GPGPU Track Finding in a COMET Phase-Ⅰ Drift Chamber

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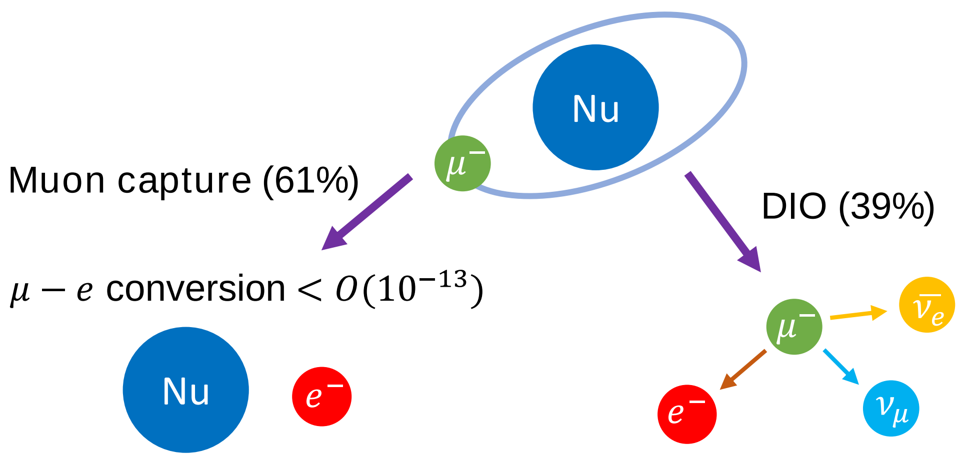
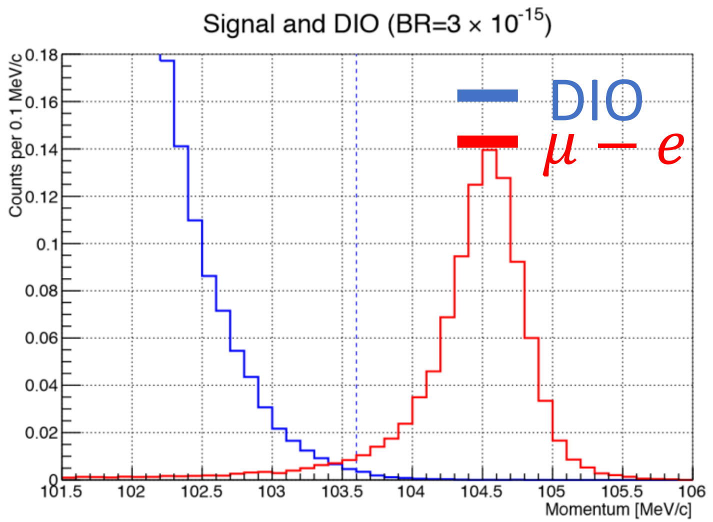
$\mu^- \to e^-$ conversion in a muonic atom

$\mu^- \to e^-$ conversion (Charged Lepton Flavor Violation)

- A discovery of the $\mu^- \to e^-$ conversion will be an evidence to New Physics.
- COMET experiment of J-PARC will investigate the $\mu^- \to e^-$ conversion in a muonic atom with the sensitivity of $O(10^{-15})$ and $O(10^{-17})$ at Phase-1 and Phase-2, respectively.

Muonic atom





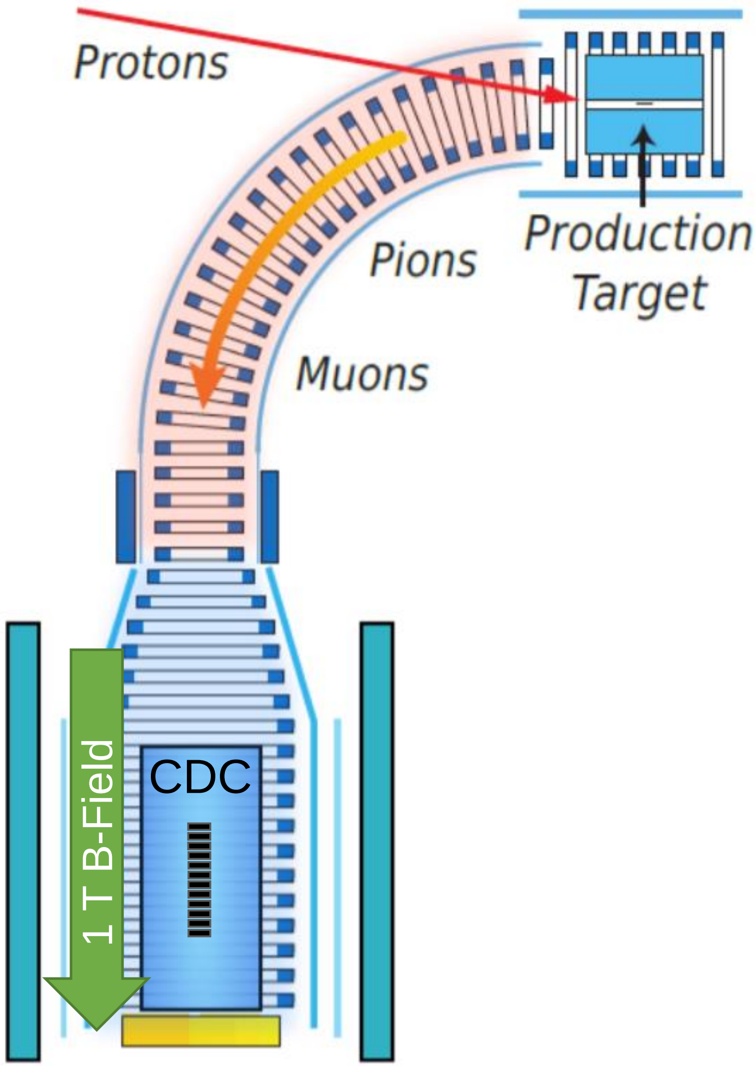
Signal and background in the $\mu^- \to e^-$ conversion

- e^- from $\mu^- \to e^-$ conversion is mono-energetic:

$$E_{\mu^- e^-} = m_\mu - B_{1s} - E_{recoil} = 104.97 \text{ MeV}$$

- Decay-in-orbit (DIO): e^- has the endpoint energy same with $E_{\mu^- e^-}$ (104.97 MeV)

COMET Phase-Ⅰ experiment overview



1. Pulsed Proton Beam

- π^- production from the proton target
- Beam bunch period : $1170\ \mathrm{ns}$

2. Muon Transport

- π^- decays into μ^-
- μ^- is transported in the curved solenoid

3. Muon Decay in a Drift Chamber

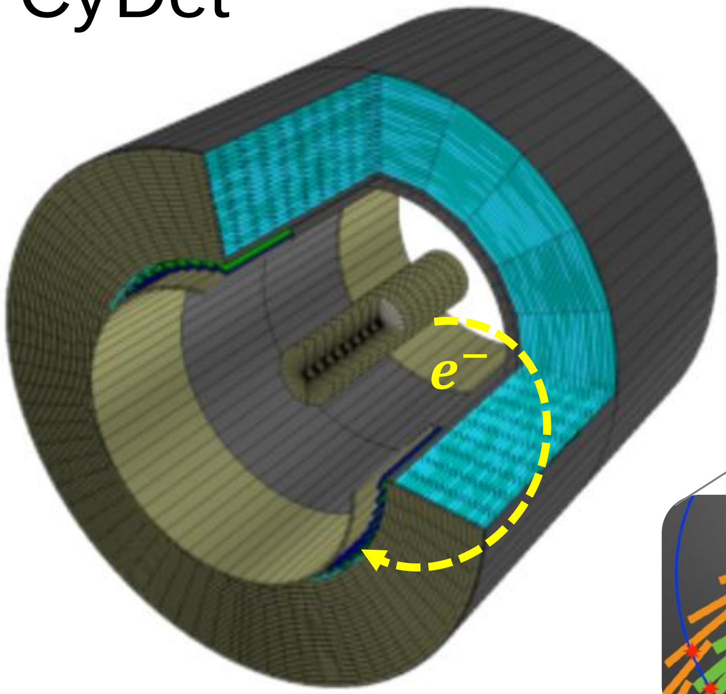
- μ^- stops at the Al muon-stopping targets in the Cylindrical Drift Chamber (CDC) forming a muonic atom

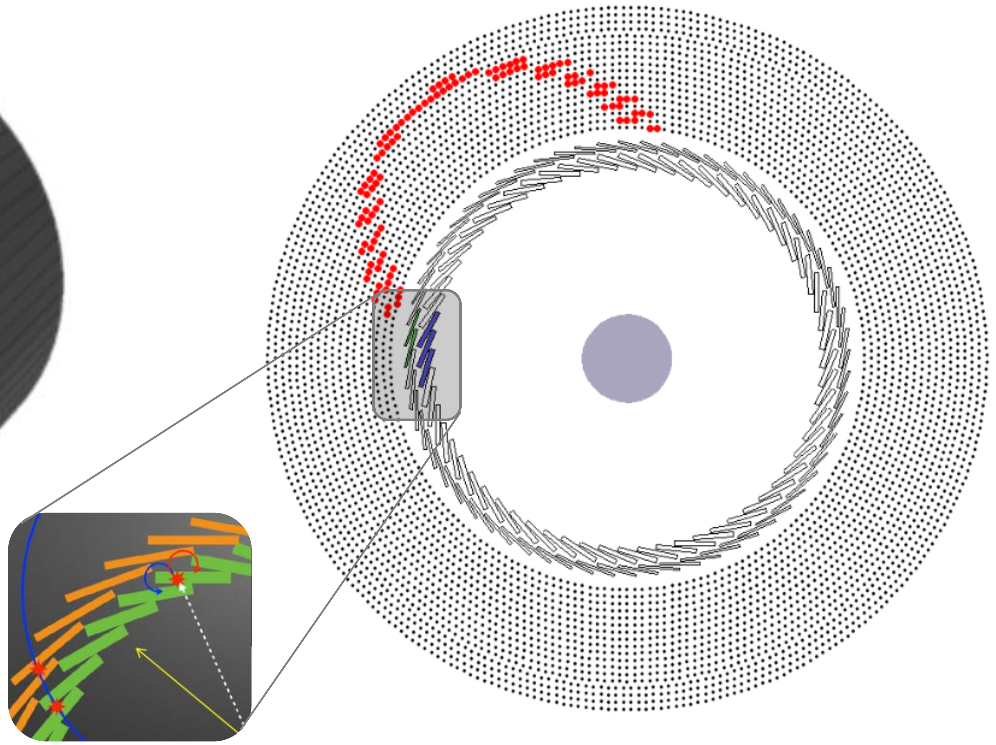
COMET Cylindrical Detector System (CyDet)

