Track Reconstruction at BESIII

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for BESIII offline software group

17th May, 2024

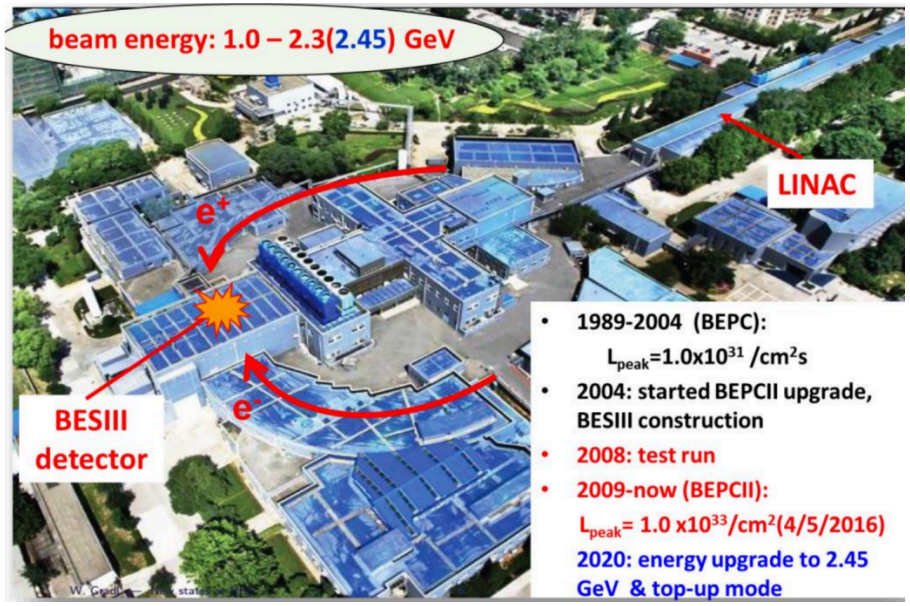
Outline

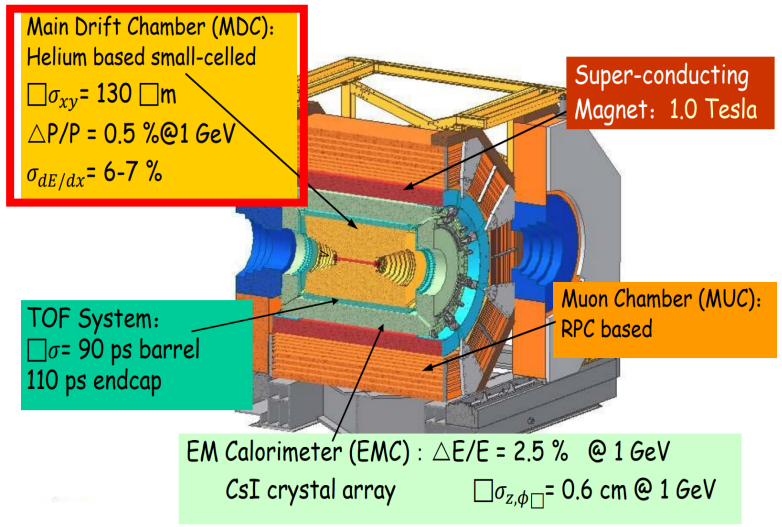
- **Tracker in BESIII : Multilayer Drift Chamber (MDC)**
- **BESIII Offline track reconstruction**
  - **Track finding, track fitting**
  - **Tracking performance**
- **Tracking with CGEM-IT and Outer DC**

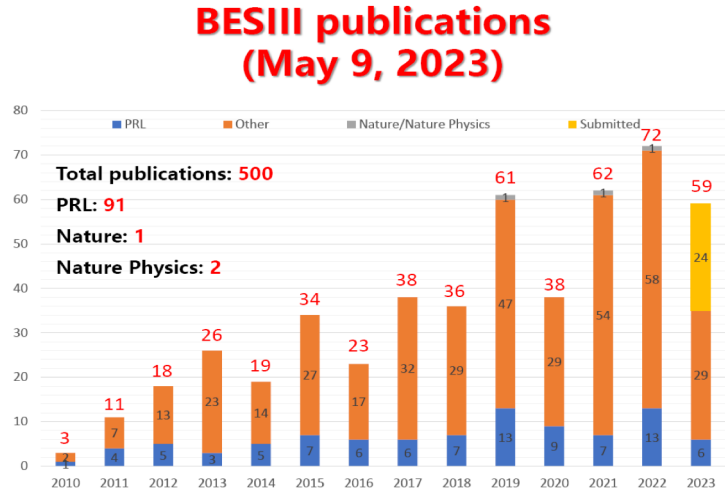
Many slides from colleagues, Jin Zhang, Yao Zhang ...

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

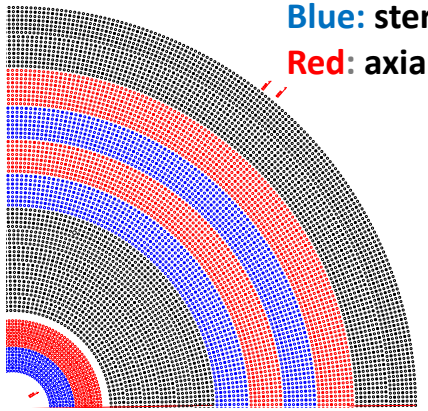




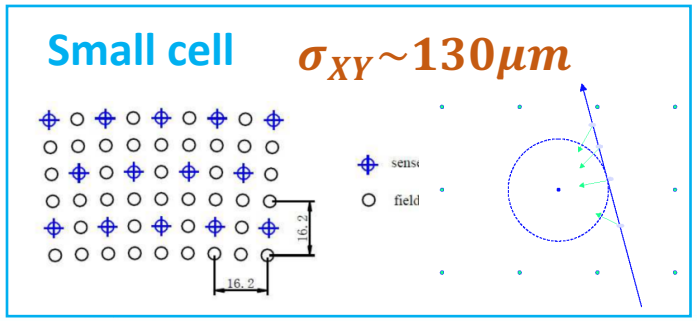


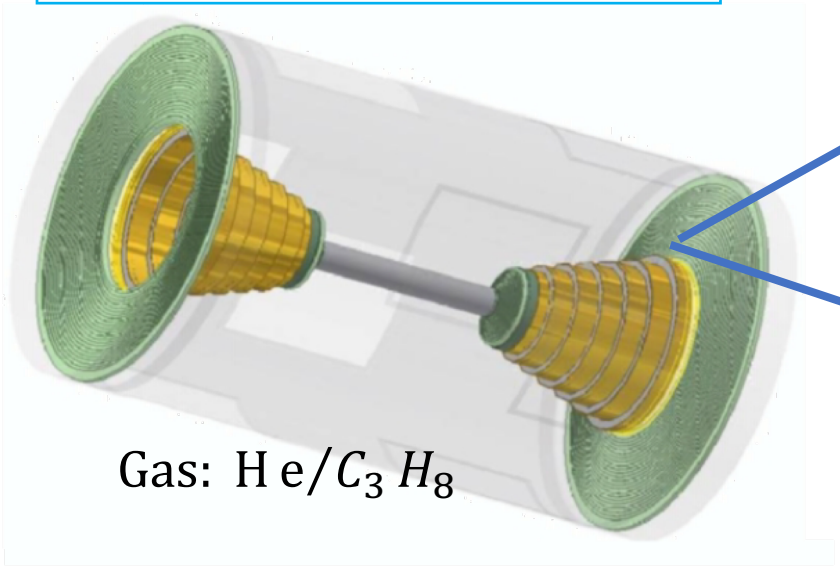
Tracker: Multilayer Drift Chamber (MDC)

