Evaluation of CDC using Cosmic Ray for COMET Phase-I Experiment

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ICEPP Symposium @Hakuba

Osaka University

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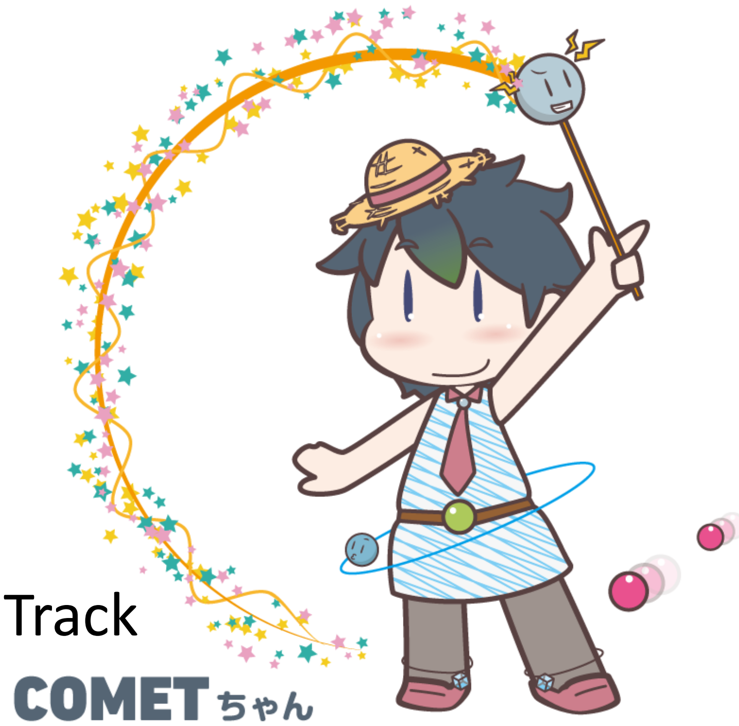
Outline

1. Introduction
   - COMET Experiment Phase-I
   - COMET CDC

2. Cosmic Ray Test for COMET CDC
   - SETUP for Cosmic Ray Test
   - Contents of My Research

3. Data Analysis
   - Spatial Resolution
   - Dependence of Incident Angle of Track
   - Dependence of Shape of Cell

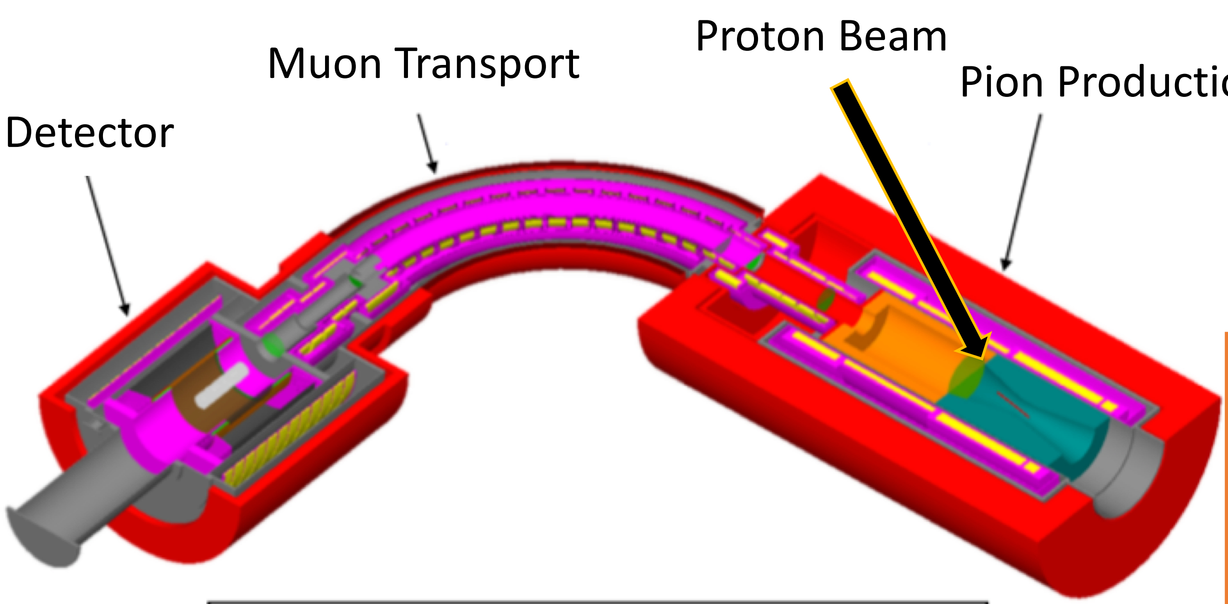
4. Summary



COMET Experiment (Phase-I)

- The COMET Phase-I experiment is seeking the transition of a muon to an electron, which is one of the Charged Lepton Flavor Violation (CLFV) processes.
  CLFV is strongly prohibited in the SM → BR $\mathcal{O}(\sim10^{-54})$
  Beyond the SM → BR $\mathcal{O}(10^{-14}\sim10^{-17})$ ⇒ Discovery of New Physics
- The COMET Phase-I is aiming at a single event sensitivity of $\underline{3.1\times10^{-15}}$
  (about 100 times higher than the previous experiment)

SINDRUM Ⅱ @ PSI
$\mathrm{BR}\,(\mu^{-}\mathrm{Au}\rightarrow e^{-}\mathrm{Au})$
$<\ 7\times10^{-13}$ 90% C.L.



COMET Phase-I Layout

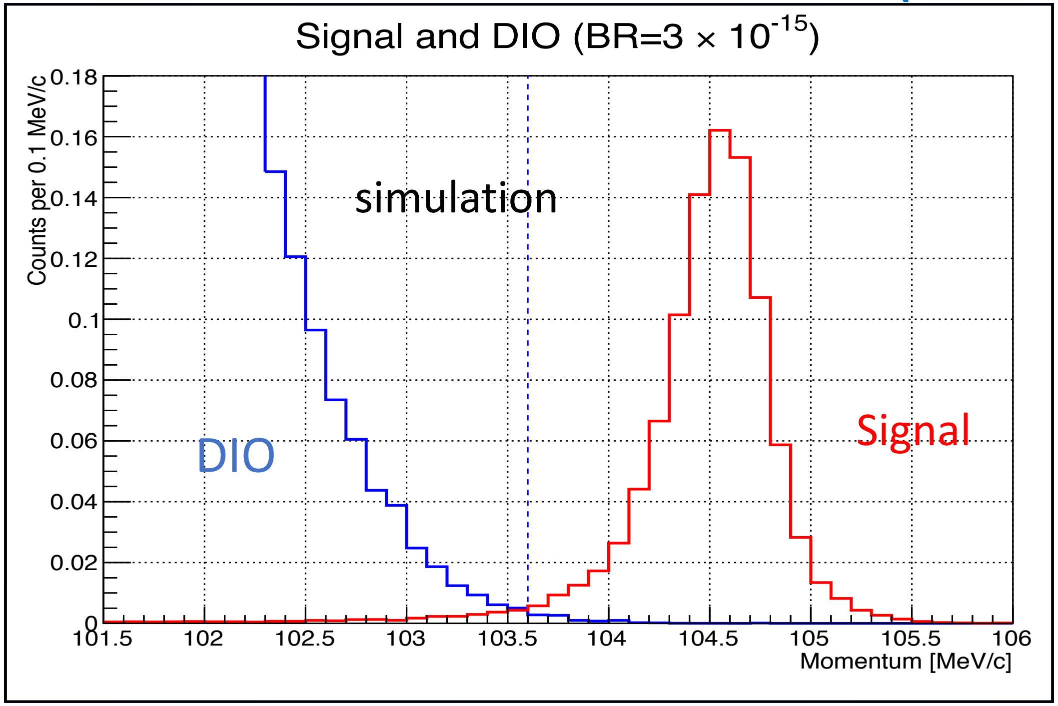
The main detector for the COMET Phase-I is the Cylindrical Drift Chamber (called CDC)

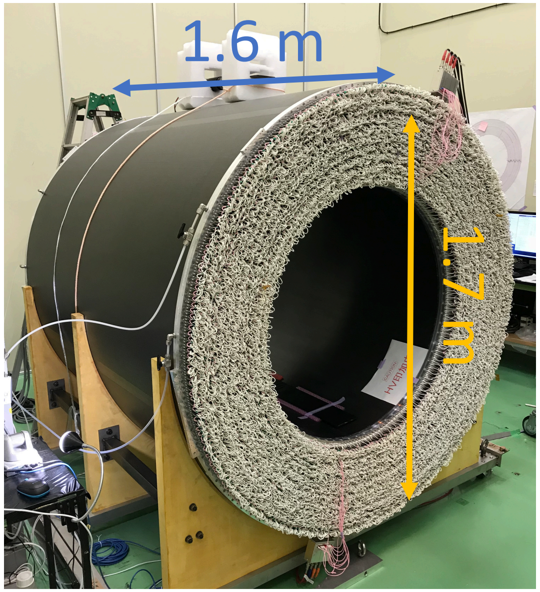
CDC (Cylindrical Drift Chamber)

- CDC is the main detector searching for the μe conversion.

$\mu\, e$ conversion : $\mu^- + \mathrm{Al} \rightarrow \mathrm{e}^-(105\mathrm{MeV/c}) + \mathrm{Al}$

Background (DIO) : $\mu^- + \mathrm{Al} \rightarrow \mathrm{e}^- + \bar{\nu}_\mathrm{e} + \nu_\mu + \mathrm{Al}$





COMET CDC

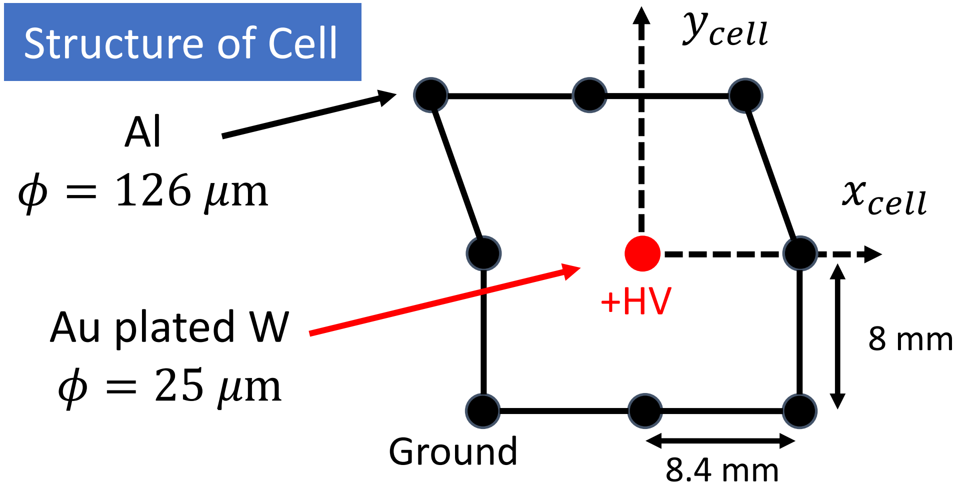
Reconstructed signal of μe conversion by CDC and background signal （simulation）

Requirements of CDC

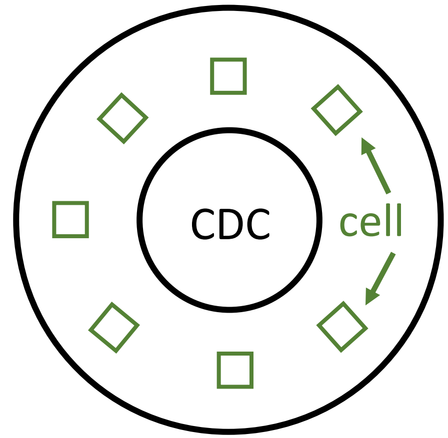
- Momentum resolution must be less than 200 keV/c (for 105 MeV/c electrons)
- Spatial Resolution must be less than 250 μm (in the 1 T magnetic field)

Status of COMET CDC

Structure of Cell



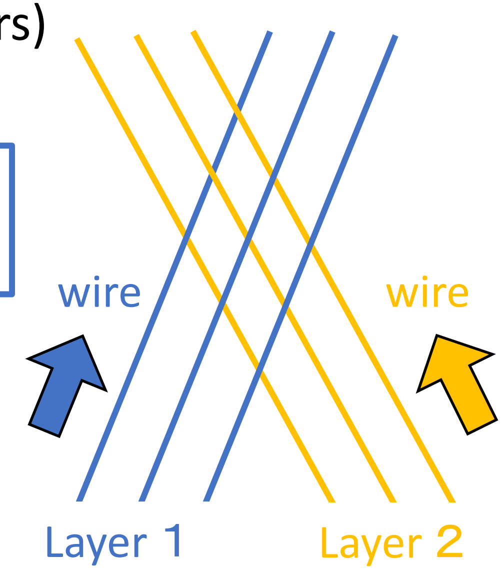
Cells are located on CDC concentrically



Structure of Layer

- CDC is arranged in 20 sense layers (including 2 guard layers) with alternating positive and negative stereo angles.

Alternatively



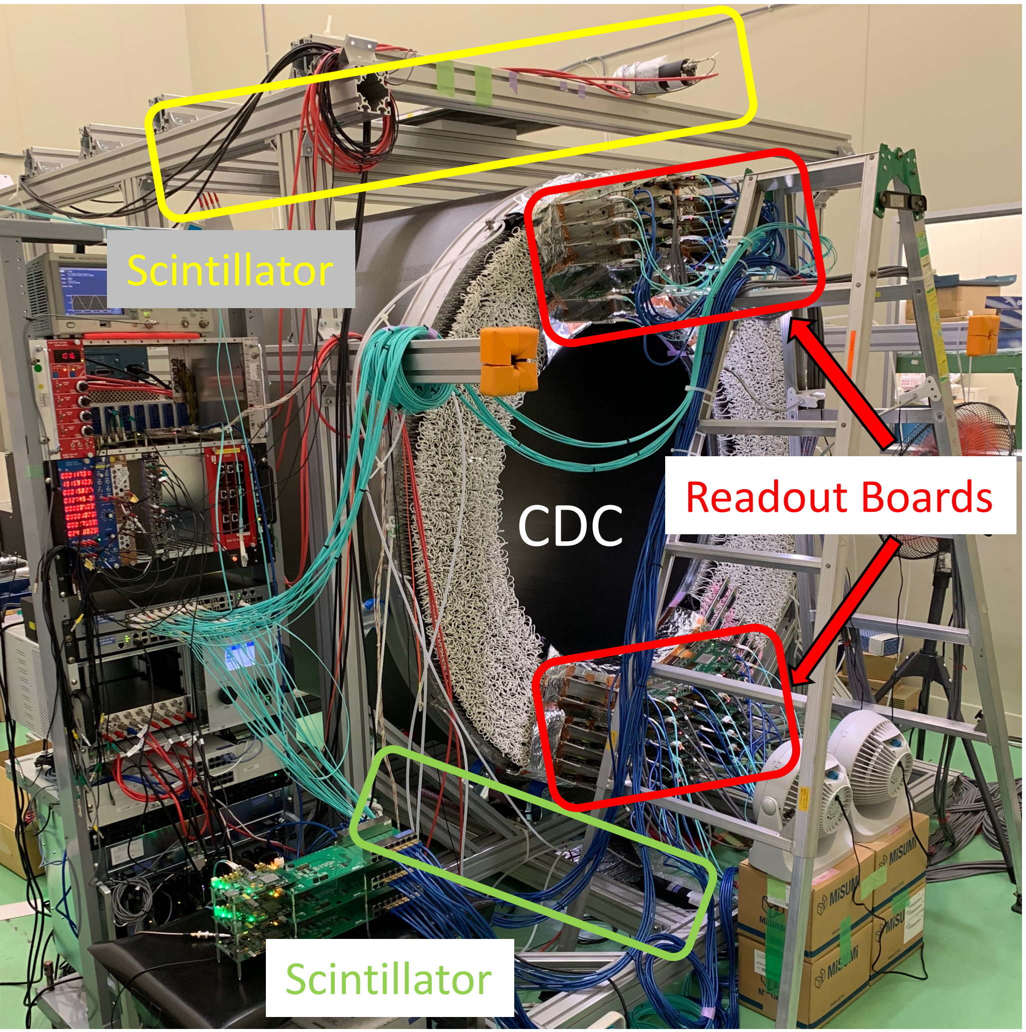
Stereo angles
65∼74 [mrad]

Gas & Magnetic Filed

Gas	Magnetic Field
$\mathrm{He}: \mathrm{i-C_4H_{10}} = 90:10$	1 T

SETUP for Cosmic Ray Test

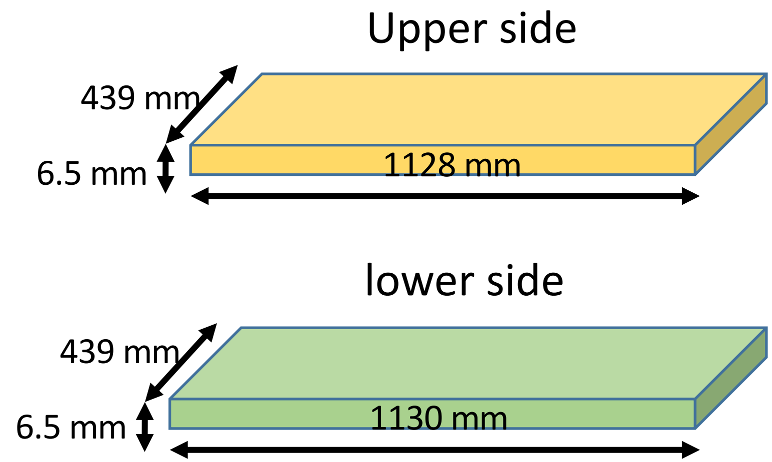
- The Cosmic Ray Test for the CDC is ongoing in KEK at Tsukuba campus.
- In this JFY, the readout area was extended from about 6 % to 35 %.



Condition

- **Applied HV** : 1825 V
- **Gas Ratio** : $\mathrm{He : i-C_4\,H_{10}} = 90:10$
- **Readout area** : about 35 %
- **Trigger** : Coincidence of 2 Scintillators
- **Trigger Rate** : about 4.5 Hz
- **Magnetic Field** : not Applied

Scintillator



My research in Cosmic Ray Test

Research Contents ･･･ Mainly evaluated 4 items.

Relation between Drift Distance and Drift Time
- Layer Dependence
- Effect of Track Incident Angle toward Cells
- Effect of Shape of Cells

Hit Efficiency
- Layer Dependence
- Drift Distance Dependence
- Difference due to Hit Condition

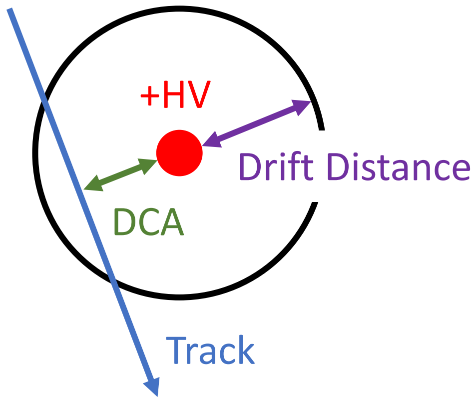
Spatial Resolution
- Layer Dependence
- Drift Distance Dependence
- Effect of Track Incident Angle toward Cells
- Effect of Shape of Cells

Alignment of CDC
- Alignment for x, z Directions
- Alignment for Incident Angle ϕ, λ
- Relation between x, z, ϕ, λ

Today I would like to talk about these items.

How to evaluate Spatial Resolution

Define the Residual which is the gap between the “Reconstructed Track” and the “Drift Distance”.

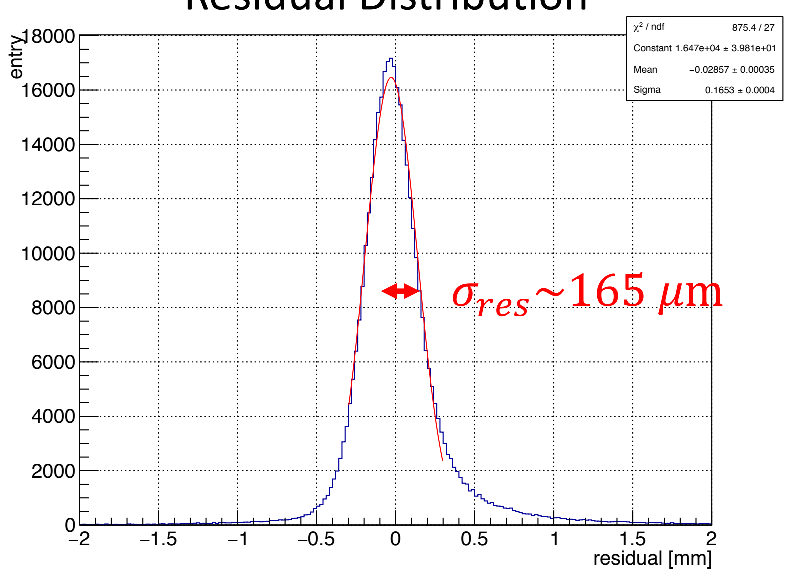


Residual = Drift Distance − DCA

(DCA : Distance of Closest Approach)

Fit the Residual Distribution with the Gauusian.

Residual Distribution



The Intrinsic Spatial Resolution σ_{intr} corresponds to the deviation σ_{res} of the fit of residual distribution.

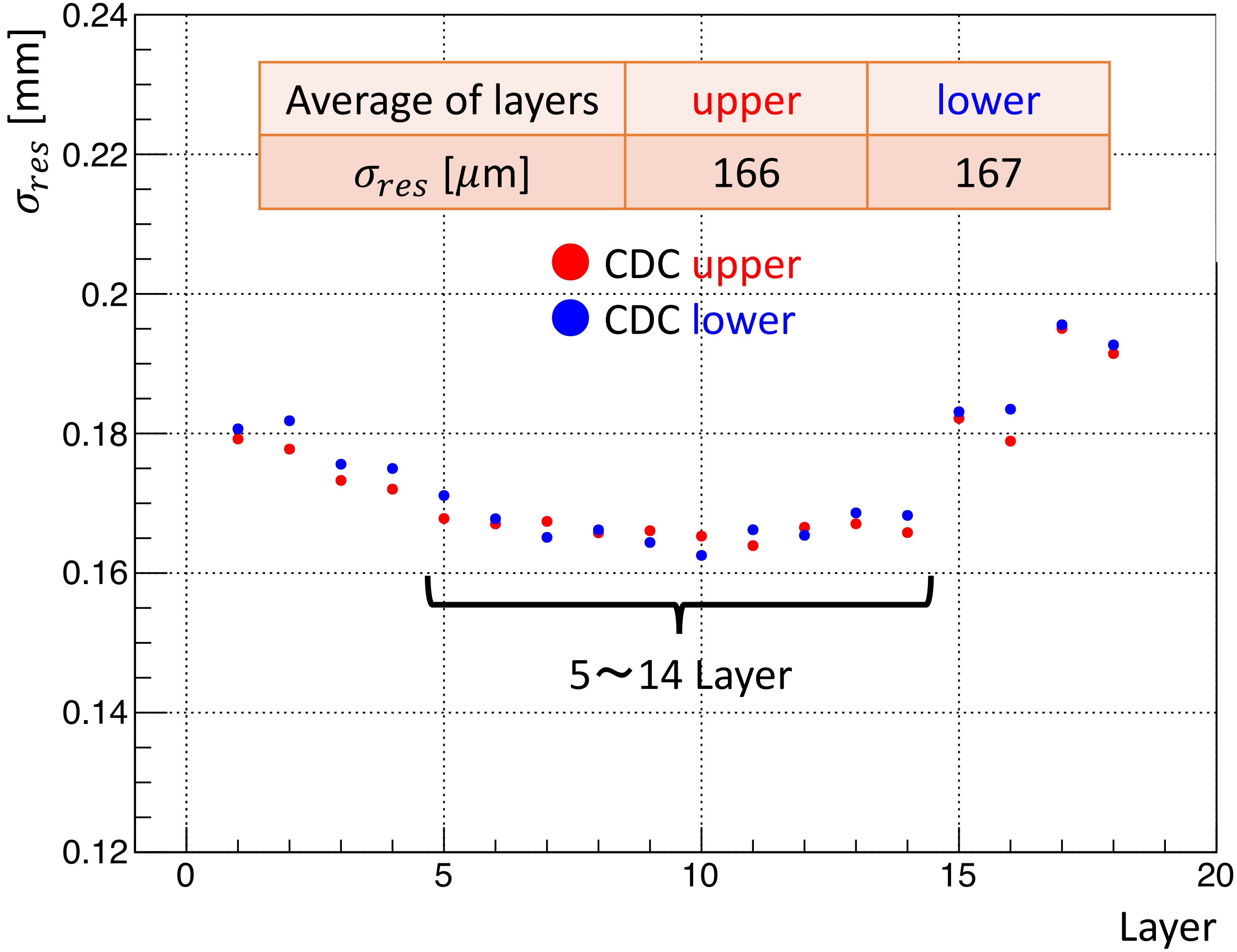
$$\boldsymbol{\sigma_{res} = \sqrt{\sigma_{intr}^2 + \sigma_{track}^2}}$$

σ_{intr} : Intrinsic Spatial Resolution

σ_{track} : Tracking Error

Layer Dependence of Spatial Resolution

- Evaluate the Spatial Resolution of the CDC on the upper side and the lower side.
- Outer Layers of the CDC have large tracking error due to the geometrical reason.
- Estimate the upper limit of the Intrinsic Spatial Resolution by taking average of inner layers.



Average of layers	upper	lower
σ_{res} [μm]	166	167

Spatial Resolution and Tracking Error

- Intrinsic Spatial Resolution → Upper limit of **167 μm** without the magnetic field.
- Tracking Error → about 40 μm according to the simulation (among inner layers).

$$\sigma_{res} = \sqrt{\sigma_{intr}^2 + \sigma_{track}^2}$$

From this eq, Intrinsic Spatial Resolution is about **162 μm.**

Previous Study using Prototype of the CDC

Gas mixture: $He-iC_4H_{10}(90/10)$				
B-field [T]	HV [kV]	ε [%]	σ_{total} [μm]	σ_{intr} [μm]
0	1.85	93	216 ± 9	185 ± 10
0	1.9	94	249 ± 9	218 ± 10
1	1.85	95	286 ± 12	254 ± 13
1	1.9	94	317 ± 19	284 ± 20

In the mostly same condition, Intrinsic Resolution was 185 μm.

This prototype has already evaluated that it is satisfied with the requirements of COMET Phase-I.

The Intrinsic Spatial Resolution is 162 μm.
-> Confirmed the CDC can be satisfied the requirement.

Effect of Incident Angle and Shape of Cell

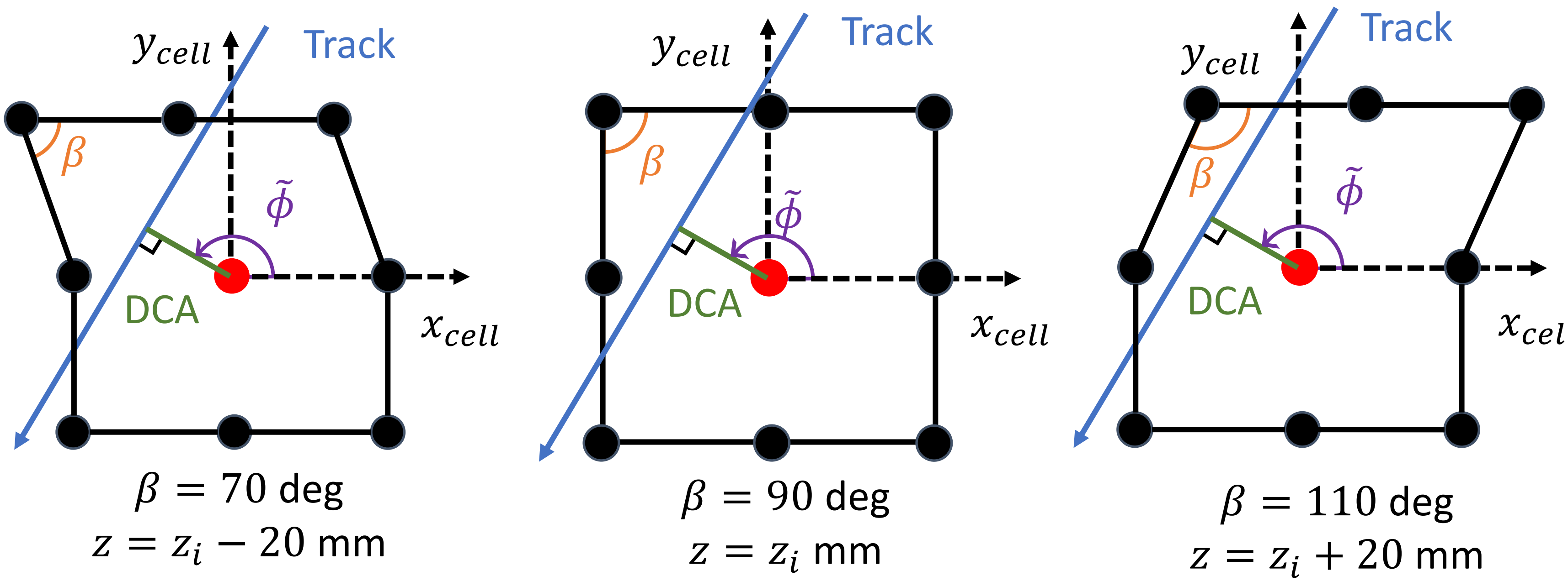
- The shape of a cell is gradually changing along to the z (beam) direction of the CDC.
- The behavior of drifted electrons differ in terms of the shape of the cell.

Therefore…

$\tilde{\phi}$: Incident angle toward the cell
β : Angle characterizing the shape of the cell

Define these two angles and

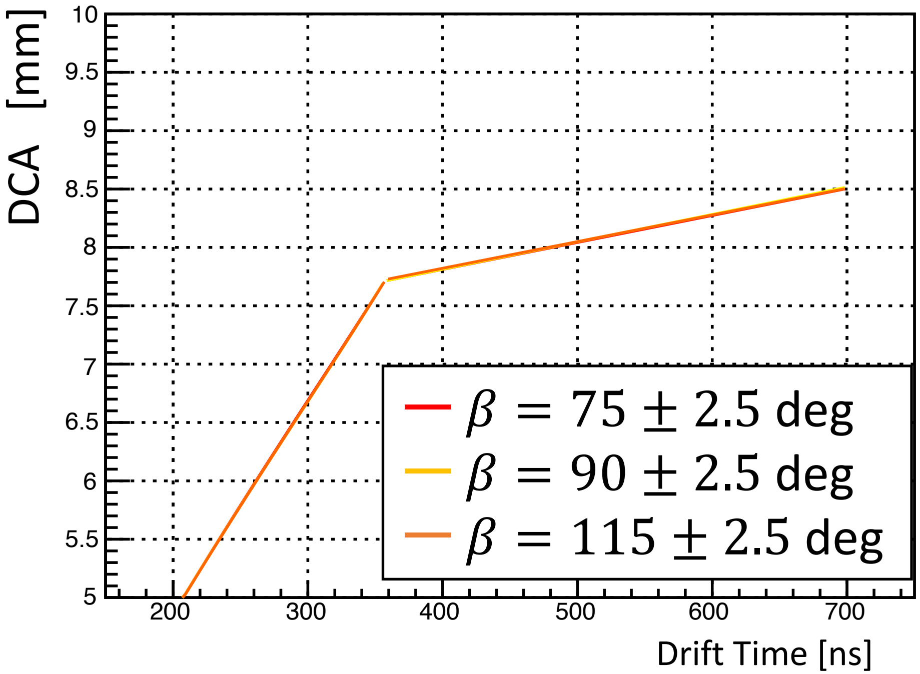
- Search for "the Relation between Drift Distance and Drift Time"
- Aim to improve the accuracy of tracking.



Relation between Drift Distance and Drift Time

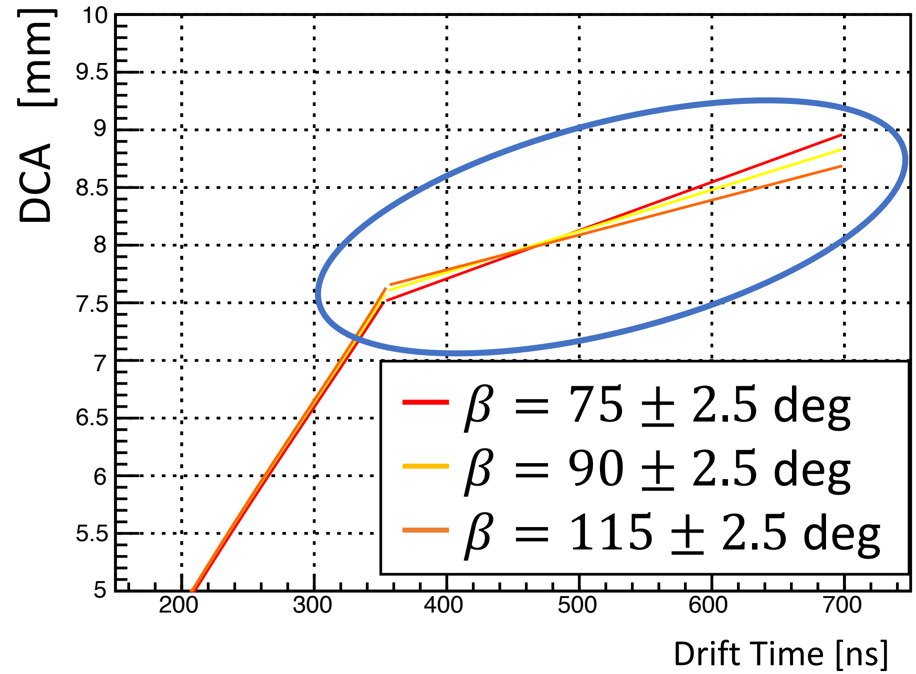
- Check the differences of "the relation between Drift Distance and Drift Time".

$\tilde{\phi}$: -5 ~ 5 [deg] (straight track)



No β dependence
Behavior of drifted electrons is almost same

$\tilde{\phi}$: 5 ~ 15 [deg] (leaning track)



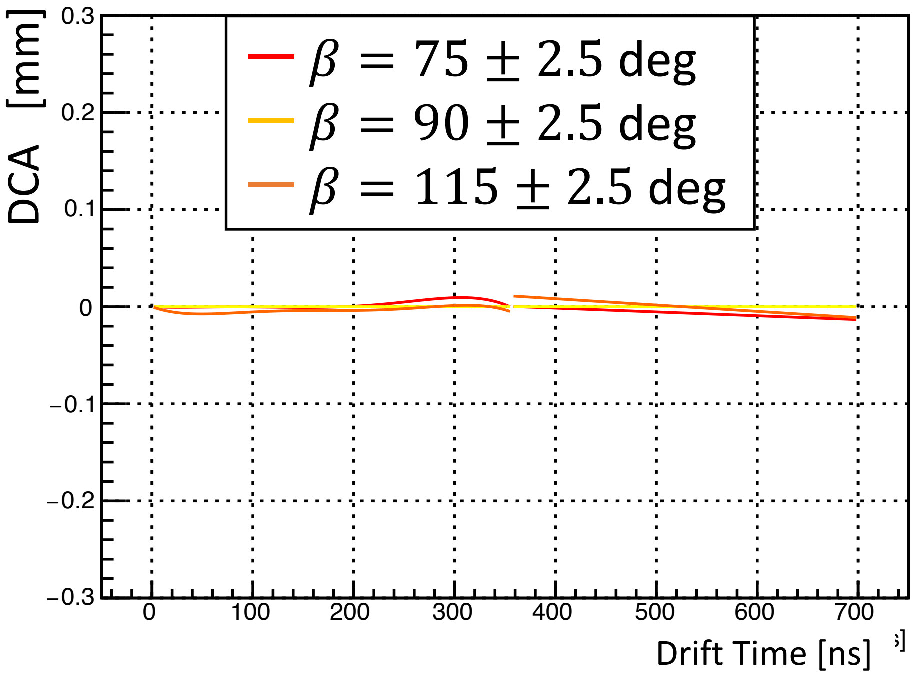
β dependence was found
Behavior of drifted electrons differ

- If the track has large incident angle, the effect of the cell will appear.
- This is because of the distortion of the electric field in the cell.

Relation between Drift Distance and Drift Time

- Check the differences of “the relation between Drift Distance and Drift Time”.

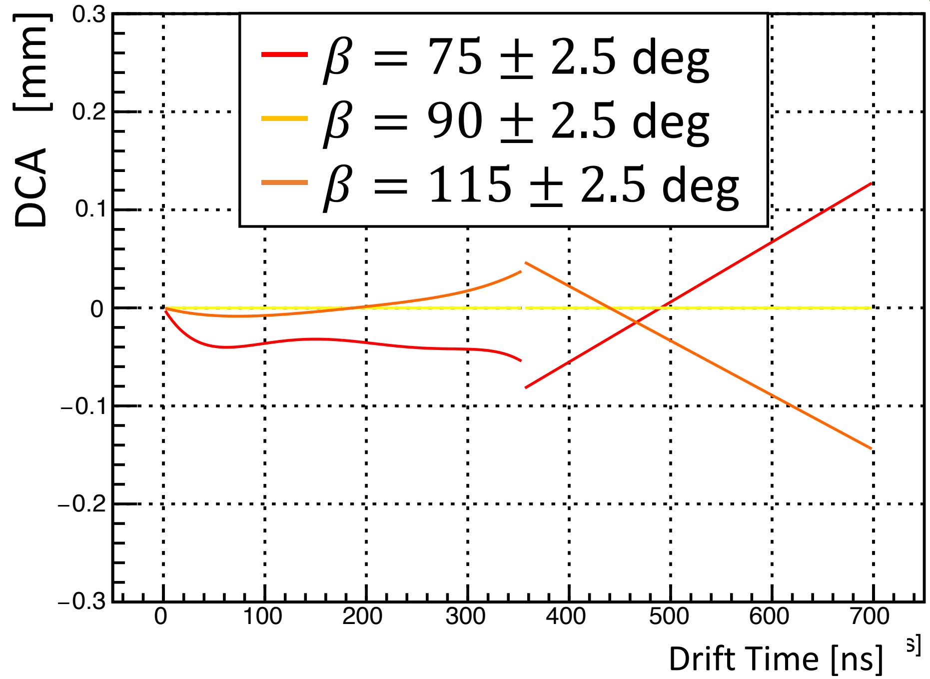
$\tilde{\phi}$: -5 ~ 5 [deg] (straight track)



No β dependence

Behavior of drifted electrons is almost same

$\tilde{\phi}$: 5 ~ 15 [deg] (leaning track)



β dependence was found

Behavior of drifted electrons differ

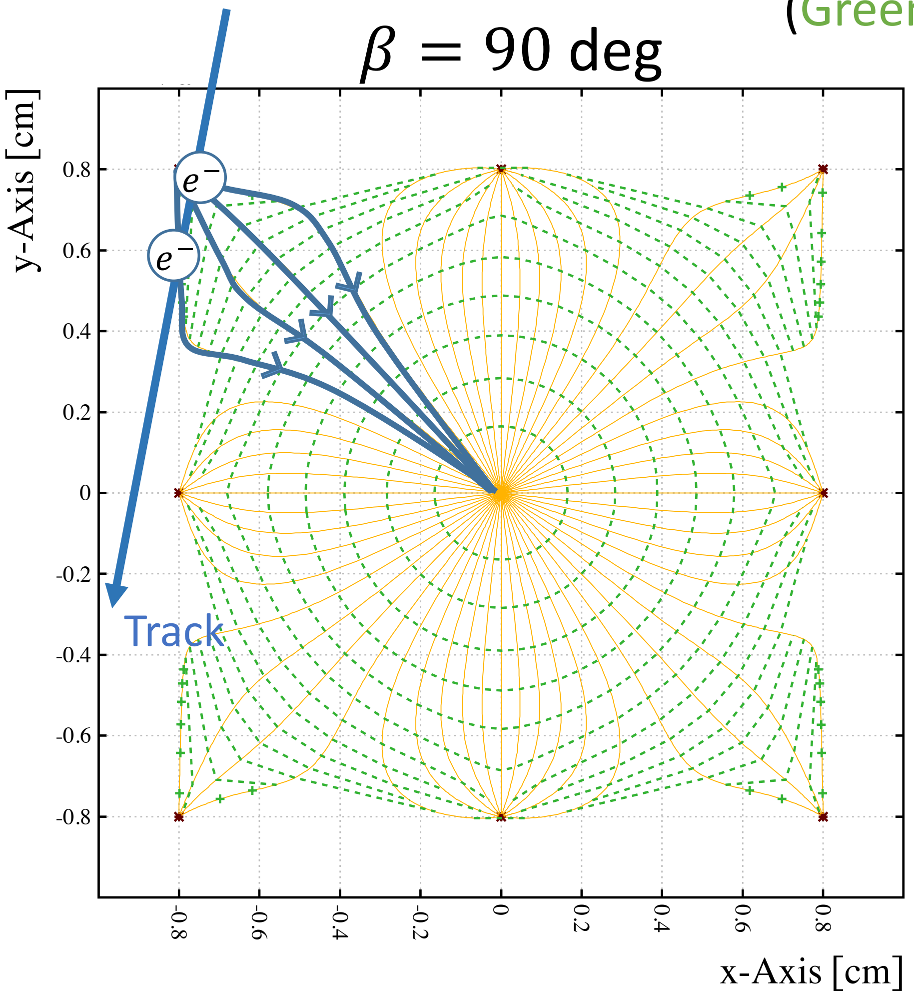
- If the track has large incident angle, the effect of the cell will appear.
- This is because of the distortion of the electric field in the cell.

Electric Filed in Cell and Drift Pass of Electrons

- The distribution of the electric field in the cell and the pass of drifted electrons.

