Development of an Electron-Tracking Compton Camera using CF_4 gas at high pressure for improved detection efficiency

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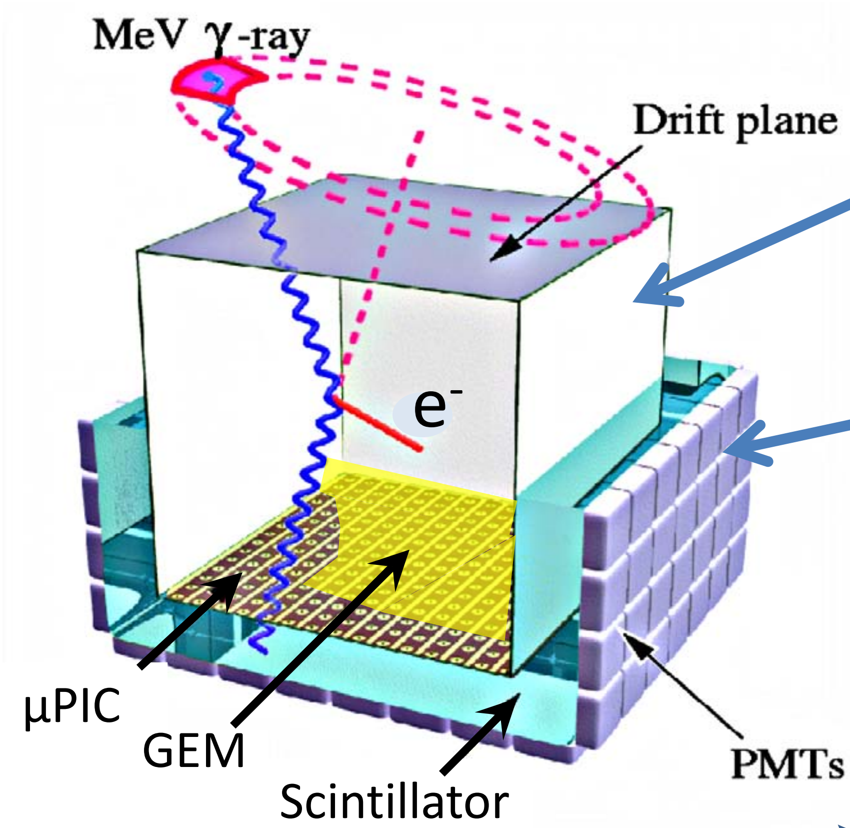
Outline

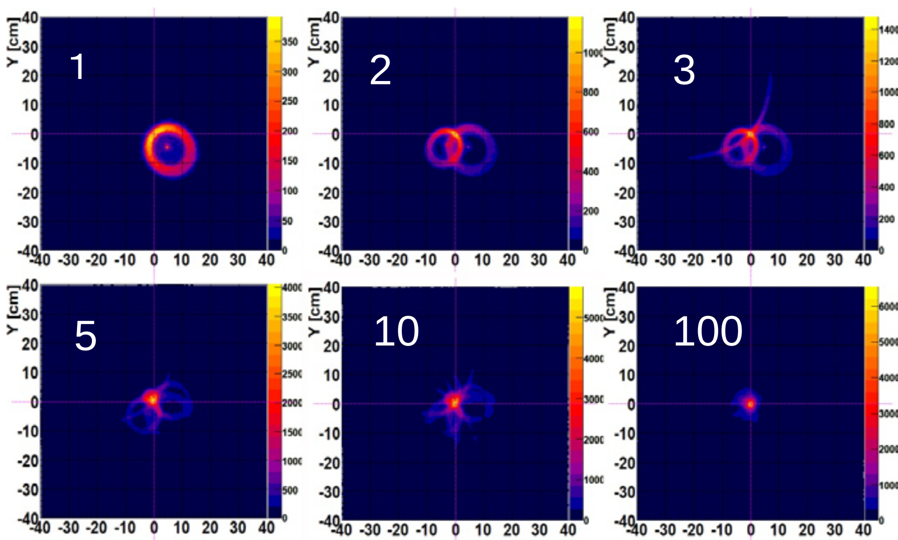
- Introduction
  - Electron-Tracking Compton Camera (ETCC)
  - Medical imaging / MeV gamma-ray astronomy
- Optimization of gas mixture
- Operation at high pressure
- Summary

