Track direction identification via track-fitting quality for cosmic-ray background suppression in the COMET experiment

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9th International Workshop @ The University of Tokyo, Tokyo, Japan

Contents

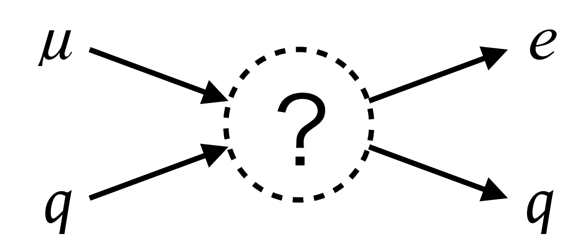
See also:
M. Moritsu et al., arXiv:2508.15344

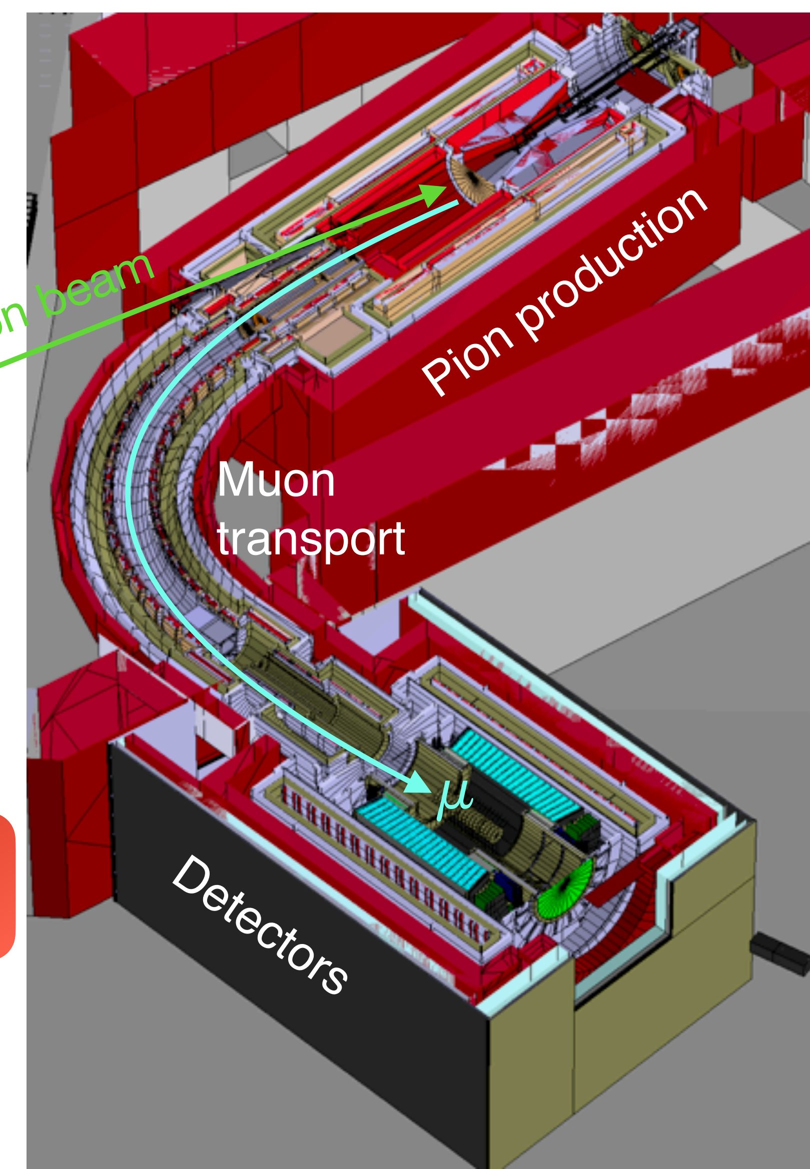
- Introduction
  - The COMET experiment & the tracking system
- Motivation
  - Cosmic-ray background in the COMET experiment
- Track-direction ID method
  - to eliminate reverse-traveling opposite-sign particles

μ–e conversion & COMET

- **Muon-to-electron conversion:**
  - Neutrinoless coherent transition in a nuclear field
  - Violates the Lepton Flavor conservation
  - Search for NEW physics beyond the Standard Model
- **The COMET experiment:**
  - Explores μ-e conversion at **J-PARC** with the single event sensitivity of
    - Phase-I: **3×10^{-15}** (×100 improvement)
    - Phase-II: **3×10^{-17}** (×10,000 improvement)

$$\mu^- + N \rightarrow e^- + N$$





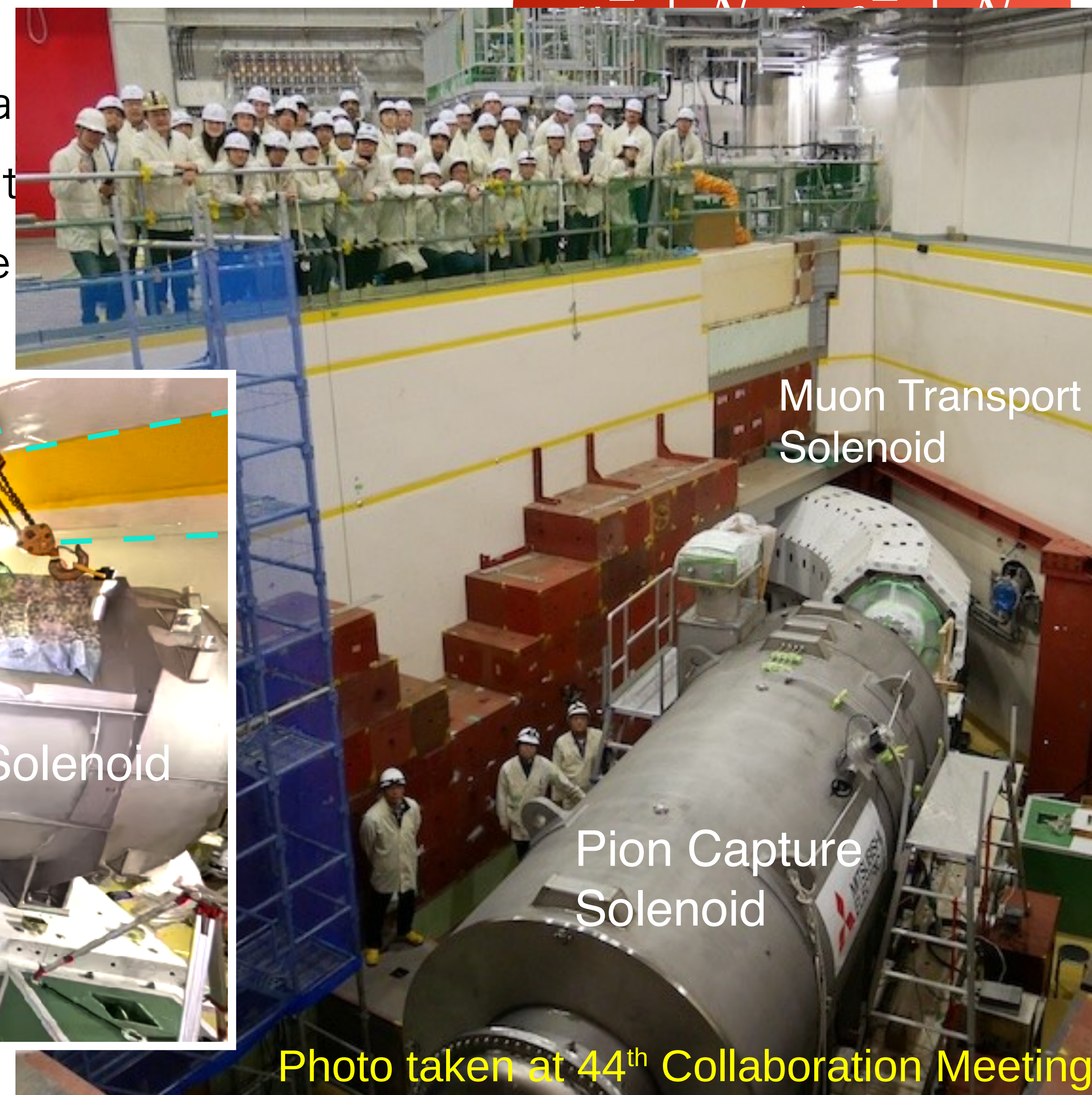
Technical Design Report
PTEP 2020, 033C01

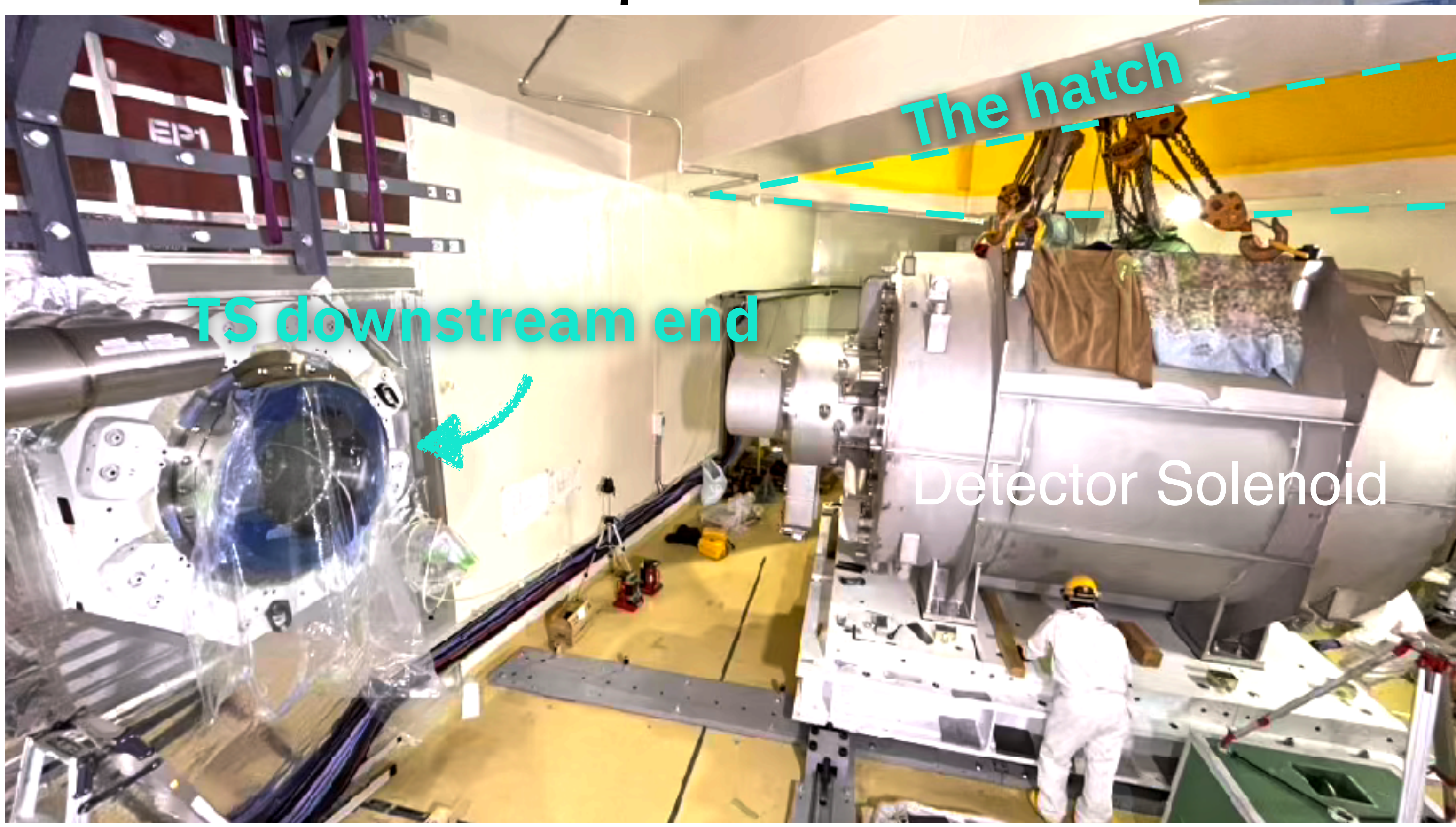
COMET Phase-I

Starts in 2027

μ-e conversion & COMET

- **Muon-to-electron conversion:**
  - Neutrinoless coherent transition in a
  - Violates the Lepton Flavor conservat
  - Search for NEW physics beyond the
- **The COMET experiment:**



