Track Reconstruction with CGEM+ODC at BESIII

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On behalf of the CGEM software group

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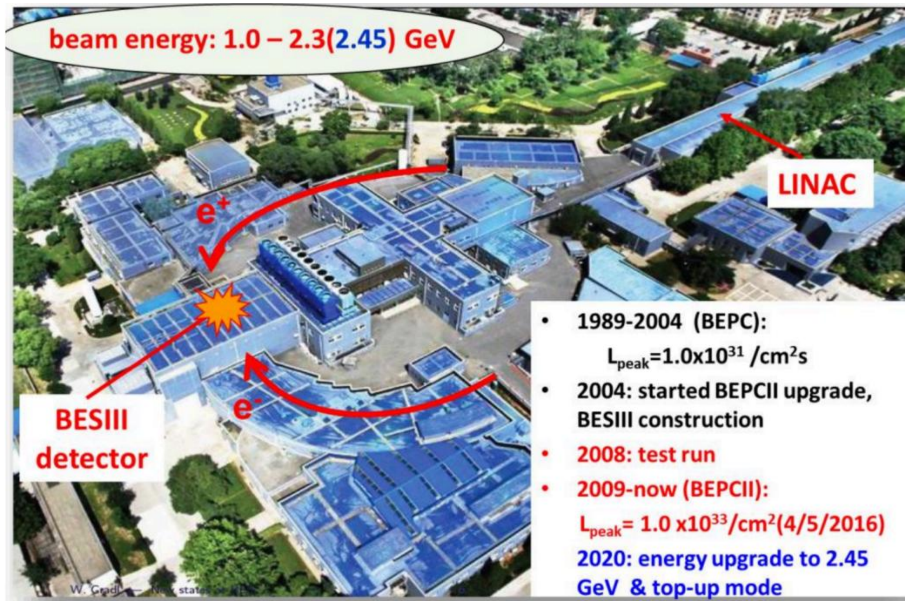
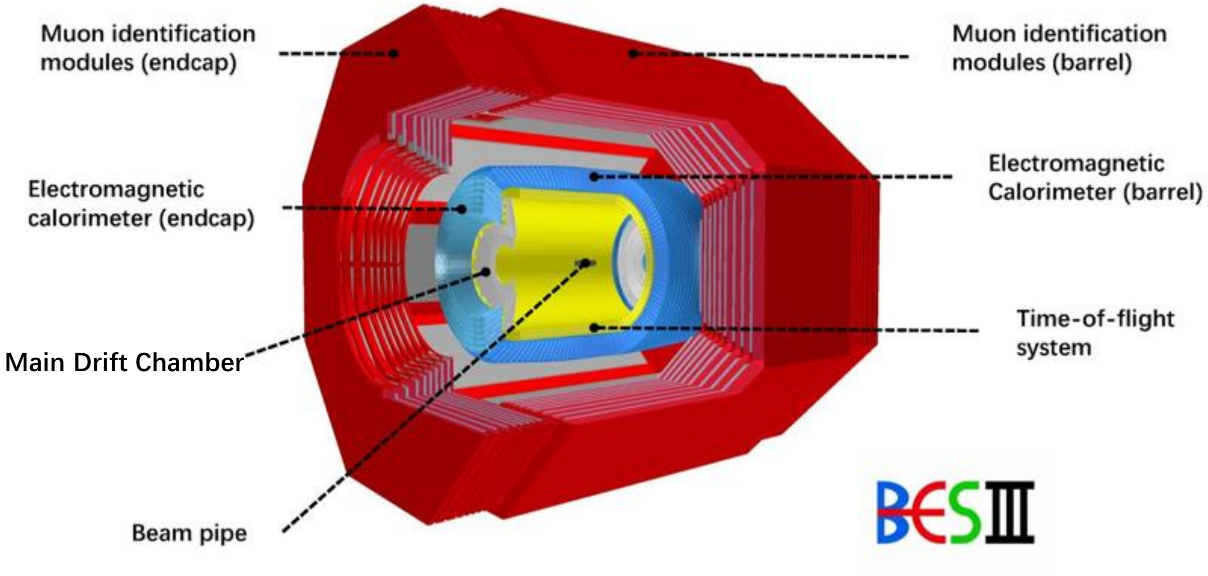
Beijing Spectrometer III (BESIII) Experiment

- BEPCII is a double-ring accelerator with a designed peak luminosity of $10^{33}\ cm^{-2}s^{-1}$
- BESIII is a multilayer detector designed for precision studies of 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

Beijing Electron Positron Collider II

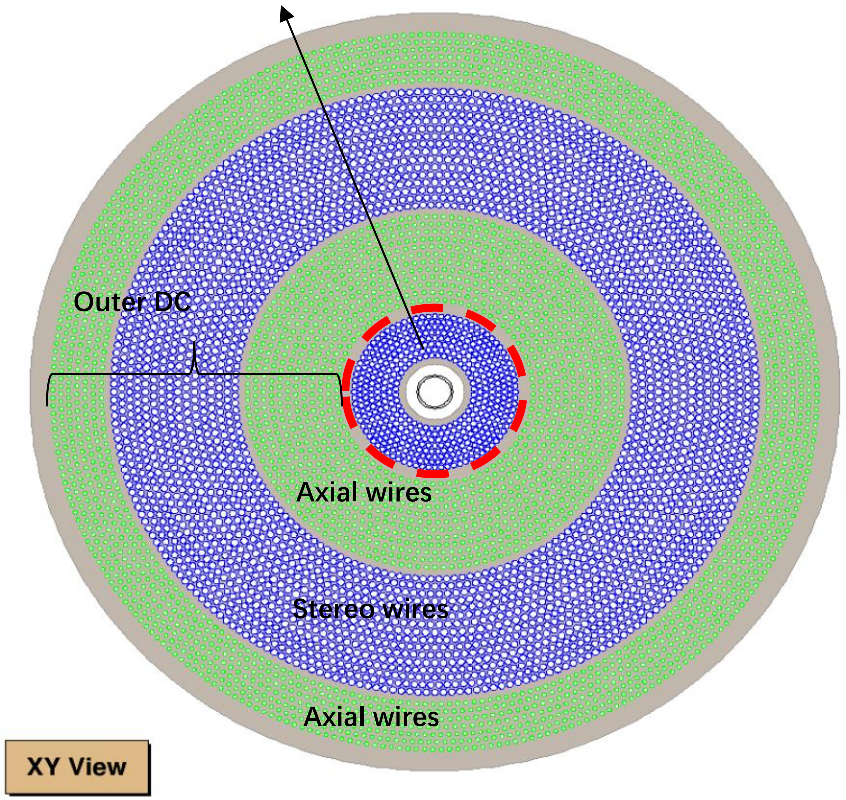


BESIII Detector

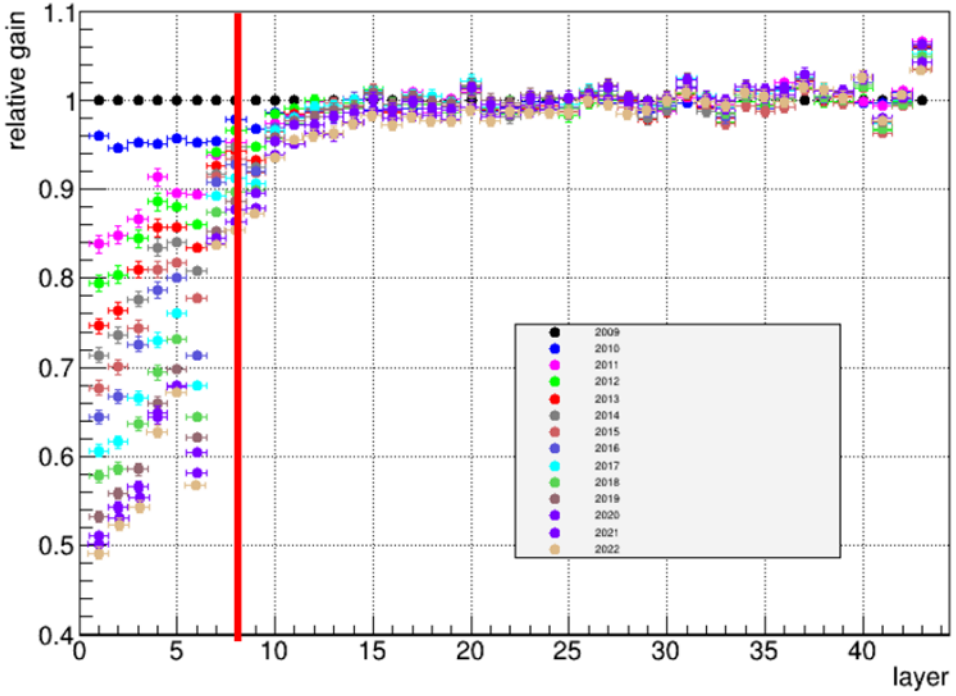


Aging of Inner Drift Chamber (IDC)

Inner Drift-Chamber (IDC)
(8 layer of stereo wires)