Electron-Tracking Compton Camera (ETCC)



μTPC (Time Projection Chamber)
--- 3D track and energy of
Compton-recoil electron

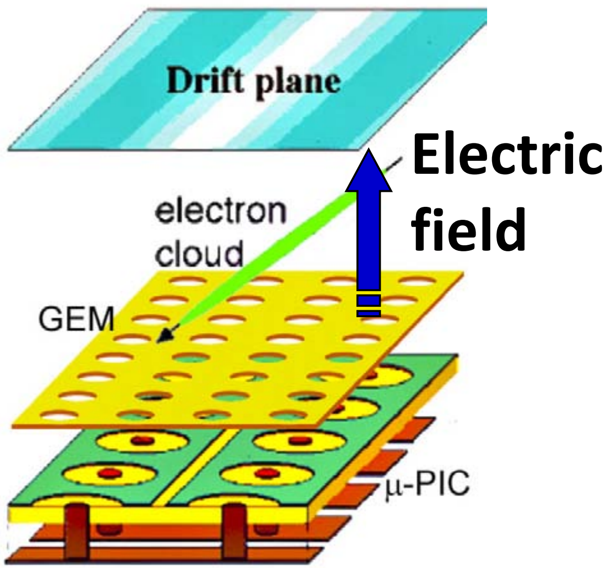
Scintillation camera
--- position and energy of
scattered gamma ray



· Determination of **direction** and energy of **each incident gamma ray**
· Large FOV (~ 3 sr)

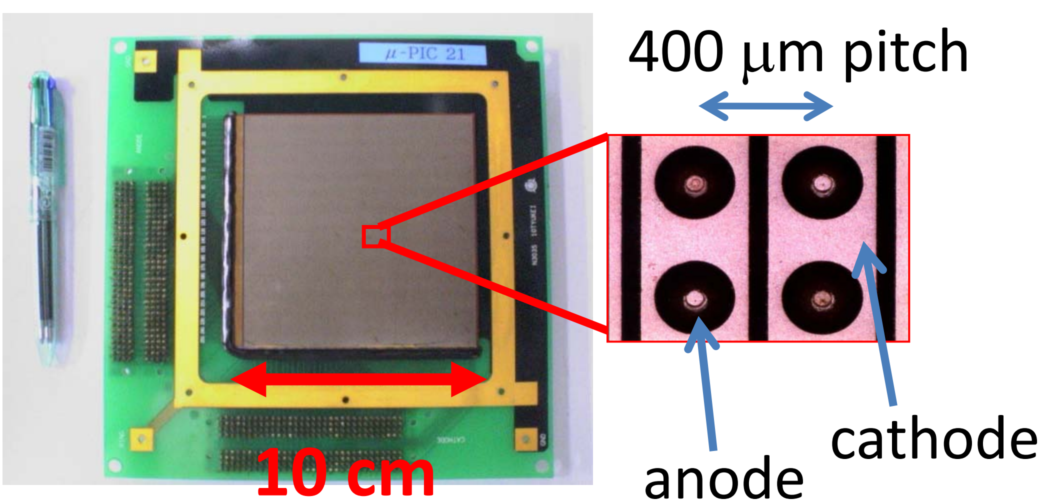
B26 K. Ueno, A22 S. Kurosawa

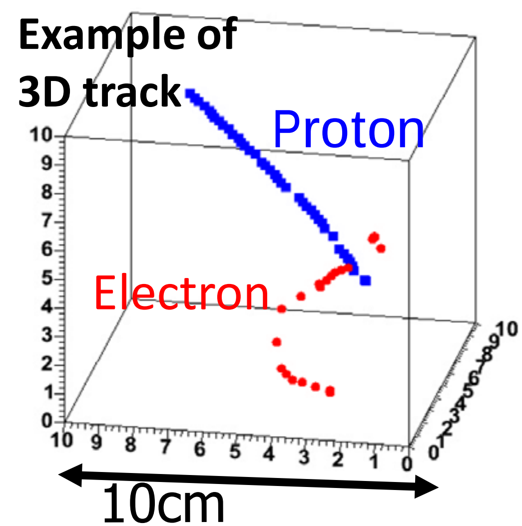
μTPC (Time Projection Chamber) for 3D electron track