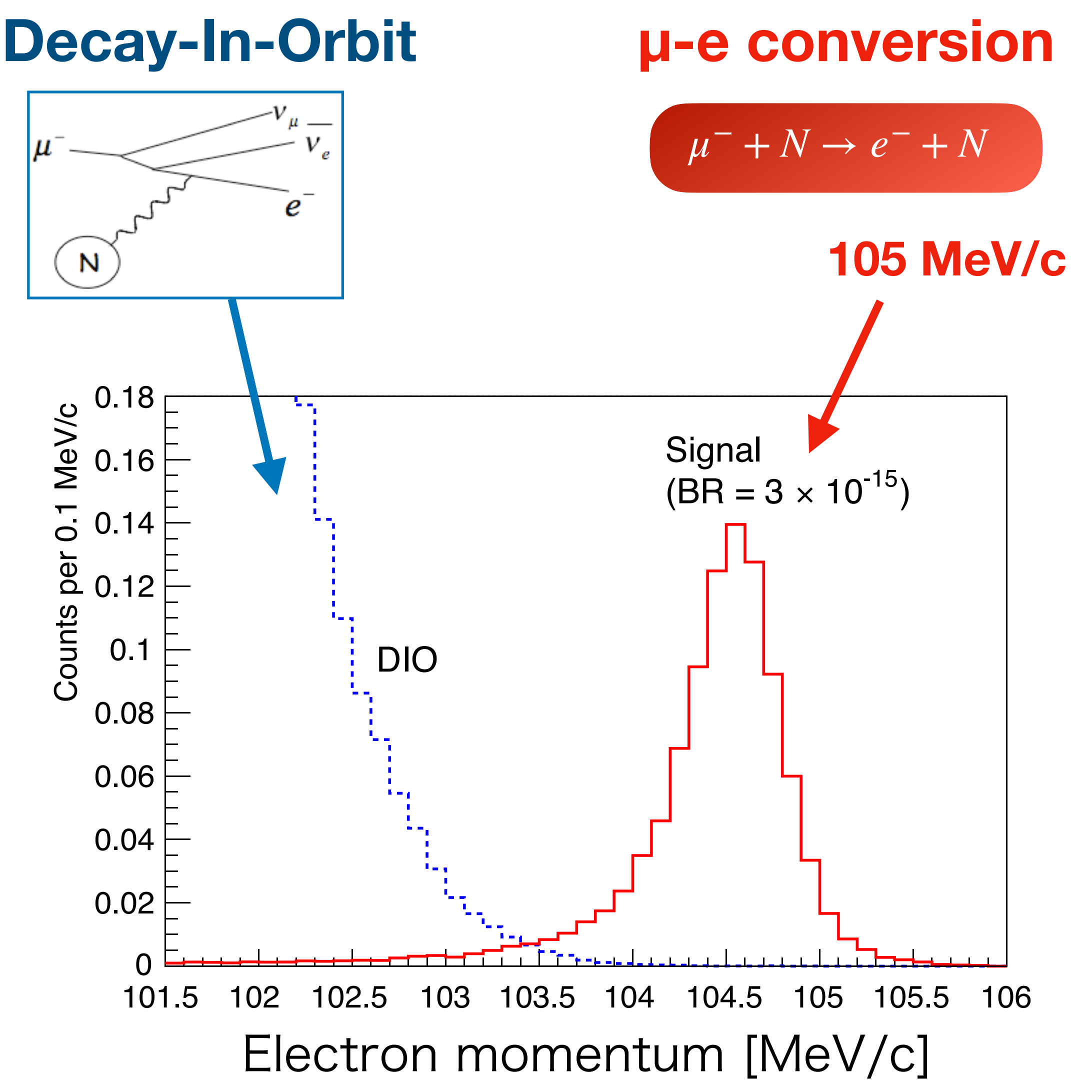


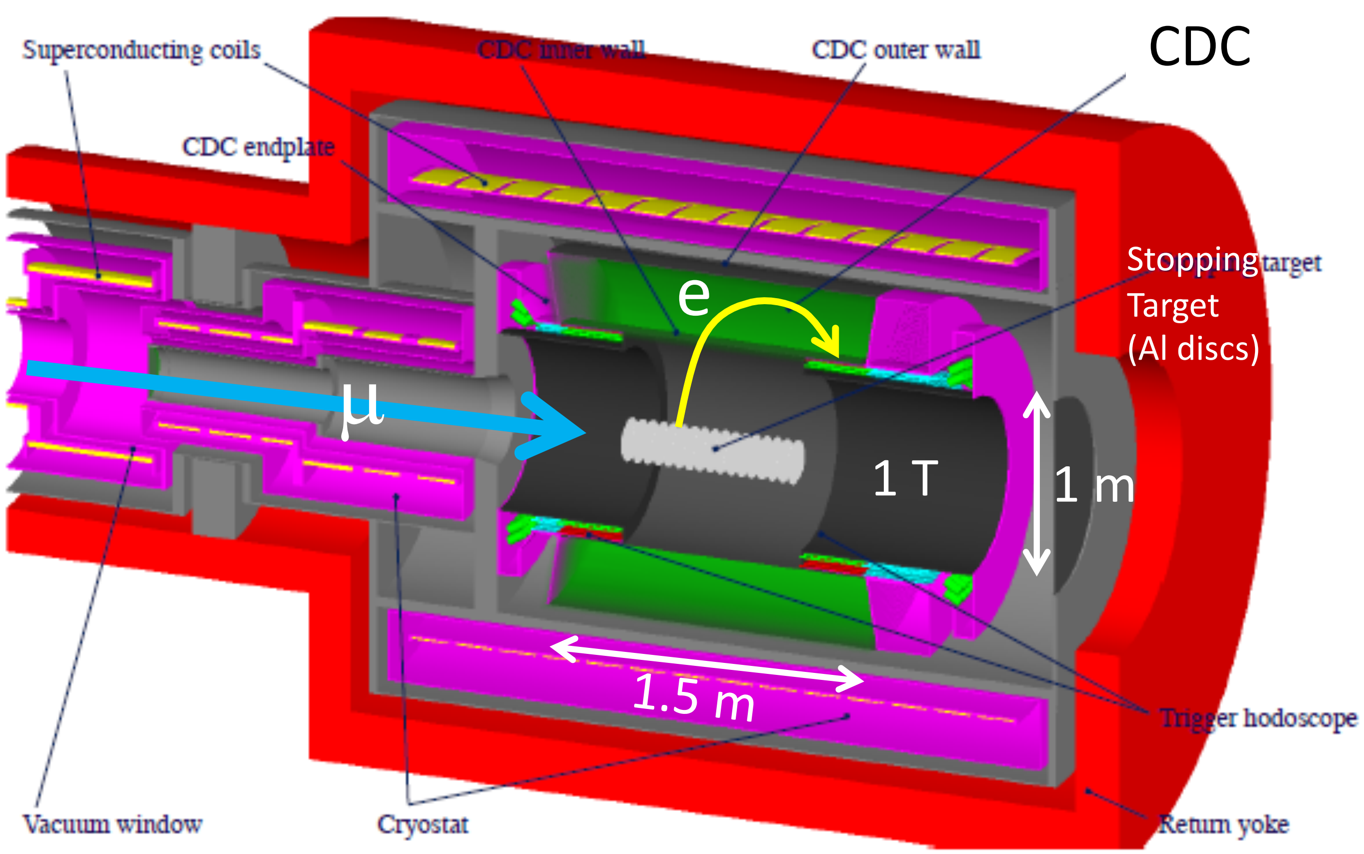
Technical Design Report
PTEP 2020, 033C01

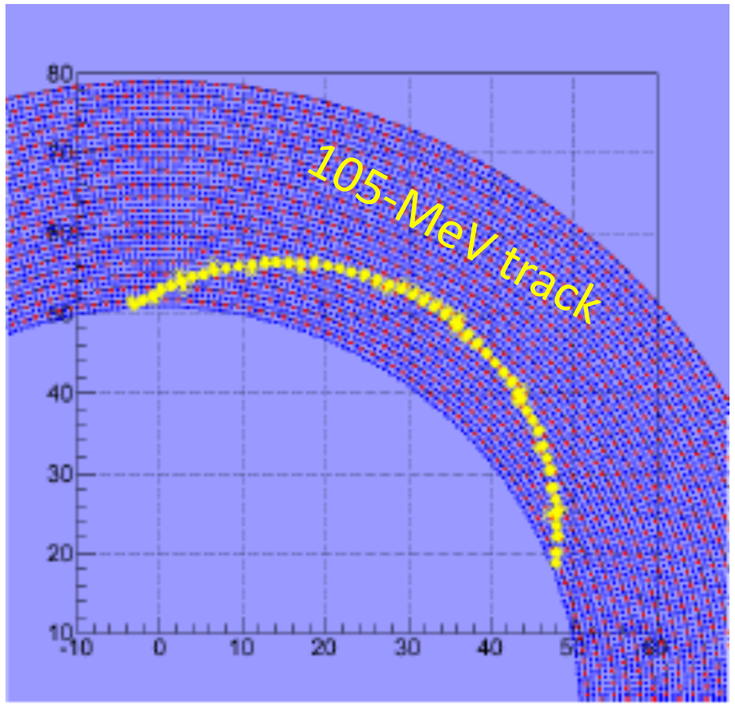
Starts in 2027

COMET CDC

A. Sato et al., NIM A 1069, 169926 (2024)







Cylindrical Drift Chamber (CDC)

- 20 layers of alternating all-stereo wires
- Low mass gas mixture = He:iC_4H_{10} (90:10)

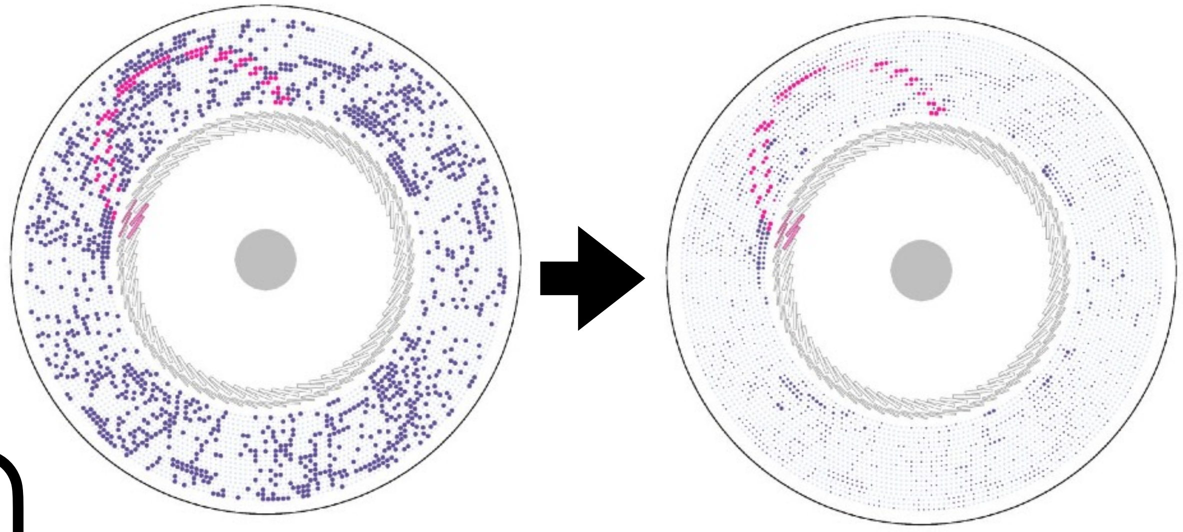
Cylindrical Trigger Hodoscopes (CTH)

- 256 segmented plastic scintillators

Track Reconstruction

Hit Classification

By using GBDT, 98% of noises are rejected
while keeping 99% of signals.

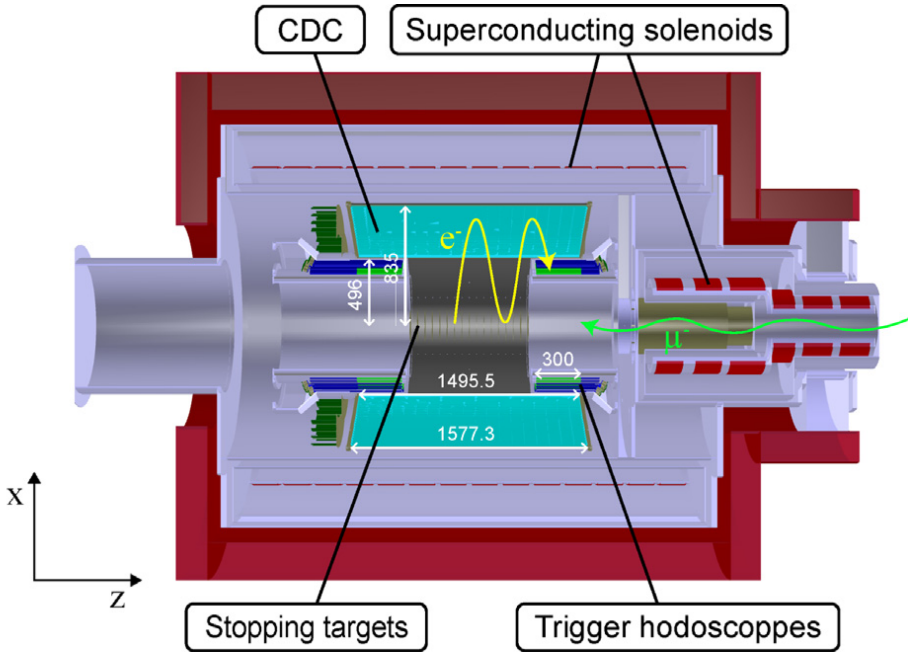


Track Finding

Hough Transformation, Deep Learning, RANSAC, etc.

F. Kaneko et al., PTEP 2025, 053C01

see also a poster by T. Xing

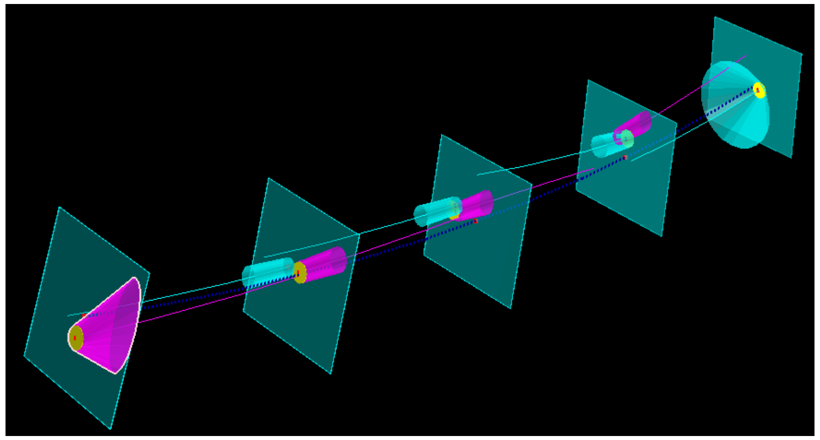


Track Turn Identification

32% of signal events are multiple turn.
We will focus on only single turn in this report.