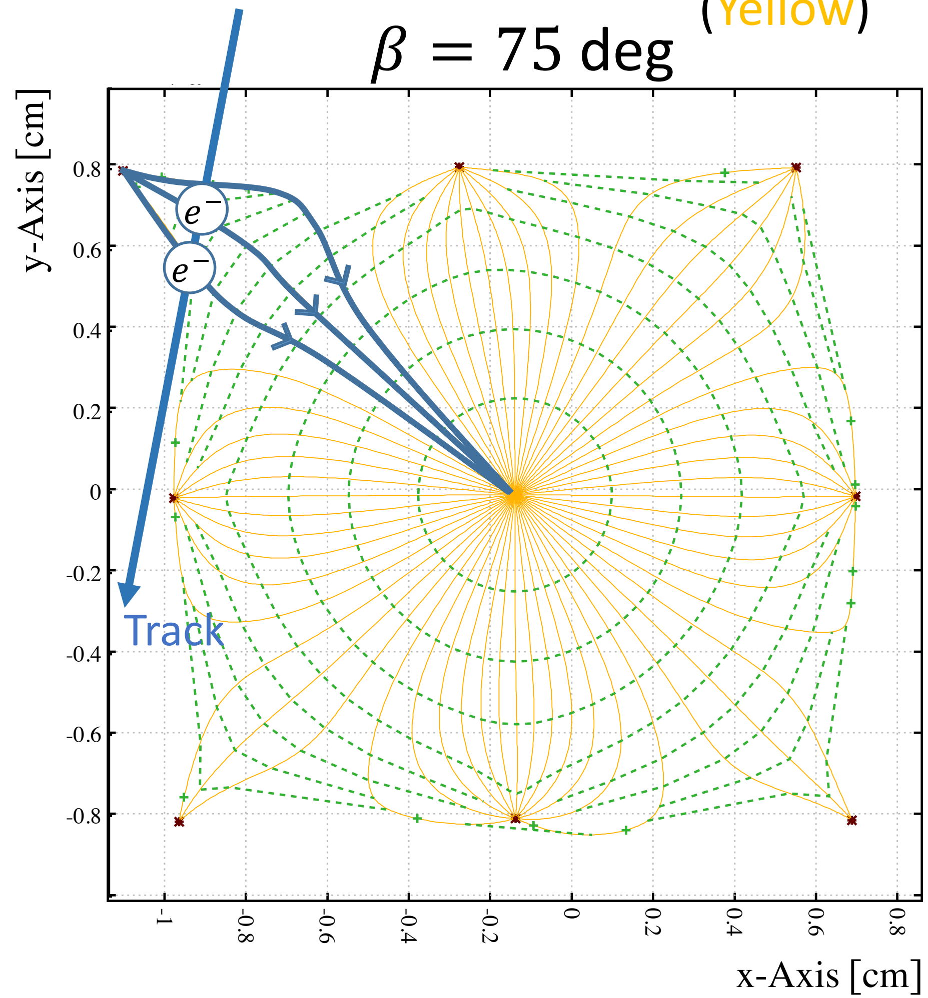
(Green) (Yellow)

$\beta = 90$ deg



Drifted electrons go around → Pass would be long

$\beta = 75$ deg

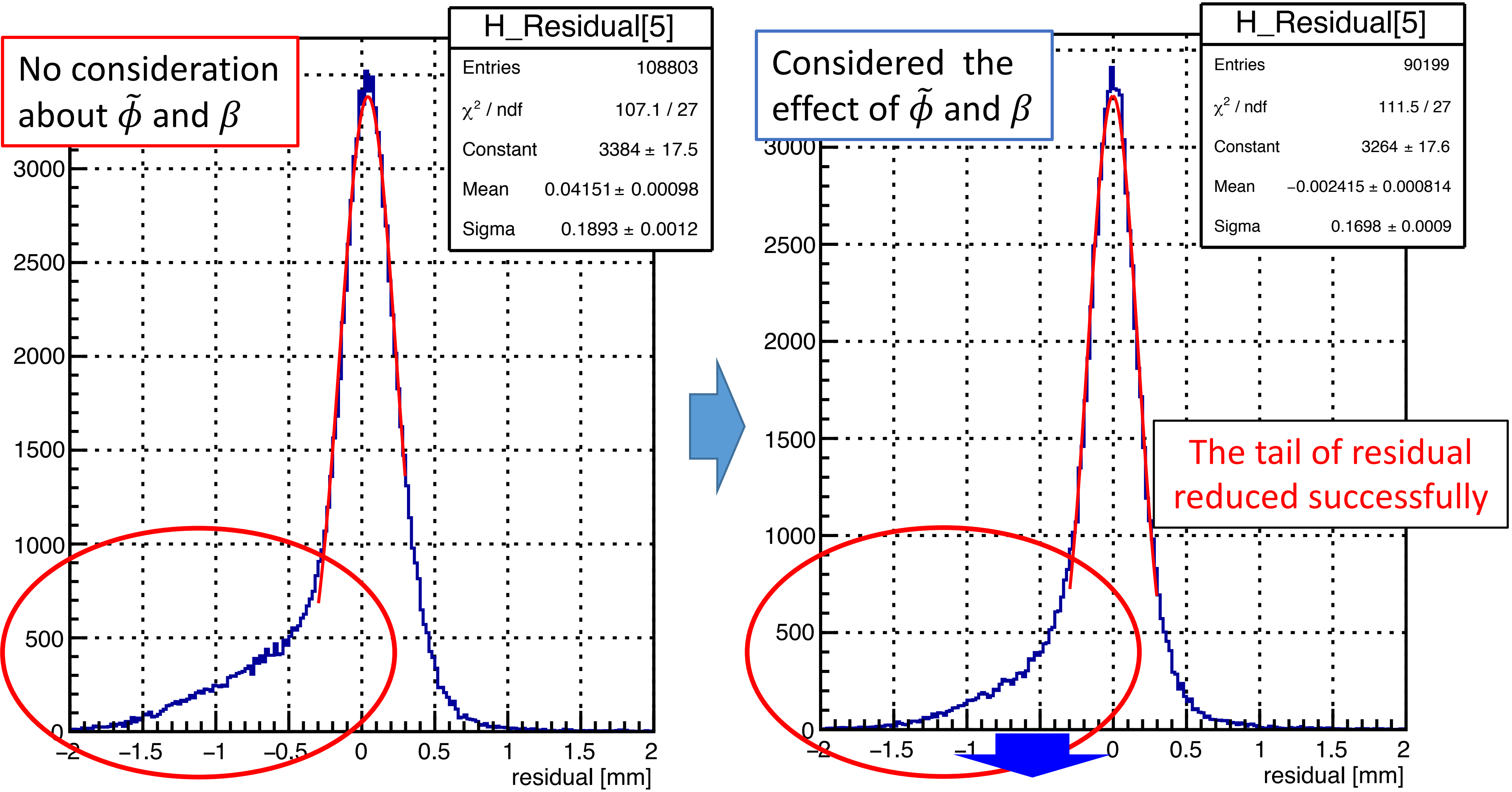


Tend to be drifted straight

Tracking considering Incident Angle and Cell

- Use "Relation between Drift Distance and Drift Time" considering angle $\tilde{\phi}$ and β -> **Do new way of Tracking**
- To compare previous tracking and new one, use the residual distribution.

Example : Residual Distribution $\tilde{\phi}$ 155 ~ 165 [deg] (leaning track) (DCA > 5.0 mm)

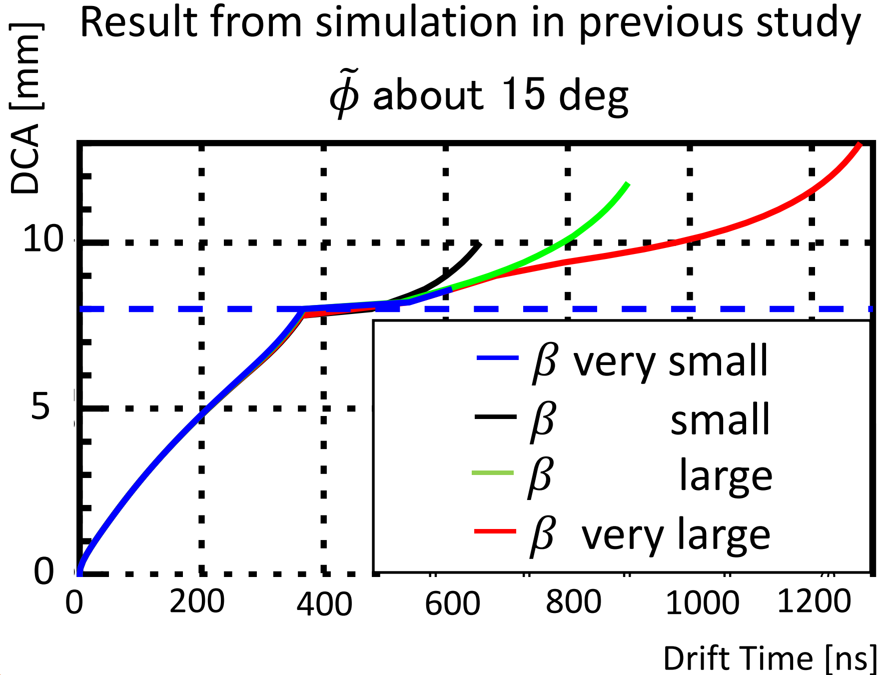


Comparison of Simulation and Real Data

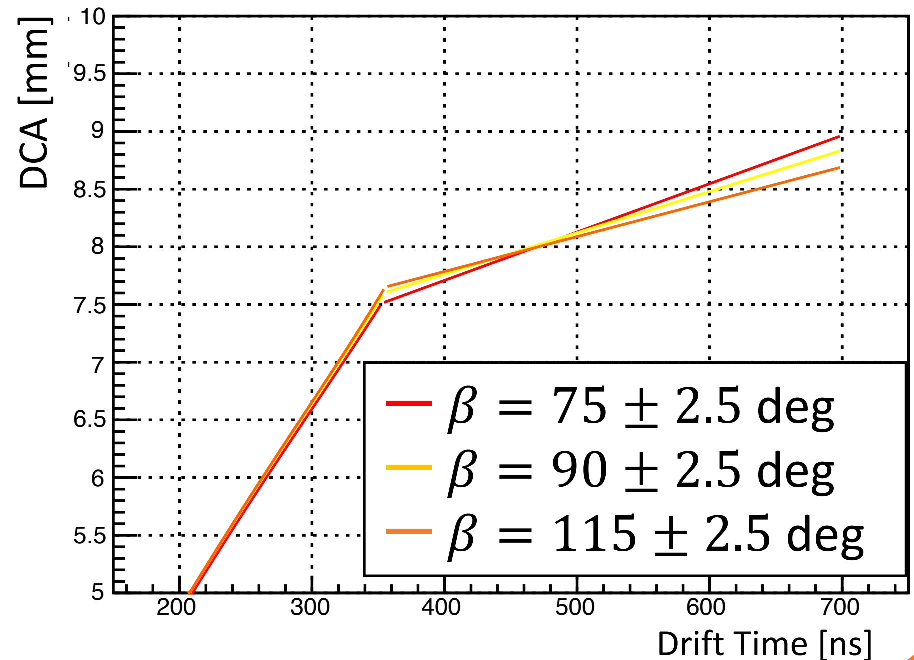
- Compare the simulation with real data about
  "the relation between Drift Distance and Drift Time" with respect to angle $\tilde{\phi}$ and β.

Result from simulation in previous study

$\tilde{\phi}$ about 15 deg



Result from my research $\tilde{\phi} = 10 \pm 5$ deg



Until last year,
β dependence study using real CDC
had not precisely researched yet.

Tendency of result from my research
is consistent with that of simulation.

Summary

1. Introduction
   - the COMET experiment aims to search for the μe conversion process.
   - the Main detector in COMET phase-I is CDC.

2. Cosmic Ray Test
   - The Cosmic Ray Test is ongoing at KEK to evaluate the performance of the CDC.
   - Evaluated Relation between Drift Distance and Drift Time, Spatial Resolution, Hit Efficiency and Alignment.

3. Data Analysis
   - The readout area was extended from about 6 % to 35 %.
   - the intrinsic spatial resolution of the CDC without the magnetic field is 162 μm, and this is satisfied with the requirement.
   - In the relation between Drift Distance and Drift Time, there is the dependence of incident angle $\tilde{\phi}$ of the track toward the cell, and shape of the cell β.
   - I developed the tracking algorithm considering the angle $\tilde{\phi}$ and β, and it successfully reduced the tail of the residual distribution.

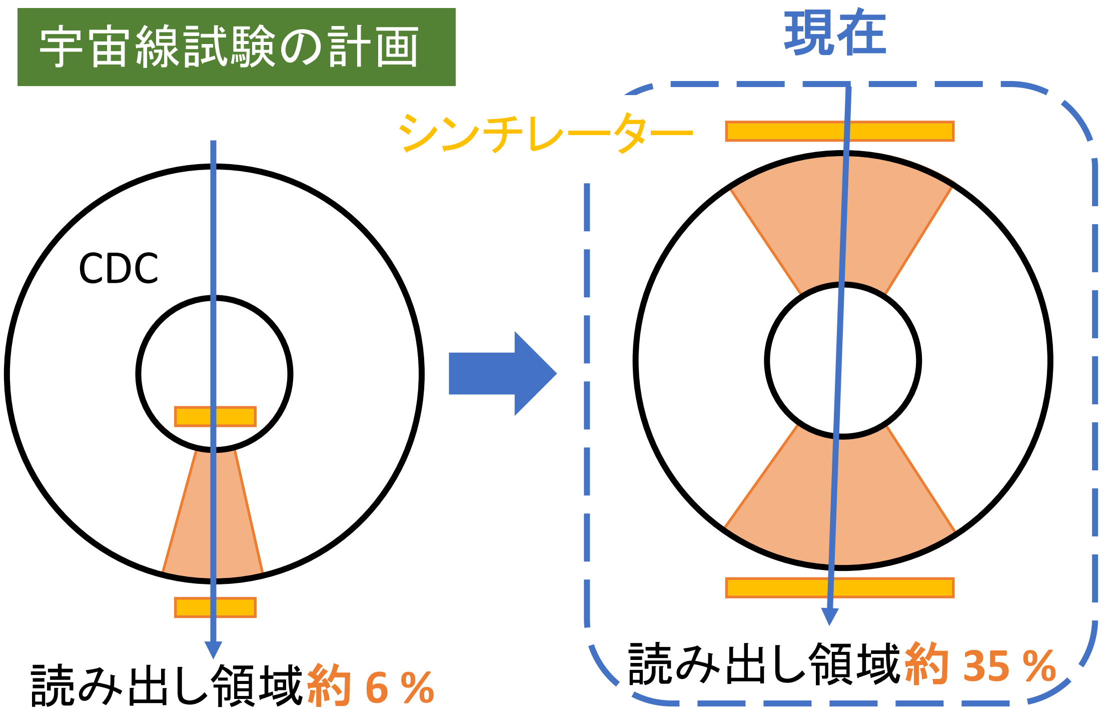
Back Up

宇宙線試験

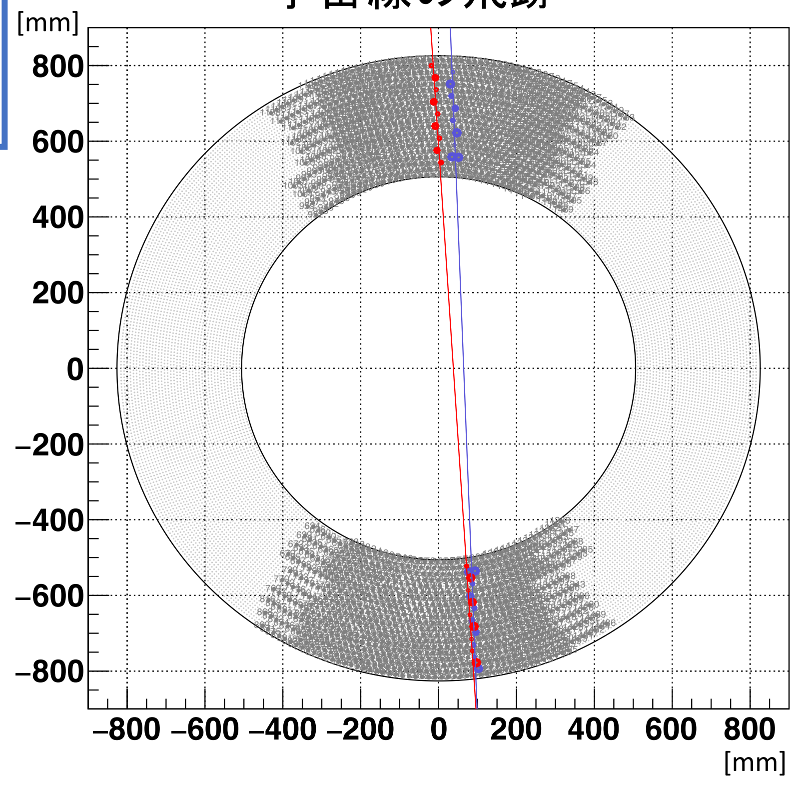
宇宙線試験

- CDC の宇宙線試験は KEK で行われている。
- Phase-I の開始に先立ち、性能の確認を行う。
- セットアップを徐々にアップデートし、
  データの読み出し領域を拡大。
  -> 詳細な性能評価試験を行っていく。

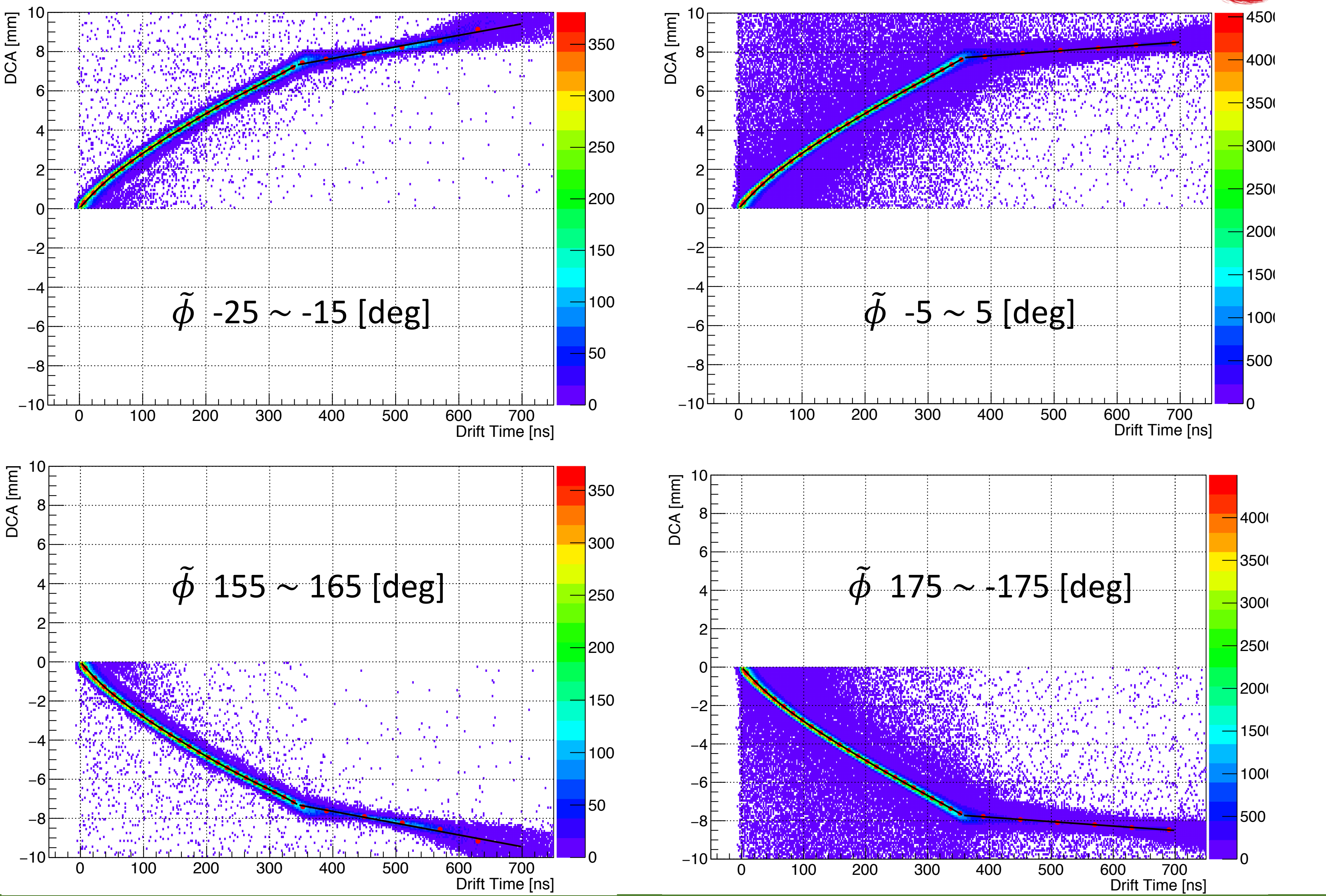
宇宙線試験の計画



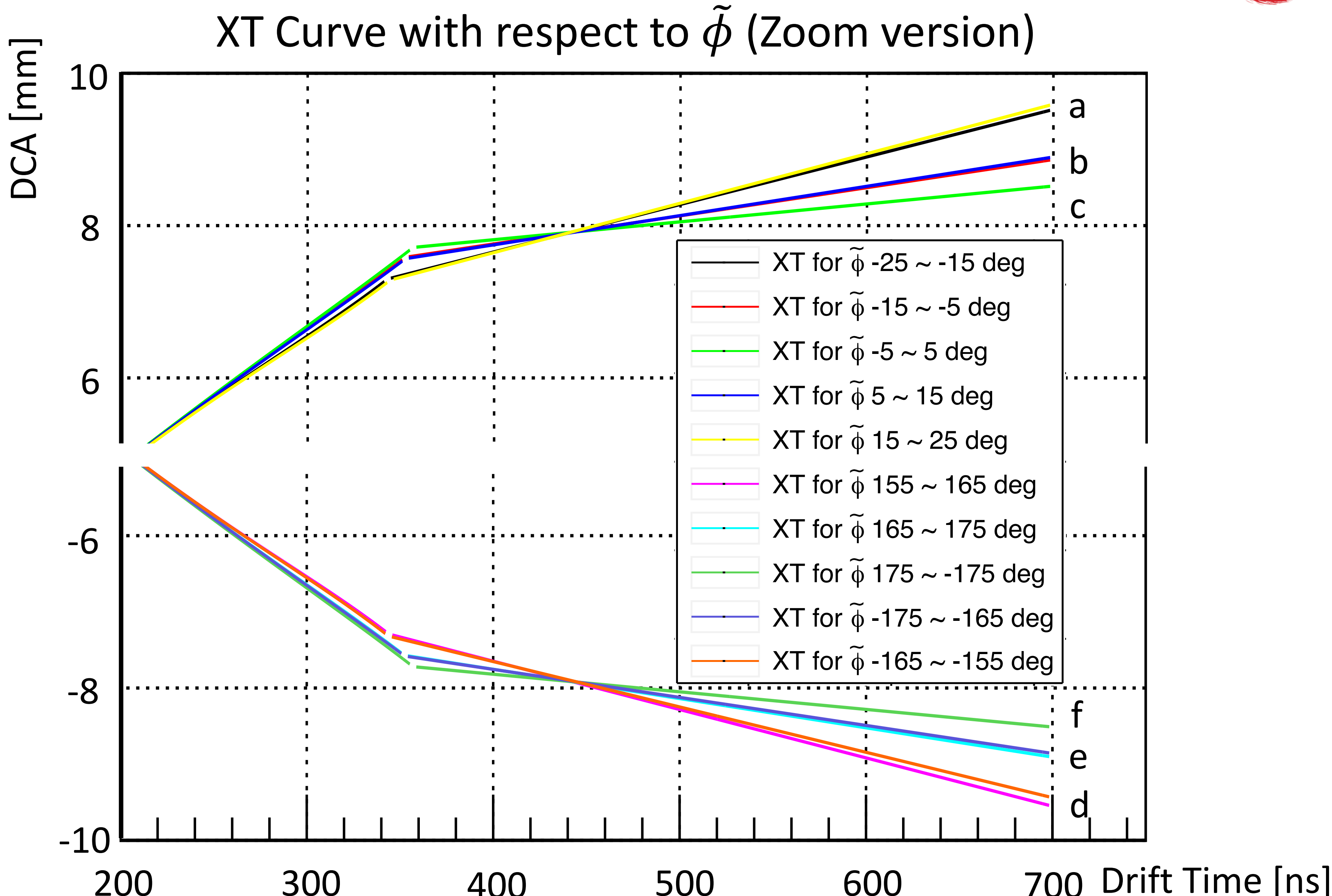
CDC で再構成した
宇宙線の飛跡

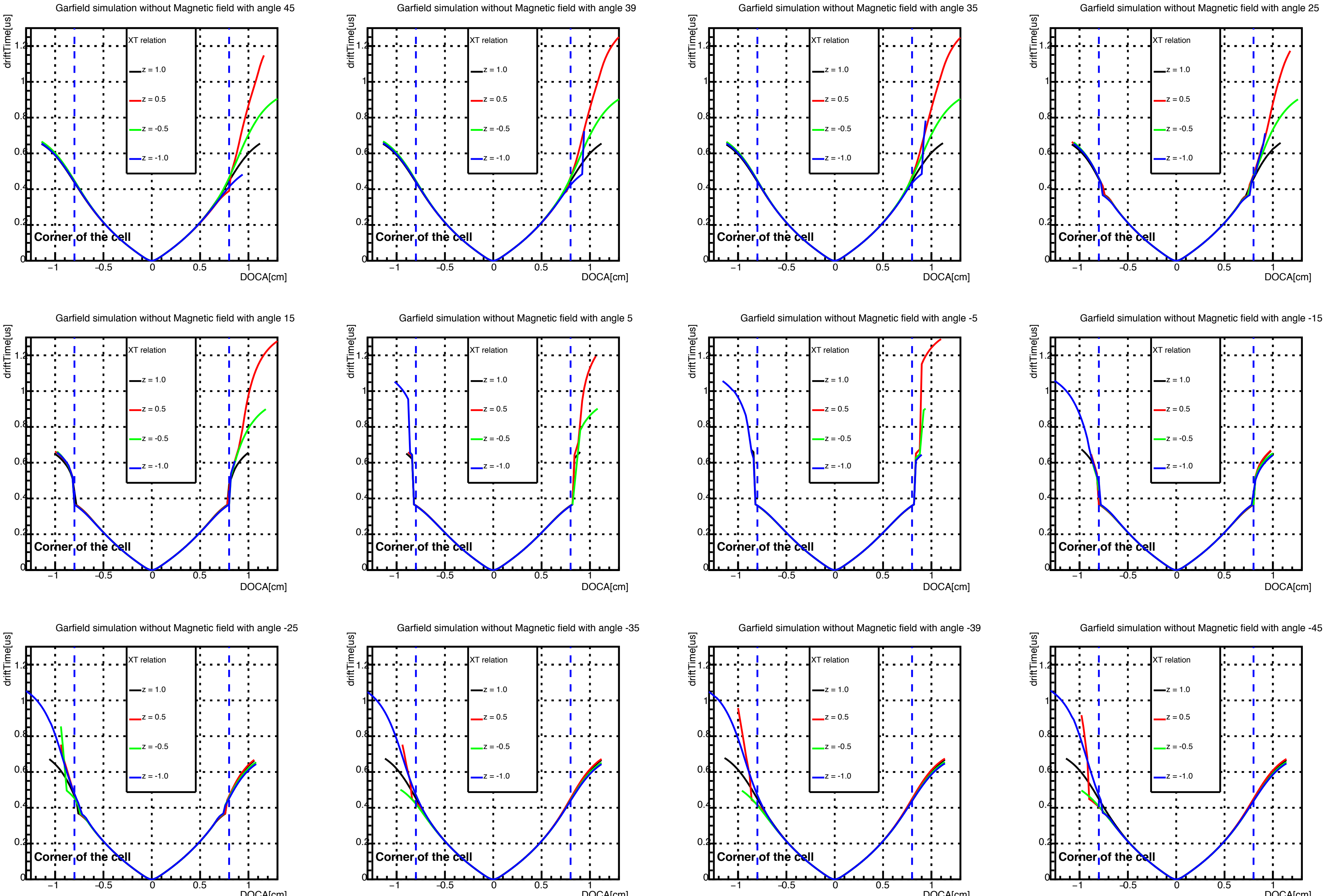


XT Curve with each incident angle $\tilde{\phi}$



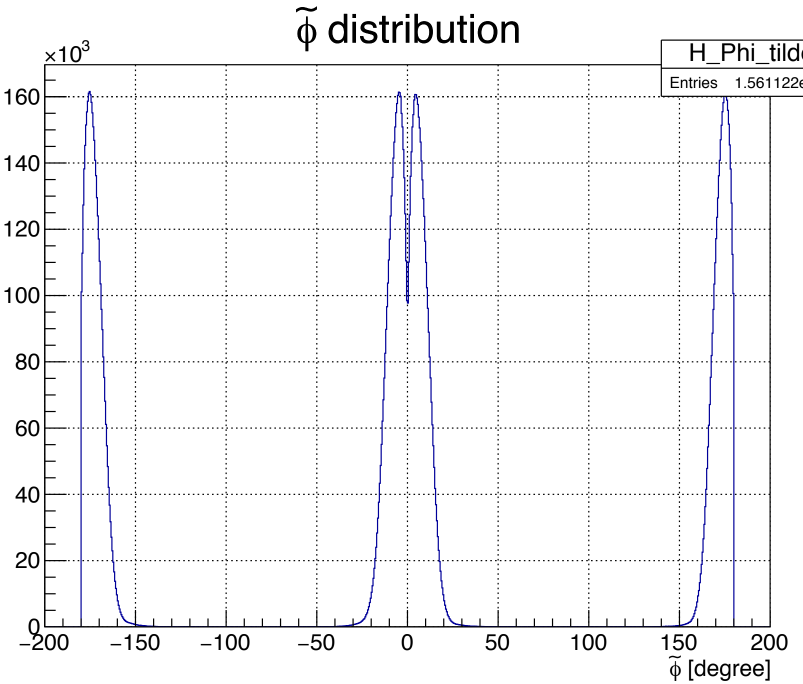
XT Curve with each incident angle $\tilde{\phi}$

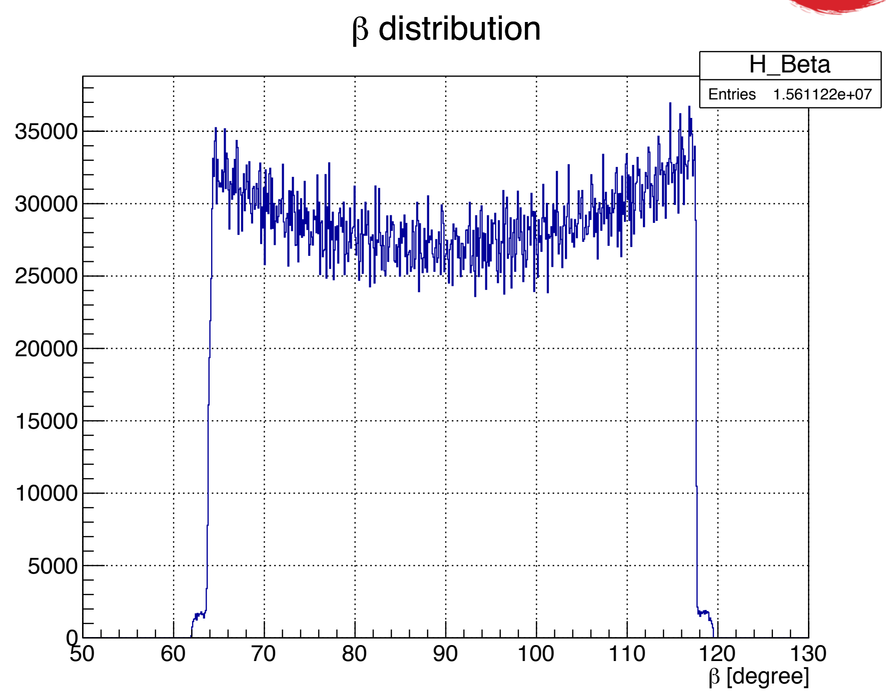




Garfield simulation without Magnetic field with angle 45
Garfield simulation without Magnetic field with angle 39
Garfield simulation without Magnetic field with angle 35
Garfield simulation without Magnetic field with angle 25
Garfield simulation without Magnetic field with angle 15
Garfield simulation without Magnetic field with angle 5
Garfield simulation without Magnetic field with angle -5
Garfield simulation without Magnetic field with angle -15
Garfield simulation without Magnetic field with angle -25
Garfield simulation without Magnetic field with angle -35
Garfield simulation without Magnetic field with angle -39
Garfield simulation without Magnetic field with angle -45
driftTime[us]
DOCA[cm]
XT relation
z = 1.0
z = 0.5
z = -0.5
z = -1.0
Corner of the cell

角度 $\tilde{\phi}$, β の分布





- これらの分布を参考に角度 $\tilde{\phi}$ と β を 10 分割した。

$\tilde{\phi}$: 分割範囲(10度毎)　[degree]

1 : -25 ~ -15
2 : -15 ~ -5
3 : -5 ~ 5
4 : 5 ~ 15
5 : 15 ~ 25
6 : 155 ~ 165
7 : 165 ~ 175
8 : 175 ~ 180, -180 ~ -175
9 : -175 ~ -165
10 : -165 ~ -155

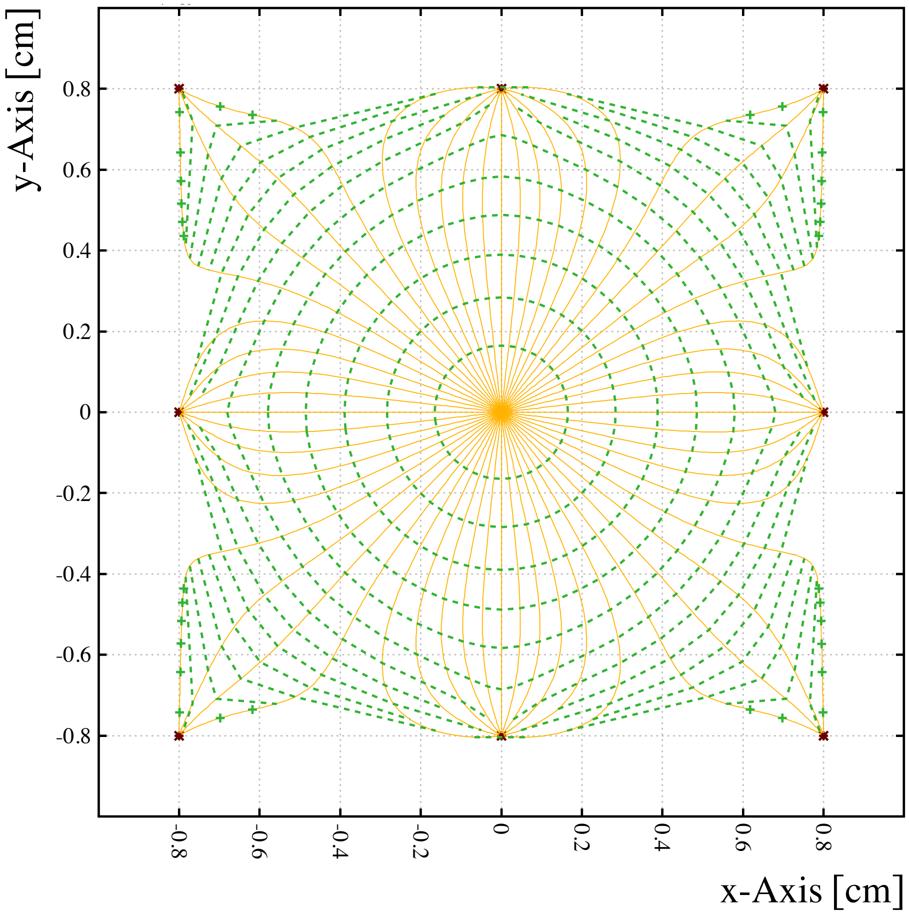
β : 分割範囲(5度毎)　[degree]

1 : 67.5 ~ 72.5
2 : 72.5 ~ 77.5
3 : 77.5 ~ 82.5
4 : 82.5 ~ 87.5
5 : 87.5 ~ 92.5
6 : 92.5 ~ 97.5
7 : 97.5 ~ 102.5
8 : 102.5 ~ 107.5
9 : 107.5 ~ 112.5
10 : 112.5 ~ 117.5

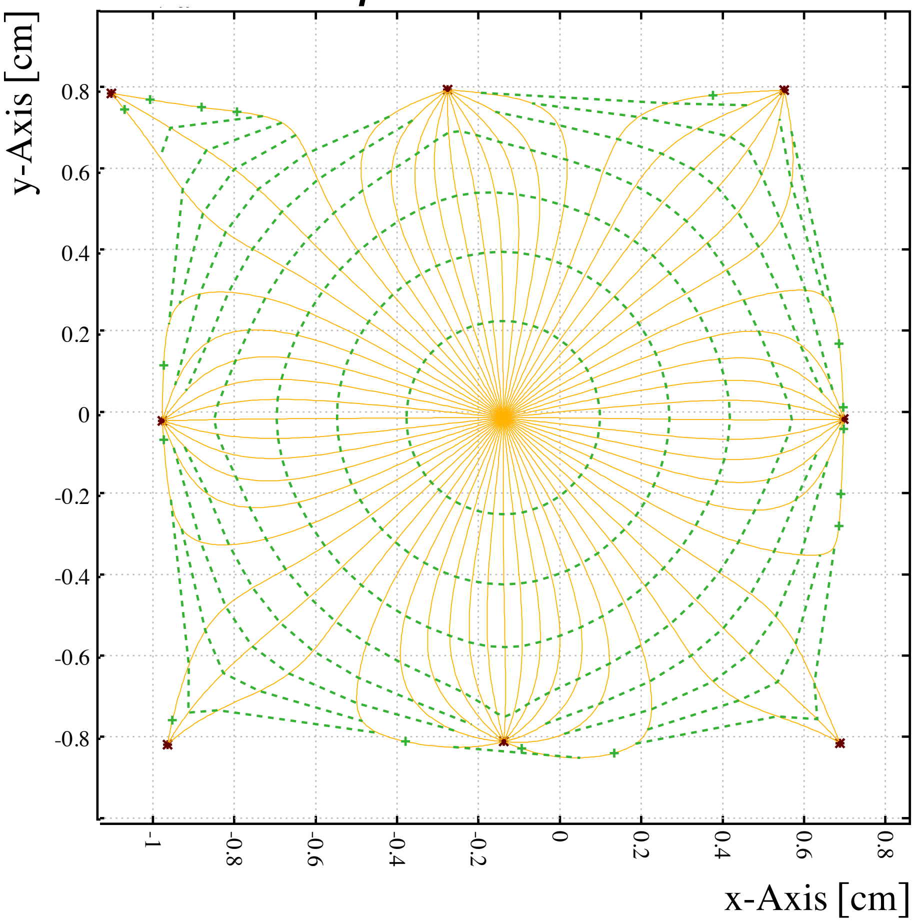
セルの電場分布とドリフト経路

- シミュレーションによるセルの電場分布（緑）と電子のドリフト経路（黄色）

$\beta = 90$ 度



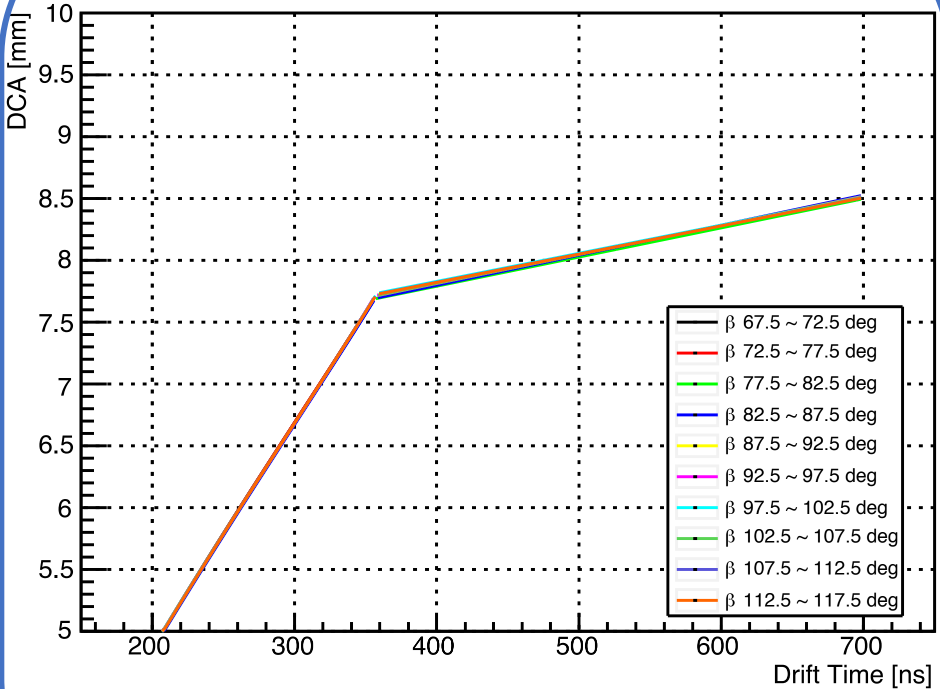
$\beta = 75$ 度



ドリフト距離とドリフト時間の関係

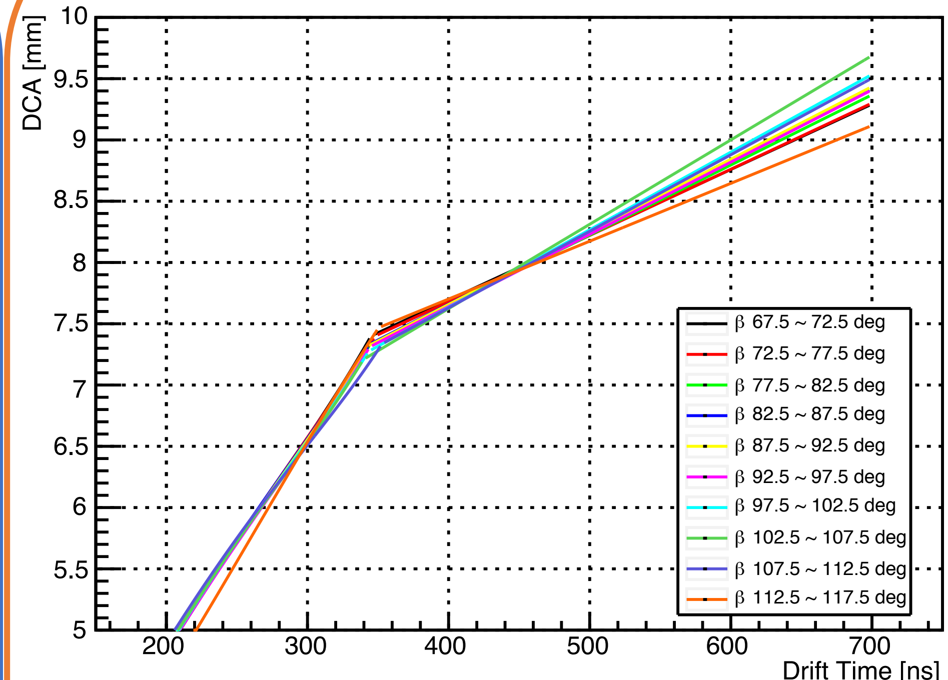
- 飛跡の入射角度 $\tilde{\phi}$ によってはセルの形状 β の依存性が確認された。

$\tilde{\phi}$: -5 ~ 5 [deg]



β の依存性なし
電子のドリフトの振る舞いは同じ

$\tilde{\phi}$: -25 ~ -15 [deg]