Cylindrical Drift Chamber (CDC)
- He[90]:C4H10[10] gas mixture
- 18 sense layers with alternating stereo angles
- 4482 sense wires in total

CyDet Trigger Hodoscope (CTH)
- Placed at the end of up/down stream
- Scintillator and Cherenkov detector
- Triggered when e^- makes a four-fold coincidence

CyDet



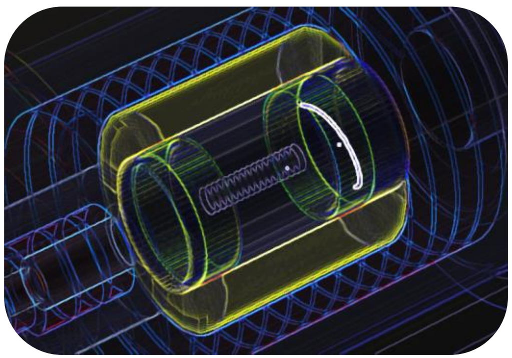


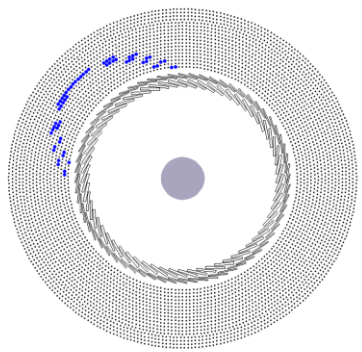
Challenges in Track Finding

e^- events are divided into two types: Single turn and Multiple turn events

- The fraction of the multiple turn events $\sim 30\ \%$
- Multiple turn events usually have low a longitudinal momentum (p_z)

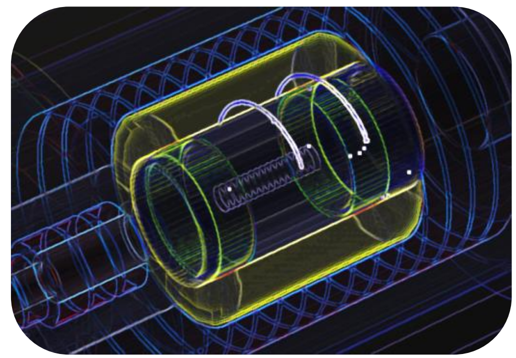
Single turn event

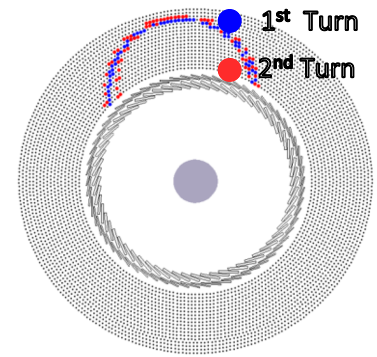




- Finding the hit candidates is not necessary
- Tracking seed can be obtained with $z-\phi$ plot and helix fitting

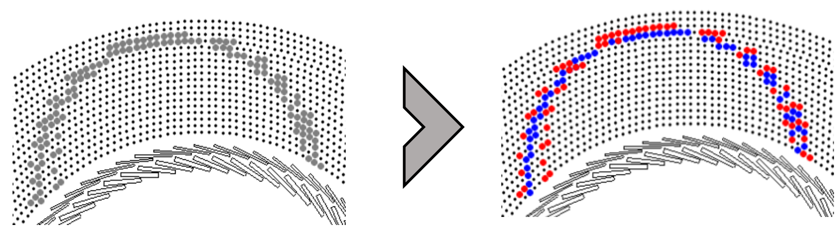
Multiple turn event





- Discriminating the hits for each turn partition of the track is challenging due to:

1) Uncertainty in tracking seeds
2) Dense distribution of hits



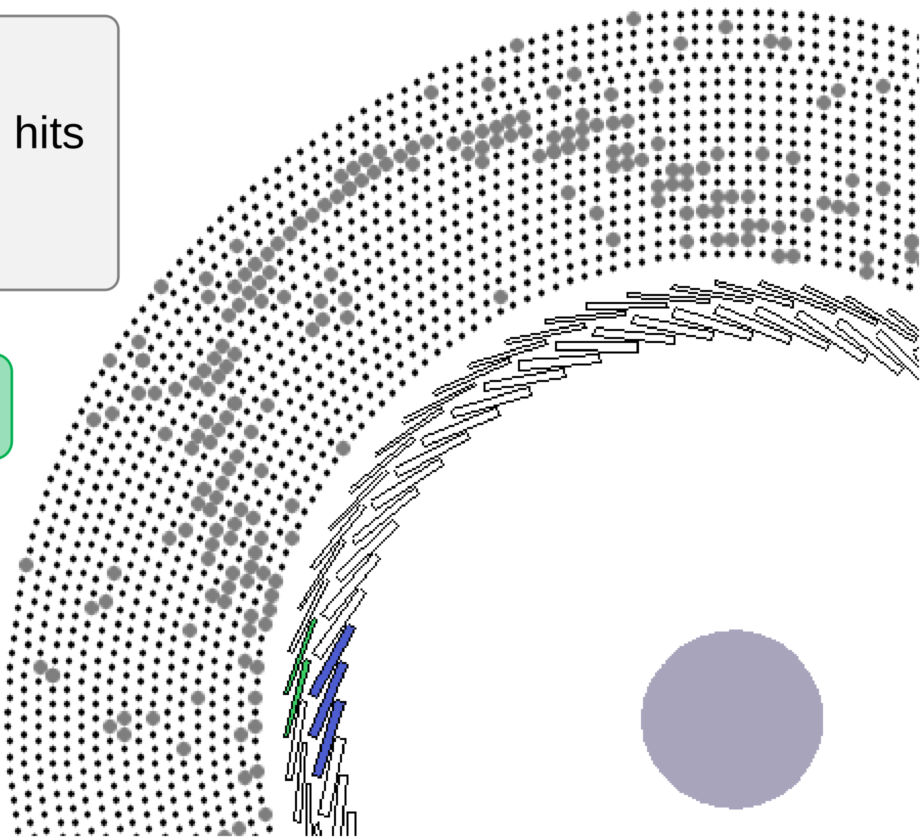
Tracking Overview

1. Noise Hits Filtering
・ Filter most of noise hits (~99 %) by pattern recognition (E. Gillies, Connecting The Dots 2018)

2. Track Finding
・ Classify the turn numbers for the signal hits
・ Obtain tracking seeds $(\vec{x}_0, \vec{p}_0)$
⇒ Main strategy: Scanning the seeds

GPGPU is implemented

3. Track Fitting
・ Obtain $|p|$ of the track using Kalman filtering (GENFIT2)



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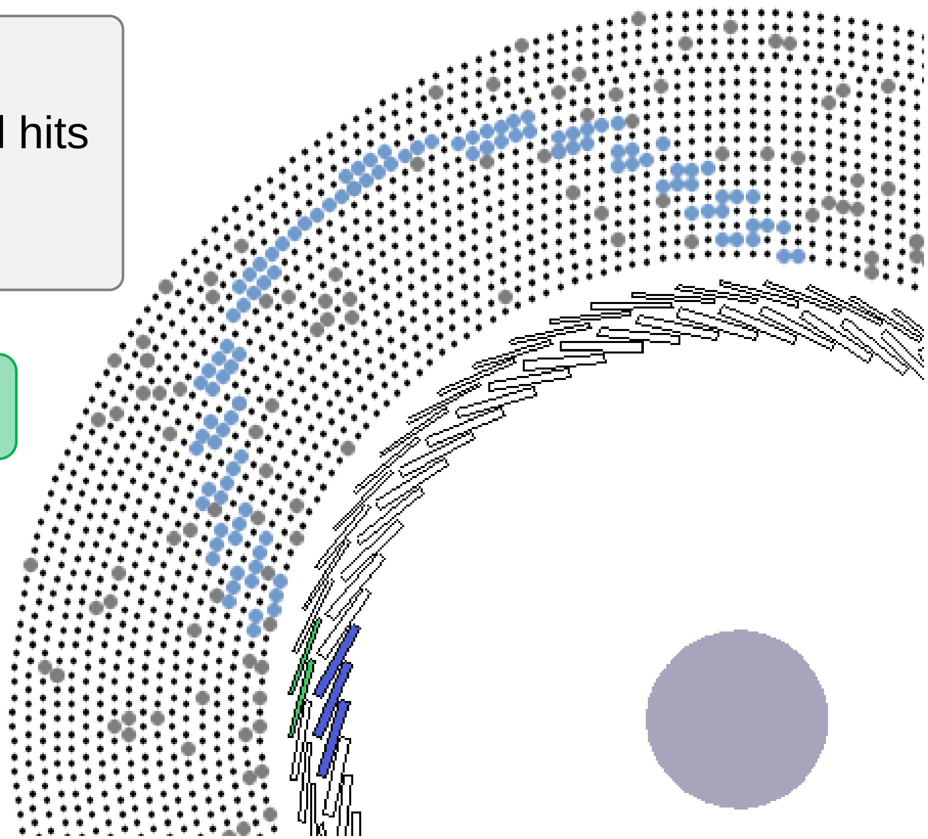

