Introduction of ILC-TPC

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1.Principle of TPC

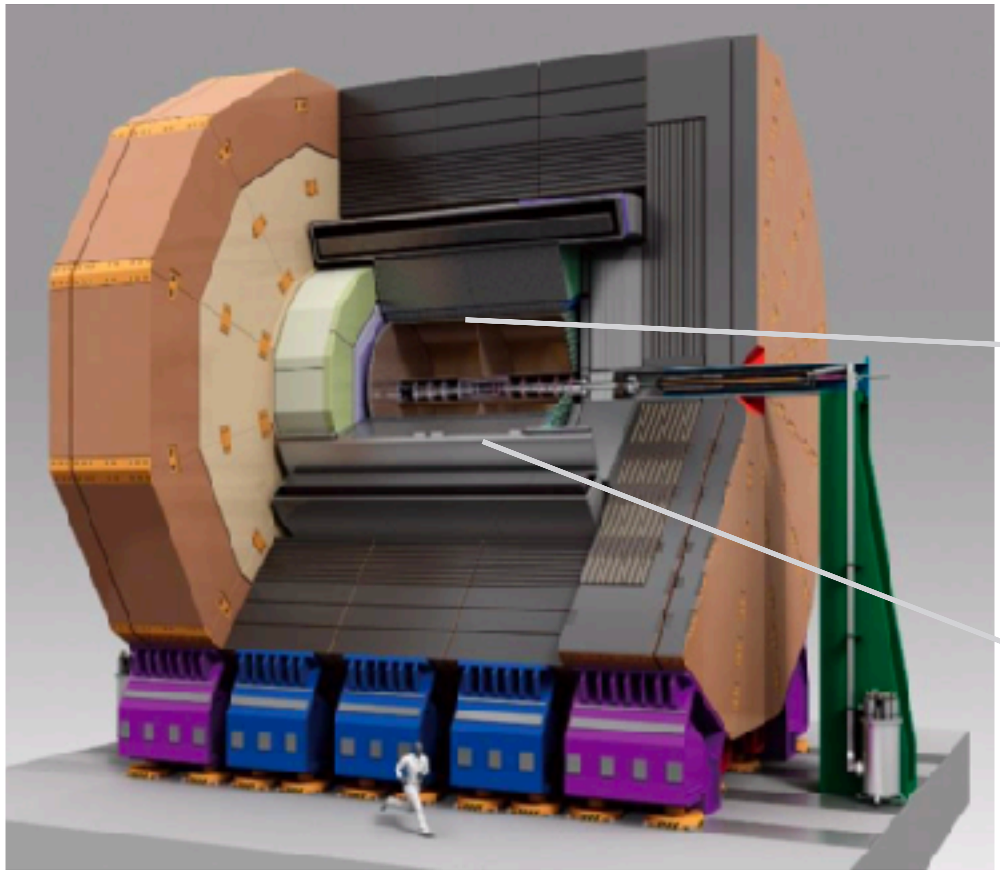
- What is TPC?
- What do we need to know at TPC?
- Momentum resolution
- Position resolution
- Gas

2. Readout module of TPC

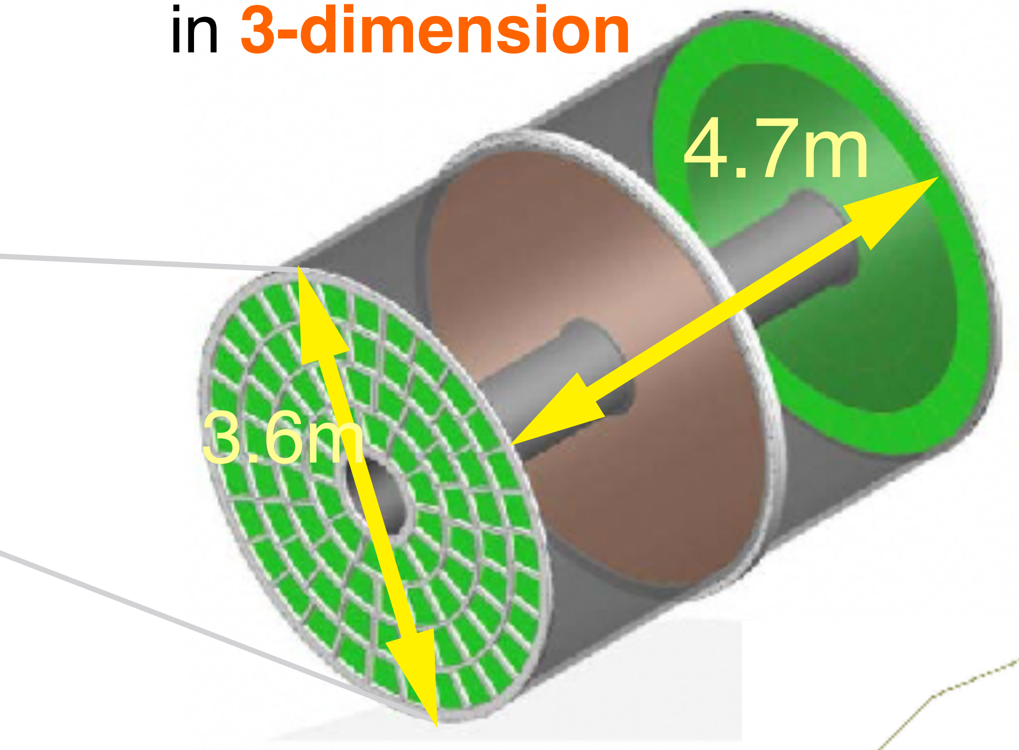
- Introduction of various modules
- New technology
- Ion backflow

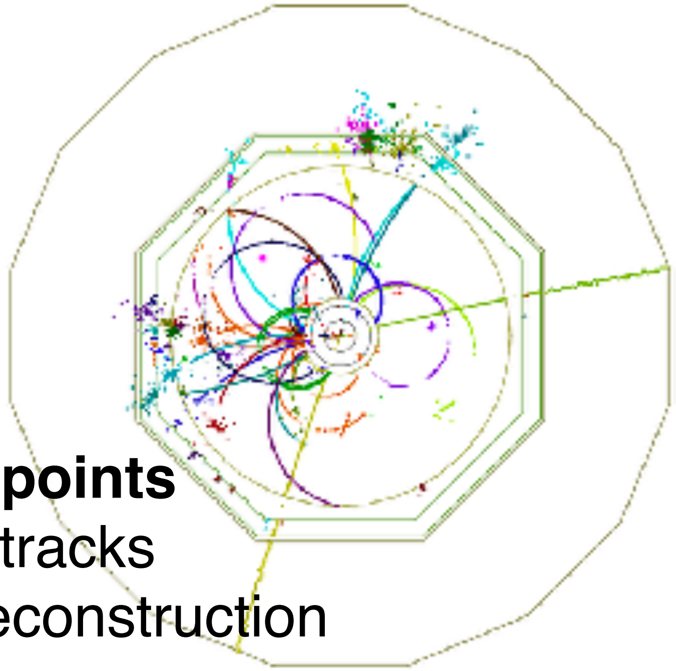
3.Summary

Time Projection Chamber (TPC)



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





~200 hit points
Can see tracks
before reconstruction

What we want to know

"Two 4-vectors"

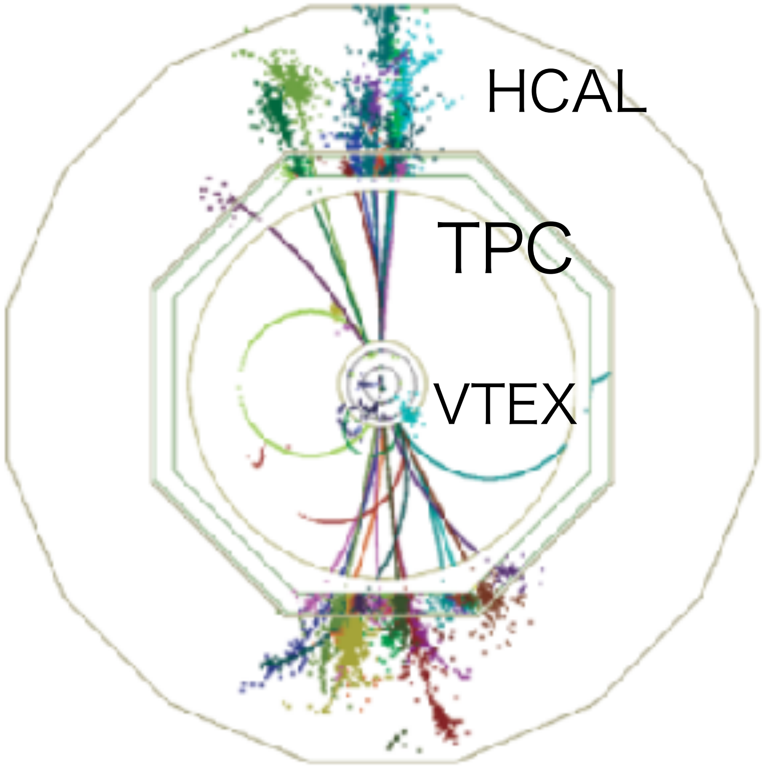
$$\boxed{\begin{array}{l} p^\mu = (E/c,\ p) \\ x^\mu = (ct,\ x) \end{array}}$$

+ Charge

for every particle produced

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

What can we know at TPC?



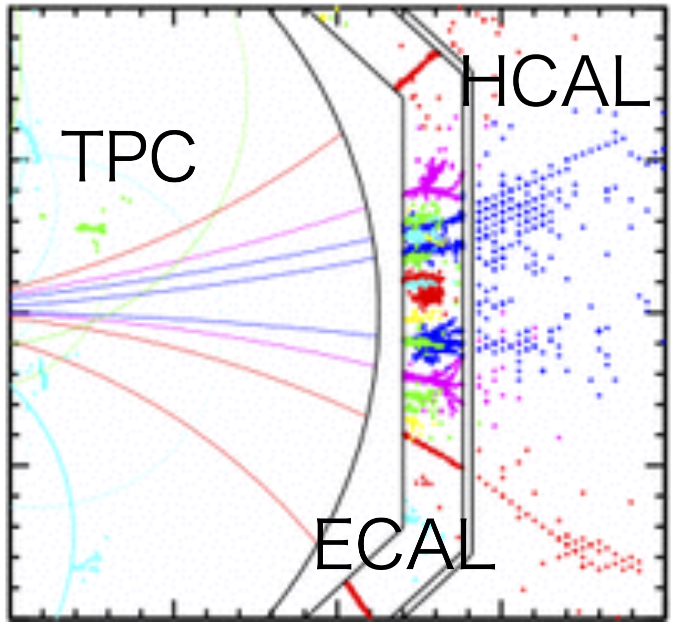
1.Momentum measurement

← Today's topic

Measure the **curvature radius** of the tracks in **B=3.5T**

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

(TPC only)



https://www.ilcild.org

2.2-track separation

Make a 1:1 correspondence between track and Calorimeter

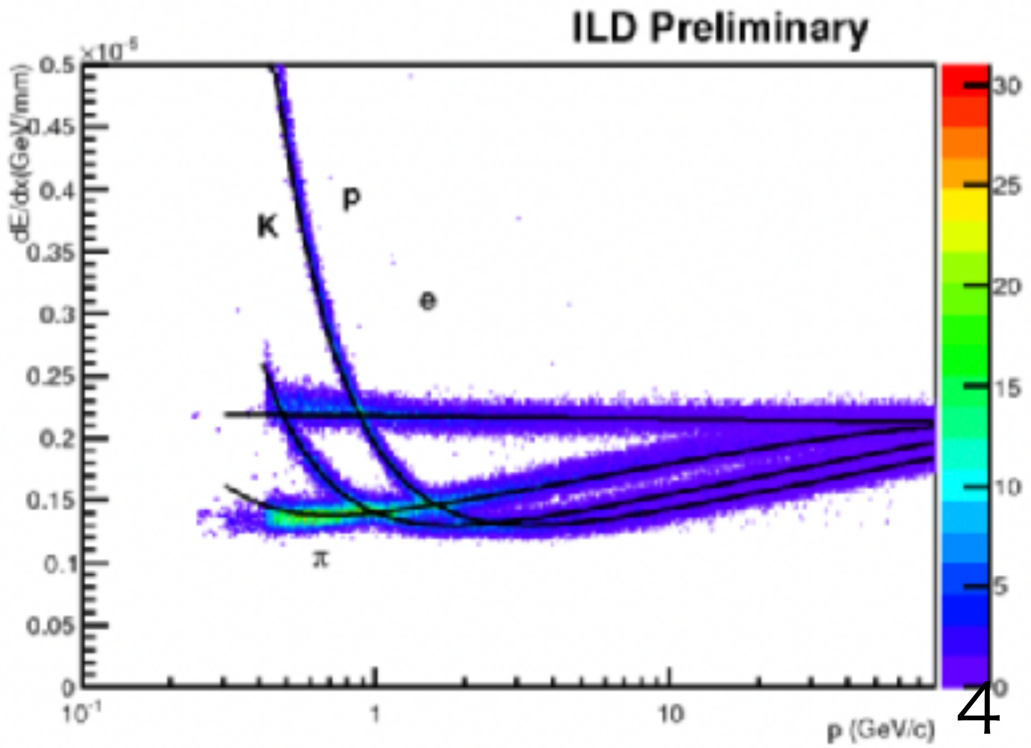
2hit resolution in rϕ $\simeq 2\,\mathrm{mm}$

2hit resolution in z $\simeq 6\,\mathrm{mm}$

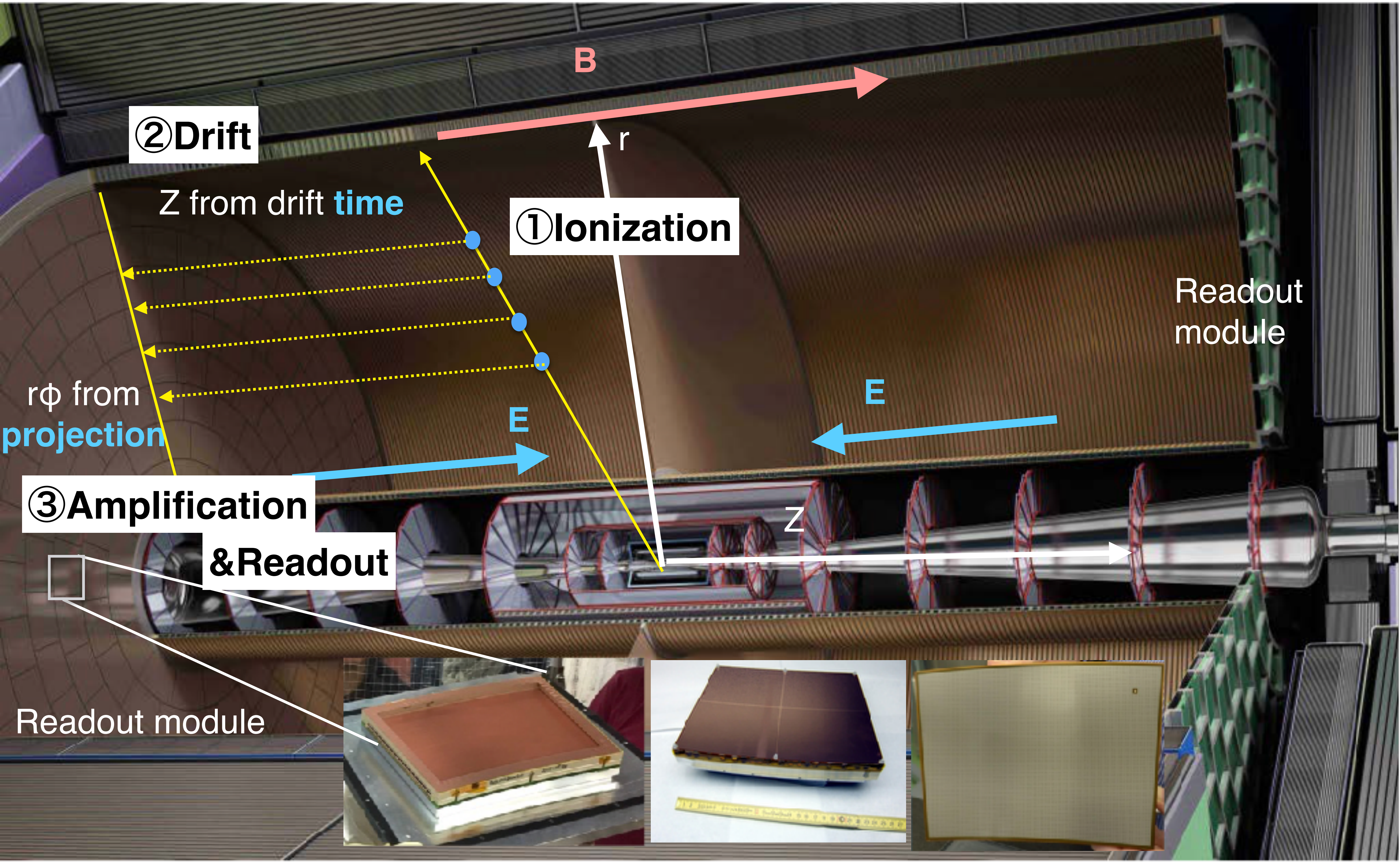
3.Particle ID

Measure the **dE/dx (loss energy of particles)**

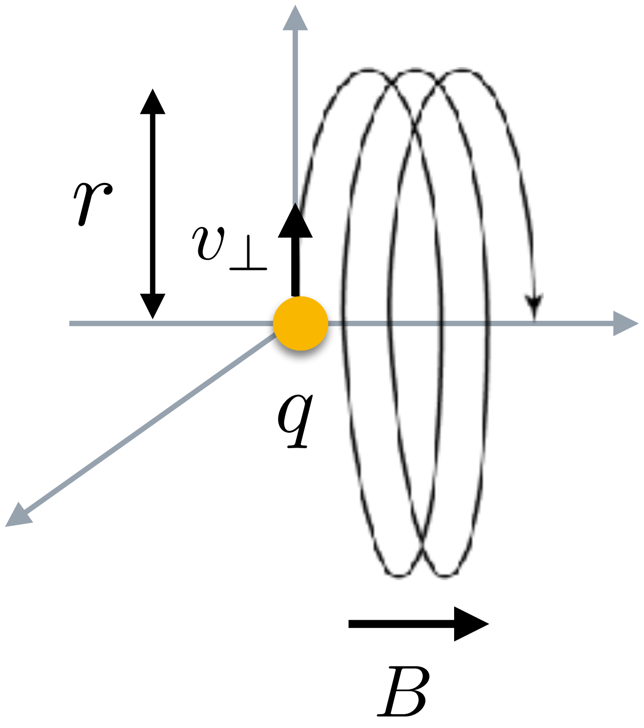
←dE/dx is different for each particle.



Fundamental principle of TPC



Momentum resolution



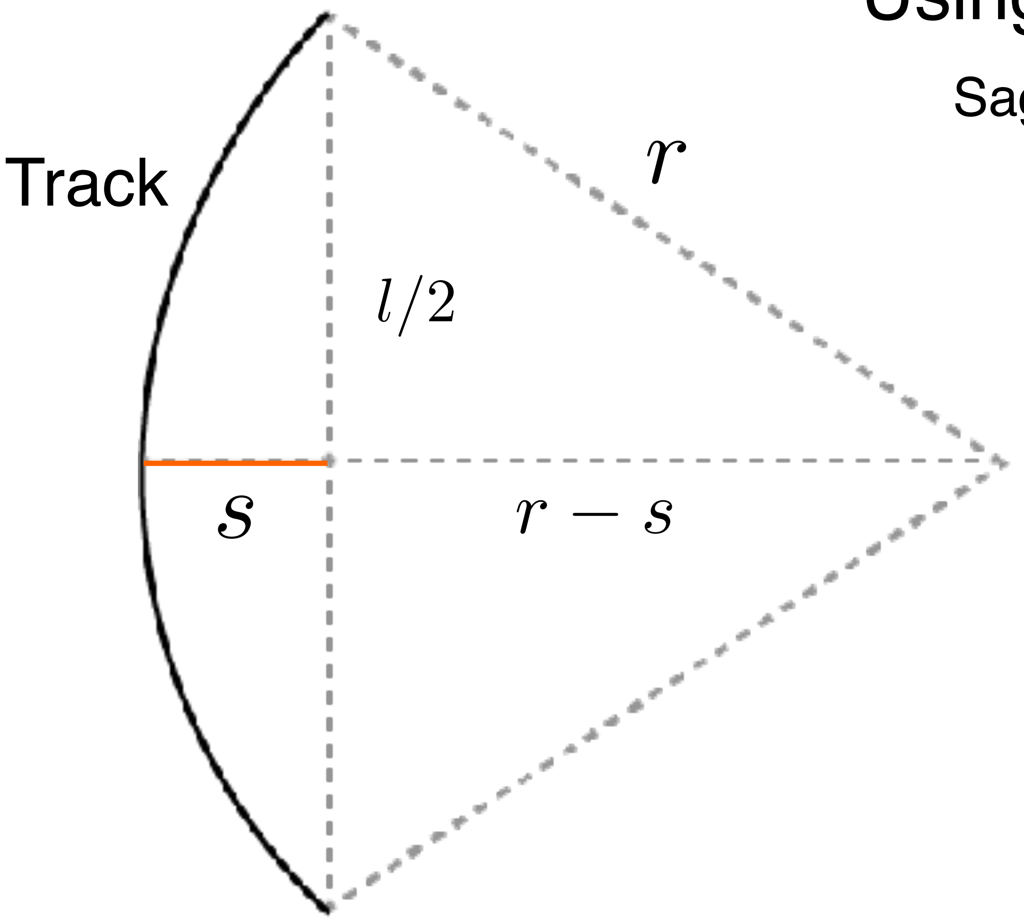
A charged particle follows a **helix** in uniform B-field

Radius: r Transverse momentum: $p_\perp$

Velocity : $v_\perp$ Charge: q

$$F = qv_\perp B \;,\quad F = mv_\perp^2/r$$

$$\rightarrow \boxed{p_\perp\,[\mathrm{GeV/c}] = 0.3 \cdot B[\mathrm{T}] \cdot \underline{r[\mathrm{m}]}}$$



Using **sagitta** to calculate curvature radius of track

Sagitta: s curvature radius of track: r Arm length: l

$$r^2 = (l/2)^2 + (r-s)^2 \quad (s \ll r)$$

$$\rightarrow \quad 2rs = (l/2)^2 + s^2 \simeq l^2/4$$

$$\rightarrow \quad r \simeq l^2/(8s)$$

$$\boxed{\kappa := \frac{1}{p_\perp} \simeq \left(\frac{8\alpha}{Bl^2}\right) s \rightarrow \sigma_\kappa^{meas} := \frac{\sigma_{p_\perp}}{p_\perp^2} \simeq \left(\frac{8\alpha}{Bl^2}\right) \sigma_s}$$

Ex)Q. p = 1GeV, B = 3T ? A. r = about 1m

Momentum resolution

Gluckstern Formula

$$\frac{\sigma_{p_\perp}}{p_\perp} = \sqrt{\underbrace{(\sigma_\kappa^{meas})^2}_{\text{Detector resolution}} + \underbrace{(\sigma_\kappa^{MS})^2}_{\text{Multiple scattering}}}$$

