Performance evaluation of a GEM-based readout module for the ILC TPC with a large aperture GEM-like gating device by a beam test

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Outline

I mainly talk about the spatial resolution

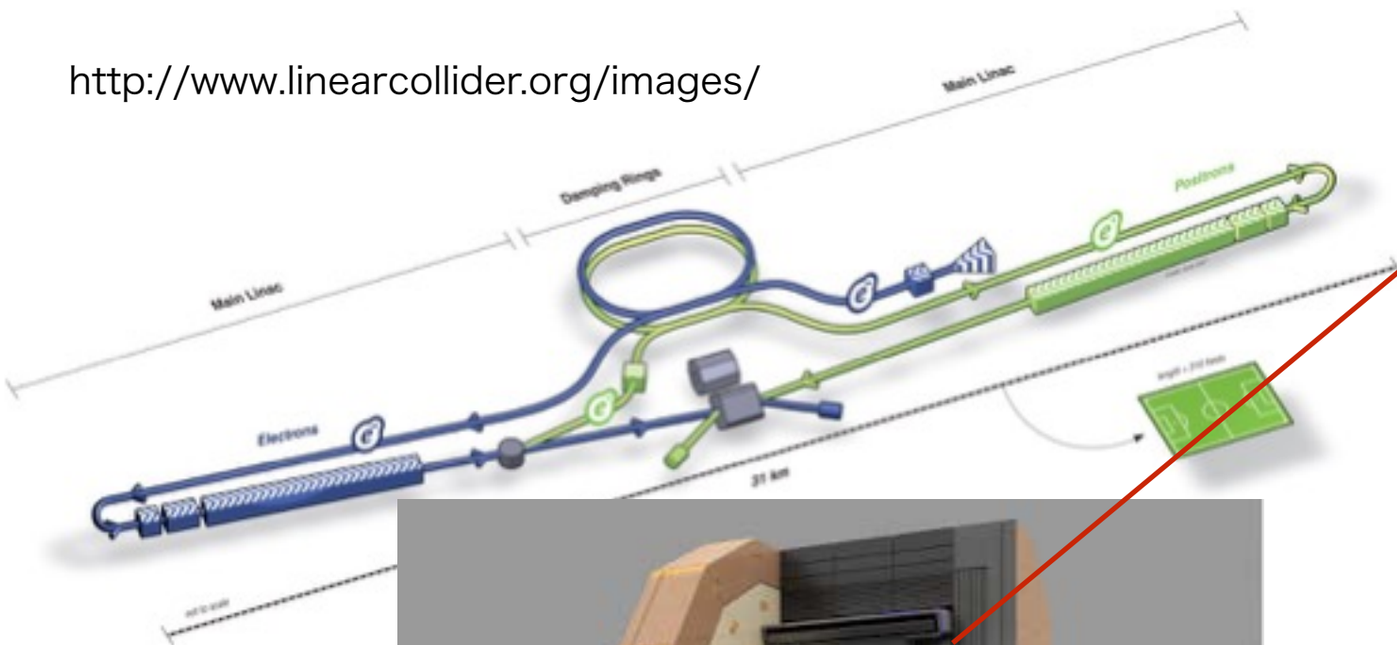
1. About TPC
2. Momentum Resolution Goal
   & Ion Feedback Problem
3. A large aperture GEM-like gating device
4. Beam test
5. Results - Pad response
6. Results - Spatial resolution
7. Analysis of Angled Track
8. Summary

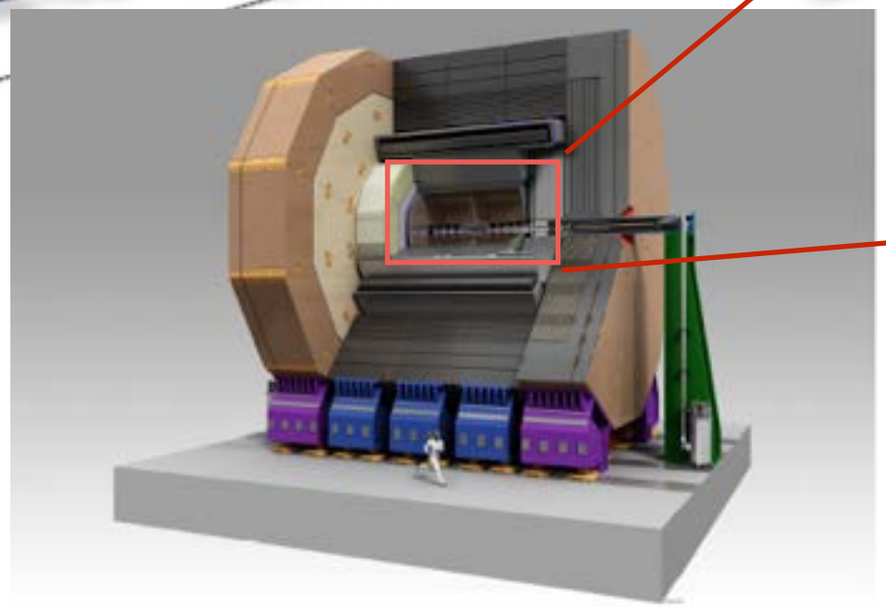
TPC

International Linear Collider

Electron positron Collider (250～500 GeV)

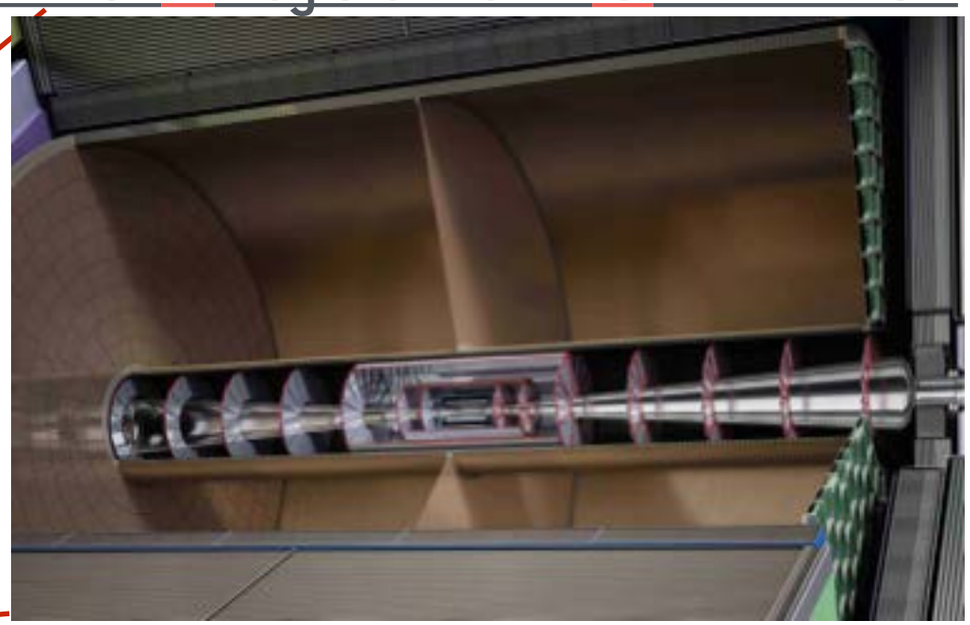
http://www.linearcollider.org/images/





International Large Detector

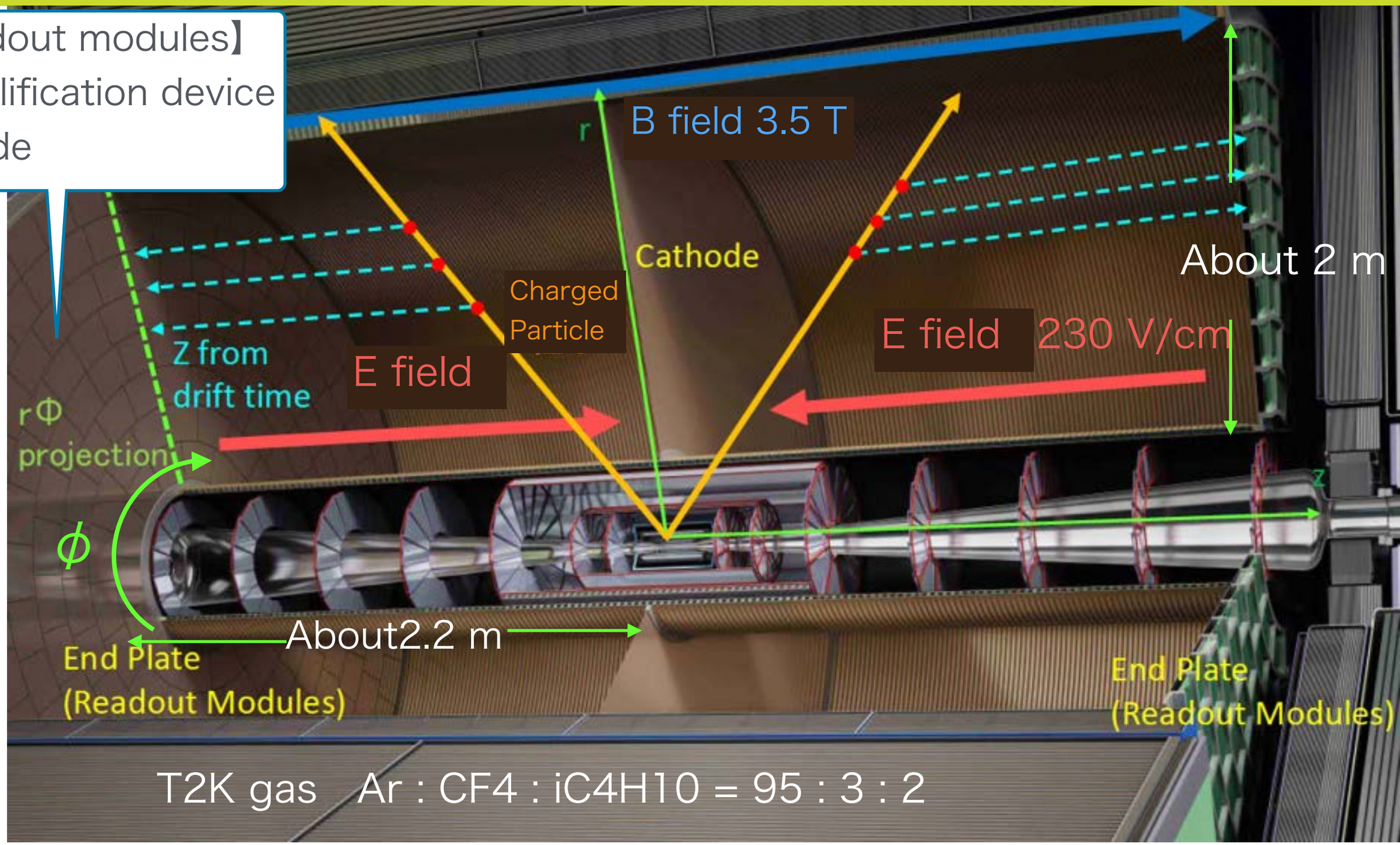
Time Projection Chamber



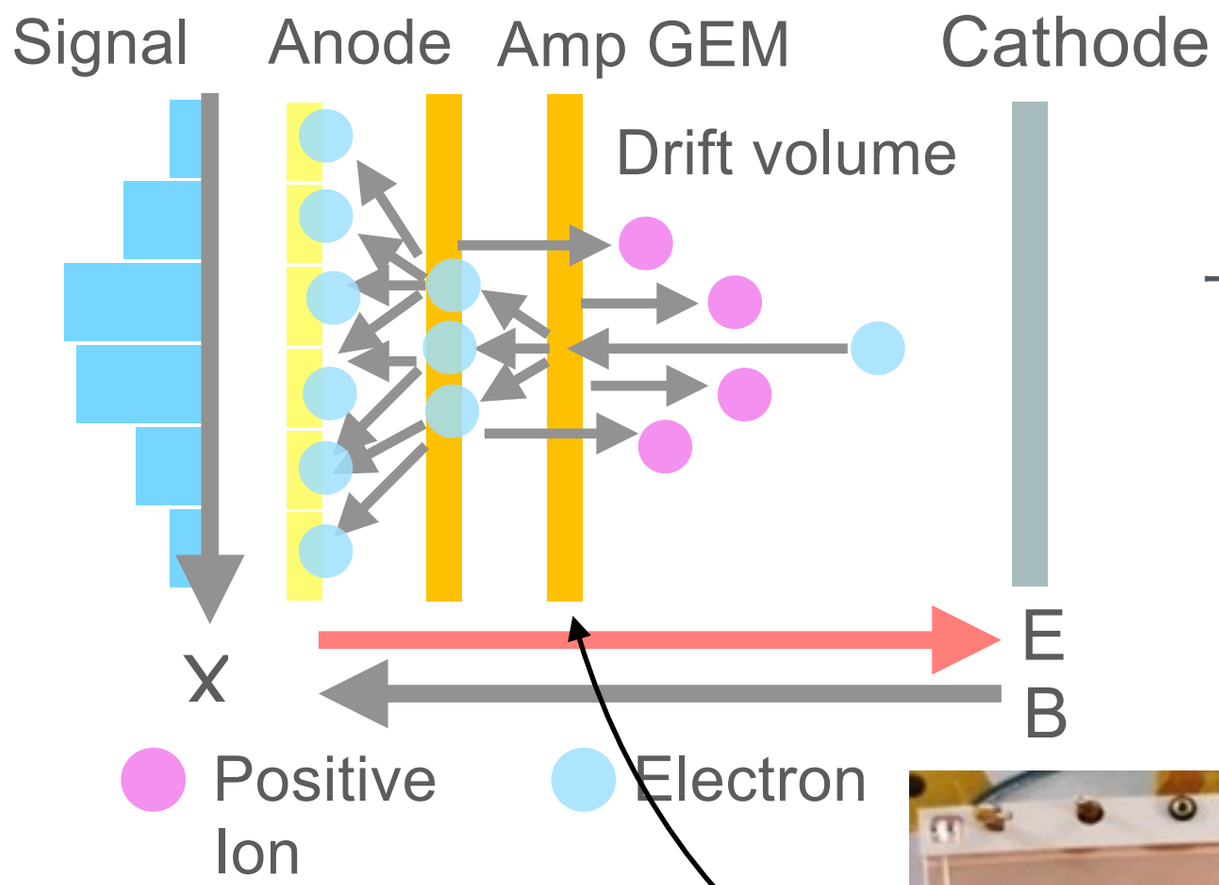
reconstruct tracks, measure their momentum and dE/dx. (charged particles)

TPC

【Readout modules】
- Amplification device
- Anode



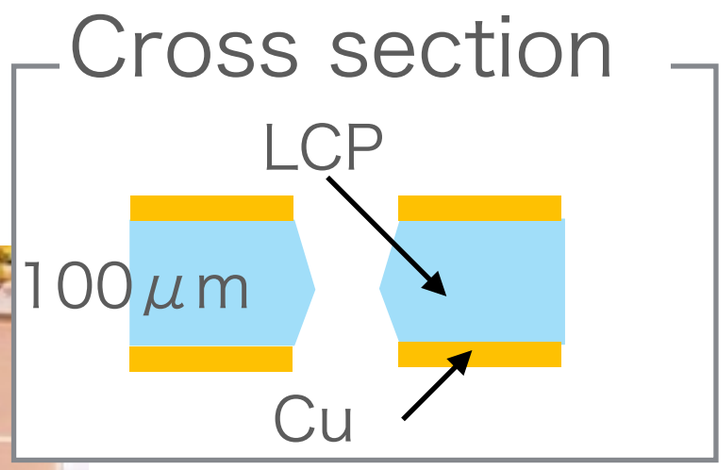
A GEM-based readout module

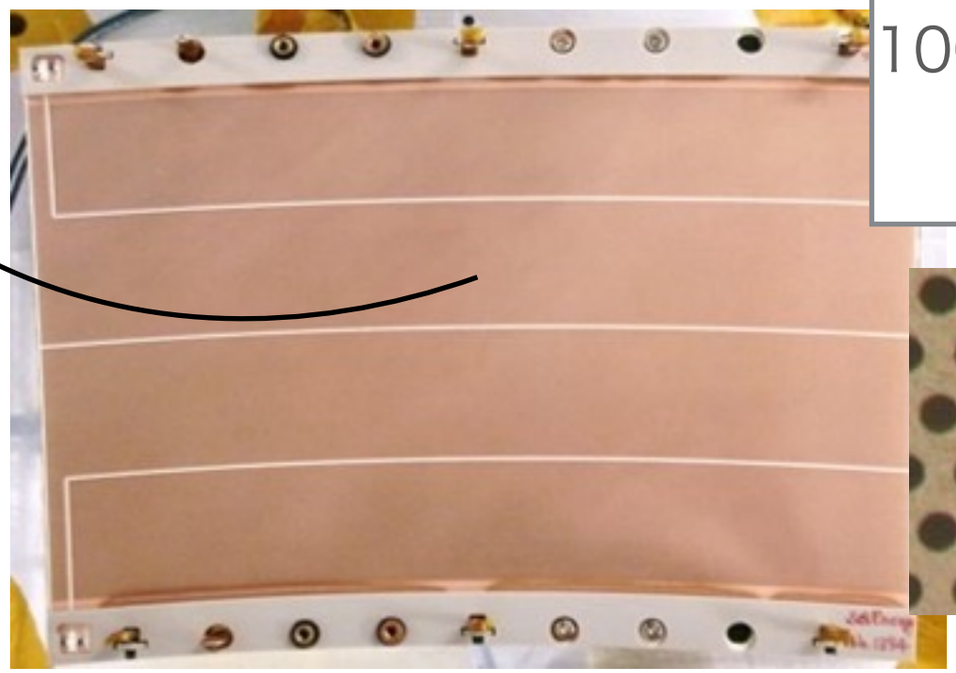


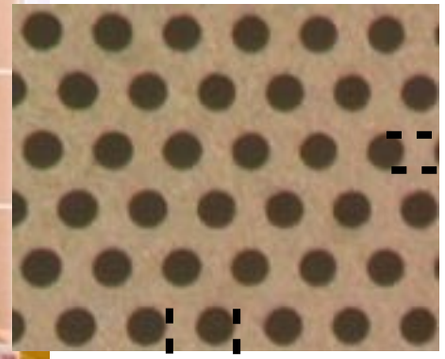
To get signals, we need an amplification device.

The amplification device：

Gas Electron Multiplier







The electrons are amplified in holes by avalanche cascades.

Momentum Resolution Goal

Momentum resolution Goal: $\sigma_{\frac{1}{P_T}} = 1 \times 10^{-4} GeV^{-1}$

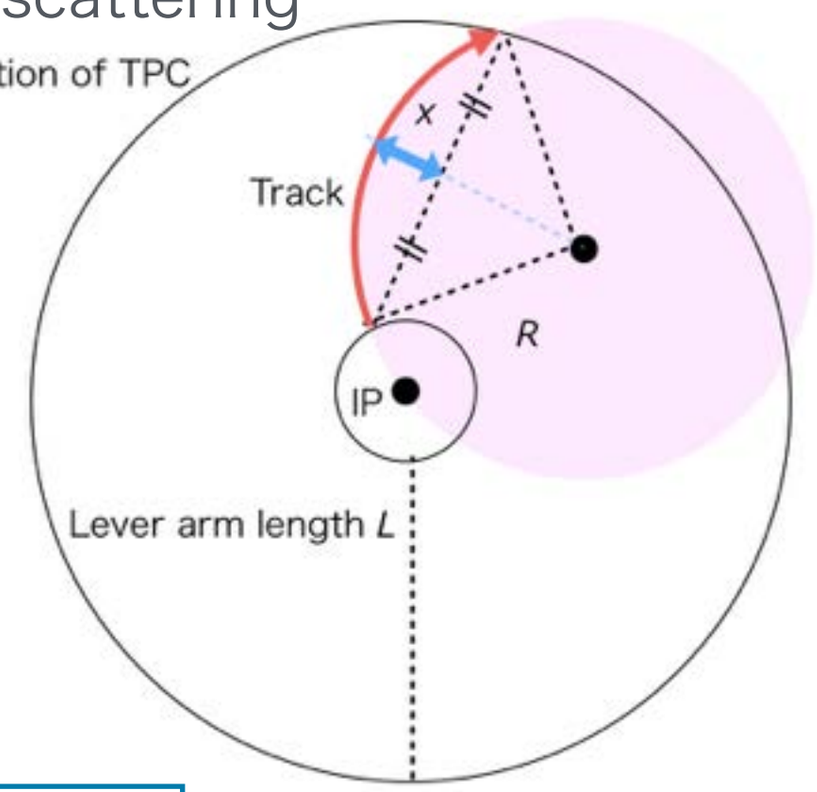
Glueckstern Formula

R.L. Gluckstern, NIM 24 (1963), 381

$$\frac{\sigma_{P_T}}{P_T} \simeq \sqrt{\left(\frac{\alpha' \sigma_x}{BL^2}\right)^2 \left(\frac{720}{n+4}\right) P_T^2 + \left(\frac{\alpha' C}{BL}\right)^2 \left(\frac{10}{7}\left(\frac{X}{X_0}\right)\right)}$$

Multiple scattering

Momentum resolution depends on Position resolution σ_x, Measurement points n, Magnetic field B, Lever arm length L



ILC-TPC :n= 220points B=3.5T L=1.5m

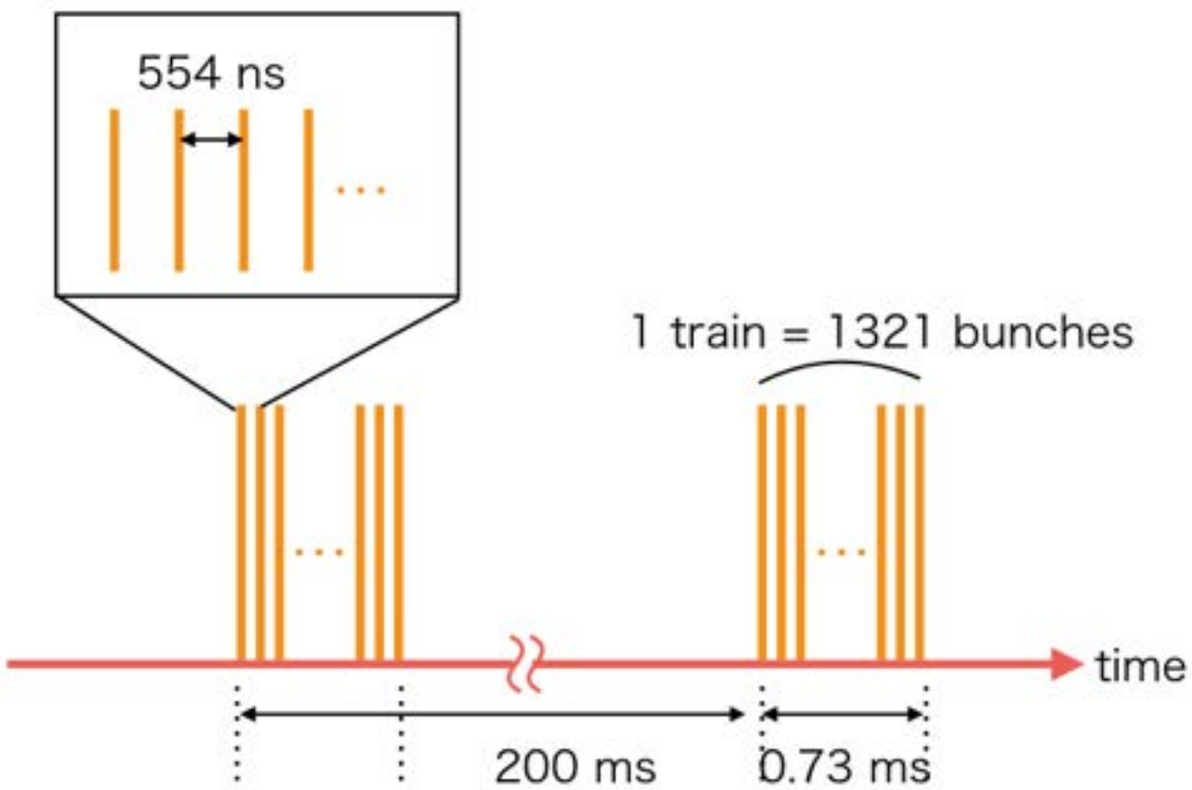
↓

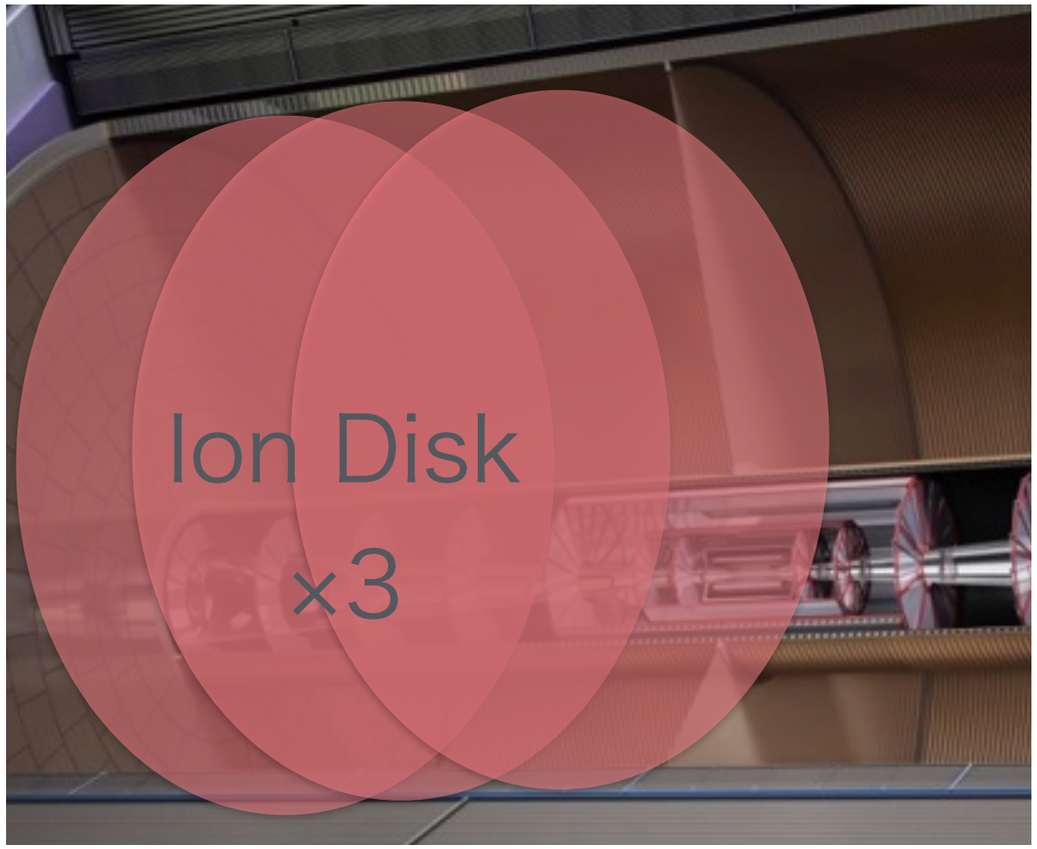
Spatial resolution goal : $\sigma_{r\phi} < 100 \mu m$