MDC

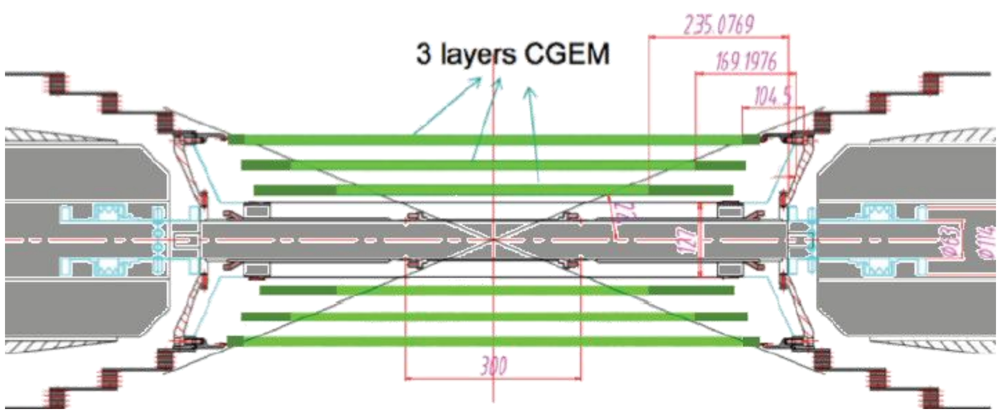


relative gain loss per year of the IDC tracker

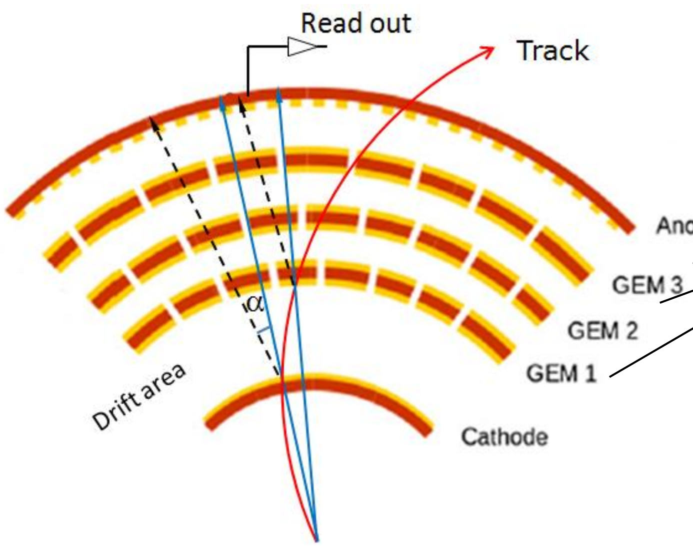
Due to the aging of the inner MDC (8 layer of stereo wires), it has been replaced with the CGEM detector in early 2025

Inner Tracker Upgrade: Inner Drift Chamber (IDC) → CGEM-IT

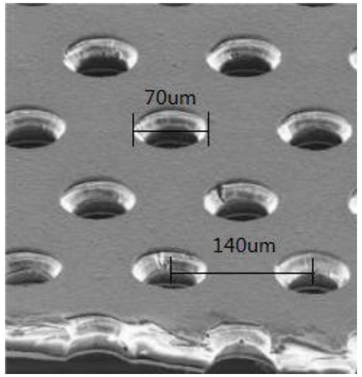
CGEM (Cylindrical Gas Electron Multiplier) as Inner Tracker



BESIII-CGEM detector

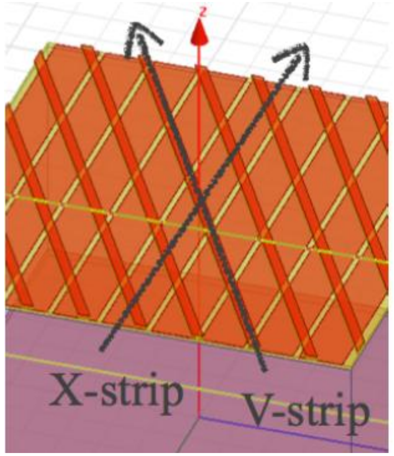


One layer of CGEM detector



GEM foil

High voltage is applied across both sides of GEM foi

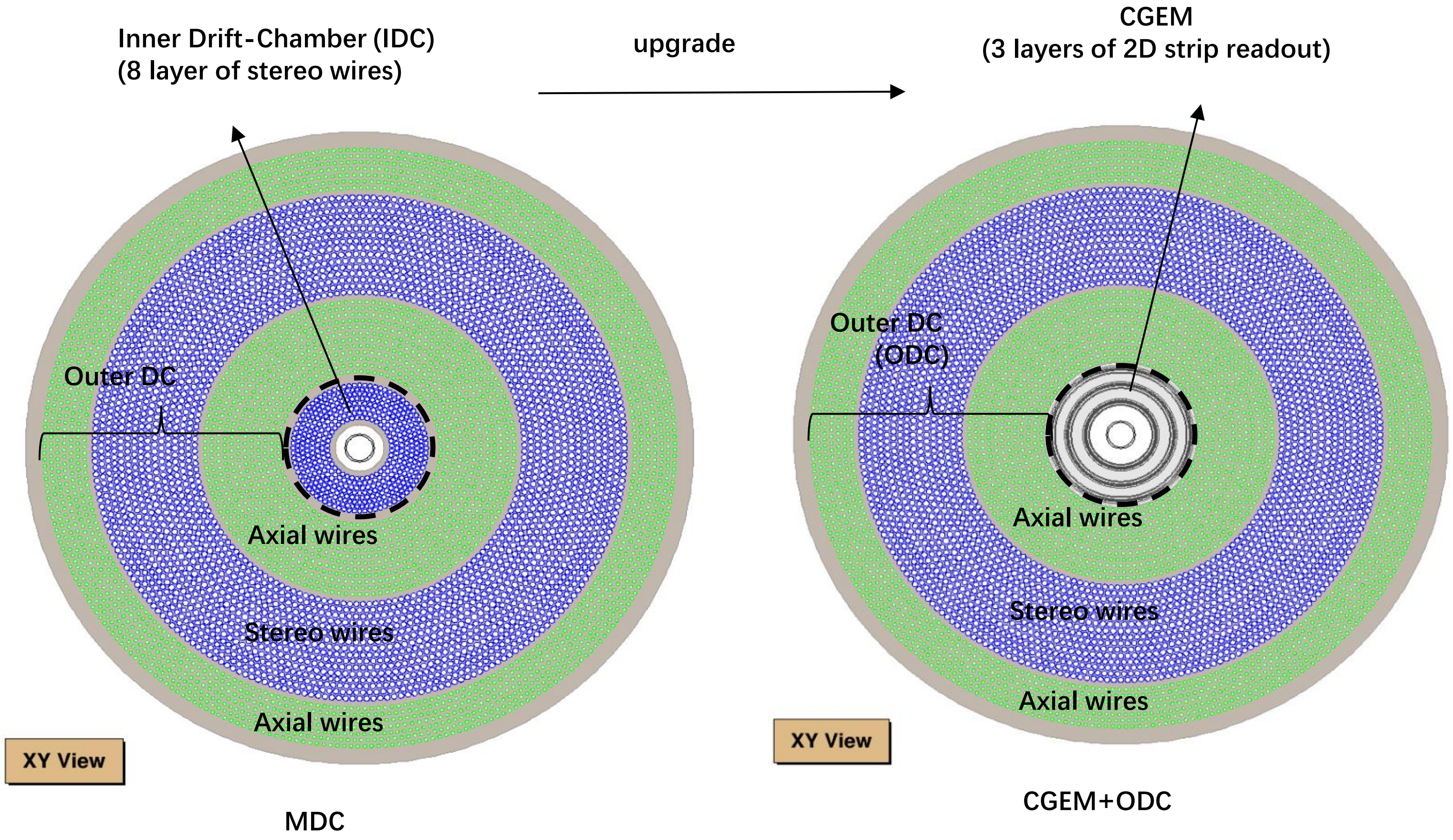


Anode readout strips

The BESIII CGEM detector consists of three layers of cylindrical GEM detectors.

- Drift area: ionization
- Triple-GEM foils generate avalanche of electrons
- X and V readouts provide both charge and time measurements

Tracking system: CGEM+ODC



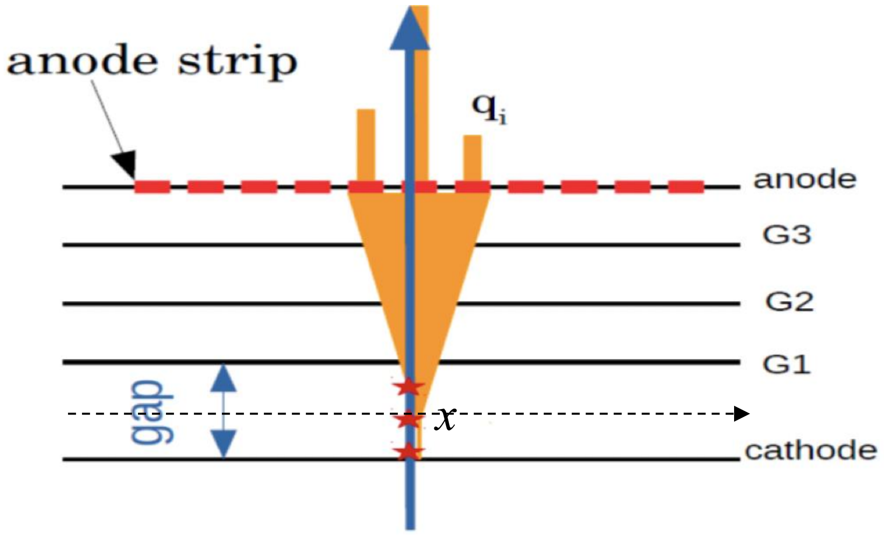
3 layers of cylinder GEM detector replace inner DC

