Drift Chamber Tracking for COMET

Patrice Lebrun[1], Wilfrid da Silva[1] , Joe Stao[2], Siyuan Sun[3],

Yohei Nakatsugawa[4], Chen Wu[5], Tianyu Xing[6], Ye Yuan[5] , Yao Zhang[5]
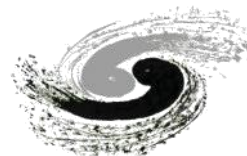
1 Sorbonne University/IN2P3
2 Saitama University
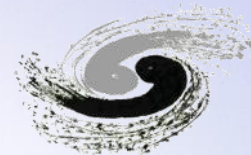3 Osaka University
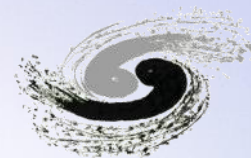4 Wakayama Medical University
5 IHEP, CAS, China

22 July 2025

Outline

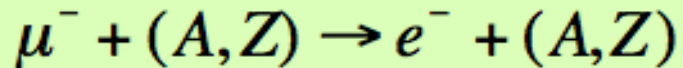- Introduction to COMET

- COMET Tracking detectors

- Tracking algorithms

- Summary

Y. Zhang, 2nd workshop on Tracking in
Particle Physics Experiments

CLFV and μN → eN Conversion

- $\mu - e$ conversion: neutrinoless muon nuclear capture

$$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$$

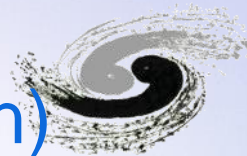**Charged lepton flavor violated**

- Background signature
  - No accidental background
    - Can utilize high luminosity
  - Beam background can be suppressed by pulsed beam
 - Physics background can be handled with current detector technology

Background in the SM
Decay In Orbit (DIO)

Nucleus

μ^- ν_μ

$\bar{\nu}_e$ $\bar{e}$

$\mu \rightarrow e\ \bar{\nu}_e \nu_\mu$

Signal beyond the SM
μ - e conversion
muonic atom

Nucleus

μ^-

$\bar{e}$

$\mu N \rightarrow e\ N$

Y. Zhang, 2nd workshop on Tracking in Particle Physics Experiments
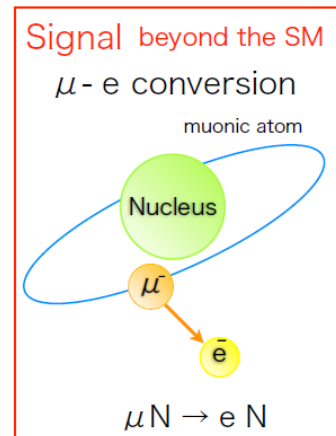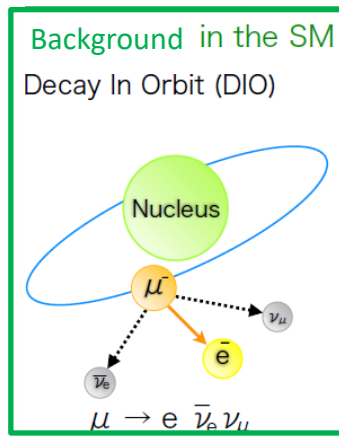
COMET(COherent Muon Electron Transition)

- Search for μ-e conversion in Japan J-PARC hadron hall
  - Measure the ratio of muon to electron conversions to the # of μ captures by nuclei
  - Using $8\ GeV, 56\ kW$ proton beam to generate muon beam
  - Mono-energetic of 105MeV electron
- Experiment Target:
  - $B(\mu^- + Al \rightarrow e^- + Al) = 2.6 \times 10^{-17}$ (S.E.S)
  - This is 10000 times improvement!

$$\text{BR}(\mu^- N \rightarrow e^- N) \equiv \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow \text{all})}$$
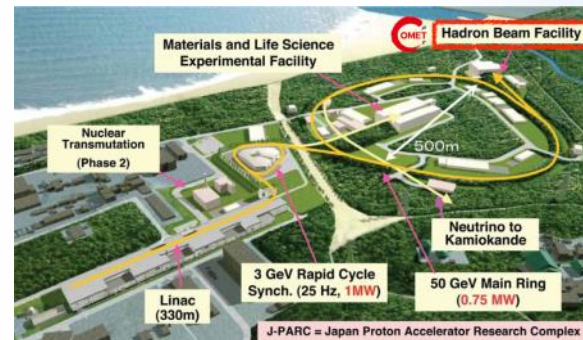
COMET Phase-I and Phase-II
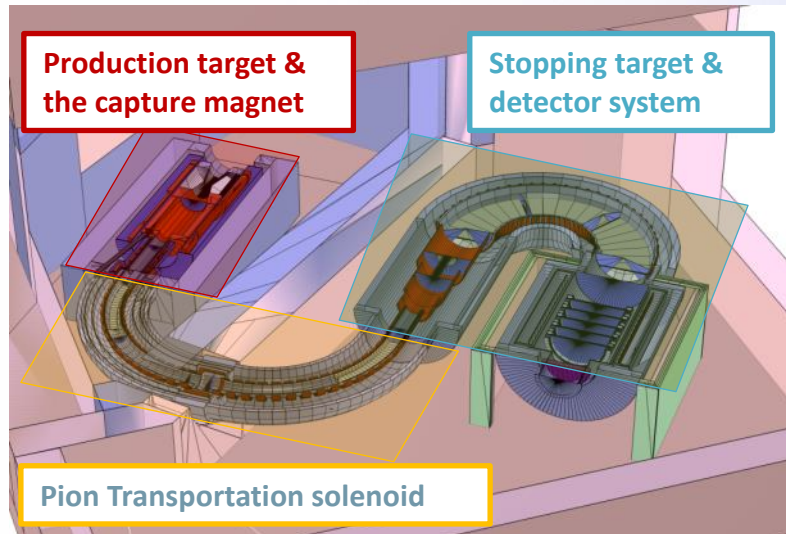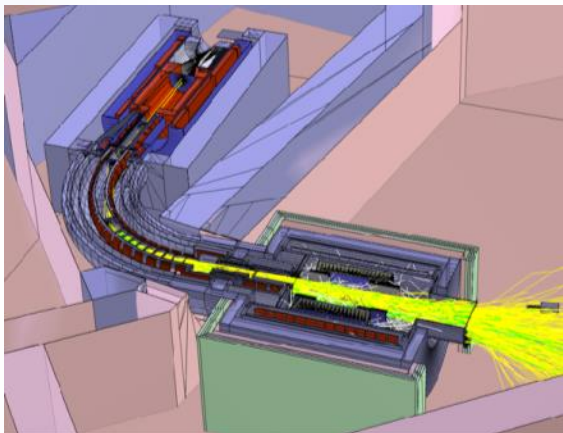
Goals of Phase- I

