Study of the spatial resolution of a GEM based TPC

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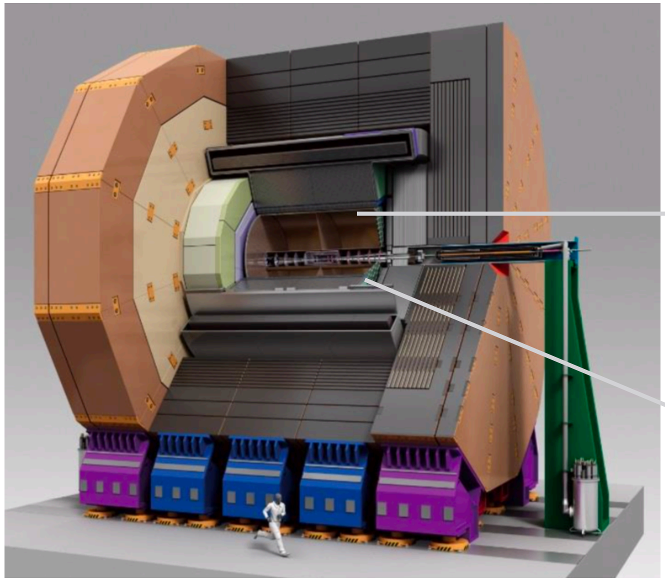
9, March 2021

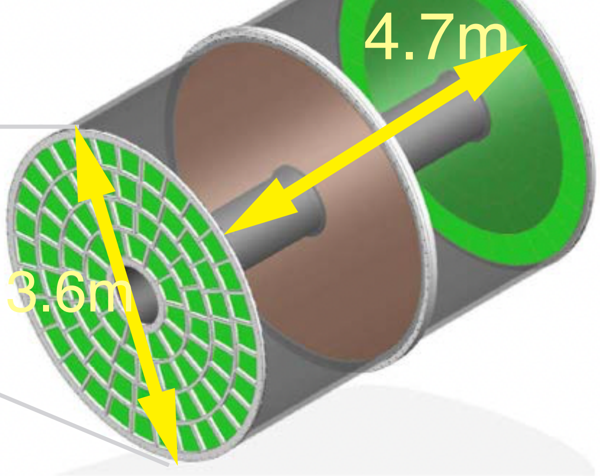
SOKENDAI

Time Projection Chamber (TPC)

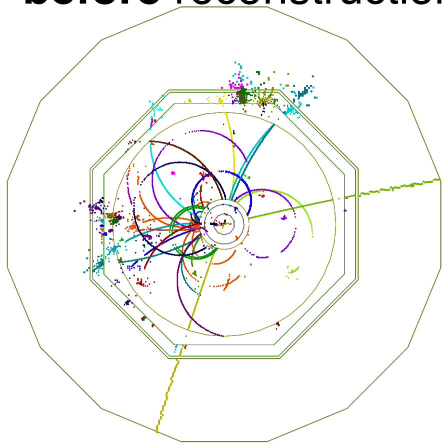
arXiv[1306.6329], ILC Technical Design Report: Volume 4, Part III



Reconstruct tracks of **charged** particles in **3-dimension**



~200 hit points
Can see tracks
before reconstruction



Two main roles at the TPC:

- ☐ Momentum measurement

  Measure the curvature radius of the tracks in B=3.5T and drift length 2.2 m

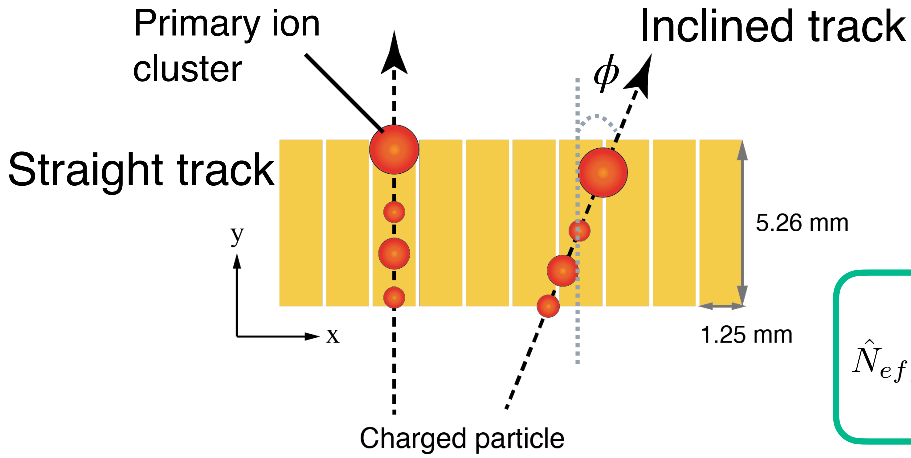
$$\frac{\sigma_{p_\perp}}{p_\perp} \simeq 1 \times 10^{-4} p_\perp [\mathrm{GeV/c}]$$

➡ **There are about <u>200</u> points of position resolution** $\sigma_x \simeq 100[\mu\mathrm{m}]$

- ☐ Particle identification measured by *dE/dx*

Incident angle effect on the spatial resolution

R.Yonamine,K.Fujii [https://doi.org/10.1088/1748-0221/9/03/C03002]



$$N_{eff} \simeq \left[\left\langle \frac{1}{\sum_i k_i} \right\rangle_{N,k} \left\langle \left(\frac{G}{\bar{G}} \right)^2 \right\rangle_G \right]^{-1}$$

$$\hat{N}_{eff} \approx \left[\left\langle \sum_{i=1}^{N} \left\langle \left(\frac{\sum_{j=1}^{k_i} G_{ij}}{\sum_{i=1}^{N} \sum_{j=1}^{k_i} G_{ij}} \right)^2 \right\rangle_G^{k_i, \sum_{i=1}^{N} k_i} \right\rangle_{N,k} \right]^{-1}$$

$$\sigma_x^2(Z; w, L\tan\phi, C_d, N_{eff}, \hat{N}_{eff}, [f]) = [A] + \frac{1}{N_{eff}}[B] + [C] + \frac{1}{\hat{N}_{eff}}[D]$$

Hodoscope effect (S-shape systematics) important for the short drift distance

Effects of diffusion + gas gain fluctuation + finite pad pitch

Electronic noise

Angular Pad effect

L : Pad row pitch

$$\frac{1}{\hat{N}_{eff}}[D] = \frac{L^2 \tan^2\phi}{12\hat{N}_{eff}}$$

My study: **estimate $\hat{N}_{eff}$ from beam test and simulation**

Analytic expressions for $\hat{N}_{eff}$

R.Yonamine, K.Fujii [https://doi.org/10.1088/1748-0221/9/03/C03002]

$$\hat{N}_{eff} \approx \left[\left\langle \sum_{i=1}^{N} \left\langle \left(\frac{\sum_{j=1}^{k_i} G_{ij}}{\sum_{i=1}^{N} \sum_{j=1}^{k_i} G_{ij}} \right)^2 \right\rangle_G^{k_i, \sum_{i=1}^{N} k_i} \right\rangle_{N,k} \right]^{-1}$$

$$\hat{N}_{eff} \simeq \left[\left\langle \frac{\sum_{i=1}^{N} k_i^2}{\left(\sum_{i=1}^{N} k_i \right)^2} \right\rangle + \frac{1}{N_{eff}} - \frac{1}{N_{eff}^{\text{w/o}\,G}} \right]^{-1}$$

w/ gas gain fluctuation **w/o gas gain fluctuation**

N : the number of primary ionization **clusters**

$\left(N_{eff}^{\text{w/o}\,G} \simeq \left[\left\langle \frac{1}{\sum_i k_i} \right\rangle_{N,k} \right]^{-1} \right)$

