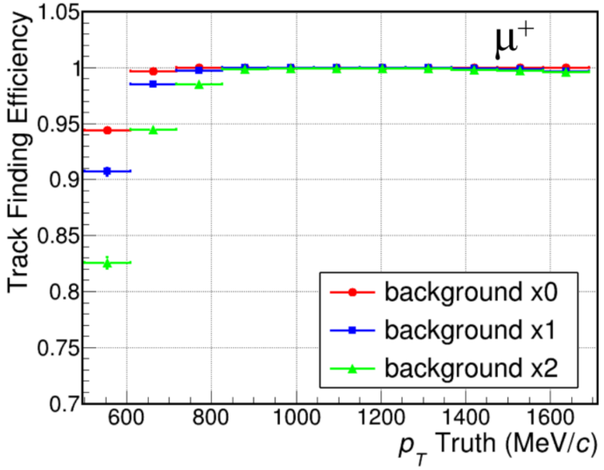
Performances of Hough-based Track Finding

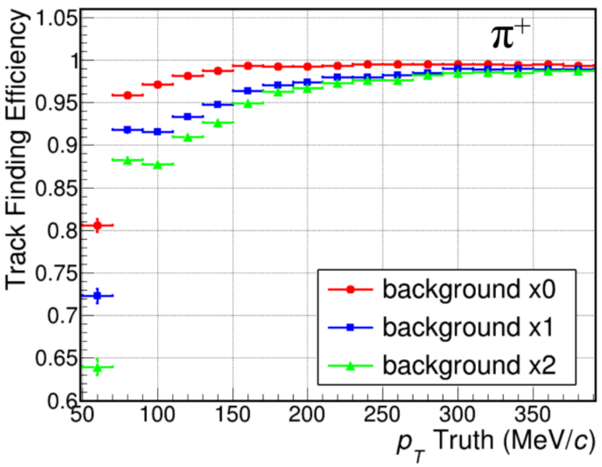
- ψ(3686) → π+π- J/ψ, J/ψ → μ+μ- is studied in **full simulation**

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**

Hough Transform for displaced tracks

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

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

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

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

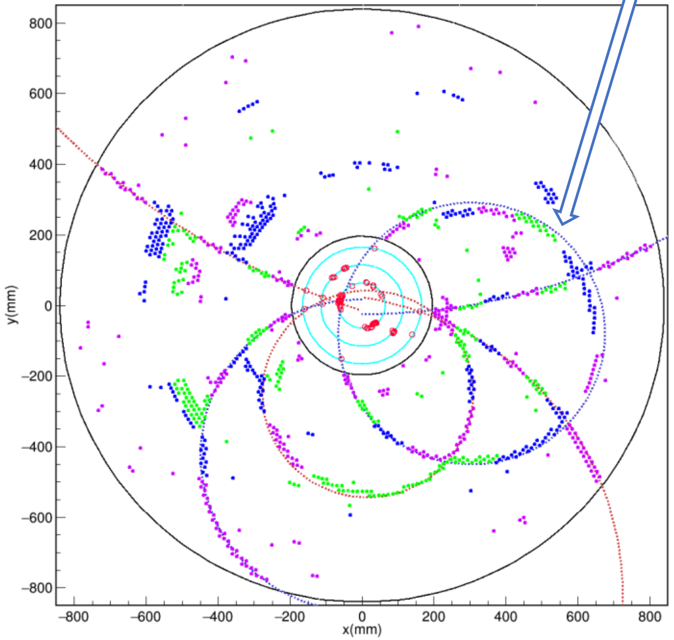
(Trajectory) Circles ***passing the origin point ->*** **conformal straight lines**

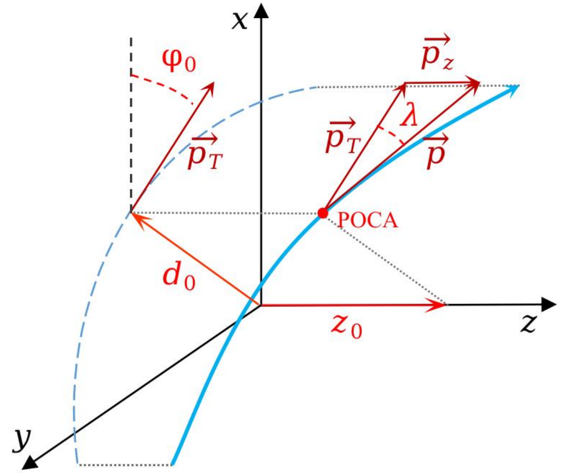
(Drift) Circles ***not passing the origin point ->*** **conformal circles**

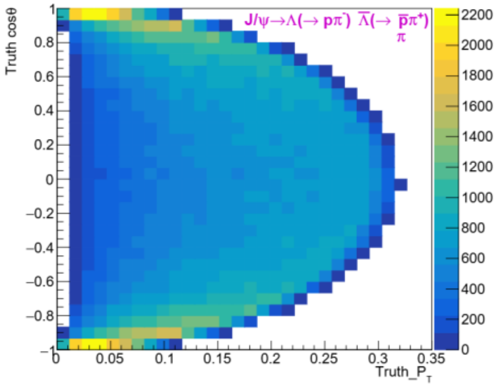
The real factors affecting the traditional conformal-mapping–Hough-transform are:

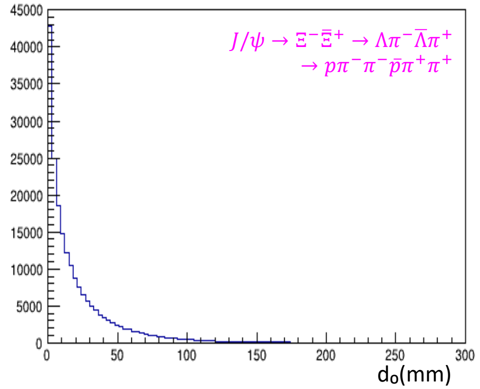
- whether the **2D circle** from the track projection is **geometrically close** to the **origin** (**i.e., whether the d_0 is small enough**).
- the size of the **2D circular radius** relative to the scale **(i.e., pT)**

