# Track Reconstruction in BESIII Multilayer Drift Chamber

Jin Zhang[1], Yao Zhang[2]

1. Sun yat-sen University
2. Institute of high energy physics

On behalf of the BESIII offline software group

2023年粒子物理实验计算软件与技术研讨会

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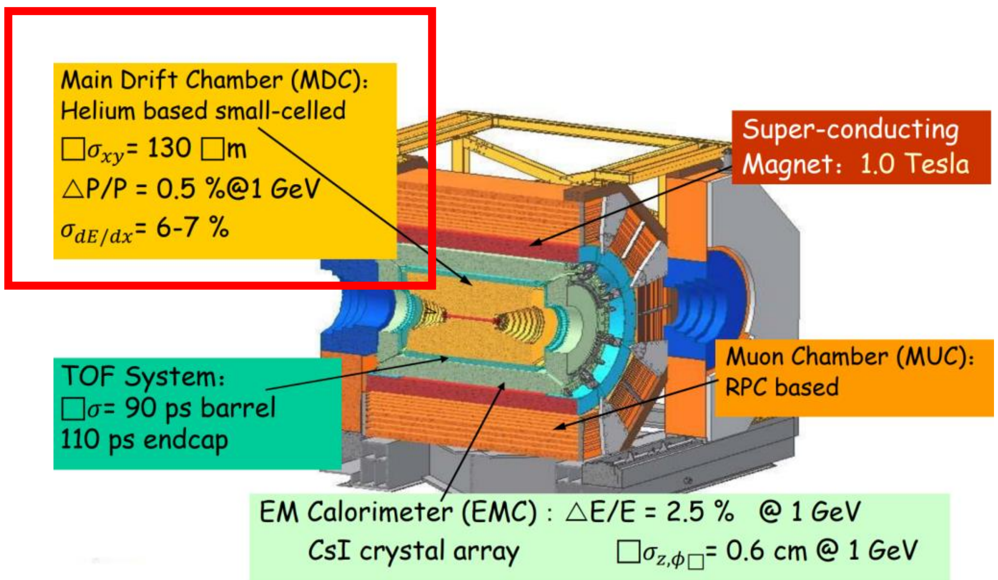
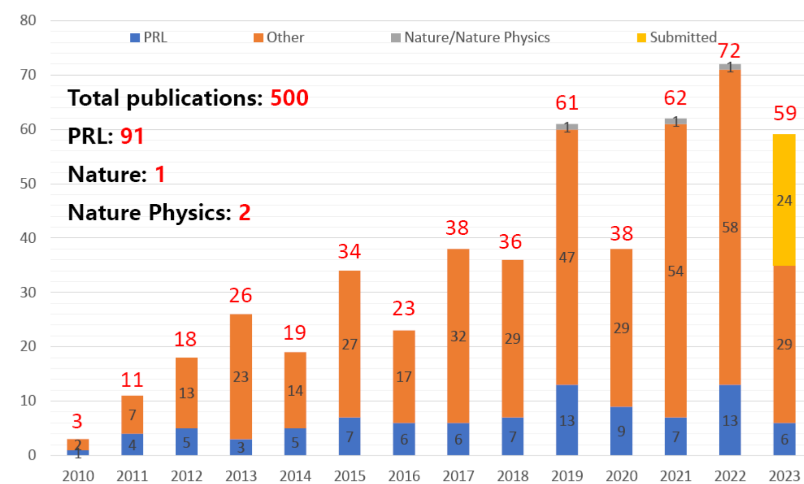
# Beijing Spectrometer(BESIII) Experiment

- 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.



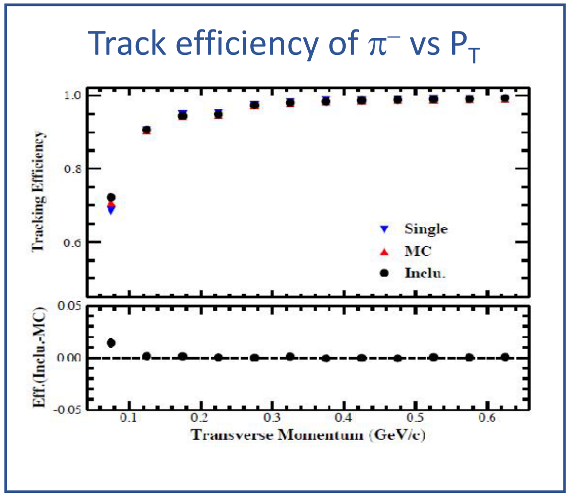

**BESIII publications (May 9, 2023)**



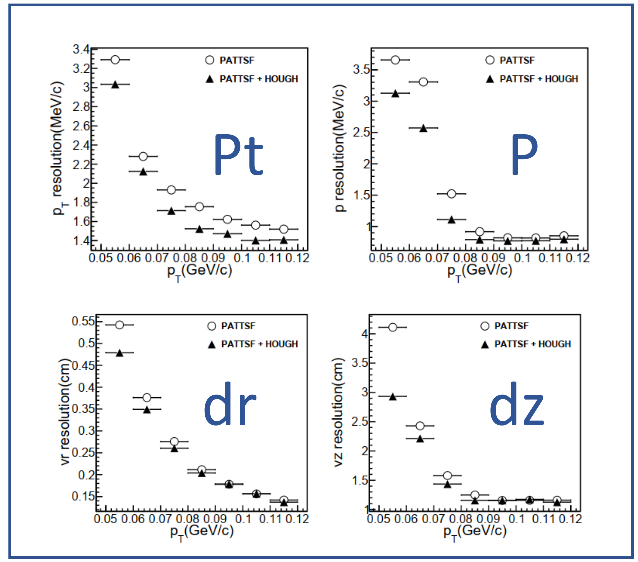

**Util May 9th 2023, 500 papers have been submitted!**

# Track Reconstruction in MDC(i)

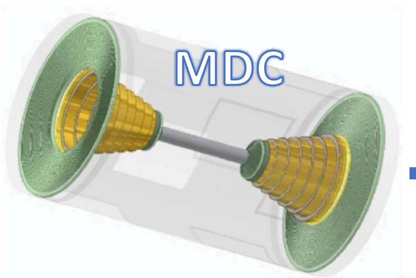
EFFCIENCY




RESOLUTION




SPEED



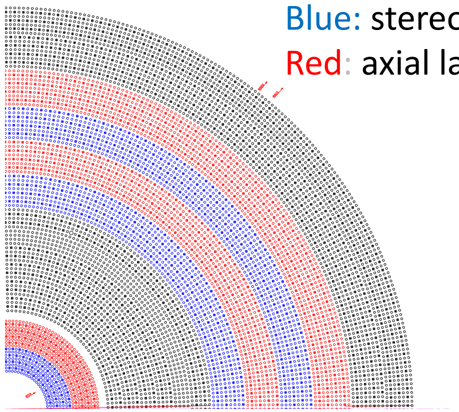

Tracker → Momentum

Vertex → Impact parameters

- Tracker, also Vertex detector (MDC Inner Tracker)
- Critical for precise measurement of momentum and vertices

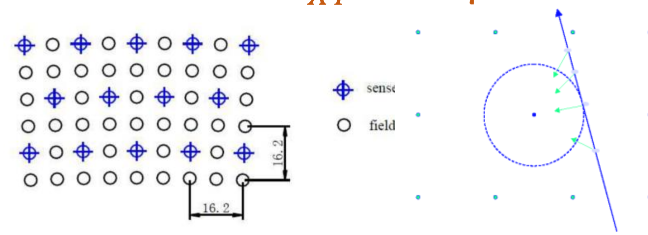
# Track Reconstruction in MDC(ii)

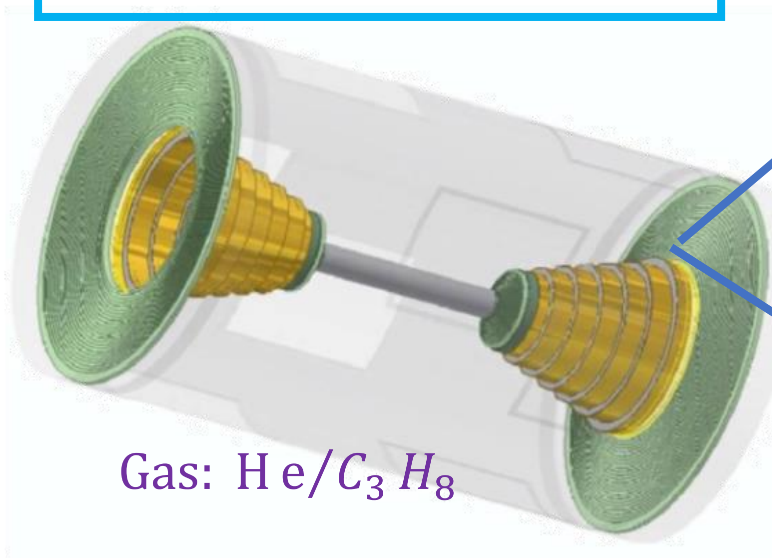
## Geometry

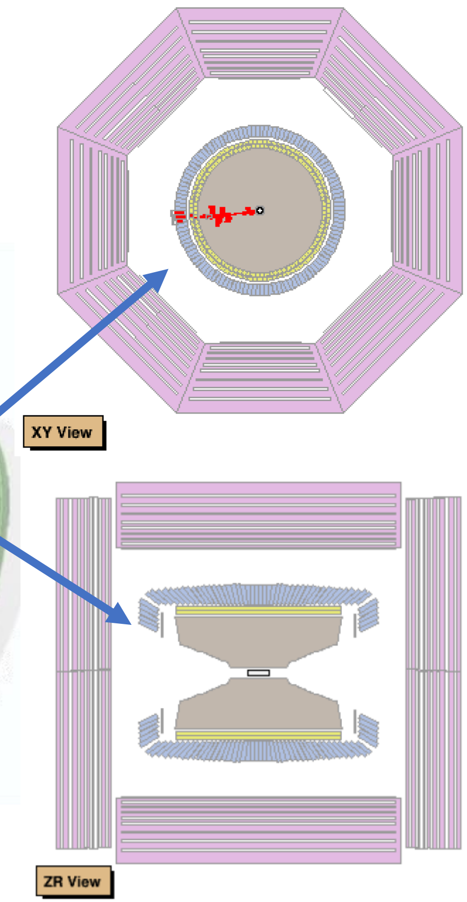



- 43 layers, Axial layer : 2D / Stereo layer : 3D
- 11 superlayers
- Inner Chamber : 8 stereo layers
- |cosθ|<0.93