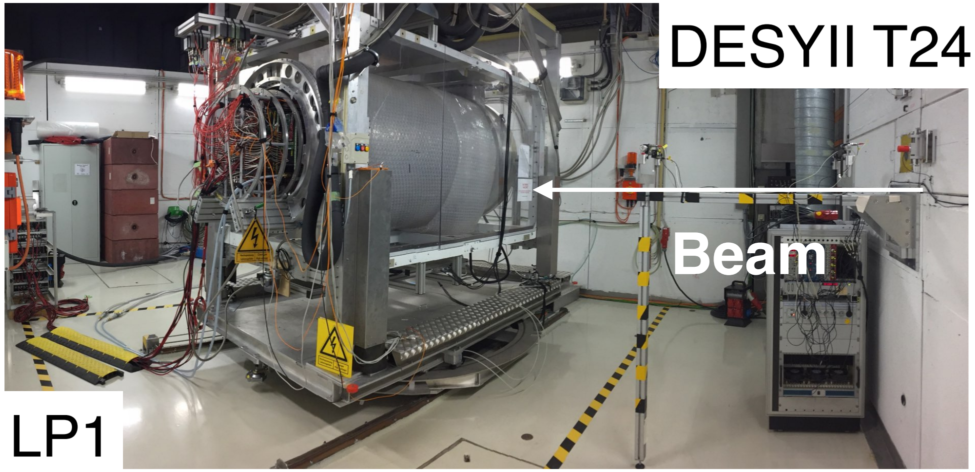
G: Gas gain

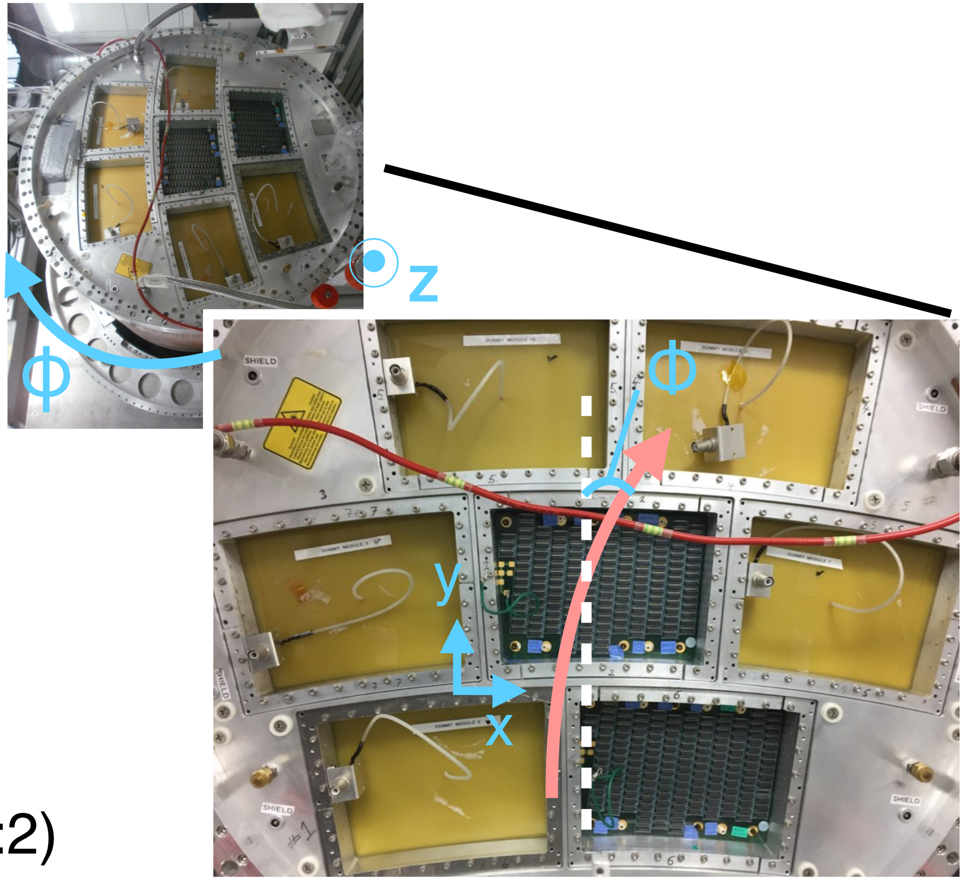
k_i : the number of seed electrons orginating from the i-th primary cluster

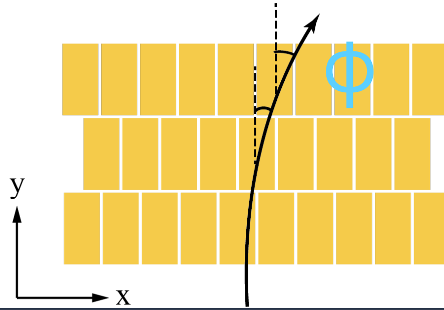
$\hat{N}_{eff}$ can be decomposed into two parts, due to **cluster size fluctuation** and **gas gain fluctuation**.

2016 beam test of Asian GEM modules

The original purpose of the beam test was to compare performance of the Asian modules with and without the gating foil.





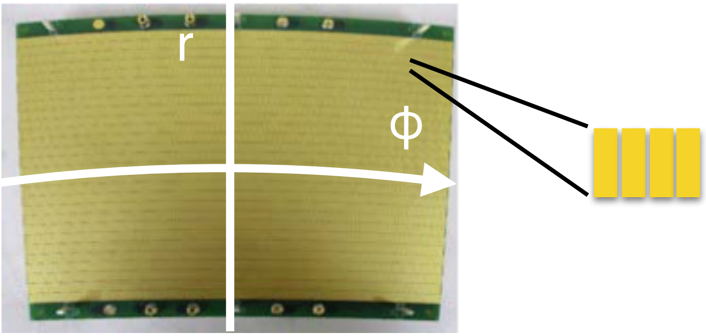


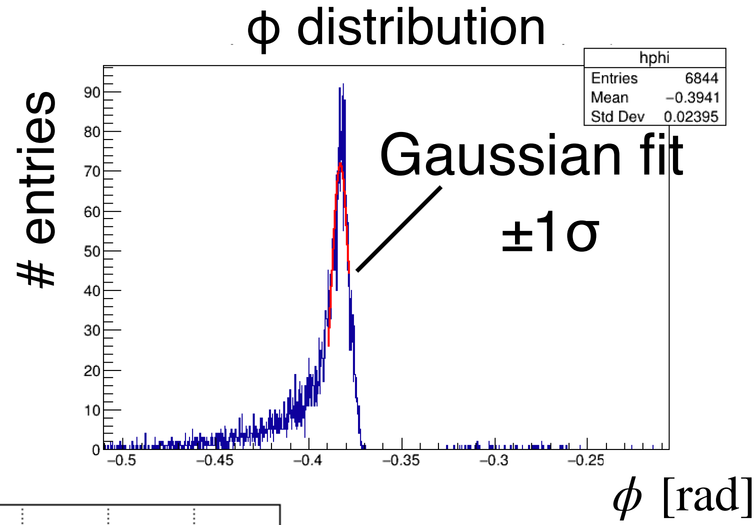
Set up

- Electron Beam = 5 GeV
- B = 1 T
- T2K gas (Ar:CF4:iso-C4H10 = 95:3:2)
- Analysis frame work : Marlin TPC
- Data set used : ϕ= -20°, 0°, 10°, 20°

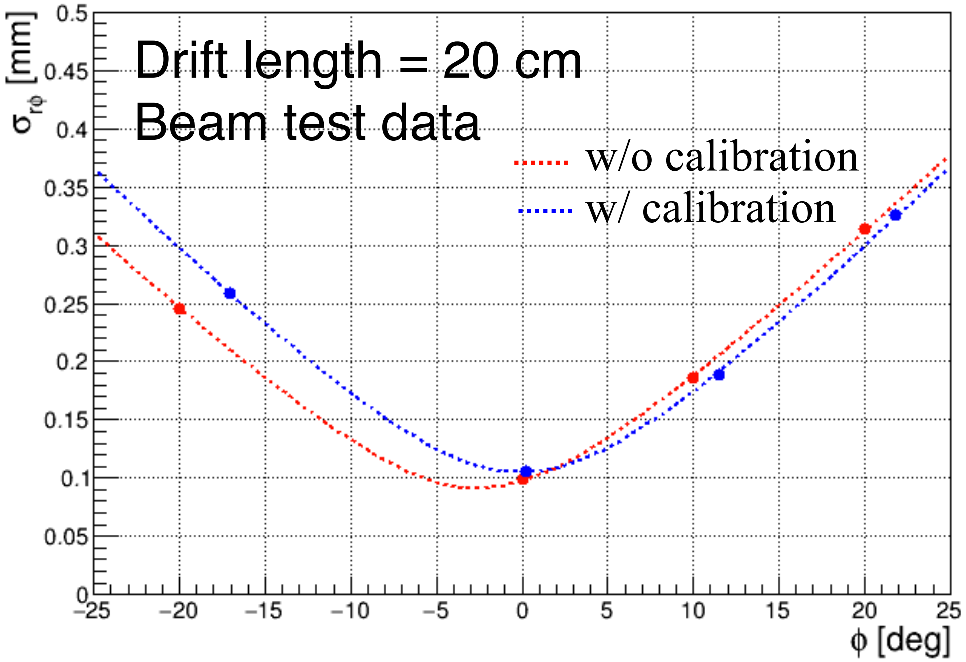
ϕ angle calibration

The readout pad rows are curved to cover the **fan-shaped** anode plane of each module