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







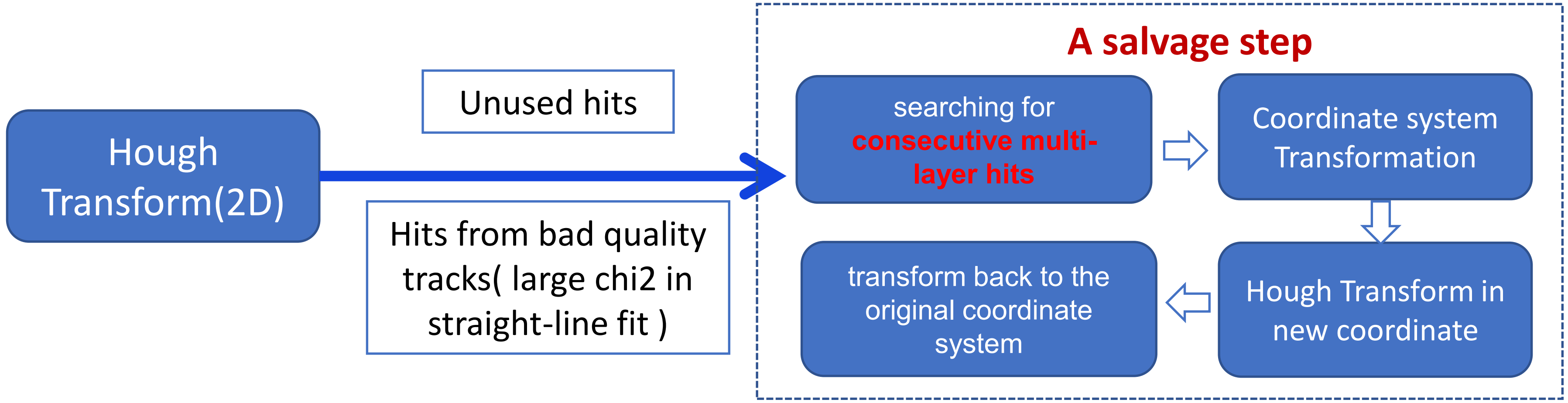


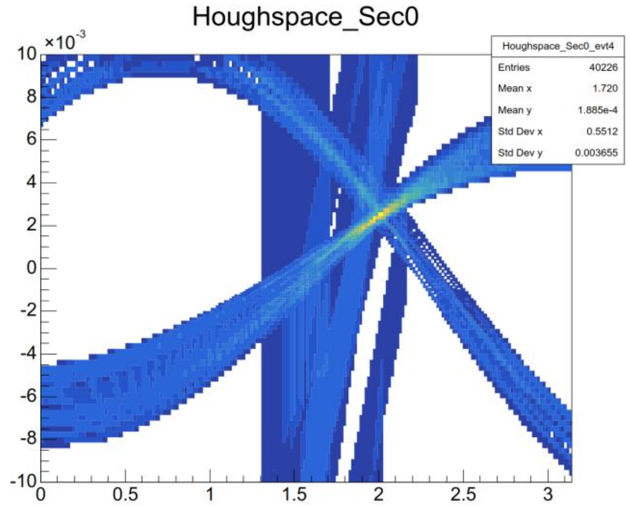
Hough Transform for displaced tracks

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

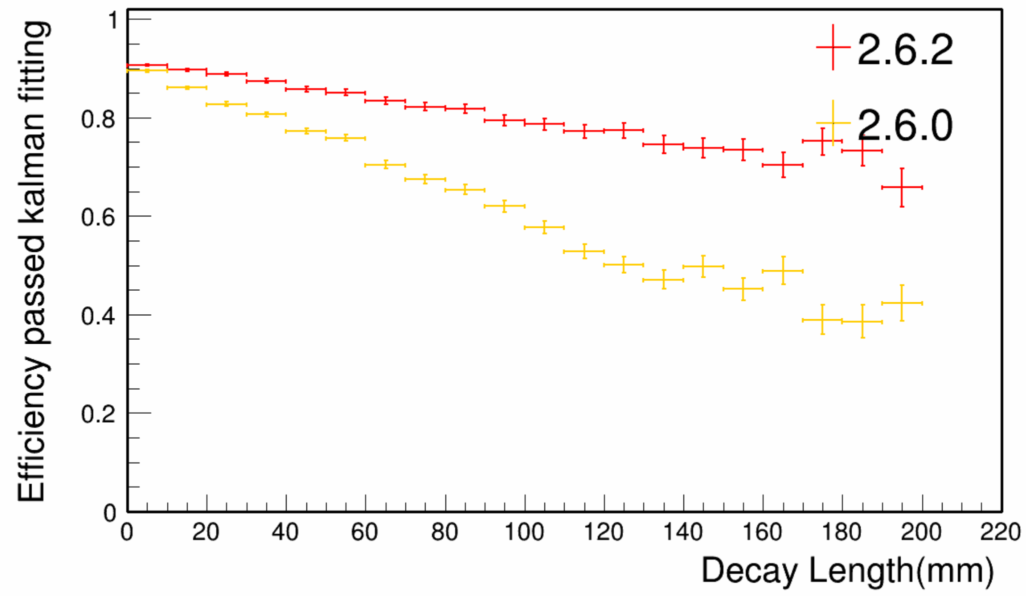


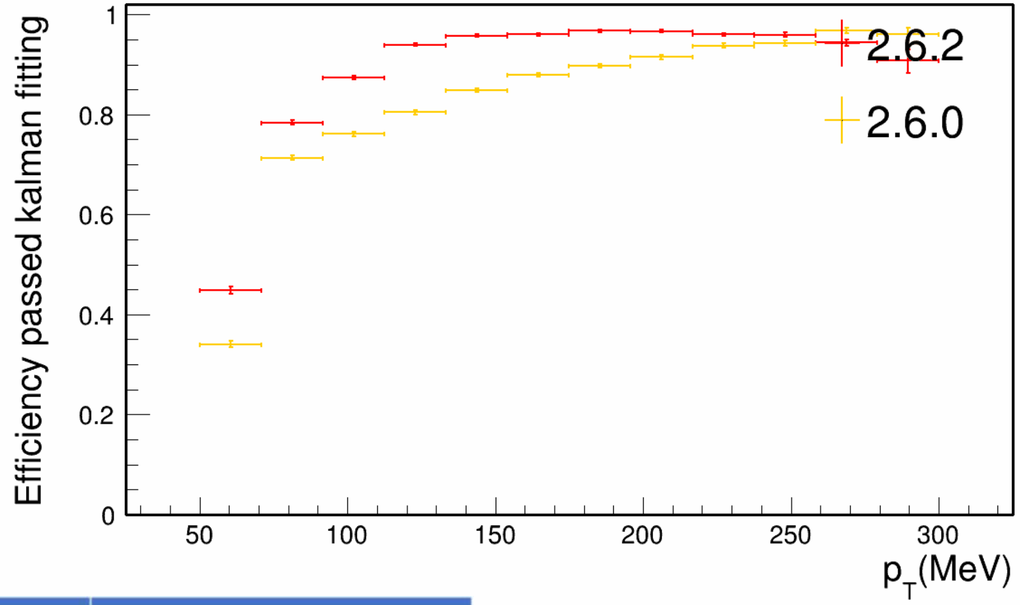


- Salvage step is performed after the initial 2D track finding: **hits on candidate tracks with large fit χ^2 will be reused.**
- A new Hough Map is built with seeds information.
- Many optimizations for very close track candidates and subsequent clone tracks.

Performances of particles with long decay vertices

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





ITKM + MDC, W/O bkg	OSCAR 2.6.0		OSCAR 2.6.2	
	Eff. (%)	Ref. Eff.(%)	Eff. (%)	Ref. Eff.(%)
Charged tracks	21.1		53.2	
Λ、Ξ^- reconstruction	18.2	86.4	42.6	80.1
$\bar{\Lambda}$、$\bar{\Xi}^+$ reconstruction	15.6	85.3	34.4	80.7
4C kinematic fit	11.8	76.1	22.2	64.6

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

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

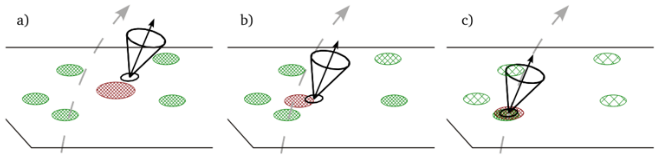
Kalman filter: Iterative bi-directional Kalman filter is applied in GENFIT2

- 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

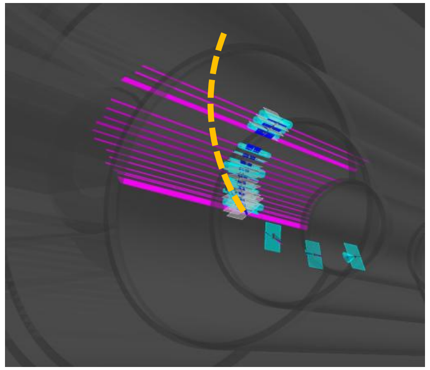


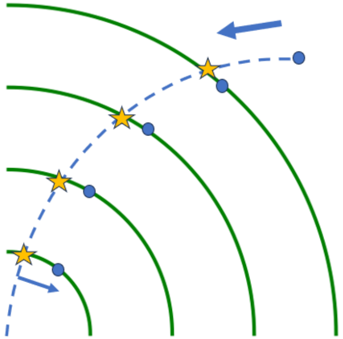
a) At first, all measurements get similar weights, and all will be considered.
b) After update, measurement with large errors are assigned smaller weight.
c) As the temperature decreases, measurements with large errors are given even less weight.
- the weight drops below the threshold, reject

Track reconstruction in the ATLAS experiment : The deterministic annealing filter

