Track Reconstruction in BESIII

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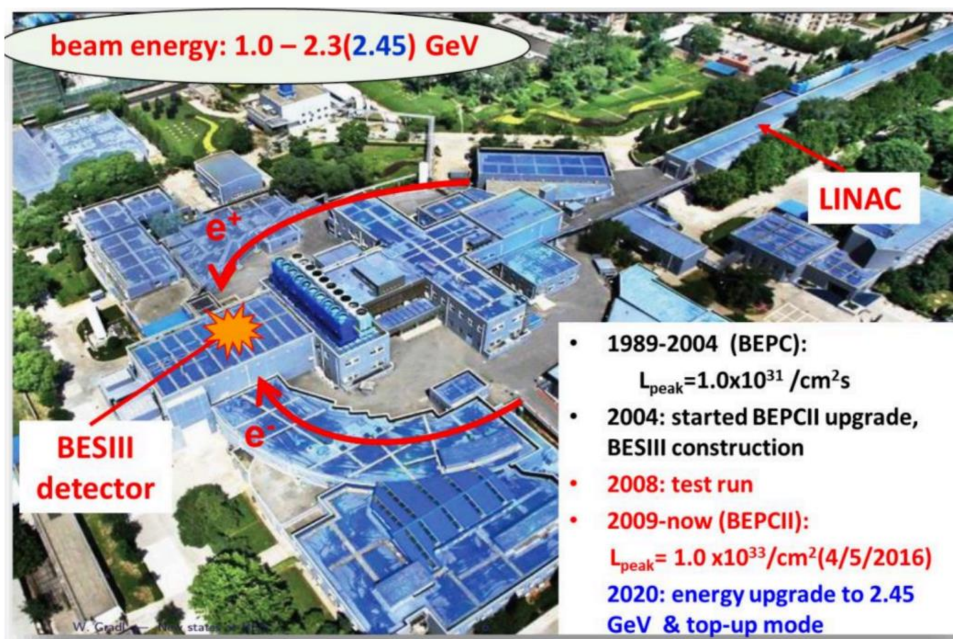
16th Jan 2024

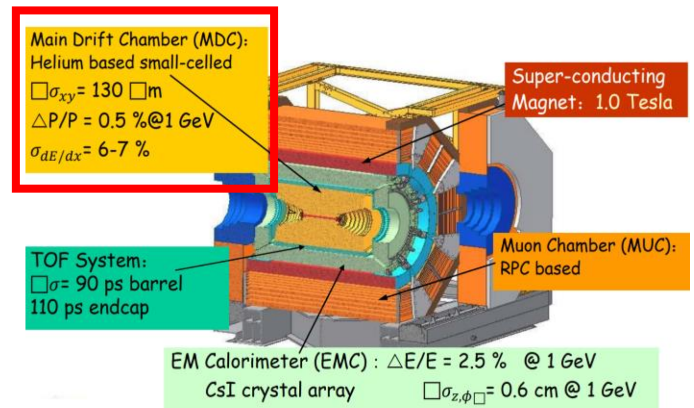
Outline

- **Tracker in BESIII : Multilayer Drift Chamber**
- **BESIII Offline track reconstruction**
  - **Track finding, track fitting**
  - **Tracking performance**
- **Tracking with CGEM**
- **GNN-based tracking in BESIII**

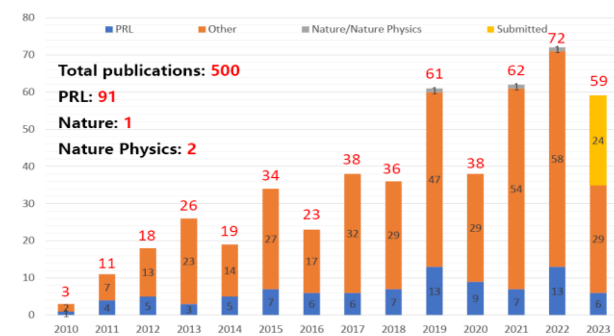
Beijing Spectrometer(BESIII) Experiment

- **BEPCII is a double-ring accelerator with a designed peak luminosity of 10^{33} $cm^{-2}s^{-1}$**
- **BESIII covers the areas including the charm physics, charmonium physics, tau physics, QCD studies and light hadron spectroscopy.**
- **Both the accelerator and the detector worked remarkably well, the world largest data samples of J/ψ have been collected.**
- **The Experiment can run for many more years**



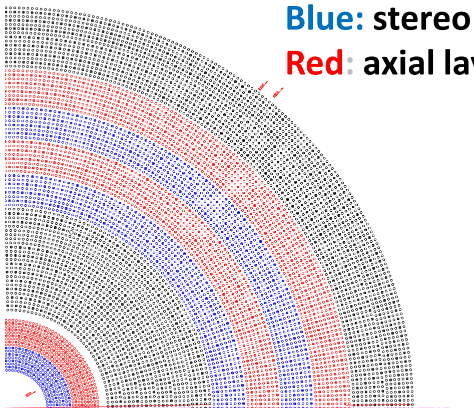


BESIII publications (May 9, 2023)



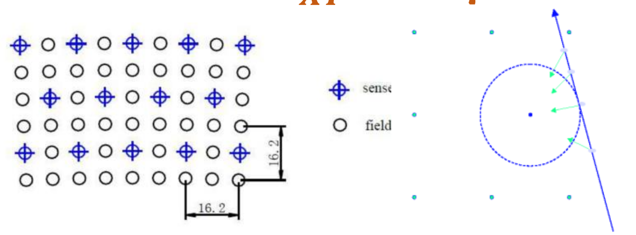
Tracker: Multilayer Drift Chamber (MDC)

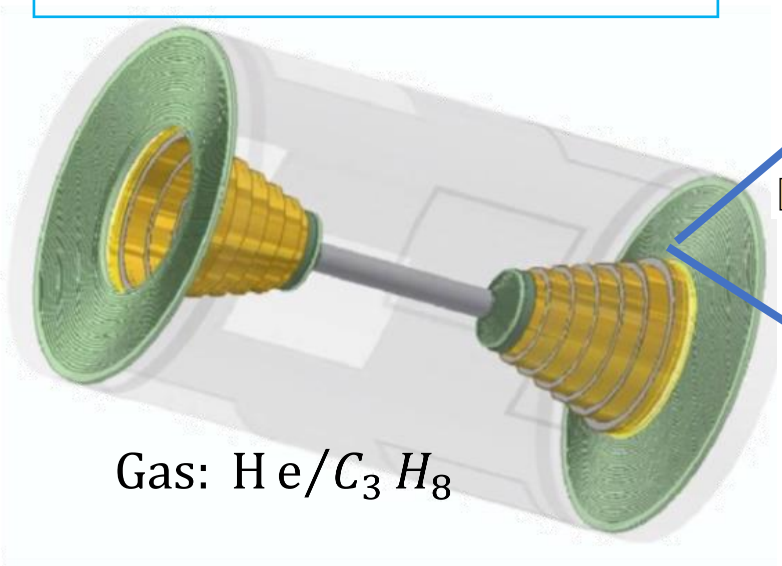
Geometry

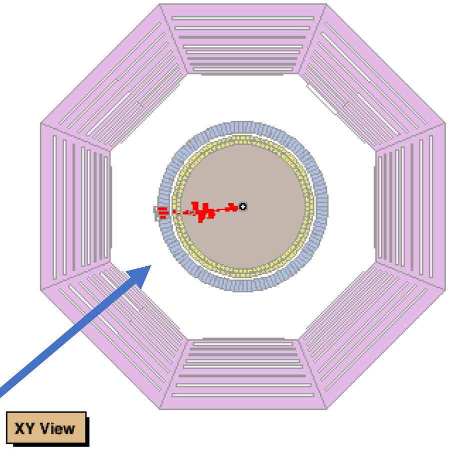


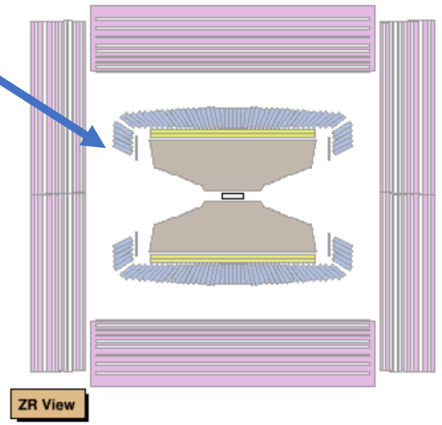
- 43 layers, Axial layer : 2D / Stereo layer : 3D
- 11 superlayers
- Inner Chamber : 8 stereo layers
- |cos θ |<0.93

Small cell $\sigma_{XY} \sim 130\mu m$









- ➢ High tracking efficiency, in a large momentum region
- ➢ Good momentum resolution: 0.5% @1GeV/c
- ➢ Good dE/dx resolution: 6~7%
- ➢ Working in 1T magnetic field