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




- Typical Helix model $\mathbf{P} \equiv (d_0, \phi_0, \kappa, z_0, \tan\lambda)$
- 2D – 3D , local method in superlayer is the basis for Track Finding
- Inner Chamber: crutial for transverse and longitudinal impact parameters ($d0$ and $z0$)

# Track Reconstruction in MDC(iii)

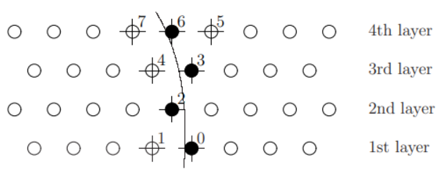
## Track Finding

2D Track Finding

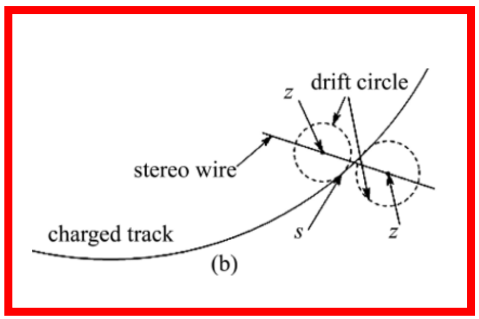
3D Track Finding

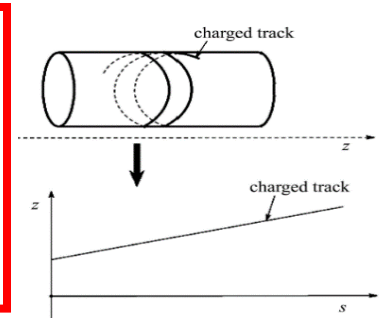
Pick up axial-wire hits → 2D track → stereo-wire hits using 2D track → s-z fit with left/right ambiguity → 3D helix

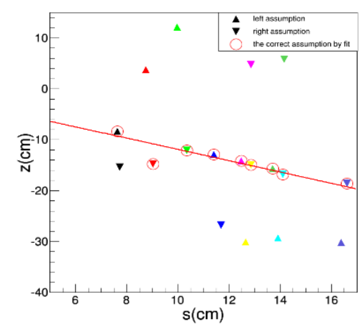
Local method in super layer




Global method : Hough Trans



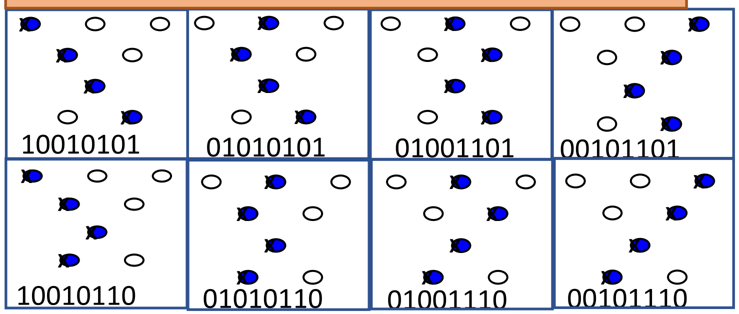

- Local && Global track method in 2D Track Finding
- 2D(circle) track parameters is key input for stereo-wire calculation
- All candidate hits are fitted to 3D(helix) tracks

## Track Fitting: RungeKutta + Kalman

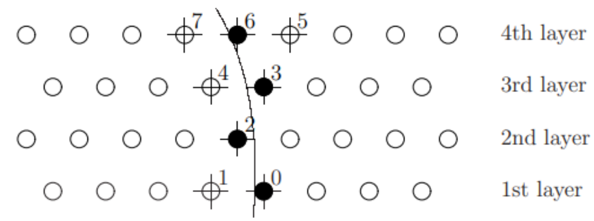
# Template matching

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

4-hit pattern, 8 wire group dictionary

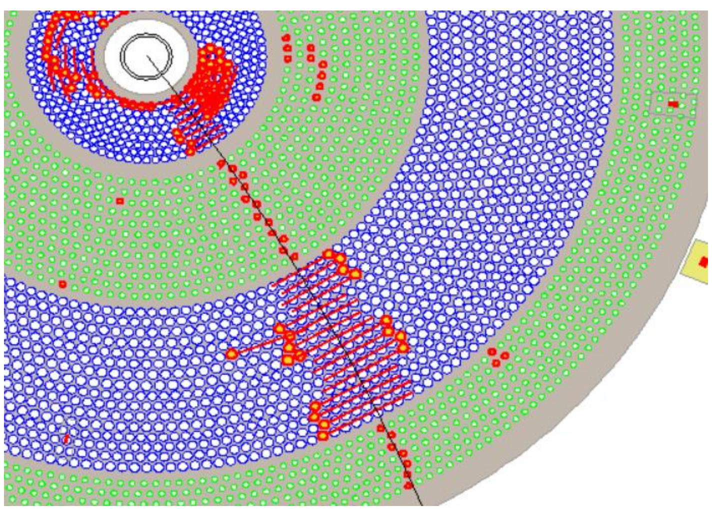



Matching pattern in superlayers



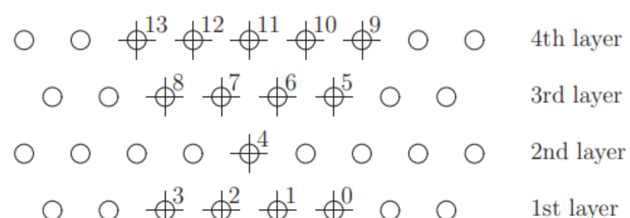

Match template in superlayers → Link axial Segment → Circle fitting → Link stereo segment → Helix fitting

- Pros : Advantageous for high transverse momentum(pt) tracks



Straight : high efficiency for matching
Long : More track segments

- Cons : Azimuth coverage angle of segment groups does not meet the requirements for low pt track segment finding

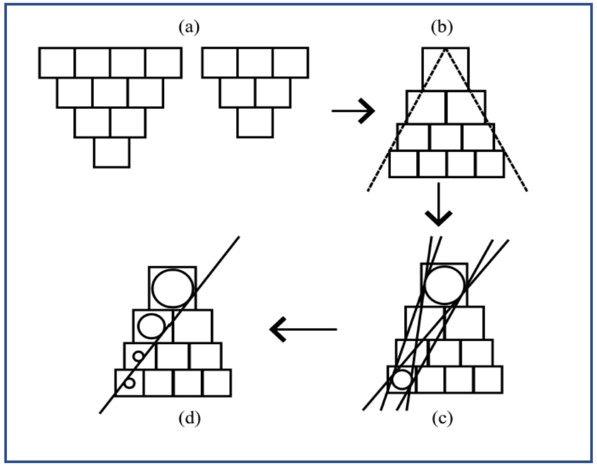



a 14-wire group

Extending template to 14 wire group

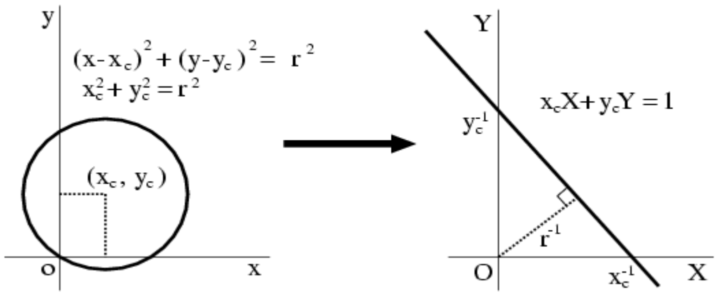
# Segment Finding using Conformal Transform

- Similar segment finding method with PAT, but for the higher curvature tracks in superlayers
  - Considering measurements: using drift circle information
  - 8-hit pattern -> Common tangents of drift circles : using Conformal Transform