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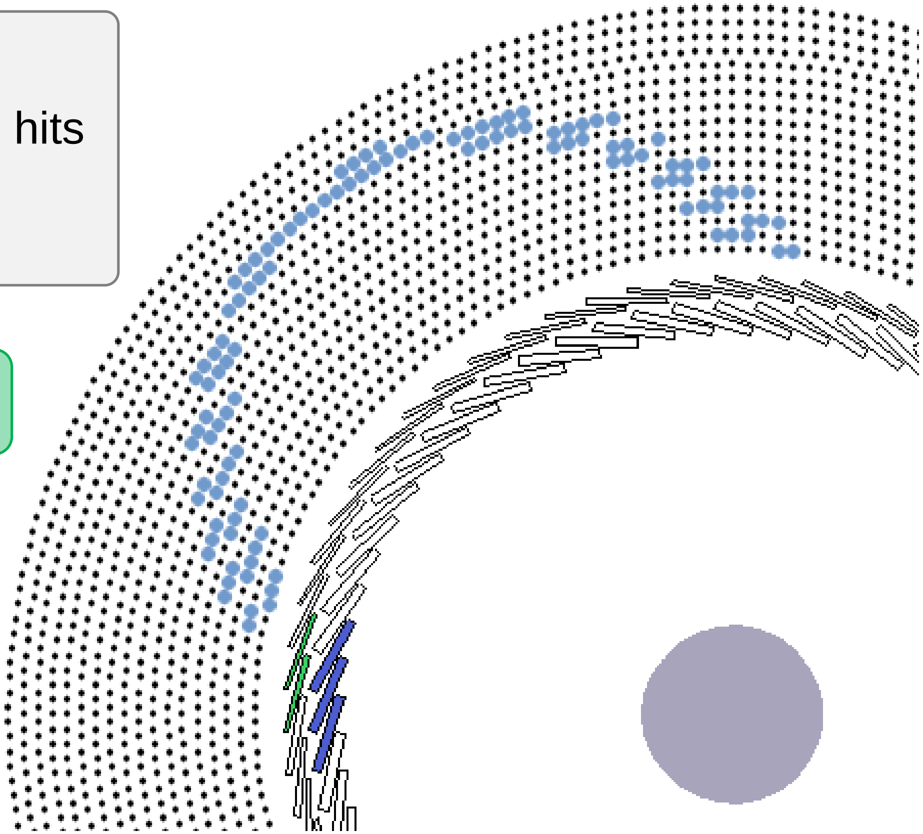

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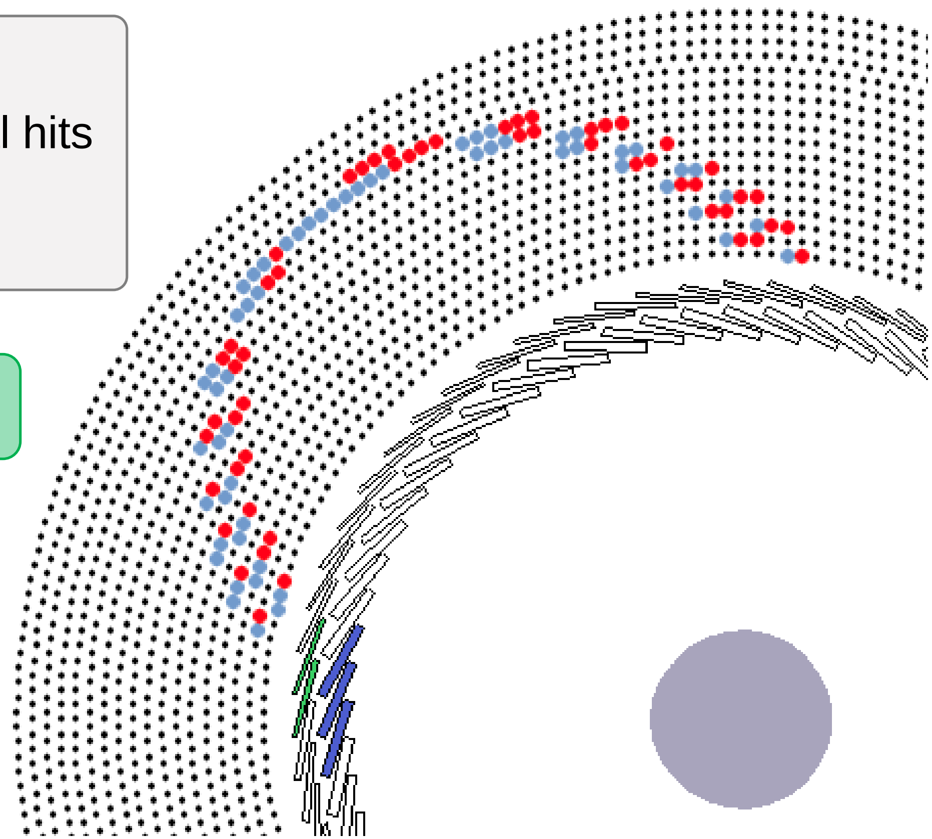

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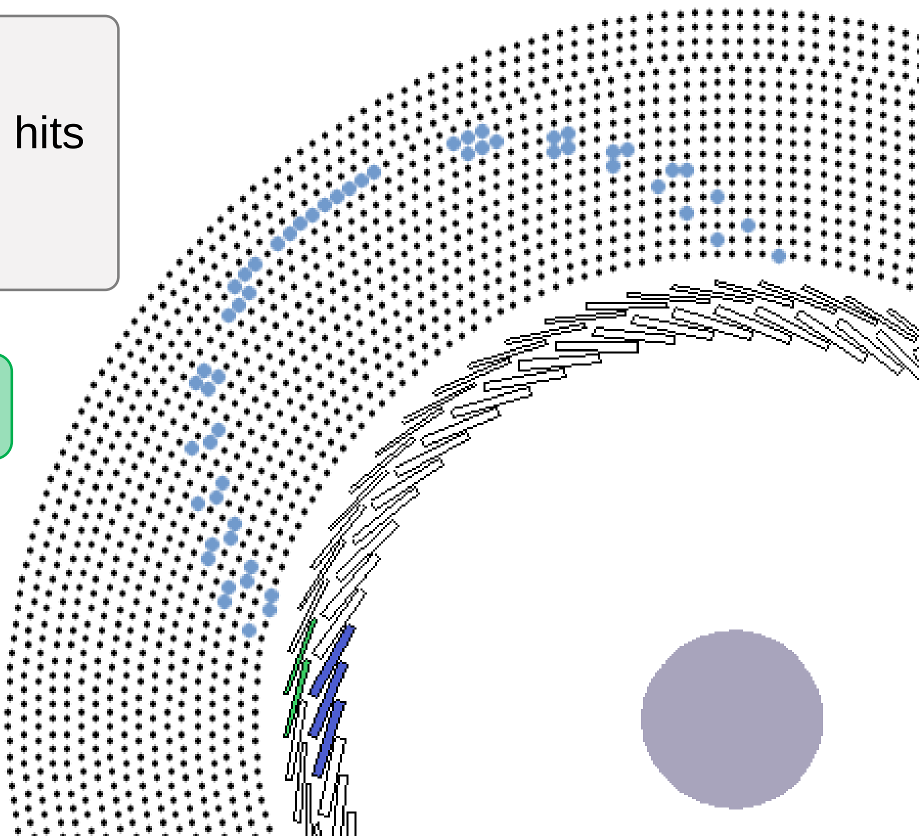

