Simulation Study of Quadruple-foils GEM Detector

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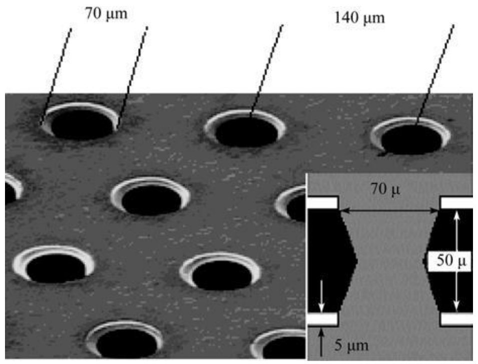
Outline

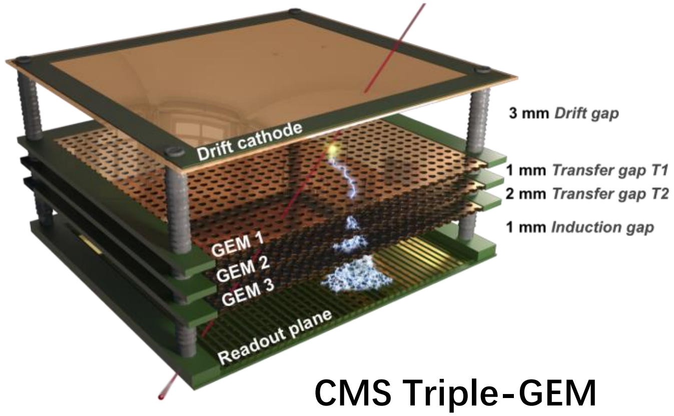
01 Motivation

- **Traditional gas detector → Micro Pattern Gas Detector(MPGD)**
  - adapt to the working environment of high radiation flux and high counting rate on high energy and luminosity particle collider;
  - adapt to high magnetic and electric field;
  - possess better performance



GEM foil structure

- **GEM (Gas Electron Multiplier):**
  - Good performance: stable and cheaper/lower discharge damage/less aging problems and longer service life…
  - multilayer GEM foils structure: to acquire greater gain, operate at lower voltage …
  - GEM technology is widely used in LHC experiments upgrade



CMS Triple-GEM structure

- **Motivation of quadruple-GEM study :**
  - CMS upgrade GEM has triple foils. By adding another foil, one expects to get lower operating voltage; lower discharge probability; and lower IBF.
  - Compare triple and quadruple-GEM performance

01 Research contents

- **Structural design of triple-GEM and quadruple-GEM**
  - Study the effect of aligned and misaligned hole-position between different foils
- **Simulation study of primary ionization, drift, diffusion, avalanche multiplication, induced signal readout process (calculate weighting field using Shockley-Ramo theorem)**
- **simulation study of the quadruple GEM performance, compare with triple GEM**
  → Step by step multi-GEM parameterized simulation technique (STEPS)

status (-: on going):

performance	method	result
time resolution	√	√
spatial resolution	√	√
energy resolution	√	√
effective gain	√	√

performance	method	result
transparency (electron/IBF)	√	√
drift study	√	√
transport parameters	√	√
discharge probability	-	-
charging-up effect	-	-

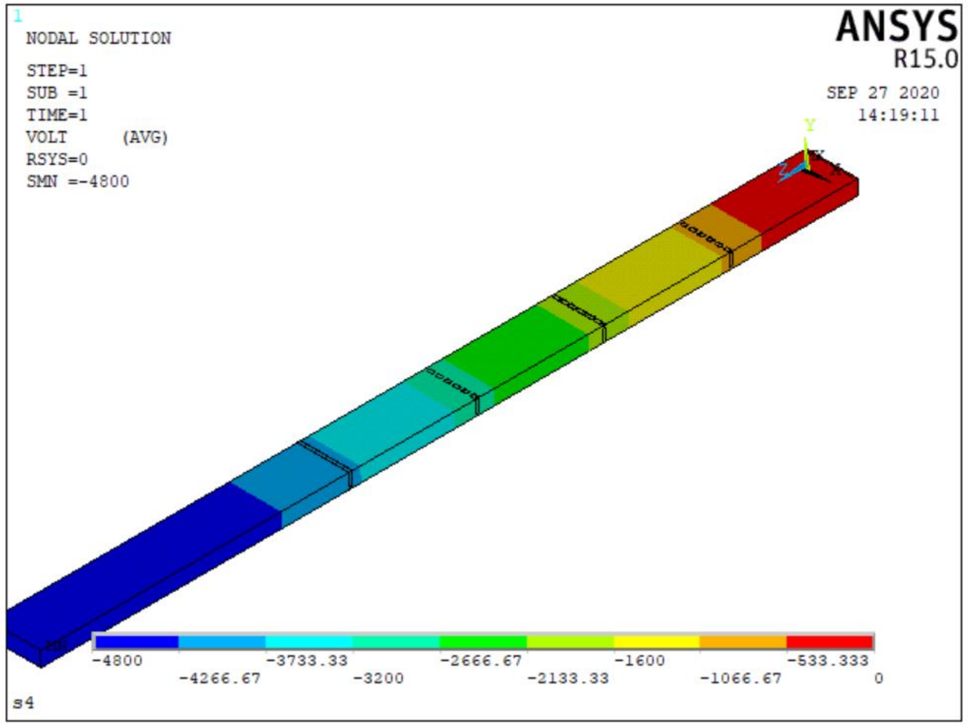
02 Simulation study methods

Electric field calculation: ANSYS

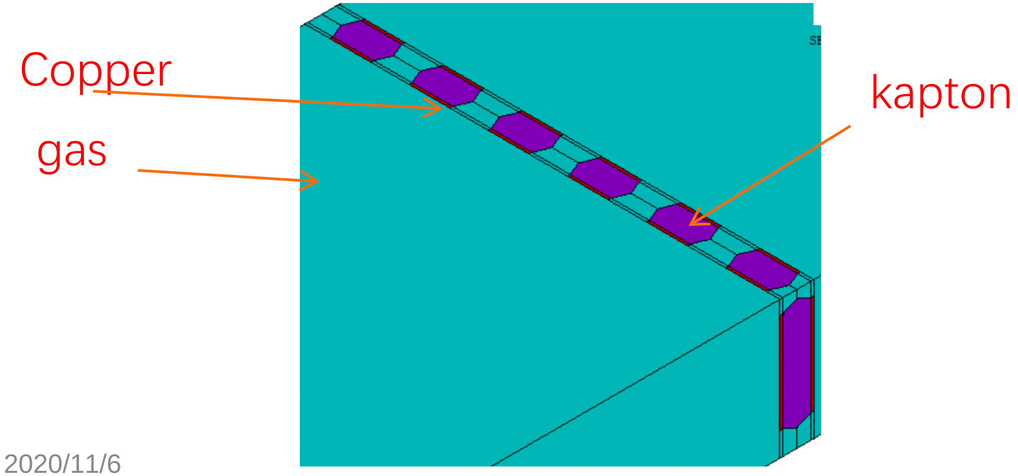
build unit model of triple GEM and quadruple GEM by GUI operation or command flow

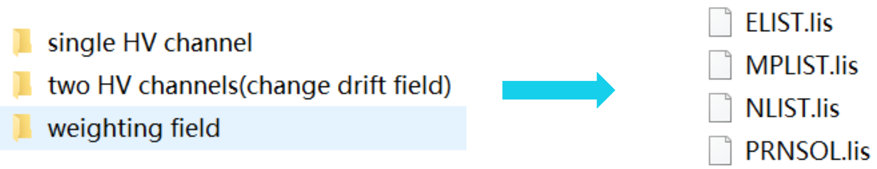
GUI operation:

1. generate four random vectors for moving hole positions; (0,0)→(x_i,y_i) i=1,2,3,4
2. establish the basic framework of unit model;
3. assign material attributes and mesh;
4. apply voltage at the boundary and solve;
5. generate files containing the list of elements/nodes/materials and nodal solutions;
6. import generated files into garfield++.



the contour plot of quadruple GEM electric potential

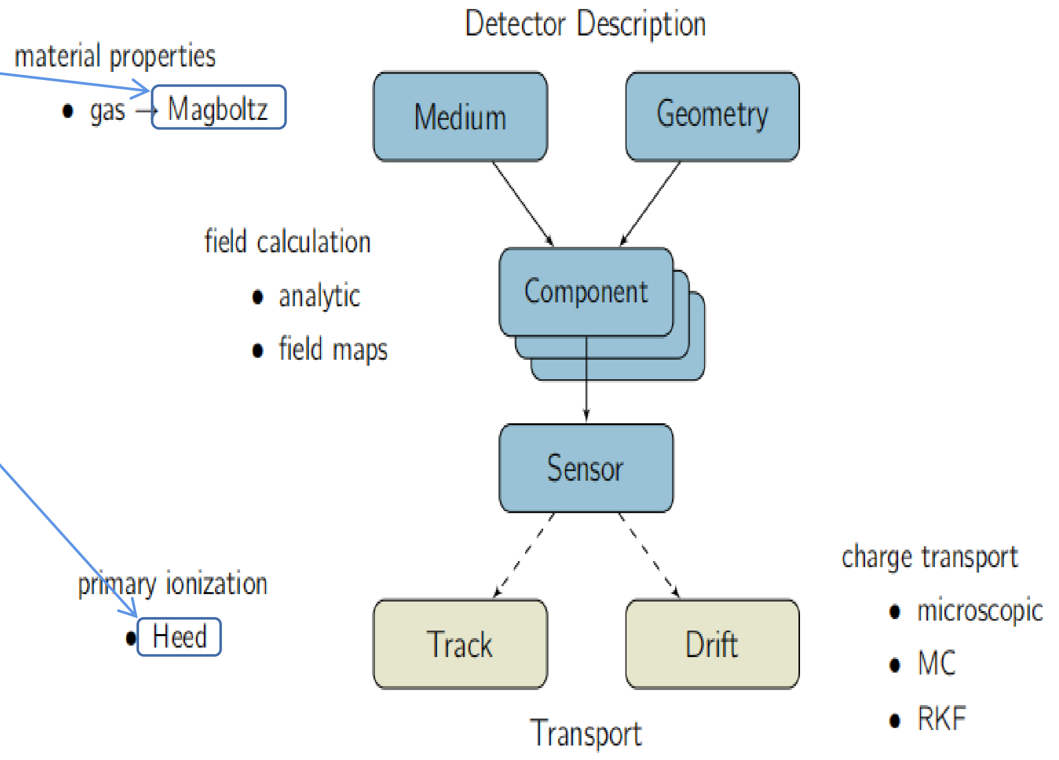




02 Simulation study methods

Gas simulation: Garfield++

1. Magboltz for gas properties calculation
2. Garfield++ for initialization (gas/field/sensor/particle)
3. Heed for preliminary ionization and calculating energy loss (primary ionization/drift/diffusion)
4. Garfield++ for avalanche process (get position/time/energy information from avalanche process)
5. signal readout process (weighting field) (an additional electric field to calculate the induction signal)

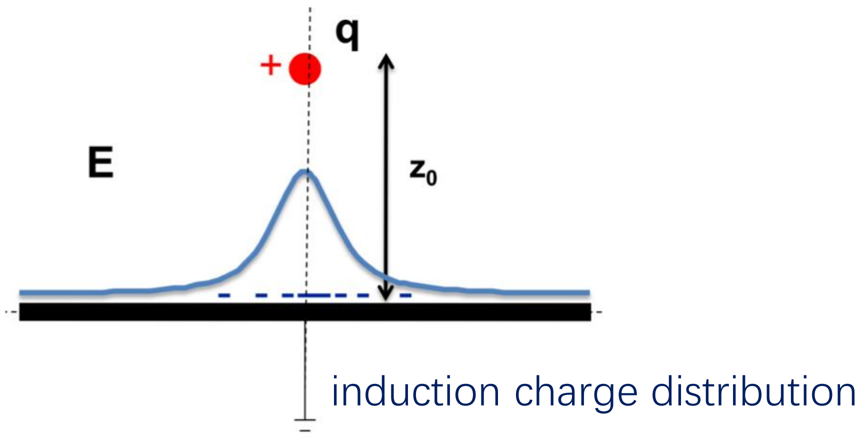


Overview of the main classes in Garfield++ and their interplay

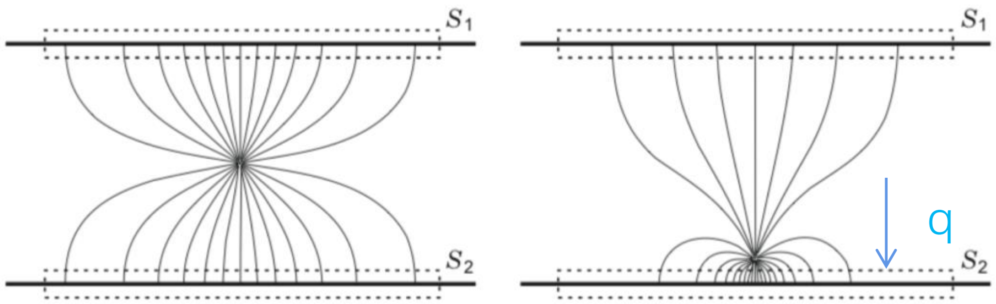
Data analysis: ROOT

- time/spatial/energy resolution,
- effective gain,
- electron transparency, IBF,
- drift properties, etc)

02 Simulation study methods: Calculation of induction signal



current flow begins instantaneously when the charge begins to move.



the amount of charge induced on the readout electrode is increasing continuously.

1. solve the poisson equation at each step on the drift of the electron-ion pair (very complicated)
2. solution (Shockley-Ramo theorem):

$$i(t) = q \cdot \vec{E}_w \cdot \vec{v}$$

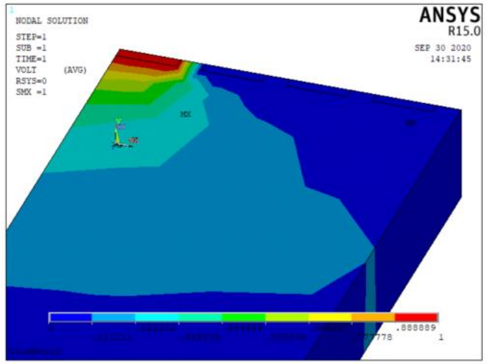
with q: charge; E_w: weighting field; v: velocity

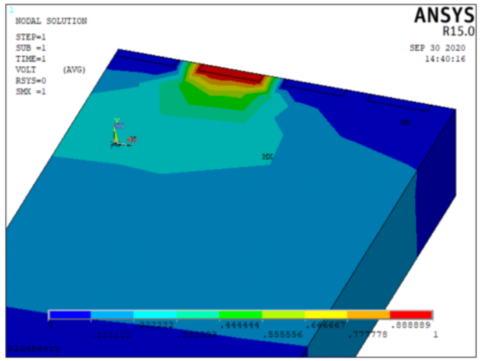
$$Q(t) = \int_0^t i(\tau)d\tau = q\int_{x1}^{x2} \vec{E}_w d\vec{x}$$

How to get the weighting field?