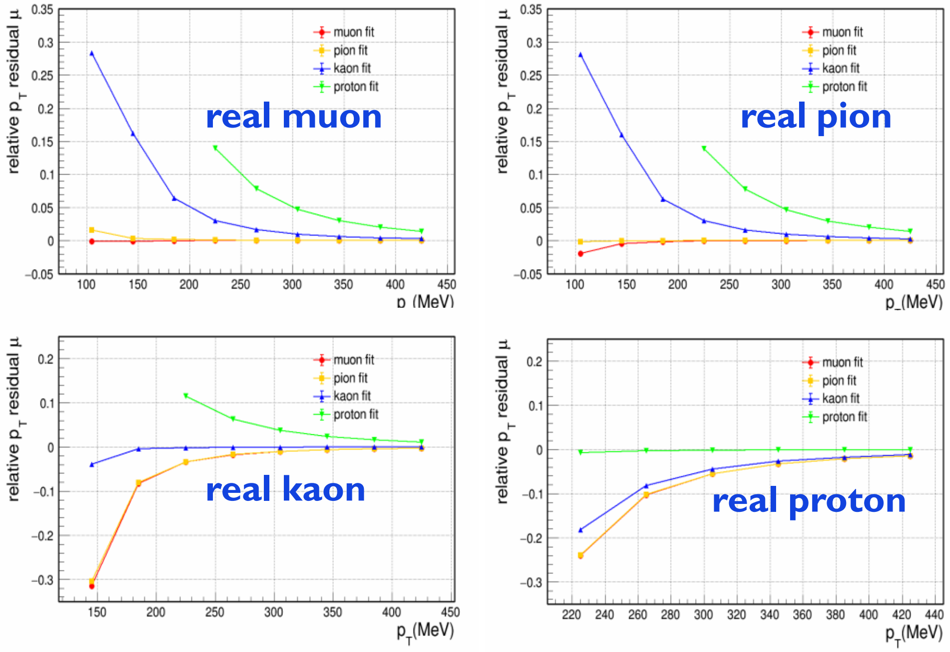
Track Fitting based on GENFIT2

- At low momenta
  - Make curling trajectory in chamber
  - particles are significantly affected by material effects
- For curling Tracks
  - The hits in the latter half of the loop are subject to severe material effects -> Only hits from first half are fed to fitting algorithm, benefit for momentum resolution and converging efficiency
- Due to material effects, loss of ITK hits during track finding will lead to the worse parameter resolution
  - Algorithm **retrieving ITK hits** to improve the accuracy of track parameters.





- The different particle hypotheses mainly differ in their **masses**, which translates to **different material effect**
  - Using all five hypotheses increases computational cost.



- The lower the particle momentum, the greater the difference between particle hypotheses with significantly different masses
- Using **π, K, p for high momentum** is enough

Track Fitting Performances

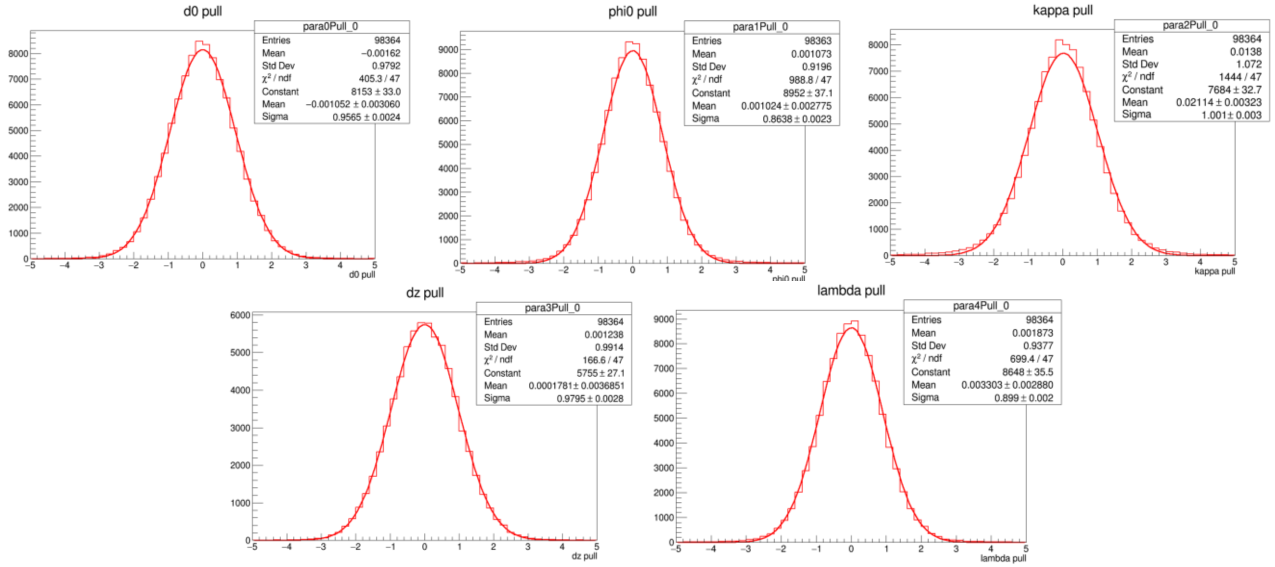
- **The pull distributions are approximately consistent with standard normal distributions**

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

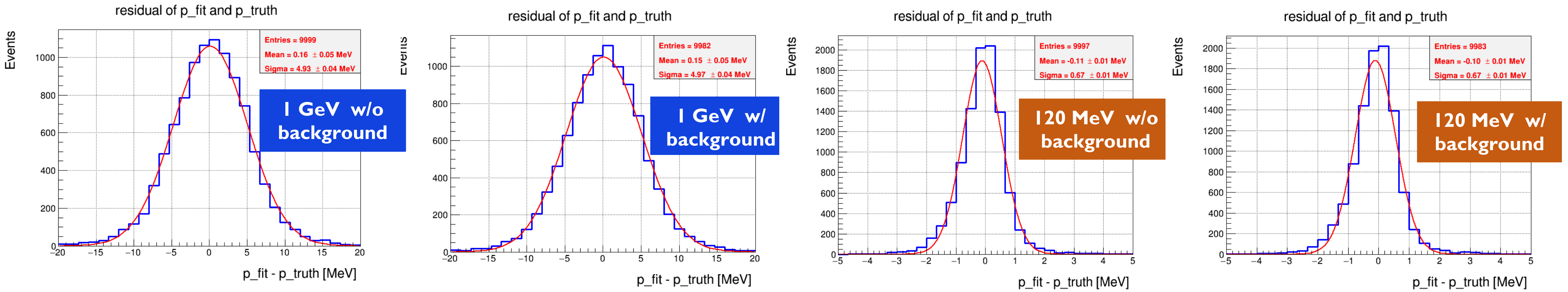
v_{fit} : the estimated value

v_{truth} : the true simulated value

σ_v : the estimated uncertainty parameter



➢ **Fitting results for 10000 simulated 1GeV / 120MeV momentum muons at θ=60°, w/ and w/o background**

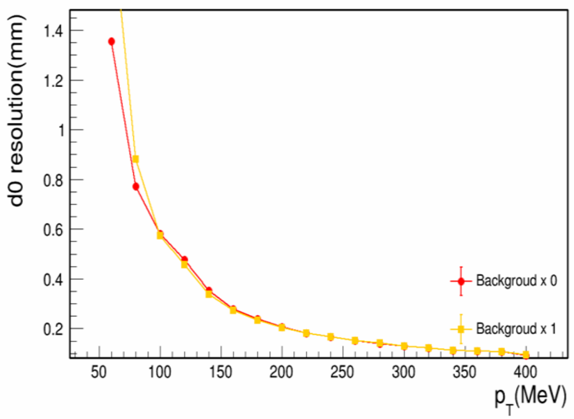


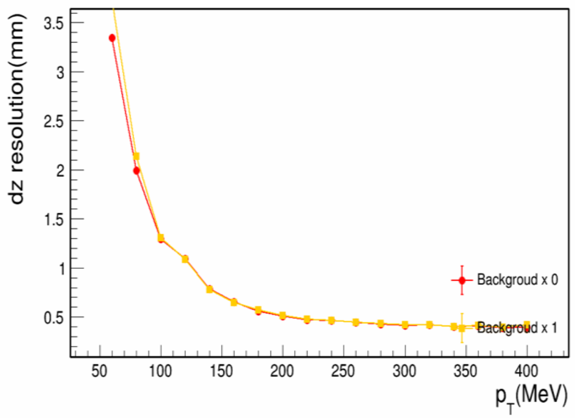
- **The Fitting convergence efficiency is greater than 99%**
- **achieves good momentum resolution for both High/Low momentum tracks (<0.5% @ 1GeV, w/ w/o background)**