We divide the tracking system into seven areas based on the structure of the detector and the type of wires

Area number	Inner Detector Structure	Number of layers
Area-1	CGEM	3
Area-2	Axial wires	12
Area-3	Stereo wires (-)	4
Area-4	Stereo wires (+)	4
Area-5	Stereo wires (-)	4
Area-6	Stereo wires (+)	4
Area-7	Axial wires	7

CGEM cluster reconstruction

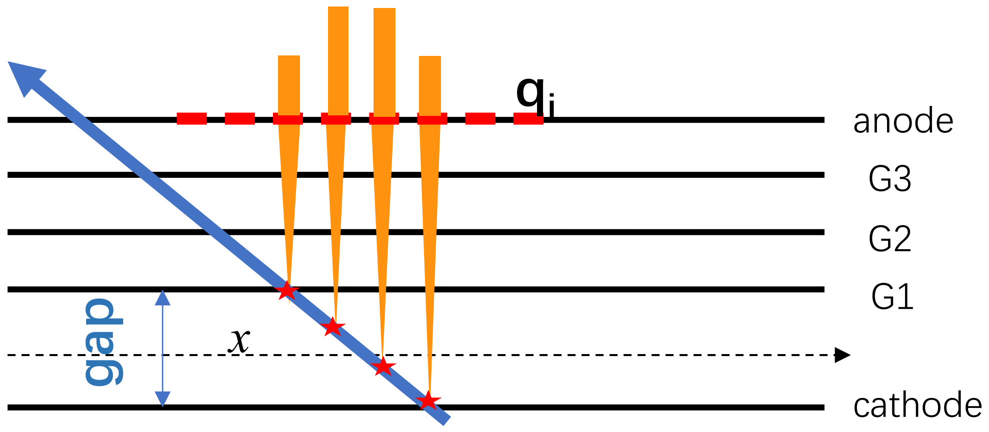
- Charge Centroid (CC)



$$x = \frac{\sum_{i=1}^{n} q_i x_i}{n}$$

Good performance for track direction close to the ionization electrons drifting

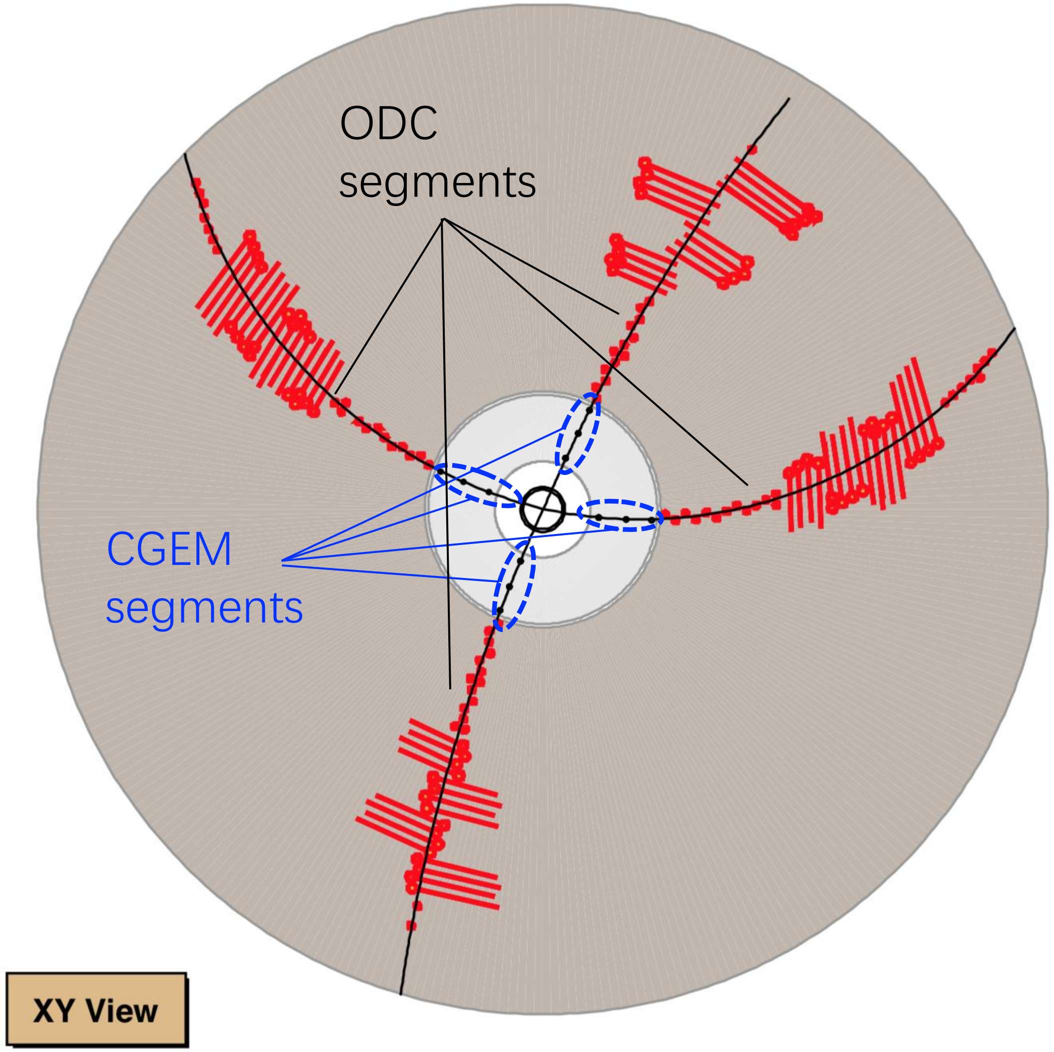
- Micro Time Projection Chamber (μ-TPC)



$$d = a \cdot x + b \text{ by fitting } (x_i, d_i = v \cdot t_i)$$

Good performance for track direction very different from the ionization electrons drifting

Track reconstruction with CGEM+ODC

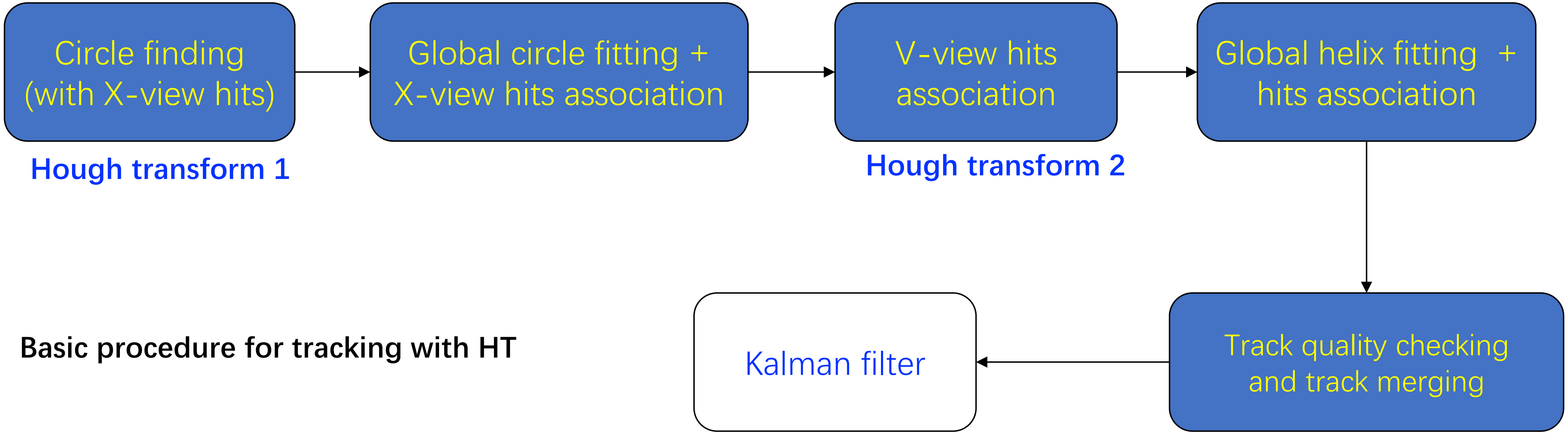


$\psi(3686)\rightarrow\pi+\pi-J/\psi\rightarrow\pi+\pi-e+e-$

- The inputs of track reconstruction are CGEM clusters and outer-DC hits
- Track finding
  - ✓ Global method : **Hough Transform**
  - ➢ Local method : **Cellular Automata** (in development)
- Track fitting
  - ✓ Circle fitting with Taubin method
  - ✓ 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 Taubin/Least-Square method is after each step



Basic procedure for tracking with HT

Circle finding with 2-D Hough transform

- Circle finding with all X-view hits
- Use 2D histogram to find peaks in parameter space (number of bins optimized with single μ^-)