DCA 6 mm 以降で β の依存性あり
電子のドリフトの振る舞いが異なる

- 飛跡の入射角度が大きいと、セルの形状の効果が現れる。
- このような差が生じるのは、セル内の電場の歪みが原因。

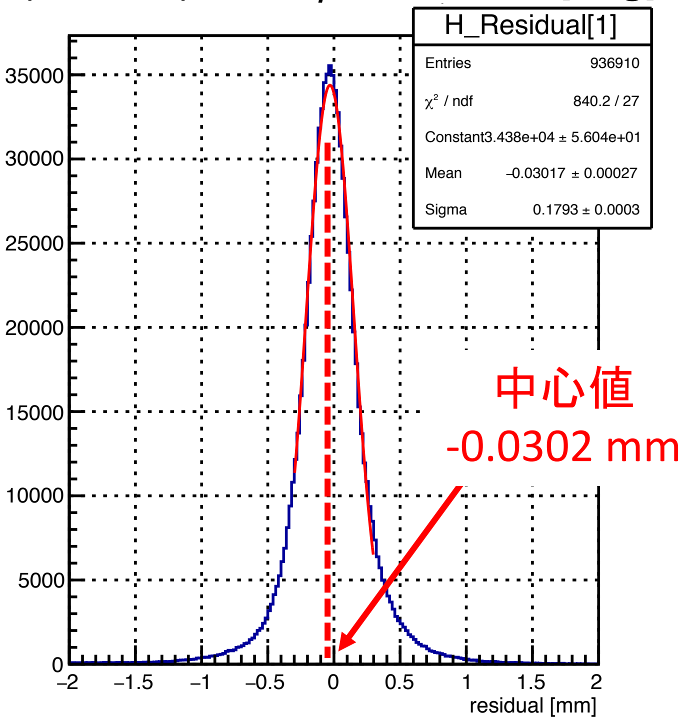
角度 $\tilde{\phi}$ と β ごとの飛跡再構成

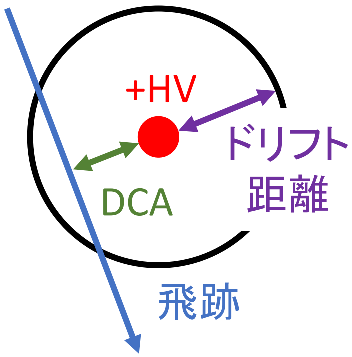
- 角度 $\tilde{\phi}$ と β ごとのドリフト距離と時間の関係を用いて、再度飛跡再構成をした。
- 飛跡再構成の精度向上の比較には、残差分布の中心値を用いる。

残差分布の中心値が 0 に近いほど、飛跡再構成の精度は良い、と言える。

例 :

(改善前) 残差 $\tilde{\phi}$: -15 ~ -5 [deg]





残差 = ドリフト距離 − DCA

(DCA : Distance of Closest Approach)

角度 β に関しては集約し、$\tilde{\phi}$ ごとに残差分布を作成。

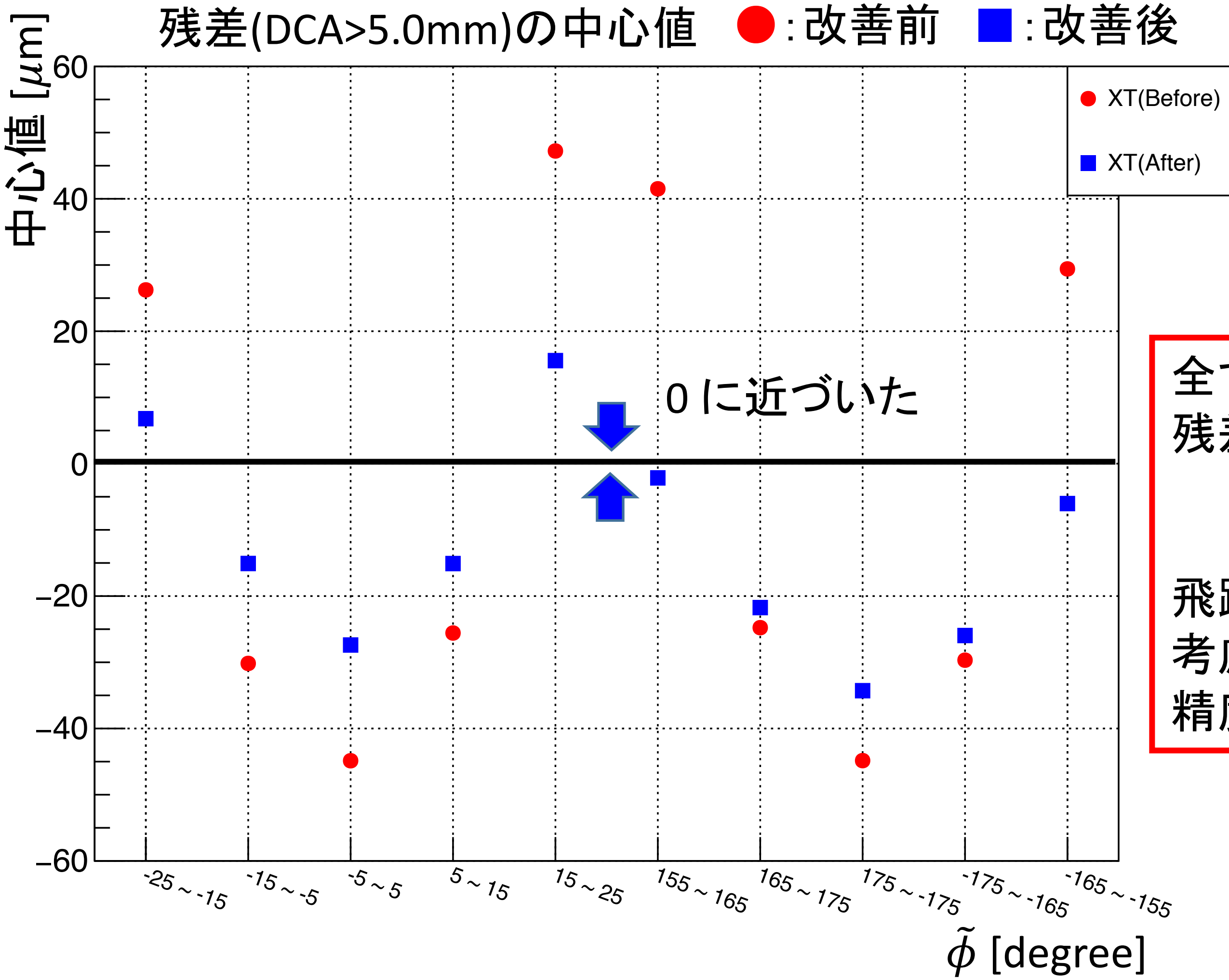
「ドリフト距離と時間の関係」の改善の効果を残差分布の中心値を見ることにより比較し、角度 $\tilde{\phi}$ ごとの改善率を求めた。

残差の中心値の比較

- 飛跡再構成の精度向上を、残差の中心値を見ることで確かめた。

残差分布の中心値が 0 に近いほど、飛跡再構成の精度は良い、と言える。

残差(DCA>5.0mm)の中心値 ●:改善前 ■:改善後



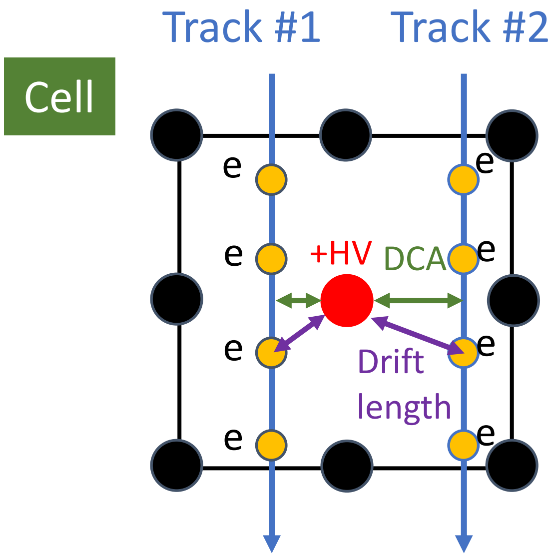
全ての $\tilde{\phi}$ の角度範囲において、残差の中心値が 0 に近づいた。

↓

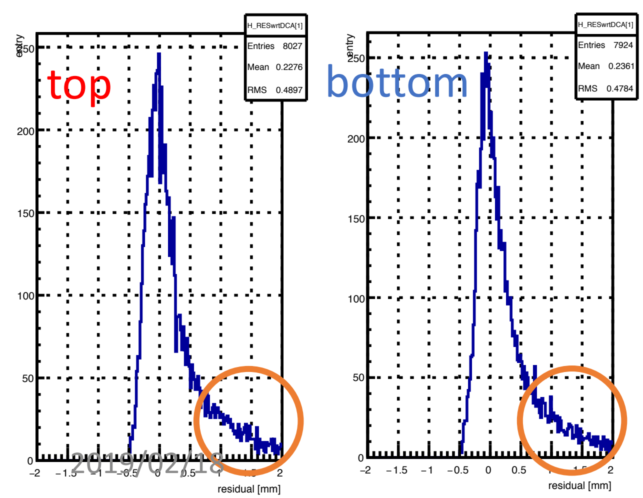
飛跡の入射角度とセルの形状を考慮した飛跡再構成は精度の向上に繋がる。

Effect of the number of primary electrons

- If the track goes through very near the sense wire and make less electrons, there would be more possibility of having larger drift length than DCA.



Residual (DCA 0~0.5 mm) of layer 4~15



Near the sense wire such as track #1

More like DCA < Drift Length

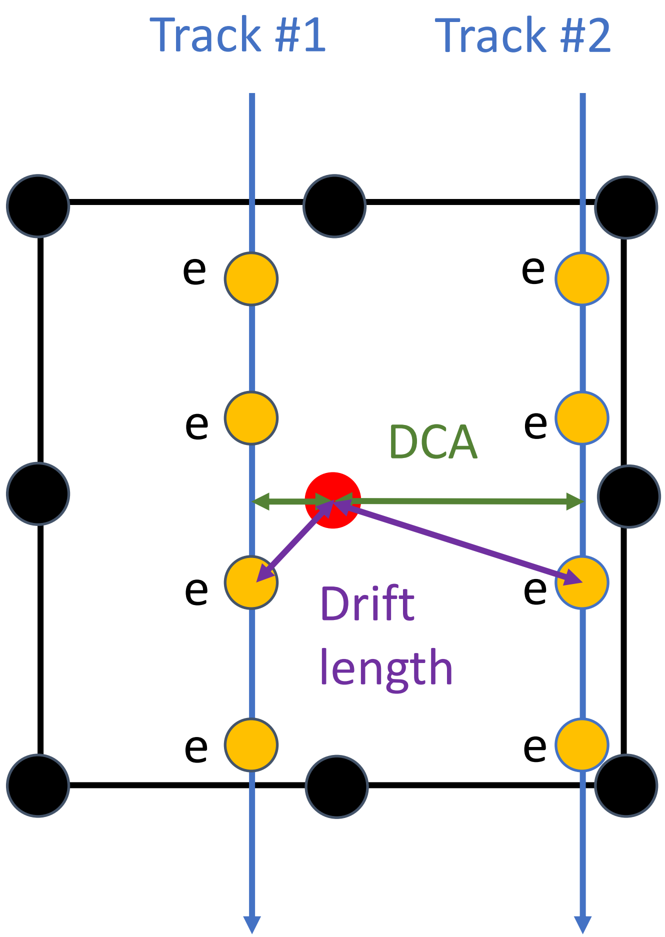
Because the number of primary electrons is not so large.

Gas	X_0 (m)	W (eV)	dE^{MIP}/dx (keV/cm)	n_T^{MIP} (cm^{-1})	n_p^{MIP} (cm^{-1})
$He-iC_4H_{10}(85/15)$	954	38	1.14	40	18
$He-iC_4H_{10}(90/10)$	1310	39	0.88	29	14
$He-iC_4H_{10}(95/5)$	2102	40	0.61	19	9
$He-C_2H_6(50/50)$	630	32	1.63	60	27
$He-CH_4(73/27)$	2166	39	1.47	17	11
$He-CH_4(80/20)$	3073	40	0.47	13	8

TABLE 2.2: *Comparison of different Helium-based low-Z gas mixtures, where X_0 is the radiation length, W is mean energy to generate one electron-ion pair, dE^{MIP}/dx, n_T^{MIP}, and n_p^{MIP} mean is energy loss per cm, the number of electron-ion pairs per cm, and the number of primary ions per cm for minimum ionizing particles, respectively.*

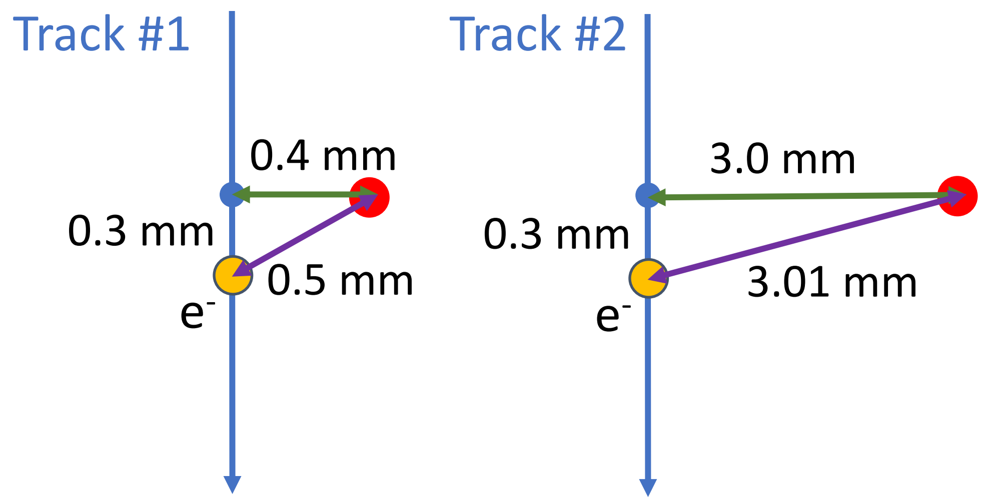
This tail is also coming from the same reason.

Cosmic Ray Track near the Sense Wire



Example

Residual = drift length - DCA



Residual = 0.1 mm **Residual = 0.01 mm**

Near the sense wire such as track #1

More like DCA < Drift Length

Because the number of primary electrons is not so large.

Contribution of Spatial Resolution to Momentum Resolution

- Momentum Resolution σ_{P_t} is descried by the equation below.

$$\left(\frac{\sigma_{P_t}}{P_t}\right)^2 = (aP_t)^2 + b^2$$

Spatial Resolution term

$$a = \frac{\sigma_{r\phi}}{0.3BL^2}\sqrt{\frac{720}{N+5}}$$

Multiple Scattering term

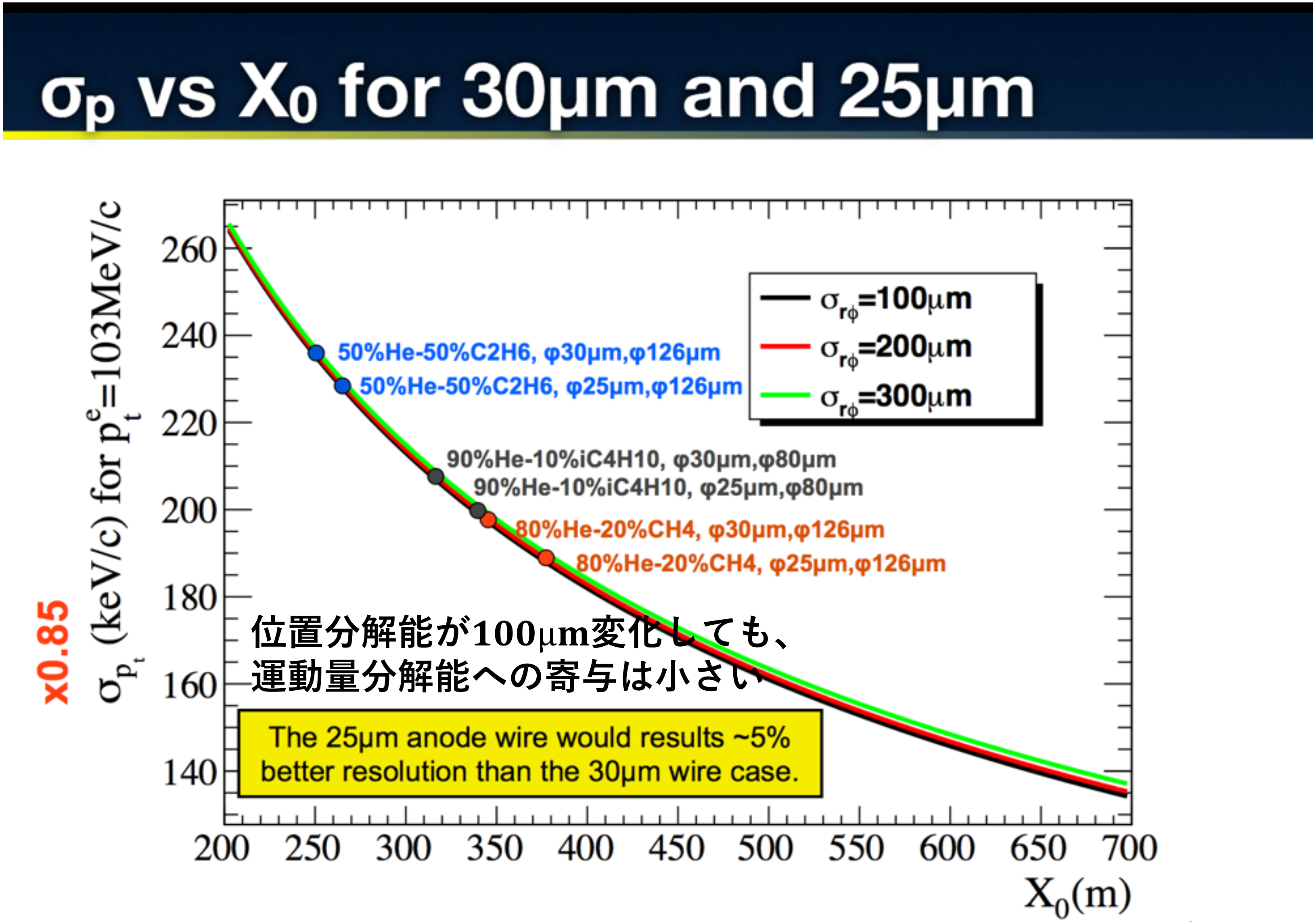
$$b = \frac{0.054}{LB}\sqrt{\frac{L}{X_0}}\left[1 + 0.038\ln\left(\frac{L}{X_0}\right)\right]$$

B : Magnetic Field (Tesla)
L : Length of a Track used for Measurement (m)
$\sigma_{r\phi}$: Spatial Resolution at each Measurement Point (m)
N : The Number of Measurement Points
X_0 : Length of a Track in the Gas (m)
P_t : Transverse Momentum (GeV/c)

Assuming
$B = 1$ T
$L = 1$ m
$N = 70$
$X_0 = 507$ m
$P_t = 103$ MeV/c

- If Spatial Resolution $\sigma_{r\phi}$ differs from 200 μm to 300 μm, Momentum Resolution changes only about 1 %.

Contribution of Spatial Resolution to Momentum Resolution

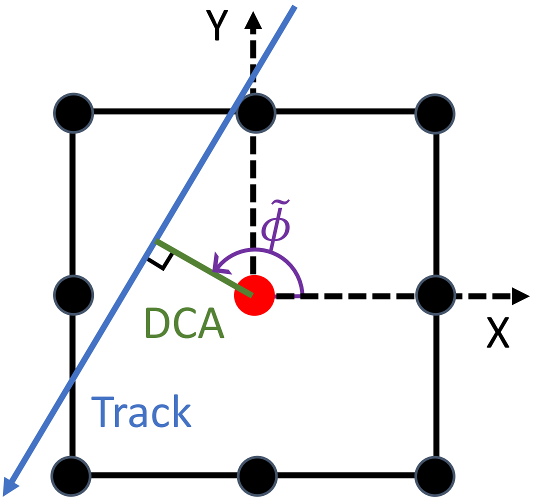


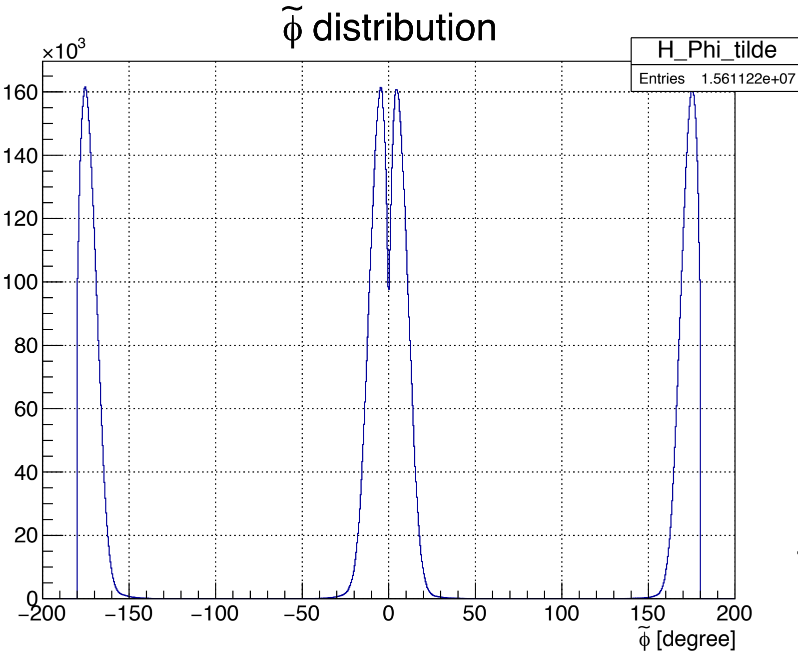
From Akira Sato (Osaka)

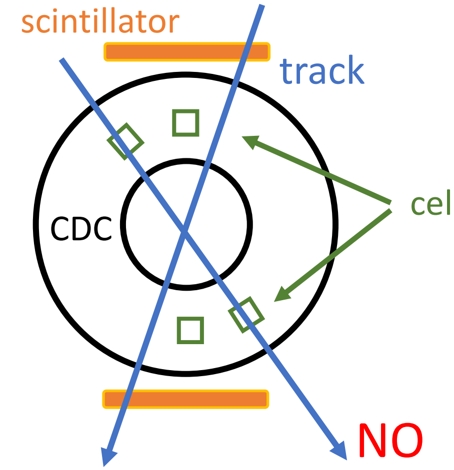
Definition of Angle of Track and Cell

Definition of $\tilde{\phi}$

- $\tilde{\phi}$ characterizing the incident angle of the track regarding to each cell.

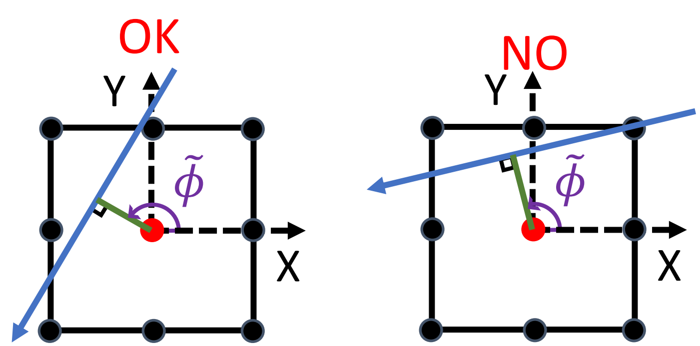




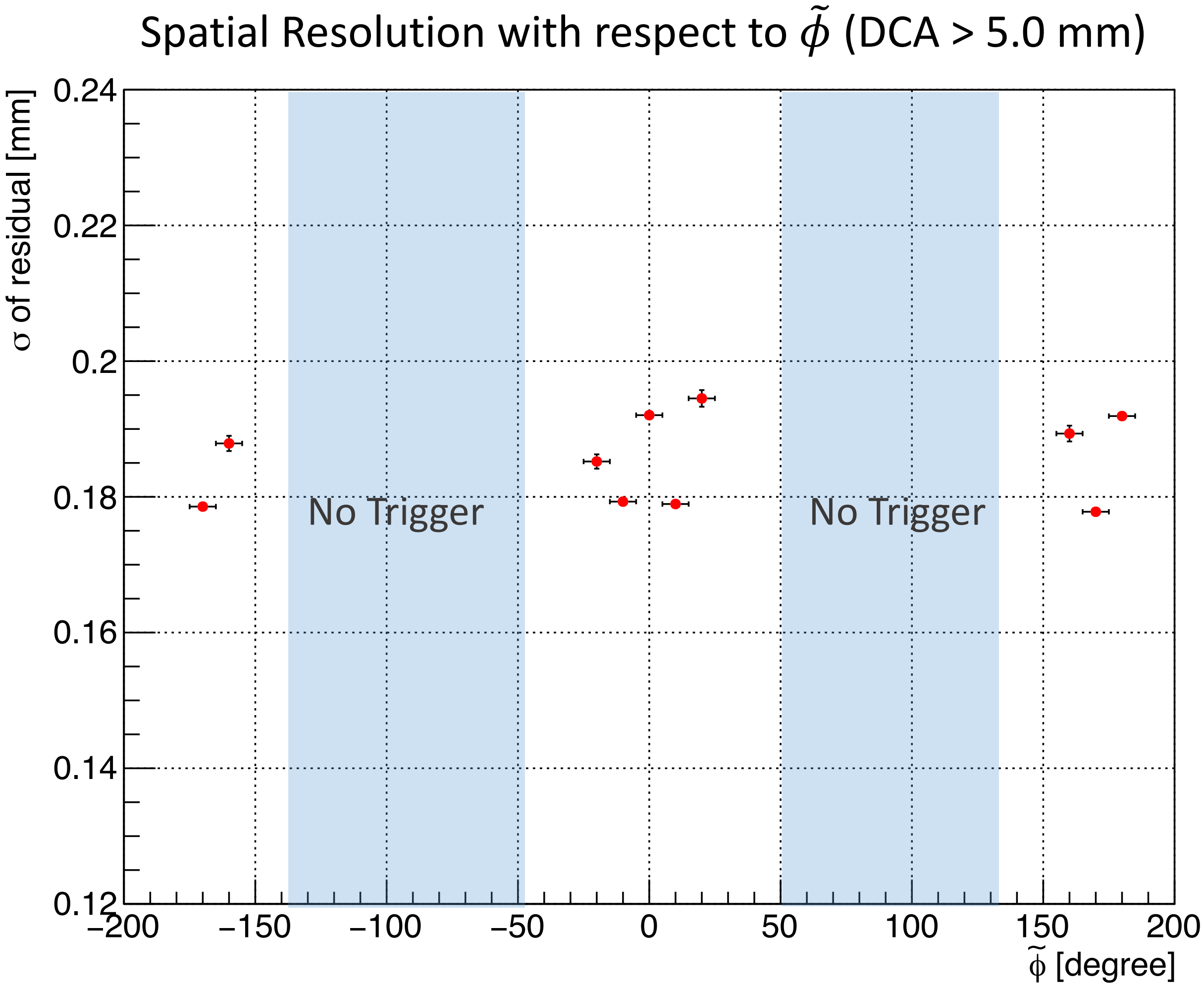


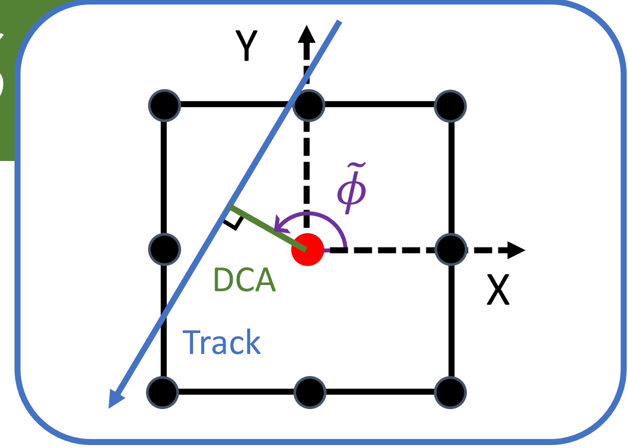
Tracks come from upward

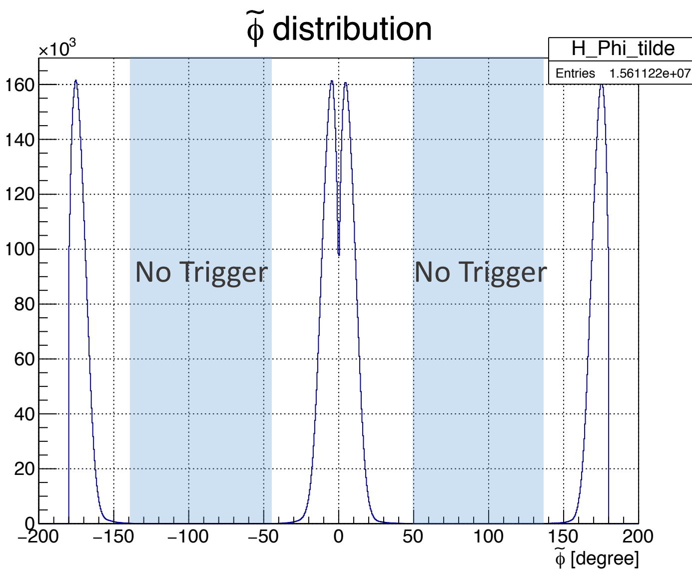
- Most of cosmic-ray tracks come from upward and they don't pass through the cell toward the X axis in the cell.
- Tracks with angle 0 deg and 180 deg are limited due to the geometrical reason, so the double peaks appear.



Spatial Resolution with respect to $\tilde{\phi}$

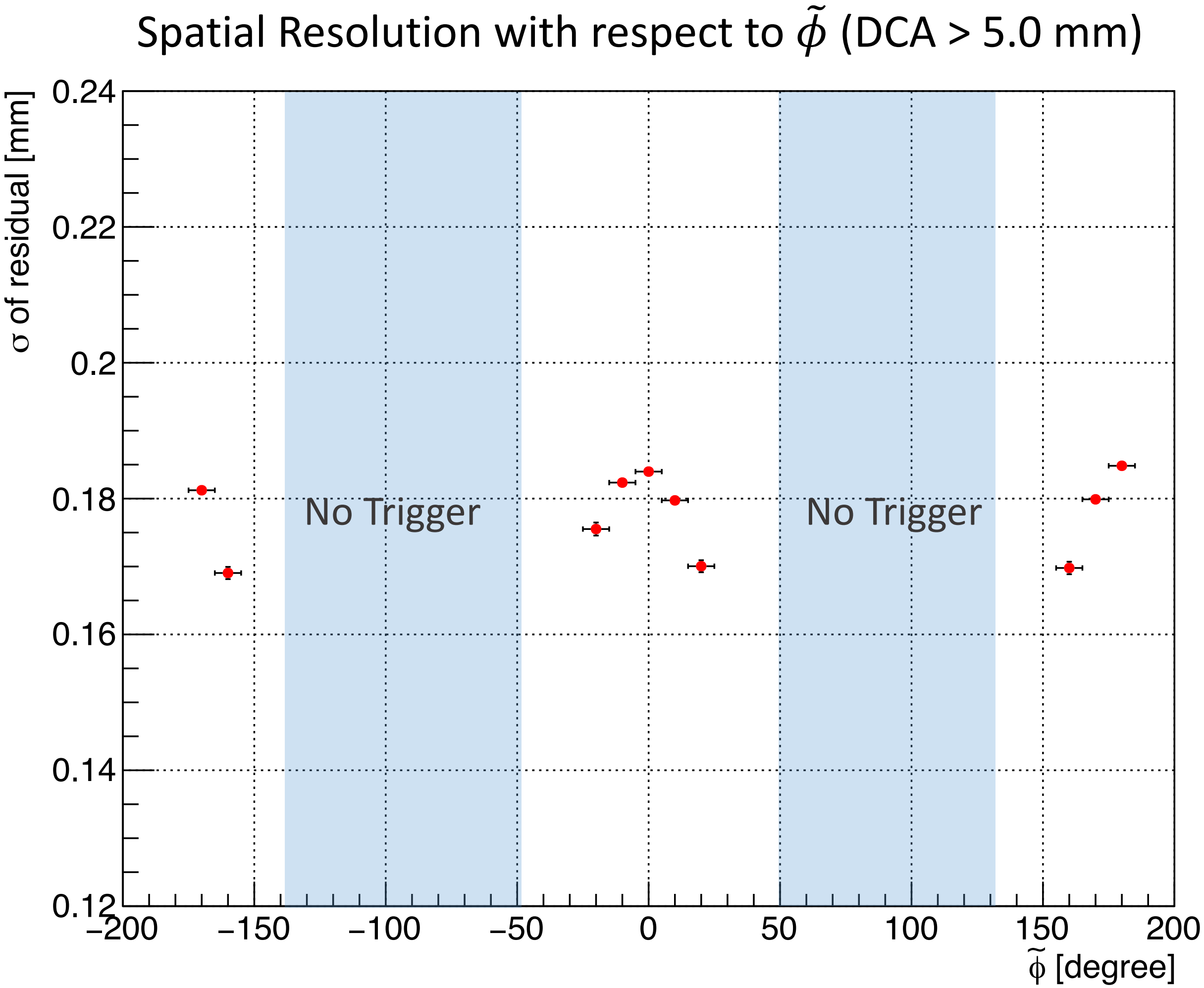


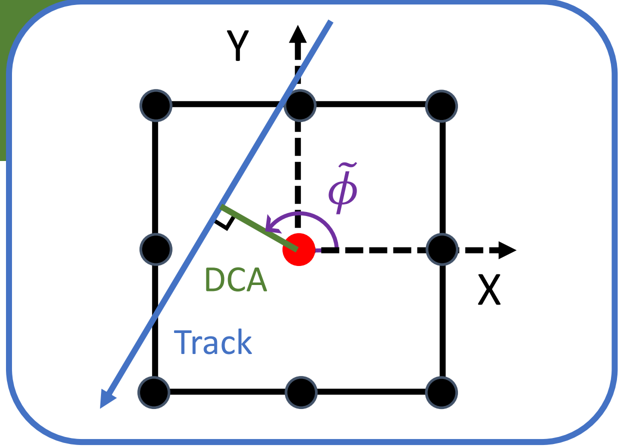


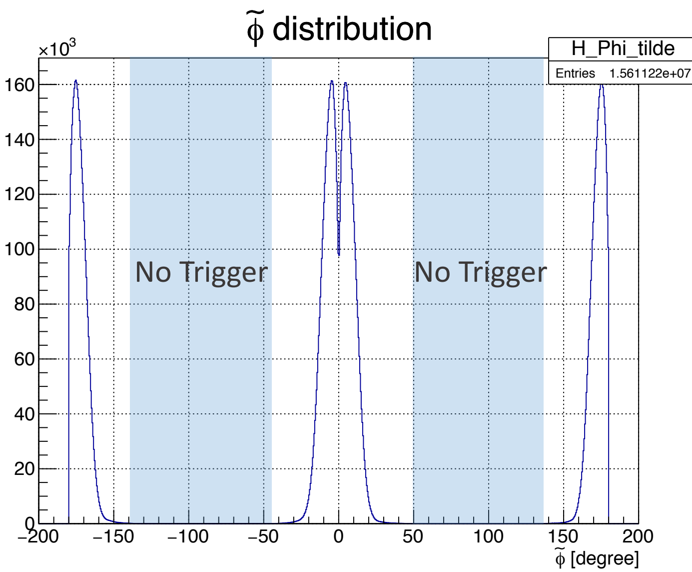


Before considering the effect of $\tilde{\phi}$ and β.

Spatial Resolution with respect to $\tilde{\phi}$



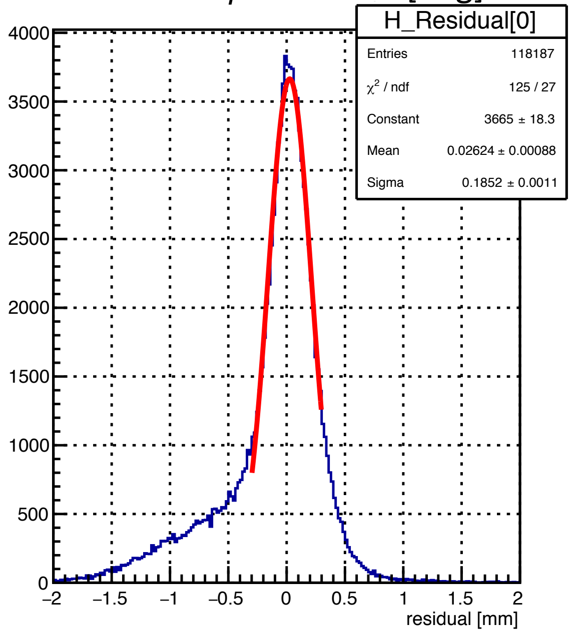




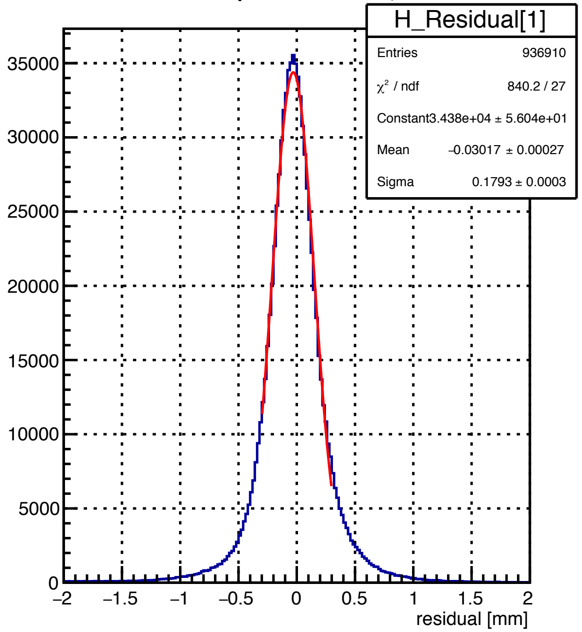
After considering the effect of $\tilde{\phi}$ and β.

- $\tilde{\phi}$ -5~5 and -175~175 have worst resolution because of the effect of diffusion in the gas.
- In the some range of angles, the spatial resolution improved.