However the ion feedback prevent us to achieve this goal

Ion Feedback Problem

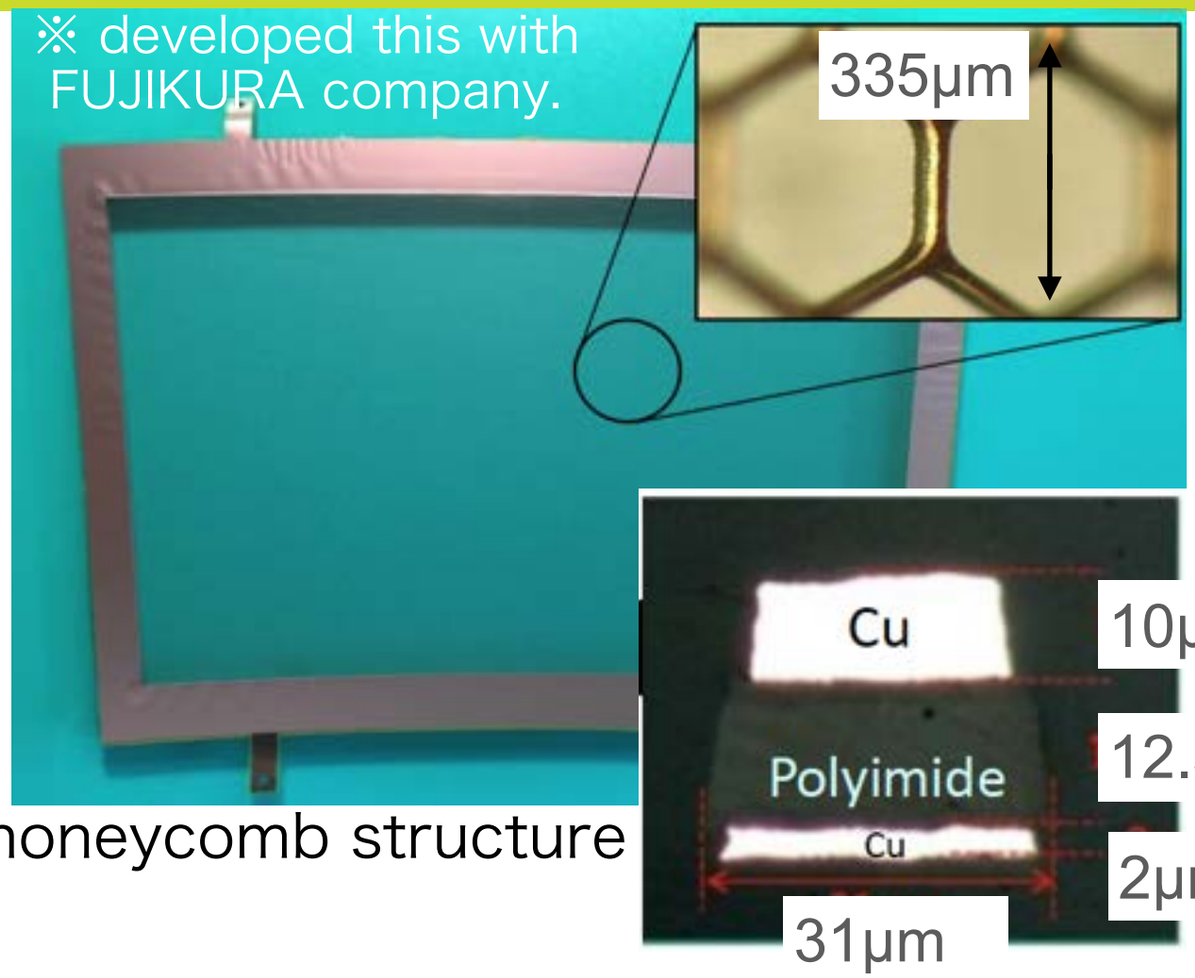
Positive ions created by gas amplification back-flow into the drift volume
→distort electric field→deteriorate position resolution





The ions for a single bunch train form a disk with about 1cm thickness.
Since the ion drift velocity is O(1000) times slower than that of electrons, there will be up to 3 ion disks in the drift volume.
Hit point distortion due to the 3 ion disks : 60 μm

A Large Aperture GEM-like Gating Device

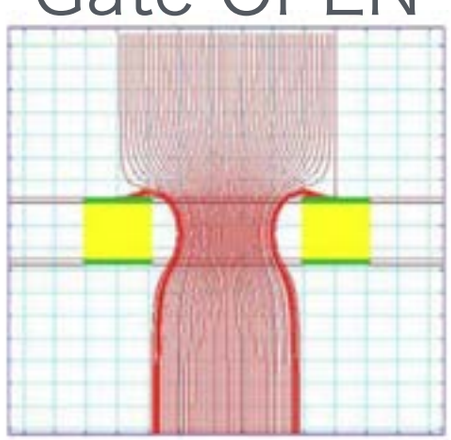


honeycomb structure

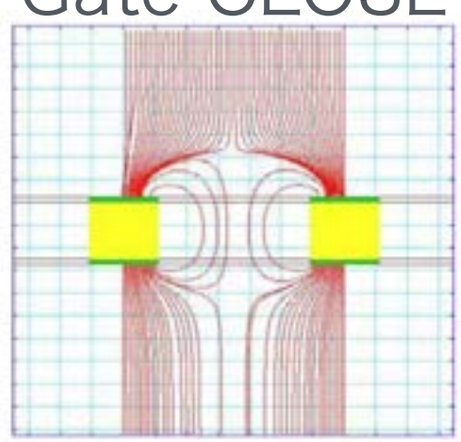
Gating Foil: the insulator sheet put between capper electrodes.

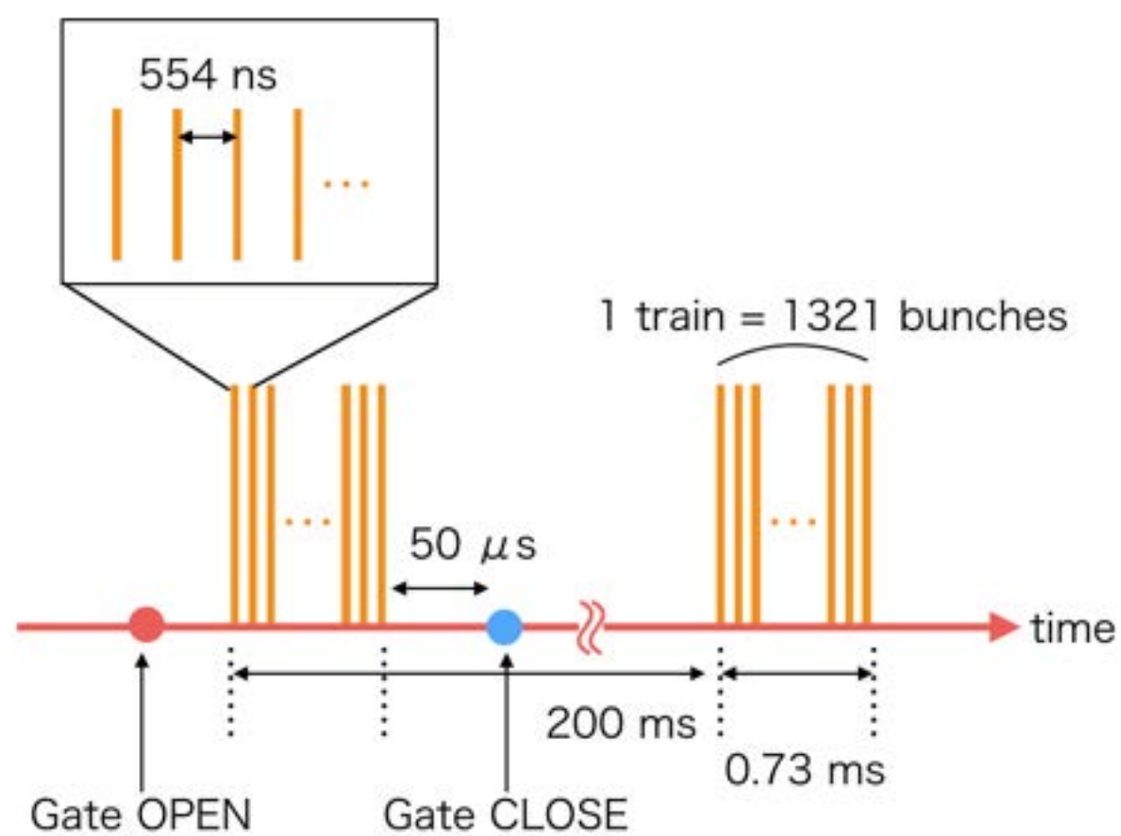
It works by adding electric potential difference to copper electrode.

Gate OPEN



Gate CLOSE

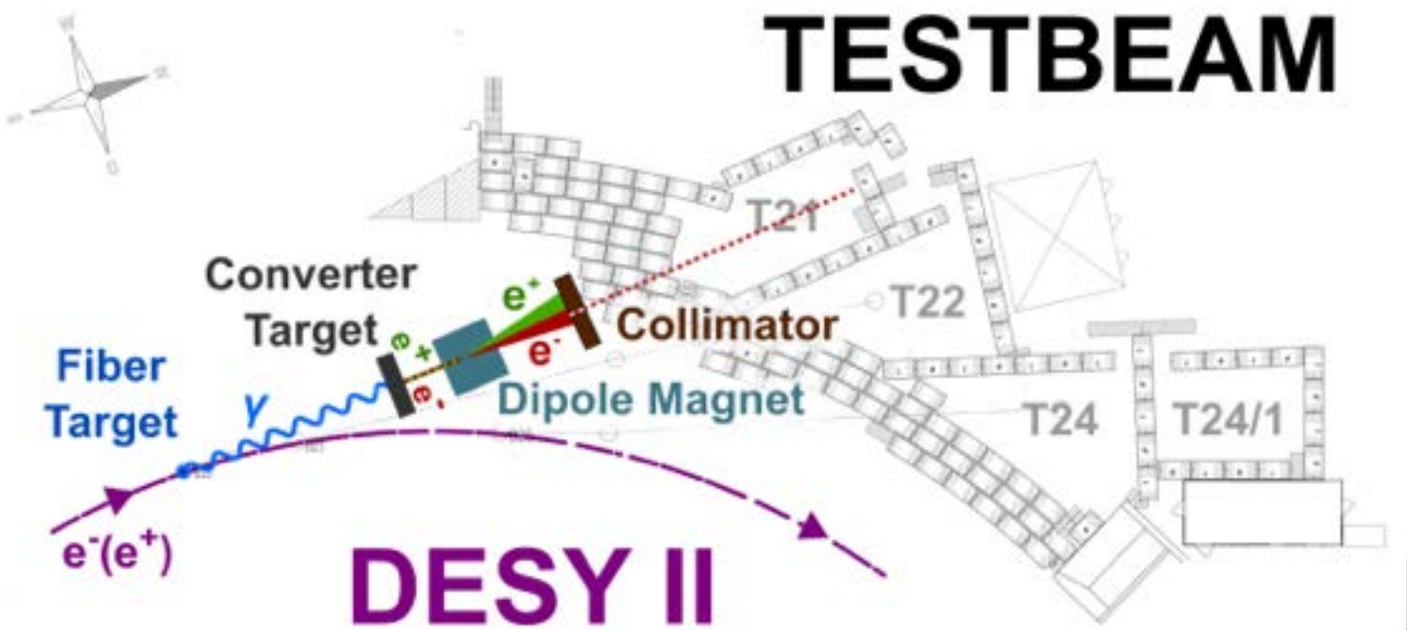


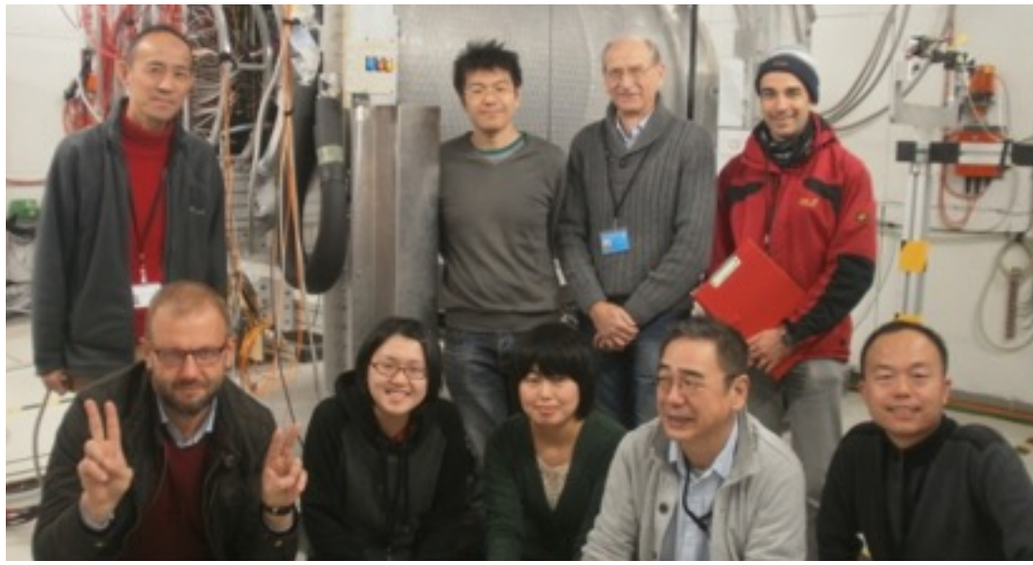


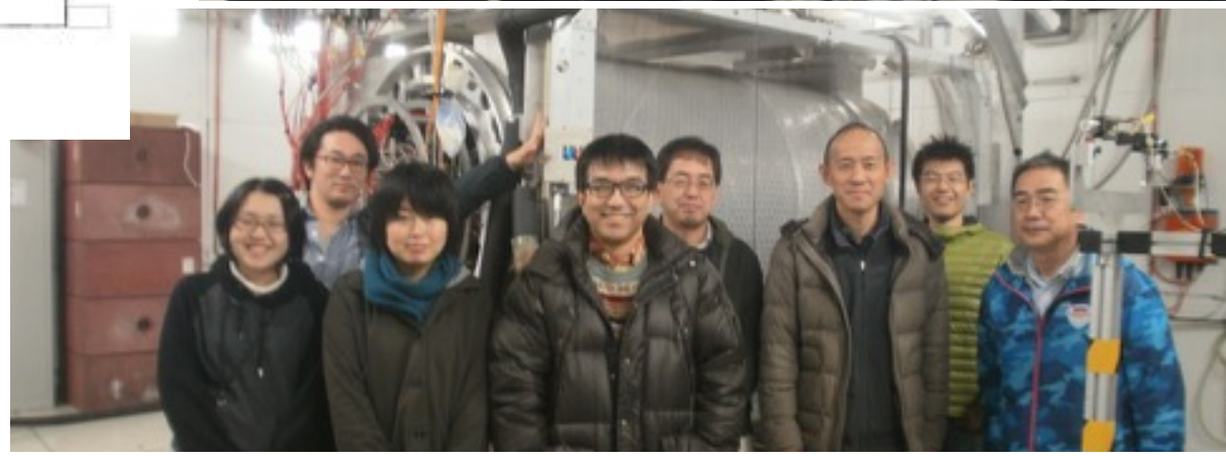
Beam test

Purpose : check performances of the module
with the gating foil

Oct.31-Nov.13, 2016（beam time）@DESY TPC large prototype





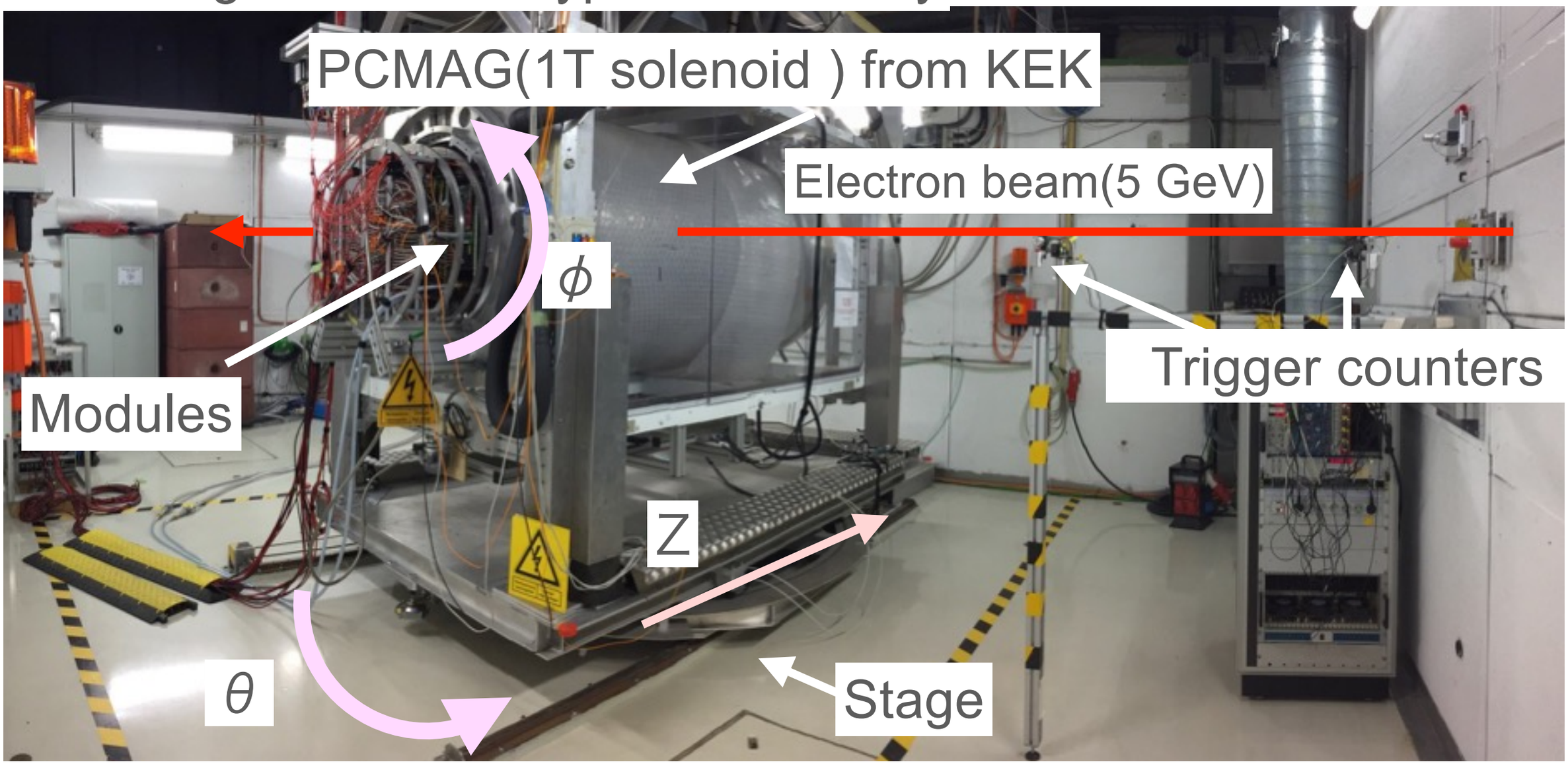


The first beam test of a GEM-readout TPC module with a gating foil

20 participants from Japan, France, Germany, China, Sweden

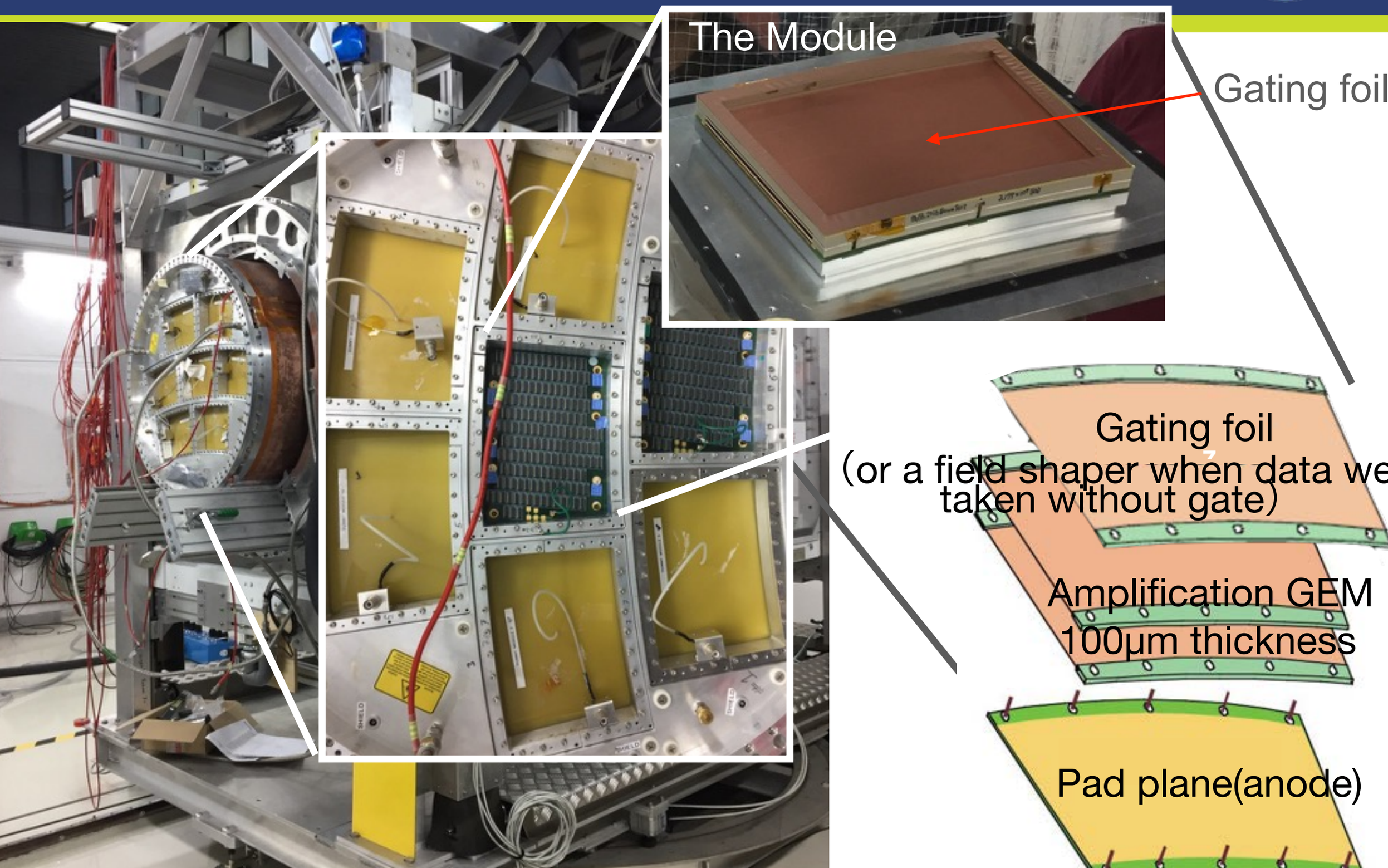
Setup

DESY Large TPC Prototype Test Facility



The electron beam passes two trigger counter and through the prototype.
The sensitive volume of the TPC is inside a solenoid. The TPC is mounted on a movable stage so we can change drift distance(Z) and two angles, θ and ϕ.