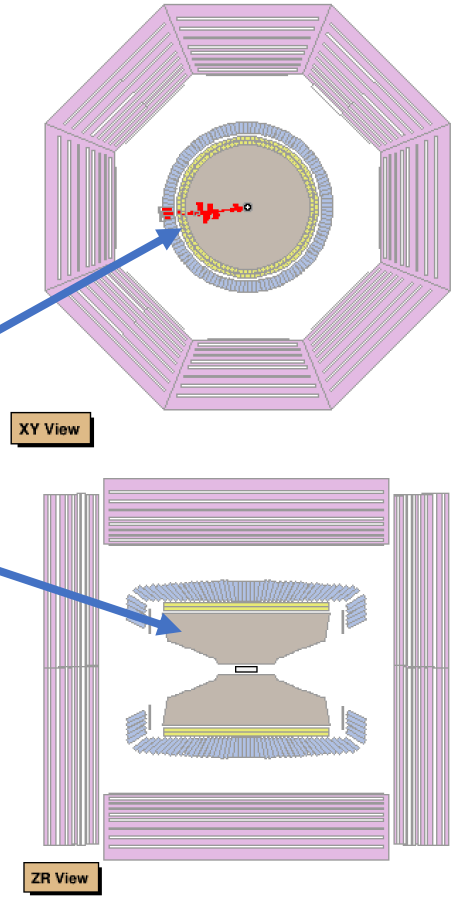
Geometry



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







- 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

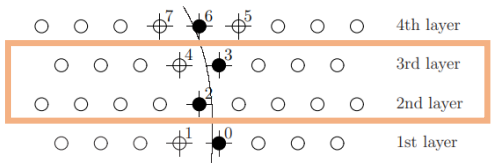
overview

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

2D Track Finding

Pick up axial-wire hits → **2D track**

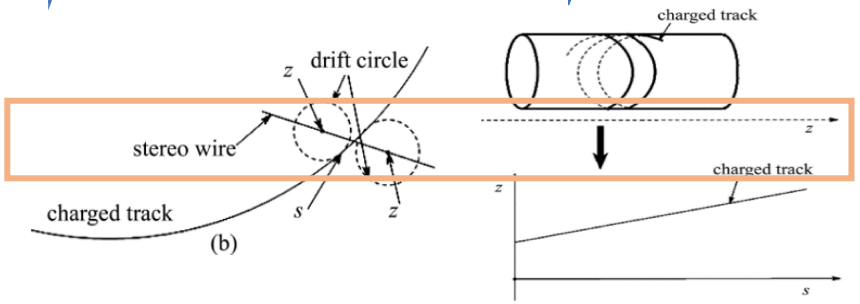
Local method in super layer

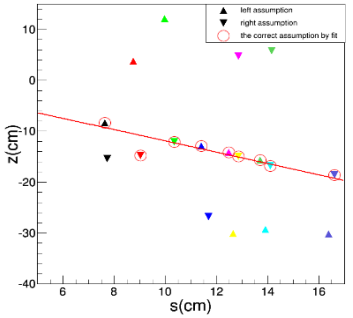


Global method : Hough Trans

3D Track Finding

stereo-wire hits using 2D track → s-z fit with left/right ambiguity → **3D helix**

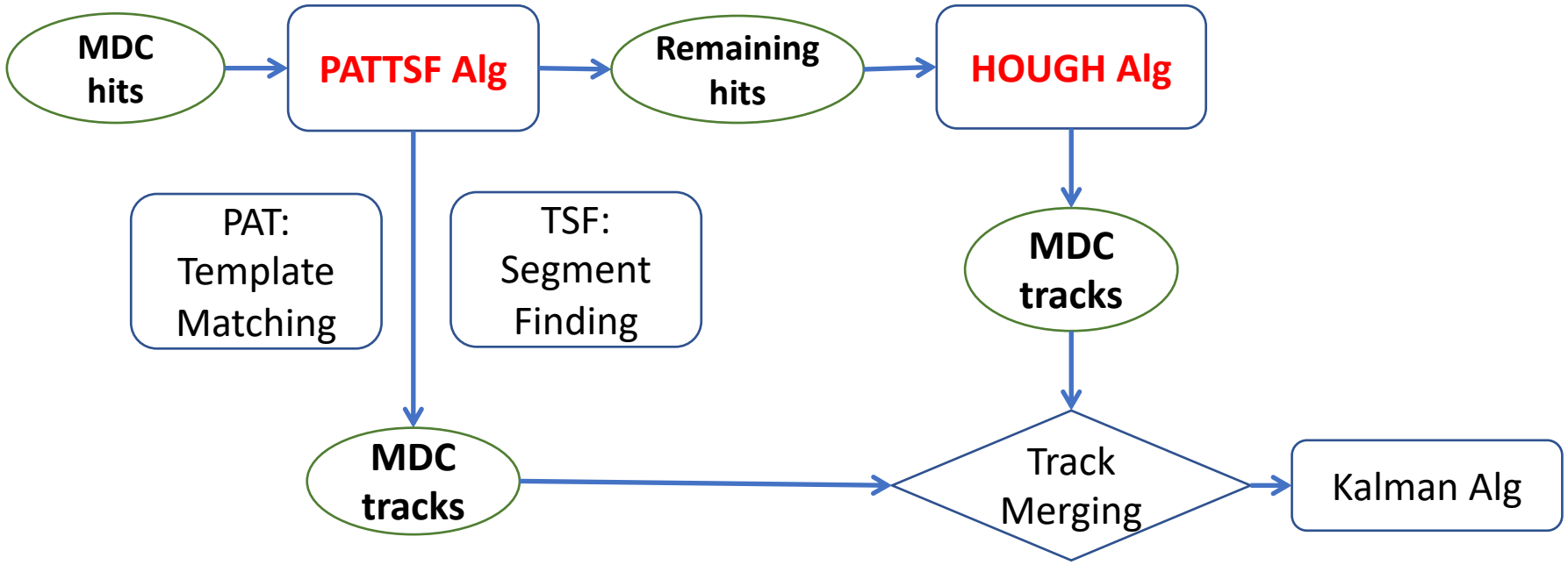




- **Local/Global approach in 2D Track Finding**
- **2D(circle) track parameters is key input for stereo-wire calculation and 3D tracking**