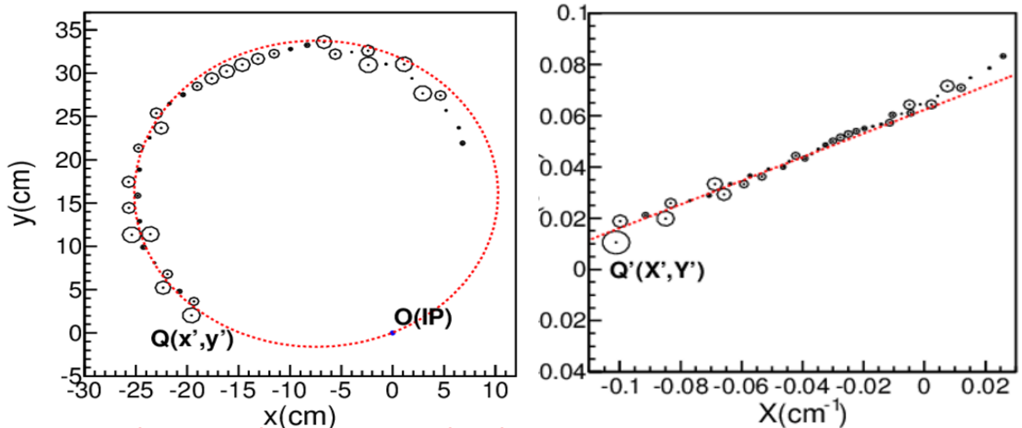



## Conformal Transform

$$X = \frac{2x}{x^2 + y^2}, Y = \frac{2y}{x^2 + y^2}$$




## Conformal Transform in MDC




Circle track -> straight line

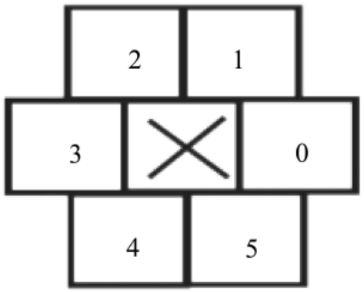
Drift circles -> new circles tangent to the straight line

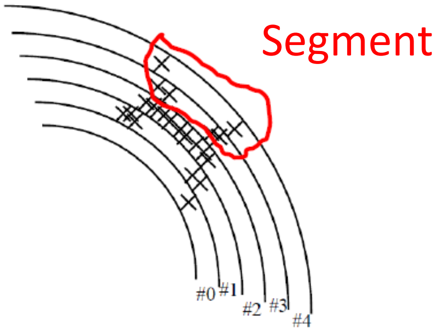
High failure rate for curling tracks with multiple hits in the same layer

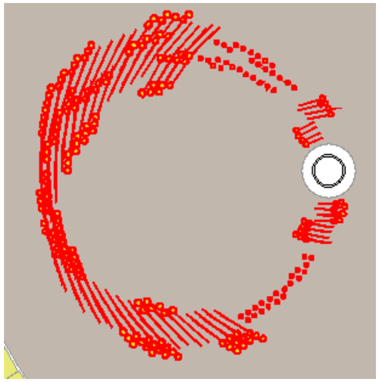
# Road method For Curling Tracks

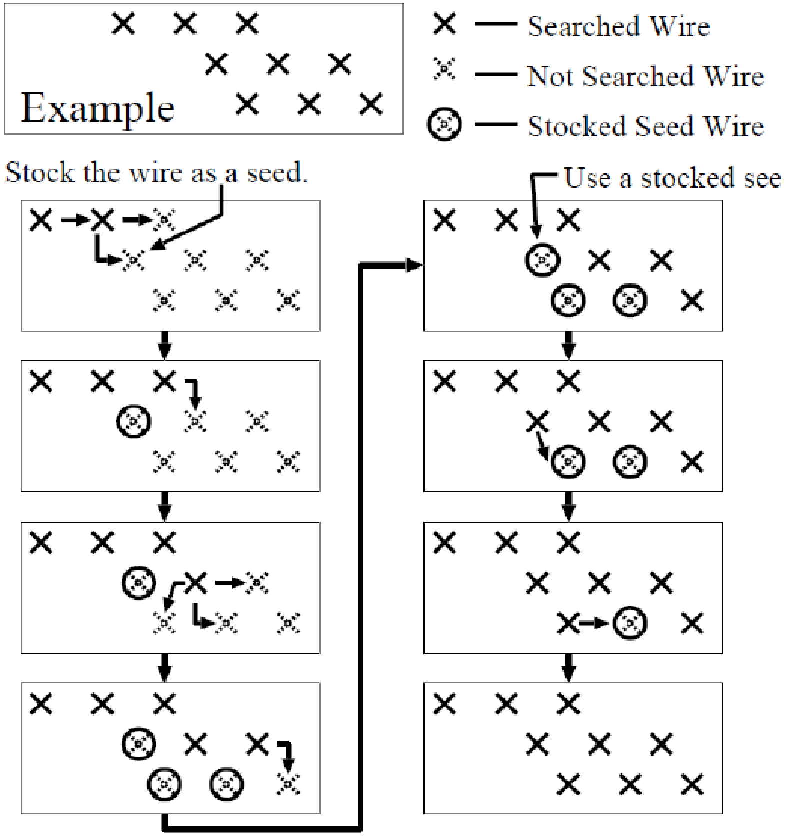
- ➢ Segment finding： for continuous neighbor hits in superlayers
- Road： from one segment -> circle fitting -> pick up close hits
- No drift circle information

Neighbor hits





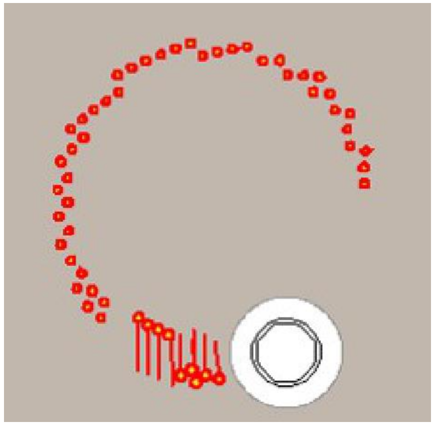

Not feasible for multi-turn tracks

# Low Transverse Momentum Track

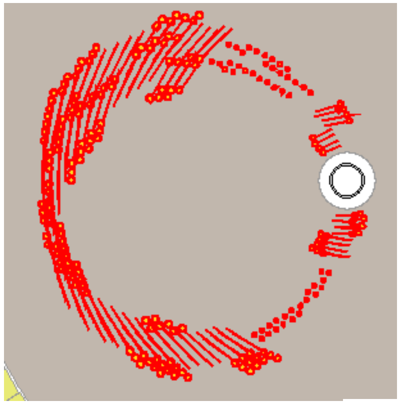
## ➢ Geometrical problem : pt < 120MeV

Curling, multiturn curves in XY plane

Passing less superlayers



Leaving multiturn curves

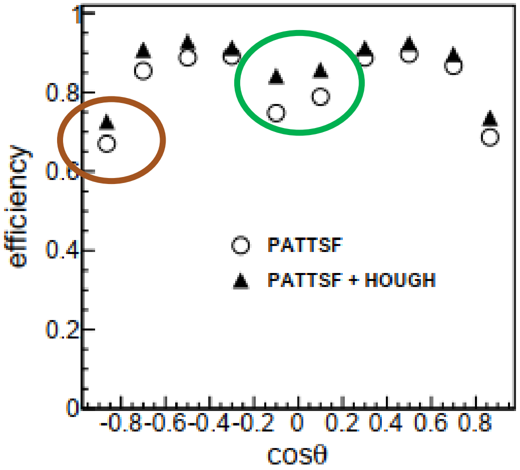


Severe impact on Inner Tracker - Hits overlapping

Difficult to tell hits in 1st

Tracking performance closely related to dip angle ($\cos\theta$)

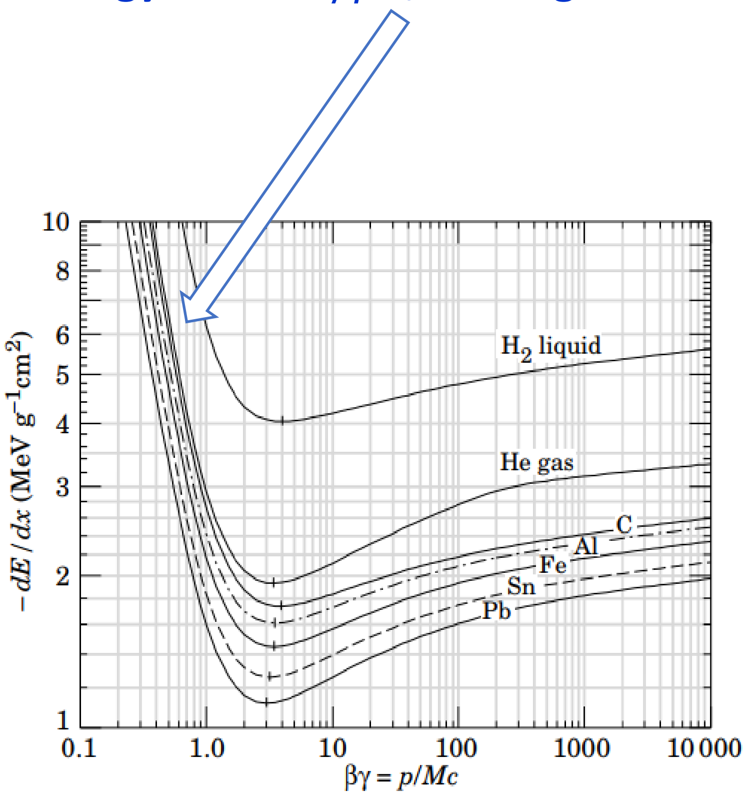
- Large $|\cos\theta|$: quickly flies out along z
  - Short tracks with insufficient hits
  - Only Inner stereo hits for z information
- Small $|\cos\theta|$: curling in MDC
  Multiturn tracks



