Track fitting using GENFIT at STCF

Zhenna Lu, SYSU

8th July 2024

On behalf of the STCF tracking group

2024超级陶粲装置研讨会， 兰州

Outline

- Introduction to track fitting and GENFIT
- Track Fitting Algorithms
  - Kalman Filter
  - Deterministic Annealing Filter
- Application of GENFIT in OSCAR
- Improvement of low momentum track fitting with GENFIT in OSCAR
- Summary and Next

Introduction to track fitting and GENFIT

- **Track fitting**
  - estimate properties of tracks at target (reference) position
    - Precise measuring of position, momentum (with magnetic field), charge
  - The classical track fitting process begins with the hits identified within a subset provided by the track finding algorithm

- **GENFIT – A Generic Track Reconstruction toolkit**
  - Experiment-independent, modular track-fitting framework
  - Open source C++ code
  - Larger user community(e.g., BelleII, PANDA, SHiP, AFIS …)
  - ➢ Providing some typical track fitting tools, e.g., **Kalman Filter, Deterministic Annealing Filter**

Kalman Filter

- An algorithm to obtain the optimal estimate of a system
  - **Predict step**: initial estimate for current state x_k^{k-1} using state transition model.

$$x_k^{k-1} = F_{k-1} x_{k-1} + w_{k-1}$$

  - **filter step**: Correct predicted state with measurement.

$$K_k = P_k^{k-1} H_k^T (V_k + H_k P_k^{k-1} H_k^T)$$

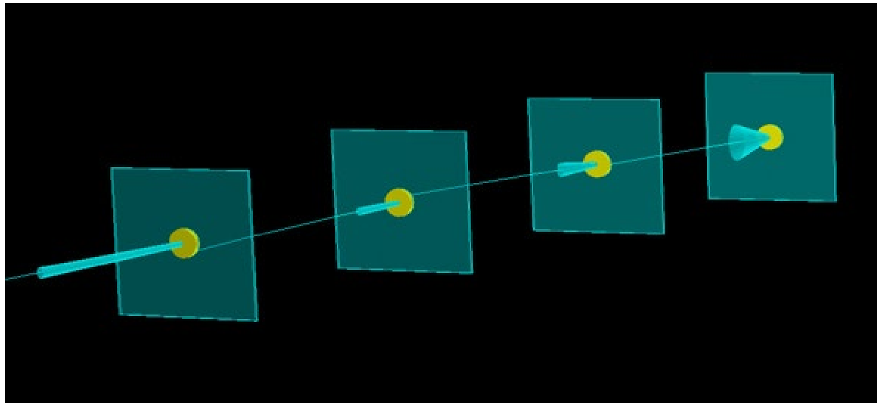
$$x_k = x_k^{k-1} + K_k (m_k - H_k x_k^{k-1})$$

  - **Smooth step**: processing the hits in reverse order, incorporating the information from subsequent hits into the current hit

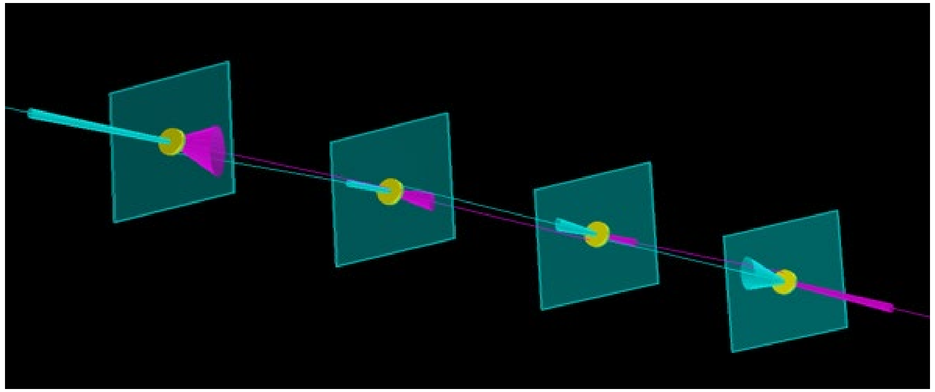
Kalman Filter in GENFIT

- The iterative bi-directional Kalman filter is applied
  - 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