#20156,
w/ field shaper,
ϕ=20°,
B=1T,
row =16

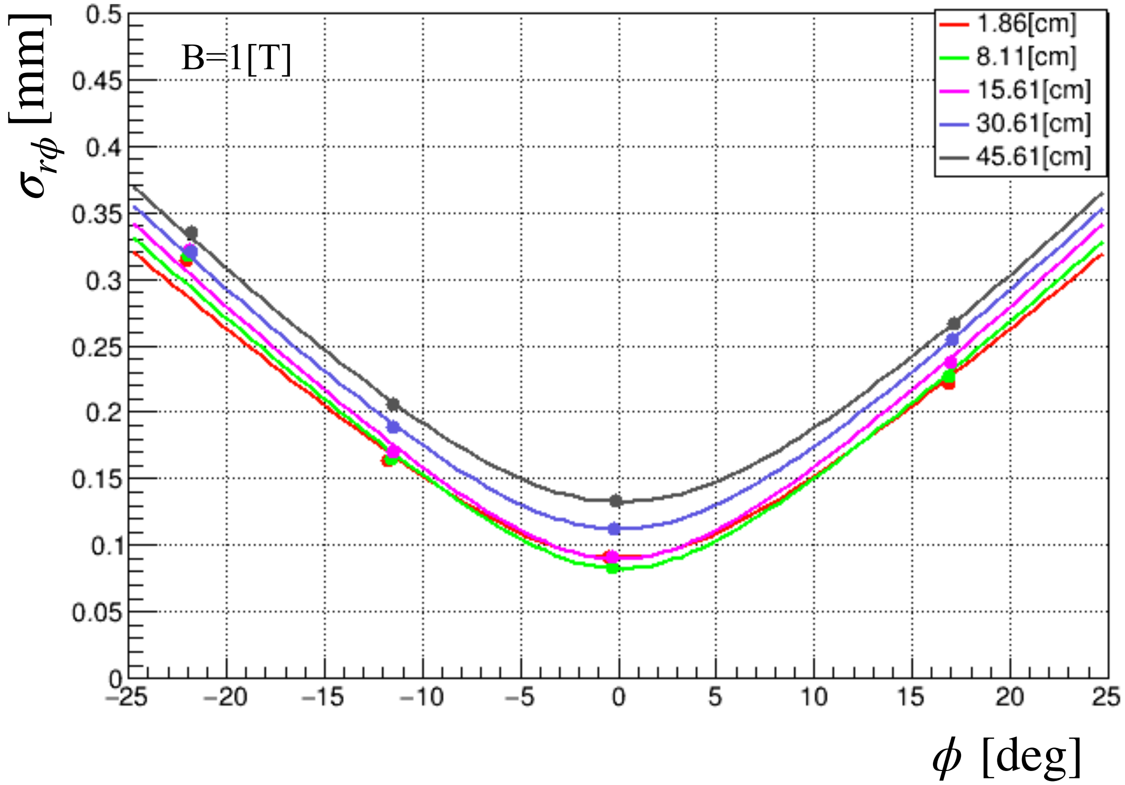


Fitting function

$$\sigma_{r\phi} = \sqrt{\sigma_0^2 + \sigma_{ang}^2 \tan^2(\phi - \phi_0)}$$

After calibration, minimum at ϕ_0 = -0.04 ± 0.12° from -2.5 ± 0.1°

Spatial Resolution at different drift distances as a function of ϕ (beam test data)



Fitting function

$$\sigma_{r\phi} = \sqrt{\sigma_0^2 + \sigma_{ang}^2 \tan^2(\phi - \phi_0)}$$

$$\sigma_{ang}^2 \equiv \frac{L^2}{12\left(\hat{N}_{eff}(\phi = 0)/\cos\phi\right)}$$

The function fits the data reasonably well.

→ϕ dependance is consistent with the theory.

We get $\hat{N}_{eff}$ from fit results.

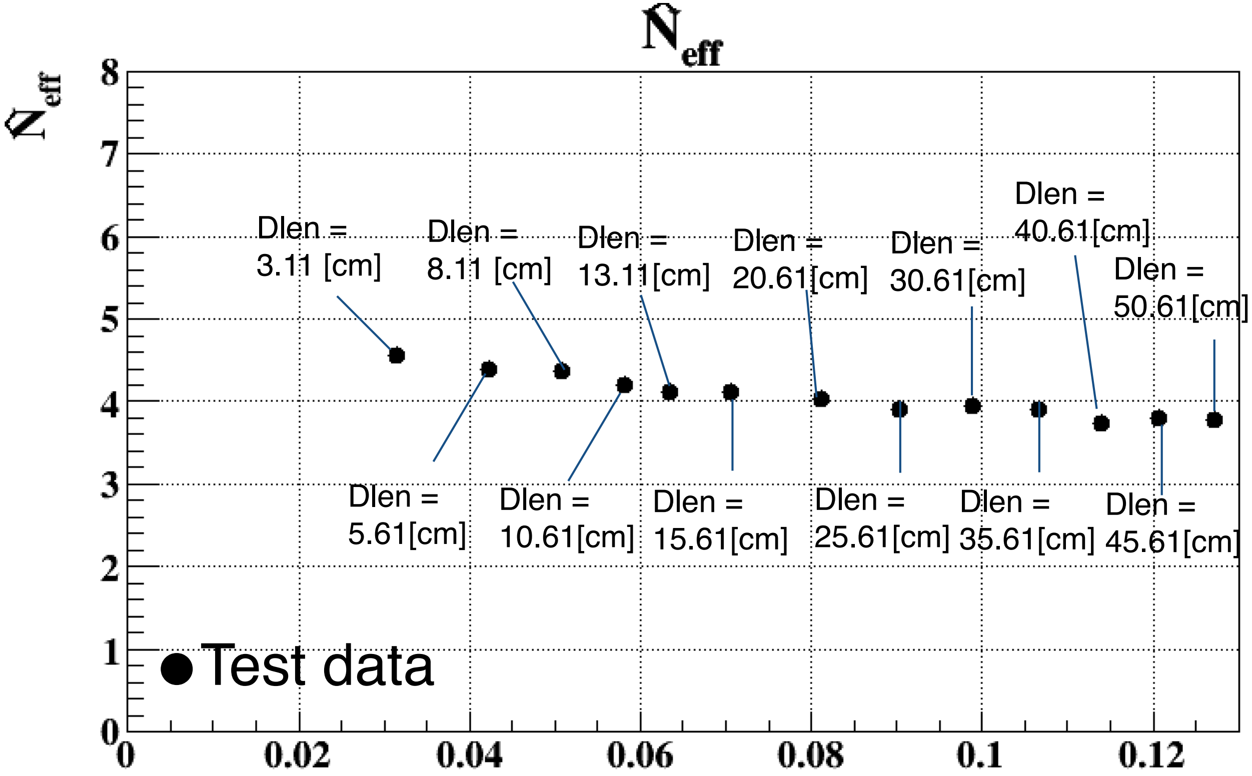
Beam test data results- $\hat{N}_{eff}$

$\hat{N}_{eff}$ value defined by the fitting function

$$\hat{N}_{eff}(\phi = 0) = \frac{L^2 \tan^2 \phi \cos \phi}{12\sigma^2_{ang}}$$

the effective number of **primary clusters**

- L(Pad row pitch) = 0.536 [cm]



($\sigma_d = C_d\sqrt{Drift\,length[\mathrm{cm}]}$,
C_d : diffusion constant)

