Drift Chamber Tracking for COMET

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1 IHEP, CAS, China

25 Nov 2025

Outline

- Introduction to COMET
- COMET Tracking detectors
- Tracking algorithms
- Summary

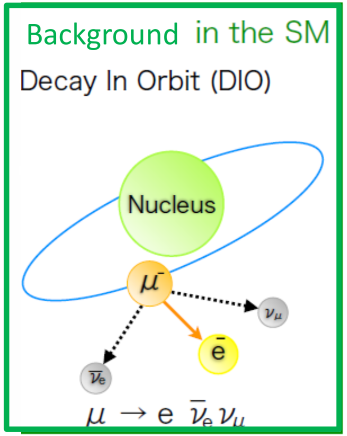
CLFV and $\mu N \rightarrow eN$ Conversion

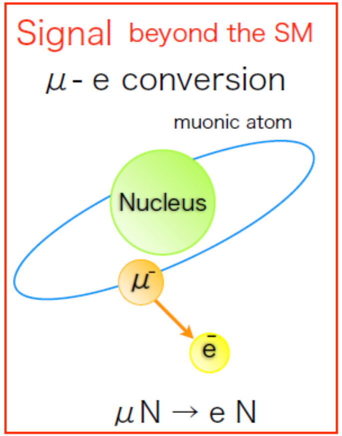
- $\mu - e$ conversion: neutrinoless muon nuclear capture

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

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



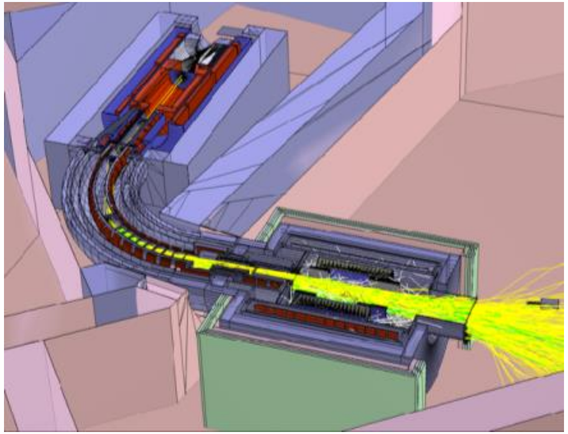


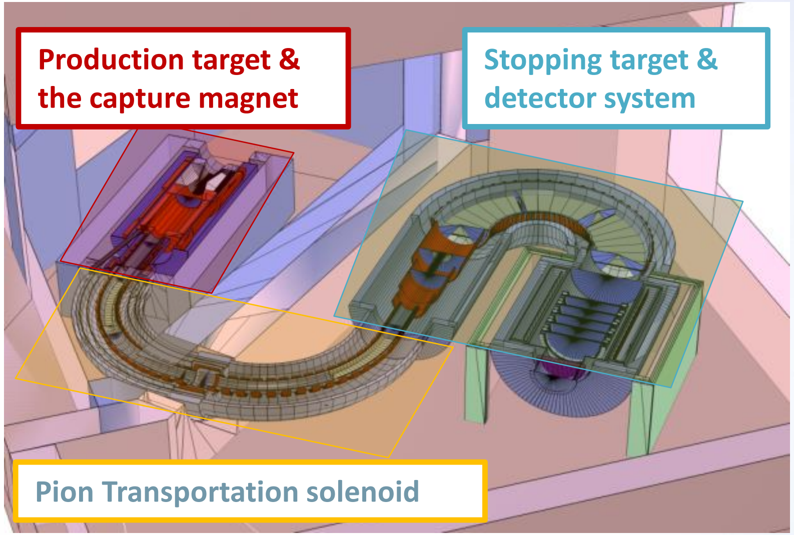
COMET(COherent Muon Electron Transition)

- 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:
  - $B(\mu^- + Al \to e^- + Al) = 2.6 \times 10^{-17}$ (S.E.S)
  - This is 10000 times improvement!

$$\mathrm{BR}(\mu^- N \to e^- N) \equiv \frac{\Gamma(\mu^- N \to e^- N)}{\Gamma(\mu^- N \to \mathrm{all})}$$