GEM (Gas Electron Multiplier) (F. Sauli (1997))
+ μPIC (micro PIxel Chamber) ← 2D readout
micro pattern gaseous detector
∴ 2D readout + Drift time → 3D track

Prototype μTPC size : 10 × 10 × 10 cm^3
Gas : **Ar/C_2H_6 (90:10) at 1 atm**, sealed
Position resolution : ~ 150 μm (1D)
Stable gas gain : ~ 30000 (μPIC : ~ 3000, GEM : ~ 10)

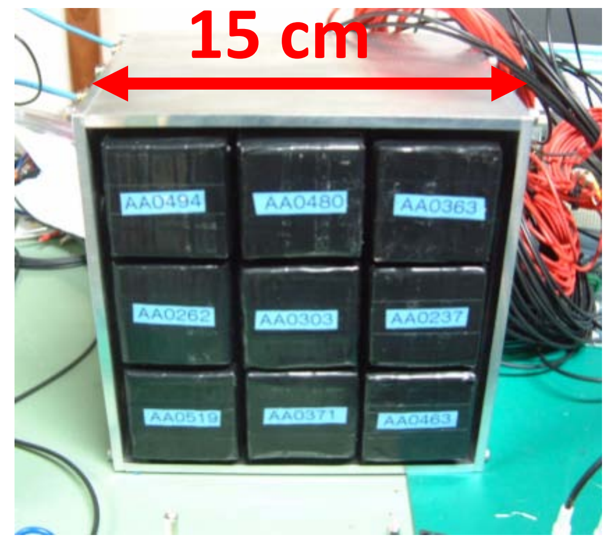


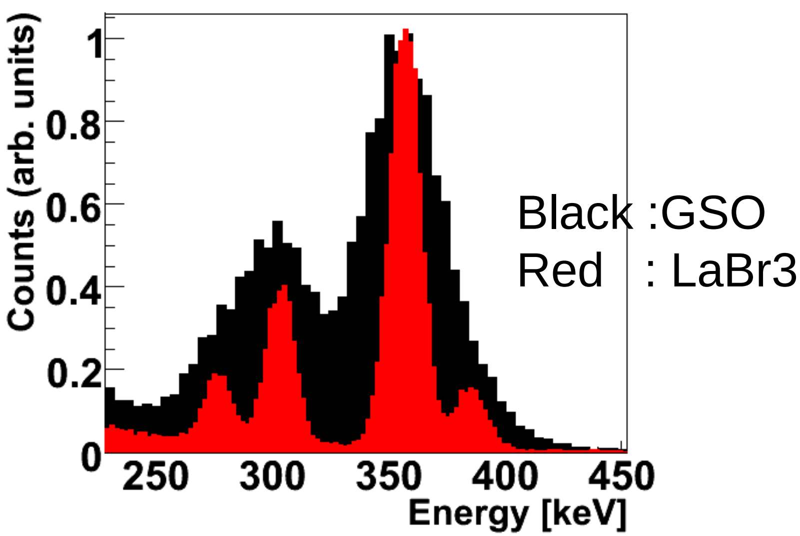


GSO and $LaBr_3$ Scintillation Cameras

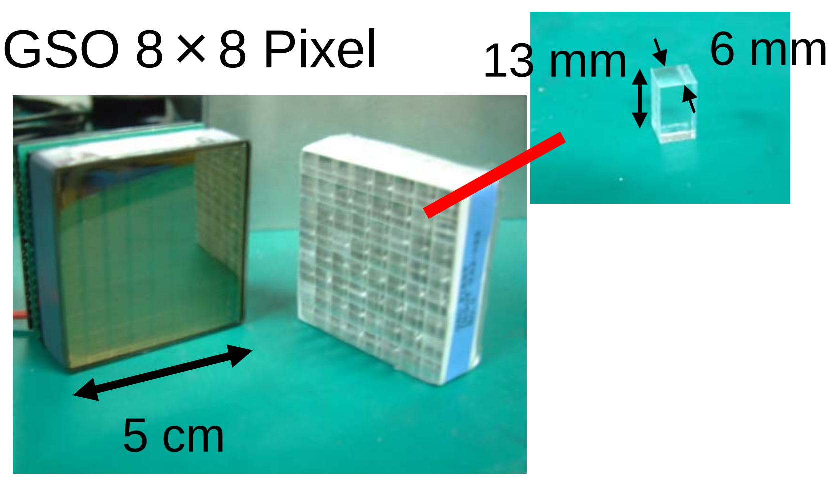
15 x 15 cm^2 Camera
(GSO or $LaBr_3$
+ Multi anode PMT (H8500, HPK))