Transversmomentum: $p_\perp$

Spatial resolution in the r-ϕ plane per point: σ_x

The number pf sampling points: N

Thickness measured in radiation length units: X/X_0

Leaver arm length: l Magnetic field: B

Const.: α, C

$$= \sqrt{\underline{\left(\frac{\alpha\sigma_x}{Bl^2}\right)^2 \left(\frac{720}{N+4}\right) p_\perp^2} + \underline{\left(\frac{\alpha C}{Bl}\right)^2 \frac{10}{7} \left(\frac{X}{X_0}\right)}}$$

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

ILD detector requires overall

$$\frac{\sigma_{p_\perp}}{p_\perp} \simeq 2 \times 10^{-5} p_\perp [\mathrm{GeV/c}]$$

TPC is required

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

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

in B = 3.5 T and drift length = 2.2 m

Position resolution

$$\sigma_x = \sqrt{\sigma_0^2 + \frac{C_d^2 \cdot z}{N_{eff}}}$$

drift length: z
Transverse diffusion: C_d
The effective number of electrons: N_{eff}

<u>Transverse diffusion constant C_d</u>

$$C_d(B, E) = \frac{1}{\sqrt{1 + \boxed{\omega^2 \tau^2}}} C_d(0, E)$$

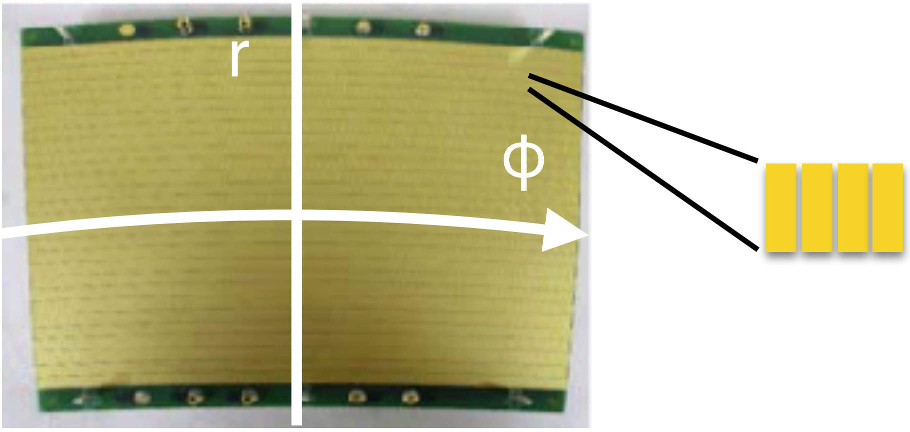
Cyclotron frequency: ω
Mean free time: τ

Electrons are affected by diffusion → position resolution is worse

➡ **A large ωτ is needed to reduce transverse diffusion**

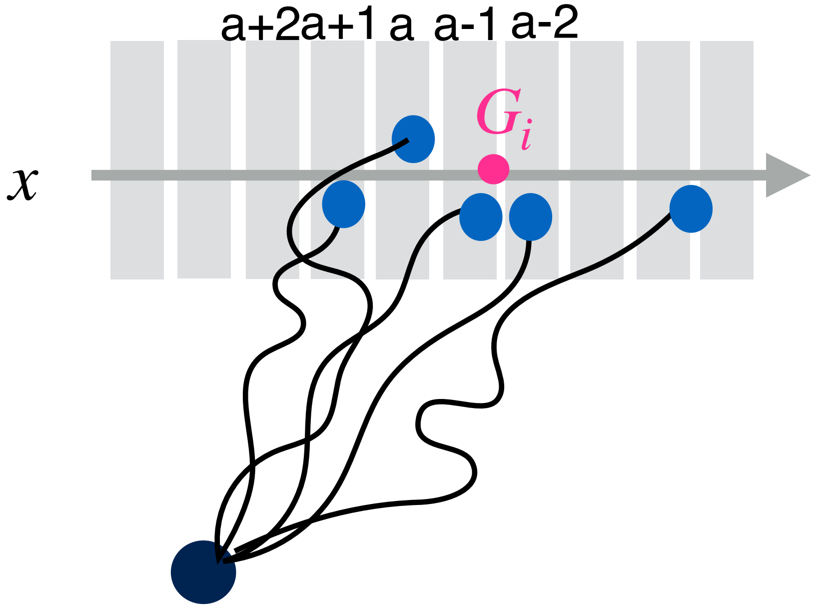
※ In TPC, Lorentz force suppresses transverse diffusion of drift electrons by curling them around the magnetic field

Effect of gas gain fluctuation



Effective number of electron N_{eff}

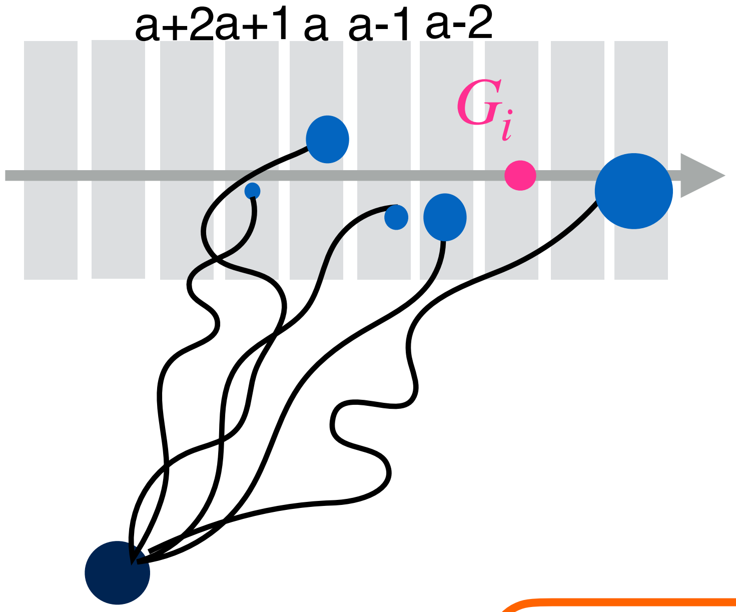
W/o gas gain fluctuation



$$N_{eff} := \frac{1}{\langle 1/N \rangle} < \langle N \rangle$$

 # electrons

W/ gas gain fluctuation



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

 # electrons **gas gain fluctuation**

Ex) 4 GeV pion, pad pitch 6mm, pure Ar

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

We need to select “good” gas

What is “good” gas?

- Sufficient electrons
- Suppress diffusion in high B-field region

Gas mixture (T2K gas)

$$Ar : \underbrace{CF_4 : Iso\text{-}C_4H_{10}}_{\text{“Quencher”}} = 95 : 3 : 2\ [\%]$$

CF_4 “Quencher”

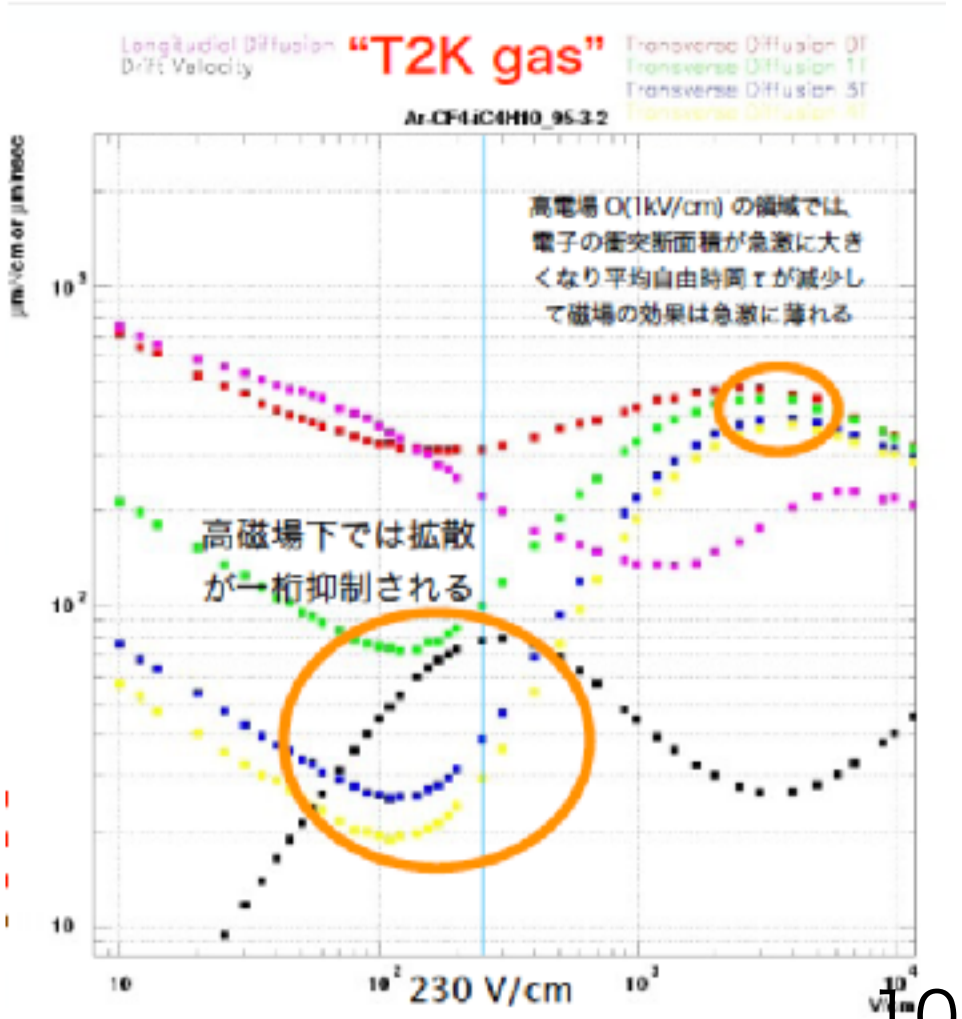
Ar - CF4 mixture has large τ

$$C_d(B,E) = \frac{1}{\sqrt{1+\boxed{\omega^2\tau^2}}}C_d(0,E)$$

→ fast drift velocity as compared typical chamber gas

→ **Large** ωτ

ex) 7.5 cm/μs (230V/cm)



$Iso\text{-}C_4H_{10}$ “Quencher”

+ “**Penning effect**”

Ionization potential

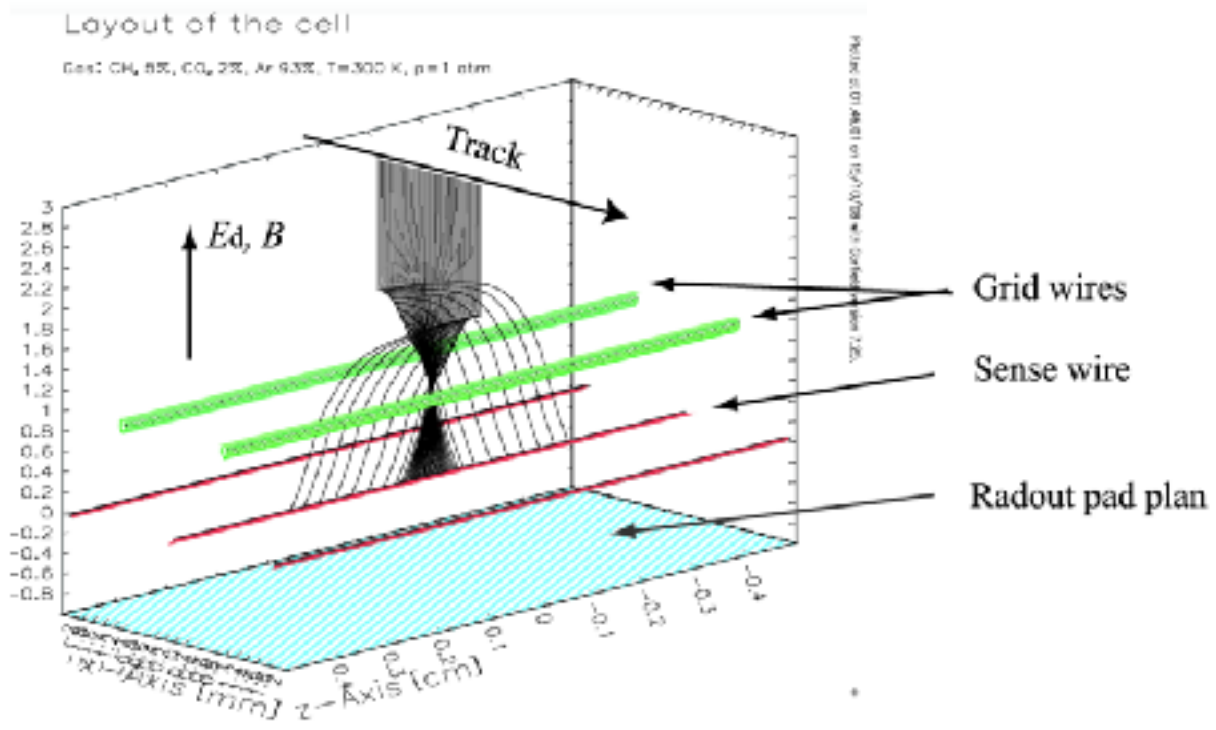
$$Iso\text{-}C_4H_{10} < Ar$$

$$\underbrace{Ar^*}_{\text{meta-stable Ar}} + Iso\text{-}C_4H_{10} \rightarrow Ar + (Iso\text{-}C_4H_{10})^+ + \boxed{e^-}$$

Additional e

Readout Module

Multi-Wire Proportional Chamber (MWPC)



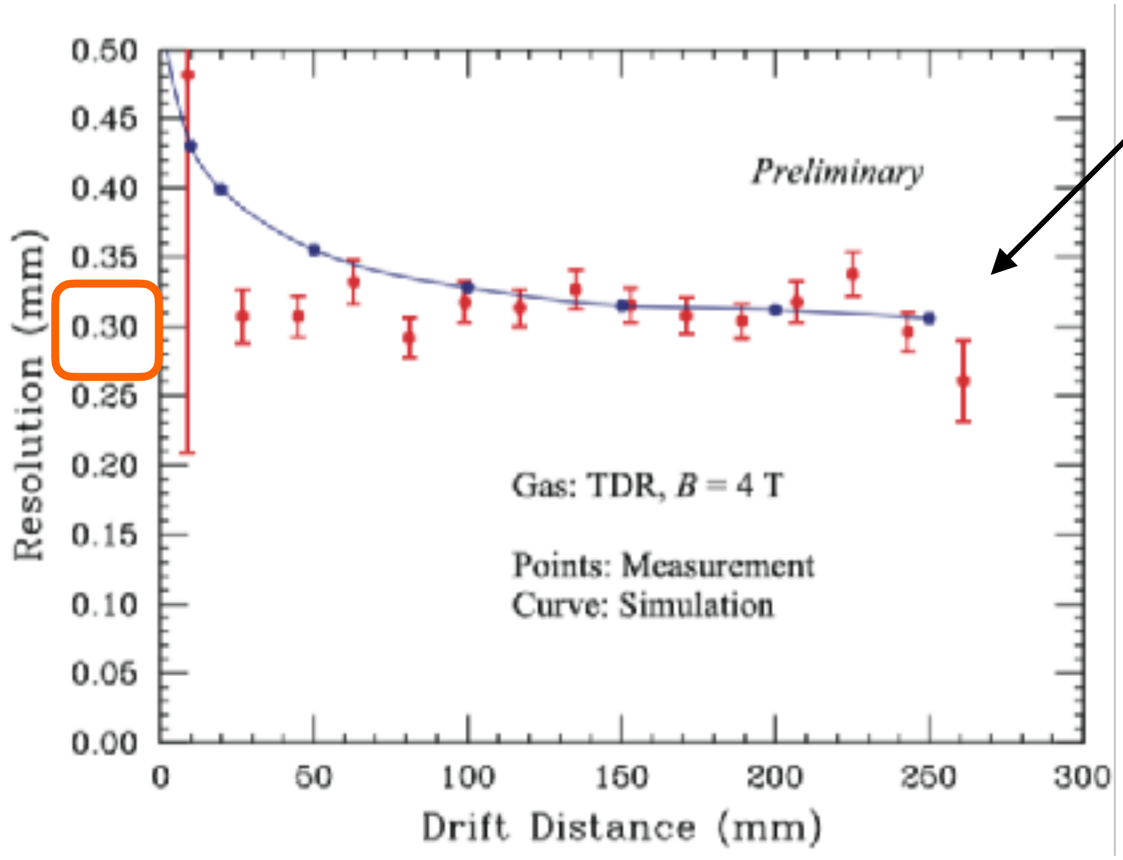
ILD: B-field 3.5T

☑ Limiting the spatial resolution

←E×B spread seed electrons along sense wire

Ex) σ_x = 300 μm

Cannot achieve ILD requirement!



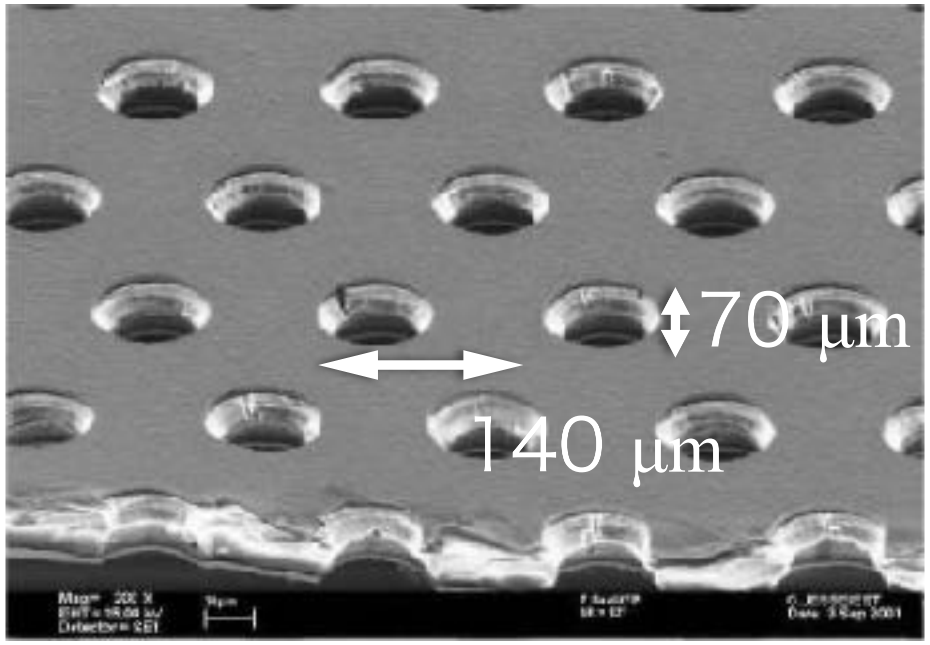
☑ 2mm 2-track separation is difficult

☑ Need support structure to tighten wire

➡ **MPGD**

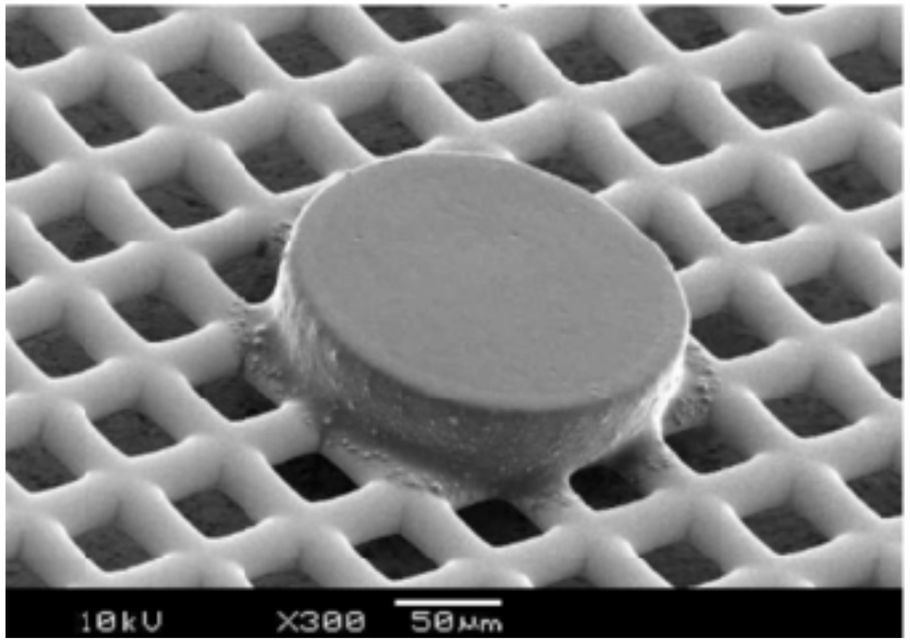
Micro-Pattern Gaseous Detector (MPGD)

GEM (Gas Electron Multiplier)



F.Sauli, NIM A 386(1997)531

MICROMEGAS



SEM image of micro-mesh by scienergy company

Why MPGD?