Forward fitting



Backward fitting



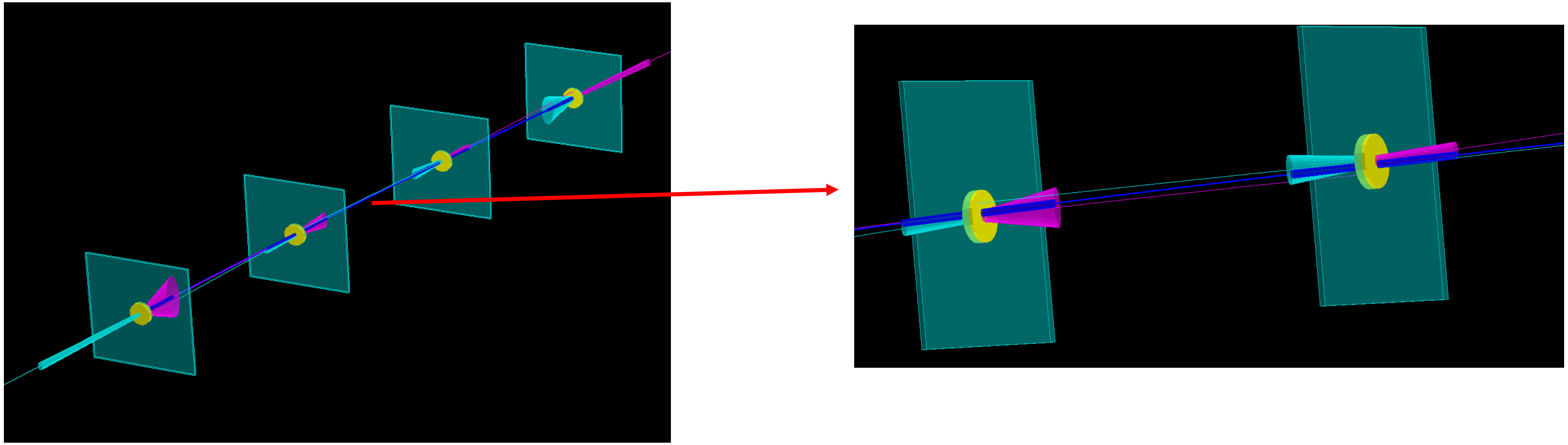
Kalman Filter in GENFIT

- **Smoothing in GENFIT**
  - Combine the parameters obtained by forward fit and backward fit
  - Gives more accurate states than either forward or backward updates alone

cyan: forward fitting

red: backward fitting

blue: smoothed track



Deterministic Annealing Filter

- Iterative Kalman filter with **weighting** and **annealing** process
- assignment probabilitie for each measurement
- Can be used to reject outliers or to resolve left/right ambiguities

The weights Φ_k^i are normalized according to

$$p_k^i = \frac{\Phi_k^i}{\Sigma_j\left(\Lambda_k^j + \Phi_k^j\right)}$$

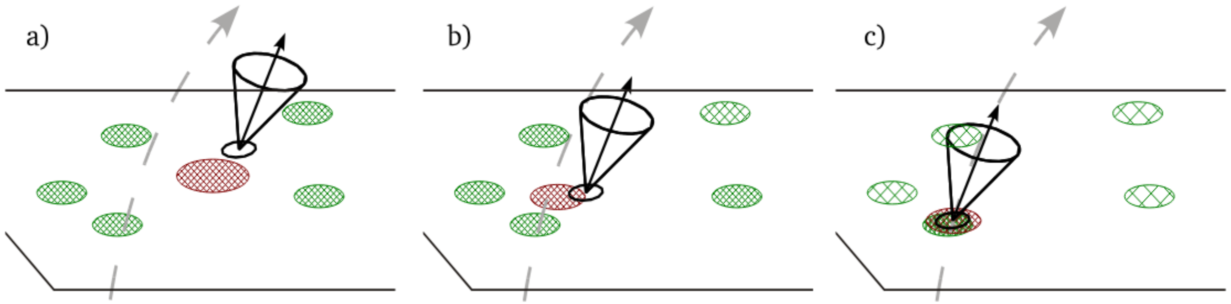
$$\Phi_k^i = \frac{1}{(2\pi)^{\frac{dim(\vec{m}_k^i)}{2}}\sqrt{T\,det\,V_k^i}}\,exp\left(-\frac{1}{2T}\left(\vec{m}_k^i - H_k\vec{x}_{k|n}^*\right)^T\left(V_k^i\right)^{-1}\left(\vec{m}_k^i - H_k\vec{x}_{k|n}^*\right)\right)$$

$$\Lambda_k^j = \frac{1}{(2\pi)^{\frac{dim(\vec{m}_k^i)}{2}}\sqrt{T\,det\,V_k^i}}\,exp\left(-\frac{\beta\cdot\lambda}{2}\right)$$

$\vec{x}_{k|n}^*$ **the smoothed track state at layer k**

Track reconstruction in the ATLAS experiment : The deterministic annealing filter

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.

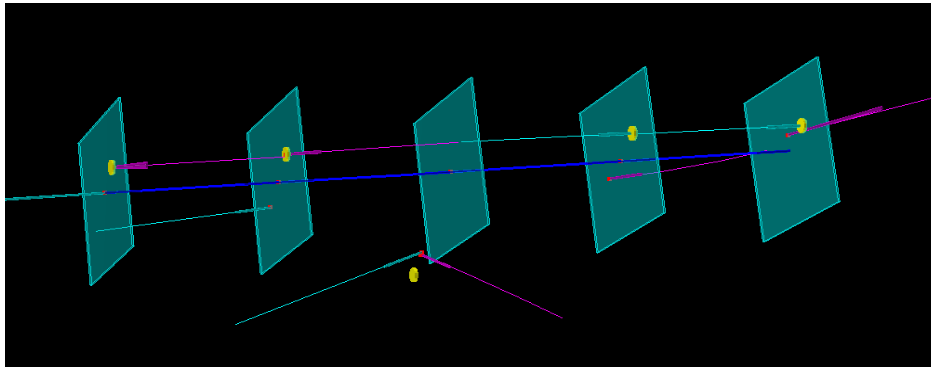
c) As the temperature decreases, measurements with large errors are given even less weight.