– calculate the electrostatic field for each electrode by:

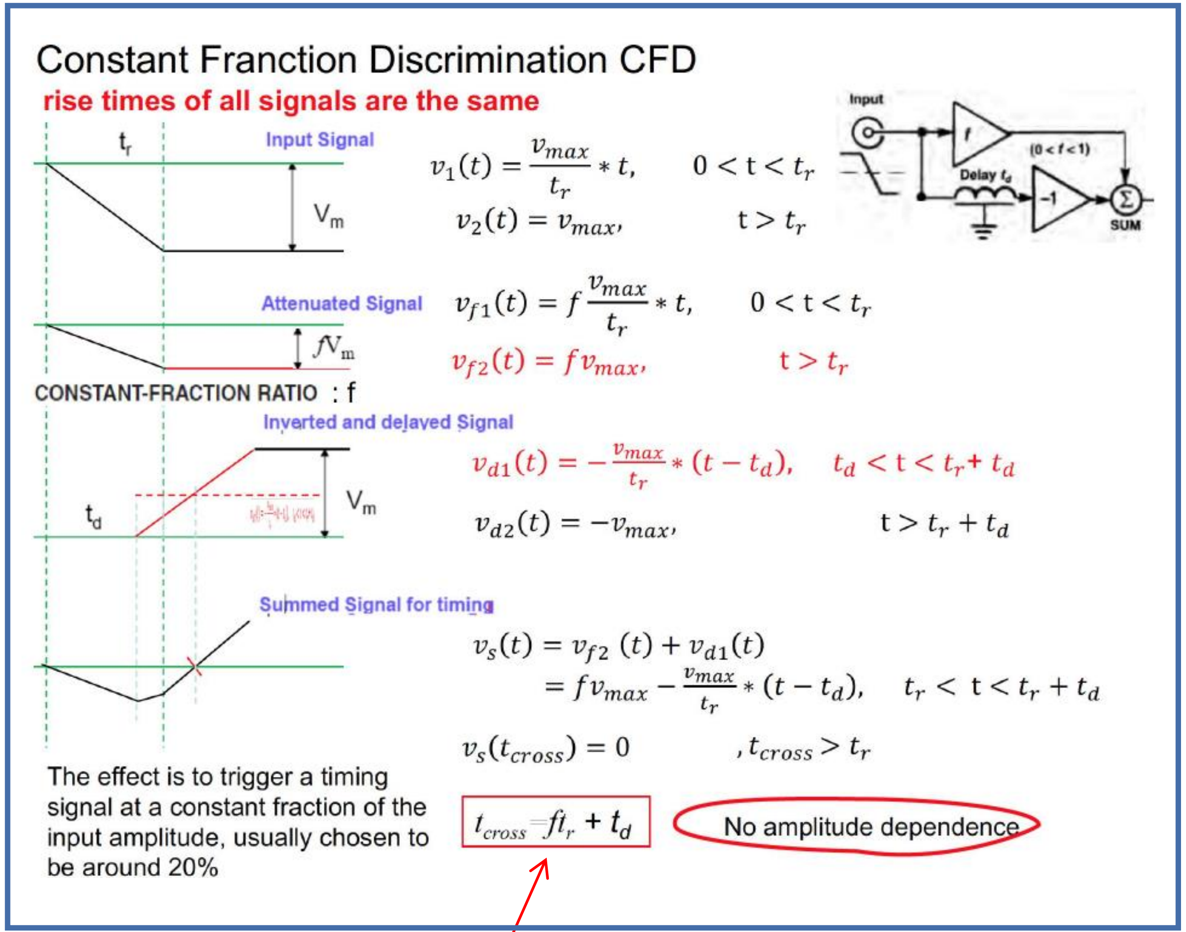
- removing the signal charge
- setting the electrode to U = 1V and all others to 0 V





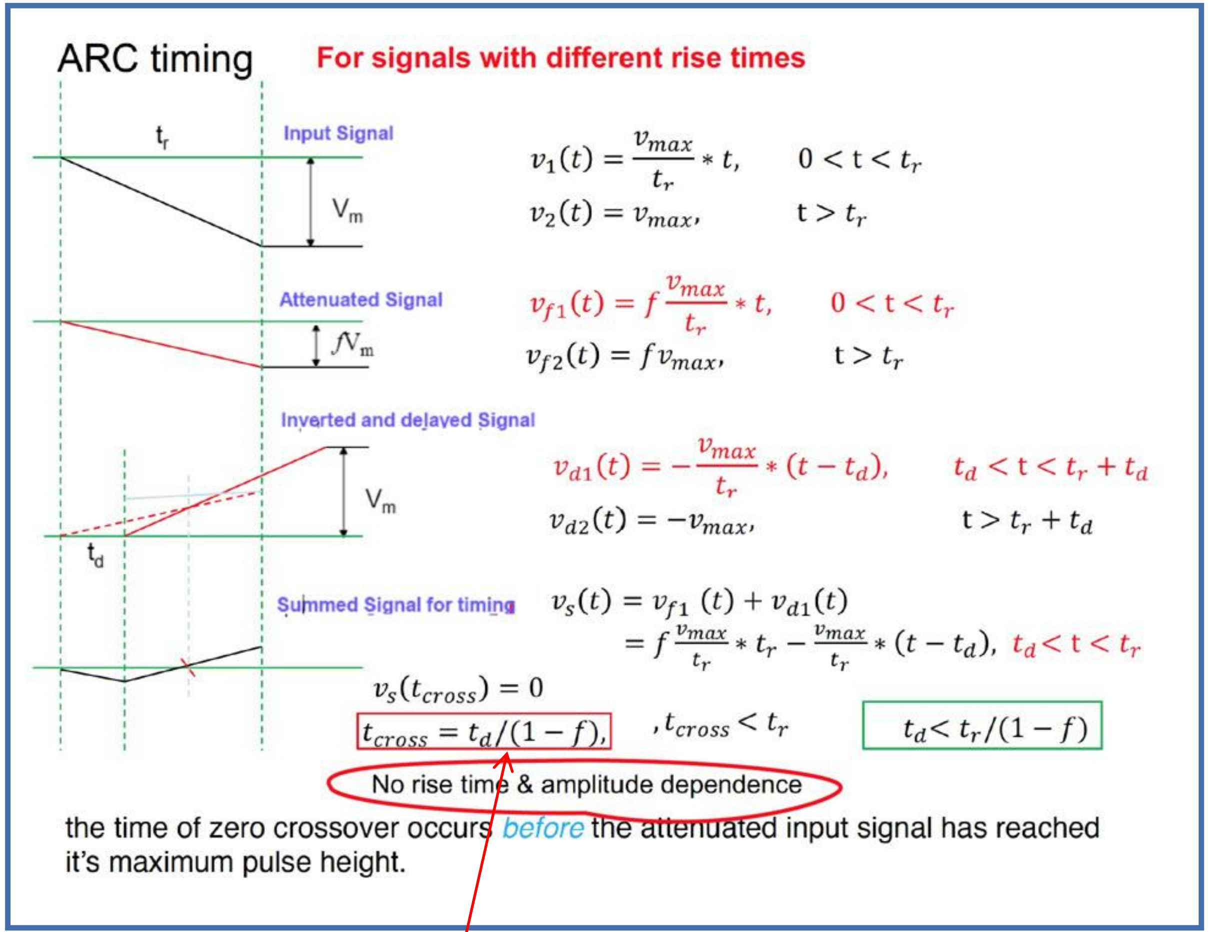
02 Simulation study methods: Time resolution

Constant Franction Discrimination (CFD) timing method



eliminate the influence of pulse amplitude

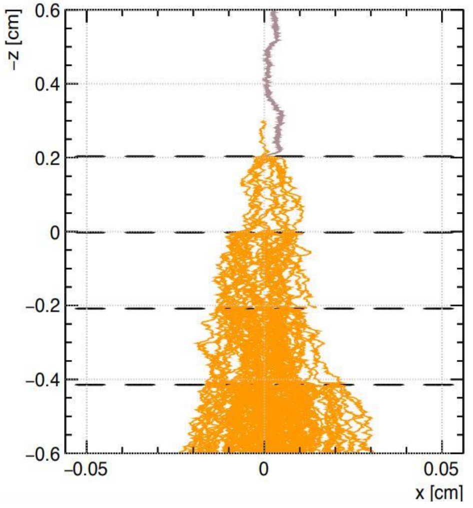
Amplitude and Rise time Compensated (ARC) timing method



eliminate the influence of pulse amplitude and rise time

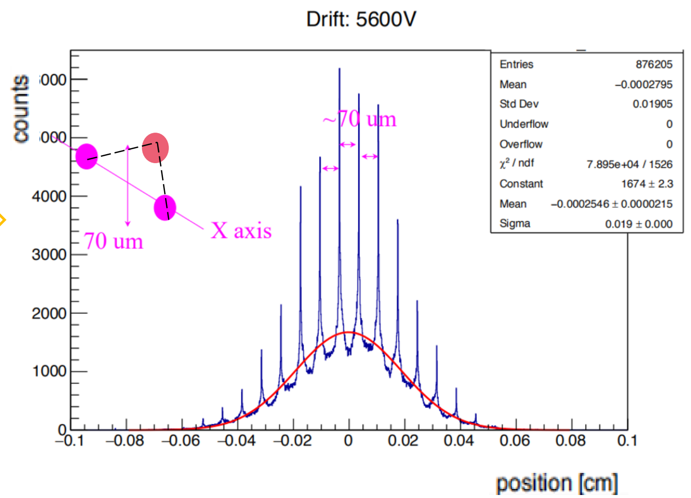
02 Simulation study methods: Spatial resolution

Calculated from the position distribution of the end of the electron trajectories inside the readout gap

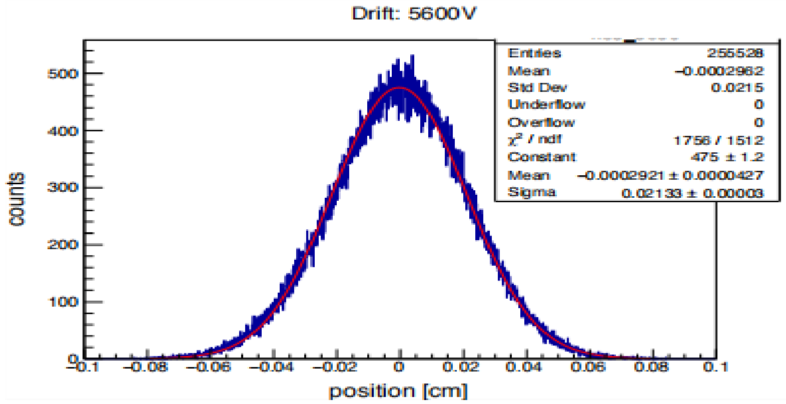


electron and ion trajectories

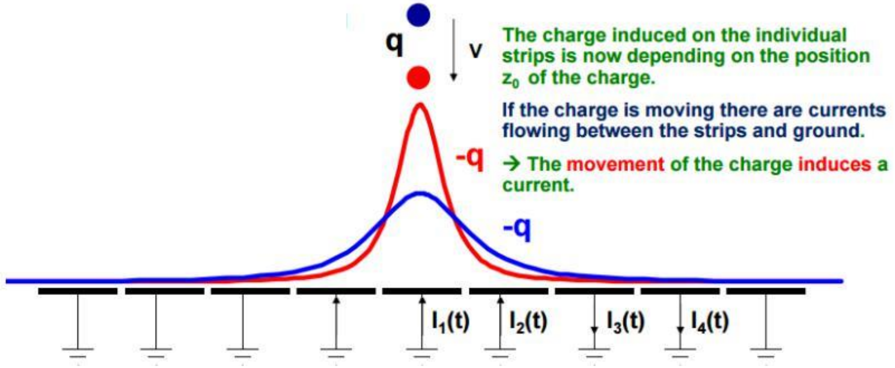
→ position distribution of the end of the electron trajectories inside the readout gap



position distribution of the end of the electron trajectories inside the whole GEM



center of gravity method



$$X = \sum \frac{X_i A_i(X)}{A(X)} \qquad Y = \sum \frac{Y_i A_i(Y)}{A(Y)}$$

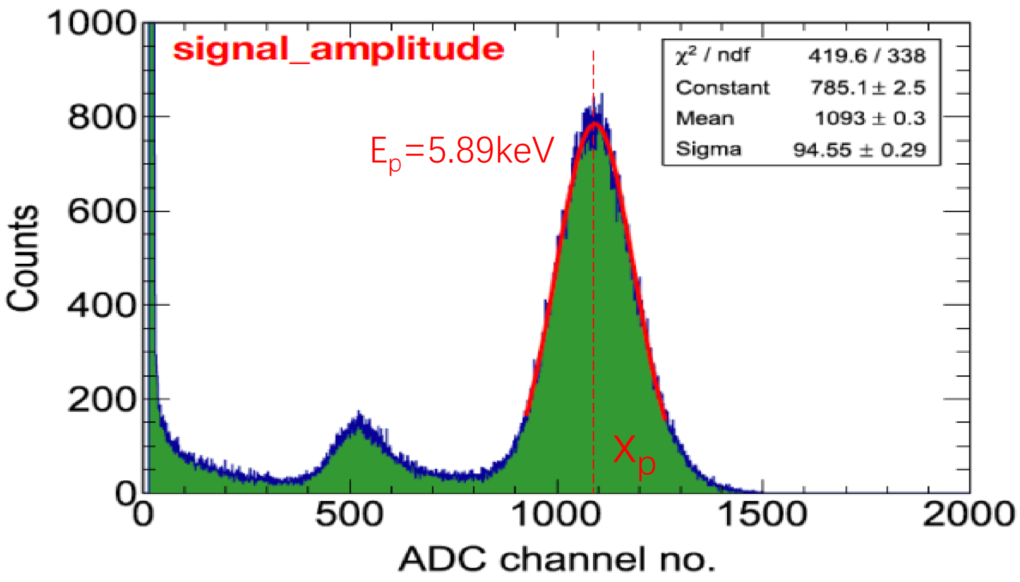
X_i, Y_i: Coordinates of the strips
$A_i(X)$, $A_i(Y)$: Charge on strips
$A(X)$, $A(Y)$: Total charge

- the amount of charge is proportional to the signal amplitude;
- use four electodes.

02 Simulation study methods: Energy resolution

Procedure:

- energy calibration
- get the pulse-height spectrum of ^{55}Fe X-ray source
- transform it to the energy spectrum
- fit the photopeak and calculate the FWHM (absolute energy resolution △E) and △E/E_p (relative energy resolution)

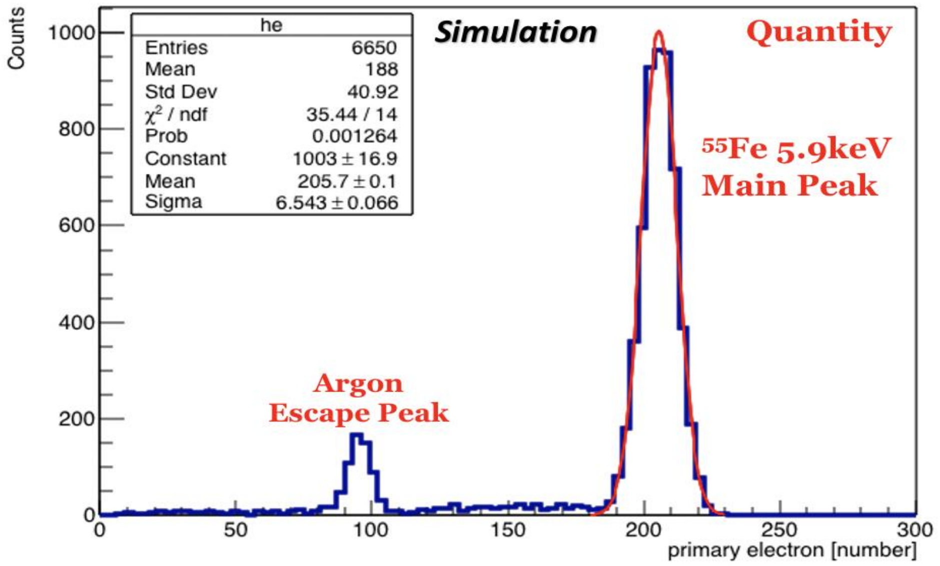


^{55}Fe spectrum at 4400 V for the GEM detector.

$$E(x) = Gx + E_0$$

$$x : channel\ number$$

$$E : deposited\ energy$$



■ Primary electron number (generated by single photon) distribution of simulated ^{55}Fe source.

