Track Reconstruction using Hough Transform and GENFIT2

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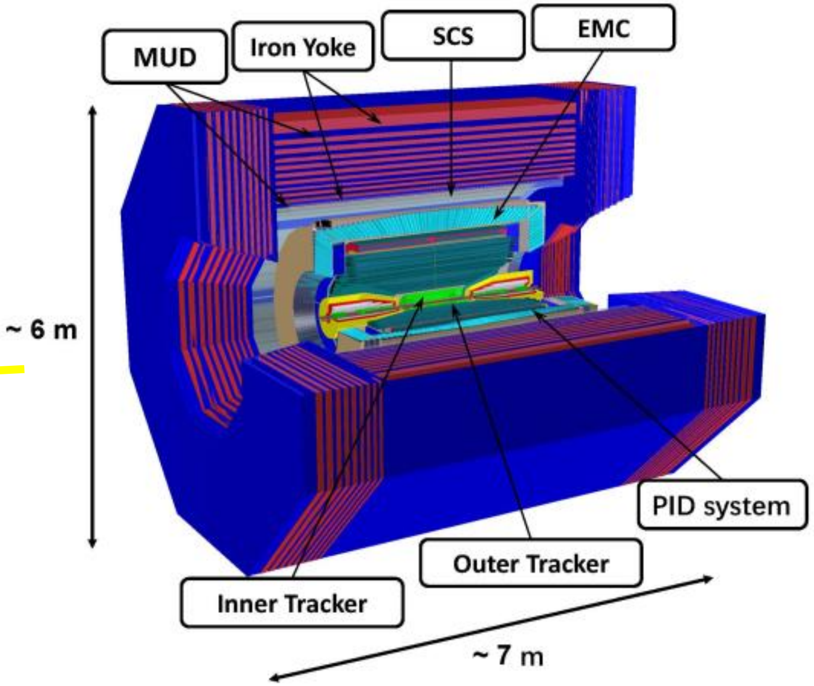
Outline

- **Introduction to STCF and the tracking system**
- **The baseline track reconstruction algorithms**
  - **Hough Transform based track finding**
  - **Track fitting using GENFIT2 framework**
- **Summary and outlook**

Super Tau-Charm Facility(STCF)



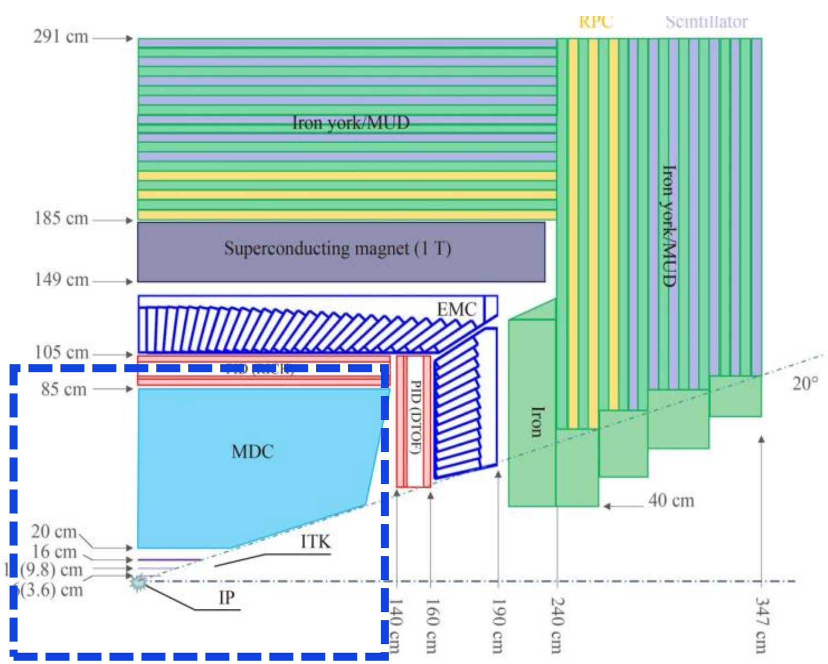
- Electron-positron collider (China)
- E_{cm}=2-7GeV, L> $0.5 \times 10^{35}\ cm^{-2}\ s^{-1}$(peak)
- Potential for an upgrade to increase L and realize polarized beam

reveal the mystery of how quarks form matter and the symmetry of fundamental interactions

Tracking System:
Drift Chamber(MDC) +Inner Tracker(ITK)

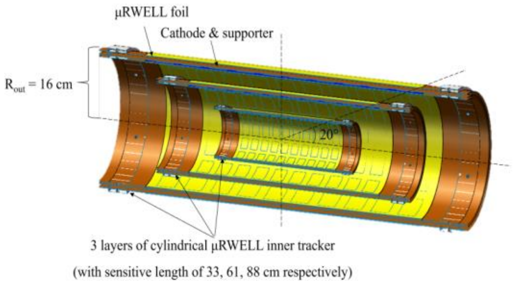
works in a **1T** magnetic field

- **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

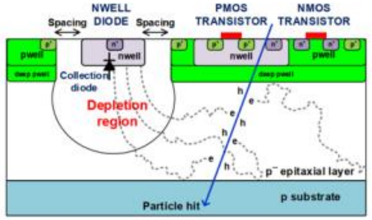


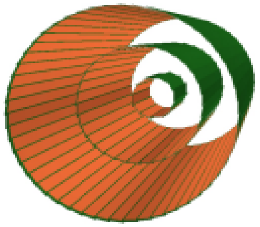
Figures from STCF CDR (arXiv: 2303.15790)

ITK Gaseous option : MPGD

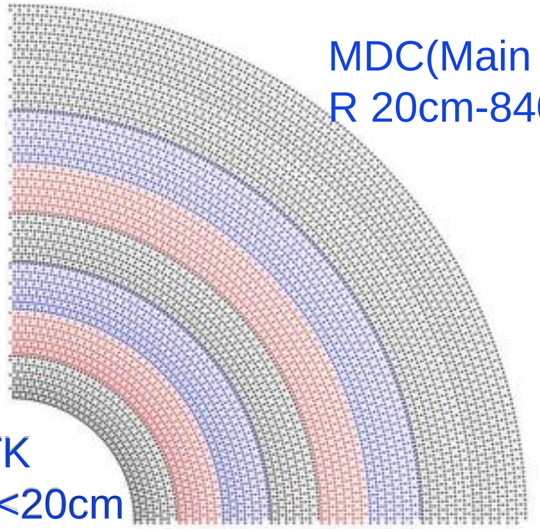


ITK Silicon option: CMOS MAPS





MDC(Main Drift Chamber)
R 20cm-840cm



ITK
R<20cm

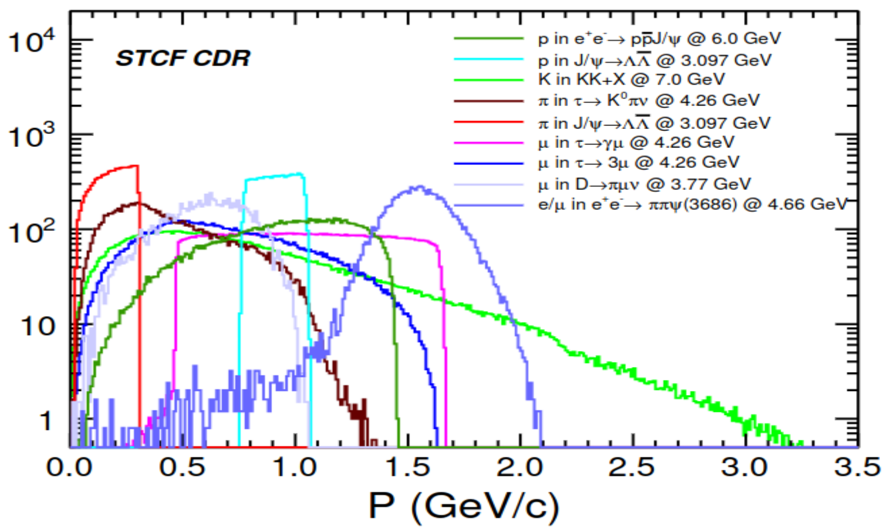
The studies in this talk is based on the MDC + ITK MPGD