Tracking at BESIII

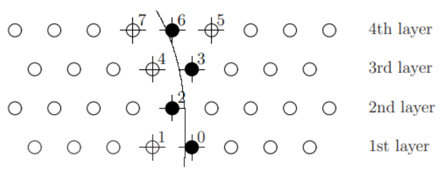
Considering MDC design, every track finding algorithm starts from 2D (x-y plane)

2D Track Finding

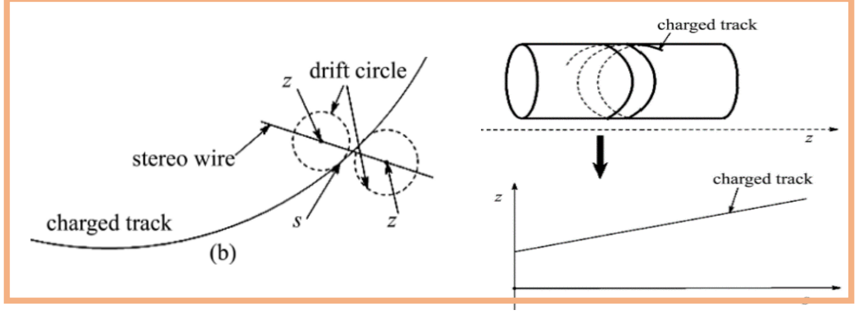
3D Track Finding

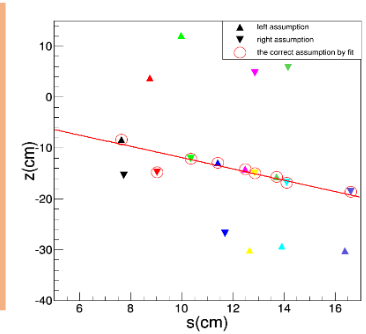
Pick up axial-wire hits ⇨ **2D track** ⇨ stereo-wire hits using 2D track ⇨ s-z fit with left/right ambiguity ⇨ **3D helix**

Local method in super layer



Global method : Hough Trans

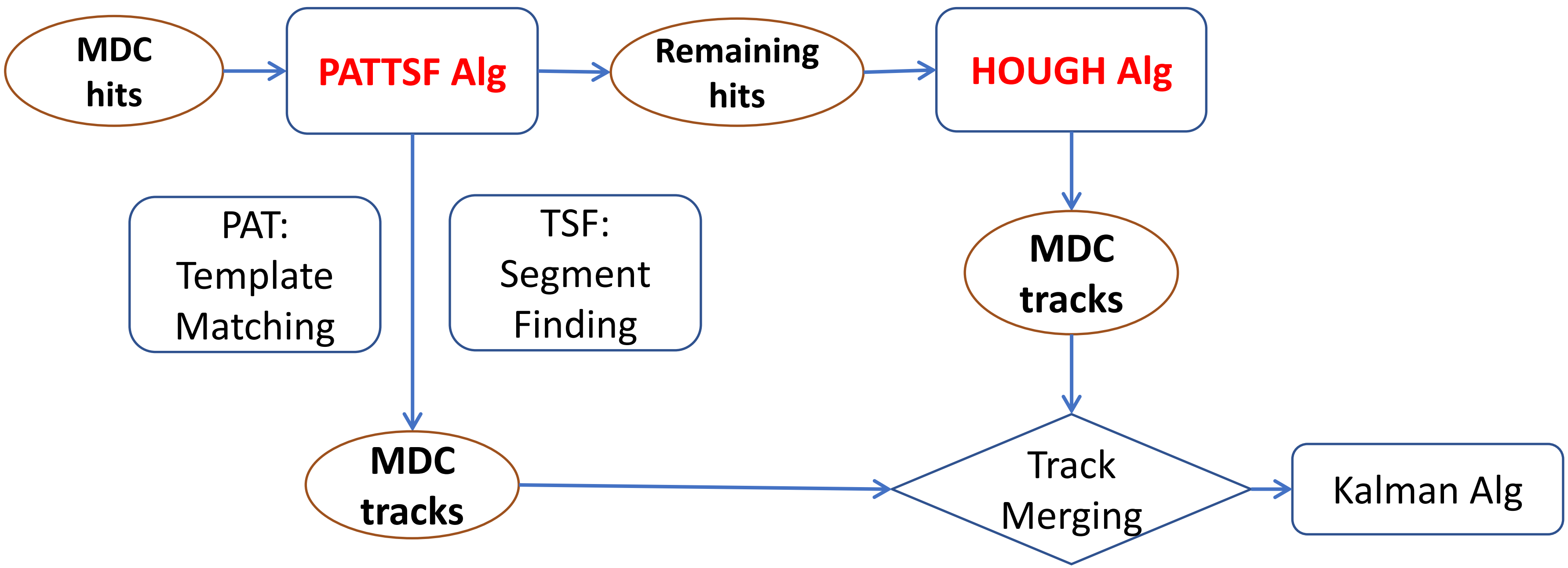




- **Local/Global approach in 2D Track Finding**
- **2D(circle) track parameters is key input for stereo-wire calculation and 3D tracking**

Offline Track Reconstruction

Baseline Track Reconstruction workflow at BESIII



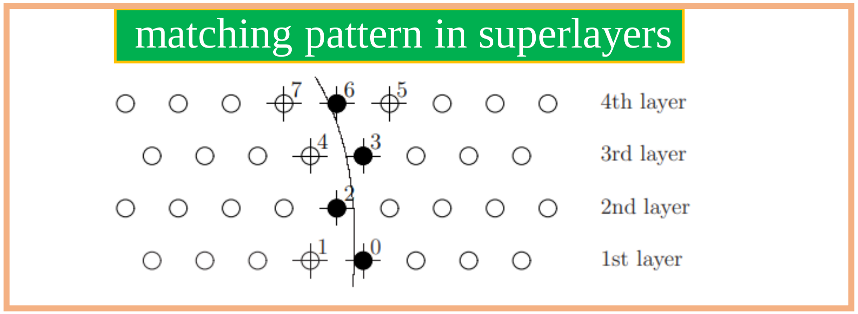
- Local approach PATTSF： search/match track segments in superlayers
- For low transverse momentum tracks with less hits/segments : HOUGH

- Hough transform also works as the baseline approach of CGEM-ODC software

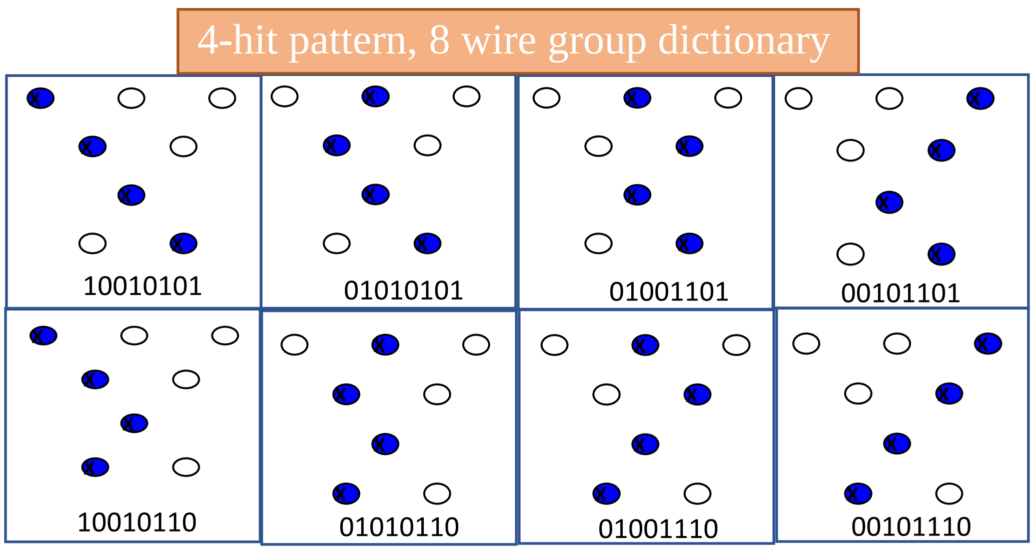
Local Approach I : Template Matching

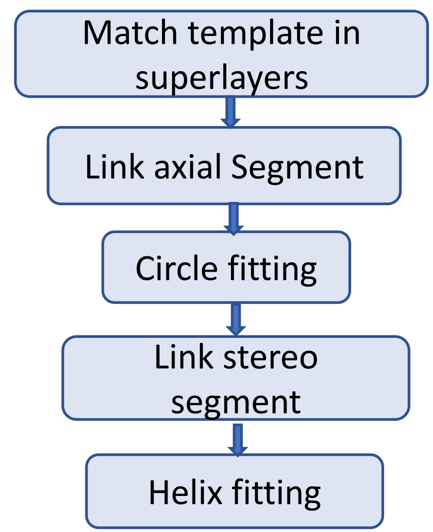
From Zhangyao

- **Particularly suitable for cell-based MDC geometry**
- **Division of chambers into cells provides a natural basis to define "template"**
- **Superlayer structure chamber && Symmetrical geometry along phi**