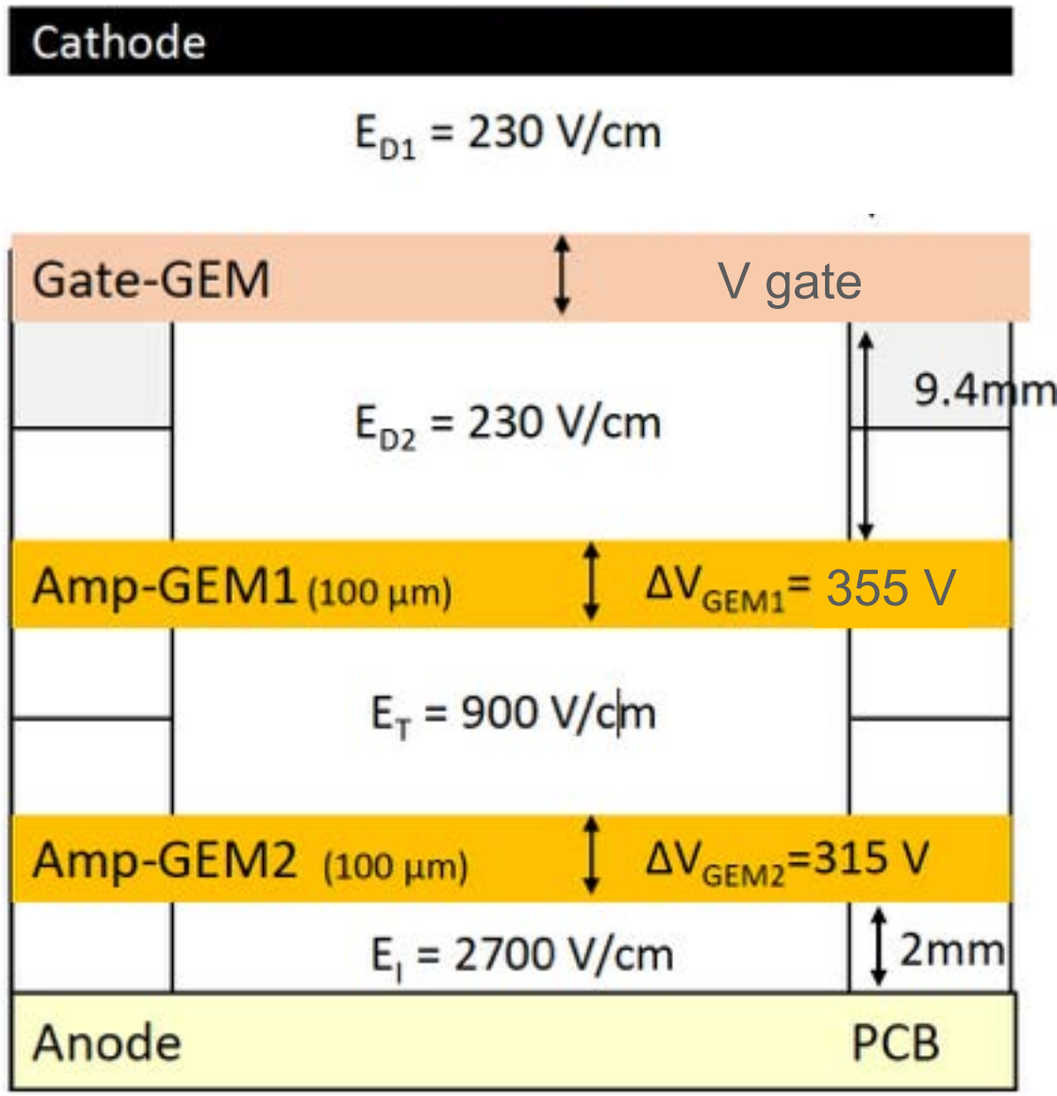
Module with Gating foil



The data I analyzed in this study

Center Module	with gatingGEM	without gatingGEM

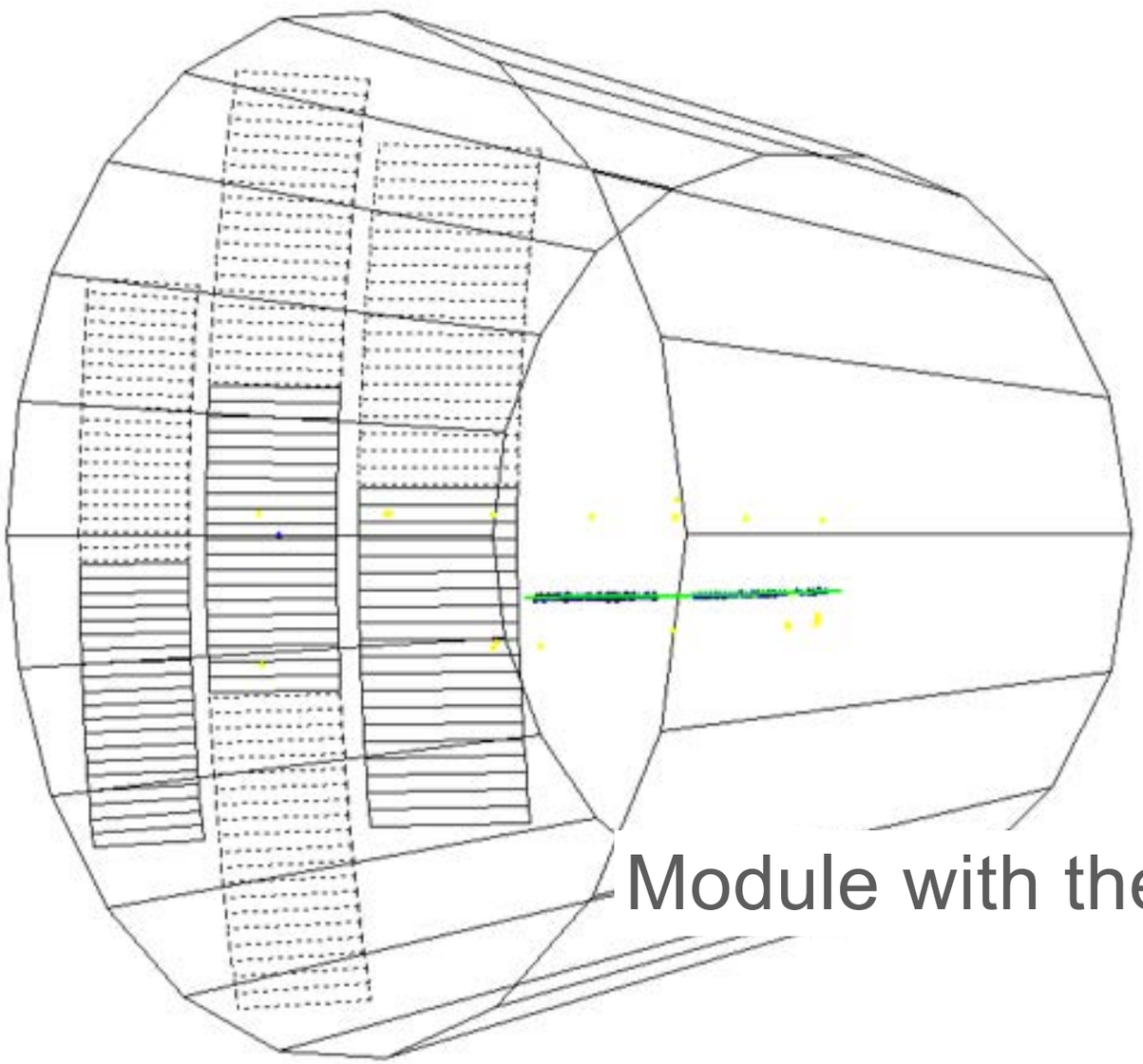
Z[cm] (Drift distance)	2.5,5,7.5,10,12.5,15,20 25,30,35,40,45,50,55
ϕ [degree]	0, -20
θ [degree]	0
V_{gate}[V]	3.5
B[T]	1



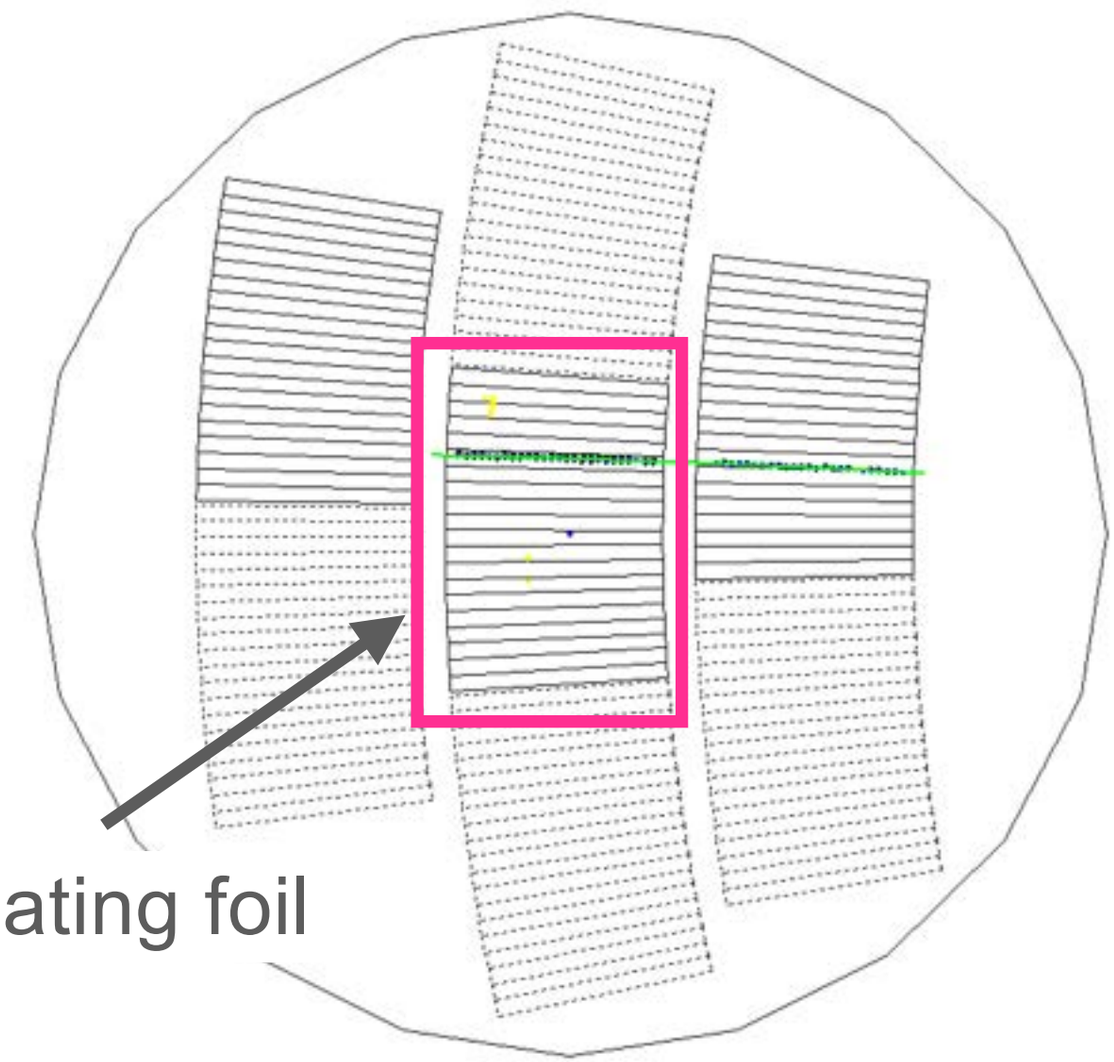
Beam: 5 GeV electron beam
Gas:T2K gas (Ar : CF_4 : Iso-C_4H_{10} = 95 : 3 : 2 [%])
Flame work:MarlinTPC（20000event/1 run）

Typical event

3D view



Projection onto the rφ plane

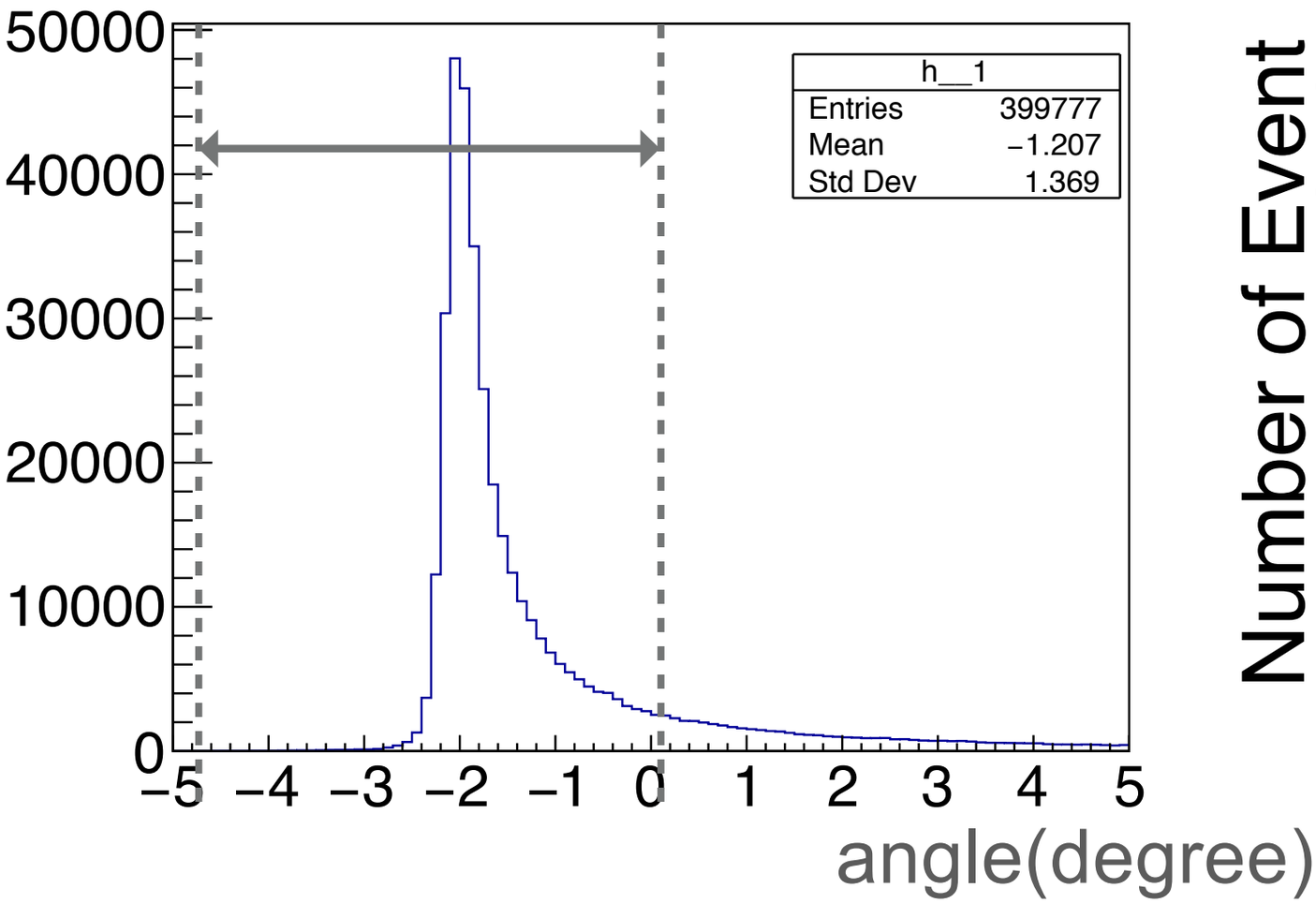


Module with the gating foil

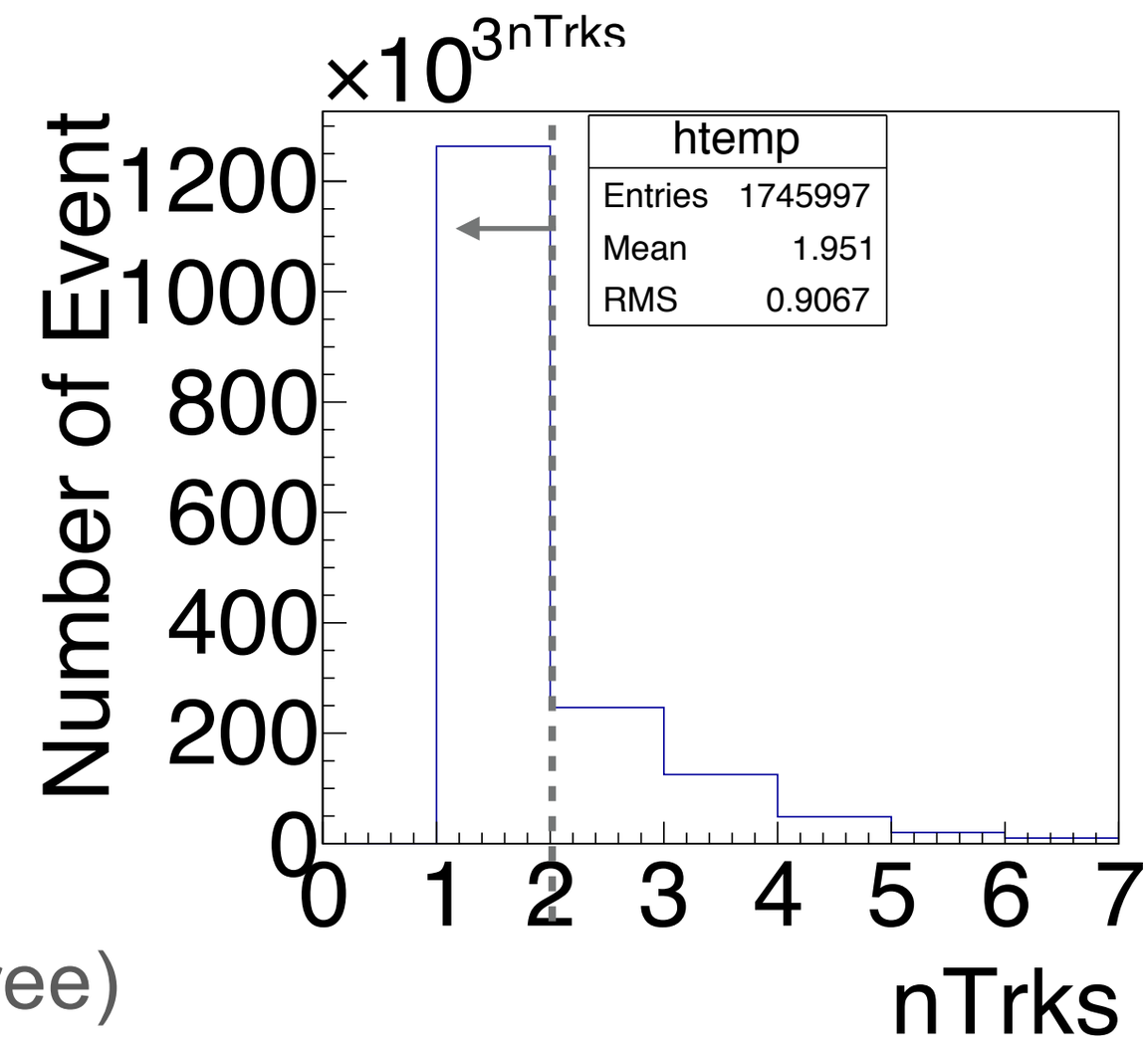
The beam goes through our module with the gating foil in the region far enough from the module boundaries.

Event Selection

Track angle cut[degree]
ex) -4.49< ϕ_{0loc} <0.09



# of tracks per event
nTrks = 1

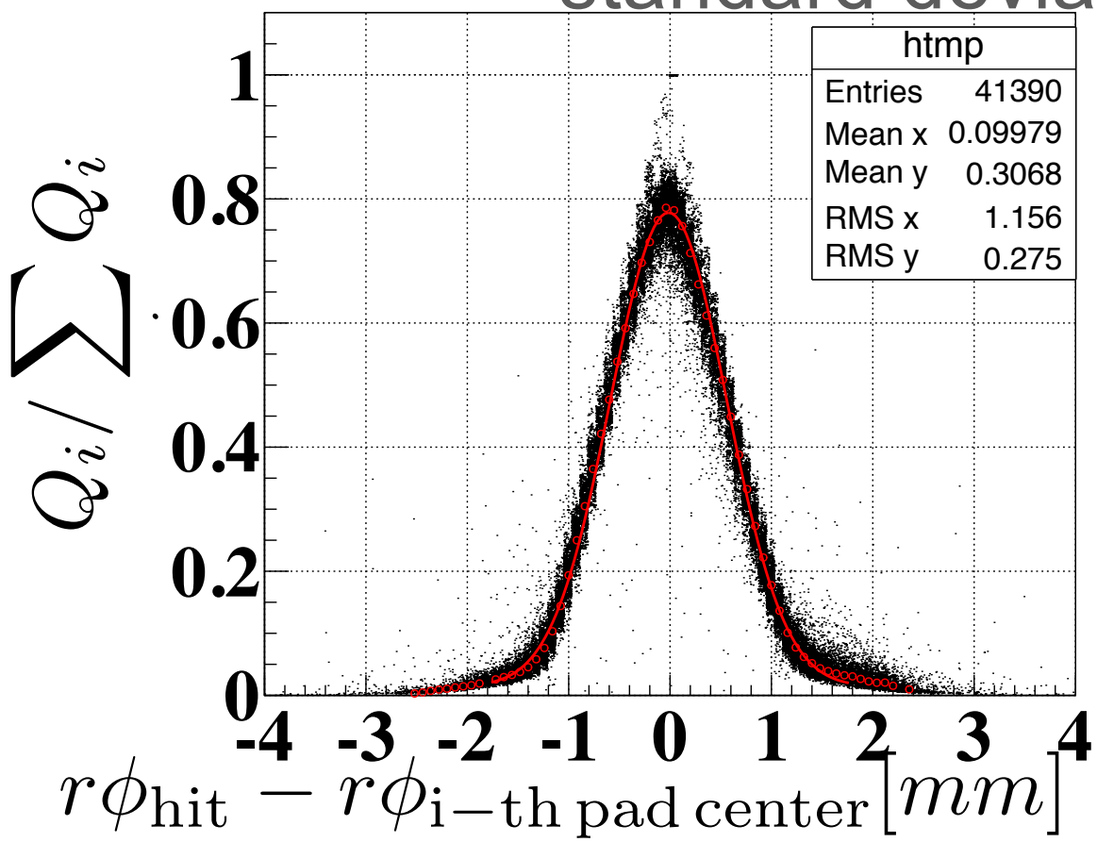


I applied a track angle cut to exclude angled tracks and a cut on nTrks to eliminate events with multiple tracks caused by electromagnetic showers created upstream.