☑ The distance between holes is small

→ E×B effect is small

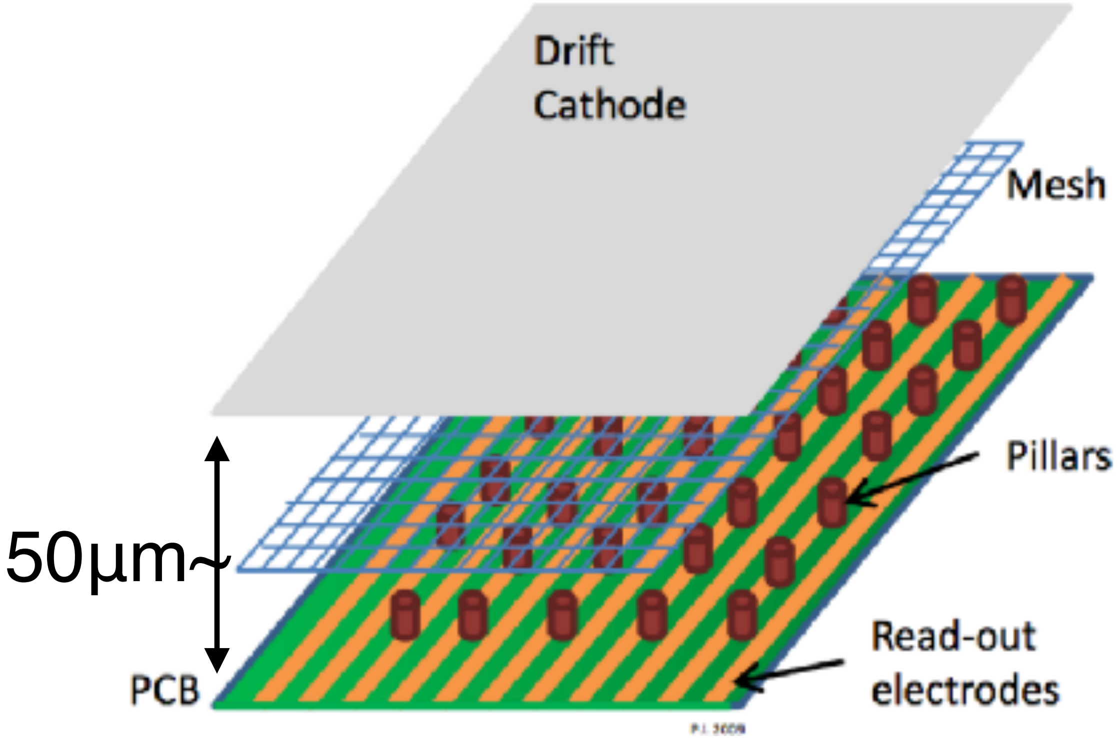
→ **We can get more precise position information**

☑ Supporting structure is simplified (compared to multi-wire chamber)

→ **Dead regions are reduced**

MICROMEGAS

Micro-mesh Gaseous Detector Structure



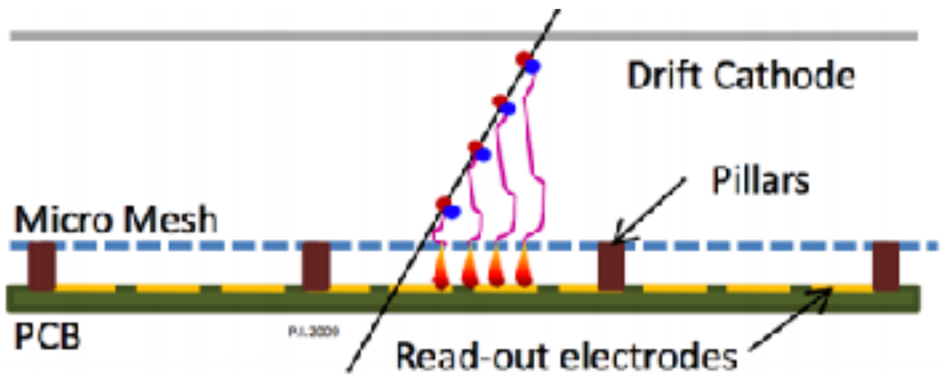
General structure of MICROMEGAS

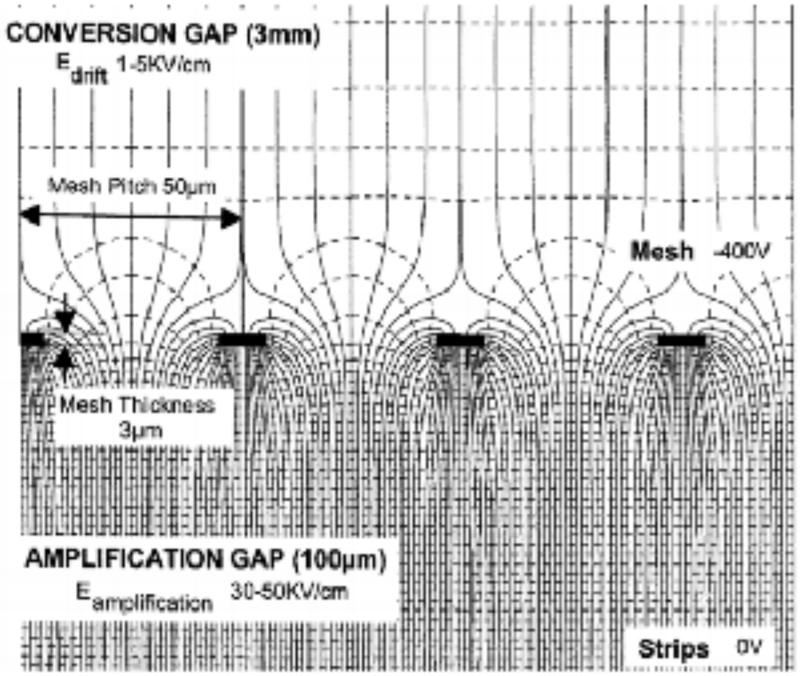
☑ Y.Giomataris(Saclay) proposed in 1996

☑ Only **one** amplification gap provides sufficient amplification factor

☑ Resistive anode is needed to avoid hodoscope effect

Ex) σ_{PRF} = 12 µm (Typically)





E-field in MICROMEGAS

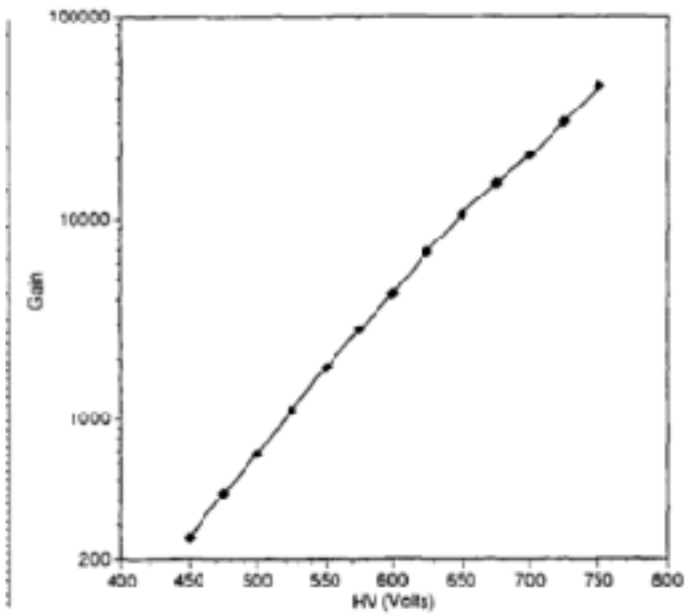


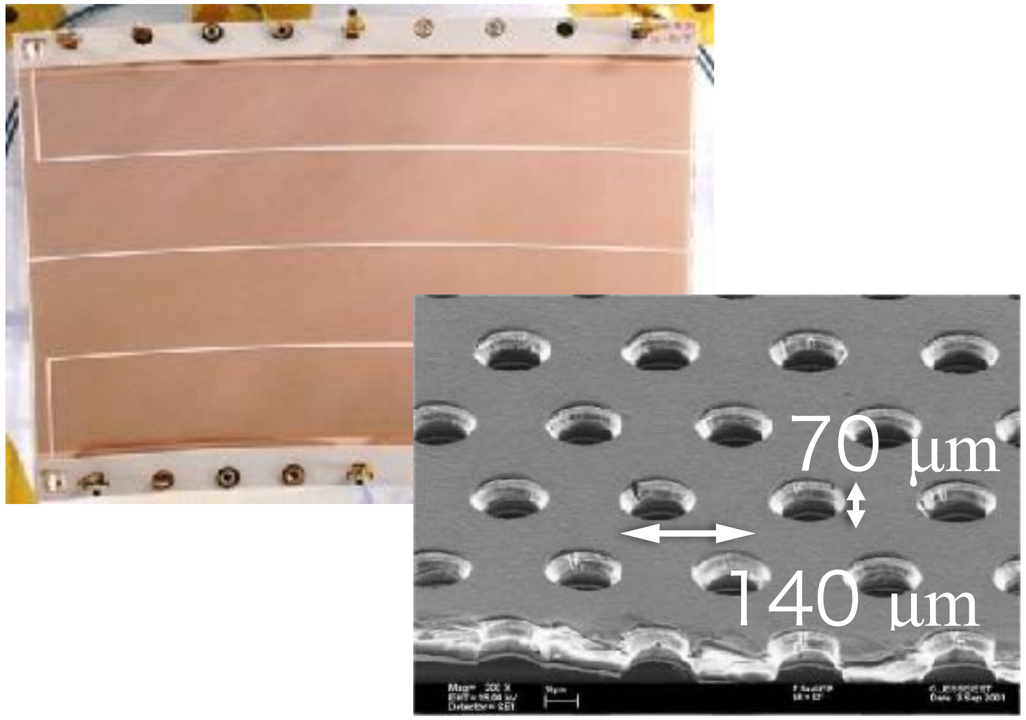
Fig. 9. Variation of gas-gain with anode voltage. The gas mixture was Ar + (10%) CH, at atmospheric pressure.

Charge amplification in MICROMEGAS

GEM

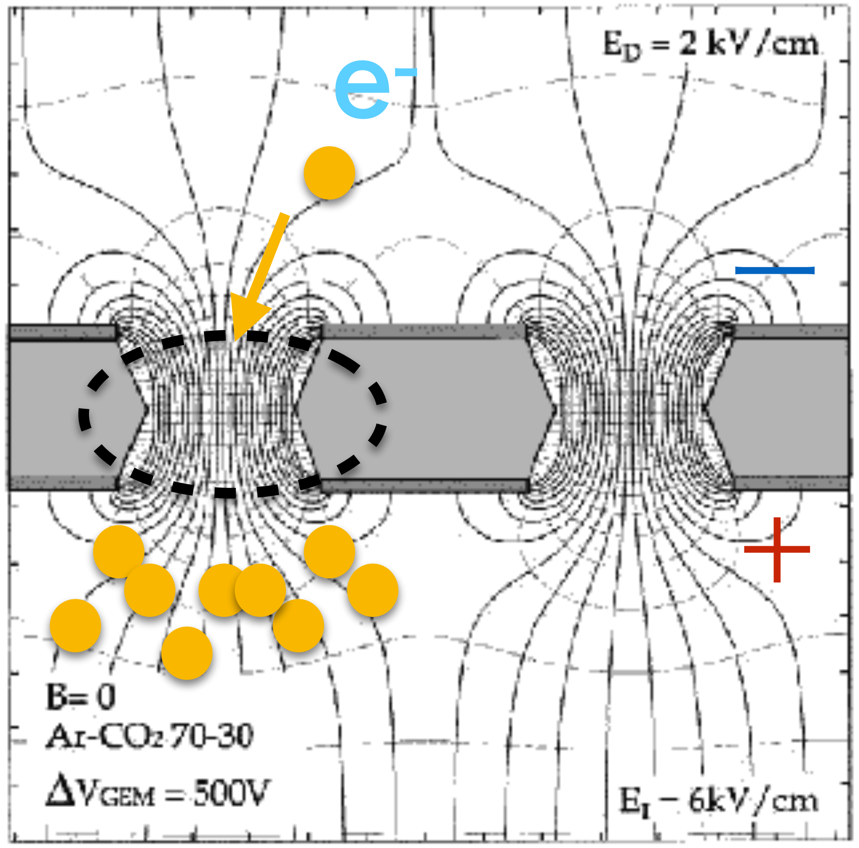
F.Sauli, NIM A 386(1997)531

Gas Electron Multiplier

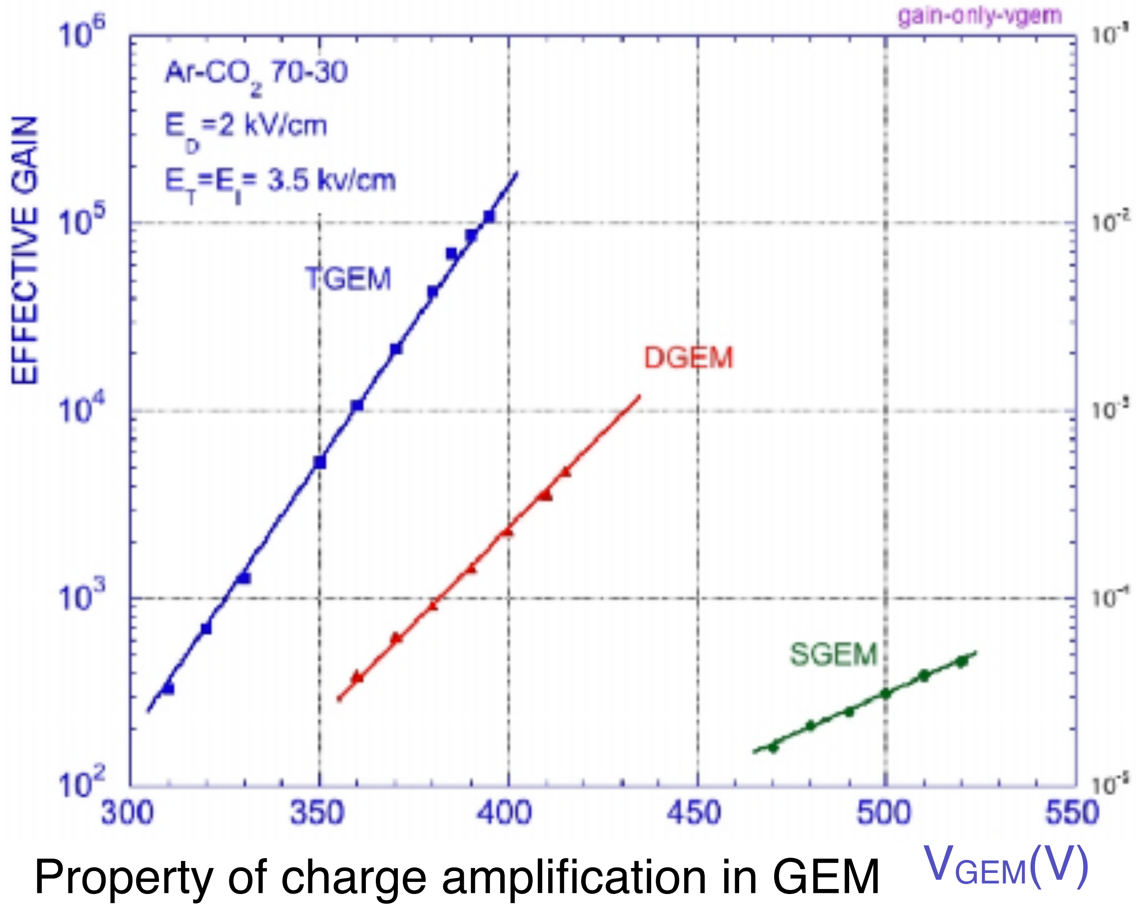


- ☑ F.Sauli(CERN) proposed in 1997
- ☑ Often used in **multiple** GEM

σ_{PRF} ~ 300 µm
→**suitable for ordinary pad readout**



E-field in GEM

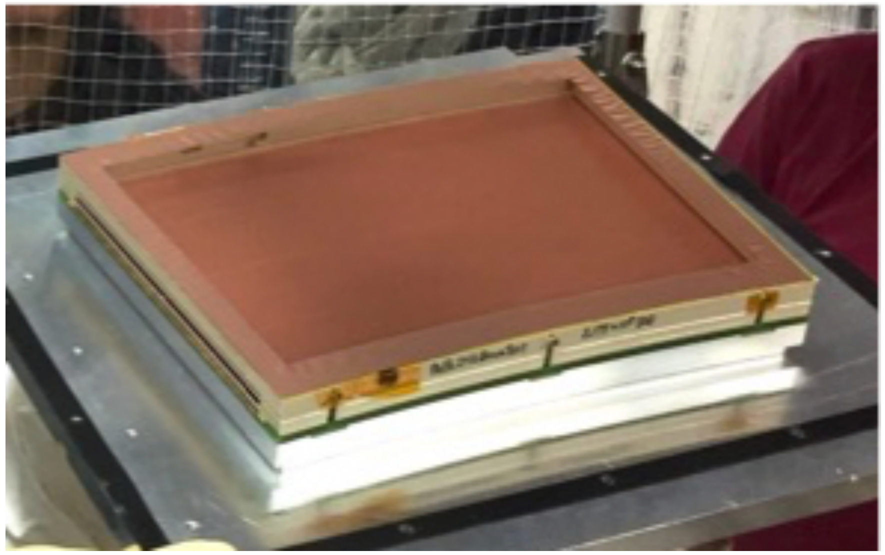


Property of charge amplification in GEM

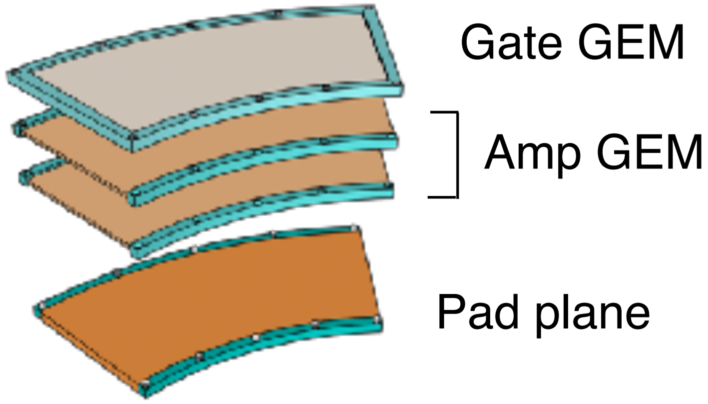
Candidates of readout module - Analog(Pad) readout

GEM

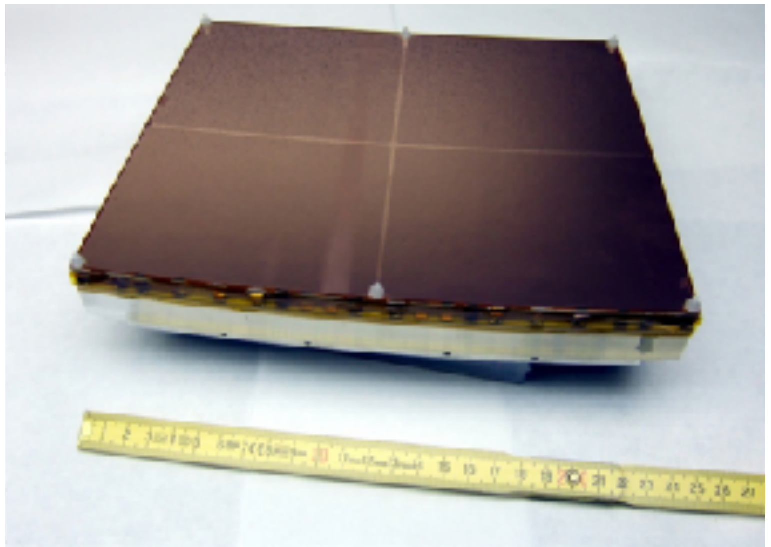
Asian module



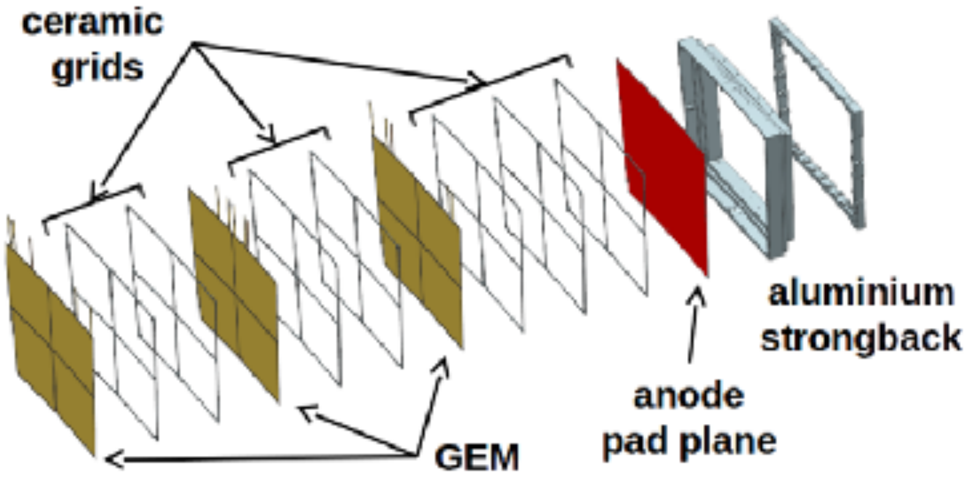
Double GEM



DESY module



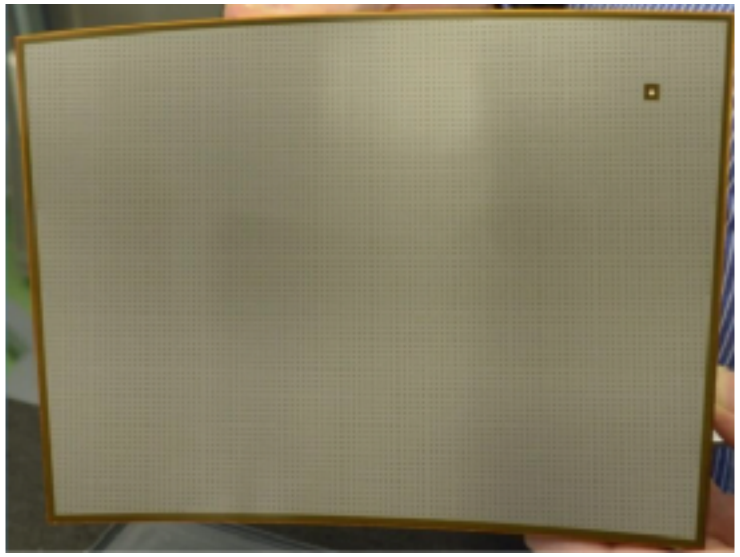
Triple GEM



arXiv:2006.08562

MICROMEGAS

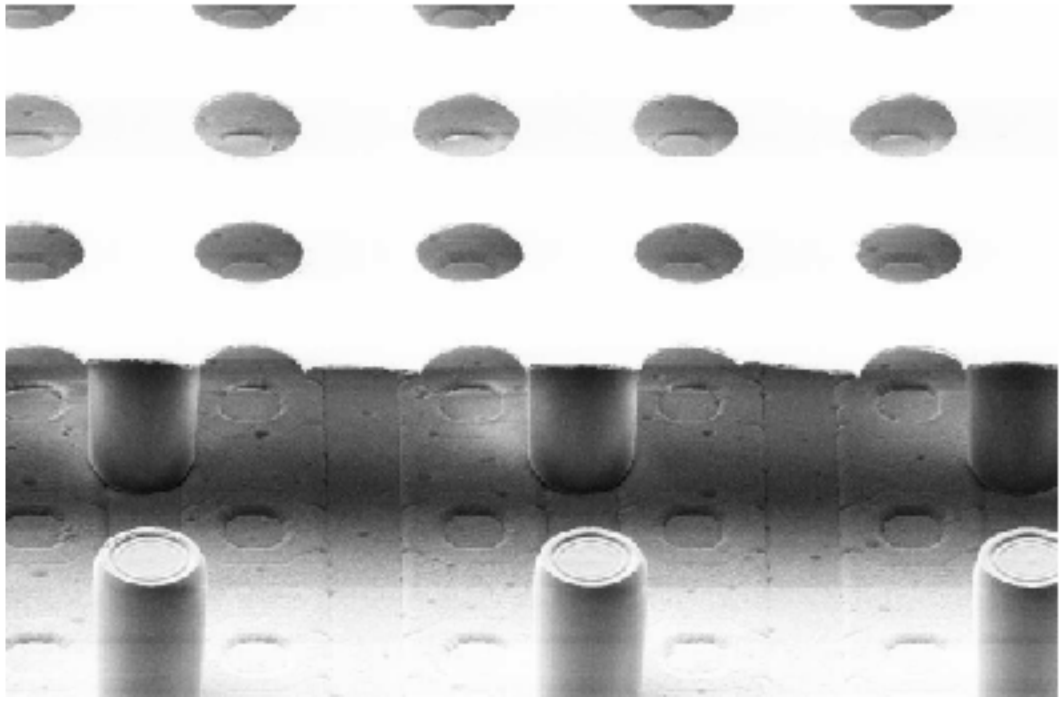
Saclay-Carleton module

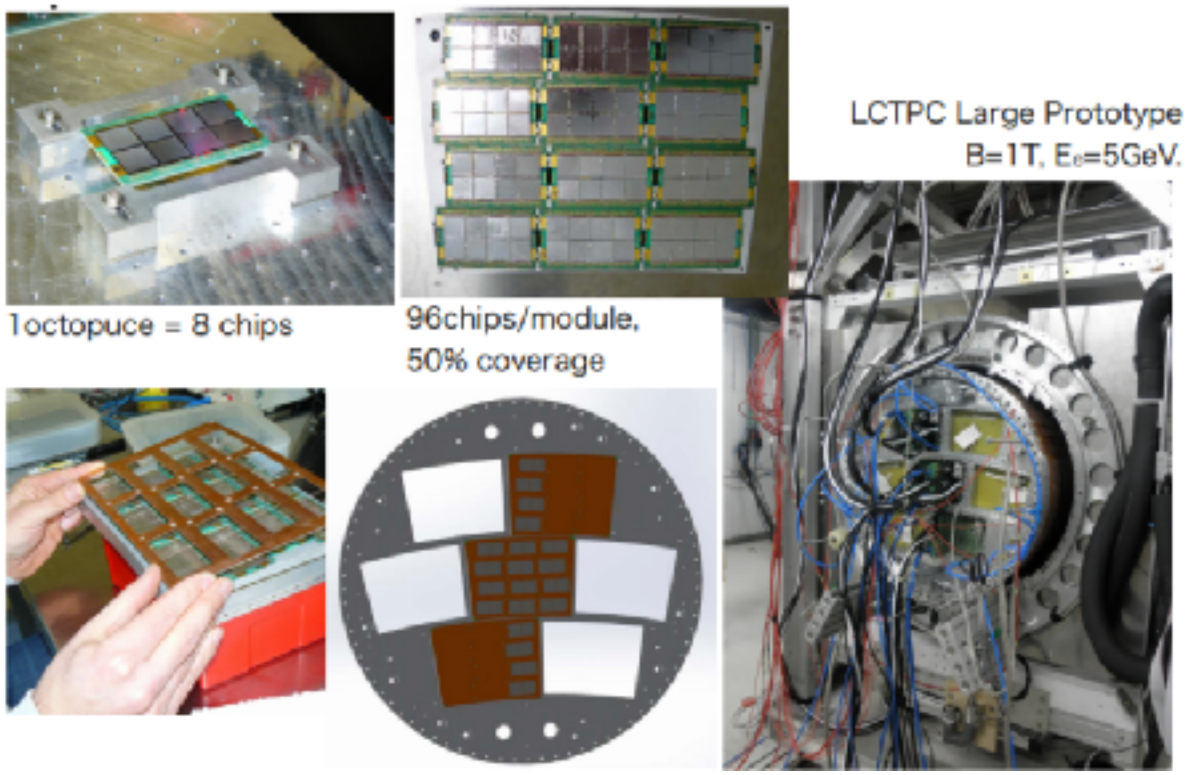


(Resistive anode)

