STCF MDC Simulation and Reconstruction

STCF Offline Software Group

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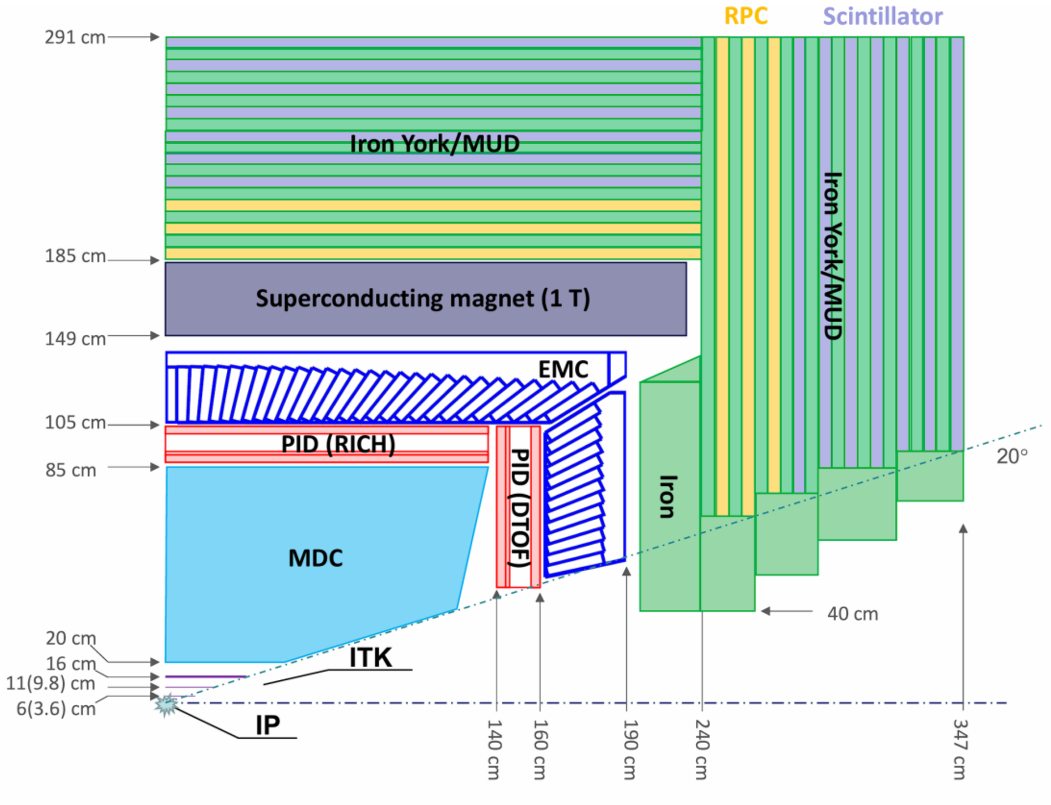
Outline

- STCF Detector System
- Simulation of Particle-Material Interactions
- Simulation of Detector Response (Digitization)
- Track Reconstruction
- Summary and Prospect

STCF Detector System

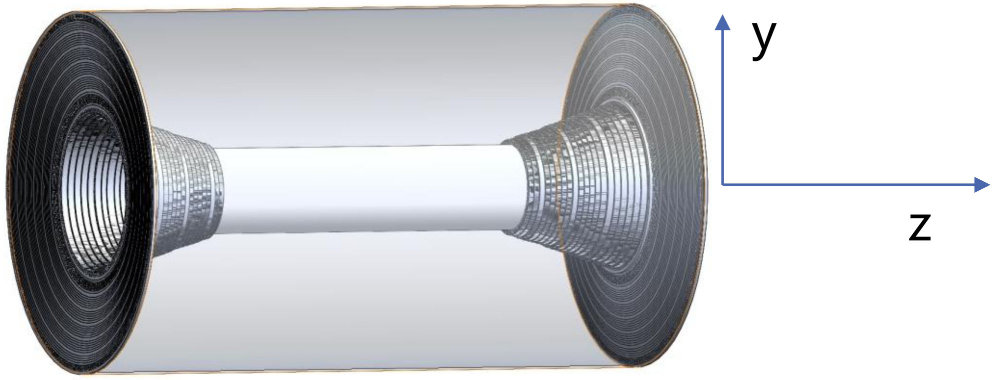
Detector Concept and Performance



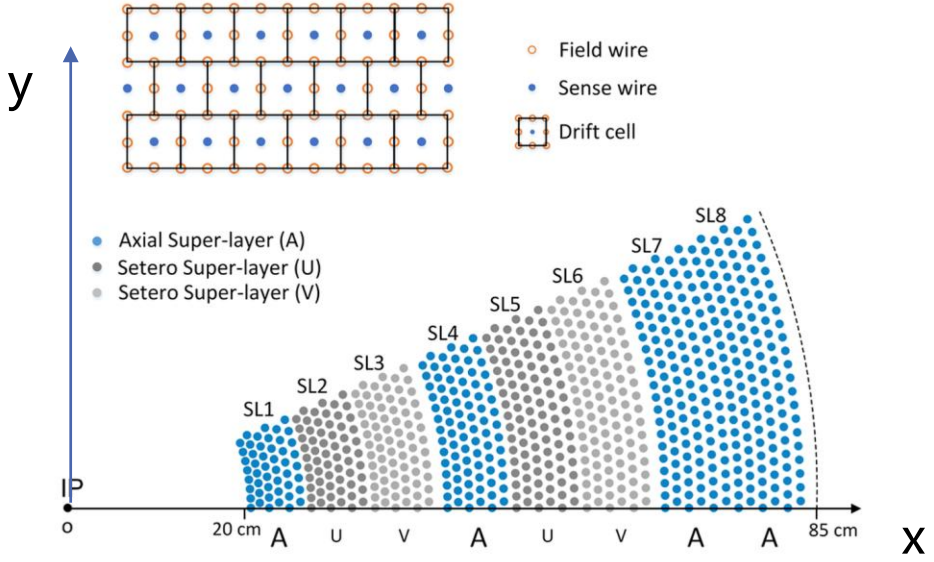
Schematic layout of the STCF detector concept

- **Designed for physical requirement under 2 orders of magnitude higher luminosity**
- **ITK**
  - Material < 1% X_0 with 3 layers
  - Spatial resolution σ_{xy} < 100 μm
- **MDC**
  - Material < 5% X_0
  - σ_{xy} < 130 μm, σ_p/p < 0.5% @ 1GeV/c
  - dE/dx resolution < 6%
- **RICH & DTOF**
  - PID π/K PID efficiency > 97% up to 2GeV/c @ mis-ID rate 2%
- **EMC**
  - σ_E < 2.5%, σ_{pos} < 5 mm, σ_t < 300ps @ 1GeV
- **MUD**
  - μ PID efficiency > 95% with π/μ mis-ID rate < 3.3% @ 1GeV/c

Conceptual Design of MDC



- Sensitive region: 0.3% X_0
- Gas: 60%He+40%C_3H_8
- Sense wires: 20 μm diameter tungsten with 0.5 μm gold coat
- Field wires: 100 μm diameter aluminum with 0.5 μm gold/silver coat

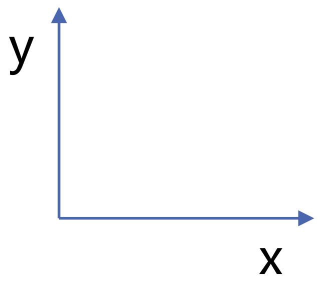


Layer configuration of one sector of the MDC

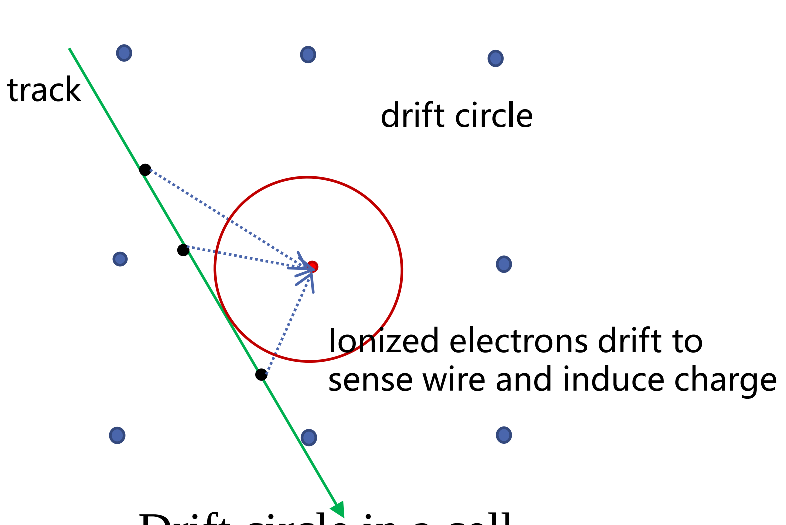
Table 6.2.1: The main parameters of the STCF MDC conceptual design.