- the weight drops below the threshold, reject

A Demonstration of DAF fitting in GENFIT

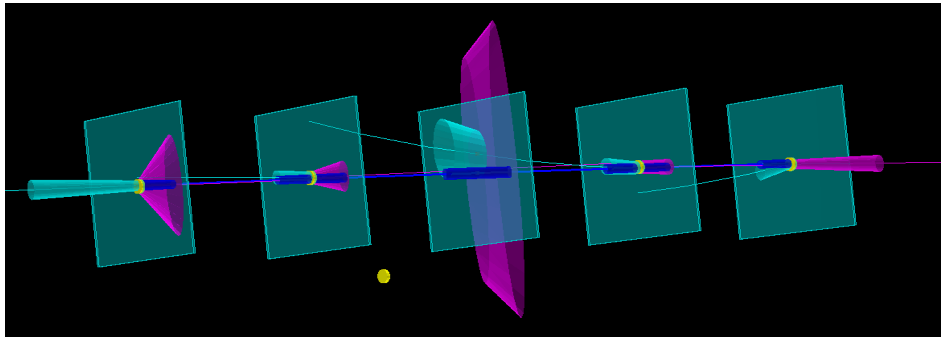
- reject outliers

iteration 1



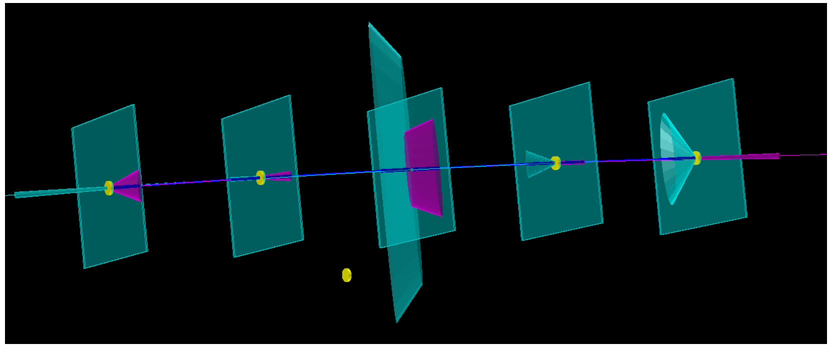
old weights	1	1	1	1	1
new weights	0.0805671	0.0466704	**7.64619e-20**	0.0620372	0.0620372

iteration 2



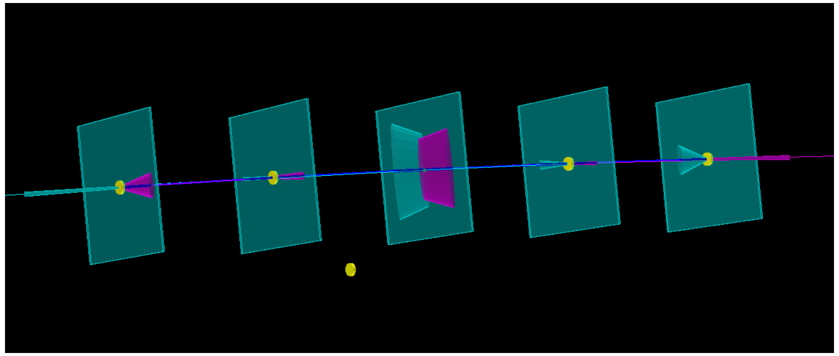
old weights	0.0805671	0.0466704	**7.64619e-20**	0.0620372	0.0620372
new weights	0.594671	0.585524	**3.81322e-171**	0.585042	0.592371

iteration 3



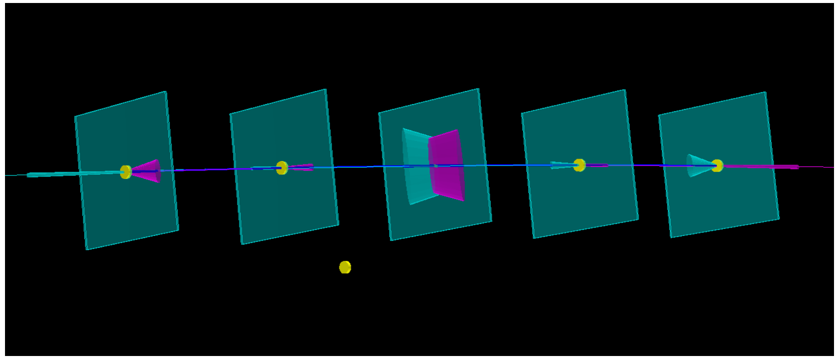
old weights	0.594671	0.585524	**3.81322e-171**	0.585042	0.592371
new weights	0.896426	0.887211	**0**	0.884235	0.895077

iteration 4



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

iteration 5

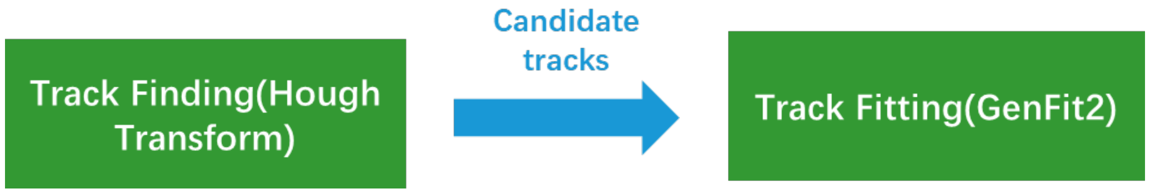


old weights	0.999995	0.999991	**0**	0.999989	0.999994
new weights	1	1	**0**	1	1

- the maximum change in absolute value of weight → 0 < threshold (default 0.001)
- meet the convergence criterion