When X-rays with different energies are incident, the channel values corresponding to the photopeak are obtained. get multiple groups of (x_p, E_p) to fit linearly

02 Simulation study methods

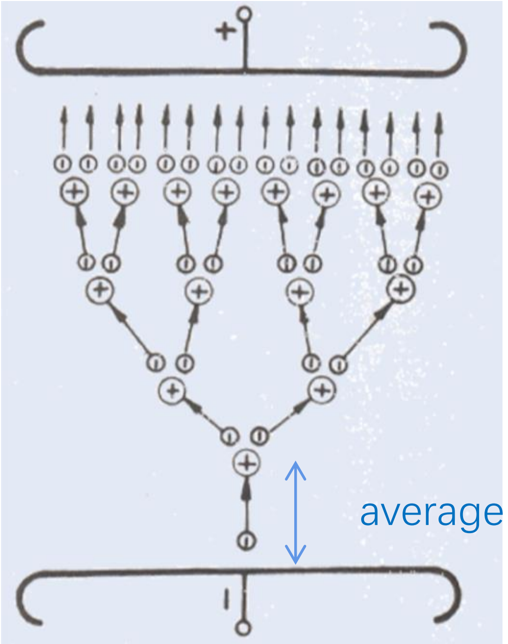
Effective gain: $G_{effective} = \frac{n_t}{n_i}$

- n_i: primary electrons generated in drift gap
- n_t: final electrons collected in induction gap

$$dn = n\frac{dr}{\lambda} = \alpha n dr$$

$$n = n_0 \exp(\int_{r_1}^{r_2} \alpha(r)dr) = n_0 M$$

α--Townsend coefficient



development of an electron avalanche

Transport parameters

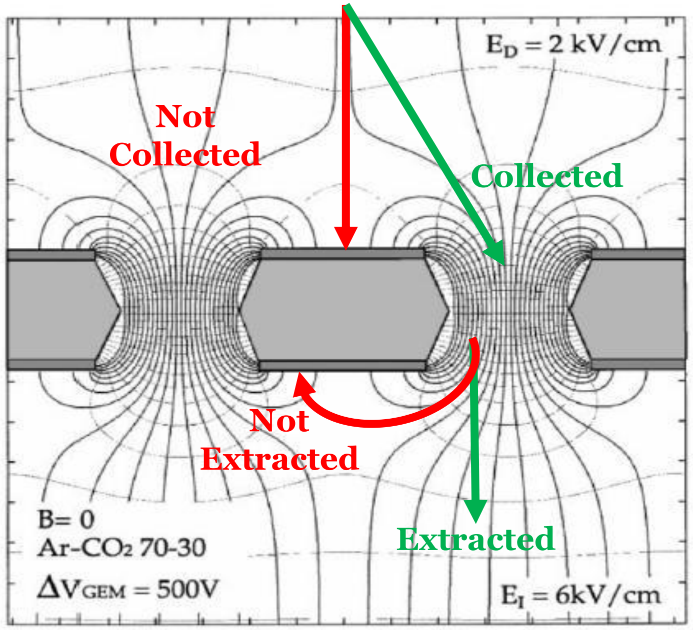
	definition
drift velocity	average velocity along the E field lines
diffusion coefficients	diffuse outward from creation point (Gaussian distributed with a spread)
Townsend coefficient	decide the number of e^-/ion along the drift line at each point (multiplication/loss)
attachment coefficient	

calculation method:
use class Medium from Garfield++
(member function name)

- ElectronVelocity
- ElectronDiffusion
- ElectronTownsend
- ElectronAttachment

obtain the relationship between parameters and reduced electric field strength E/p

02 Simulation study methods: Transparency



schematic view of the electric field line, electric potential through a GEM hole

$$T_i = \varepsilon_{coll}\varepsilon_{extr}, i = 1,2,3,4$$

electron transparency for i_{th} GEM foil

electron transparency for primary electrons:

n_d: primary electrons generated in drift gap

n_c: primary electrons collected by GEM1

$$T_0 = \frac{n_c}{n_d}$$

IBF (Ion Back Flow ratio):

n_i: final ions collected in induction gap

n_{di}: backflow ions in drift gap

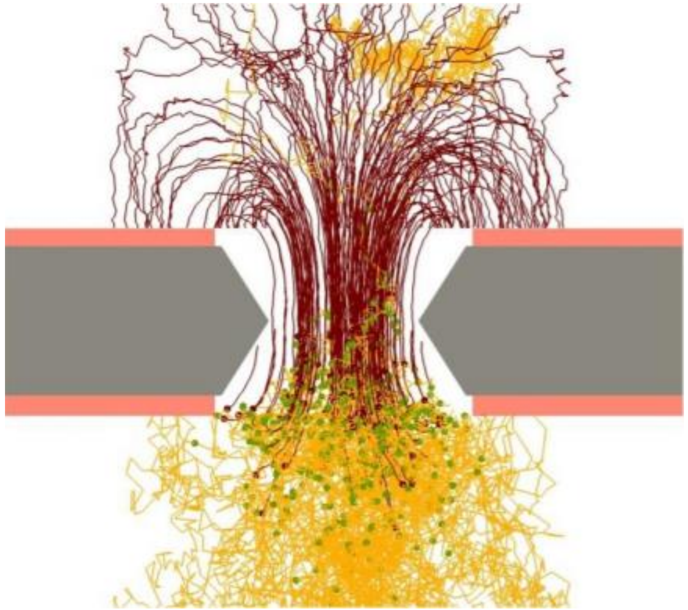
$$R_i = \frac{n_{di}}{n_i}$$

Collection efficiency

$$\frac{\#\text{ electrons into the hole}}{\#\text{ generated electrons}}$$

Extraction efficiency

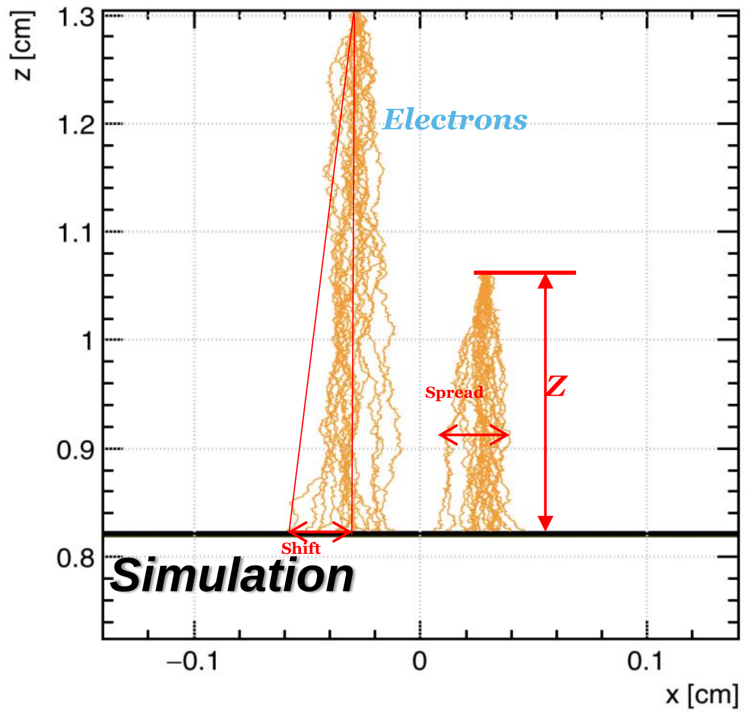
$$\frac{\#\text{ electrons from the hole}}{\#\text{ electrons in the avalanche}}$$

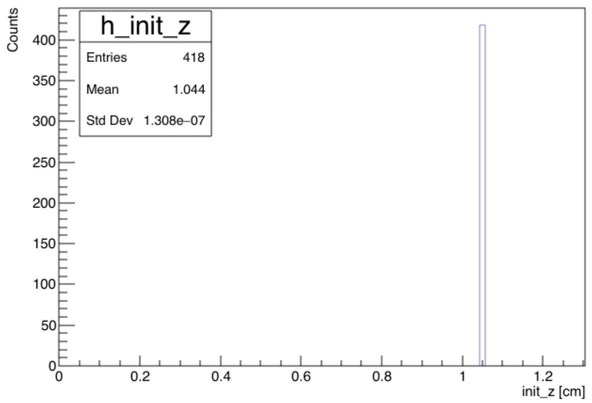


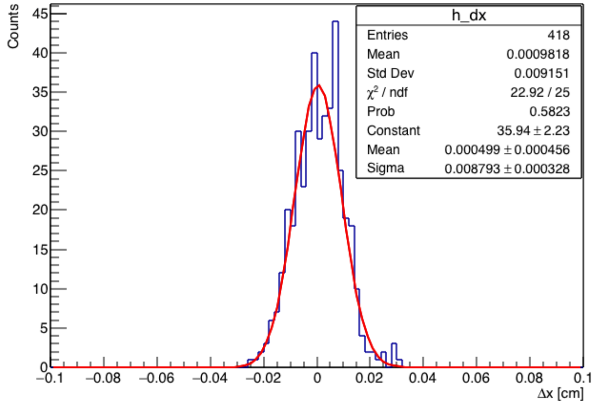
schematic view of the electron flow and ion back flow through a GEM hole

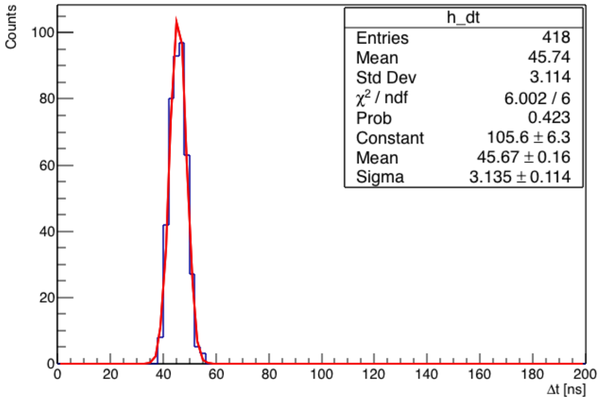
02 Simulation study methods: Drift

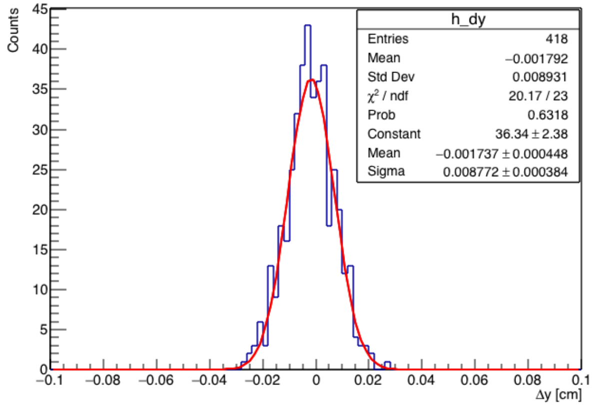
- position z dependence of shift&spread (trajectory position deviation/diffusion of electron end points) of electrons moving in electric-magnetic fields
  (no magnetic fields-->shift is almost zero)
- independent variable z-->dependent variable x/y/t/e distribution-->shift&spread
  ($\mu_x,\mu_y,\mu_t,E,\sigma_x,\sigma_y,\sigma_t,\sigma_E \sim z$)











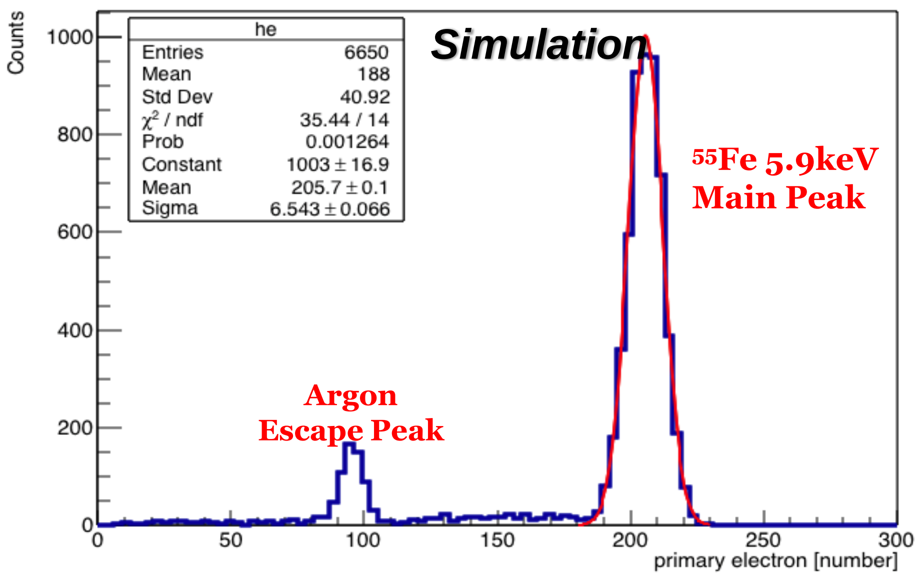
02 Simulation study methods: STEPS

Step by step multi-GEM Parameterized Simulation Technique (STEPS)

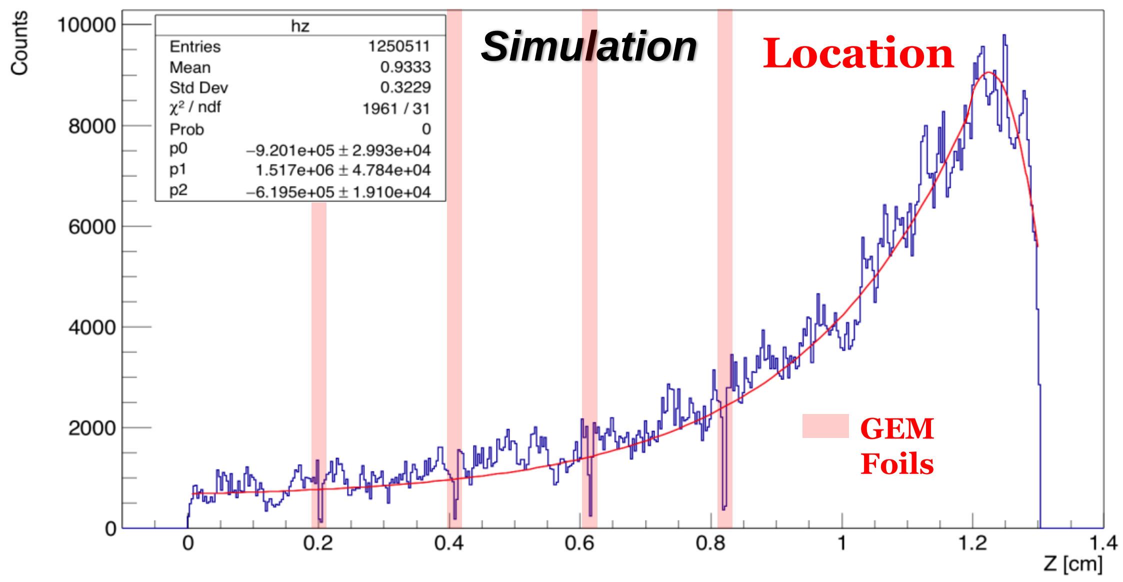
Insert Particle → Ionization → Drift → Transparency → Multiplication → Induction

Insert Particle | Ionization

Where are the primary electrons located and how many are there?



- Primary electron number (generated by single photon) distribution of simulated ^{55}Fe source.