- Number of pixels: 576
- Pixel size $6 \times 6 \times 13$ mm^3 (GSO)
  $6 \times 6 \times 15$ or 20 mm^3 ($LaBr_3$)
- GSO Energy resolution :10.0 % (@662keV, FWHM)
- $LaBr_3$ Energy resolution: 6.5% (@662keV, FWHM)
- Position resolution: 6mm





GSO 8×8 Pixel



MeV gamma-ray camera projects

Medical : Advantage point:

wide energy dynamic range (300 – 3000 keV) and **wide FOV**

(SPECT < 300 keV, PET 511 keV)

Scinti : $LaBr_3$

1. Multi RI Tracer Imaging
   --- The development of new RI drugs
2. Proton Therapy
   --- Real time monitor of prompt gamma rays to measure Bragg-peak position

Astronomy :

Sub-MeV gamma-ray Imaging Loaded-on-balloon Experiment (SMILE)

Scinti : GSO

1. SMILE-I (2006, launched)
   - Operation test of ETCC @35 km
   - Measurement of diffuse cosmic and atmospheric gamma rays (~ 400 photons) ~ 4 hours
2. SMILE-II (2011)
   - Observation of Crab Nebula or Cygnus X-1 ~ 3 hours

Examples of Medical Imaging

Zn-65-Porphyrin imaging (1116 keV)

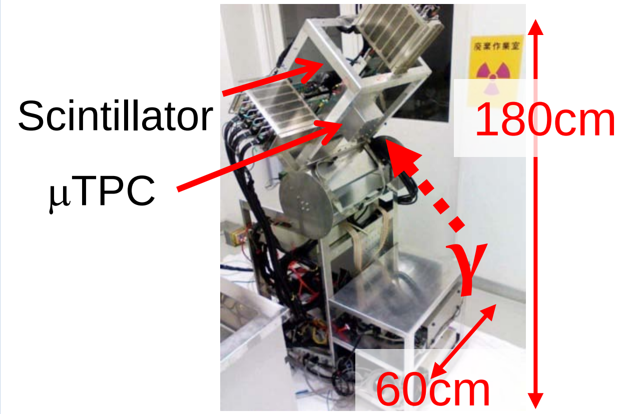
Porphyrin was accumulated in RGK-36 which is the tumor of rat stomach cancer.

Spatial resolution
~ 10 mm (FWHM)

Energy window : ±10%
1004 ~ 1228 keV

Activity : 0.16 MBq
Time : 110.5 hours
Events : 173 events

ETCC for medical use



Scinti : $LaBr_3$

2 sources imaging
Time : 6 hours

For High Sensitivity

✵ Increase detection area

- Multi-head camera ($10 \times 10 \times 10$ cm$^3 \times 2,3,\ldots$)
- Developing a large size ETCC ($30 \times 30 \times 30$ cm^3)