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

Detectors: Straw Tracker + ECAL

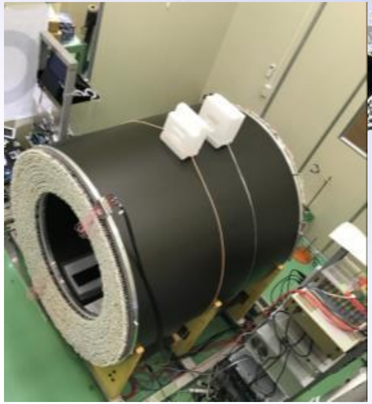
Goal of Phase- II

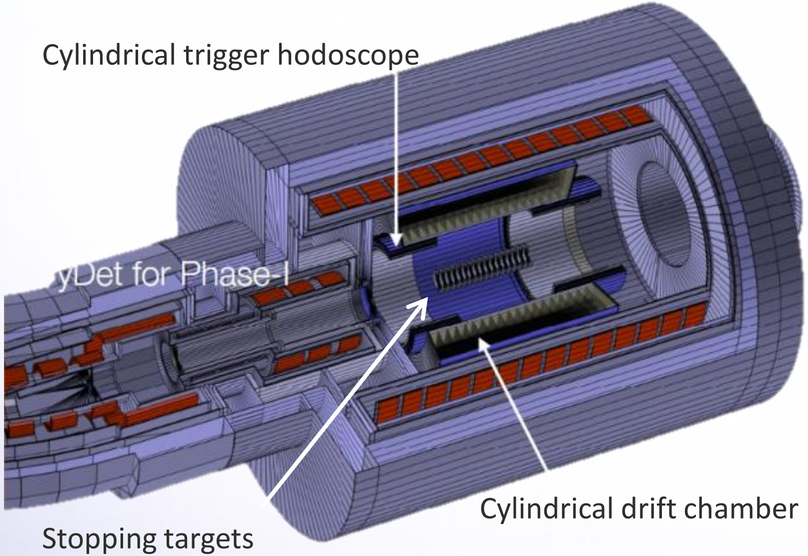
- **search of μ-e conversion**

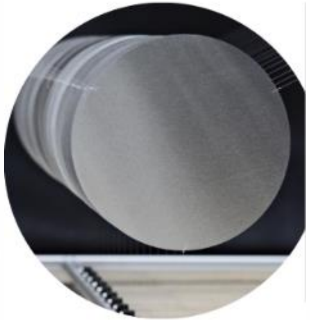
single event sensitivity: **2.6×10^{-17}** which is 10,000 better than the current limit

Tracking detectors of COMET Phase-I

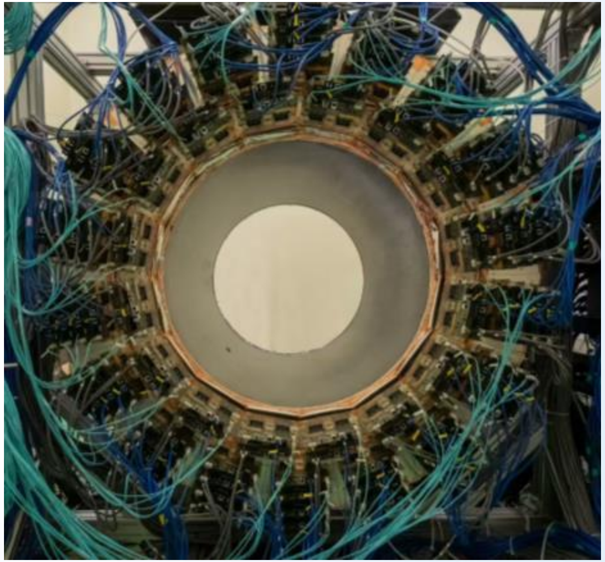
- Cylindrical Drift chamber (CDC)
- Trigger hodoscope
- Al muon-stopping targets







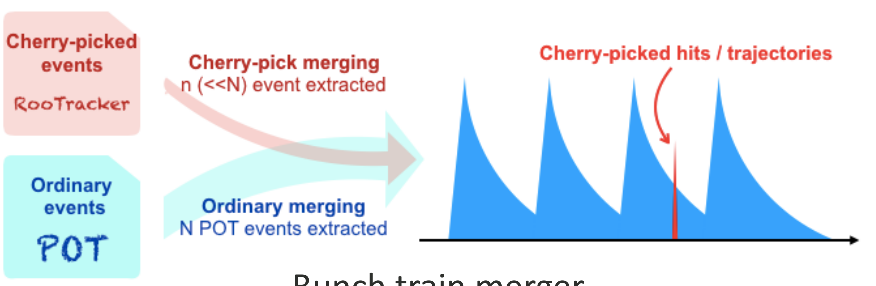
muon-stopping target



Cylindrical drift chamber

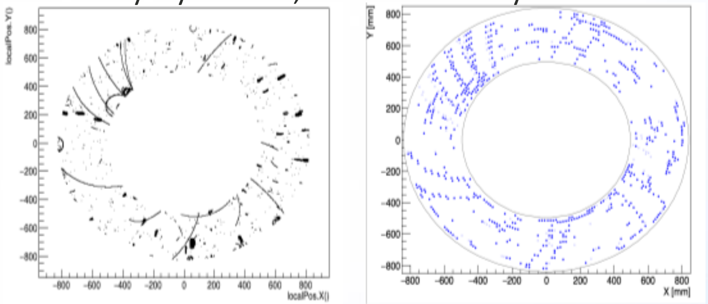
Proton Beam and Bunch Train Merger

- 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 = 1170*ns*.