Candidates of readout module - Digital(Pixel) readout

GridPix(TimePix + Protection Layer + Micromegas)





Prototype test

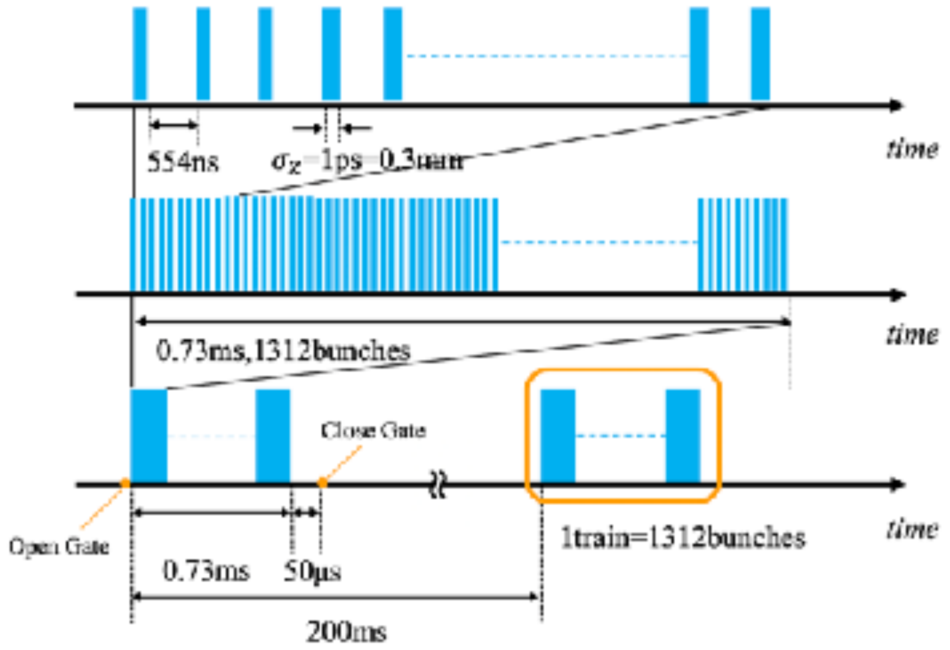
- ☑ Free from gas gain fluctuation effect on spatial resolution
- ☑ Expect 20-30% improvement of position resolution
- ☑ No angular pad effect
- ☑ Theoretically the best but not yet ready for full implementation of a module

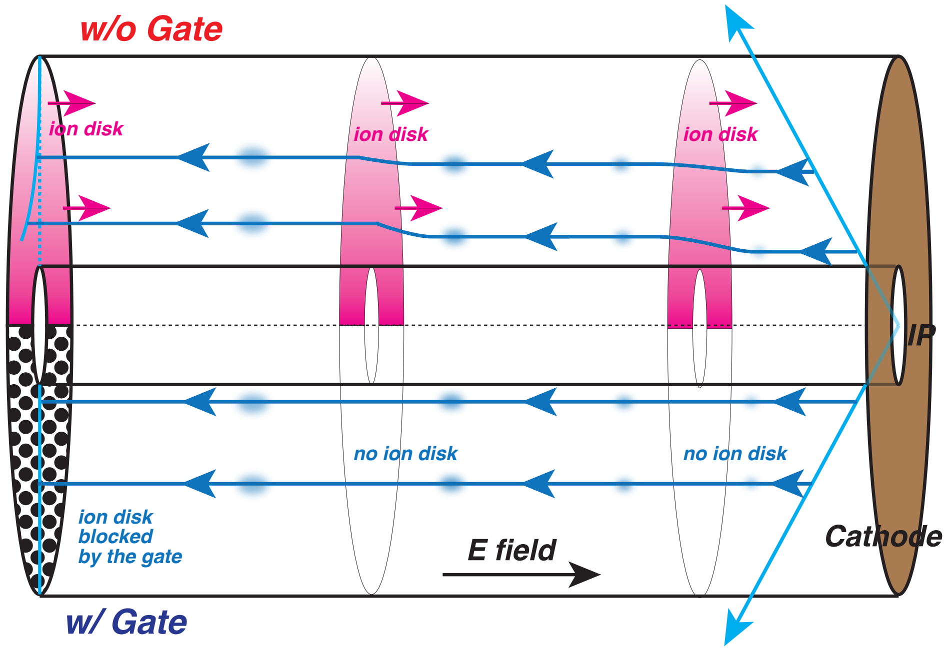
EPJ Web of Conferences 174, 02001 (2018)

Positive ion backflow

In ionization process, not only electron but also **positive ions** are produced

→ Positive ions **flow back in the drift region**
→ Making the distortion of E-field
→ **Position resolution is worse**





How many are positive ions(disk) in TPC?

Positive ions make **ion disk**(1cm) in 1train

Drift velocity(Iso-C_4H_{10} ion) : 0.37 cm/s
Drift E-field : 230 V/cm
Distance between trains : 200 ms

Positive ions flow 74 cm forward

Drift length(Max) : 2.2 m

$$\longrightarrow \quad 2.2\,\mathrm{m}/0.74\,\mathrm{m} \simeq 3$$

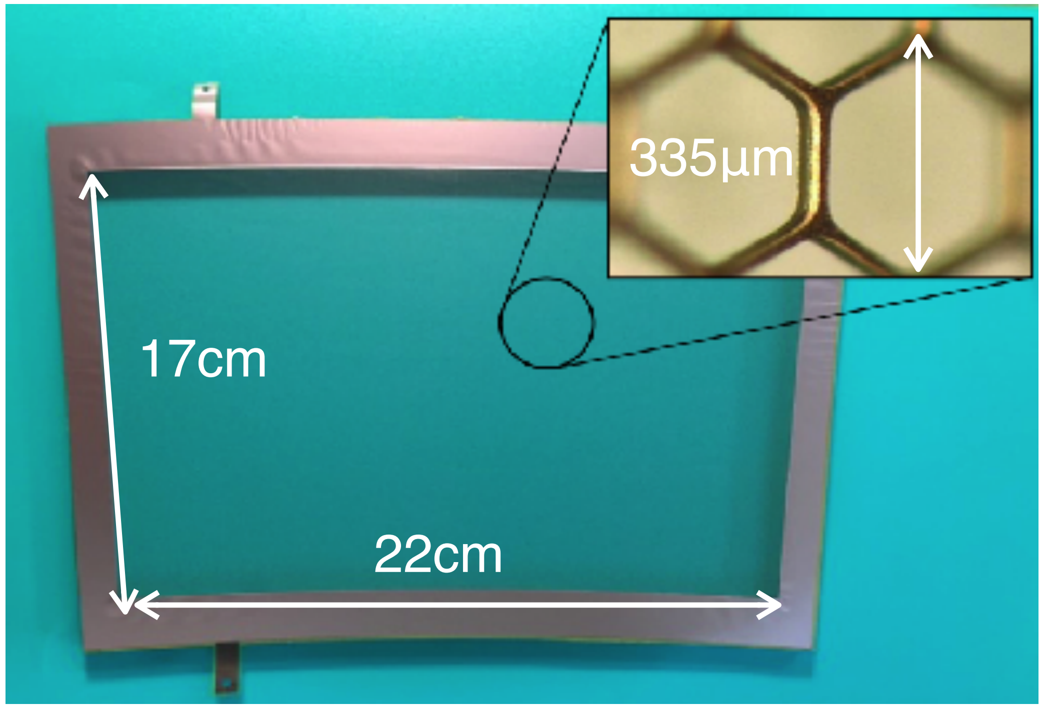
Not ignore

Maximum distortion is 60 μm

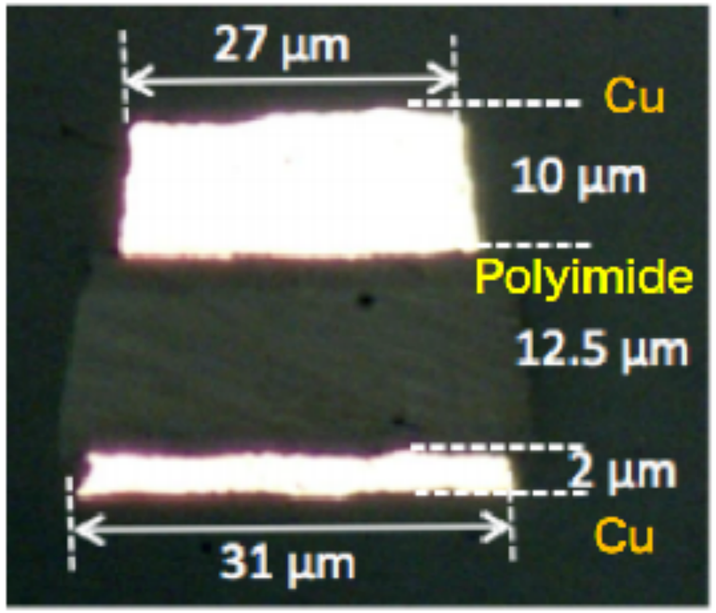
K. Fujii, "Positive Ion Effects (LCTPC collaboration meeting presentation)."

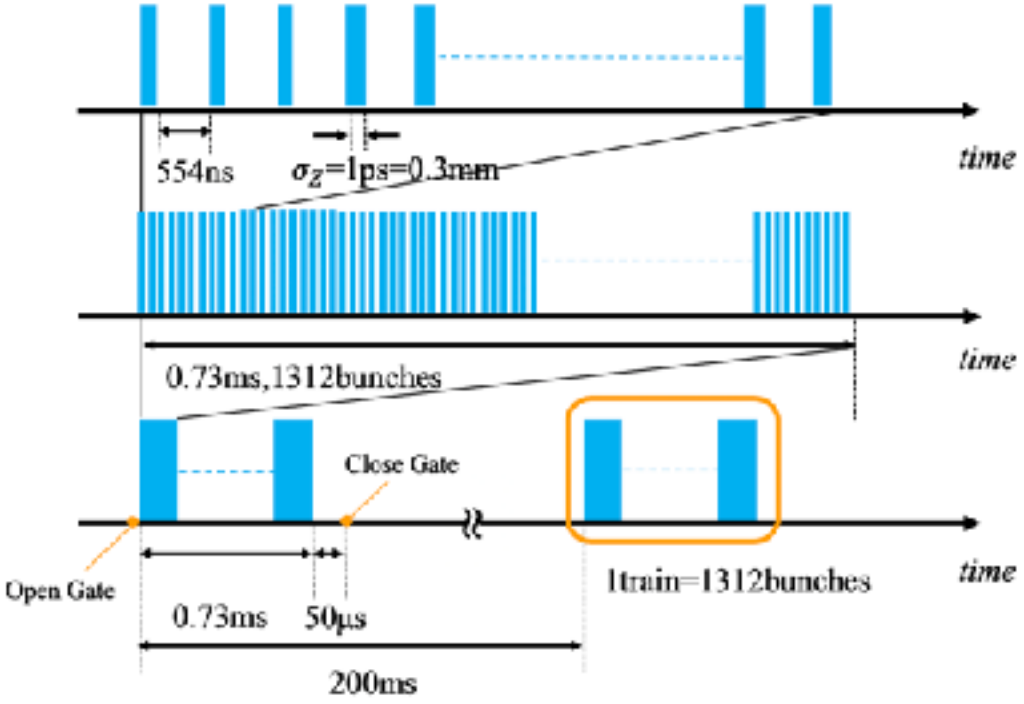
D. Arai, "Ion Problem Report (LCTPC Workpackage Meeting # 145)."

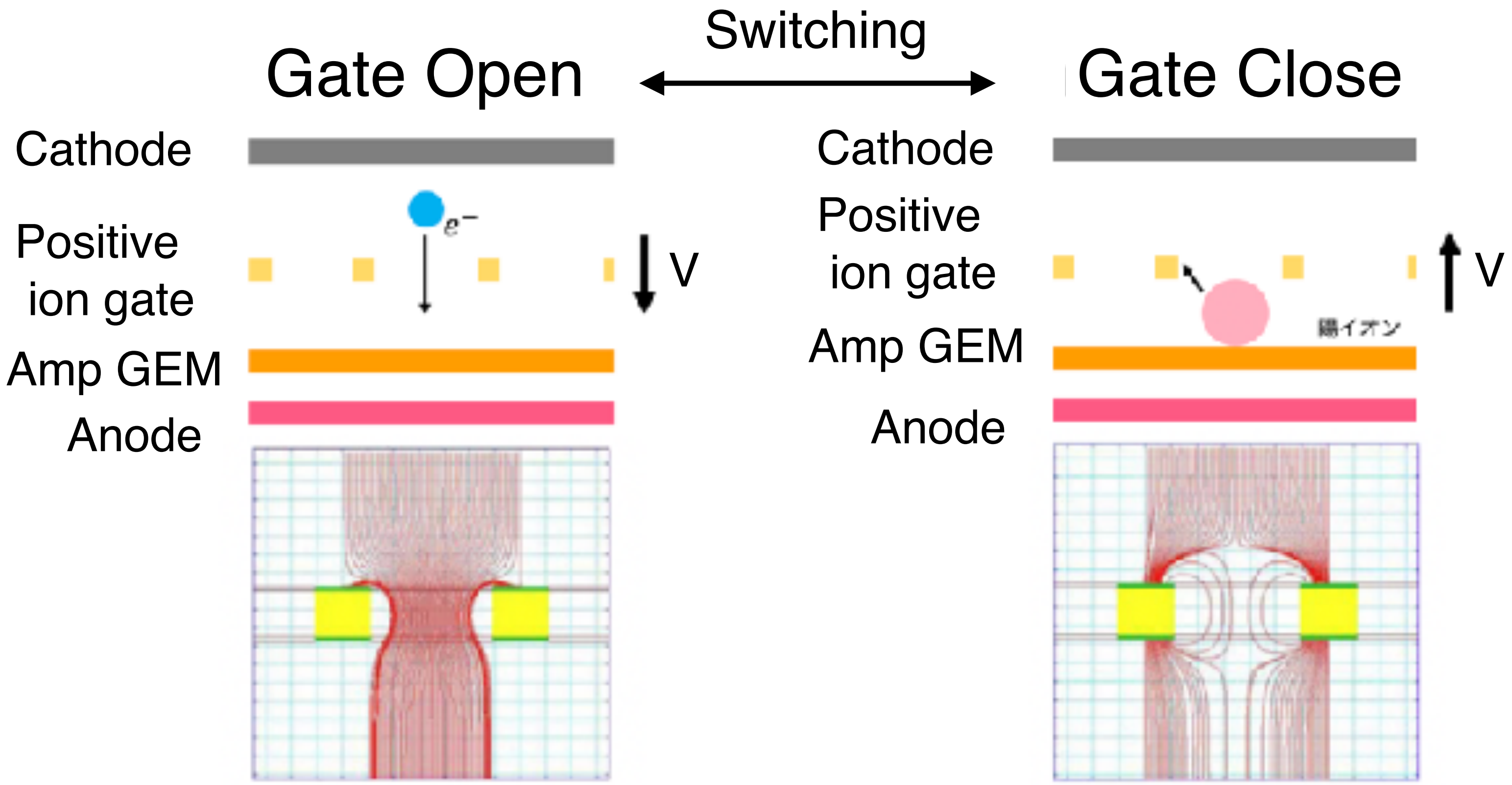
Gating Foil



Cross-section plane







Gating foil can keep small distortion in GEM

Summary

☑ What to know in the tracker

“**Two 4-vectors**” $p^\mu = (E/c, p)$, $x^\mu = (ct, x)$ + **Charge**

☑ TPC : Time Projection Chamber

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

  Strong points

  - dE/dx → Particle ID
  - 200 hits
  - Long-lived particle measurements

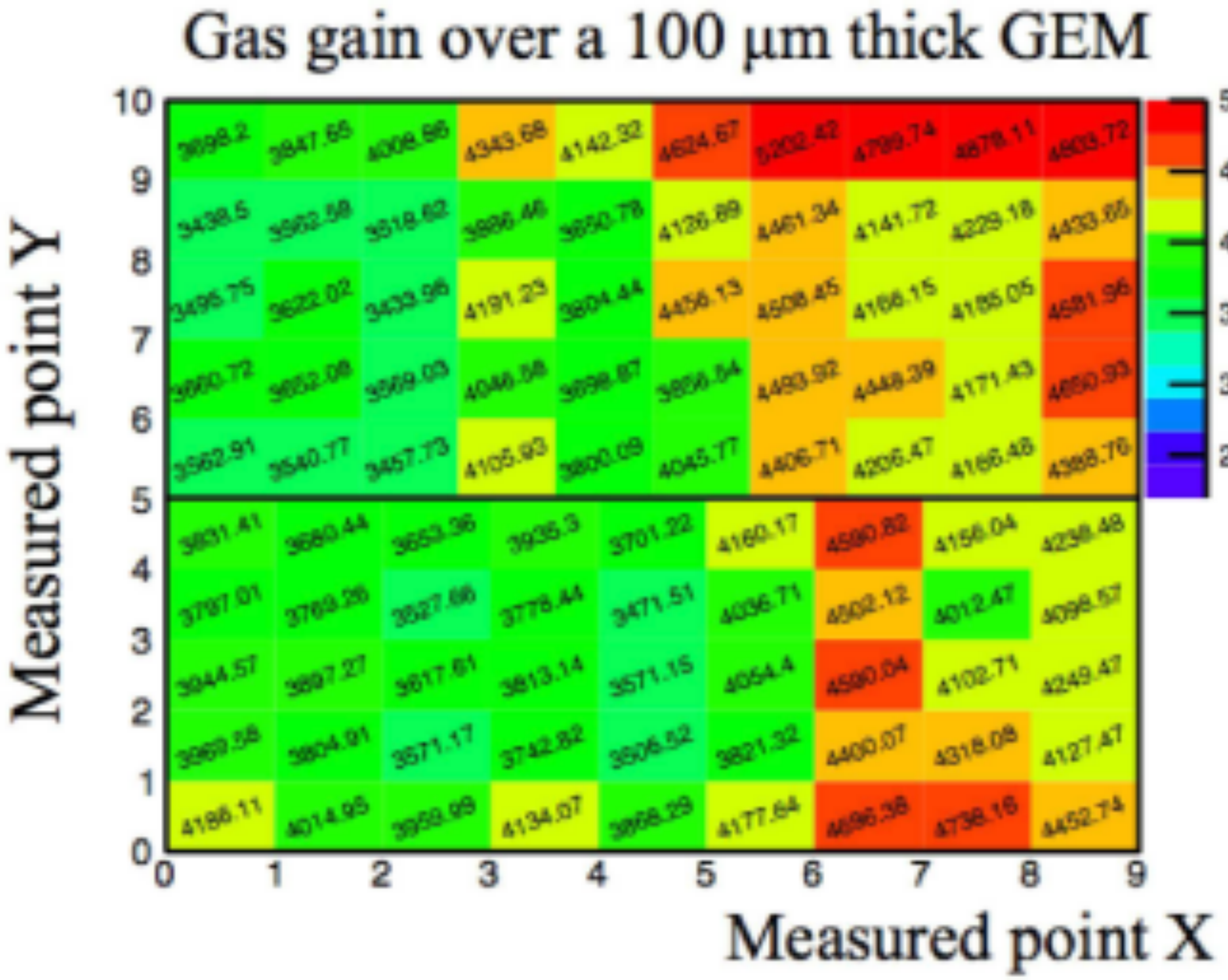
☑ TPC R&D

- Proof of principle : done → No show stopper
- Engineering stage : now
  New technology ex) Pixel readout