Superlayer	Radius (mm)	Num. of Layers	Inclination (mrad)	Num. of Cells	Cell size (mm)
A	200.0	6	0	128	9.8 to 12.5
U	271.6	6	39.3 to 47.6	160	10.7 to 12.9
V	342.2	6	-41.2 to -48.4	192	11.2 to 13.2
A	419.2	6	0	224	11.7 to 13.5
U	499.8	6	50.0 to 56.4	256	12.3 to 13.8
V	578.1	6	-51.3 to -57.2	288	12.6 to 14.0
A	662.0	6	0	320	13.0 to 14.3
A	744.0	6	0	352	13.3 to 14.5
total	200 to 827.3	48		11520	

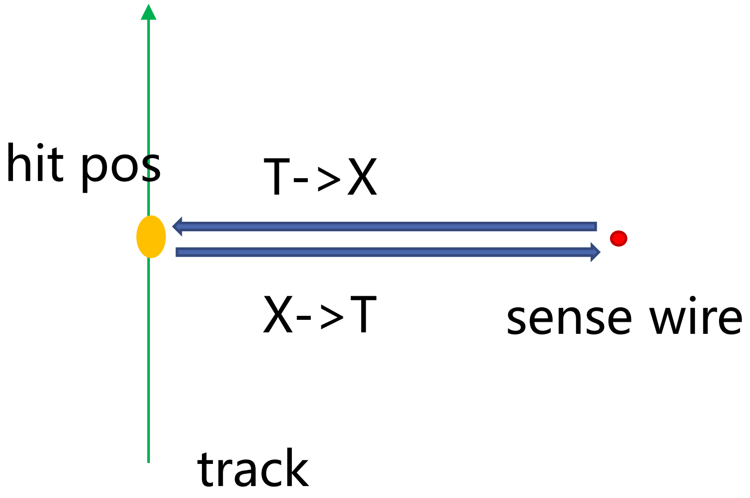
MDC Working Process



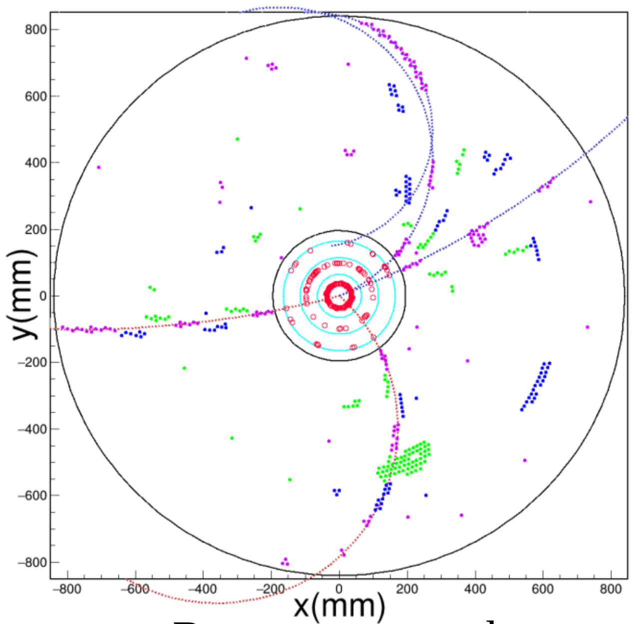
- Mainly for track reconstruction: cooperate with ITK
  - MDC (cm level cell size) can not measure hit position directly.
  - Drift time and distance can be converted each other.
- Part of trigger system: pattern matching
- PID: dE/dx reconstruction



Drift circle in a cell



Conversion between drift time and distance



Reconstruct tracks

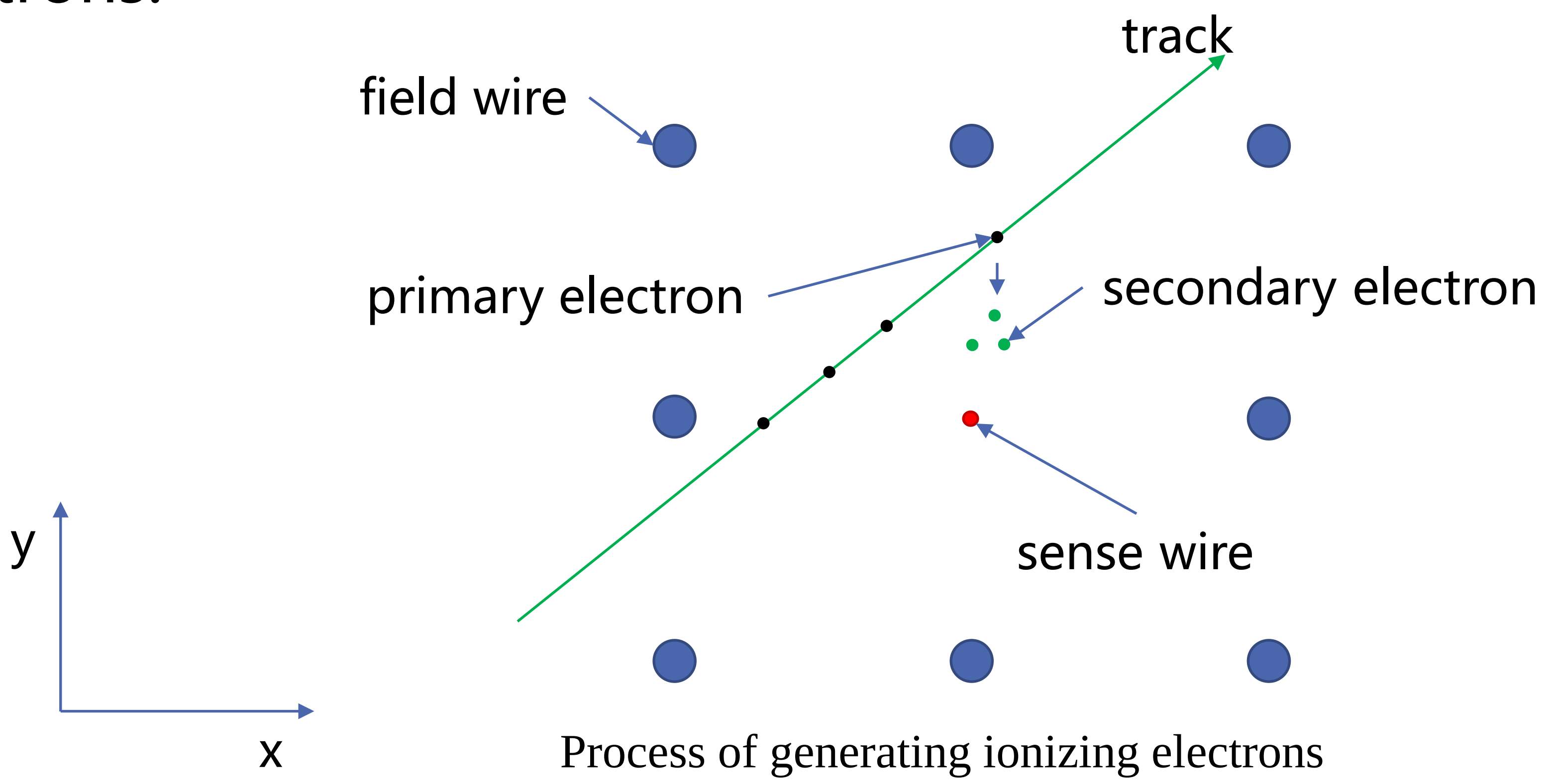
Simulated Drift Chamber for Research

- Simulations are used to guide the design of the actual device.
- Build reconstruction program in advance
- Use simulation for research of reconstruction, and event generation based on actual experiment in the future
- Effects of high luminosity are considered

Simulation of Particle-Material Interactions

Ionization Simulation

- GEANT4 Photoabsorption Ionization (PAI) model is used, generating primary ionizing electrons.
- Garfield++ is used to generate secondary electrons.