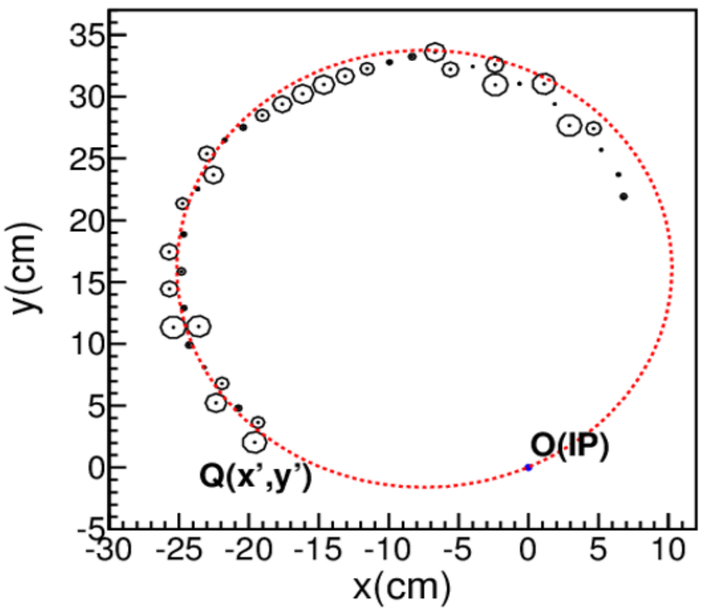
# Low Transverse Momentum Tracks

## ➢Material effect

- **The momentum resolution and the impact parameter resolution are dominated by multiple scattering**
- **Energy loss ~ $1/\beta^2$, leading to effective deflections of particle**




dramatic change of curvature



# Legendre Transform For Low Momentum Track(i)

## Hough/Legendre transform in MDC

- Global method relies not on segment on superlayers
- Considering drift distance information
- More hits in the initial step