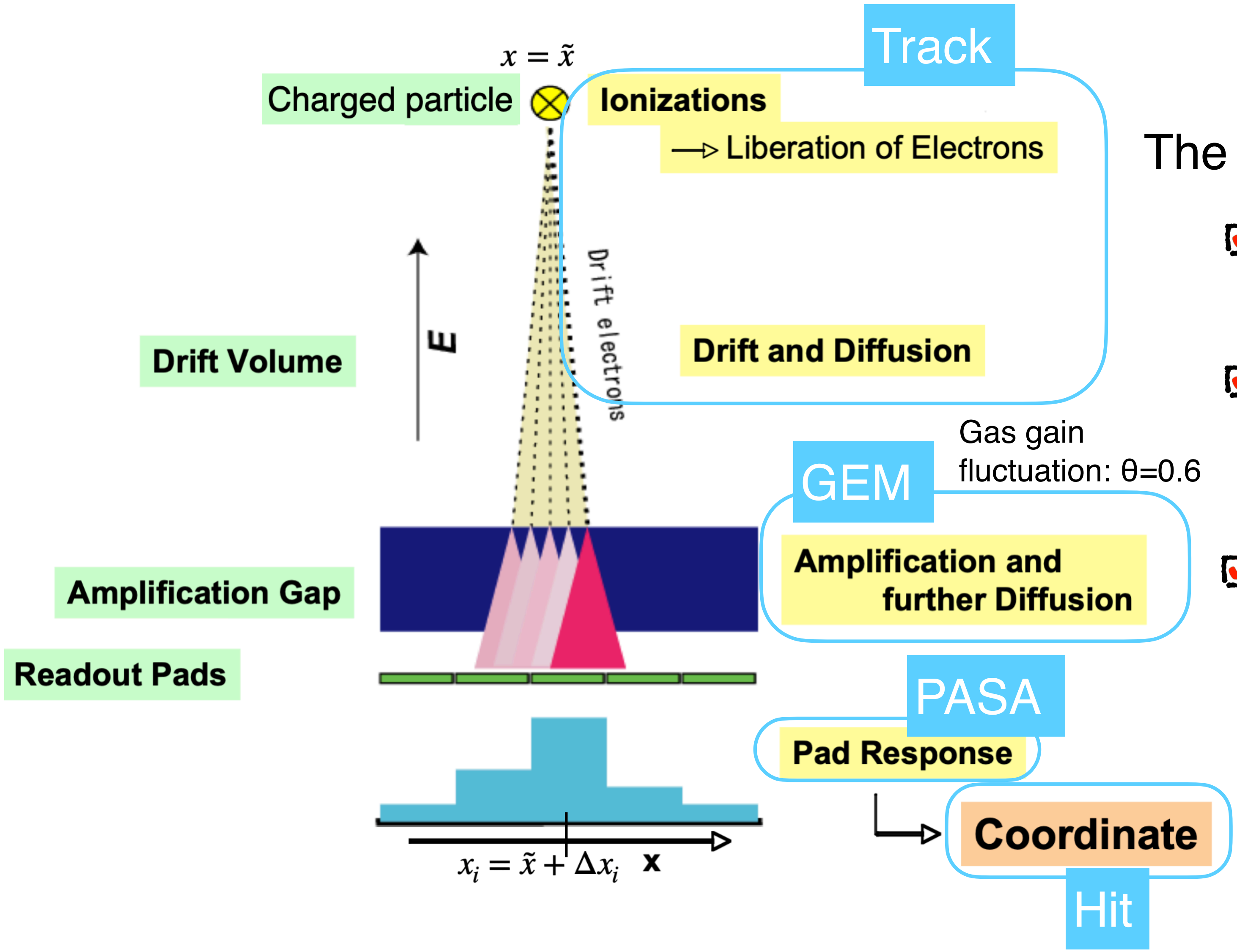
$$\hat{N}_{eff} \ll \left\langle \hat{N} \right\rangle \simeq 20$$

$\left\langle \hat{N} \right\rangle$: The average number of cluster

TPC simulator

✳ C++

We have developed a new TPC simulator



The implemented effects

- ☑ finite pad size effect (S-shape systematics)
- ☑ finite Pad Response Function width (hodoscope effect)
- ☑ the magnetic field effect (curling effect of primary electrons)

Comparison of an approximate formula with the $\hat{N}_{eff}$ value as defined by the fitting function

Approximate formula **ignoring the pad size**

$$\hat{N}_{eff} \approx \left[\left\langle \sum_{i=1}^{N} \left\langle \left(\frac{\sum_{j=1}^{k_i} G_{ij}}{\sum_{i=1}^{N} \sum_{j=1}^{k_i} G_{ij}} \right)^2 \right\rangle_G^{k_i, \sum_{i=1}^{N} k_i} \right\rangle_{N,k} \right]^{-1}$$