Track Fitting

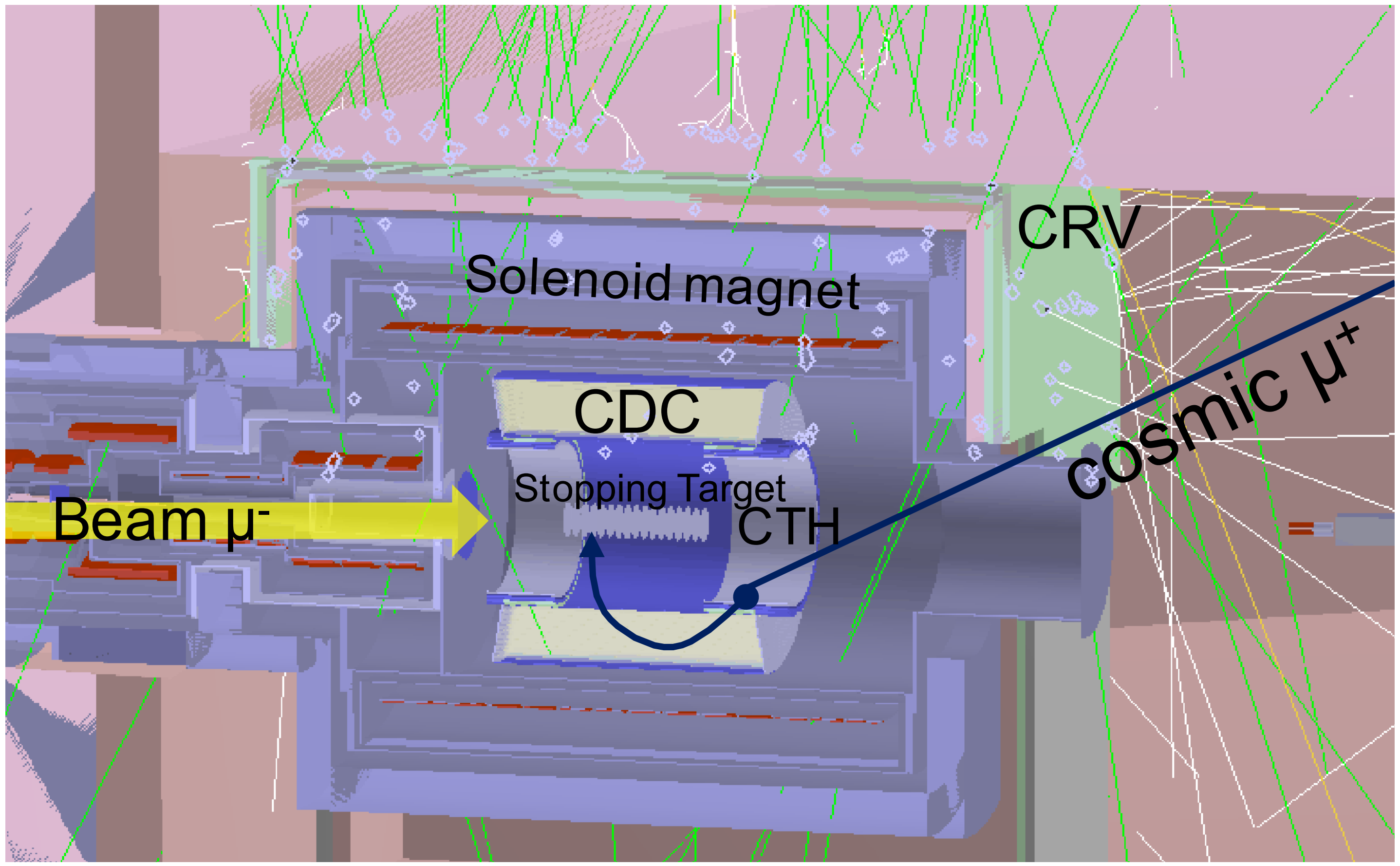
We use Deterministic Annealing Filter in GENFIT2



Motivation

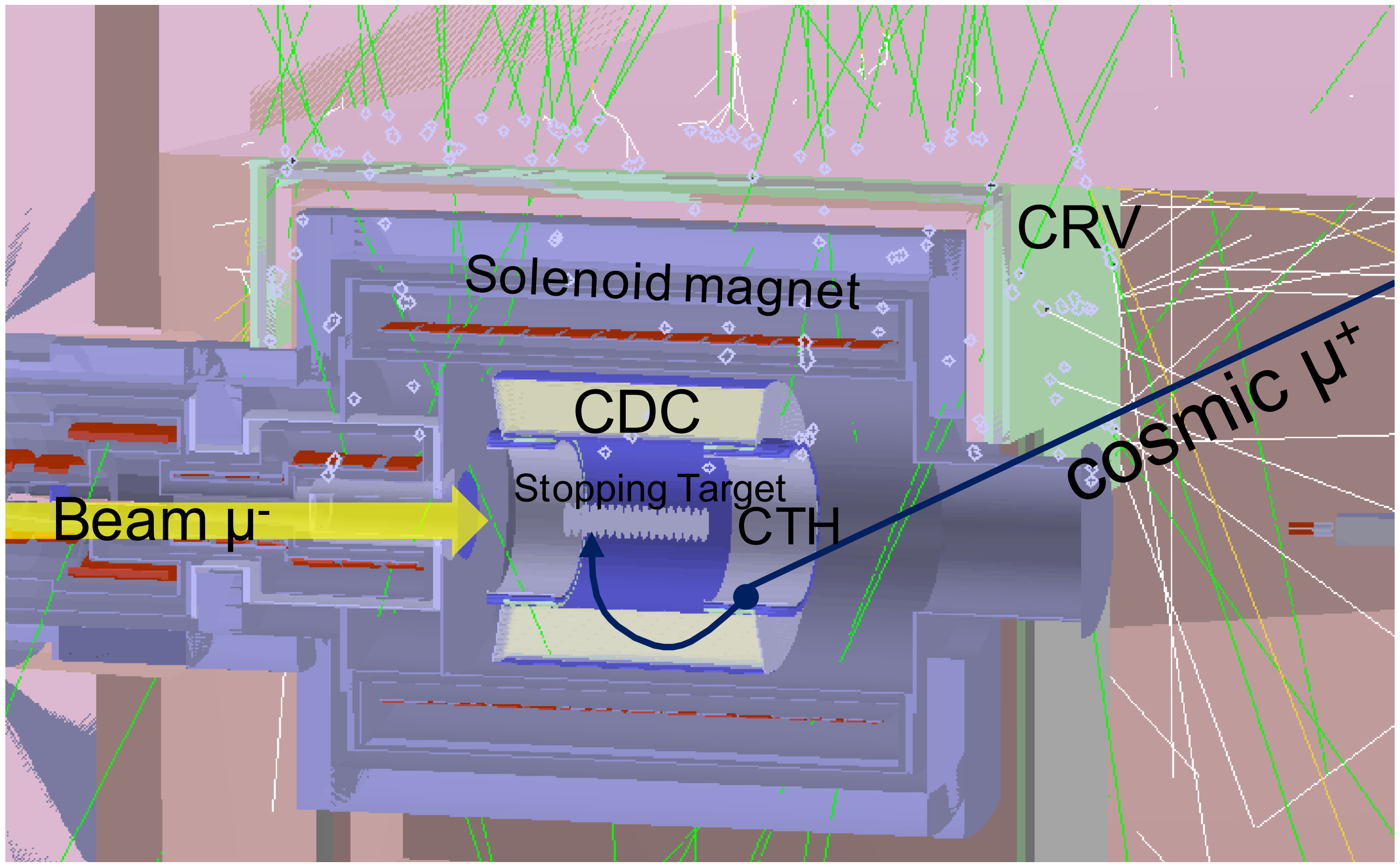
Cosmic-ray background in the COMET experiment

Motivation — Cosmic-ray BG



- **Cosmic rays** may create 105-MeV electrons that come into a detector and make trigger.
- Cosmic-ray induced BG is basically eliminated by **veto counter** arrays which cover Detector Solenoid (DS) Magnet,
  - ✓ with 99.99% veto efficiency.
- However, there are uncovered holes through which cosmic rays **may sneak into** DS.

Motivation — Sneaking cosmic-ray BG



Sneaking cosmic μ^+

can be a significant BG.

- does not hit CRV (sneaking from downstream hole of DS),
- scattered by CTH support frame,
- hits CTH and enters CDC from the reverse direction compared to the signal electron track, and
- finally hits stopping target.

In the latest simulation, without any measure, 2.4 ± 0.9 BG events remains.

Notice Why μ^+ (not μ^-)

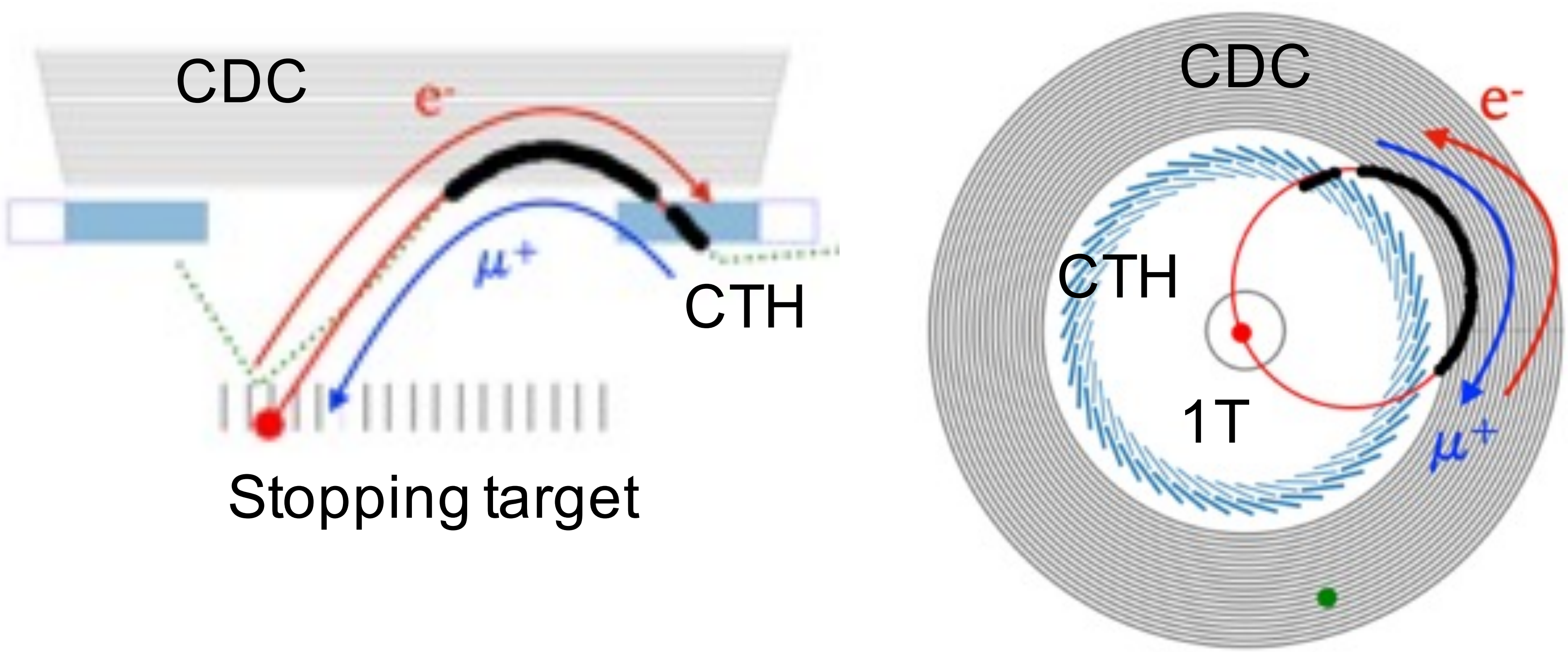
The trajectory of positive charged particles with reverse track direction looks the same as the signal electron track.

→ Next page

Feature of sneaking μ+ BG

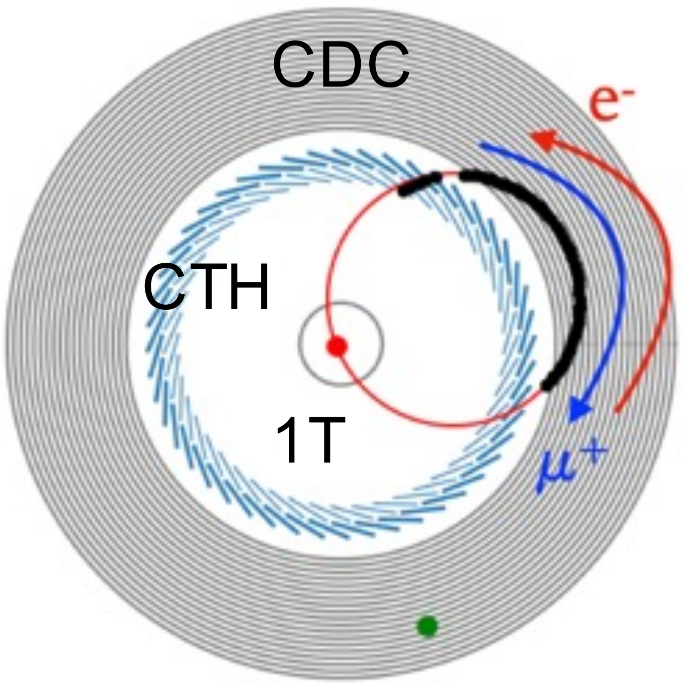
	μ-e Conv. Signal	Sneaking cosmic BG
Particle	e^-	μ^+
Speed β	1	0.7
Track direction	Target → CDC → CTH (Normal)	CTH → CDC → Traget (Reverse)

for 105 MeV/c



Can we know track direction ?