Task of Tracking and The Landscape in STCF

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

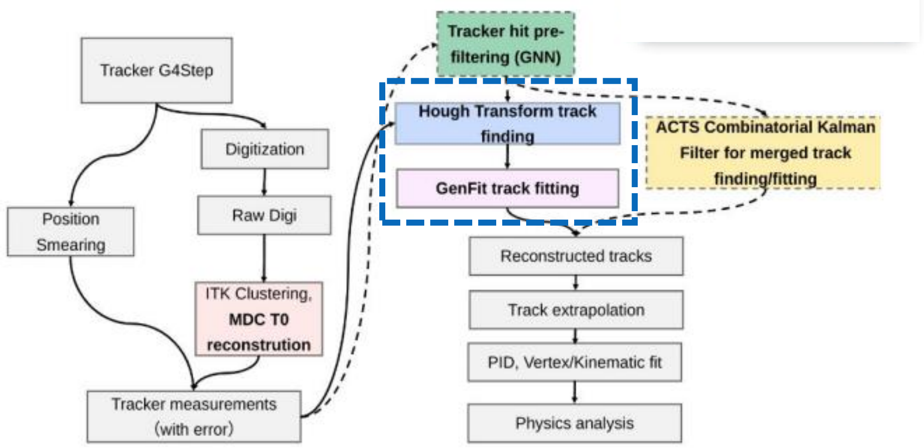
- Most physics channel have number of particles with **p < 0.4 GeV**
  - Obvious Material effect
  - Looping < 125MeV, insufficient measurements
- **High background** : negatively impact efficiency and resolution
- Long-live particles

Momentum distributions of charged particles



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

An Overview of Track Reconstruction in STCF



- **Baseline : Hough + GENFIT2**
  - **Global track reconstruction based on Hough transform and DAF**
    - **process the hits form ITK and MDC simultaneously**
    - **enhancing the ability to search for candidate tracks**
    - **Extended Kalman Filter(DAF) using GENFIT2**
- Local method (ACTS)
  - Seeding + Combinatorial Kalman Filter (CKF)
- Machine learning techniques: tracking with GNN
  - GNN for background filter
  - clustering(track finding) using DBSCAN、RANSAC

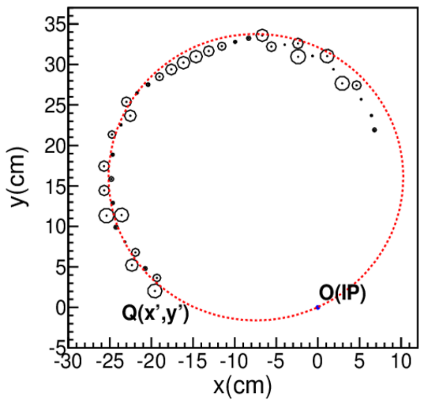
This report focuses on the current baseline Track reconstruction workflow : Hough + DAF(GENFIT2)

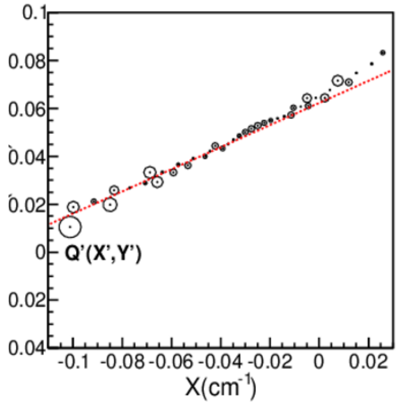
Track Finding based on Hough Transform

- Hough Transform / Legendre Transform
- Implementation and studies of Hough Transform in OSCAR framework
- Studies of track finding efficiency

Hough Transform / Legendre Transform

Conformal Mapping



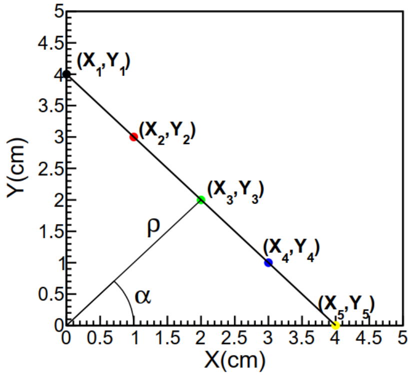


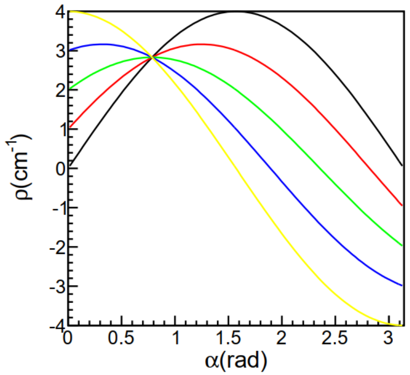
- **(Trajectory) Circles** ***passing the origin point ->*** **conformal straight lines**
- **(Drift) Circles** ***not passing the origin point ->*** **conformal circles**

conformal circles are tangent to conformal straight line

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



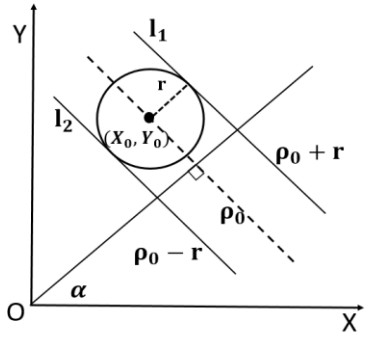


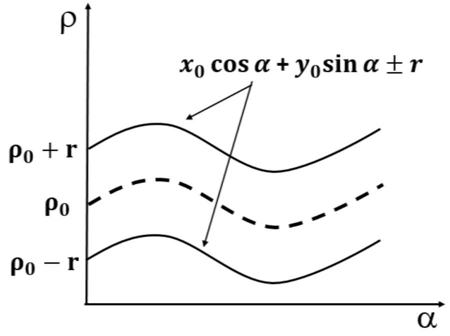
For Drift Chamber ： Legendre transform

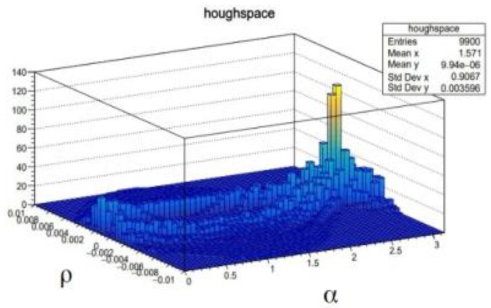
- **One drift circle->two curve lines on Hough space**

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

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







To better utilize the MDC information, Legendre transform is applied in STCF

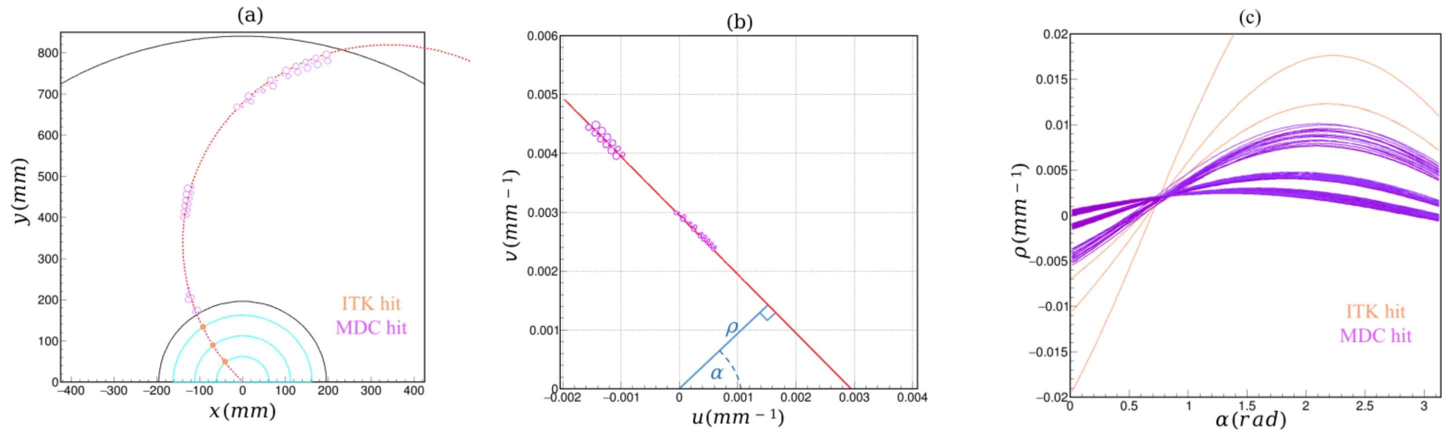
Implementation of Hough Transform in OSCAR (2D)