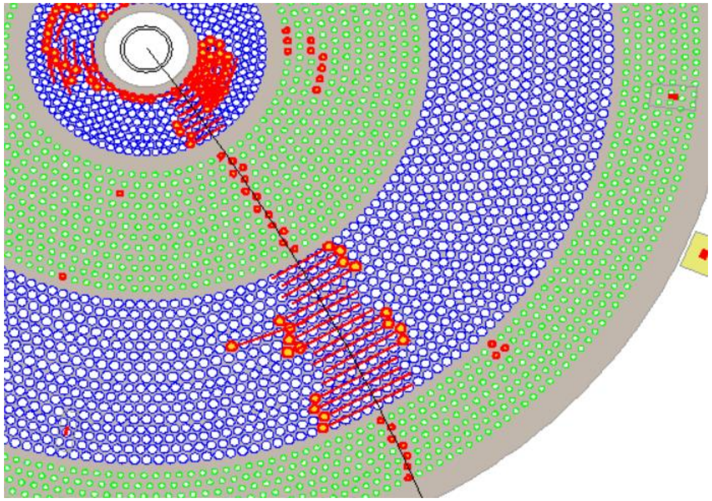
PAT Algorithm





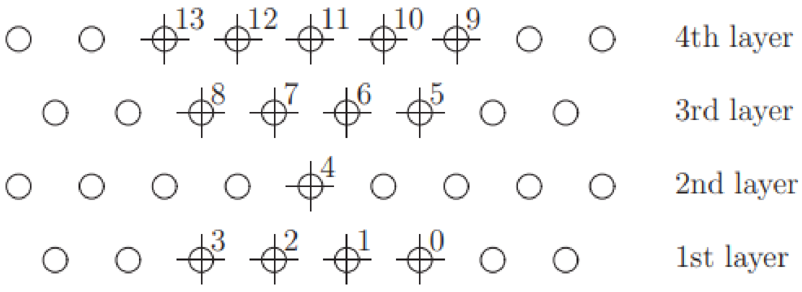
Extended Template Matching Approach

- **Advantageous for high transverse momentum(pt) tracks**



Straight : high efficiency for matching
Long : More track segments

- **Azimuth coverage angle of segment groups doesn't meet the requirements for curling track segment**
- **In BESIII an extending template with 14 wires is studied considering MDC geometry**

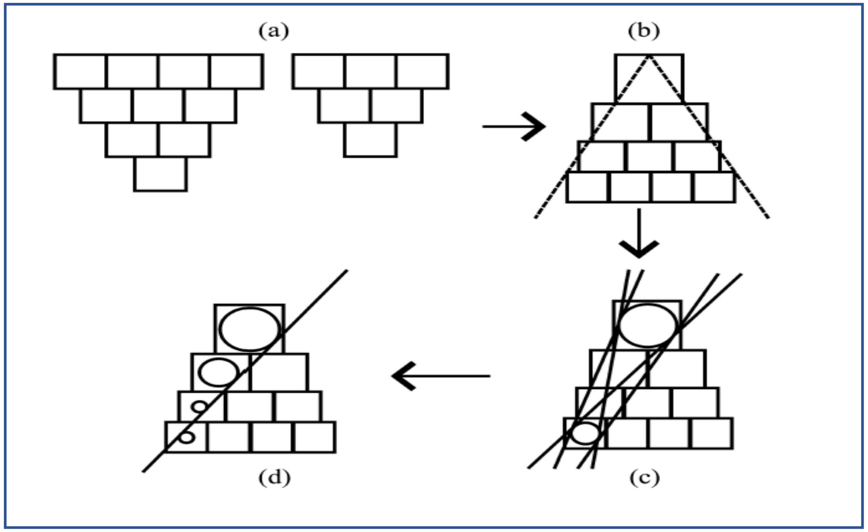


a 14-wire group

Local Approach II : Segment Finding

TSF Algorithm

- **Segment finding approach in superlayers, but for higher curvature tracks than PAT**
- **Using drift distance measurement**
  - **hit pattern in superlayer -> Common tangents of drift circles : using Conformal Transform**
  - **Key : searching for common tangents in superlayers**



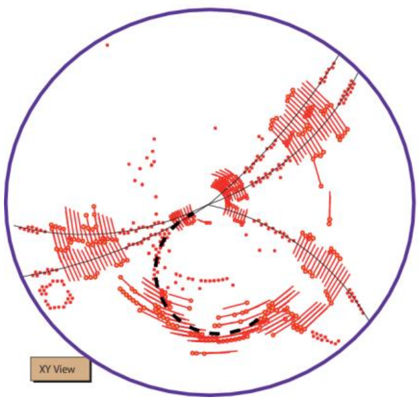
(a) Two original types of TSF
(b) Four-layer type pattern in the
(c) Conformal plane fitted out by the drift circles of the inner and outer hits
(d) Append other hits in this model

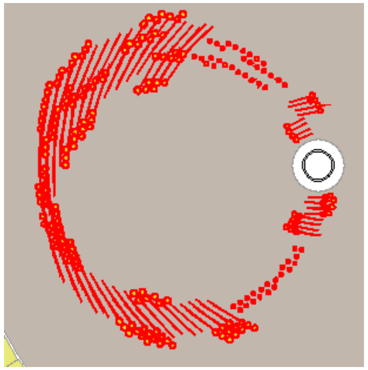
Low Transverse Momentum Track

➢ Geometrical trouble : pt < 120MeV/c

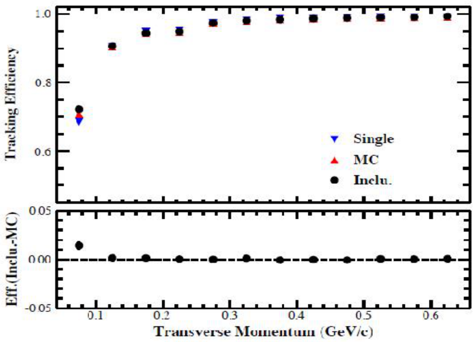
Low pT tracks bring difficulties for local Segment matching based algorithm

- Tracks with large pz : Short tracks with insufficient hits
- Tracks with small pz : curling in MDC, leaving multiturn tracks



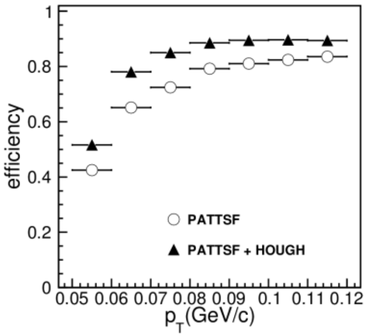


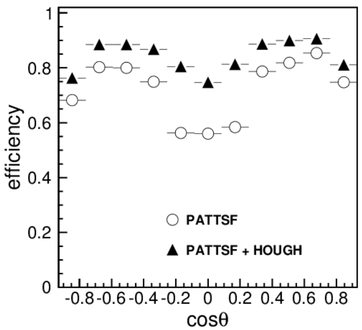
Track efficiency of π^- vs P_T



➢ Hough transform

- Global method not influenced by segment on superlayers
- Using hits effectively for low pT tracks
- Available to be a combination of CGEM and OUTER Drift-Chamber