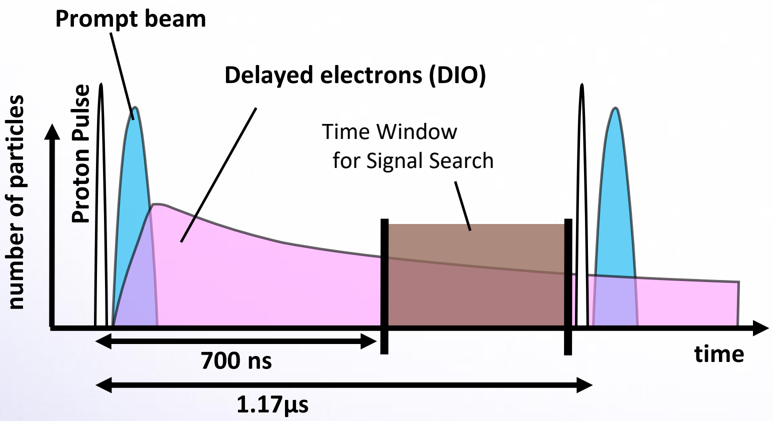


Bunch train merger

By Siyuan Sun, Osaka University

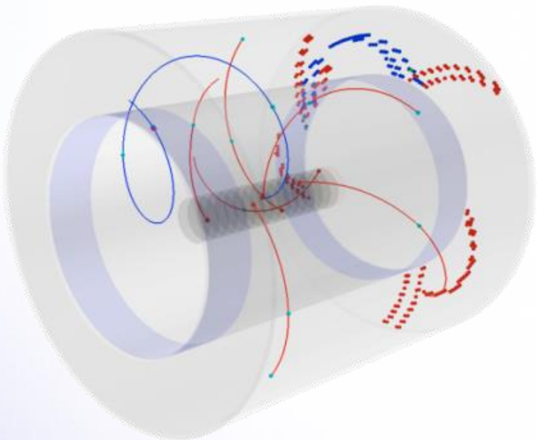


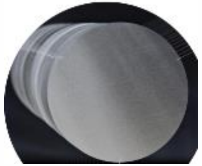
Event display of beam background, occupancy ~20%

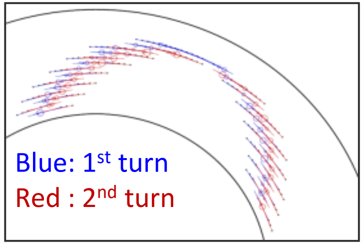


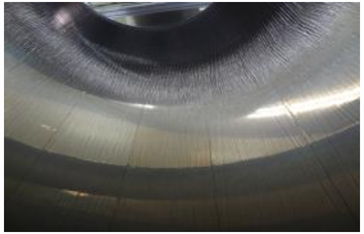
Time structure of proton beam bunch

Challenges for COMET CDC tracking









Initial position differs in a wide range

- **No vertex constraint**
- **No seed from other-detector**

105*MeV/c* electrons and ~40% multi-turn tracks

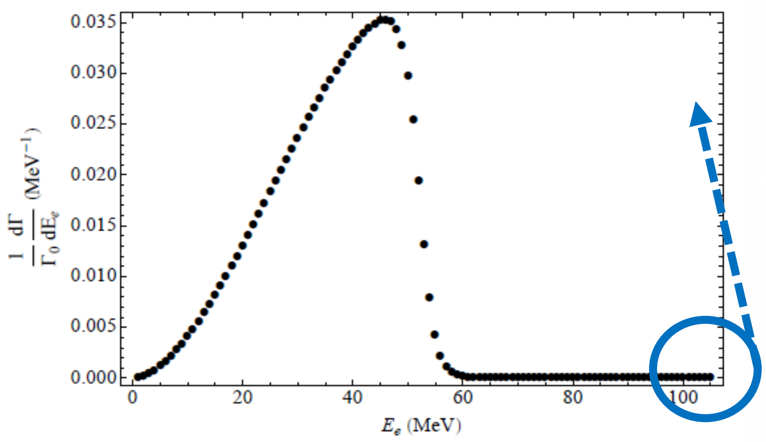
- **All curled low momentum tracks**
- **Overlapping hits from different turns**
- **Bremsstrahlung**

All stereo wires

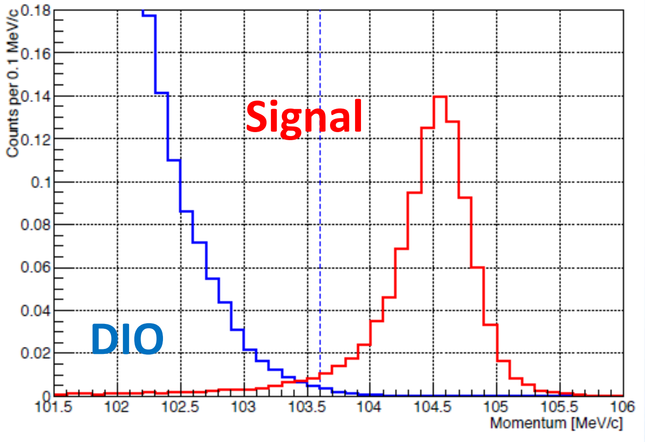
- **No direct measurements on Z**

Requirements for COMET Tracking

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

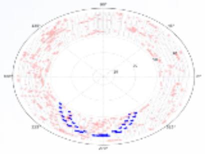


Branching ratio of DIO background



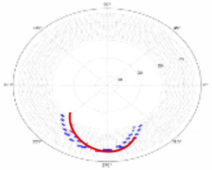
Momentum distribution of COMET Phase-I

Tracking Procedure



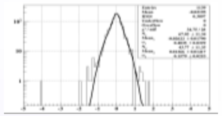
Hit filtering

GBDT, FPN, etc.



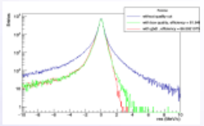
Track finding

GPU tracking
Hit combination scanning
Deep learning



Track fitting

Kalman fitting/genfit2
Multi-turn kalman fitting



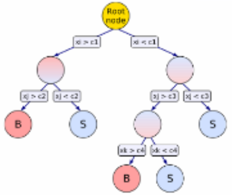
Track selection
/BG suppression

GBDT,fitting

Hit filtering with GBDT

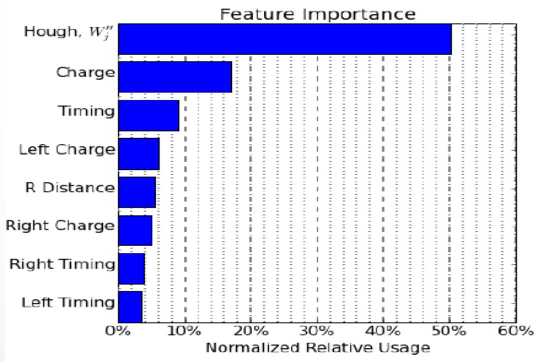
By Ewen L. Gillies, Imperial College London