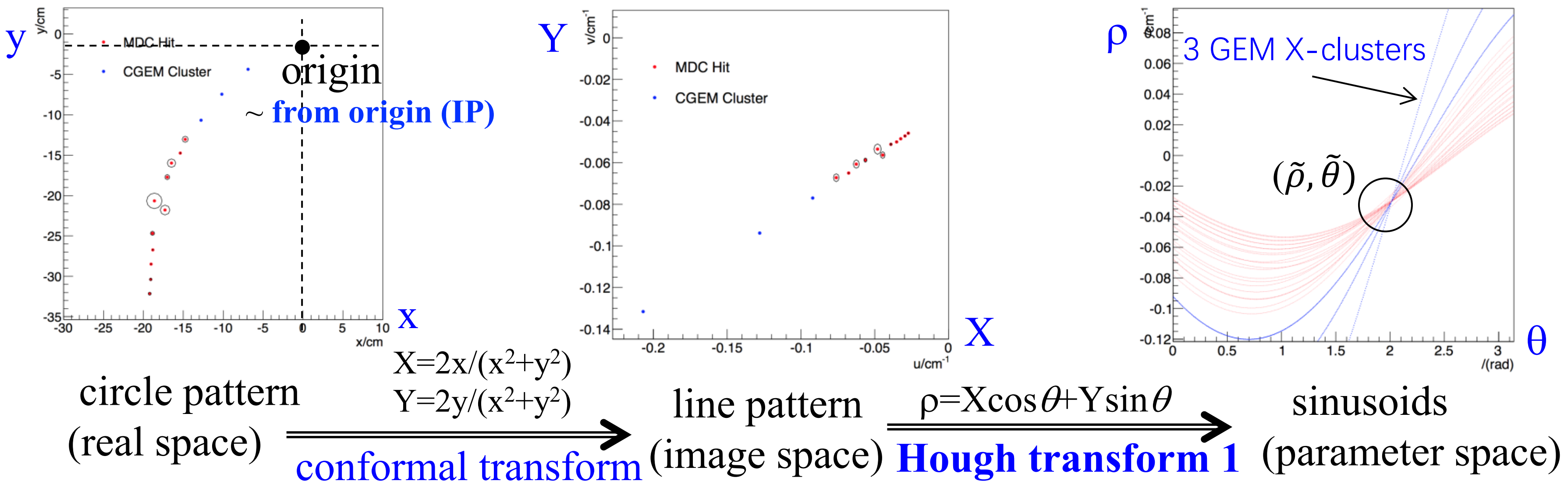
- Get track parameters from peak position :

$$(\tilde{\rho}, \tilde{\theta}) \Leftrightarrow (\varphi_0, \kappa)$$

- Pre-selection of X-view hits to the track candidate (selection criteria studied with single μ^-)
- Global circle fitting + fine X-view hits association

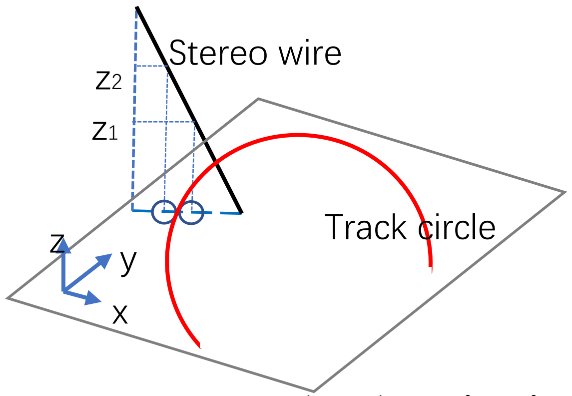
A good assumption for most tracks: circles passing origin

(But not good for tracks from significantly displaced vertex)

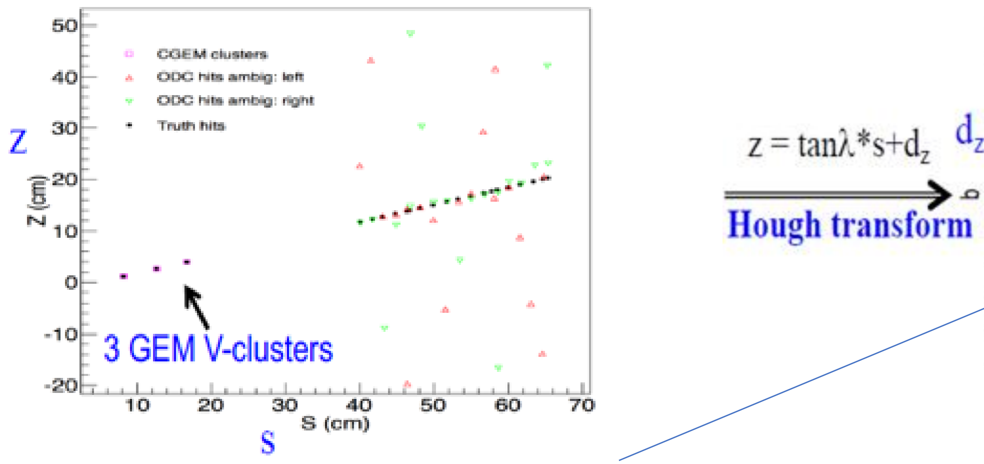


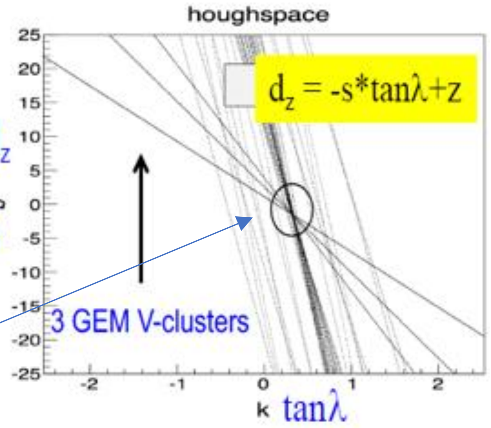
V-view hits association

- For each circle candidate, the intersected V-view hits can be represented in a ***s-z*** plane
  - ➢ *z* coordinate can be calculated by tangency between drift circle and track circle in x-y plane
  - ➢ *s* is trajectory length in the transverse plane



- V-view hits belong to the same track are co-linear in ***s-z*** plane (image space)
- Use **Hough transform** to convert (***s, z***) pairs into lines in **d_z-tanλ** plane (parameter space)





- The cell with the maximum votes (peak) => parameters **dz, tanλ** (number of bins optimized with single μ^-)
- Associate V-view hits (selection criteria studied with single μ^-)

MC events reconstruction with CGEM+ODC vs MDC

- CGEM+ODC
  - Simulation: CGEM toy clusters with **100% efficiency** and **130 μm spatial resolution** (for the following studies) + standard ODC
  - Reconstruction: Only the global method **Hough Transform** used for track finding

- MDC
  - Simulation: standard full MDC simulation
  - Reconstruction: MDC track finding algorithms (PAT, TSF, CurlFinding)

J/ψ→ppbar

Francesca De Mori

2 prongs

Good charged tracks ($|dr|<1.0$cm, $|dz|<10$cm, $|\cos\theta|<0.93$)

Cut flow	MDC	CGEM+ODC (new)
Two good tracks	84.7%	83.9%
Back to back	81.8%	81.2%
E/p<0.5 for proton	81.8%	81.1%
$\|\Delta p\|<3\sigma$	78.0%	75.7%
PID	76.8%	74.6%

✓ Comparable track efficiency

✓ Close in final selection!

$\psi(3686) \to \pi^+\pi^- J/\psi \to \pi^+\pi^-\mu^+\mu^-$

4 prongs

Event selection

- Four good charged tracks ($|dr|<1.0$cm, $|dz|<10$cm, $|\cos\theta|<0.93$), total charge =0
- Separate muon and pion by momentum ($p<0.8$ GeV/c: $\pi^{+/-}$, $p>0.8$ GeV/c: $\mu^{+/-}$)
- Four-Constraint kinematic fit (four-momentum conservation)

Cut flow	MDC	CGEM+ODC (new)
4 good tracks, $Q_{total}=0$	**64.2%**	**64.2%**
$\pi^+\pi^-\mu^+\mu^-$ assignment with p	**63.7%**	**63.6%**
$\chi^2_{4C}<200$	**56.7%**	**55.1%**

✓ Comparable good track efficiency
✓ Very close final efficiency after kinematic fit

$e^+e^- \rightarrow \pi^+\pi^-\psi(3686)[\rightarrow \pi^+\pi^- J/\psi[\rightarrow \mu^+\mu^-]]$@4.612 GeV

6 prongs

Good charged tracks ($|dr|<1.0$cm, $|dz|<10$cm, $|\cos\theta|<0.93$)