2D Tracking

3D Tracking

Kalman Filter fitting

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

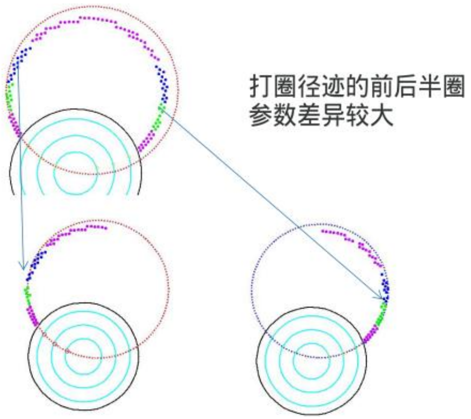


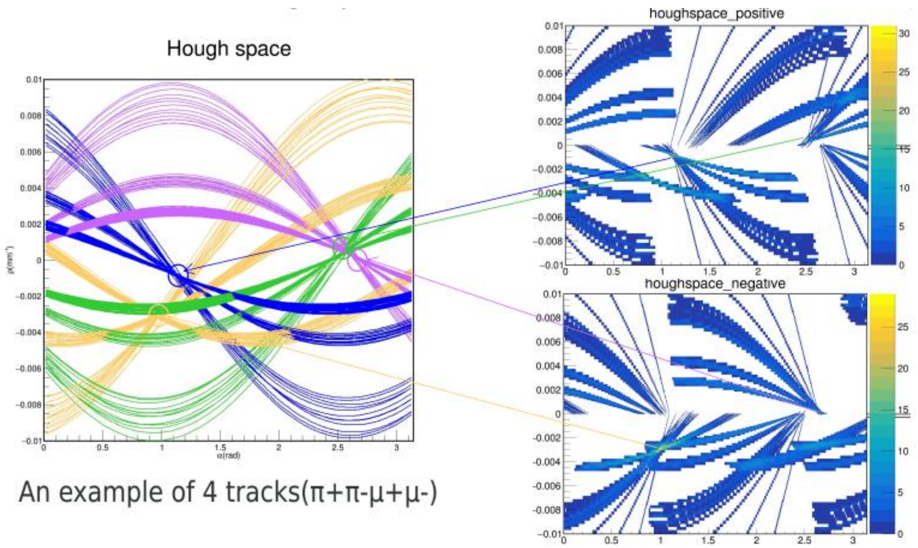
I. Conformal transform: **circular trajectories -> conformal straight lines**
II. **Handling ITK and MDC measurements simultaneously**, populating the Hough Space（2D histogram）
III. Peak finding approach to identify candidate tracks(circles) in Hough Space
IV. Global chi-square fit for circle tracks

Implementation of Hough Transform in OSCAR (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 $\rho d\rho/d\alpha$

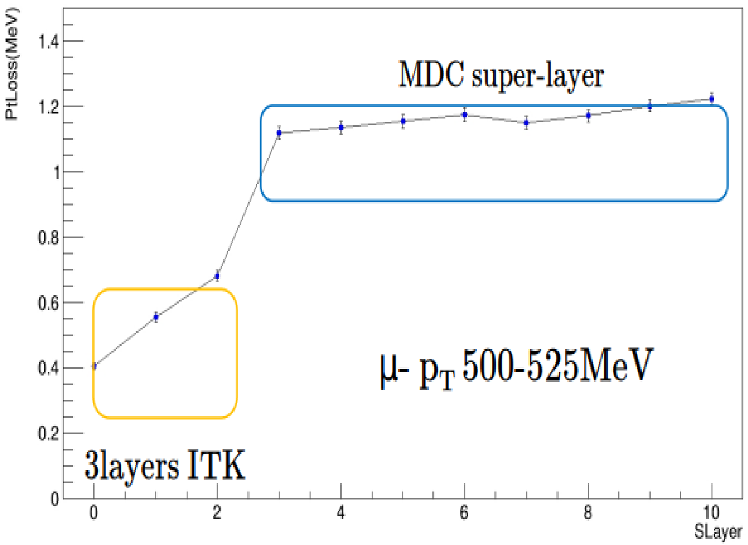
    → **hits from different charged particles don't interfere with each other when peak finding**
  - Peak detecting method and merging of duplicate tracks
  - Weighted chi-square fit is applied in the 2D track fitting process
  - Given the significant momentum change before and after particles enter MDC, only MDC hits are used for the 2D circle fit





An example of 4 tracks(π+π-μ+μ-)

reduction in p_T upon entering MDC



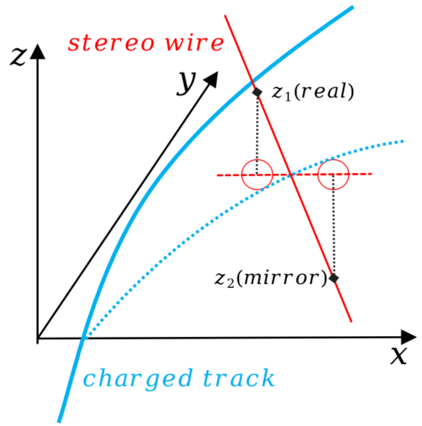
Implementation of Hough Transform in OSCAR (3D)

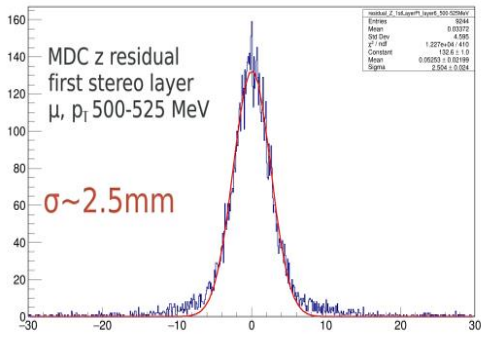
2D Tracking

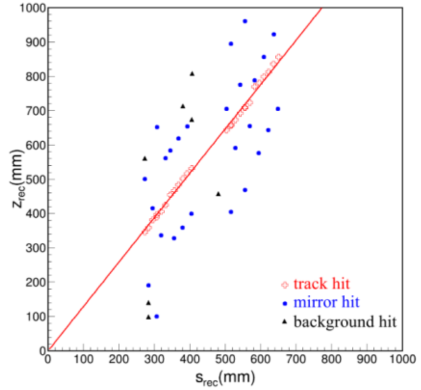
3D Tracking

Kalman Filter fitting

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







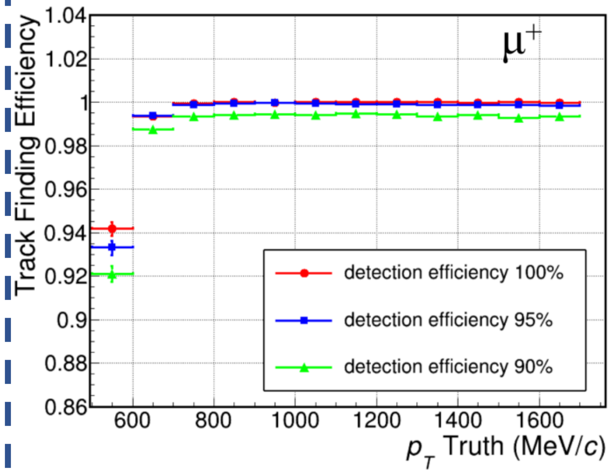
I. Match MDC stereo wire hits, and calculate z position, flight path(s) values
II. The trajectory is a straight in the s-z space → similar to the 2-D track finding:
Hough transform on SZ plane
Left/right ambiguity is considered in **Hough(SZ) Space**
III. A global chi-square fitting is performed to retrieve the parameters of helix track

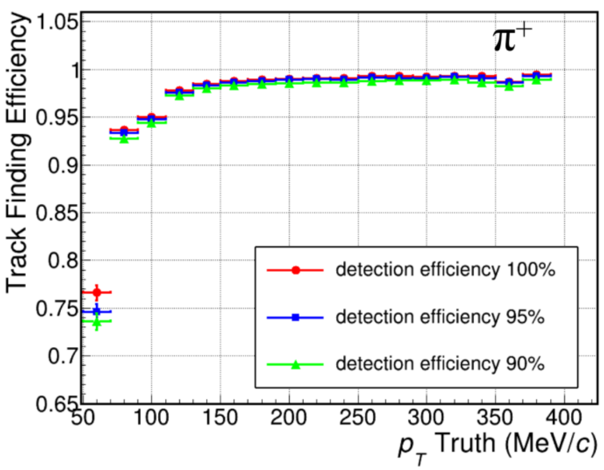
✓ Track merging in the last step is considered
✓ On-going optimizations for low momentum tracks to enhance efficiencies of stereo hits for specific cases, i.e., large dip angles, second vertices track