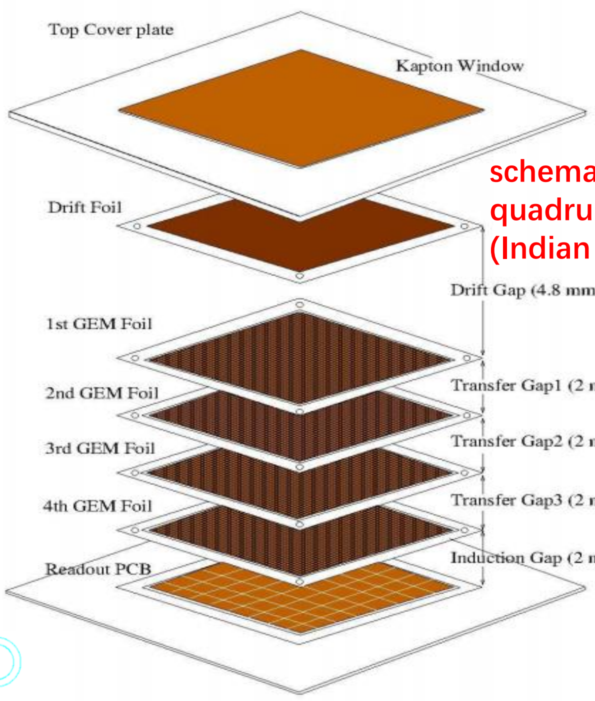


- Distribution of primary electron generation position. Fitting with exponential and parabola curves.

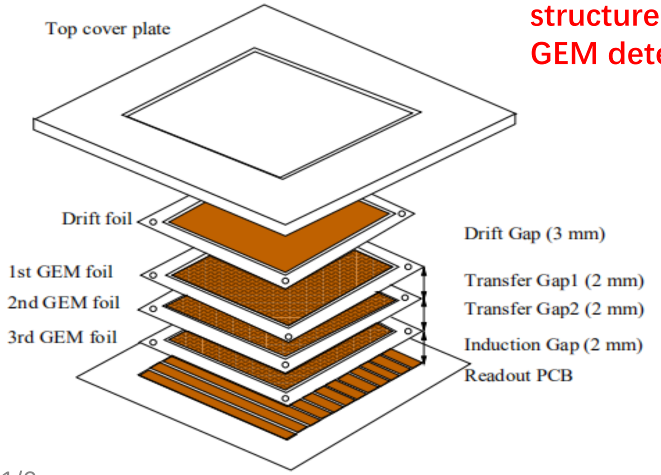
02 Simulation study methods: GEM models

Structure schematic and design parameters of triple- and quadruple-GEM

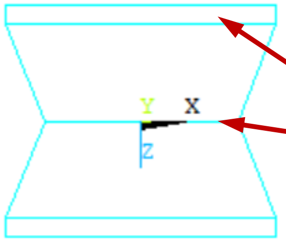
	triple-GEM	quadruple-GEM
drift gap	3mm	4.8mm
transfer gap1	2mm	2mm
transfer gap2	2mm	2mm
transfer gap3	/	2mm
induction gap	2mm	2mm
copper coating thickness	5µm	5µm
kapton thickness	50µm	50µm

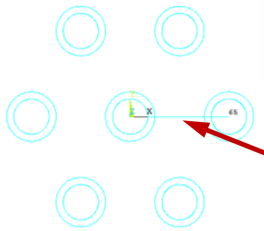


schematic design of a quadruple GEM detector (Indian model)



structure of a triple-GEM detector





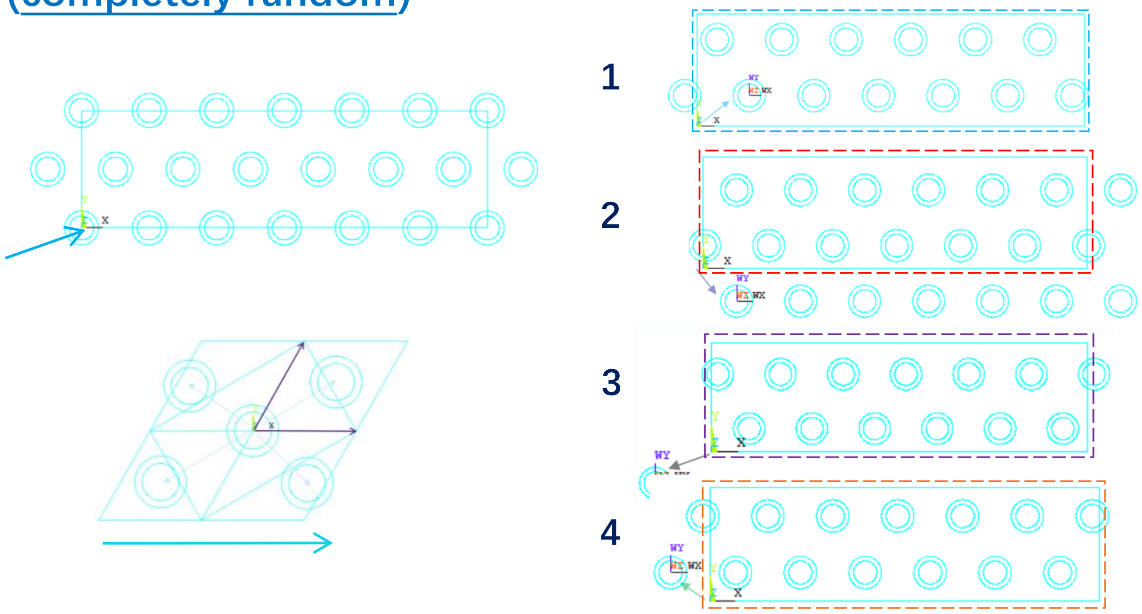
Foil and hole parameters

outer radius	inner radius	pitch	width of rim
35µm	25µm	140µm	0µm

02 Simulation study methods: Hole alignment

Aligned or mis-aligned hole position between different GEM foils

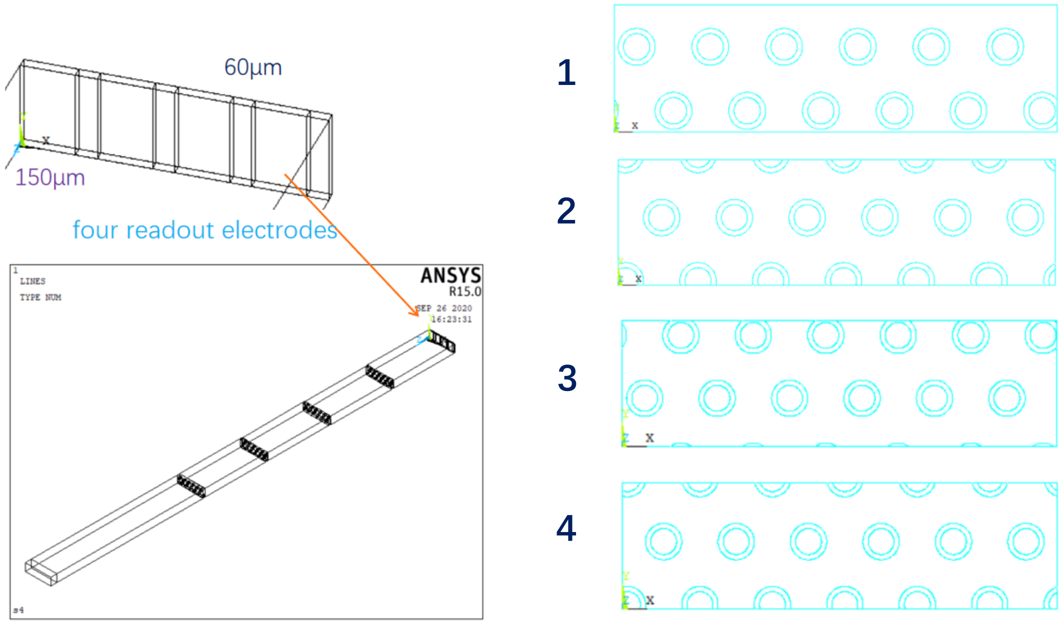
① quadruple-GEM unit model with misaligned holes (completely random)



the positions of the hole center of each foil are translated by random vector

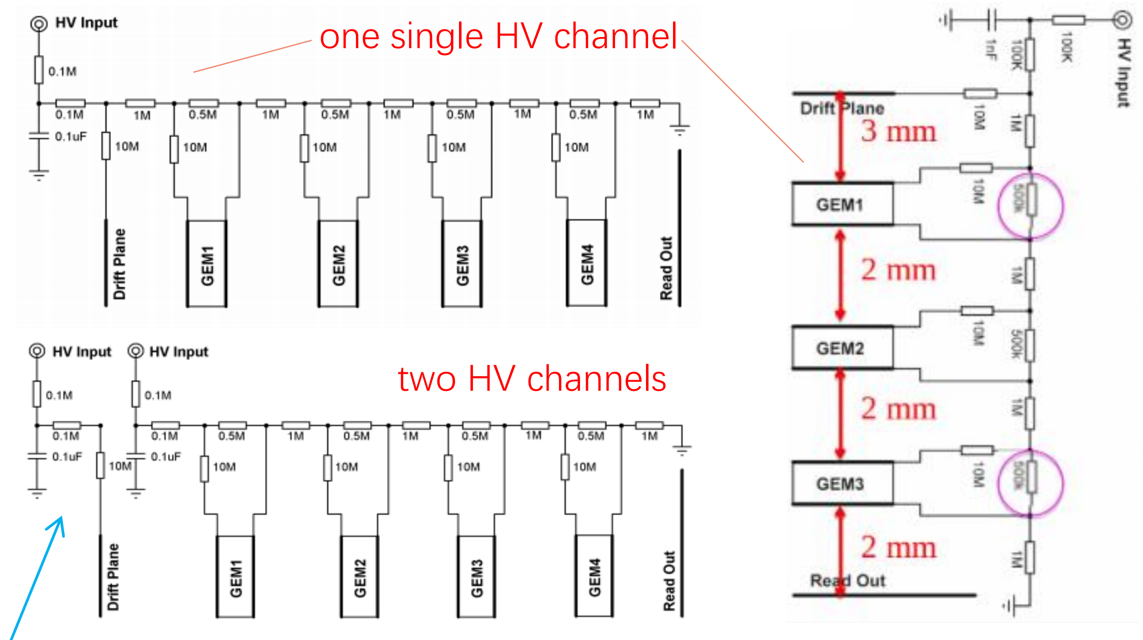
	1	2	3	4
△x/μm	112.965	73.6804	-125.5574	-85.8721
△y/μm	65.9124	-71.1602	-69.4351	60.554

② quadruple GEM unit model with misaligned holes (the positions of the center of the holes between two adjacent foils are staggered by ~ 50 μm)



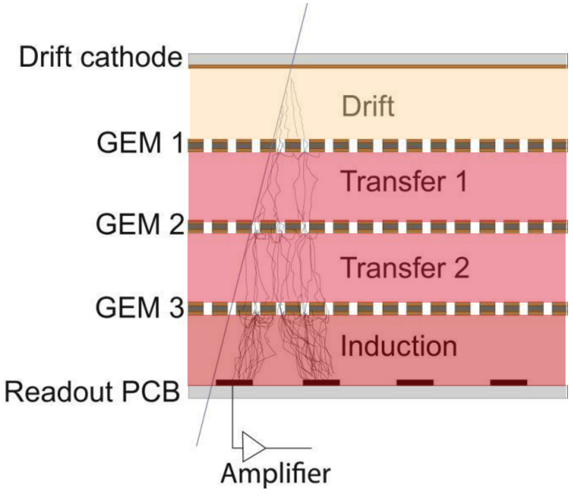
	1	2	3	4
△x/μm	-27.7893	13.4953	-25.4049	10.269
△y/μm	40.8279	9.1926	-28.3703	8.8028

02 Simulation study methods: Voltage setting



the resistor chain used for 4_{th}GEM and 3_{th}GEM voltage divider

indenpendent



	quadruple GEM		triple-GEM
	4/1.voltage/V	4/2.voltage/V	3/1.voltage/V
drift electrode	A	B	C
GEM1 top	6/7*A	4200	9/11*C
GEM1 bottom	5.5/7*A	3850	8/11*C
GEM2 top	4.5/7*A	3150	6/11*C
GEM2 bottom	4/7*A	2800	5/11*C
GEM3 top	3/7*A	2100	3/11*C
GEM3 bottom	2.5/7*A	1750	2/11*C
GEM4 top	1.5/7*A	1050	/
GEM4 bottom	1/7*A	350	/
readout electrode	0	0	0