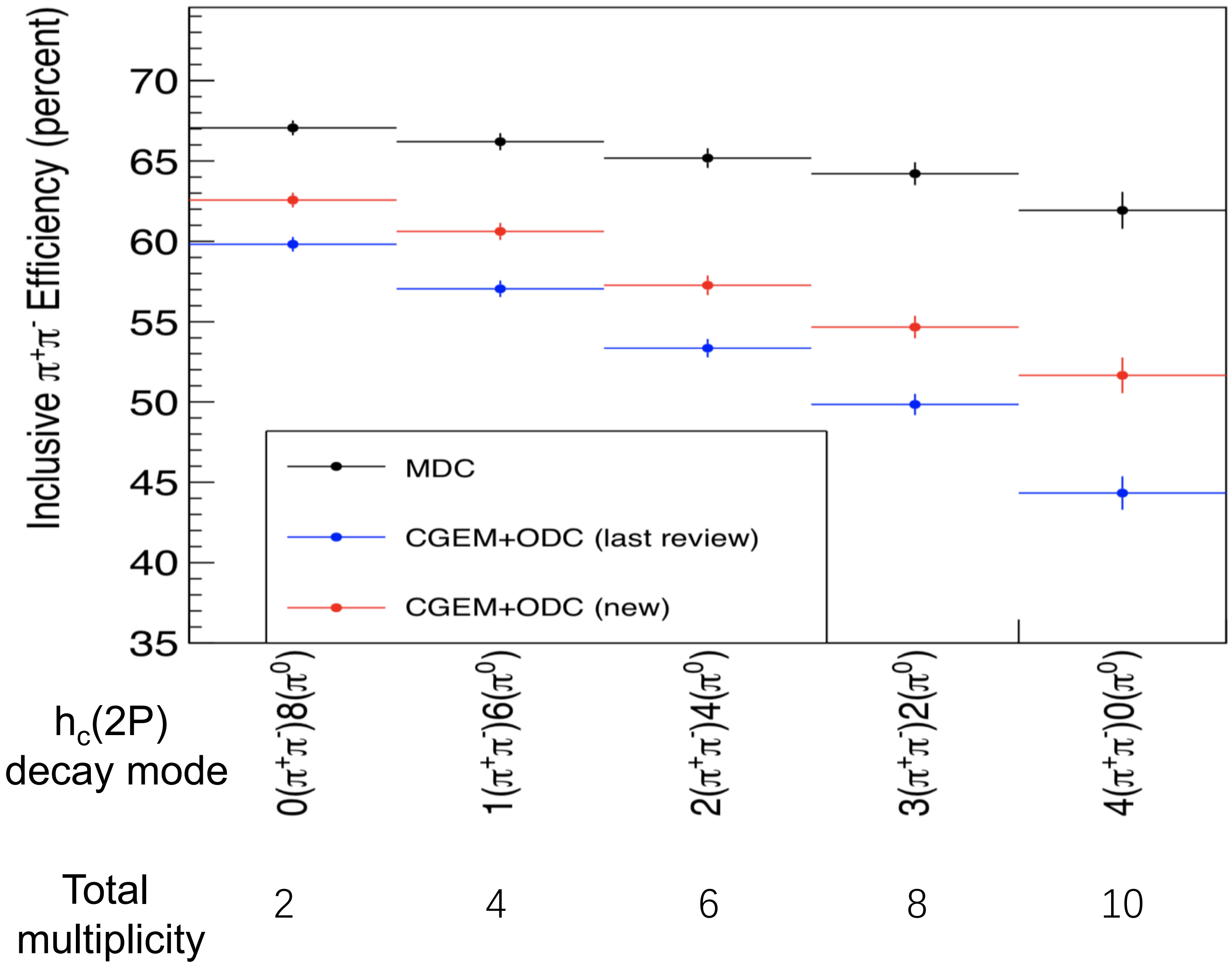
Cut flow	MDC	CGEM+ODC
>=6 good tracks	**64.2%**	**68.6%**
=6 good tracks, $Q_{total}=0$, kinetic PID ($4\pi\mu^+\mu^-$)	**47.6%**	**50.3%**
$\psi(3686)$, J/ψ mass window, 4C kinematic fit successful	**41.7%**	**42.0%**
$\chi^2_{4C}<100$	**39.5%**	**39.0%**

Six-prong, final selection efficiency comparable

$e^+e^- \rightarrow \pi^+\pi^- h_c(2P)$@4.66 GeV

Low momentum and multi-prongs

Ryan Mitchell



- Inclusive $\pi^+\pi^-$ efficiency by counting $h_c(2P)$ signals on the $\pi^+\pi^-$ recoiling mass
- As a function of multiplicity of charged tracks

Improvement significant and general for different multiplicities
More work in progress

$J/\psi \to K_S K^+ \pi^-$

Mingrun Li

With secondary vertex

Comparable good track efficiency

Cut Flow	MDC	CGEM-665i
Total Events	100000	100000
n(|cosθ| < 0.93) >= 4	72786	$\boxed{72261}$
Number of Combinations of p+ p- from $K_S = 1$ (decayLen/decayLenErr > 2 && 0.45 < mass < 0.55)	56958	51713
Only 1 positive and 1 negative good track for K, π (Rvxy0 < 1 && Rvz0 < 10)	51380	46253
PID (K, π)	29391	24914
4C-fit OK	26797	$\boxed{22196}$

Need further optimization and other tracking method like CA

ODC track finding

- After CGEM installation, to check/calibrate detectors (other than CGEM), the first round of charged track reconstruction is performed with Outer Drift Chamber (ODC) hits only using previous MDC tracking algorithms (PAT, TSF, CurlFinding)

- By this chance, the global track finding with Hough Transform (Global HT for short) is optimized and tested with ODC hits only as well

- Main optimization:
  - Relaxed pre-selection criteria of the X-view hits with HT
  - Iterative selection of X-view hits and circle fitting
  - Add s-z fit to determine initial track parameters (besides s-z HT) to improve V-view hits selection

Selection efficiency for J/ψ MC events

Only ODC hits used for charged track reconstruction

Xiaobin Ji

simulation	CGEM+ODC	
Track finding	**Previous MDC tracking algorithms**	**Global Hough Transform**
Decay channel	Number of events after selection	
e^+e^-	35063	**34506**
$\mu^+\mu^-$	38602	**38099**
ppbar	40204	**40067**
$\rho\pi$	18228	**18545**
$K_SK\pi$	43987	**43556**

Track reconstruction efficiencies by Global HT very close to those by MDC tracking

Selection efficiency for ψ(2S) MC events

Only ODC hits used for charged track reconstruction

Jingxu Zhang, Wenjing Zheng, Liangliang Wang

simulation	CGEM+ODC	
Track finding	Previous MDC tracking algorithms	**Global Hough Transform**
Decay channel	**Event selection efficiency (%)**	
e^+e^-	70.47	**70.58**
$\mu^+\mu^-$	82.14	**82.71**
ppbar	74.90	**74.32**
$\pi^+\pi^- J/\psi(\rightarrow\mu^+\mu^-)$	41.77	**42.24**

Track reconstruction efficiencies by Global HT very close to those by MDC tracking

Selection efficiency for Bhabha events from data

- Sample: Bhabha events (2025-06-18)
  - selected mainly with EMC shows
  - rough number requirement on ODC hits

Hailin Song

Only ODC hits used for charged track reconstruction

Track finding	Previous MDC tracking algorithms	Global Hough Transform
2 good charged tracks, Q=0	94.0%	**94.9%**
Back to back	87.5%	**88.3%**
E/E_beam cut	84.9%	**85.6%**
p/E_beam cuts	81.7%	**82.4%**

Track reconstruction efficiencies by Global HT very close to those by MDC tracking

Status of Global track finding with Hough Transform

- ✓ For MC events with 2, 4, 6 charged tracks, the reconstruction efficiency for CGEM+ODC very close to the previous MDC track finding algorithms for MDC

- ✓ For the same MC (CGEM+ODC) and Bhabha (data with CGEM) events, the reconstruction efficiencies are comparable with the previous MDC track finding algorithms using ODC hits only

- ➢ For events with high multiplicity, low momentum tracks and secondary vertices, the efficiency is lower and needs more optimization and the local method CA (in progress)

- ➢ Collision data is to be used to tune CGEM simulation and to optimize reconstruction with realistic efficiency and resolution of CGEM (of course, with alignment/calibration)

Cellular Automaton (CA)

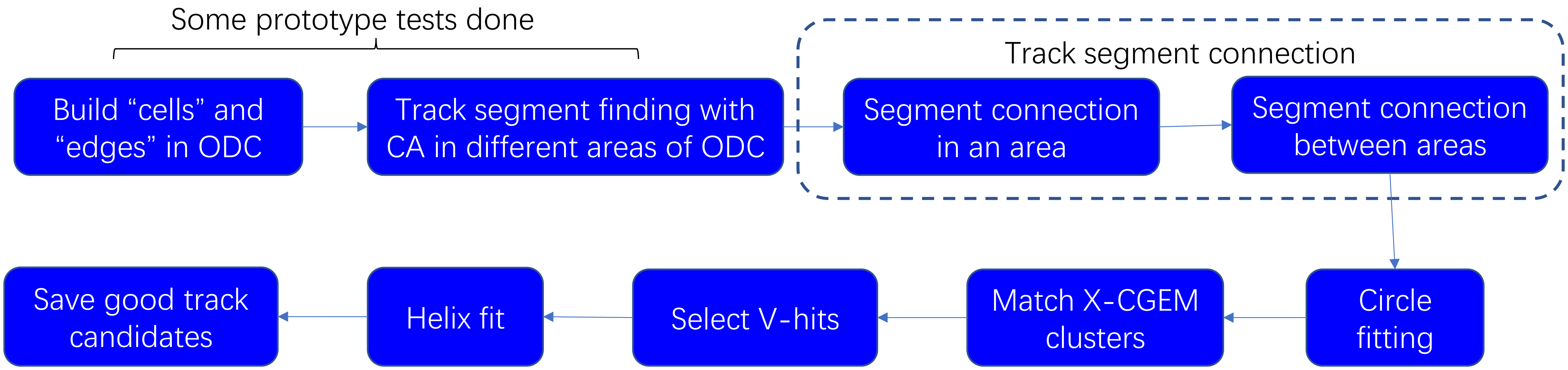
- Basic Idea of CA
  - It consists of a set of cells
  - Each cell has a state
  - Status of cells are updated in discrete time steps
  - State updating rule: new state of each cell depends on its own state and its neighbors' states