Algorithm Performances of Hough-based Track Finding

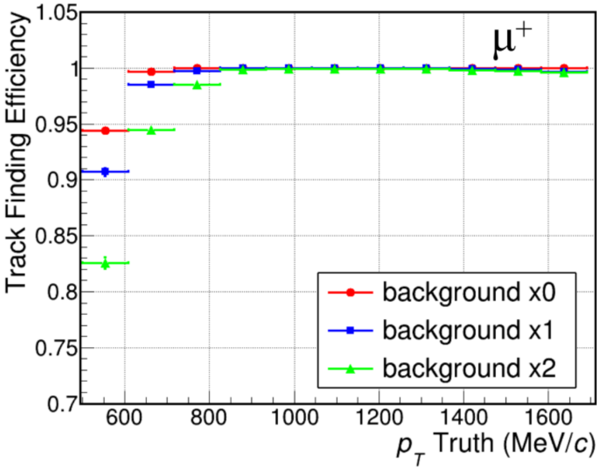
- ψ(3686) → π+π- J/ψ, J/ψ → μ+μ- is studied in **full simulation**

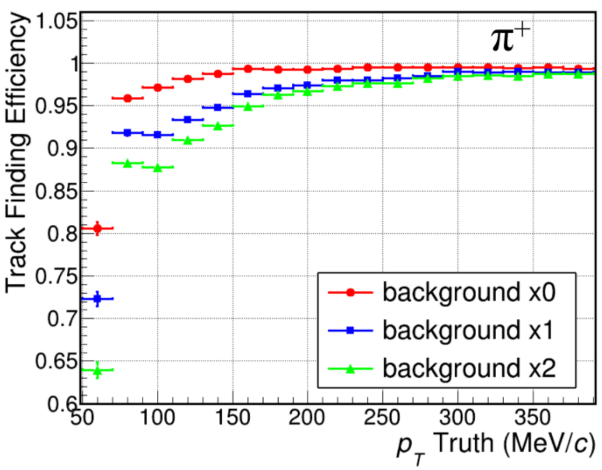
Track finding efficiency : N1 / N2
N1: Number of reconstructed tracks matching with the truth tracks
N2: Number of truth tracks with simulated hits >= 5, within 20°<θ<160°





- 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**

Track Fitting based on GENFIT2

- Introduction of GENFIT2
- Fitting algorithms in GENFIT2 and the implementation in STCF
- Track fitting performances

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 5 different particle hypotheses
  - Reference Deterministic Annealing Filter (RefDAF) is used as the default fitting algorithm
  - For curling tracks, hits from first half are provided to fitting algorithm

Track Fitting Algorithms in GENFIT2

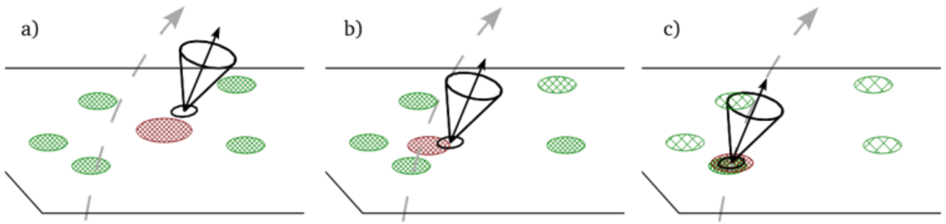
Kalman filter: Iterative bi-directional Kalman filter is applied in GENFIT2

- Forward fitting: from inner detection module to the outer
- Backward fitting: the result of the forward fitting is used as the starting value for the fit proceeds in the backwards direction
- 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 each measurement as used as weight
- available to reject 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

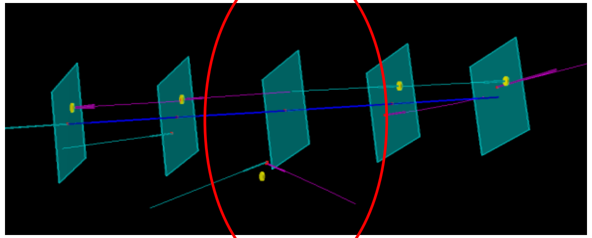
Track reconstruction in the ATLAS experiment : The deterministic annealing filter

Demonstration of DAF fitting in GENFIT2

An example rejecting outliers provided in GENFIT2 framework

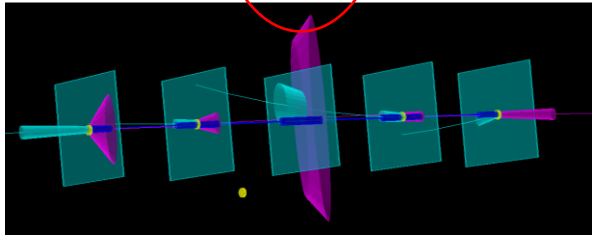
outlier

iteration 1



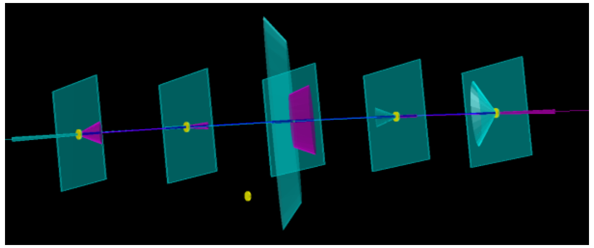
Initial weights	**1**	**1**	**1**	**1**	**1**
new weights	0.08056	0.04667	**7.69e-20**	0.06203	0.0620372

iteration 2



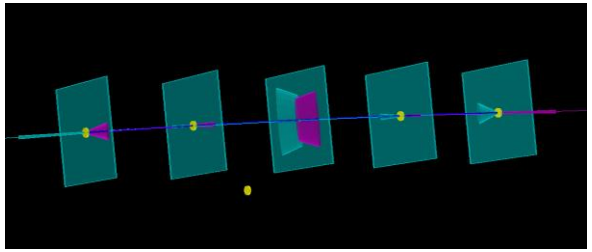
old weights	0.08056	0.04667	**7.69e-20**	0.06203	0.06203
new weights	0.59467	0.58552	**3.82e-17**	0.58504	0.59237

iteration 3



old weights	0.594671	0.585524	**3.81e-17**	0.585042	0.592371
new weights	0.896426	0.887211	**0**	0.884235	0.895077

iteration 4



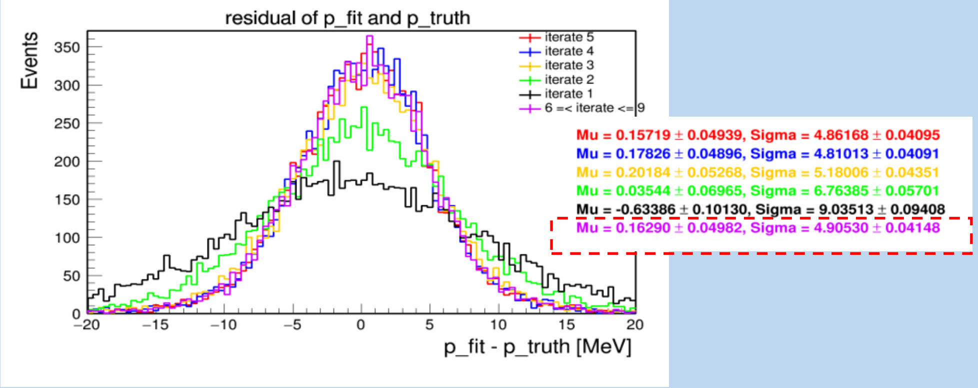
old weights	0.896426	0.887211	**0**	0.884235	0.895077
new weights	**0.999995**	**0.999991**	**0**	**0.999989**	**0.999994**

- At the end of fitting, the weight of outliers -> 0, the weight of signal hits -> 1