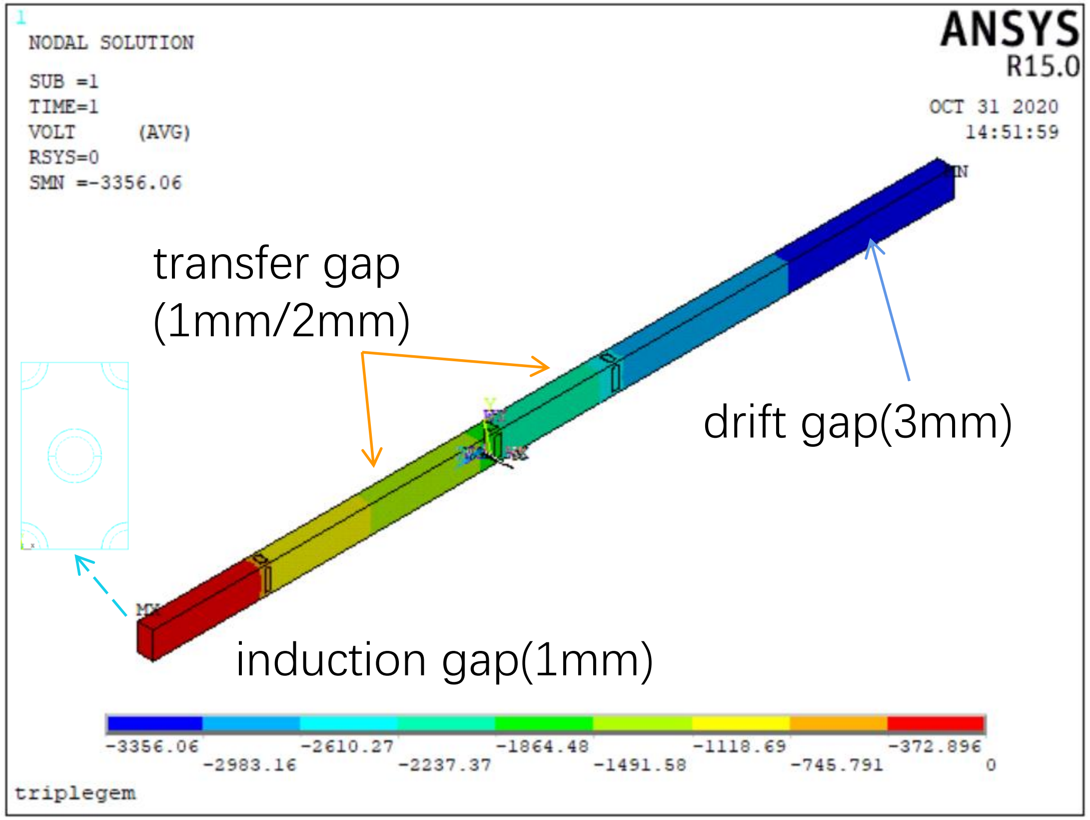
E_d=(B-4200)×10/(4.8×1000)kV/cm

$\Delta V_{4GEM\text{-}single}$= A*1/14

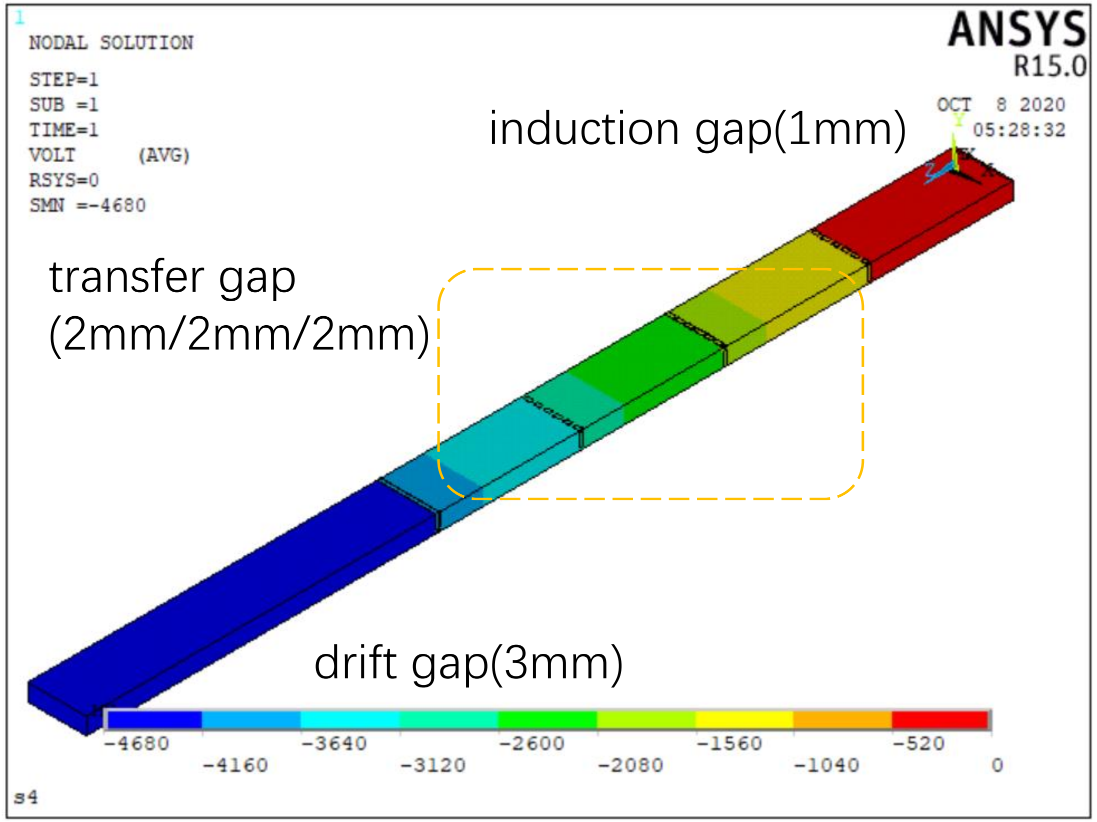
$\Delta V_{3GEM\text{-}single}$= C*1/11

03 Simulation results: Electric field calculation

Unit model of triple-GEM(aligned holes) and quadruple-GEM (aligned and misaligned holes)

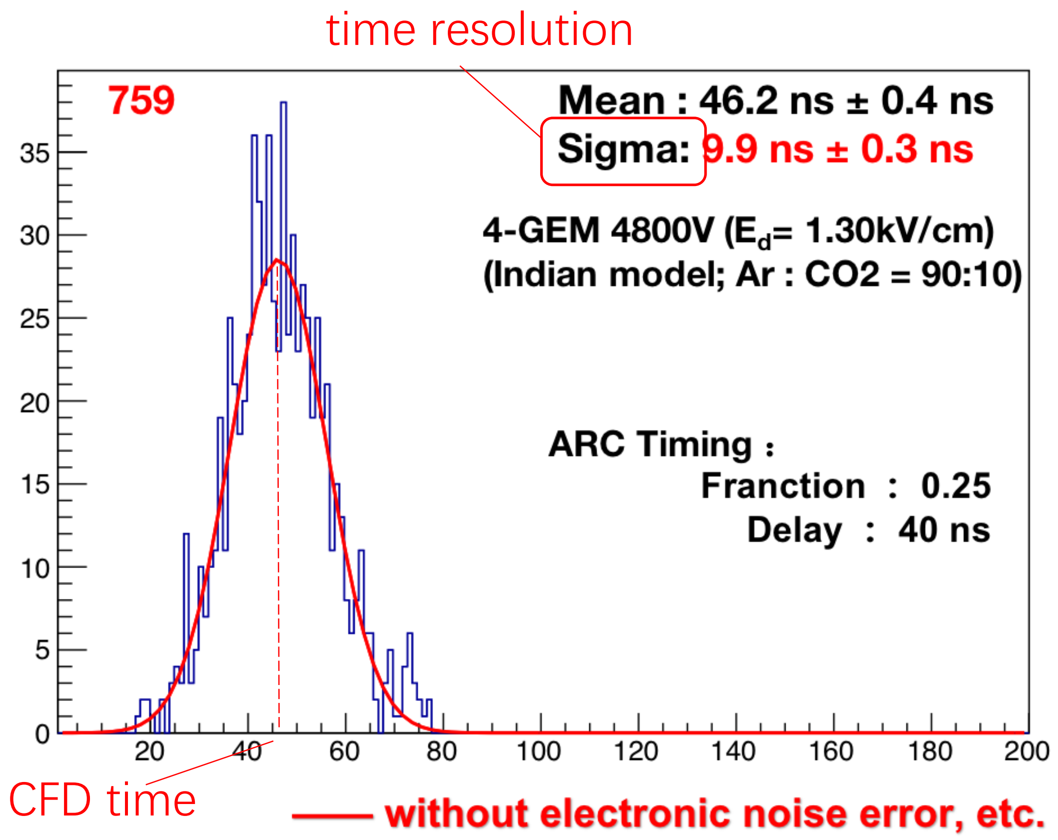


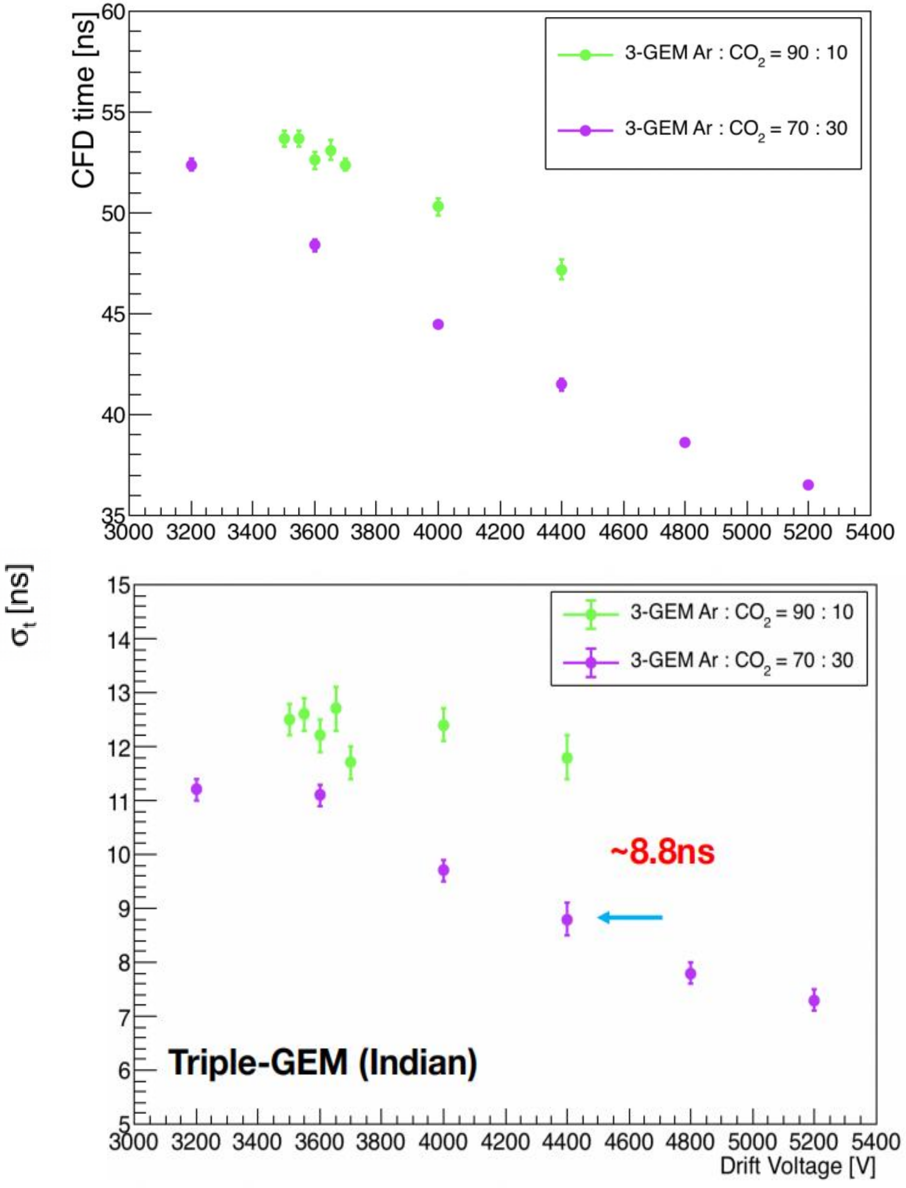
the contour plot of triple GEM electric potential



the contour plot of quadruple GEM electric potential

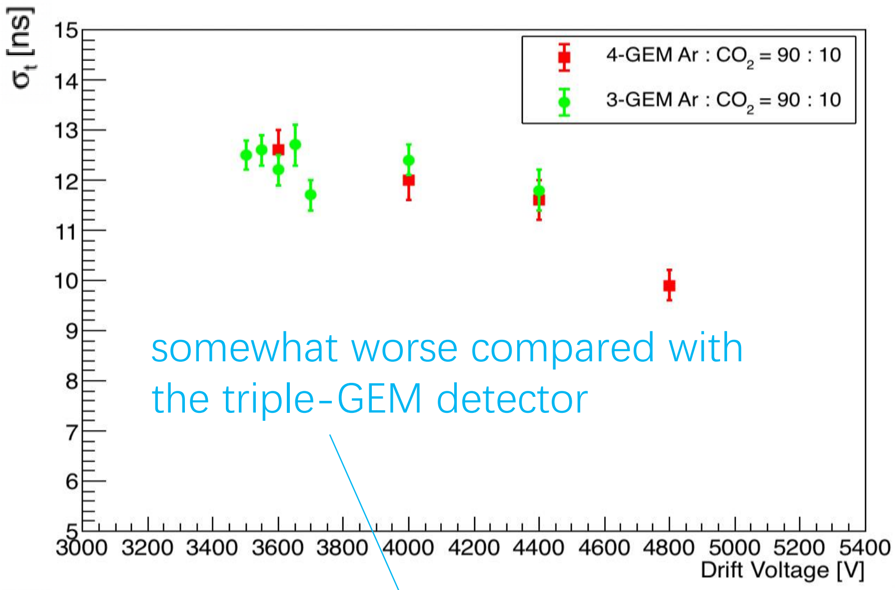
03 Simulation results: Time resolution



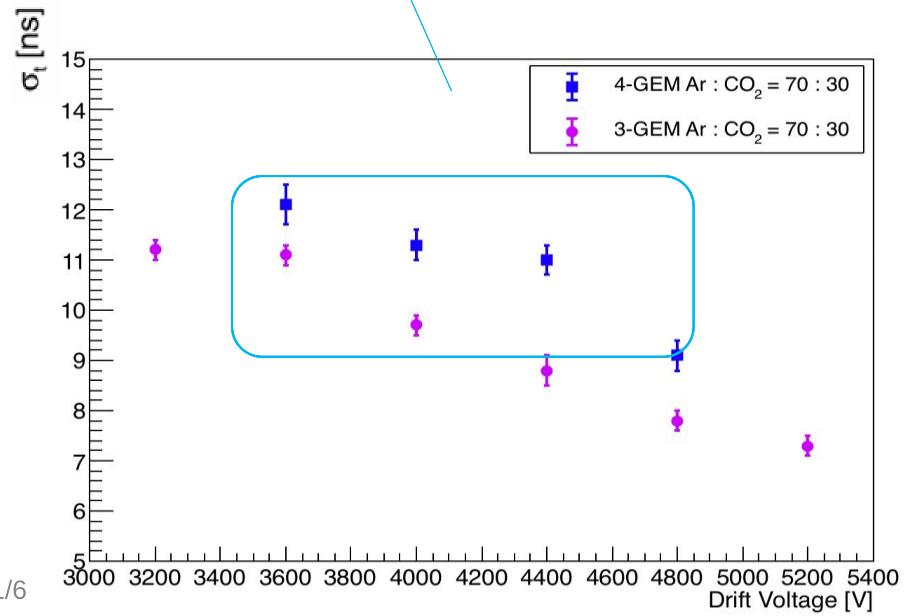


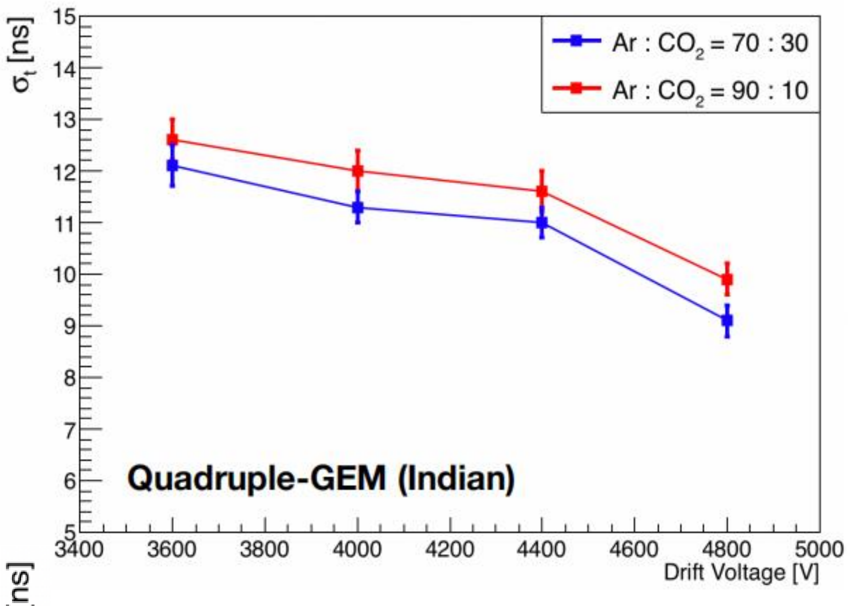
- CFD time:injecting time-->constant fraction timing point