Pad responce and GM resolution

Pad responce (σ_{PR})

standard deviation

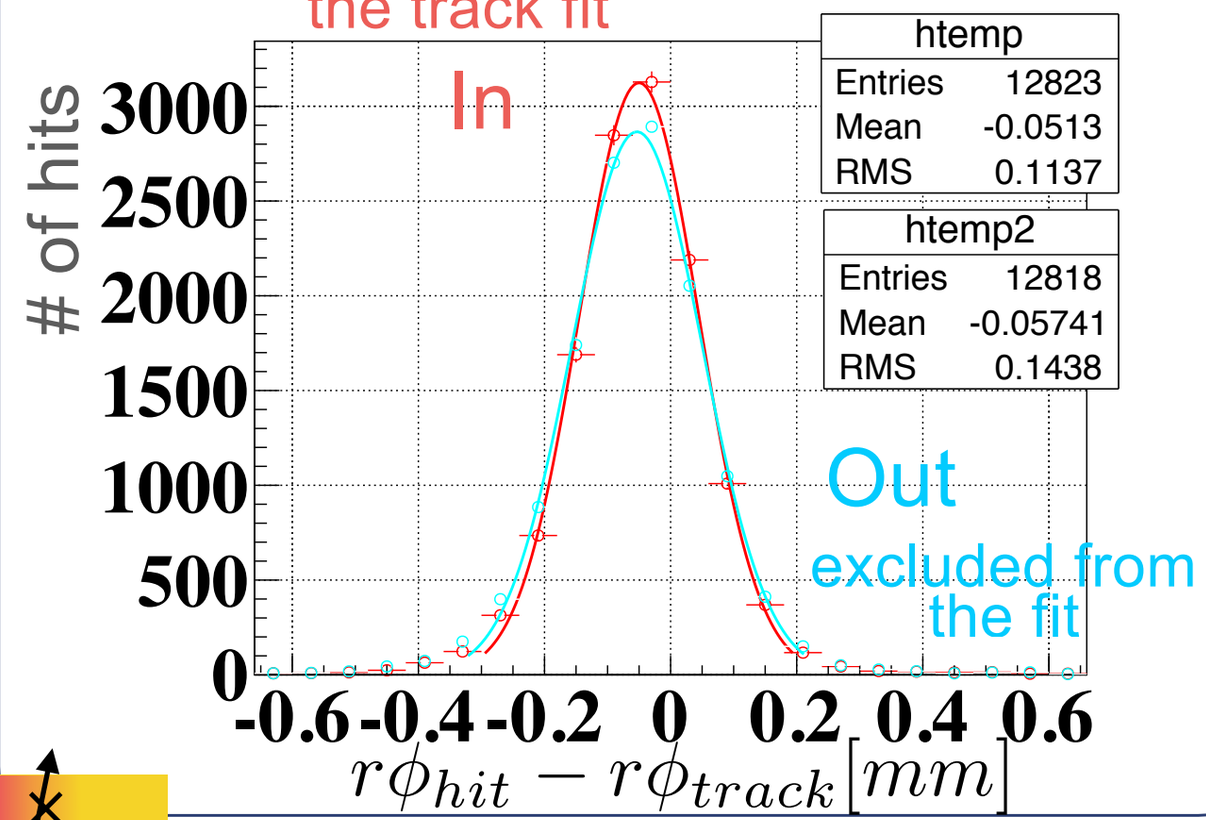


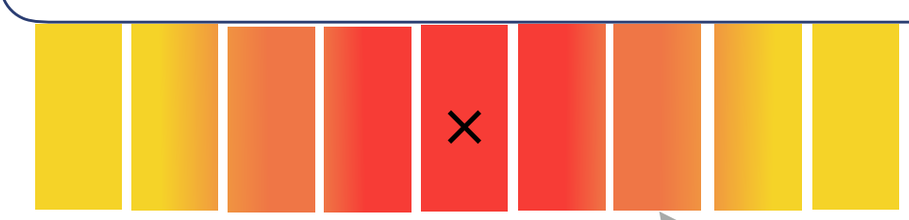
i= -4, -3, .., 0, ..3, 4

GM resolution ($\sigma_{r\varphi}$)

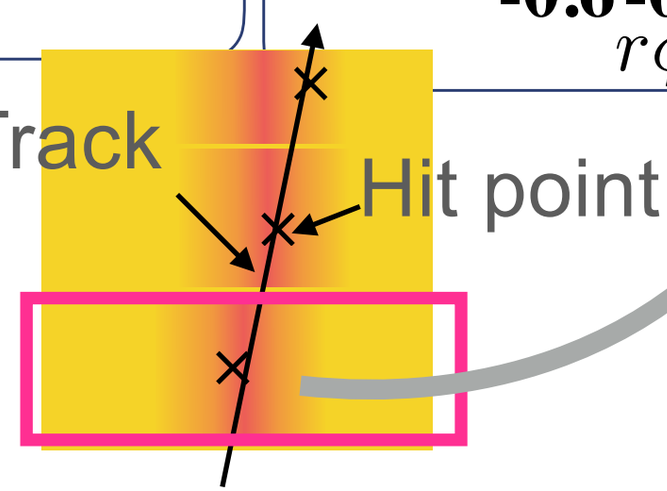
$$\sigma_{r\phi} = \sqrt{\sigma_{r\phi(in)}\sigma_{r\phi(out)}}$$

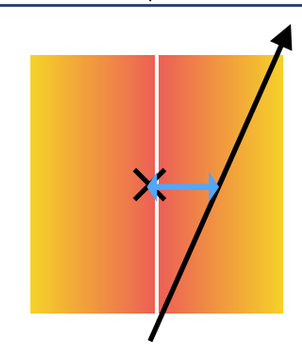
hit in question included in the track fit





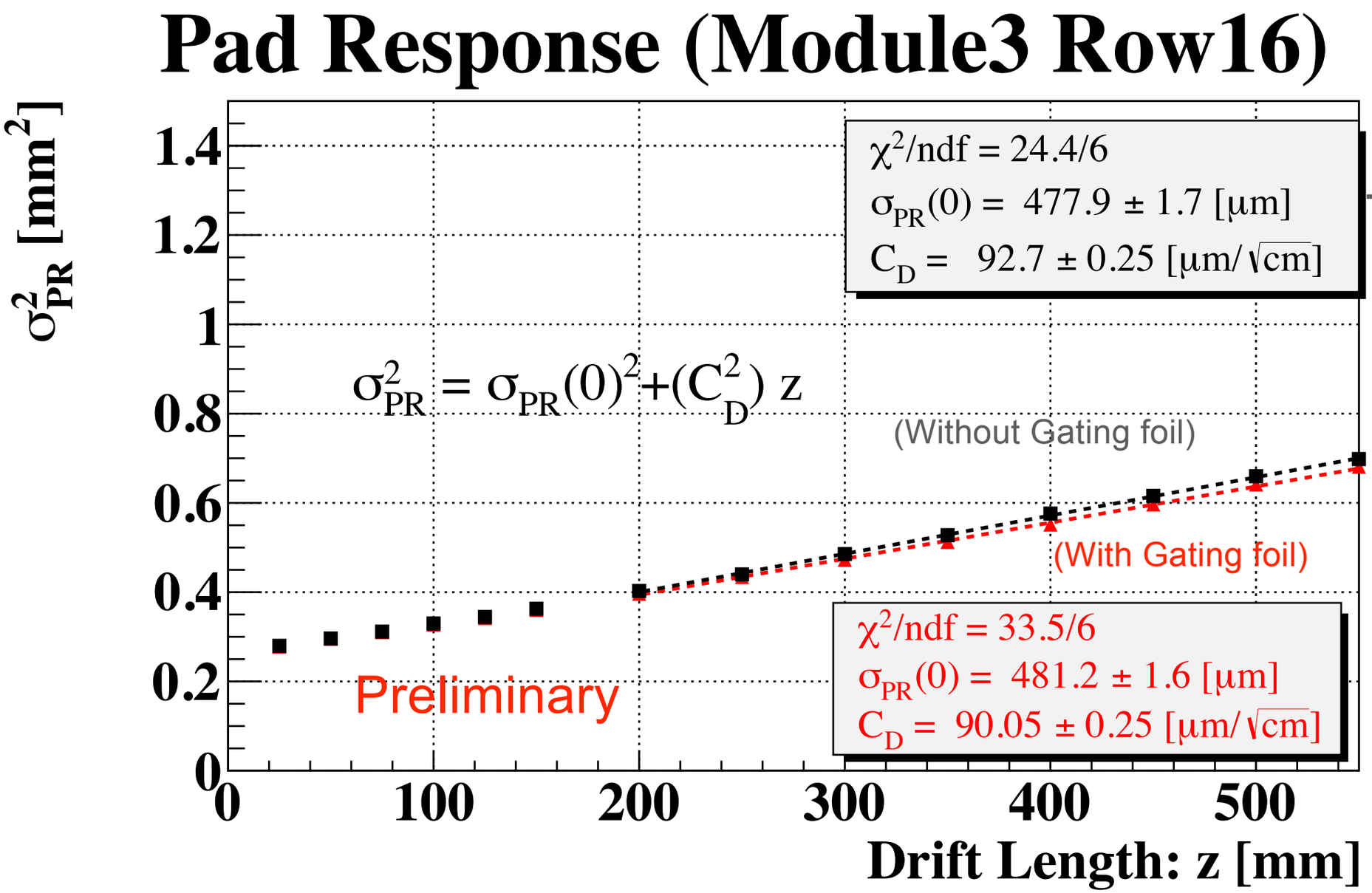
1 row





residual

Diffusion Constant



Track angle cut[degree]

(With Gate)

-4.49< ϕ_{0loc} <0.09

(Without Gate)

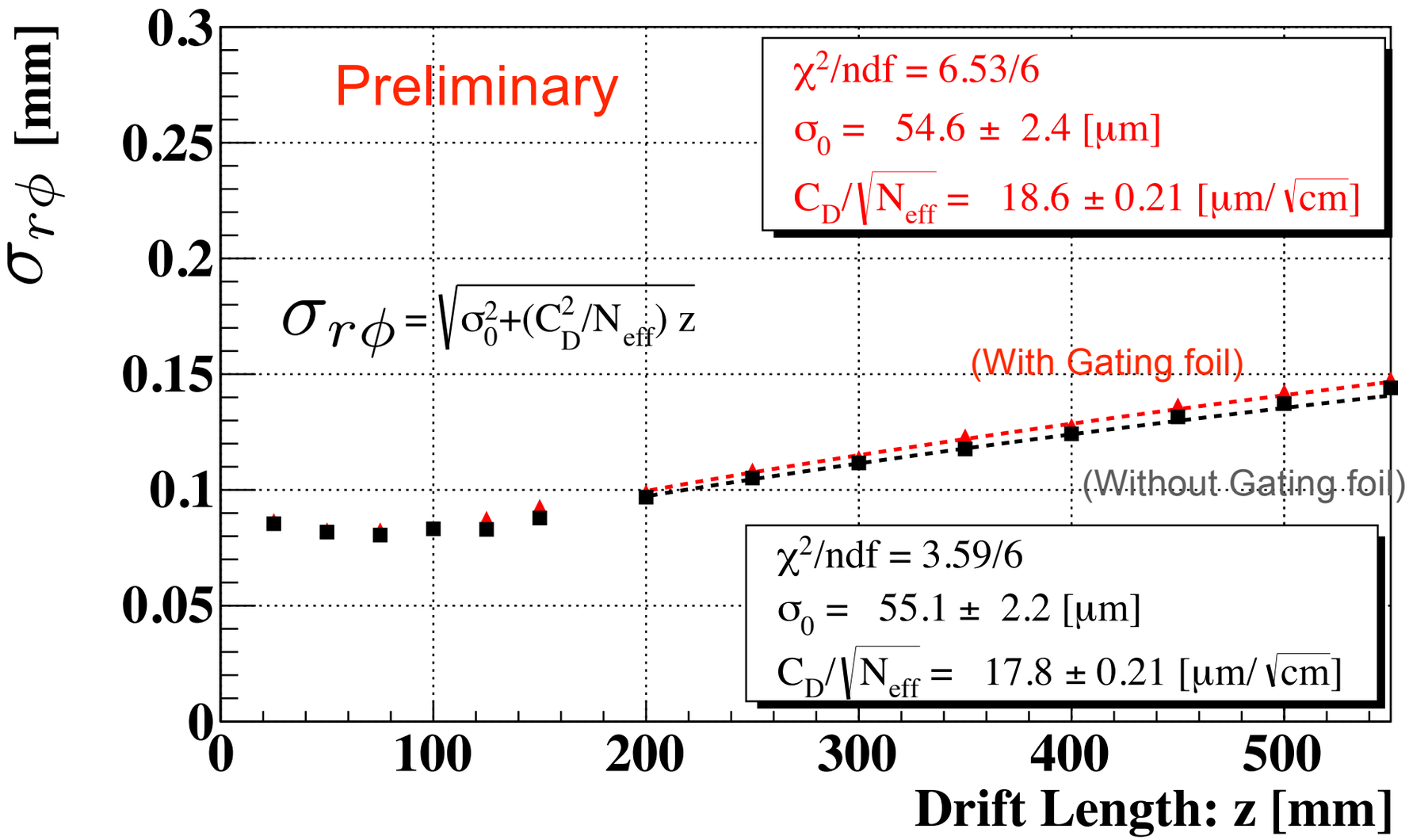
-6.78< ϕ_{0loc} <-2.77

The difference between Cd of with gate and its of without gate is significant. They should be almost same.

→We are trying to find the reason.

Spatial resolution（rφ）

GM Resolution(module3 row16)



Track angle cut[degree]

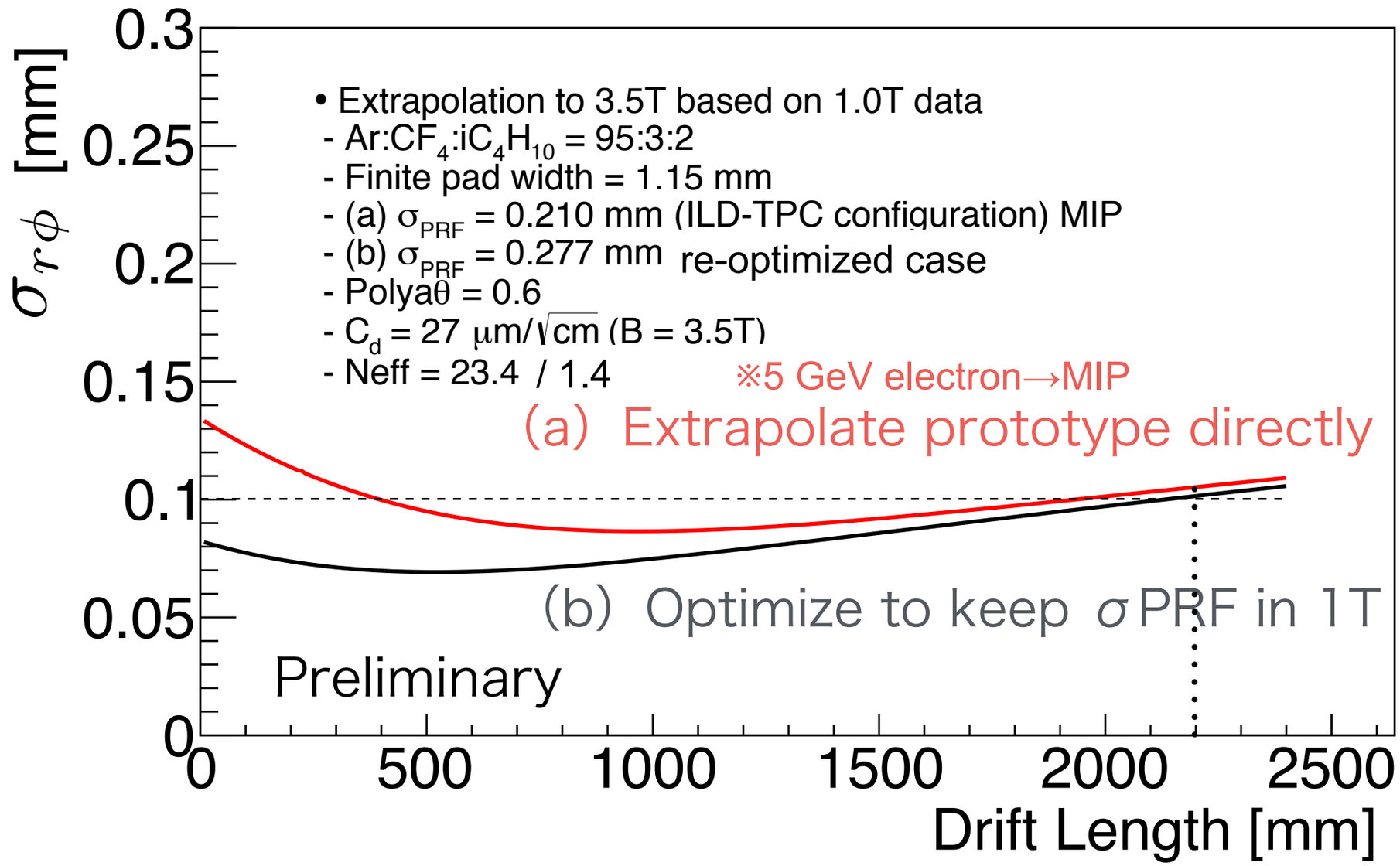
(With Gate)

-4.49< ϕ_{0loc} <0.09

(Without Gate)

-6.78< ϕ_{0loc} <-2.77

The extrapolation to B=3.5 T



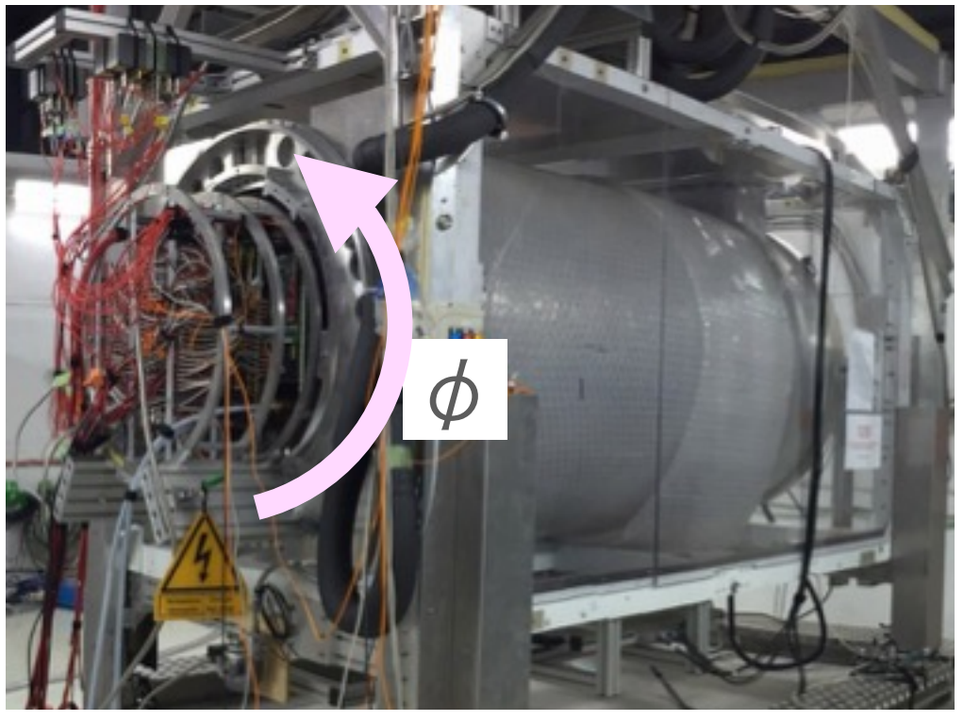
When we decide hit points by center of gravity, the graph is (a) because of bias.

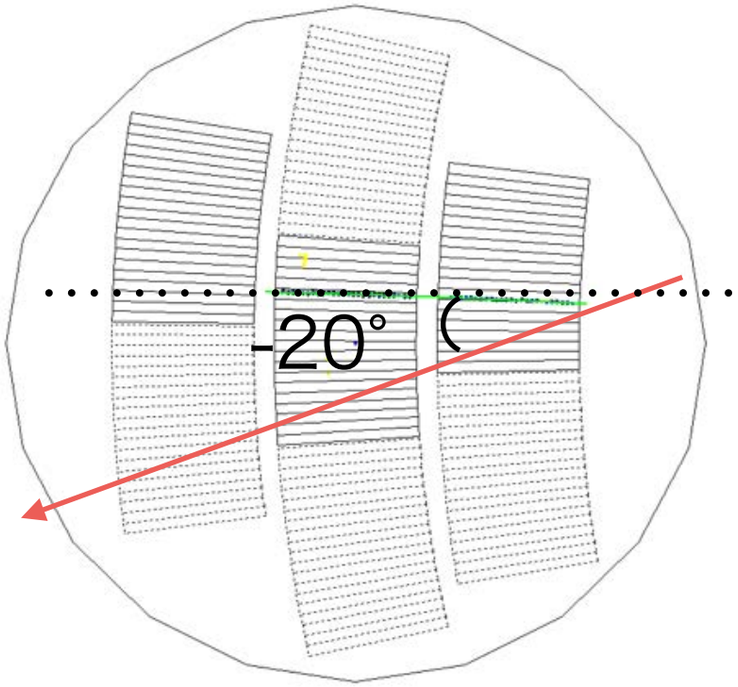
When we optimize to keep σPRF in 1T, we get graph (b)

→The spatial resolution (100 μm) can be achieved

Analysis of Angled Track(ϕ=-20°)

I analyzed the angled track data with gating foil. (ϕ=-20°)





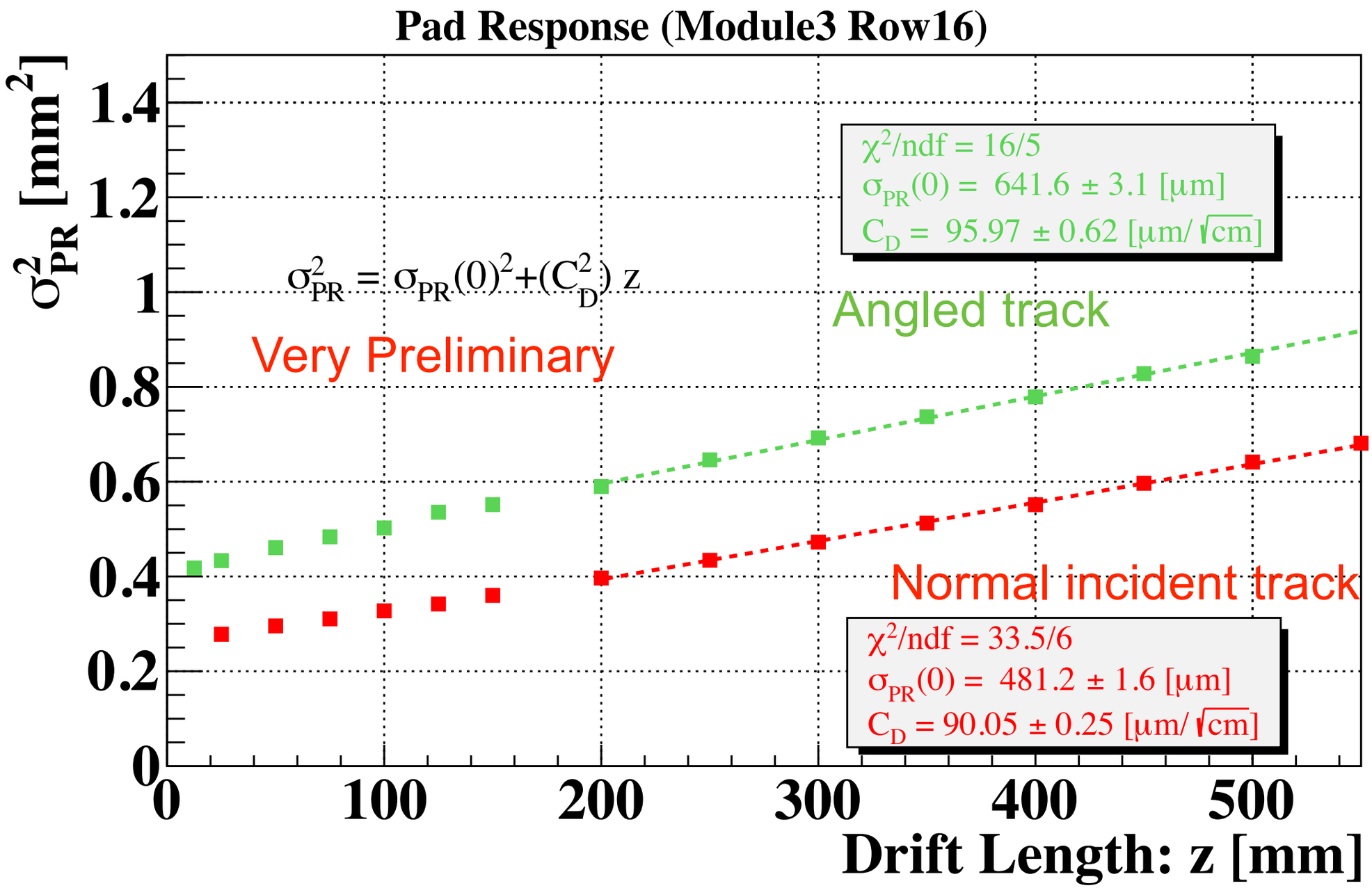
I applied a track angle cut and a cut on number of Tracks.