✵ Improvement of detection efficiency

- **Optimization of gas**
- **Operation at high pressure**

2 times better than our prototypes

Selection of gas sealed in μTPC

Ar/C_2H_6 (90:10) → CF_4 gas mixture

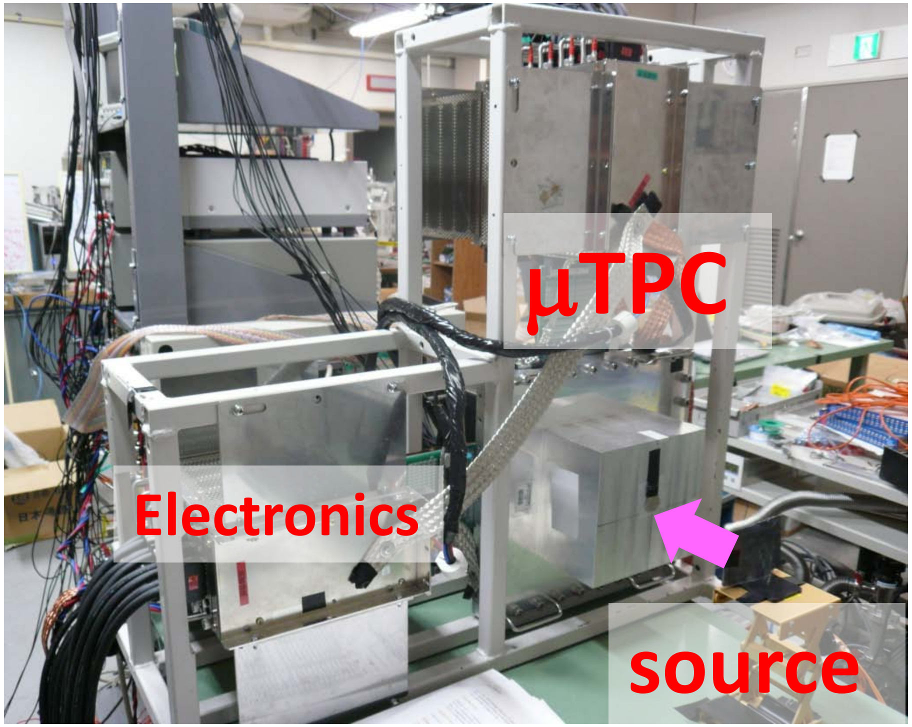
Merit of CF_4 gas

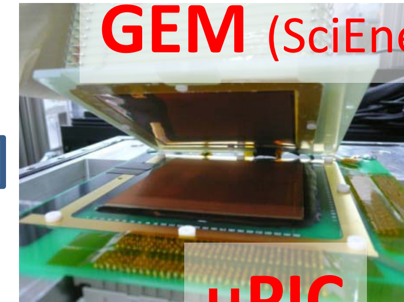
- Small diffusion → better position resolution (for μTPC)
  → better angular resolution (for ETCC)
- low Z (C : Z=6, F : Z=9) and 42 electrons in one molecule
  → Compton scattering is dominant → higher efficiency (for ETCC)

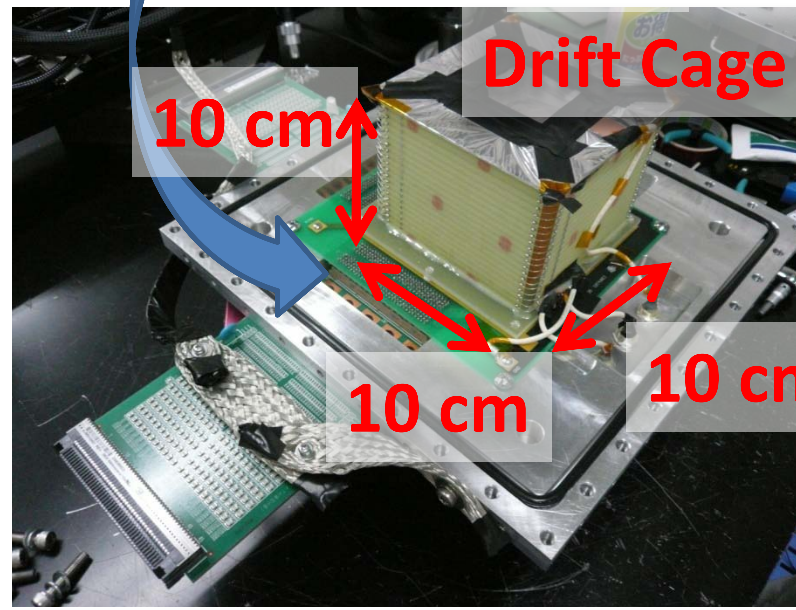
Demerit of CF_4 gas

- Low gas gain → isoC_4H_{10} gas (penning effect)
- High dependence of drift velocity on electric field →
  worse position resolution ?