1. Background measurements

direct measurement of potential background sources for the full COMET experiment by using the actual COMET beam line

2. Search for μ-e conversion

a search for μ-e conversion at the intermediate sensitivity which would be **3.1×10⁻¹⁵** which is 100-times better than the present limit (SINDRUM-II)

3. Beam characterization

Production target & the capture magnet

Stopping target & detector system

Pion Transportation solenoid

Detectors: Straw Tracker + ECAL
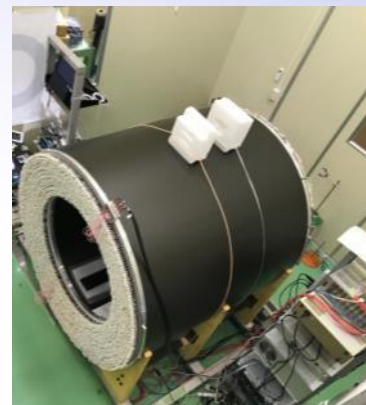
Goal of Phase- II

• **search of μ-e conversion**

single event sensitivity: **2.6×10⁻¹⁷** which is 10,000 better than the current limit
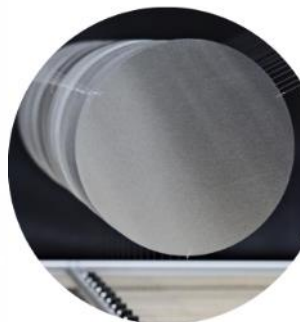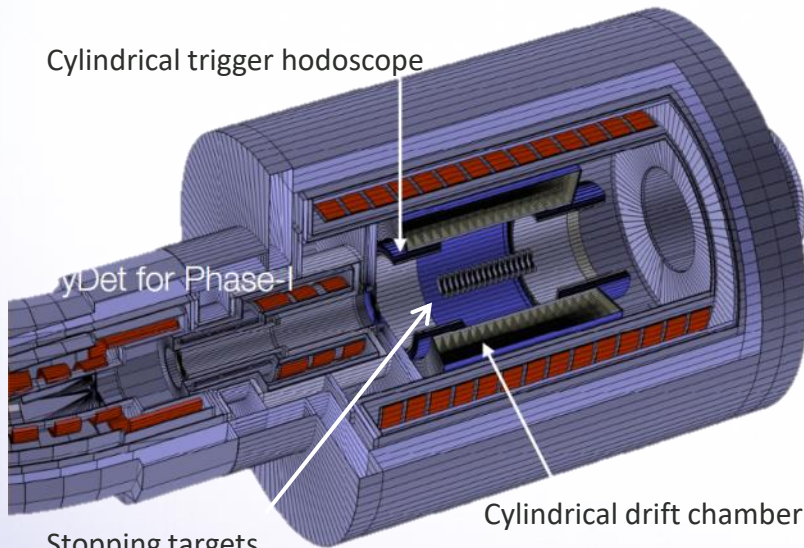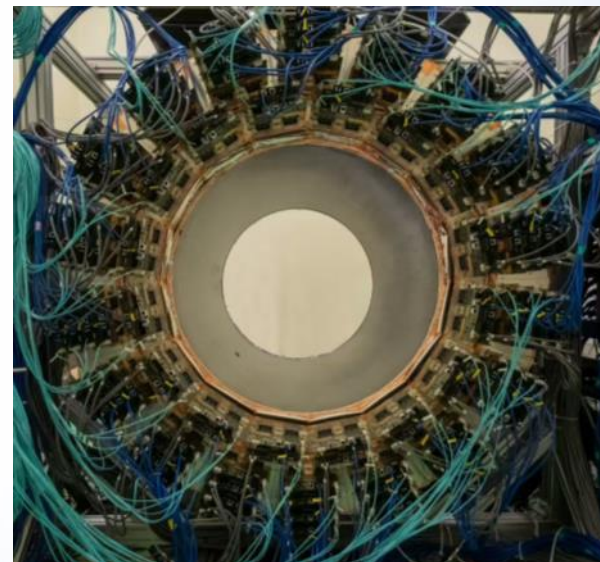
Tracking detectors of COMET Phase-I

- Cylindrical Drift chamber (CDC)
- Trigger hodoscope
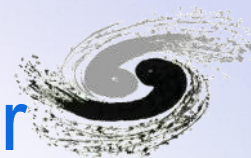- Al muon-stopping targets


Cylindrical trigger hodoscope

Stopping targets

Cylindrical drift chamber

muon-stopping target

Cylindrical drift chamber

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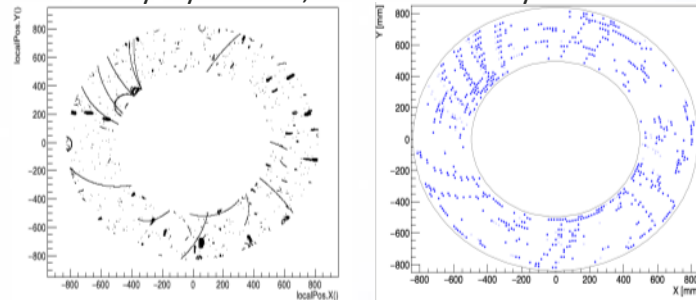
Proton Beam and Bunch Train Merger