- Track finding with CA is **a local approach**

- Why Choose Local Approach?
  - To better separate hits from different tracks or backgrounds, more constraints needed during the track finding
  - To handle tracks that do not pass through the origin (secondary vertex tracks)

Local Track finding with Cellular Automata

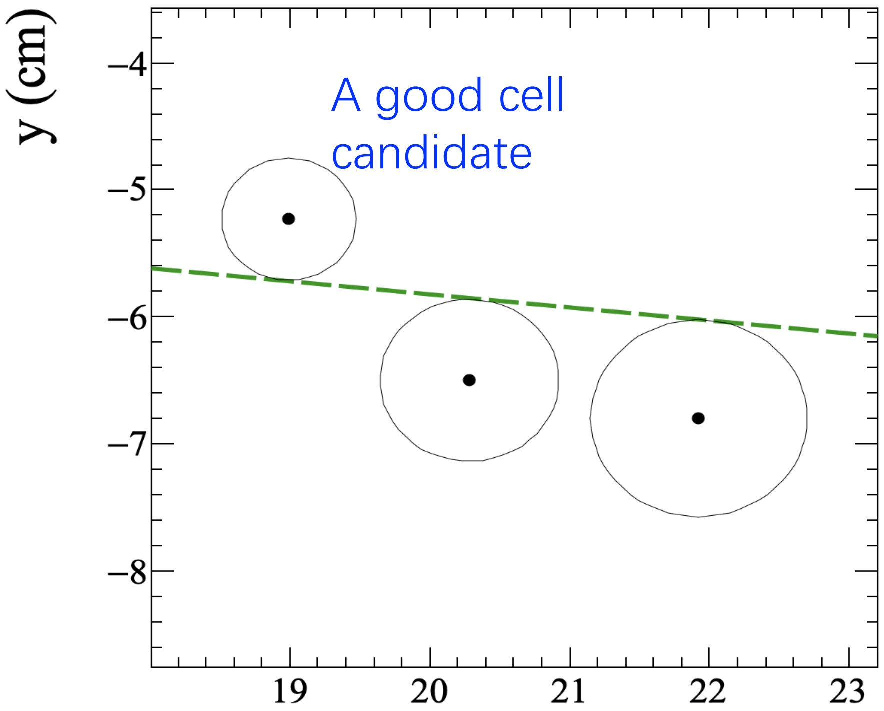
- Flowchart for the track finding with Cellular Automata (CA)
  - Build "cells" and "edges" (**more constraints applied at this stage**)
  - Make (acyclic directed) graphs
  - Track (segment) finding => (longest) path finding (with automaton)
  - Track segment connection => complete track



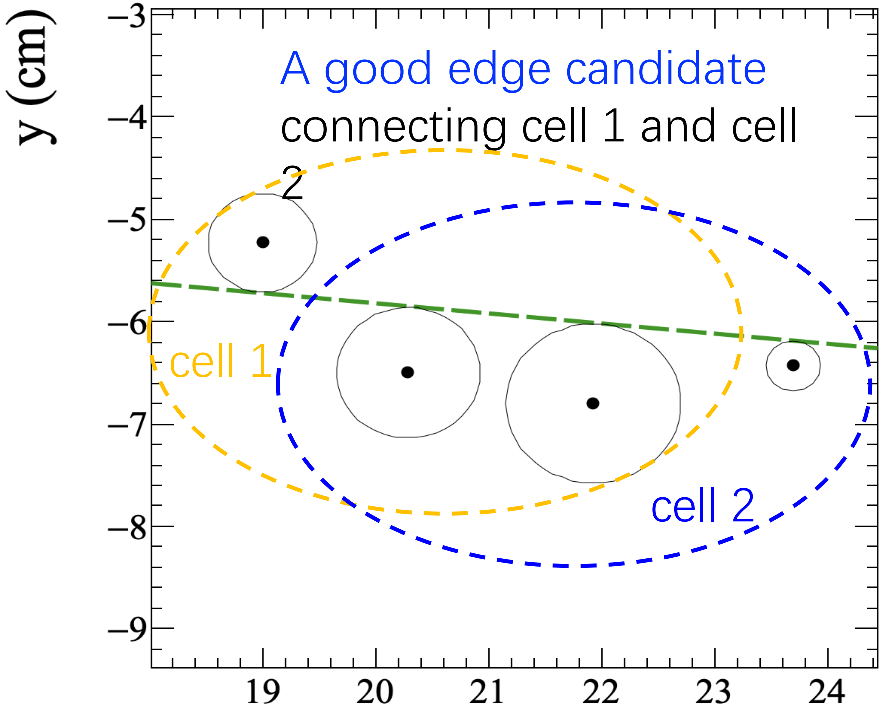
Flowchart for the track finding

"Cell" and "edge"

- Hit points are clustered based on neighboring relationship between wires
- Construct cells and edges in each cluster



Three adjacent DC hits passing a linear fit

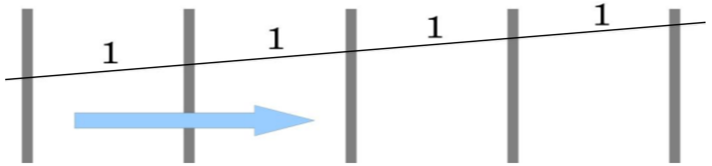


Four adjacent DC hits passing a linear fit

Graph and path finding

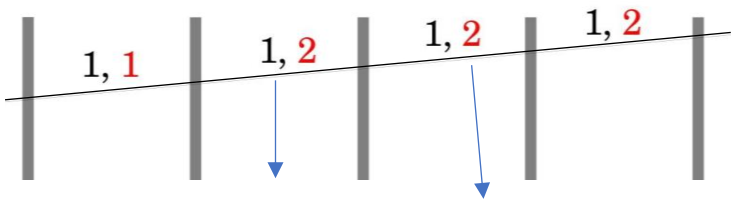
- Cells and edges can form a directed graph
- Track segment finding => longest path finding in a graph with cellular automata

Initial State



All cells are initialized with a state of 1.

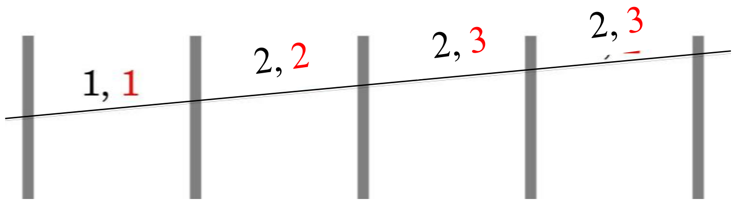
First Update



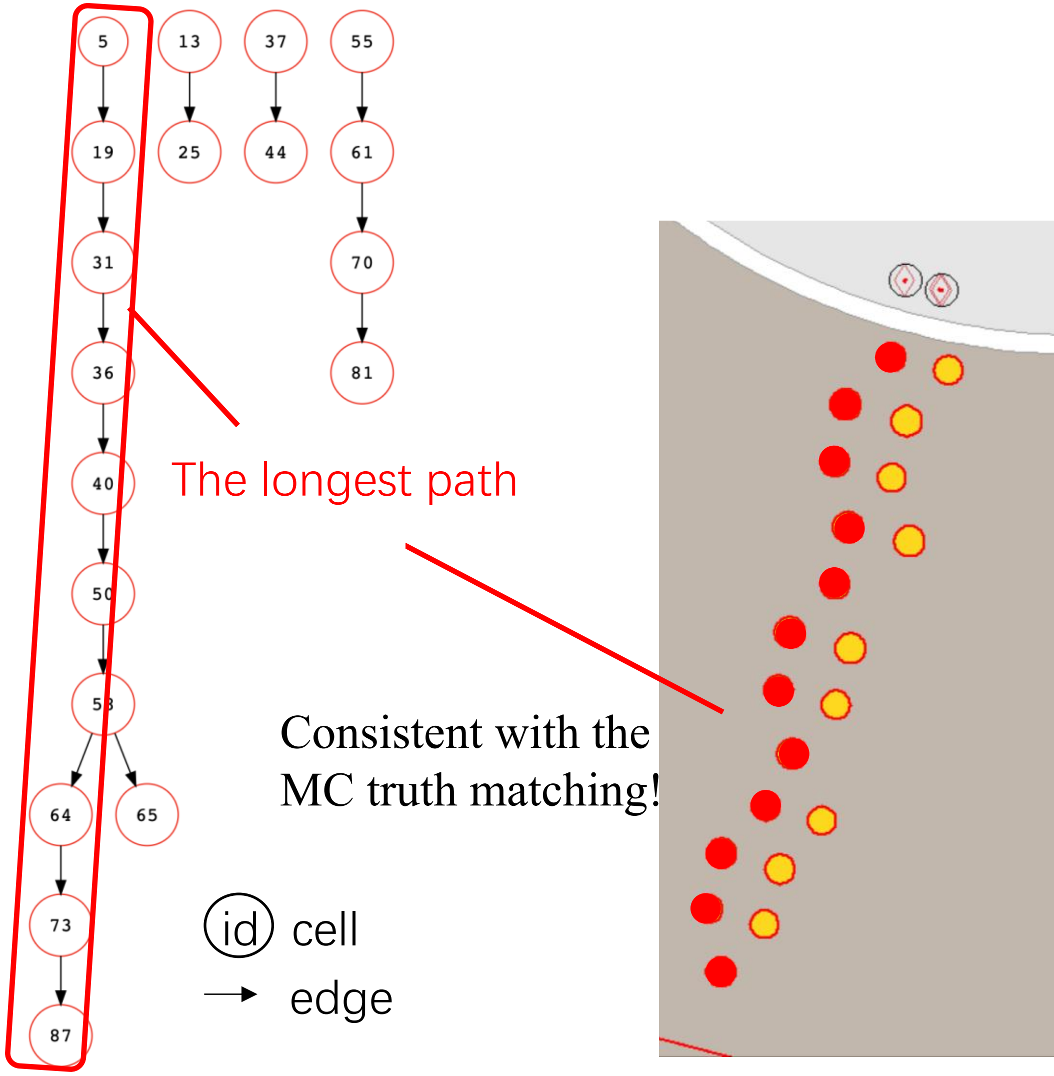
Black: state before update *Red: state after update*

the status will increase for those cells which have a matching left neighbor with equal status

Second Update



Based on this idea, we use the Depth-First Search algorithm to find the longest path.