Offline Track Reconstruction

Baseline Track Reconstruction workflow at BESIII

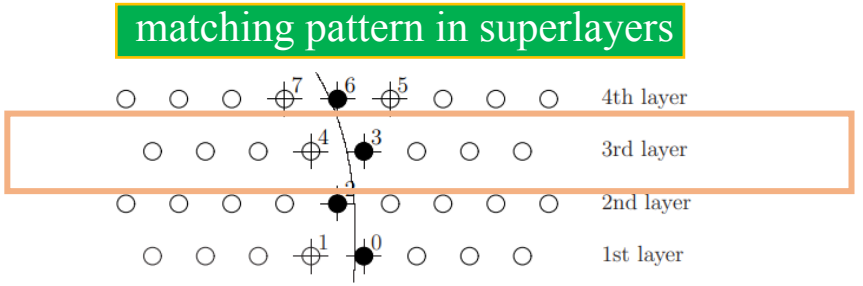


- **Local approach PATTSF : search/match track segments in superlayers**
- **For low transverse momentum tracks with less hits/segments : HOUGH**
- **Hough transform also works as the baseline approach of CGEM-ODC software**

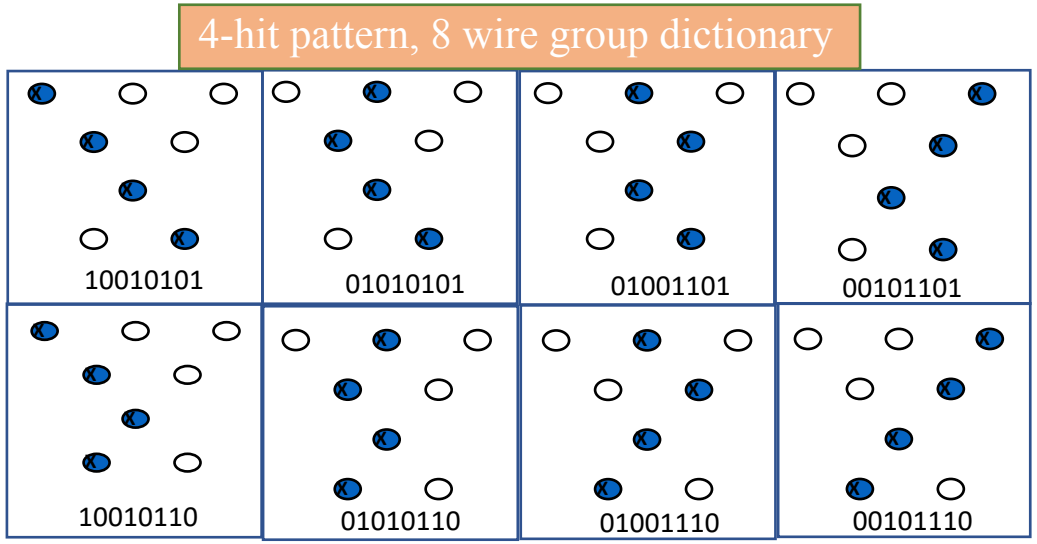
Local Approach I : Template Matching

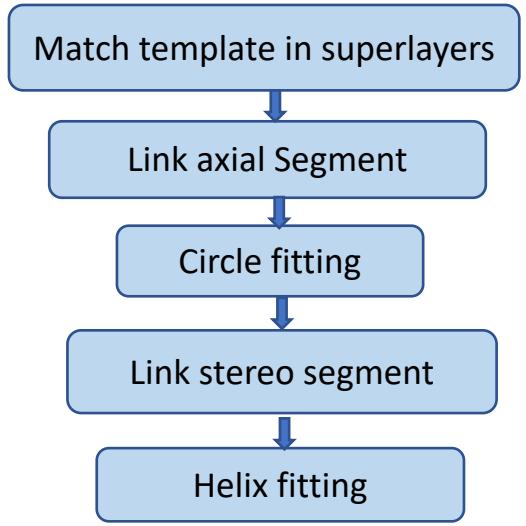
From Zhangyao

- **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



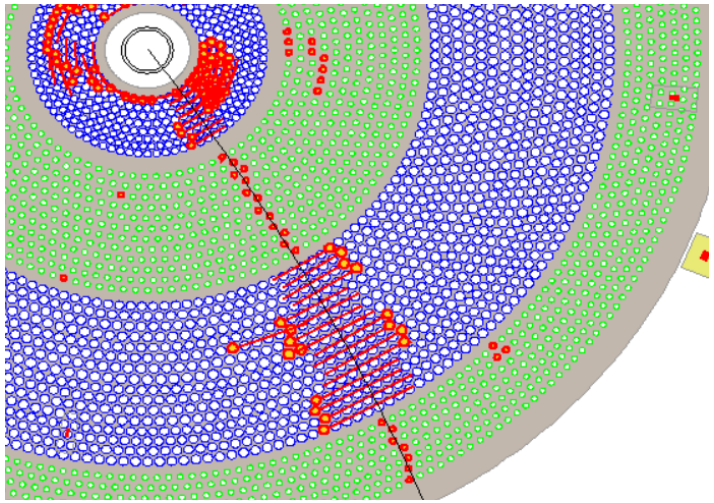
PAT Algorithm





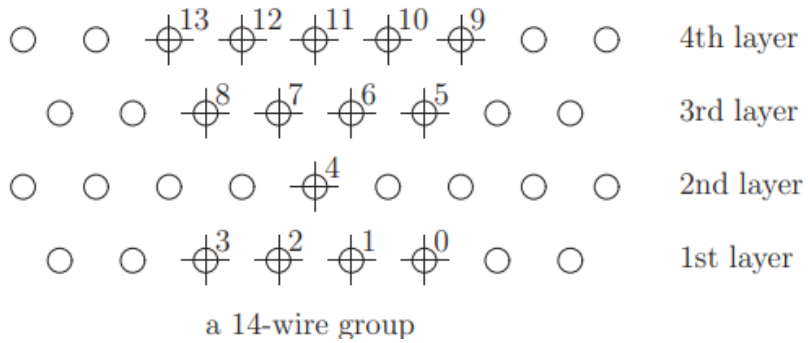
Extended Template Matching Approach

- **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**

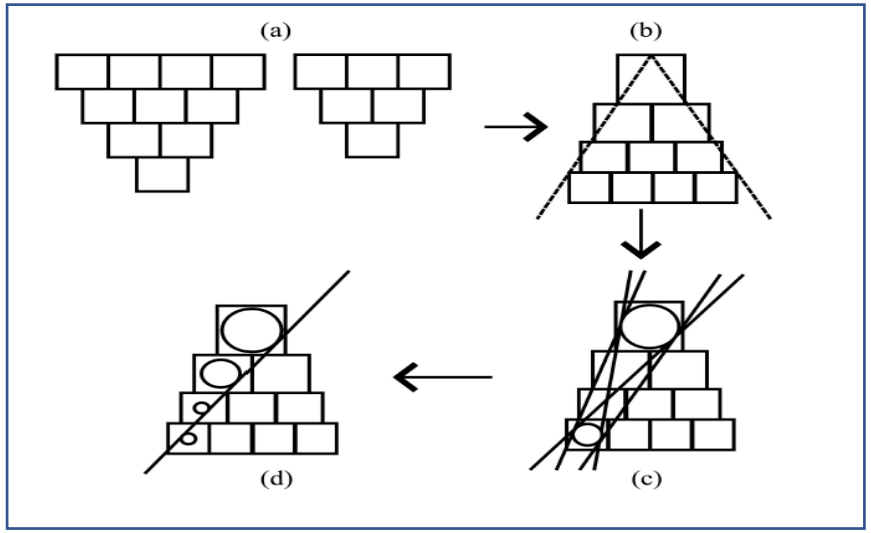


a 14-wire group

Local Approach II : Track 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**