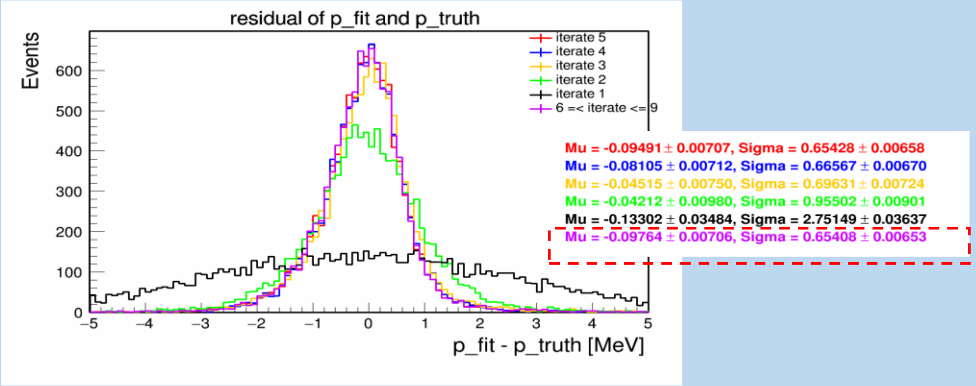
RefDAF Algorithm in OSCAR

- **During the fitting iteration process, momentum resolution is studied w/ and w/o background, for 1GeV and 120MeV muons**

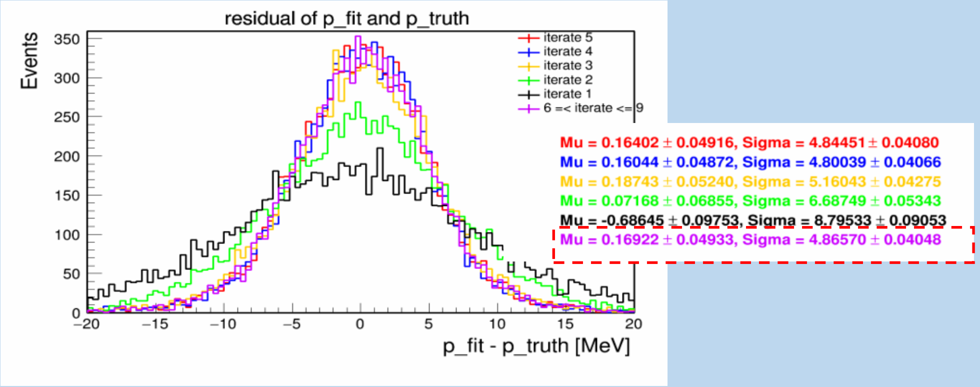
1GeV with background



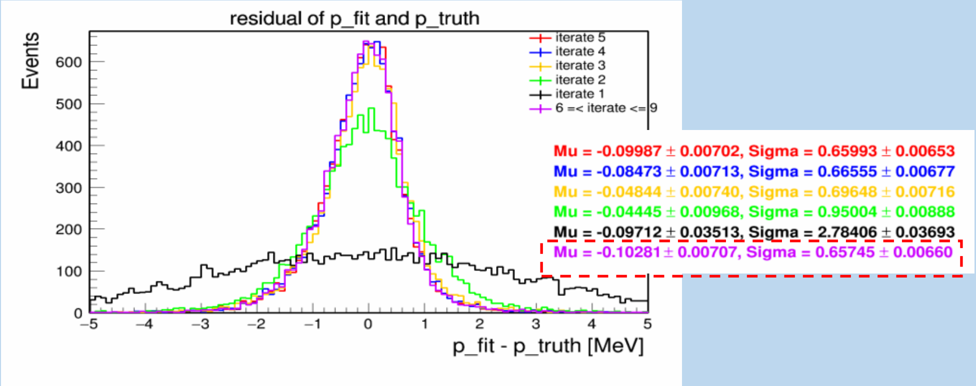
120MeV with background



1GeV without background



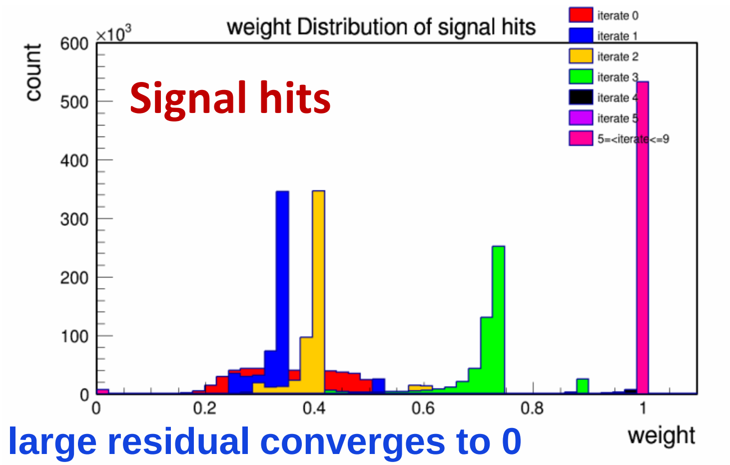
120MeV without background



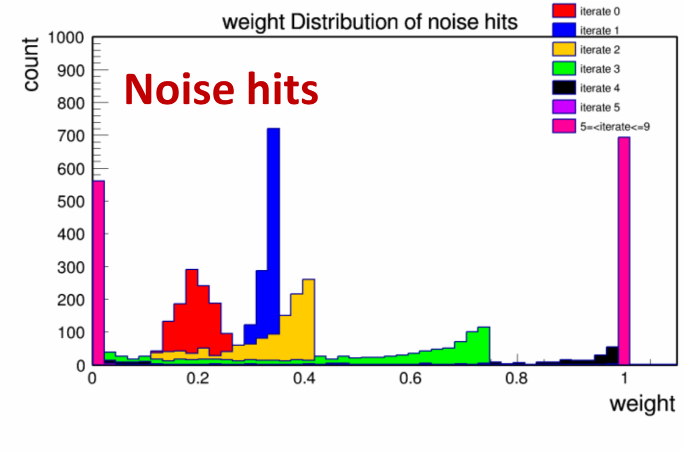
- **The ambiguity of hits is not initialized before fitting, it is managed in DAF**
- **The fitter generally converges after 5 iterations**
- **The influence of noise hits is minimal in RefDAF**

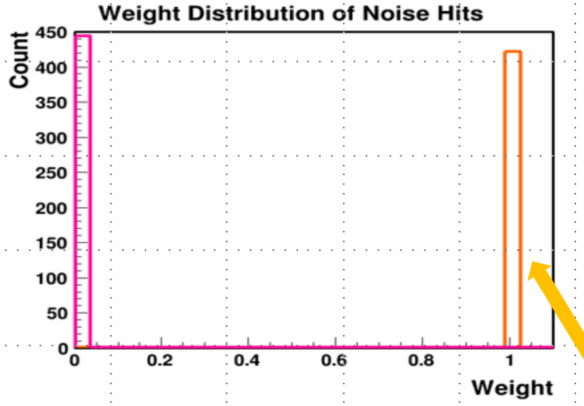
Noise Rejection of DAF in OSCAR

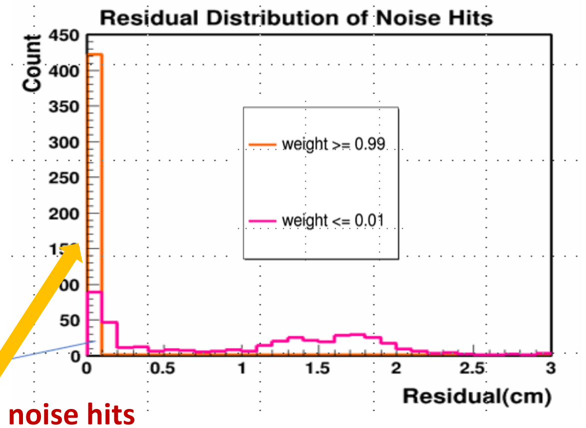
- **The noise rejection capability is studied with 120MeV muon, with 1X background**
  - **In the DAF iteration process, the weight of signal hits converges to 1 when reaching stability**
  - **Signal hits are clearly separated by weight**



- **The weight of noise hits with large residual converges to 0**
- **the remaining noise hits are very close to real tracks(residual<0.05cm)**