Track angle cut[degree]
(Normal incident track)
-4.49< ϕ_{0loc} <0.09

(Angled track)
13.84< ϕ_{0loc} <16.13

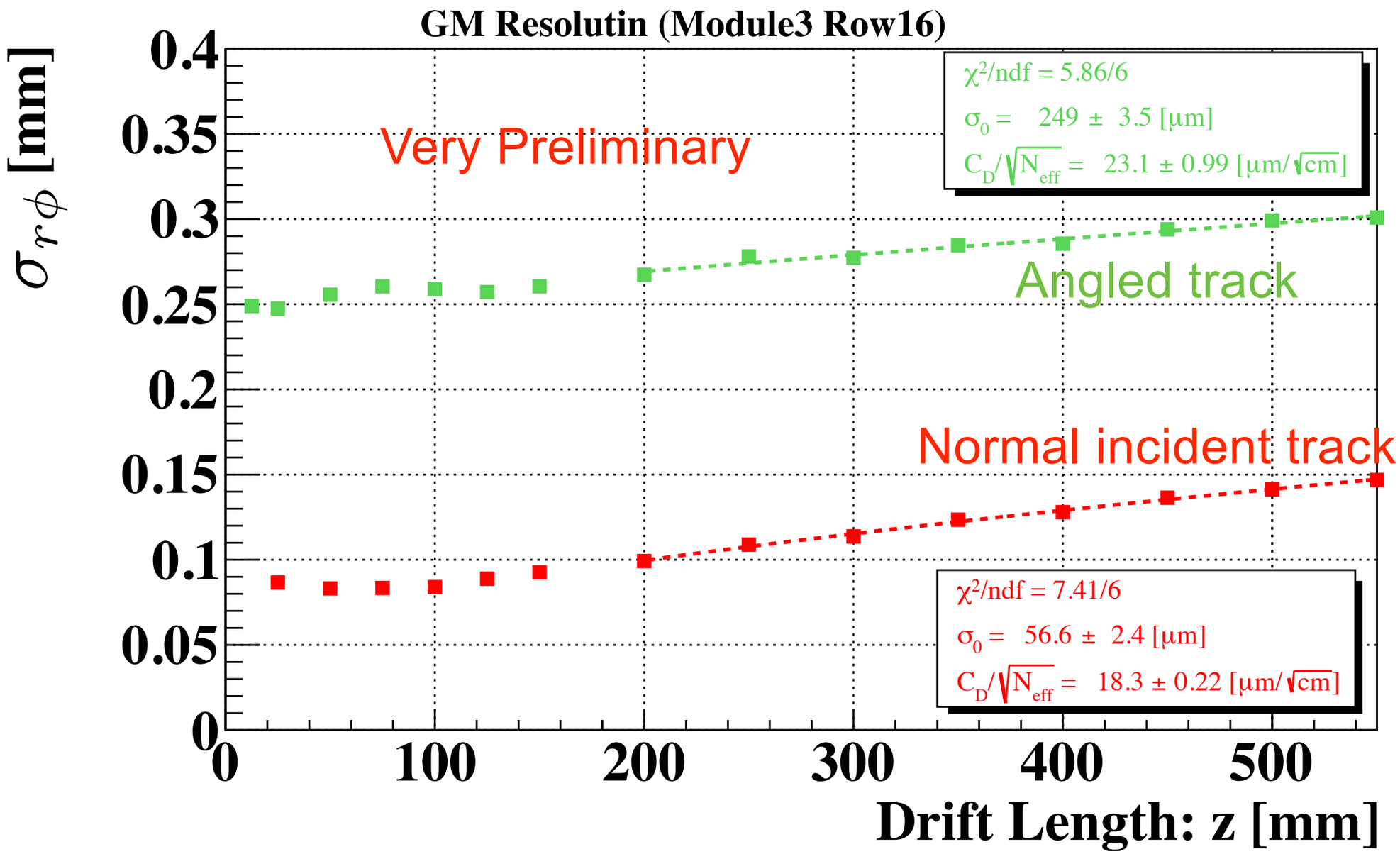
I compared the pad response, spatial resolution and Neff(number of effective electron) between the normal incident track and angled track.

Pad Responce(ϕ=-20°)



These 2 data is the data with the gating foil, so the difference of Cd is not caused the gating foil.

Spatial Resolution(ϕ=-20°)



The angler pad effect caused the deterioration of spatial resolution.

Compare N effective

with gate	ϕ=0°	ϕ=-20°
Cd [μm/√cm]	90.05±0.25	95.45±0.21
Cd/√Neff	18.6±0.3	23.1±0.99
N_{eff}	23.4±0.6	17.1±1.5

We expect the Neff of -20° angled track is 6% more than vertical one.

However the Neff of -20° angled track is reduced.

I checked sum of charge, but the charge of angled cut is increased about 6%.

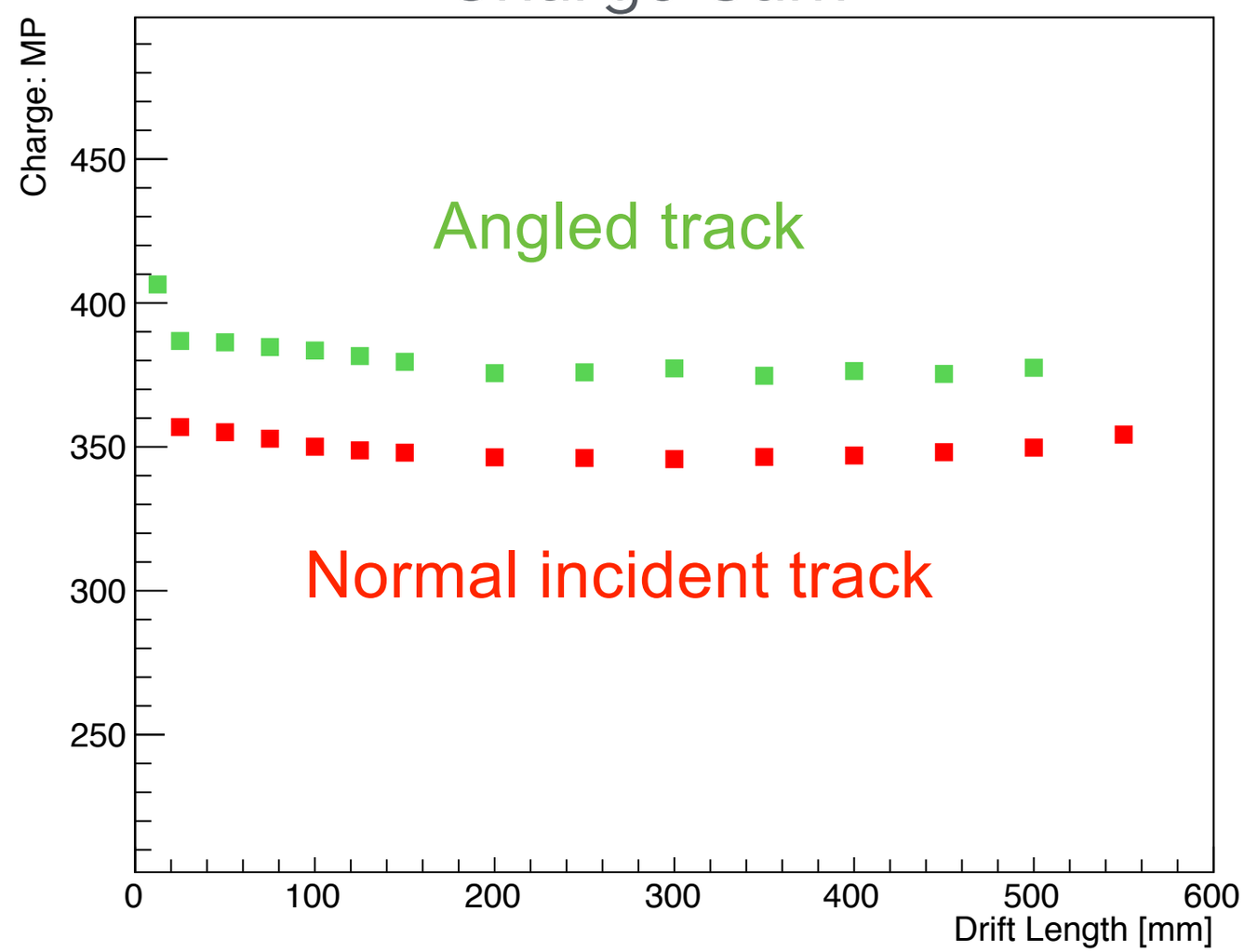
→I will check the method to calculate Neff for angled data or cut values.

N effective

$$N_{eff} = \left[\left\langle \frac{1}{N} \right\rangle \left\langle \left(\frac{G}{\bar{G}} \right)^2 \right\rangle \right]^{-1}$$

N:number of electron G:Gas gain

Charge Sum



Summary

We checked performances of the module with the gating foil by analyzing beam test data.

- The extrapolation of the beam test result to 3.5 T/2.2 m drift ILD-TPC shows that achieve spatial resolution goal of 100 μm with the gating foil
- I started to analyze the angled track data. We expect the Neff of -20° angled track is 6% more than vertical one, but the result is different

Future work

- Understand Cd difference
- Understand difference of Neff about angled data from theory

Back up Slides

The Difference of Diffusion Constant[1]

The difference of Cd is caused by the condition?
(Temperature, Pressure)

	with gating foil)	without gating foil
Temperature[K]	291.28	290.4
Pressure[hPa]	1010.79	1005.31
Cd[%]	94.0 μm/√cm +/- 0.2	94.2 μm/√cm +/- 0.3

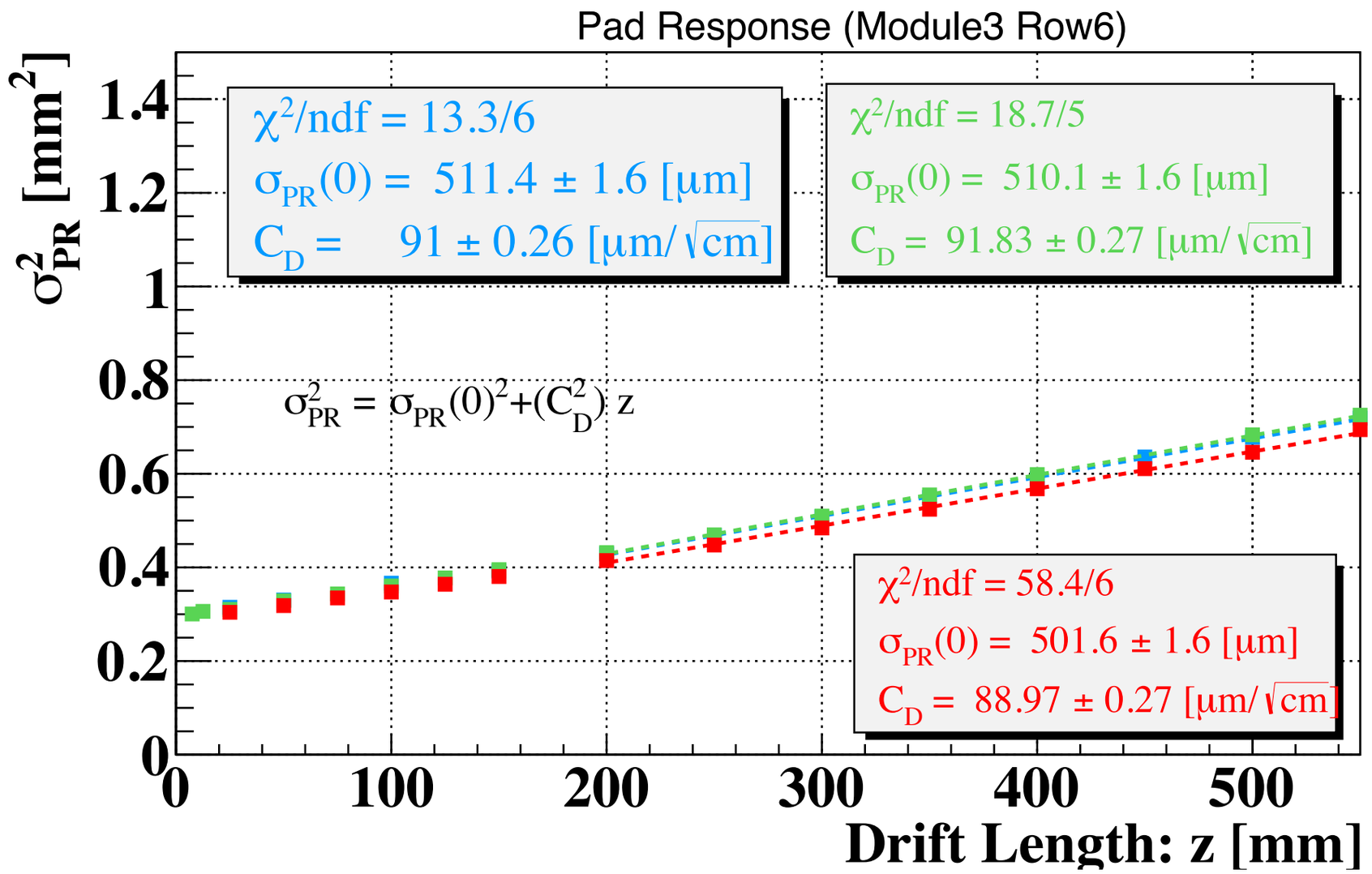
There is little difference.

→The difference is not caused by the condition.

The Difference of Diffusion Constant[2]

The difference is caused by the gating foil?

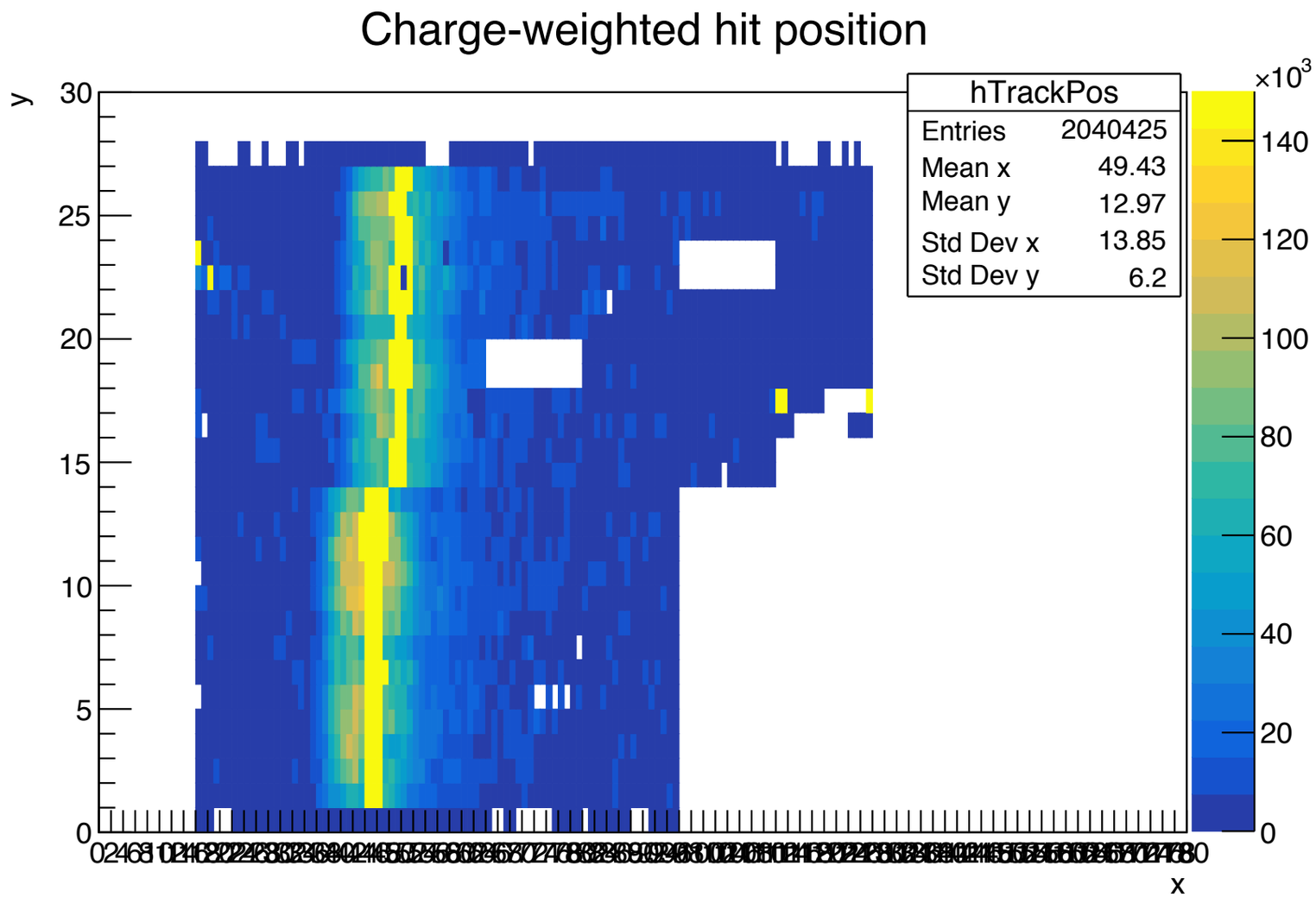
→I analyzed 2 more data set with Gate.



The difference is significant even the almost same condition.

So we use measured Cd values to calculate transmission.

Data Quality Cuts

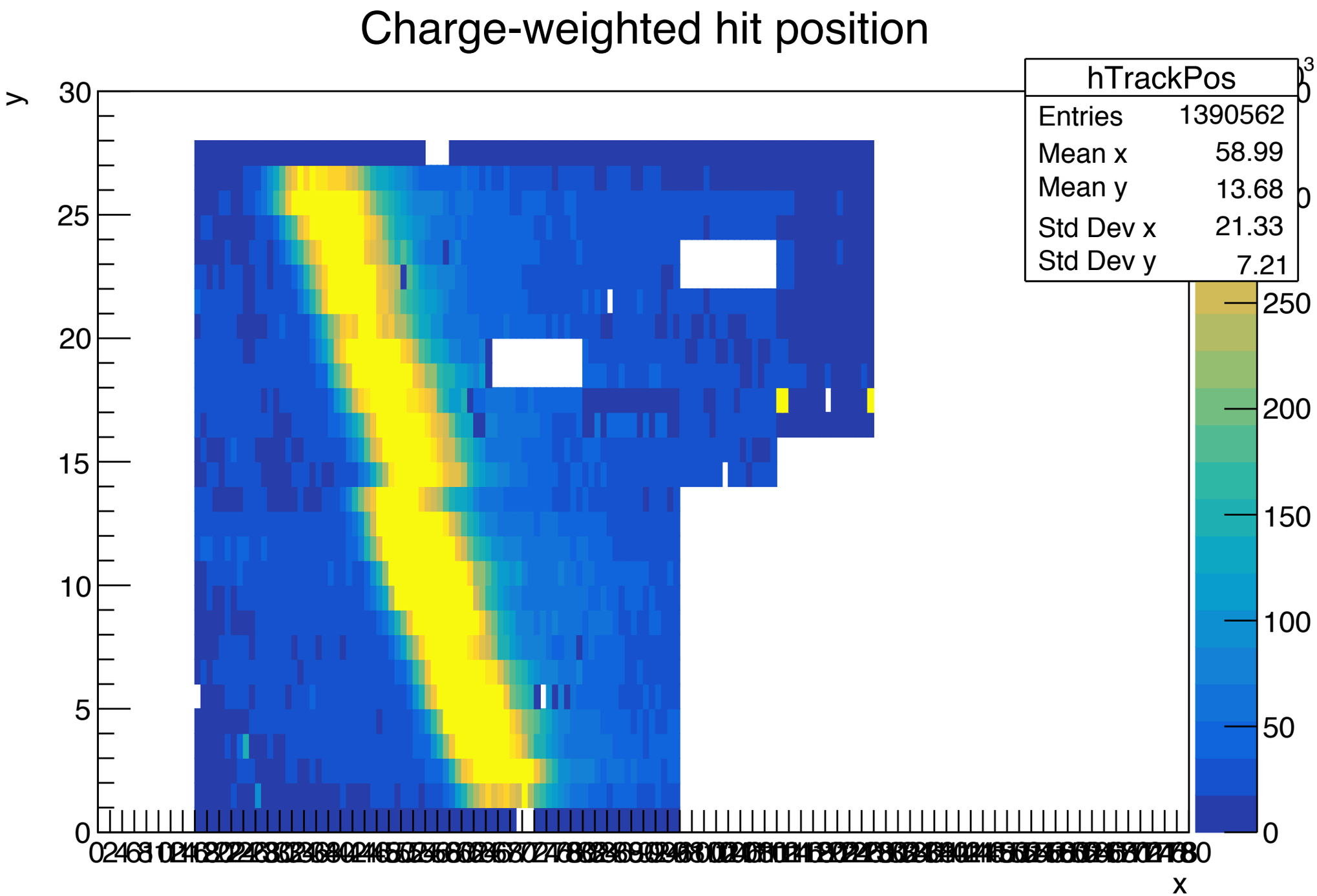


exclude row number 0, 22, 27.

Row 0, 27 may has distortion of electric field because they are the edge of module.

Row 22 has dead pad.

Dead channel

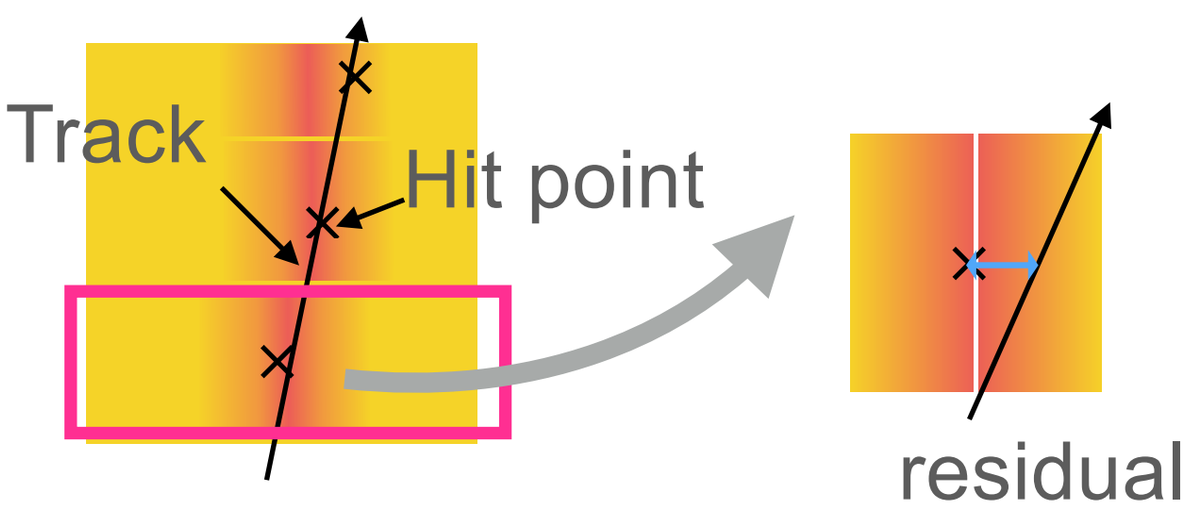


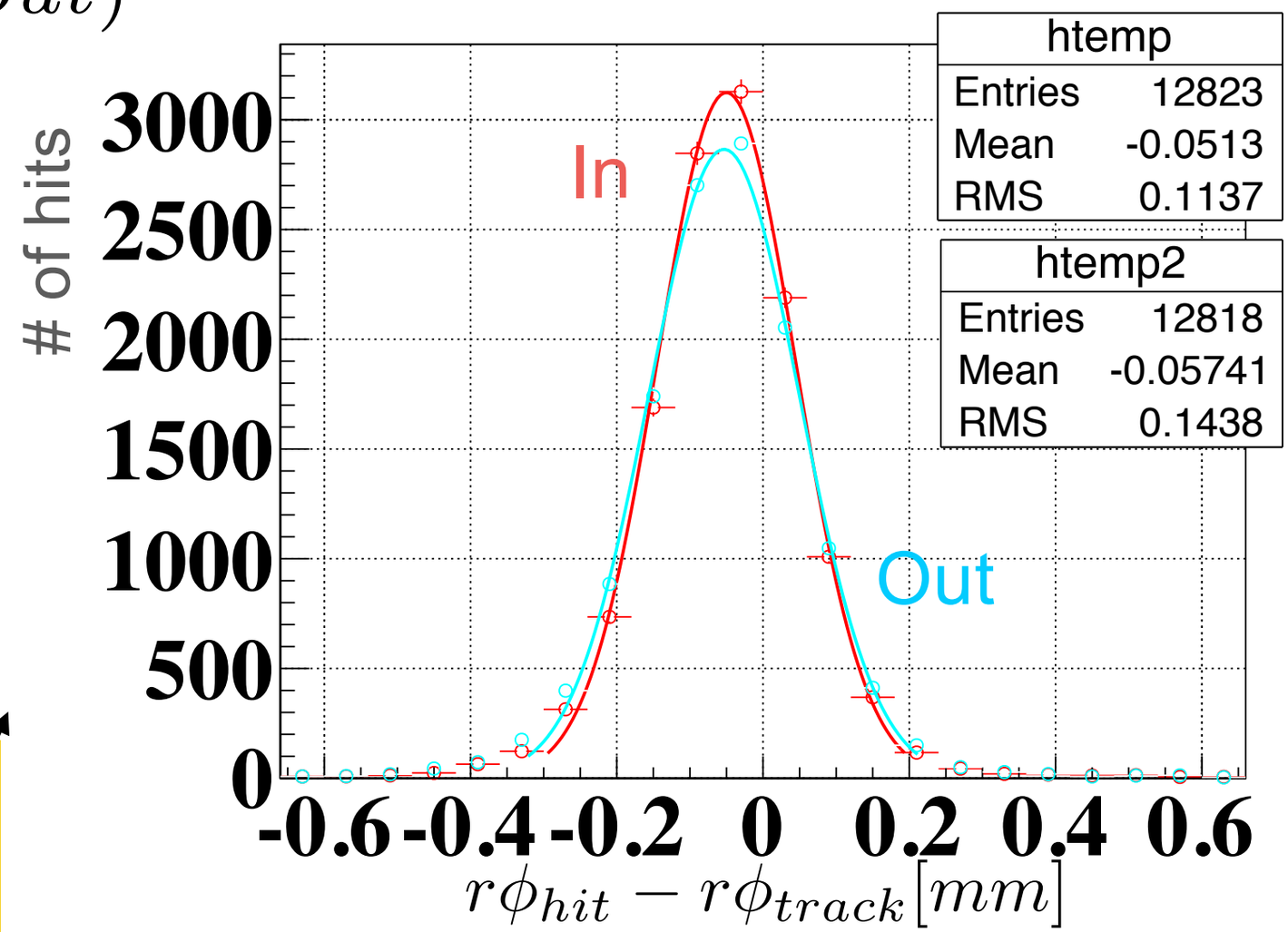
How to get spatial resolution

$$\sigma_{r\phi} = \sqrt{\sigma_{r\phi(in)}\sigma_{r\phi(out)}}$$

$\sigma_{r\phi(in)}$ hit in question included in the track fit

$\sigma_{r\phi(out)}$ excluded from the fit





How to estimate Electron transmission

Neff : Effective number of ionization electrons

which decides spatial resolution

$$N_{eff} = \left[\left\langle \frac{1}{N} \right\rangle \left\langle \left(\frac{G}{\bar{G}} \right)^2 \right\rangle \right]^{-1}$$

G : gas amplification

$\bar{G}$: average of gas amplification

Ratio of Neff≒Electron transmission ratio

$$\frac{N_{eff}(\mathrm{w/\,Gate})}{N_{eff}(\mathrm{w/o\,Gate})} \approx R_{e.t.}$$

How to get Neff

For large enough drift distances, spatial resolution with respect to drift distance can be written in the following form

$$\sigma_{r\phi}(Z) = \sqrt{\sigma_0^2 + \frac{C_d^2}{N_{eff}} \cdot Z}$$

$\sigma_{r\phi}$: spatial resolution for azimuth angle ($r\phi$)

σ_0: spatial resolution without electron diffusion(constant term)

C_d : diffusion constant

N_{eff} : Effective number of ionization electrons $N_{eff} = \left[\left\langle \frac{1}{N} \right\rangle \left\langle \left(\frac{G}{\bar{G}}\right)^2 \right\rangle\right]^{-1}$

Z : drift distance

G : gas amplification

$\bar{G}$: average of gas amplification

The diffusion constant can be obtained from pad responce.