Application of GENFIT in OSCAR

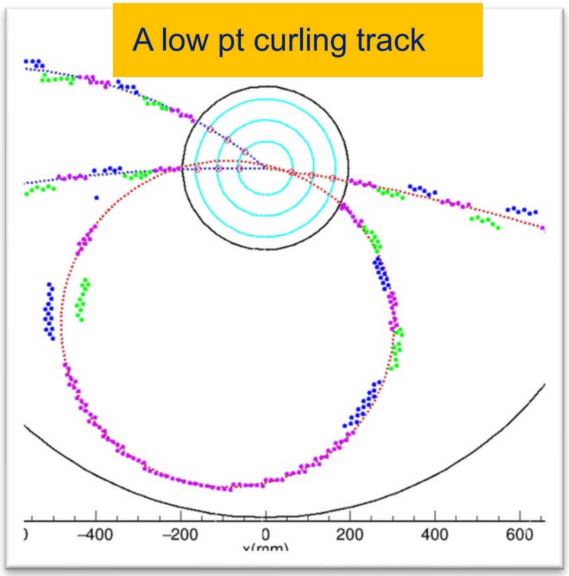
- **GENFIT2 is implemented in OSCAR**
  - Candidate tracks from Hough tracking algorithm are input to GenFit for track fitting



  - Deterministic Annealing Filter(DAF) is used as the default fitting algorithm
  - Process with 5 different particle hypotheses
  - High performance for high transverse momentum tracks, but there’s room for improvement with low momentum tracks

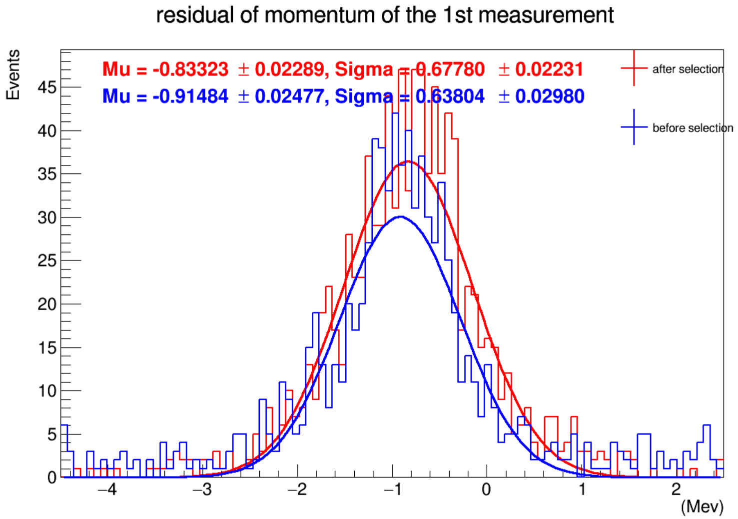
Optimization of low momentum fitting

- At low momenta, particles are significantly affected by material effects
- Make curling trajectory in chamber
- leading to greater energy loss and significant errors in the reconstructed track parameters
  - The hits in the latter half of the loop are subject to severe material effects
  - Consider using the first half loop of hits



Simulated sample : 120MeV， 40<|cosθ|<90

- fit tracks with only first half hits / all hits
- 1st half hits are selected using geometric information from MC truth



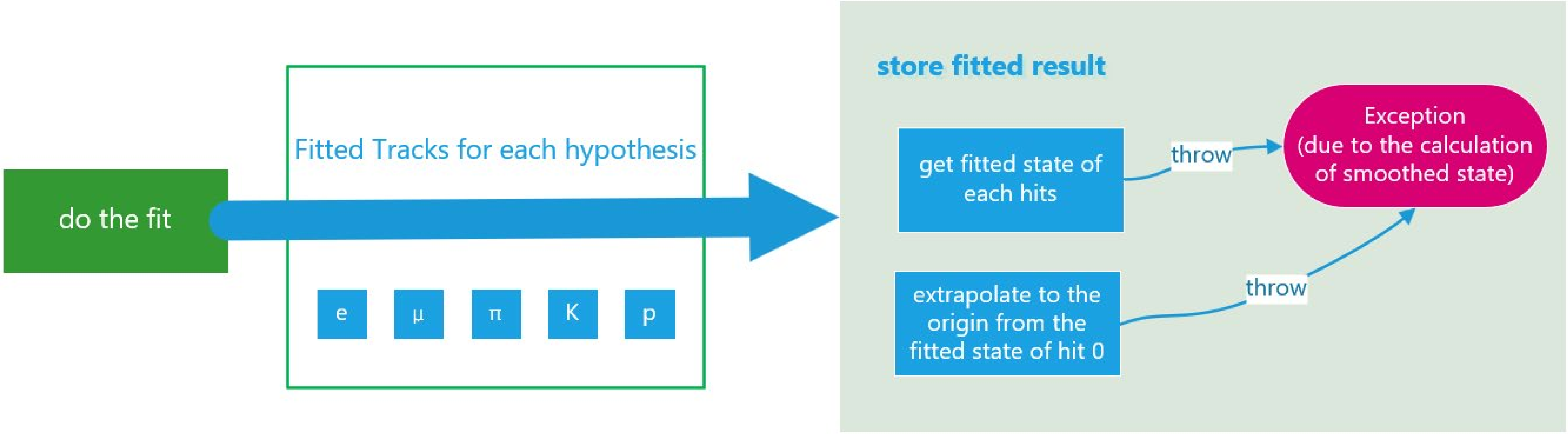
The momentum resolution is better when only using the 1st half hits

How to feed the 1st half hits to fitting algorithm?