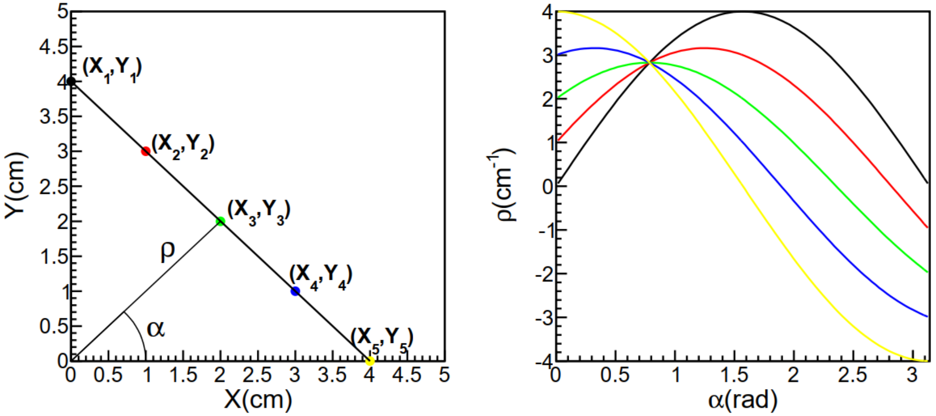




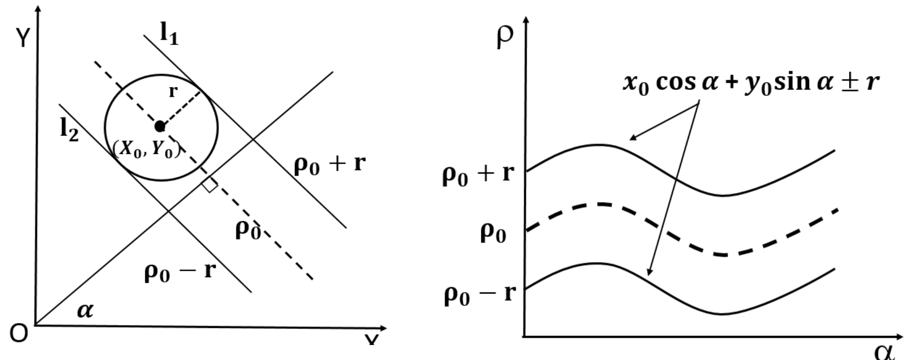
Hough Transform / Legendre Transform

Hough transform

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



Hough/Legendre transform in MDC

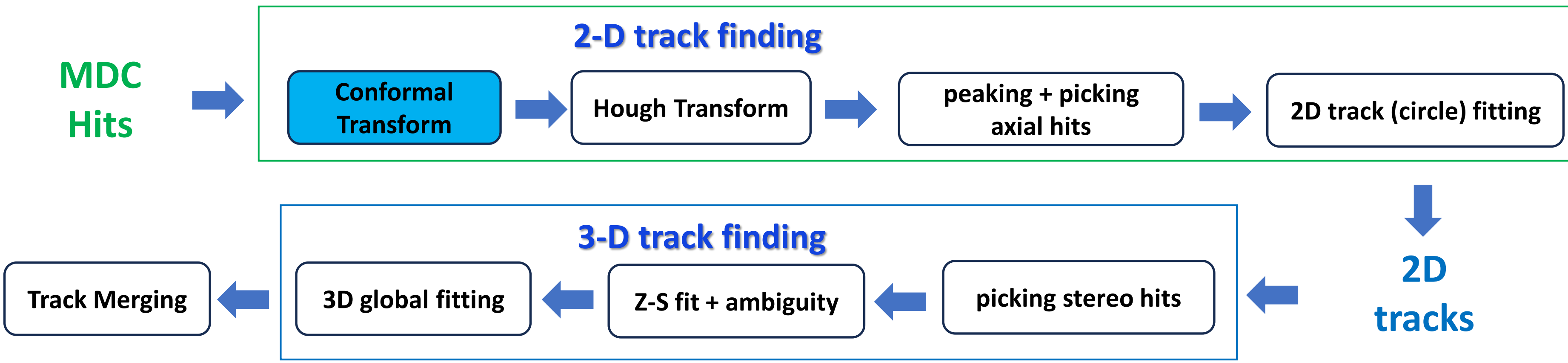


$$\rho = X\cos\alpha + Y\sin\alpha + r, (upper\ half\ circle)$$

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

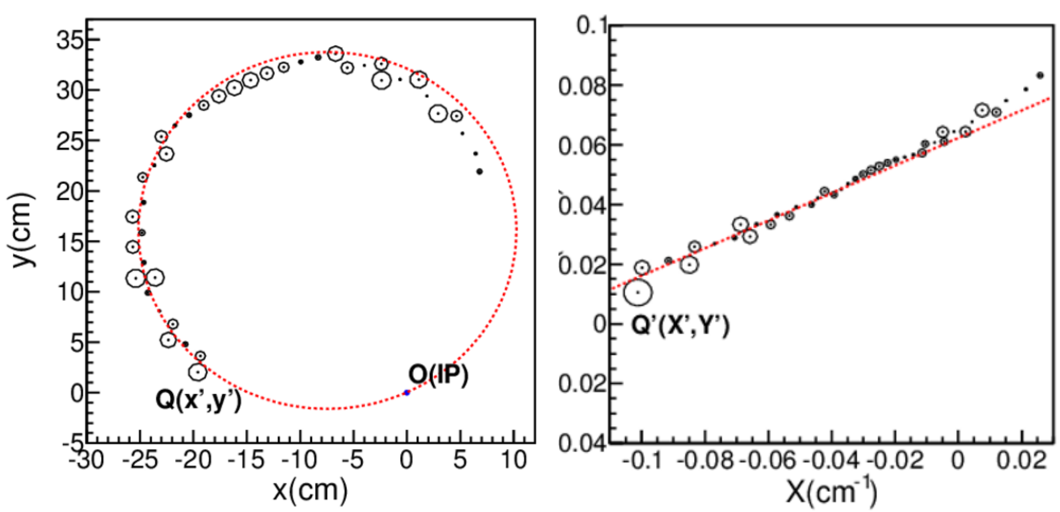
One drift circle->two curve lines on Hough space

Global Approach : Hough Transform in BESIII

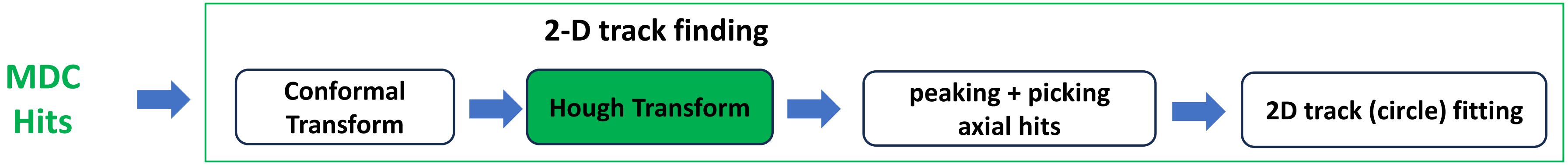


I. Conformal transform

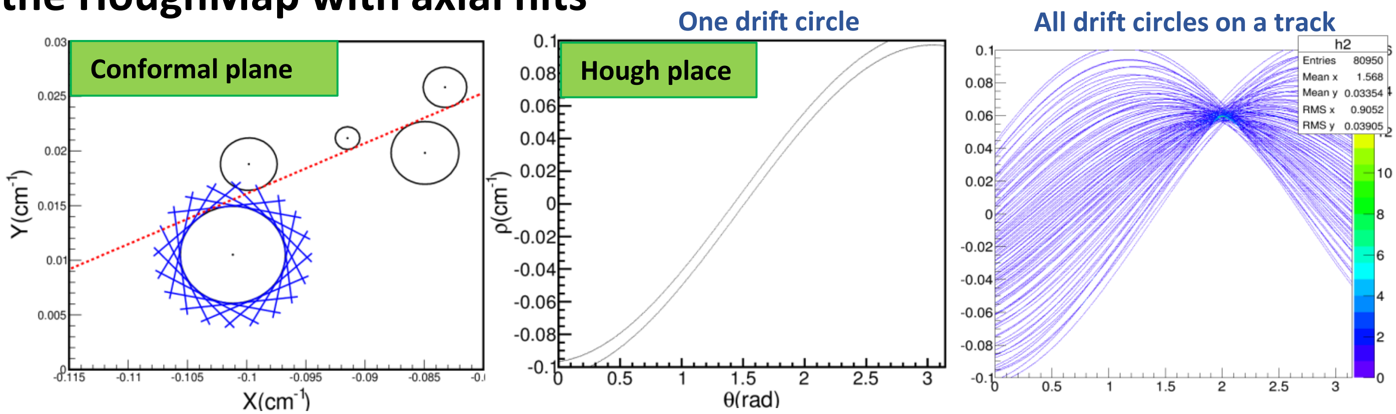
- (Track) Circles passing the origin point transform into straight lines
- (Drift) Circles not passing the origin point transform into new circles



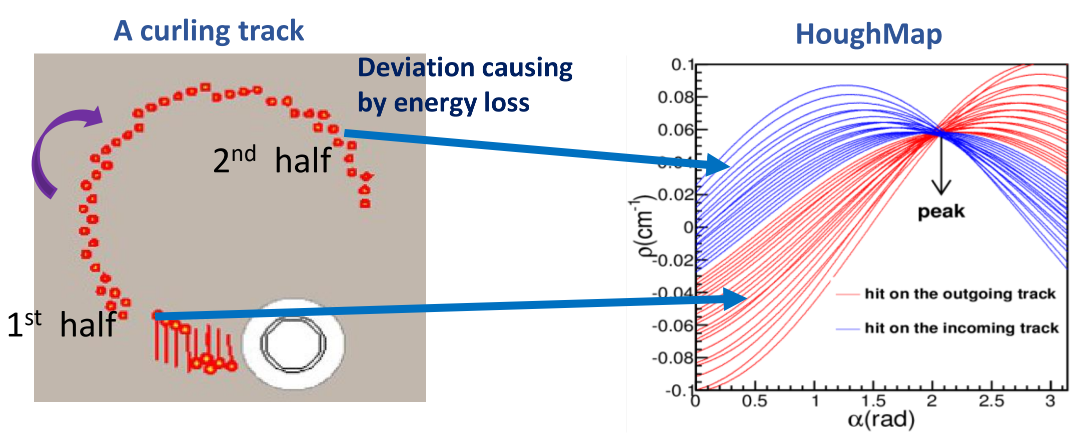
Global Approach : Hough Transform in BESIII



II. Filling the HoughMap with axial hits



- **Split the map into 2 different clockwise using slope of the curves**
- **2^{nd} half hits occurs large deviations ; treat high pt head-to-head tracks**