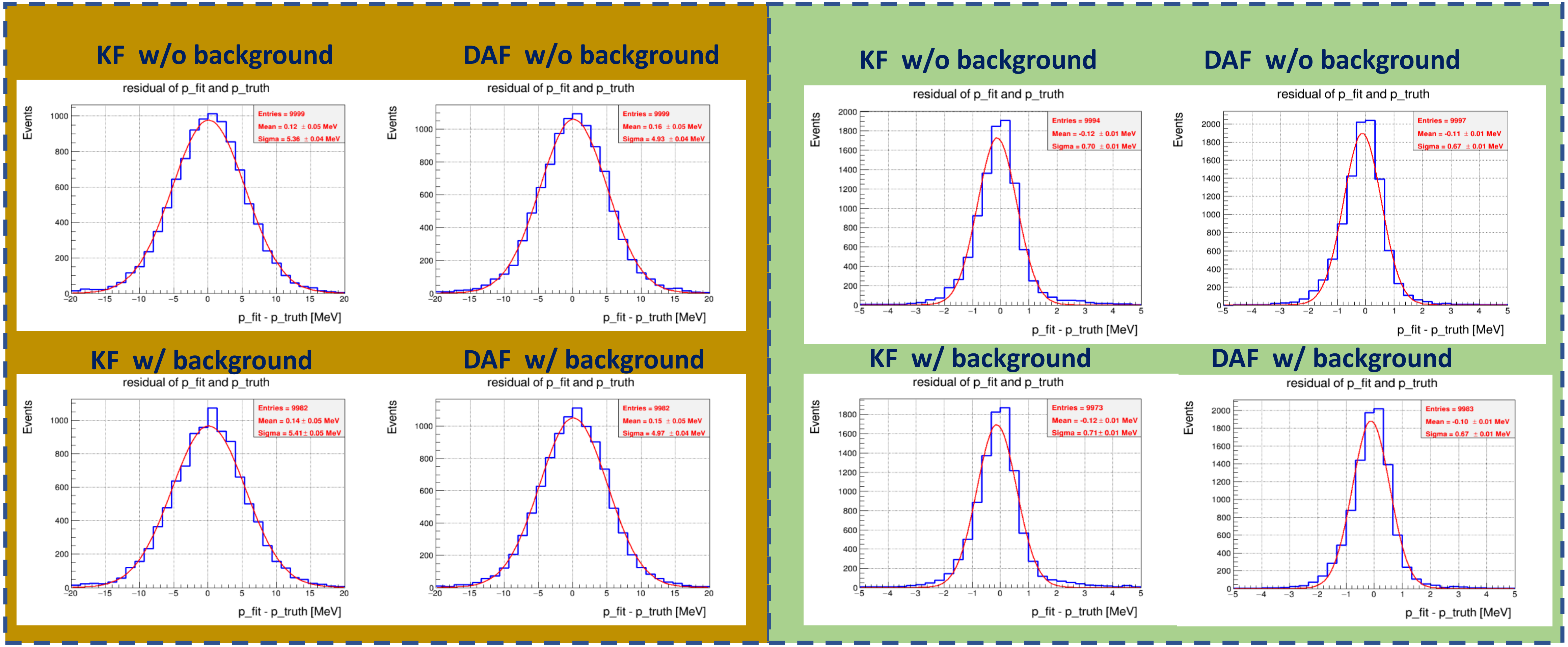


Remaining noise hits

Fitting Performance for High/Low momentum tracks

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

1GeV muon, θ=60°, KF vs DAF | **120MeV muon, θ=60° , KF vs DAF**



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

Summary and Outlook

- The baseline track reconstruction workflow based on Hough transform and GENFITII is implemented and studied in STCF offline software framework
  - Using Hough Transform, **with reduced detector efficiency and different background levels**, **a high tracking efficiency can be achieved to meet the requirements of STCF**
  - The DAF algorithm in GENFIT2 shows the **stability and robustness against background**, **in both high momentum and low momentum**

- The baseline track reconstruction provide the reliable toolkit for detector optimizations

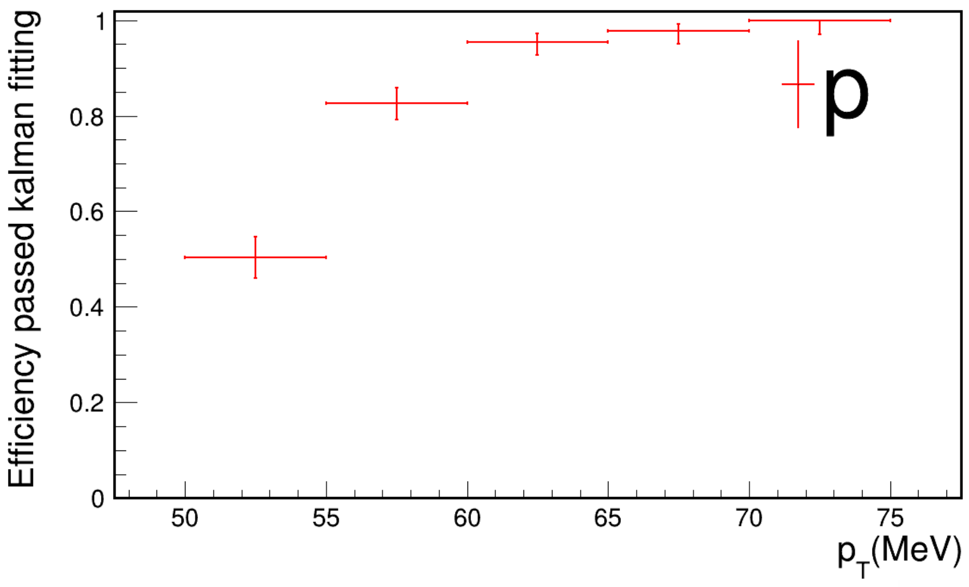
- More realistic detector scenario, such as X-T calibration, will be taken into account

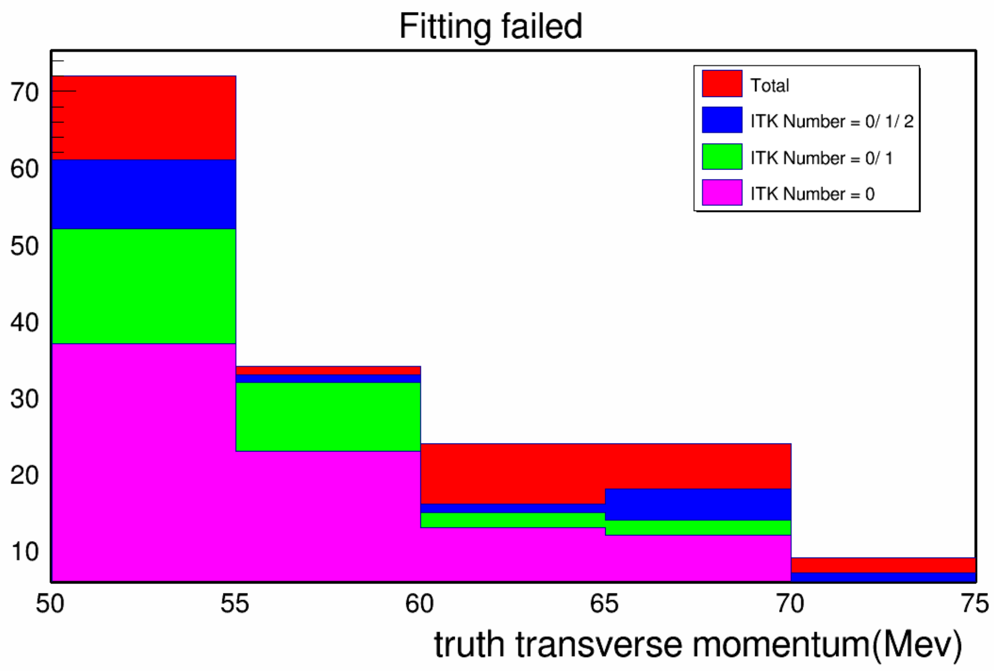
- In certain specific cases, including reconstruction of particles with p~50MeV or tracks with secondary vertices are under studying, and additional requirements are expected to be identified across more physics channels

Backup

Track reconstruction for very slow tracks

- **Track reconstruction for tracks with very low momentum is being studied, with p(50-75MeV) single muon**
  - **Reconstruct efficiency in this region is highly related to the dip angle distribution**
  - **The loss of ITK hits in track finding significantly impacts track fitting efficiency**