LCTPC Asian group

GEM gain stability

☑ Non-uniformity of the gas gain in Asian module

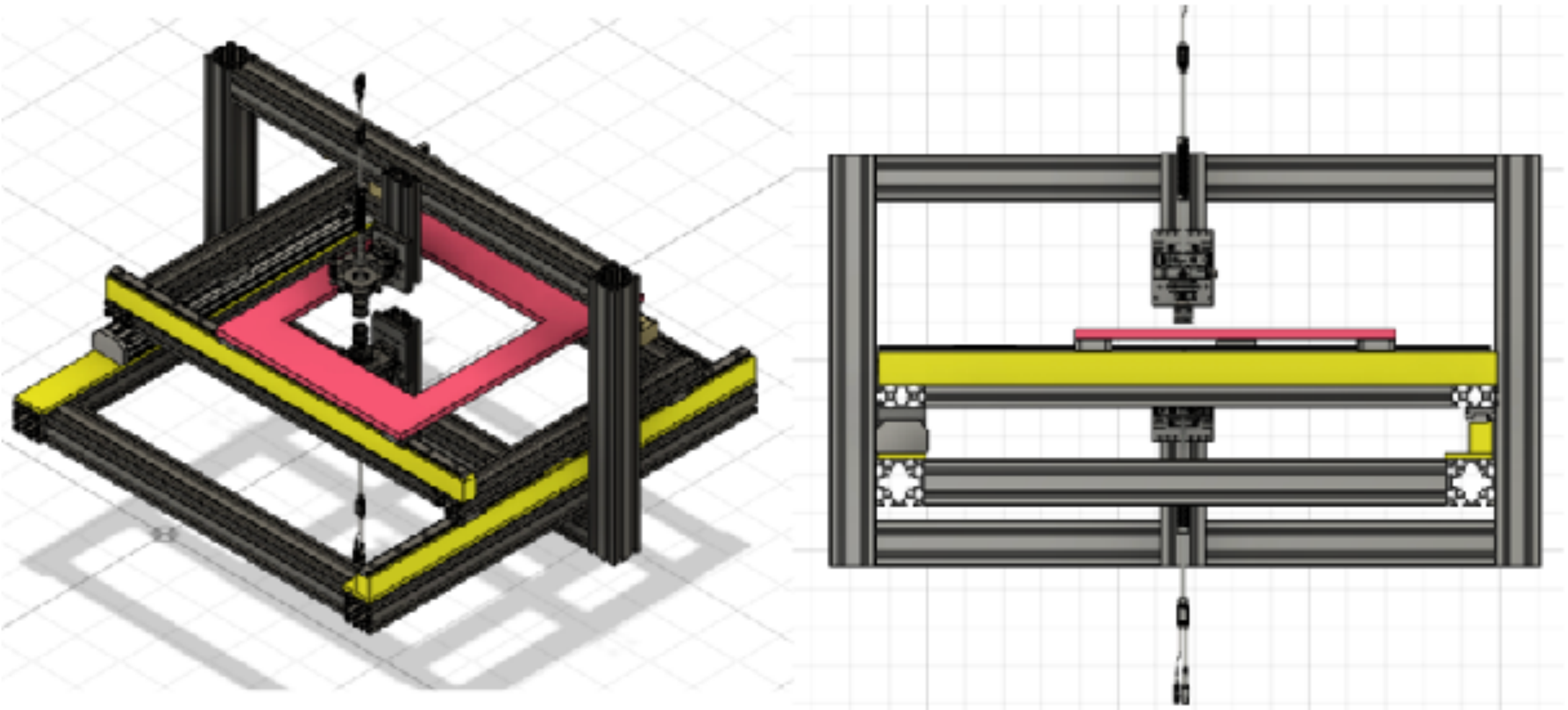


arXiv: 1701.05421

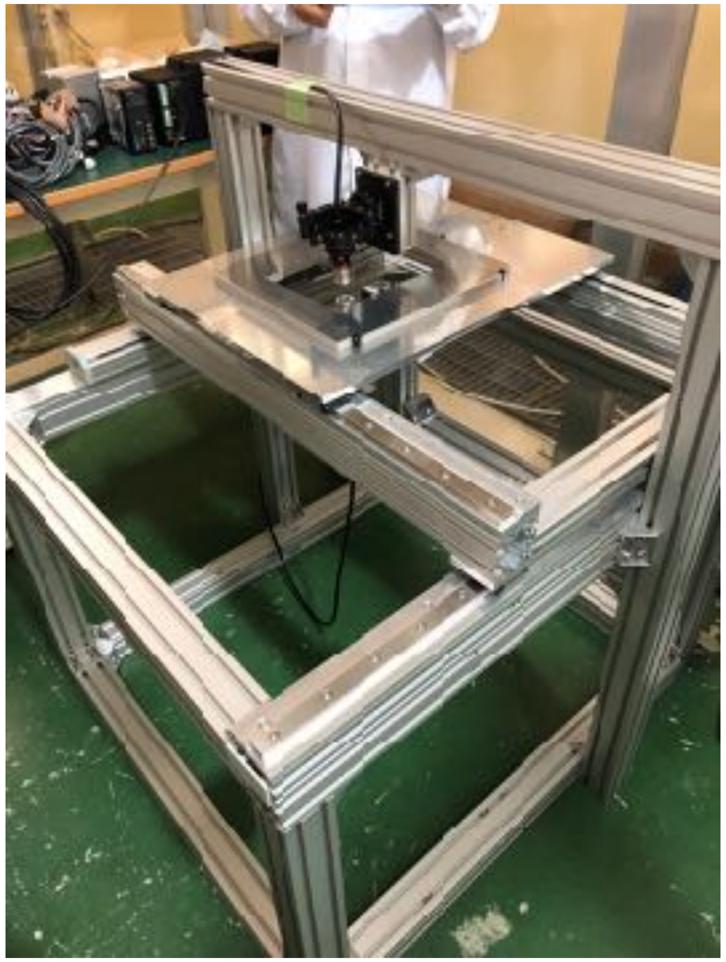
In our simulation study,
the gas gain strongly depends on **<u>the thickness of GEM</u>**

→ Preparing measurement system of GEM thickness

GEM thickness measurement



Measurement system

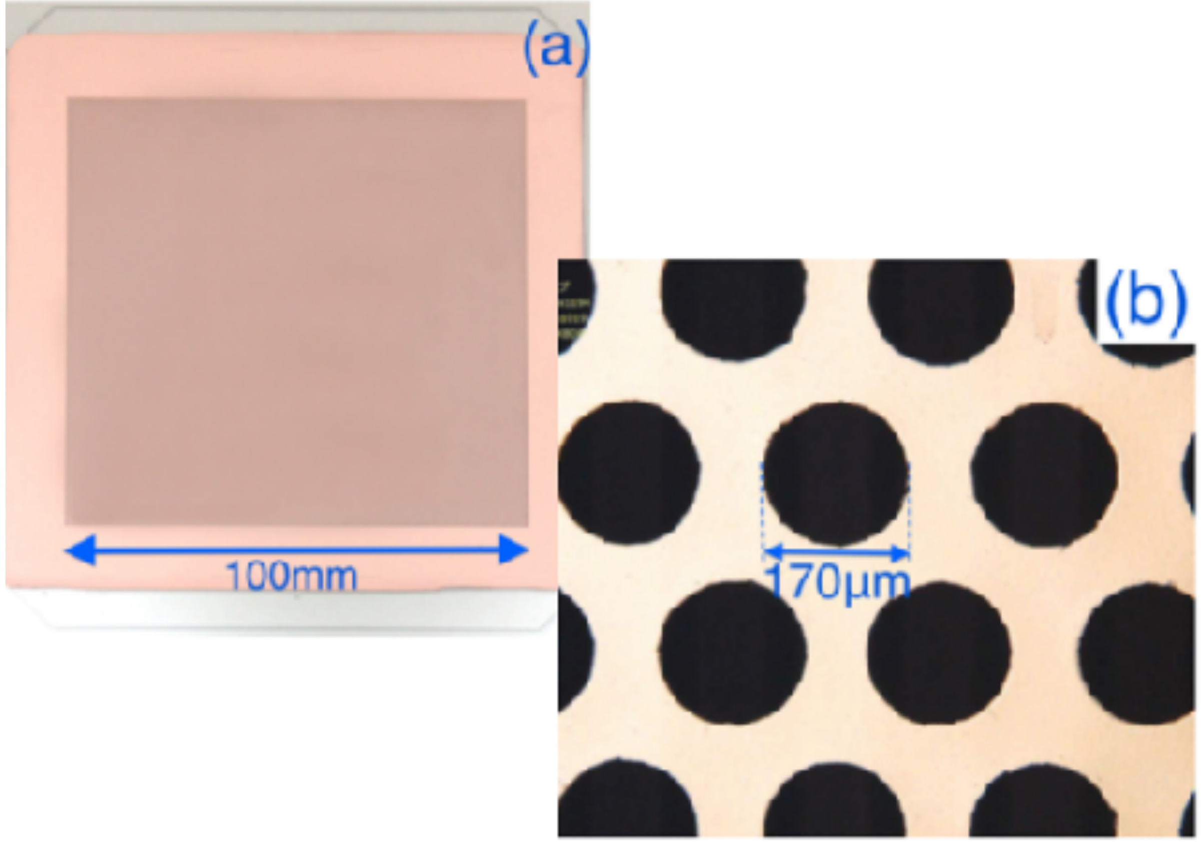


GEM insulation material

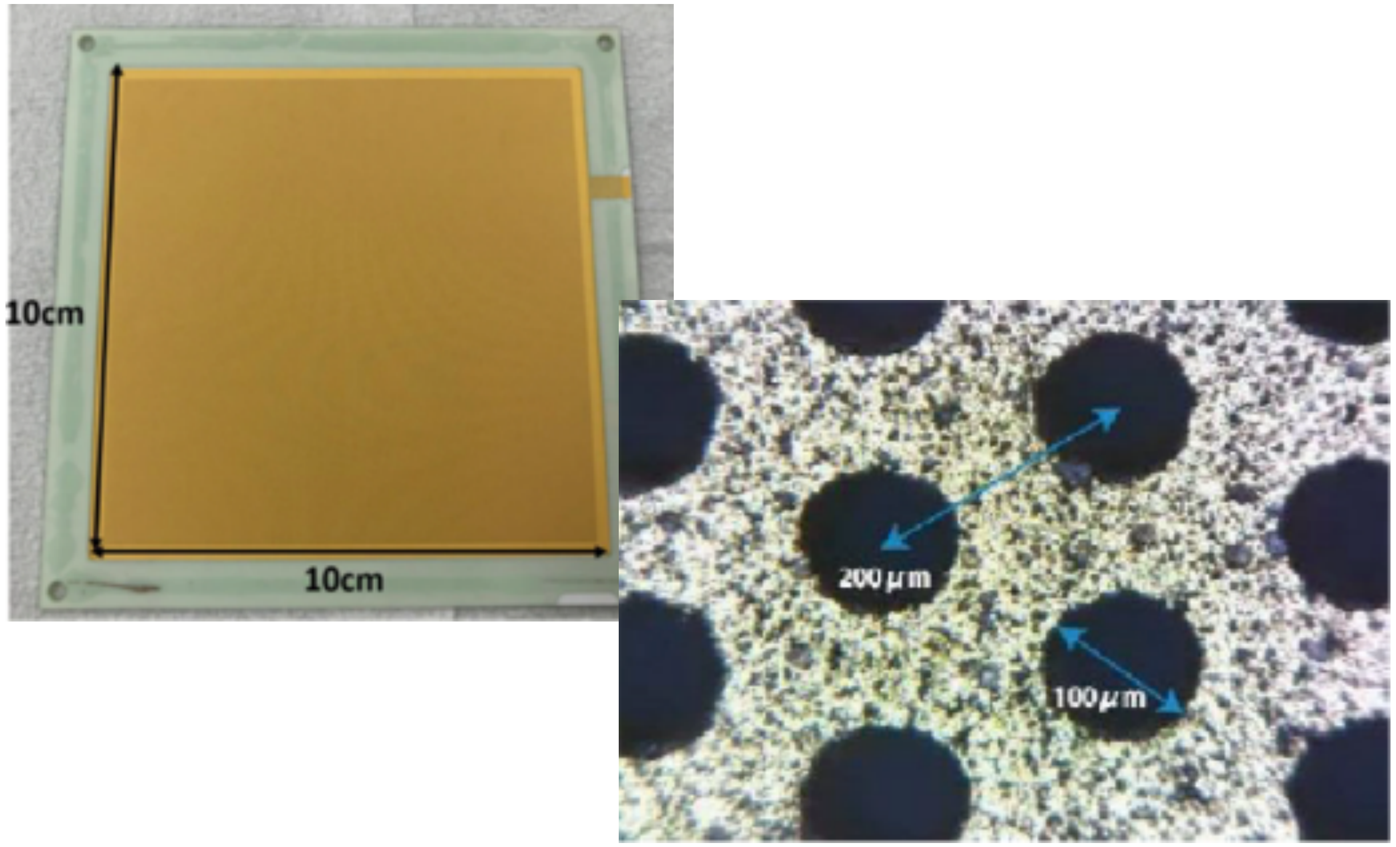
Avoid discharge in GEM ⟶ New insulation material

Glass GEM

LTCC



T.Fujiwara et al 2014 JINST 9 P 11007



Y.Kato 2020 J.Phys. Conf. Ser. 1498 012010

☑ Polyimid → glass

☑ Low Temperature Co-Fired Ceramics

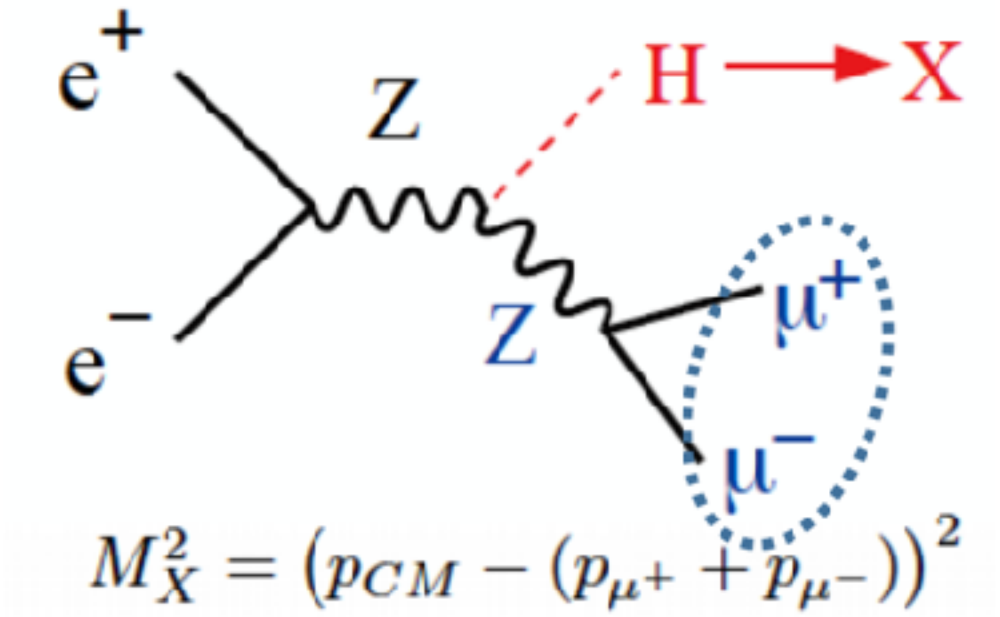
Back up

Why is TPC?
(Supplementary documents)

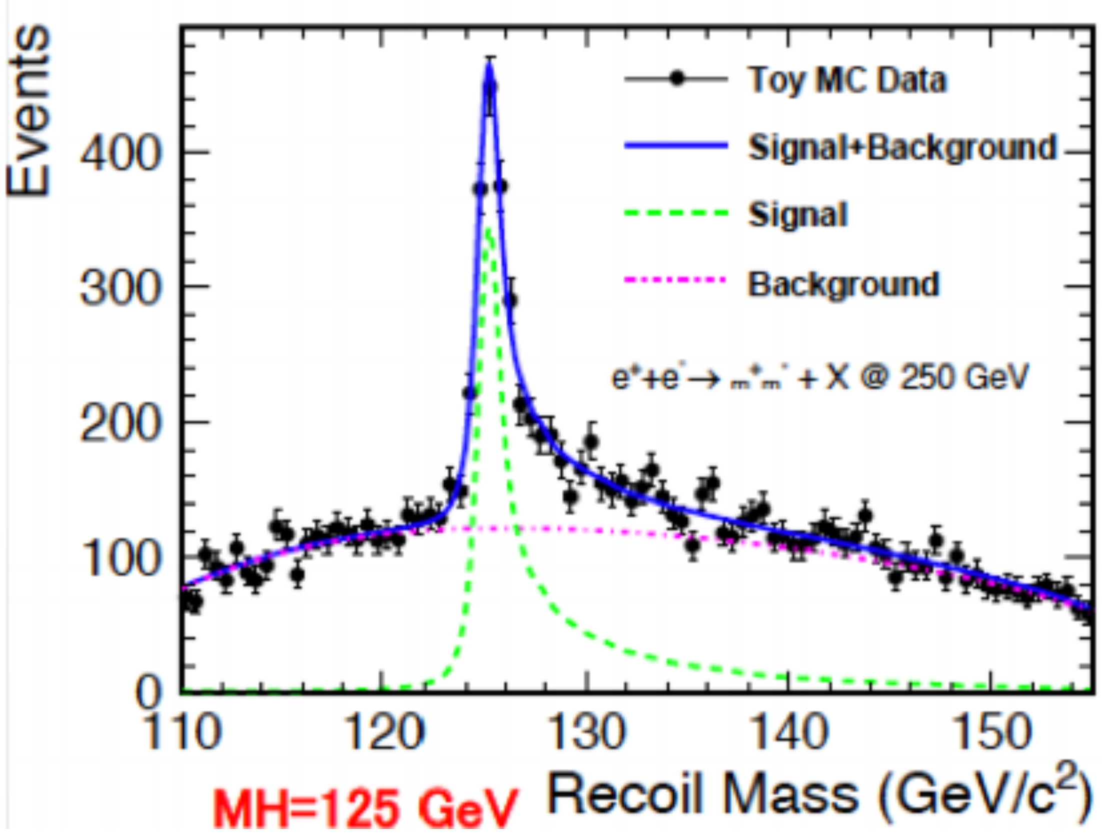
Why we need high momentum resolution?

ILC target : Higgs **precise** measurement

Higgs mass measurement by Recoil mass method



$$M_X^2 = (p_{CM} - (p_{\mu^+} + p_{\mu^-}))^2$$



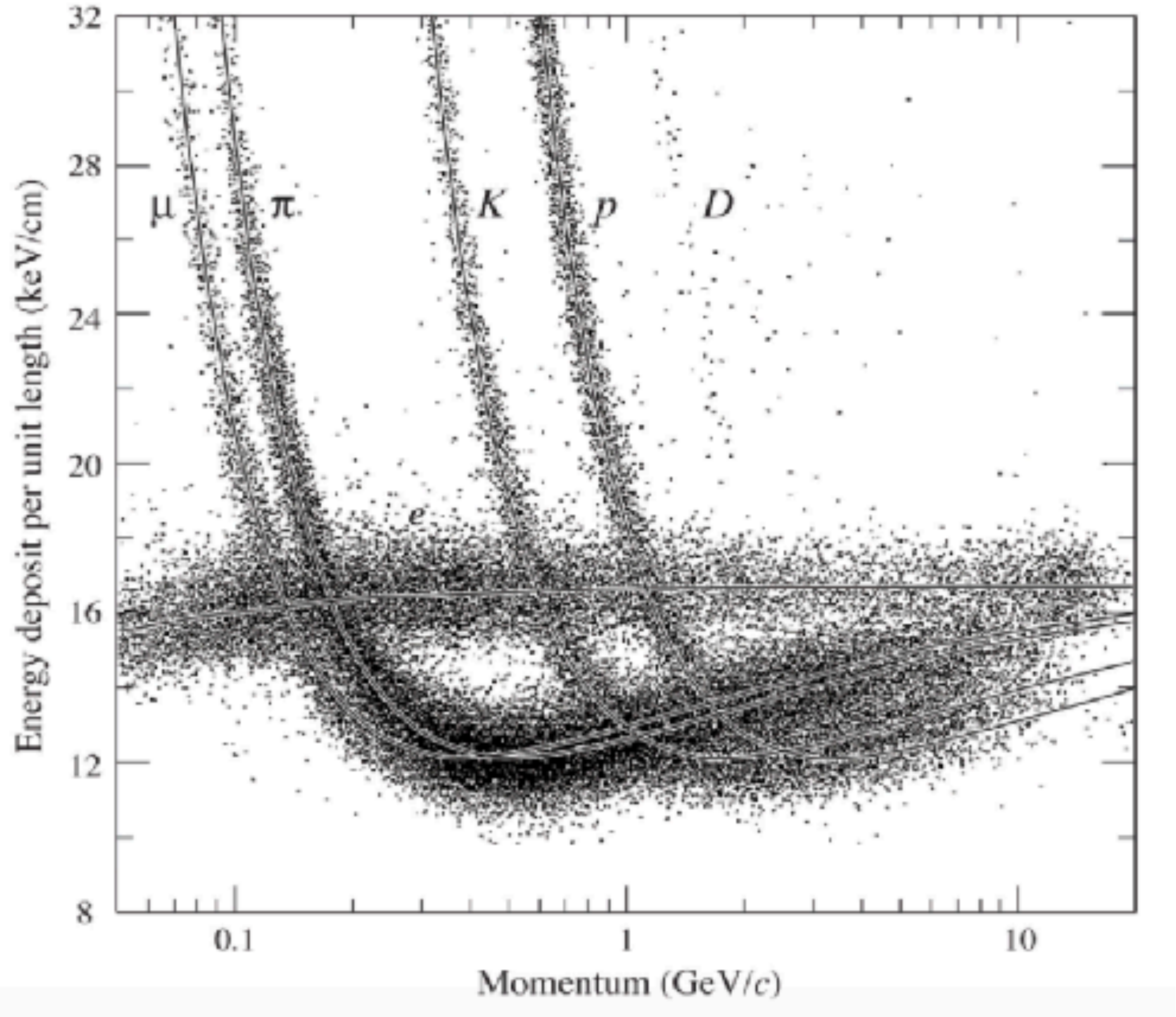
1. Know 4-vector momentum in the initial state in the case e^+e^- collider
2. Measure momentum of μ pair
3. Prove Higgs mass without measure Higgs directly

Recoil mass resolution depends on momentum resolution

→ **Essential to high momentum resolution!**

Energy deposit (dE/dx)

Charged particles lost energy when particles pass materials ⟶ dE/dx



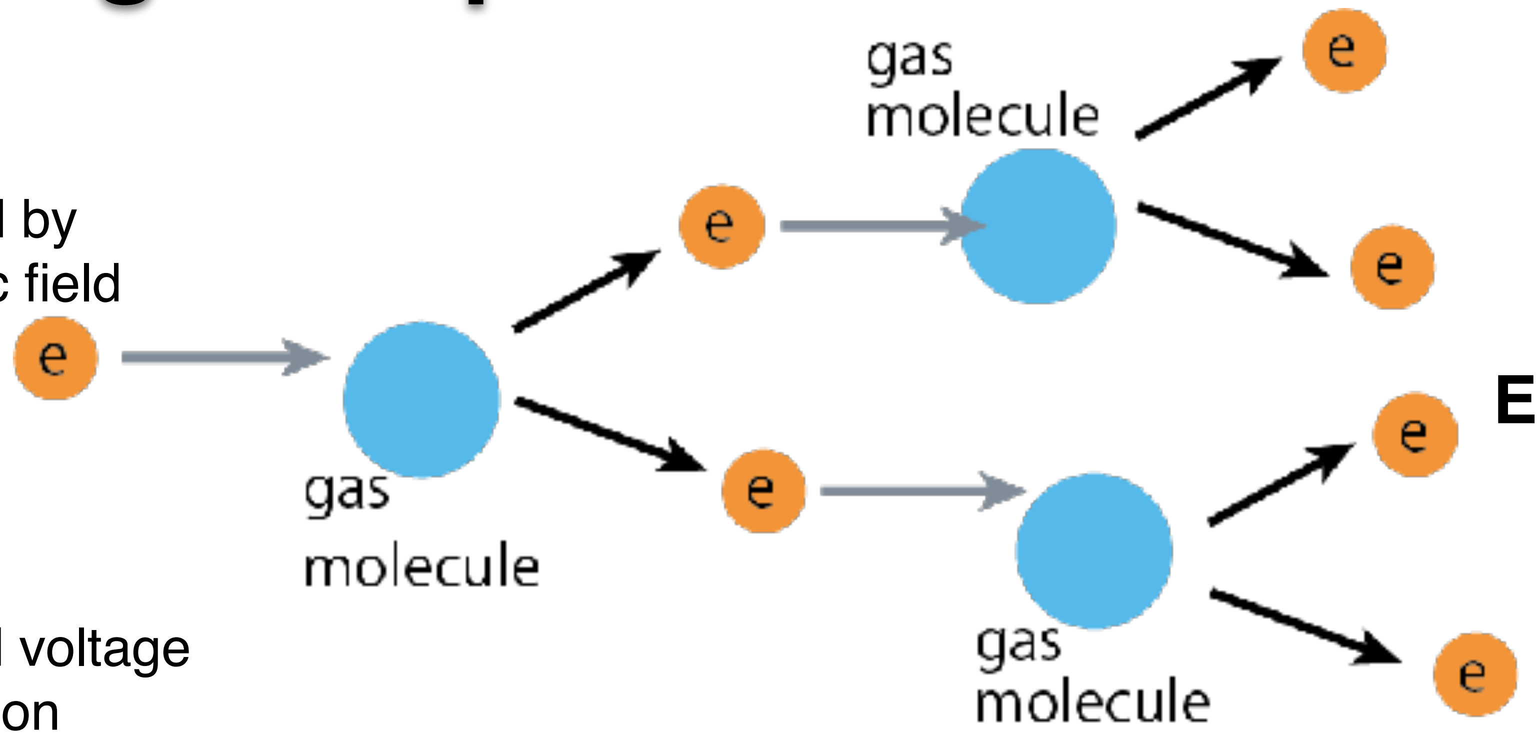
dE/dx for momentum is particle specific

⟶ **Particle identification**

ILD detector requires overall $dE/dx \sim 5\%$

Readout module of TPC
(Supplementary documents)