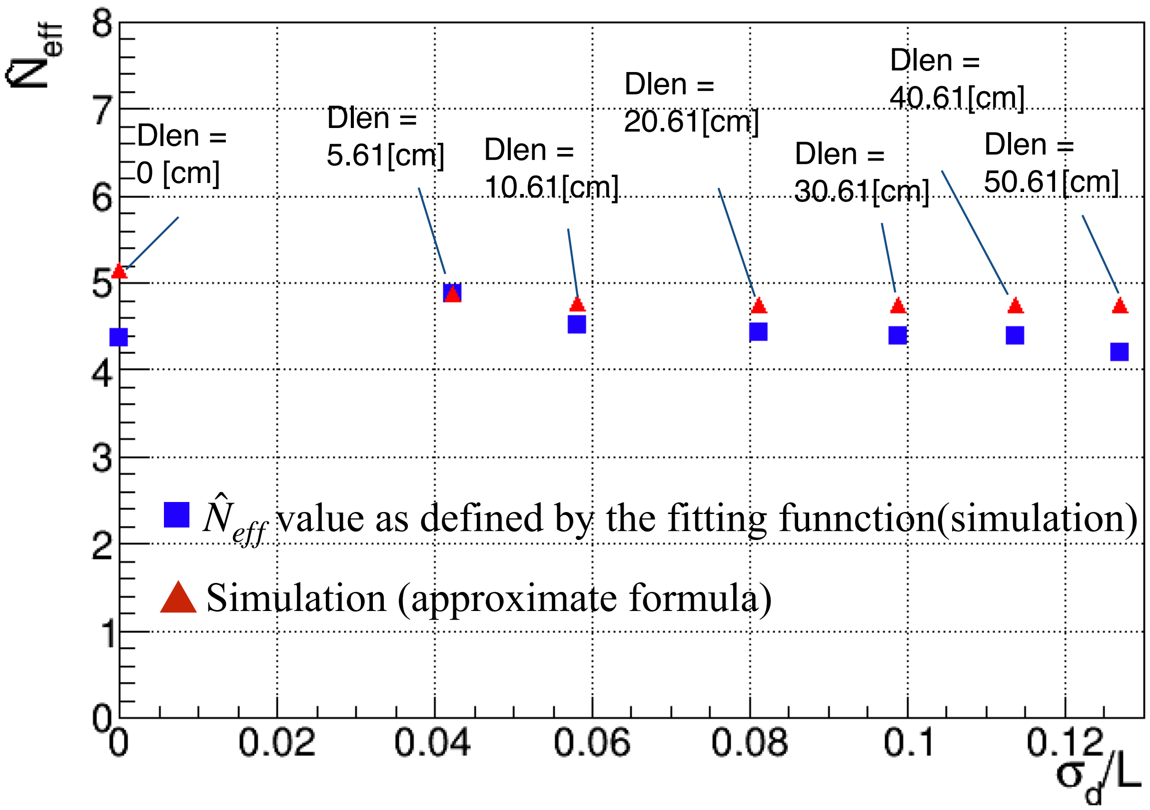
i : primary cluster

j : electron

k_i : the number of seed electrons orginating from the i-th primary cluster

G : gas gain

N : the number of primary ionization **clusters**



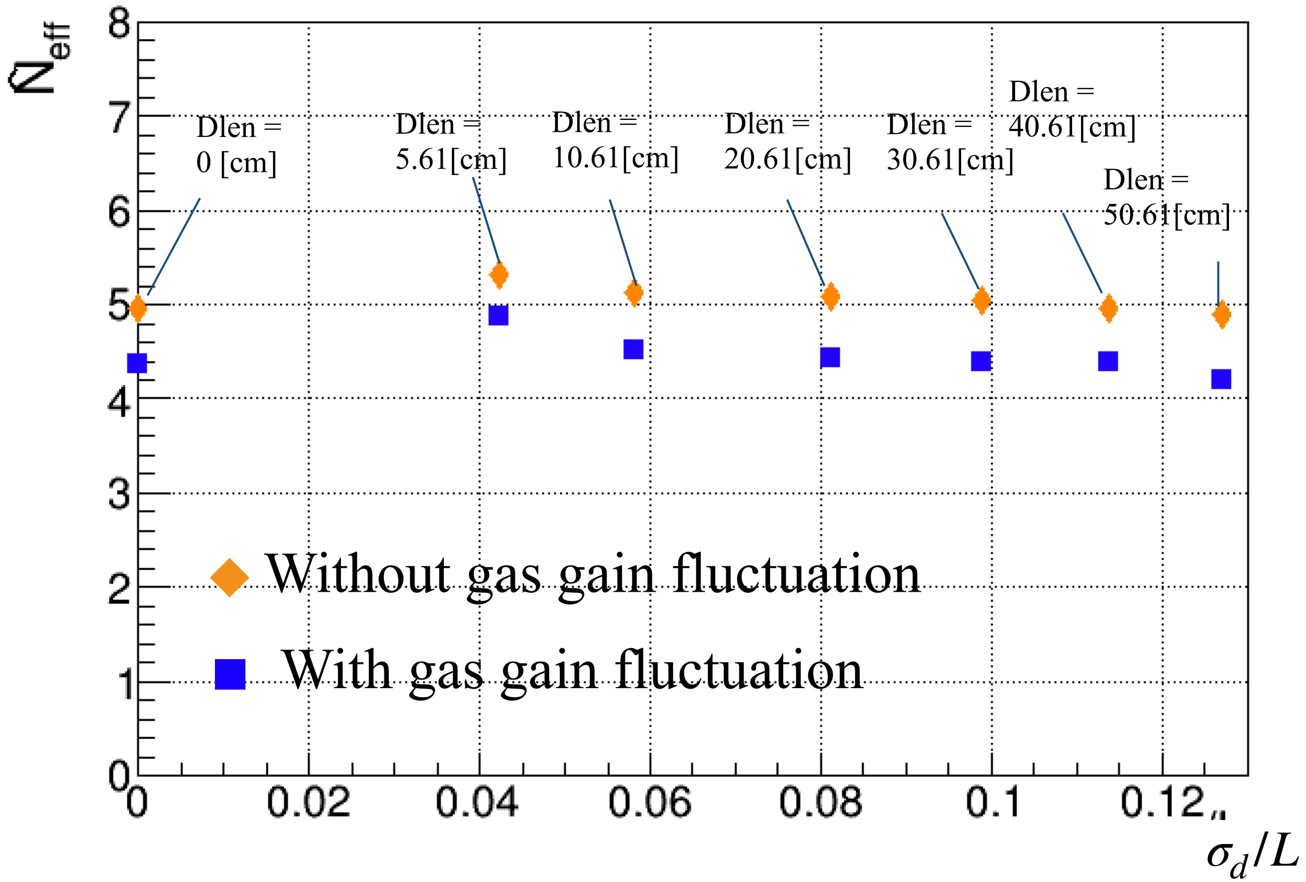
($\sigma_d = C_d\sqrt{Drift\,length[\mathrm{cm}]}$, C_d : diffusion constant)

Approximate formula reproduces the fitted result quite well

$\hat{N}_{eff}$ w/ and w/o gas gain fluctuation

Contribution from gas gain fluctuation

$$\hat{N}_{eff} \simeq \left[\left\langle \frac{\sum_{i=1}^{N} k_i^2}{\left(\sum_{i=1}^{N} k_i\right)^2} \right\rangle + \frac{1}{N_{eff}} - \frac{1}{N_{eff}^{\text{w/o }G}} \right]^{-1}$$

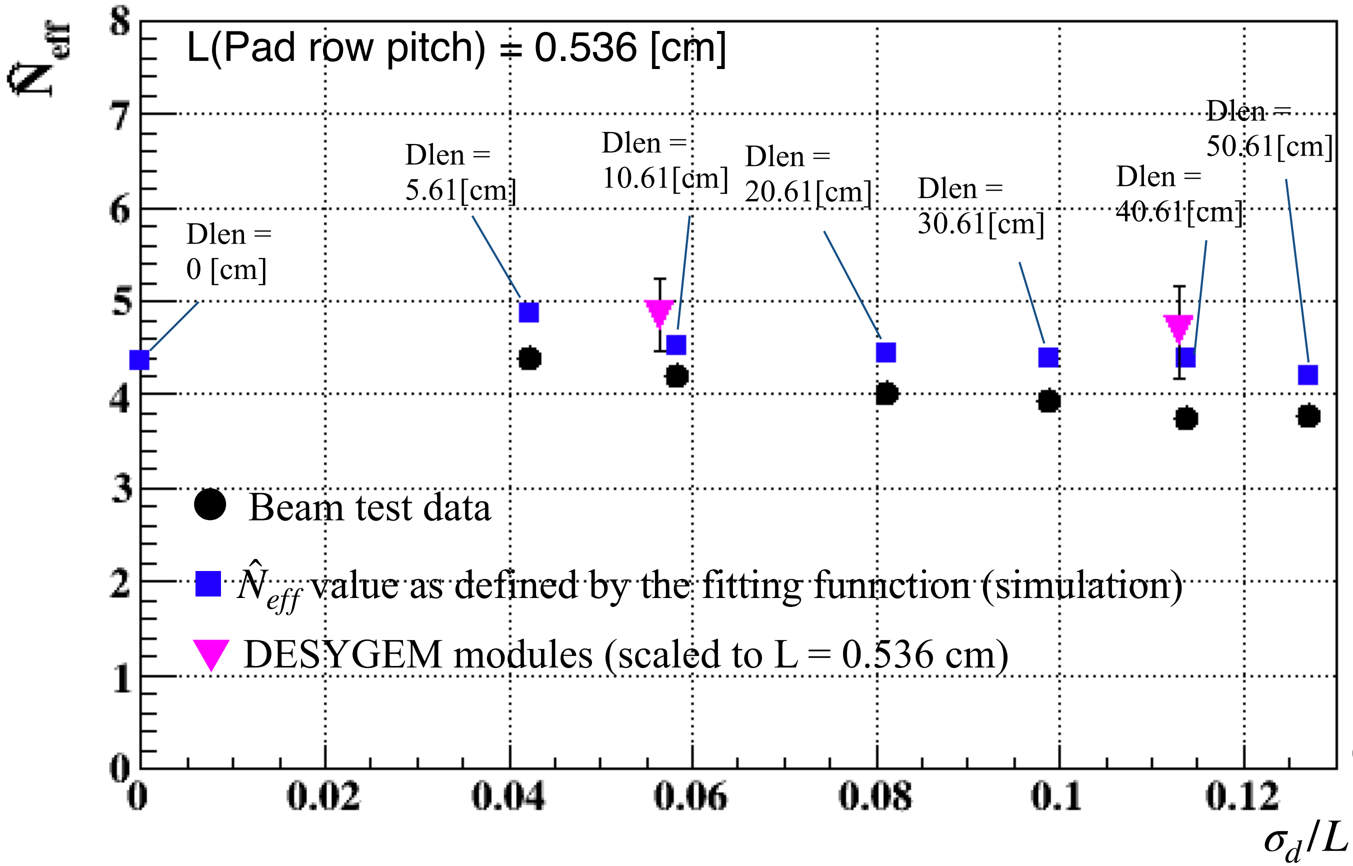


The gas gain fluctuation significantly reduces $\hat{N}_{eff}$ at all distances

Comparison beam test with simulation -$\hat{N}_{eff}$

$\hat{N}_{eff}$ value defined by the fitting function

$$\sigma_{ang}^2 = \frac{L^2 \tan^2\phi}{12\left(\hat{N}_{eff}(\phi=0)/\cos\phi\right)} \longrightarrow \hat{N}_{eff}(\phi=0) = \frac{L^2\tan^2\phi\cos\phi}{12\sigma_{ang}^2}$$



($\sigma_d = C_d\sqrt{Drift\,length[\mathrm{cm}]}$,
C_d : diffusion constant)

The measured and simulated $\hat{N}_{eff}$ agree to about 5~10%.