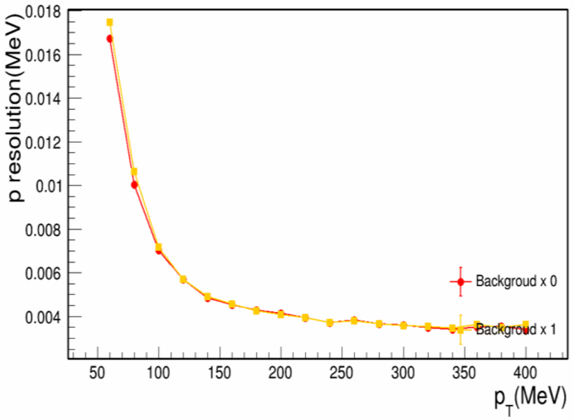
Track Fitting Performances

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

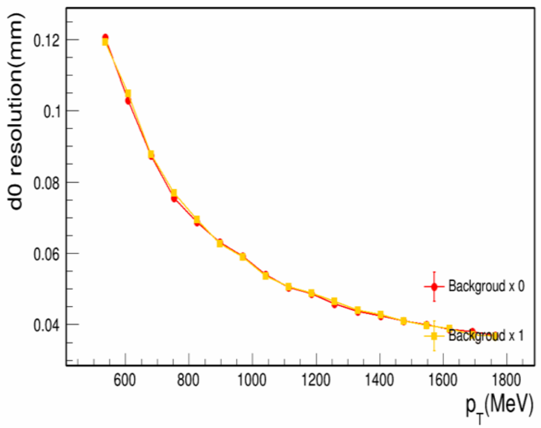
Pion

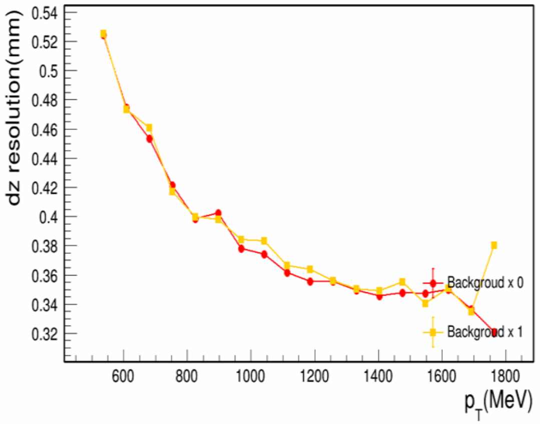


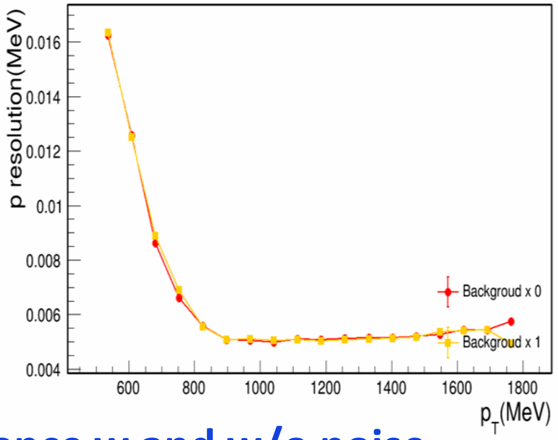




Muon







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

Tracking with ACTS

- Introduction to ACTS
- Implementation of ACTS into OSCAR
- Tracking of displaced tracks with ACTS

ACTS （A Common Tracking Software）

A common tracking software (ACTS) is a modern open-source tracking toolkit led by CERN, developed based on tracking experience from the LHC.

- ➢ Creating a toolbox of re-usable tools for experiments
- \- detector agnostic top level tools
- \- specification possibility for dedicated detectors/experiment
- \- component library design

- ➢ Applicable to current and future HEP experiments

ATLAS sPHENIX CEPC ePIC

acts-telescope@cern.ch

FASER DMX LUXE Lohengrin

- ➢ Establish a feature rich toolbox
- \- C++17 standard (preparing move to C++20)
- \- Minimal dependencies (CMake, Eigen)
- \- Plugins to enhance functionality
- \- Enables parallel processing

Acts

Geometry & Material

Event Data Model

Track Finding & Fitters

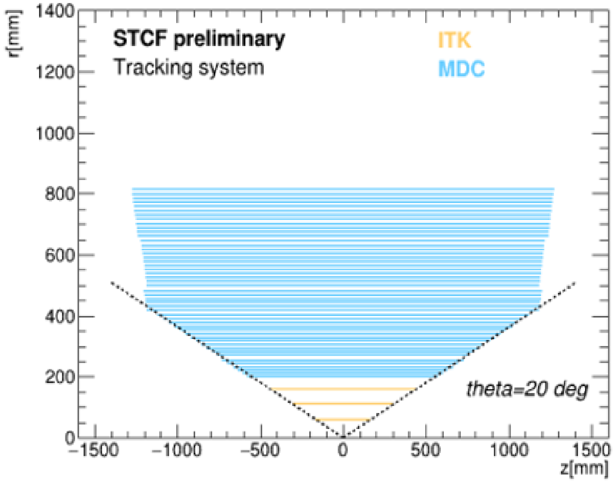
Vertexing

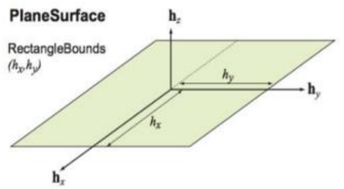
R&D lines (ML, GPU)

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

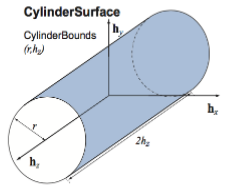
ACTS Tracking Geometry and Material in STCF

- Full simulation geometry based on Geant4 is converted into ACTS tracking geometry with ACTS plugin

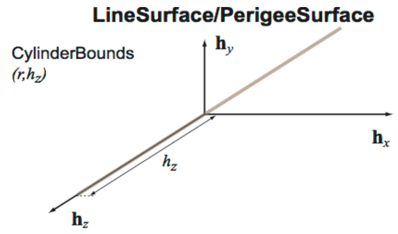




ITKM→PlanarSurface

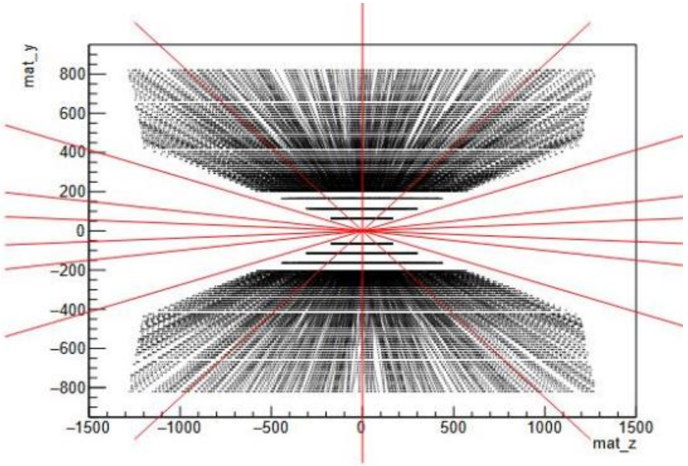


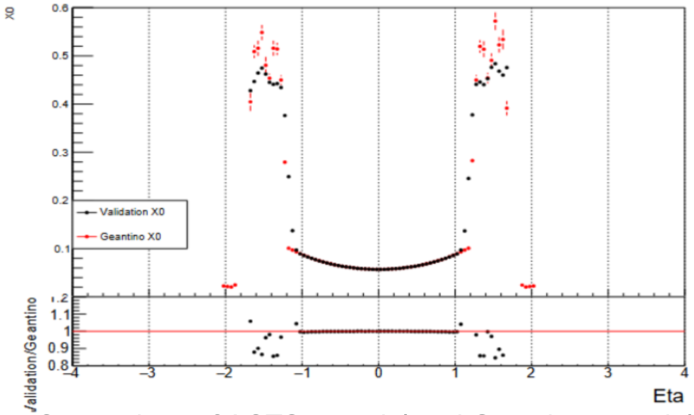
ITKW→CylinderSurface



MDC cell→LineSurface

- Detailed material is mapped to ACTS geometry surface with its internal tool
  - Except at the endcap region, the two are consistent **within 1%** across different angles.