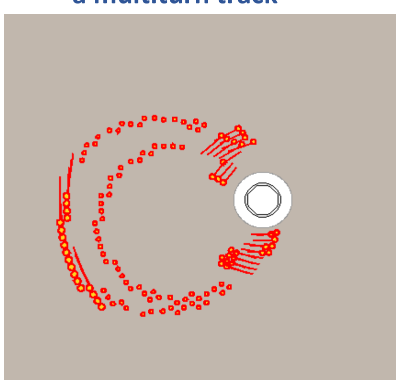
Global Approach : Hough Transform in BESIII

MDC Hits → **2-D track finding**: Conformal Transform → Hough Transform → peaking + picking axial hits → 2D track (circle) fitting

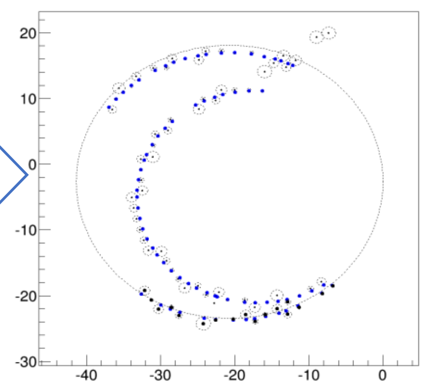
III. Applying Peaking approach and picking axial hits with using distanceTotrack

- **2D track parameters are retrieved from peak finding method**
- **Axial hits then picking up with its distance**
- **Multi-turn tracks can be partially separated**

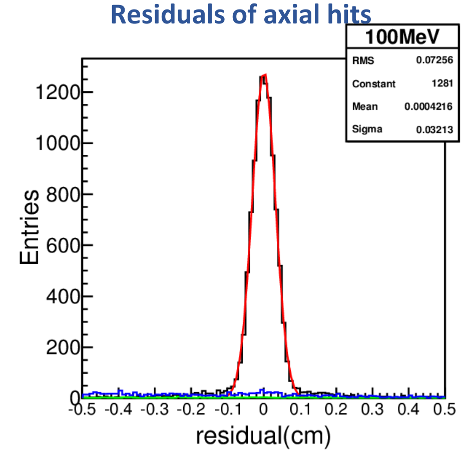
a multiturn track



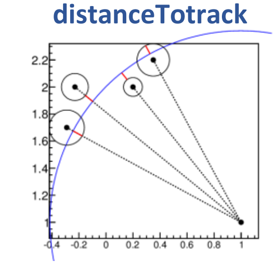
candidate 2D tracks by peaking method



Residuals of axial hits



distanceTotrack

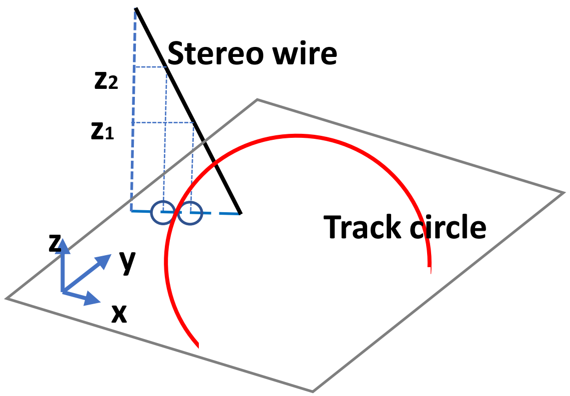


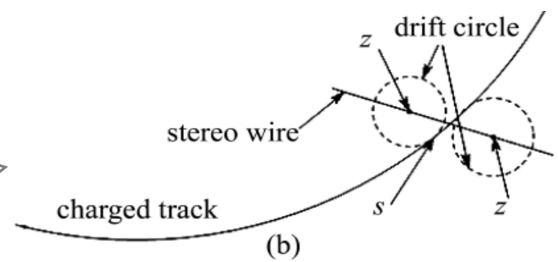
Global Approach : Hough Transform in BESIII

3-D track finding

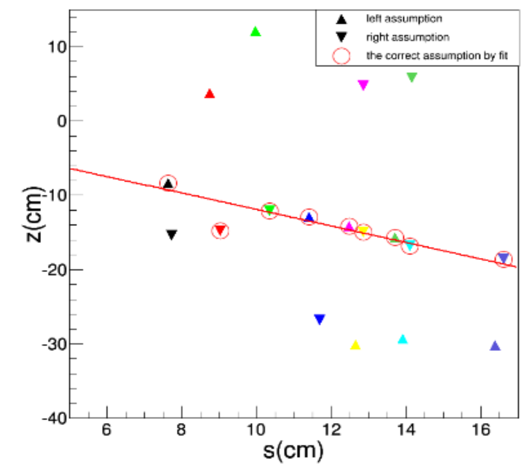
Track Merging ⇐ 3D global fitting ⇐ Z-S fit + ambiguity ⇐ picking stereo hits ⇐ 2D tracks

- When 2D Hough tracking is done, do 2D circle fitting to get track on x-y space





s: flight length in x-y place
z: hit position on wire



- 3D tracking to pick stereo hits and get initial 3D parameters
- Left/right ambiguity is considered

- A global fitting is performed to retrieve the parameters of helix track

Track Fitting in BESIII

From Wang Liangliang

- **During Track finding, Least Square Method is performed to an ideal circle/Helix**

$$\tilde{\mathbf{p}} = \overset{0}{\mathbf{p}} + (\mathbf{A}^{T}\mathbf{W}\mathbf{A})^{-1}\mathbf{A}^{T}\mathbf{W}\cdot(\mathbf{m} - \mathbf{f}(\overset{0}{\mathbf{p}}))$$

- $\tilde{\mathbf{p}}$: Track parameters after an iteration
- $\overset{0}{\mathbf{p}}$: Track parameters
- $\mathbf{A}$: $\partial\mathbf{f}(\mathbf{p})/\partial\mathbf{p}$ at $\mathbf{p} = \overset{0}{\mathbf{p}}$
- $\mathbf{W}$: Weighting matrix (inverse of error matrix)
- $\mathbf{m}$: Measurements vector
- $\mathbf{f}$: Measurement function

  - **Track parameters converged with iterations**
  - **Track candidate selection, Hits selection with chi^2**
  - **Provide initial track parameters**

- **Kalman filter is performed following track finding, considering inhomogeneous magnetic field, energy loss and uncertainty from multiple scattering**

$$\mathbf{p}_{k|k} = \mathbf{p}_{k|k-1} + \mathbf{K}_k(\mathbf{m}_k - \mathbf{H}_k\mathbf{p}_{k|k-1})$$

- $\mathbf{p}_{k|k}$: Filtered track parameters at measurement k
- $\mathbf{p}_{k|k-1}$: Predicted track parameters from k-1 measurements
- $\mathbf{K}_k$: Gain matrix
- $\mathbf{m}_k$: the k-th measurement
- $\mathbf{H}_k$: Derivative matrix

Track are fitted with 5 particle hypothesis

Tracking Performance

From Liufang

Four Datasets: 10Billion J/psi events (2009+2012+2018+2019)

By applying Event Selection for pion sample from $J/\psi \to \pi^+\pi^-\pi^0$

- **Definition of the tracking efficiency**

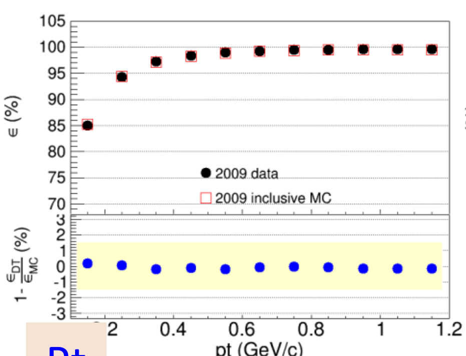
$$\varepsilon = \frac{N}{N'}$$

N: No. events with two good charged tracks and net zero charge

N′: SUM of No. events with one good charge track and
No. events with two good charged tracks and net zero charge

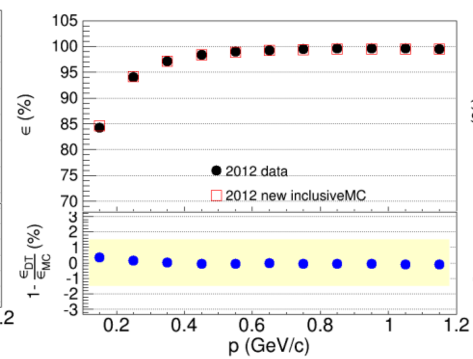
Error for the tracking efficiency: $\delta = \mathrm{sqrt}[\varepsilon(1-\varepsilon)/N']$