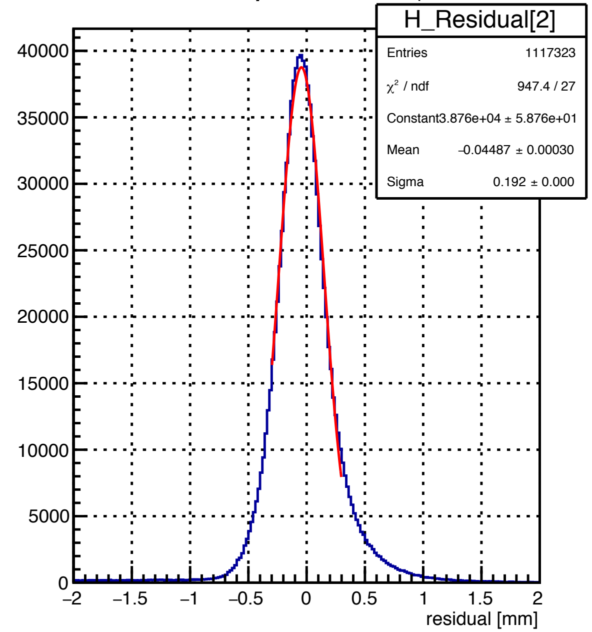
Residual $\tilde{\phi}$ -25 ~ -15 [deg]



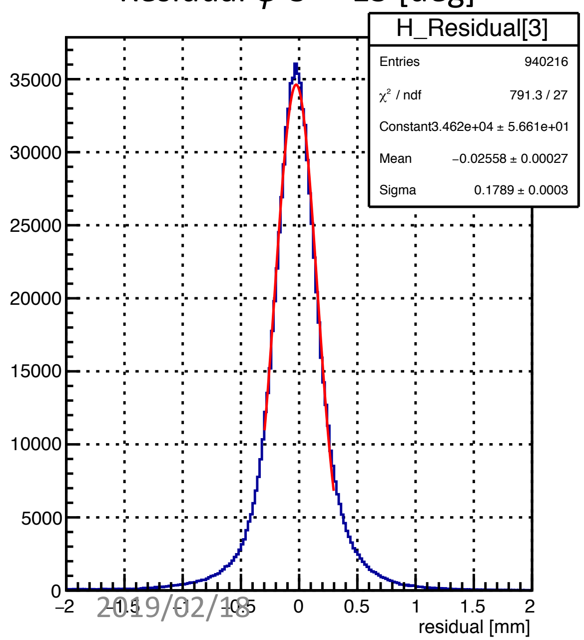
Residual $\tilde{\phi}$ -15 ~ -5 [deg]



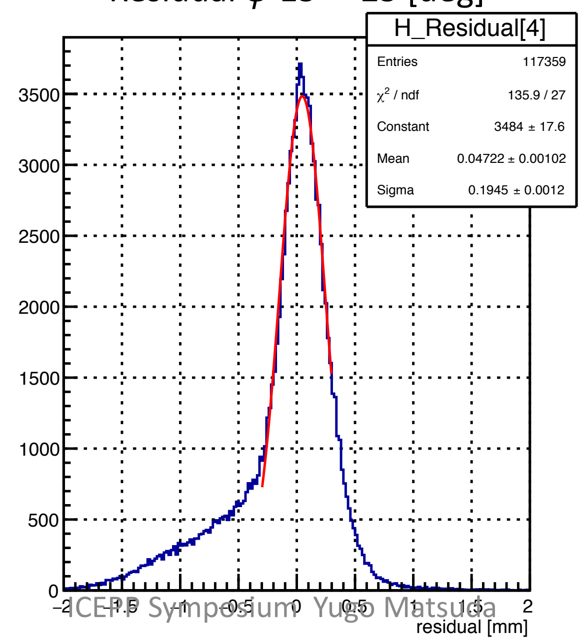
Residual $\tilde{\phi}$ -5 ~ 5 [deg]



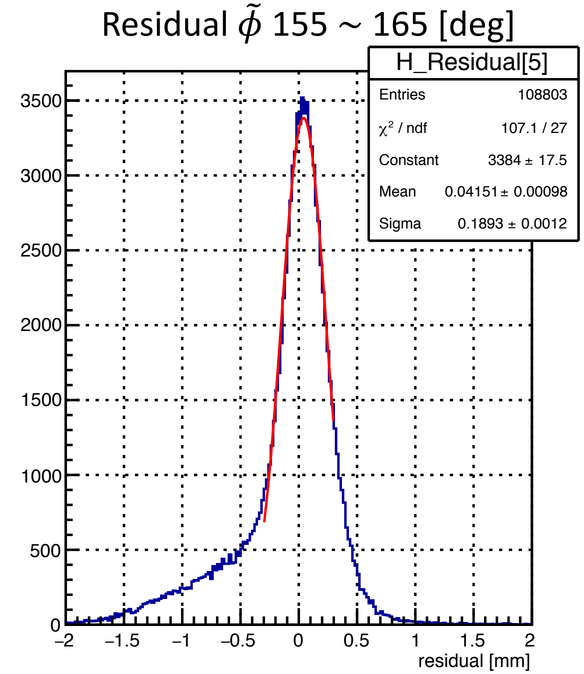
Residual $\tilde{\phi}$ 5 ~ 15 [deg]

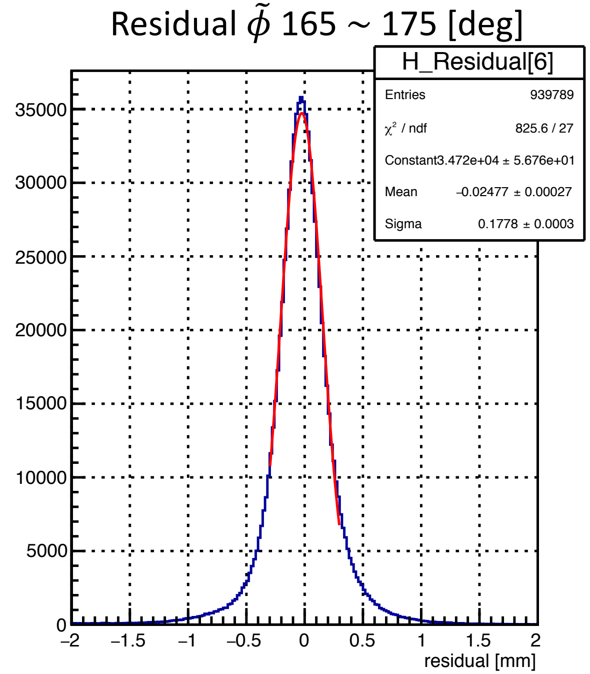


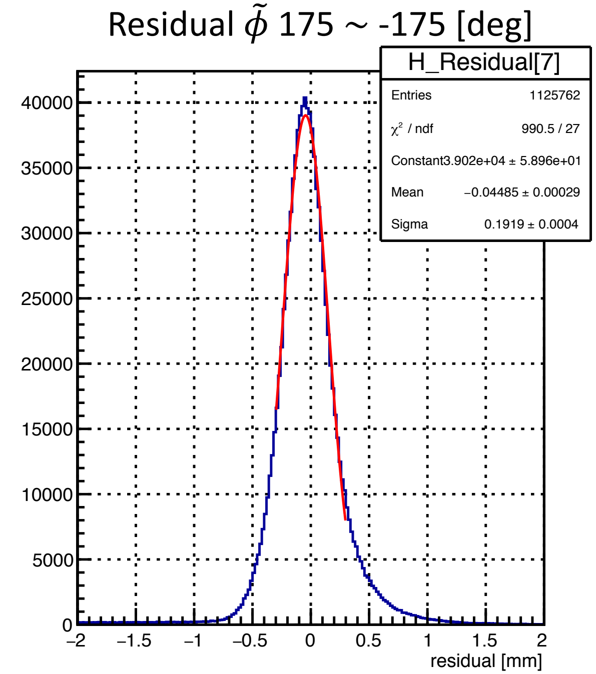
Residual $\tilde{\phi}$ 15 ~ 25 [deg]

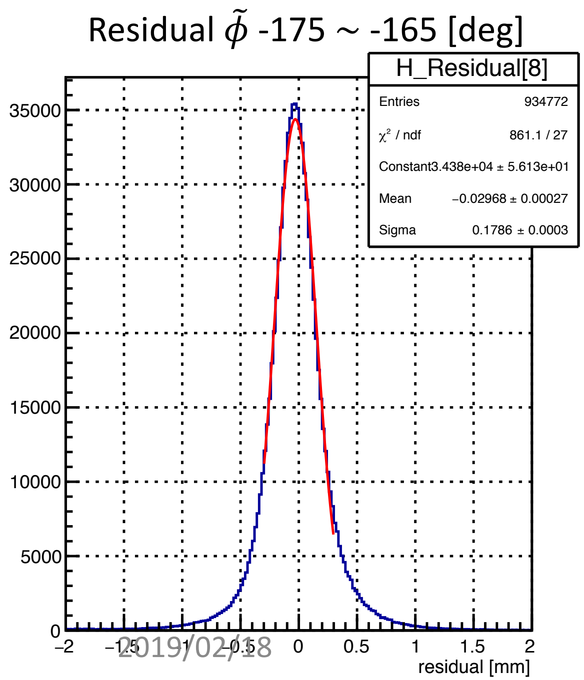


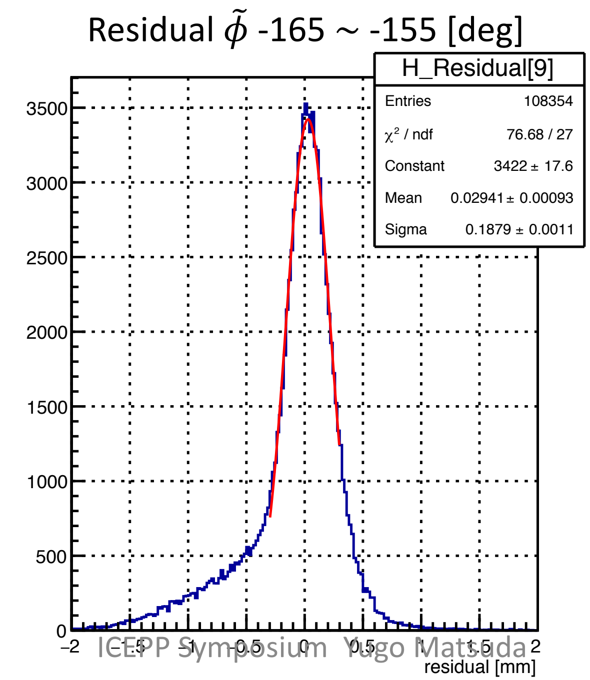
Before Correction





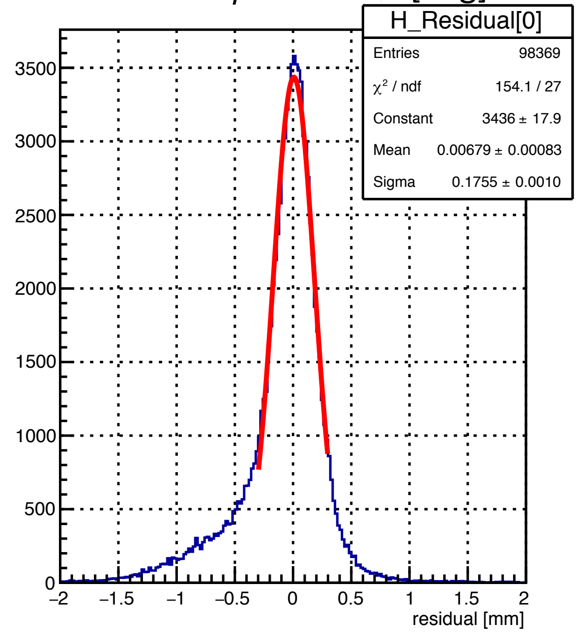




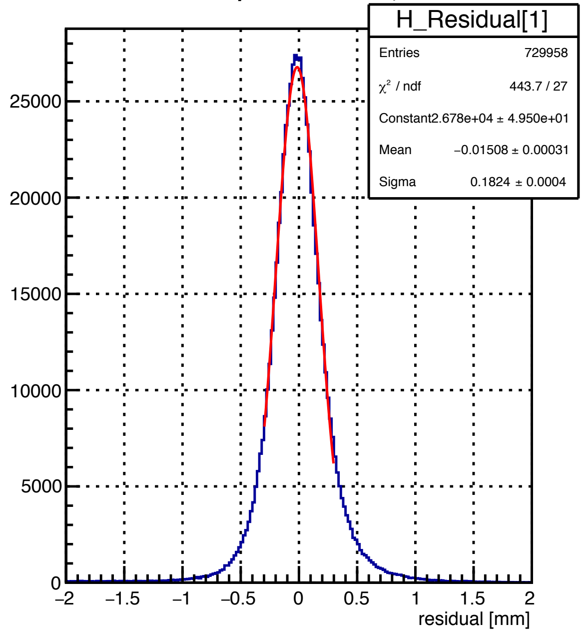


Before Correction

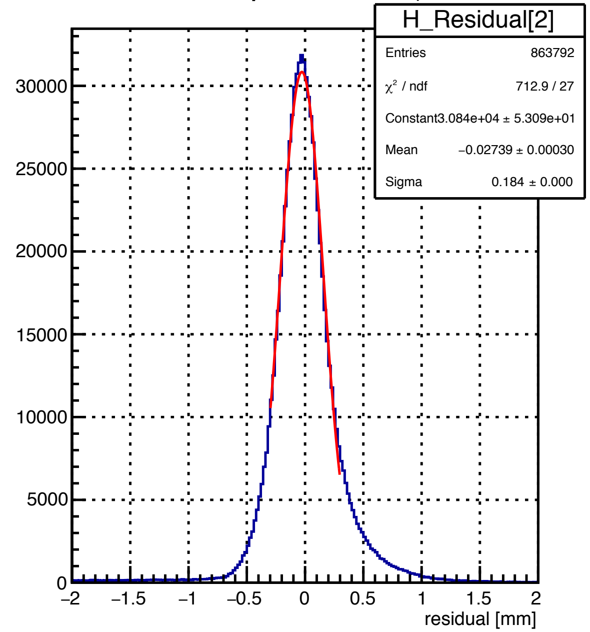
Residual $\tilde{\phi}$ -25 ~ -15 [deg]



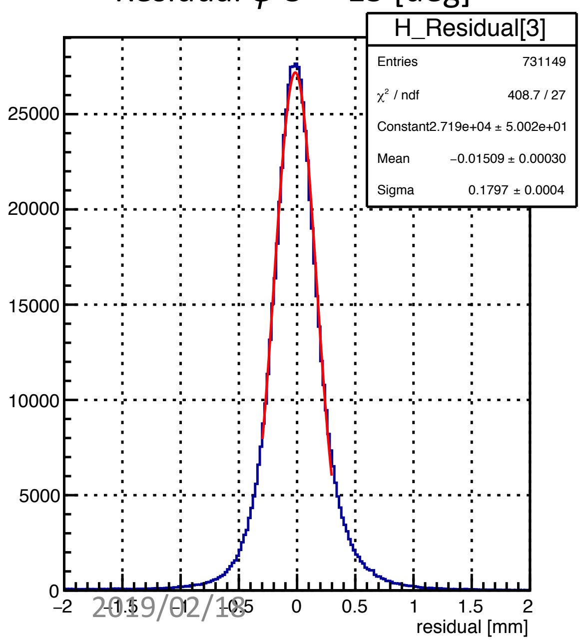
Residual $\tilde{\phi}$ -15 ~ -5 [deg]



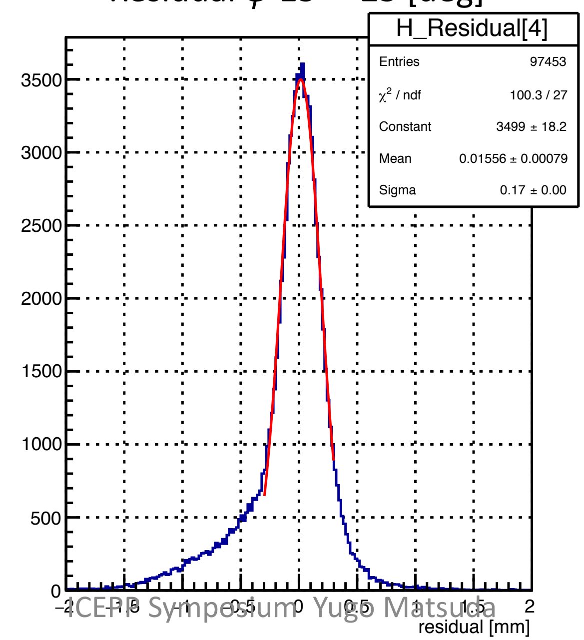
Residual $\tilde{\phi}$ -5 ~ 5 [deg]



Residual $\tilde{\phi}$ 5 ~ 15 [deg]

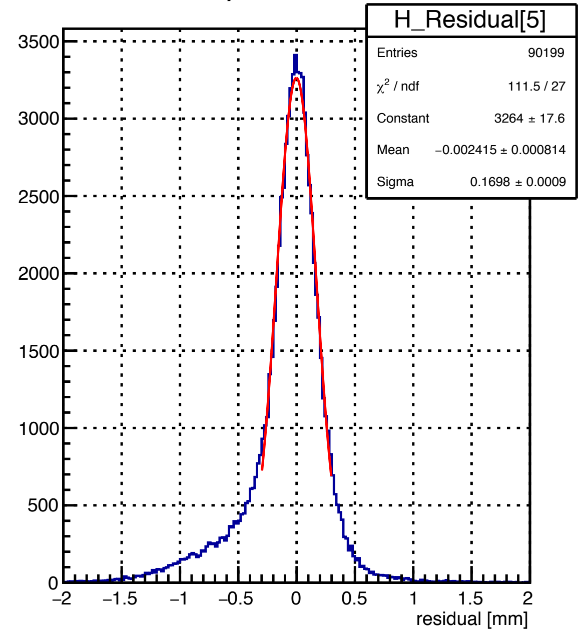


Residual $\tilde{\phi}$ 15 ~ 25 [deg]

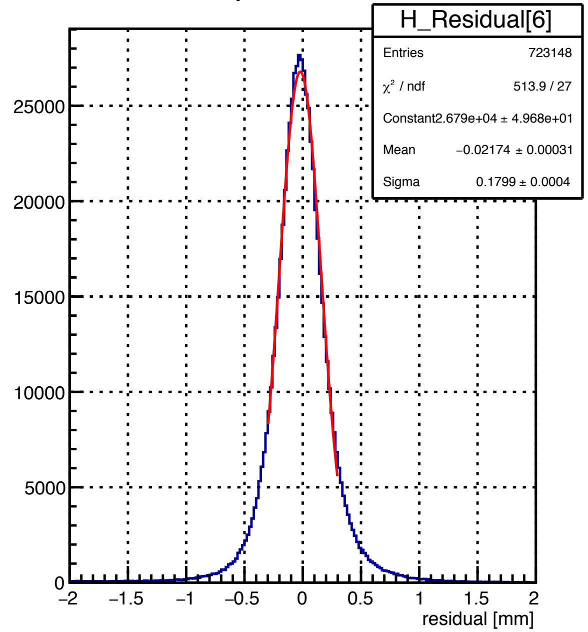


After correction

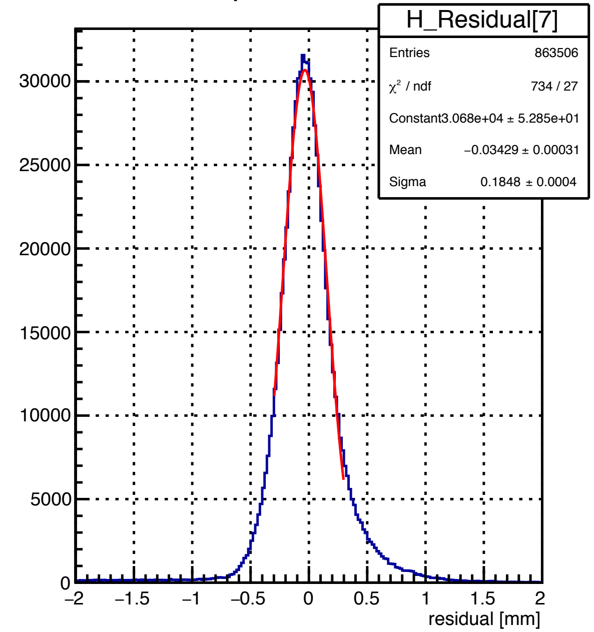
Residual $\tilde{\phi}$ 155 ~ 165 [deg]



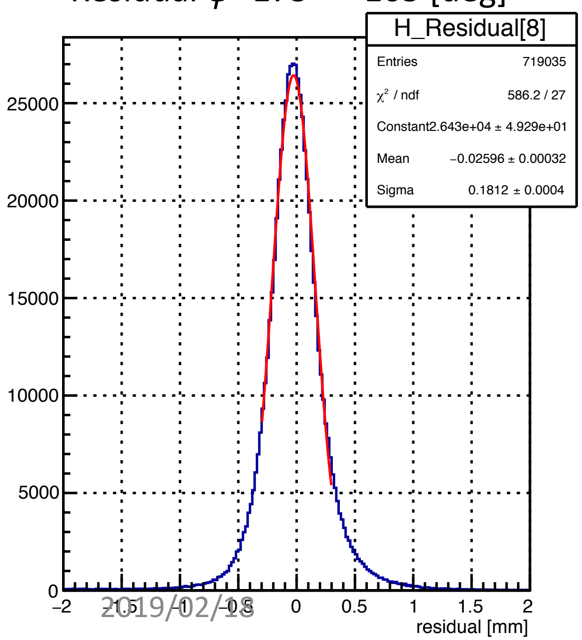
Residual $\tilde{\phi}$ 165 ~ 175 [deg]



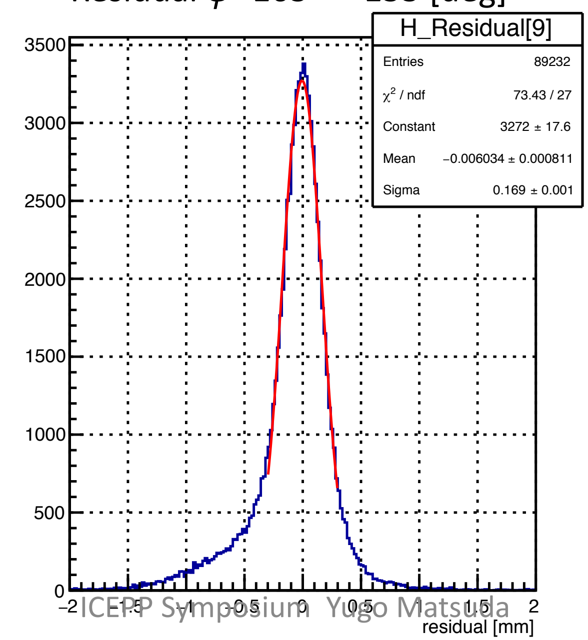
Residual $\tilde{\phi}$ 175 ~ -175 [deg]



Residual $\tilde{\phi}$ -175 ~ -165 [deg]



Residual $\tilde{\phi}$ -165 ~ -155 [deg]

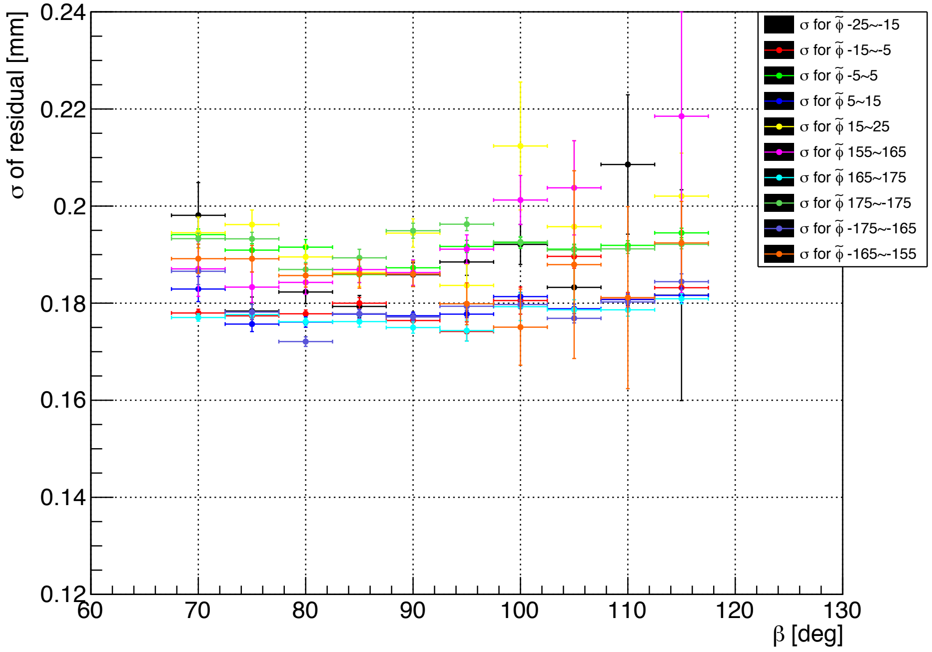


After correction

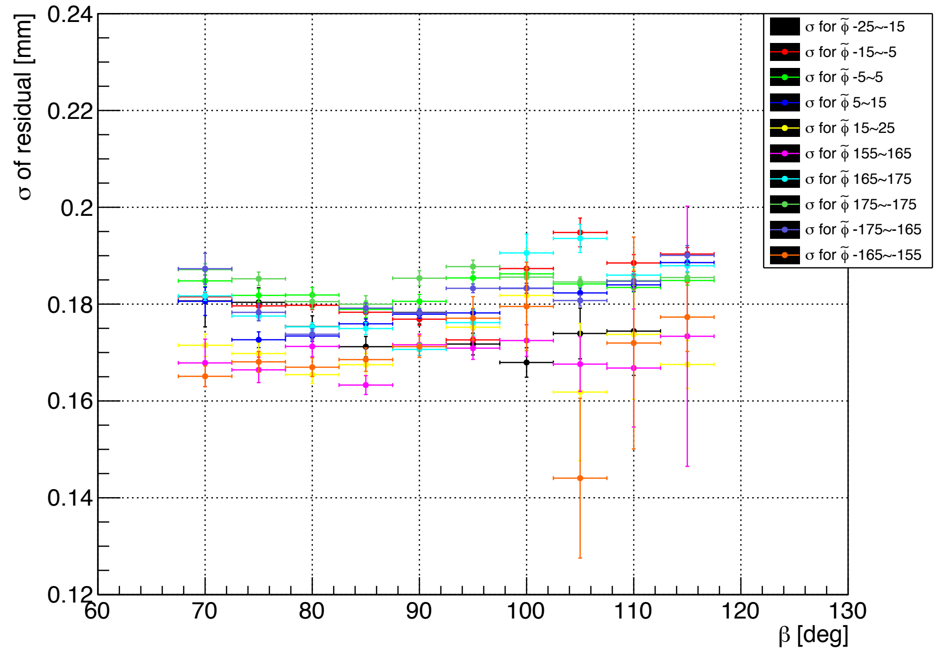
Spatial Resolution with respect to $\tilde{\phi}$ and β

Spatial Resolution with respect to $\tilde{\phi}$ and β (DCA > 5.0 mm)

Before considering the effect of $\tilde{\phi}$ and β



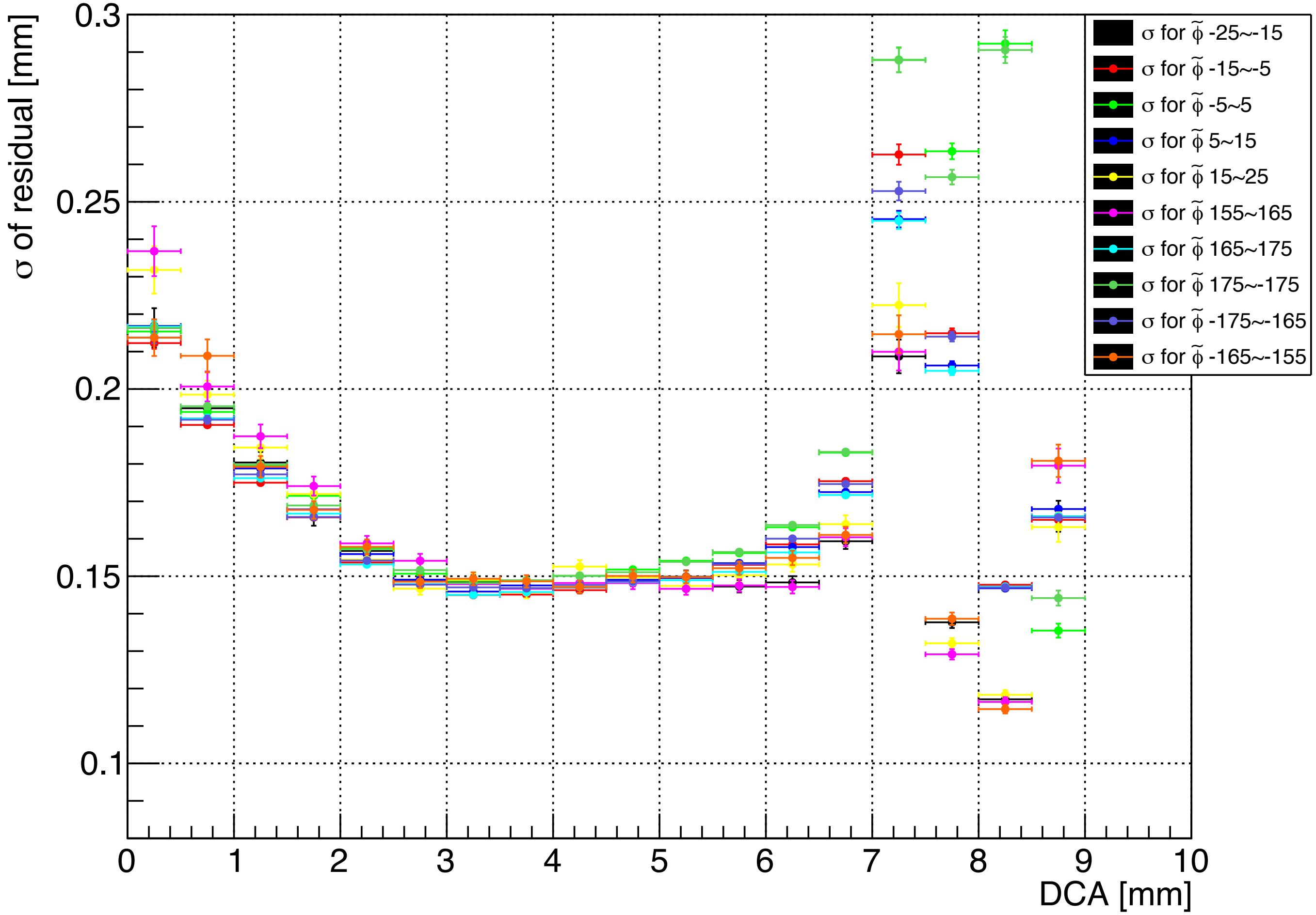
After considering the effect of $\tilde{\phi}$ and β



Most of angles of spatial resolution improved.
But could not see the dependence of β clealy.

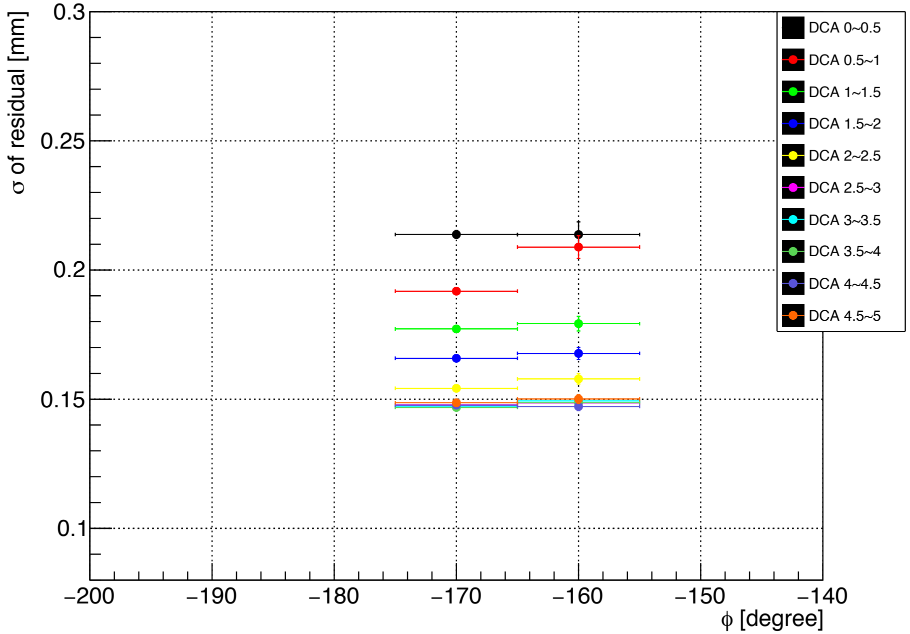
Spatial Resolution vs DCA with respect to $\tilde{\phi}$

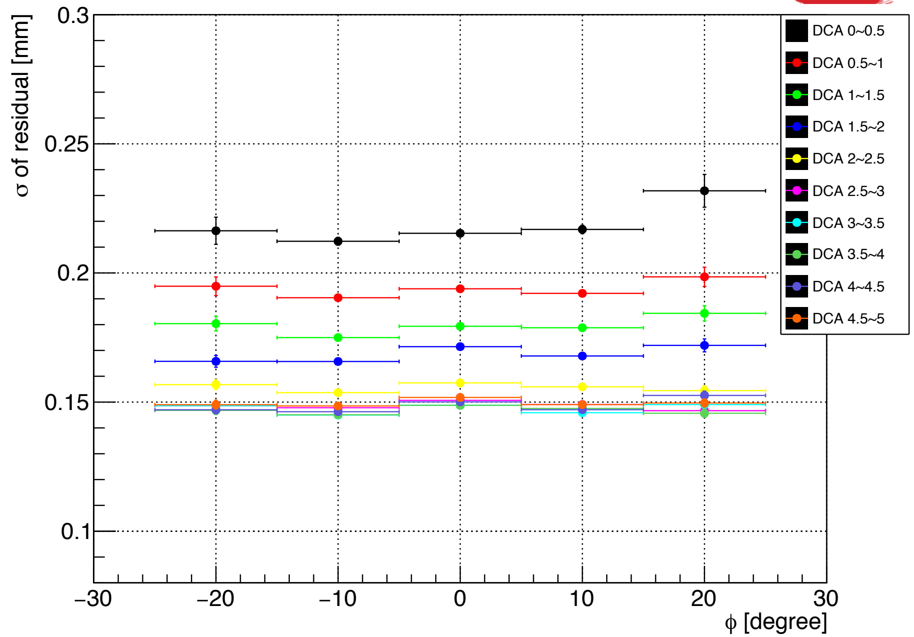
“Spatial resolution vs Distance of Closest Approach” for each angle $\tilde{\phi}$

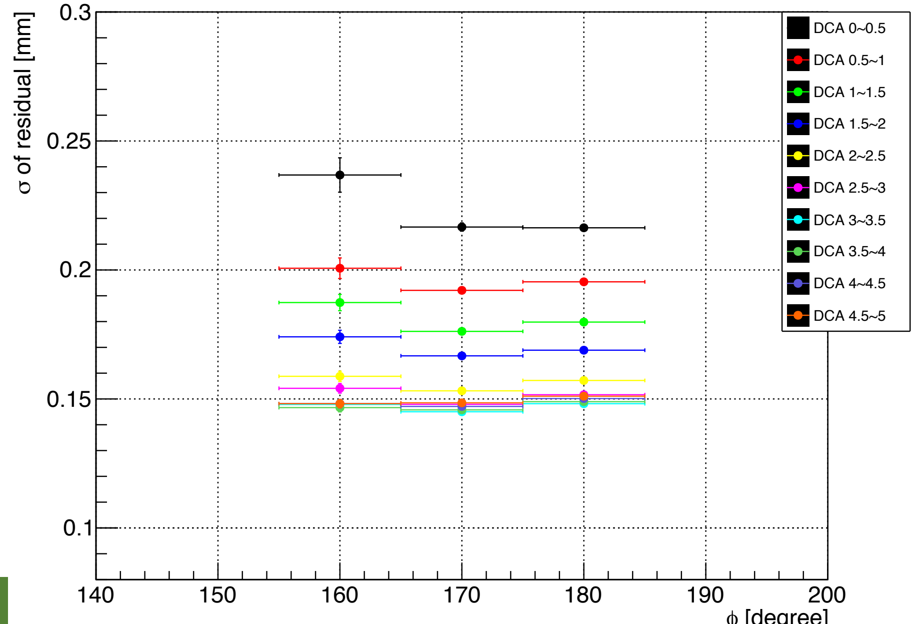


- If tracks have large incident angle, the spatial resolution become bad.
- DCA > 5.0 mm, resolutions change according to the incident angle.

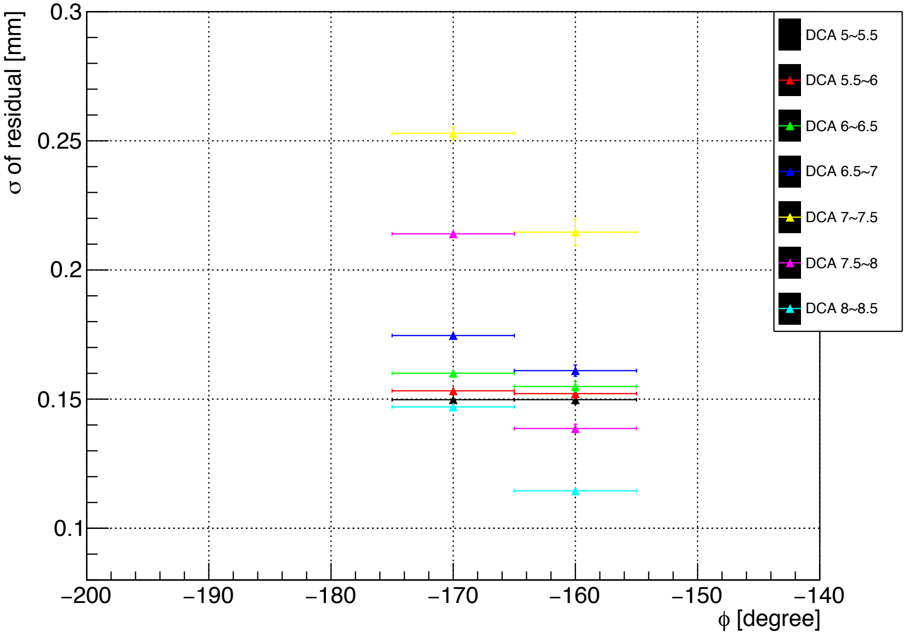
Spatial Resolution vs DCA with respect to $\tilde{\phi}$

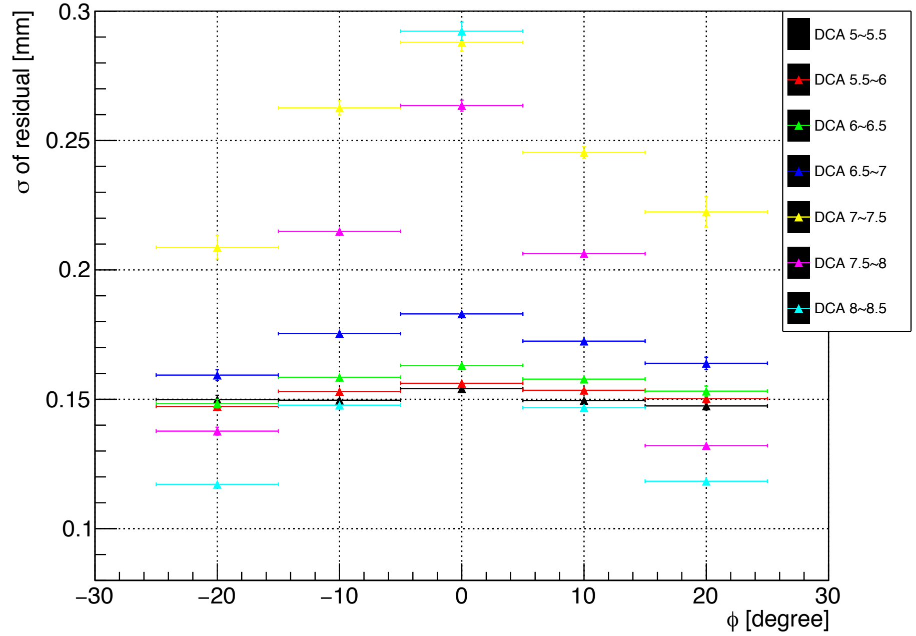


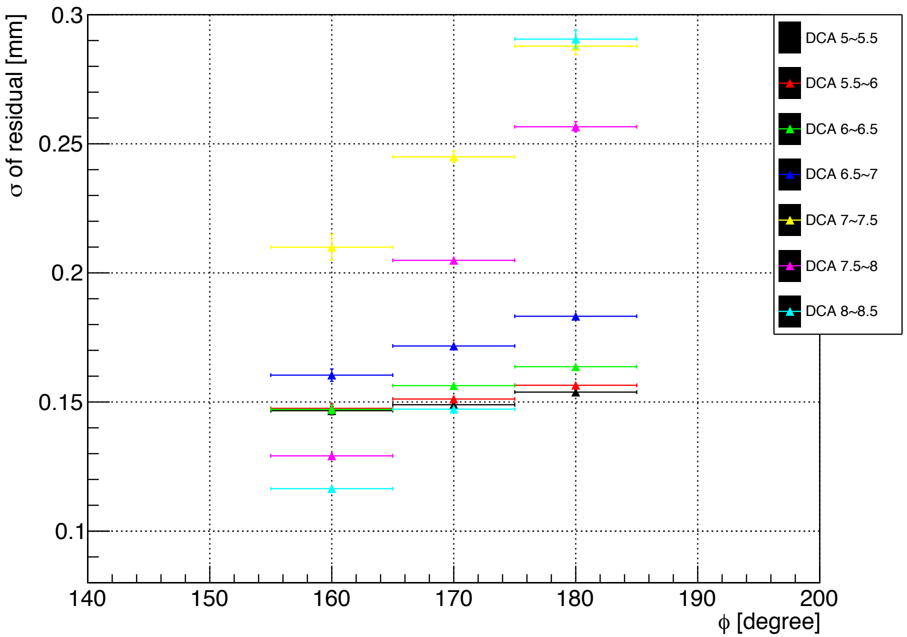




Spatial Resolution vs DCA with respect to $\tilde{\phi}$





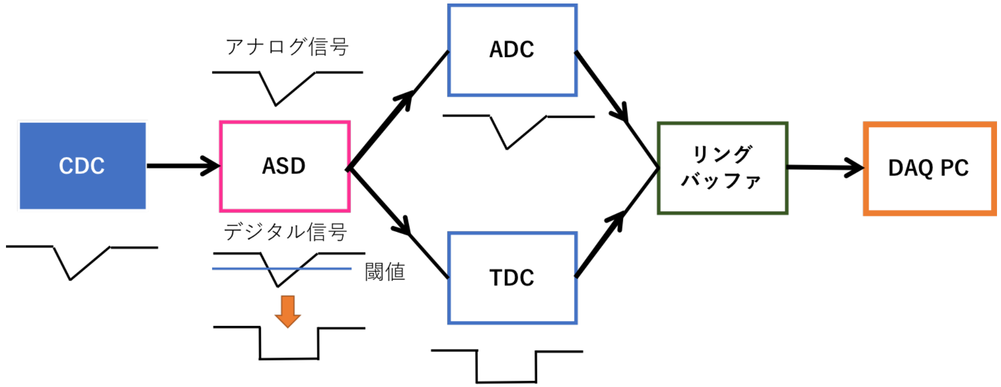


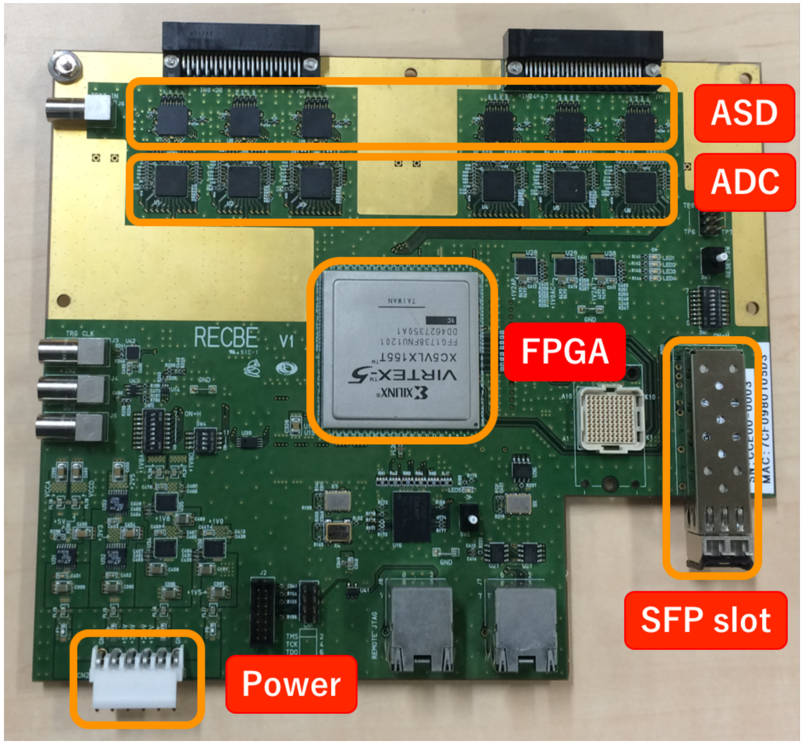
RECBE (Readout board for CDC)

元はBelle IICDCの信号読み出しボード
COMETでは、一部改造して用いている。

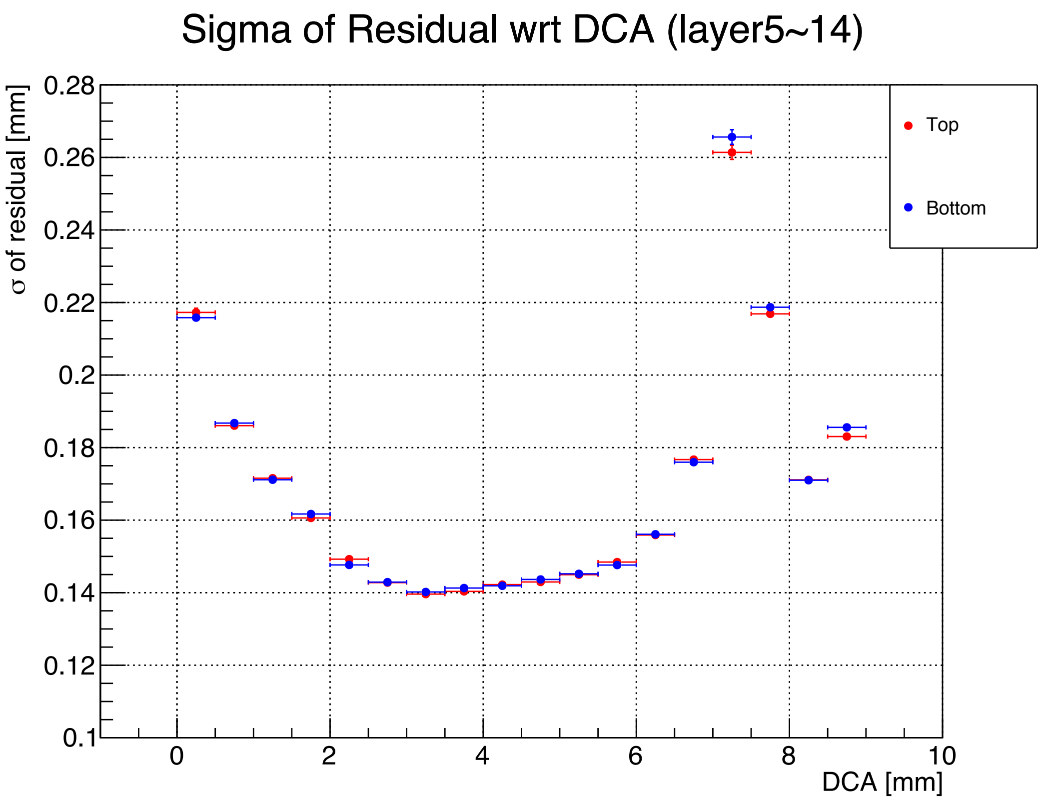
COMET RECBEの主要性能

システムクロック	120 MHz
TDC 時間分解能	1.0416 ns（960 MHz）
ADC サンプリングレート	30 MHz
ウィンドウサイズ	最大 8 μs
リングバッファサイズ	約 8 μs