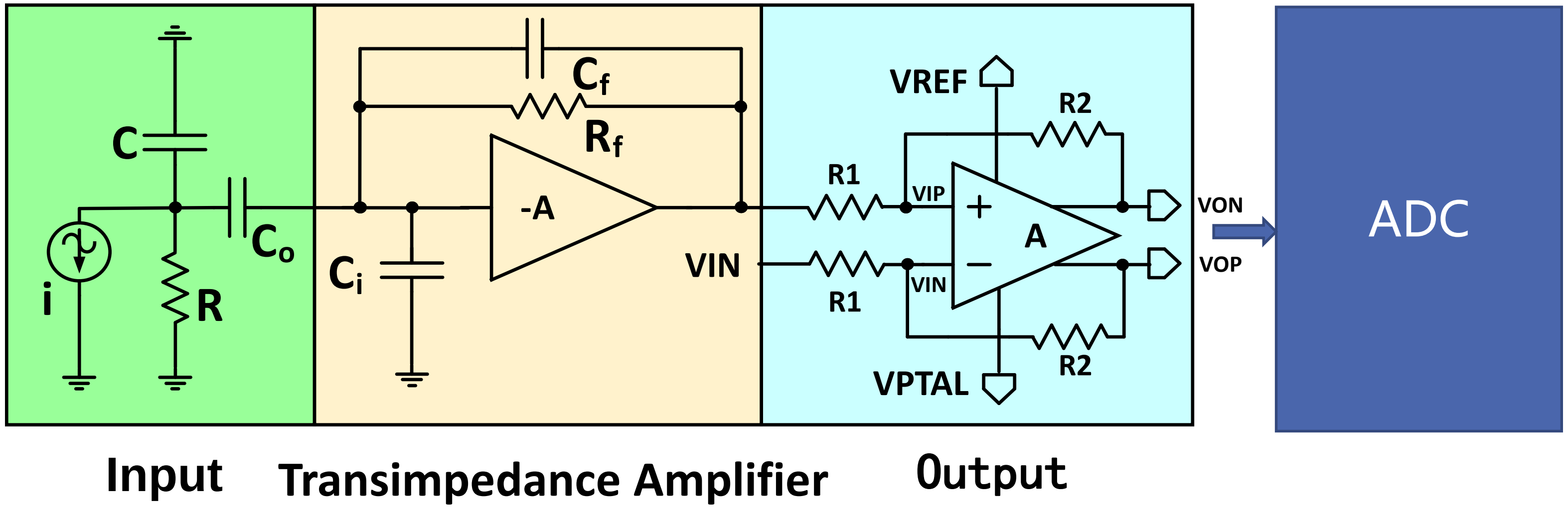


Process of generating ionizing electrons

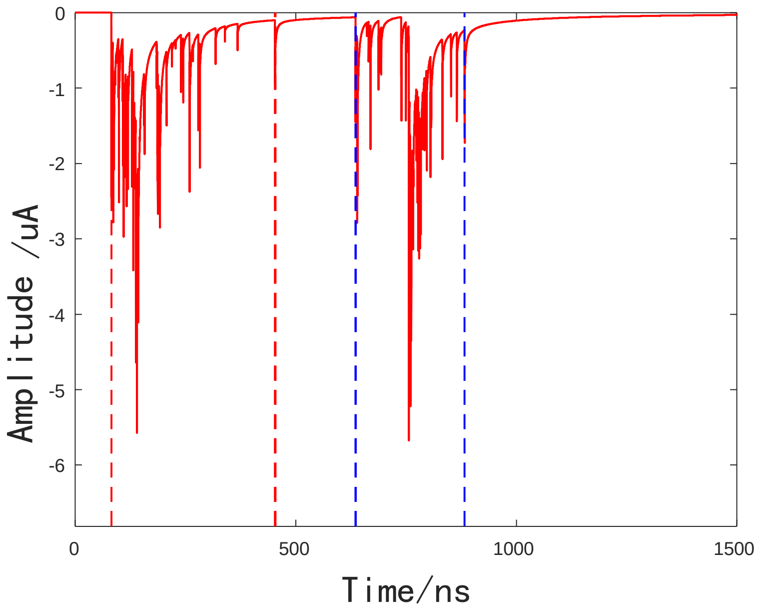
Simulation of Detector Response (Digitization)

Signal Output of MDC

- MDC is designed to read the signal arrival time (T_{TDC}) and charge ($\propto \Sigma$ADC).
- They should be simulated according to the principle of detection.



Scheme of MDC electronics

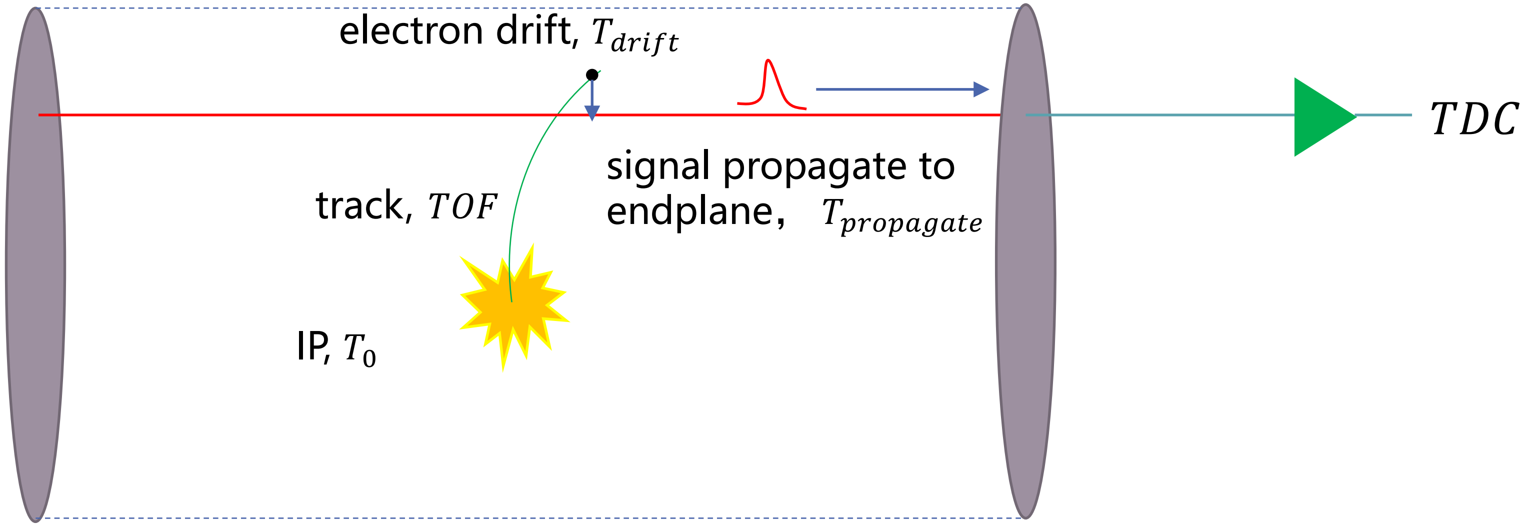


Induced current waveform

Components of Output Time T_{TDC}

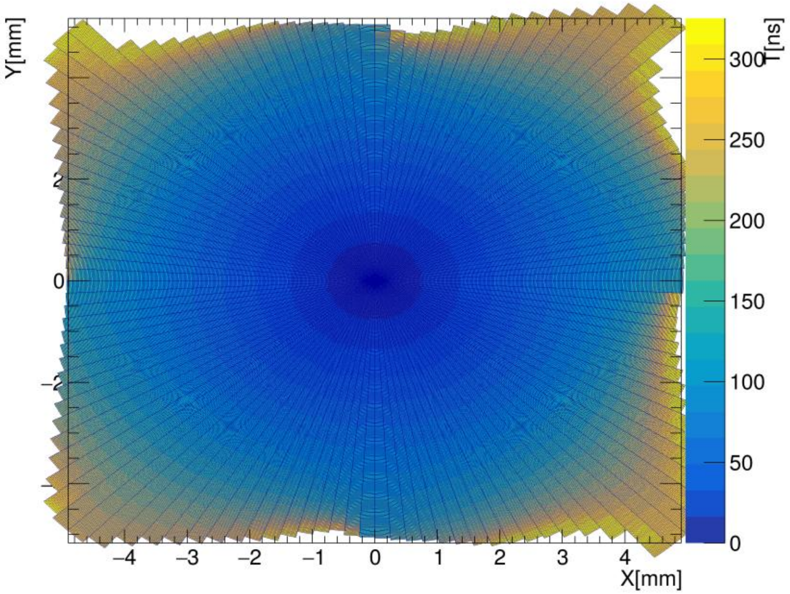
$$T_{TDC} = T_0 + TOF + T_{drift} + T_{prop}$$

- T_0 : The starting time of an event.
- TOF : Time taken for particle to fly from IP to MDC cell. (tracklenth/c)
- T_{drift} : Minimal time taken for electrons, produced when a particle hits the cell, to reach the signal wire.
- T_{prop} : Time taken for signal propagate to endplane. (5ns/m)

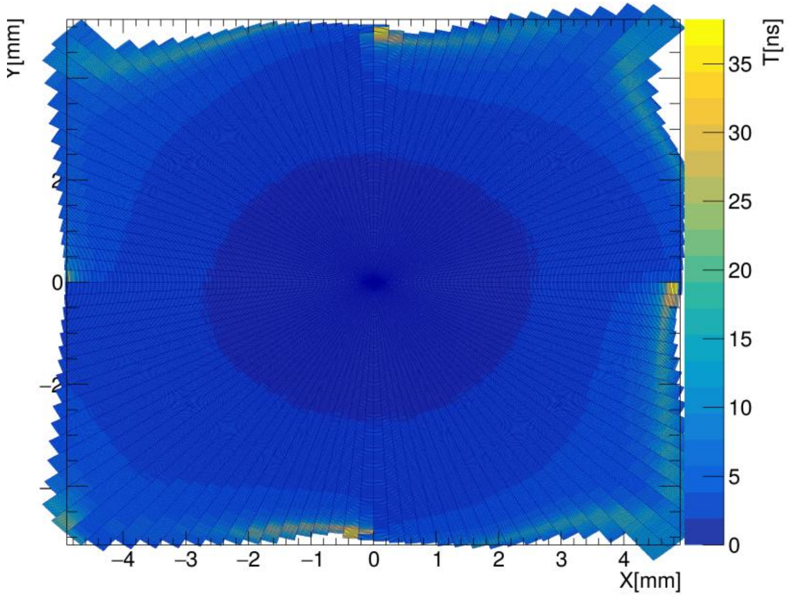


Electron Drift Time Simulation

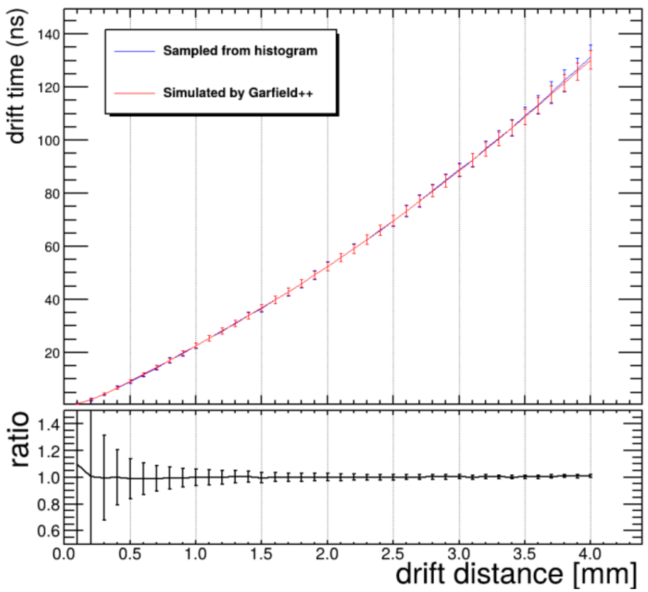
- Simulate the drift of electrons in electric fields using Garfield++, then record the time when every electron hits the sense wire. (~5s CPU time / electron)
- To solve the problem of unacceptable time consumption, we established the relationship between electrons' positions and their drift times, then we can use sampling method.
- The consumption time has been reduced by a factor of $10^4$of the original.