2009 dataset

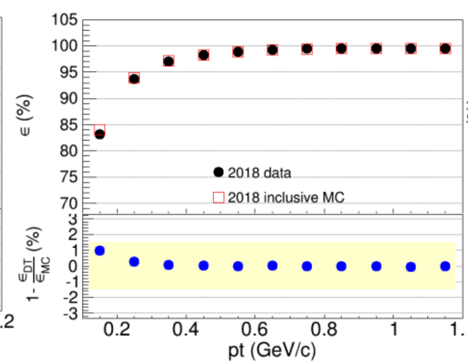


Pt

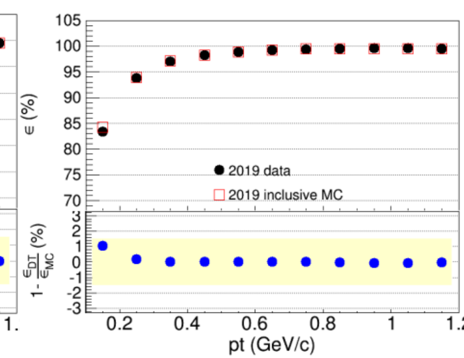
2012 dataset



2018 dataset



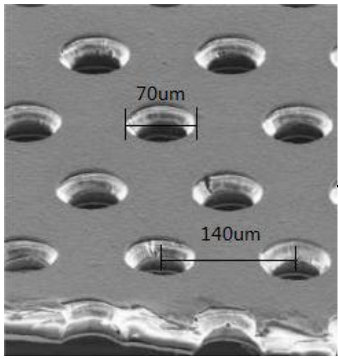
2019 dataset



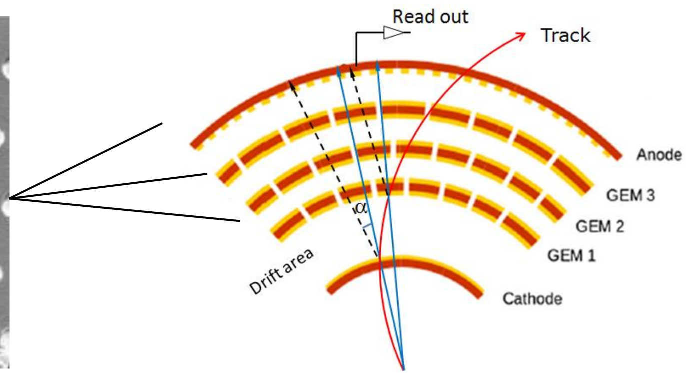
Tracking With New Inner Tracker : CGEM

CGEM (Cylindrical Gas Electron Multiplier)

From Wang Liangliang

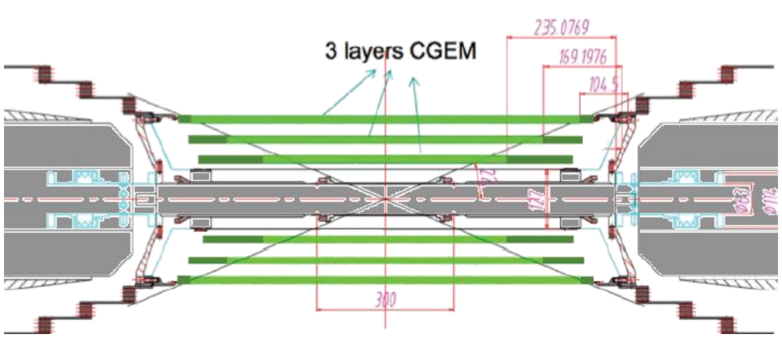


GEM

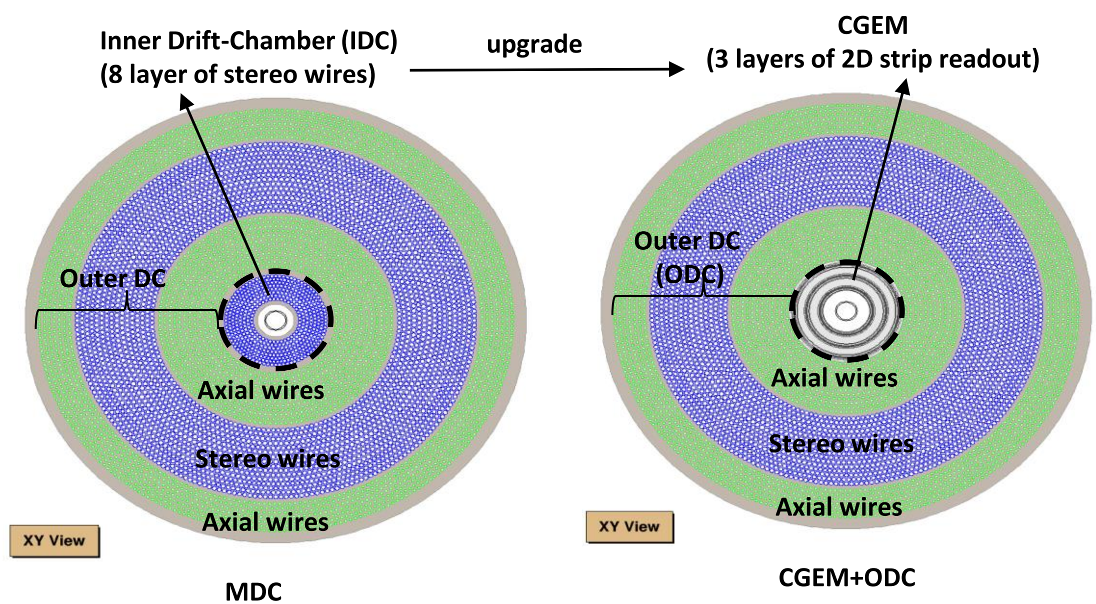


GEM detector

- Anode and cathode and 3 layers of GEM foil
- X&V reader

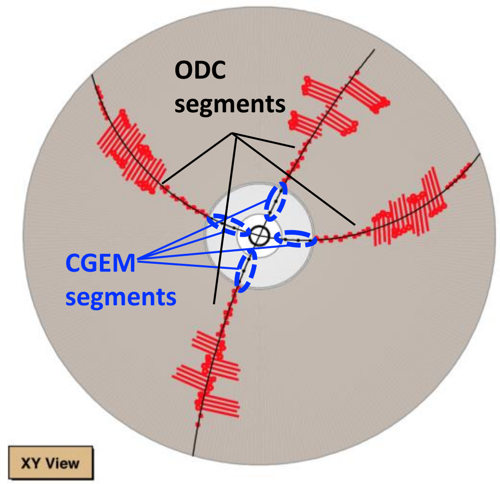


- 3 layers of cylinder GEM detector
- replace MDC inner chamber



Tracking With New Inner Tracker : CGEM

From Wang Liangliang



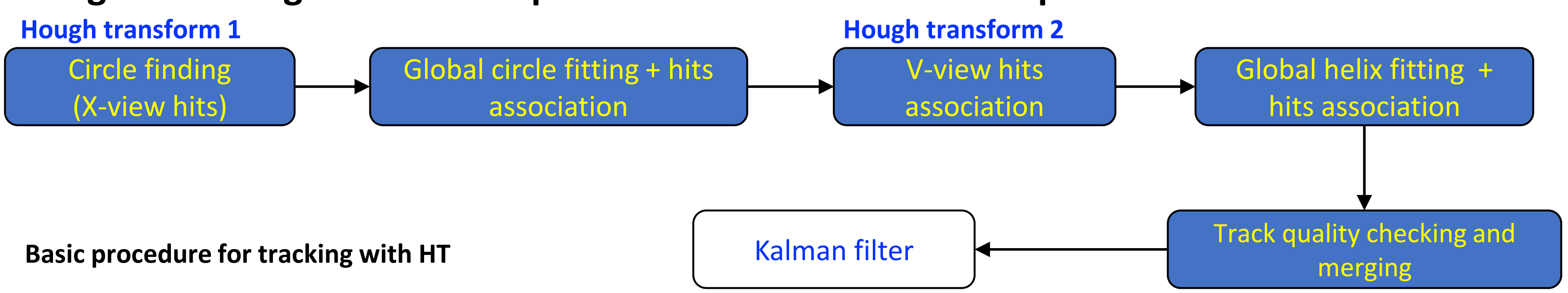
$\psi(3686) \rightarrow \pi^+\pi^- J/\psi \rightarrow \pi^+\pi^- e^+e^-$

Two tasks

- Track finding
  - ✓ Global method
- Track fitting
  - ✓ Least-Square Method (LSM) with helix model
  - ✓ Kalman Filter (KF)

Global track finding with Hough Transform

- The procedure includes two key steps:
  - ① Circle finding
  - ② V-view hits association
- Both steps use Hough transform to get track candidates and initial track parameters
- A global fitting with Least-Square method is after each step



Basic procedure for tracking with HT

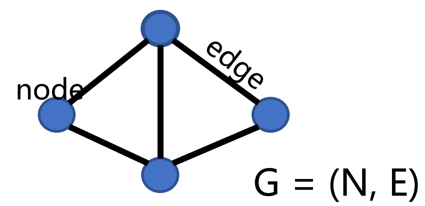
All parts of CGEM software have implementations, now in tuning/optimization/improving