The hits in the first and second half of the loop can be distinguished in the ealier Hough tracking package

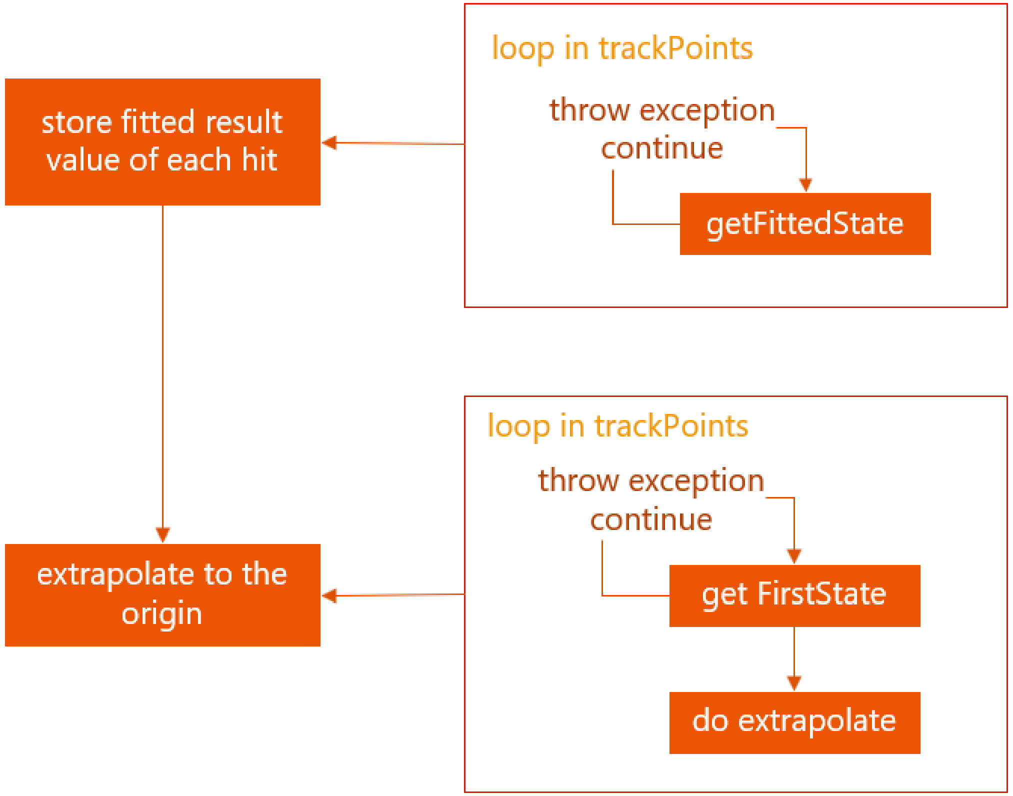
Improvement of fitting workflow

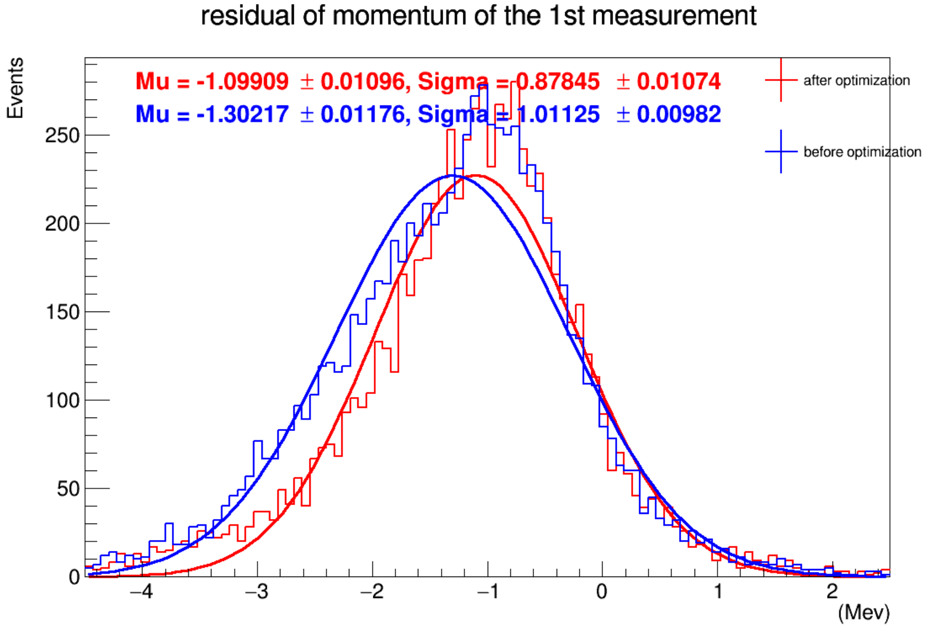
- After calling GENFIT for fitting, the fitting results of the track for each particle hypothesis will be obtained
- When obtaining the smoothed state of the fitting results of each hit, exceptions may be thrown due to abnormal matrix operation.