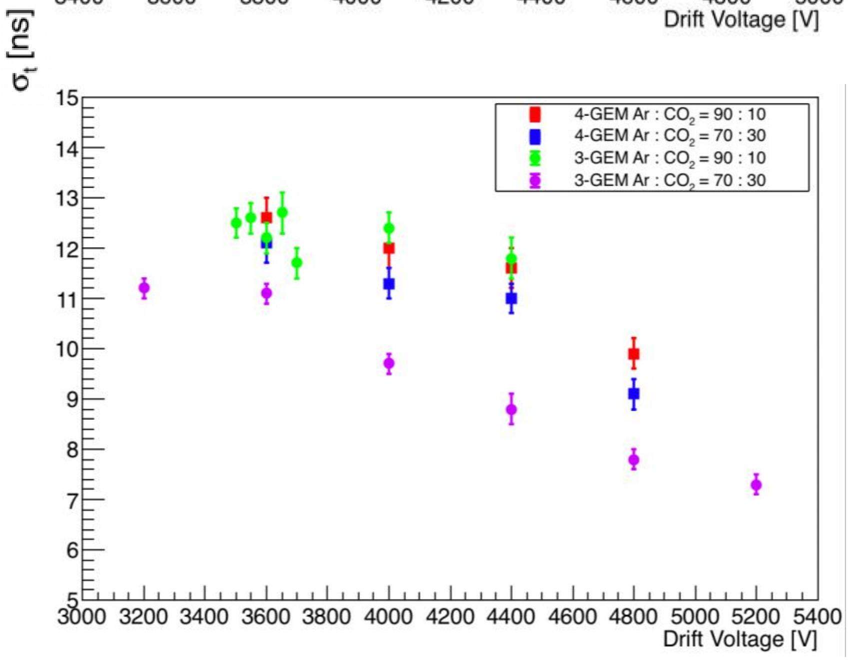
03 Simulation results: Time resolution



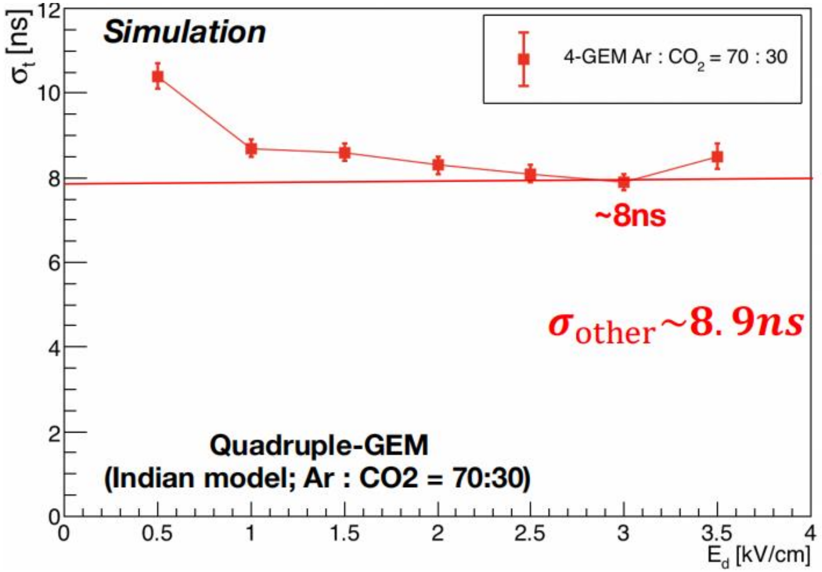
somewhat worse compared with the triple-GEM detector



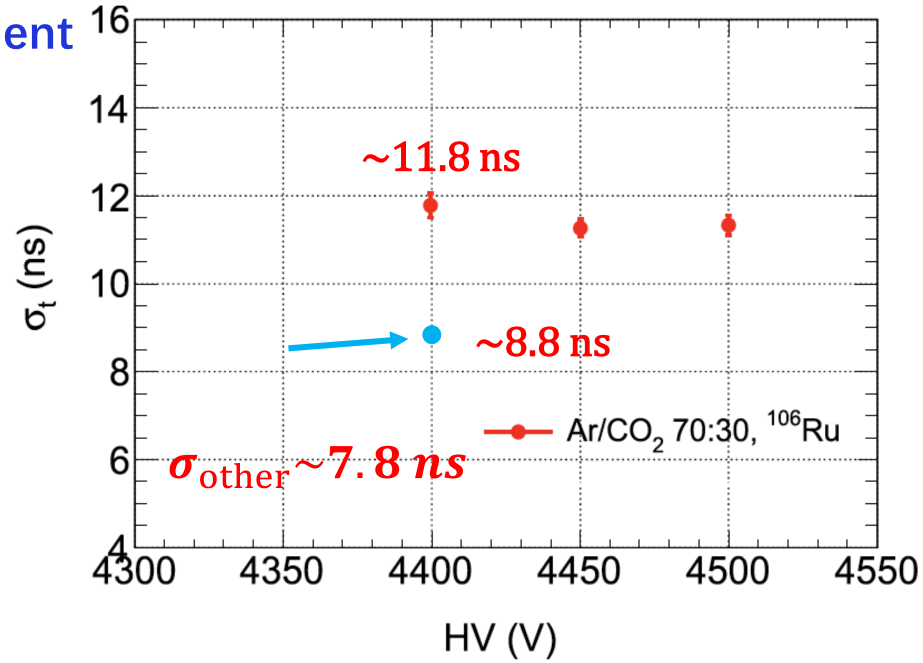


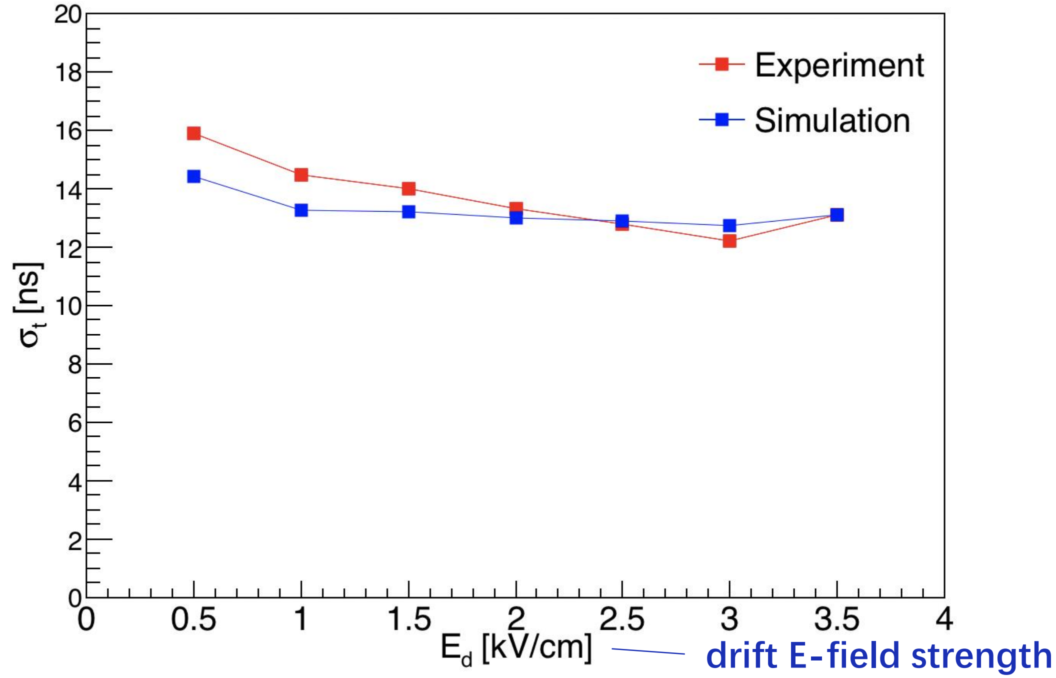


03 Simulation results: Time resolution



experiment

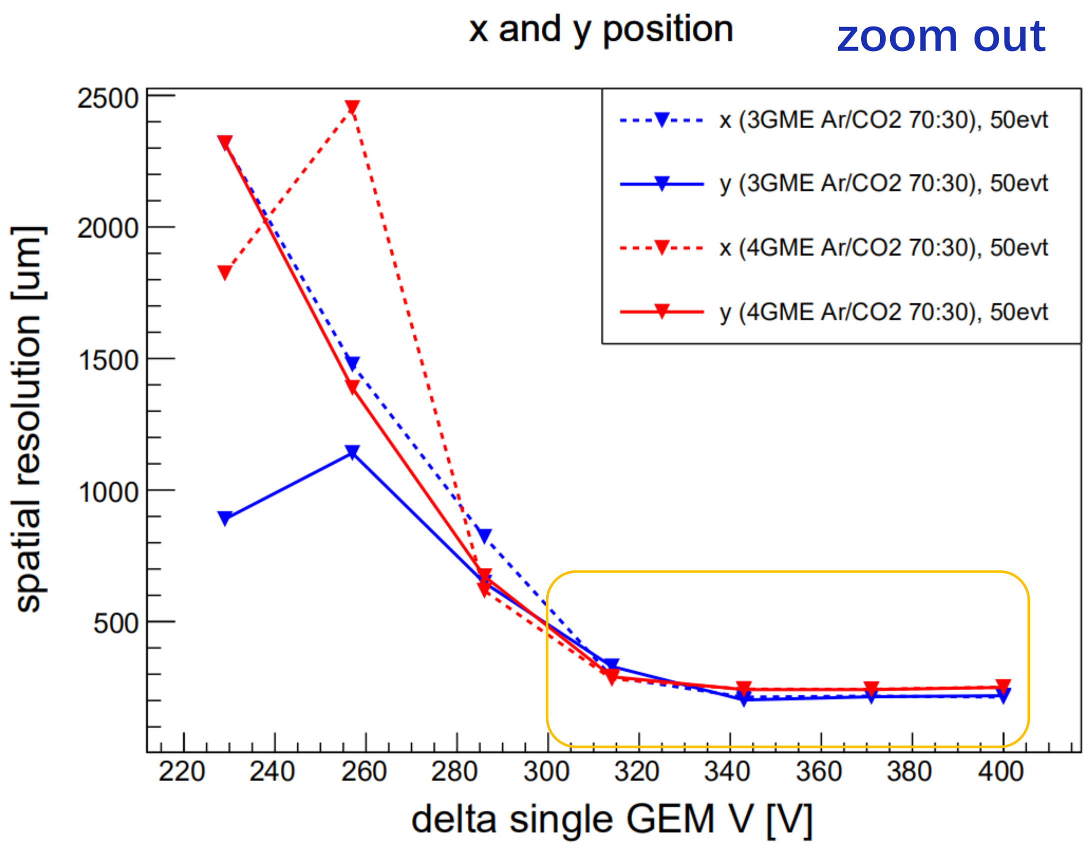


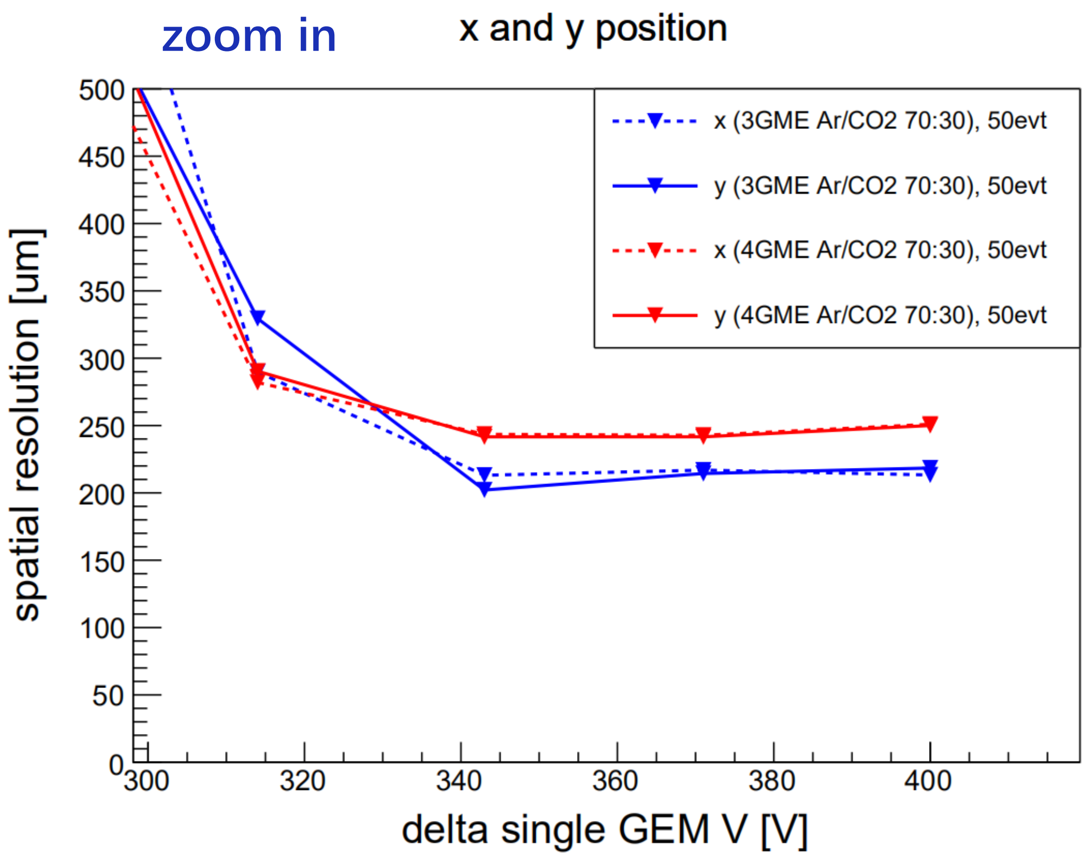


★Simulated electronics noise (~10ns) has been added into simulation results. Error bars are not shown in this figure.

★The simulation results are somewhat close to the experimental results.