- 3kW proton prompt beam:
  - ~ 10^{19} protons on pion targets
  - (in 150 days running time)
- Bunch structure of proton beam
  - Bunch size ~ 10^7 POT
  - Bunch spill/width ~100ns
  - Extinction factor 3×10^{-11}
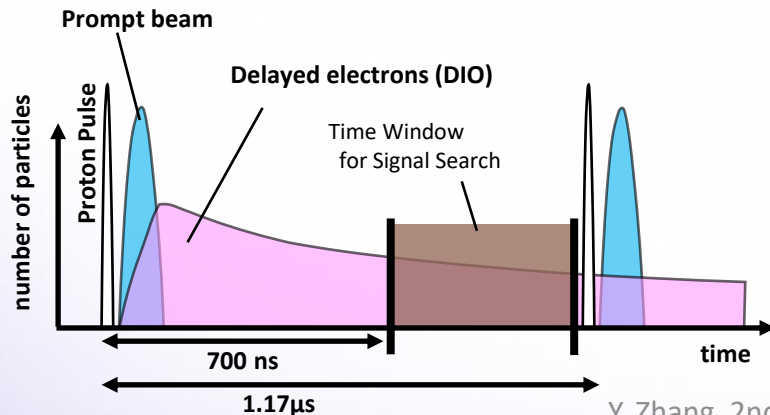 - Bunch separation time = 1170ns.
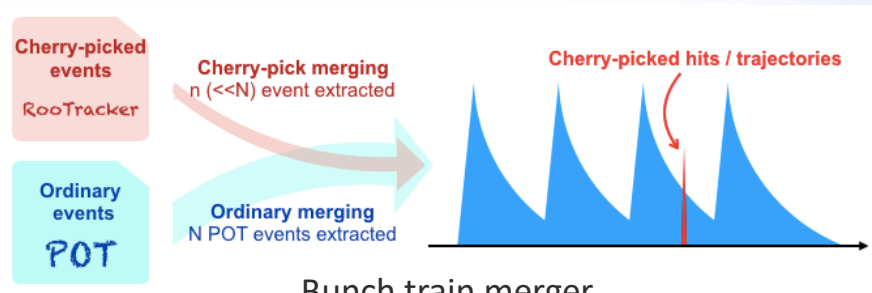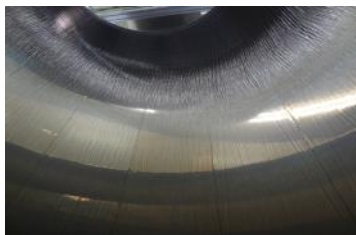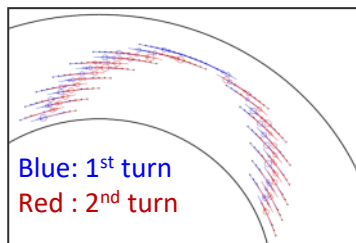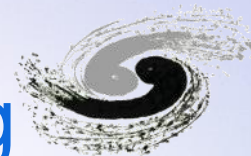

Bunch train merger

By Siyuan Sun, Osaka University

Event display of beam background, occupancy ~20%

Time structure of proton beam bunch

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Challenges for COMET CDC tracking

Blue: 1st turn
Red : 2nd turn

Initial position differs in a wide range
- **No vertex constraint**
- **No seed from other-detector**
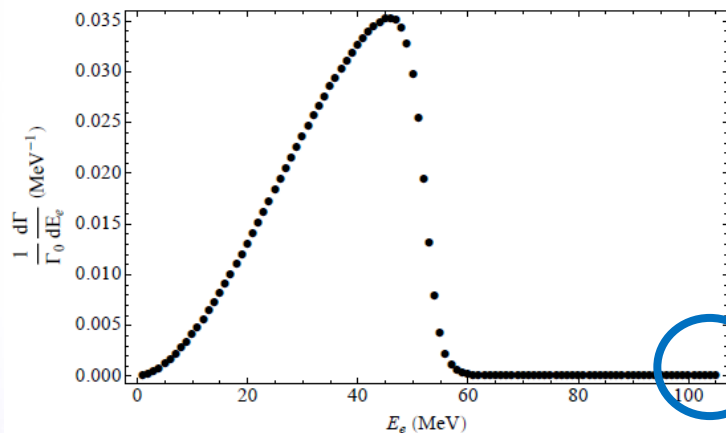
105MeV/c electrons and ~40% multi-turn tracks
- **All curled low momentum tracks**
- **Overlapping hits from different turns**
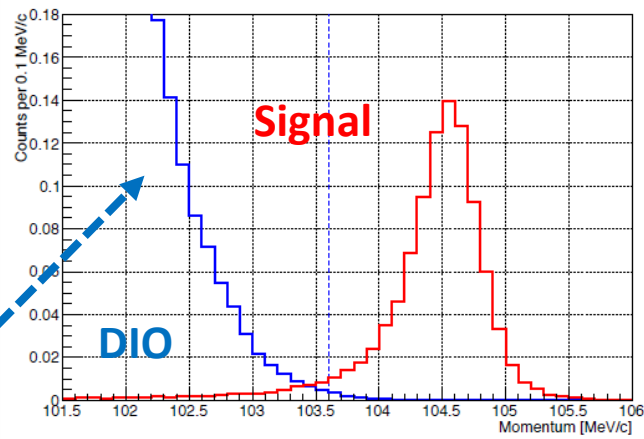- **Bremsstrahlung**

All stereo wires
- **No direct measurements on Z**

Requirements for COMET Tracking

- Estimate track seed by stereo measurements
- Distinguish tracks from different turns
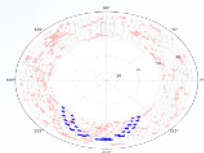- Suppress high momentum tail of reconstructed tracks
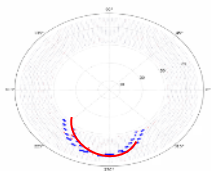

Branching ratio of DIO background
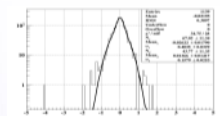
Momentum distribution of COMET Phase-I

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Particle Physics Experiments

Tracking Procedure

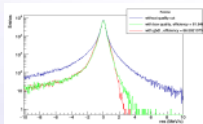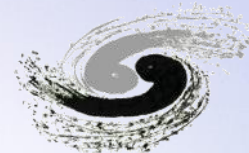|		
	Hit filtering	GBDT, FPN, etc.
	Track finding	GPU tracking Hit combination scanning Deep learning
	Track fitting	Kalman fitting/genfit2 Multi-turn kalman fitting
	Track selection /BG suppression	GBDT,fitting

Hit filtering with GBDT

By Ewen L. Gillies, Imperial College London

- Hit filtering using **G**radient **B**oosted **D**ecision **T**rees (GBDT)
- Classify hits using local, neighbor and shape features
- Reweighted Inverse Hough Transform
- Fit initial track with random hit collection (RANSAC)