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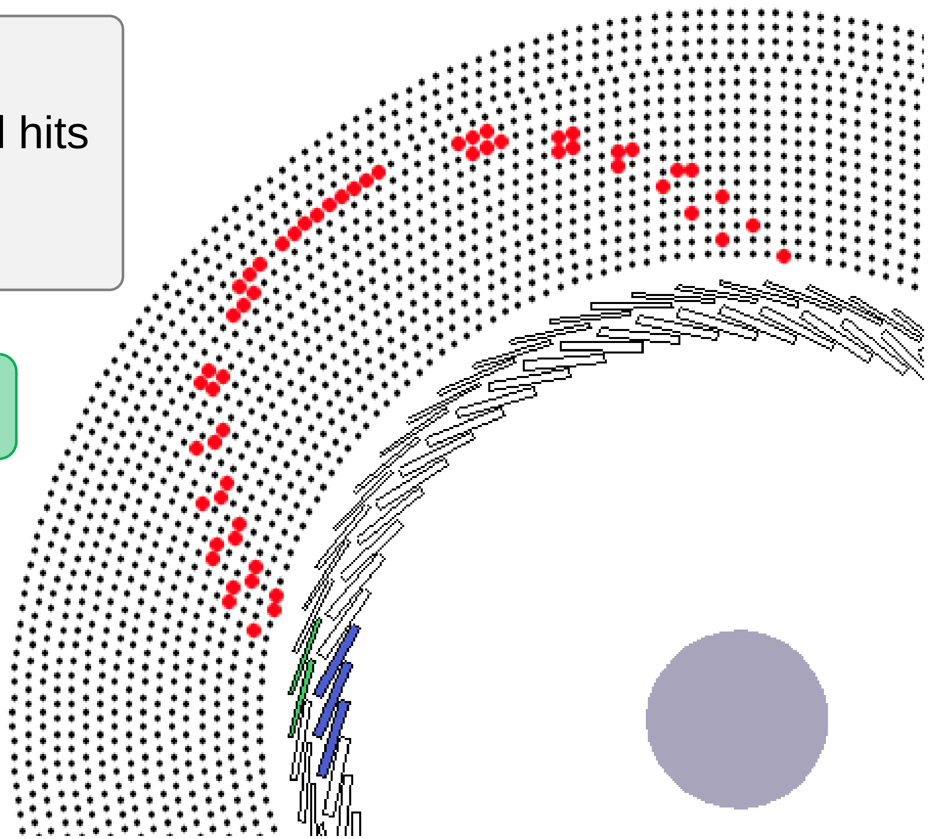
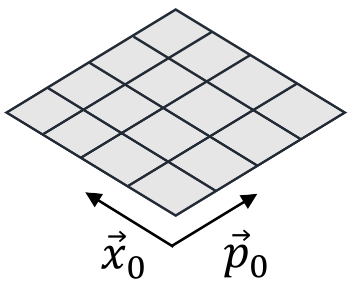
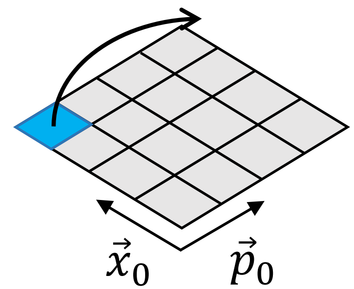


Track Finding: Scanning the Seeds (1)

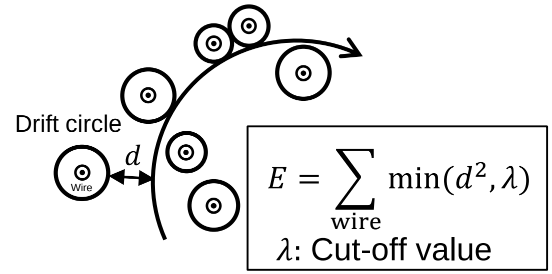


Prepare a set of the possible track seeds

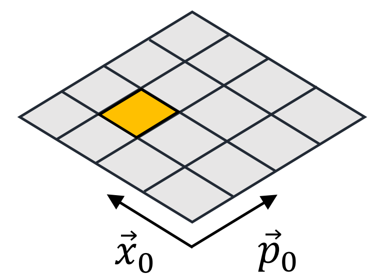
Loop to Find the Best Seed



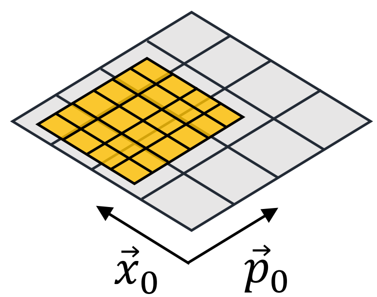
For each tracking seed, generate RK 4th track with an adaptive step size



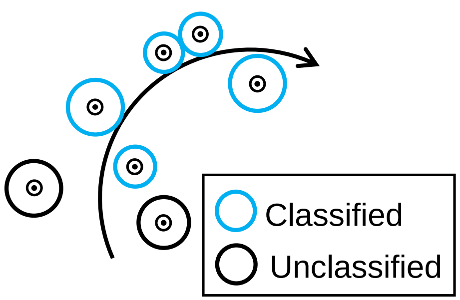
Calculate the χ^2-like value (E) by obtaining the distance (d) to the drift circle



Find the best seeds with the lowest χ^2-like value



Prepare seeds around the best seeds with a smaller cell size



If $d < \lambda$, classify the hit for the current turn partition

Track Finding: Scanning the Seeds (2)

Limiting factors

The track finding of one-way scanning from the entrance of CDC has a limited resolution due to:

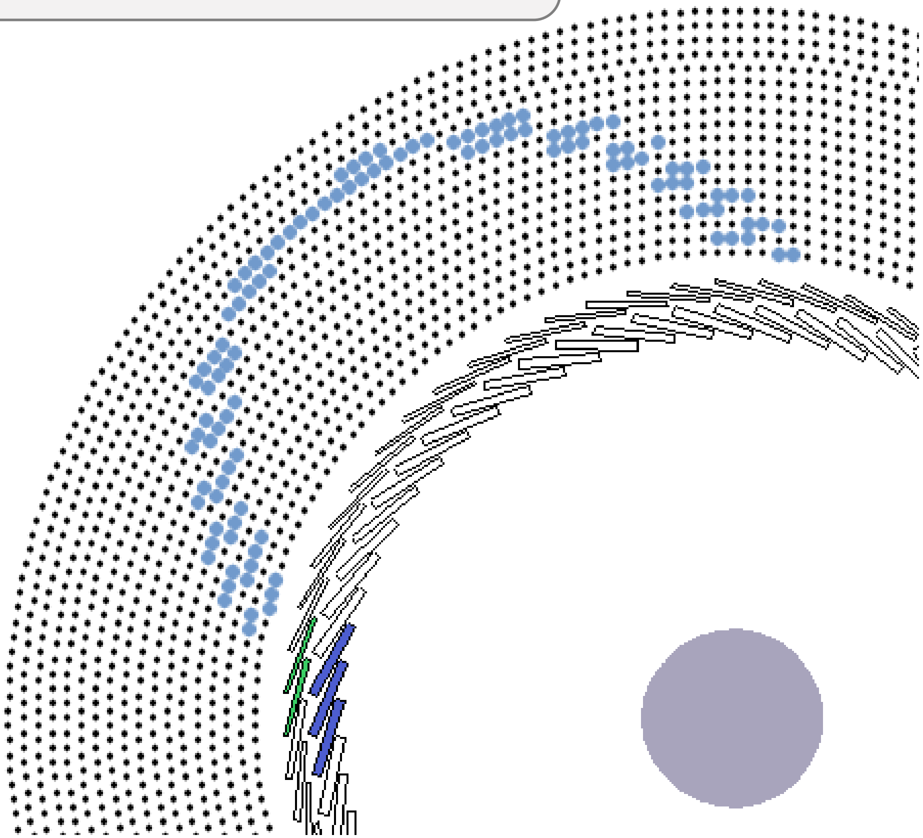
1) Interpolation error of B field during Runge-Kutta extrapolation
2) Multiple scattering from the wires and gas mixture

Bidirectional scanning

・ For a better resolution, a bidirectional scanning was employed: from both of the entrance and exit of CDC

・ When adding up χ^2-like value, the wires far from the seed are not counted by checking the extrapolation length

・ After classifying hits, applied a track quality cut:
 Number of commonly found hits ≥ 20



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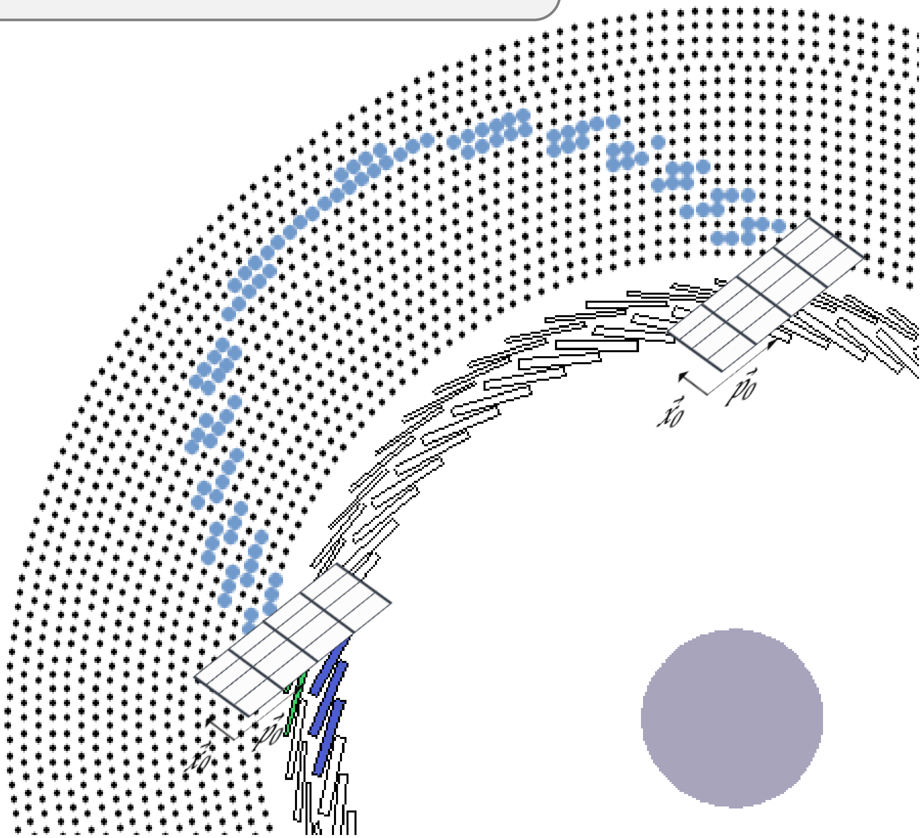