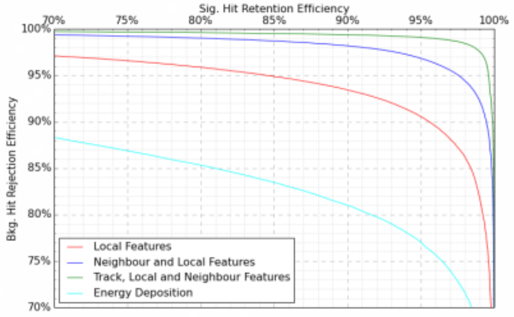
- Hit filtering using **G**radient **B**oosted **D**ecision **T**rees (GBDT)
- Classify hits using local, neighbor and shape features
- Reweighted Inverse Hough Transform
- Fit initial track with random hit collection (RANSAC)

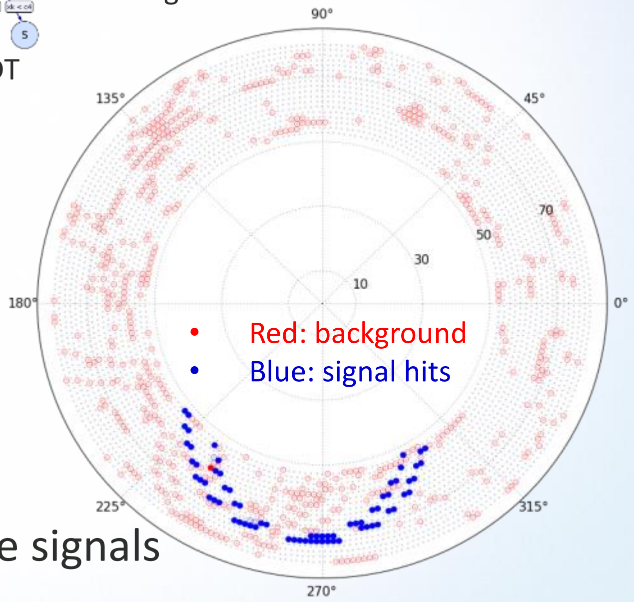


GBDT

neighbor features







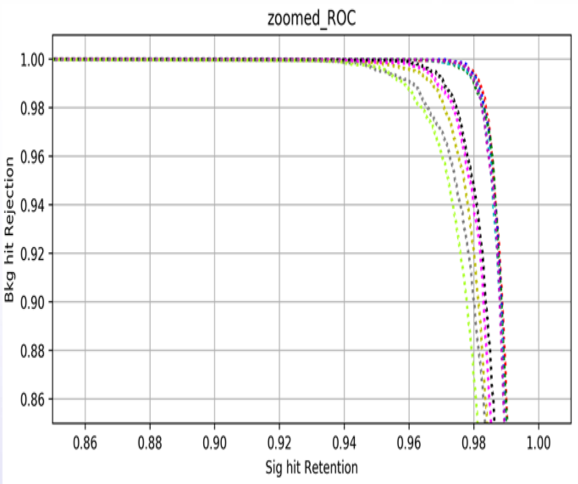
- Red: background
- Blue: signal hits

99 % of background can be rejected while keeping 99% of the signals

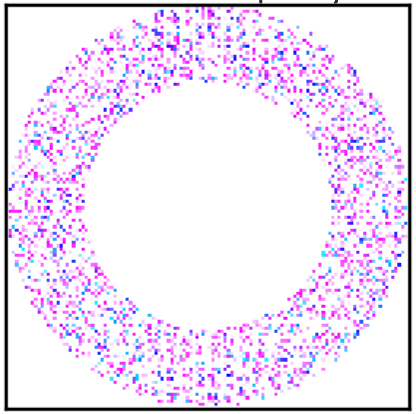
Hit filtering with DnCNN,FPN

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

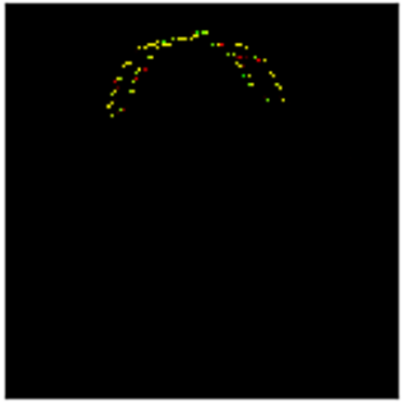
- First turn extraction
  - Convolutional Neural Network(DnCNN)
  - Feature Pyramid Network(FPN) with random noise