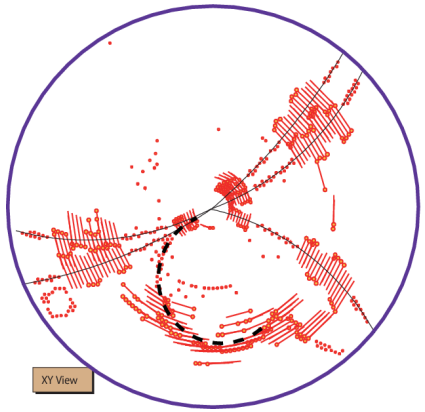
(a) Two original types of TSF
(b) Four-layer type pattern in the
(c) Conformal plane fitted out by the drift circles of the inner and outer hits
(d) Append other hits in this model

Low Transverse Momentum Track

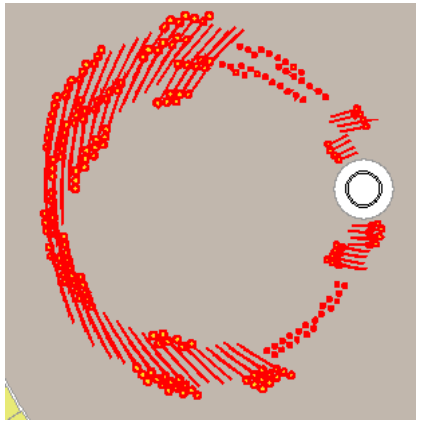
➢ Geometrical trouble : p_T < 120MeV/c

Low p_T tracks bring difficulties for local Segment matching based algorithm

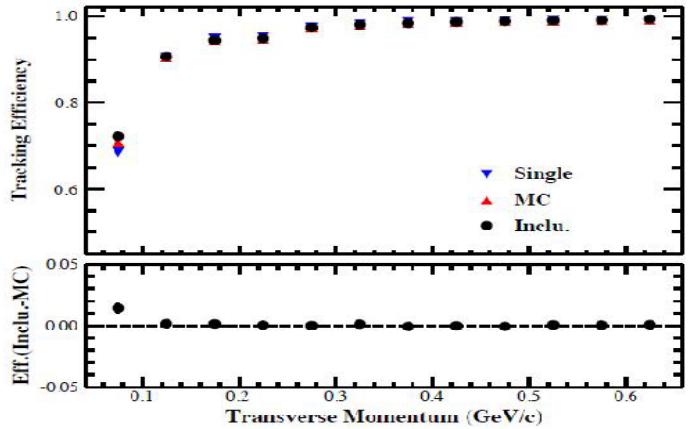
Tracks with large pz :
Short tracks with insufficient hits



Tracks with small pz :
looping in MDC, leaving multiturn tracks

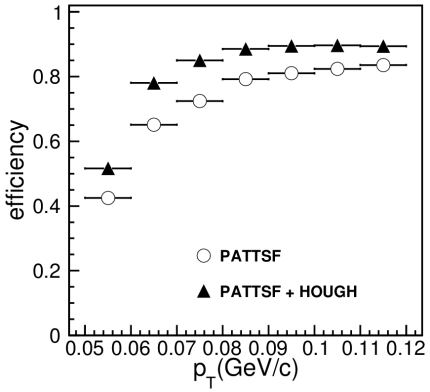


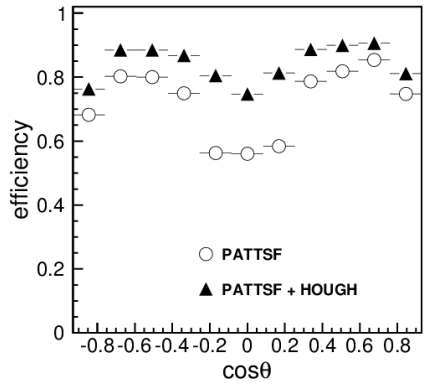
Track efficiency of π^- vs P_T



➢ Hough transform

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



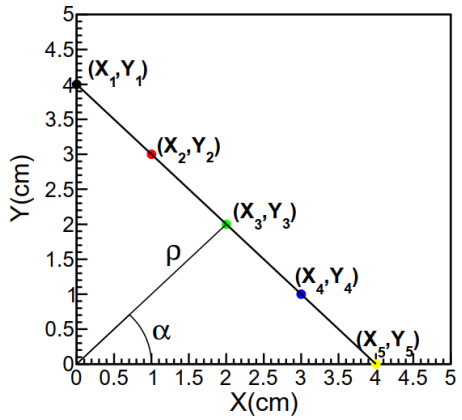


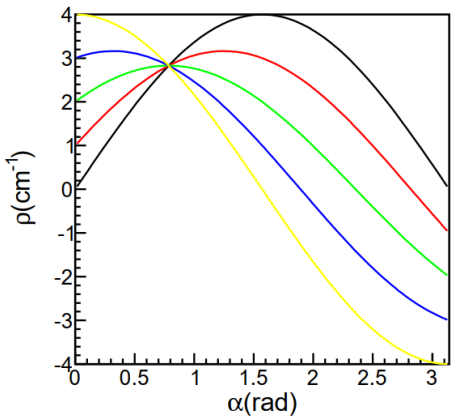
Hough Transform / Legendre Transform

Hough transform：Transform a point in real space to a line or a curve in parameter space

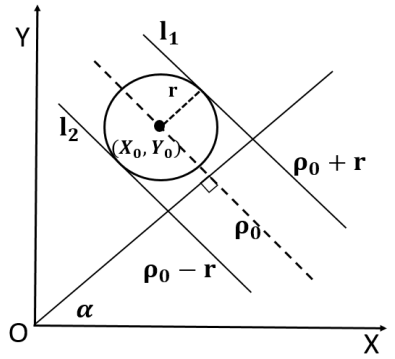
Points rest on a line in real space ←→ lines or curves focus in Hough space