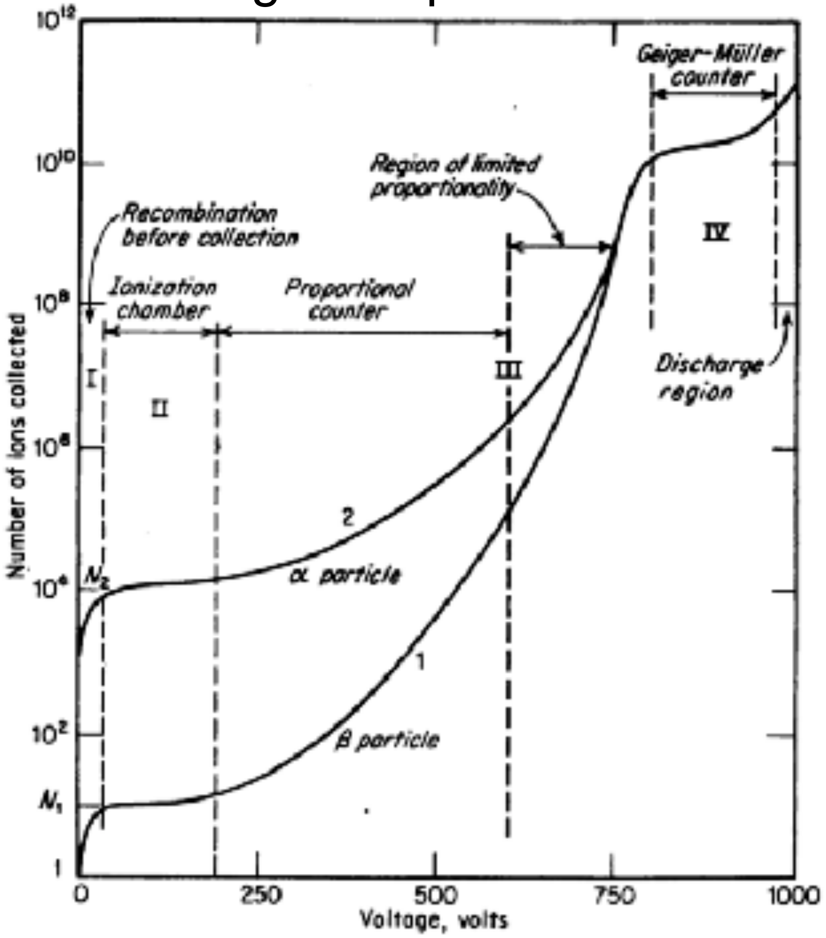
Principle of gas amplification



Accelerated by
high electric field

Electron avalanche

Dependence of applied voltage
for gas amplification



F.Sauli, “Principle of operation of multiword promotional and drift chamber”, CERN 77-09, 1977

The average increase of electrons

$$dn = n\alpha dx$$

Electrons #

Townsend coefficient

α = α(E(x)) , integrate along electric field line

$$n = n_0 \exp\left[\int_{x_1}^{x_2} \alpha \, dx\right]$$

n_0 : the number of electrons before gas amplification

Electrons are increased **exponentially**

Electronic transparency on gating foil

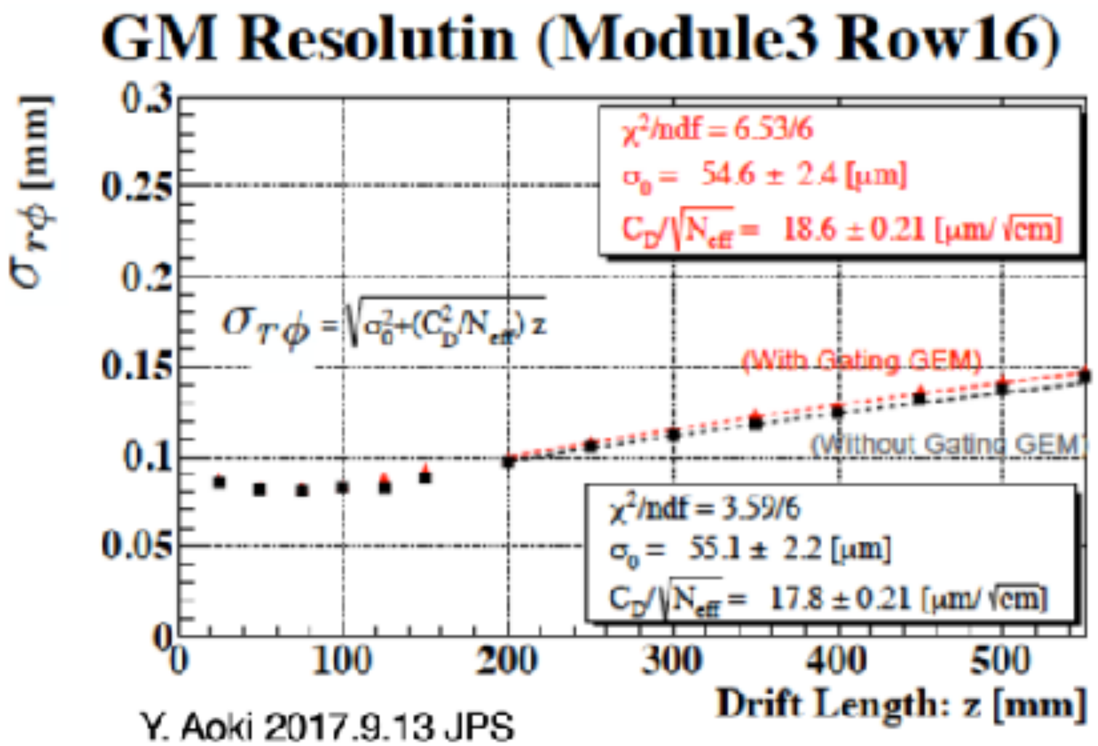
Gating foil is required ☑ Preventing positive ions
☑ Passing through electrons

→ Electronic transparency(= Optical openness) **is important**

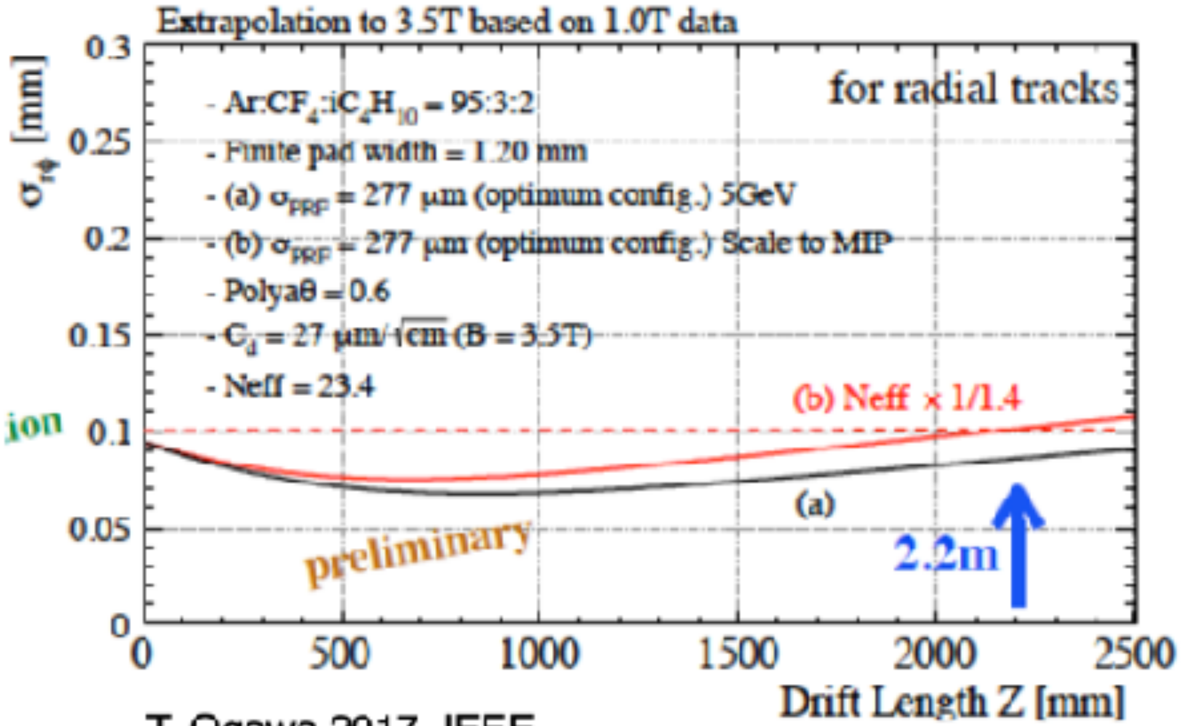
Goal of gate module

Electronic transparency > 80% ← gating foil is 82%
Rate of blocking ions ~ O(10^{-4})

Beam test result with gating foil



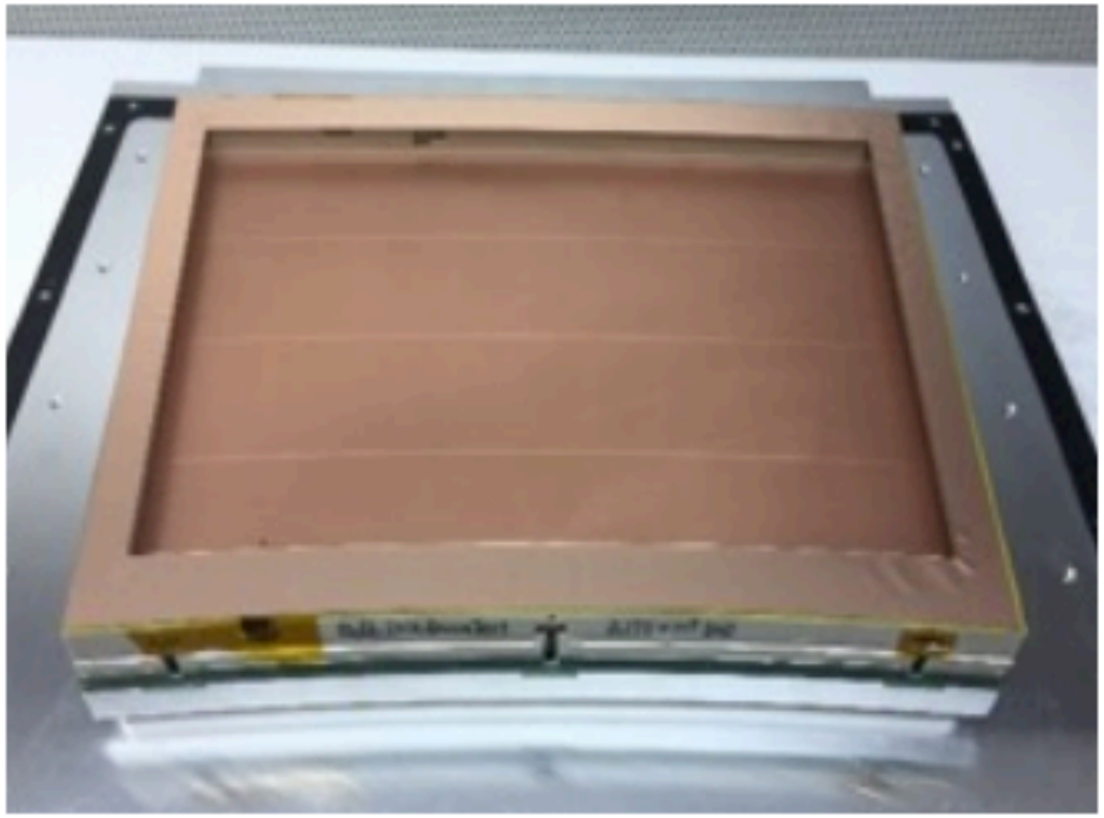
Y. Aoki 2017.9.13 JPS



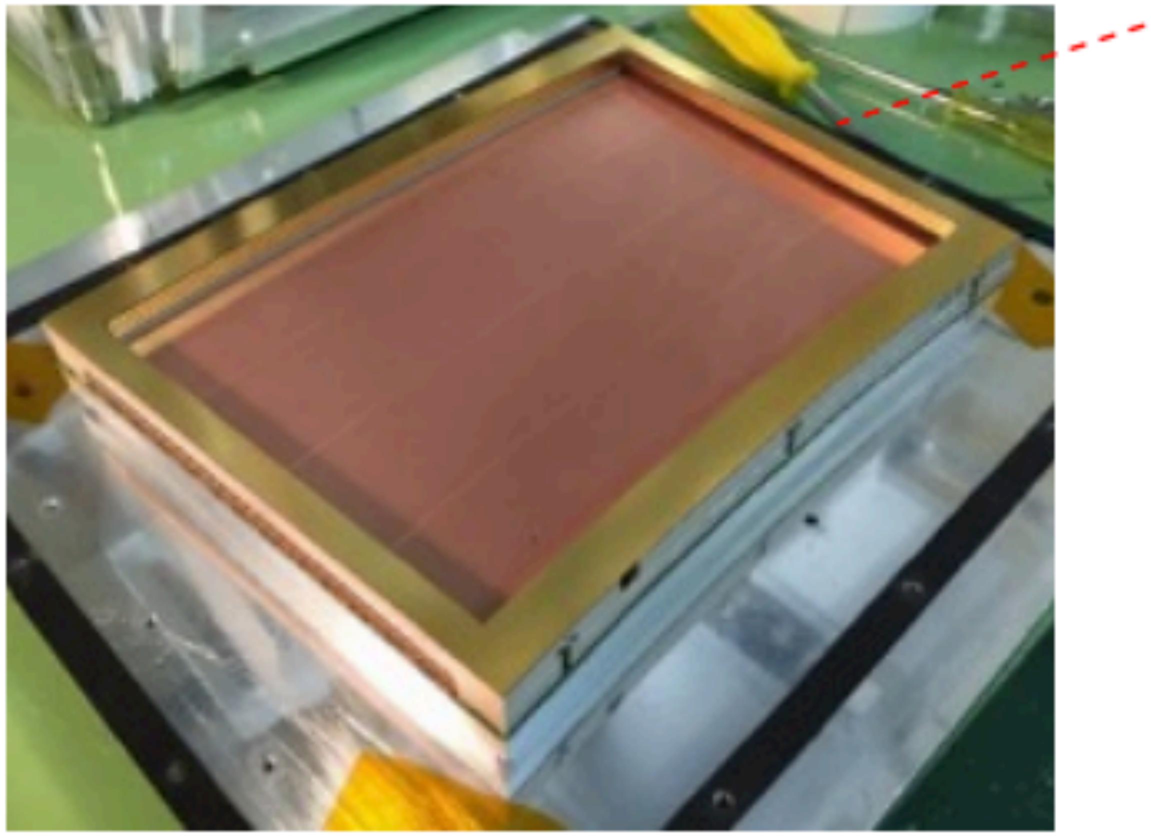
T. Ogawa 2017, IEEE

Position resolution achieved 100μm when we extrapolate to B-field 3.5T and drift length 2.2m

Gating foil (Asian GEM module)



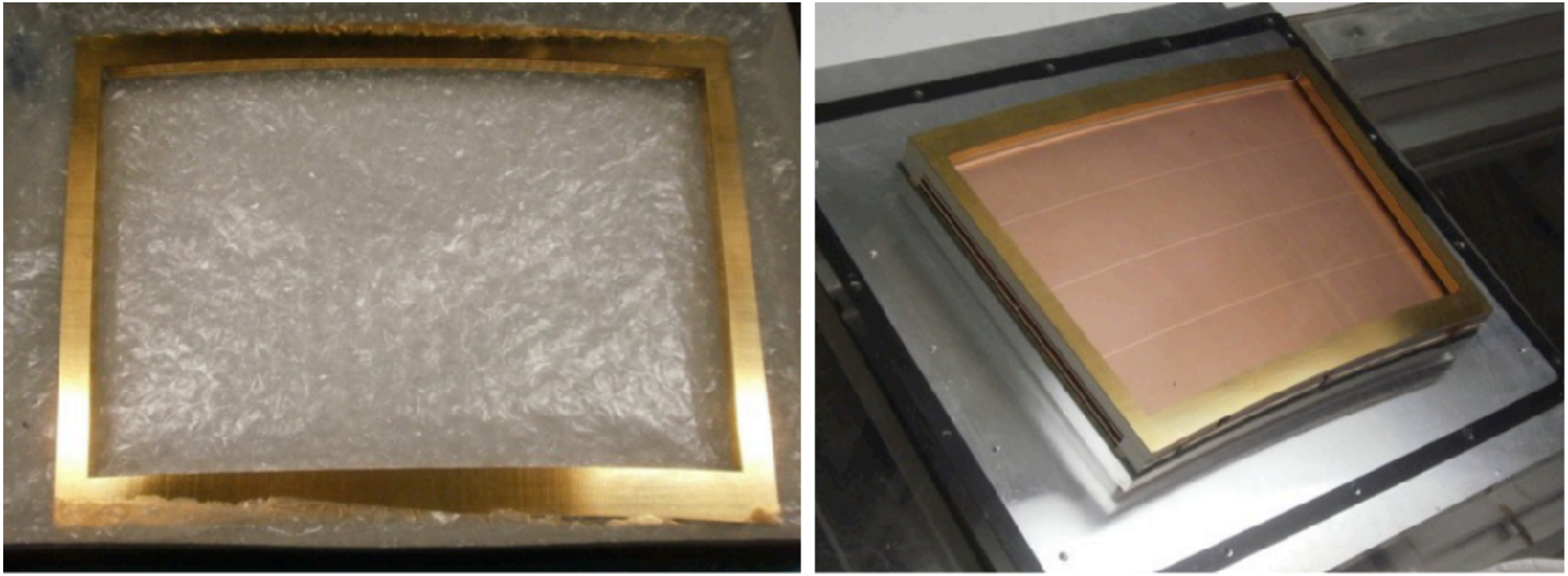
With gating foil



Without gating foil

Field Shaper

Arrange E-field

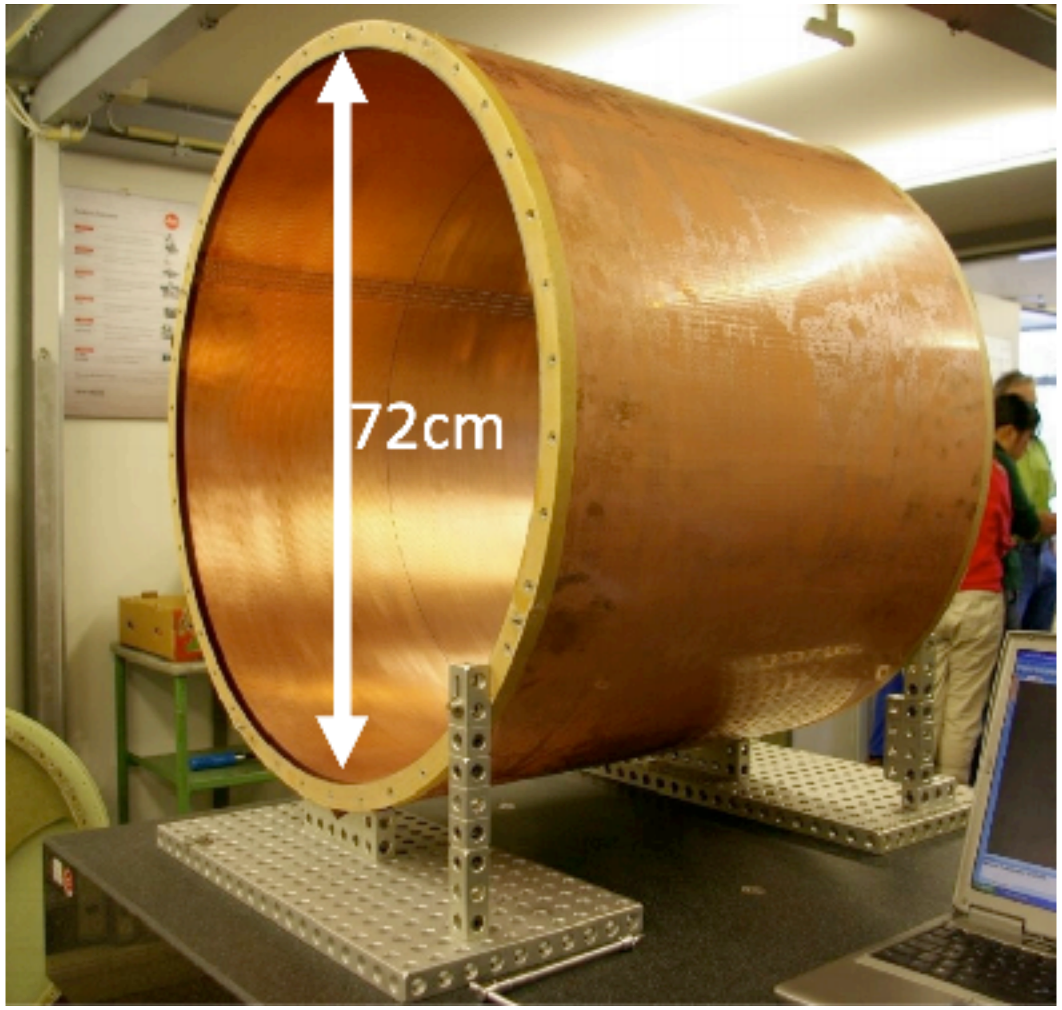


Field Cage

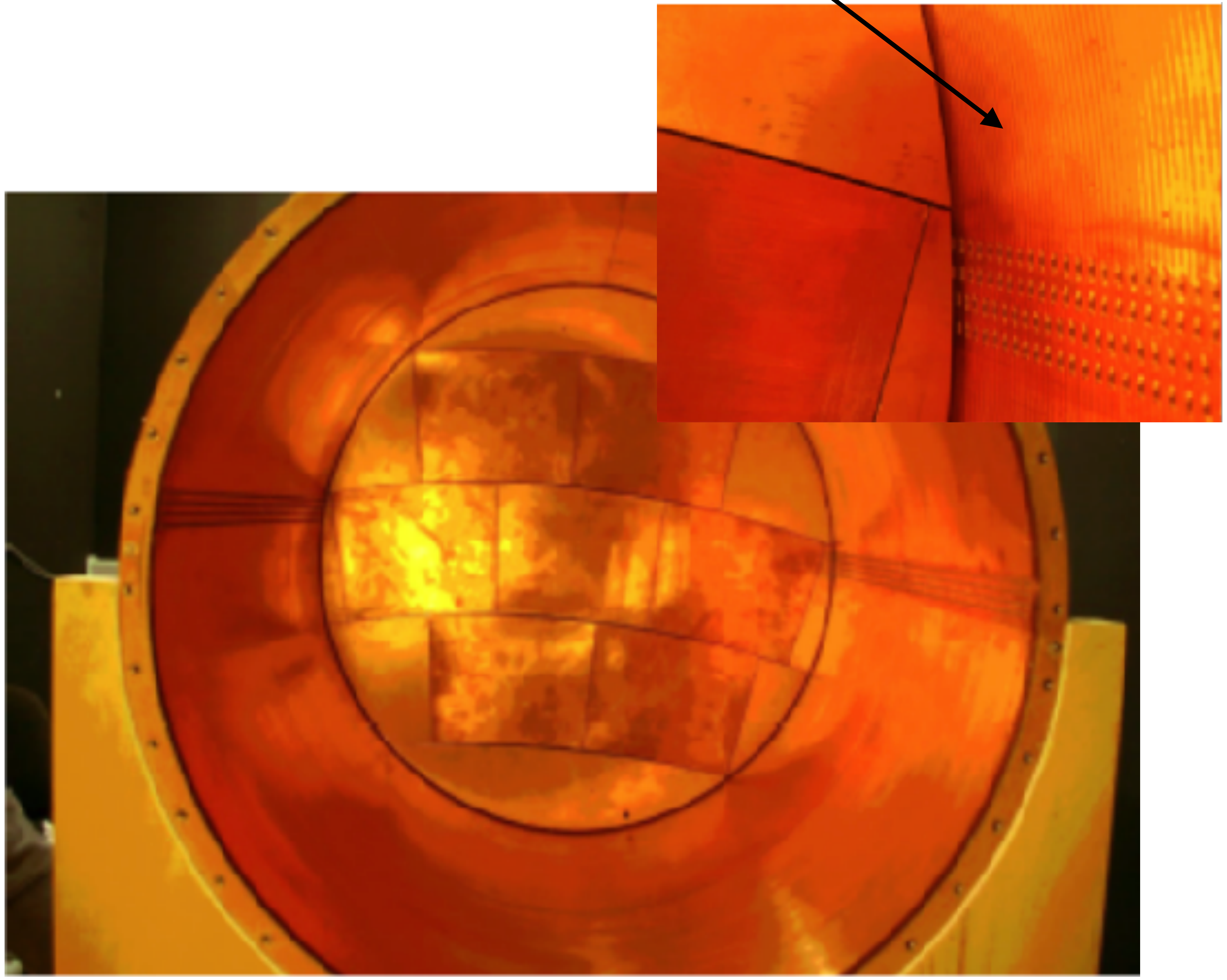
EUDET-Memo-2006-03, T.Behnke, 2006

Cylindrical Gas Vessels + Electric field shaper

To ensure the drift field quality, the inner layer of the field cage's wall will be a foil carrying **field strips** with 2.8 mm pitch.