RECBE写真



$$f(x)_{ion} = p_0 \sin(\arctan(p_1/x))$$

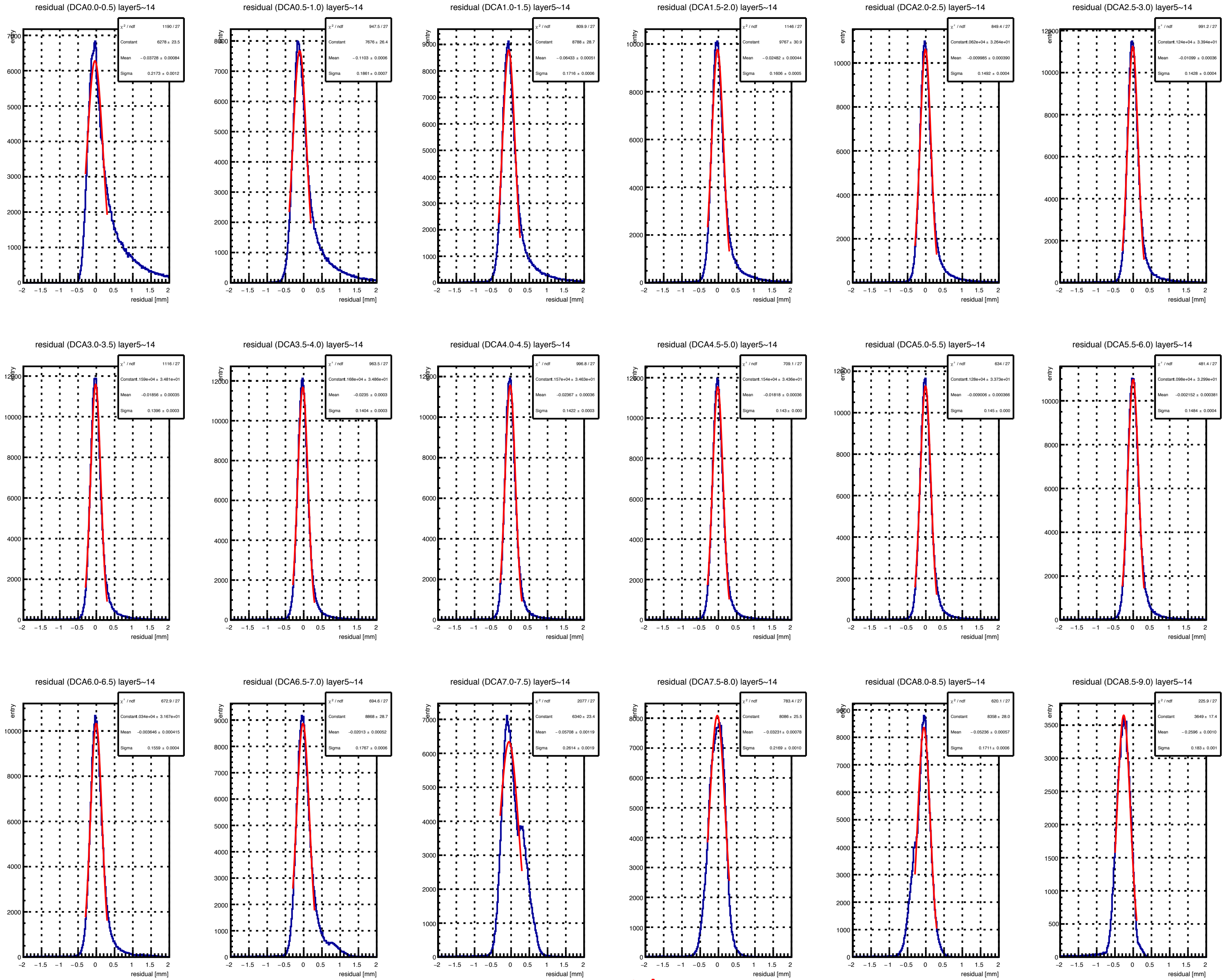
$$f(x)_{diff} = \sqrt{p_2 x}$$

$$f(x)_{el} = f(x)_{dv} p_7$$

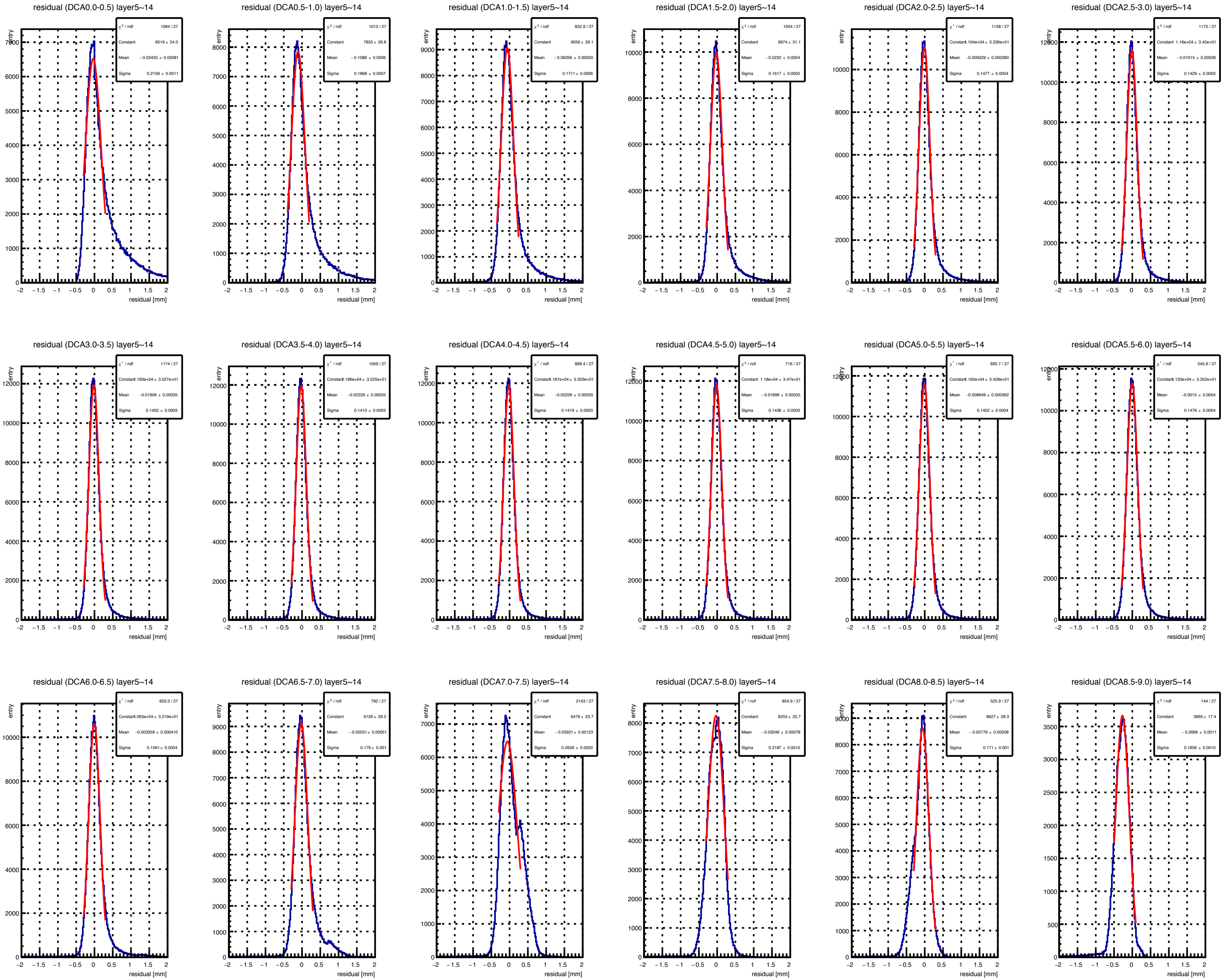
$$f(x)_{track} = p_8$$

$$(\ f(x)_{dv} = p_3 + p_4 x + p_5 x^2 + p_6 x^3\ )$$

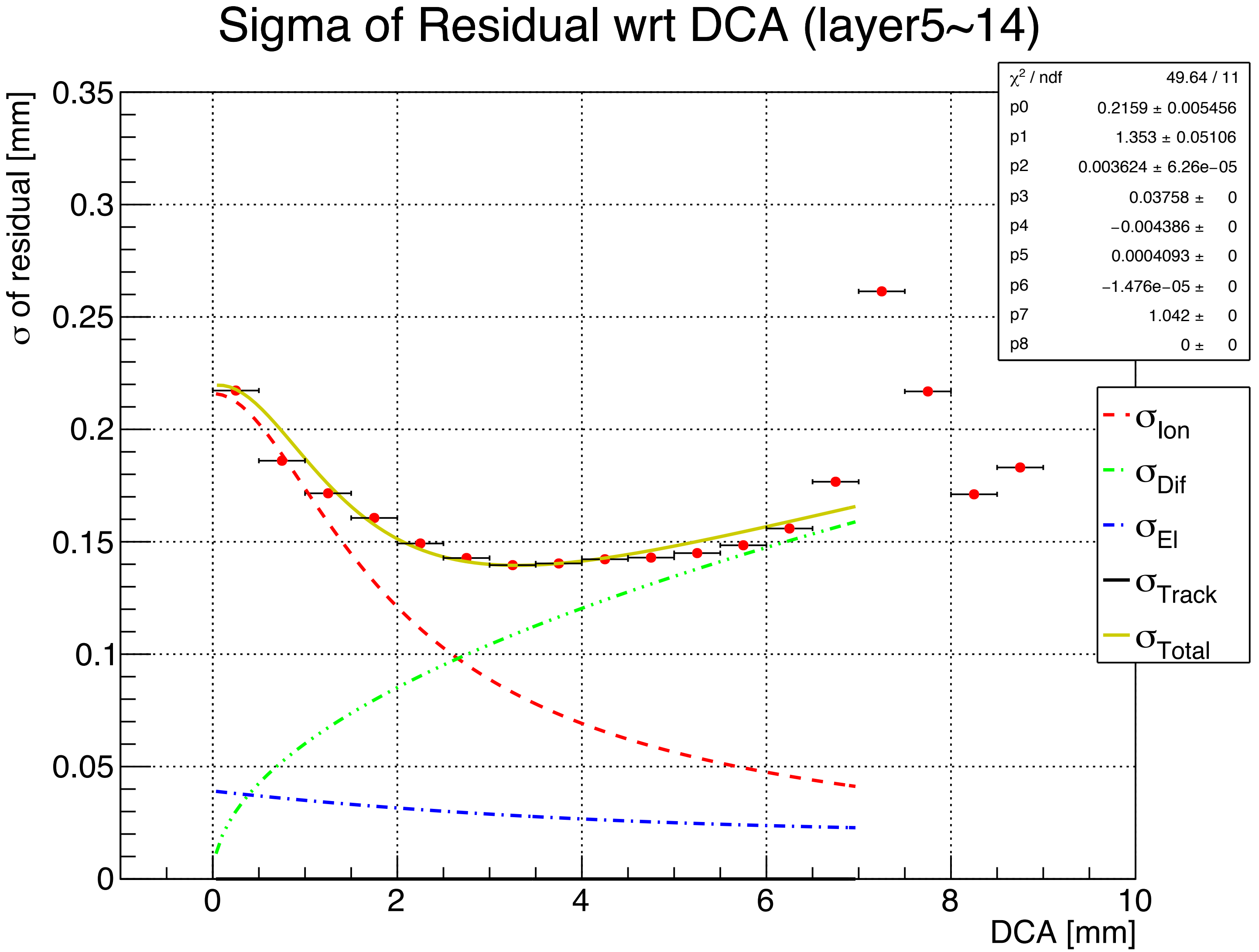
$$f(x)_{total} = \sqrt{f(x)_{ion}^2 + f(x)_{diff}^2 + f(x)_{el}^2 + f(x)_{track}^2}$$


residual (DCA0.0-0.5) layer5~14
residual (DCA0.5-1.0) layer5~14
residual (DCA1.0-1.5) layer5~14
residual (DCA1.5-2.0) layer5~14
residual (DCA2.0-2.5) layer5~14
residual (DCA2.5-3.0) layer5~14
residual (DCA3.0-3.5) layer5~14
residual (DCA3.5-4.0) layer5~14
residual (DCA4.0-4.5) layer5~14
residual (DCA4.5-5.0) layer5~14
residual (DCA5.0-5.5) layer5~14
residual (DCA5.5-6.0) layer5~14
residual (DCA6.0-6.5) layer5~14
residual (DCA6.5-7.0) layer5~14
residual (DCA7.0-7.5) layer5~14
residual (DCA7.5-8.0) layer5~14
residual (DCA8.0-8.5) layer5~14
residual (DCA8.5-9.0) layer5~14
entry
residual [mm]

Top side


residual (DCA0.0-0.5) layer5~14
residual (DCA0.5-1.0) layer5~14
residual (DCA1.0-1.5) layer5~14
residual (DCA1.5-2.0) layer5~14
residual (DCA2.0-2.5) layer5~14
residual (DCA2.5-3.0) layer5~14
residual (DCA3.0-3.5) layer5~14
residual (DCA3.5-4.0) layer5~14
residual (DCA4.0-4.5) layer5~14
residual (DCA4.5-5.0) layer5~14
residual (DCA5.0-5.5) layer5~14
residual (DCA5.5-6.0) layer5~14
residual (DCA6.0-6.5) layer5~14
residual (DCA6.5-7.0) layer5~14
residual (DCA7.0-7.5) layer5~14
residual (DCA7.5-8.0) layer5~14
residual (DCA8.0-8.5) layer5~14
residual (DCA8.5-9.0) layer5~14
entry
residual [mm]

Bottom side

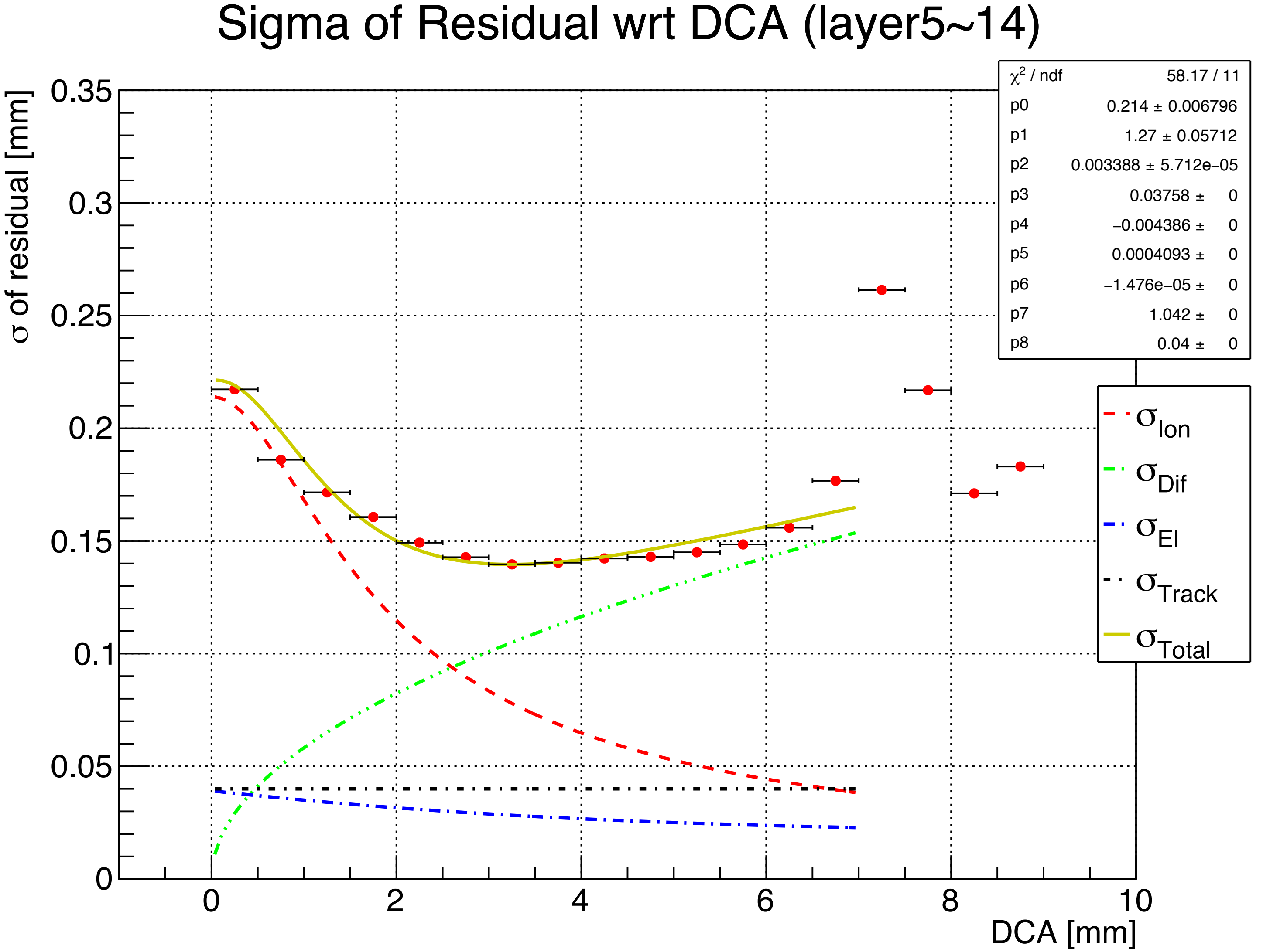


My research

$$N_p = 7.7 \pm 0.3 \text{ cm}^{-1}$$
$$D = 190 \pm 2\ \mu\text{m} \cdot \text{cm}^{-1}$$

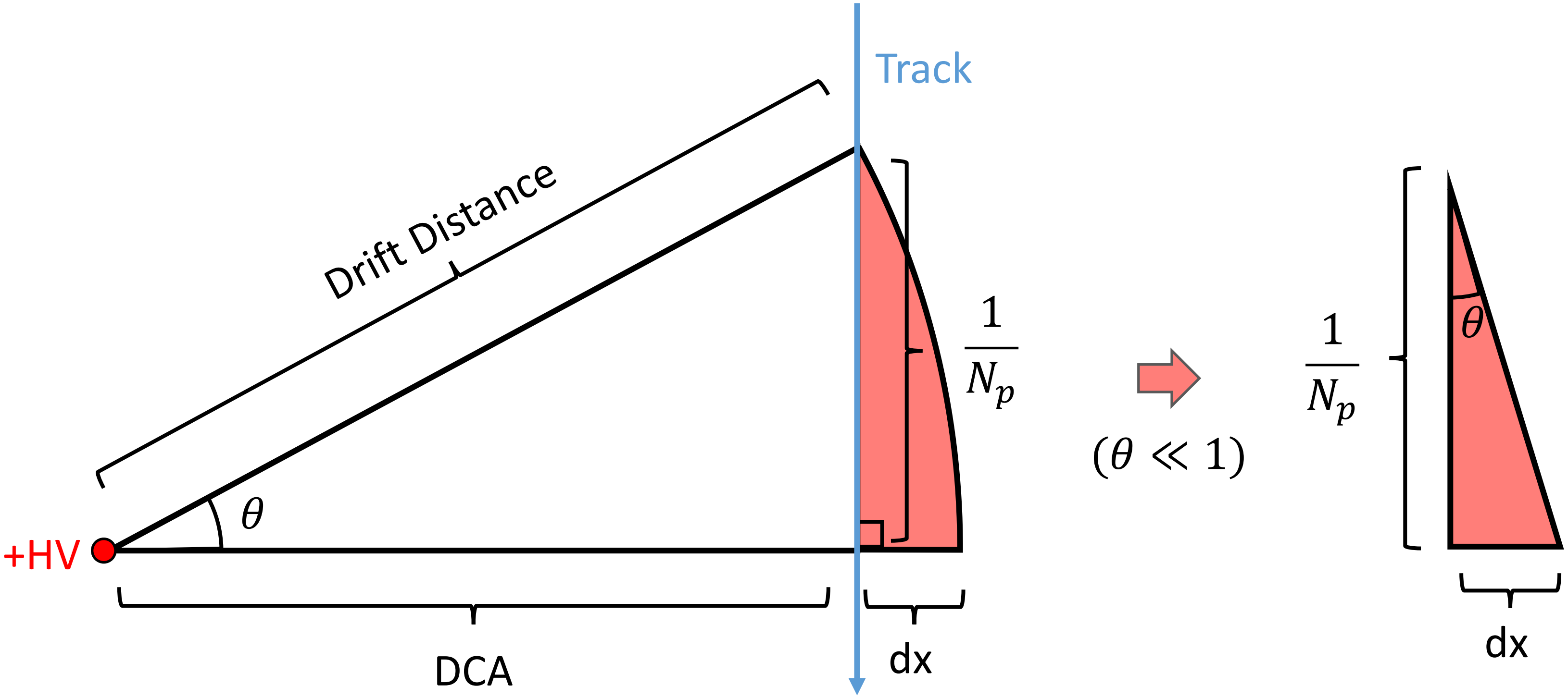
KLOE

$$N_p = 12.3 \pm 0.2 \text{ cm}^{-1}$$
$$D \sim 140\ \mu\text{m} \cdot \text{cm}^{-1}$$



My research $N_p = 7.9 \pm 0.4\ \mathrm{cm}^{-1}$, $D = 184 \pm 2\ \mu\mathrm{m} \cdot \mathrm{cm}^{-1}$

KLOE $N_p = 12.3 \pm 0.2\ \mathrm{cm}^{-1}$, $D \sim 140\ \mu\mathrm{m} \cdot \mathrm{cm}^{-1}$

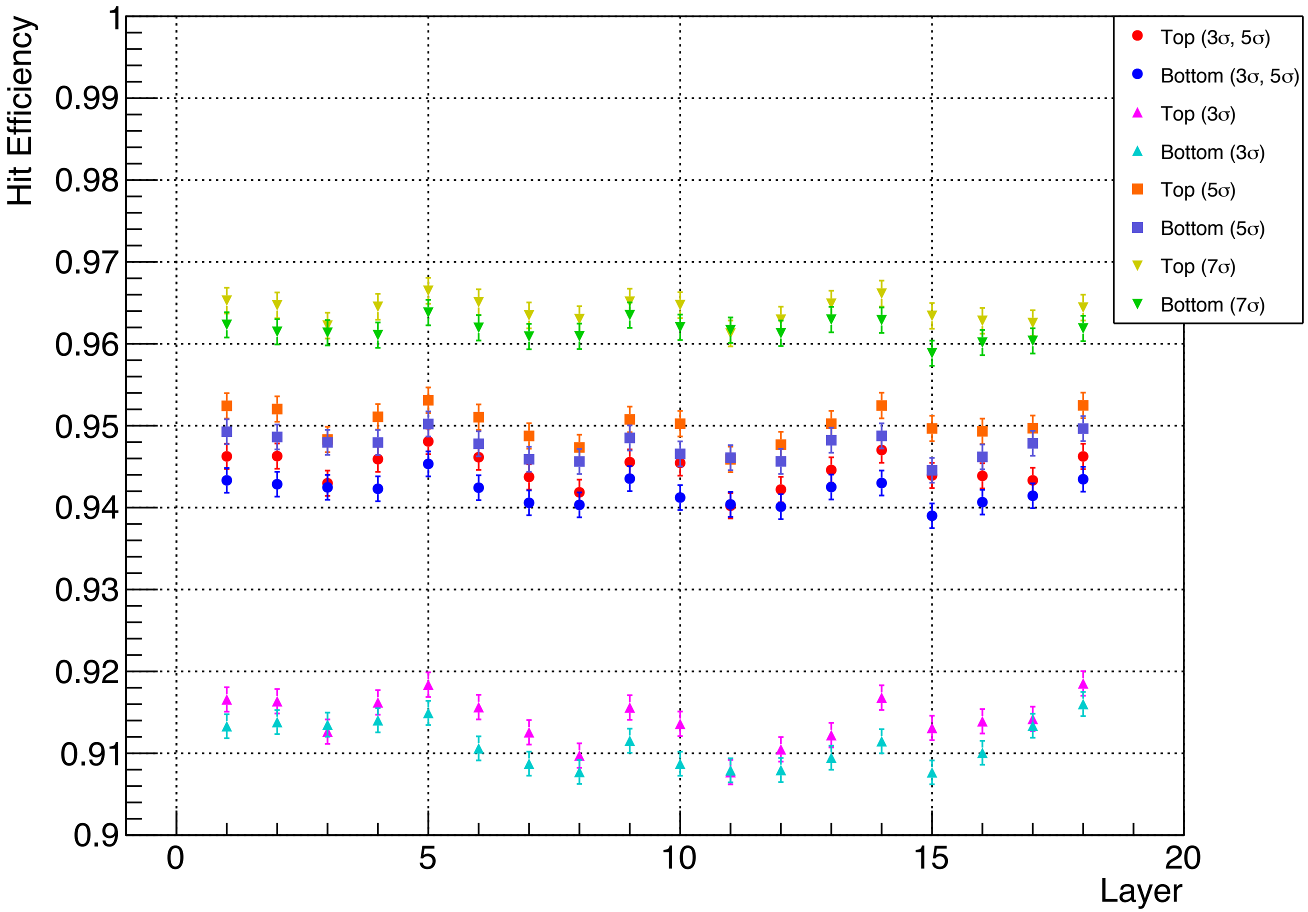


$$dx = \text{Drift Distance} - \text{DCA}$$

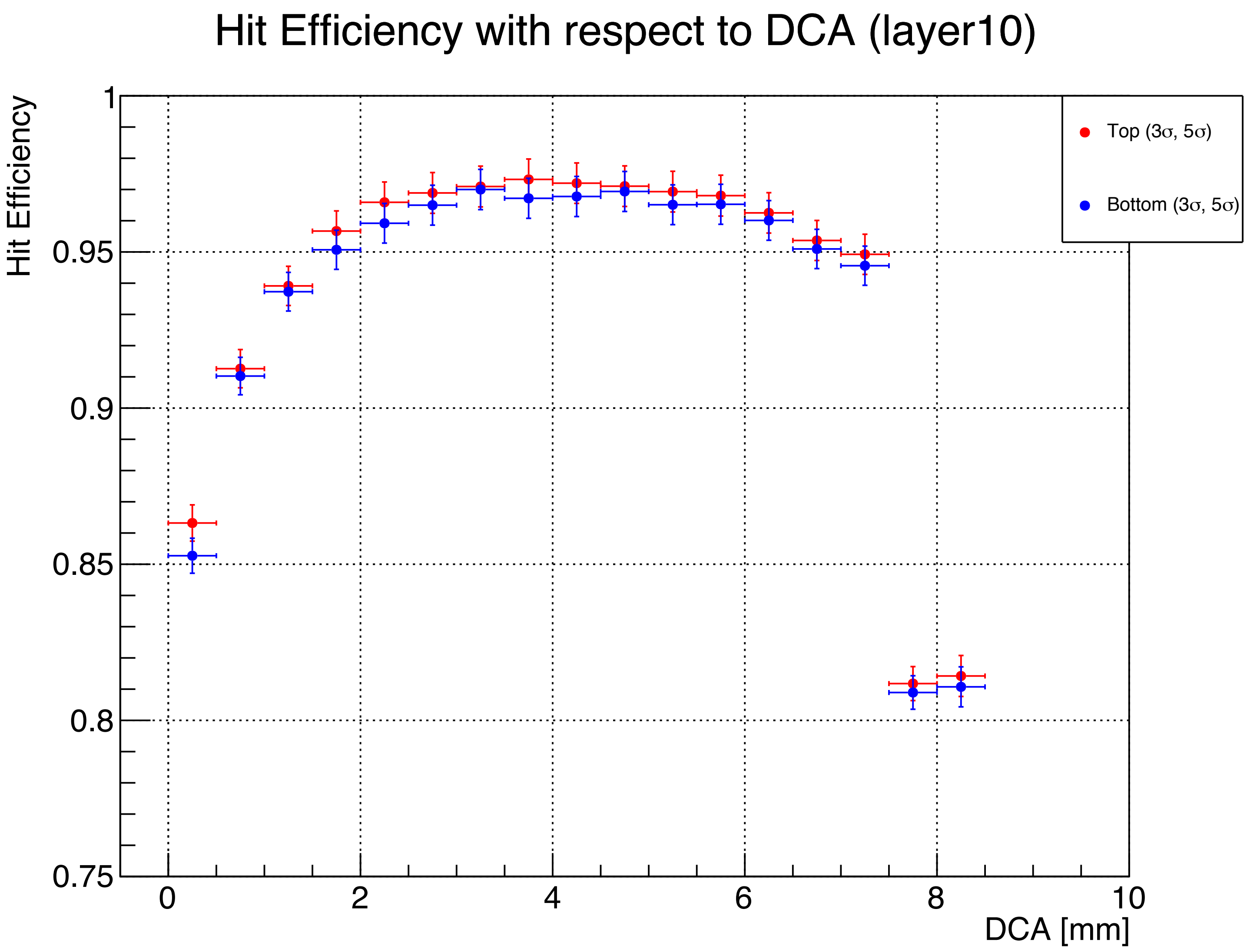
$$\sim \frac{1}{N_p}\tan\theta\ (\theta \ll 1) \sim \frac{1}{N_p}\sin\theta\ (\theta \ll 1) = \frac{1}{N_p}\sin\left(\arctan\frac{1/N_p}{\text{DCA}}\right)$$

$$\boxed{f(x)_{ion} = p_0 \sin\left(\arctan\frac{p_1}{x}\right)}$$

Hit Efficiency

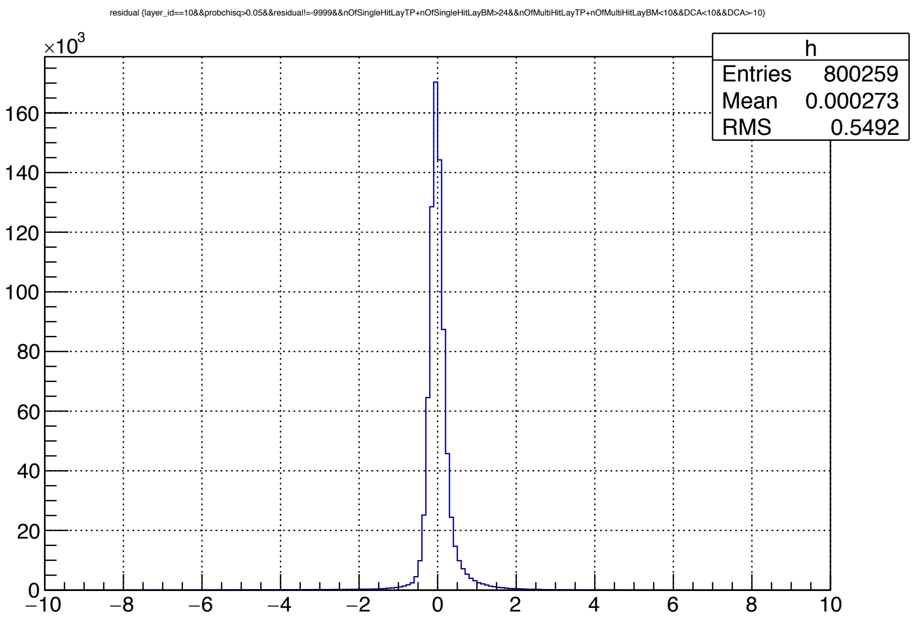


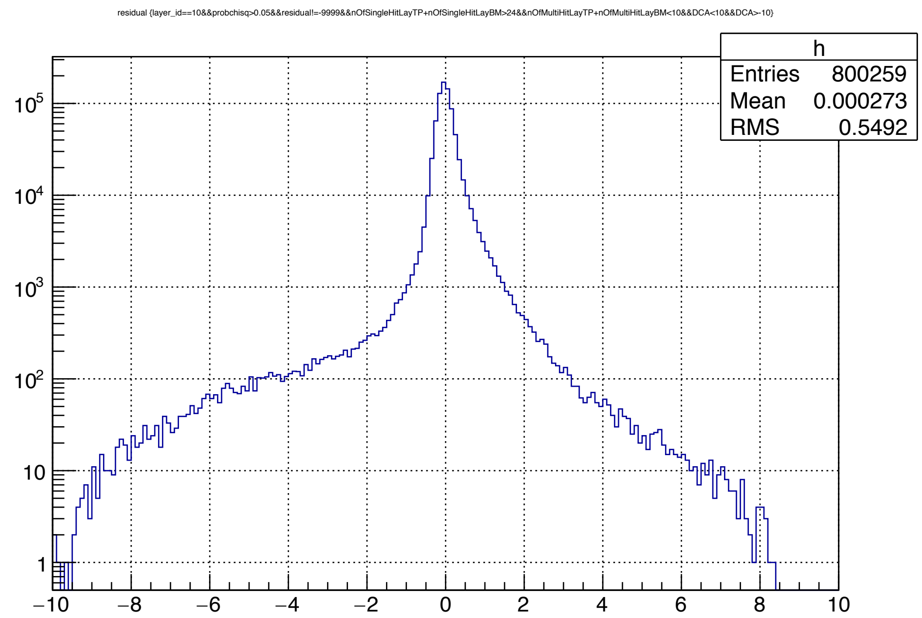
CDC の位置	ヒット検出効率のレイヤー平均 %			
	$3\sigma_{residual}$	$3\sigma_{residual}$ & $5\sigma_{residual}$	$5\sigma_{residual}$	$7\sigma_{residual}$
上方	91.4	94.5	95.0	96.4
下方	91.1	94.2	95.0	96.2



Hit Efficiency with respect to DCA (layer10)
Hit Efficiency
1
0.95
0.9
0.85
0.8
0.75
0
2
4
6
8
10
DCA [mm]
Top (3σ, 5σ)
Bottom (3σ, 5σ)

Residual distribution of layer 10





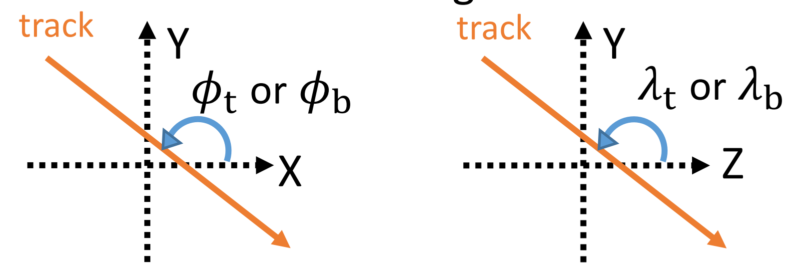
The Way to Check the Position of the Track

Cosmic Ray should pass through top side and bottom side of CDC.

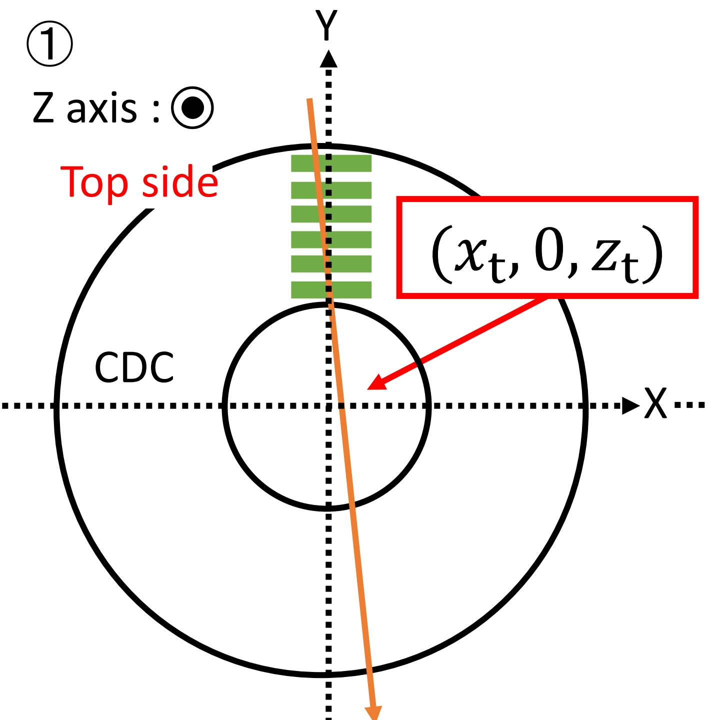
Compare:

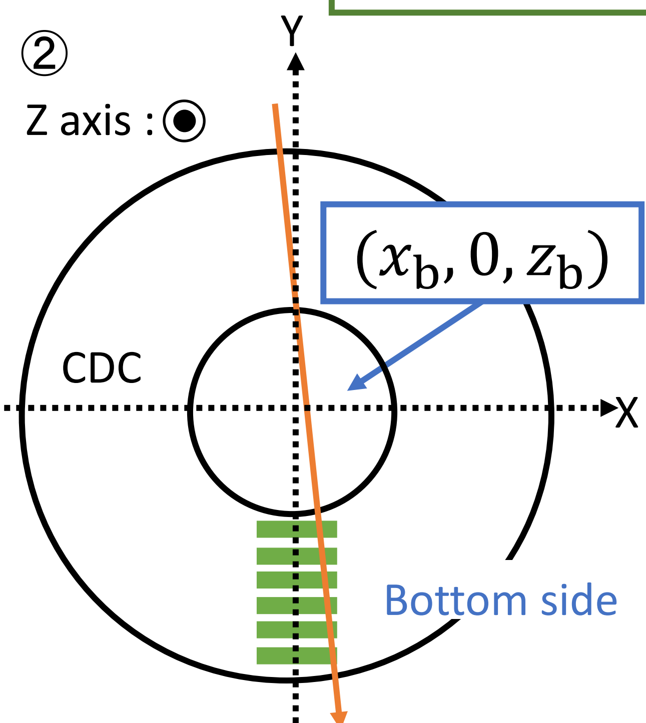
① Track reconstructed by top
② Track reconstructed by bottom

Definition of Incident Angles



Angle in X-Y plane   Angle in Y-Z plane

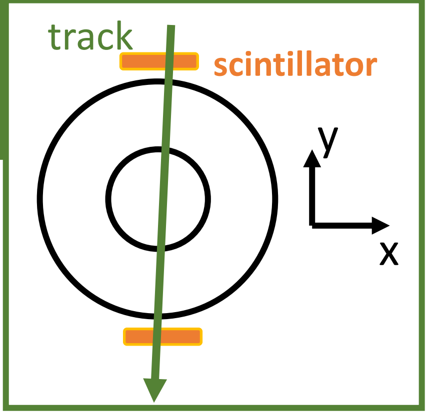




Evaluate these Values

$$\Delta x = x_\mathrm{t} - x_\mathrm{b}$$
$$\Delta z = z_\mathrm{t} - z_\mathrm{b}$$
$$\Delta \phi = \phi_\mathrm{t} - \phi_\mathrm{b}$$
$$\Delta \lambda = \lambda_\mathrm{t} - \lambda_\mathrm{b}$$

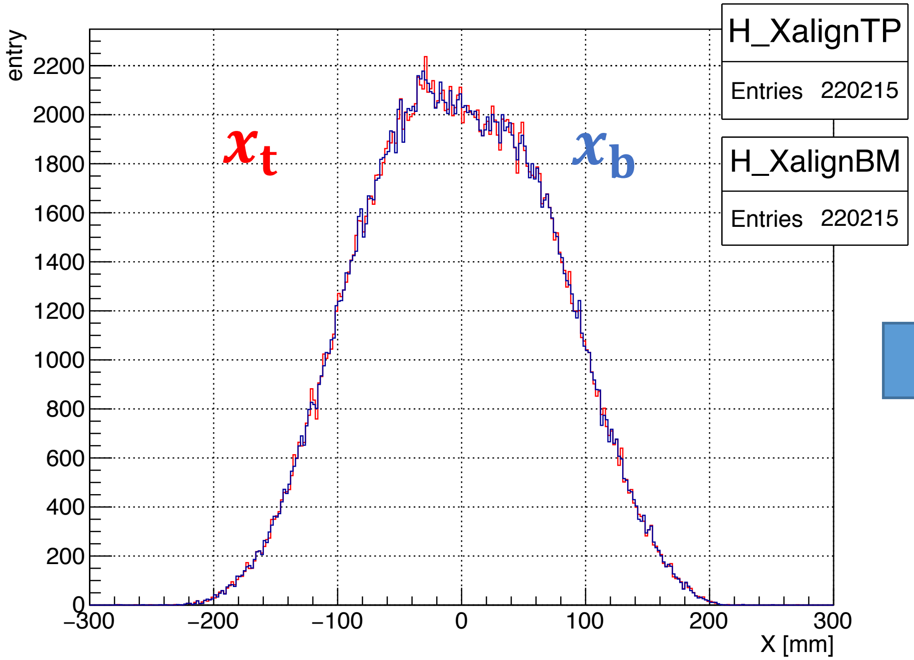
Comparison of the Position of the X

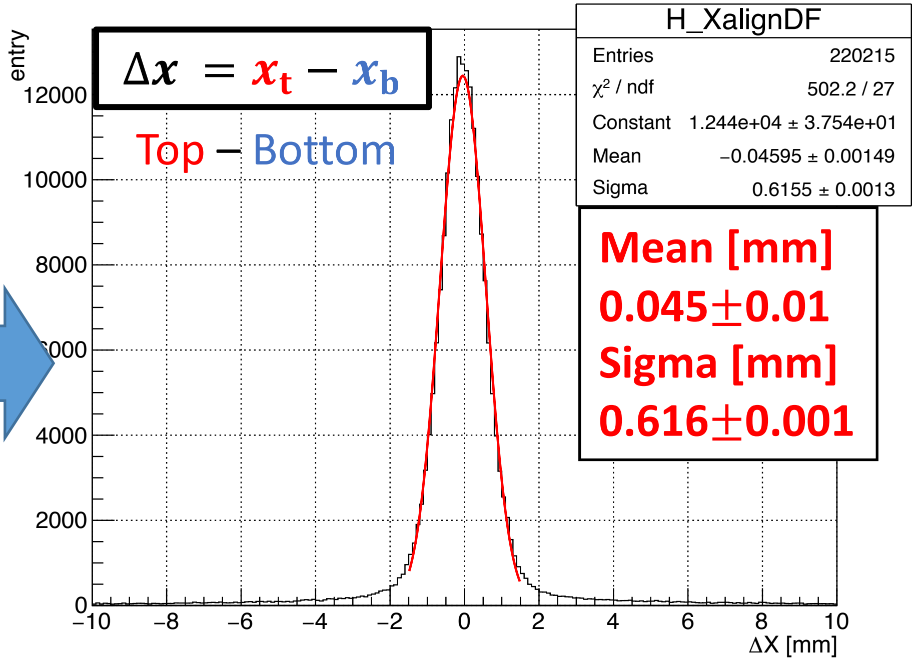


- Distribution of X (Y=0).