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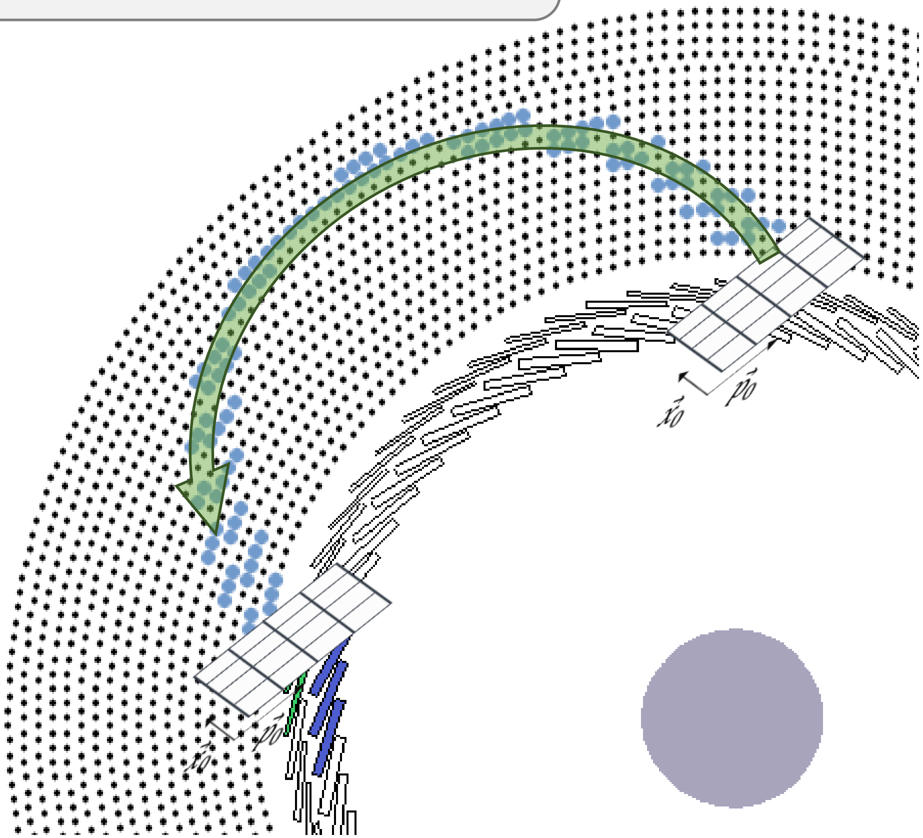

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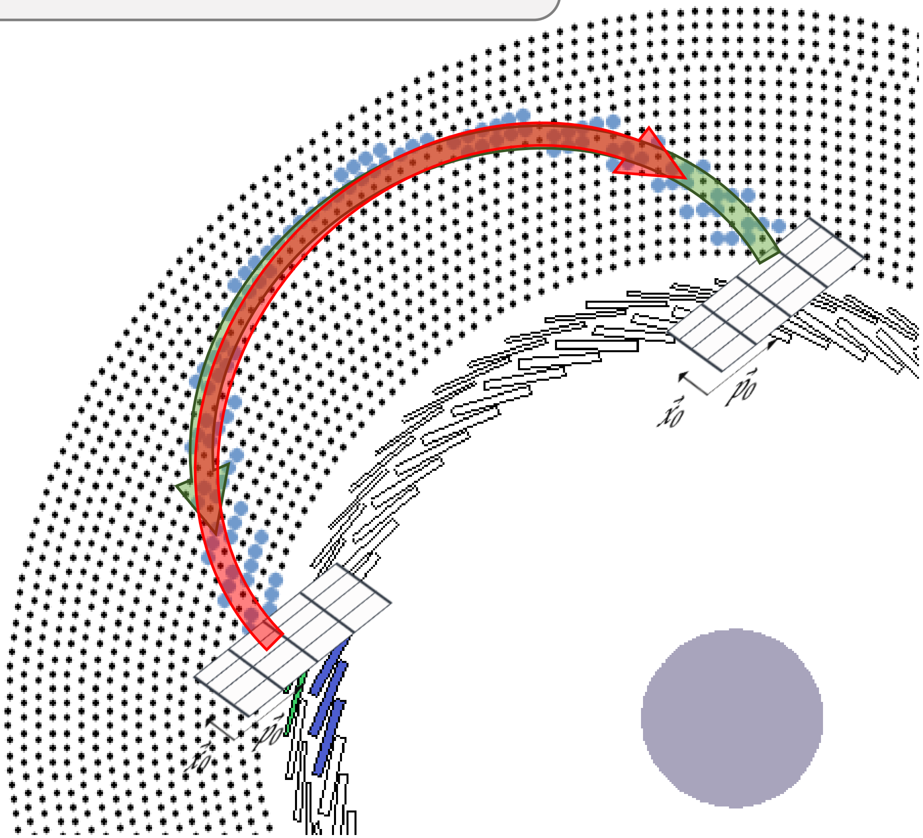
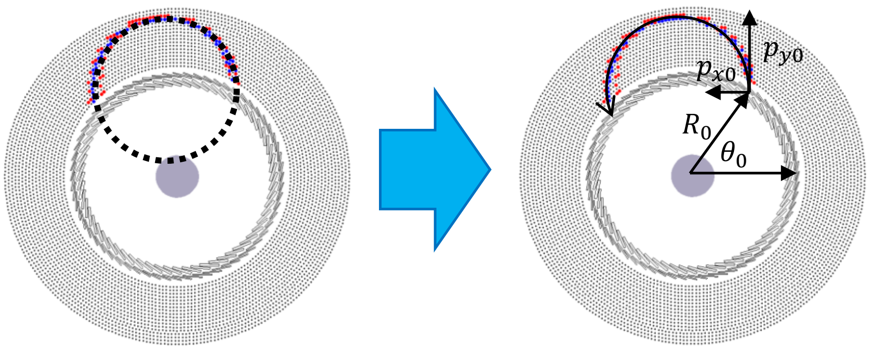


Preparing the Track Seeds

Transverse seeds: $\boldsymbol{\theta_0, p_{x0}, p_{y0}}$

・ Radial seed (R_0) is fixed as the radius of the CDC entrance

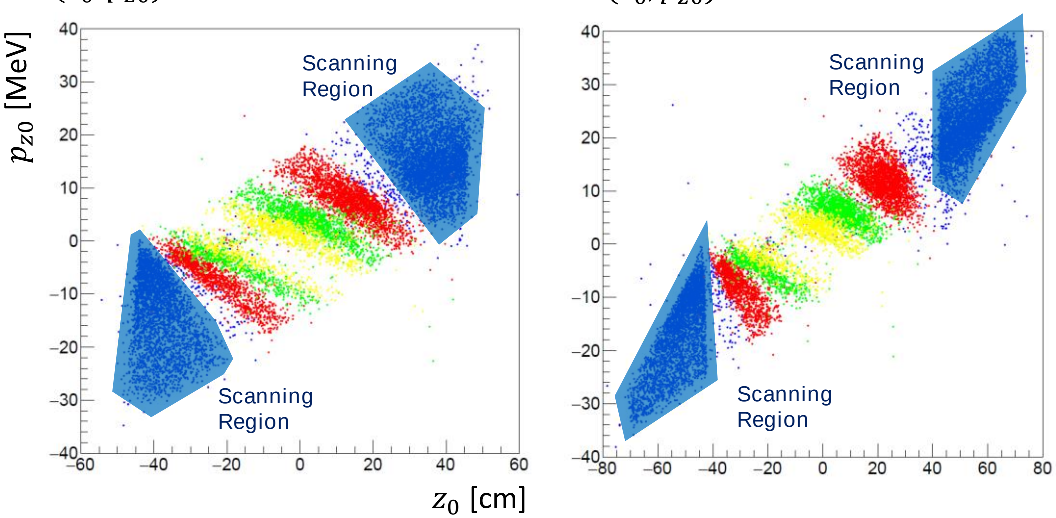
・ θ_0, p_{x0}, p_{y0} can be roughly obtained using Hough transform (circle fitting)



Longitudinal seeds: $\boldsymbol{z_0, p_{z0}}$

・ The range of (z_0, p_{z0}) of the last turn partition is shared regardless of the number of turns due to the fixed location of trigger hodoscopes and the cylindrical property

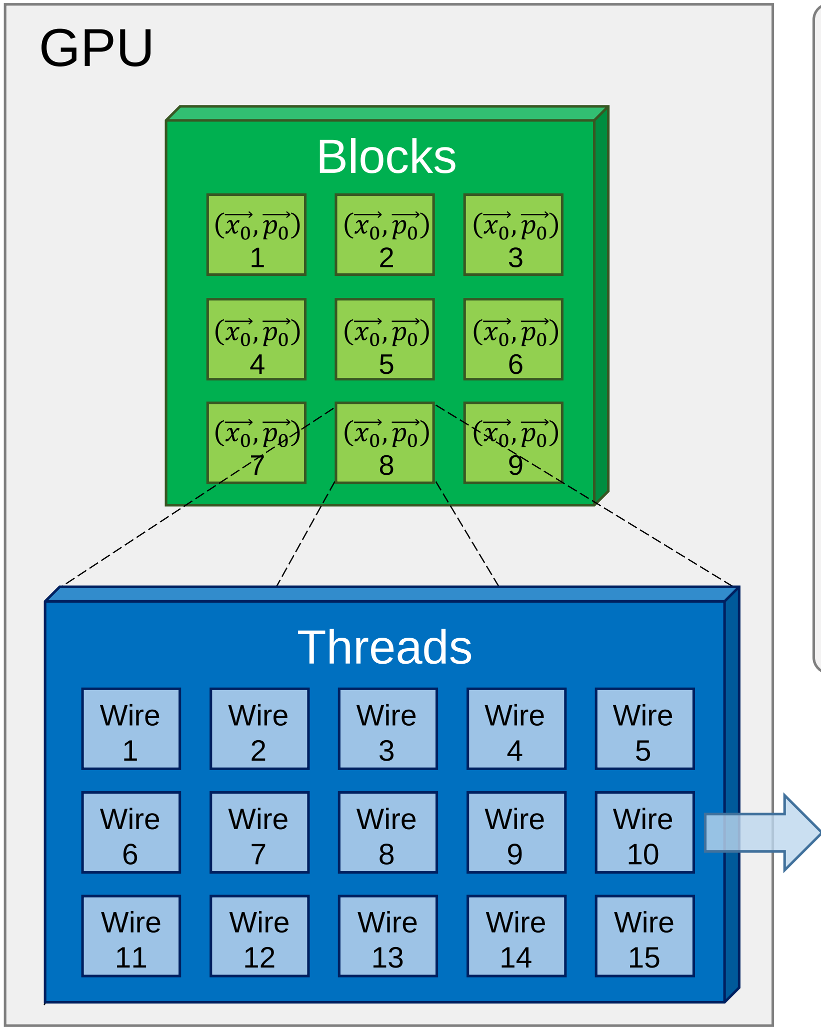
(z_0, p_{z0}) distribution at the entrance (z_0, p_{z0}) distribution at the exit