We normally assume the track direction is from Target to CTH.



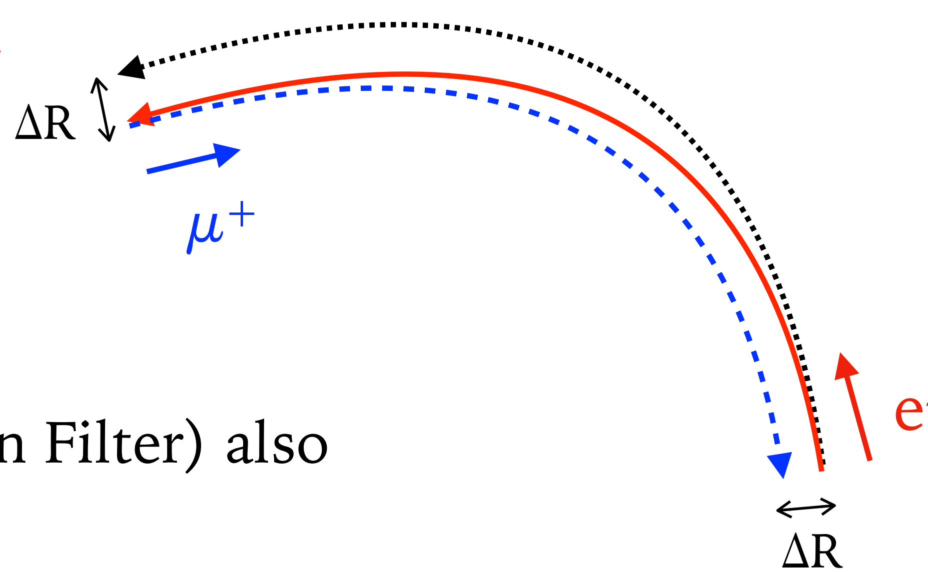
TOF miscorrection

- In order to know correct drift time, **time-0** is corrected according to TOF between CTH and each CDC hit.
- If the track is reverse, this makes miscorrection of at longest **9.7 ns** for reverse μ^+.
  - 9.7 ns × 25 μm/ns* = **240 μm**
  - (comparable to spatial resolution of 150 μm)

* Drift velocity for He:iC_4H_{10} (90:10) ~ typically 25 μm/ns

Idea

This miscorrection will make the difference in χ^2 between normal & reverse direction hypotheses.



Note:
Material effect (energy loss correction in Kalman Filter) also makes χ^2 worse for reverse tracks.

Track-direction ID method

Simulation & Analysis

MC event generation

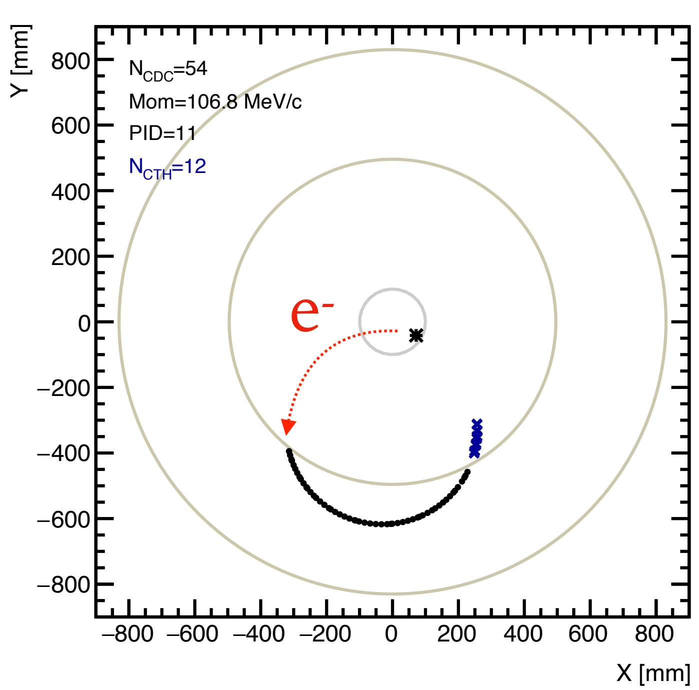
Signal e^- MC sample

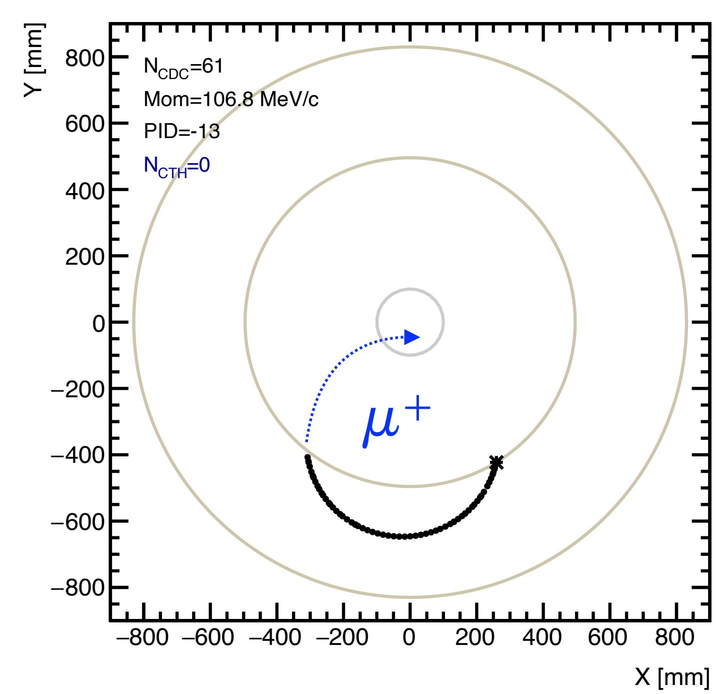
- electron e^-
- 100—110 MeV/c
- From stopping target disks
- CDC max layer >= 5
- Require CTH hits
- Single turn only
- Spatial resolution: 150 μm

Reversed →

Reversed μ^+ MC sample:

- muon μ^+
- 100—110 MeV/c
- From CTH to target disks
- CDC max layer >= 5
- Single turn only
- Spatial resolution: 150 μm





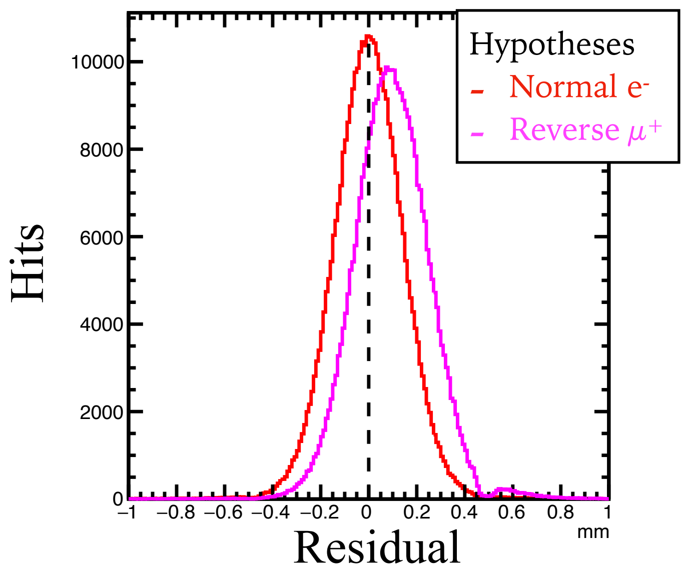
Track Fitting with 2 Hypotheses

Compare 2 hypotheses

Normal-direction e^- vs Reverse-direction μ^+

This induces **miscorrection of TOF**

Signal e^- MC sample



Track Fitting with 2 Hypotheses

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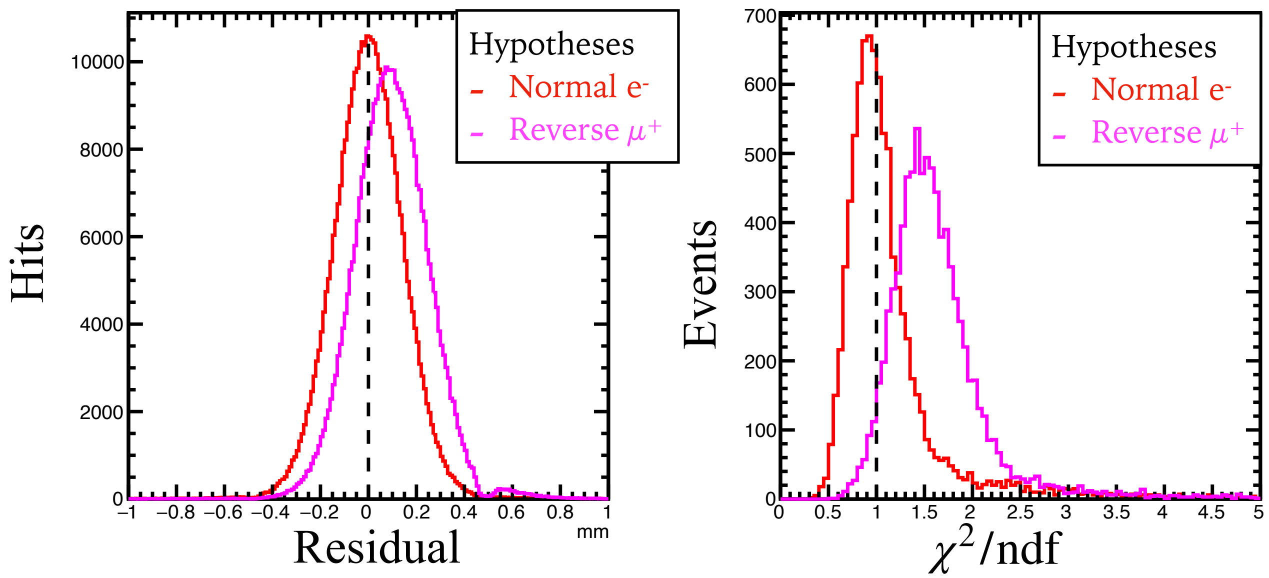


Difference does exist !