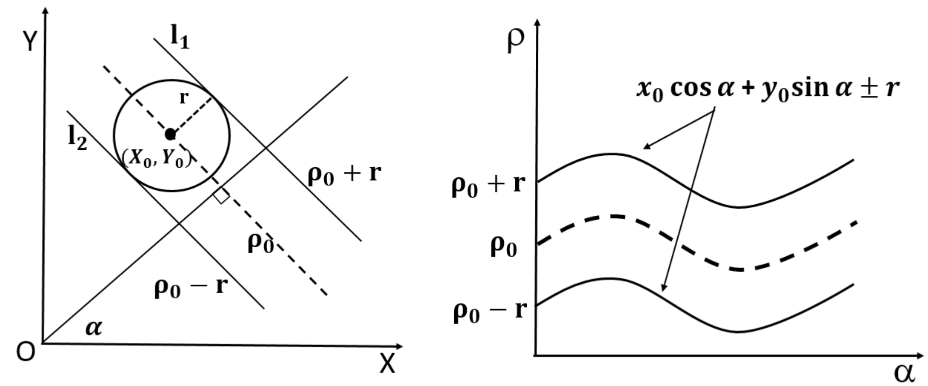
## steps

I. Conformal transform

II. Legendre Transform

III. Vote lines in histogram

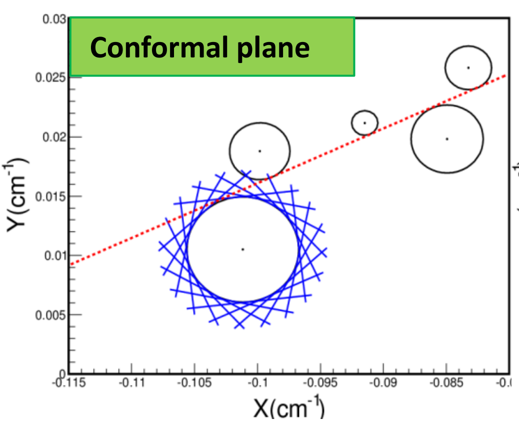
IV. Peak finding method



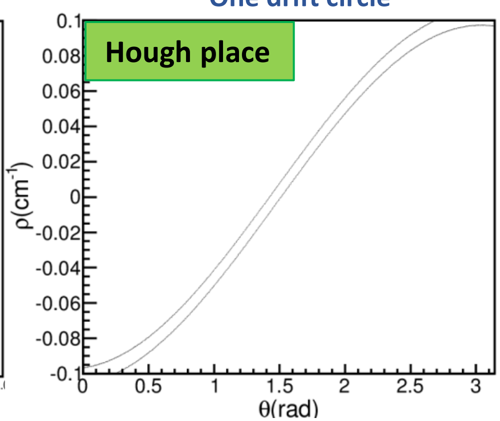

One drift circle->two curve lines on Hough space

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

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

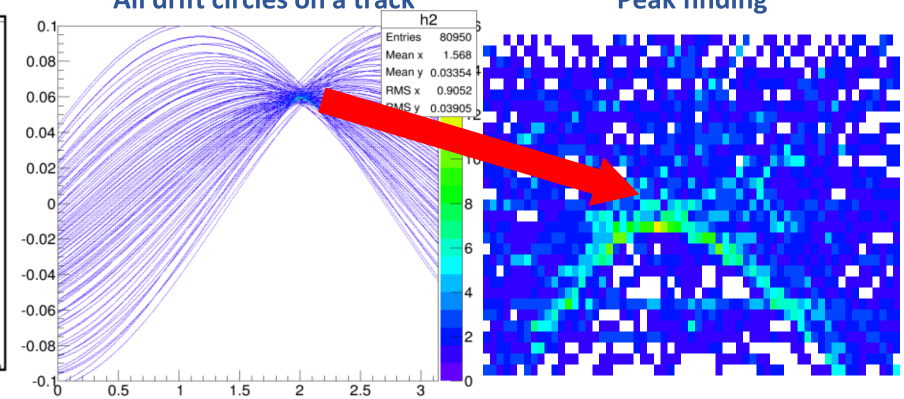



One drift circle



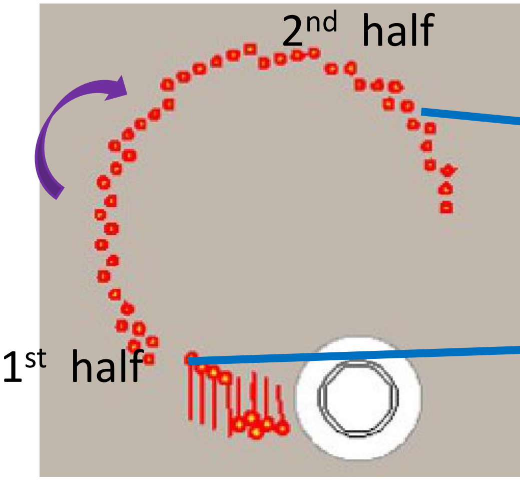

All drift circles on a track

Peak finding

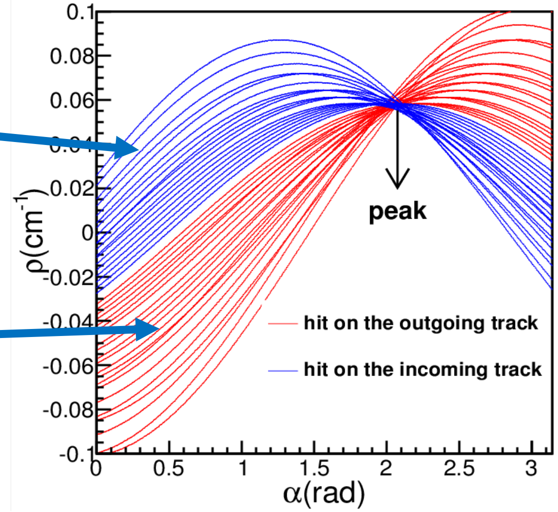


# Legendre Transform For Low Momentum Track(ii)

**A curling track**

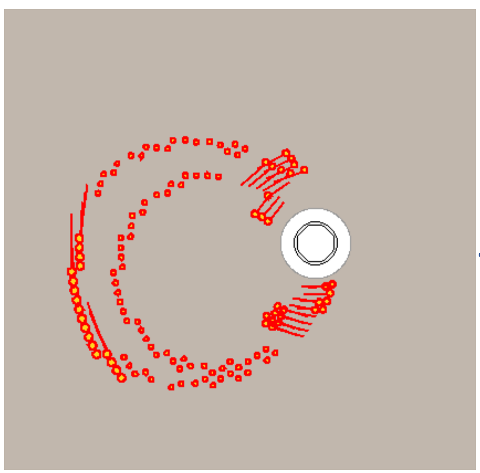



HoughMap

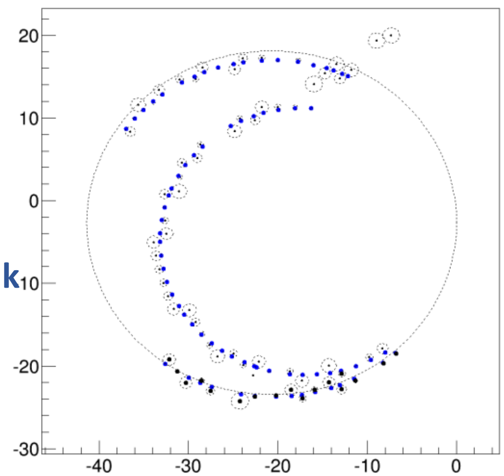



Deviation causing by energy loss

**A multiturn track**



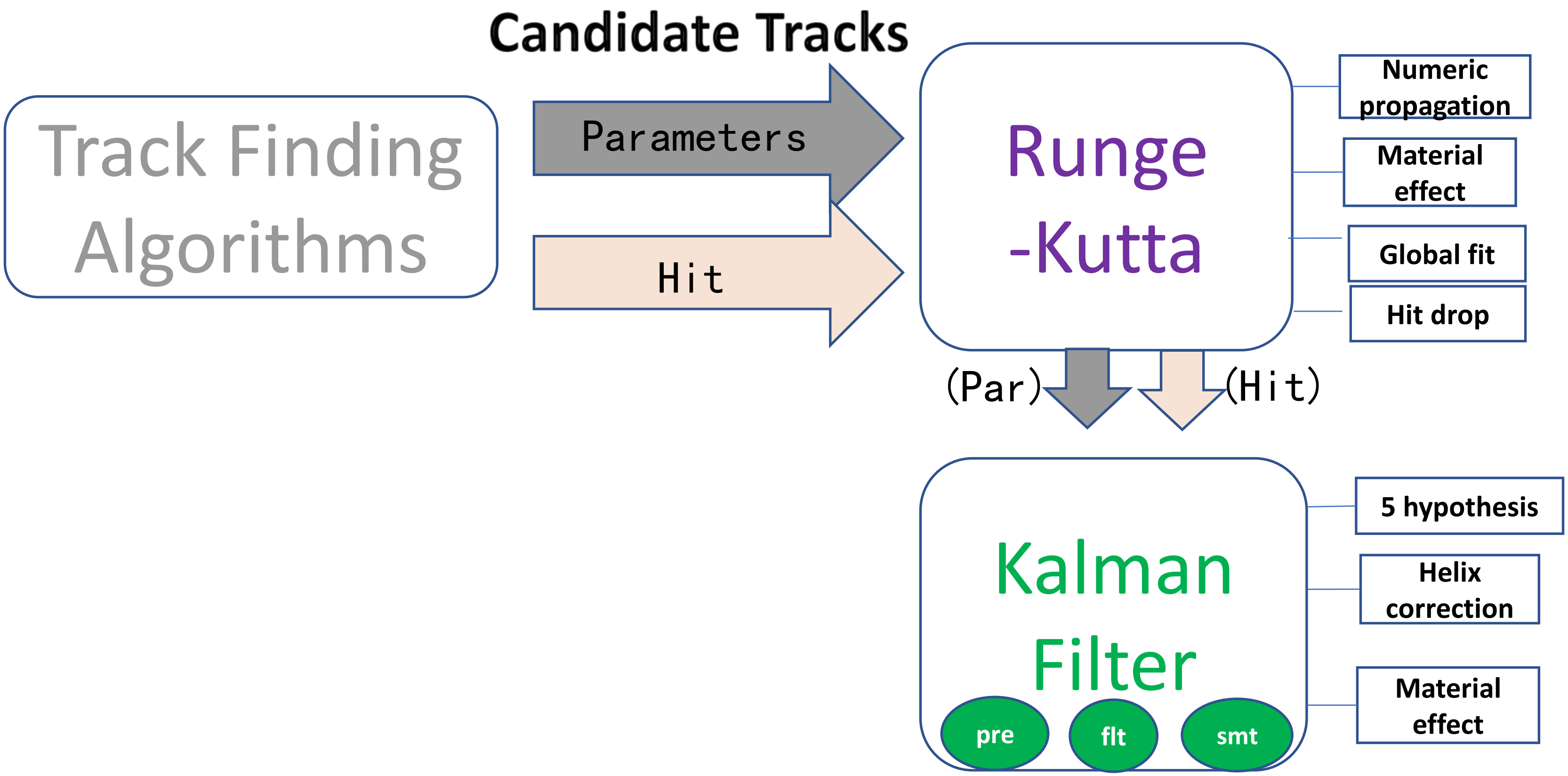
**Tracks found by peak finding method**



Many optimizations for multiturn tracks in detail

# Track Fitting in BESIII

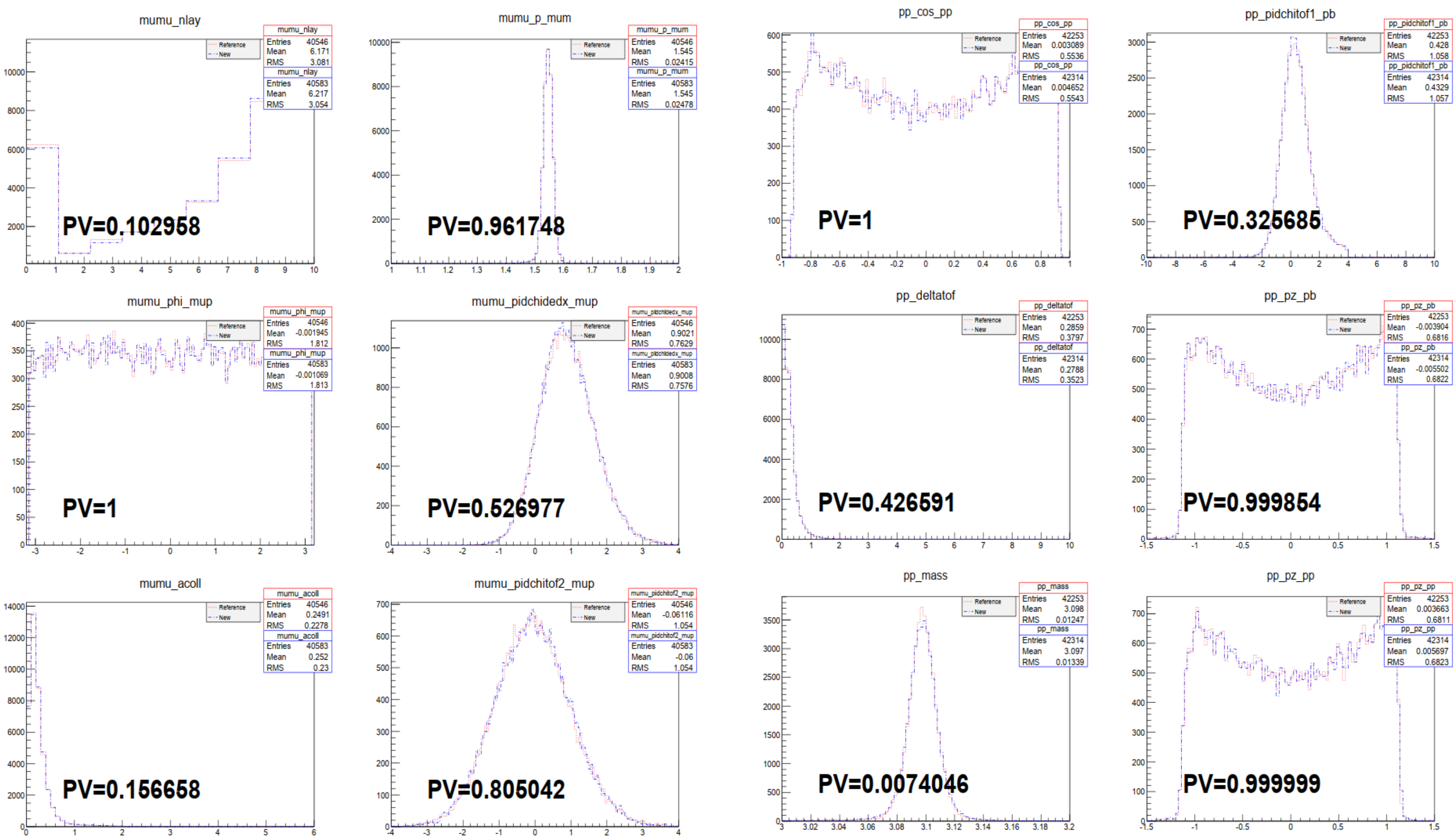
- Candidate tracks from Track Finding algorithms as input
- Two fitting algorithms : Runge Kutta -> Kalman Filter



- BESIII reconstruction software have been validated, providing reliable data for BESIII physics
- Stability and long term maintenance relies on lots of work in data quality check