GBDT

neighbor features

Feature Importance

Red: background
Blue: signal hits
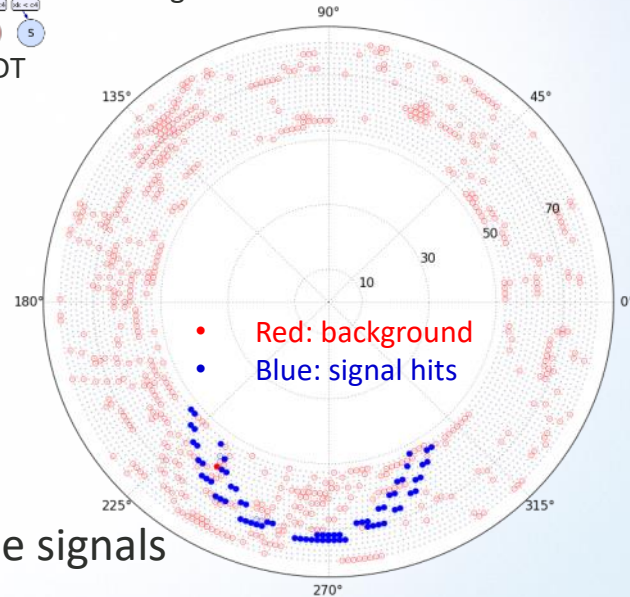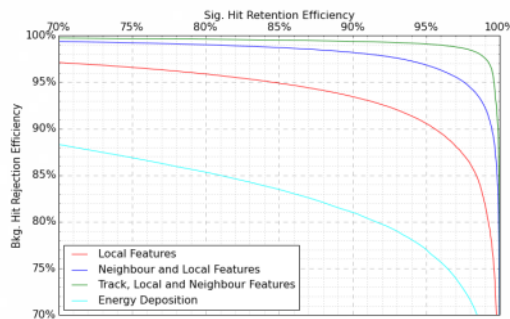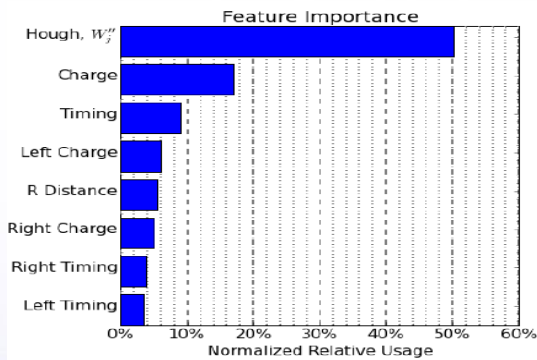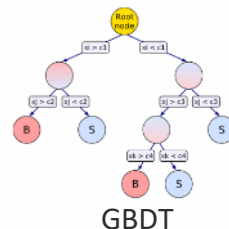
99 % of background can be rejected while **keeping 99%** of the signals
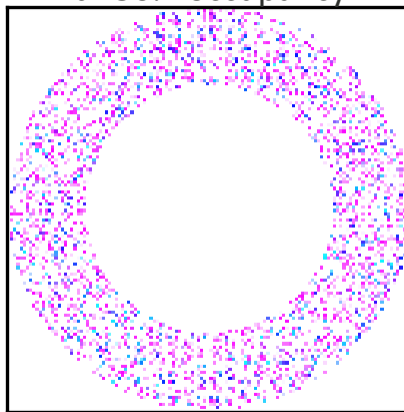
Hit filtering with DnCNN,FPN

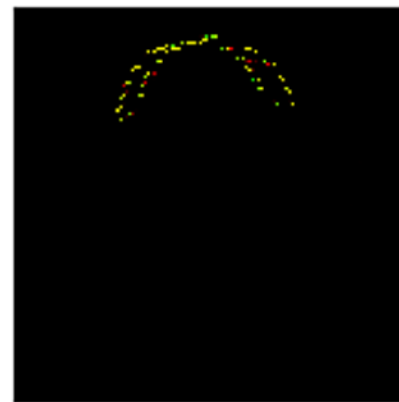By J. SATO,Ikuya, Saitama University
Chen Wu, IHEP

- ## First turn extraction

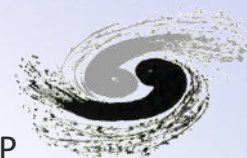 - Convolutional Neural Network(DnCNN)

  - Feature Pyramid Network(FPN) with random noise
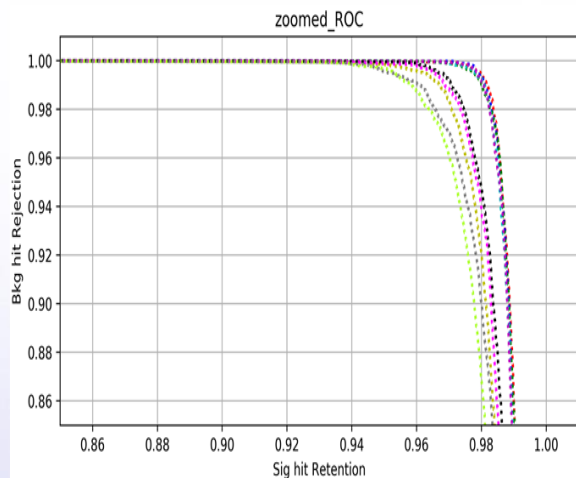
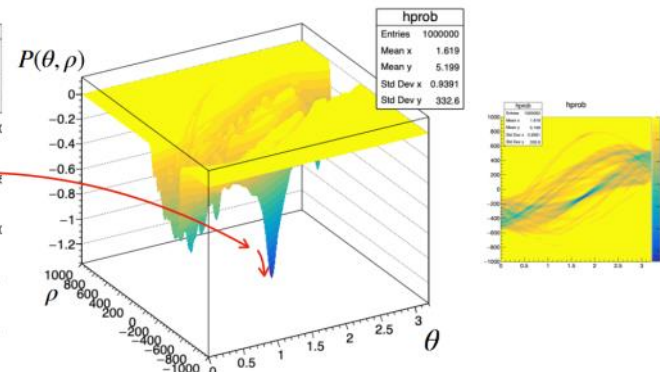Event display
with 50% occupancy
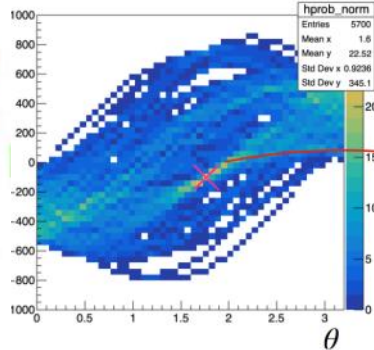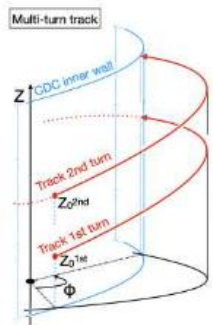