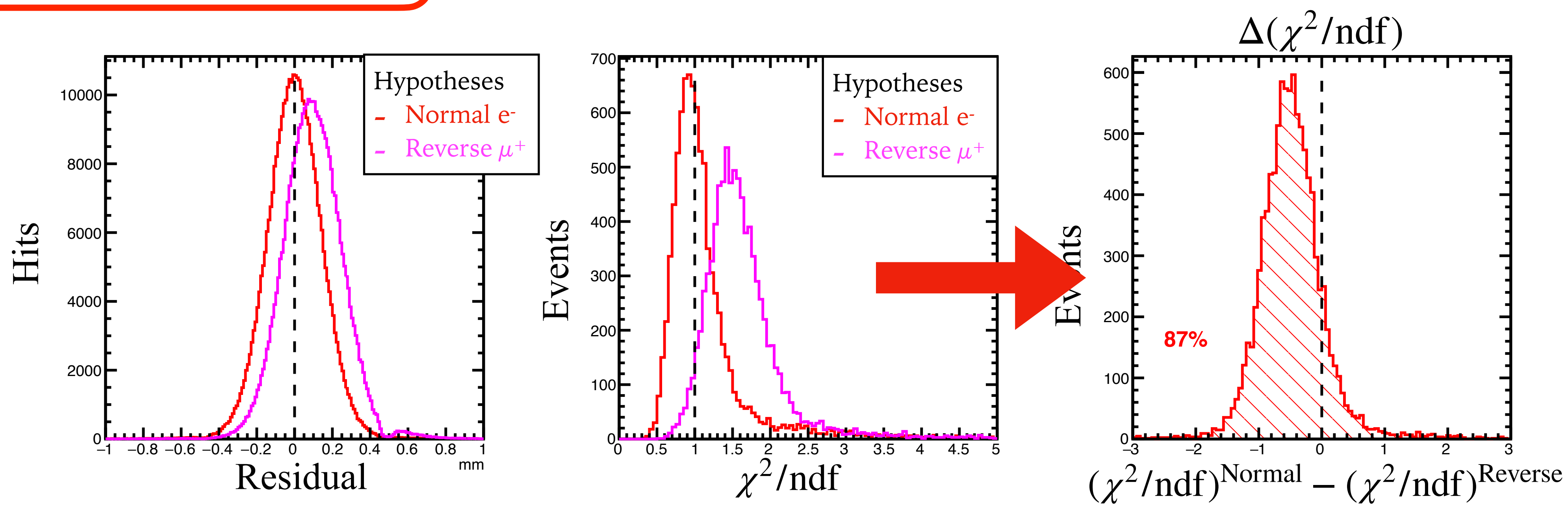
Track Fitting with 2 Hypotheses

Compare 2 hypotheses

Normal-direction e^- vs Reverse-direction μ^+

This induces **miscorrection of TOF**

Signal e^- MC sample



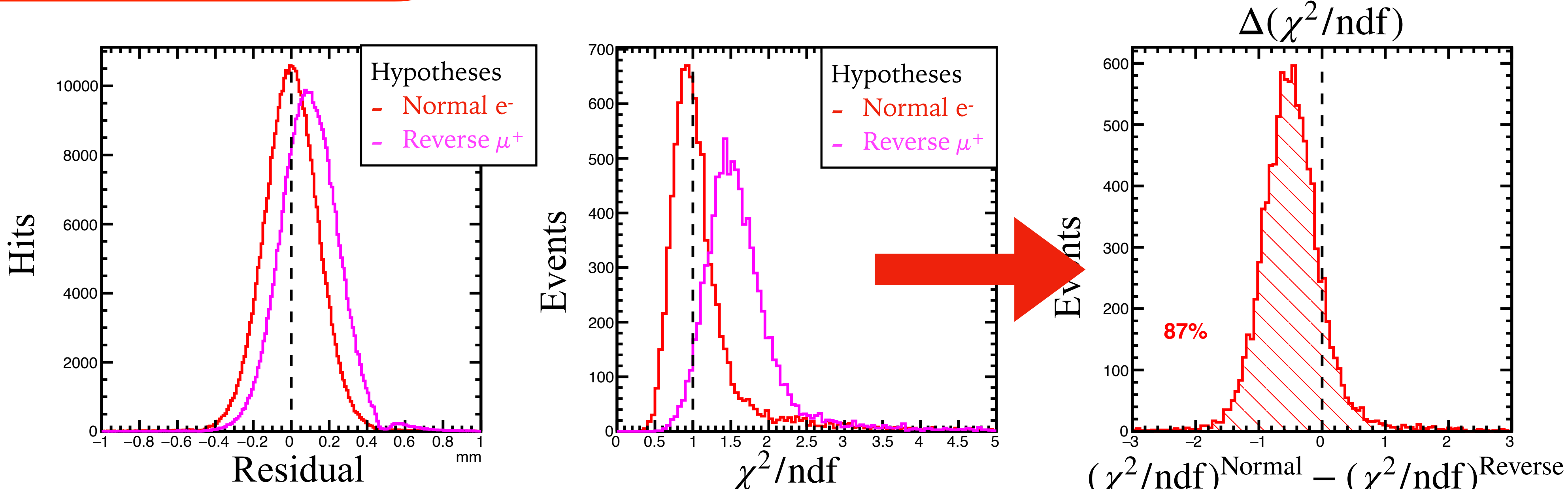
Track Fitting with 2 Hypotheses

Compare 2 hypotheses

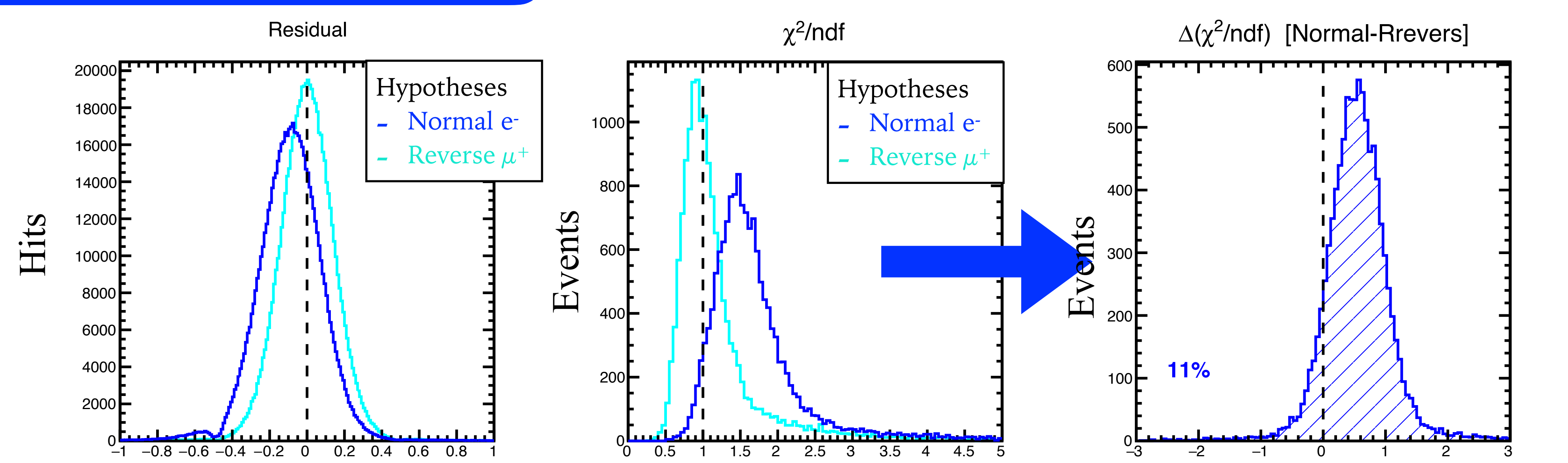
Normal-direction e^- vs Reverse-direction μ^+

This induces **miscorrection of TOF**

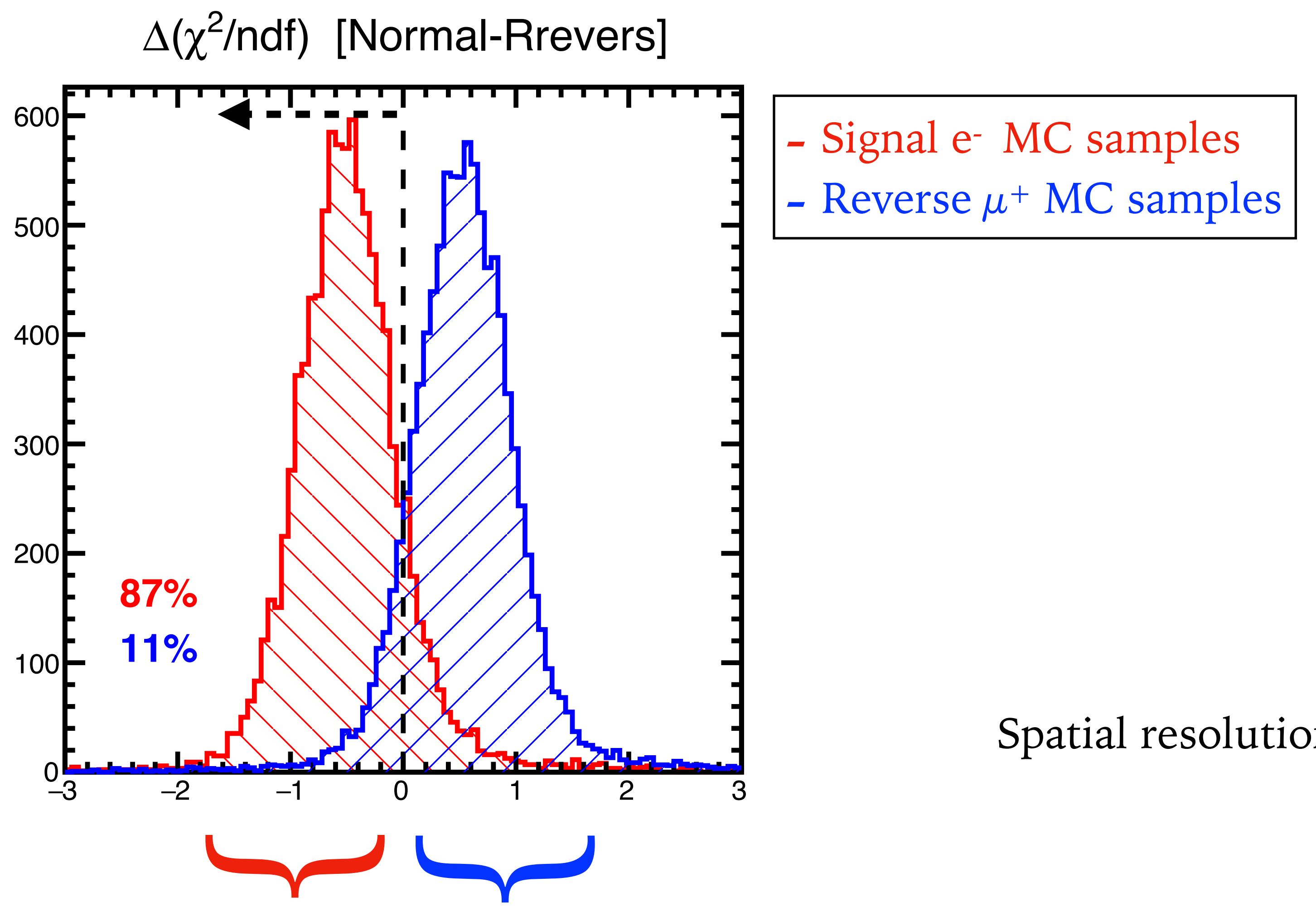
Signal e^- MC sample



Reversed μ^+ MC sample



Signal retention & BG rejection



Spatial resolution = 150 μm

If we set threshold as
$\Delta(\chi^2/\mathrm{ndf}) < 0$,

87% of signal e^- are retained

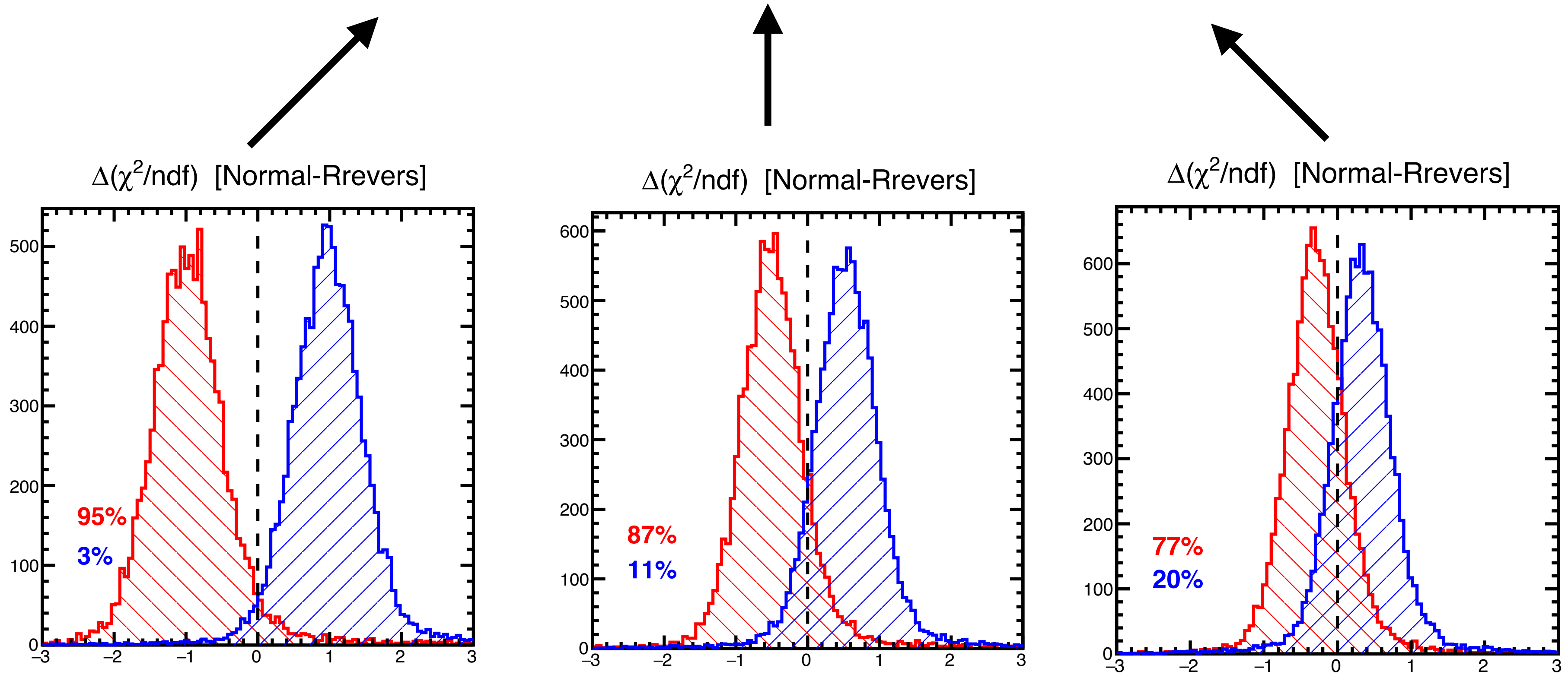
89% of reverse μ^+ are eliminated

BG can be suppressed to **11%**

Dependence of spatial resolution

$\Delta(\chi^2/ndf) < 0$

Spatial Resolution	100 μm	150 μm	200 μm
Signal Retention (e^-)	95%	87%	77%
Contamination (μ^+)	3%	11%	20%



✓ Rejection power is sensitive to spatial resolution.