# Performance validation for new Release

## Amounts of histogram checking before new version releases



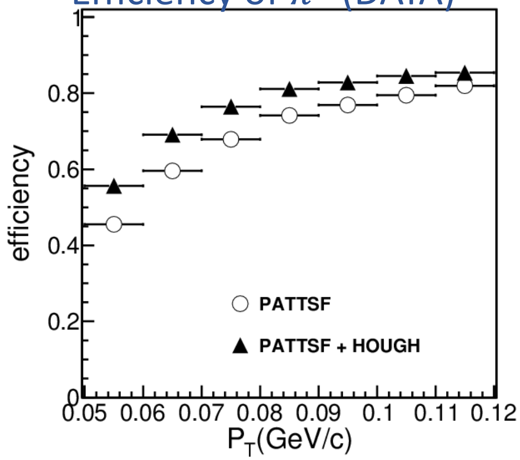

Slides from Xiaobin Ji

# Performance validation for new Release

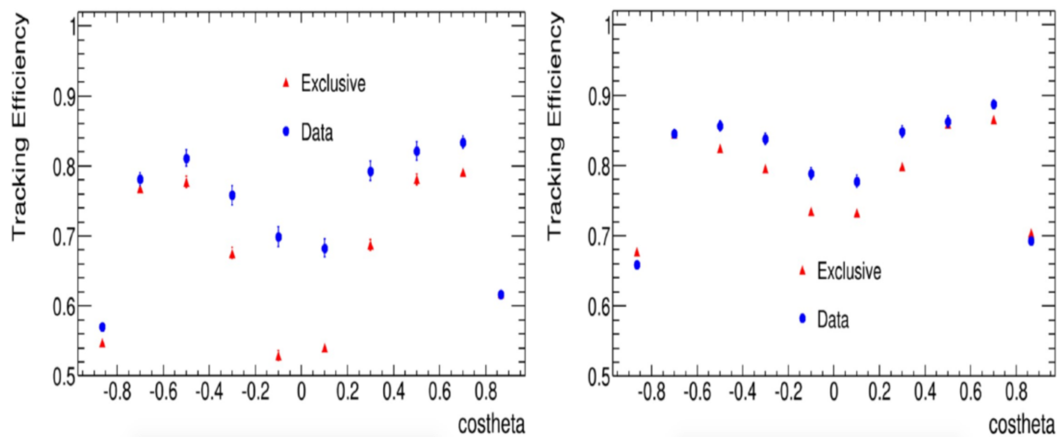
When reconstruction upgrades, validations in different physics channels

$J/\Psi \to p\bar{p}\pi^+\pi^-$

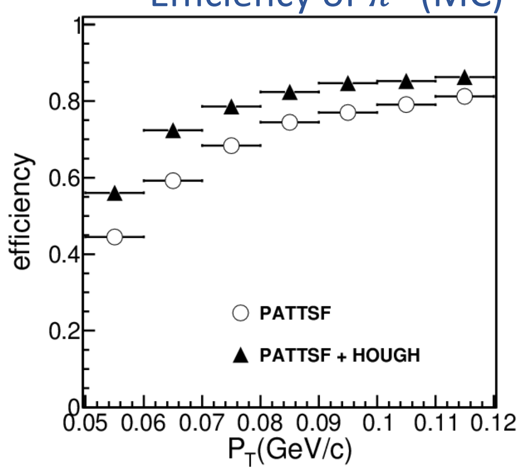
Efficiency of $\pi^+$(DATA)



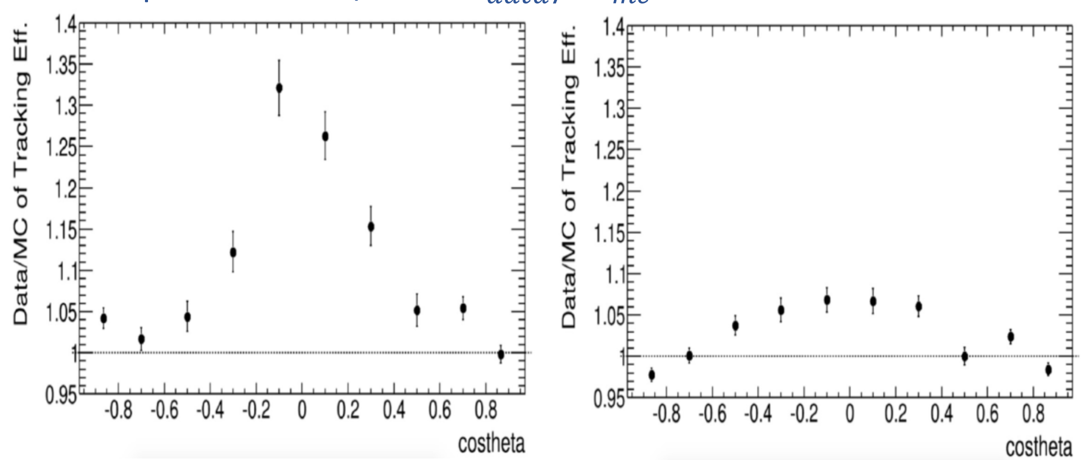

Comparison of MC/data efficiency vs cosθ




Efficiency of $\pi^+$(MC)



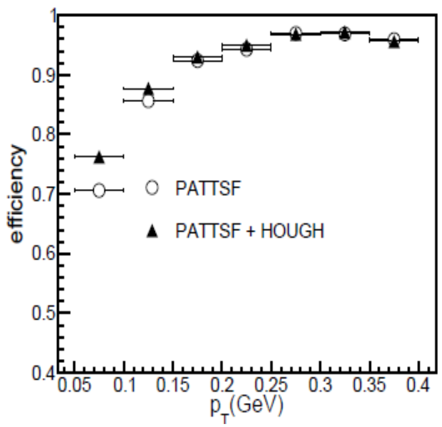

Comparison of MC/data $eff_{data}/eff_{mc}$ vs cosθ



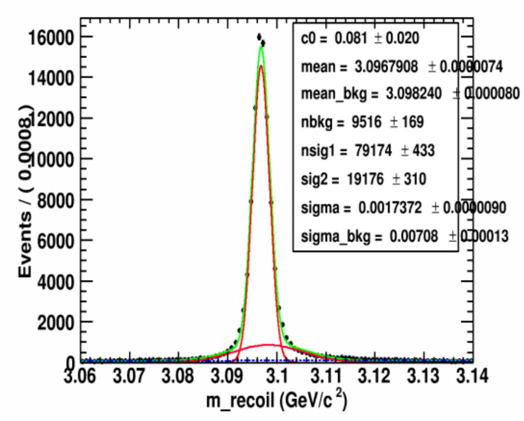
# Performance validation for new Release

## Ψ(2s)-> $\pi^+\pi^-$J/Ψ , J/Ψ ->$e^+e^-$

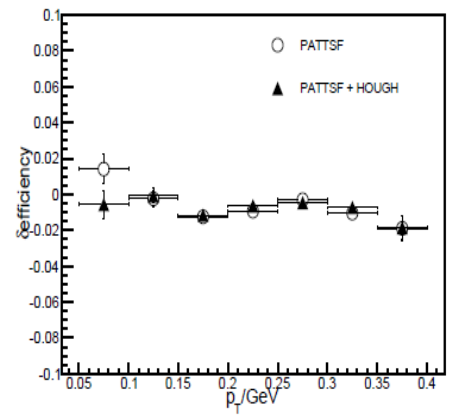
Efficiency of $\pi^+$(DATA)




J/Ψ Recoil mass (PATTSF+HOUGH)

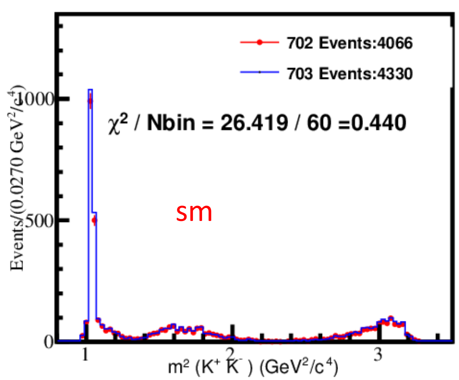


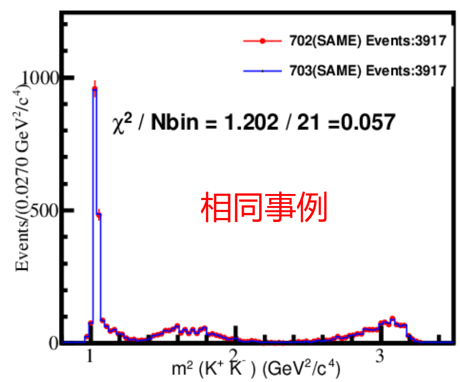

Efficiency of $\pi^+$(DATA-MC)