Relationship between electron position and drift time (z-axis) in a MDC cell



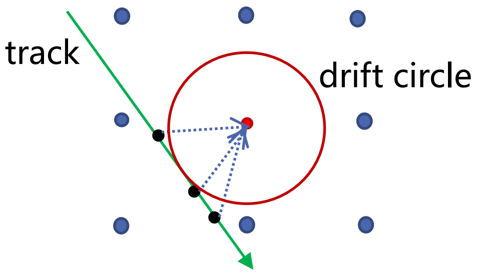
Uncertainty of drift times (z-axis) in a MDC cell

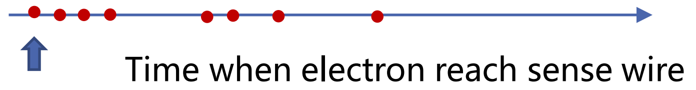


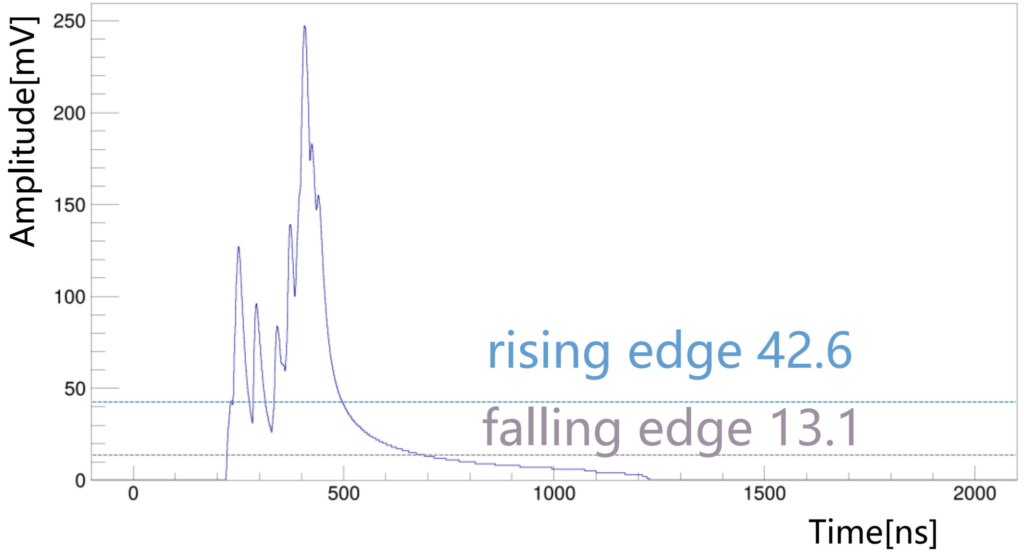
Drift time in single point between 2 methods

Signal Time Simulation

- Add waveforms of single electron to generate the composite waveform, then convolute the electronic response curve onto this waveform.
- The signal threshold-crossing time is determined as the signal time.
- Waveforms of single electron also sampled from a pre-generated waveforms collection.



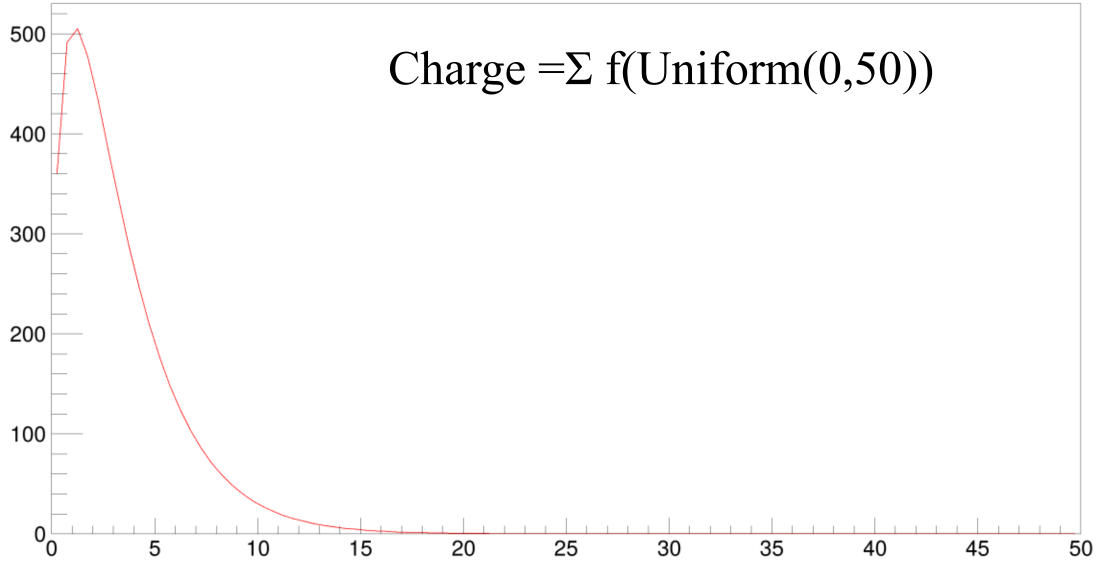




A composite waveform

Signal Charge

- Single-electron charge follows a Polya distribution derived from fitting the simulated charge deposition spectrum.
- Total signal charge is determined by sampling according to the number of electrons (~80 per MDC cell) instead of intergrating waveforms.
- Total signal charge is proportional to energy loss of particle.



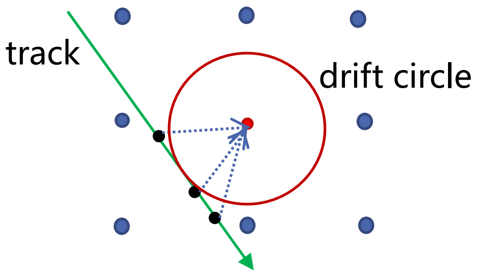
Charge Polya distribution of layer 0

Track Reconstruction and Performance

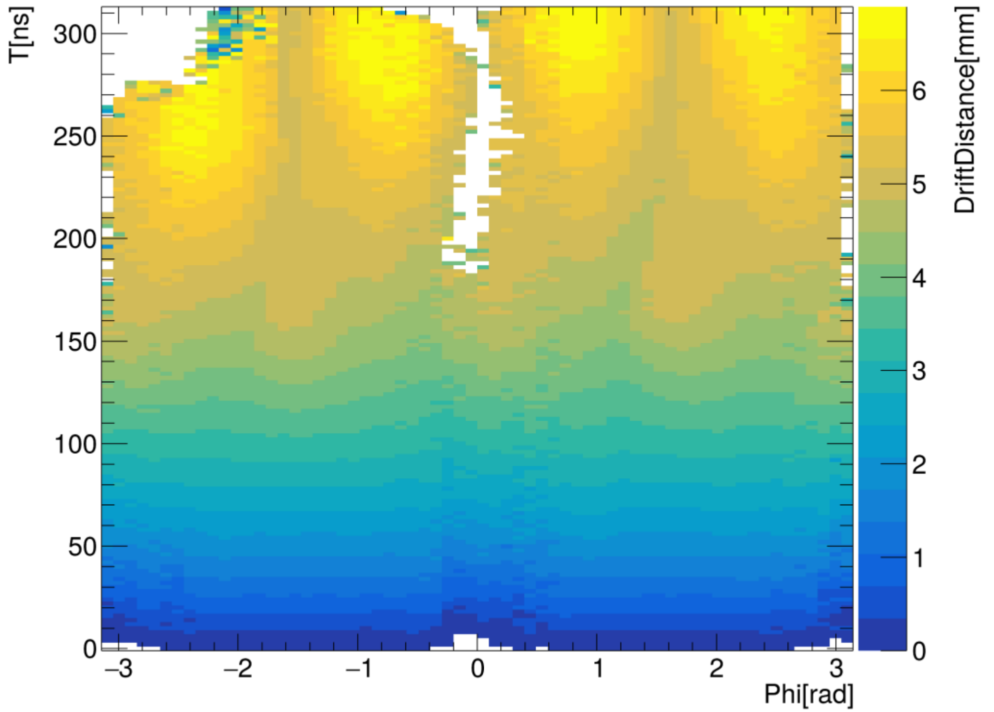
- T-X Relation
- Track Finding and Fitting
- Fast T0 Reconstruction
- dE/dx Reconstruction and PID

Drift Time to Distance Conversion

- Position can not be measured directly, but converted from drift time using T-X relation.
- $T_{drift} = TDC - T_0 - TOF - T_{prop}$. T_0 is assumed known in standalone research of MDC
  - ➢ Use whole detector system to calculate T_0