Event display
with 50% occupancy

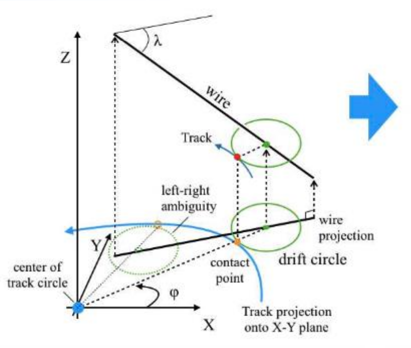


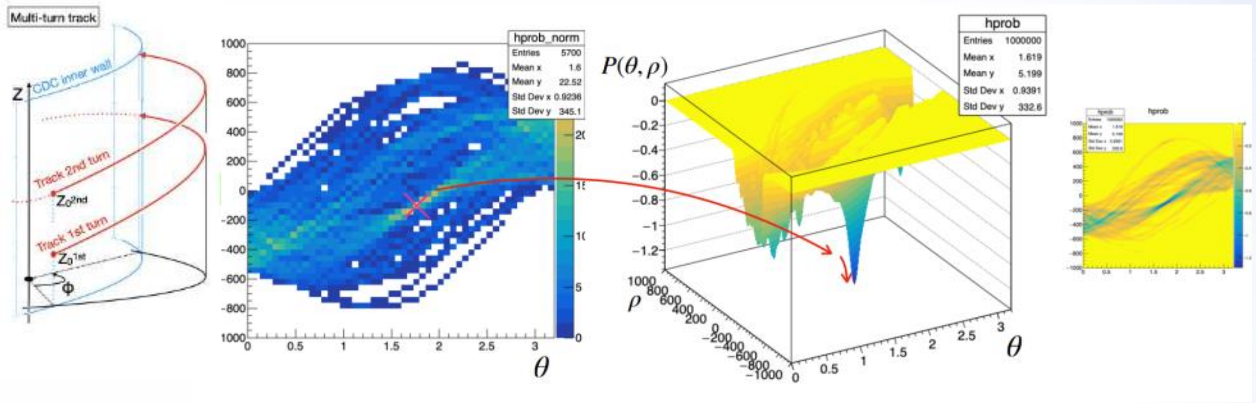
Hit filtering after NN



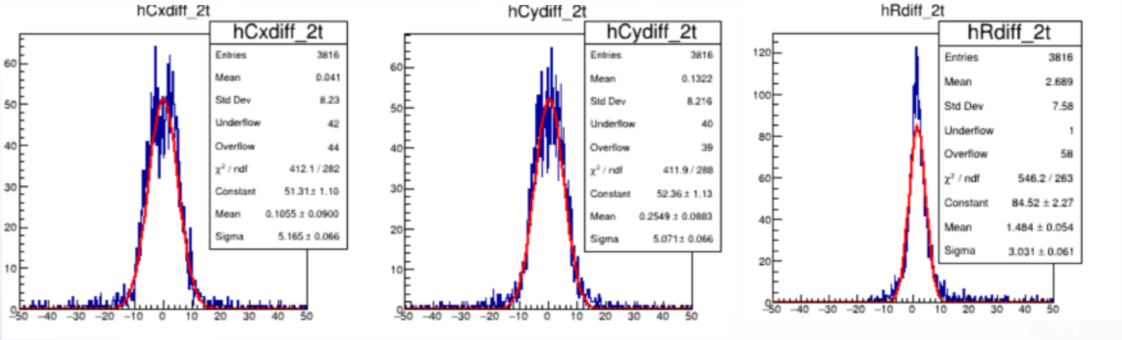
Track Finding with Hough Transform

By Yohei Nakatsugawa, IHEP





Circle-linear finding



CPU assumption:0.3 sec /1 turn.

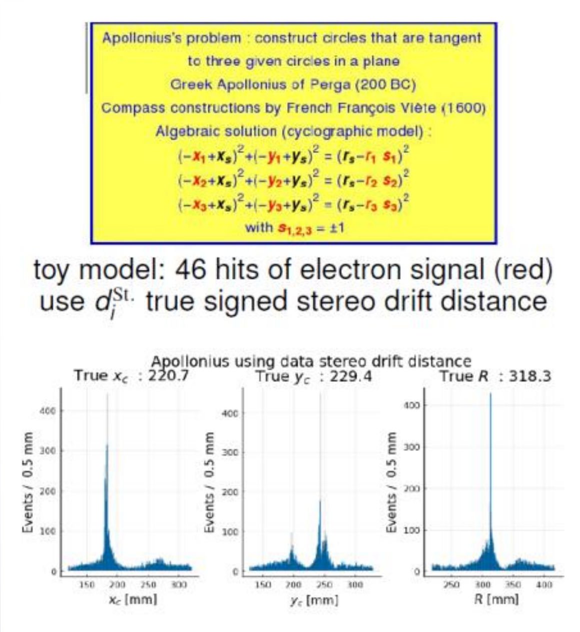
GPU-accelerated algorithm-The Apollonius Problem

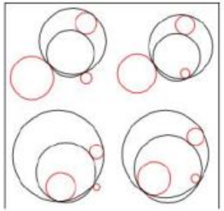
by Wilfrid da Silva, Patrice Lebrun, Sorbonne University/IN2P3

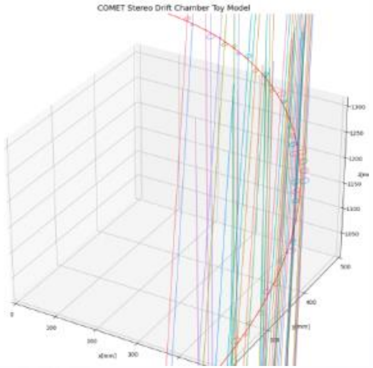
arXiv:2401.04576

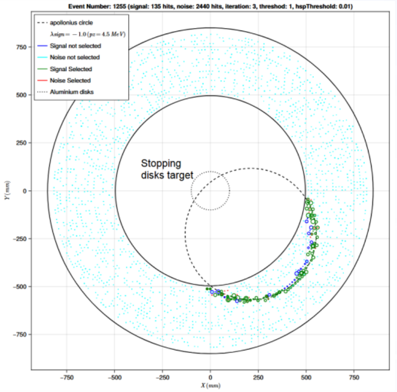
Apollonius Problem applied to a Stereo Drift Chamber