Optimize the gas mixture







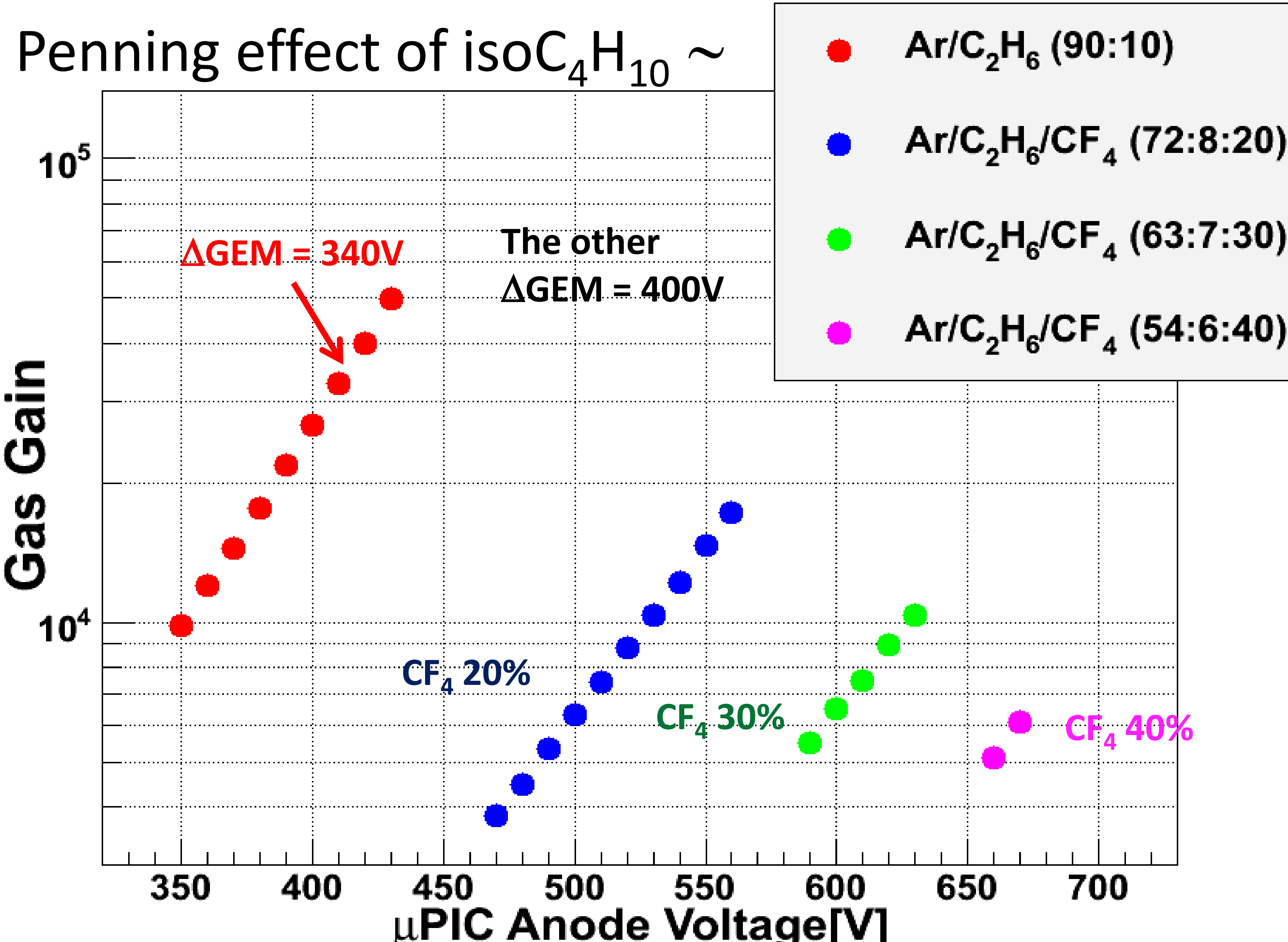
Gas
- **Ar/C_2H_6 (90:10)**
- **Ar**
- **CF_4**
- **$isoC_4H_{10}$**