Field cage of large prototype

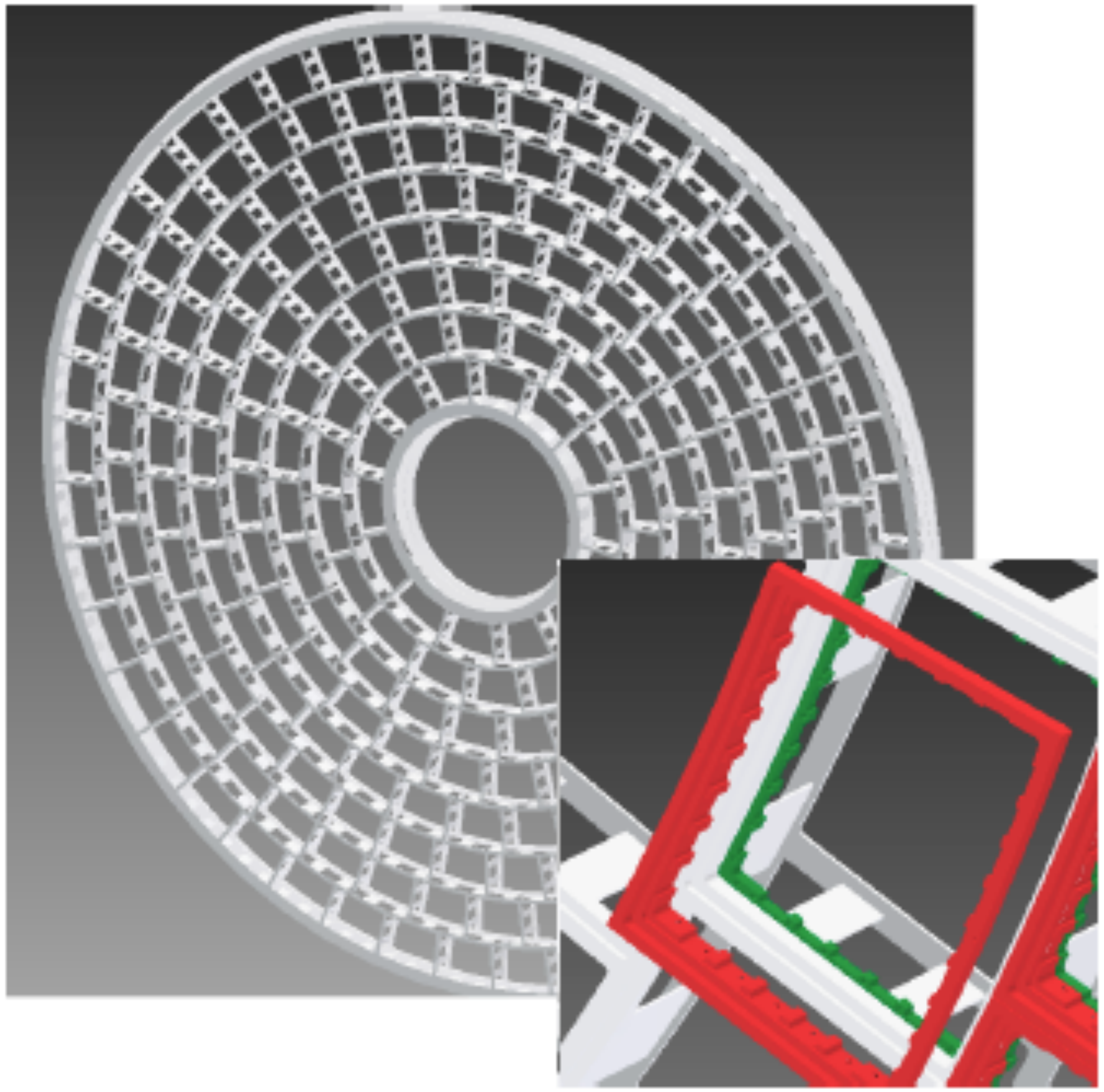


Inside of field cage of large prototype

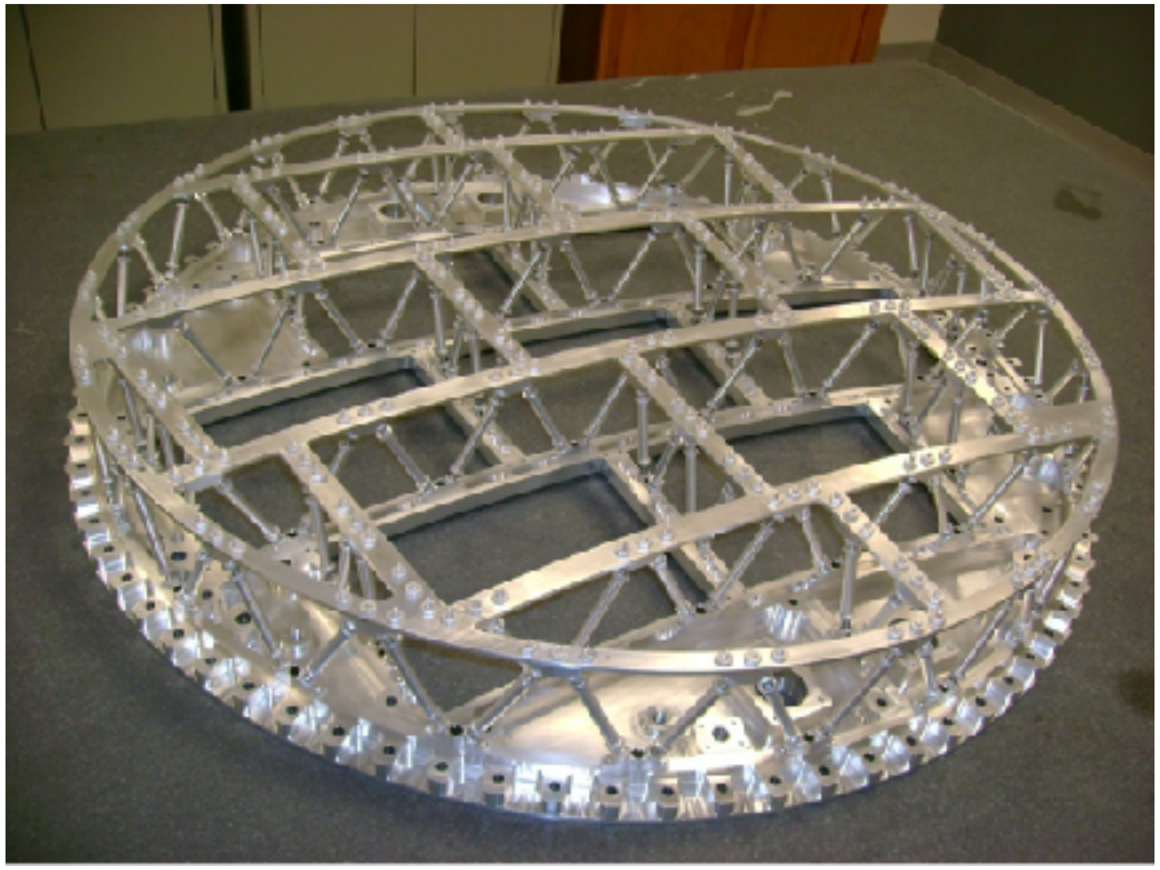
End Plate

Closes the TPC gas volume and supports the modules

“It is important that he endplate is designed to have low mass, while retaining the required mechanical and thermal stability” — *ILC TDR vol4*



End plate in TDR

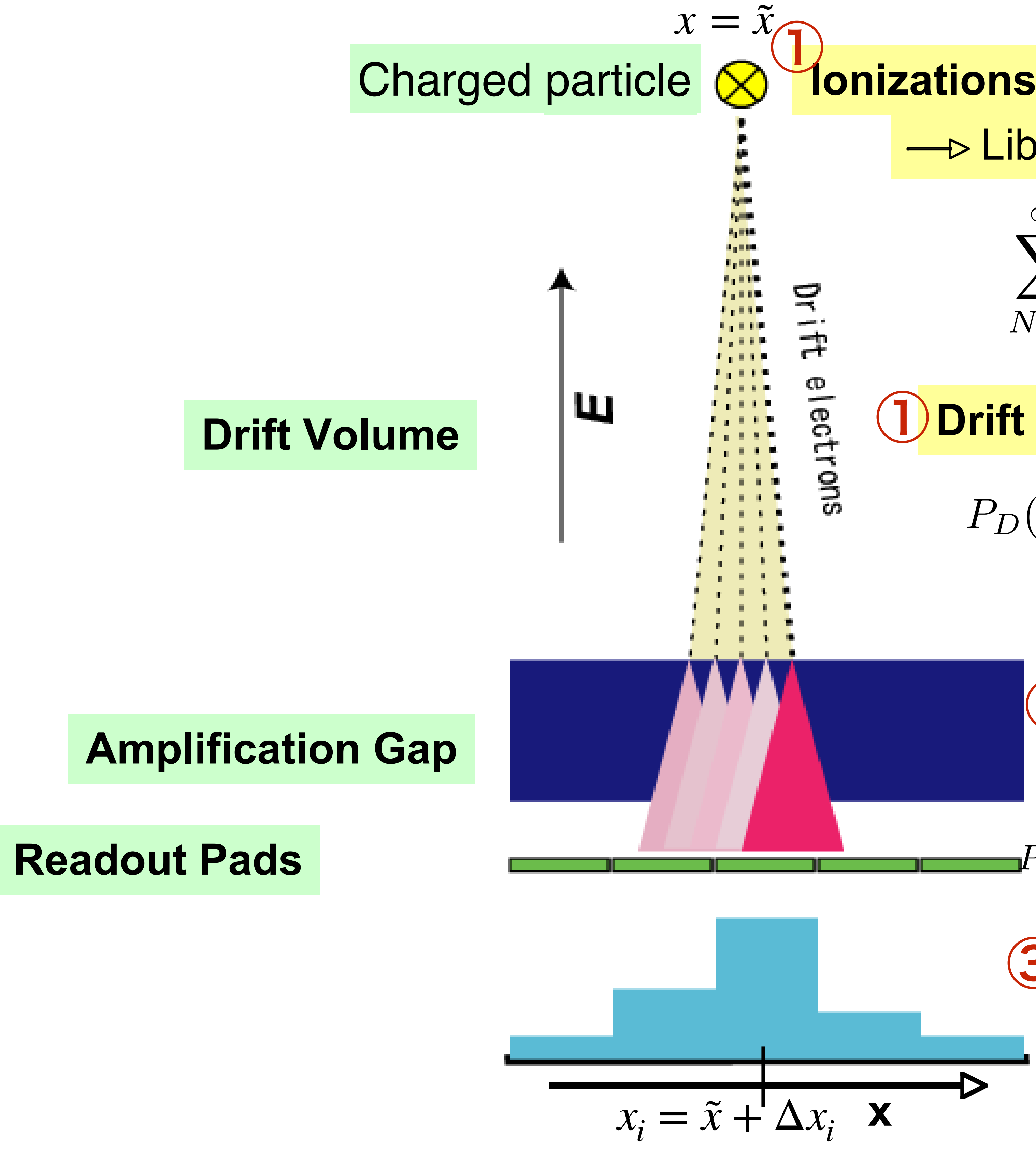


End plate in large prototype

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

Spatial resolution of TPC

Fundamental processes in coordinate measurements



Charged particle

Drift Volume

Amplification Gap

Readout Pads

① **Ionizations**

⟶ Liberation of Electrons

$$\sum_{N=1}^{\infty} P_I(N; \bar{N})$$

ϕ=0
No δ-rays

① **Drift and Diffusion**

Gaussian

$$P_D(\Delta x_i; \sigma_d) = \frac{1}{\sqrt{2\pi\sigma_d}} \exp\left[-\frac{1}{2}(\frac{\Delta x_i}{\sigma_d})\right]$$

$$\sigma_d = C_d\sqrt{z}$$

C_d : Transverse diffusion const.

② **Amplification and further Diffusion**

$$P_G\left(\frac{G}{\bar{G}}; \theta\right) = \frac{(\theta+1)^{\theta+1}}{\Gamma(\theta+1)}\left(\frac{G}{\bar{G}}\right)^{\theta} \exp\left(-(\theta+1)\left(\frac{G}{\bar{G}}\right)\right)$$

③ **Pad Response**

$\bar{G}$: Gas gain average

⟶ **Coordinate**

Ionization Statistics

For simplicity, let’s first consider the case in which the x-coordinate(arrival point) of each seed electron can be measured exactly

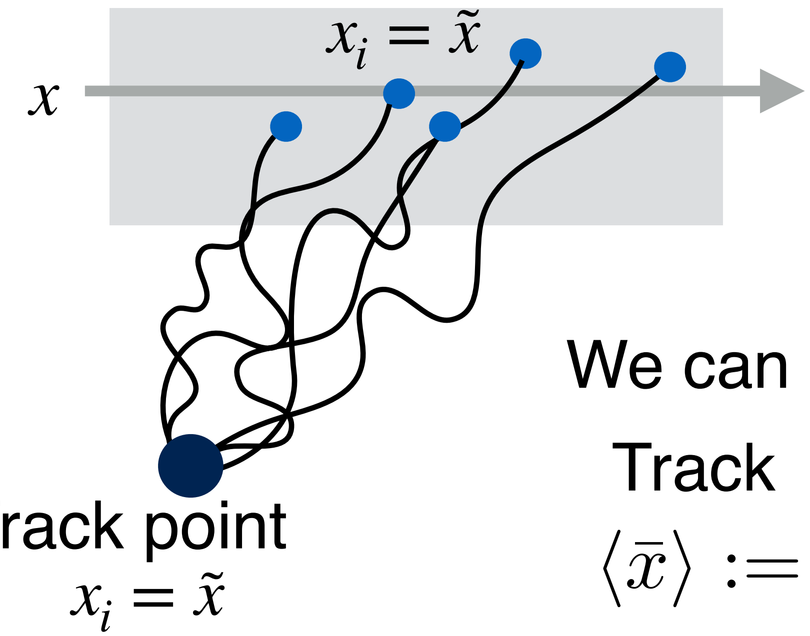
・Pad pitch → 0 ・No fluctuation of gas gain

$$P(\bar{x};\tilde{x}) = \sum_{N=1}^{\infty} P_I(N;\bar{N}) \prod_{i=1}^{N}\left(\int_{-\infty}^{+\infty} d\Delta x_i P_D(\Delta x_i;\sigma_d)\right) \delta\left(\bar{x} - \boxed{\frac{1}{N}\sum_{i=1}^{N} x_i}\right)$$

Ionization statistics

Gaussian diffusion

Ideal readout pad



$$P_D(\Delta x_i;\sigma_d) = \frac{1}{\sqrt{2\pi\sigma_d}} \exp\left[-\frac{1}{2}(\frac{\Delta x_i}{\sigma_d})\right]$$

$\sigma_d = C_d\sqrt{z}$ C_d : Transverse diffusion const.

z : Drift length

We can assume $\tilde{x} = 0$

Track

$$\langle \bar{x} \rangle := \int d\bar{x} P(\bar{x})\bar{x} = 0$$

Variance

$$\sigma_{\bar{x}}^2 := \int d\bar{x} P(\bar{x})\bar{x}^2 = \sigma_d^2 \left\langle \frac{1}{N} \right\rangle =: \sigma_d^2 \frac{1}{N_{eff}}$$

$$\boxed{N_{eff} := \frac{1}{\langle 1/N \rangle} < \langle N \rangle}$$

Spatial resolution depends on
the inverse of the average of its inverse!

Gas gain fluctuation

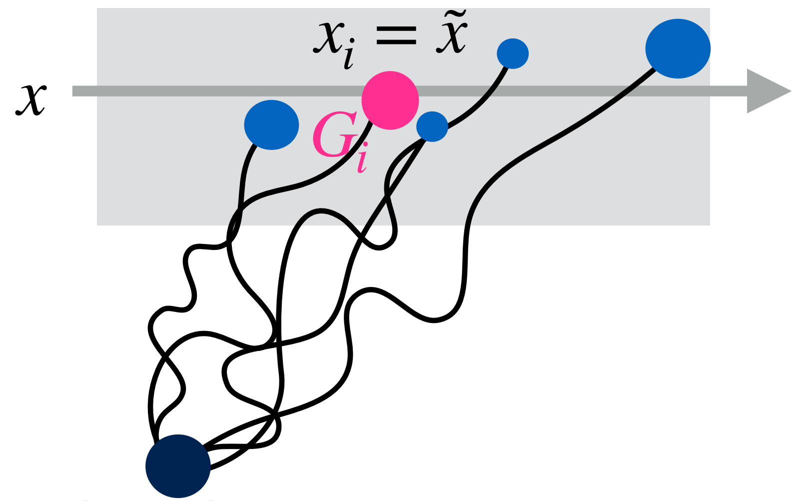
Now include gas gain fluctuation.

- Pad pitch → 0
- Gas gain fluctuation G_i

$$P(\bar{x};\tilde{x}) = \sum_{N=1}^{\infty} P_I(N;\bar{N}) \prod_{i=1}^{N} \left[\int_{-\infty}^{+\infty} d\Delta x_i P_D(\Delta x_i;\sigma_d) \times \int d\left(\frac{G_i}{\bar{G}}\right) P_G\left(\frac{G_i}{\bar{G}};\theta\right) \right] \delta\left(\bar{x} - \boxed{\frac{\sum_{i=1}^{N} G_i x_i}{\sum_{i=1}^{N} G_i}}\right)$$

Gas gain fluctuation

Gain-weighted mean



We can still assume $\tilde{x} = 0$

Track $\quad \langle \bar{x} \rangle := \int d\bar{x} P(\bar{x}) \bar{x} = 0$

Variance $\quad \sigma_{\bar{x}}^2 := \int d\bar{x} P(\bar{x}) \bar{x}^2 \approx \sigma_d^2 \left\langle \frac{1}{N} \right\rangle \left\langle \left(\frac{G}{\bar{G}}\right)^2 \right\rangle =: \sigma_d^2 \frac{1}{N_{eff}}$

We used $\sum_{i=1}^{N} G_i \approx N\bar{G}$ (If N is large enough)

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

gas gain fluctuation therefore further reduces the effective number of electrons

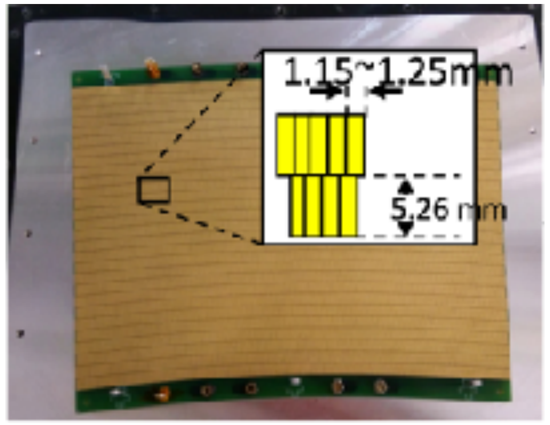
Finite Pad Pitch

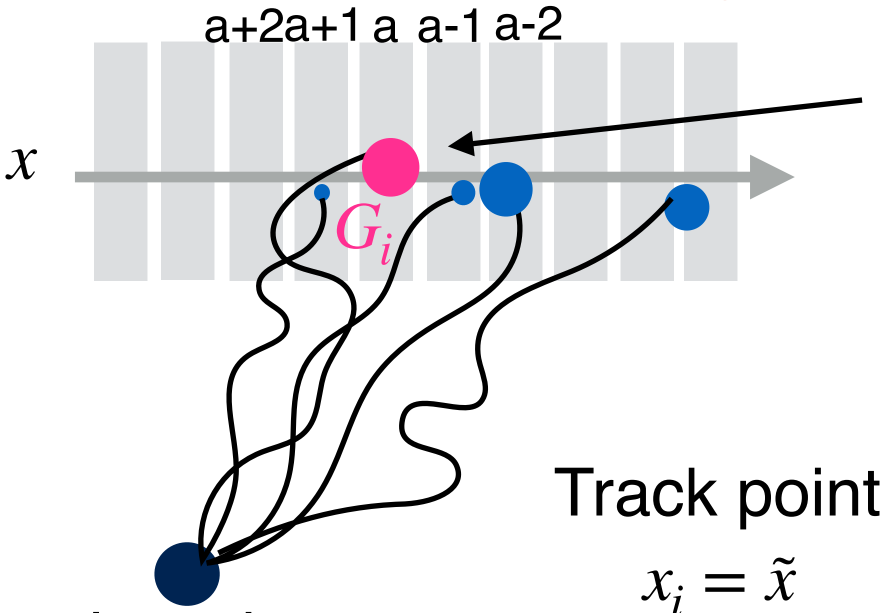
Let's finally consider the effect of finite pad pitch!