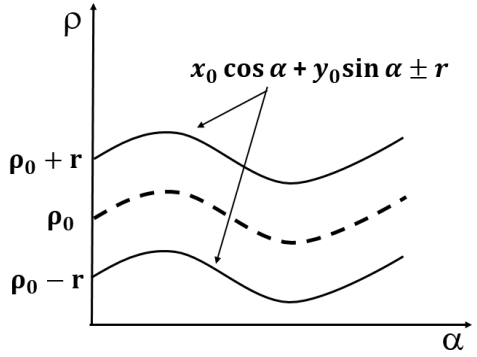
e.g. for a line：





Hough/Legendre transform for MDC hits



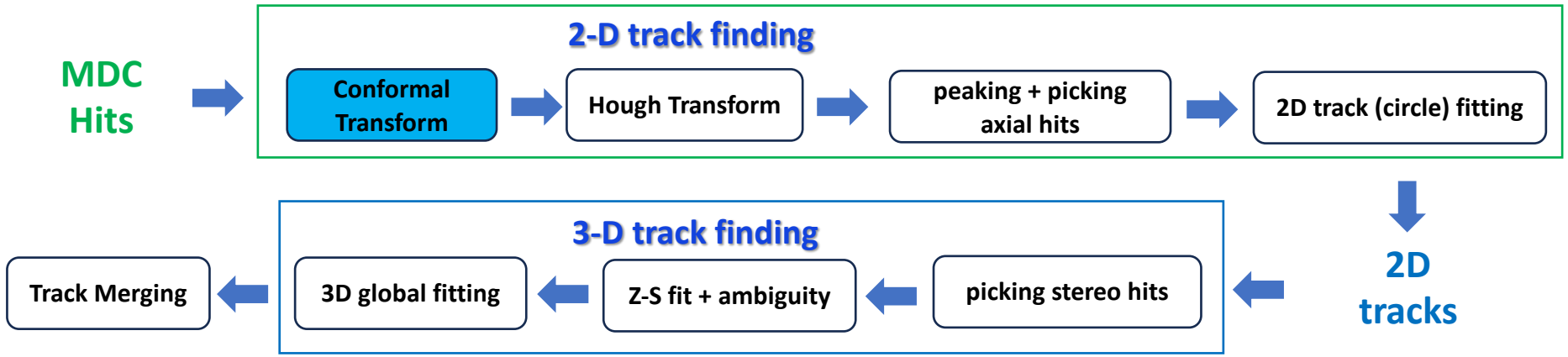


$$\rho = X\cos\alpha + Y\sin\alpha + r, (upper\ half\ circle)$$

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

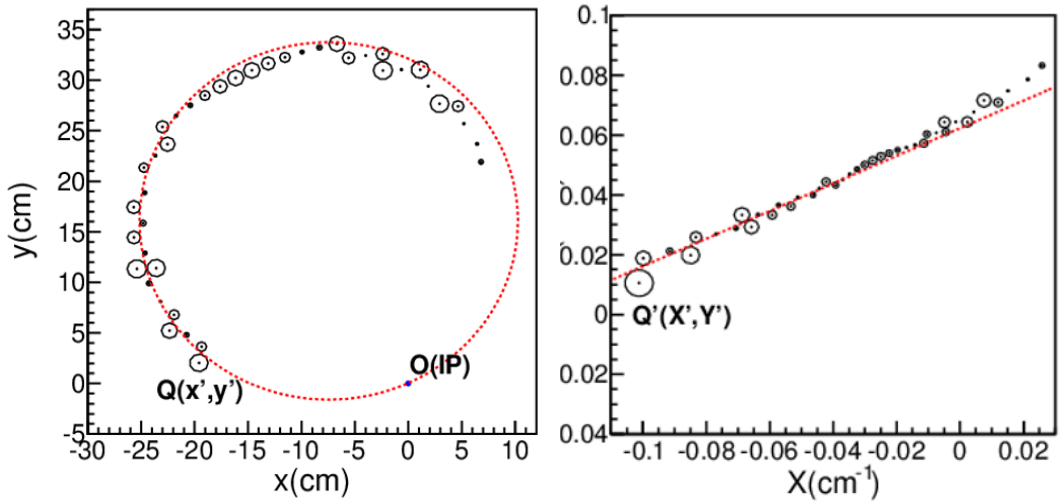
One drift circle. ←→ two curve lines on Hough space

Global Approach : Hough Transform at BESIII

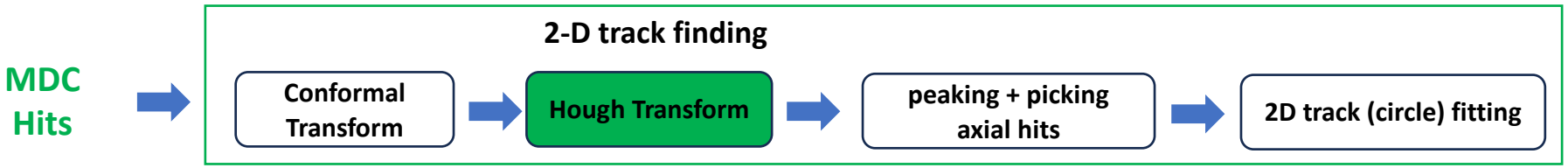


I. Conformal transform

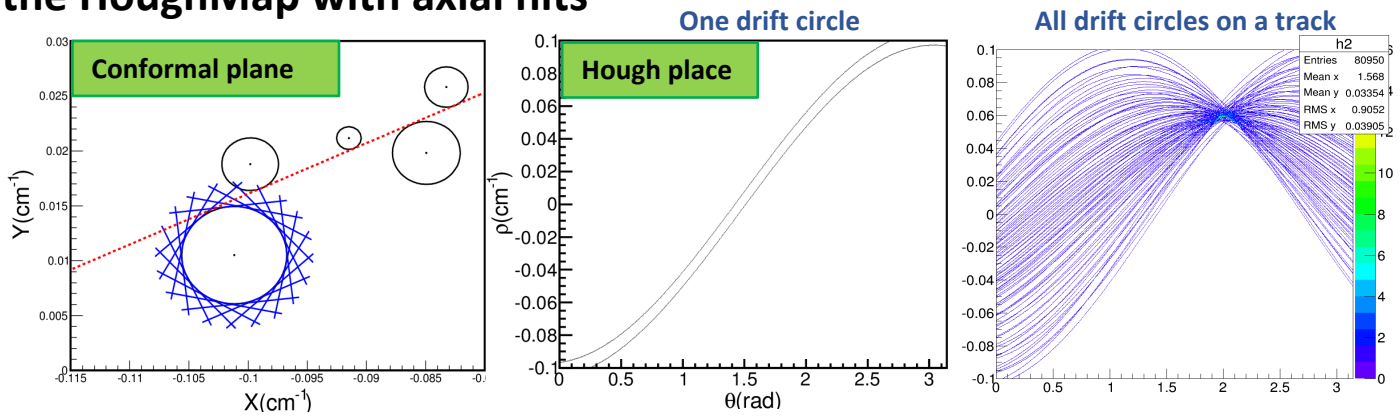
- **(Track) Circles passing the origin point transform into straight lines**
- **(Drift) Circles not passing the origin point transform into new circles**



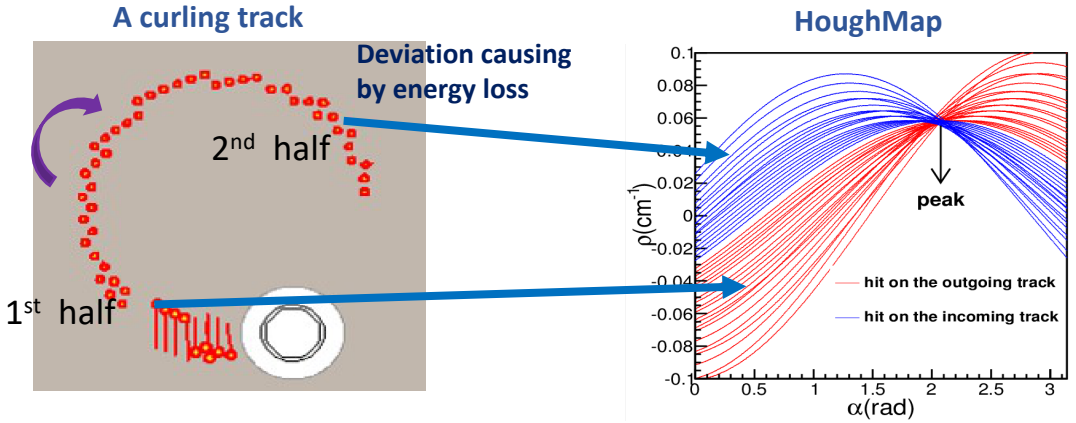
Global Approach : Hough Transform at BESIII