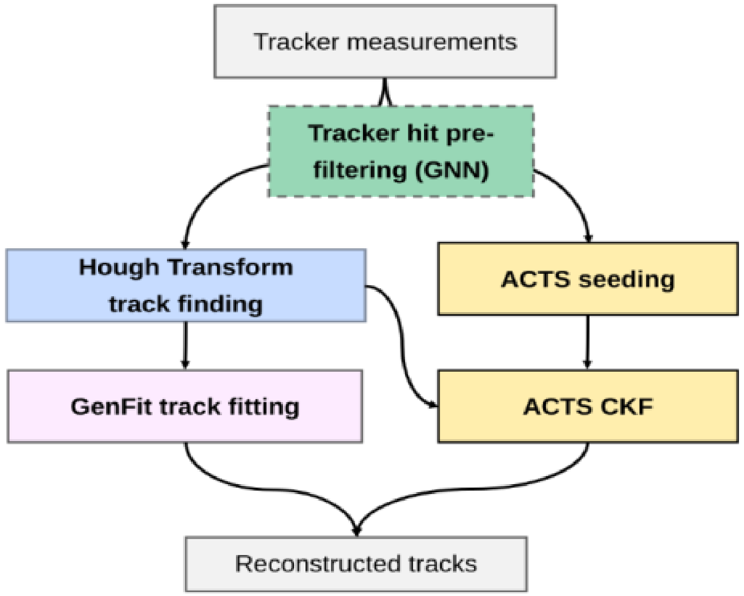




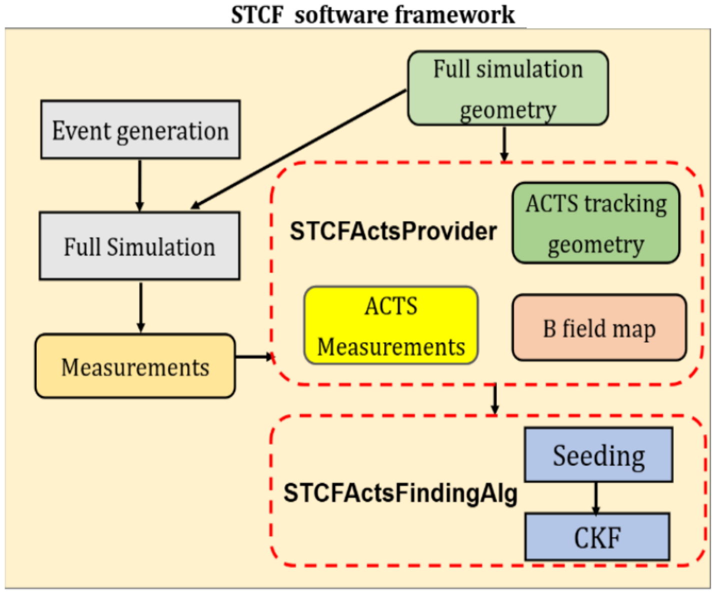
Comparison of ACTS material and Geantino material

Implementation of ACTS into OSCAR

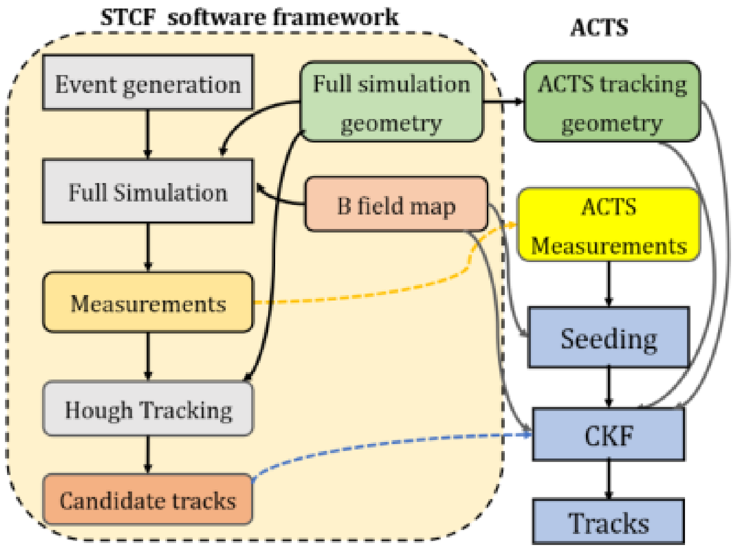
- As another tracking option, **ACTS is integrated into STCF and implemented in OSCAR**.
- The reconstruction process can also run within the **ACTS standalone framework**.
- Tracking approach: Seeding and CKF(combinatorial Kalman Filter)
- A study aimed at improving seeding efficiency for long-lived particles using Hough transform

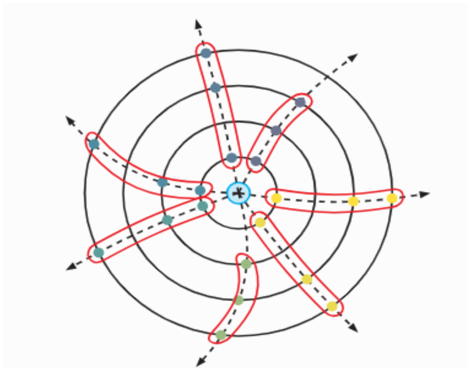


ACTS in OSCAR

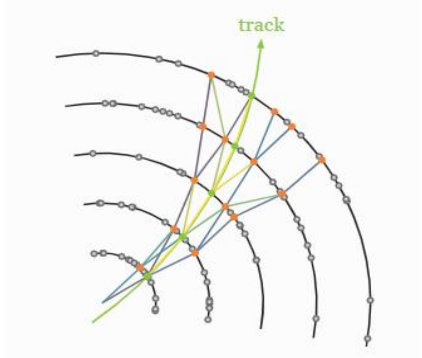


ACTS standalone





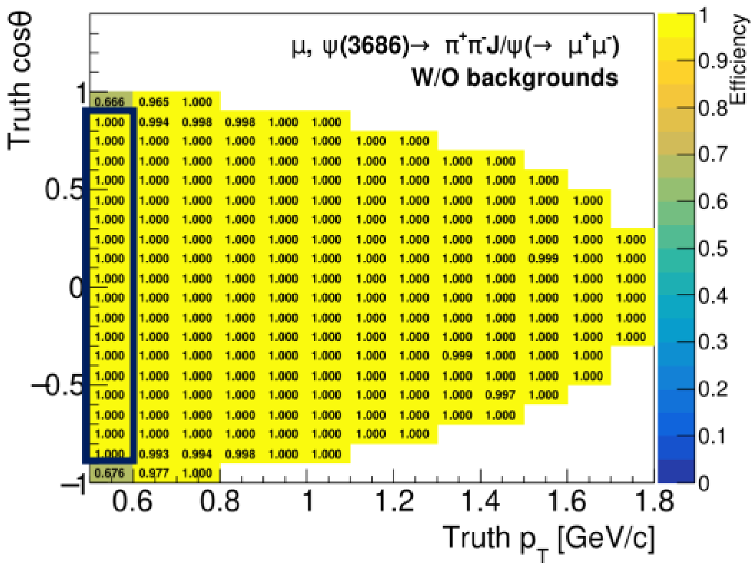
Seeding(only ITK hits)