Hit filtering after NN

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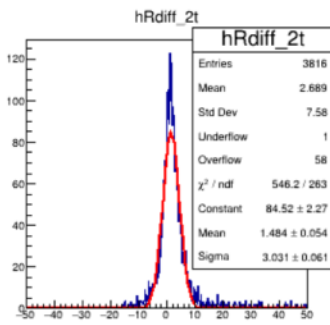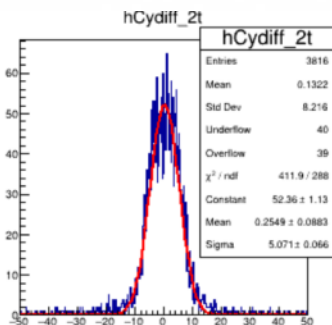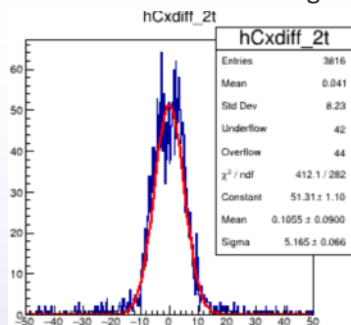Particle Physics Experiments

Track Finding with Hough Transform

By Yohei Nakatsugawa, IHEP
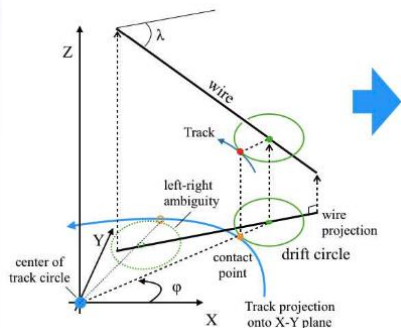
Circle-linear finding

CPU assumption:0.3 sec /1 turn.

GPU-accelerated algorithm-The Apollonius Problem

by Wilfrid da Silva, Patrice Lebrun, Sorbonne University/IN2P3
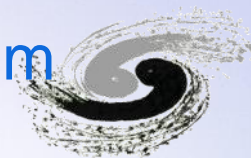
Apollonius Problem applied to a Stereo Drift Chamber
Algorithm based on interval arithmetic with GPU device

Apollonius's problem : construct circles that are tangent
to three given circles in a plane
Greek Apollonius of Perga (200 BC)
Compass constructions by French François Viète (1600)
Algebraic solution (cyclographic model) :

$$(-x_1 + x_s)^2 + (-y_1 + y_s)^2 = (r_s - r_1 \, s_1)^2$$
$$(-x_2 + x_s)^2 + (-y_2 + y_s)^2 = (r_s - r_2 \, s_2)^2$$
$$(-x_3 + x_s)^2 + (-y_3 + y_s)^2 = (r_s - r_3 \, s_3)^2$$

with $s_{1,2,3} = \pm 1$

toy model: 46 hits of electron signal (red)
use $d_i^{St.}$ true signed stereo drift distance

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Particle Physics Experiments
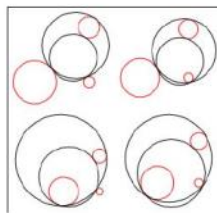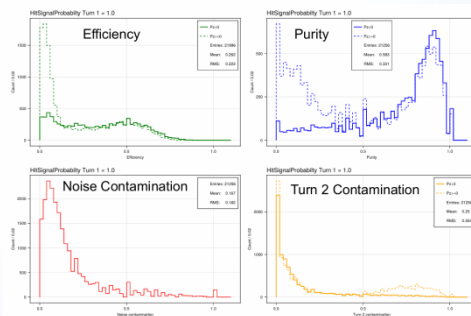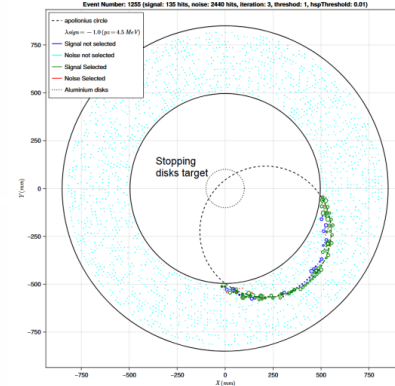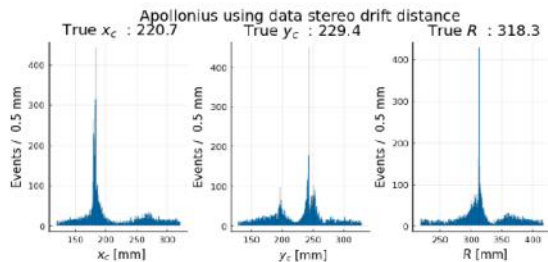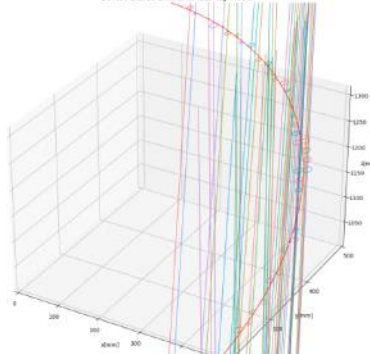
Cellular Automaton for Track Finding
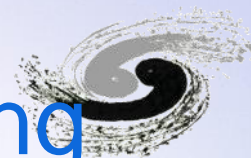
- Connecting neighboring segments which satisfy certain fixed local features
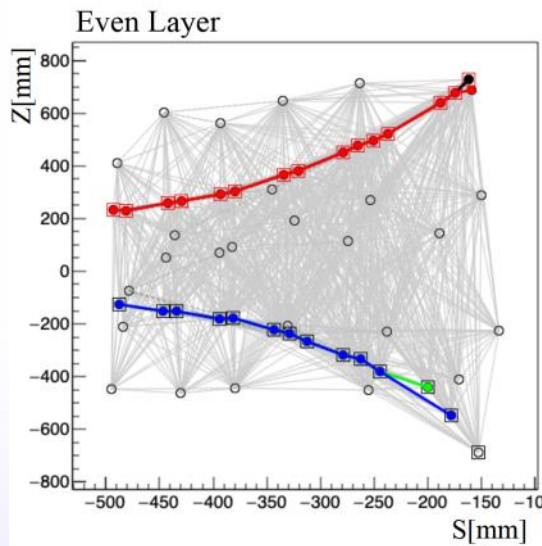
By Yohei Nakatsugawa, Wakayama Medical University
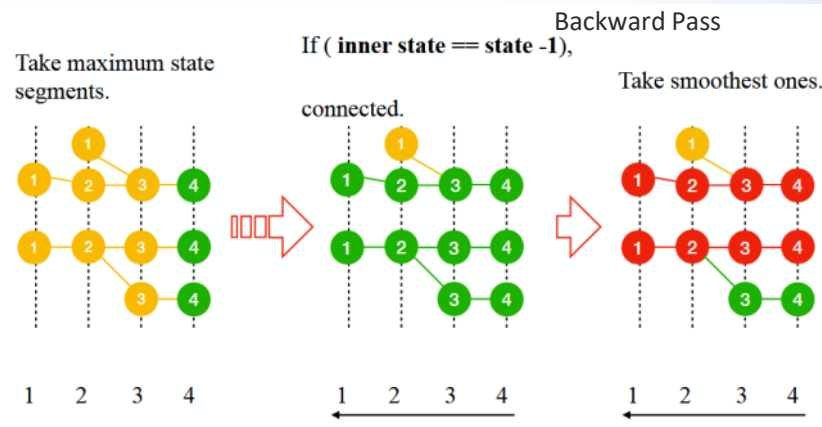
- Tracking efficiency @10% occupancy
  - 92% for single turn
  - 69% for double turn