03 Simulation results: Spatial resolution

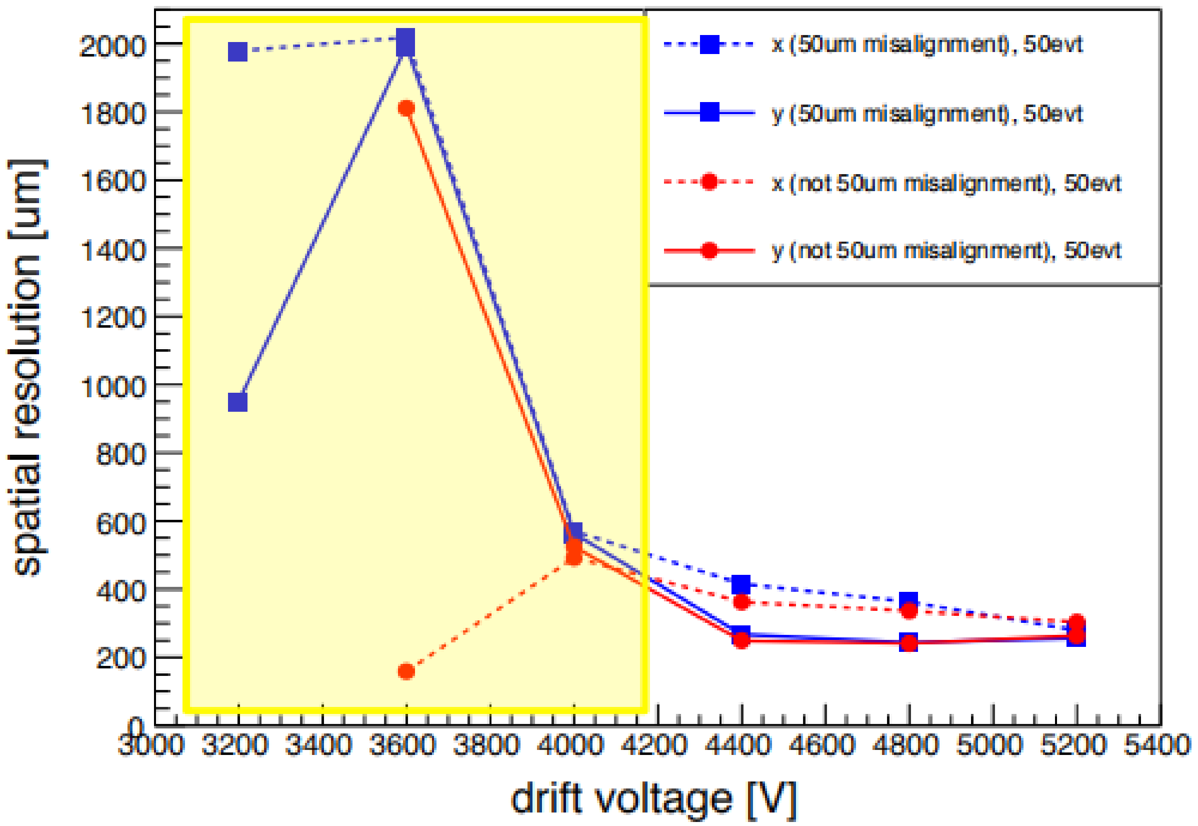




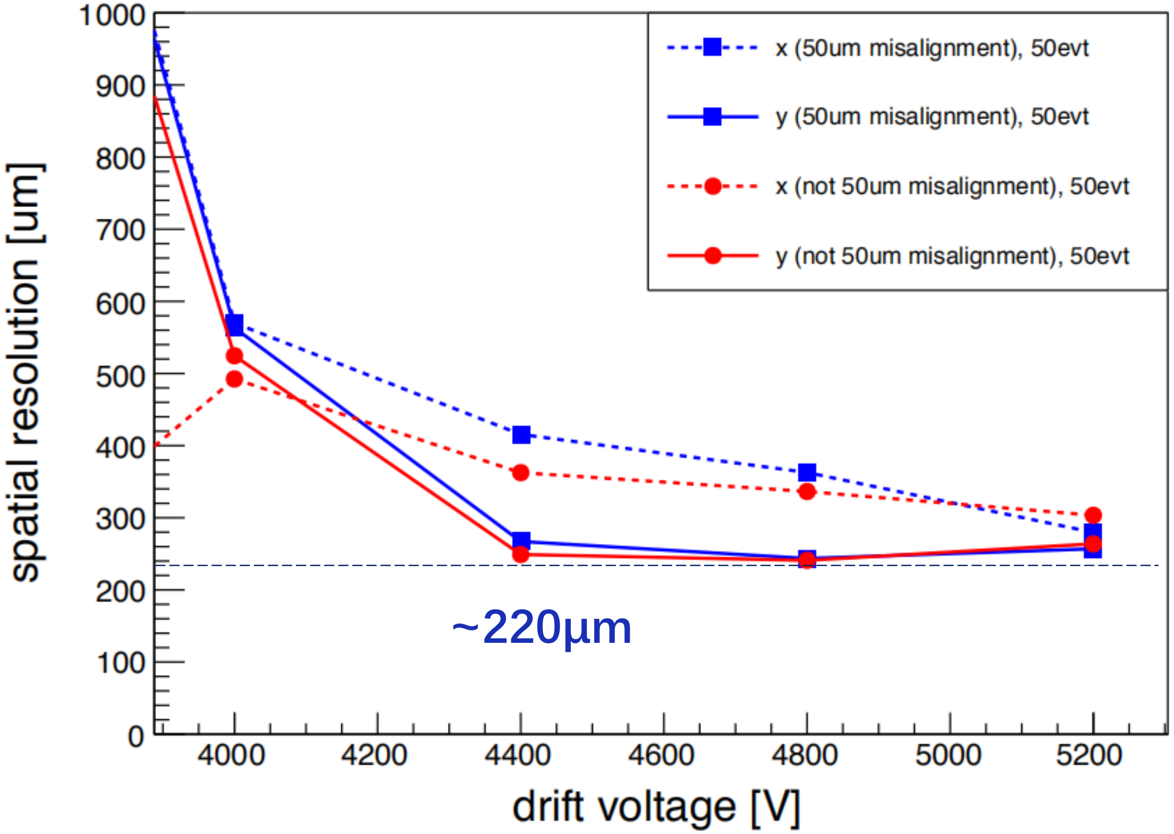
- At very low voltage, the spatial resolutions calculated by method one are poor and has large fluctuations,
- At very high voltage, quadruple-GEM's has worse spatial resolution. .

03 Simulation results: Spatial resolution

zoom out



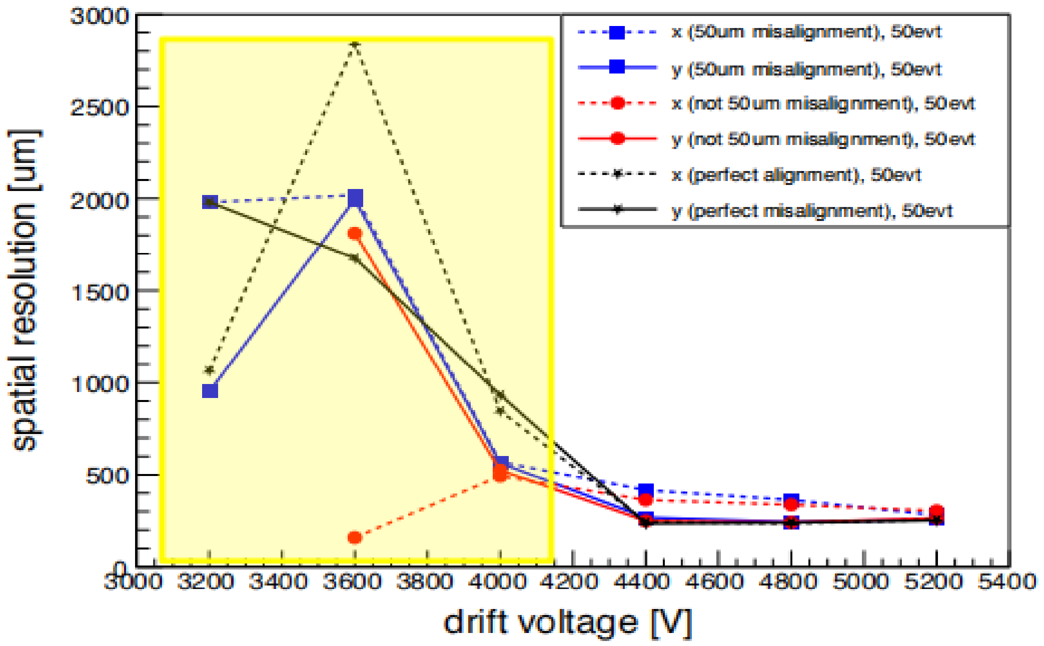
zoom in



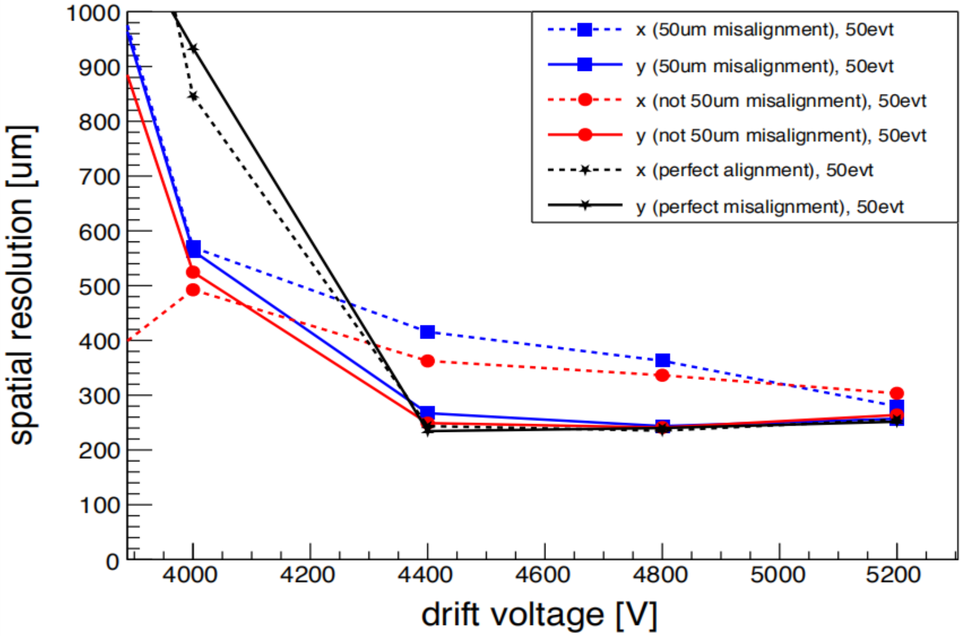
- At very low voltage, the spatial resolutions are poor and has large fluctuations,
- At very high voltage, the spatial resolutions of hole mis-alignment model① are somewhat better than model②, spatial resolutions in y are better than in x direction.

03 Simulation results: Spatial resolution

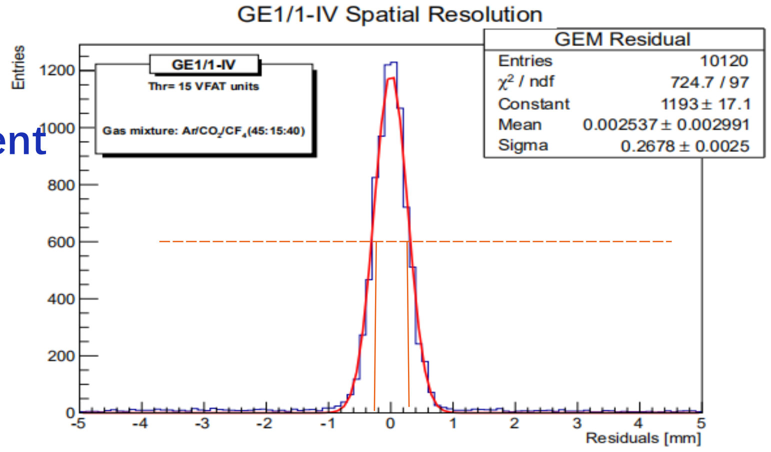
zoom out



zoom in

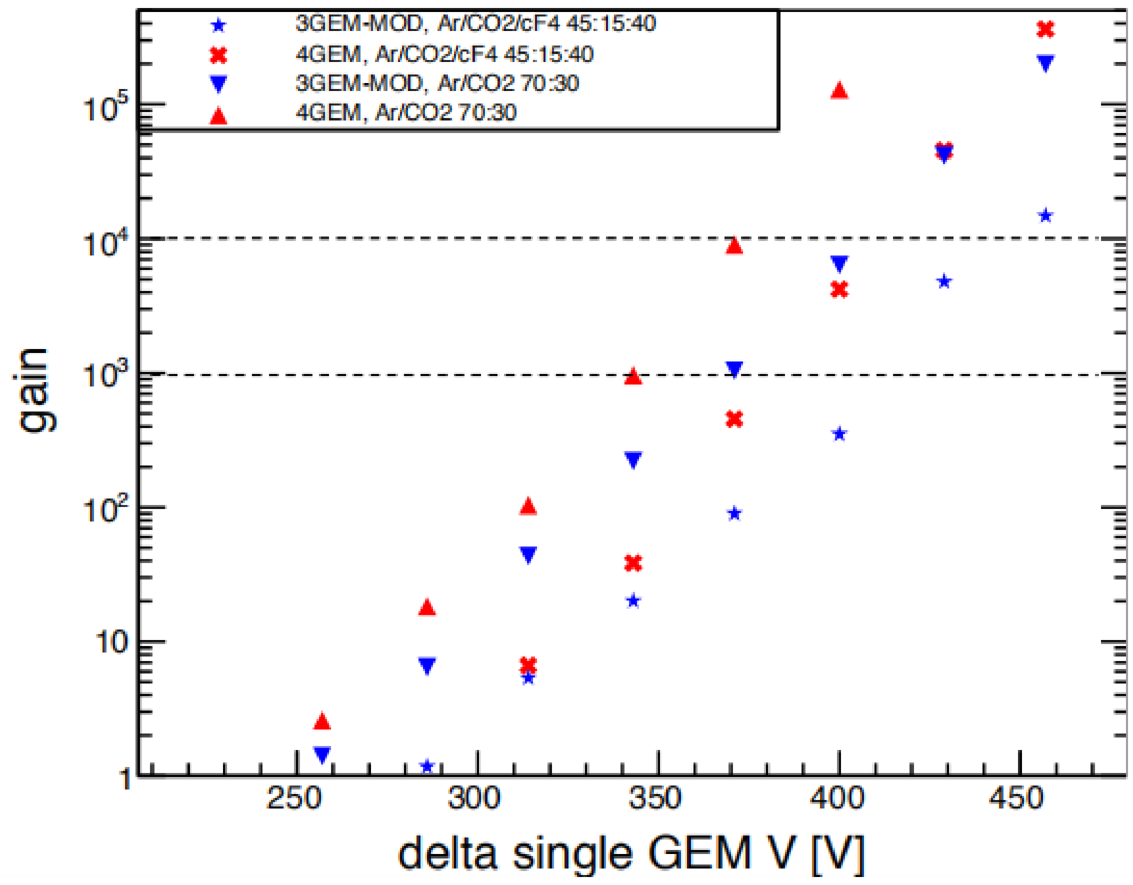


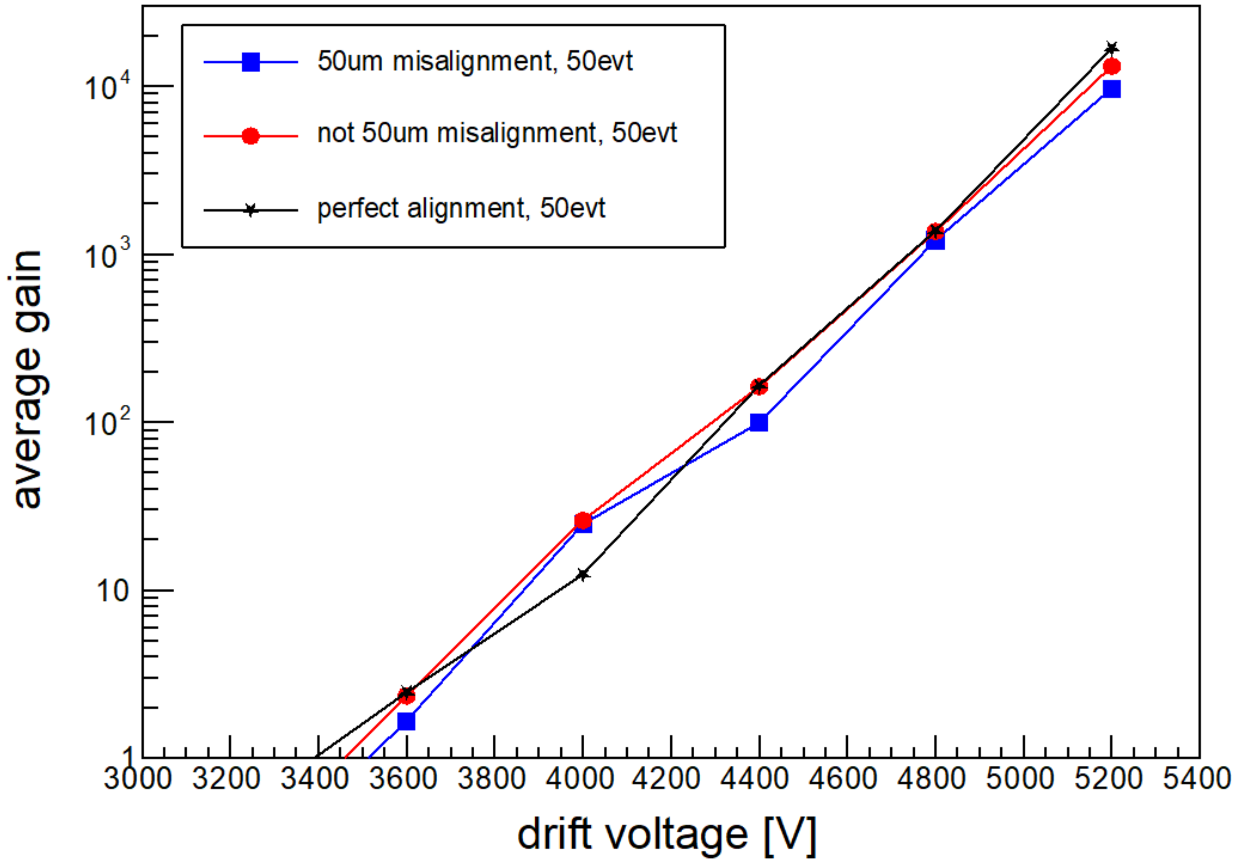
experiment
~300μm



- At very low voltage
  → poor spatial resolution + large fluctuations
- At very high voltage
  → aligned model < model① < model②
  → y position < x position

03 Simulation results: Effective gain





- electronegative gas → effective gain decreases
- aligned or mis-aligned hole layouts has almost no effect on gain.
- a magnitude difference between the simulation and experiment results is observed.