We expect **~150 μm** resolution based on a prototype test

Wu et al., NIM A 1015, 165756 (2021)

Reduction of BG events

Spatial Resolution	100 μm	150 μm	200 μm	Without Direction ID method
Signal Retention (e^-)	95%	87%	77%	100%
Contamination (μ^+)	3%	11%	20%	100%
BG events	0.07	0.26	0.48	2.4

Latest Prediction

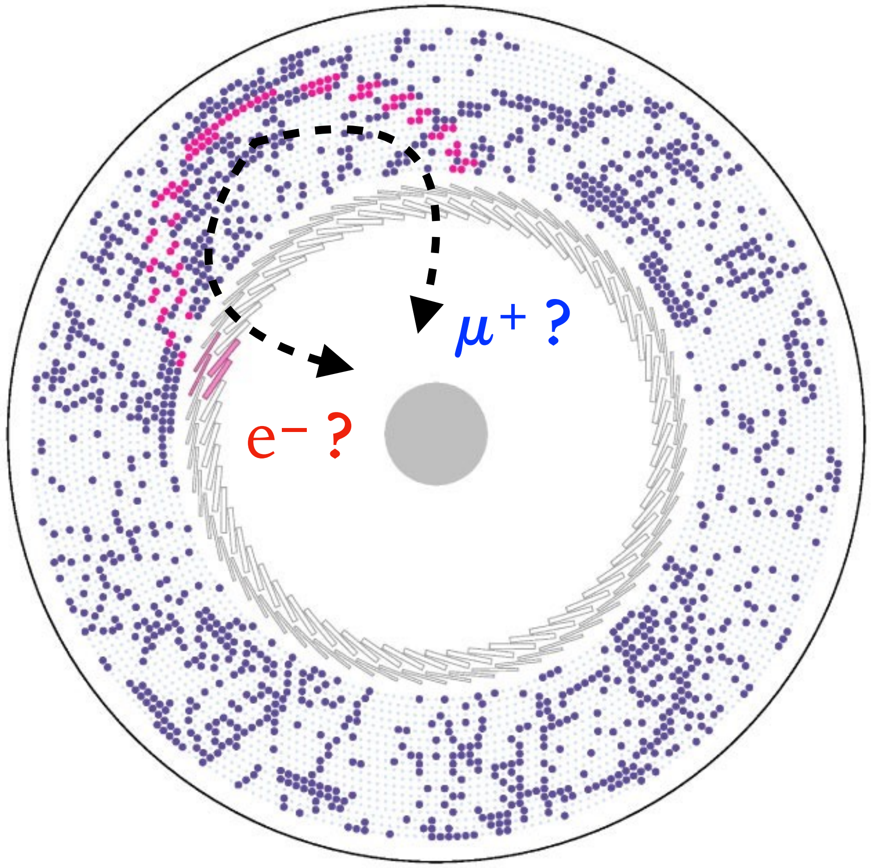
Assuming 150 μm spatial resolution,

Sneaking cosmic μ^+ BG can be reduced to **0.26** events

Next step — Outlook

- There is room to improve reduction power by using machine learning with multi-variate analysis, instead of simple comparison of χ^2/ndf.

- We have to check the performance with many noise hits.



Summary

See also:
M. Moritsu et al., arXiv:2508.15344

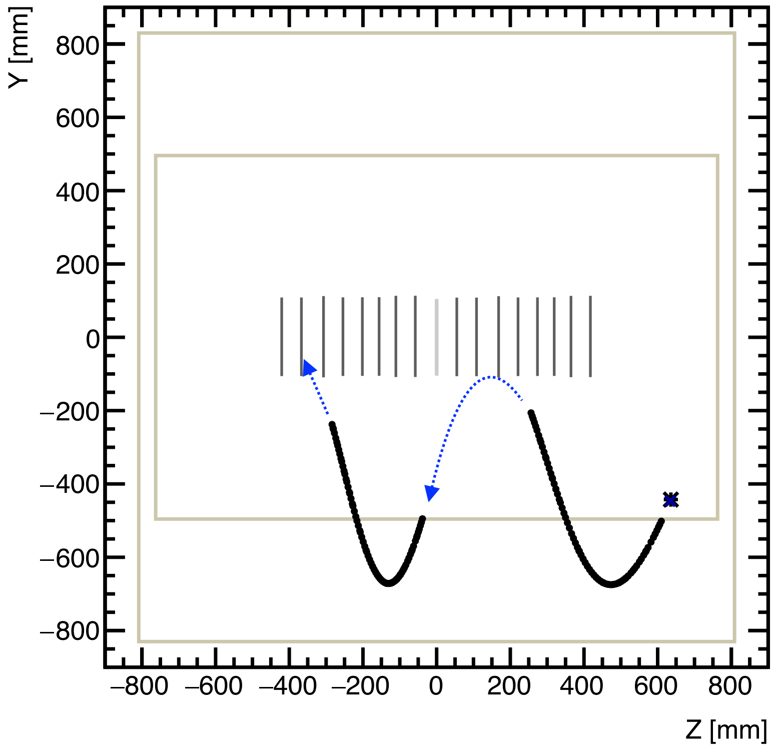
- Cosmic-ray muons is one of severest backgrounds in the COMET experiment.
- **Track-Direction ID** method was developed
  - to suppress sneaking cosmic μ^+ BG.
  - Demonstrated that reverse μ^+ track can be suppressed by an order of magnitude, with signal e^- track retention efficiency of ~90% (assuming 150 μm spatial resolution).
    - ✓ Note reduction power is sensitive to the CDC spatial resolution.

◉ Prospect

- A study is on going to improve reduction power by using machine learning with the noise hits.

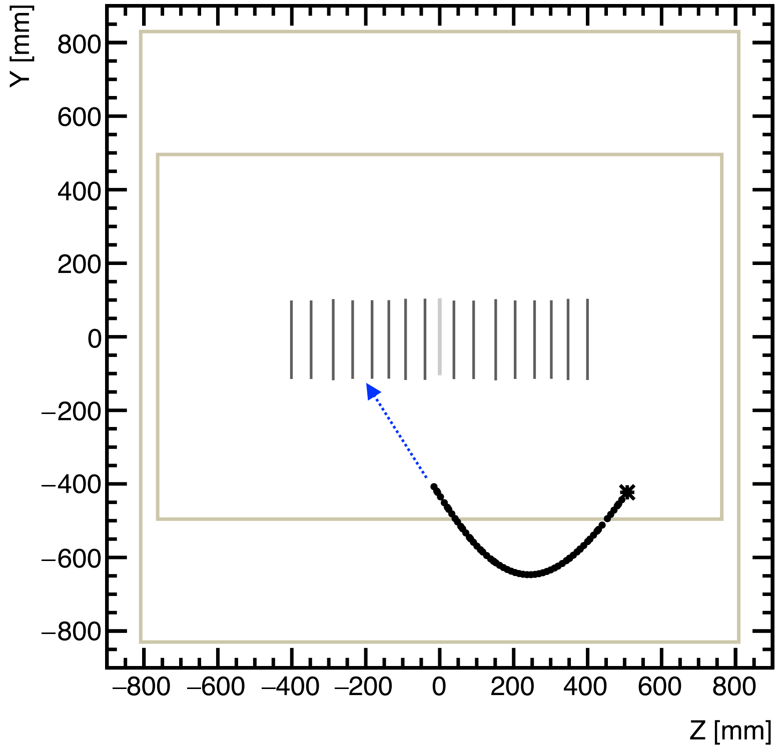
Backup

Note for multiple-turn events



If a track has multiple turns,
the direction will be easily identified
by checking momentum attenuation
in-between the turns.

Therefore, we deal with
only single-turn events in this study.