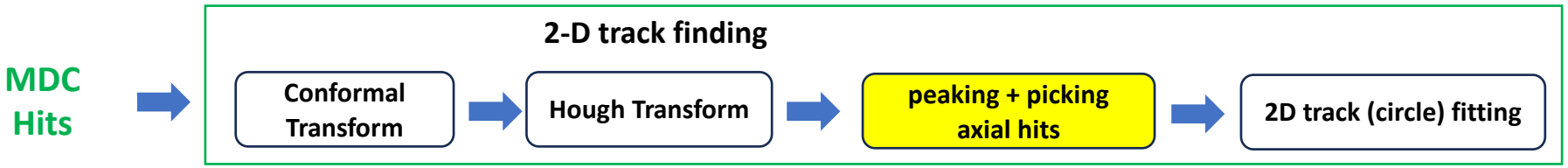
II. Filling the HoughMap with axial hits



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



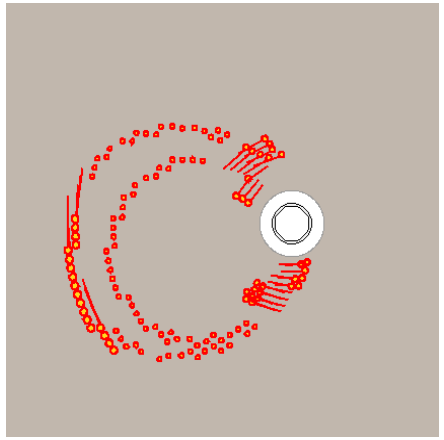
Global Approach : Hough Transform at BESIII



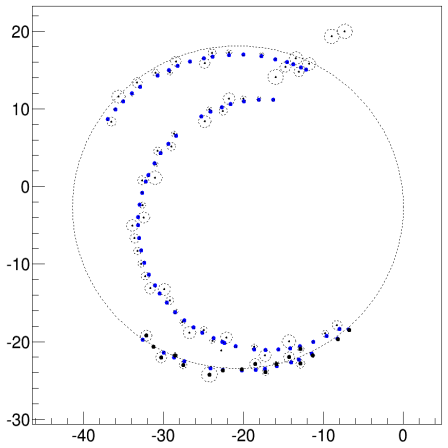
III. Applying Peaking approach and picking axial hits with using distance to track

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

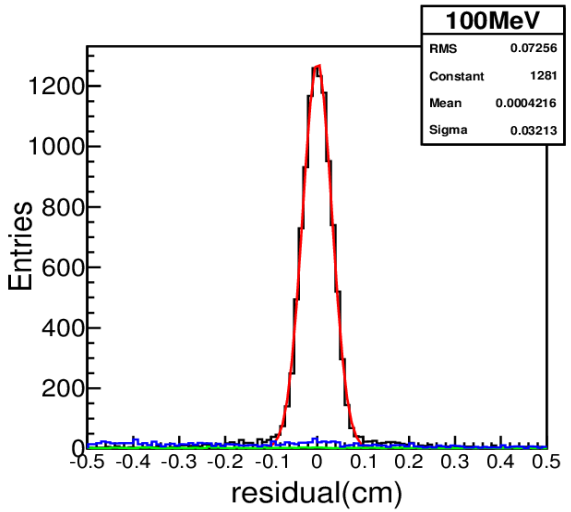
a multiturn track



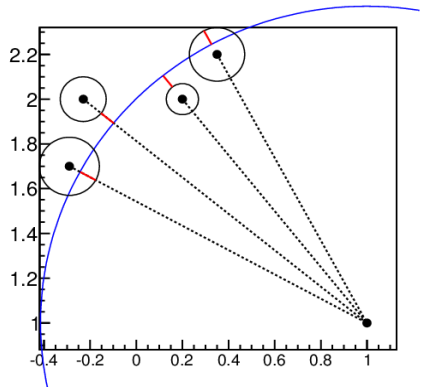
candidate 2D tracks by peaking method



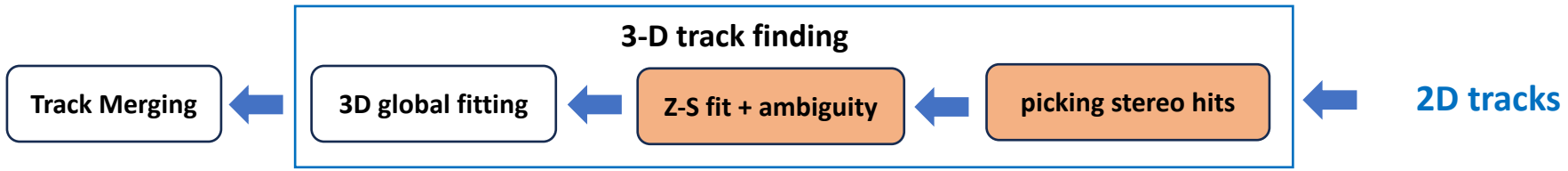
Residuals of axial hits



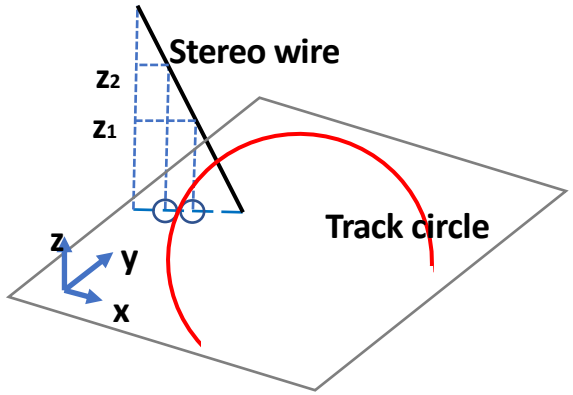
Distance To track

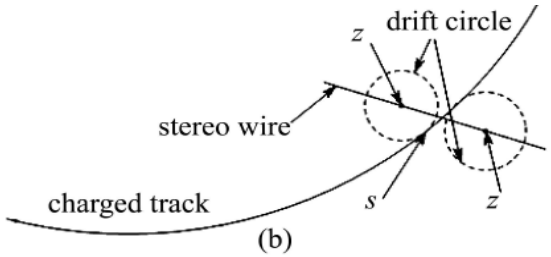


Global Approach : Hough Transform at BESIII

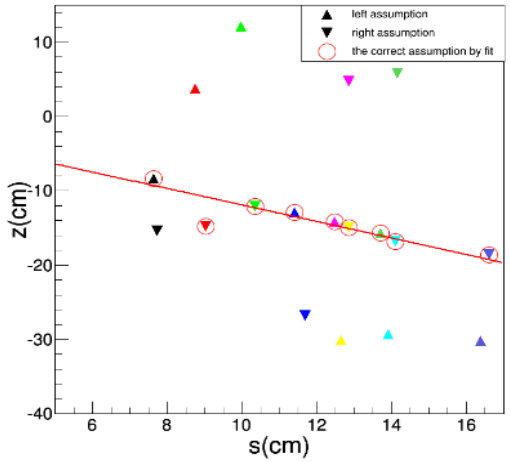


- **When 2D Hough tracking is done, do 2D circle fitting to get track on x-y space**