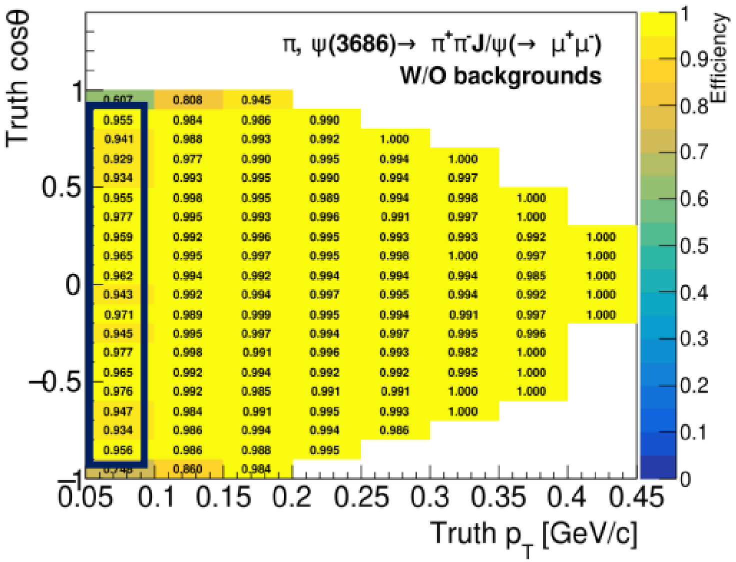


CKF(connect MDC hits + fitting)

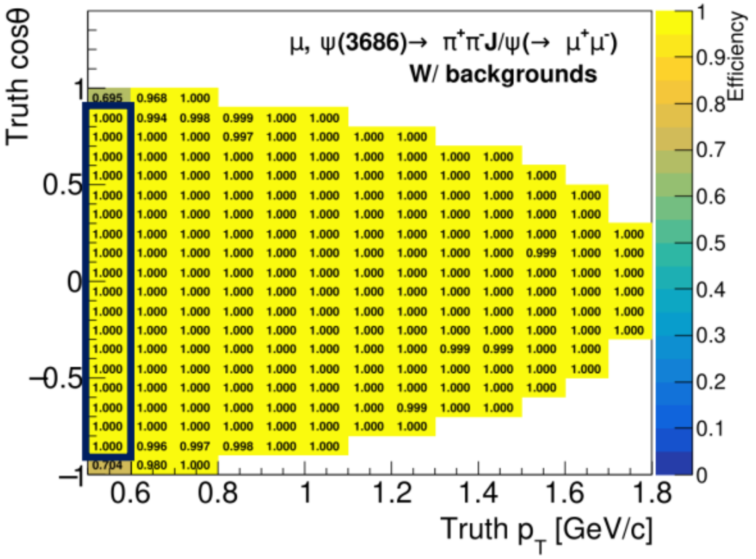
Tracking Efficiency (Seeding + CKF) , Standalone ACTS

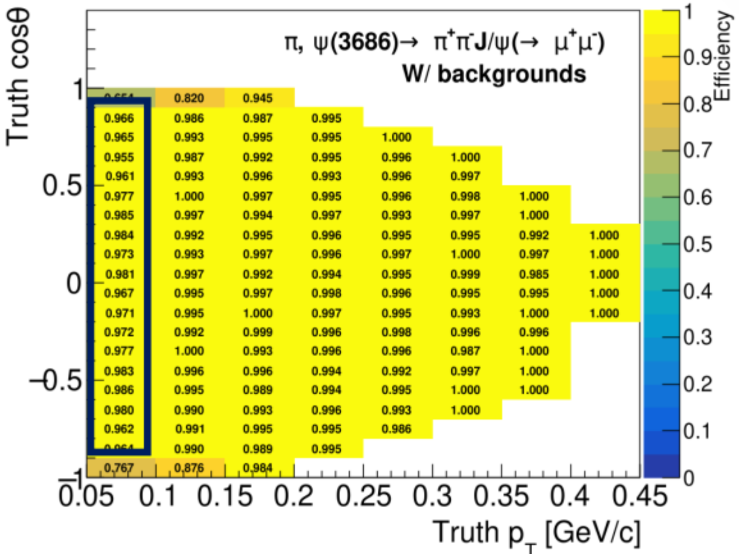
- **Without background**
- For μ ， $|\cos\theta| < 0.9,\ 500 < P_T < 600\text{MeV}$ 范围内，tracking eff ~100%
- For π， $|\cos\theta| < 0.9,\ 50 < P_T < 100\text{MeV}$ 范围内，tracking eff >93%





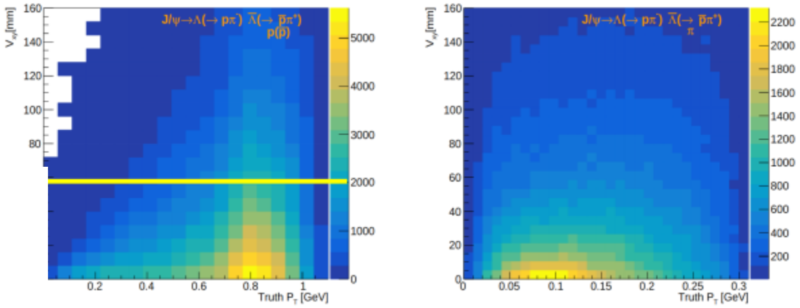
- **With background**
- For μ ， $|\cos\theta| < 0.9,\ 500 < P_T < 600\text{MeV}$ 范围内，tracking eff ~100%
- For π， $|\cos\theta| < 0.9,\ 50 < P_T < 100\text{MeV}$ 范围内，tracking eff >96%

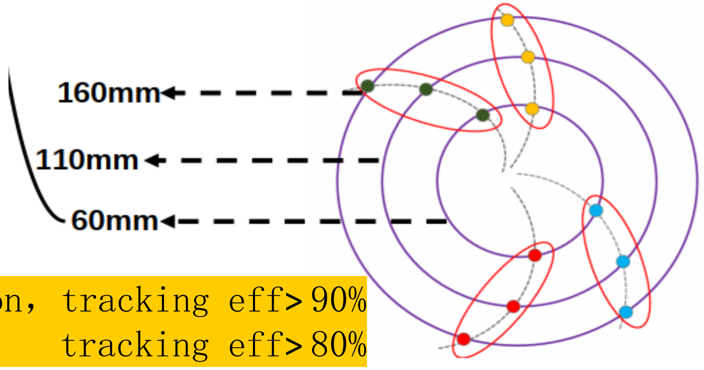




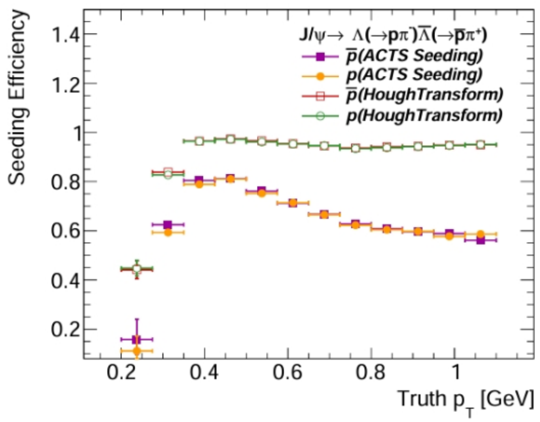
Tracking of displaced tracks With ACTS

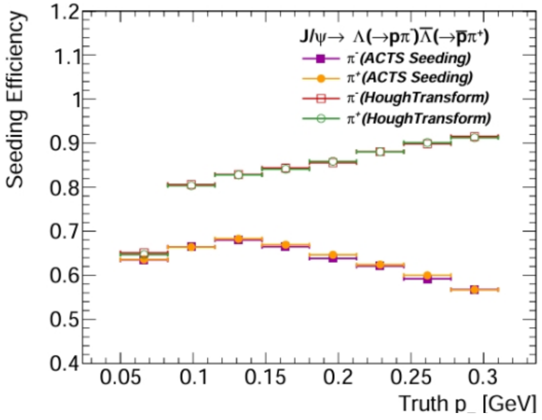
- Long-lived particles at STCF, may decay either inside or outside the inner tracking detector, and therefore may **leave few or even no hits on the ITK**.
- The performance of the ACTS' seeding algorithm is significantly limited.
- **Hough transform are considered as alternative seeding methods.**