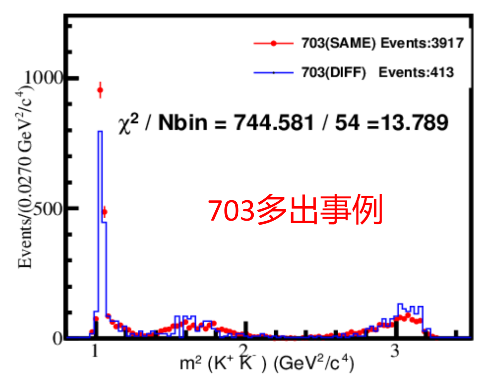



## $Ds^+ \rightarrow K^+K^-\pi^+$

Dalitzs plots projecting on $m^2(K^+K^-)$



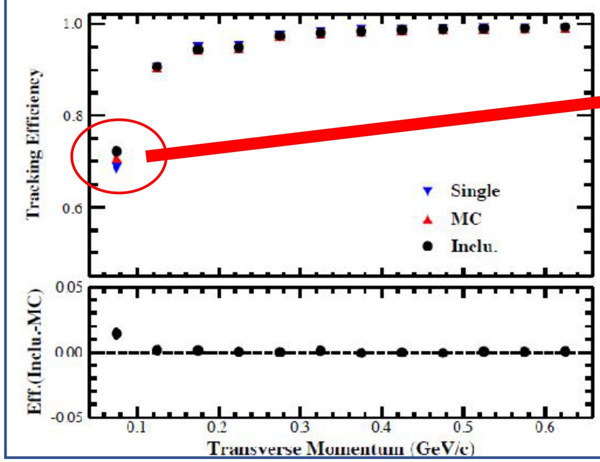



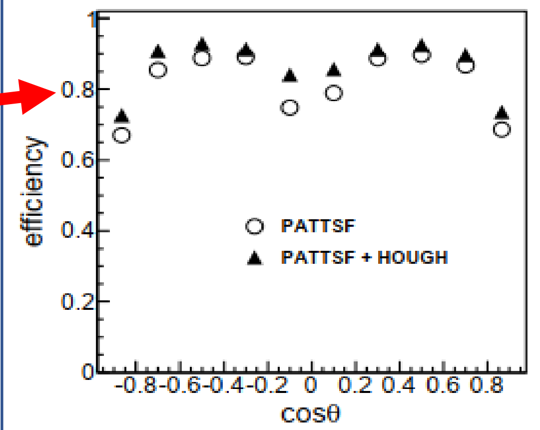
# Track Reconstruction Performance

## EFFCIENCY

Track efficiency of $\pi^-$ vs $P_T$




Efficiency vs cos




*Efficiency – Reconstruction efficiency, not comparison definition to MC Track

Track selection and event selection

1) 径迹级别

a) 要求径迹的顶点：$|v_r| < 1cm, |v_z| < 10cm$

b) 要求径迹的角度：$|cos\theta| < 0.93$

c) 对于带电径迹，要做带电粒子鉴别（PID）

2) 事例级别

a) $Mass_{p\pi} > 1.15GeV/c^2$

b) 带电径迹至少三条

c) 对于非"missing track"，有且只有一条径迹

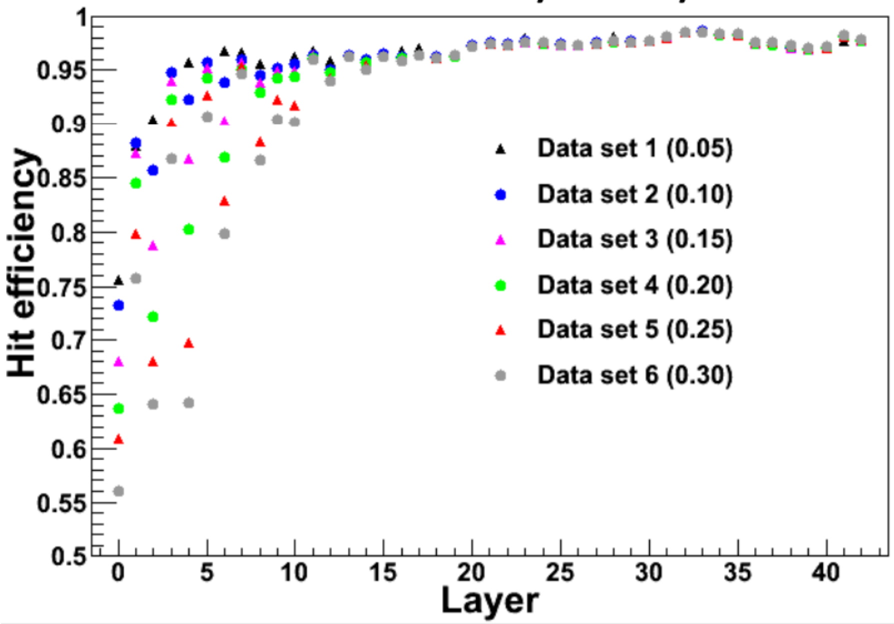
d0 cut ~ -10%

z0 cut ~ -10%

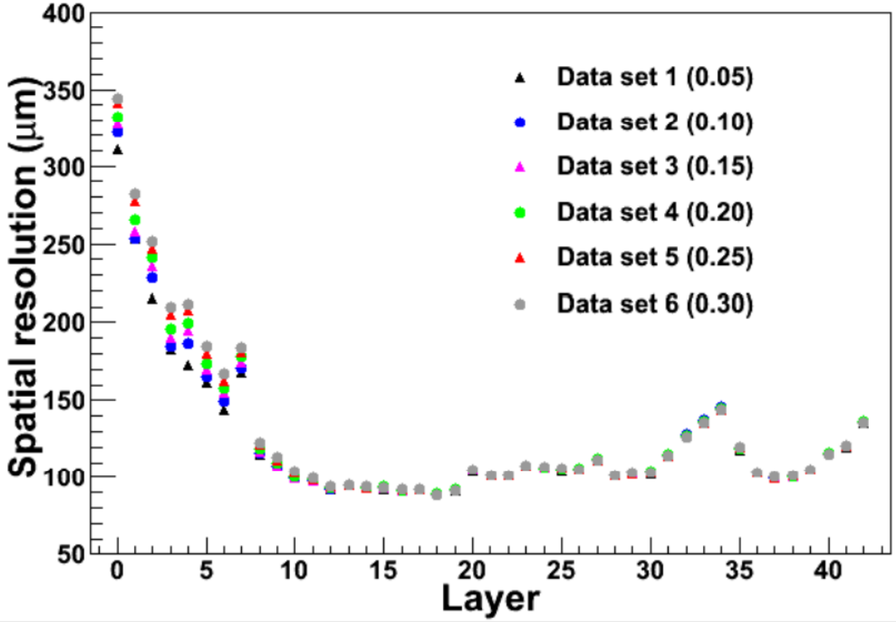
➢ The loss of efficiency is not the loss of the entire track, in most cases the track parameters are not well reconstructed and then lost

# Hit efficiency/Spatial resolution vs noise level

Rec Hit efficiency vs layer




Spatial resolution vs layer

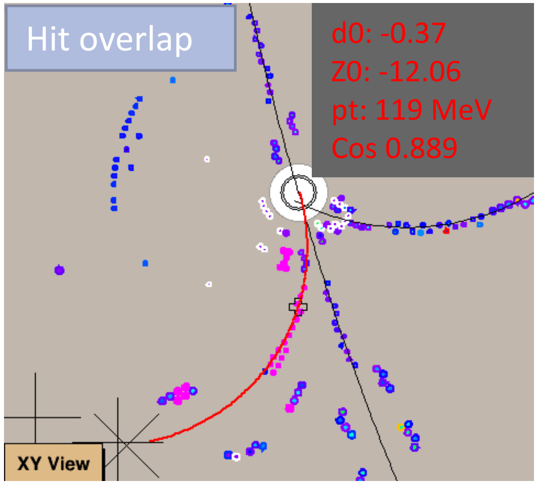


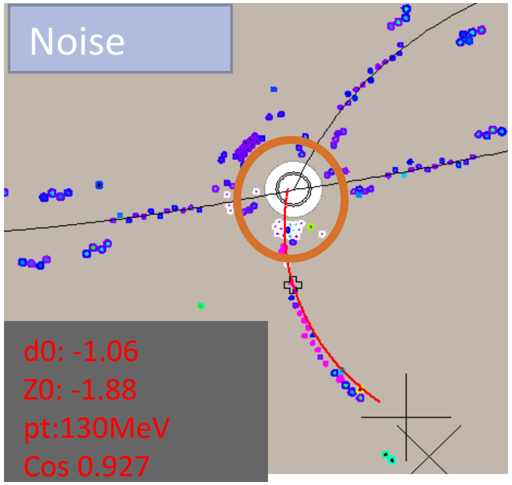

Rec hit efficiency = number of times used in track fit / number of times with tracks pass

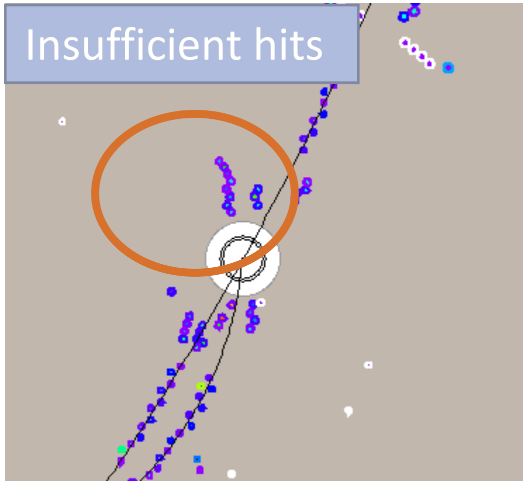
Impact parameters resolution dominated by Inner Chamber