Ransac Track Finding
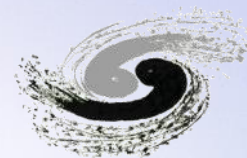
by IHEP, Tianyu Xing, Yao Zhang

A data set with many outliers for which a line has to be fitted.
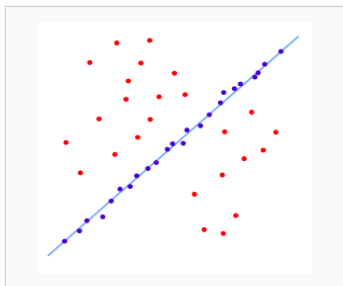
Fitted line with RANSAC; outliers have no influence on the result.

$$\sigma_x = 0.24 \text{ mm}, \sigma_y = 0.24 \text{ mm}, \sigma_y = 4.3 \text{ mm},$$

$$\sigma_{px} = 1.0 \text{ MeV/c}, \sigma_{py} = 1.0 \text{ MeV/c}, \sigma_{pz} = 4.9 \text{ MeV/c}$$
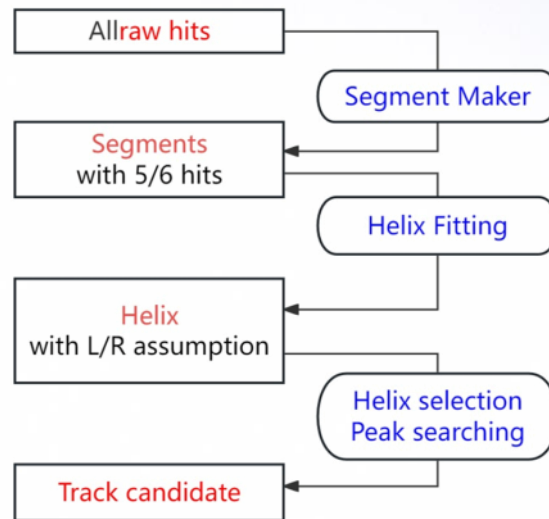
	Geometrical Acceptance	Tracking		Totally	Tail	Momentum resolution (body/tail)
		finding	fitting			
Single Turn	14.0%	96.2%	99.4%	12.7%	1.6%	214keV/533keV
		95.6%				

Multiple Turn Tracking by GPU Scanning
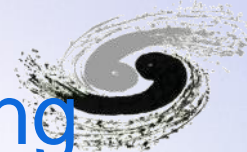
By Beomki Yeo, KAIST

arXiv:1911.09340v3

- Parallelized track seeds parameter scanning with GPU
  - Find the optimal the seeds by investigating the residual sum of hits and track
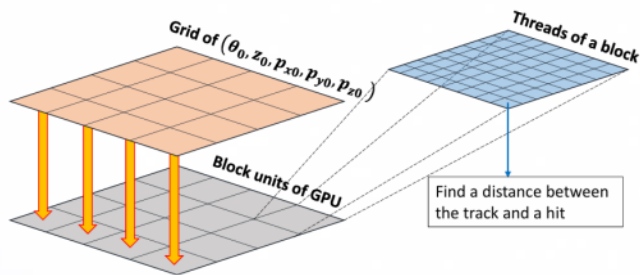
For each track, calculate the chi-square-like energy defined by:

$$E = -\frac{1}{\beta}\Sigma_k \log\left(n_k e^{-\beta\lambda} + \Sigma_{i=1}^{n_k} e^{-\beta M_{ik}}\right) \approx \Sigma_k \min(\{M_{ik}\}, \lambda) \text{ if } \beta \to \infty$$
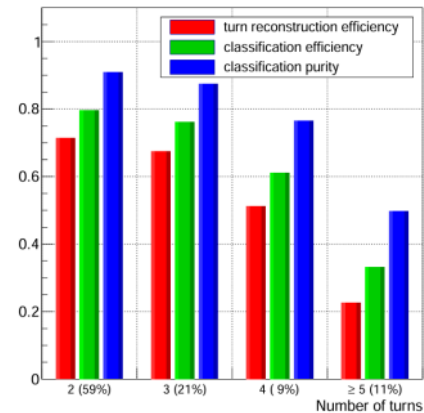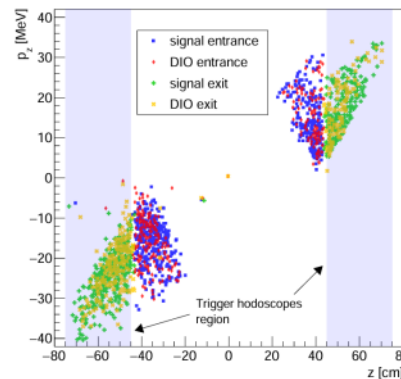
Track fitting

- Based on GenFit https://github.com/GenFit/GenFit/   By Yao Zhang, IHEP
  - An experiment-independent **generic track fitting** framework
  - Open sourced, active development and large user community
  - Official track fitting for BelleII, also used by PANDA, CEPC, BESIII, GEM-TPC etc.
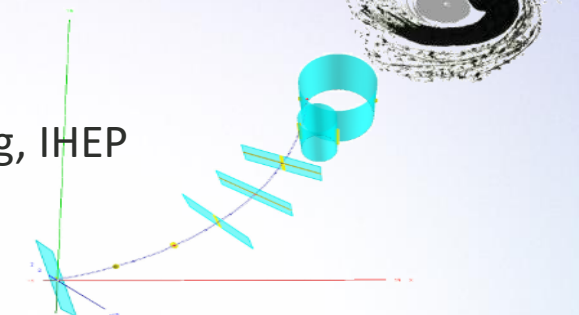
(a) Measurements with covariance (yellow), planar detectors and drift isochrones (cyan), respectively, and reference track (blue).