Improvement of fitting workflow

- Add protection when getting the fitted state
- Ensure that when an exception is thrown for a particle hypothesis, the fitting results of other hypotheses can be stored .





The resolution of the 1^{st} measurement improved, and the mean value was also corrected.

Summary

- GENFIT is introduced to OSCAR as track fitting package following Hough transform

- Considering the capability of the DAF algorithm to exclude oulier/noise hits, DAF is adopted as the track fitting algorithm after Hough track finding

- Some preliminary optimization has been done, especially for low-pt curling track

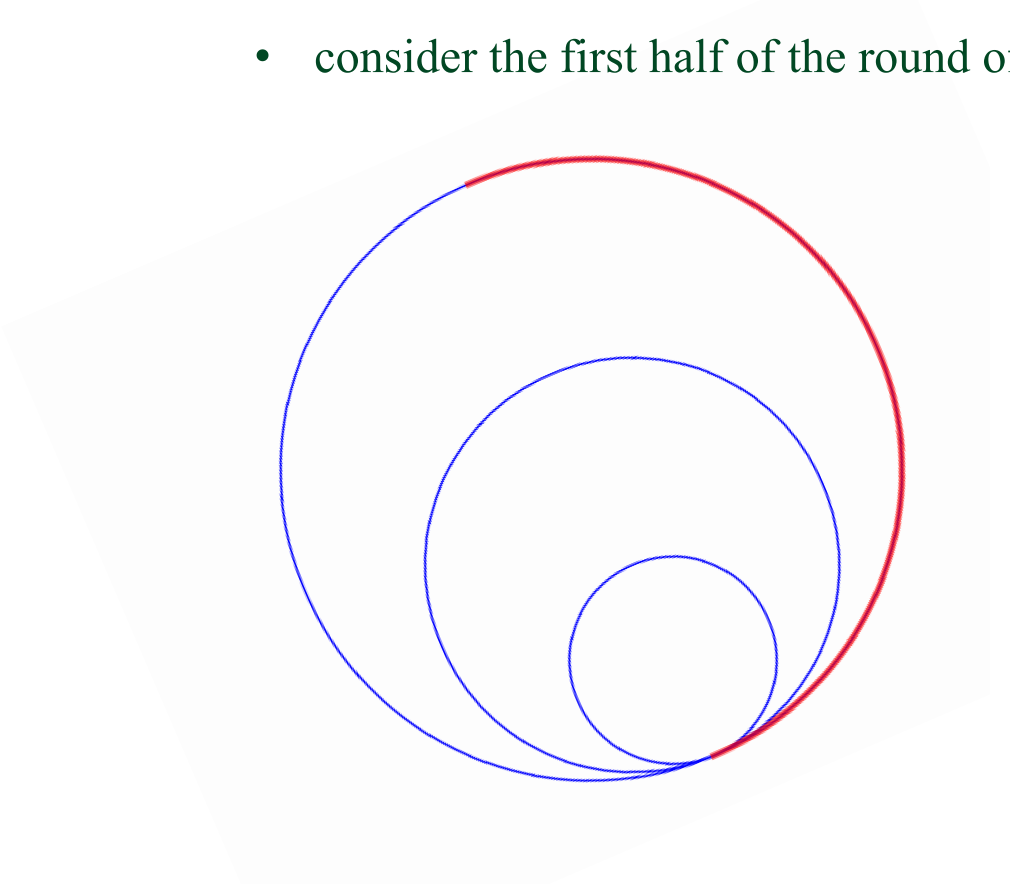
Next

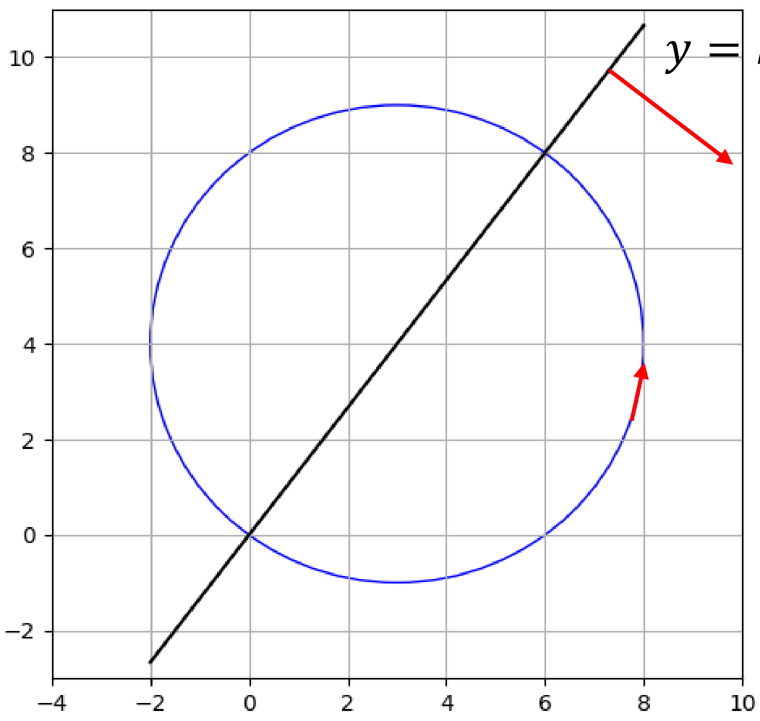
- Combine track finding to improve the track reconstruction performance, especially for low momentum tracks
- Considering noise hits, more optimization is to be done