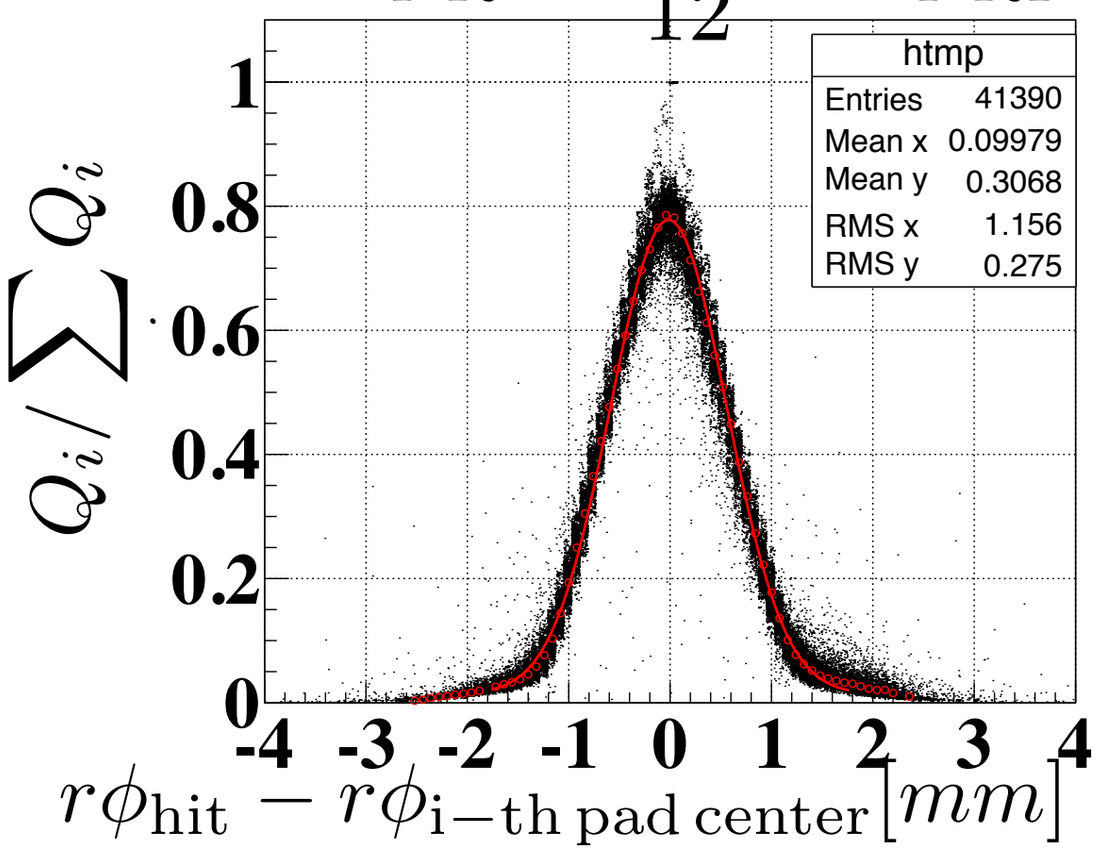
I'll explain how to get Cd from pad response.

Pad responce（σ_{PR}）

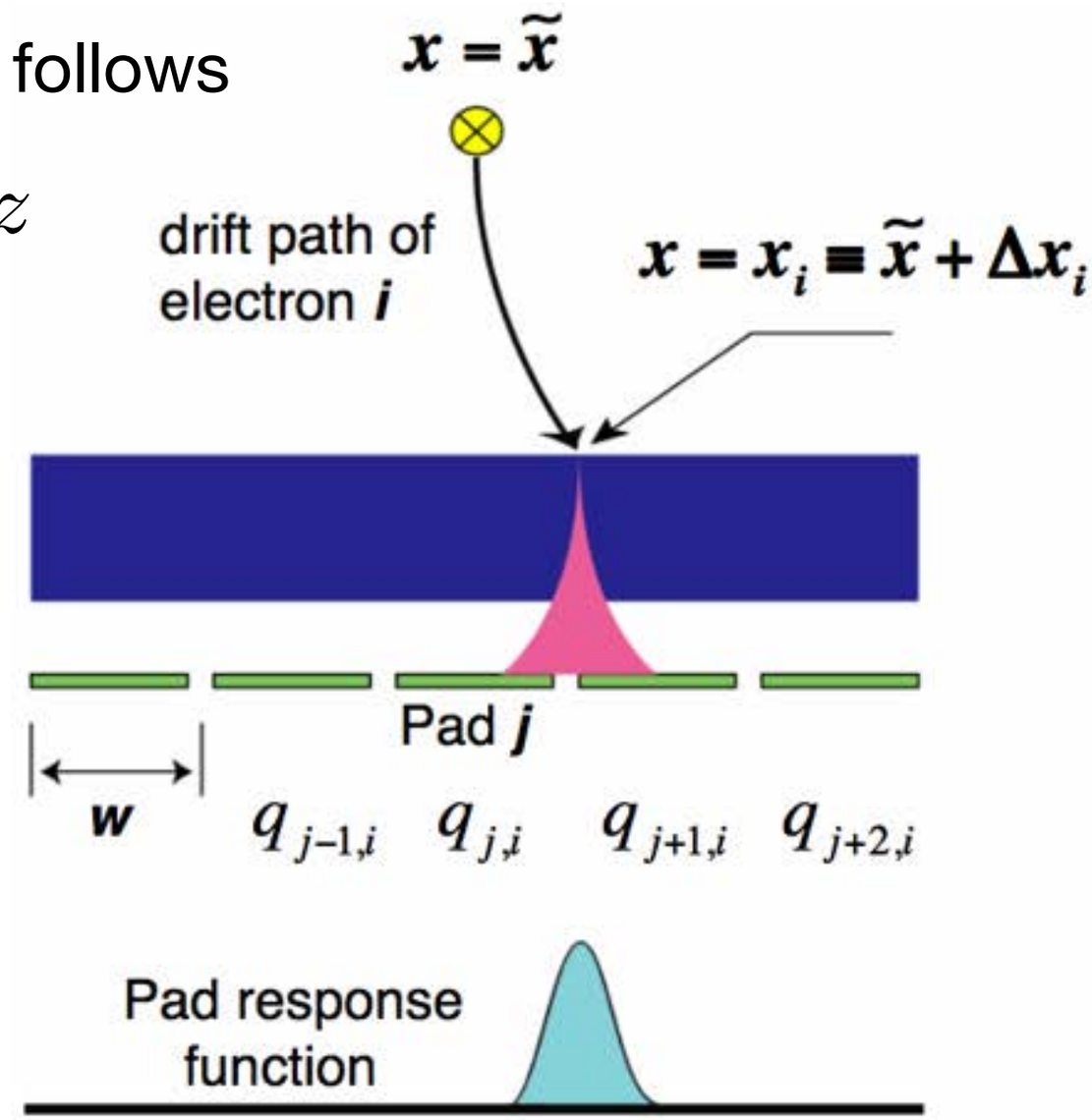
The width of the pad response function（σ_{PR}）is obtained as follows
First, we plot the charge fraction on each pad as a function of the distance of the pad center from the hit point. Then we fit this distribution to a Gaussian and get σ_{PR} as the standard deviation.

On the other hand, σ_{PR} can be expressed as follows

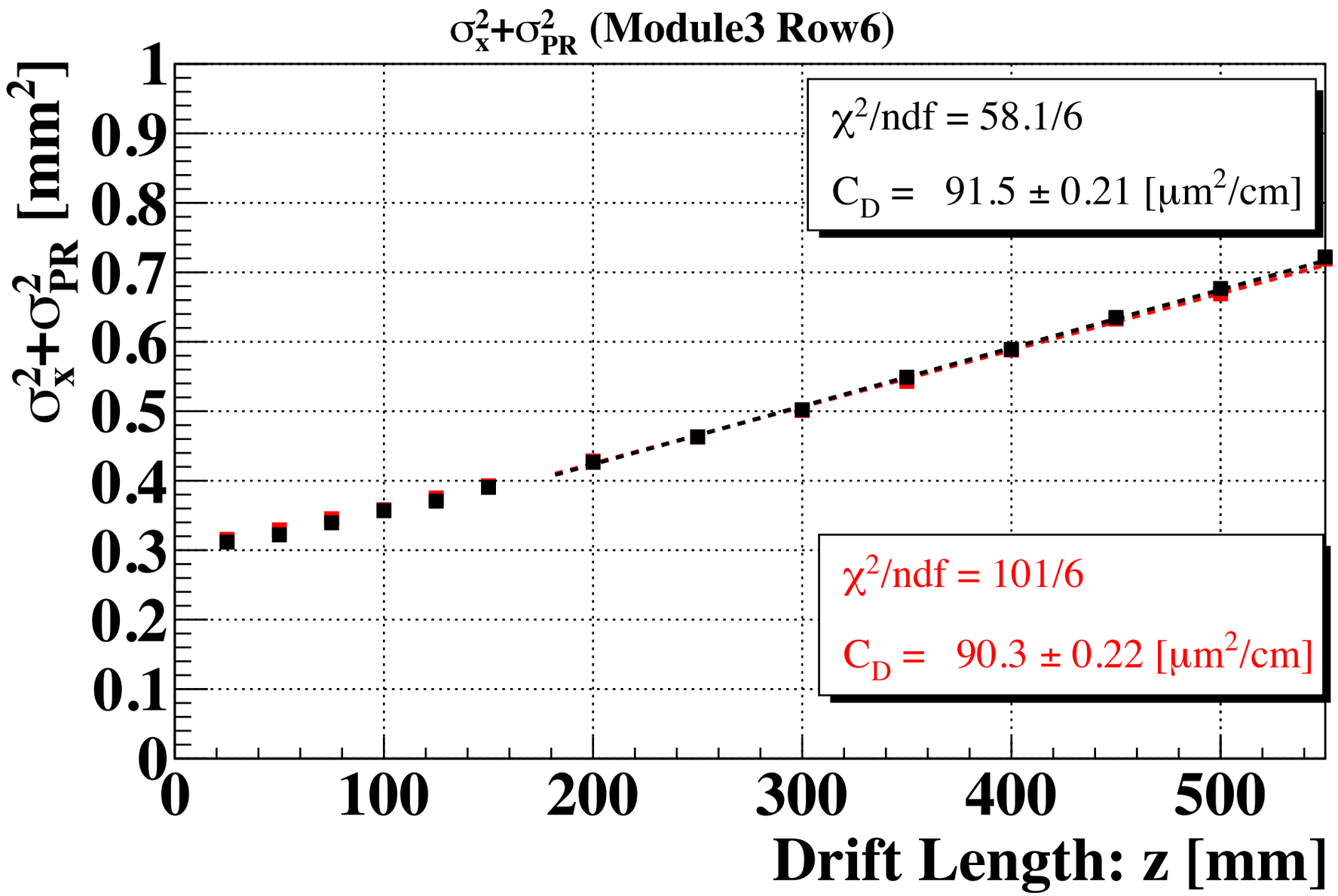
$$\sigma_{PR}^2 = \frac{w^2}{12} + \sigma_{PRF}^2 + C_d^2 z$$



i= -4, -3, .., 0, ..3, 4

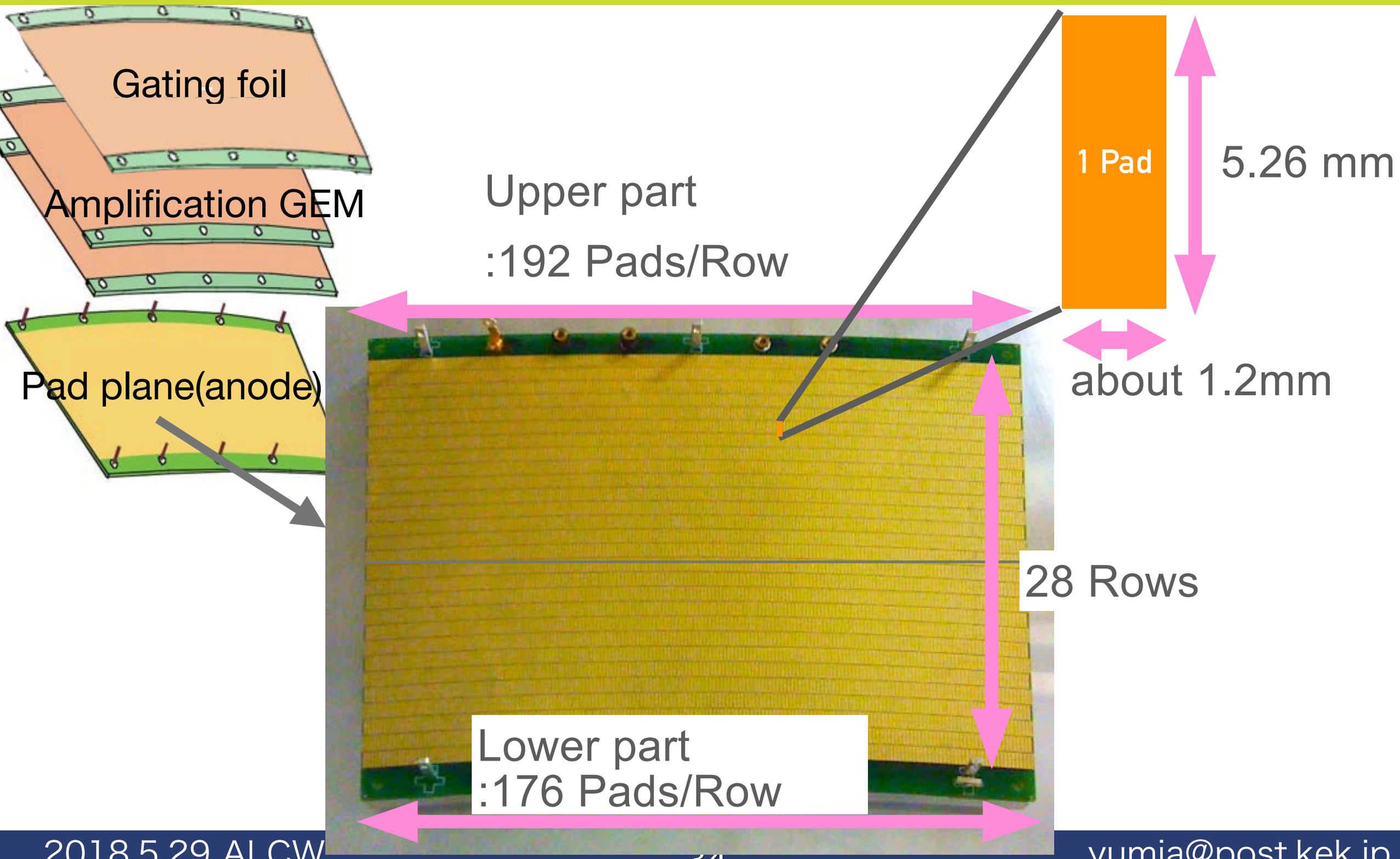


Diffusion Constant



To reduce short term effect, I calculated $\sigma_{r\phi} + \sigma_{PR}$.
The difference of Cd is less than its by ordinary way.

Readout Pads



The Electron transmission

	Cd(w/ gate) [μm/√cm]	Cd(w/o gate) [μm/√cm]
measurement	90.05±0.25	92.7±0.25

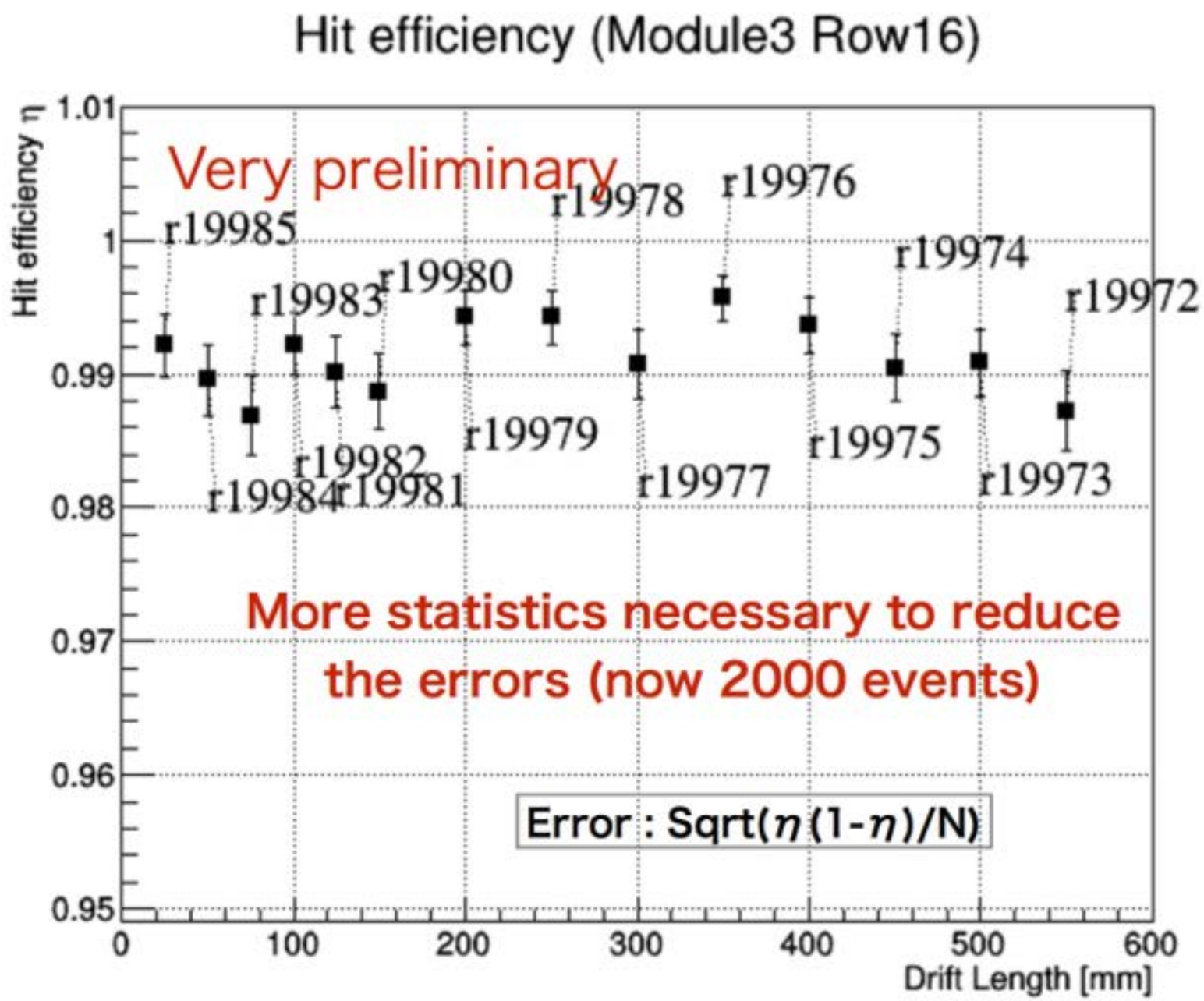
	w/ gate	w/o gate
Cd/√Neff	18.6±0.3	17.8±0.3

Cd [μm/√cm]	N_{eff}(w/ gate)	N_{eff}(w/o gate)	ratio[%]
measurement	23.4±0.6	27.2±0.8	86.4±3.1

We get about 86 % electron transmission rate with gating foil.

We achieved the target electron transmission rate of > 80%.

Data quality check - Hit efficiency



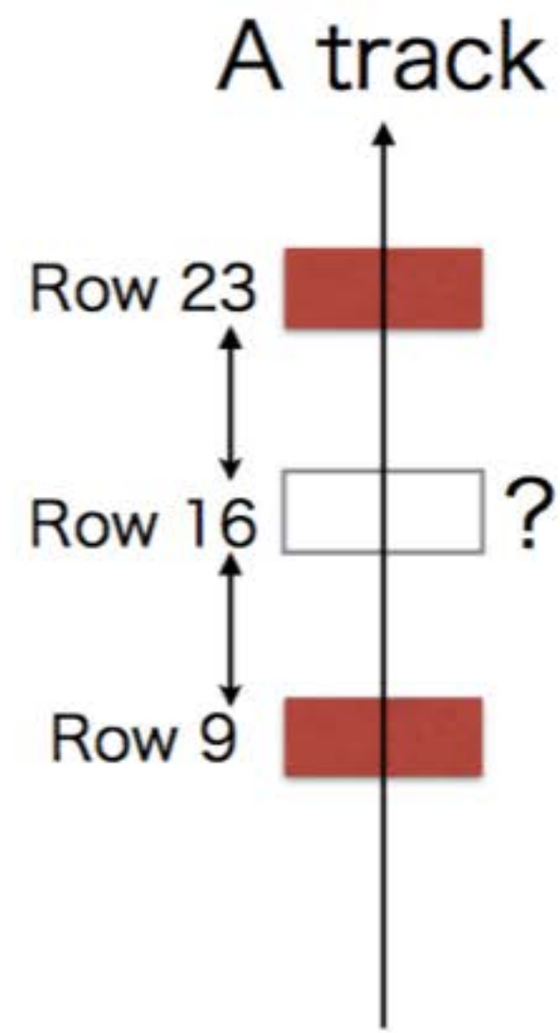
- Mi

With Gating foil

Hit efficiency estimation

Looked at row-16 (module 3)

7rows away to avoid
effects by the diffusion.