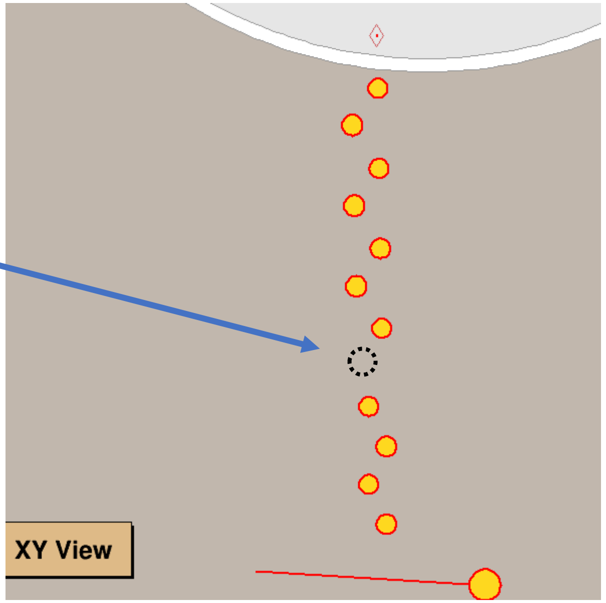


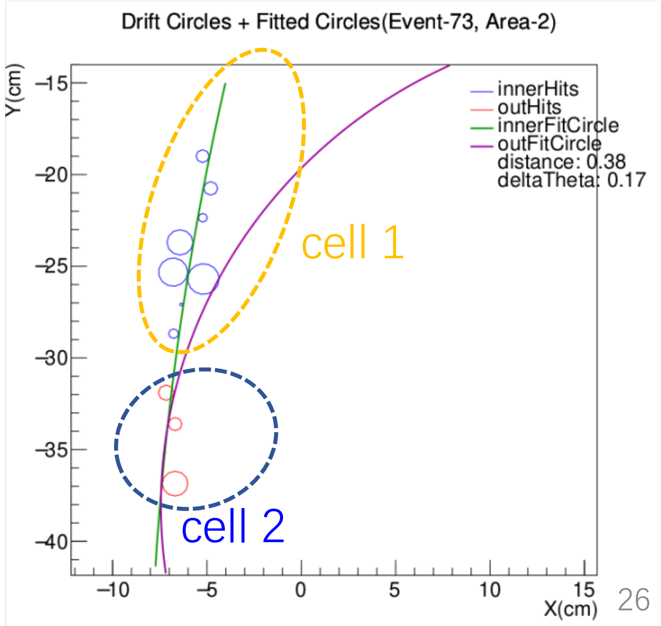
An example of track finding in Area-2.

Track segment connection (in an area)

- If one detector layer fails to respond, the track splits into several short segments
- "cell" and "edge"
  - A short segment is treated as a cell.
  - Build edges
    - They **share a common neighbor**
    - Their direction is similar
    - Their fitted circle parameters are matched

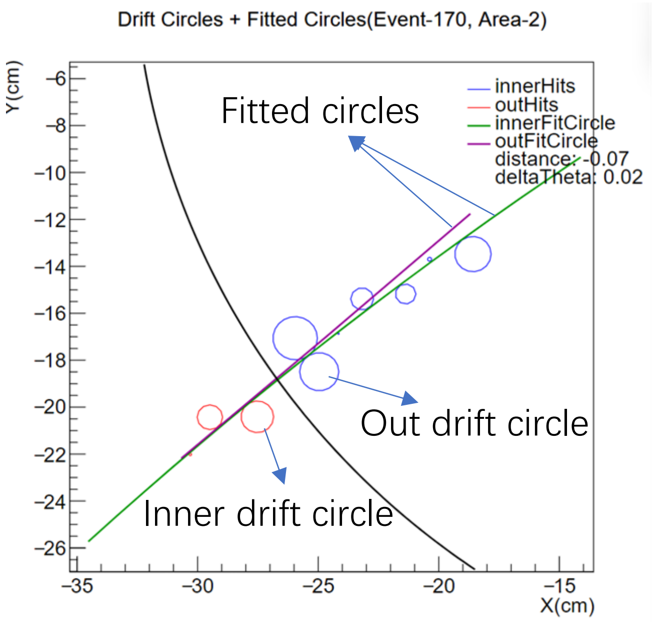
Due to the small number of hits and Left-right ambiguity of the drift chamber hits, the circle fitting performance is poor, making it difficult to directly match the fitted circle parameters.

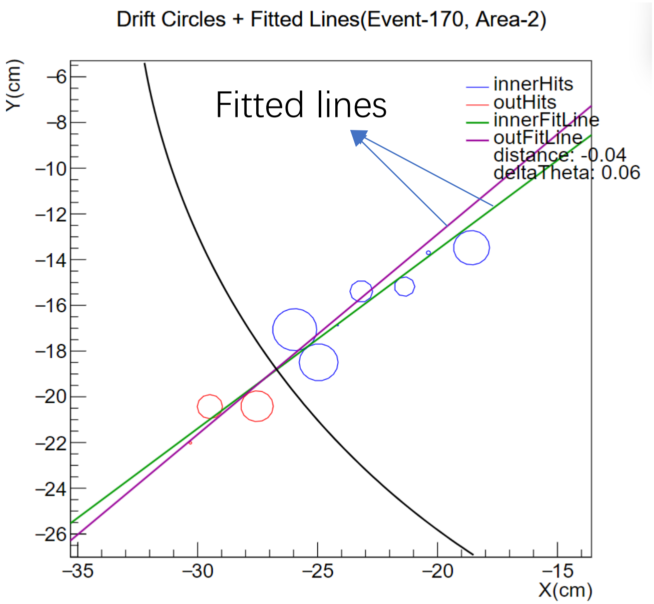




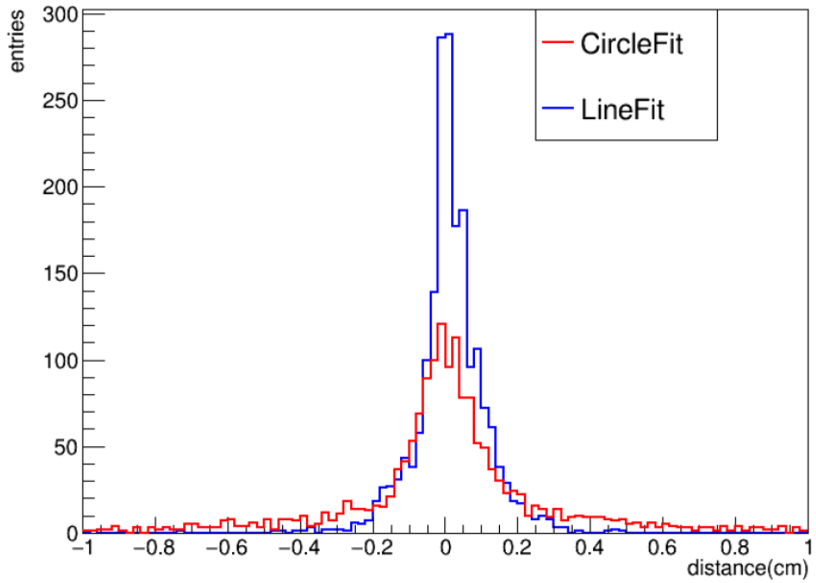
Track segment connection (in an area)

- Solution: use line fit and reference surface
  1. Choose a middle layer between the two segments as a **reference surface**
  2. Perform line/circle fitting on each short segment
  3. Compute the intersection point between each fitted line/circle and the reference surface
  4. Compute the **distance** between intersection points
  5. Make edges connecting pairs with distance (from line fitting) less than 4 mm





Statistics of Distance between Intersection Points



Line fitting shows better stability in statistical results.