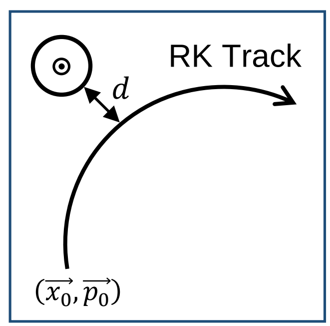
- (z_0, p_{z0}) of the n-th (last) turn
- (z_0, p_{z0}) of the (n-1)-th turn
- (z_0, p_{z0}) of the (n-2)-th turn
- (z_0, p_{z0}) of the (n-3)-th turn

⇒ Track finding starts from the last turn partition of the track

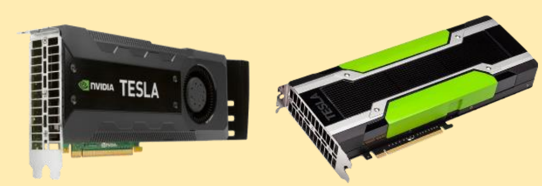
GPU (CUDA) Algorithmic Schematics



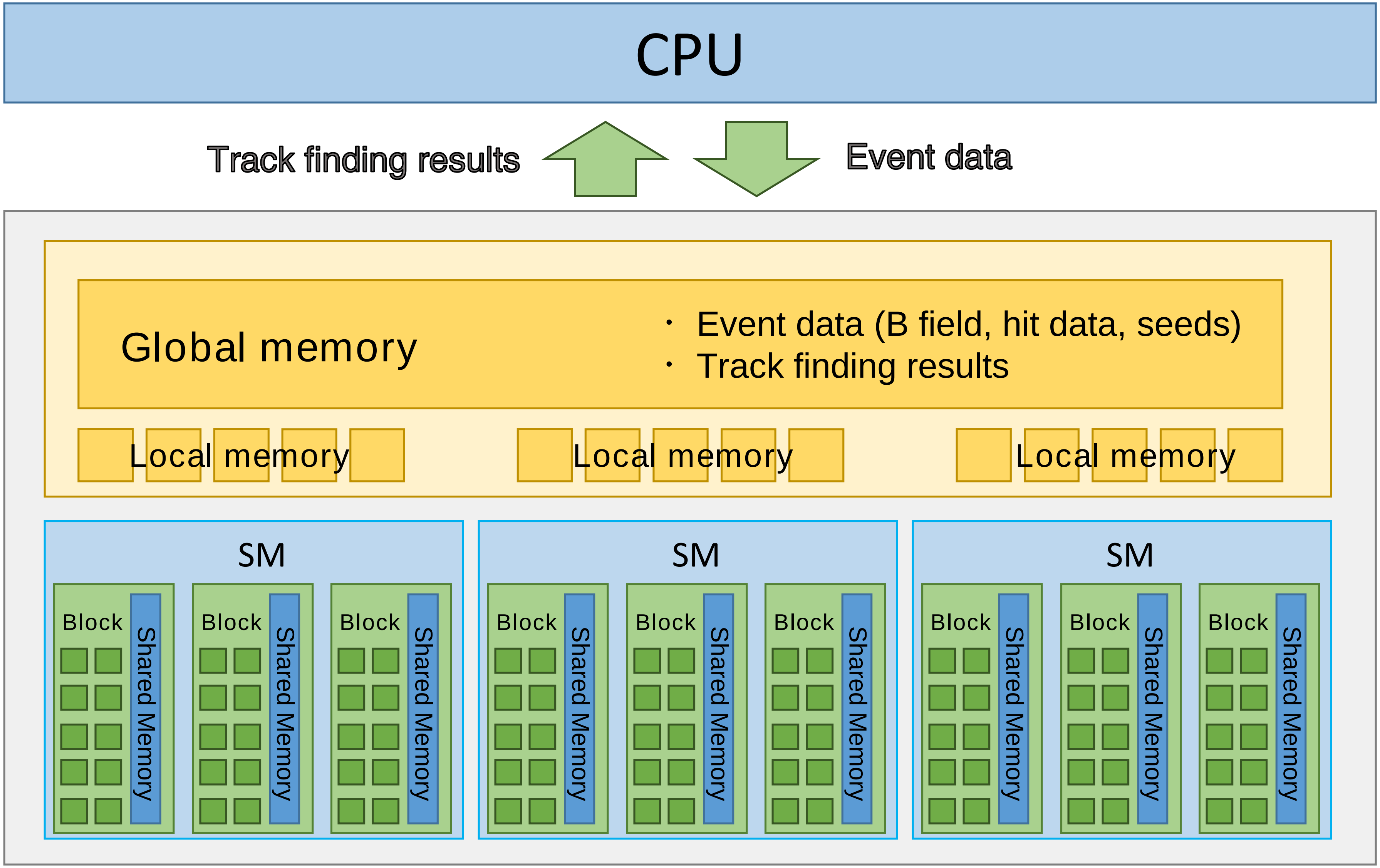
- GPU is composed of blocks (= group of threads). A thread is the minimal calculation unit
- Each tracking seed $(\vec{x}_0, \vec{p}_0)$ is delivered to each block to calculate χ^2-like value.
(# of blocks = # of tracking seeds)
- Each thread in a block calculates the distance (d) between an RK track and the drift circle of a wire.
(# of threads in a block = # of activated wires)



Mainly studied GPU:
Tesla K40 & K80



GPU (CUDA) Memory Hierarchical Schematics



* SM = Streaming multiprocessor

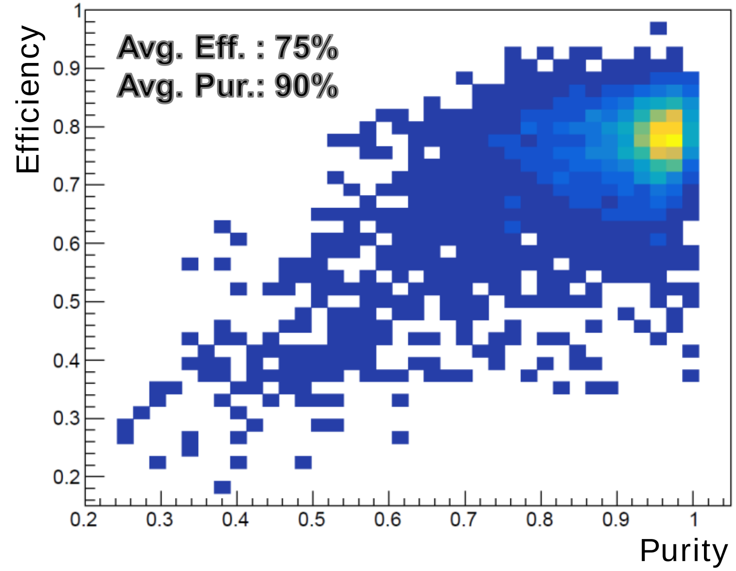
Efficiency and Purity of the Scanning Method

Track finding quality

Classification efficiency $= \frac{C_{n\to n}}{C_n}$

Classification purity $= \frac{C_{n\to n}}{C_{1\to n}+C_{2\to n}+\cdots+C_{n\to n}}$

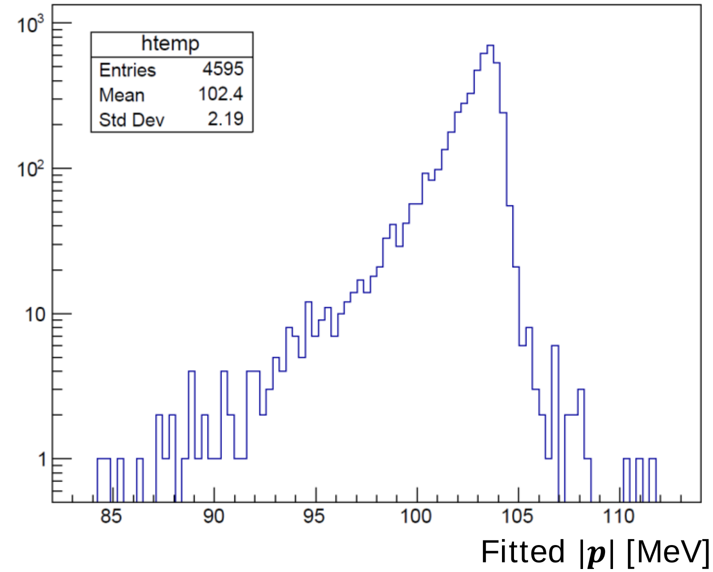
C_n: Total number of hits from last turn
$C_{i\to n}$: Number of hits of i-th turn classified as the last turn hit