Top side x_t : X position of tracks made from **upper** readout.

Bottom side x_b : X position of tracks made from **lower** readout.





Mean [mm]
0.045±0.01
Sigma [mm]
0.616±0.001

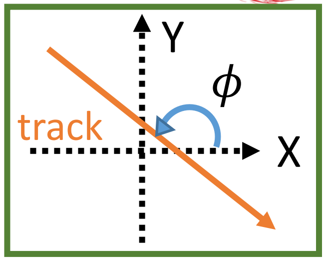
- Mean of Δx is 0.045±0.01(stat.)±0.03(syst.) mm

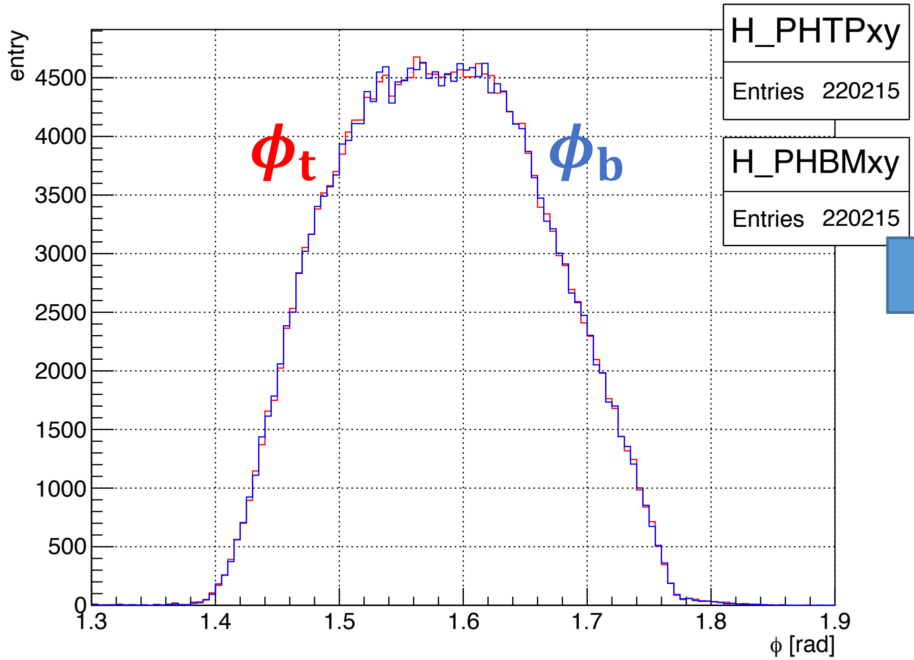
Comparison of the Incident Angle ϕ (X-Y Plane)

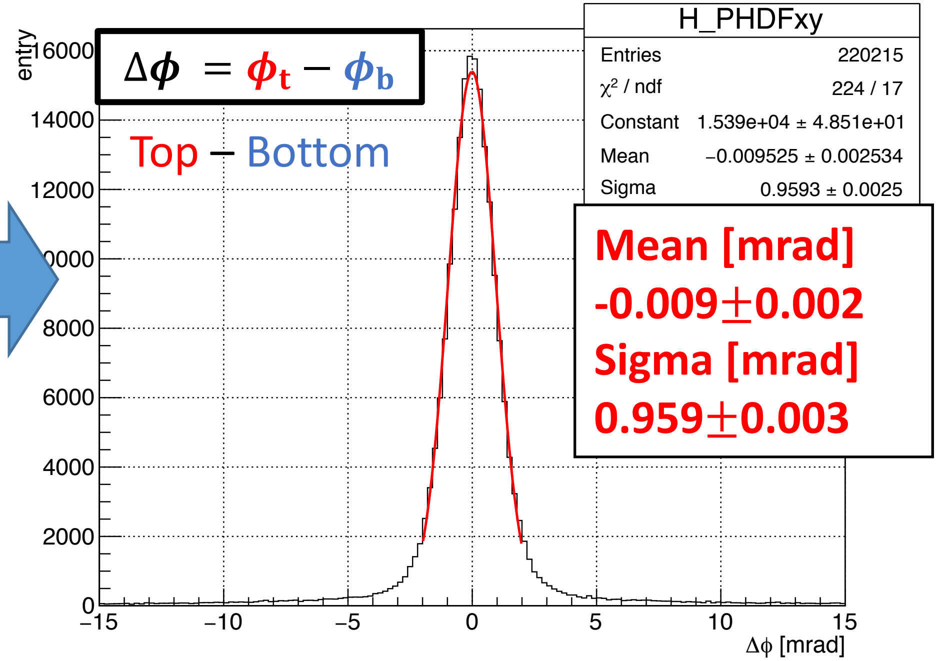
- Distribution of incident angle ϕ (X-Y plane).

Top side ϕ_t : Incident angle of tracks made from **upper** readout.

Bottom side ϕ_b: Incident angle of tracks made from **lower** readout.

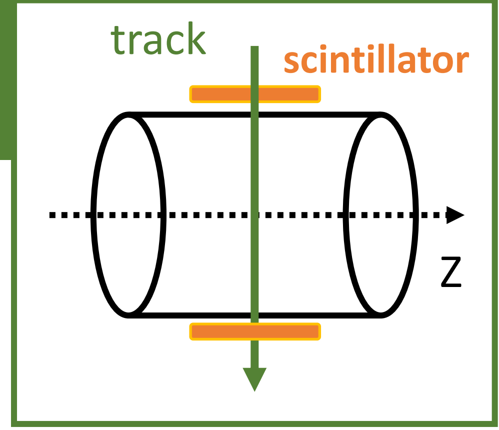






- Mean of $\Delta\phi$ is -0.009±0.002(stat.)±0.012(syst.) mrad.

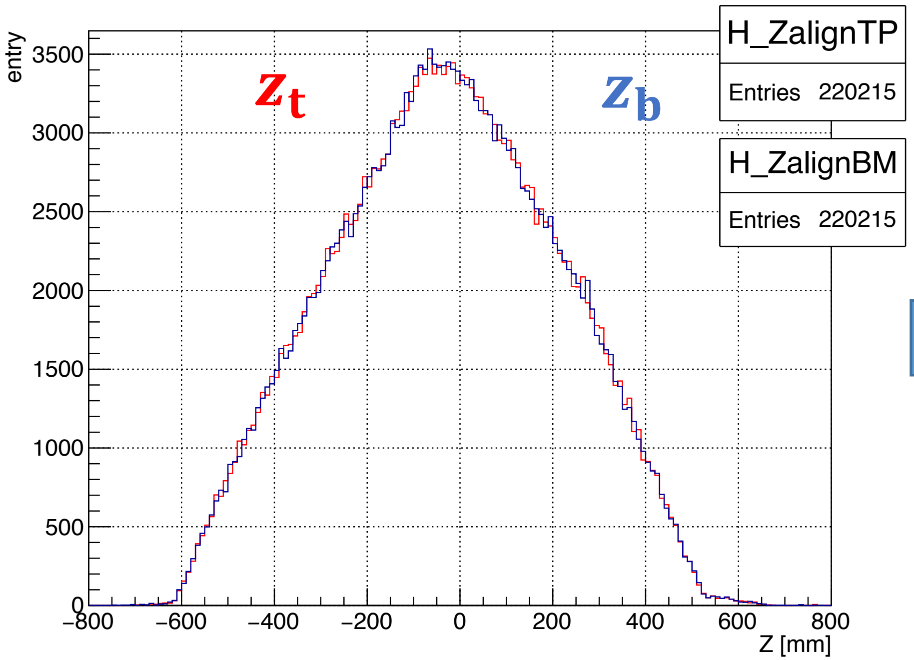
Comparison of the Position of the Z

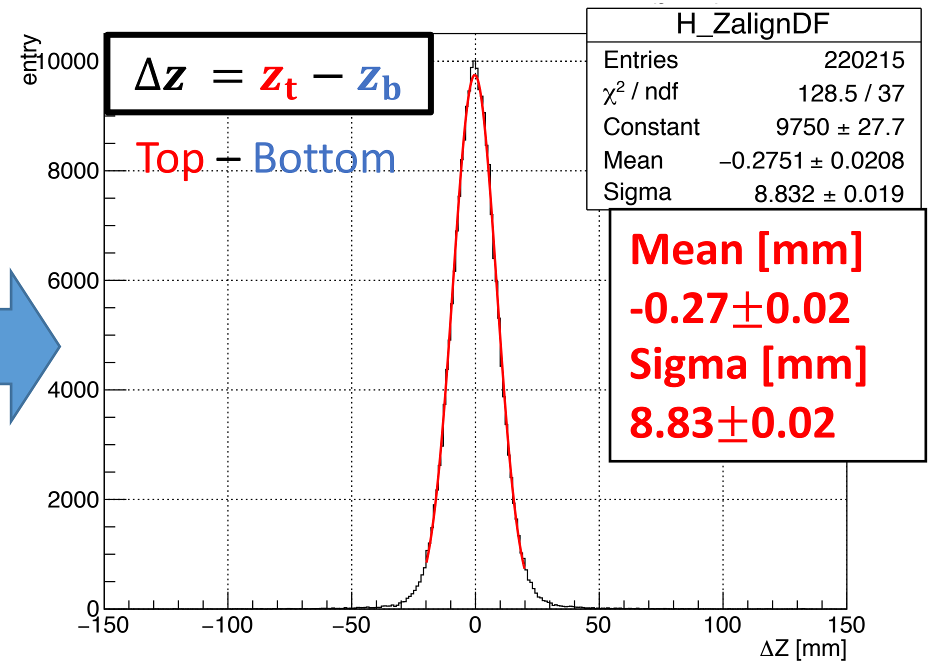


- Distribution of Z (Y=0).

Top side z_t : Z position of tracks made from **upper** readout.

Bottom side z_b : Z position of tracks made from **lower** readout.





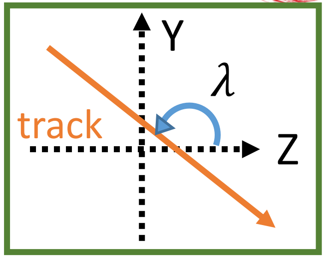
- Mean of Δz is -0.27$\pm$0.02(stat.)$\pm$0.02(syst.) mm.

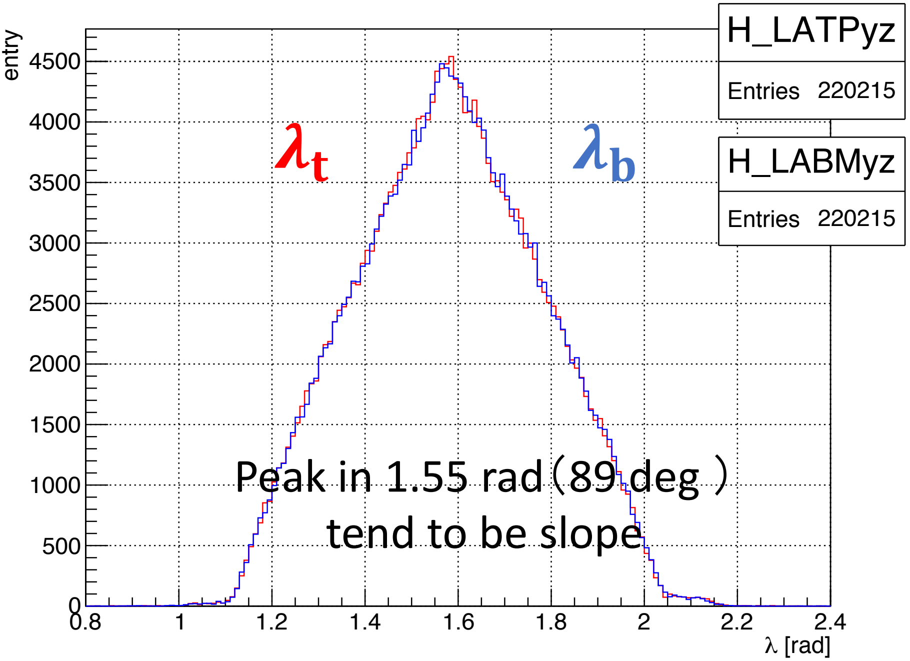
Comparison of the Incident Angle λ (Y-Z Plane)

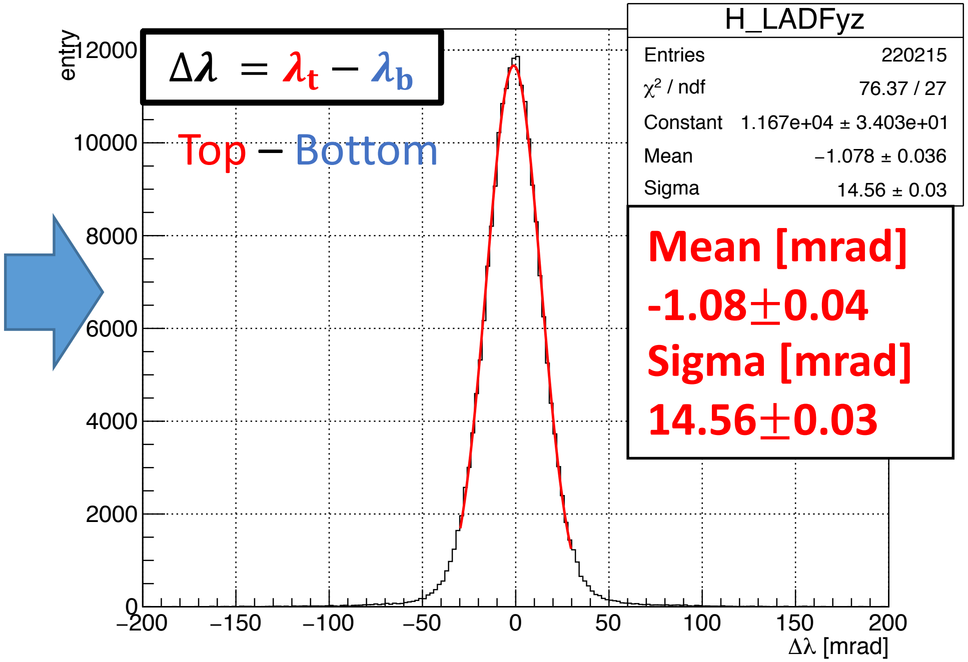
- Distribution of incident angle λ (Y-Z plane).

Top side λ_t : Incident angle of tracks made from **upper** readout.

Bottom side λ_b : Incident angle of tracks made from **lower** readout.







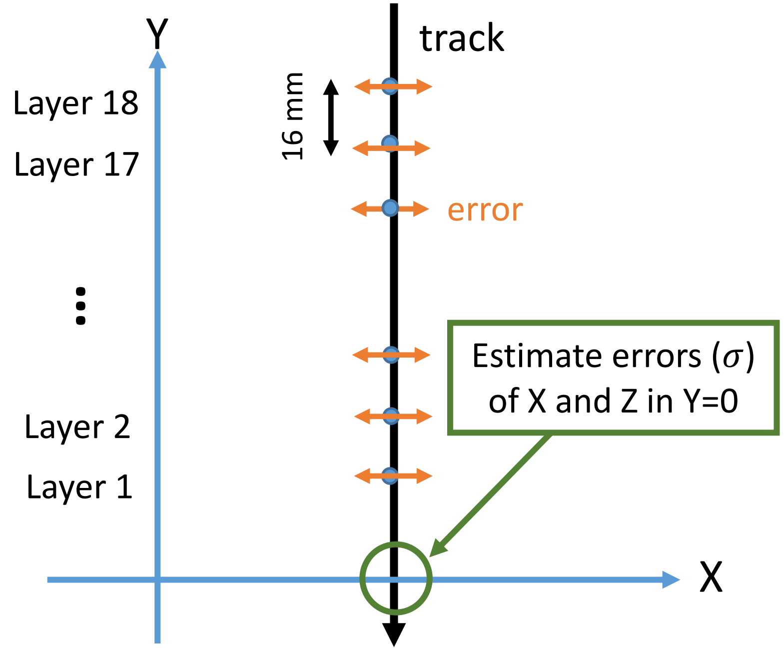
- Mean of $\Delta\lambda$ is -1.08$\pm$0.04(stat.)$\pm$0.16(syst.) mrad.

Confirmation from CDC Spatial Resolution

- Evaluate and confirm how "sigma" of Fit should be, by considering spatial resolution of CDC.

Estimation Condition

1. Assume 18 layers are located side by side parallelly with 16 [mm] space, which is the same size as a cell.
2. Use spatial resolution obtained from analysis as errors of X and Z direction.



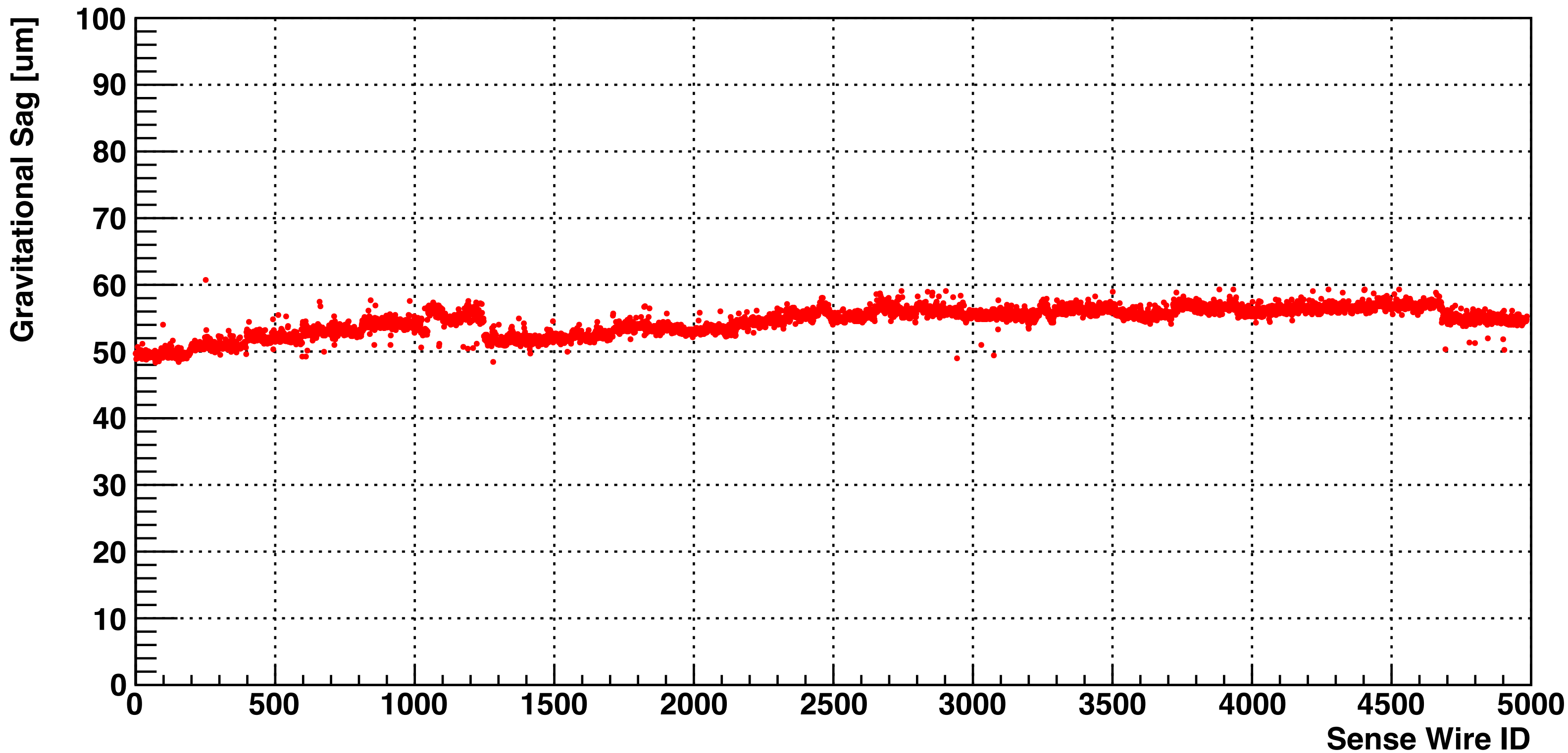
- Calculate errors (Y=0) for residual among position of wires and a straight line.

	Real data σ	Estimation σ	Ratio
$\sigma_{\Delta x}$	0.616±0.001 mm	0.539 mm	**1.14**
$\sigma_{\Delta \phi}$	0.959±0.003 mrad	0.803 mrad	**1.19**
$\sigma_{\Delta z}$	8.83±0.02 mm	8.09 mm	**1.09**
$\sigma_{\Delta \lambda}$	14.56±0.03 mrad	12.05 mrad	**1.21**

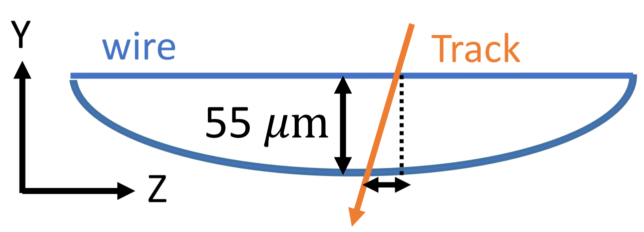
- Thinking roughly about these errors, there are small differences.
- So it can be said the width (σ) of $\Delta x, \Delta z, \Delta \phi, \Delta \lambda$ are reasonable value considering spatial resolution of CDC.

Gravitational Wire Sag (Sense Wire)

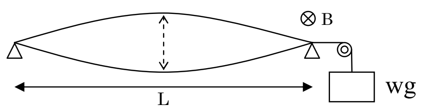
- Gravitational Wire Sag of Sense Wire at the center of CDC (Z=0 mm).



- The wire sag of each wire is around 50 ~ 58 μm.



Wire tension assurance



Resonant Frequency: $f = \frac{1}{2L}\sqrt{\frac{wg}{\rho}},$

Nominal value	Material	Diameter	Tension	Sag
Sense	(Au-)W	25 μm	50 g	~50 μm
Field	Al	126 μm	80 g	~120 μm

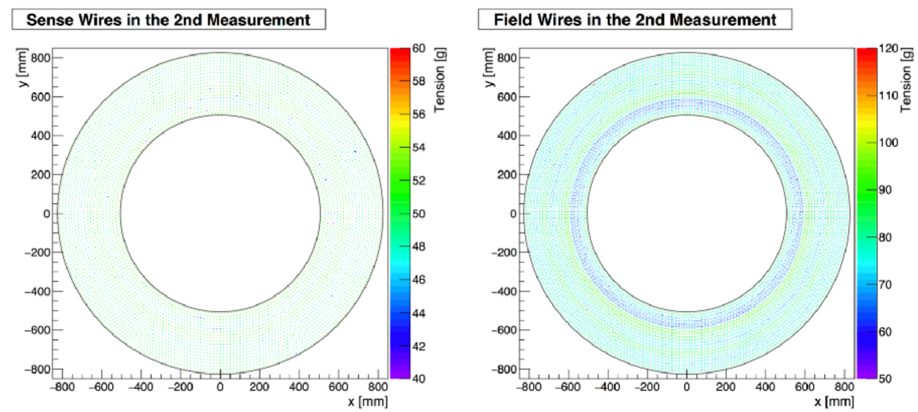
L = 1477~1593 mm

Gravitational Sag: $s = \frac{\rho L^2}{8wg}.$

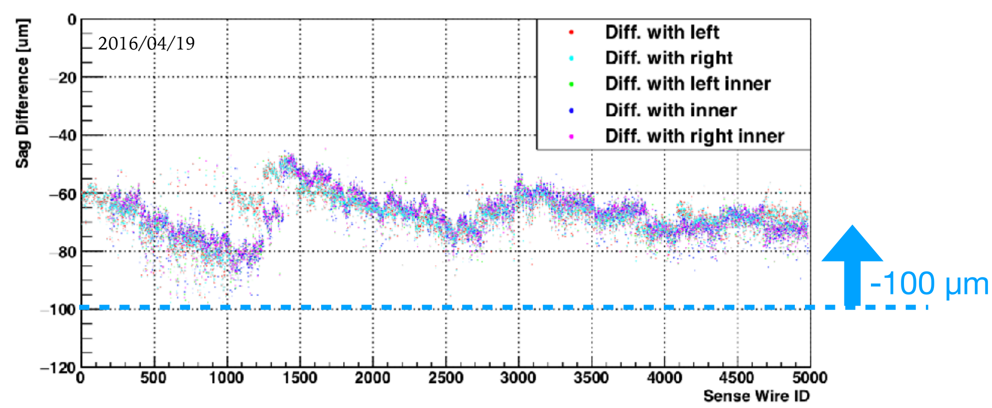
Criteria

- Sag for sense wire < 70 μm
- Sag difference with neighbor wires < 100 μm

After replacing bad wires, all the wires satisfy the criteria.



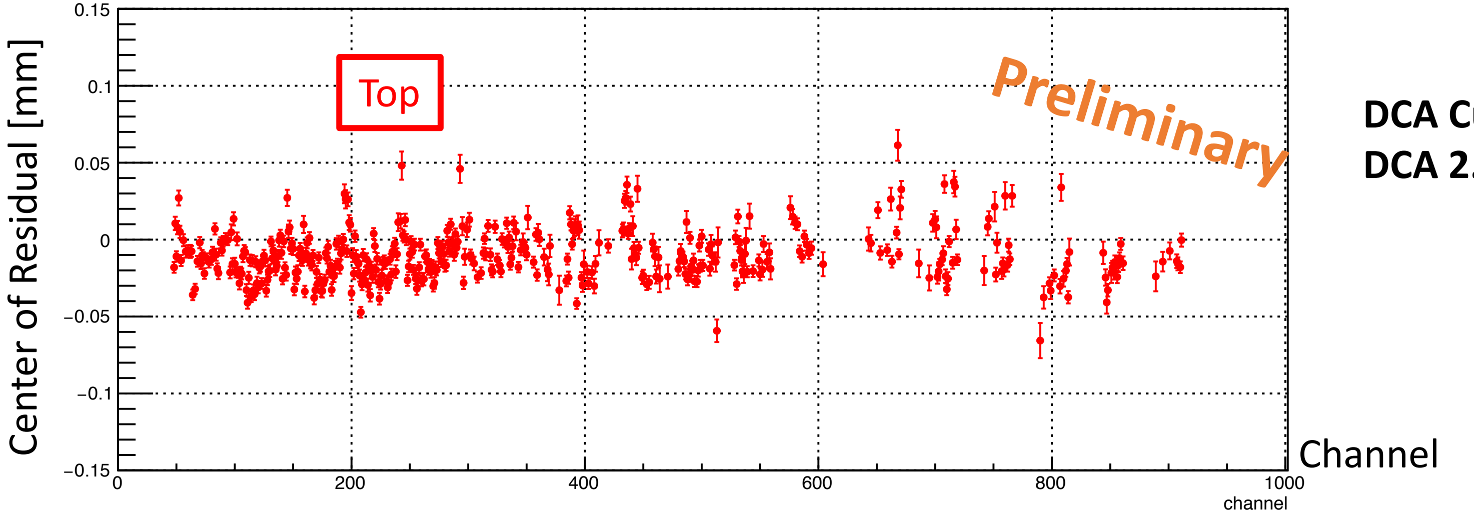
(b) Sag differences between a sense wire and surrounding field wires



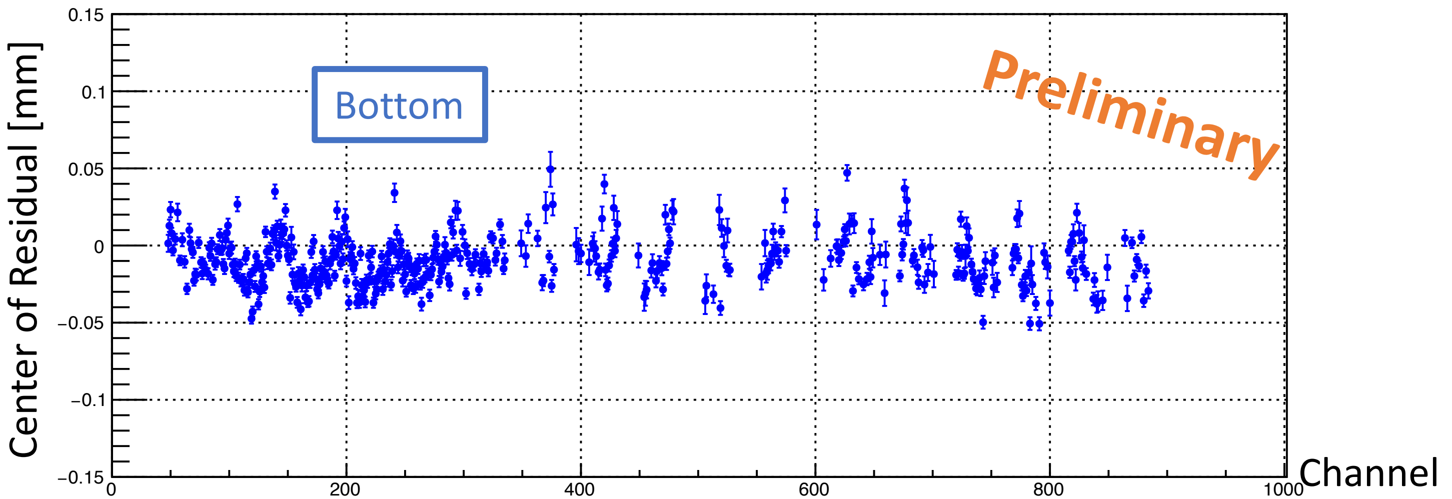
From Manabu Moritsu (KEK)

Center of Residual (wire-by-wire)

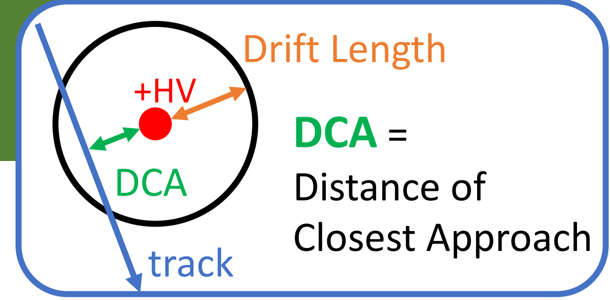
- Mean value of wire-by-wire residual is corresponding to the wire position.



DCA Cut is applied.
DCA 2.0~6.5 [mm]



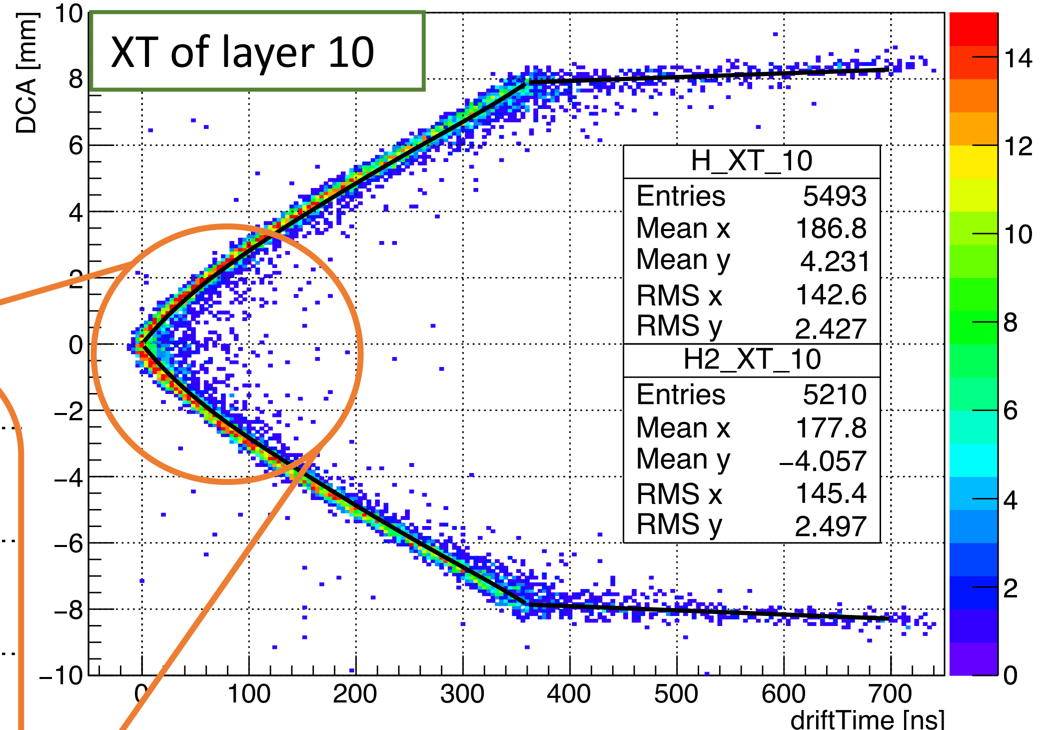
Problem in fitting of XT Curve

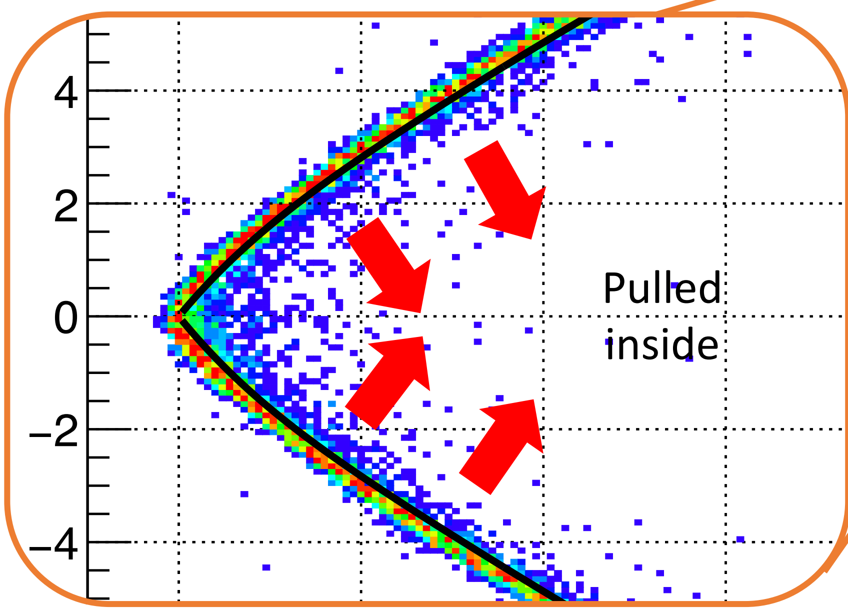


- The previous way for fitting the XT Curve.

Fit function for the XT Curve

$$f(t) = \begin{cases} 0 & t < 0\ \text{ns} \\ 5^{\text{th}}\ \text{pol} & 0\ \text{ns} \leq t < 360\ \text{ns} \\ \text{linear} & 360\ \text{ns} \leq t < 700\ \text{ns} \\ \text{N/A} & t \leq 700\ \text{ns} \end{cases}$$



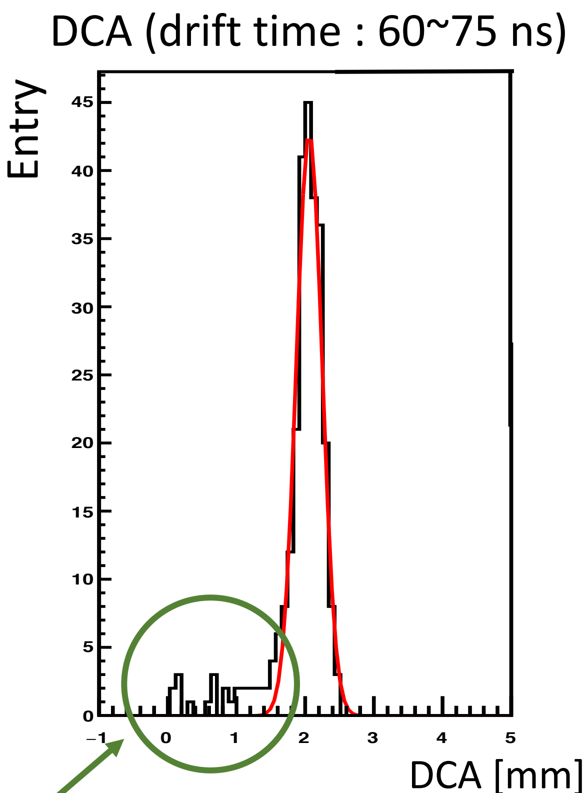


Just fit a 2D histogram with fit functions.
Fit line had been pulled inside of the XT and not been in the center (red area) of the XT.

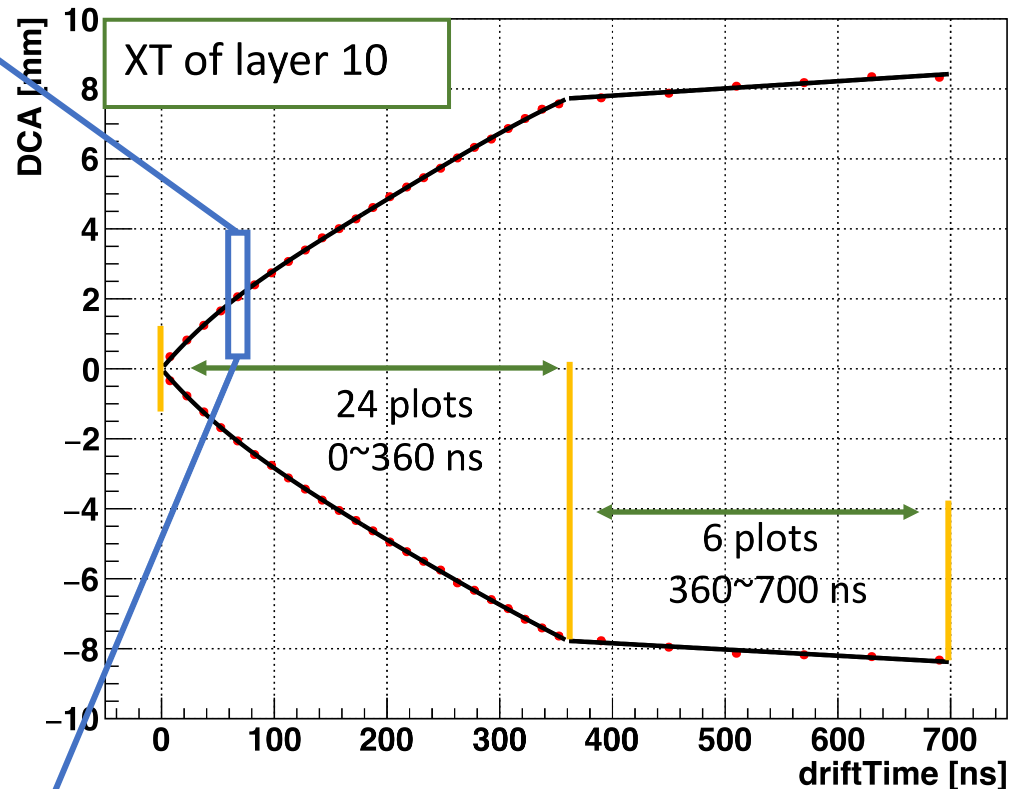
Improvement of Fitting

- XT Curve is divided by each drift time. -> make DCA distributions for each of them.
- Fit each DCA distribution with gaussian and obtain the peak of it.

An example of DCA distribution



Exclude the effect of inner entries from the gaussian fitting



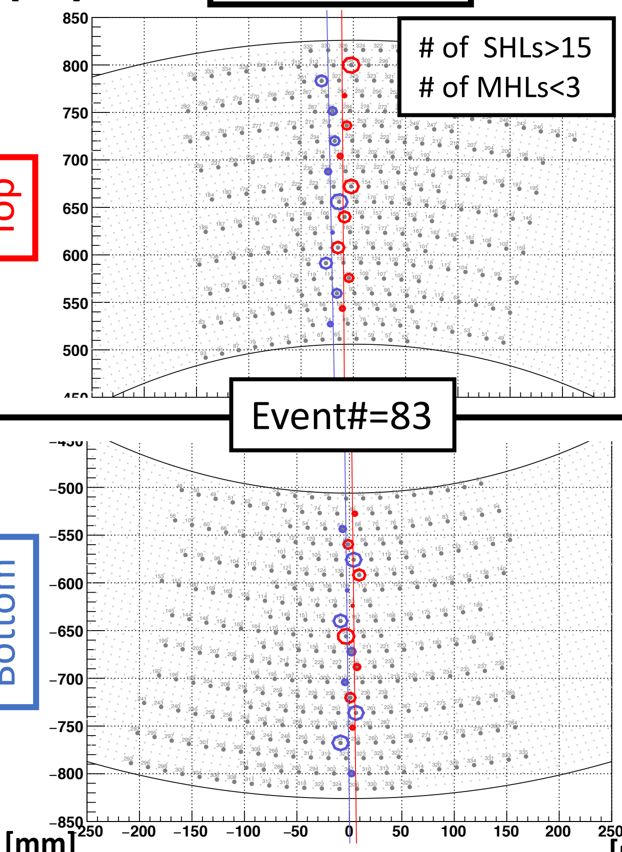
- Make XT Curve again by using only peak of the DCA.
- Then fit it again and apply this to the real XT.

Tracking Efficiency

- Checked how many events can be drawn the track.
- Mainly 3 types of tracks were found in the Cosmic Ray Data (total 52248 events).