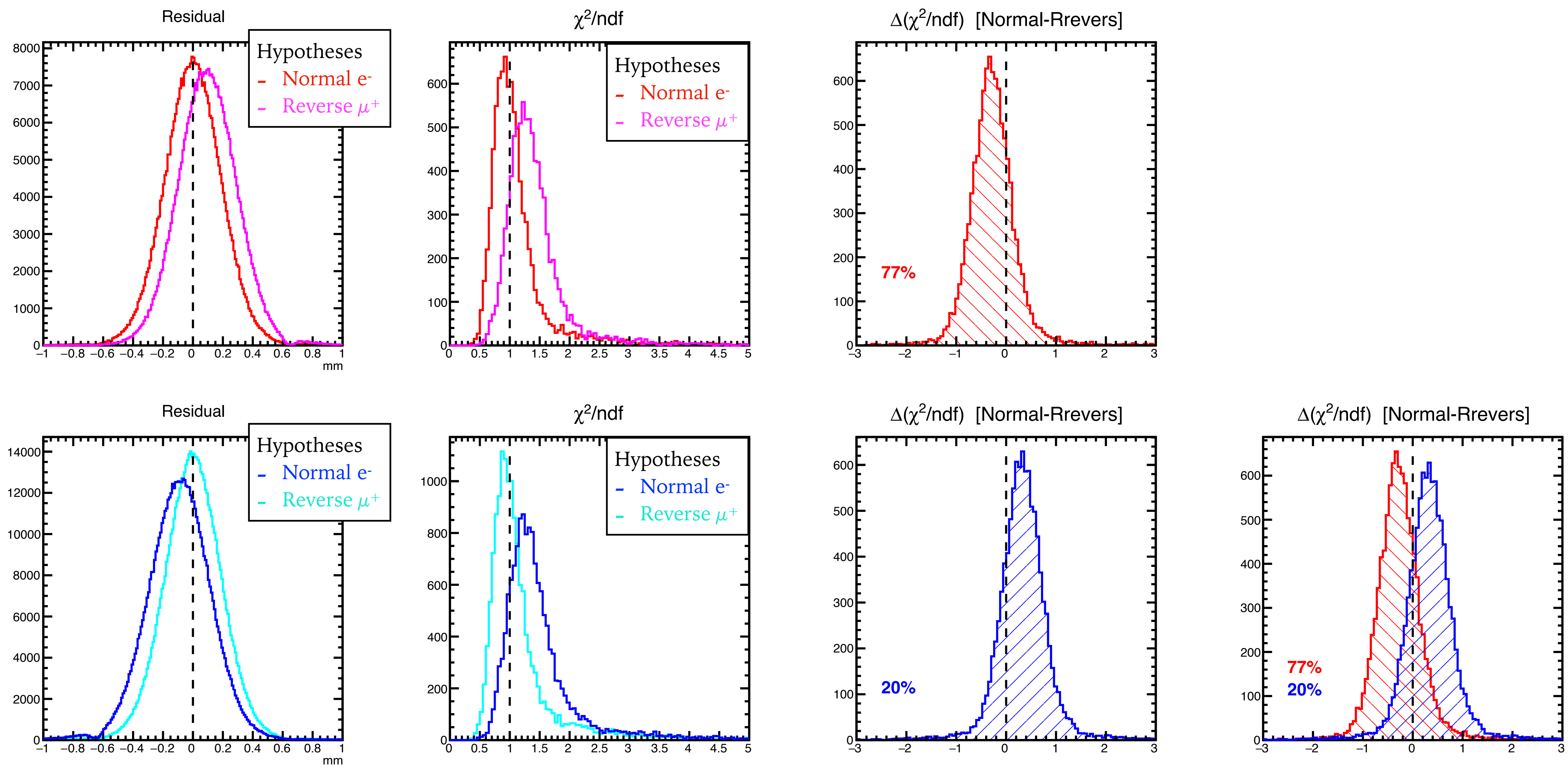
Spatial resolution = 200 μm

Compare 2 hypotheses

Normal-direction e- vs Reverse-direction μ+

Signal e- MC sample

Reversed μ+ MC sample



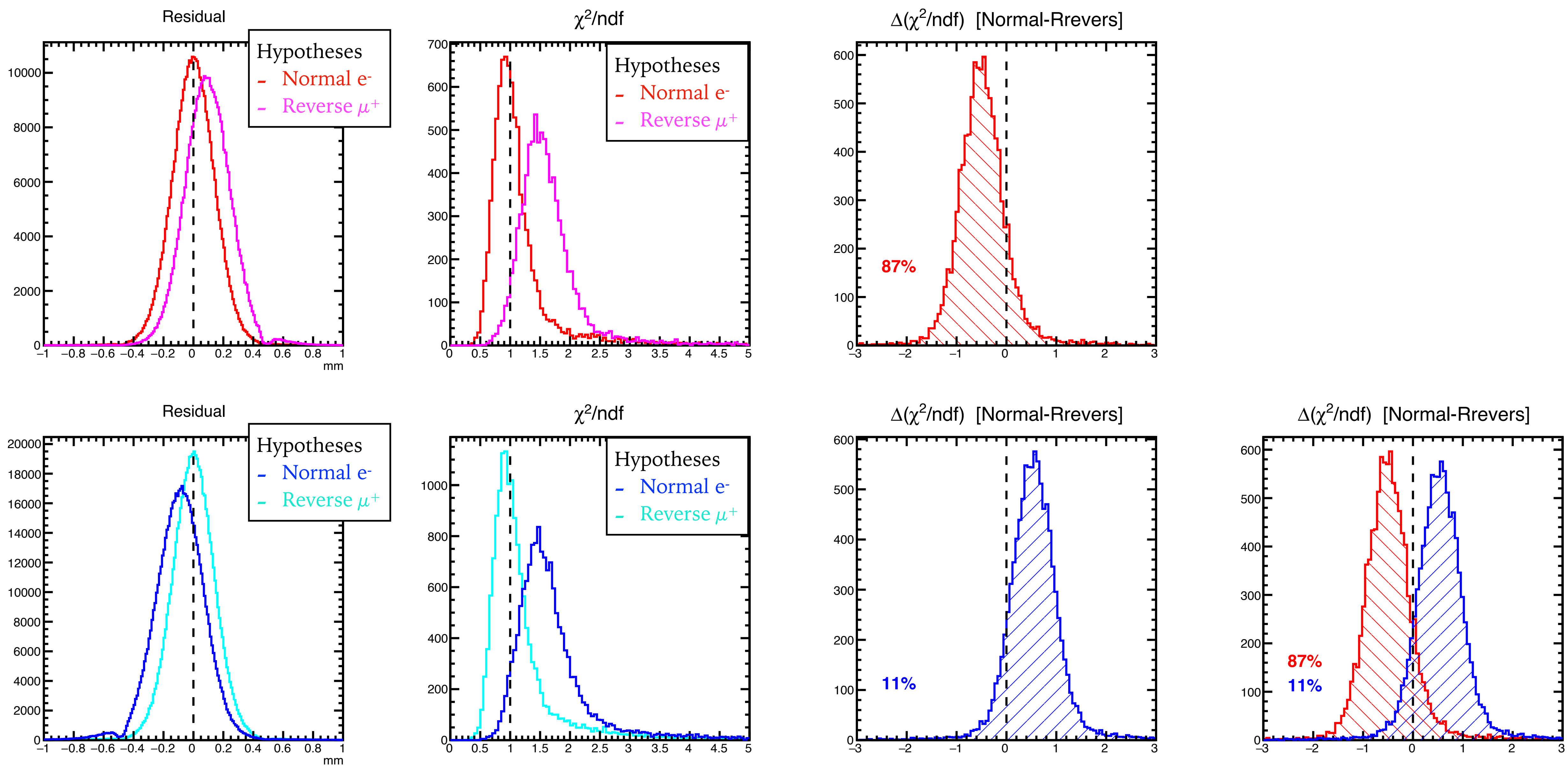
Spatial resolution = 150 μm

Compare 2 hypotheses

Normal-direction e- vs Reverse-direction μ+

Signal e- MC sample

Reversed μ+ MC sample



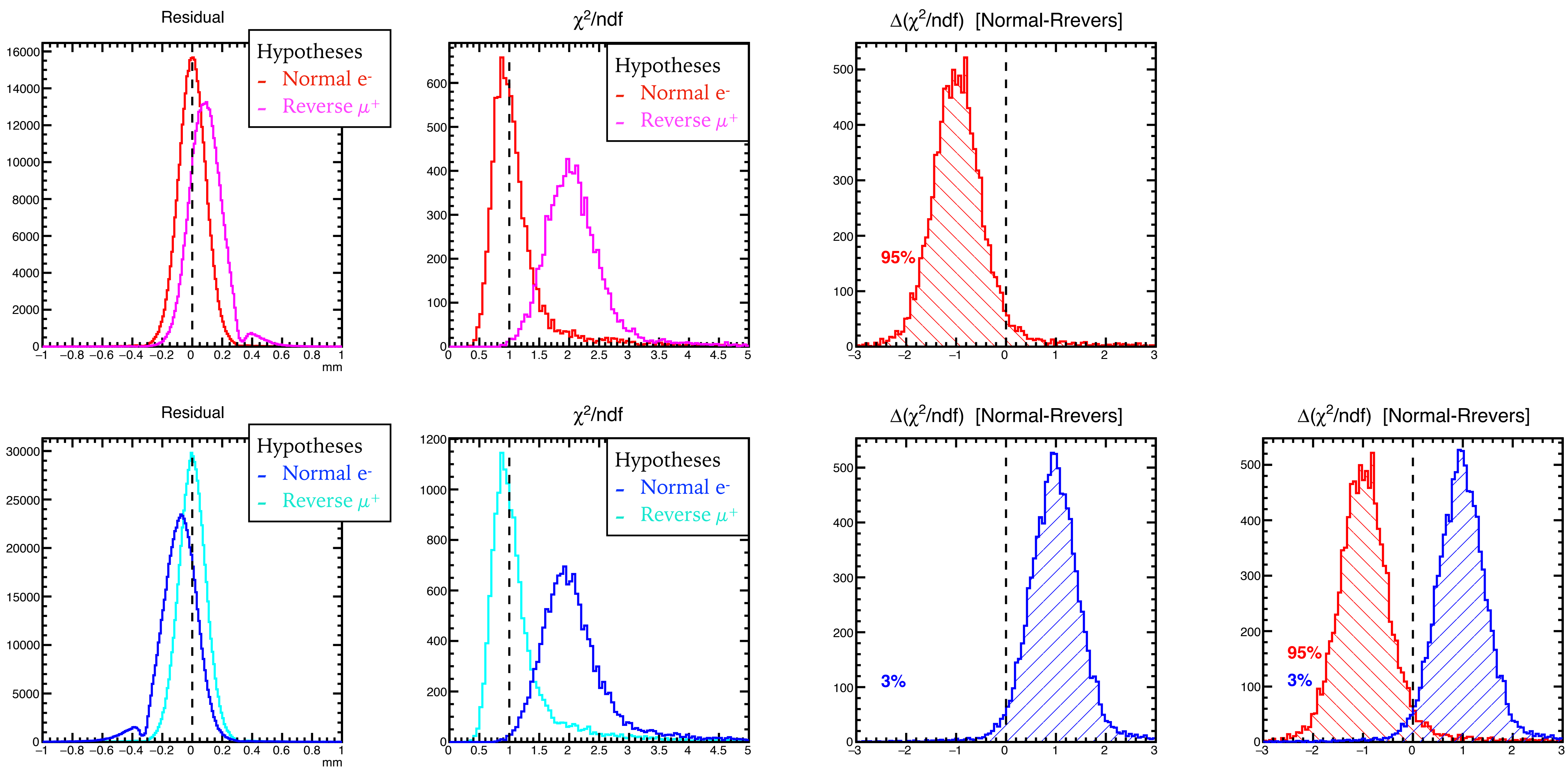
Spatial resolution = 100 µm

Compare 2 hypotheses

Normal-direction e- vs Reverse-direction µ+

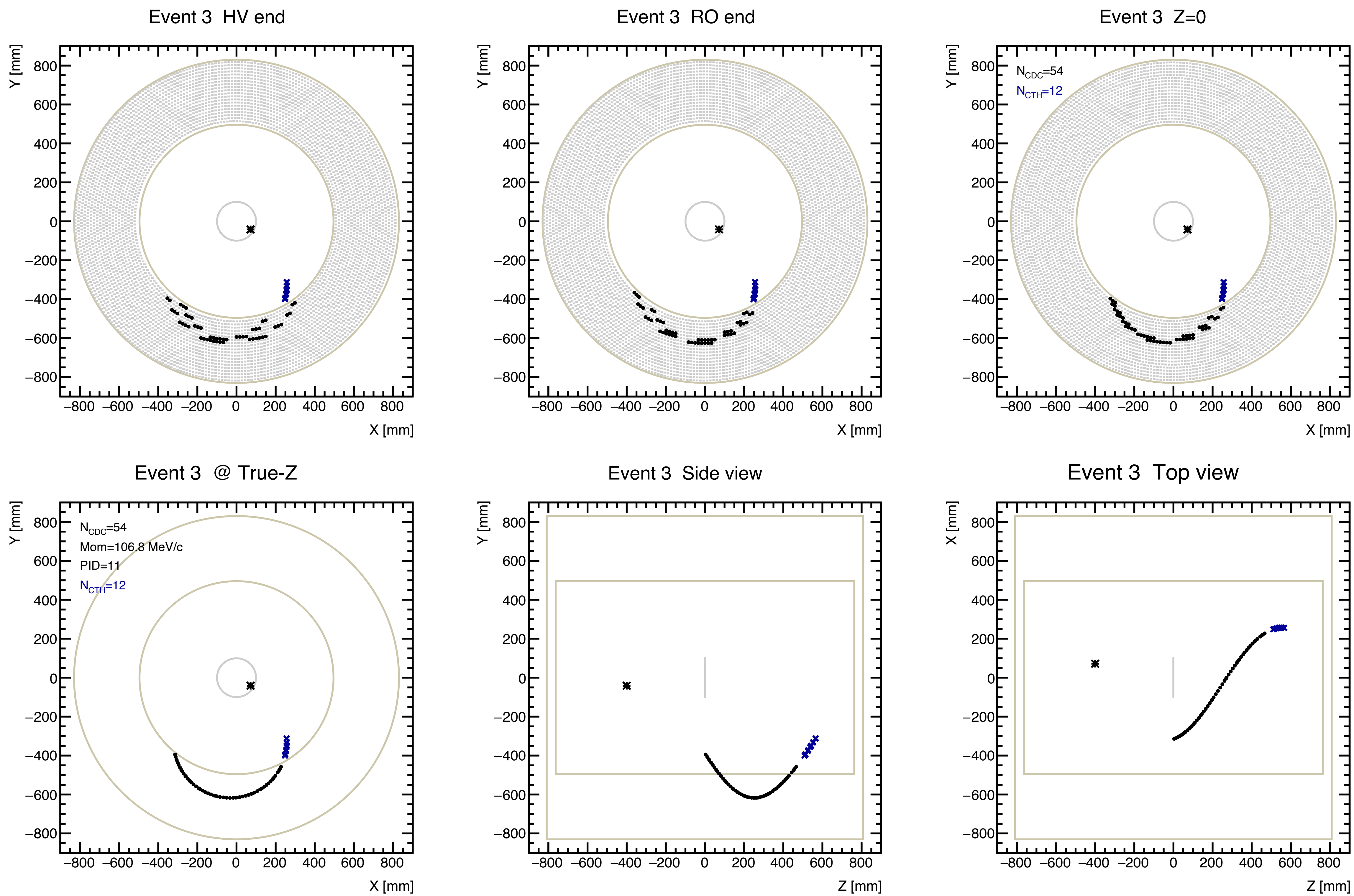
Signal e- MC sample

Reversed µ+ MC sample



Event display example

Signal e^- MC sample



How to discriminate reverse μ+ ?

1. Cherenkov radiation ☹️

μ^+ with β=0.7 exceeds the Cherenkov threshold of Acrylic (n=1.49), β_{th}=0.67.

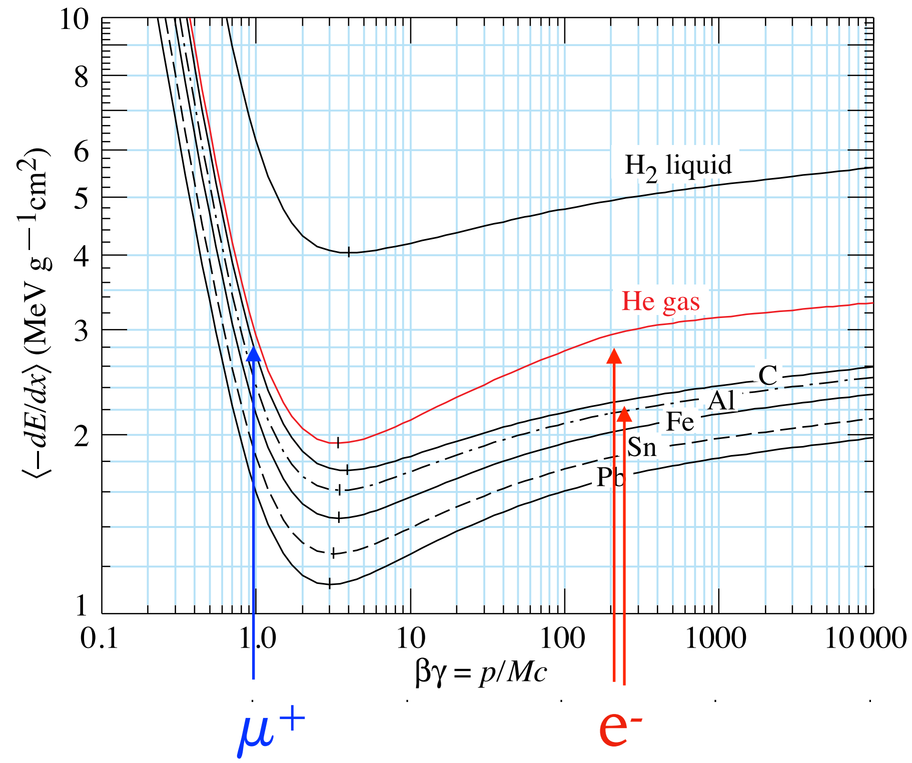
(Perhaps the number of photons may help to some extent.)

Radiator with refractive index less than 1.4 is the best.

How to discriminate reverse μ+ ?