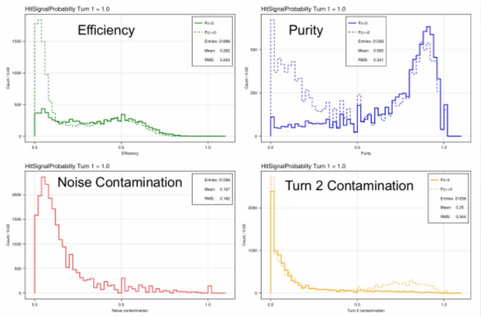
Algorithm based on interval arithmetic with GPU device







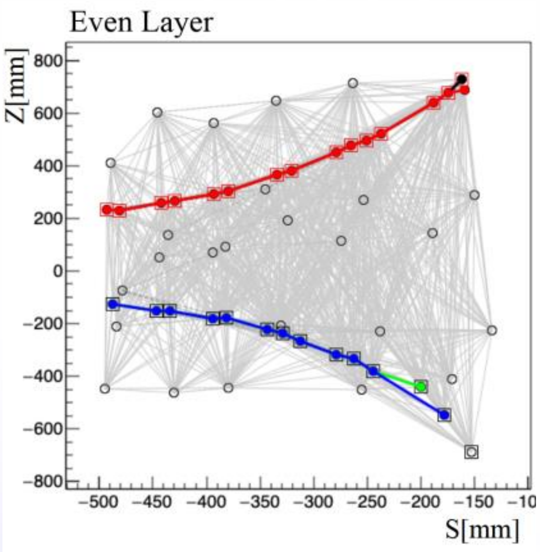


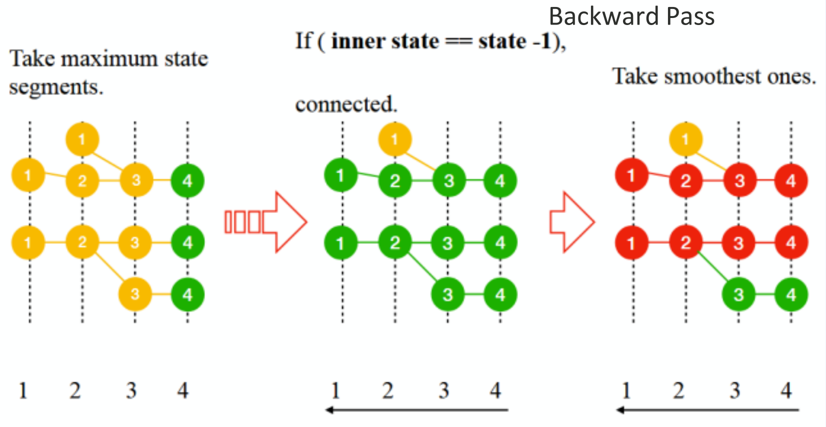


Cellular Automaton for Track Finding

By Yohei Nakatsugawa, Wakayama Medical University

- Connecting neighboring segments which satisfy certain fixed local features



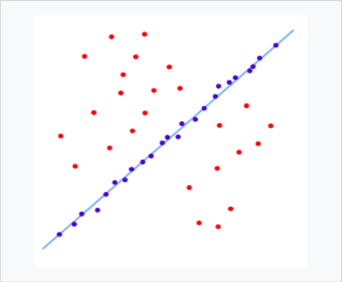


- Tracking efficiency @10% occupancy
  - 95% for single turn
  - 94% for double turn

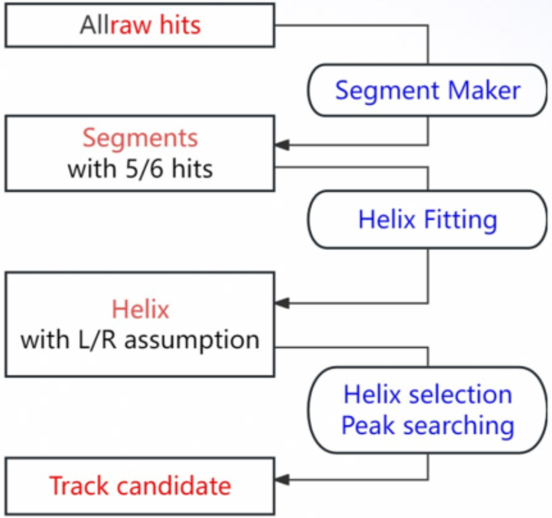
Ransac Track Finding

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.