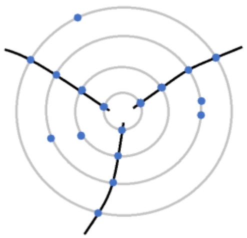
GNN based tracking

From Qin Xiaoshuai

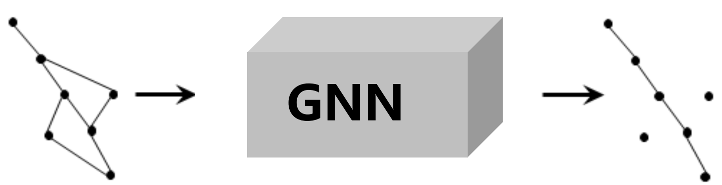
Graph Neural Network

- **A type of neural network that are specifically designed to operate on graph-structured data**
- **Graph: nodes, edges**
- **Graph → Track**
  - **Nodes → Hits**
  - **edges → track segments**



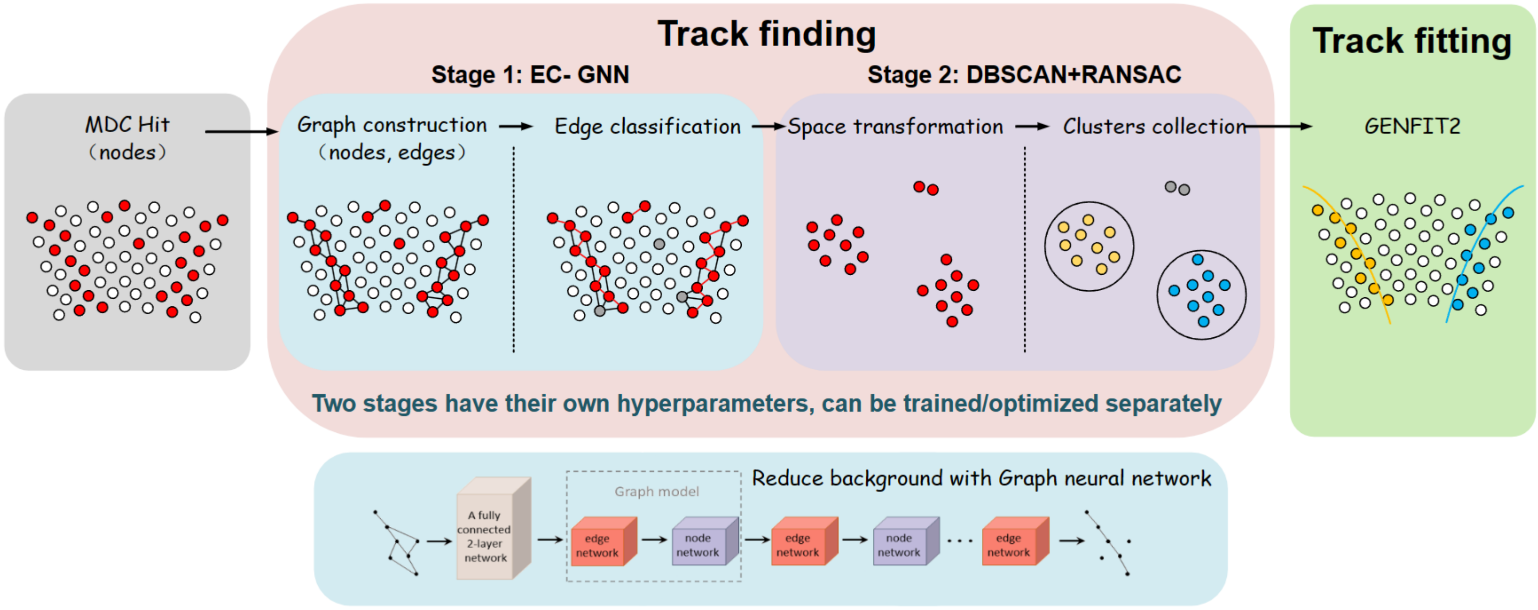


- **GNN key idea: propagate information across the graph using a set of learnable functions that operate on node and edge features**
- **Edge classification - GNN**
  - **High classification score**
    - → ***the edge belongs to a true particle track***
  - **Low classification score**
    - → ***it is a spurious or noise edge***

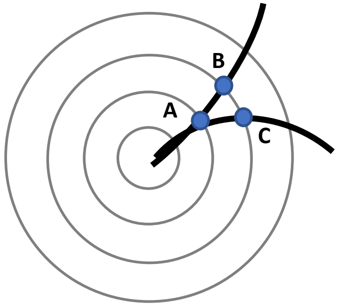


GNN based tracking

From Qin Xiaoshuai



Graph construction



To reduce the number of fake edges during graph construction

Pattern Map based on MC simulation

- **Edge assignment based on Pattern Map**
  - Hit and its neighbors on the same layer and next layer
  - Hit and its neighbors' neighbors on one layer apart

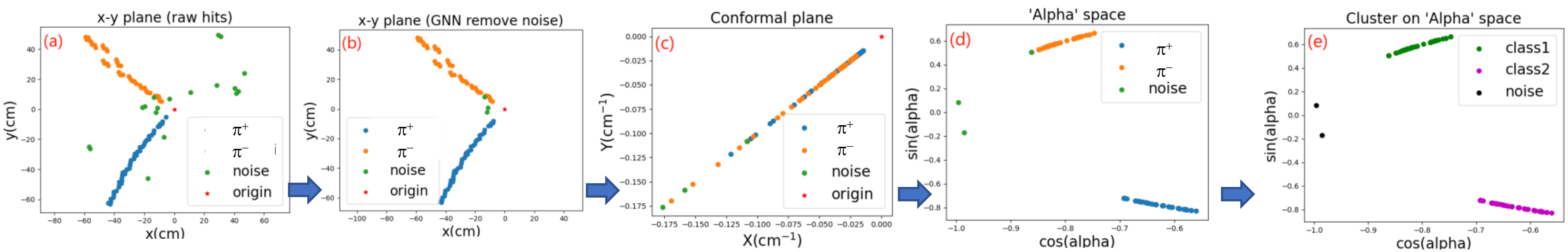
Graph representation

- Node features (raw drift time, position coordinates r, ϕ of the sense wires)
- edge labels for training data

GNN based tracking

From Qin Xiaoshuai

Clustering of Tracks Based on DBSCAN+RANSAC



a) Original MC data sample: J/Ψ → $\rho^0 \pi^0$ → γ γ $\pi^+ \pi^-$

b) Remove noise via GNN

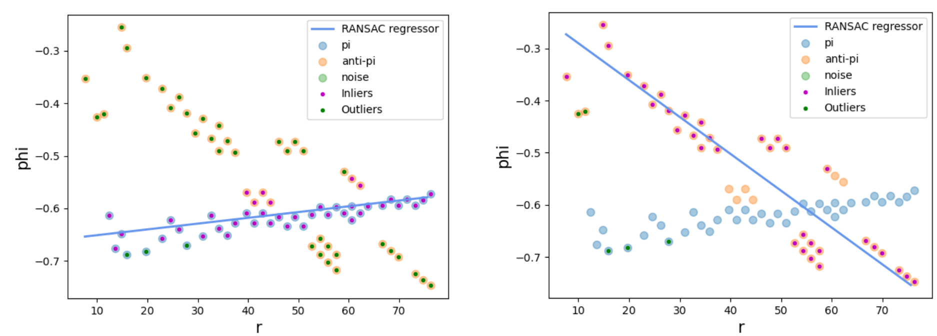
c) Transform to Conformal plane

- $X = \frac{2x}{x^2+y^2}$ $Y = \frac{2y}{X^2+y^2}$
- Circle passing the origin transform into a straight line

d) Transform to 'α' parameter plane

- α as the angle between the straight line and X axis
- The parameter space as cosα and sinα

e) **DBSCAN** clustering in 'α'parameter plane



RANSAC to improve separation of hits from crossing tracks:

- Divide hits where too many hits belong to one cluster
- Threshold and parameterization need further optimization.

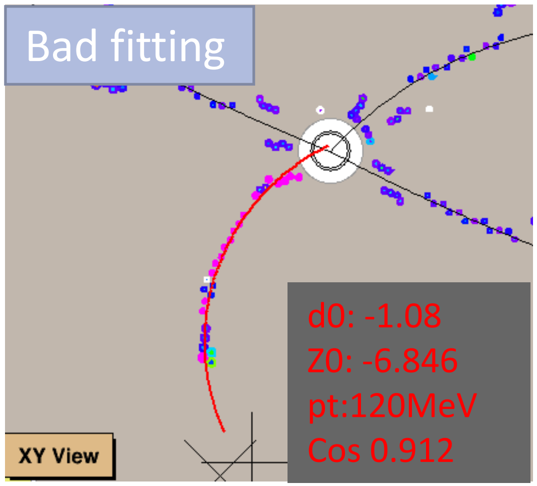
Summary

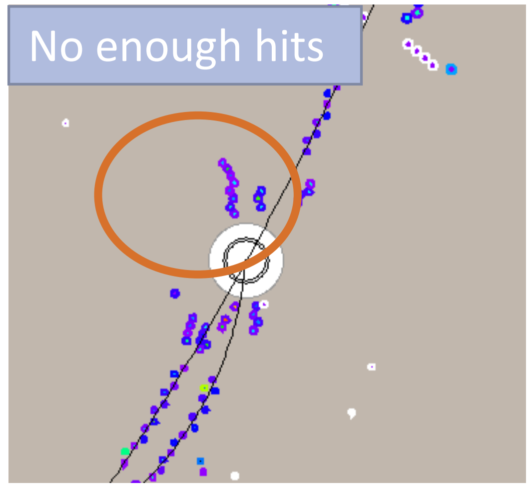
- BESIII Track reconstruction software have been validated with the collision data taken over years, reliable and high performant
- In the past decades, many methods has been tested and validated, some has been used in offline data reconstruction process
- BESIII experiment provides a good platform for the research of new strategies, some modern methods are being studied in BESIII