Geometrical Acceptance	NL5	NHIT+Chi2+NDF+CL3	Total
17.37%	73.55%	80.49%	10.28%

single turn
σ_{core} ~ 169 keV

double-turn
σ_{core} ~ 132keV

>=3 turn tracks
σ_{core} ~ 132 keVs

2025-7-22

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18 18
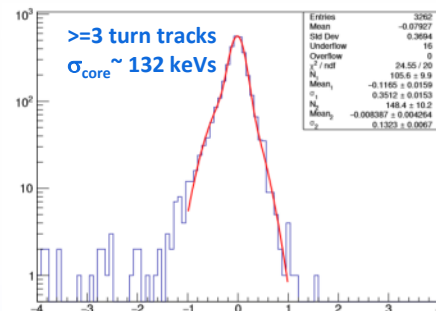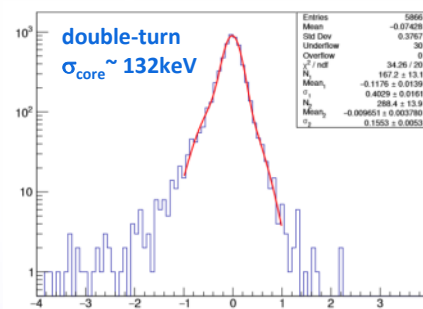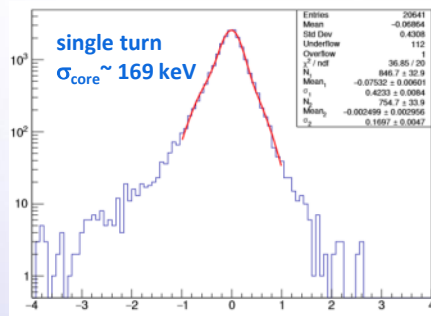
Multi-turn track fitting

By Yao Zhang, IHEP

- Multi-turn fitting with 1st turn assumption based on GenFit
    - Fitting with competition between hits
    - Several measurements per layer are taken into account by using their weighted mean
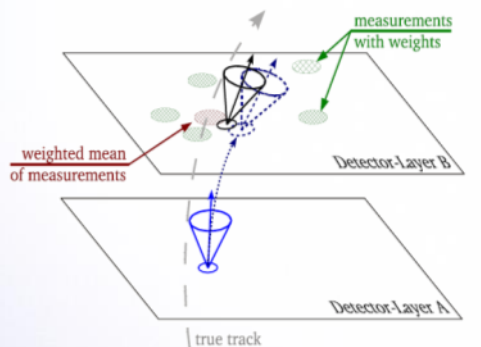
Weighted mean of measurement and it's cov. matrices

$$\left(\tilde{V}_k\right)^{-1} \equiv \tilde{G}_k = \sum_i p_k^i G_k^i \qquad \tilde{m}_k = \tilde{V}_k \cdot \left(\sum_i p_k^i G_k^i \cdot \vec{m}_k^i\right)$$

DAF, competition between tracks and between mirror hits

$$p_{i_k j} = \frac{\varphi_{i_k j}}{\sum_l \sum_\alpha \varphi_{i_\alpha l} + c}.$$

ε=71.3%
σ_{core}=187kev

Entries	2566
Mean	-0.03257
RMS	0.4336
Underflow	5
Overflow	3
χ^2 / ndf	66.22 / 48
N_1	55.32 ± 6.33
Mean$_1$	-0.04989 ± 0.02728
σ_1	0.5779 ± 0.0355
N_2	194.1 ± 7.4
Mean$_2$	-0.0008336 ± 0.005173
σ_2	0.1877 ± 0.0061
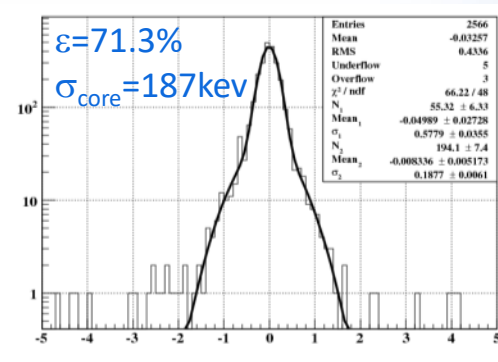
Good Quality Track Selection
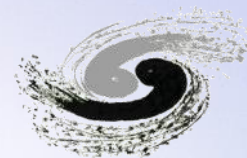
By Chen Wu, IHEP
Dorian Pieters , Osaka University

- The kink responsible for right and left part of the residue tail
- High quality track using an GBDT quality selection
  - Good events or Signal events are event with |residue| < 1MeV /c
  - Bad events or Signal events are event with residue > 2MeV /c

kink

GBDT Parameters: Ranked by separation power

| Input Variable	Brief Description	Separation
NHit	Number of Hit	1.975e-01
Chi2	χ^2	1.407e-01
NDF	degrees of freedom	1.332e-01
FittedMomX	Fitted momentum along beam axis	1.185e-01
MaxLayer	max layer of hit fitted	8.982e-02
chi2Const	Pearson test on hit residue	8.343e-02
errmomX	Fitted error on p_X- from GENFIT M_{error}	5.331e-02
errmomY	Fitted error on p_Y - from GENFIT M_{error}	4.145e-02
errmomZ	Fitted error on p_Z- from GENFIT M_{error}	3.982e-02
errZ	Fitted error on Z - from GENFIT M_{error}	3.611e-02
errX	Fitted error on X - from GENFIT M_{error}	3.570e-02
errY	Fitted error on Y - from GENFIT M_{error}	3.050e-02
NHitFailed	NHit rejected by GENFit	0.000e+00
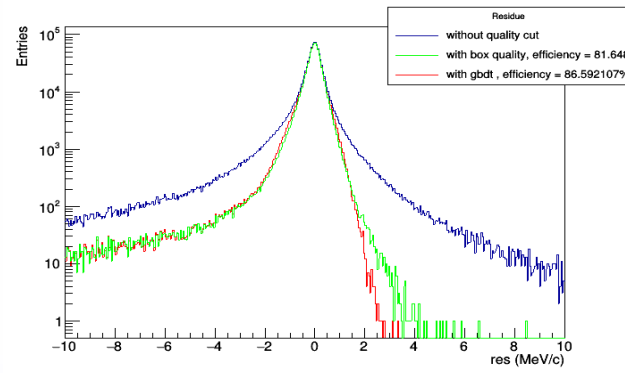
Keep 87% of the signal with GBDT

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Identification of Sneaking Cosmic Ray Muon

By M. Moristu IHEP

- Suppressing sneaking cosmic-ray background by track fitting

- Reverse μ^+ MC samples were generated and evaluated

Naive Idea:
TOF miscorrection will make a difference in χ^2
between normal & reverse direction hypotheses.