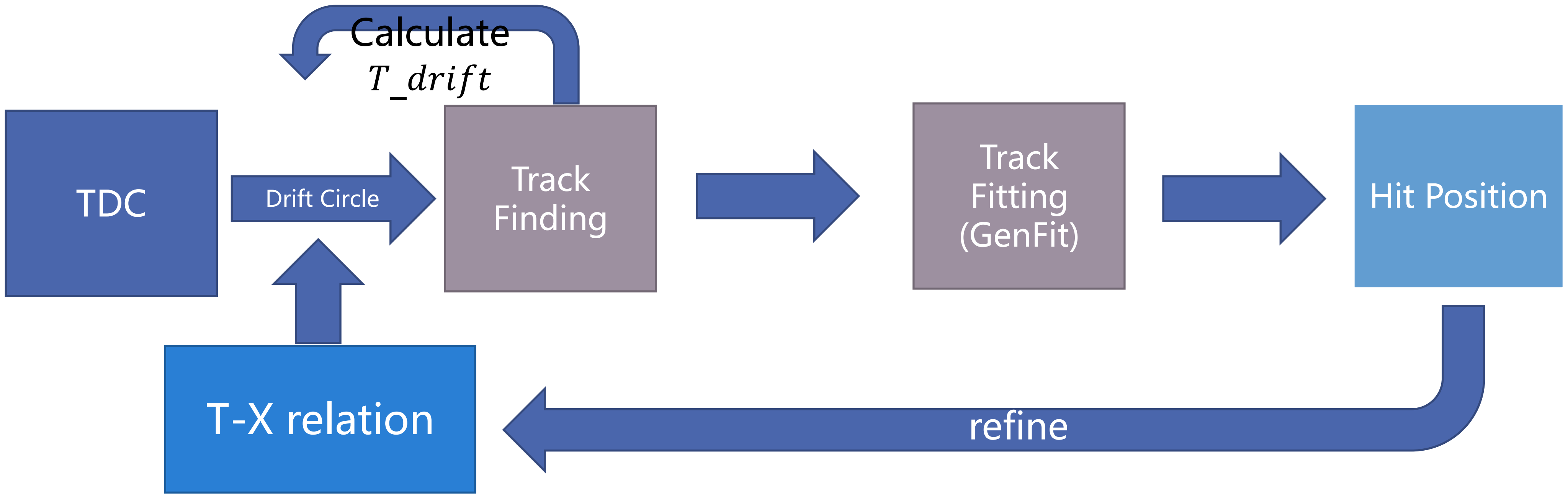
Drift circle in a cell



From drift time to drift distance (z-axis) in layer 0

The Process of Track Reconstruction

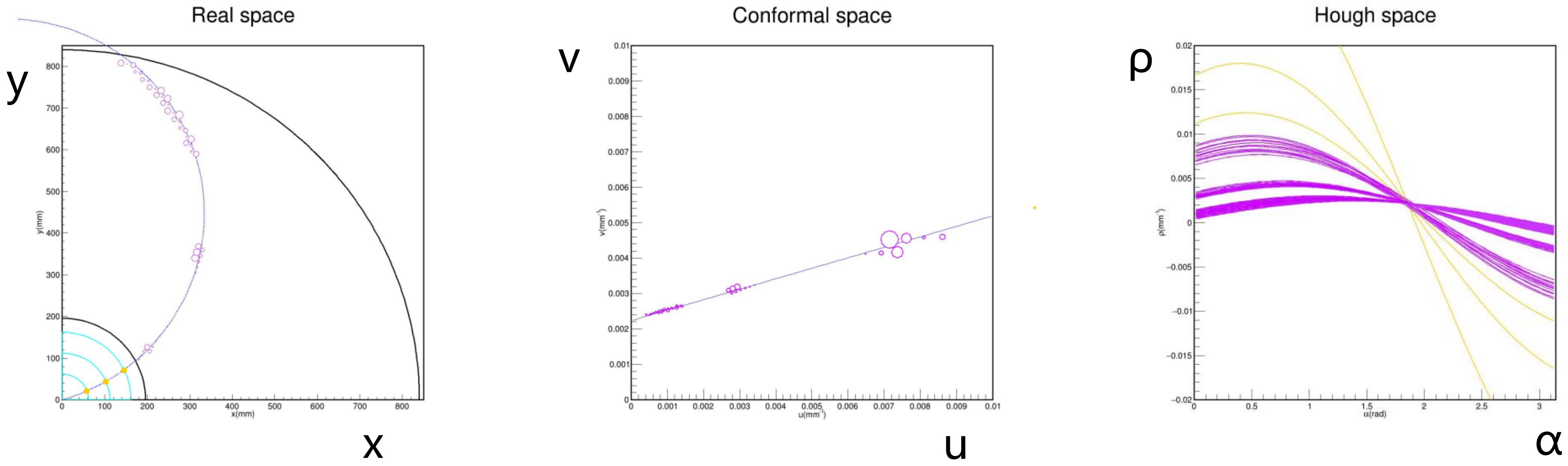
- $T_{drift} = T_{TDC} - T_0 - estimated(TOF + T_{prop})$at the beginning, then find tracks
- $T_{drift} = T_{TDC} - T_0 - TOF - T_{prop}$ based on track parameters.
- T-X relation is built iteratively through track reconstruction.



First Iter: T = pol2(R), fitted from simulation

Track Finding and Fitting

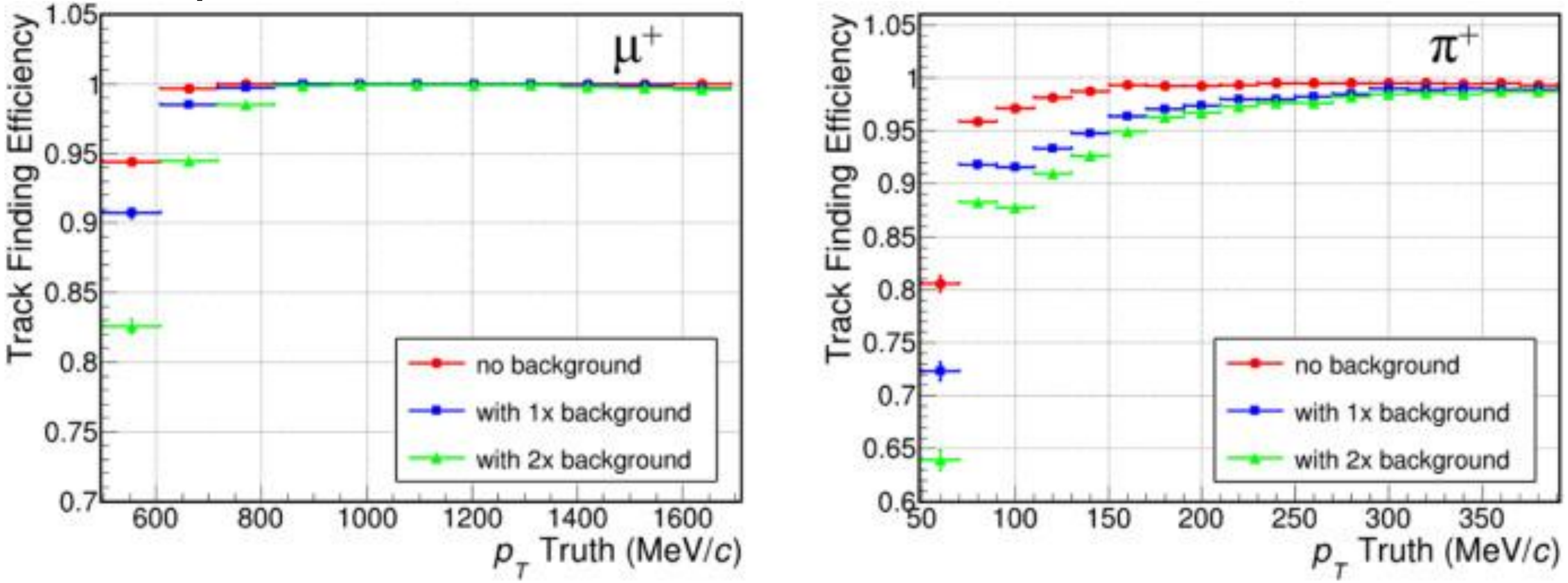
- The Hough transform algorithm converts drift circles from real space to conformal space, then to Hough space, and obtains the parameters of the track.
- The Kalman filter refines the track parameters ,hit position and momentum.



A track on the conformal plane transform to parameter space

Performance of Track Finding

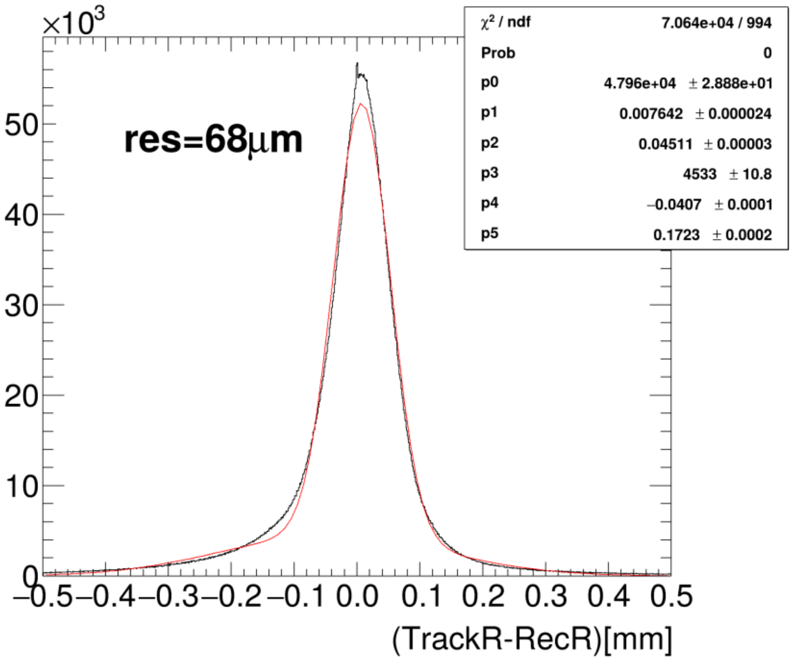
- Track finding in $\Psi(2S) \to \pi^+\pi^- J/\psi,\ J/\psi \to \mu^+\mu^-$ event.
- This algorithm is developed based on smeared MC hit distance (~120μm resolution) without character of detector.
- Tracking efficiency achieved 90% at p_T=100MeV/c, >95% at p_T>150MeV/c.