BACK UP

Hit Selection

- At low momenta, particles are significantly affected by material effects
- particles may get trapped in the detector with multiple loops
- leading to greater energy loss and significant errors in the reconstructed track parameters
  - So consider change the range of hits as the input of fitting algorithm
  - consider the first half of the round of hits





$y = kx$

hit(x,y)

$y\_test = kx$

✓ hits($y\_test > y$) will be selected

Deterministic Annealing Filter

- resolve left/right ambiguities
  - when using the DAF algorithm, **the weights of measurements need to be initialized**.
  - Genfit2 implements a technique to initialize the weights:
    - measurements with larger drift radii are assigned smaller weights, since the wire position is expected to be farther away from the trajectory.
    - In contrast, measurements with smaller drift radii, which are closer to the trajectory, get larger weights.

$$w = \frac{1}{2}(1 - \frac{r_{drift}}{r_{drift,max}})^2$$

w is the given weight, and r_{drift} is the distance of the measurement from trajectory.

  - This means that if one has an ambiguous measurement, when the measurements in per detector layer are constructed in the code, one wire position have already been selected.

Fitted information from GenFit

- isFitConvergedFully_
- isFitConvergedPartially_
- nFailedPoints_

	default value	
isFitConvergedFully_	false	When fitting converge && nFailedPoints==0, set to true
isFitConvergedPartially_	false	Set to true if the fit converges
nFailedPoints_	0	construct plane or extrapolation to plane failed +=1

isFitted=true，Fitting ends

≠

Converged

Fitted information from GenFit

- **isFitted_**=false

  ⇒ Kalman could not fit

  ① The fitting result for each point cannot be obtained.

  ② The smoothed state of the first hit can still be obtained.

- **isFitted_**=ture

  fitting process ended normally, but the obtained fit results deviate significantly, nearly approaching 0.

  (isFitConvergedFully_ && isFitConvergedPartially_ = false.)

Fitted information from GenFit

`max abs weight change = 0`

- weight do not change any more, **converged=true**
- DAF::processTrackWithRep out of loop
  - isFitted==true
  - isFitConvergedFully_ = (nFailedPoints_==0 ? true : false)
  - isFitConvergedPartially_== true
- after the loop ends, if the p-value of the forward fit and backward fit == 0
  - isFitConvergedFully_ = false
  - isFitConvergedPartially_== false

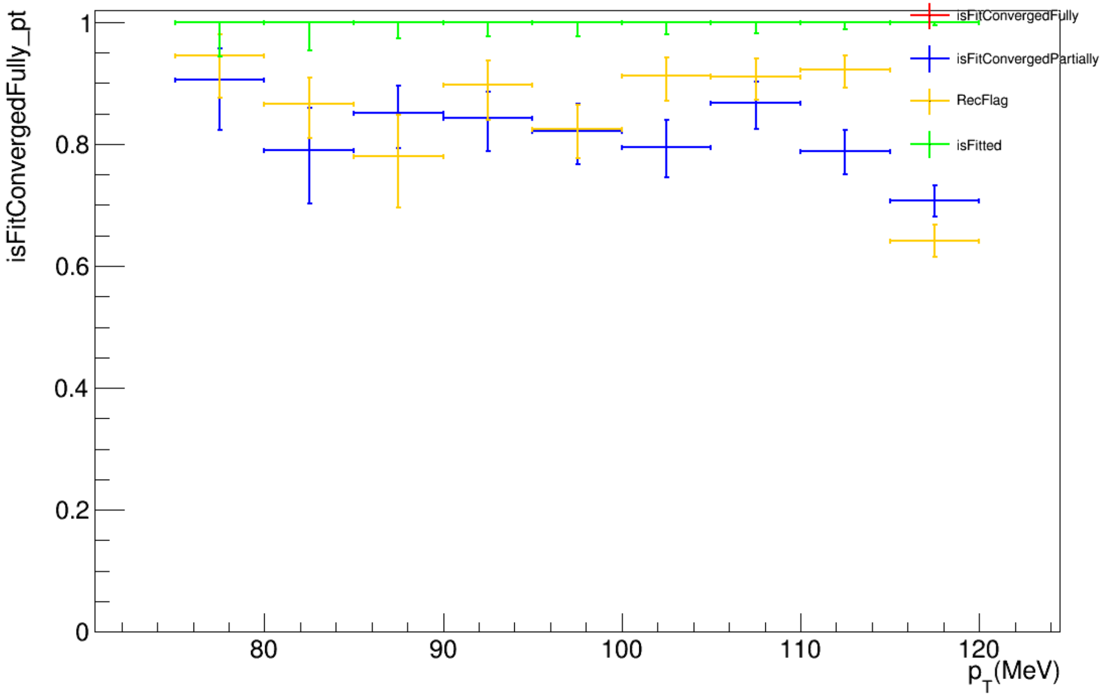
The reason why the maximum number of iterations has not reached, but not convergence

the maximum number of iterations=9

```
numIterations    = 7,
                   7, 7, 9, 6
isFitted         = 1,
                   1, 1, 1, 1
isFitConvergedFully = 1,
                   1, 1, 0, 0
isFitConvergedPartially = 1,
                   1, 1, 0, 0
nFailedPoints    = 0,
                   0, 0, 0, 0
```