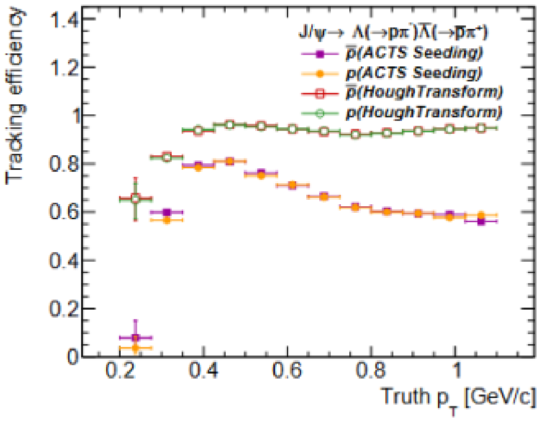


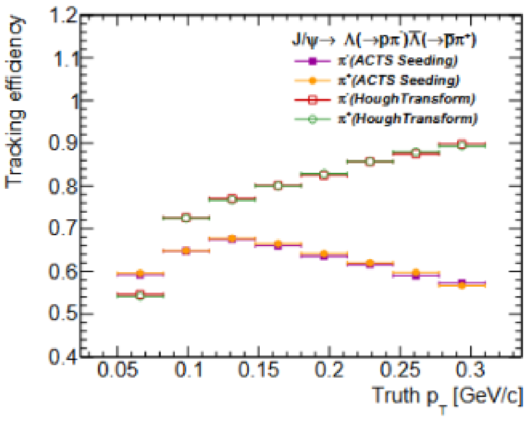
For $P_T > 400$MeV proton, seeding eff $> 90\%$
For $P_T > 100$MeV pion, seeding eff $> 80\%$





For $P_T > 400$MeV proton, tracking eff $> 90\%$
For $P_T > 100$MeV pion, tracking eff $> 80\%$



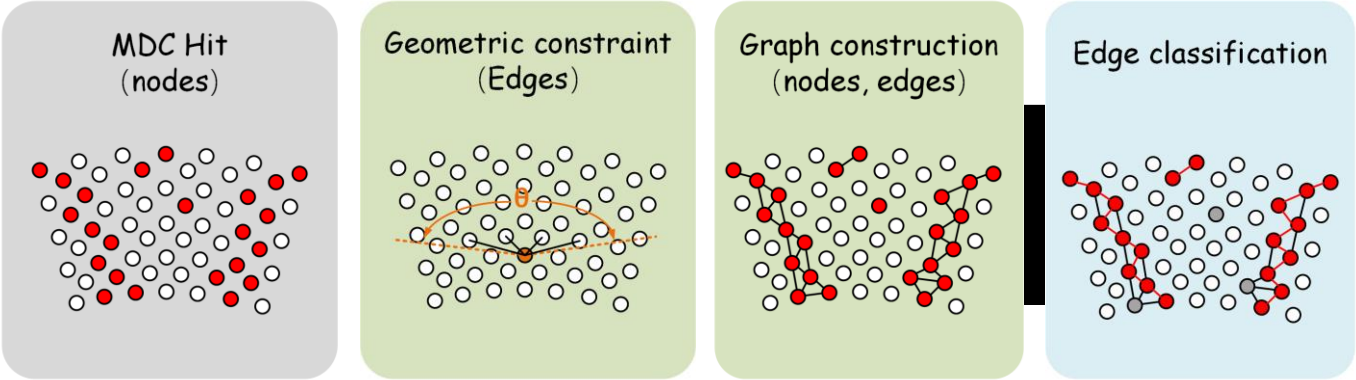


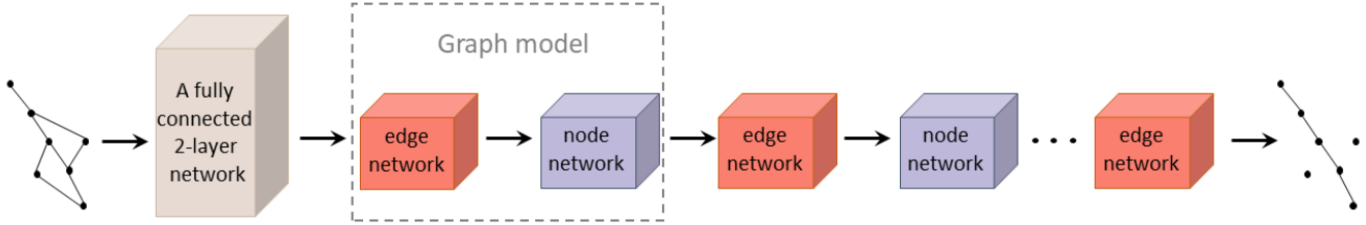
H. Li et al., NUCL SCI TECH 36, 171 (2025)

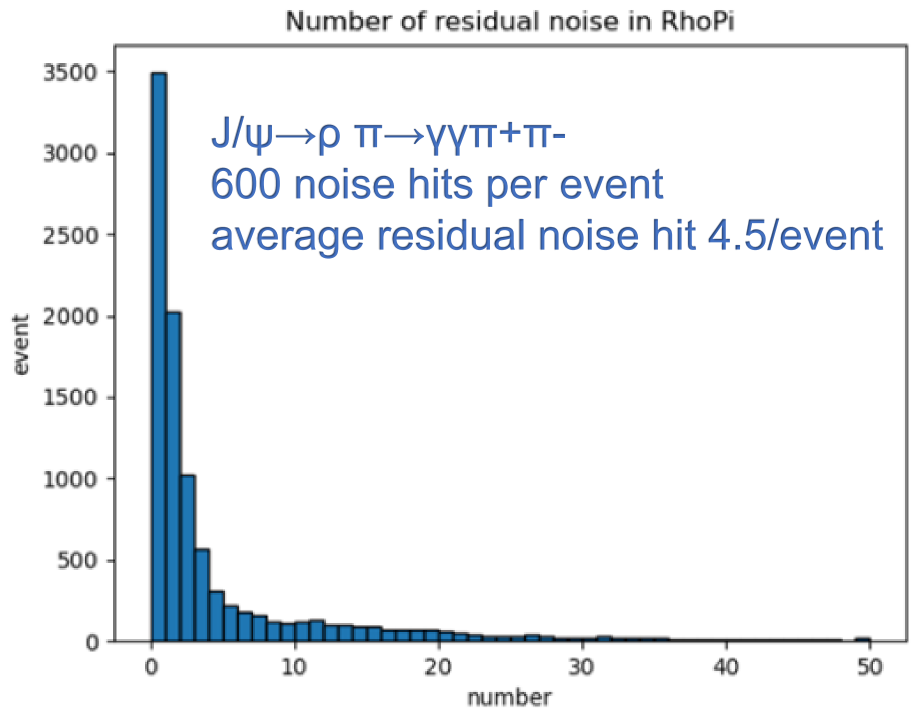
MDC backgroud filter using GNN

See Xiaoshuai's talk

- Graph nodes → Hits, Graph edges → track segments
- GNN structure: input network, node network, edge network
- Input: node features(drift distance, coordinate of signal wires), adjacen matrices, edge labels
- Output: edge weight
  - High weight → *the edge belongs to a true particle track*
  - Low weight → *it is a spurious or noise edge*