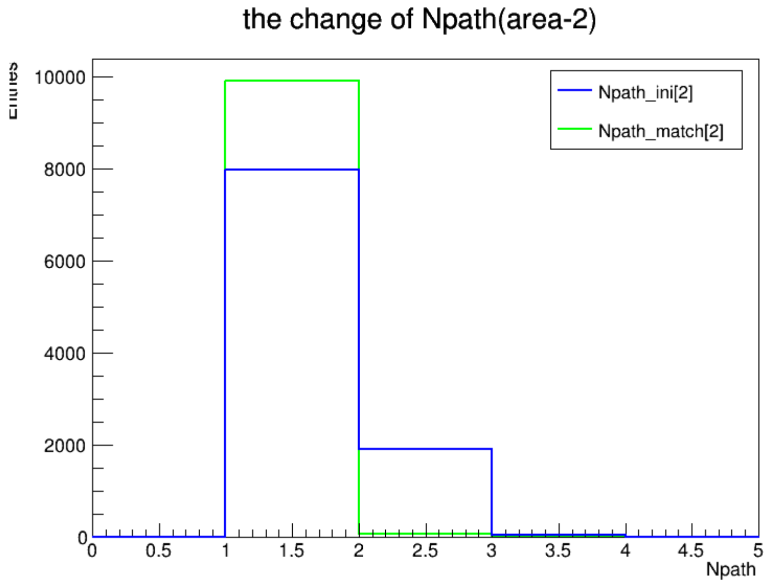
Performance

- The test sample consists of single-track μ^+ events with a transverse momentum of 0.5 GeV

- By Track segment finding with CA , most segment can be completely found

- By segment connection in area-2 , the number of track segments with multiple segments is significantly reduced

Hit Connection Rate via CA	
Number of events	10000
Total hits	357561
Total hits in segment	347673
Percentage hits in segment	97.24%
Total left hits	9888
Percentage left hits	2.76%

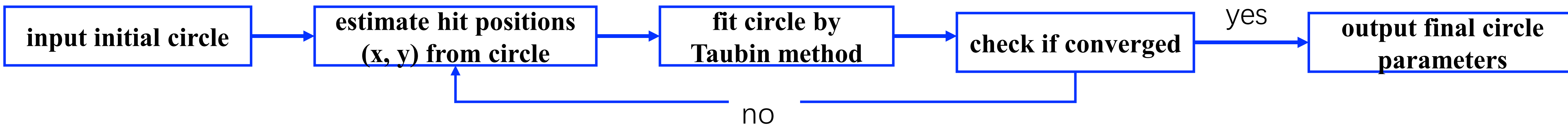


Compare the number of tracks before and after connection.

Circle fitting (ongoing study)

- Line fitting is more stable when there are only several hits, but it is not suitable for low-momentum particles. So effective circle fitting with several hits is necessary

- Circle fitting of track segment base on Taubin method



Flowchart of the Fitting Process Based on Taubin Method

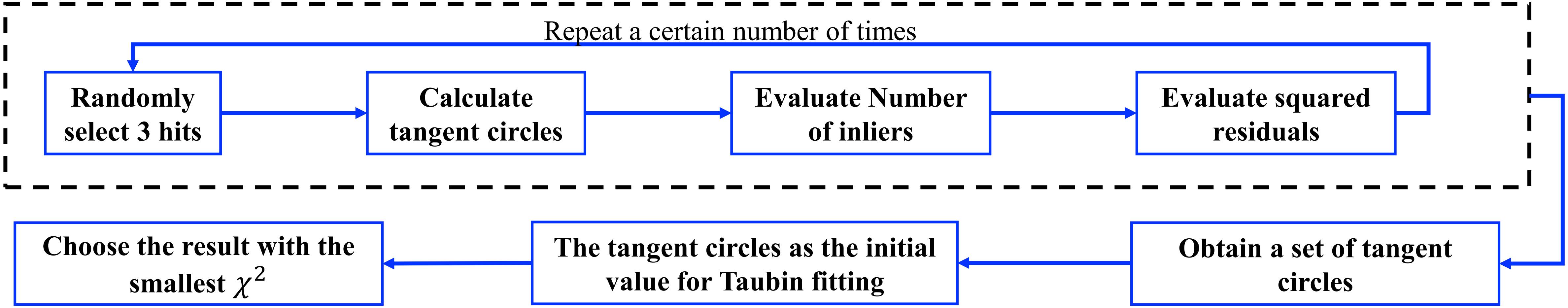
- Previous initial circle parameters of fitting
  - calculated from **axial wire positions**
  - Sometimes initial circle parameters are poor → **Incorrect Local Optima**
  - Fit quality is unstable

Circle fitting (ongoing study)

- Optimization

  1. RANSAC (Random Sample Consensus) algorithm
     - Randomly select 3 hits and calculate the eight tangent circles.
     - Select the candidate circle with the most "**inliers**"(close hits) and squared residuals less than a threshold.

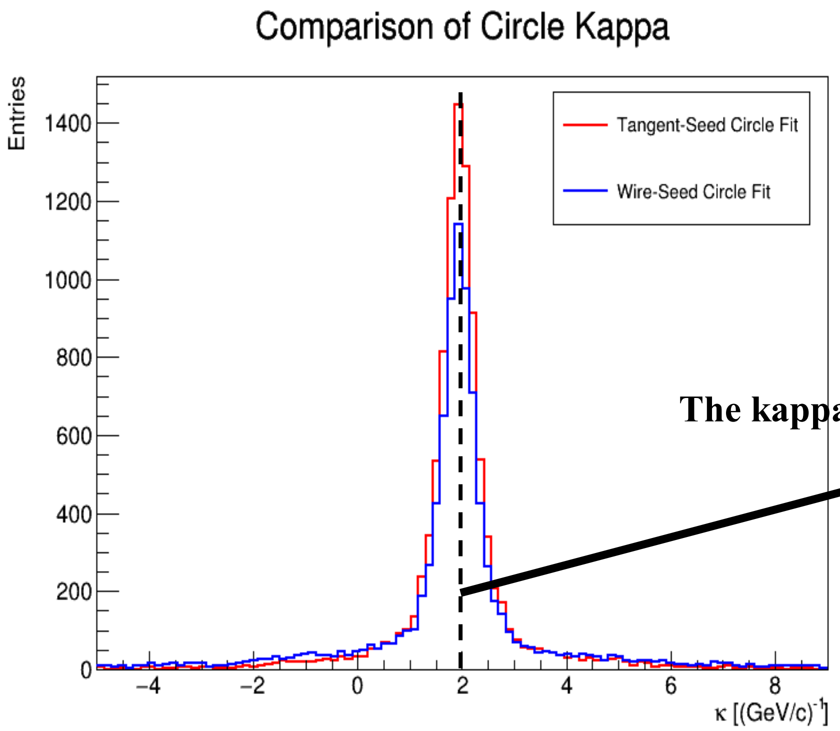
  2. Try multiple initial circles
     - Try multiple sets of initial circles
     - Select the result with the smallest χ^2



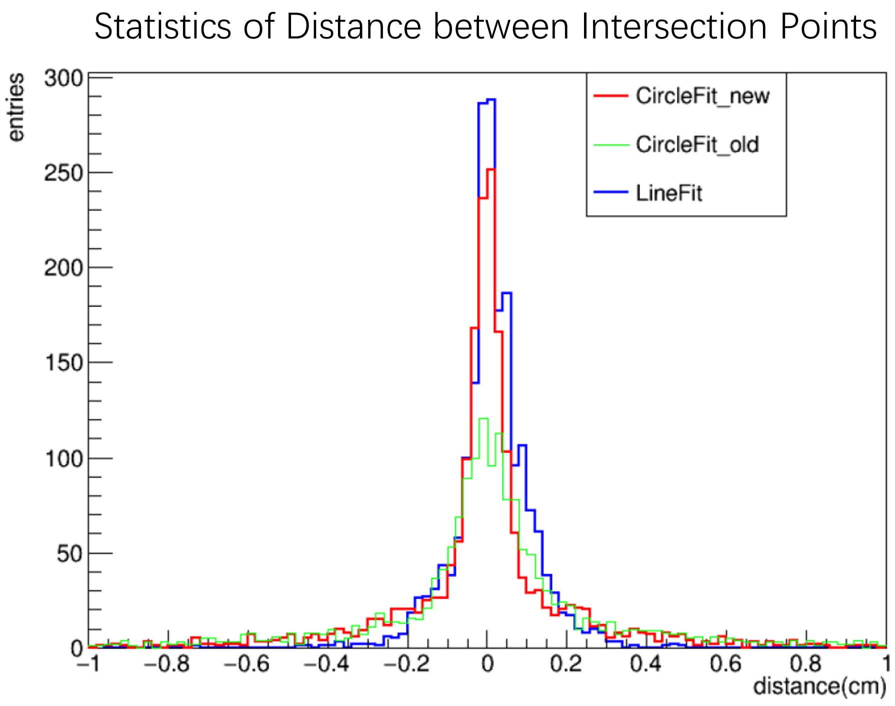
Workflow: Finding Initial Values

Circle fitting (ongoing study)

- **Performance**
  - The result by combining RANSAC and Multiple initial circles ,are more reliable than those derived directly from wire positions.



The kappa of the test sample is 2 $(GeV/c)^{-1}$



The distribution of kappa values from the optimized method is more concentrated around the true value compared to the previous method.

distance between intersection points becomes better after optimization, but the is still worse than that of the linear fit.

Summary

- ✓ BESIII inner tracker upgrade: the Inner Drift Chamber has been replaced with the CGEM
  => new track reconstruction with CGEM+ODC need to be developed

- ✓ Global track finding with Hough Transform: development done
  comparing with MDC results:
  - ✓ comparable performance for events with 2 to 6 prongs
  - efficiency is lower for low momentum tracks, high multiplicity and secondary vertices events, more optimization in progress

- ➢ Local track finding with Cellular Automat: in development

Thank you for listening!