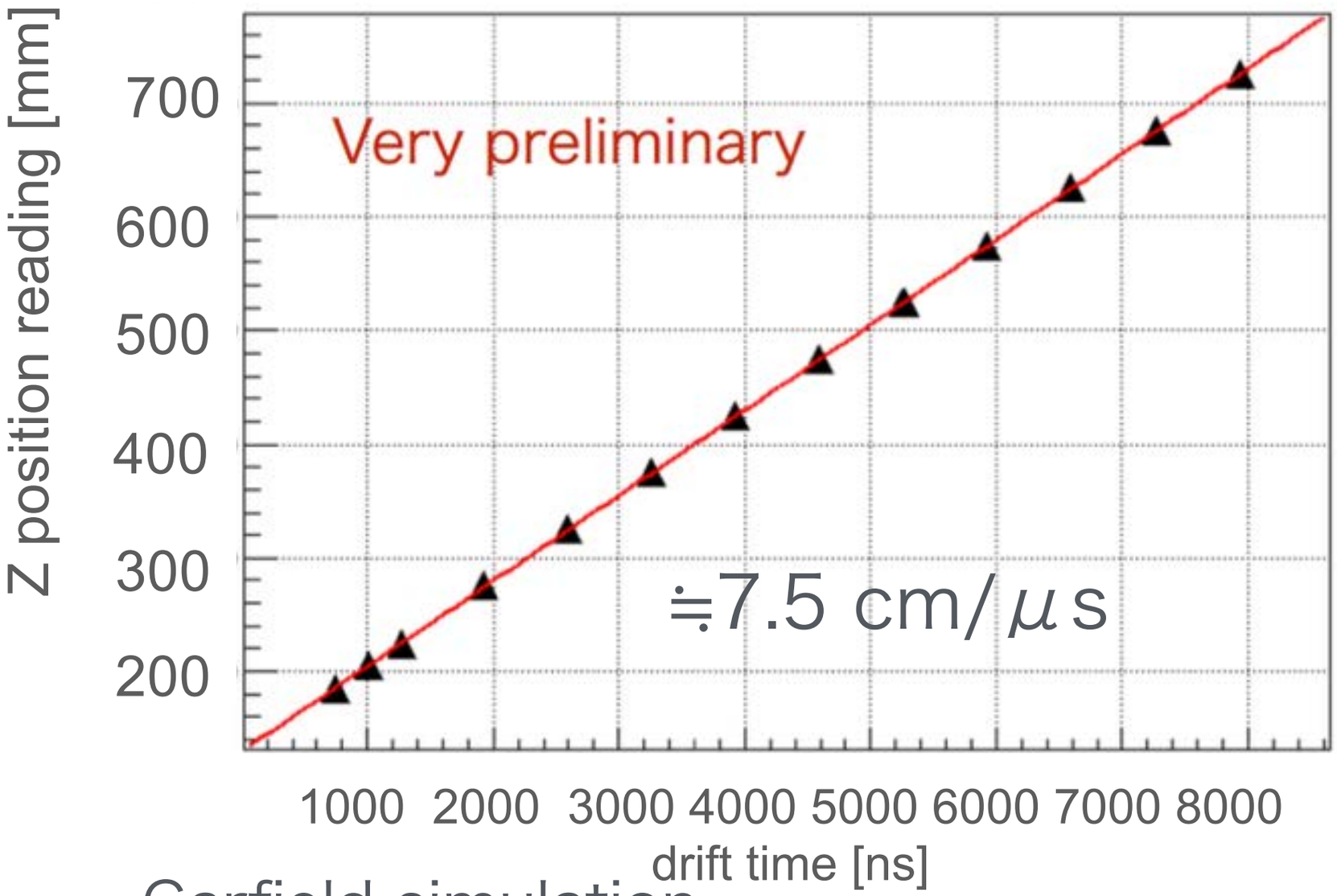


Basic idea :

Test if Row16 has a hit associated with a track
that has hits both on Row9 and Row23.

To reduce biases, minimum number of hits per track
is set to be a relatively small value (=10)
in the track reconstruction step.

Drift velocity



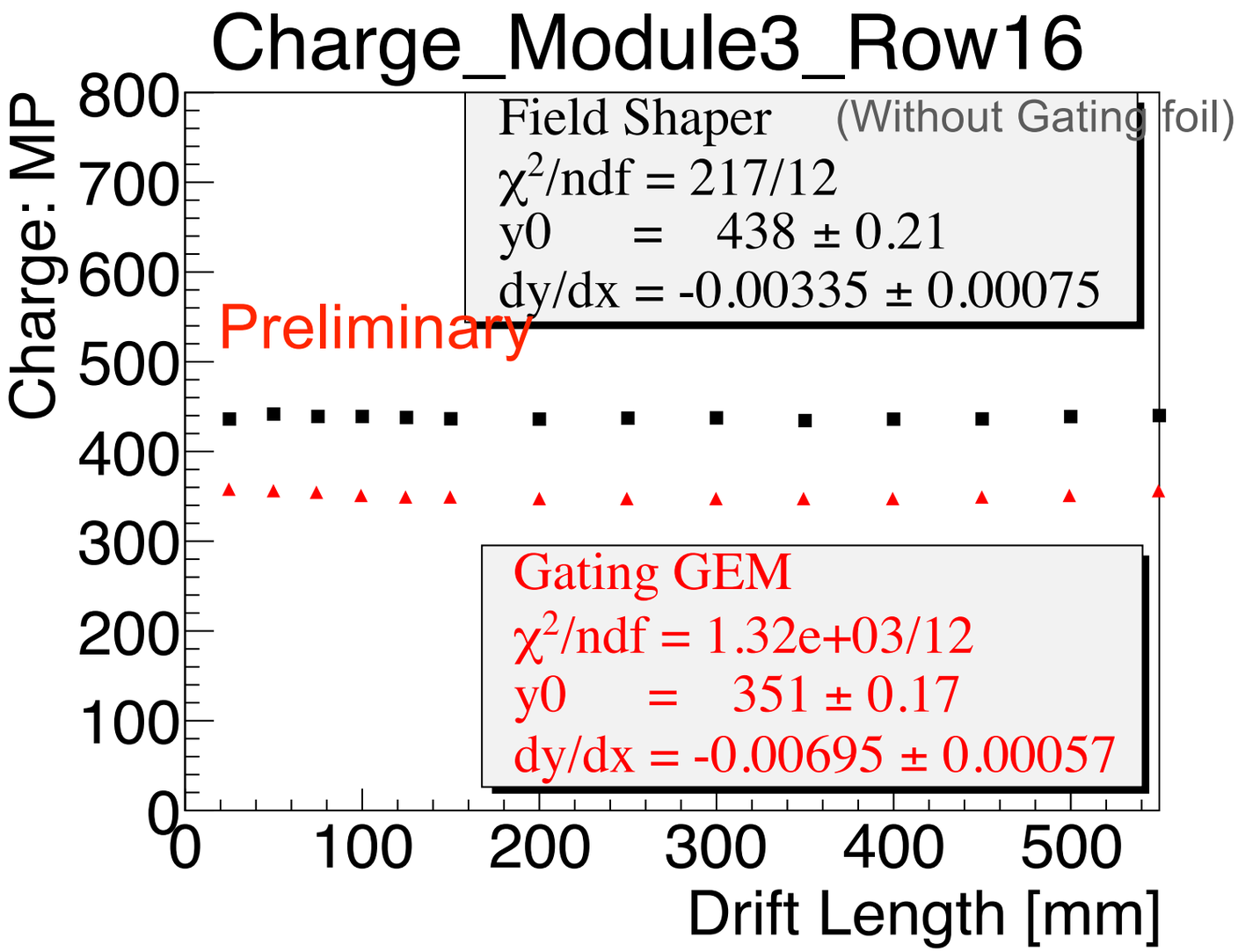
	W/ gate	W/O gate
Temp.[K]	291.28	290.4
Pres [hPa	1010.79	1005.31

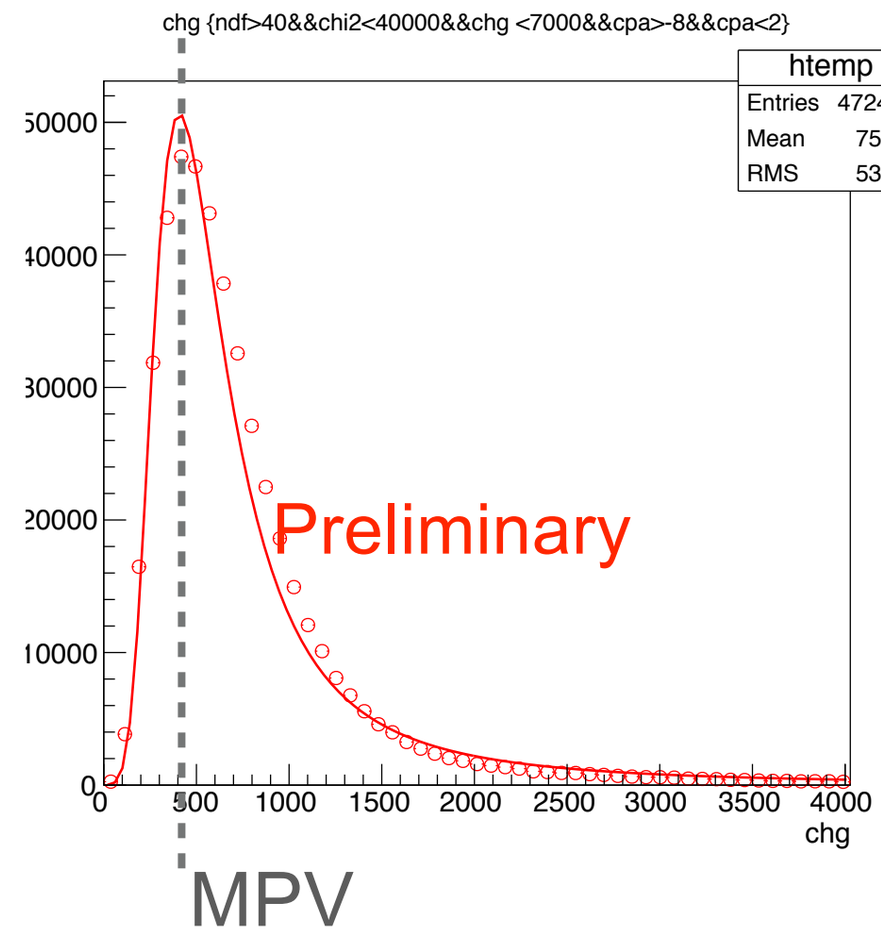
Garfield simulation

W/ gate 76.7 cm/μs +/- 0.0013%

W/O gate 7.68 cm/μs +/- 0.0022%

Result - Charge sum

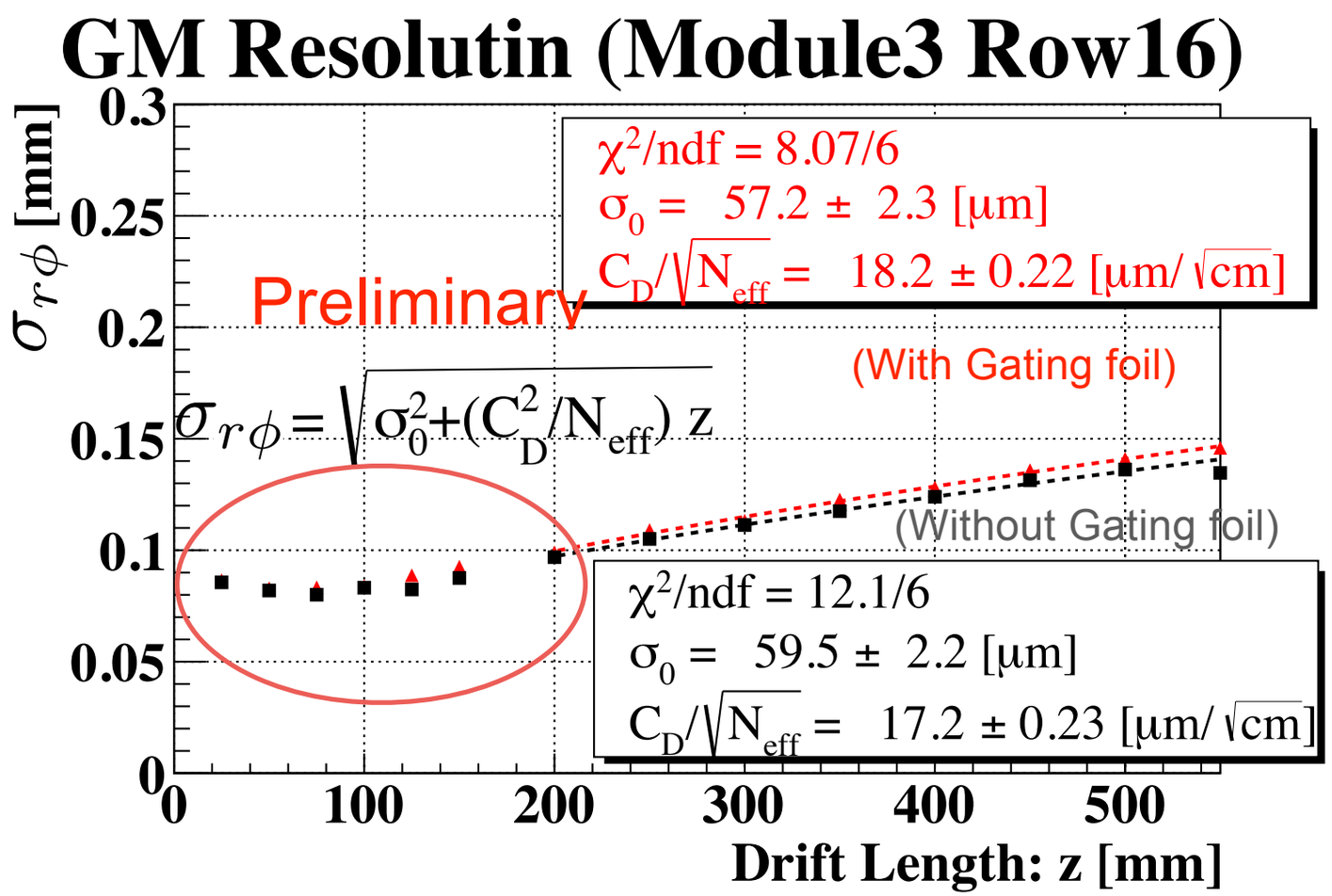




- There seems to be no electron attachment (P/T correction is not included)

	2.5	5	7.5	10	12.5	15	20	25	30	35	40	45	50	55
Ratio /%	82.0 ±0.1	80.4 ±0.1	80.4 ±0.1	79.9 ±0.1	79.7 ±0.1	79.7 ±0.1	79.4 ±0.1	79.2 ±0.1	79.0 ±0.1	79.7 ±0.1	79.6 ±0.1	79.9 ±0.1	79.7 ±0.1	80.6 ±0.2

Hodoscope effect



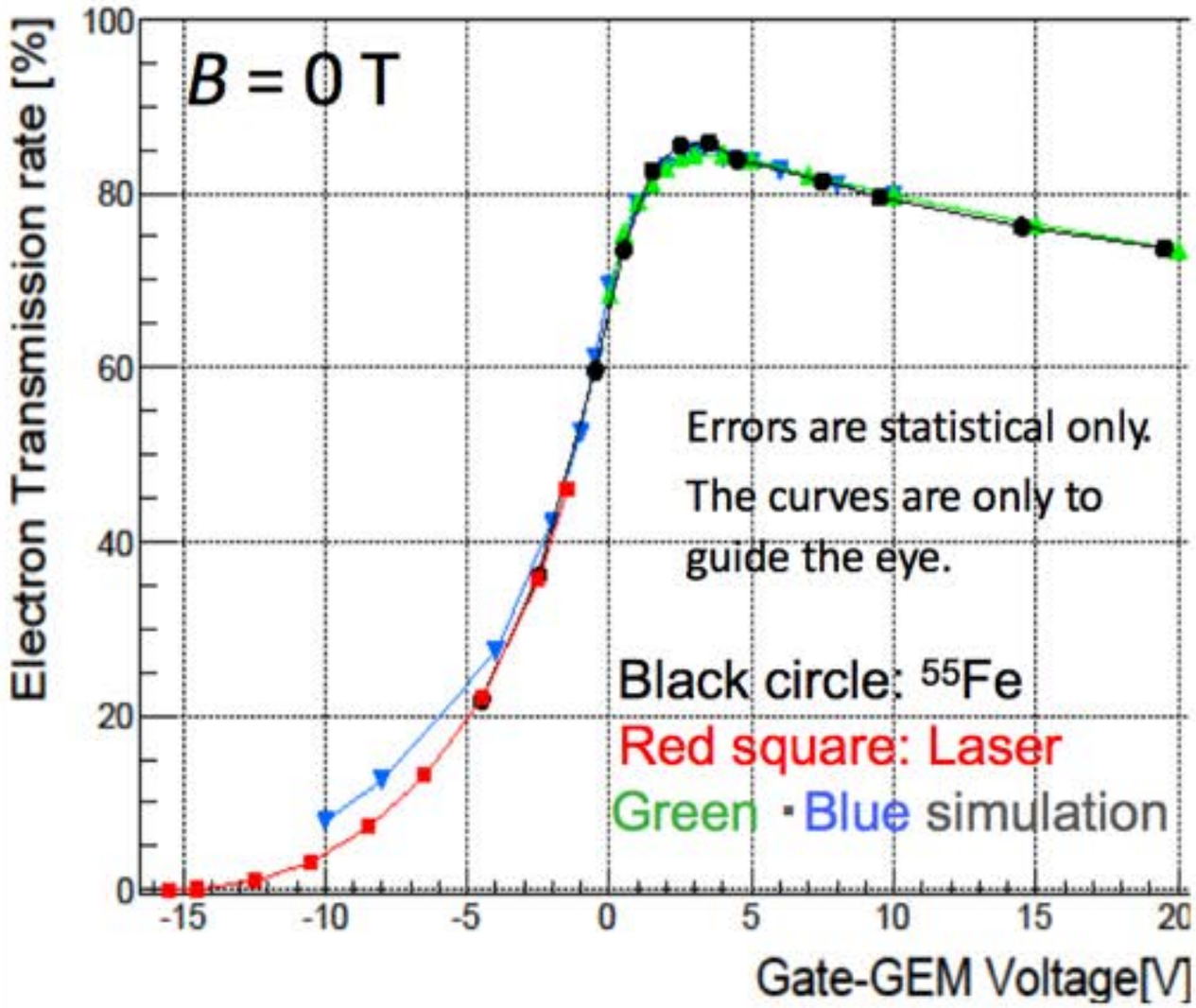
Hodoscope is one of the tracker.

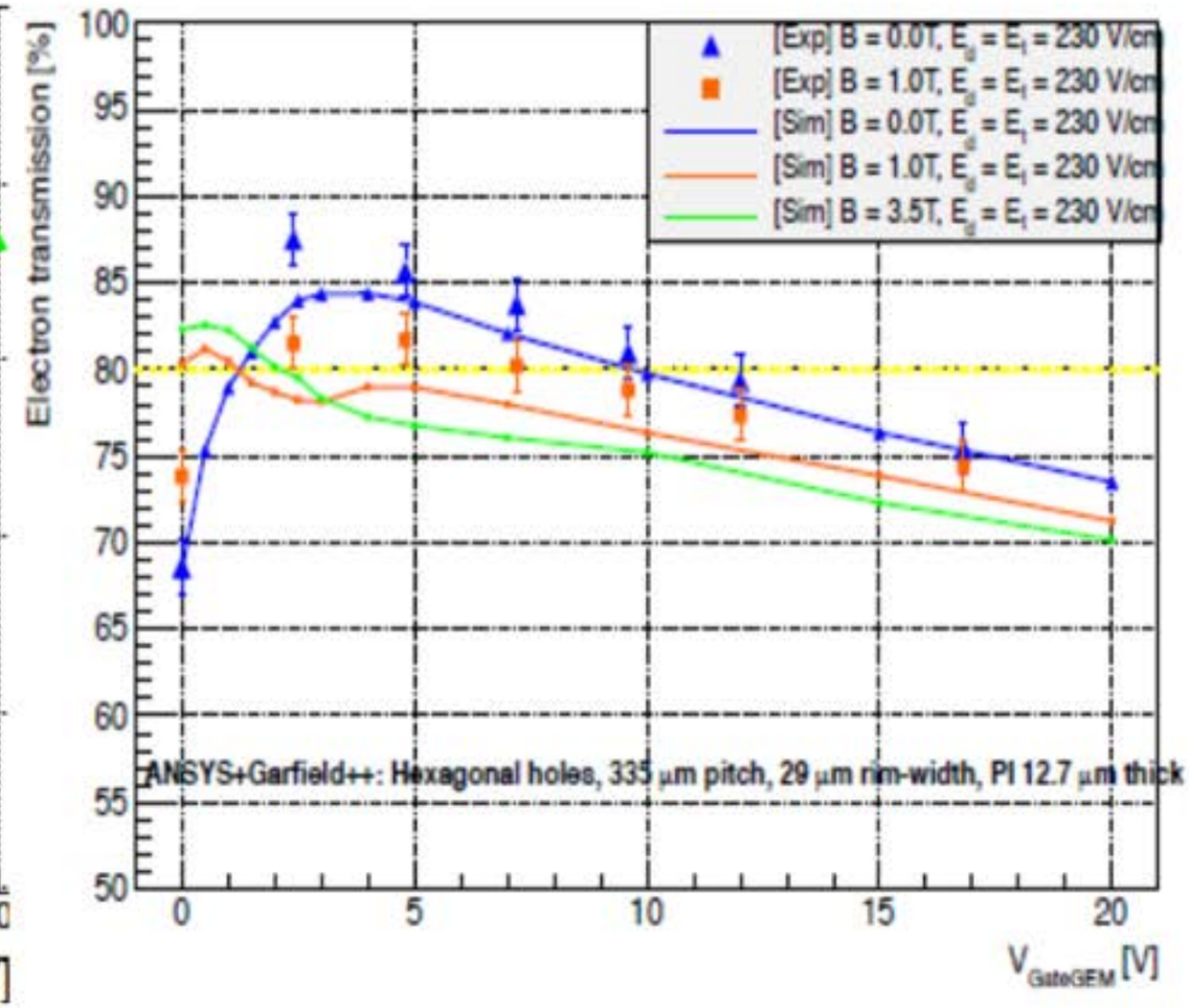
The detector using scintillators.

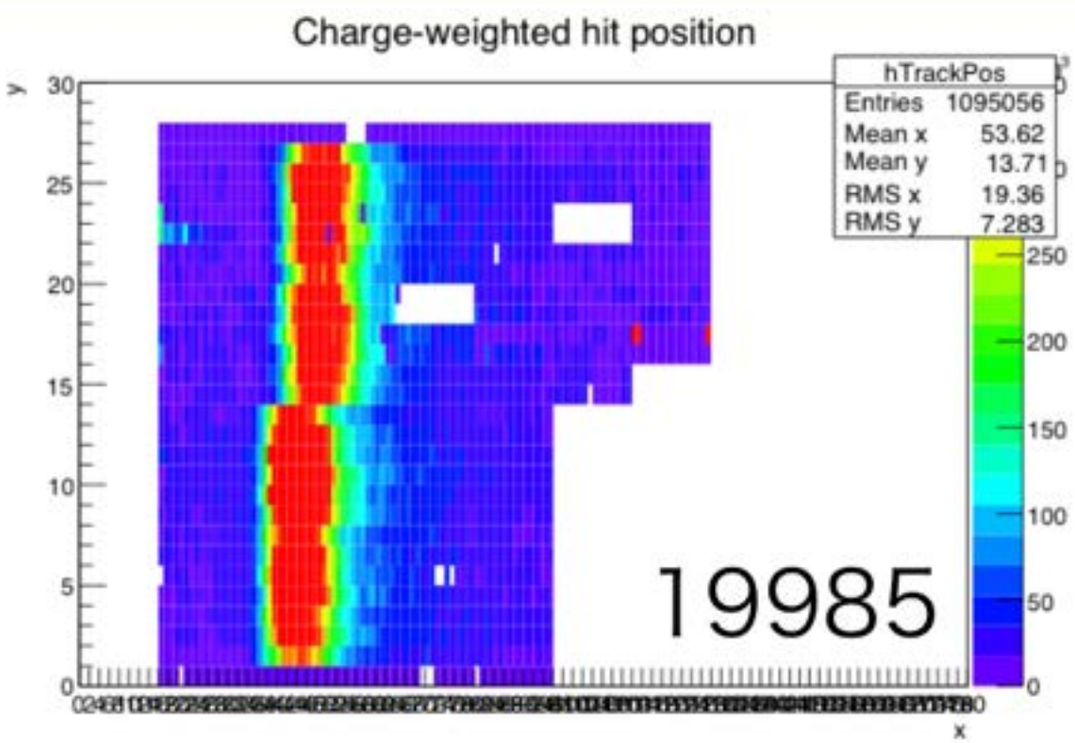
(not using the center of gravity method)

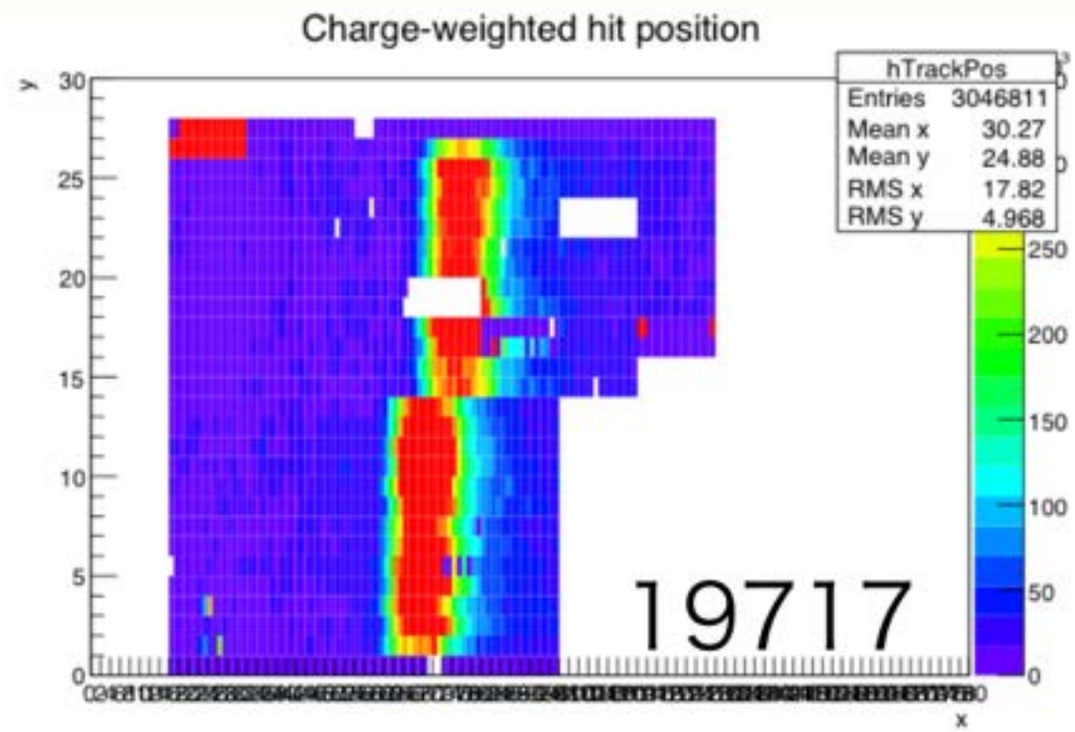
Therefore, we call the single pad effect “hodoscope effect”.