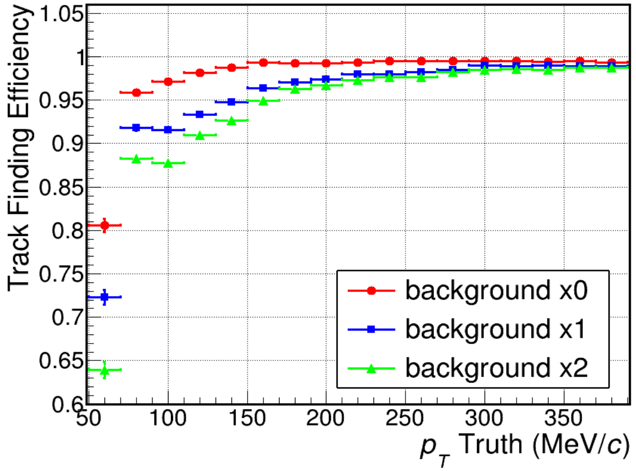


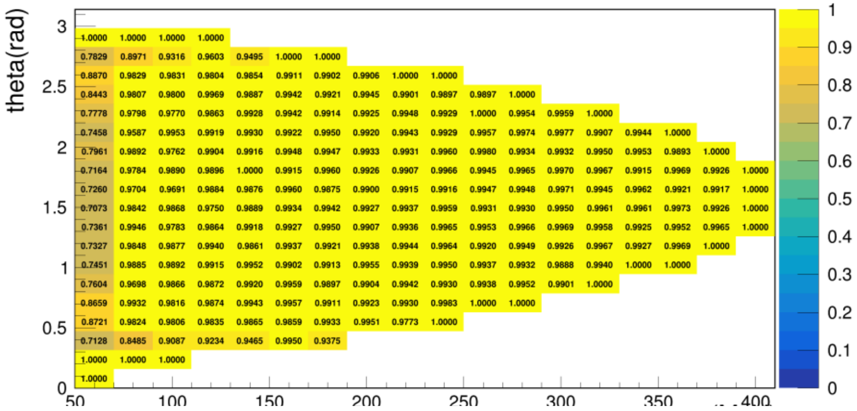


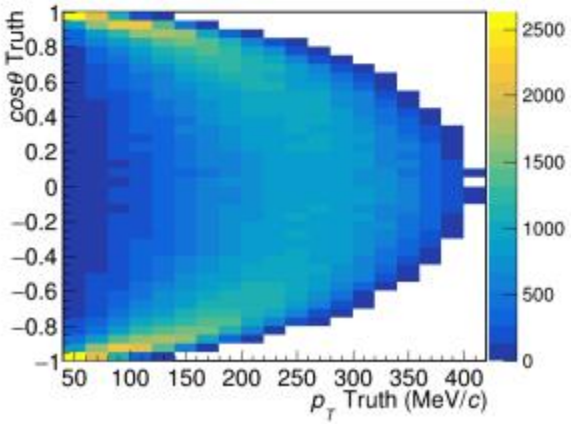
Very slow pion (p~50MeV) with additional difficulties in reconstruction

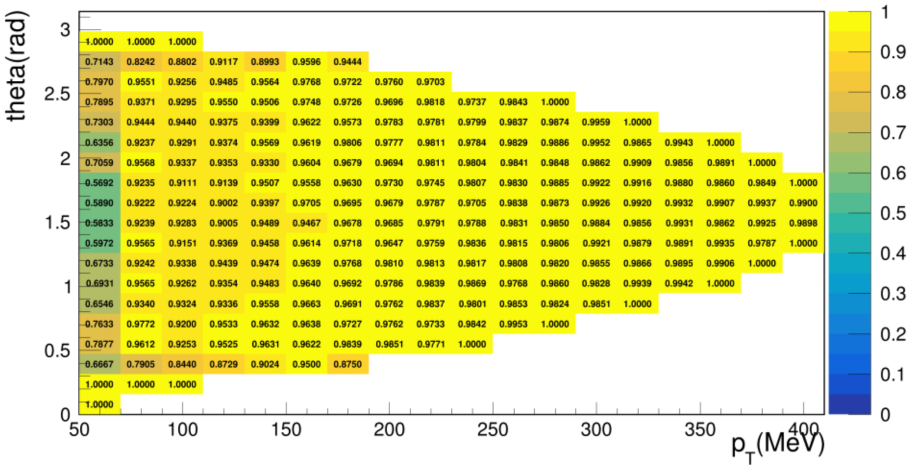
2D Efficiency with different noise level

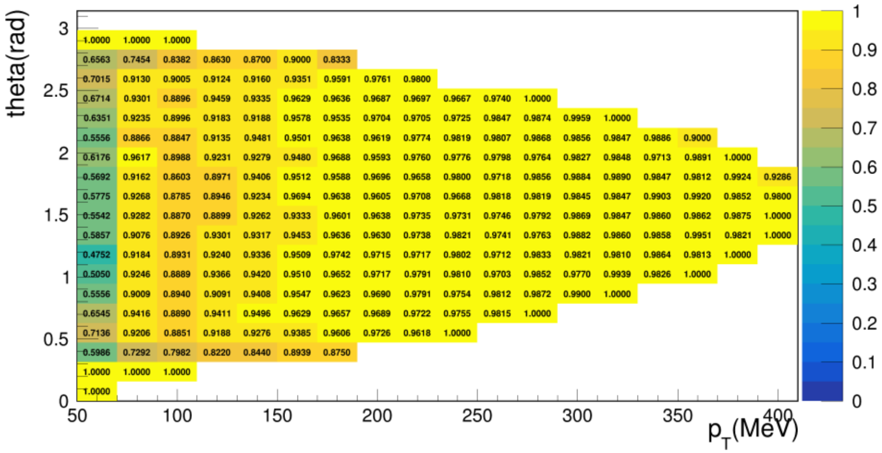
- particles in ψ(3686) → π+π- J/ψ, J/ψ → μ+μ- events are studied