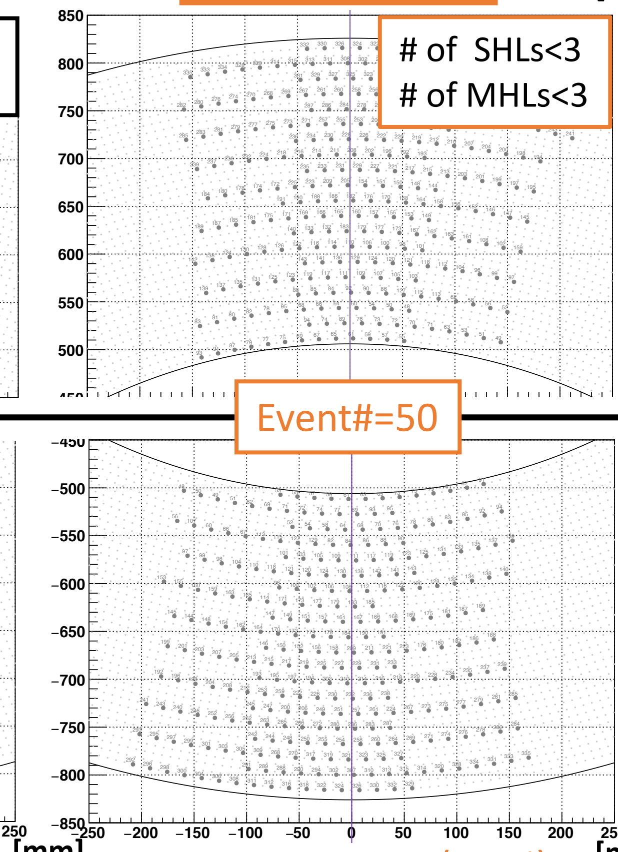
Top / Bottom

Clear Event



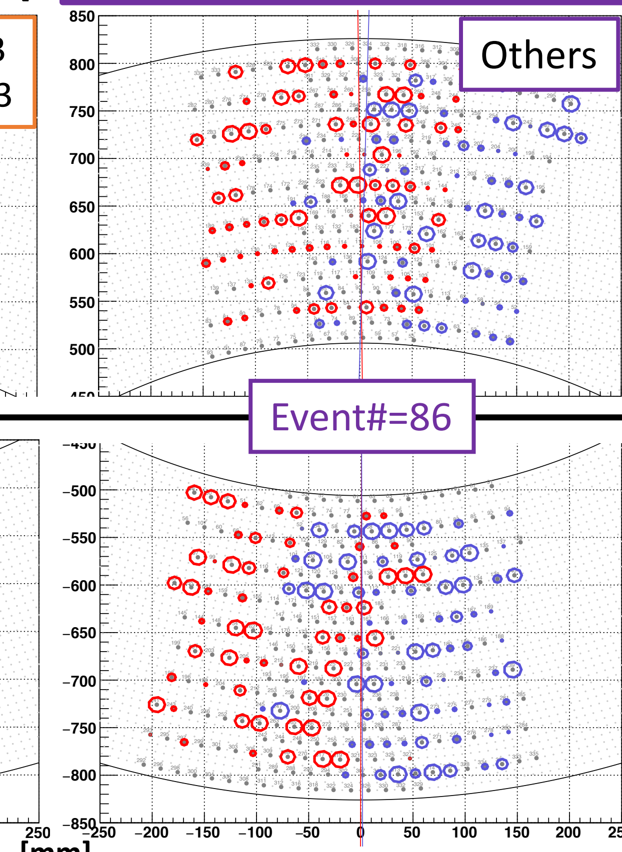
Top : 29994 (57.4%)
Bottom : 29952 (57.3%)

Accidental Hit



Top : 4017 (7.7%)
Bottom : 4463 (8.5%)

Noise or Crosstalk like Event

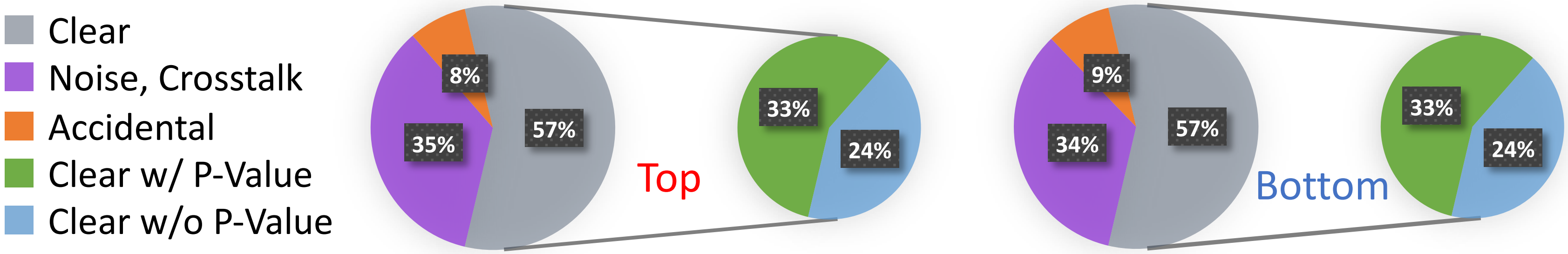


Top : 18237 (34.9%)
Bottom : 17833 (34.1%)

Total Number of Events = 52248 ➡ About 57 % of events are available without P-Value cut.

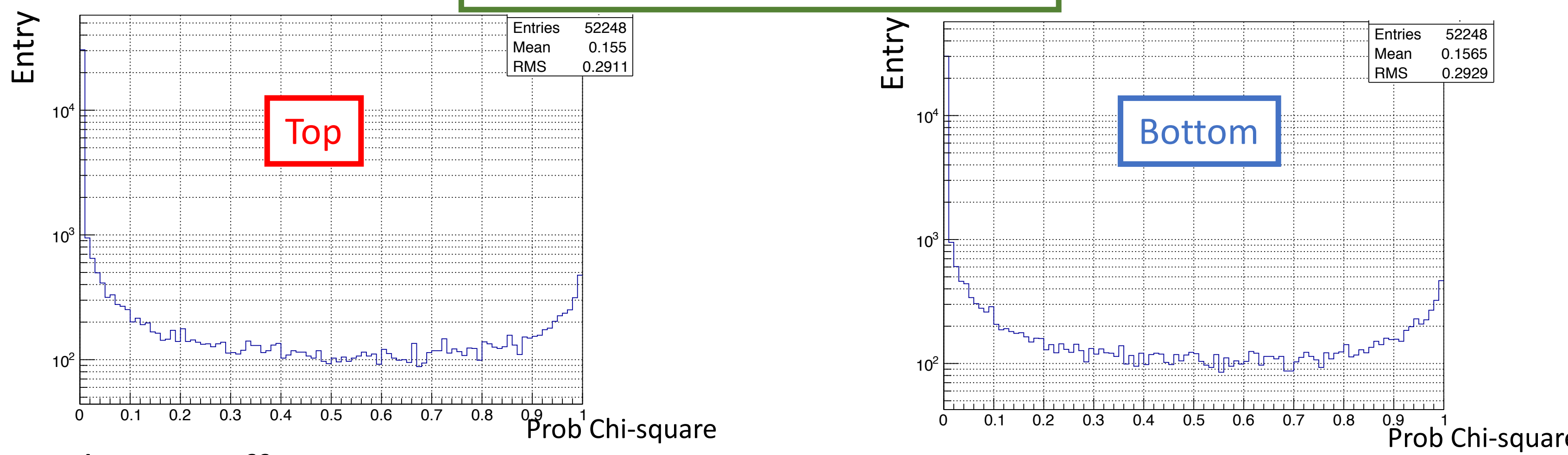
P-Value Cut Efficiency

- To pick up really clear events, P-Value cut is used for the analysis.



- From these graphs, even though tracks look clear in the event display, half of them are removed by P-Value cut of 3D tracking result.

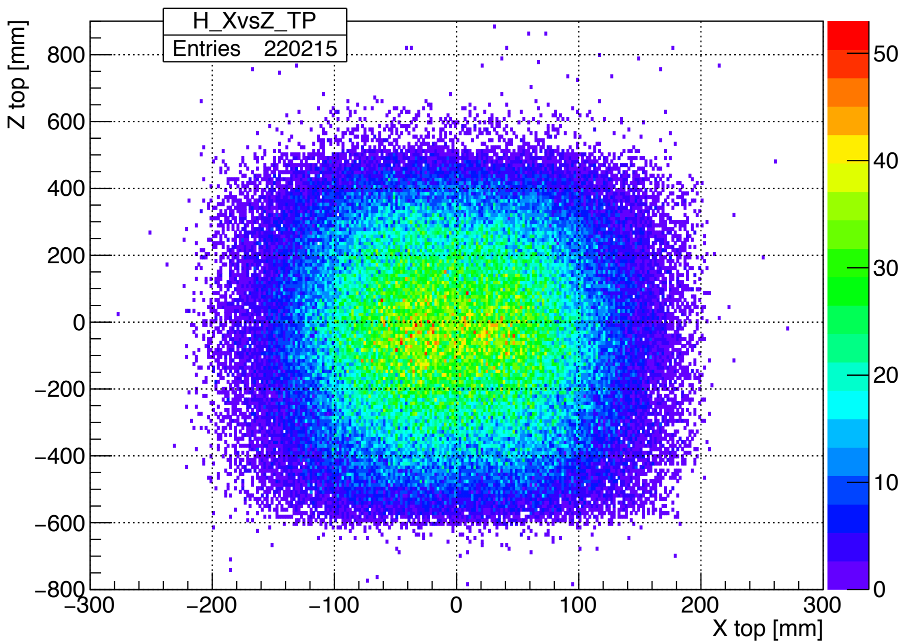
Distribution of Prob Chi-square



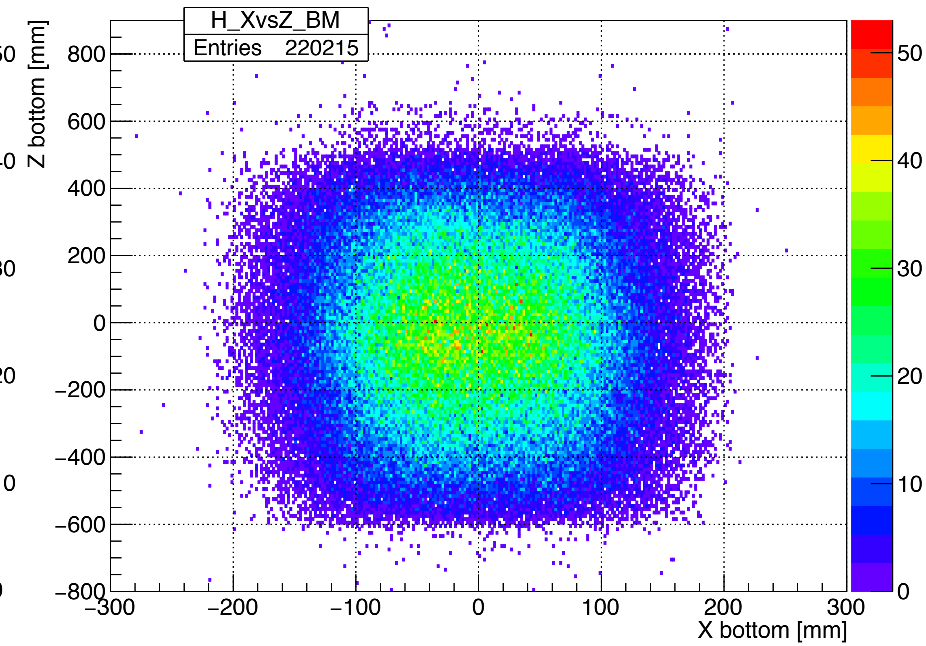
- The P-Value Cut Efficiency is,

$$\text{P Value Cut Efficiency} = \frac{\text{P Value Cut Events}}{\text{Clear Events}} \times 100 = \begin{cases} \text{Top} & : 42.23\ \%\ (12666\ \text{events}) \\ \text{Bottom} & : 42.19\ \%\ (12638\ \text{events}) \end{cases}$$

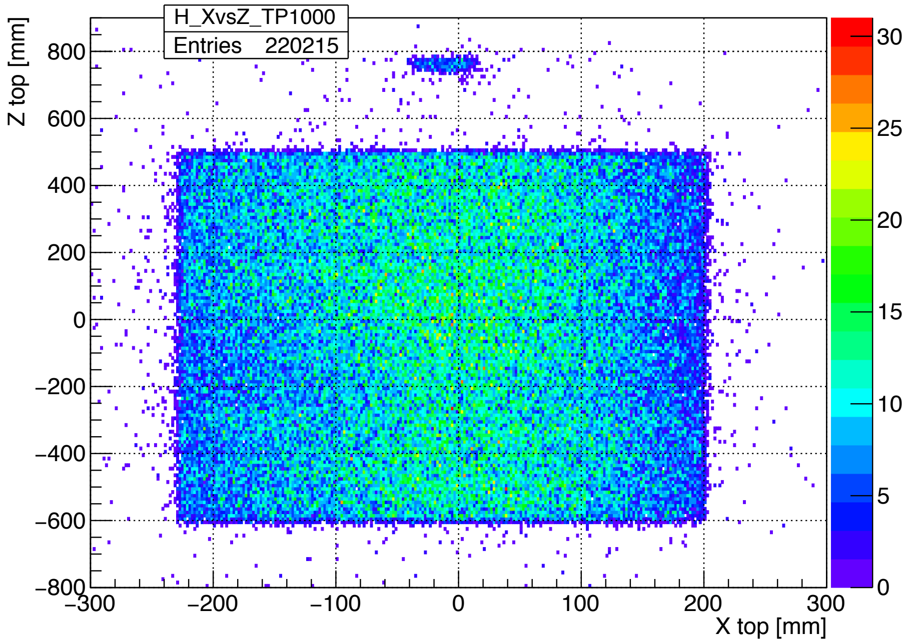
x vs z (y = 0 mm, top)



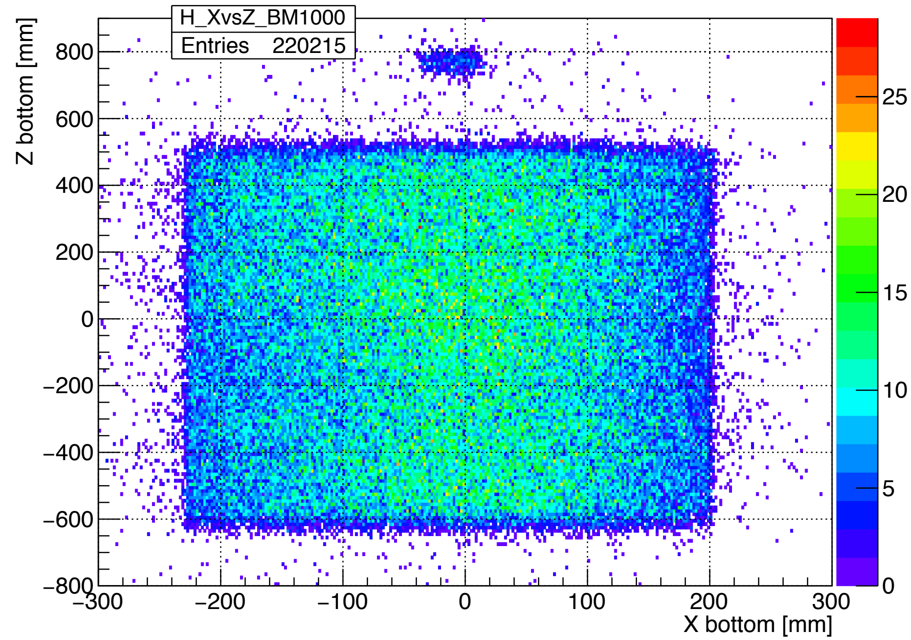
x vs z (y = 0 mm, bottom)



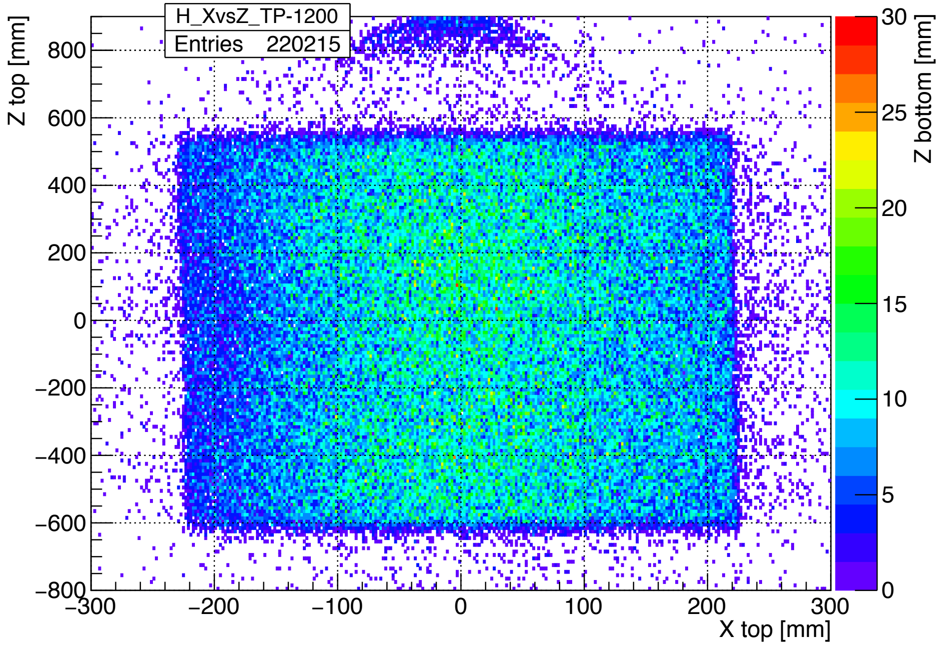
x vs z (y = 1000 mm, top)



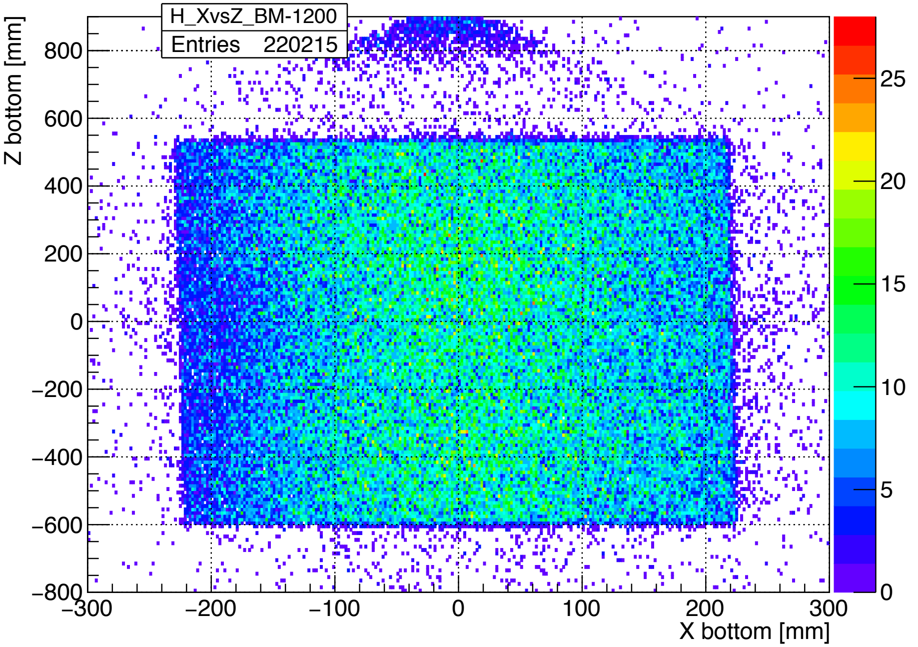
x vs z (y = 1000 mm, bottom)

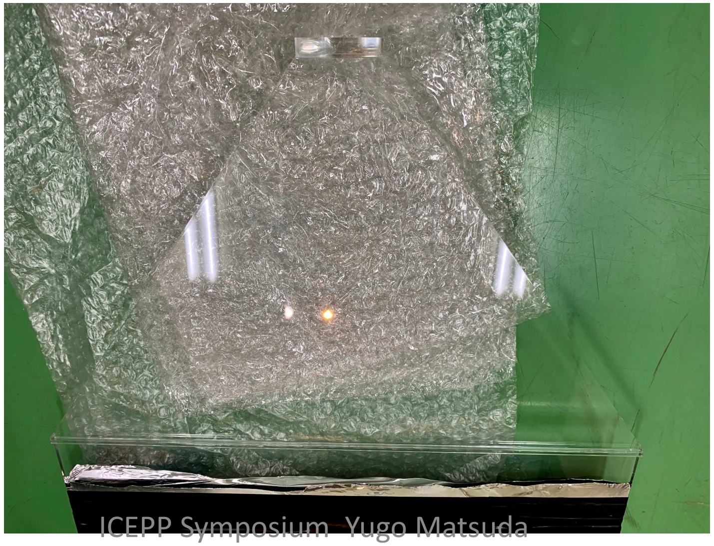


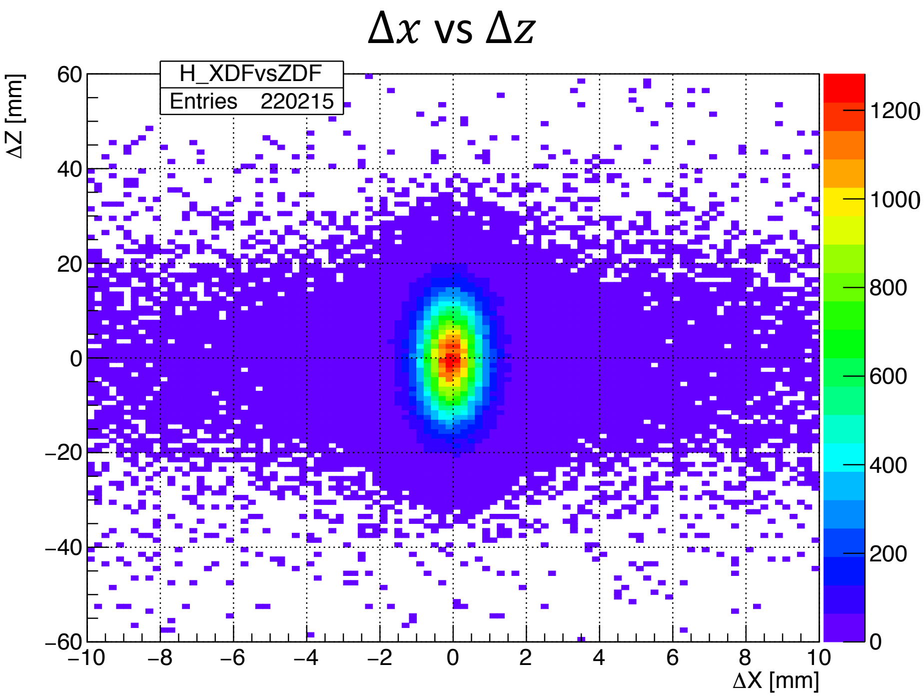
x vs z (y = -1200 mm, top)

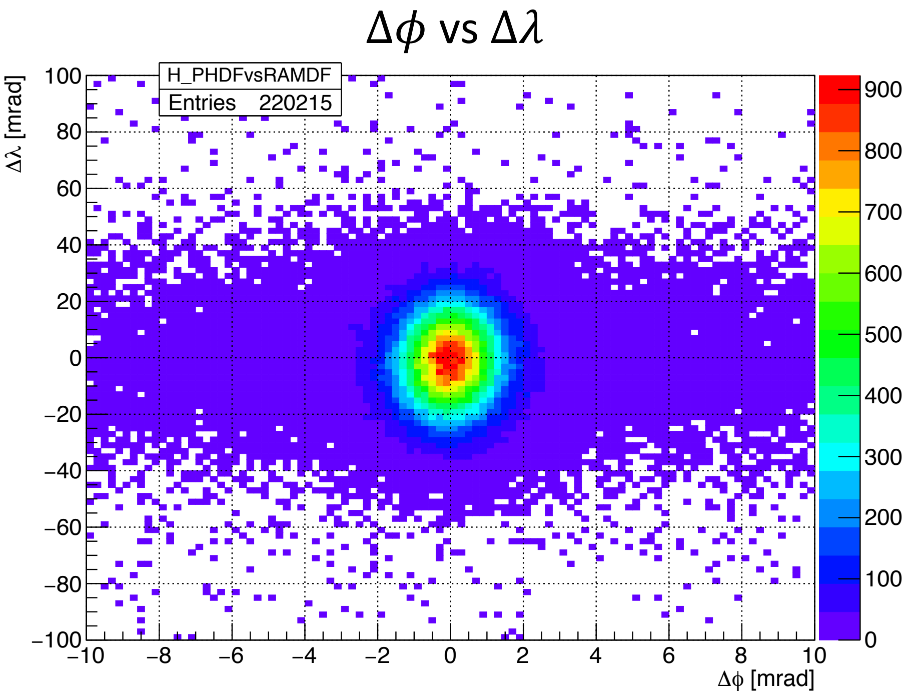


x vs z (y = -1200 mm, bottom)

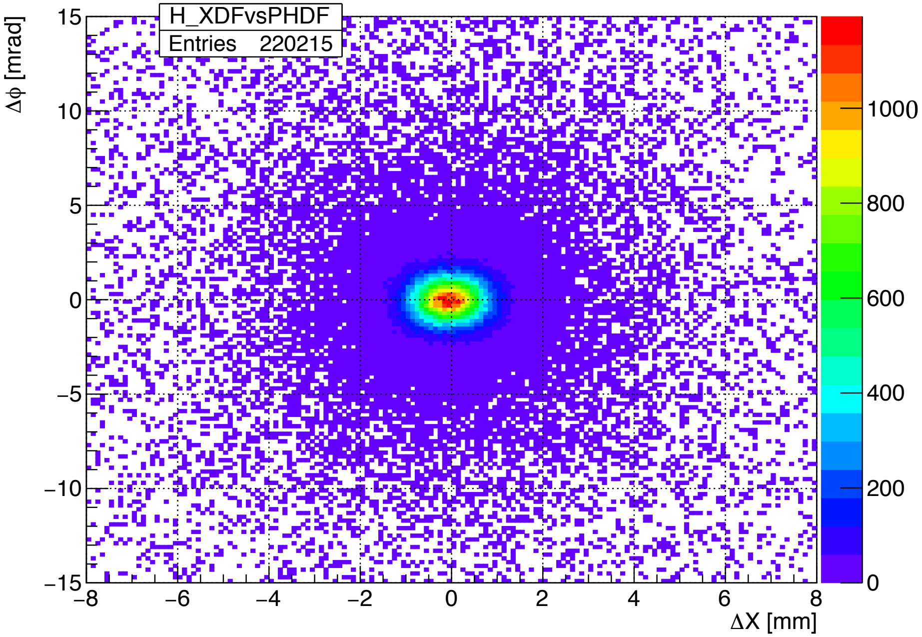




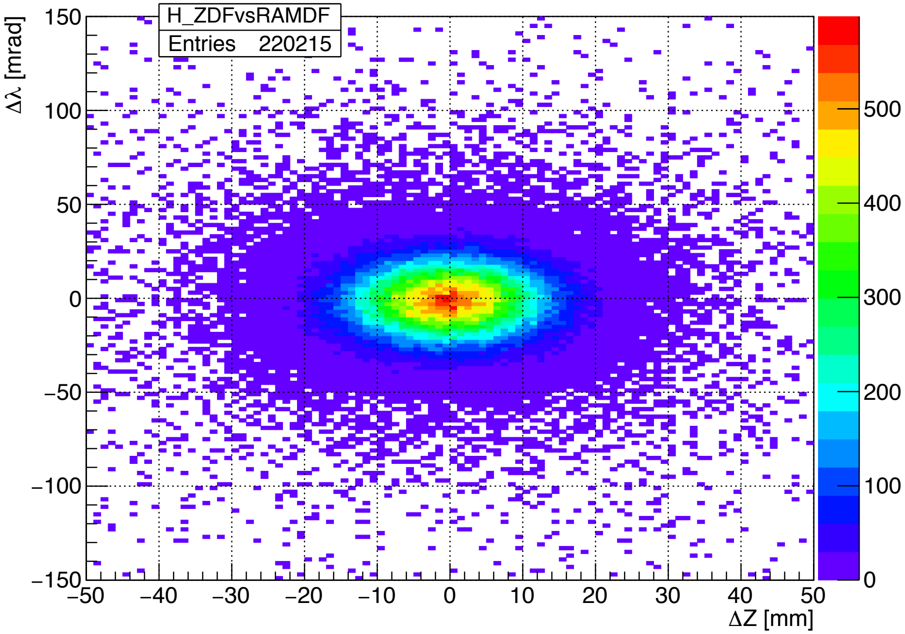

Δx vs Δz
H_XDFvsZDF
Entries 220215
ΔZ [mm]
ΔX [mm]
60
40
20
0
−20
−40
−60
−10
−8
−6
−4
−2
0
2
4
6
8
10
1200
1000
800
600
400
200
0


$\Delta \phi$ vs $\Delta \lambda$
H_PHDFvsRAMDF
Entries 220215
Δλ [mrad]
Δϕ [mrad]
100
80
60
40
20
0
−20
−40
−60
−80
−100
−10
−8
−6
−4
−2
0
2
4
6
8
10
900
800
700
600
500
400
300
200
100
0

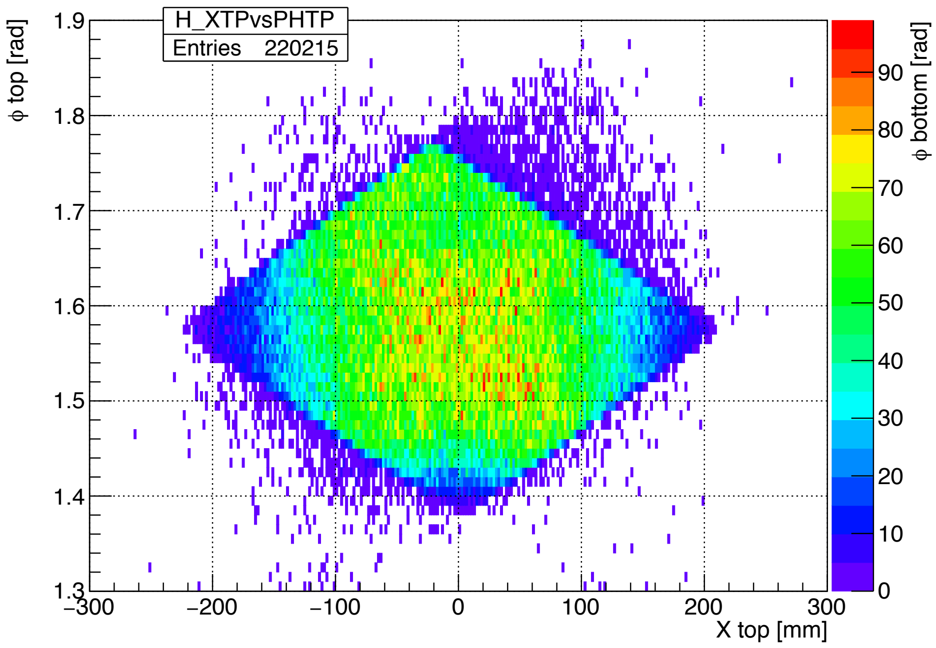
Δx vs $\Delta \phi$



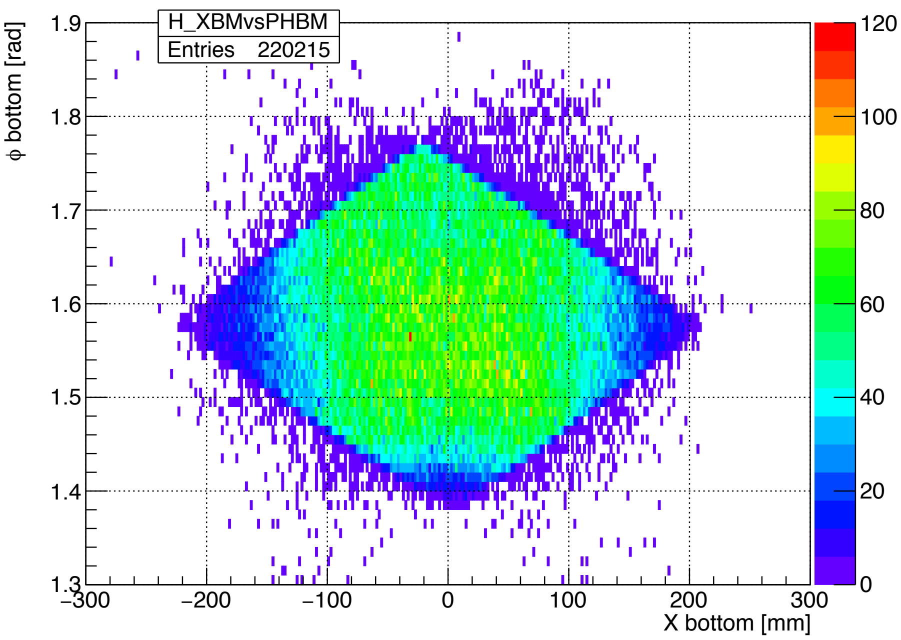
Δz vs $\Delta \lambda$



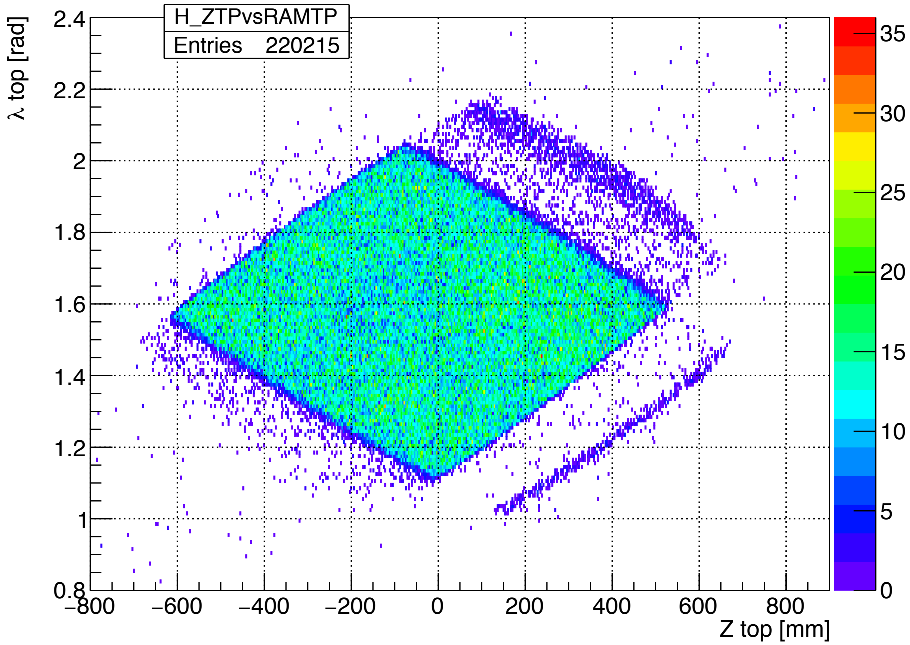
x vs ϕ (y = 0 mm, top)



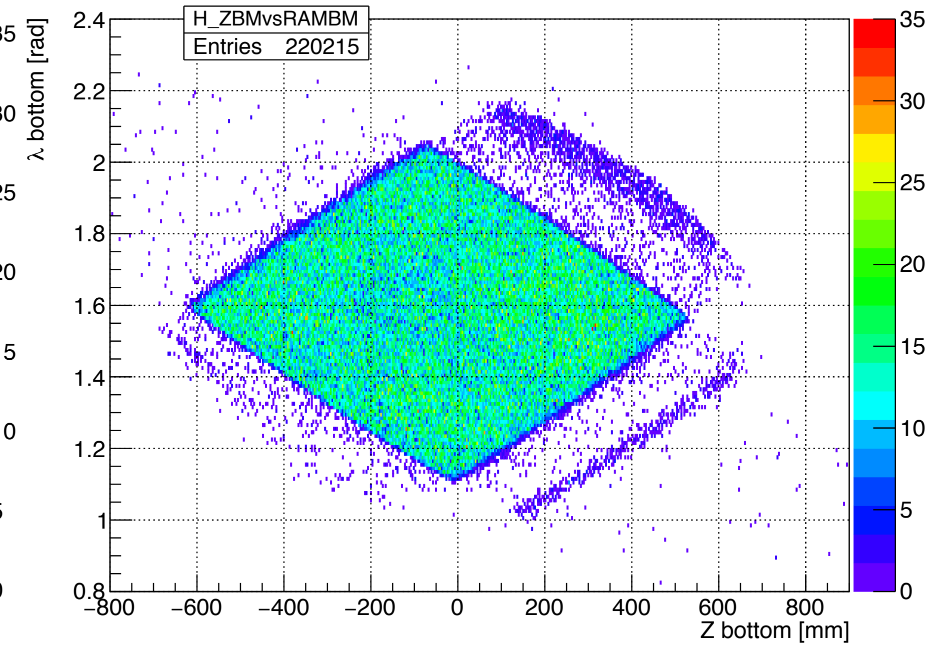
x vs ϕ (y = 0 mm, bottom)

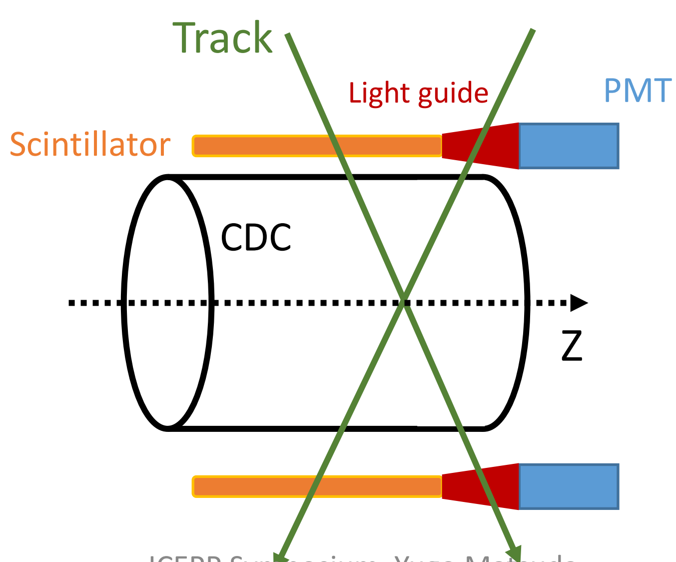


z vs λ (y = 0 mm, top)

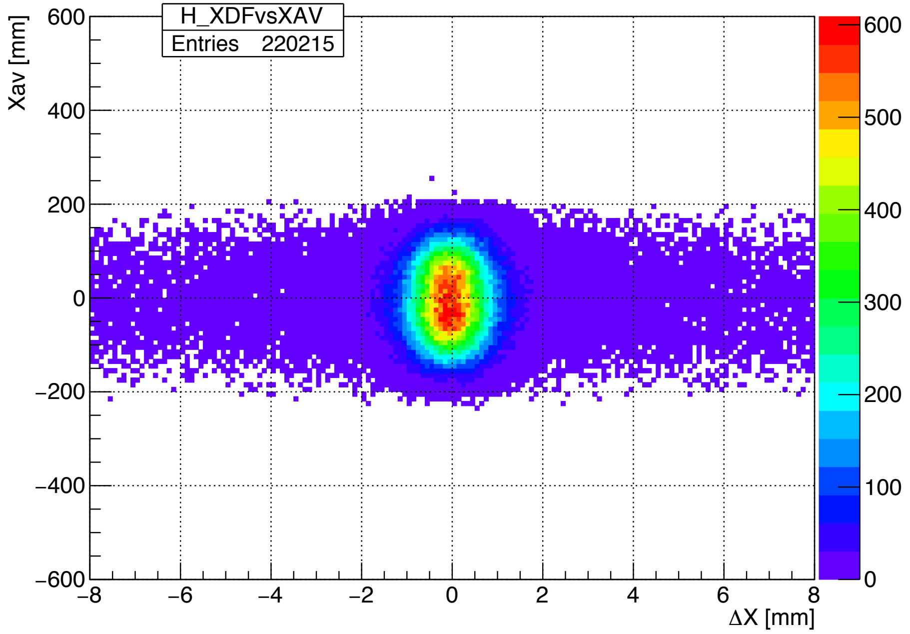


z vs λ (y = 0 mm, bottom)

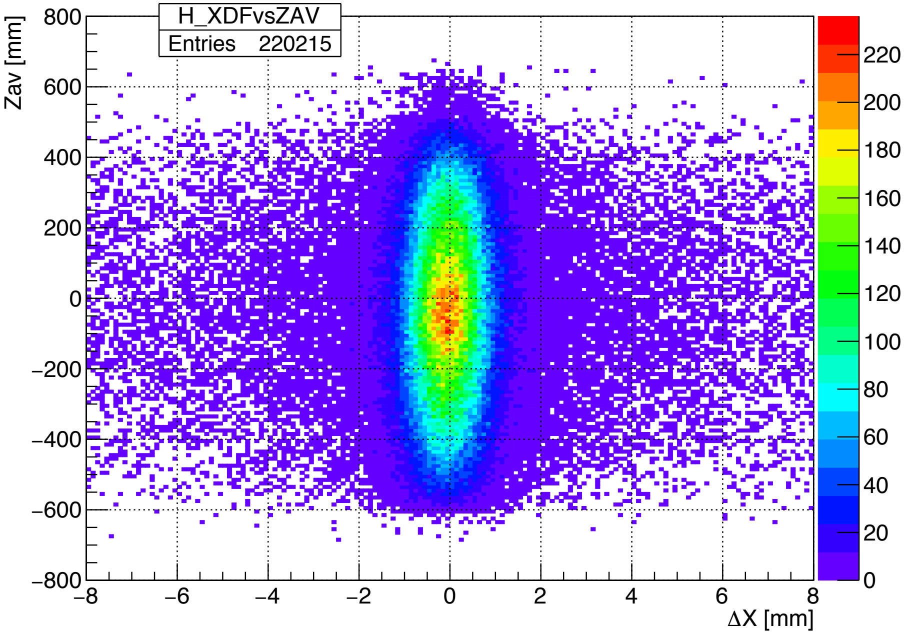




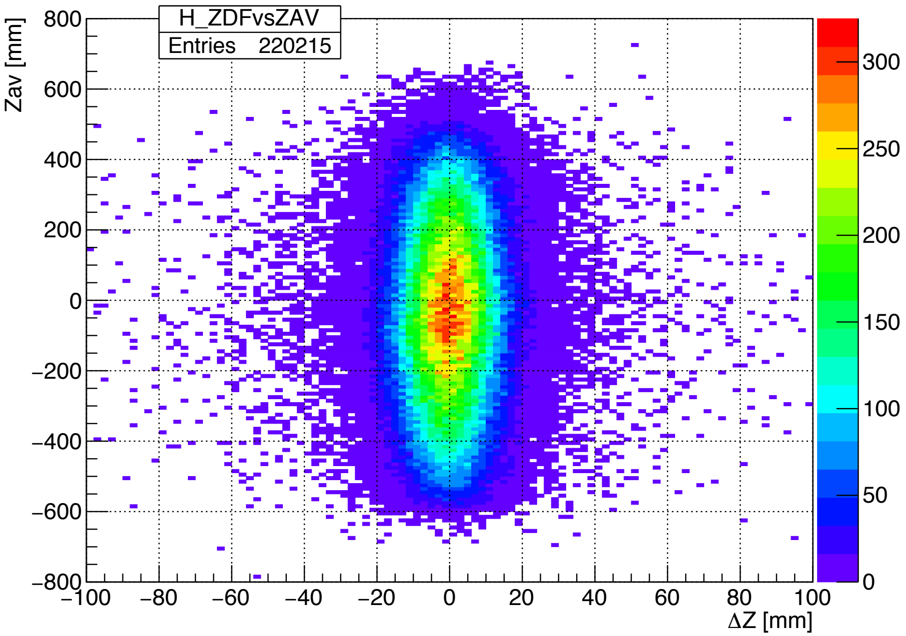
Δx vs x_{ave} (y = 0 mm)