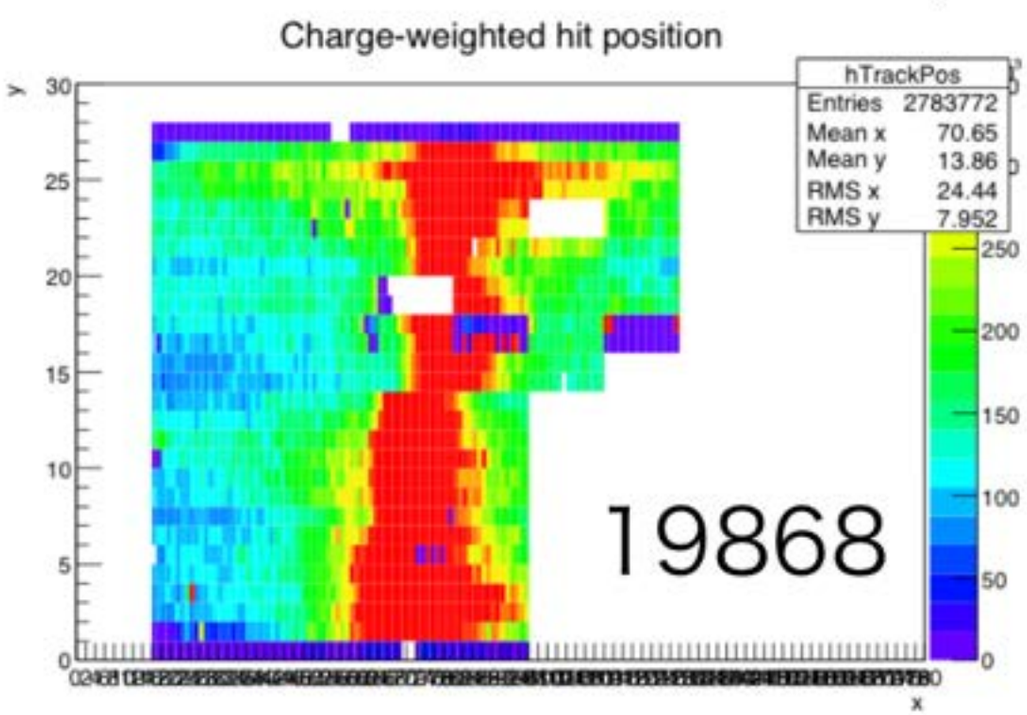
Gate GEM Voltage VS Electron transmission



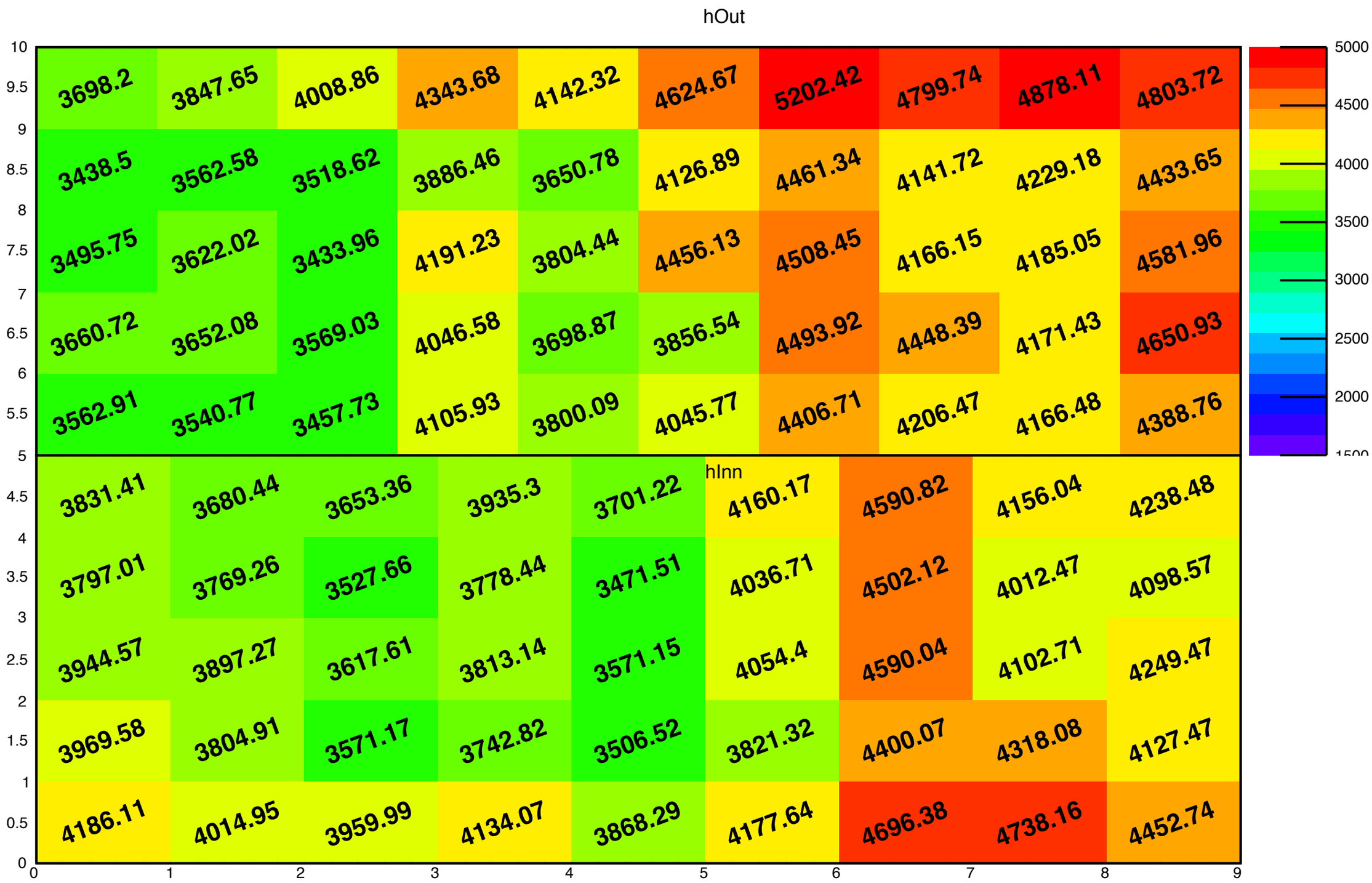



Charge-weighted hit position
hTrackPos
Entries 1095056
Mean x 53.62
Mean y 13.71
RMS x 19.36
RMS y 7.283
19985
x
y


Charge-weighted hit position
hTrackPos
Entries 3046811
Mean x 30.27
Mean y 24.88
RMS x 17.82
RMS y 4.968
19717
x
y


Charge-weighted hit position
hTrackPos
Entries 2783772
Mean x 70.65
Mean y 13.86
RMS x 24.44
RMS y 7.952
19868
x
y

Uniformity


hOut
3698.2 3847.65 4008.86 4343.68 4142.32 4624.67 5202.42 4799.74 4878.11 4803.72
3438.5 3562.58 3518.62 3886.46 3650.78 4126.89 4461.34 4141.72 4229.18 4433.65
3495.75 3622.02 3433.96 4191.23 3804.44 4456.13 4508.45 4166.15 4185.05 4581.96
3660.72 3652.08 3569.03 4046.58 3698.87 3856.54 4493.92 4448.39 4171.43 4650.93
3562.91 3540.77 3457.73 4105.93 3800.09 4045.77 4406.71 4206.47 4166.48 4388.76
hInn
3831.41 3680.44 3653.36 3935.3 3701.22 4160.17 4590.82 4156.04 4238.48
3797.01 3769.26 3527.66 3778.44 3471.51 4036.71 4502.12 4012.47 4098.57
3944.57 3897.27 3617.61 3813.14 3571.15 4054.4 4590.04 4102.71 4249.47
3969.58 3804.91 3571.17 3742.82 3506.52 3821.32 4400.07 4318.08 4127.47
4186.11 4014.95 3959.99 4134.07 3868.29 4177.64 4696.38 4738.16 4452.74
10 9.5 9 8.5 8 7.5 7 6.5 6 5.5 5 4.5 4 3.5 3 2.5 2 1.5 1 0.5 0
0 1 2 3 4 5 6 7 8 9
5000 4500 4000 3500 3000 2500 2000 1500

Data analysis & Result

1. Event Reconstruction
   - Hit Reconstruction
   - Track Reconstruction
   - Data Quality Cuts
2. How to calculate Spatial Resolution
3. How to estimate the election transmission
4. Result

Event Reconstruction

Cluster making

- make cluster from ADC

Hit making

- determine the hit point by center of gravity
- Coordinate calculation

Track finding + fitting

- determine the track parameter

Cluster making

- make cluster from ADC

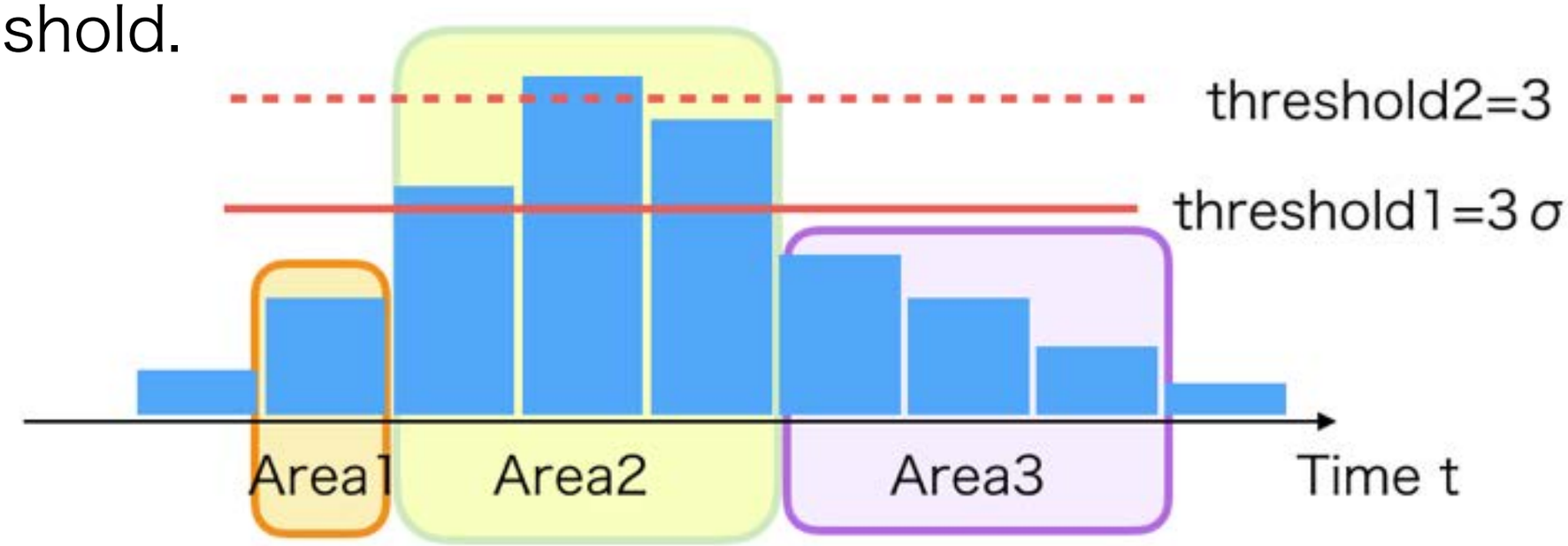
Time direction

Set pedestal σ as the standard (This time, σ=0.5)

The time bins above the threshold:3σ are regarded as a cluster

However if the peak ADC below the threshold 3 ADC counts, it is not regarded as a hit

We include in the cluster, the 1 time bin before the first time bin above the threshold, and the 3 bins after the last time bin above the threshold.

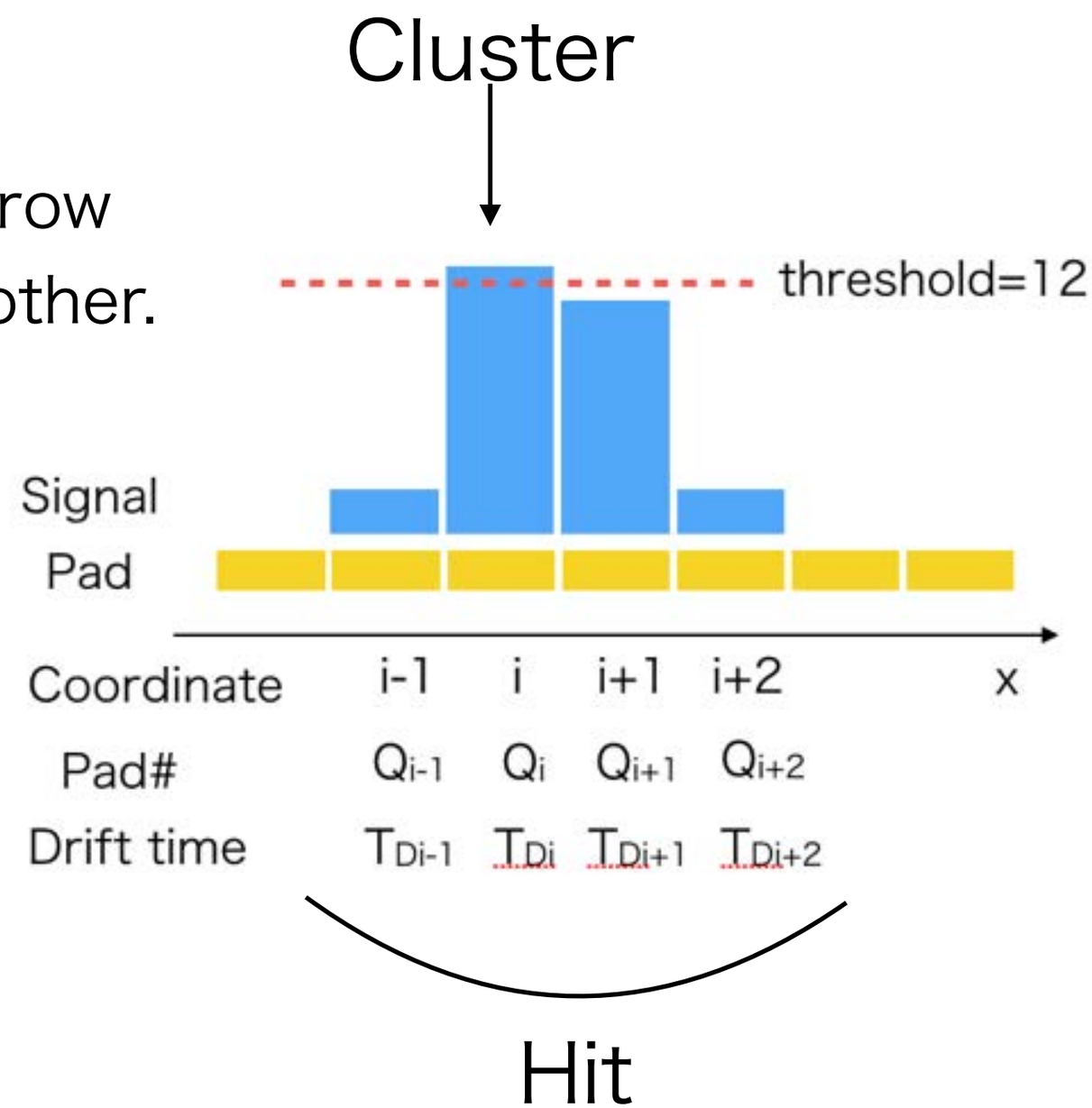


Hit making

Pad row direction

We collect all time clusters in the row direction which are touching each other.

However if the peak cluster below the threshold 12 ADC counts, it is not regarded as a hit



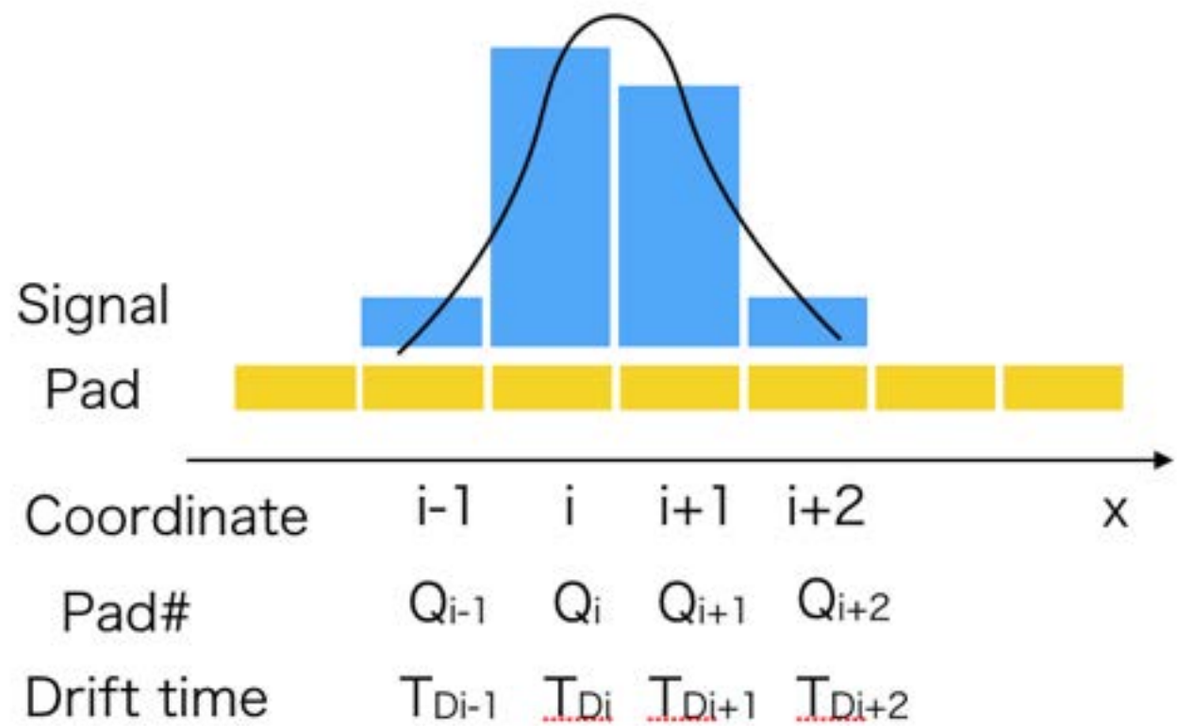
Hit making

Coordinate calculation

①Row direction

Determine the hit coordinate by the center of gravity in the pad row direction

$$C.O.G = \frac{\sum(Q_i \cdot x_i)}{\sum Q_i}$$

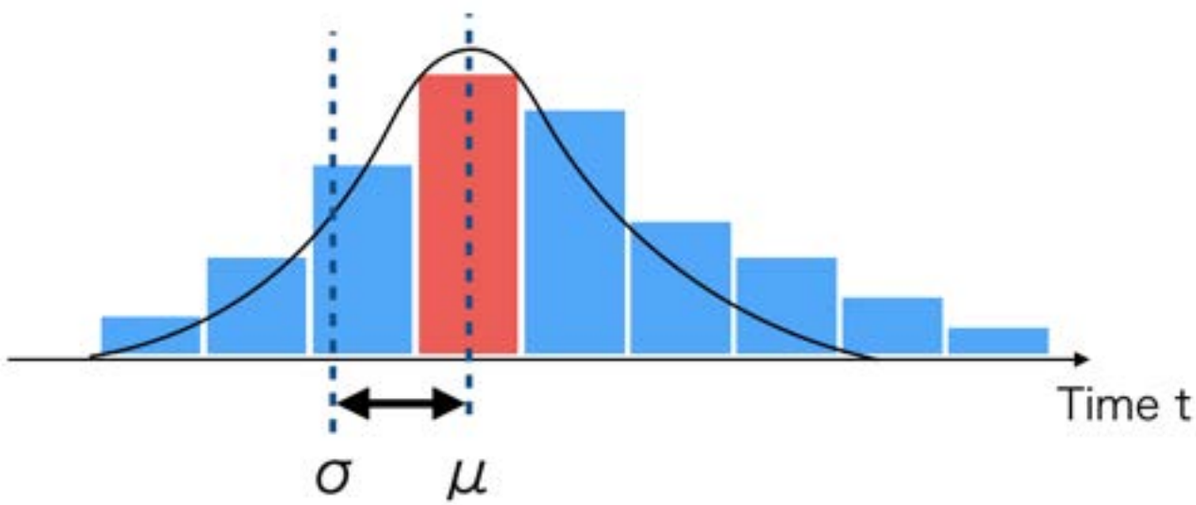


②Time

the inflection point

t = μ-σ

(50 ns/1 bin)



Track Reconstruction

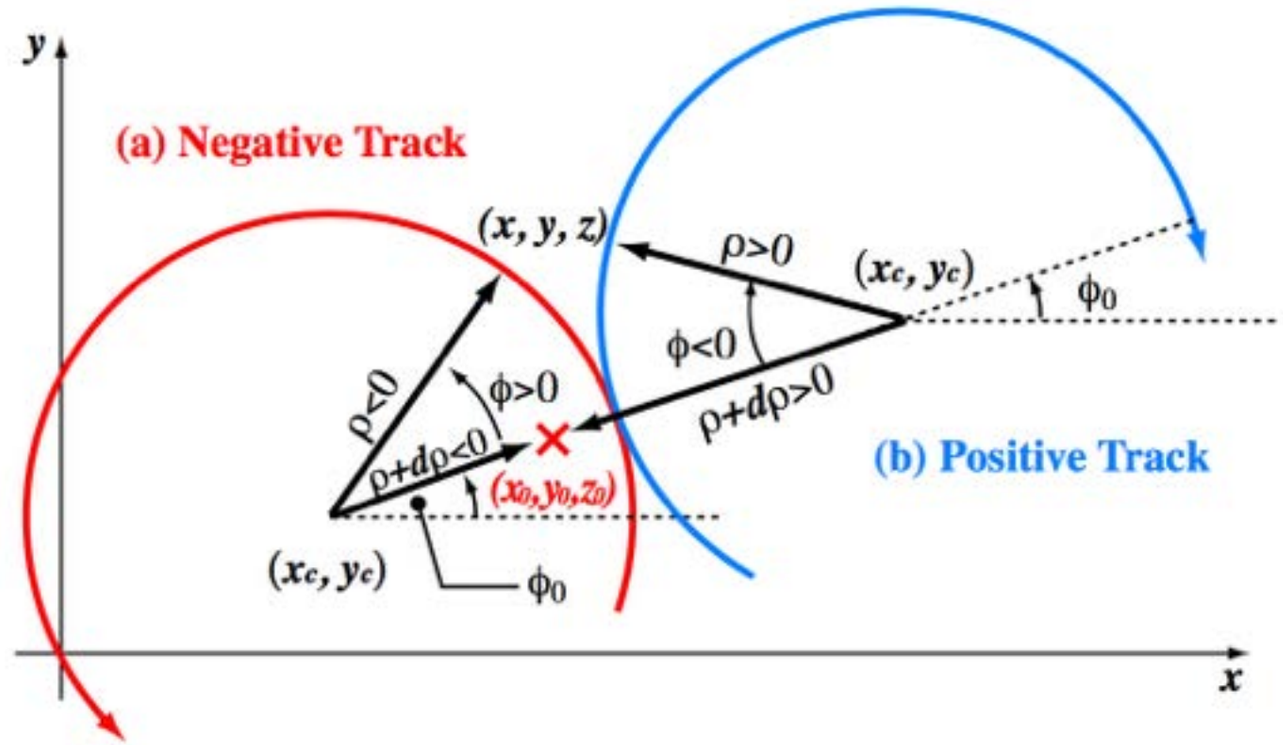
We use Kalman filter to reconstruct tracks

(MyTrackMakingKalmanFilterProcessor)

①Find a hit point around a predicted area

②Fit tracks

③Get 5 track parameters



$$\mathbf{a} \equiv (d_\rho, \phi_0, \kappa, d_z, tan\lambda)^T$$

d_ρ : The distance bitween pivot and track in the plane vertical from z-axis

ϕ_0 : azimuthal angle of the pivot to the center of the helix

κ : Q/Pt(transverse momentum)

d_z : The distance bitween pivot and track in z-axis

$tan\lambda$: The dip angle from vertical plane to helix axis