$\Delta(\chi^2/ndf)$ [Normal-Rrevers]

87%
11%
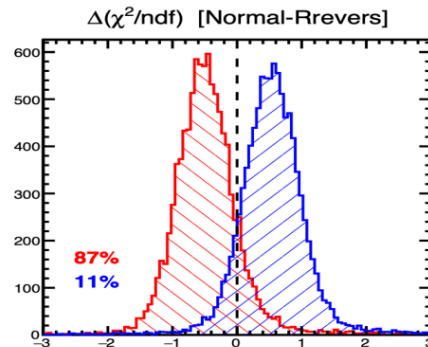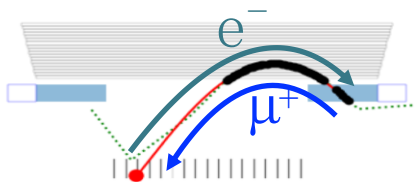
− Signal e^- MC samples
− Reverse μ^+ MC samples

Spatial resolution = 150 μm

Sneaking cosmic μ+ BG can be reduced from 2.4 to 0.26 events, with signal retention efficiency of 87%.
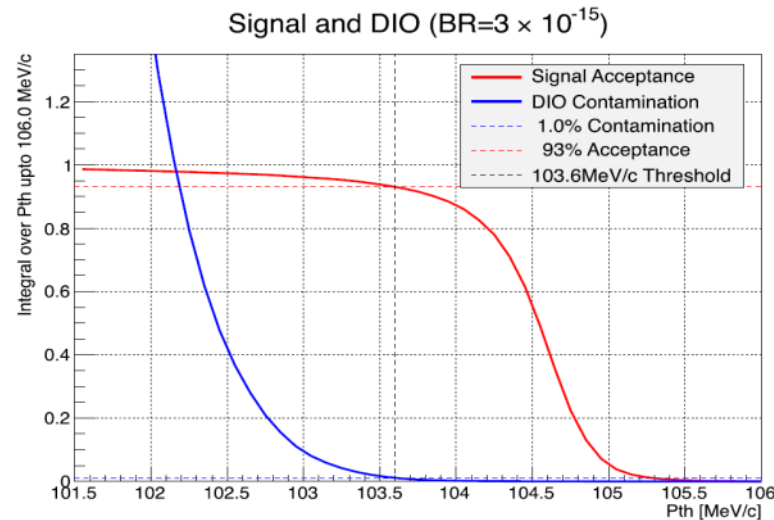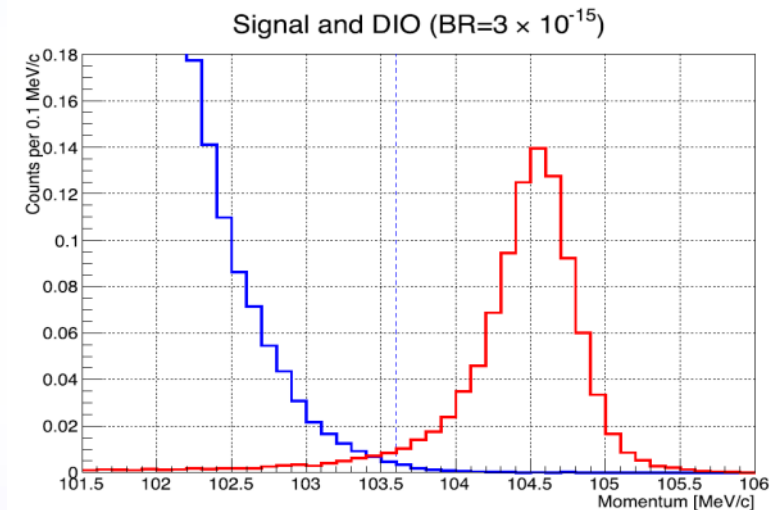
Geant4 Material effects correction

By Yao Zhang, IHEP

- The material correction in GenFit is outdated and not suitable for low momentum electrons
- A development using GEANT4 EMCalculator to compute dE/dx

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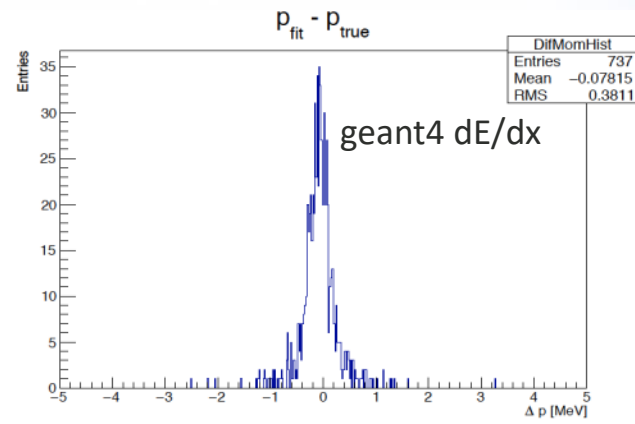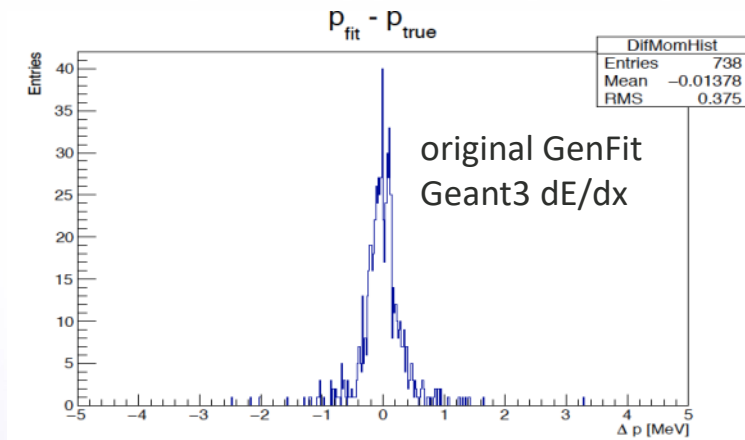
COMET Signal and Backgrounds

Signal and DIO (BR=3×10^{-15})

Signal and DIO (BR=3×10^{-15})

- **Single Event Sensitivity = 3.1 x 10^{-15}**
- At momentum window 103.6MeV/c<p_e<106MeV/c, yielding a signal acceptance of 0.93
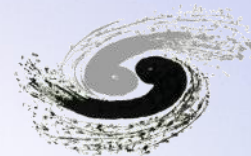
Summary

- CDC tracking is decisive to the success of the COMET Phase-I
- Multiple tracking algorithms have been implemented
  - Traditional
  - Machine learning based
  - GPU based

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Particle Physics Experiments