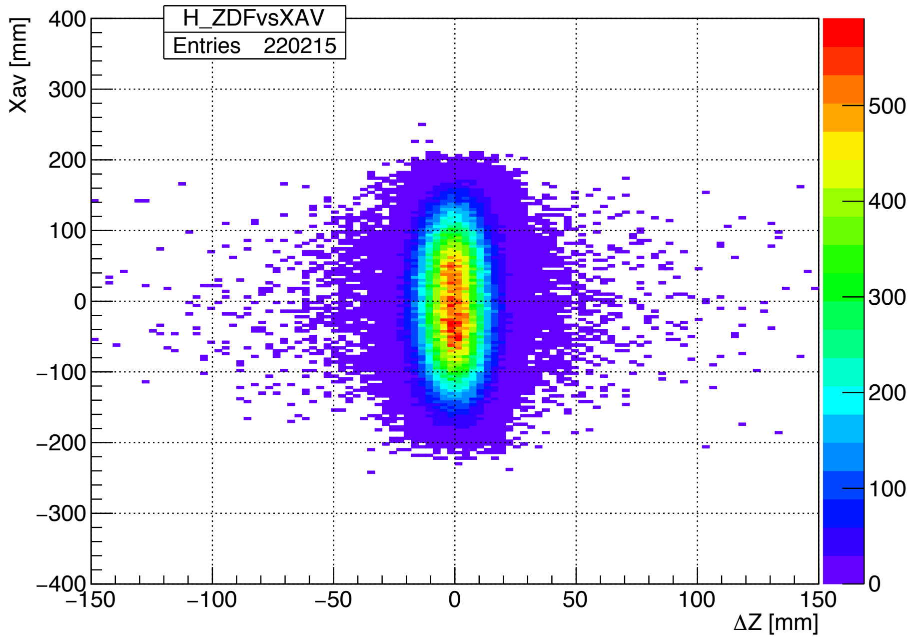
Δx vs z_{ave} (y = 0 mm)



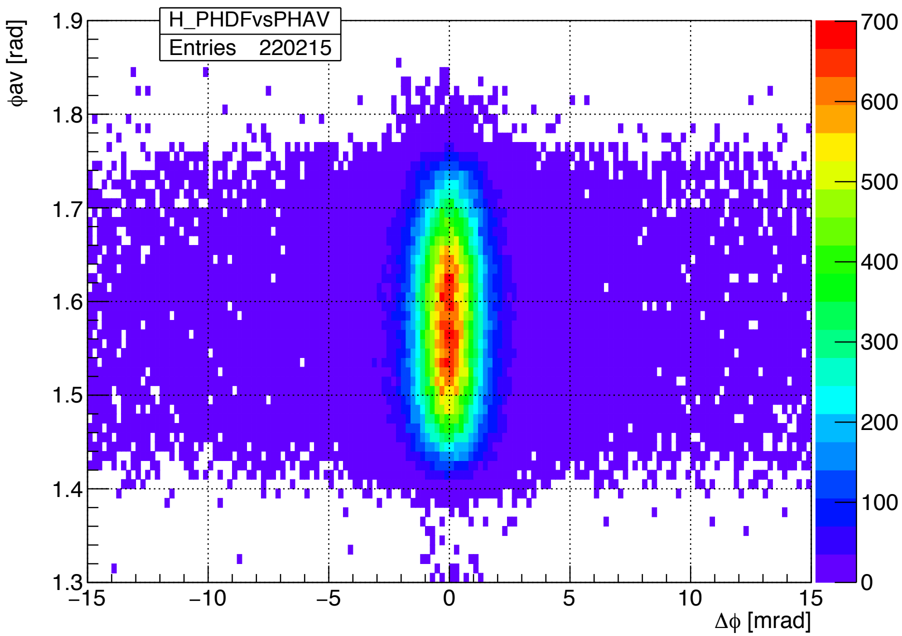
Δz vs z_{ave} (y = 0 mm)



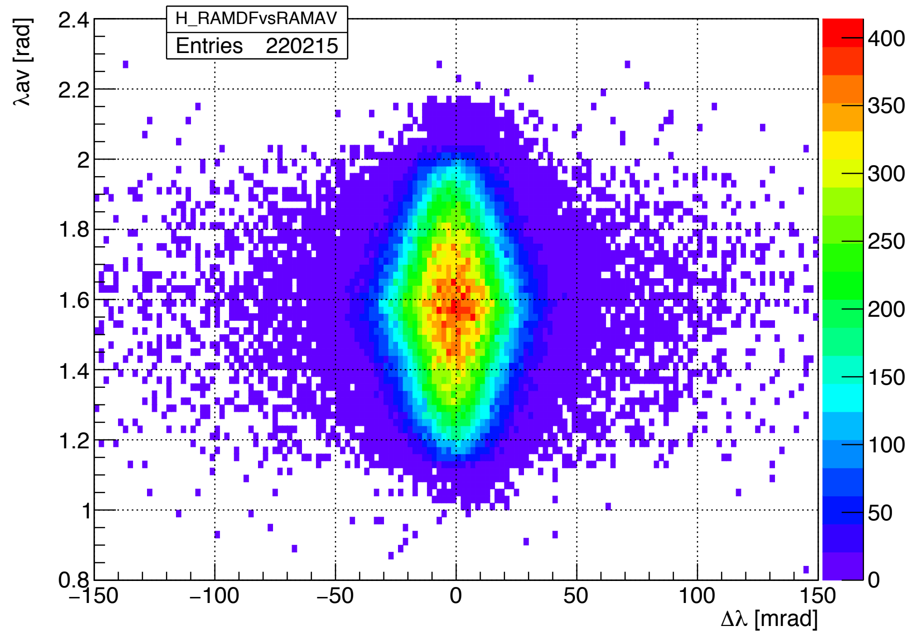
Δz vs x_{ave} (y = 0 mm)



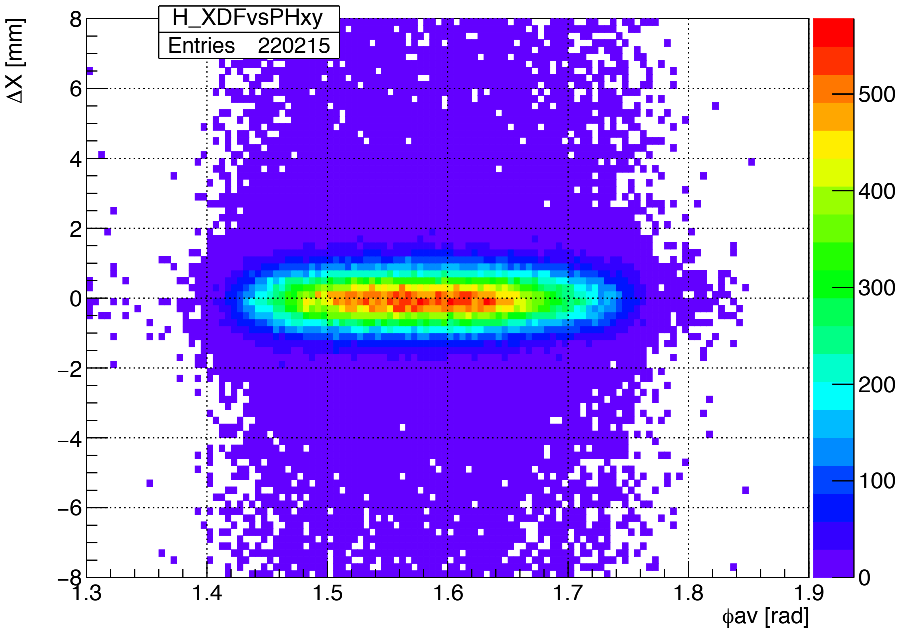
$\Delta\phi$ vs ϕ_{ave}



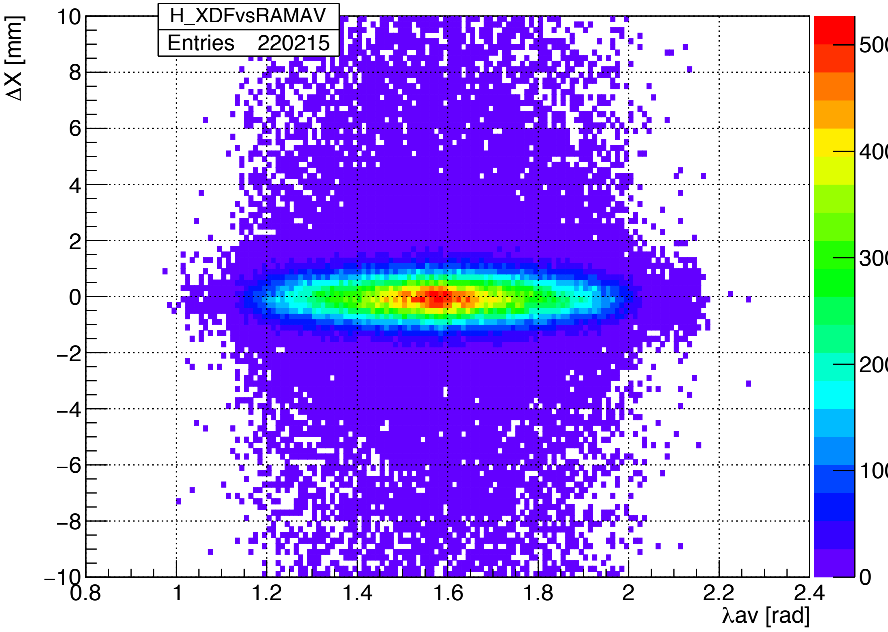
$\Delta\lambda$ vs λ_{ave}



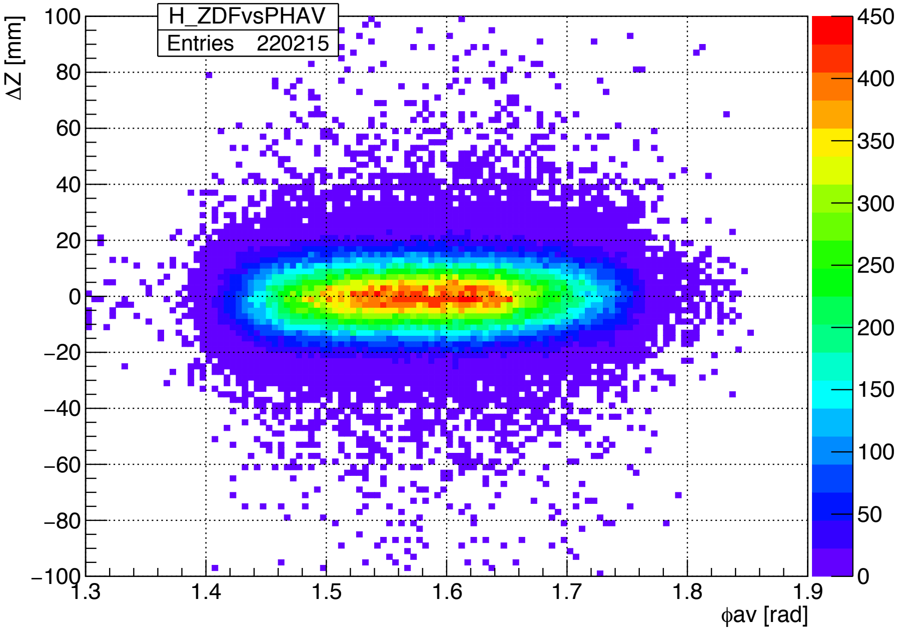
ϕ_{ave} vs Δx



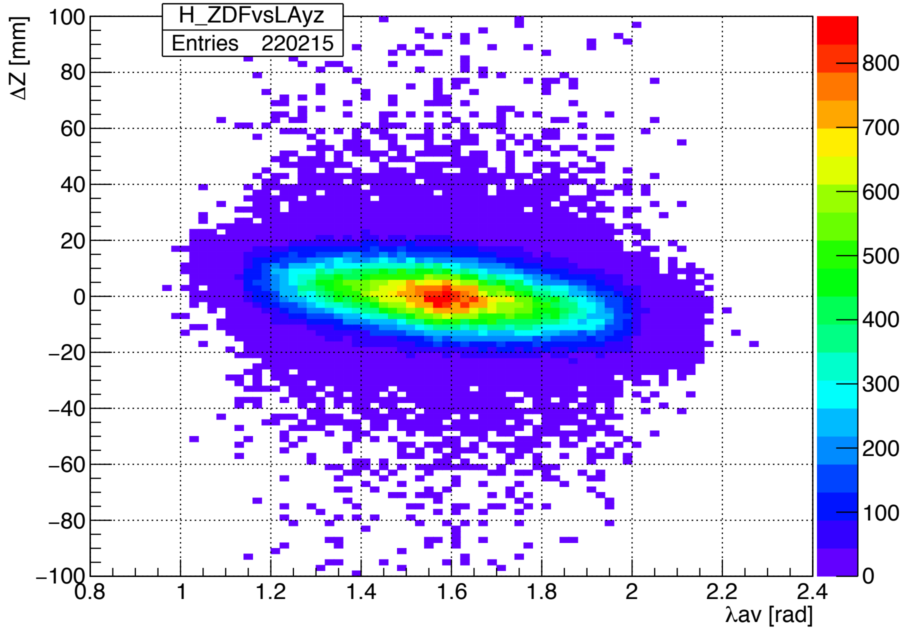
λ_{ave} vs Δx

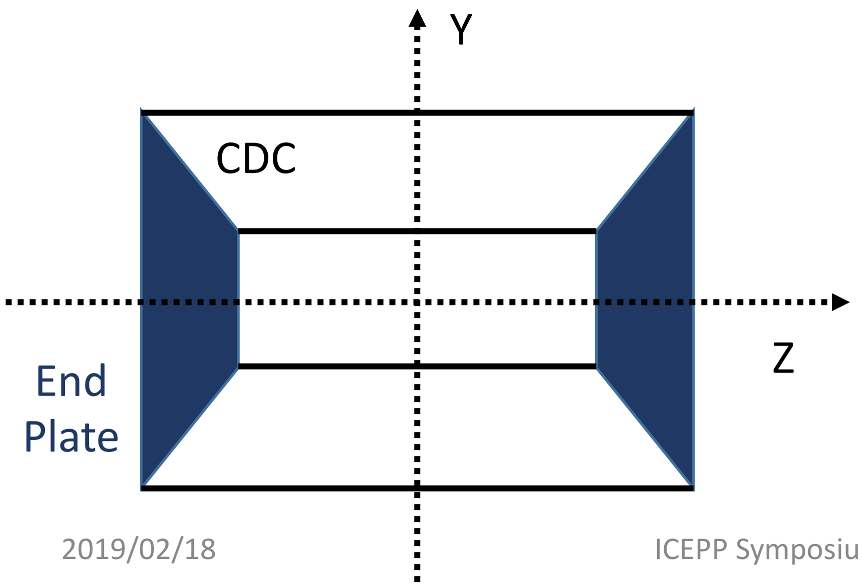


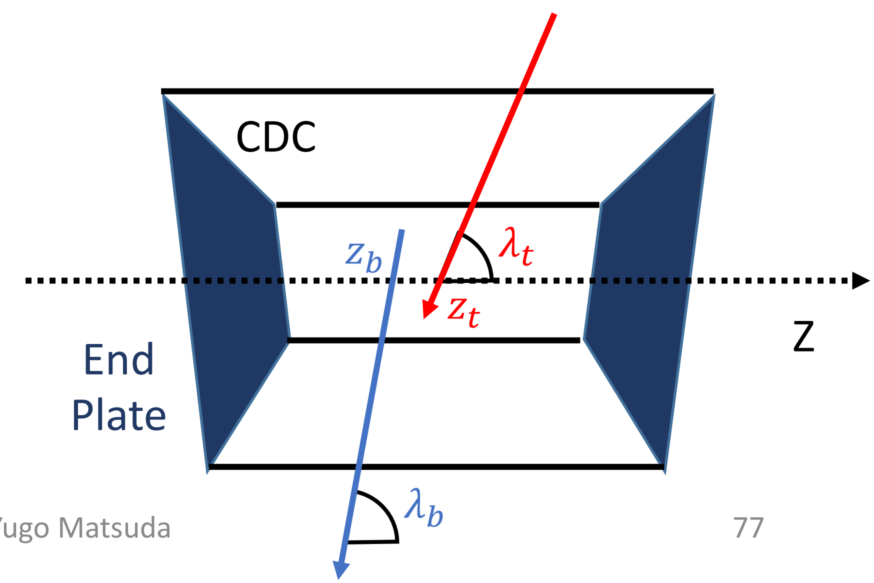
ϕ_{ave} vs Δz



λ_{ave} vs Δz

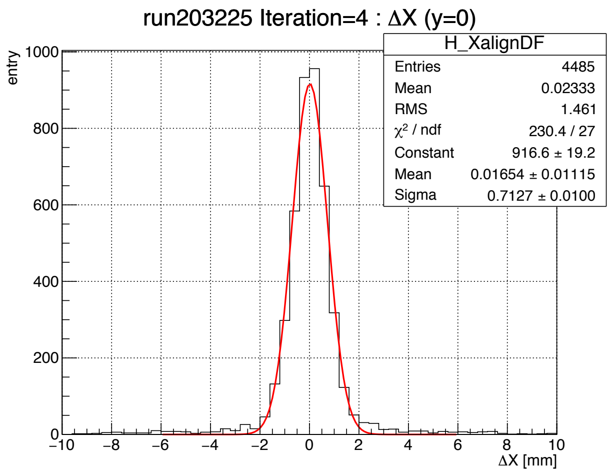


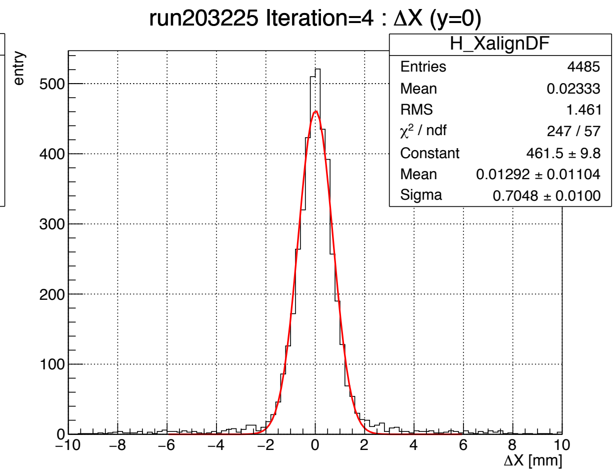


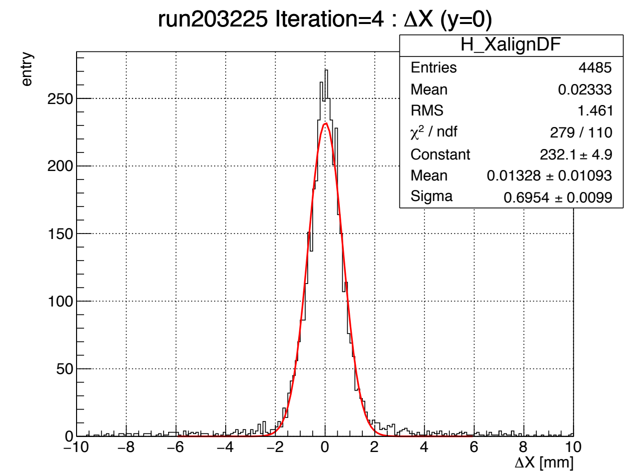


diff of mean of Δx due to binning and fit range

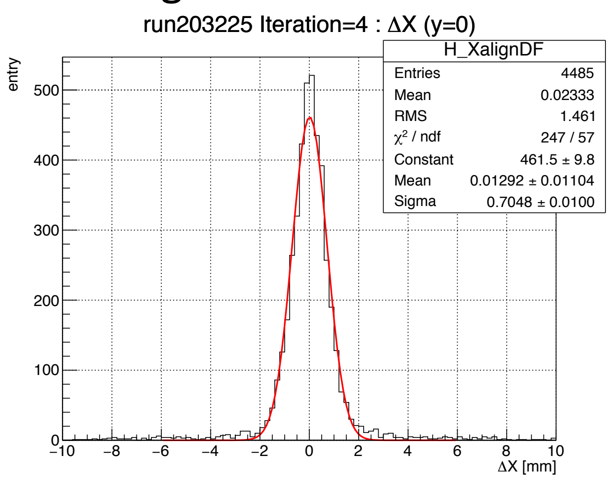
Binning σ_{bin}

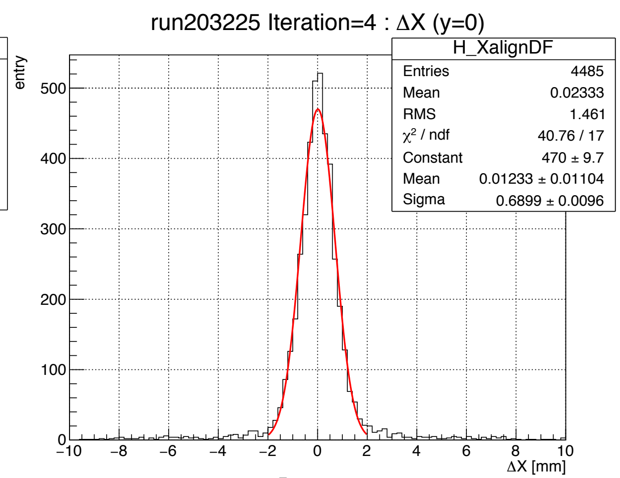


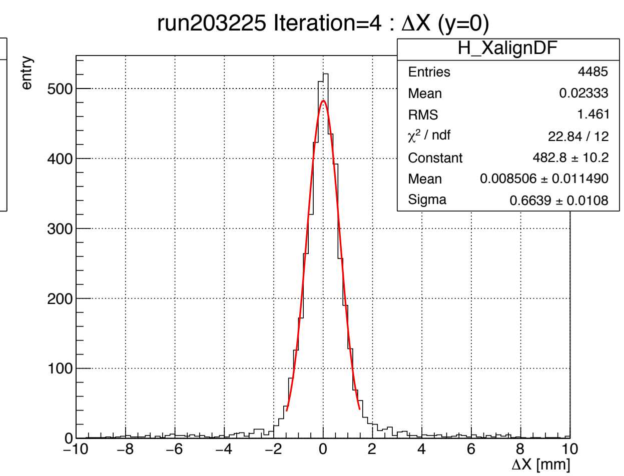




Fit Range σ_{fit}



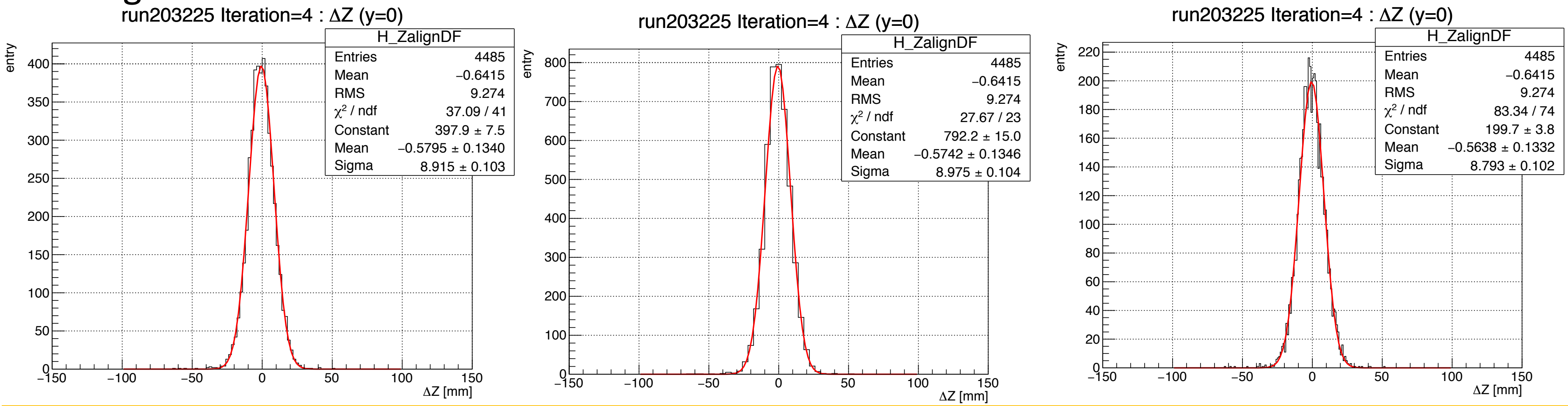




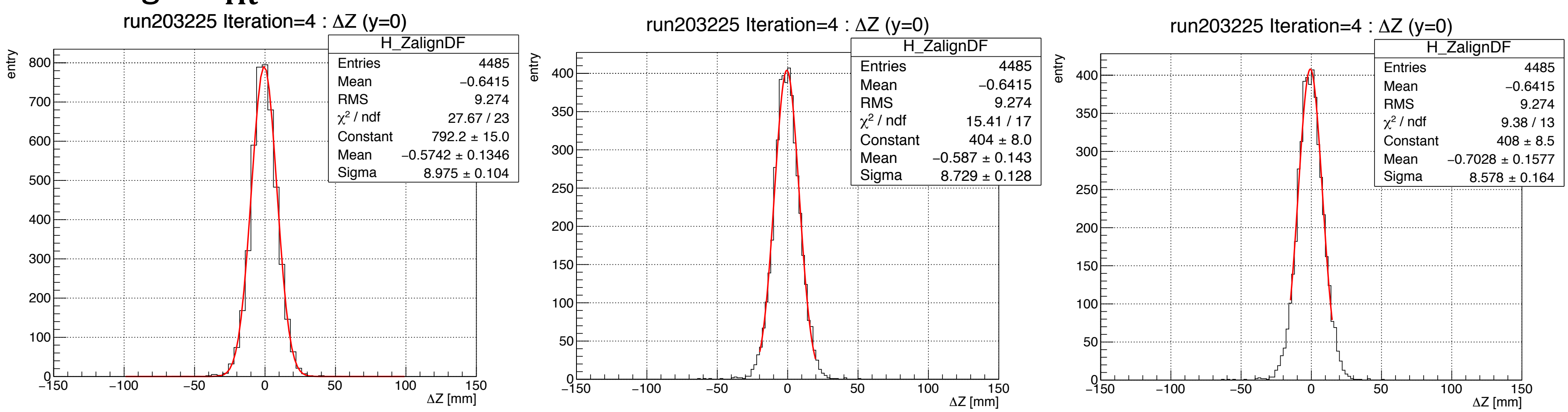
$$\sigma_{\mathrm{syst}} = \sqrt{\sigma_{\mathrm{bin}}^2 + \sigma_{\mathrm{fit}}^2}$$

diff of mean of Δz due to binning and fit range

Binning σ_{bin}



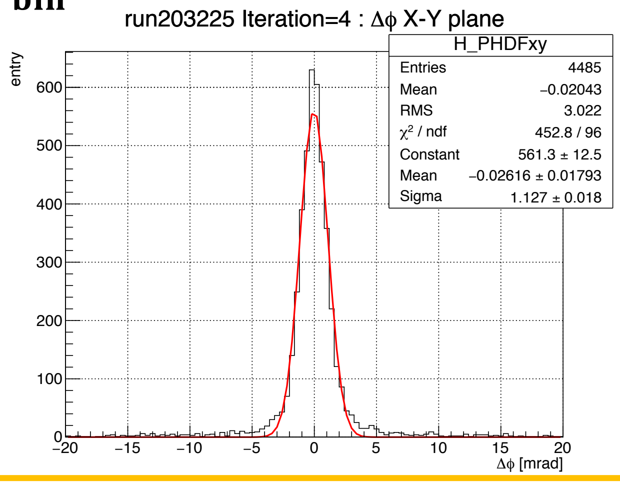
Fit Range σ_{fit}

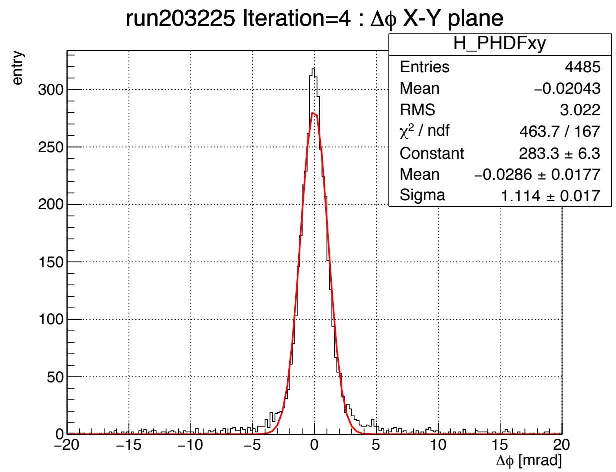


$$\sigma_{\mathrm{syst}} = \sqrt{\sigma_{\mathrm{bin}}^2 + \sigma_{\mathrm{fit}}^2}$$

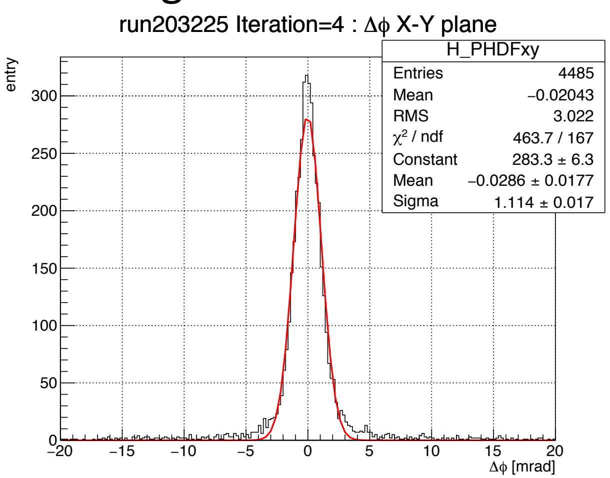
diff of mean of $\Delta\phi$ due to binning and fit range

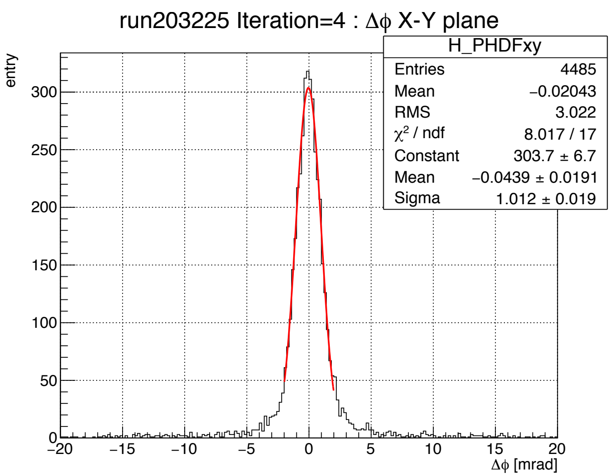
Binning $\boldsymbol{\sigma_{bin}}$

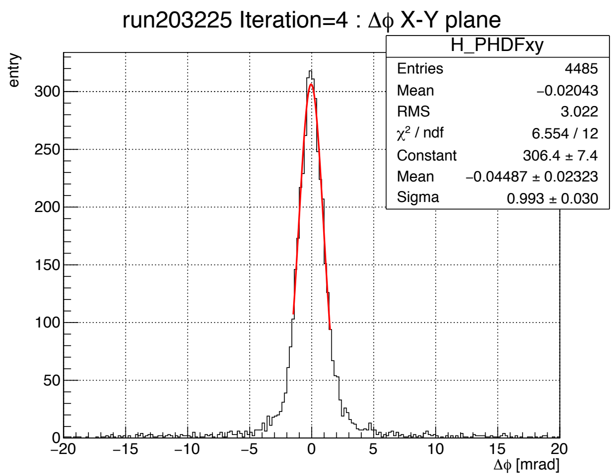




Fit Range $\boldsymbol{\sigma_{fit}}$



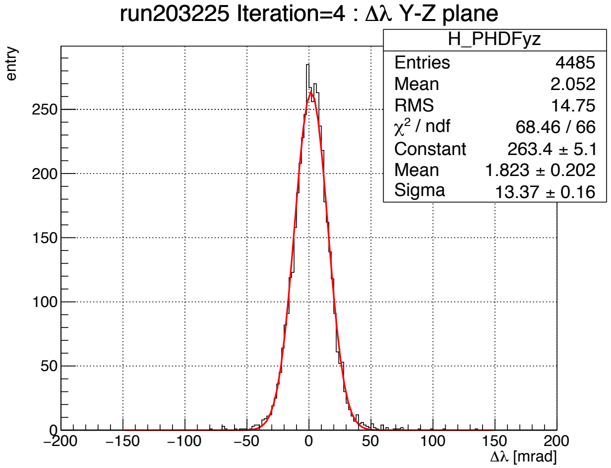


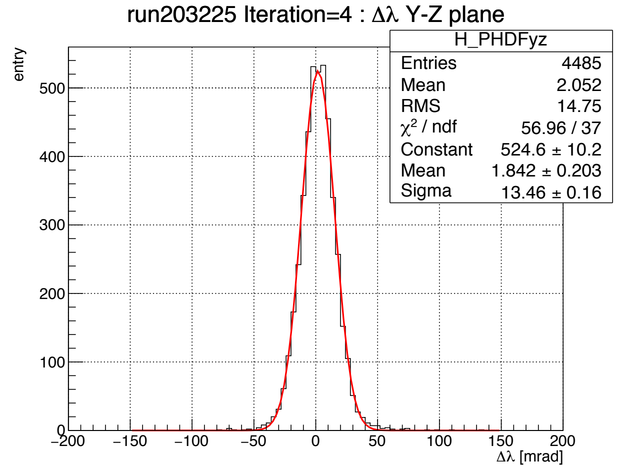


$$\boldsymbol{\sigma_{syst} = \sqrt{\sigma_{bin}^2 + \sigma_{fit}^2}}$$

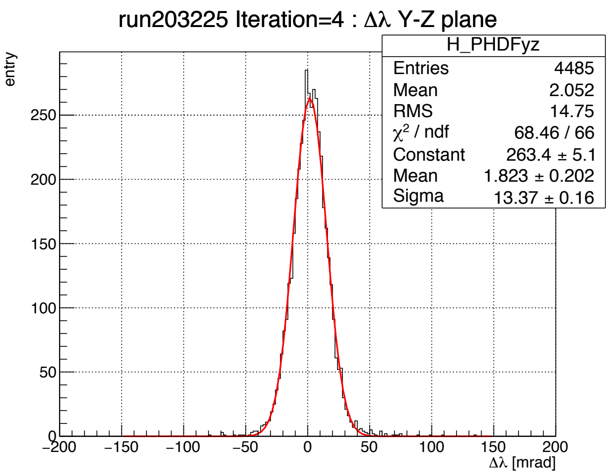
diff of mean of $\Delta\lambda$ due to binning and fit range

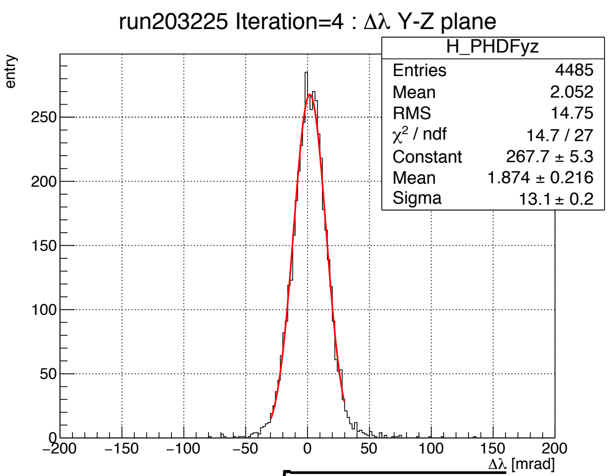
Binning $\boldsymbol{\sigma_{\mathrm{bin}}}$

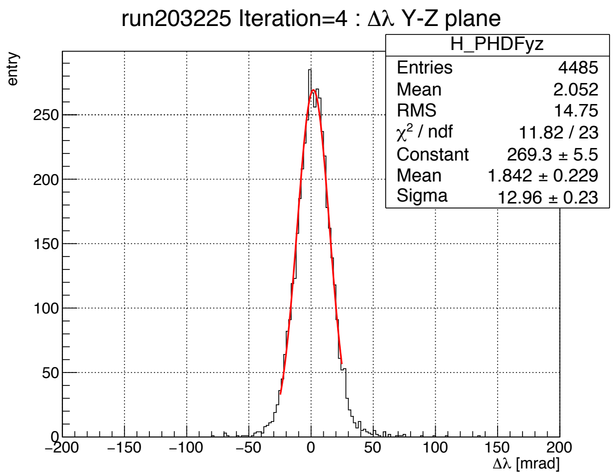




Fit Range $\boldsymbol{\sigma_{\mathrm{fit}}}$

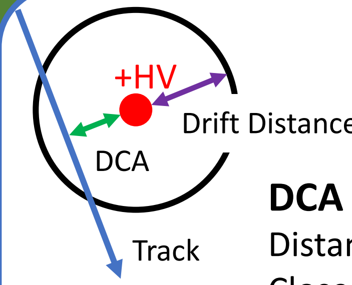






$$\sigma_{\mathrm{syst}} = \sqrt{\sigma_{\mathrm{bin}}^2 + \sigma_{\mathrm{fit}}^2}$$

Analysis of CRT – Tracking



DCA = Distance of Closest Approach

- The way to get drift time and drift distance.

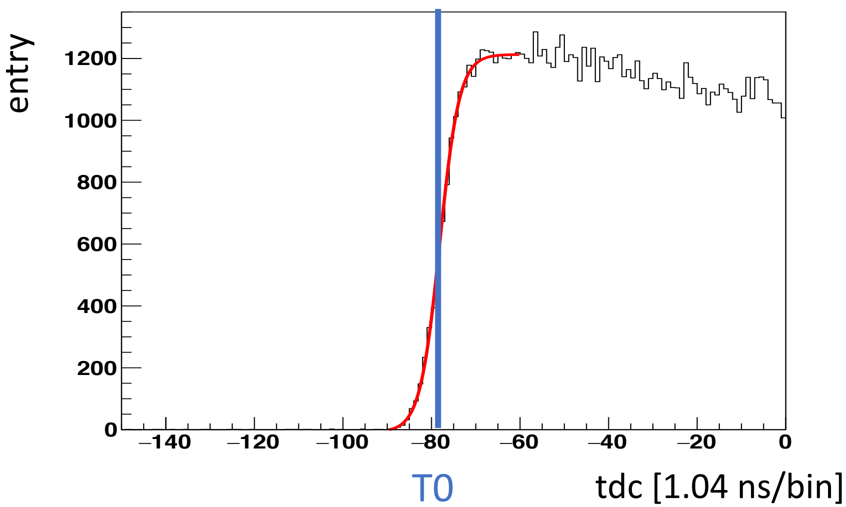
Drift Time

- Get T0 value (basement time) by fitting the tdc distribution with function:

$$f(t) = p_0 + p_1 \frac{e^{p_2 (t - p_3)}}{1 + e^{-\frac{(t - p_4)}{p_5}}} \quad \text{(by Belle II)}$$

-> able to fit more correct than gaussian.

Drift Time = tdc - trigger timing - T0



Drift Distance

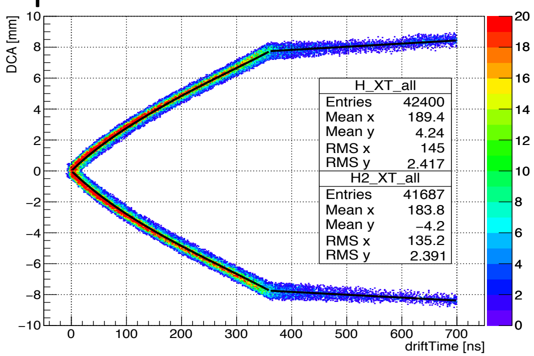
First Tracking

- Create XT Curve (DCA vs Drift Time) from the result of Garfield simulation.

Get the Drift Distance from Drift Time.

Second and more Tracking

- Use the XT Curve which is created in the last tracking result.
  -> Get Drift Distance from Drift Time
  -> Iterate this process
  to improve the XT Curve and tracking.



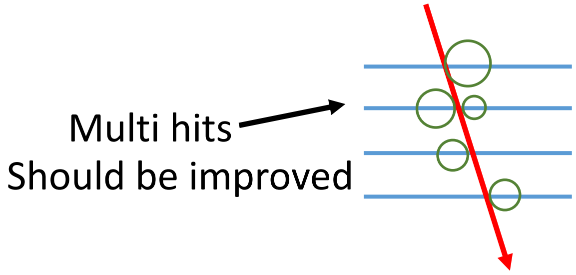
Analysis of CRT – Tracking Reconstruction

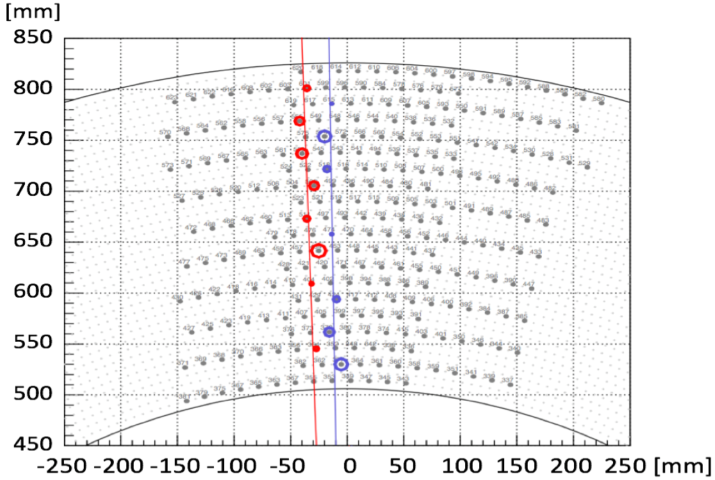
- To improve XT curve and Tracking, select appropriate hits.

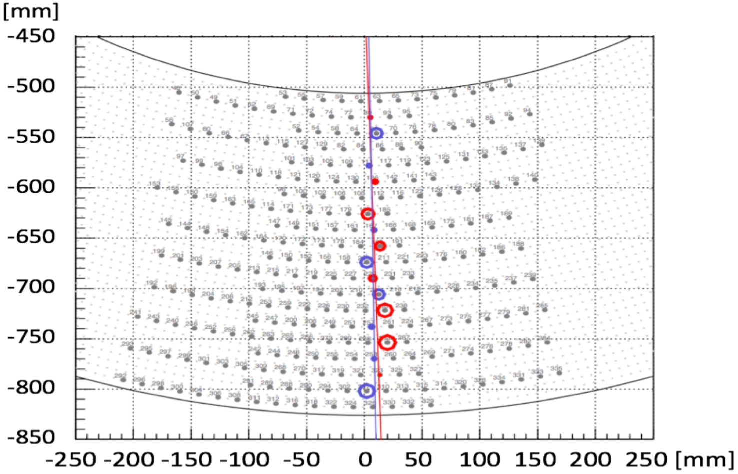
Iteration

1. Chose 1 layer and suspect this layer makes the tracking bad.
2. Select appropriate hit and cut others.
3. Make XT curve from appropriate hits.
4. Draw new track and improve XT curve from this tracking result.

Iteration







Tracking result of top side and bottom side of CDC