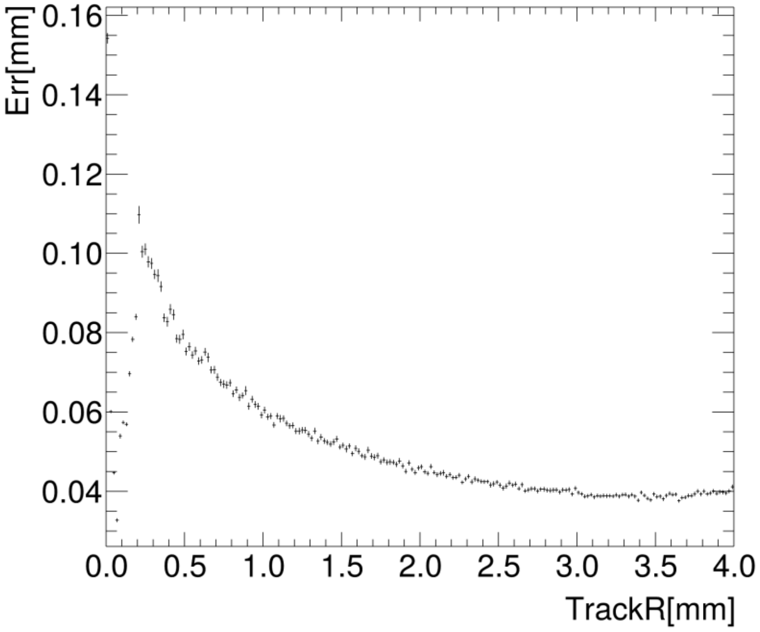
The track finding as a function of p_T with different background level

Performance of Spatial Resolution with T-X Reconstruction

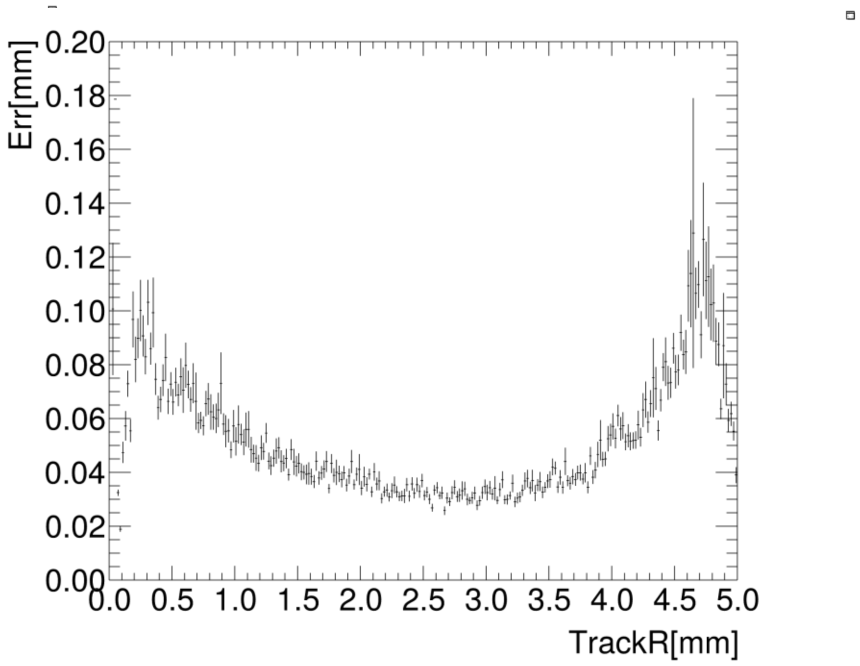
- Reconstruct $\Psi(2S) \to \pi^+\pi^- J/\psi,\ J/\psi \to \mu^+\mu^-$ event with existing track finding algorithm
- RecR is drift distance from T-X Reconstruction and TrackR is drift distance from fitted track.
- Resolution is $\sqrt{\mu^2 + \sigma^2}$ (second moment, containing bias) of fitted (double) gaussian function or histogram statistics.



Intrinsic average position resolution in all cells



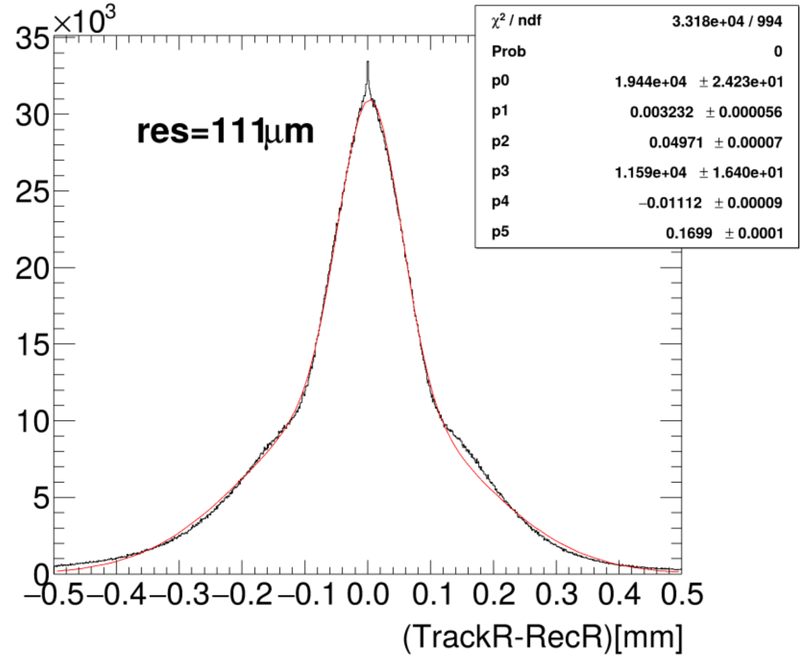
Position resolution a function of drift distance in all cells w/o edge effect



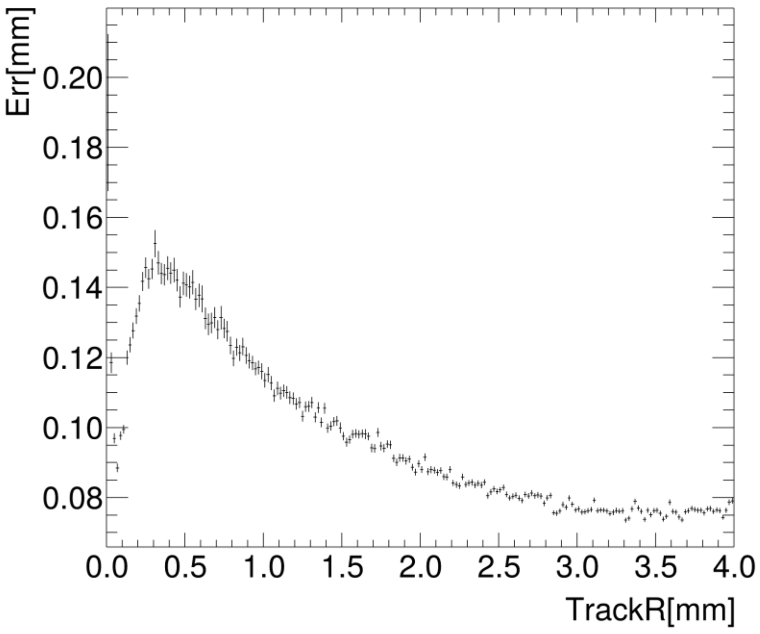
Position resolution a function of drift distance in layer 0

Simulating Mis-Alignment of Detector

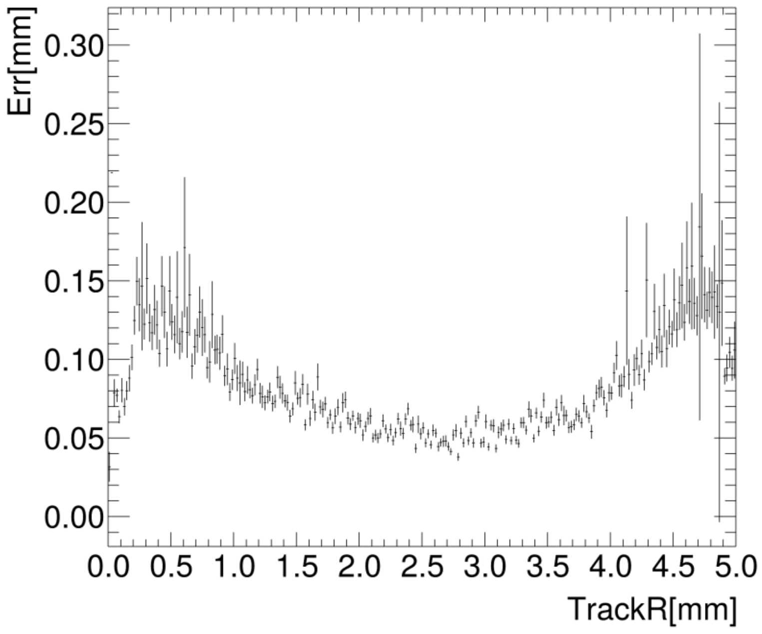
- To reach the goal of σ_{xy} ~ 120 um, uncertainty caused by detector and electronics' noise should be less than $\sqrt{120^2 - 68^2} = 98.8$ um.
- Smear RecR using Gaus(0,100) to simulate maximum uncertainty. This uncertainty is considered in following researches.