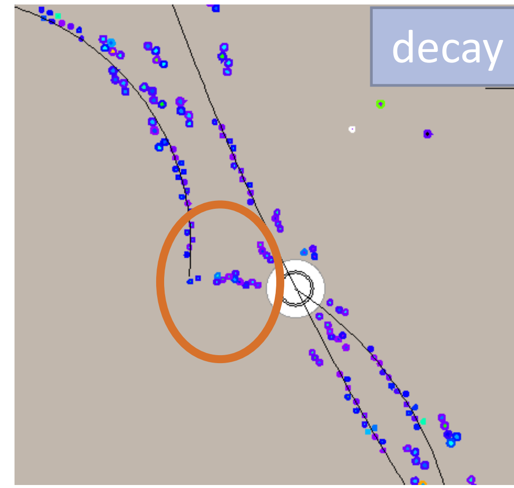
Thank you!

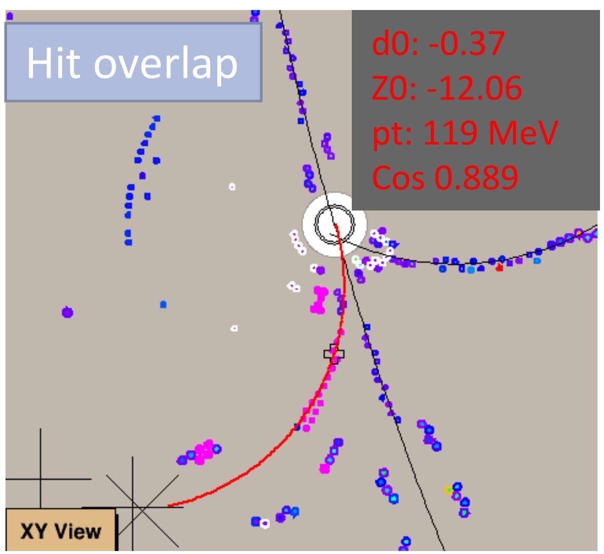
Backup

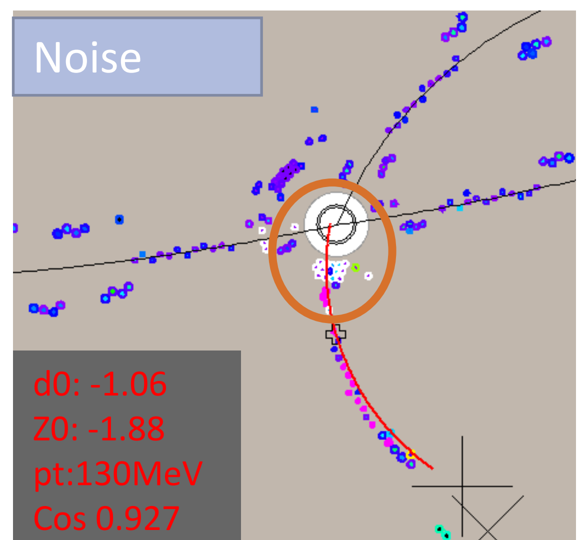
Failed reason at Large dip angle











Event Selection for pion sample from $J/\psi \rightarrow \pi^+\pi^-\pi^0$

Initial event selection:

- One or two good charged tracks with net zero charge.
- At least two good photons

Final event selection:

For π^0 signal,

- $N\gamma=2$;
- $0.110GeV<M(\gamma\gamma)<0.15GeV$&& $|\cos\theta\,\gamma\gamma| < 0.95$

For the first good charged track:

- identified as pion
- $M_{miss}(K\gamma\gamma)<0.35GeV$ (assuming that the first good charged track is kaon);
- $E/P<0.8$;
- N(hit-layer-muon)<3;

✓ π+ tracking efficiency is done by count through the decay mode $\rho+\pi-$, $\rho0\pi0$ and phase space $\pi^+\pi^-\pi^0$ with $M(\pi^-\pi^0)>1.0GeV$ (delete $\rho-\pi+$ events)

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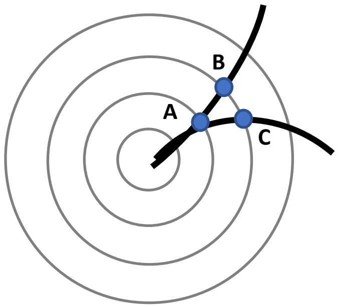
Graph construction



To reduce the number of fake edges during graph construction

Pattern Map based on MC simulation

- Definition of valid neighbors
  - Hits on the same layer
    Two adjacent sense wires on the left and right
  - Hits on the next layer
    The collection of sense wires that could potentially represent two successive hits on a track
  - Probability requirement estimated from single particle MC: $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$
- Edge assignment based on Pattern Map
  - Hit and its neighbors on the same layer and next layer
  - Hit and its neighbors' neighbors on one layer apart

Graph representation

- Node features (raw drift time, position coordinates **r, ϕ** of the sense wires)
- edge labels for training data

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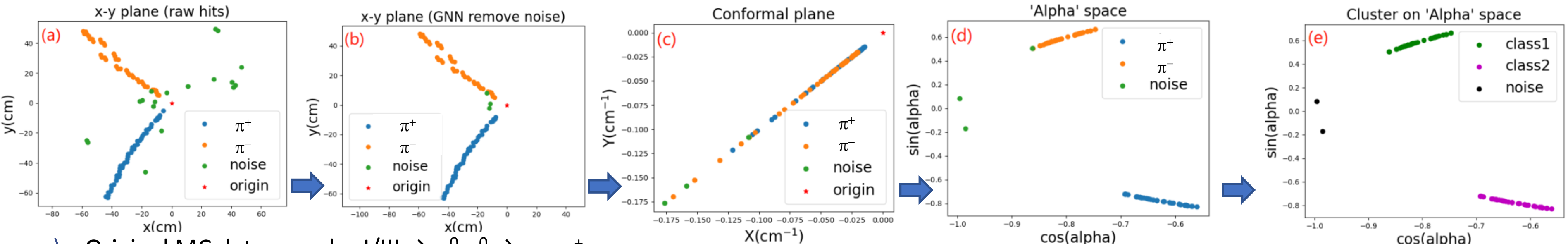

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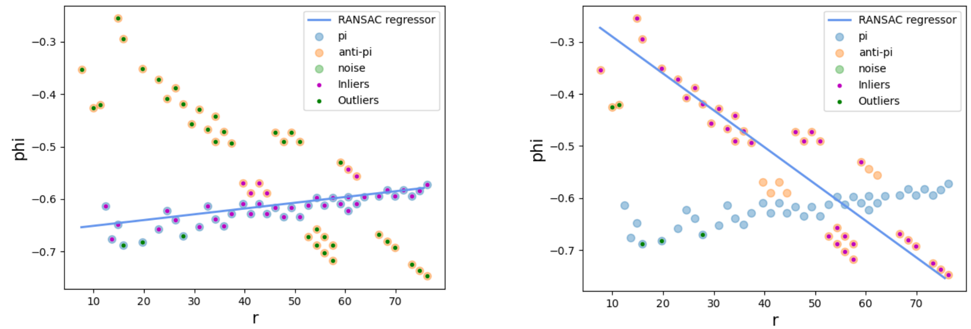

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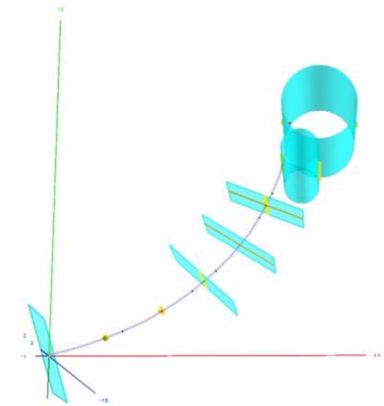
Track fitting (GNN part)

- Based on **GenFit2** (a Generic Track-Fitting Toolkit)
  - PANDA, Belle II, Fopi, GEM-TPC experiments

  - Kalman filter with reference track (need initial parameters)
  - Deterministic annealing fitter (**DAF**)， **left-right ambiguities**
  - Generalized broken line (GBL)



  - Drift chamber: **DAF**
  - What we need:
    - End points positions of sense wire, particle assumption, initial value of track momentum and position
  - Geometry: **TGeoManager**
  - **Fitting procedure:**
  - Start 1st try: drift distance roughly estimated from TDC、 ADC of sense wires.
  - Iteration to update information of drift distance, left-right assignment, hit position on z direction and entrancing angle in the cell et al.