2. dE/dx

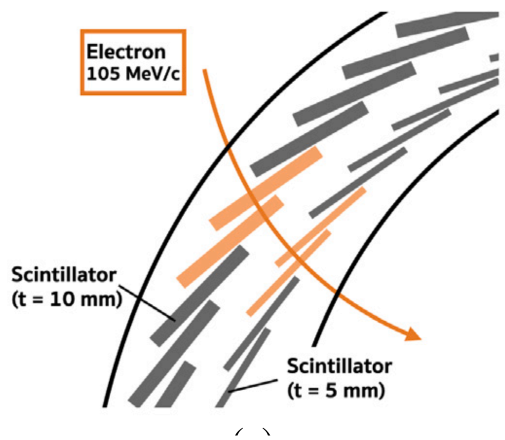
Unfortunately dE/dx in He gas for e- ($\beta\gamma$=200) and μ^+ ($\beta\gamma$=1) are almost the same.
→ difficult to separate ☹️

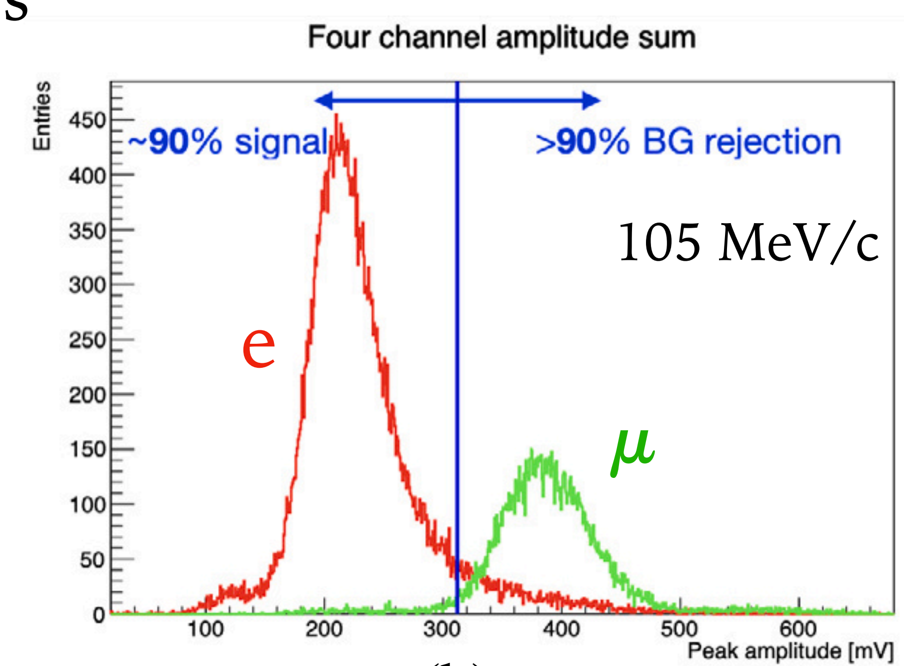


from PDG http://pdg.lbl.gov/2019/reviews/rpp2018-rev-passage-particles-matter.pdf

However, dE/dx in CTH Plastic Scintillators can have slight difference.

😄





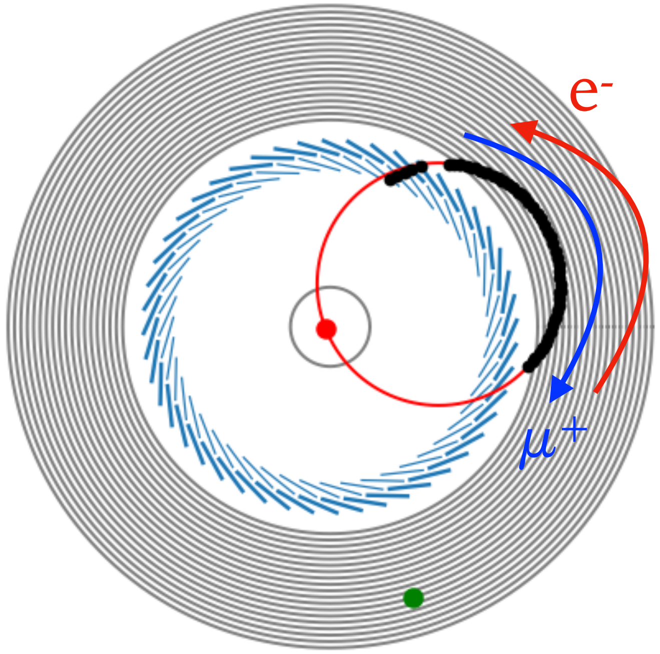
(b)

Y. Fujii et al. NIM A 1067, 169665 (2024)

Can we know track direction ?

We normally assume the track direction is from Target to CTH.

A. TOF miscorrection



In order to know correct drift time, time-0 is corrected according to TOF between CTH and each CDC hit.

For signal e^- ($\beta=1$), $-4 < \text{TOF} < 0$ ns

For reverse μ^+ ($\beta=0.7$), $0 < \text{TOF} < 5.7$ ns

This causes miscorrection of at longest **9.7 ns** for reverse μ^+.

9.7 ns × 25 μm/ns* = **240 μm**

(comparable to spatial resolution of 150 μm)

* Drift velocity for He:iC_4H_{10} (90:10) ~ typically 25 μm/ns

Naive idea

This miscorrection will make the difference in χ^2 between normal & reverse direction hypotheses.

Can we know track direction ?

B. Material effect

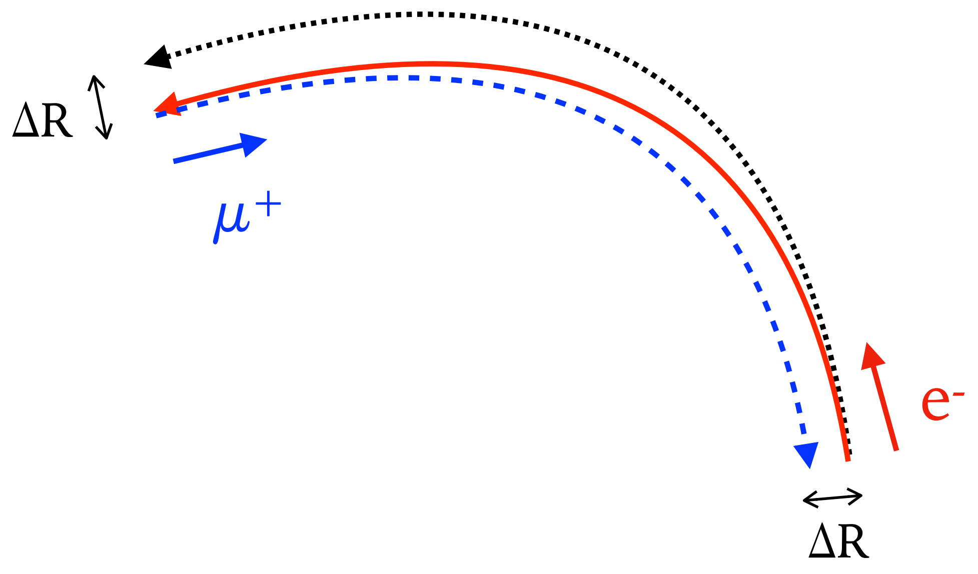
Energy loss is corrected in Kalman Filter

dE ~ 1.5 keV per cell

ΔE ~ 1.5 keV × 50 cells = 75 keV for track turn

$$\Delta R = \frac{\Delta p}{0.3B} = \frac{75\,\mathrm{keV}}{0.3 \times 1\,\mathrm{T}} = 250\,\mu\mathrm{m}$$ (Rough estimation)

(comparable to spatial resolution of 150 μm)



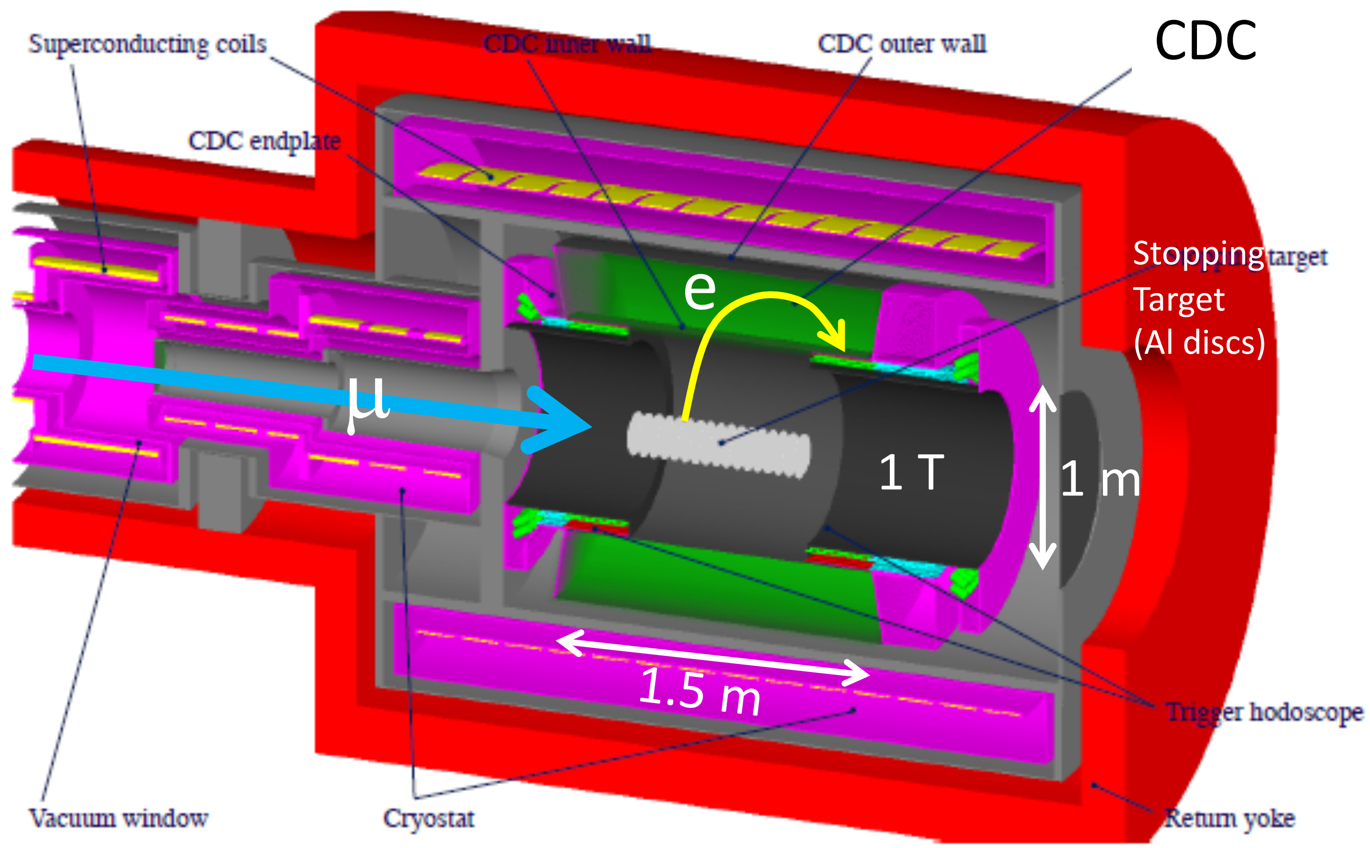
Energy loss correction also makes miscorrection if the track direction is wrong.
→ worsen χ^2 !

COMET CDC

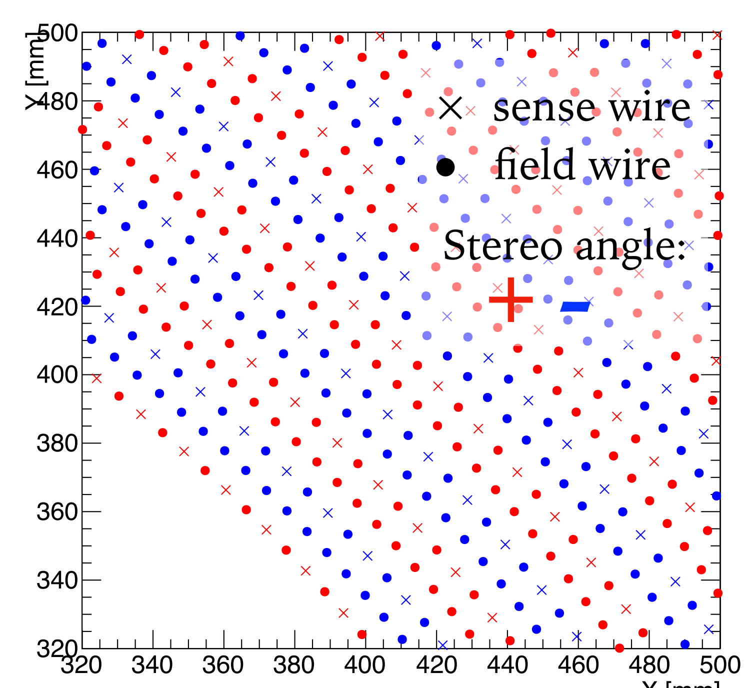
A. Sato et al., NIM A 1069, 169926 (2024)

Design parameters of the CDC.

Inner wall	Material	CFRP, Al
	Length	1495.5 mm
	Radius	495.95–496.5 mm
	Thickness	CFRP: 0.5 mm, Al: 0.05 mm
Outer wall	Material	CFRP, Al
	Length	1577.3 mm
	Radius	829.9–835.0 mm
	Thickness	CFRP: 5.0 mm, Al: 0.1 mm
Number of sense layers		20 (including 2 guard layers)
Sense wire	Material	Au-plated W
	Diameter	25 μm
	Number of wires	4986
	Tension	50 g
	Stereo angle	±(64–75) mrad
Field wire	Material	Al alloy (A5056)
	Diameter	126 μm
	Number of wires	14 562
	Tension	80 g
	Stereo angle	±(64–75) mrad
Gas	Mixture	He:i-C_4H_{10} (90:10)
	Volume	2084 L



Z=0



20 layers in total

Features

- Low mass gas = He:iC4H10 (90:10) 👈 p resolution
- Alternative all stereo wire, ±4 deg 👈 z resolution
- Large inner bore, ϕ 1 m @ 1 T 👈 suppress DIO hits

Track Fitting using GENFIT

We implemented GENFIT into the COMET software framework (ICEDUST).

GENFIT

- Generic Track Fitting Framework
- Experiment-independent, modular packages
- Open source C++ code
- Originally developed in PandaROOT at TUM
- Widely used in many experiments, e.g. Belle-II, SHiP, FOPI etc.
- Suitable for low-energy experiments
- Fitter Options:
  - Kalman Filter, Deterministic Annealing Filter etc.

GenFit in GitHub

Hoppner et al. NIM A 620, 518 (2010)

Bilka et al., arXiv:1902.04405

Works well !!