Average position resolution in all cells



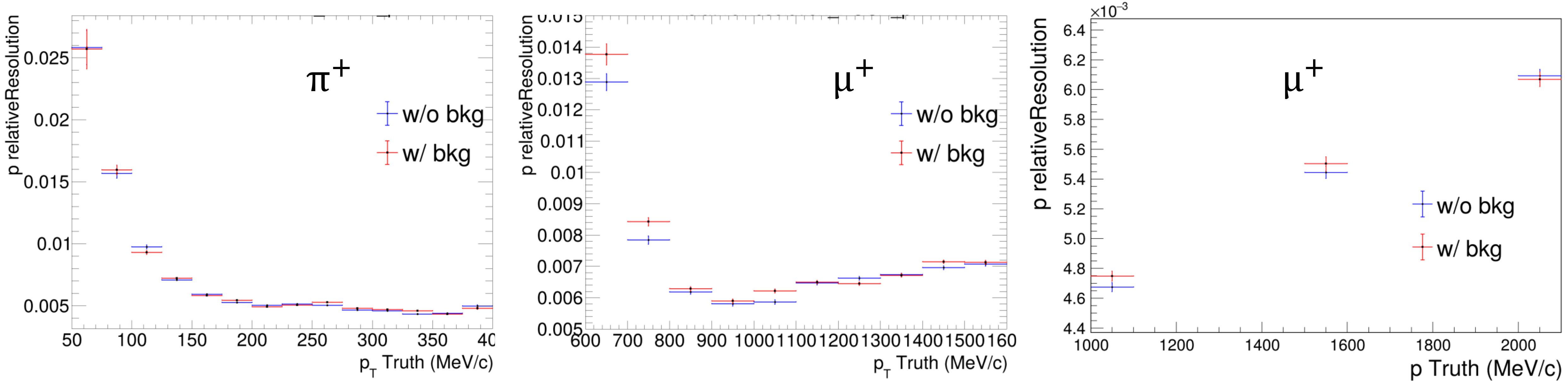
Position resolution a function of drift distance in all cells w/o edge effect



Position resolution a function of drift distance in layer 0

Performance of Track Reconstruction with T-X Reconstruction

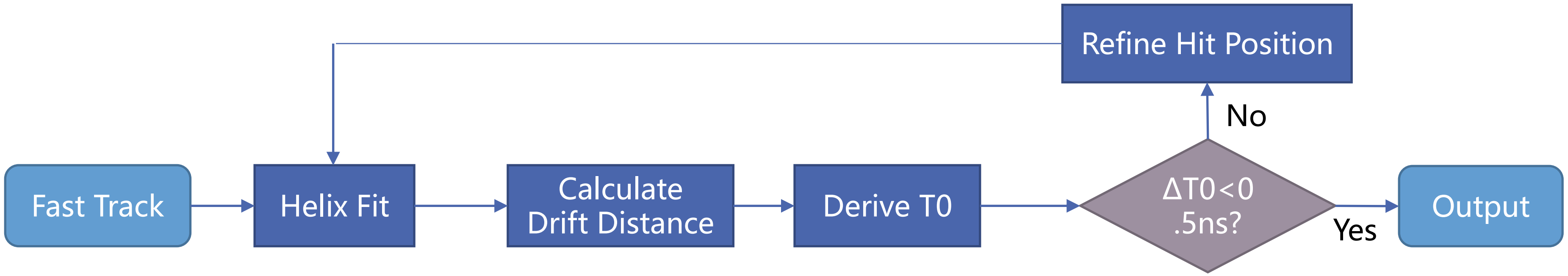
- Reconstruct $\Psi(2S) \rightarrow \pi^+\pi^- J/\psi,\ J/\psi \rightarrow \mu^+\mu^-$ event and single μ^+
- σ_p/p < 0.5% @ 1GeV/c



Momentum resolution

Fast T0 Reconstruction

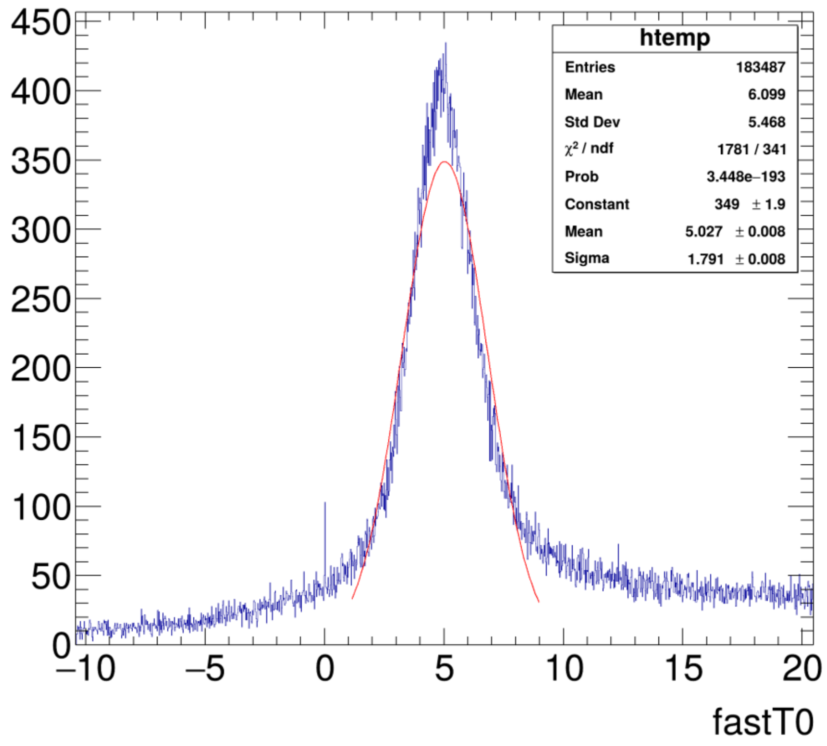
- Calculating T_0 enables alignment of track start time and collision time (<100ps resolution) to obtain precise time measurement.
- Time-of-Flight detector (RICH/DTOF) need track parameters as input to calculate T_0 , so MDC must be used to calculate a coarse T_0 first.
  - Fast tracks are found only using hit wire positions (not drift circles) by Hough transform algorithm.
  - T_0 of a hit can be extracted by $T_0 = T_{TDC} - TOF - T_{drift} - T_{prop}$
  - Track T_0 weighted by hit positional precision (from T-X relation).
  - Send track T_0 and parameters to RICH/DTOF to calculate precise T_0



Iterate process in fast T0 reconstruction

Performance of Fast T0 Reconstruction

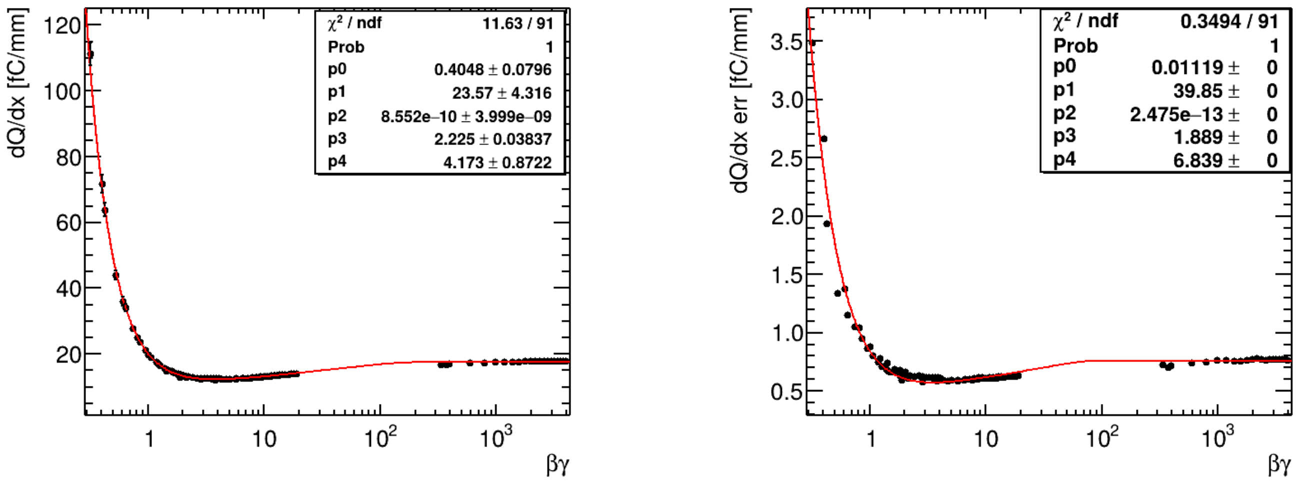
- In fast tracks of $\Psi(2S) \to \pi^+\pi^- J/\psi,\ J/\psi \to \mu^+\mu^-$ process, event T_0 resolution is 1.8ns.
- The precision of the reconstructed T_0 critically depends on the accuracy of the T-X relationship.
- This algorithm is still in the development stage.