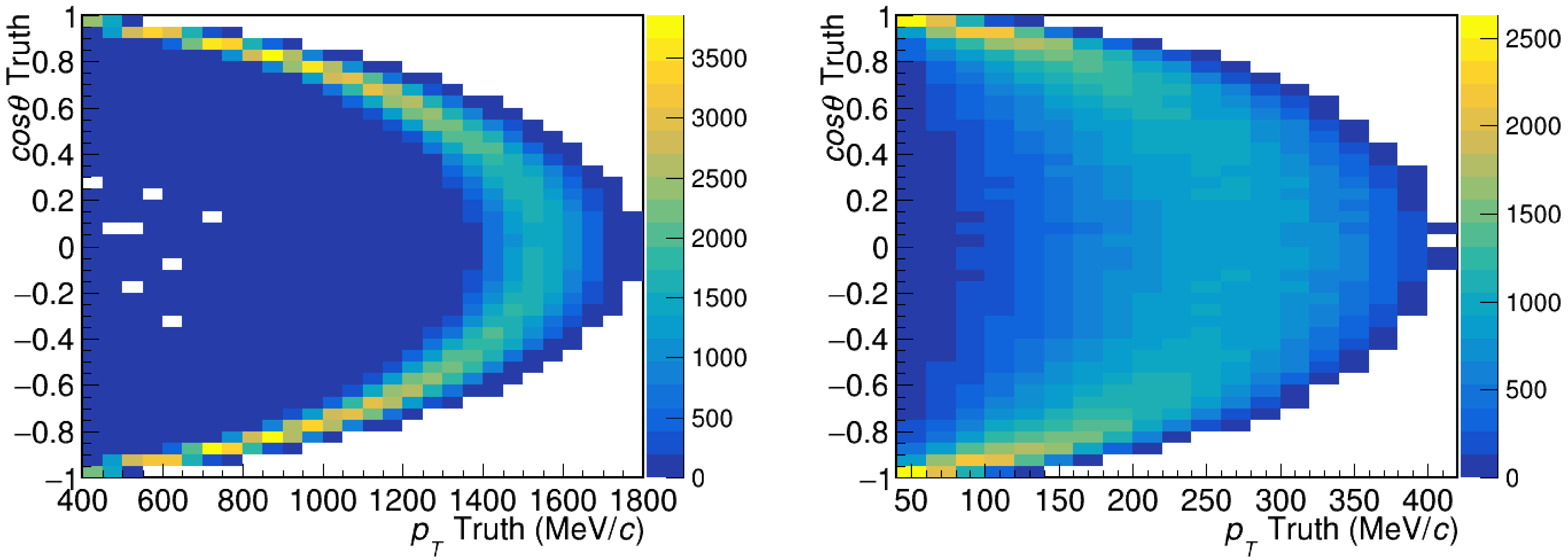


- Hit selection Efficiency $\frac{N_{signal}^{predicted}}{N_{signal}^{real}} = 91.1\%$
- Hit selection Purity $\frac{N_{signal}^{predicted}}{N_{all}^{predicted}} = 91.4\%$
- Noise removal efficiency $\frac{N_{noise}^{predicted}}{N_{noise}^{real}} = 98.6\%$

Summary and Outlook

- The complete chain for track reconstruction has been established.
- Currently, two track reconstruction algorithm are available for use.
  - ✓ Track finding based on the Hough transform + GenFit
    - Using Hough Transform, a high tracking efficiency can be achieved to meet the requirements of STCF
    - Optimizations were made for displaced tracks, resulting in a significant improvement in long-live particles
    - The DAF algorithm in GENFIT2 shows the stability and robustness, in both high momentum and low momentum
  - ✓ Seeding + CKF using ACTS
    - Excellent reconstruction performance has been demonstrated in standalone ACTS
    - Hough + CKF can improve the reconstruction efficiency of long-lived particles in ACTS on STCF
  - ➢ A GNN-based MDC noise filter has been developed, and research is underway to utilize machine learning methods for track finding
- ➢ Supporting physics study and detector optimization are among the most critical tasks
  - Detector design determine the reconstruction quality and choice of algorithms
  - Combining and tunning different algorithms to achieve better overall performance.

Backup

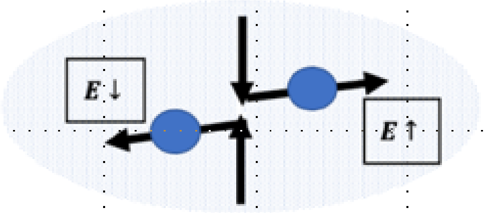


The distributions of p_T versus cosθ for μ (left) and π (right)
in ψ(3686) → π+π- J/ψ, J/ψ → μ+μ- events

Background

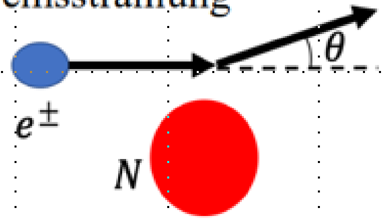
Touschek effect

- Scattering between inner beam particles
- Generation rate $\propto$ N_{bunch}, beam size^{-1}, energy^{-3}
- Main Background



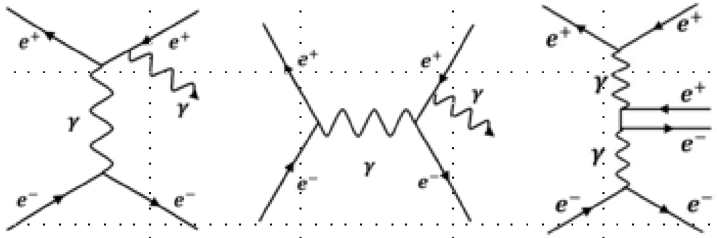
Beam-gas effect

- Effect with residual gas in the beam pipe
- Coulomb scattering，bremsstrahlung
- Generation $\propto$ pressure



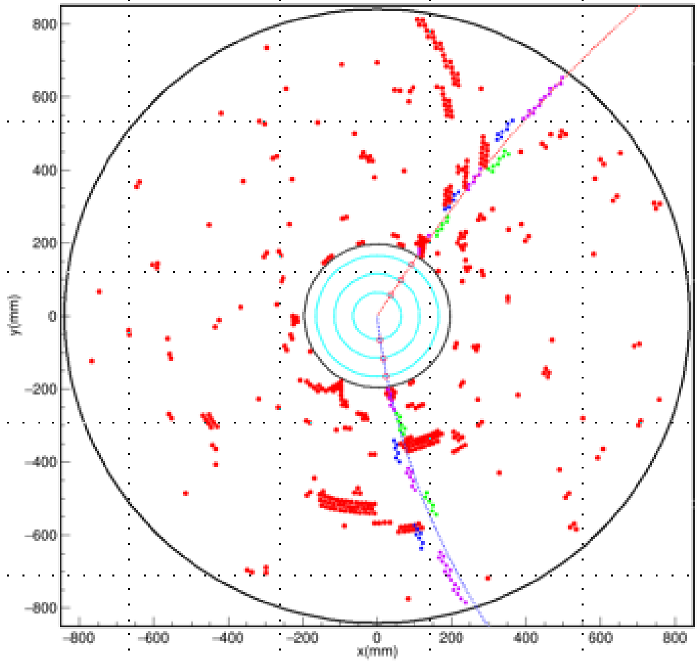
Luminosity-related background

- Radiative Bhabha: $e^+e^- \to e^+e^-\gamma$
- Two-photon process:
  $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-e^+e^-$

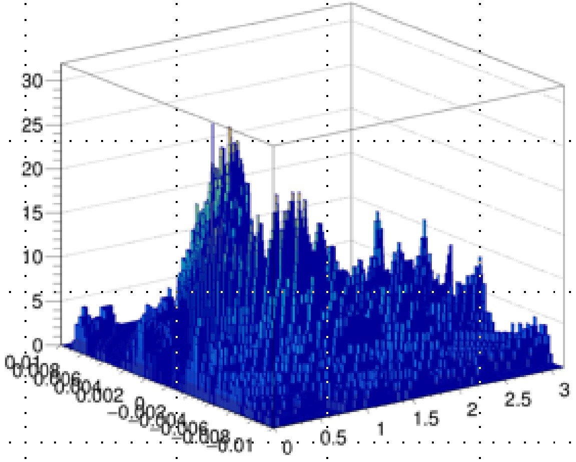


Other background

- Injection
- Synchrotron radiation



Hough map with background



Background hits count per event

ITK1	ITK2	ITK3	MDC1	MDC2	MDC3	MDC4	MDC5	MDC6	MDC7	MDC8
37.3	13.6	8.2	60.3	42.4	24.8	25.1	60.0	67.8	30.8	30.0