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 at BESIII

- During Track finding, Least Square Method (global fit) is performed to an ideal circle/Helix

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

Track parameters after an iteration

Track parameters

Weighting matrix (inverse of error matrix)

Measurement function

$\partial \mathbf{f}(\mathbf{p})/\partial \mathbf{p}$ at $\mathbf{p} = \overset{0}{\mathbf{p}}$

Measurements vector

  - Track parameters converged with iterations
  - Track candidate selection, Hits selection with χ^2
  - Provide initial track parameters for Range-Kutta fit (and Kalman filter)

- Range-Kutta Method (global fit) considering inhomogeneous magnetic field, energy loss and uncertainty from multiple scattering

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

→ f($\overset{0}{p}$, hit-position)

- Kalman filter (recursive fit) is performed finally, considering inhomogeneous magnetic field, energy loss and uncertainty from multiple scattering

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

Filtered track parameters at measurement k

Predicted track parameters from k-1 measurements

Gain matrix

the k-th measurement

Derivative matrix

Track are fitted with 5 particle hypothesis

Tracking Performance

From Liu Fang

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**

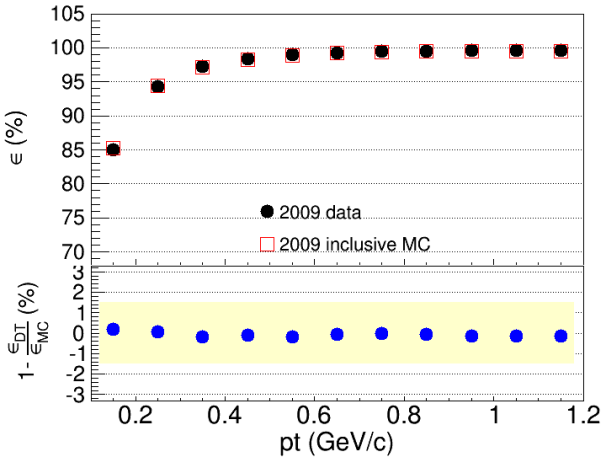
$$\varepsilon = \frac{N}{N'}$$

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

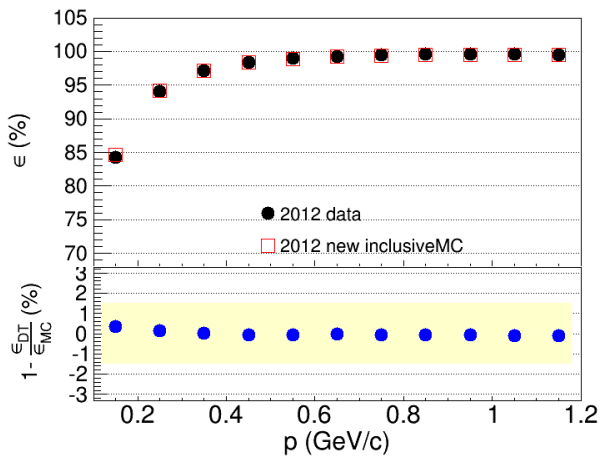
N′: SUM of No. events with one good charge track and No. events with two good charged tracks and net zero charge