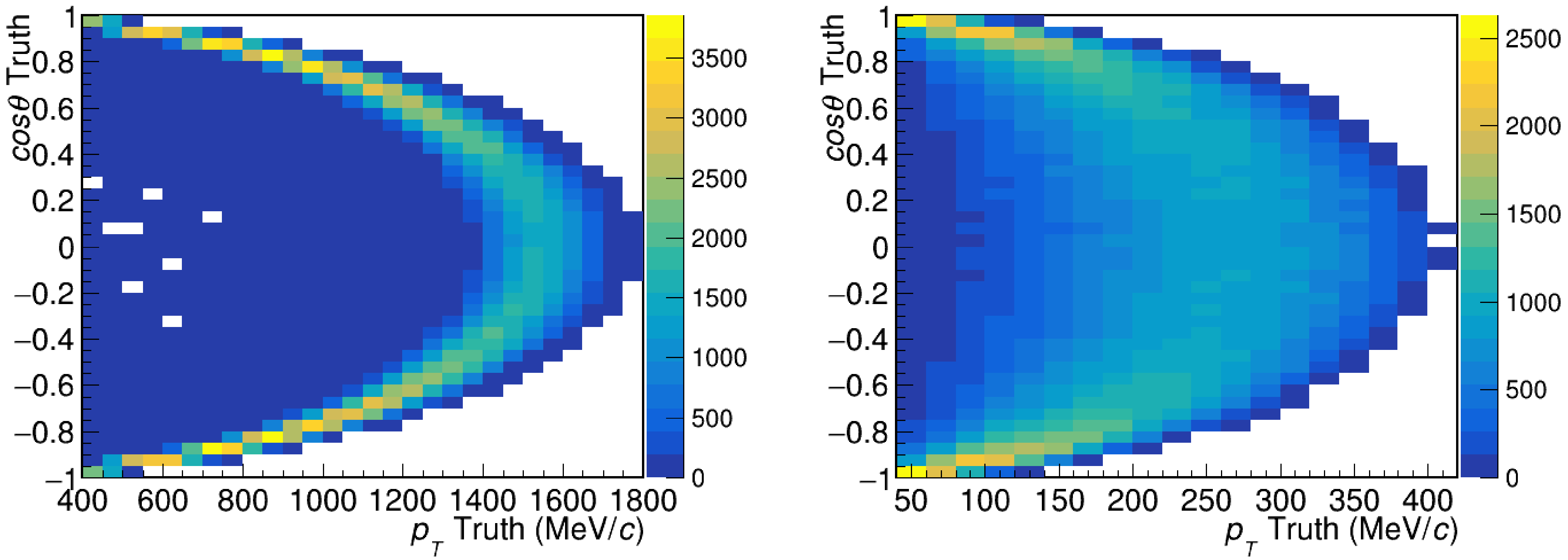








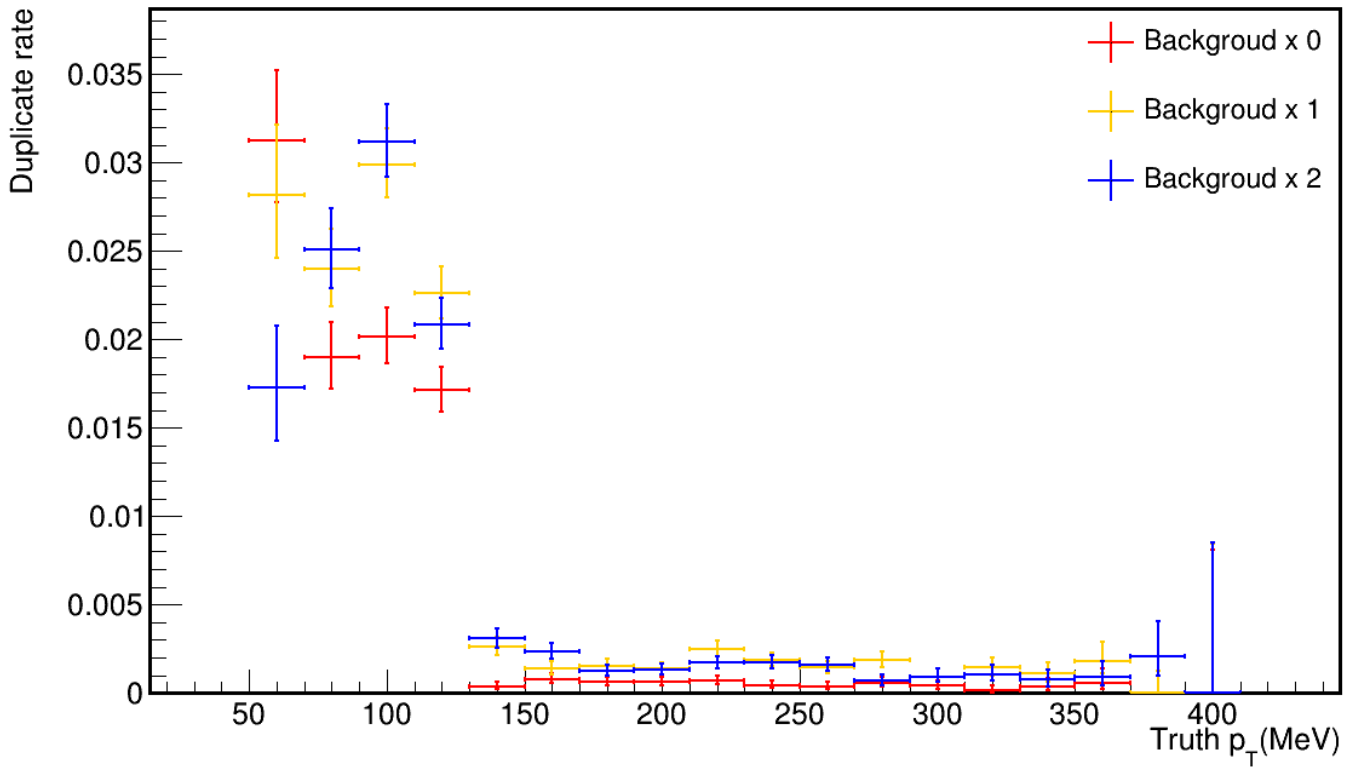
- **The drop of efficiency mostly come from very slow pion(50-75MeV), with big dip angles, which flies very fast in z direction, leaving insufficient hits**

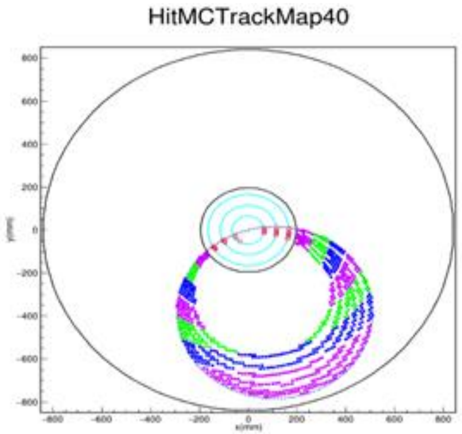


The distributions of p_T versus cosθ for μ (left) and π (right) in ψ(3686) → π+π- J/ψ, J/ψ → μ+μ- events

Duplicate rates of Hough

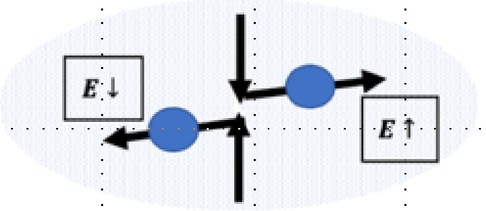
- particles in ψ(3686) → π+π- J/ψ, J/ψ → μ+μ- events are studied



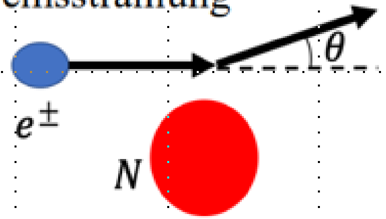


Background

Touschek effect
- Scattering between inner beam particles
- Generation rate ∝ N_{bunch}, beam size^{-1}, energy^{-3}
- Main Background

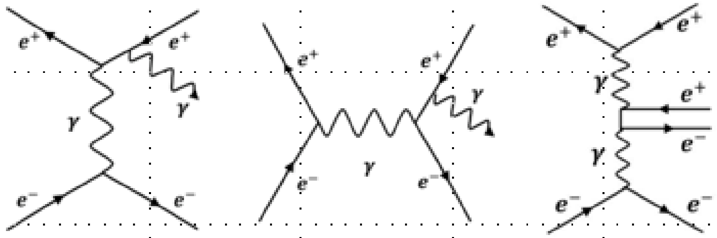


Beam-gas effect
- Effect with residual gas in the beam pipe
- Coulomb scattering，bremsstrahlung
- Generation ∝ pressure



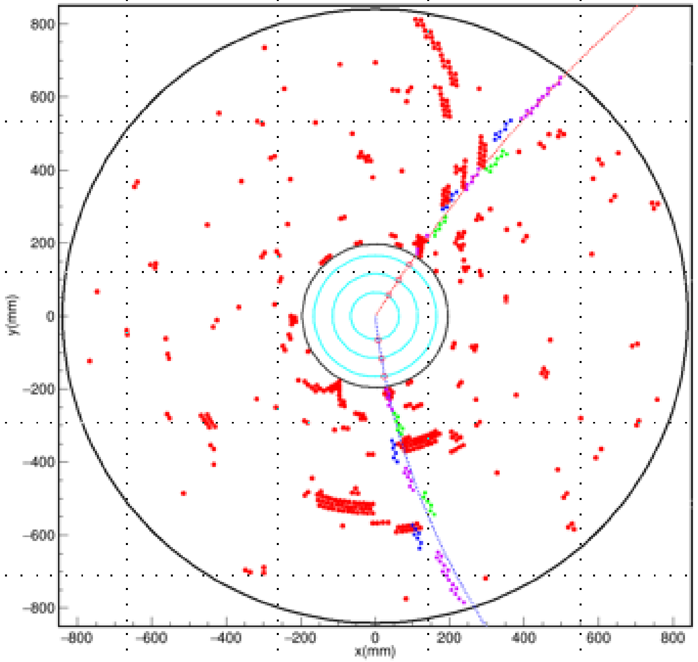
Yupeng Pei

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

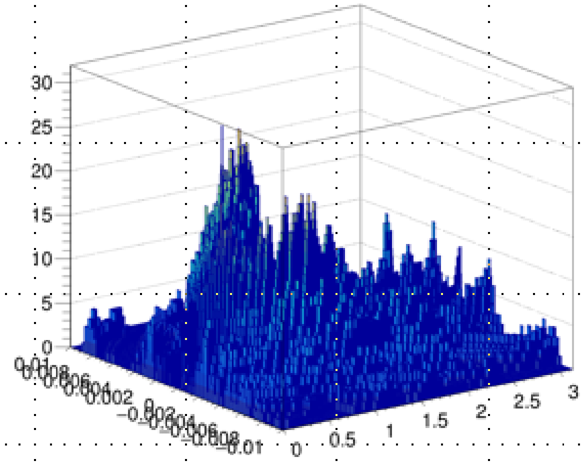


Other background
- Injection
- Synchrotron radiation

5



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