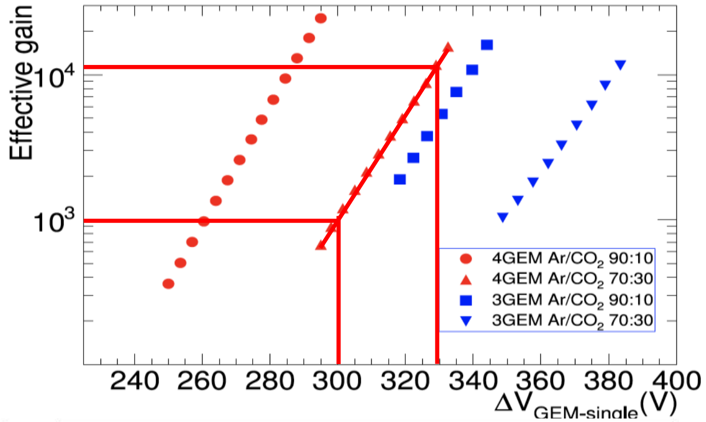
03 Simulation results: Effective gain

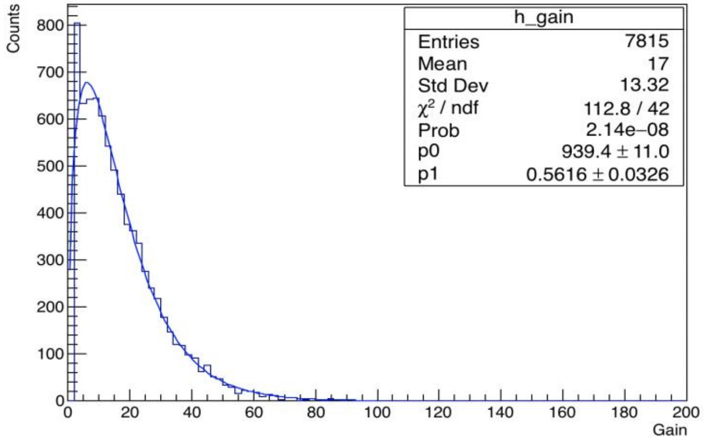
Step by step multi-GEM parameterized simulation technique(STEPS) method:

$\varepsilon_{coll,GEM1} \times Gain_{GEM1} \times \varepsilon_{extr,GEM1}$ × $\varepsilon_{coll,GEM2} \times Gain_{GEM2} \times \varepsilon_{extr,GEM2}$ × $\varepsilon_{coll,GEMN} \times Gain_{GEMN} \times \varepsilon_{extr,GEMN}$

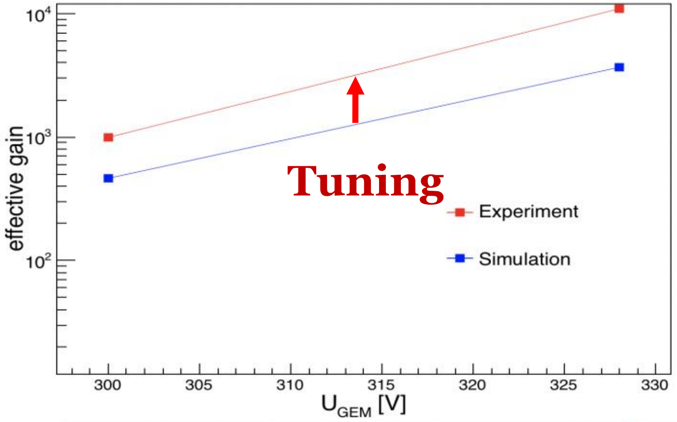
= **Effective Gain!!!**

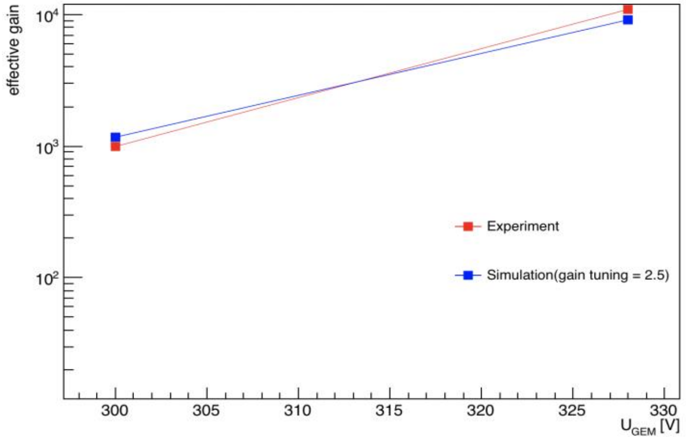
experiment





simulation





- **The fluctuations of gain can be described pretty well by the *Polya distribution*[2], but it lacks any physical interpretation.**

$$P(G) = C_0 \frac{(1+\theta)^{1+\theta}}{\Gamma(1+\theta)} \left(\frac{G}{\bar{G}}\right)^{\theta} \exp\left[-(1+\theta)\frac{G}{\bar{G}}\right]$$

- **Where $\bar{G}$ is the average gain and θ is the parameter related to relative gain variance $\sigma^2 = 1/(1+\theta)$.**

- obtain gain tuning factor on the basis of specific experiments
- tune the simulation parameters through comparing with experimental data
- Simulation calculate again

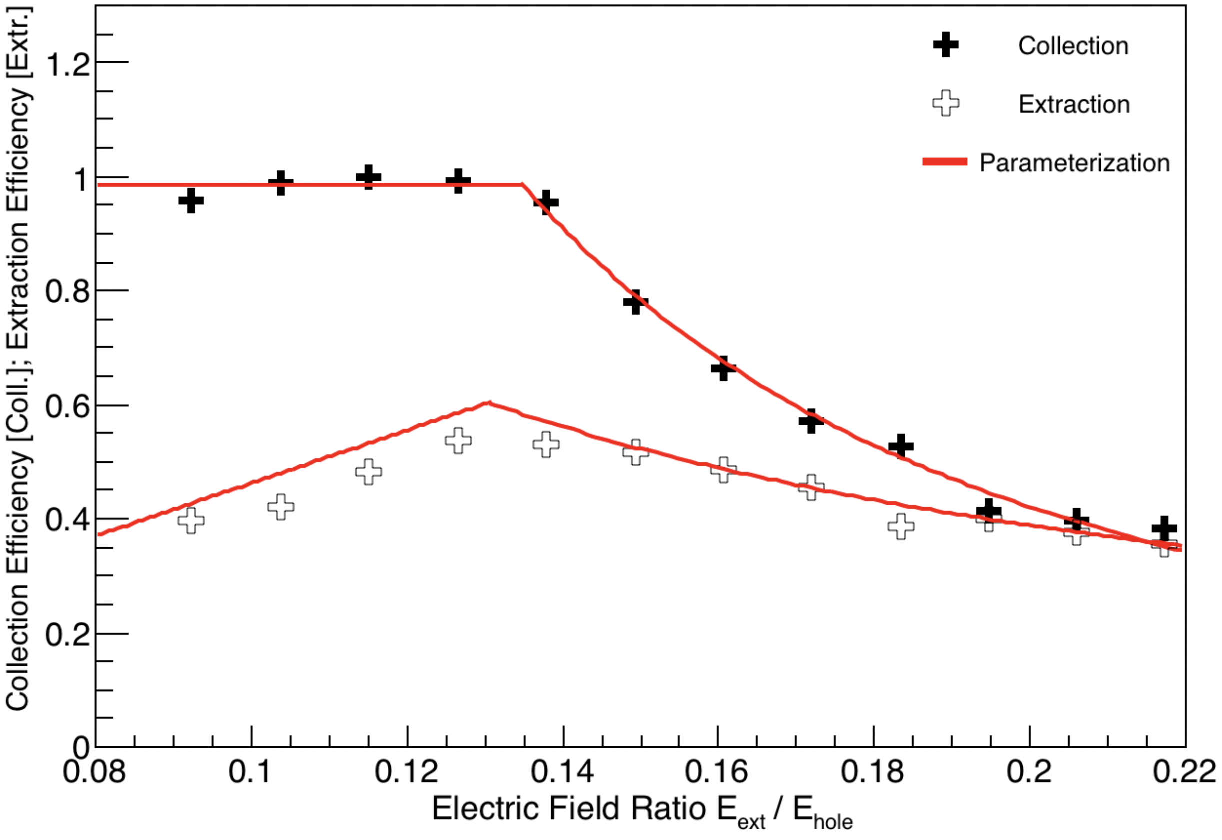
03 Simulation results: Transparency

Transparency of the GEM foil contain 2 parts:

- how many electrons can be collected by the holes
- how many electrons can be extracted out of the holes

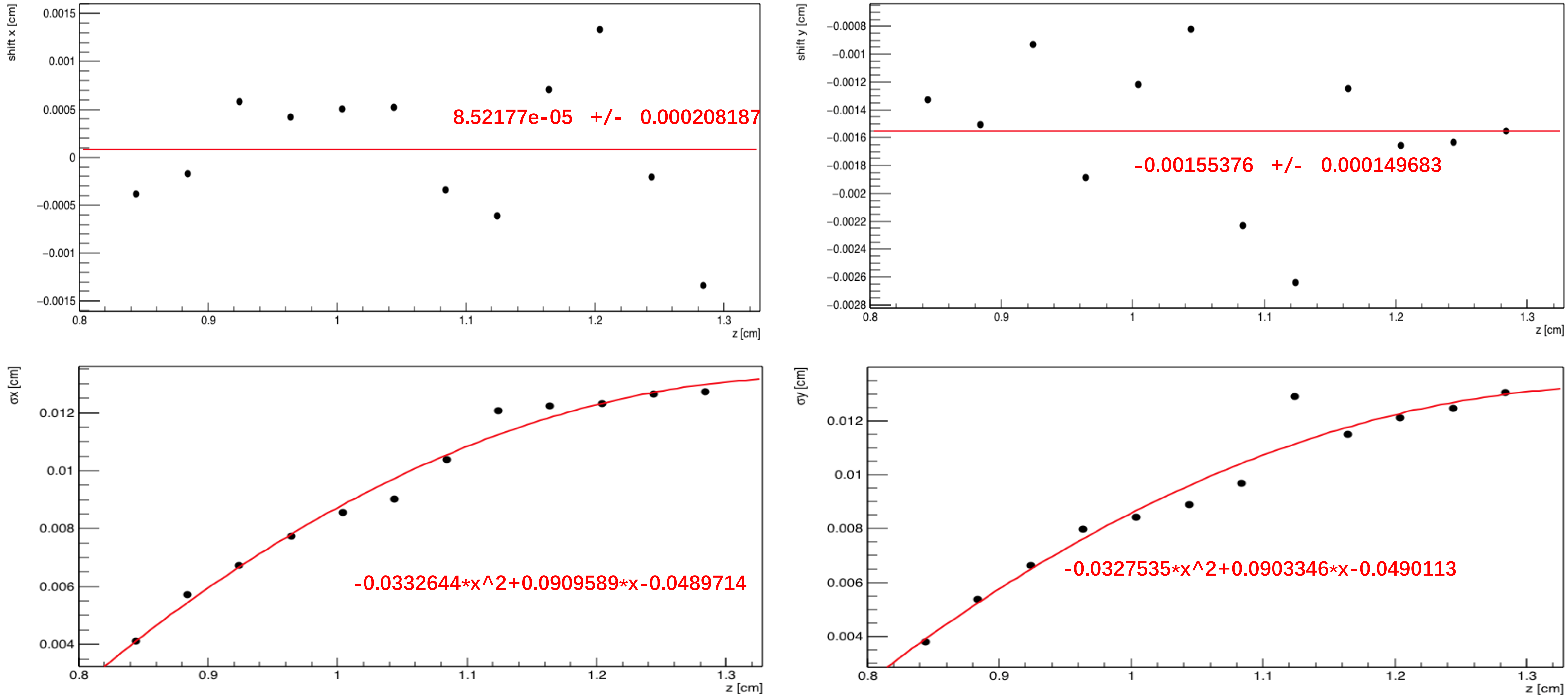
$$Coll. = \begin{cases} 0.016 \times \left(\frac{E_{ext}}{E_{hole}}\right)^{-2.03}, & \frac{E_{ext}}{E_{hole}} > 0.016^{\frac{1}{2.03}} \\ 0.016^{\frac{1}{2.03}}, & \frac{E_{ext}}{E_{hole}} \leq 0.016^{\frac{1}{2.03}} \end{cases}$$

$$Extr. = \begin{cases} \frac{0.016}{0.22} \times \left(\frac{E_{ext}}{E_{hole}}\right)^{1-2.03}, & \frac{E_{ext}}{E_{hole}} > 0.016^{\frac{1}{2.03}} \\ \frac{1}{0.22} \times \left(\frac{E_{ext}}{E_{hole}}\right), & \frac{E_{ext}}{E_{hole}} \leq 0.016^{\frac{1}{2.03}} \end{cases}$$



- figure shows how the electron transparency of one GEM foils change with electric field ratio;
- E_{ext} is the electric field strength outside the holes/E_{hole} is the field strength inside the holes;
- transparency is the product of collection and extraction efficiency.

03 Simulation results: Drift



variation of shift x&y/spread σ_x&σ_y as a function of z position

04 Summary and outlook

- We have studied triple-GEM and quadruple-GEM with aligned and misaligned hole positions at various voltage settings, simulated the primary ionization, drift, diffusion, avalanche multiplication and induction signal readout process.

- Calculation methods of various performance characteristics have been researched: time/spatial/energy resolutions, effective gain, electron transparency, Ion Back Flow ratio, drift properties, transport parameters

- Simulation results of some performance characteristics of quadruple-foils GEM detector were obtained, various comparisons have been performed:
  - between triple-GEM and quadruple-GEM;
  - between hole aligned model and two different misalignment models of quadruple-GEM;
  - between simulation and experiment results of triple-GEM and quadruple-GEM.

04 Summary and outlook

- ✓ **Time resolution:**

  the simulation results are consistent with experiment. Quadruple-GEM has somewhat worse time resolution compared with the triple-GEM at present detector structure model.

- ✓ **Spatial resolution:**

  at higher voltage the simulation results are consistent with experiment. Quadruple-GEM have worse spatial resolution than triple-GEM at present detector structure model. No obvious difference was observed for the three hole alignment models.

- ✓ **Effective gain:**

  electronegative gas causes the decrease of effective gain. Results of three quadruple-GEM hole alignment models are similar. There is a magnitude difference between simulation and experiment results using the full simulation method .The STEPS method gives more consistent results with the experiment.

04 Summary and outlook

- To optimize the calculation methods and increase the statistics to improve the GEM performance simulations, research and understand the reason of the differences between experiment and simulation (as in effective gain);
- To carry out simulation study of other performance characteristics such as energy resolution / IBF..., and to research the analysis strategy of more performance characteristic -s such as charging-up/discharge...
- More simulations on different detector layouts, to identify the key factors which may have major influences on the performances, and to optimize quadruple-foils GEM structure design;
- Study the performance characteristics of other MPGD technique, such as resistive electrodes···

Thank you~

References

[1] Patra R N , Singaraju R N , Biswas S , et al. Characteristic study of a quadruple GEM detector and its comparison with a triple GEM detector[J]. Nuclear Instruments & Methods in Physics Research, 2018, 906(OCT.21):37-42.

[2] R. N. Patra et al., Measurement of basic characteristics and gain uniformity of a triple GEM detector, Nucl. Instr. and Meth. A.862 (2017) 25.

[3]A Colaleo, A Safonov, A Sharma et al. "CMS Technical Design Report for the Muon Endcap GEM Upgrade". 2015.

* All the experiment figures in these steps are obtained from the ALICE TPC 4-layer-GEM detector model(5200V, Ar:CO2=70:30)