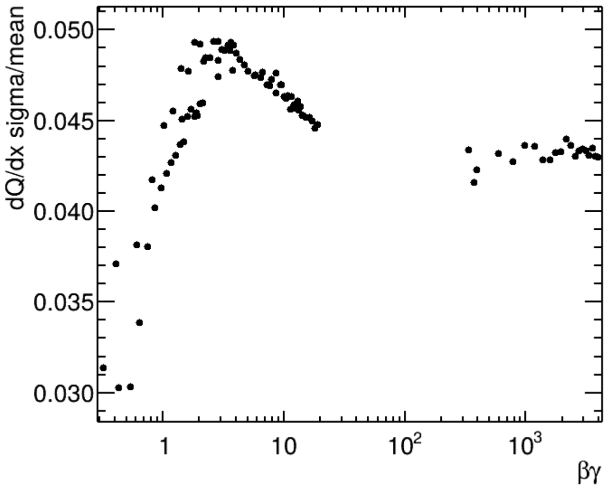
Reconstructed T0 of events from fast tracks w/o bkg

dE/dx Reconstruction and PID

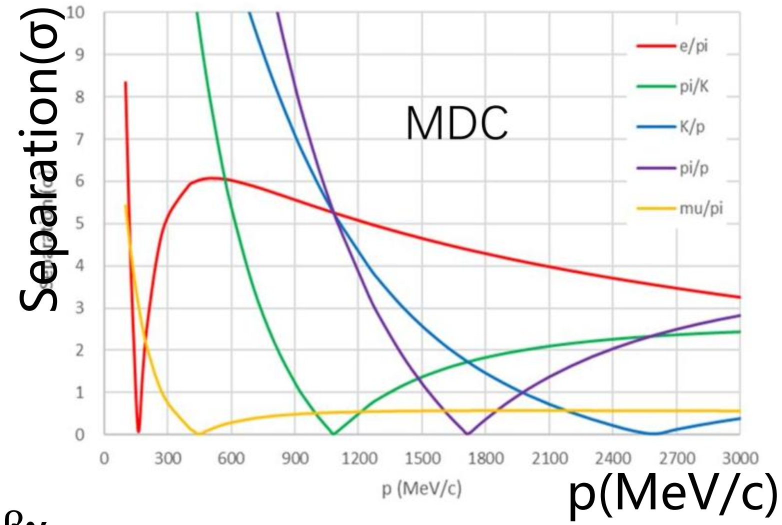
- Energy loss of charged particle is proportional to signal charge.
- After track fitting, every hit has its own track segment then hit dE/dx can be calculated.
- Track dE/dx is the average of hit dE/dx excluding 25% high points, resolution is 5%
- For K/π , the MDC PID separation power is over 3σ up to 700 MeV/c, satisfies requirement.



dE/dx and its error as function of βγ



dE/dx resolution as function of βγ



PID separation

Summary and Prospect

- An efficient pipeline of MDC time and charge signal simulation established.
- Design requirements satisfied
  - tracking efficiency 90% at p_T=0.1GeV/c, 95% at p_T>150MeV/c.
  - position resolution is 111μm
  - dE/dx resolution 5%

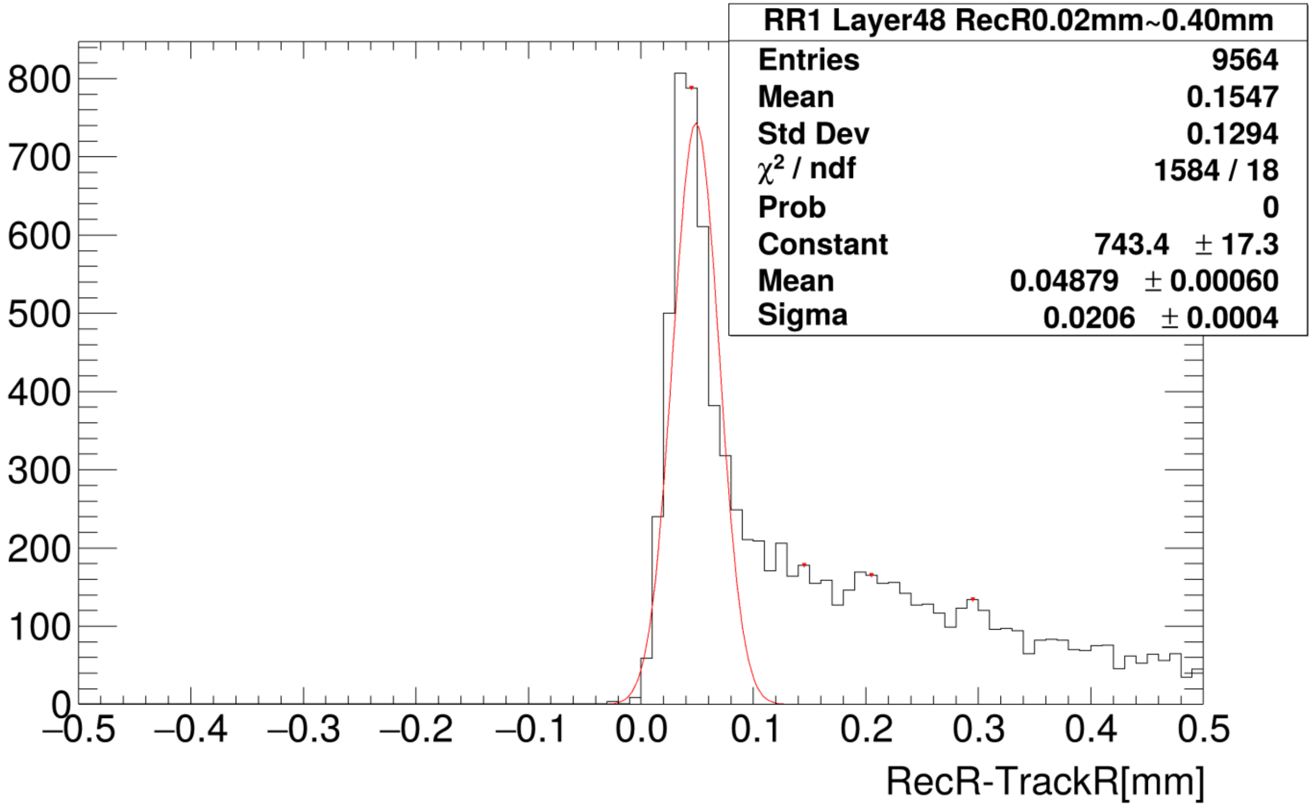
➢ Fast T0 reconstruction algorithm is still in the development stage

➢ Tracker has geometry optimization recently, it's performance should be checked.

References

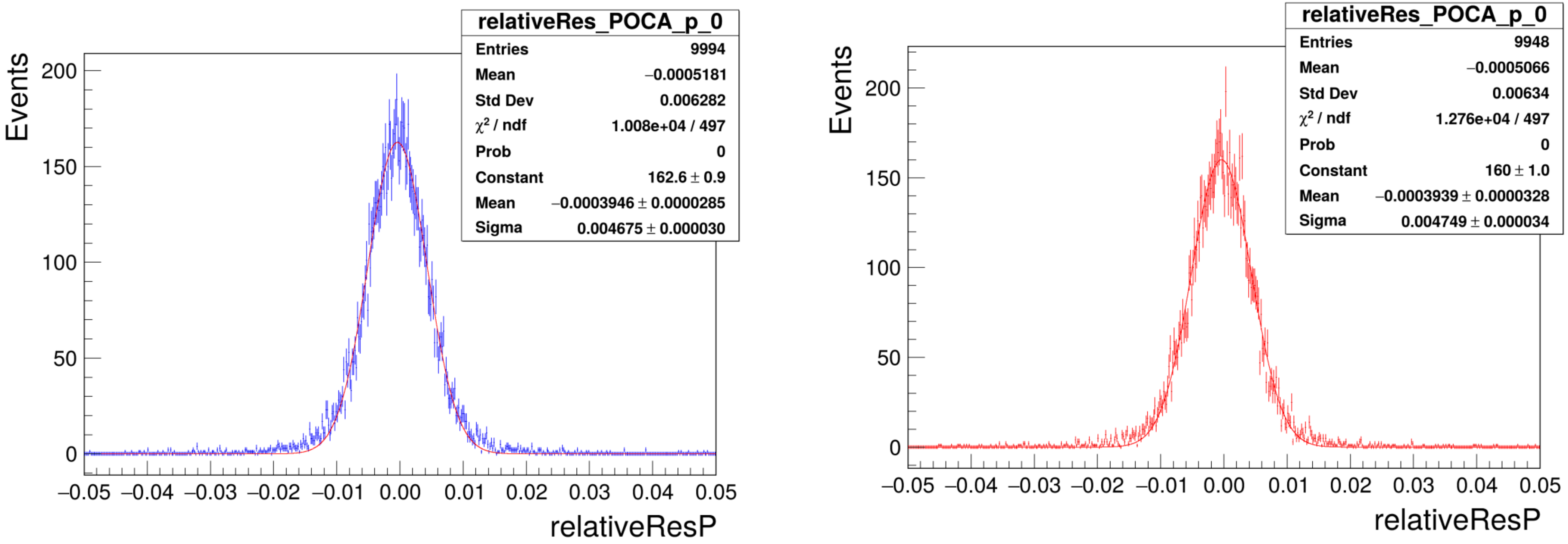
- [1] Achasov M, Ai X C, An L P, et al. STCF conceptual design report (Volume 1): Physics & detector[J]. Frontiers of Physics, 2024, 19(1): 14701.
- [2] Zhou H, Sun K, Lu Z, et al. Global track finding based on the Hough transform in the STCF detector[J]. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2025, 1075: 170357.
- [3] Basok I Y, Bobrovnikov V S, Bykov A V, et al. The spatial resolution measurements on the small prototype of the Super Charm-Tau Factory drift chamber[J]. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2024, 1064: 169419.

Backup



Drift distance residual in a region near anode wire
Calculate StdDev in (Mean-3Sigma, Mean+3Sigma) as histogram's sigma here.

Backup



Relative resolution of 1000MeV muon w/ (left) or w/o (right) baackground