Summary

☆ We used Asian GEM beam test data to confirm the **angular pad effect**.
→the ϕ dependence became consistent with the theory after calibration

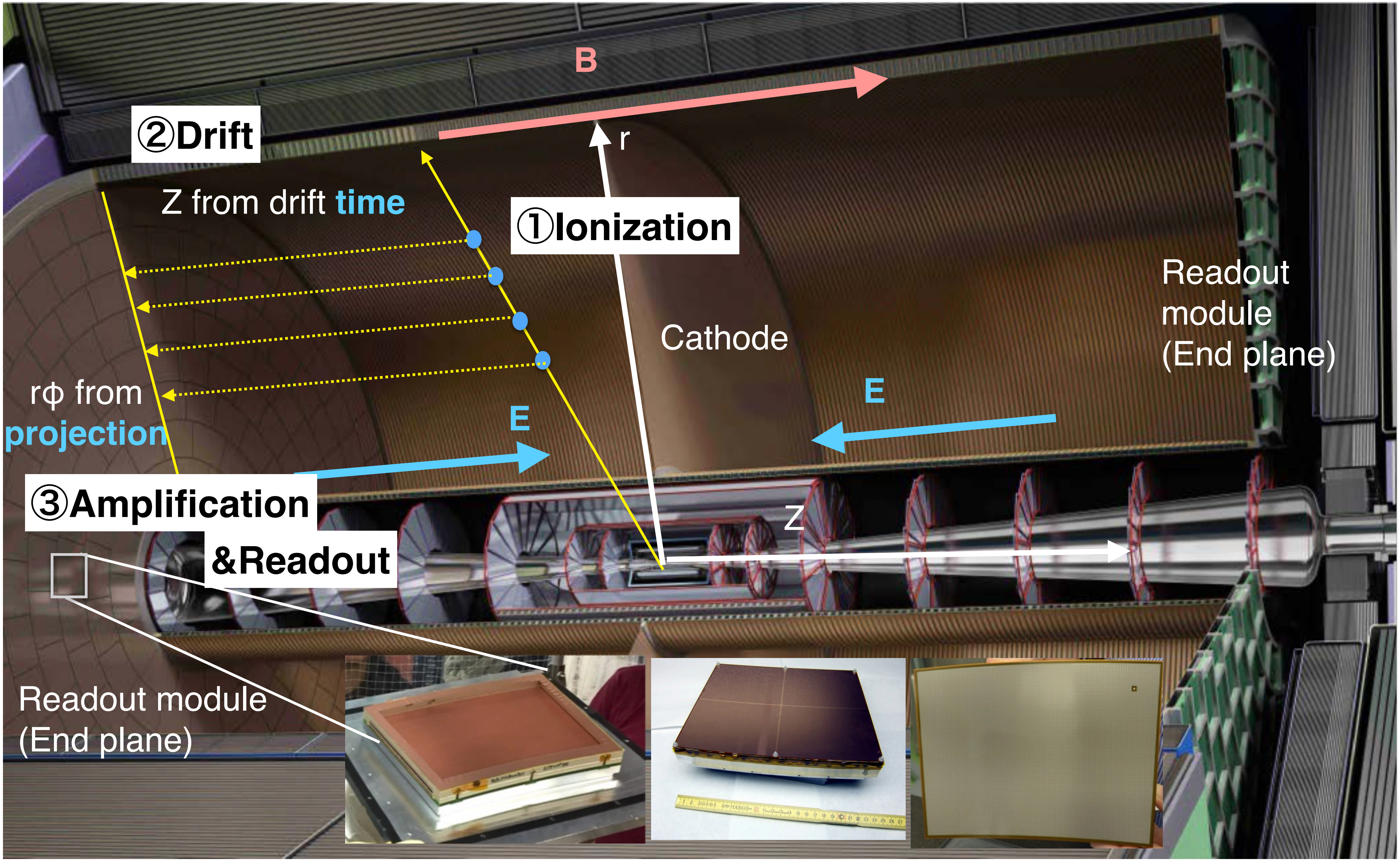
☆ The TPC simulation was improved to take into account the some effects
→the **gas gain fluctuation** has significant effect on $\hat{N}_{eff}$

☆ The measured and simulated $\hat{N}_{eff}$ agree to about 5~10%.

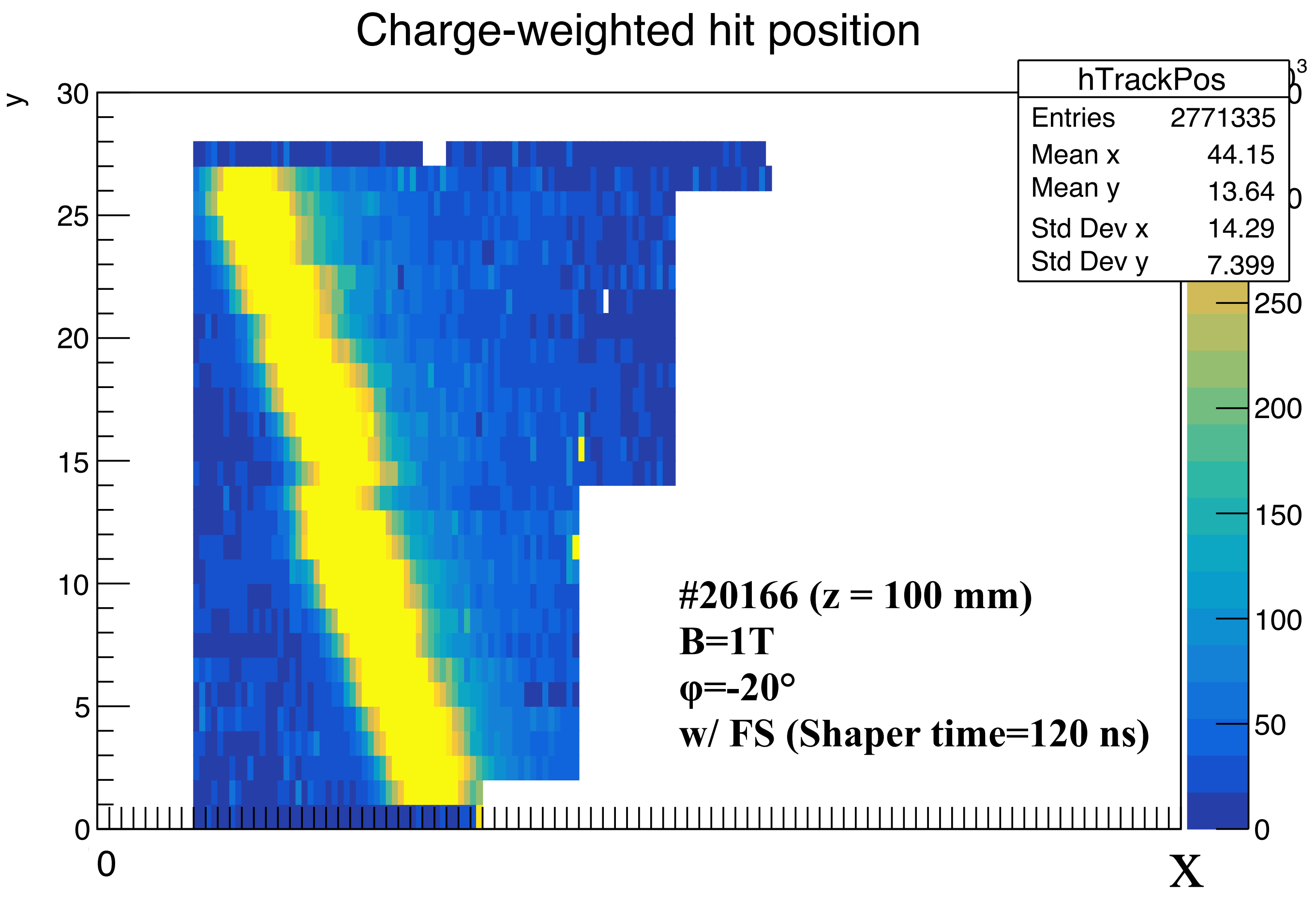
Next step

☆ The electrons ionisation process is carried out in Heed, a Garfield++ package.
(←implemented, but undergoing minor modifications.)