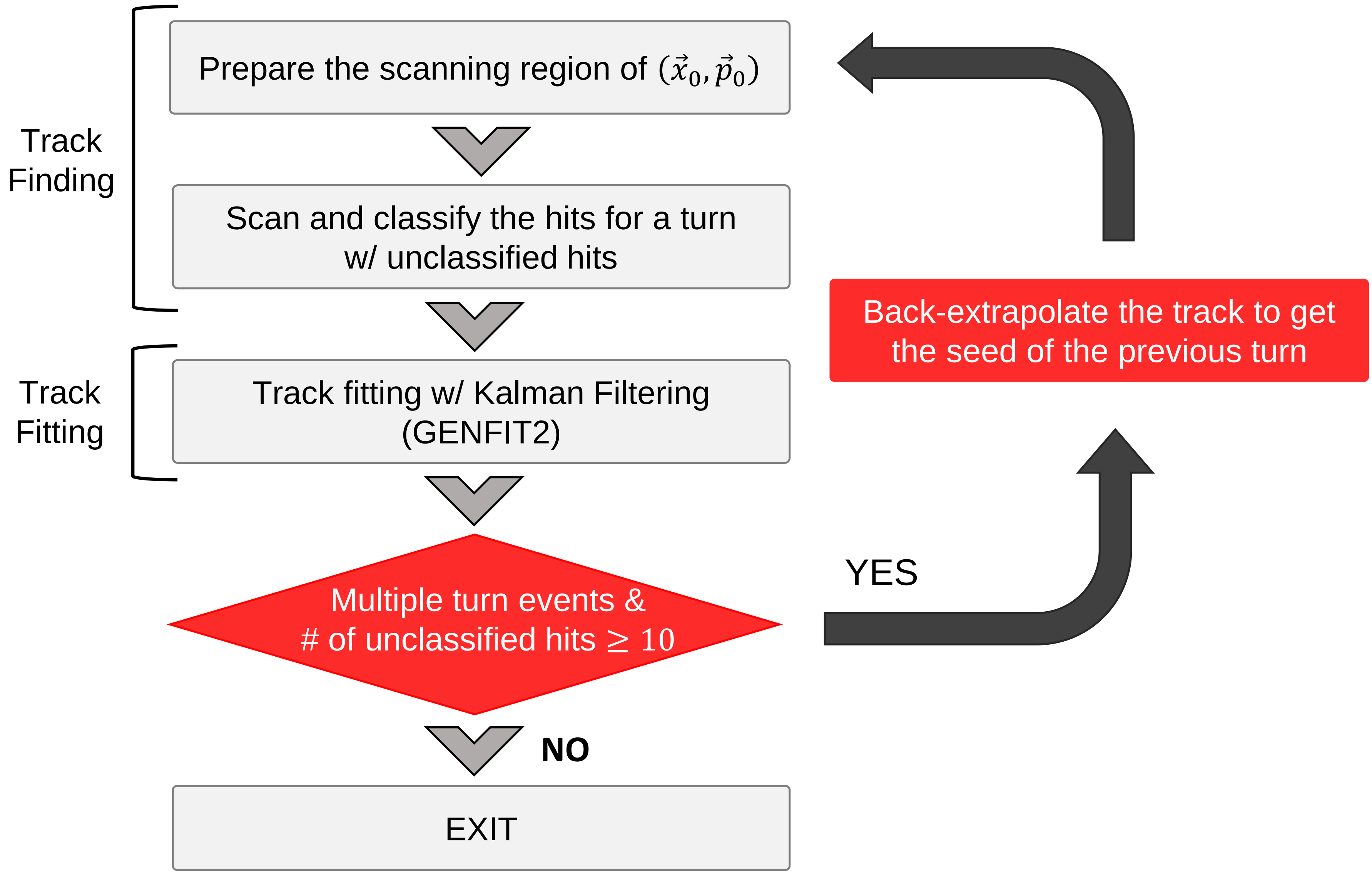
Track fitting result (GENFIT2)

Track quality cuts

1) $\mathrm{NDF} \geq 35$
2) $\chi^2/\mathrm{NDF} < 2$
3) Number of Common Hits from the bidirectional scanning ≥ 20



Overall Tracking Steps for Full Reconstruction

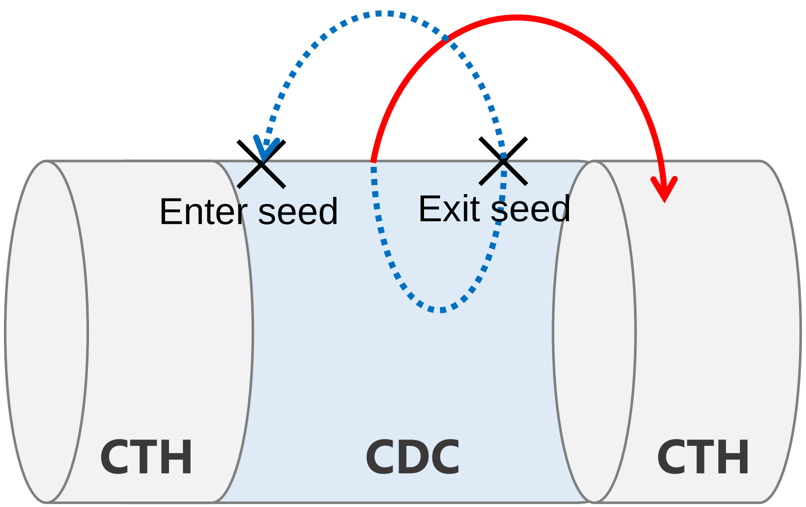


Back-Extrapolation for the Previous Turns

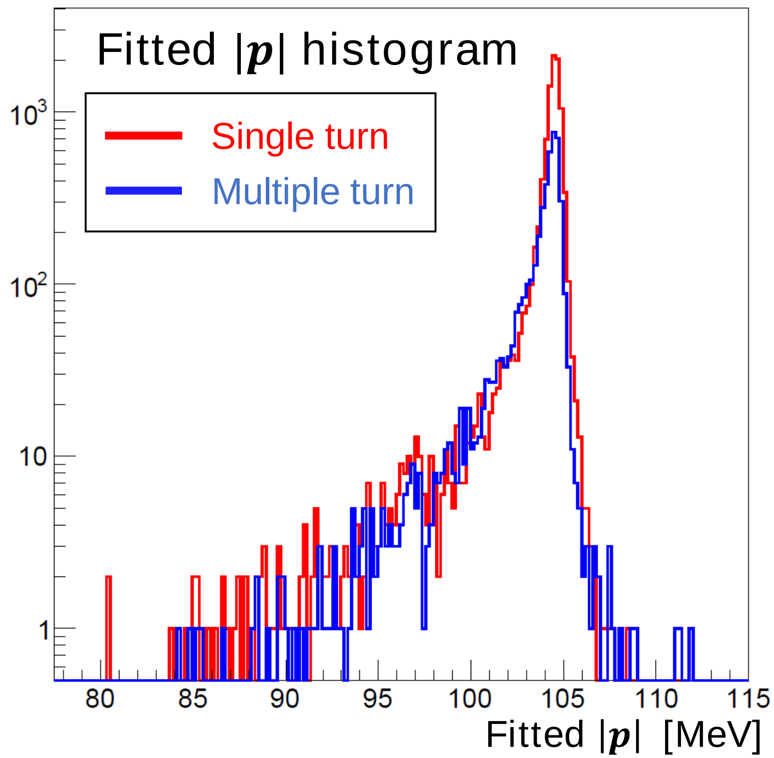
- The same method is applied to reconstruct the previous turn partition, after finishing the reconstruction of the last turn partition of the track

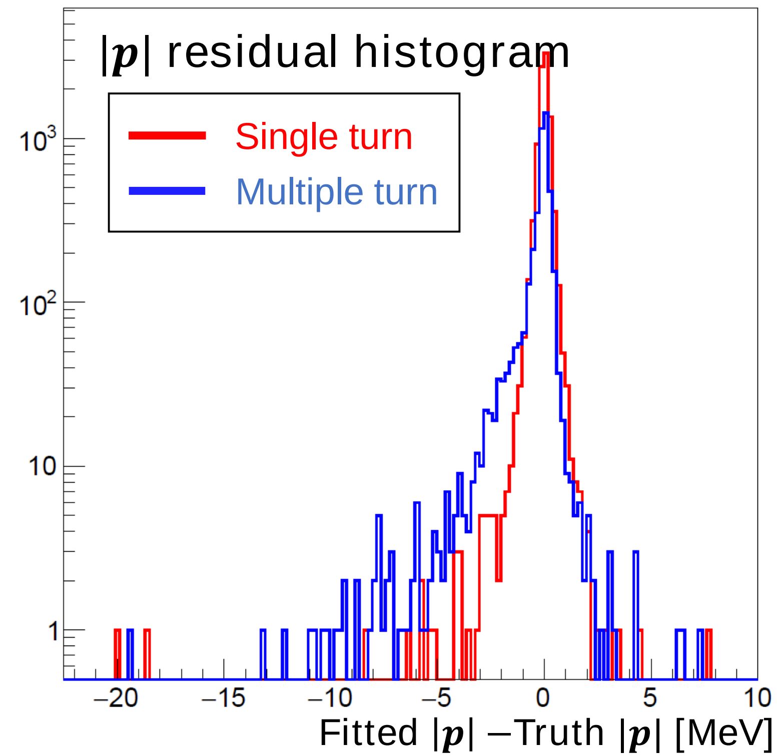
- Longitudinal track seeds (z_0, p_{z0}) is obtained by the back-extrapolating the reconstructed track $\left(\sigma_{z0} \approx 2.6 \text{ cm}, \sigma_{pz0} \approx 1.7 \text{ MeV}\right)$