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

$$\sigma_{px} = 1.0 \text{ MeV/c}, \sigma_{py} = 1.0 \text{ MeV/c}, \sigma_{pz} = 4.9 \text{ MeV/c}$$

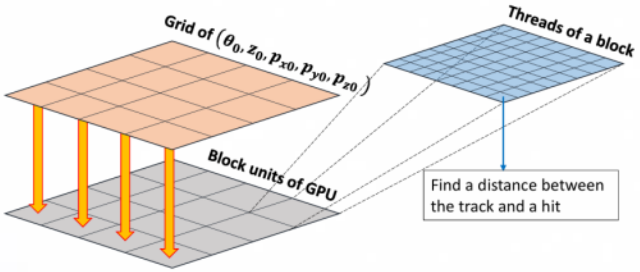
<table>
<tr><th rowspan="2"></th><th rowspan="2">Geometrical Acceptance</th><th colspan="2">Tracking</th><th rowspan="2">Totally</th><th rowspan="2">Tail</th><th rowspan="2">Momentum resolution (body/tail)</th></tr>
<tr><th>finding</th><th>fitting</th></tr>
<tr><td rowspan="2">Single Turn</td><td rowspan="2">14.0%</td><td>96.2%</td><td>99.4%</td><td rowspan="2">12.7%</td><td rowspan="2">1.6%</td><td rowspan="2">214keV/533keV</td></tr>
<tr><td colspan="2">95.6%</td></tr>
</table>

Multiple Turn Tracking by GPU Scanning

By Beomki Yeo, KAIST

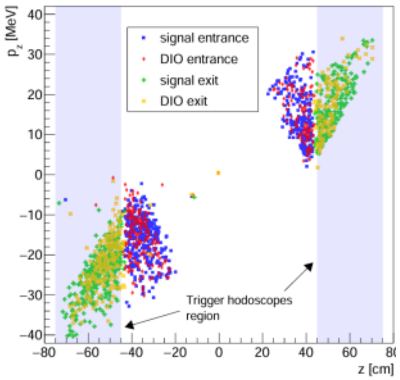
- Parallelized track seeds parameter scanning with GPU
  - Find the optimal the seeds by investigating the residual sum of hits and track

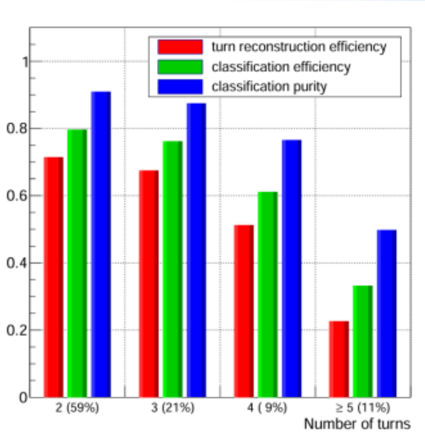
arXiv:1911.09340v3



For each track, calculate the chi-square-like energy defined by:

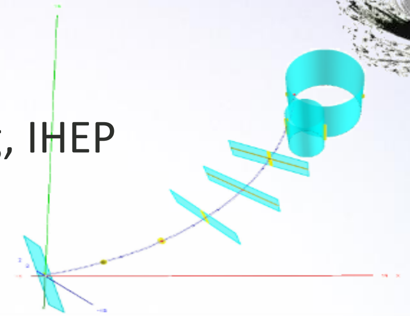
$$E = -\frac{1}{\beta}\Sigma_k \log\left(n_k e^{-\beta\lambda} + \Sigma_{i=1}^{n_k} e^{-\beta M_{ik}}\right) \approx \Sigma_k \min(\{M_{ik}\}, \lambda) \text{ if } \beta \to \infty$$





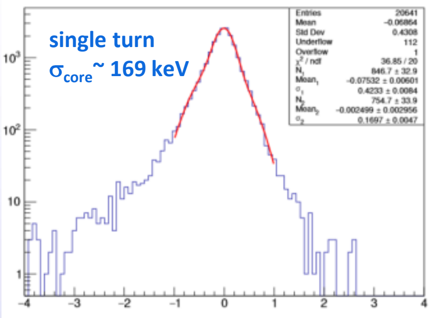
Track fitting

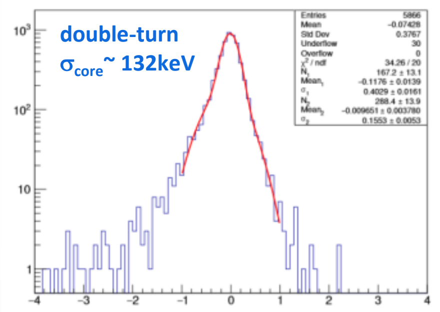
- Based on GenFit https://github.com/GenFit/GenFit/ By Yao Zhang, IHEP
  - An experiment-independent **generic track fitting** framework
  - Open sourced, active development and large user community
  - Official track fitting for BelleII, also used by PANDA, CEPC,BESIII, GEM-TPC etc.

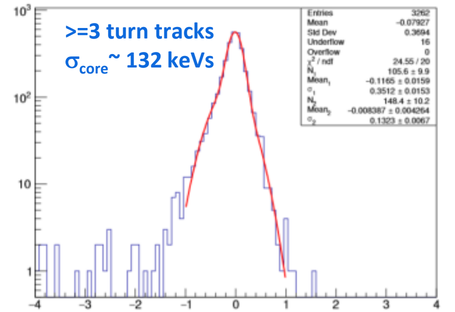


(a) Measurements with covariance (yellow), planar detectors and drift isochrones (cyan), respectively, and reference track (blue).