Fundamental principle of TPC



Charge-weighted hit position

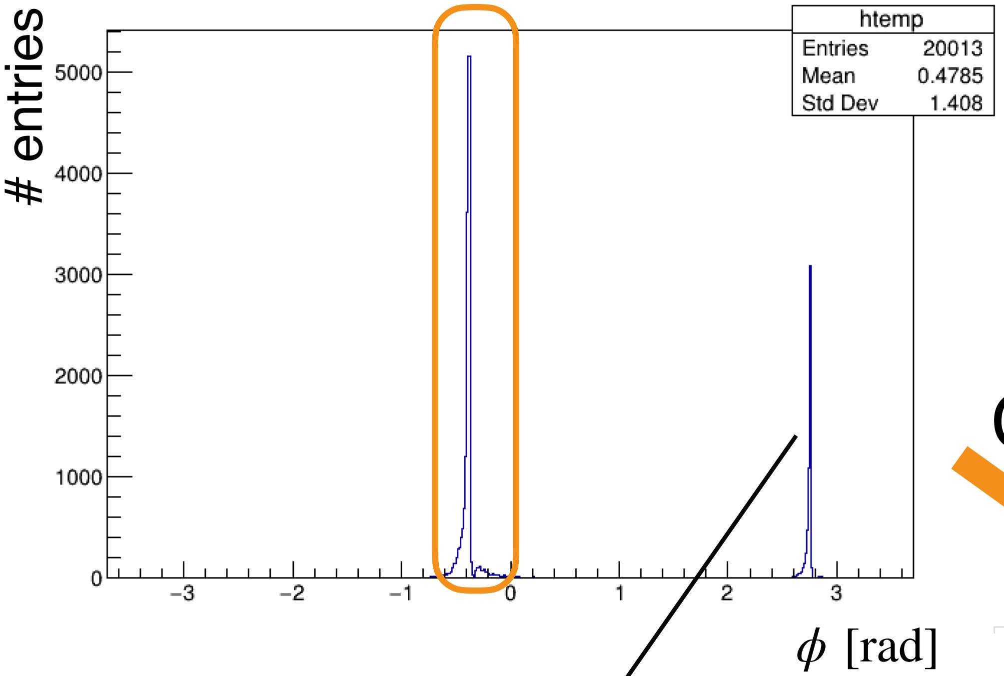


The small number of dead readout channels

How to determine ϕ

#20156, w/o gating foil, ϕ=20°, B=1T, row =16

ϕ distribution

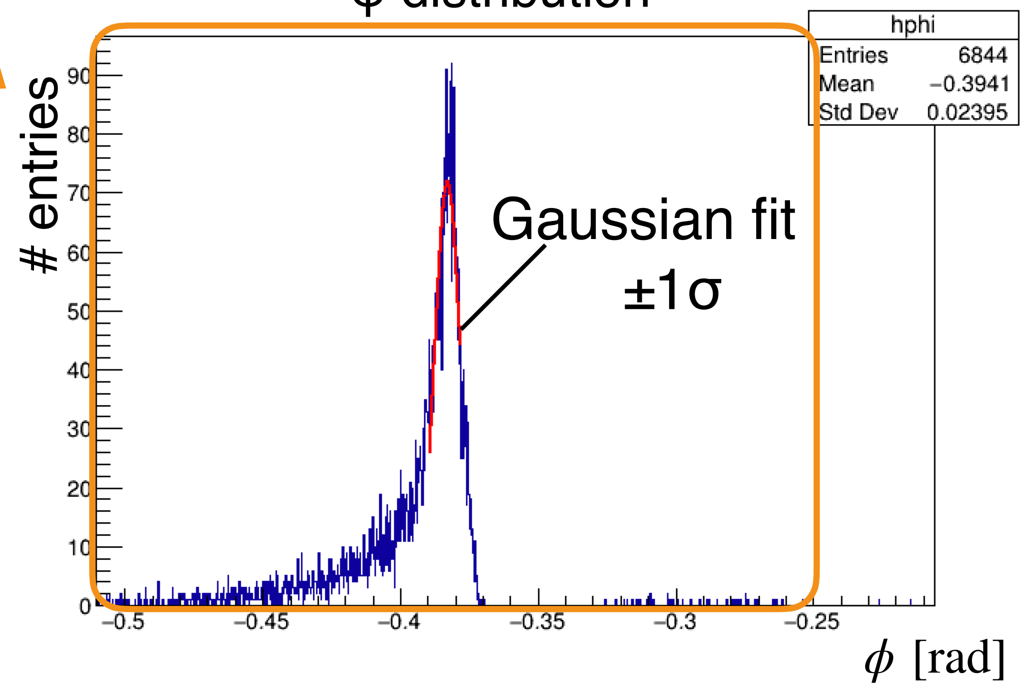


Positrons from bremsstrahlung
photon conversions before entering TPC

$-0.8 < 1/p_T(e^-) < 0$

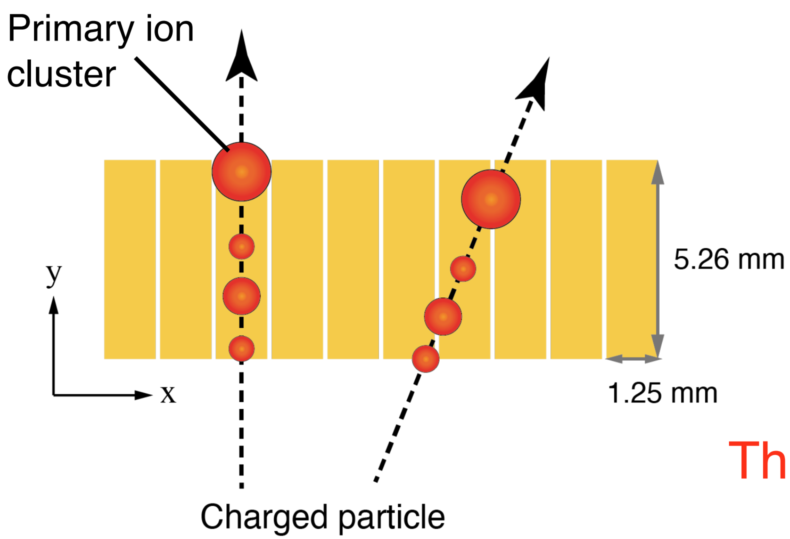
Cut

ϕ distribution



Incident angle effect on the spatial resolution

$$\sigma_x^2(Z; w, L\tan\phi, C_d, N_{eff}, \hat{N}_{eff}, [f]) = [A] + \frac{1}{N_{eff}}[B] + [C] + \frac{1}{\hat{N}_{eff}}[D]$$



Hodoscope effect and S-shape for the short drift distance

$$[A] = \int_{-1/2}^{1/2} d\left(\frac{\tilde{x}}{w}\right) \sum_{N=1}^{\infty} P_{PI}(N;\bar{N}) \prod_{i=1}^{N} \left[\sum_{k_i=0}^{\infty} \bar{\bar{P}}_{SI}(k_i)\right]$$

Primay ion cluster

Secondary ion cluster

$$\times \left\{ \left(\sum_a (aw) \sum_{i=1}^{N} \langle\langle F_a \rangle^y_{\Delta x} \rangle^{k_i}_y \left\langle \frac{\sum_{j=1}^{k_i} G_{ij}}{\sum_{i=1}^{N} \sum_{j=1}^{k_i} G_{ij}} \right\rangle_G^{k_i, \sum_{i=1}^{N} k_i} - \tilde{x} \right)^2 \right\}$$

Diffusion averaged & cluster positon average charge centroid

Systematic

The diffusion(Gas gain fluctuation)+ finite pad pitch

$$[B] = \int_{-1/2}^{1/2} d\left(\frac{\tilde{x}}{w}\right) \left\langle \left(\sum_a (aw) F_a(\tilde{x} + \Delta x) - \sum_a (aw) \langle F_a(\tilde{x} + \Delta x) \rangle_{\Delta x} \right)^2 \right\rangle_{\Delta x}$$

Diffusion-averaged charge centroid

Displacement due to diffusion for a single electron

Electric noise

$$[C] = \left(\frac{\sigma_E}{\bar{G}}\right)^2 \left\langle \frac{1}{N^2} \right\rangle_N \sum_a (aw)^2$$