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

2009 dataset

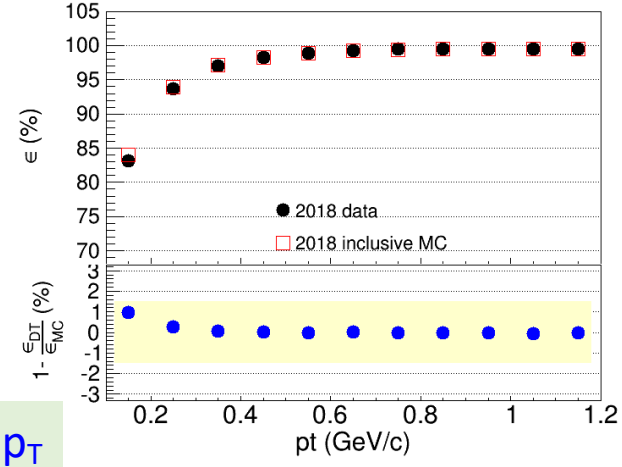


2012 dataset

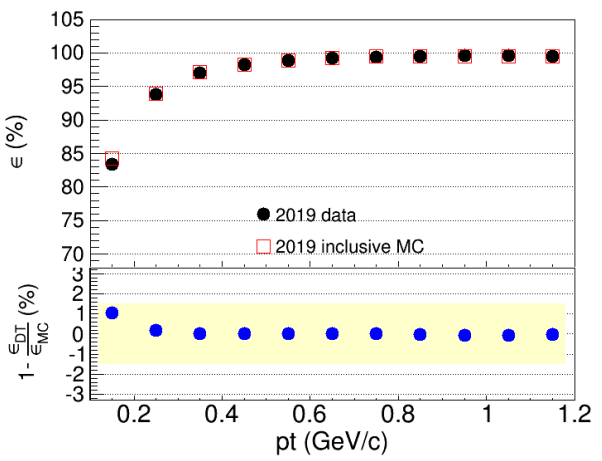


p_T

2018 dataset

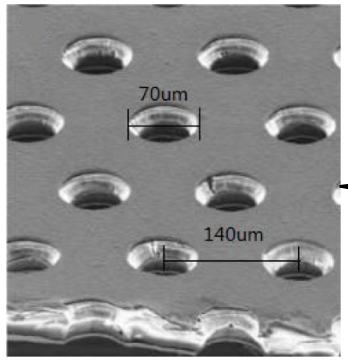


2019 dataset

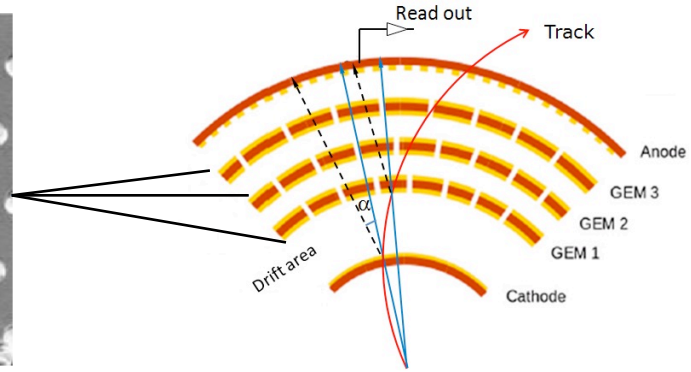


Tracking With CGEM-IT and Outer-DC

CGEM (Cylindrical Gas Electron Multiplier) as Inner Tracker

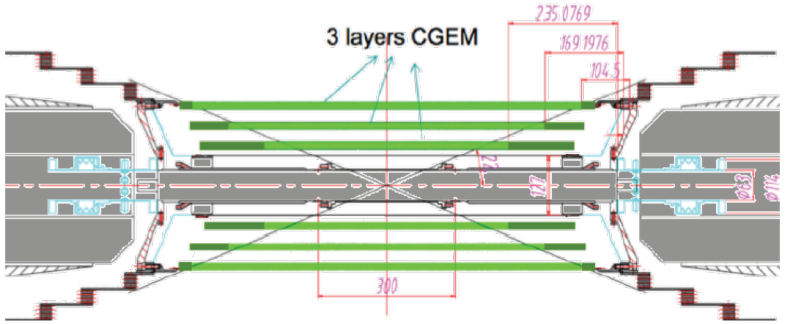


GEM foil

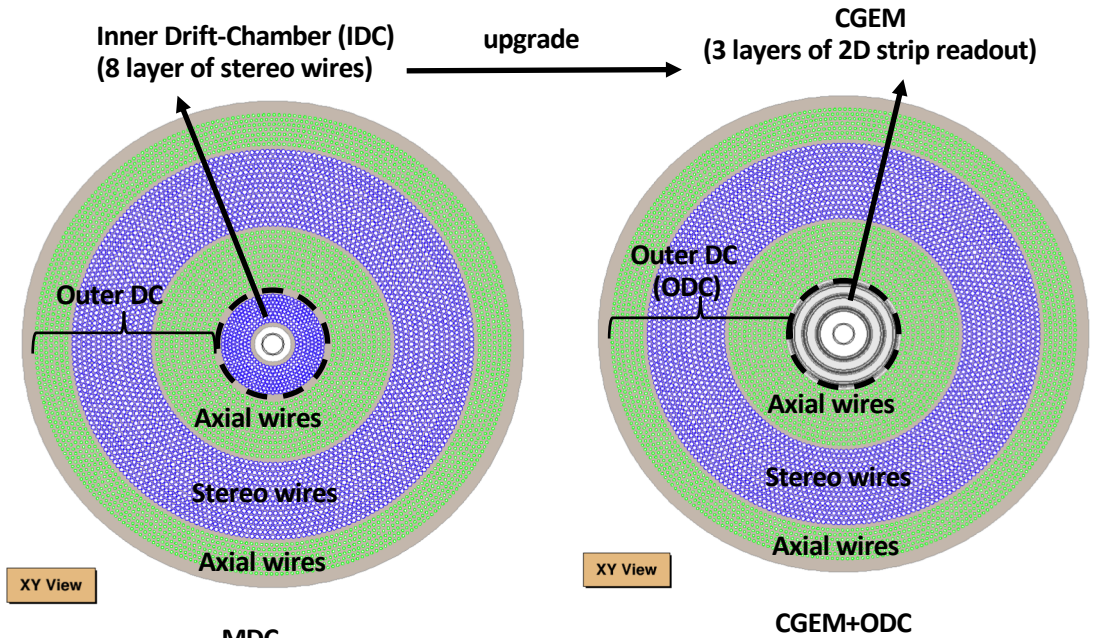


GEM detector

- Anode and cathode and 3 layers of GEM foil
- X&V readouts
- Charge and time



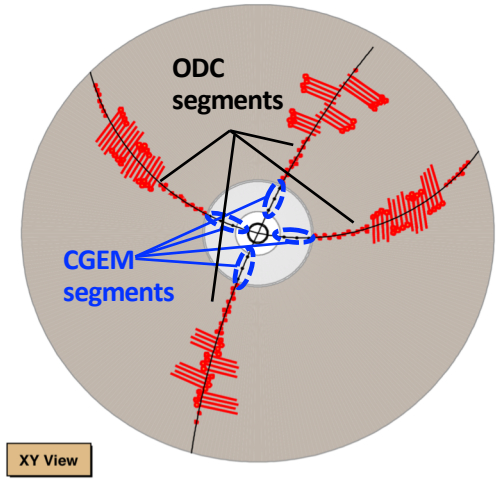
- 3 layers of cylinder GEM detector
- replace inner MDC



MDC

CGEM+ODC

Tracking With CGEM-IT and Outer-DC



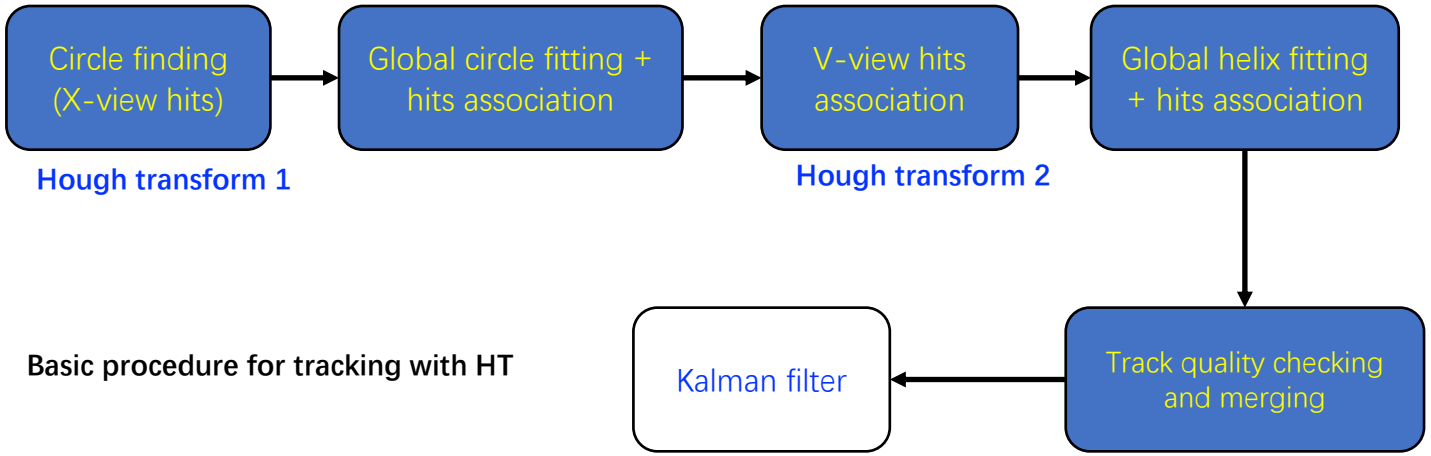
ψ(3686)→π+π−J/ψ→π+π−e+e-

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

Other tracking development and study at BESIII

- Tracking With CGEM-IT and Outer-DC using local method:
  cellular automata (CA) (still in progress)
  (same method but on TPC, see Aiqiang's talk)

- **GNN** based tracking (see Xiaoqian's talk)

Summary

- BESIII Track reconstruction software has 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
- BESIII experiment provides a good platform for the research of new strategies and modern methods

Thank you!