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



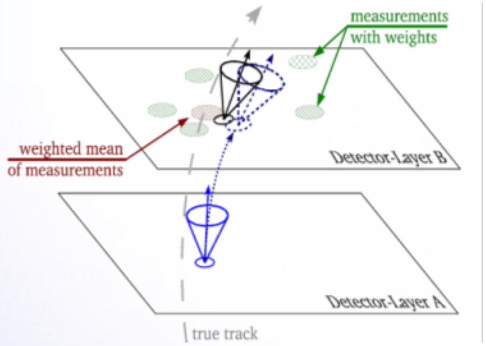




Multi-turn track fitting

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

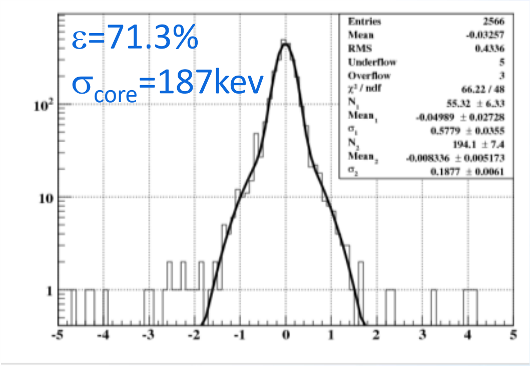


Weighted mean of measurement and it's cov. matrices

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

DAF, competition between tracks and between mirror hits

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



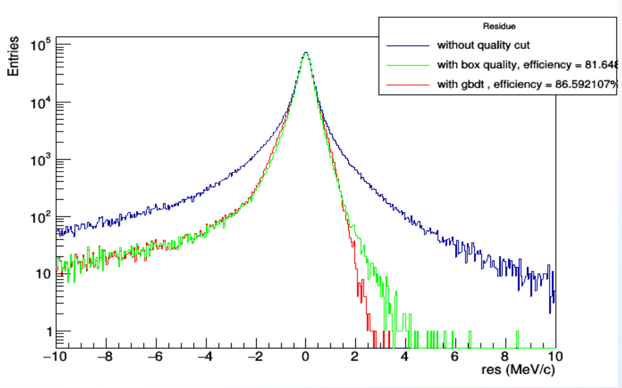
Good Quality Track Selection

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

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



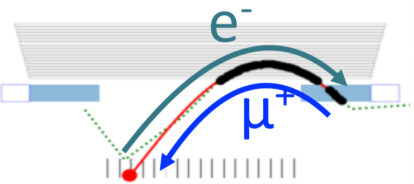
Keep 87% of the signal with GBDT

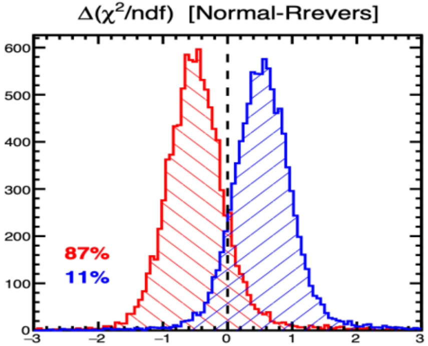
Identification of Sneaking Cosmic Ray Muon

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.



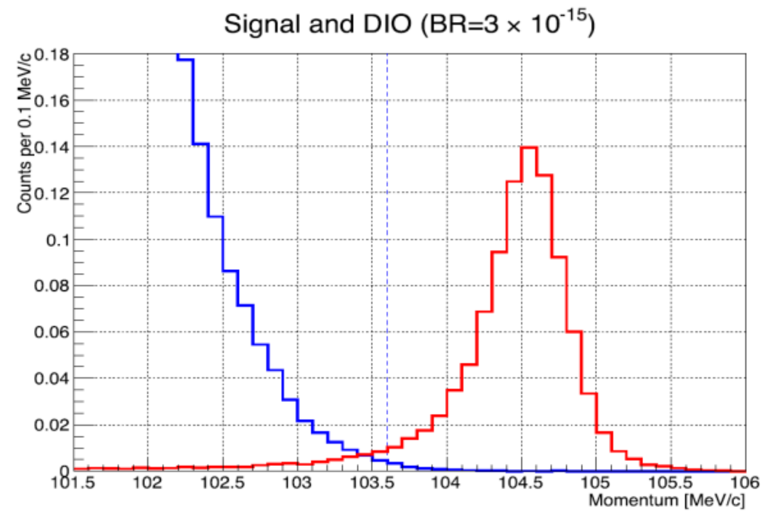


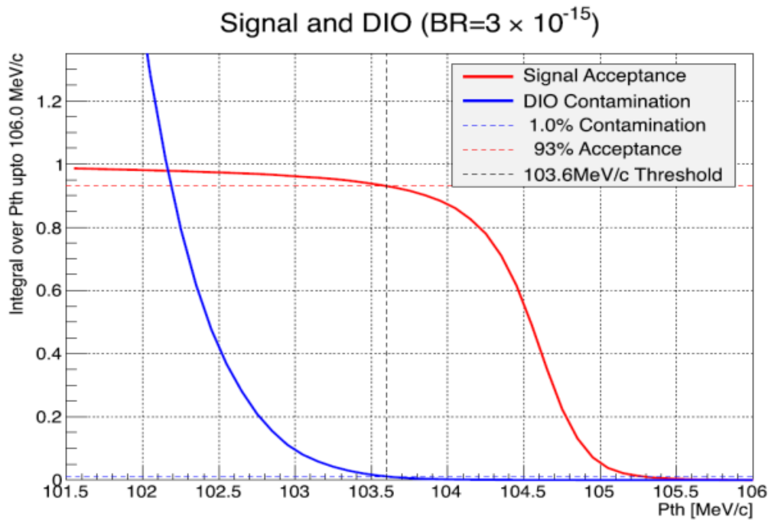
- Signal e^- MC samples
- Reverse μ^+ MC samples

Spatial resolution = 150 μm

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

COMET Signal and Backgrounds





- Single Event Sensitivity = 3.1×10^{-15}
- At momentum window $103.6 MeV/c<p_e<106 MeV/c$, 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