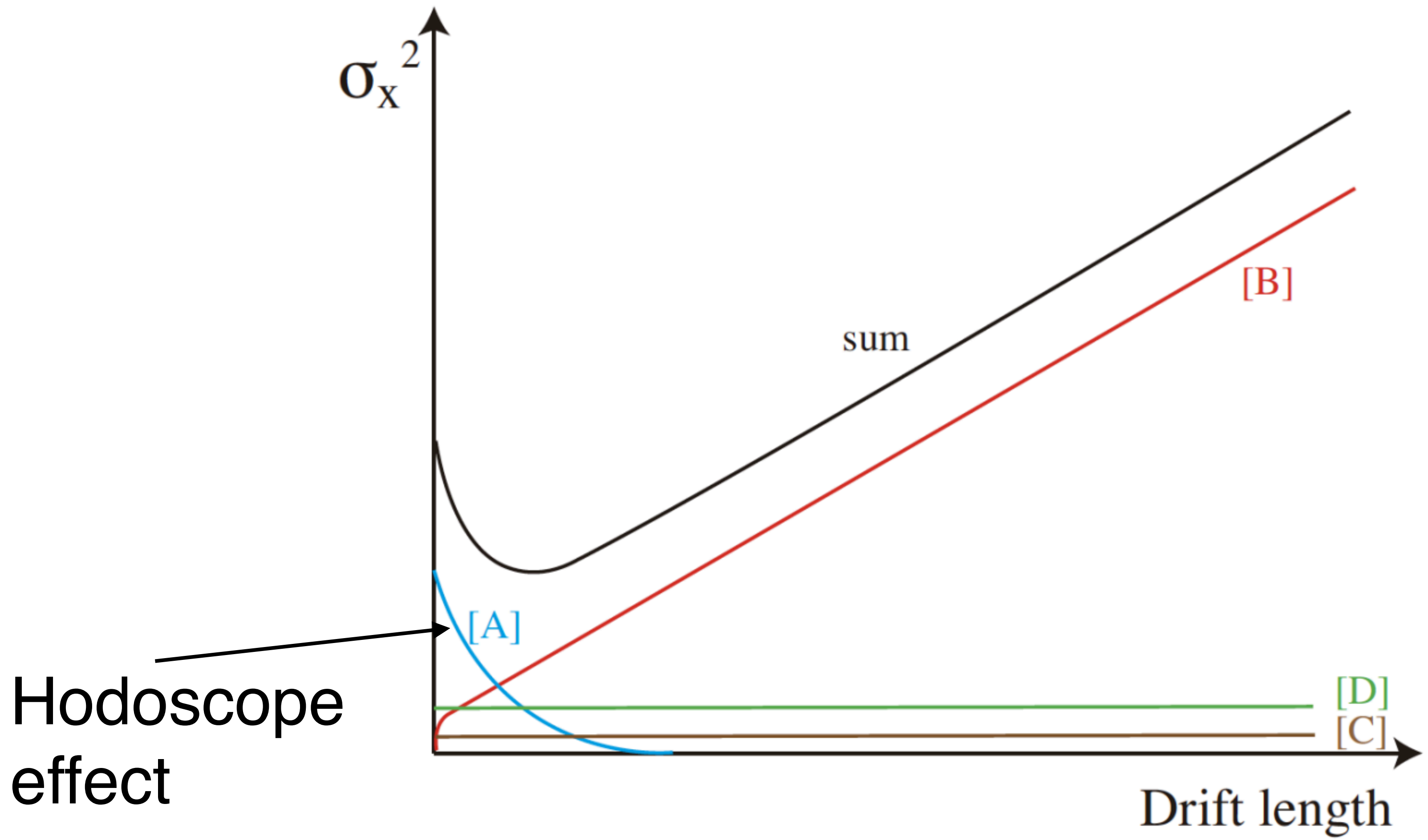
Angular Pad effect

$$\frac{1}{\hat{N}_{eff}}[D] = \frac{L^2 \tan^2\phi}{12\hat{N}_{eff}}$$

L : Pad height

R.Yonamine,K.Fujii [https://doi.org/10.1088/1748-0221/9/03/C03002]

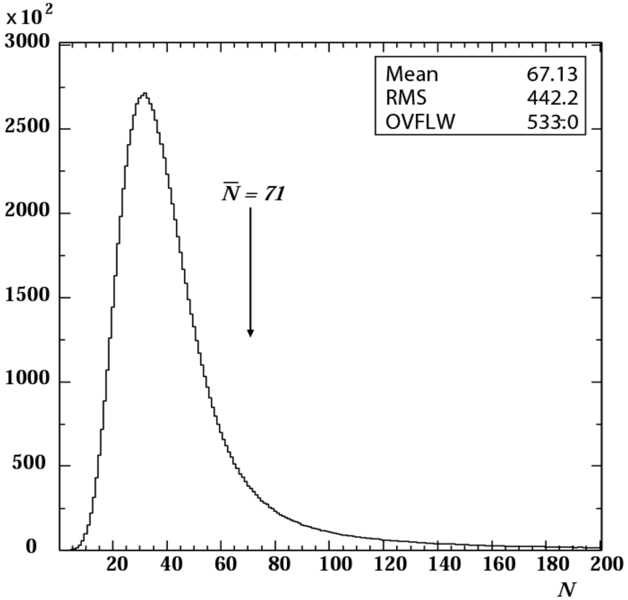
Schematic image of the spatial resolution as a fuction of drift length

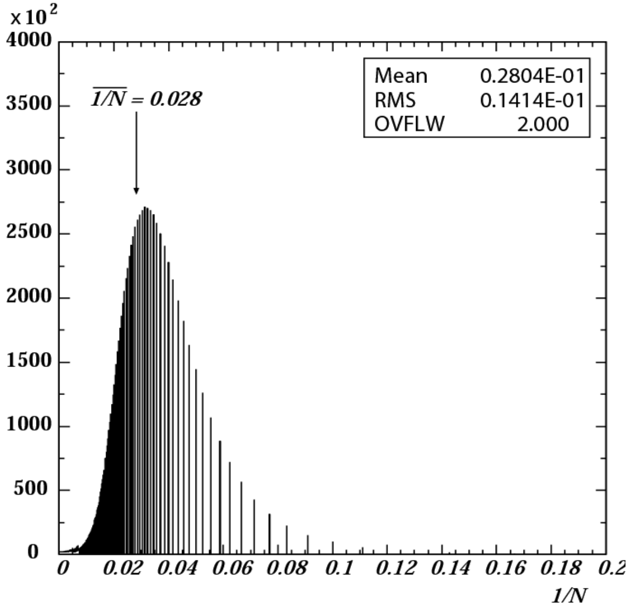


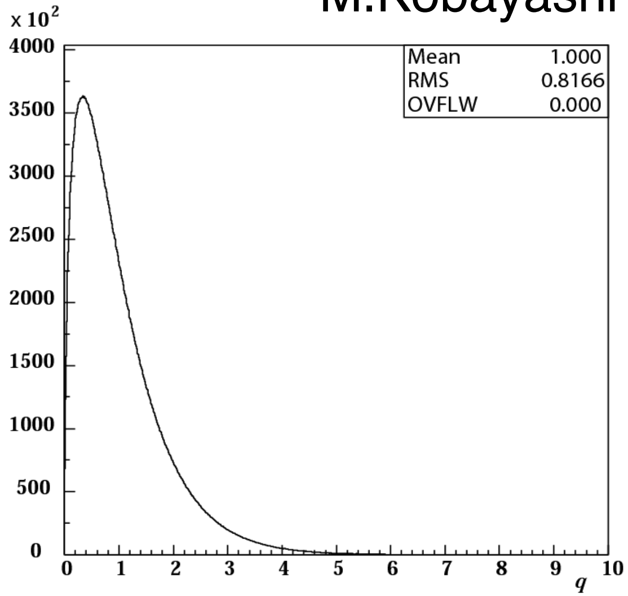
N_{eff} in typical model

4 GeV pion, pad pitch 6mm, pure Ar

M.Kobayashi







Distribution of *N* (<*N*> = 71)

Distribution of 1/*N* (<1/*N*> = 0.028)

Distribution of *Q* (*K* = 0.67)

1/2

1/3

$$\left\langle \left(\frac{G}{\bar{G}}\right)^2 \right\rangle = 1 + \left(\frac{\sigma_G}{\bar{G}}\right)^2 \equiv 1 + K$$

$$N_{eff} := \left[\left\langle \frac{1}{N} \right\rangle \left\langle \left(\frac{G}{\bar{G}}\right)^2 \right\rangle \right]^{-1} = 21 < \frac{1}{\langle 1/N \rangle} = 36 < \langle N \rangle = 71$$