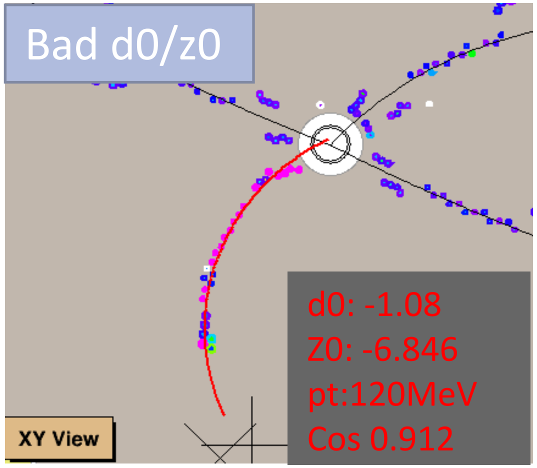
Slides from Linghui Wu

# Low Pt tracks lost at large dip angle




Manually checking 100 samples

| | ratio | |
|---|---|---|
| Hit overlap | 17% | (1) |
| Noise | 18% | (2) |
| Insufficient hits | 32% | (3) |
| Bad d0/z0 | 33% | (4) |

- (1)(2)(3) difficult to salvage
- (4) room to improve

# Challenges, Potentials, new techniques

- Challenges in some tough conditions
  - Low momentum optimizations
    - Multi-turn : hits overlapping – clone tracks, bad quality tracks
    - Obvious material effects  - uncertainties in track
  - Large dip angle track with fewer hits
    - Very difficult only with IDC
  - Long vertices track reconstruction

# Challenges, **Potentials**, new techniques

- Non gaussian errors in track fitting
  - Non gaussian errors in track fitting
    - Electron tracks - Bremsstrahlung
    - Multiple scattering – double gaussian
    - Energy loss – Landau distribution

- Robust fitting
  - Some Extended Kalman filter: Noise/outlies rejection

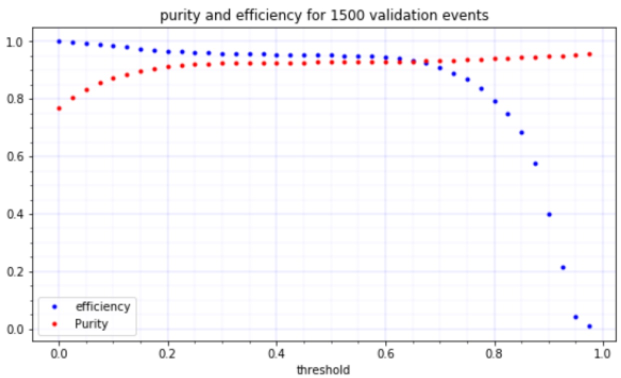
# Challenges, Potentials, **new techniques**

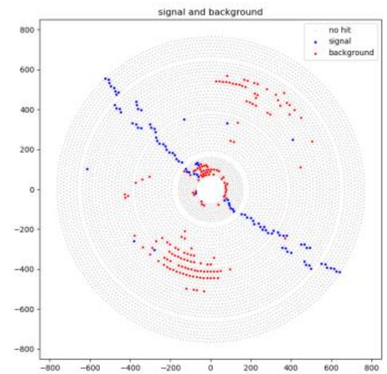
- Machine learning must be the future trend in track reconstruction

- There is a baseline reconstruction software to reconstruct the data, how to apply machine learning in MDC track reconstruction is an interesting issue

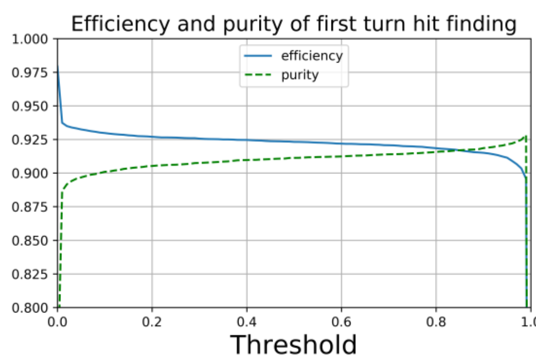
# Machine Learning In MDC Tracking

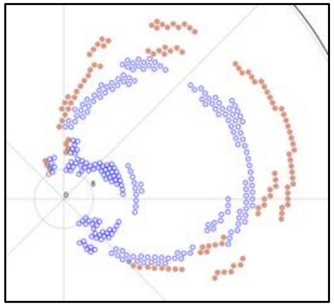
- Noise rejection with Neural network




- Machine learning tracking :Multiturn tracks identifying



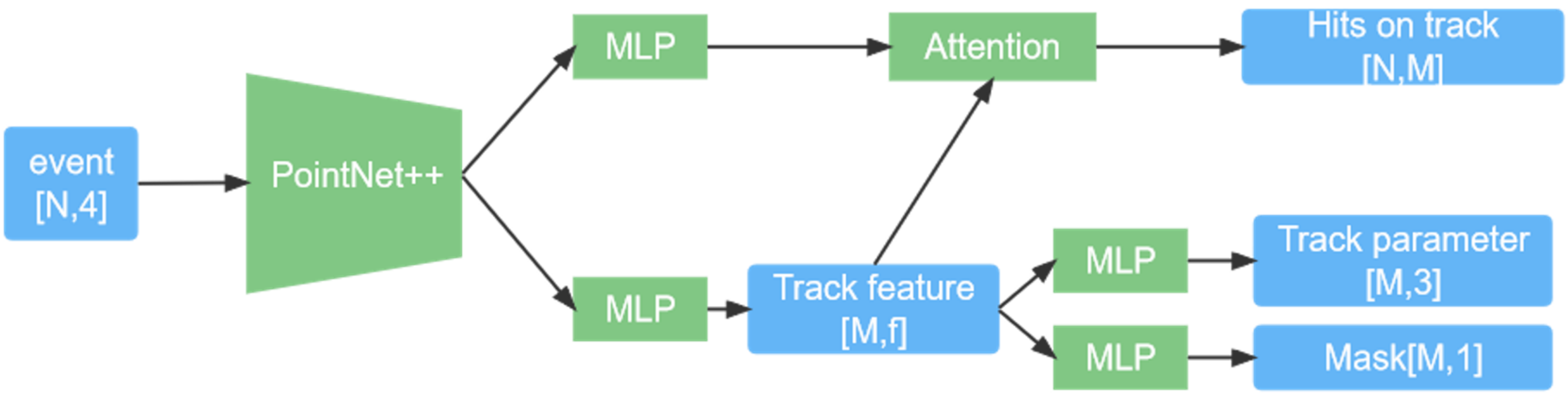



Slides supported by Yao Zhang

# Machine Learning In MDC Tracking

## Simultaneous track finding and track fitting

- PointNet model on BESIII (Main Drift Chamber data)
  - Input data： Hits(wirePos_x, wirePos_y, rawDriftTime)
  - Output:
    - 1. track index prediction for each hit (clustering)
    - 2. track parameters  for each predicted track (fitting)
  - Model:

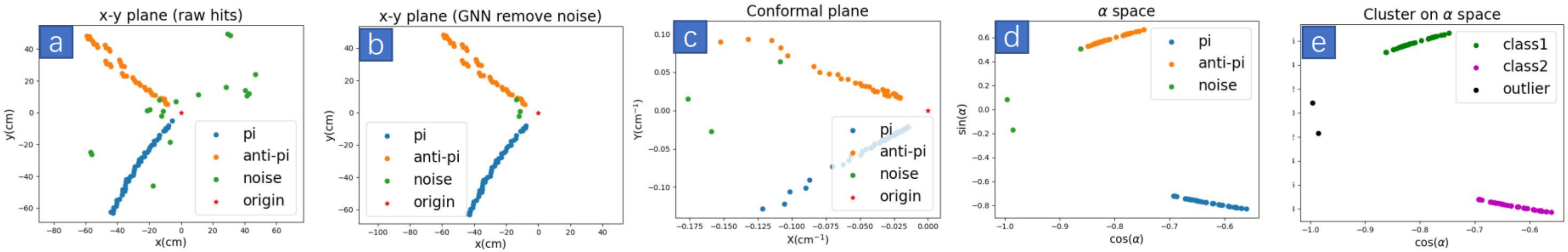



Slides from Zhibin Yang

Talk: https://indico.ihep.ac.cn/event/19620/contributions/135247/ Jun 11, 2023, 3:10 PM

# Machine Learning In MDC Tracking

## Clustering of Tracks Based on DBSCAN




a) Original MC data sample

- $J/\Psi \rightarrow \rho^0 \pi^0 \rightarrow \gamma\gamma\pi^+\pi^-$
- $\pi^+, \pi^-$ : Pt (0.2GeV - 1.4GeV)

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

- Hits connected in the X-Y plane in a straight line
- 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

- Density-Based Spatial Clustering of Application with Noise
- Hits in a cluster are considered to be in the same track

Slides from Xiaoqian Jia

Talk: https://indico.ihep.ac.cn/event/19620/contributions/135136/ Jun 11, 2023, 2:50 PM

# Summary

- BESIII Track reconstruction software have been validated with the collision data taken over years, reliable and high performant, especially at high momentum region

- There is room for progress in complex situations, and these underlying issues require the deep understanding of our detector, environment, and the interactions between particles and matter