- Finite pad pitch
- Gas gain fluctuation G_i

We can no longer assume $\tilde{x} = 0$ because of breaking of translational invariance

→Specify the track position relative to the pad center.





$$x_i = \underline{\tilde{x}} + \Delta x_i$$

Track position

Diffusion $\langle (\Delta x_i)^2 \rangle = \sigma_d^2 = C_d^2 z$

Track point

$x_i = \tilde{x}$

Electric charge on a-th pad

$$Q_a = \sum_i G_i \underline{F_a(\bar{x} + \Delta x_i)} + \Delta Q_a$$

Electronic noise $\langle (\Delta Q_a)^2 \rangle = \sigma_E^2$

Gas gain for i-th seed electron

Normalized pad response function for a-th pad $\sum_a F_a(\bar{x} + \Delta x_i) = 1$

The charge centroid method

Assume pad pitch is w

$$\bar{x} = \sum_a Q_a(aw) / \sum_a Q_a$$

Probability distribution Function for this method

$$P(\bar{x};\tilde{x}) = \sum_{N=1}^{\infty} P_I(N;\bar{N}) \prod_{i=1}^{N} \left[\int_{-\infty}^{+\infty} d\Delta x_i P_D(\Delta x_i;\sigma_d) \int d\left(\frac{G_i}{\bar{G}}\right) P_G\left(\frac{G_i}{\bar{G}};\theta\right) \right] \times \prod_a \left[\int d\Delta Q_a P_E(\Delta Q_a;\sigma_E) \int dQ_a \delta\left(Q_a - \boxed{\sum_{i=1}^{N} G_i F_a(x_i) - \Delta Q_a} \right) \right] \times \delta\left(\bar{x} - \boxed{\frac{\sum_a Q_a(aw)}{\sum_a Q_a}} \right)$$

Ionization statistics

Gaussian diffusion

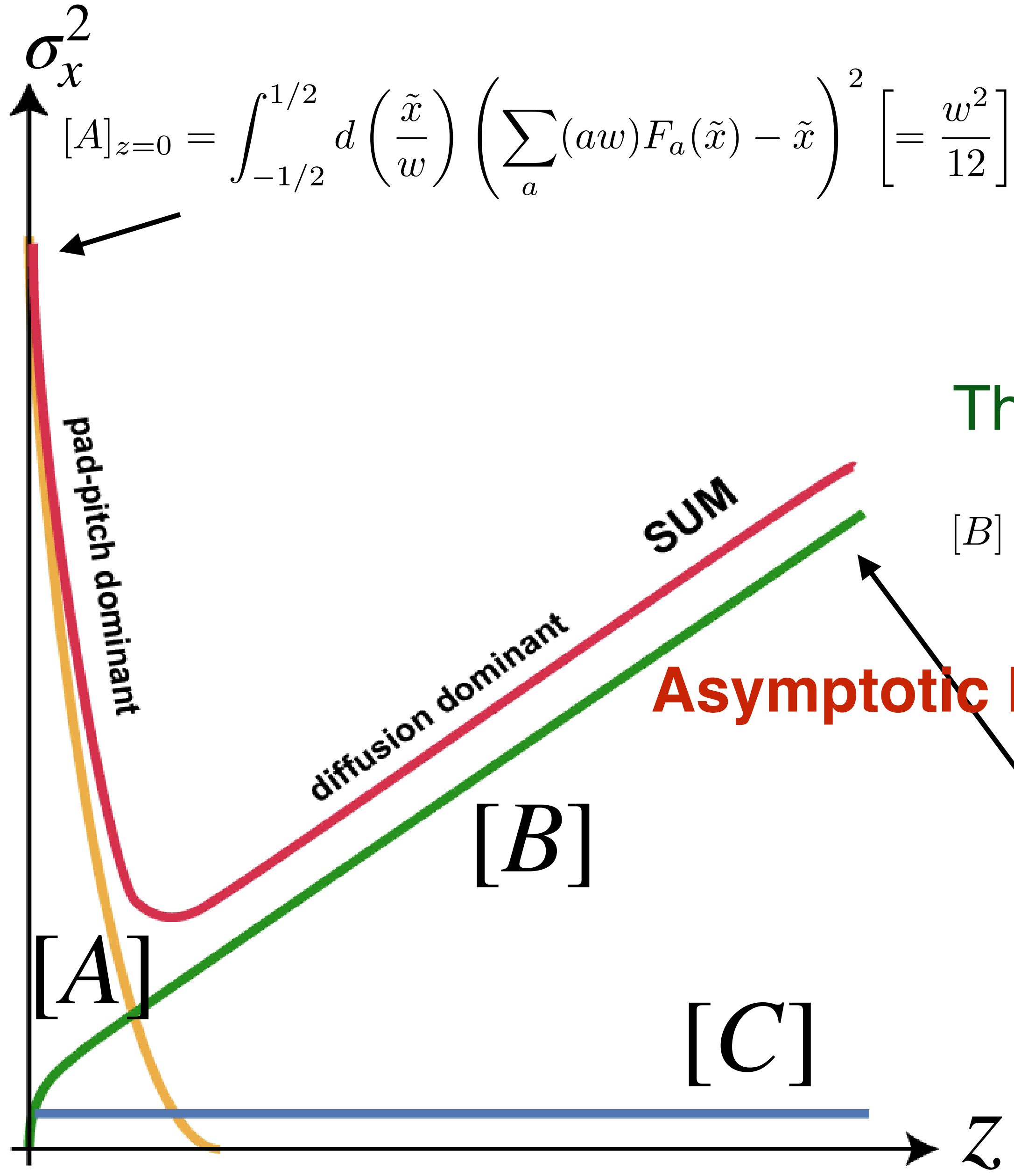
Gas gain fluctuation

Electronic noise

Variance of charge centroid

We define $\sigma_{\tilde{x}}^2 := \boxed{\int_{-1/2}^{1/2} d\left(\frac{\tilde{x}}{w}\right)} \int d\bar{x} P(\bar{x};\tilde{x})(\bar{x}-\tilde{x})^2$ Average over track position $\tilde{x}$ in the pad pitch w

Integrate over $\Delta Q_a, \Delta x_i, \frac{G_i}{\bar{G}}$ and average over N ➡ $\sigma_x^2 = [A] + \frac{1}{N_{eff}}[B] + [C]$



$$[A]_{z=0} = \int_{-1/2}^{1/2} d\left(\frac{\tilde{x}}{w}\right)\left(\sum_a (aw)F_a(\tilde{x}) - \tilde{x}\right)^2 \left[= \frac{w^2}{12}\right]_{\sigma_{PRF} \ll w}$$

Systematic error of the charge centroid method

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

Purely geometric effect

The diffusion term(Gas gain fluctuation & finite pad pitch)

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

Asymptotic behavior

$\sigma_d/w \gg 1$ (long drift distance) Hodscope effect

$$\sigma_x^2 \approx \frac{1}{N_{eff}}\left[[A]_{z=0} + \sigma_d^2\right]\left[= \frac{1}{N_{eff}}\left(\frac{w^2}{12} + \sigma_d^2\right)\right]_{\sigma_{PRF} \ll w}$$

Electric noise

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

Spatial resolution

Drift distance

The number of effective track electrons

$$\sigma_x = \sigma_x(z; w, C_d, N_{eff}, F_a)$$

Pad pitch

Diffusion const.

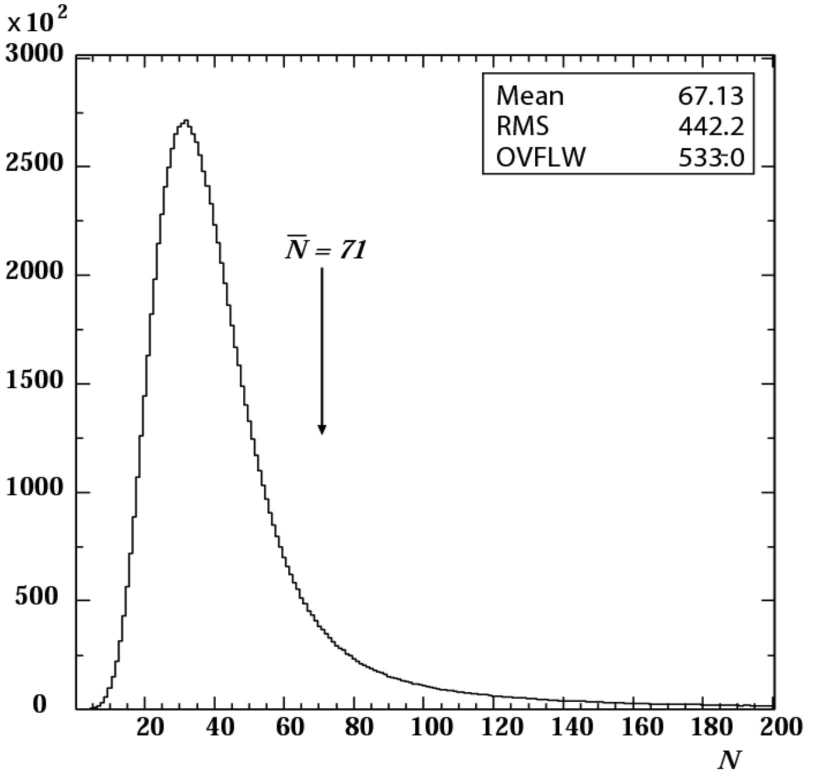
Pad responce function

- We can **analytically estimate** the spatial resolution.
- We can improve the spatial resolution based on theoretical basis!

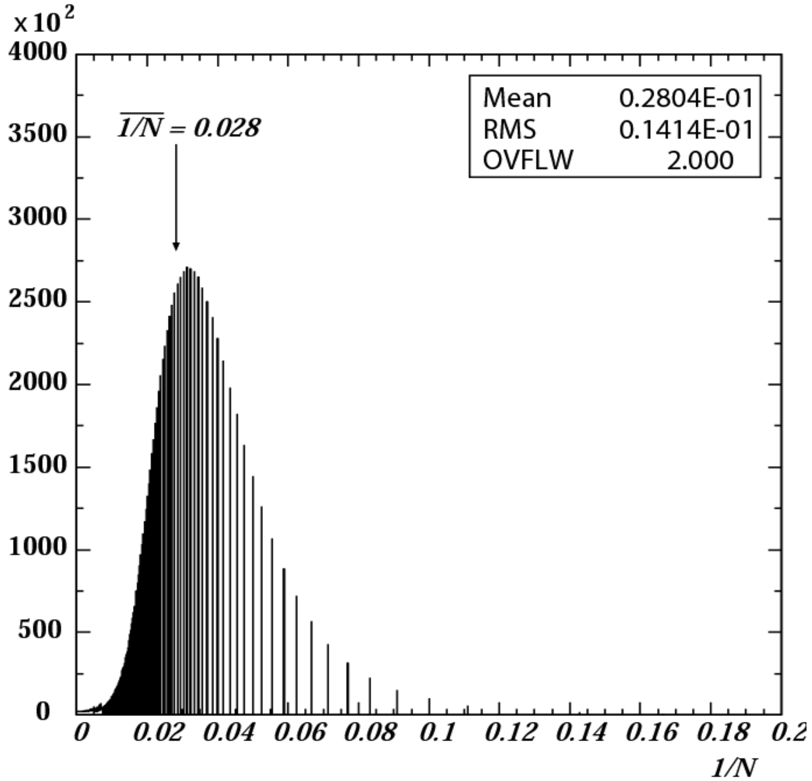
N_{eff} in typical model

4 GeV pion, pad pitch 6mm, pure Ar

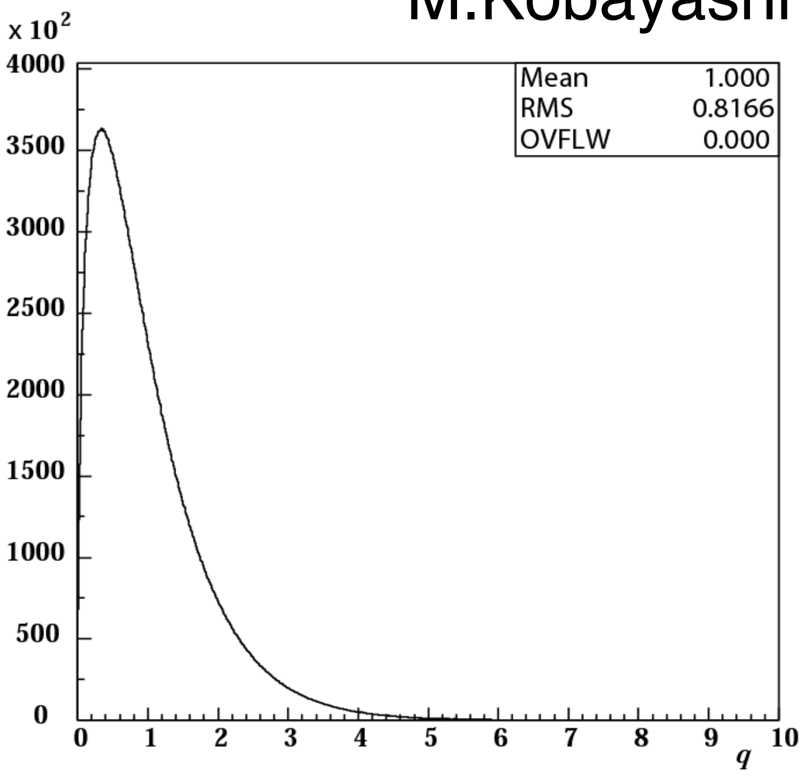
M.Kobayashi



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



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



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

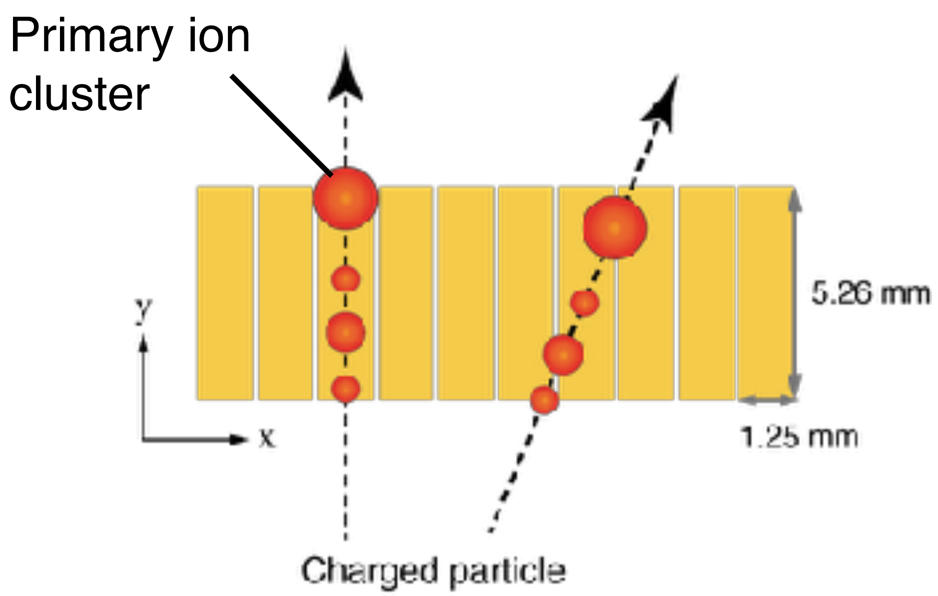
1/2

1/3

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

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

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

Effects of diffusion
+ gas gain fluctuation
+ finite pad pitch

Electric noise

Angular Pad effect

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

L : Pad row pitch

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

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

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

The effective number of electrons

gas gain fluctuation

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

 # electrons

The effective number of clusters

cluster size fluctuation

+ gas gain fluctuation

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

 # clusters

Notice

$$\bar{G} \approx \frac{\sum_i\sum_j G_{ij}}{\sum_i k_i} \longrightarrow \hat{N}_{eff} \simeq \left[\left\langle\frac{\sum_{i=1}^{N} k_i^2}{\left(\sum_{i=1}^{N} k_i\right)^2}\right\rangle + \frac{1}{N_{eff}} - \frac{1}{N_{eff}^{\text{w/o}\,G}}\right]^{-1} \left(N_{eff}^{\text{w/o}\,G} \simeq \left[\left\langle\frac{1}{\sum_i k_i}\right\rangle_{N,k}\right]^{-1}\right)$$

w/ gas gain fluctuation

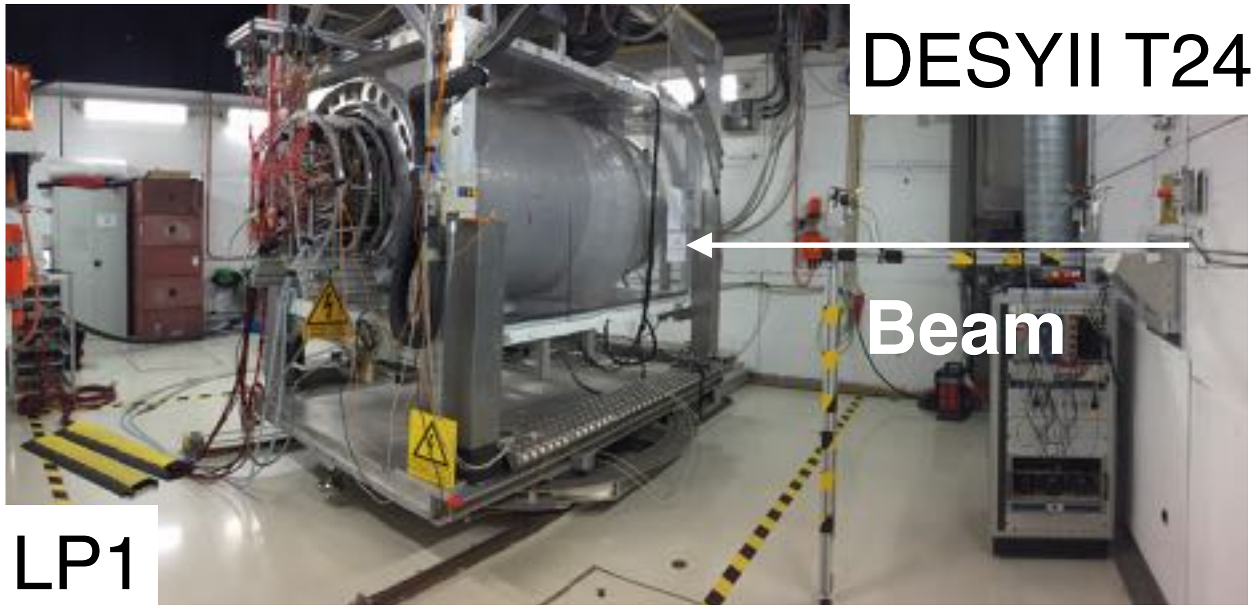
w/o gas gain fluctuation

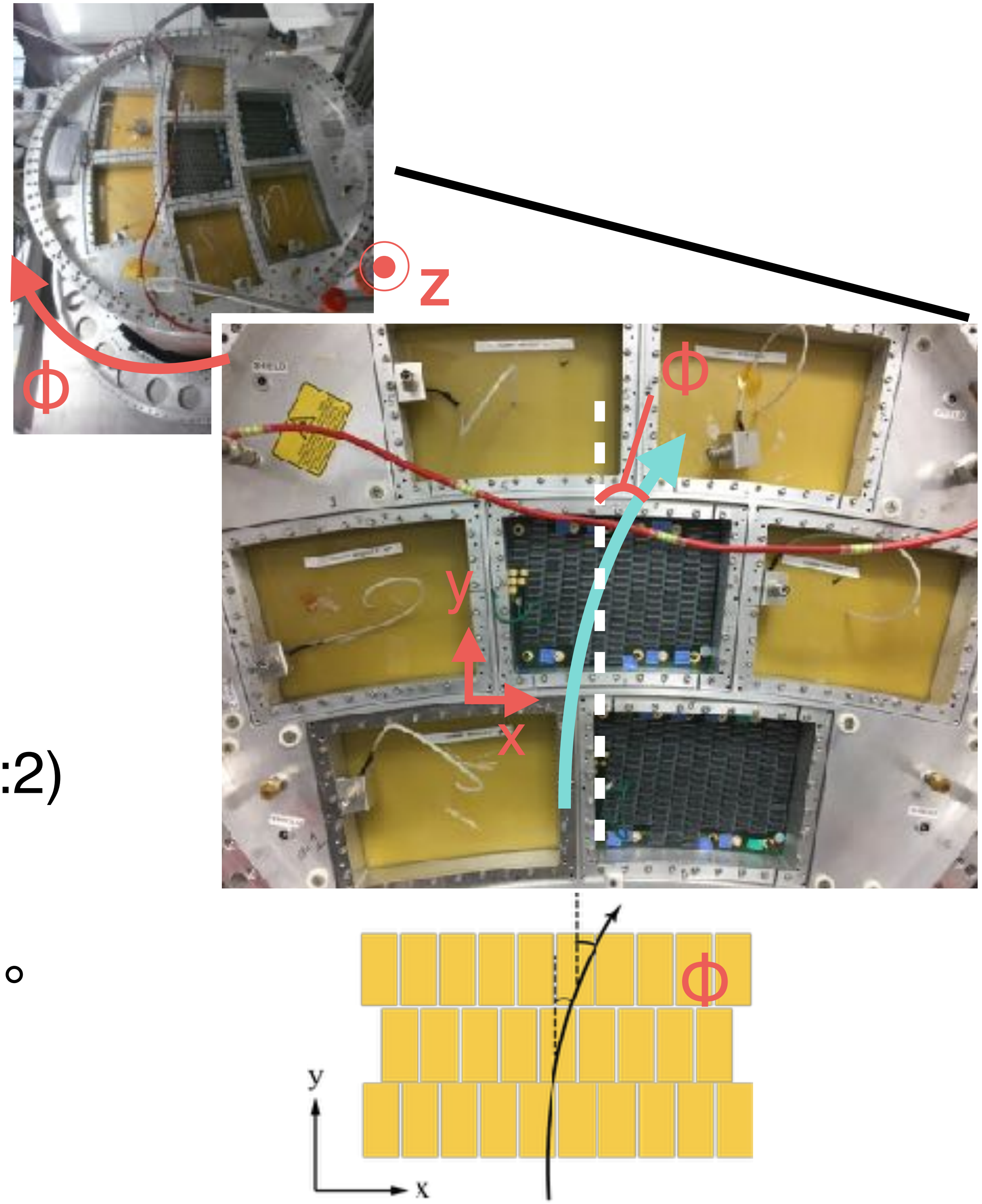
R.Yonamine, K.Fujii [https://doi.org/10.1088/1748-0221/9/03/C03002]

Beam test of TPC
(Large prototype ＠DESY)

Beam test

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
- 20000evt / 1 run
- Data set used : ϕ= -20°, 0°, 10°, 20°
  - ✦For this analysis we use data taken without the gating foil