- Transverse seeds $(\theta_0, p_{x0}, p_{y0})$ are again given by the Hough Transform (slightly better than the extrapolated values)



Track Fitting Result





· Track fitting of the multiple turn events has similar resolution with the single turn events ($|p|$ resolution for the core part ~ 300 keV)

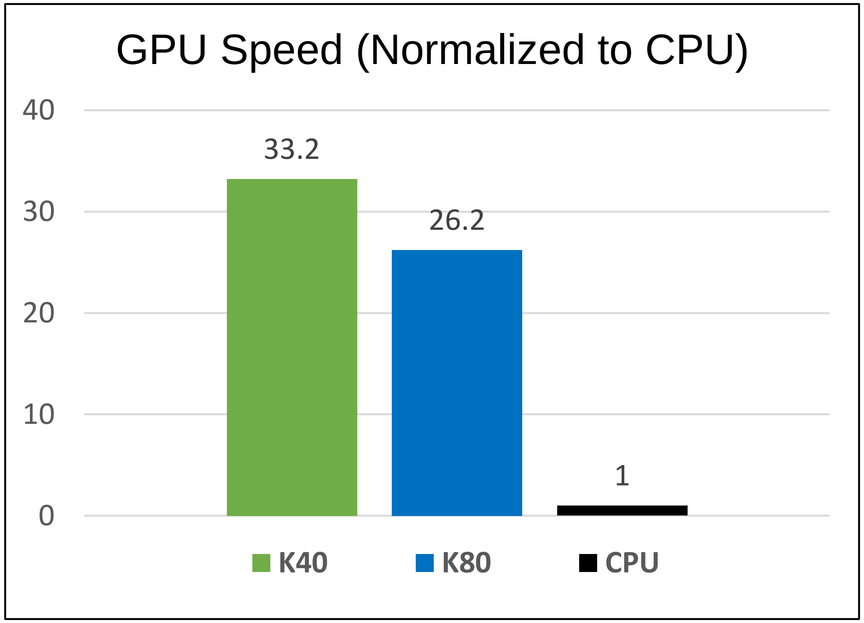
· The tracking efficiency against the CTH triggering e^- events are 50% and 53% for single turn and multiple turn, respectively.

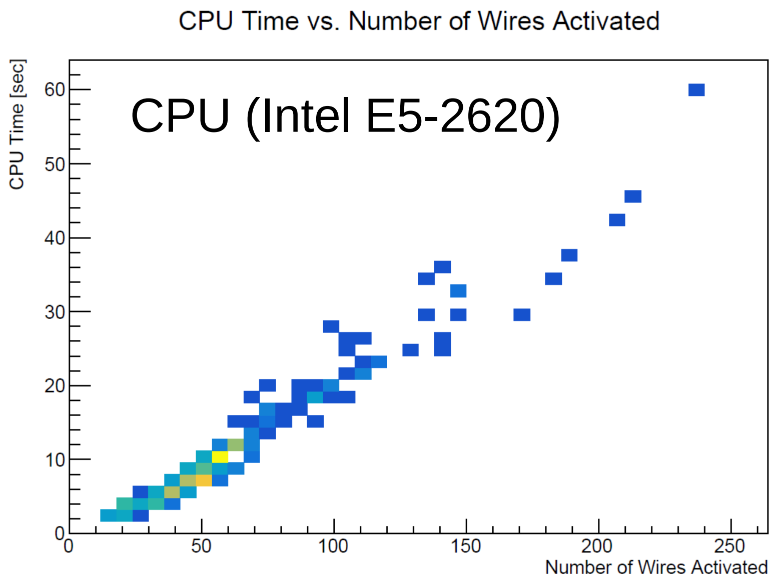
· The shoulder at the residual histogram is because few events fail in reconstructing the first turn partition

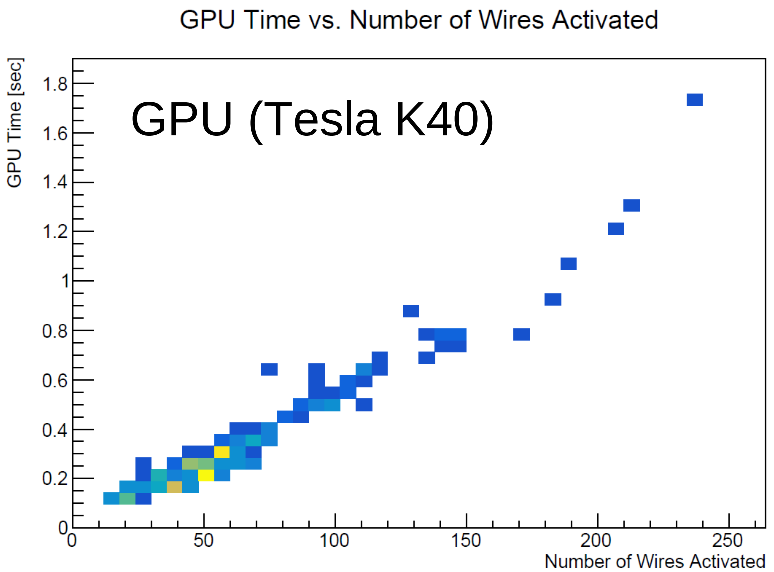
GPU vs. CPU Calculation Time

- Time taken to perform the track finding was compared with CPU
 ⇒ The scanning algorithm was serialized when measuring time taken for CPU

- GPU (Tesla K40) was >30x faster than CPU (E5-2620)





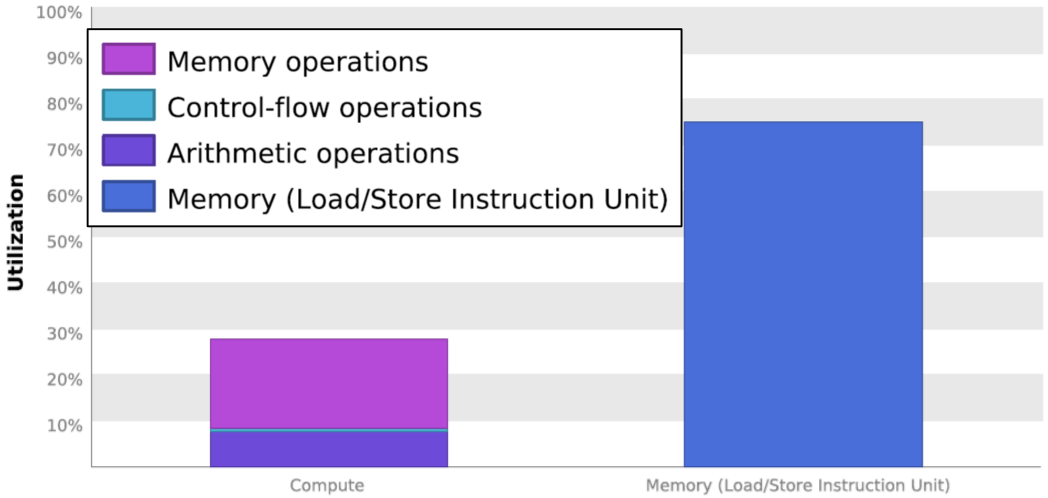


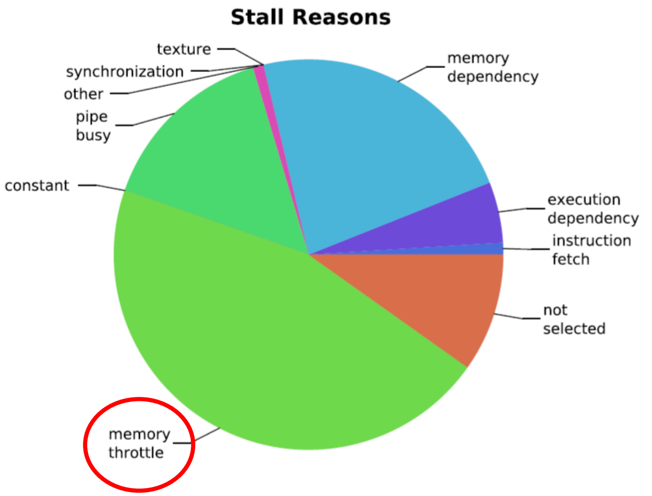
Limiting Factors in the GPU Usage

Occupancy
・ Occupancy of GPU resources is proportional to the number of activated wires (= number of threads) of the event
⇒ Occupancy is low for the events with a small number of hits

Branch divergence
・ Time taken for RK extrapolation varies for each wire
⇒ Branch divergence happens within threads

Memory bandwidth
・ GPU performance is limited by the memory throttle due to the large data transaction: B-field loading during the RK extrapolation





* Generated by NVIDIA Visual Profiler

Conclusions and Outlooks

・ COMET experiment at J-PARC will be looking for the charged lepton flavor violation through the $\mu^- \to e^-$ conversion in a muonic atom

・ In the drift chamber, track finding of the multiple turn events is very challenging because of 1) Uncertainty in the tracking seeds and 2) dense distribution of hits from different turn partitions

・ GPGPU was used to scan all possible seeds of the track in a reasonable computing time
⇒ Achieved >30x speed-up using the modern GPU
⇒ Achieved 75% of efficiency and 90% of purity

・ The optimization of various parameters in the scanning method is under way to achieve the better tracking efficiency and to reduce the computing time