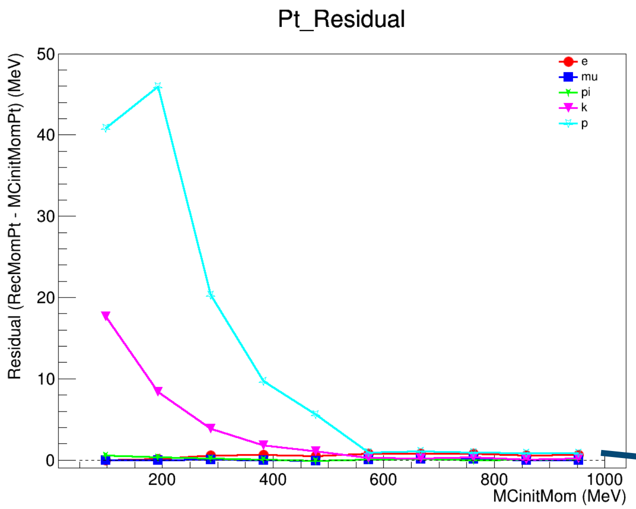
Fitted information from GenFit

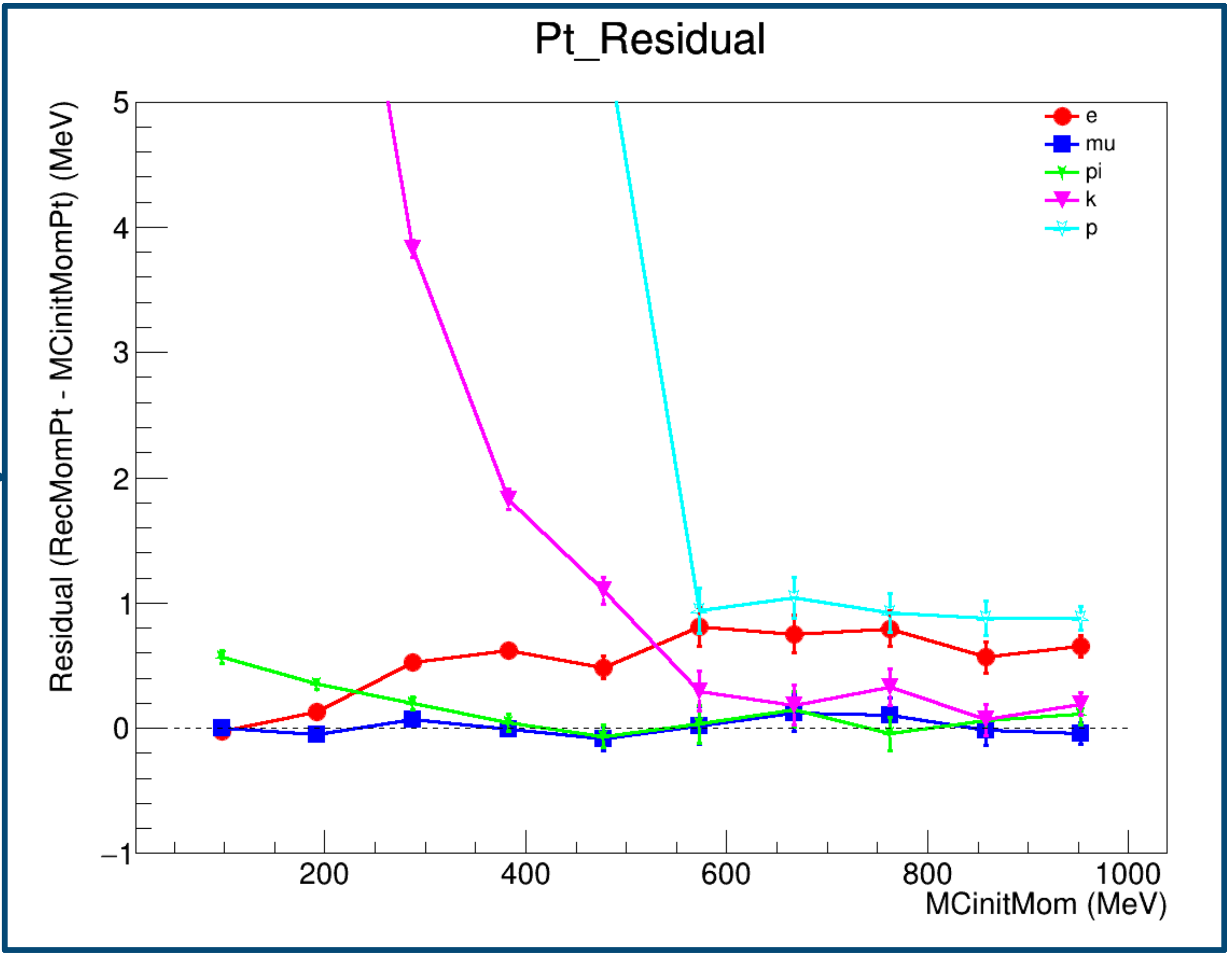
1. isFitConvergedFully_ and isFitConvergedPartially_ are largely overlapping.
2. RecFlag is mostly higher than isFitConvergedFully_ && isFitConvergedPartially_ in most cases.
3. The fitting process has ended, but it may not necessarily have converged.



Multiple particle hypotheses

1、The residual distribution of μ：





Multiple particle hypotheses

2、$The\ residual\ distribution\ of\ \pi$