Measurement
1. Gas Gain
2. Position Resolution

Requirements :
High CF_4 ratio
Gas Gain ~20,000

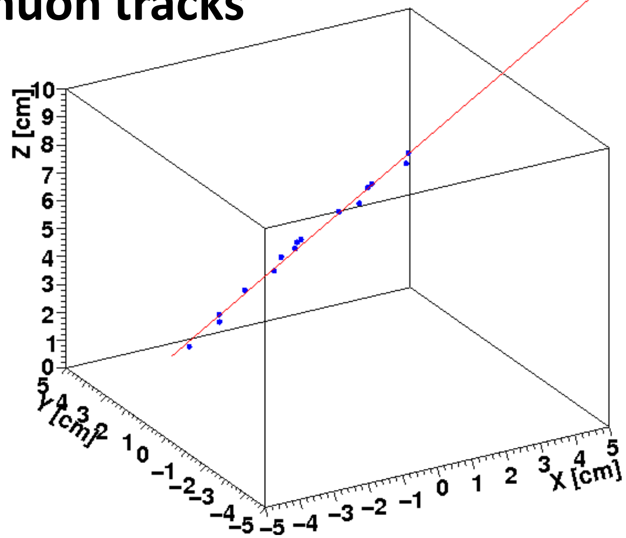
Gas Gain at 1 atm

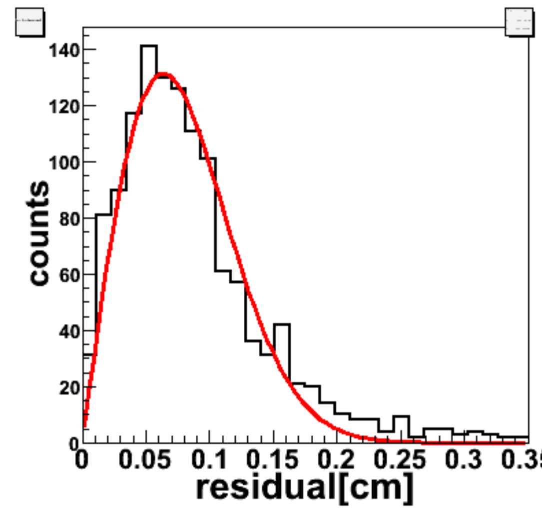
~ Penning effect of isoC_4H_{10} ~

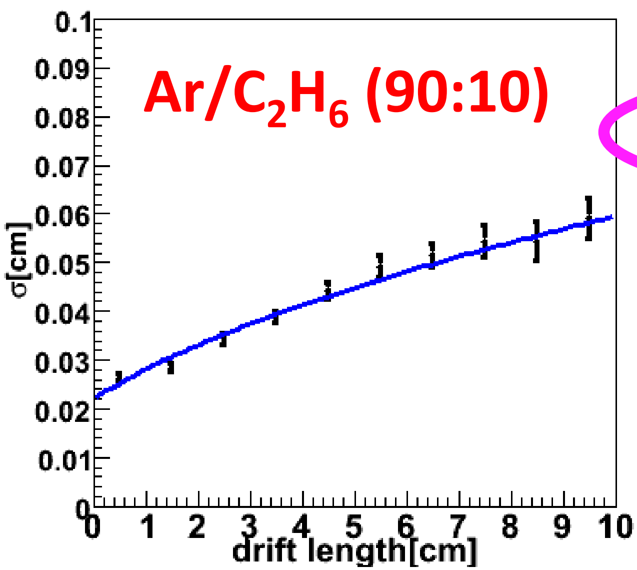


Position Resolution

muon tracks







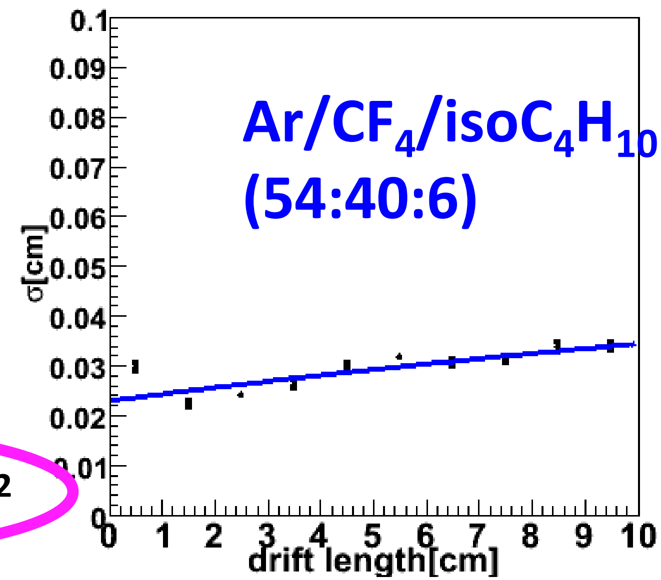
σ = 156 μm $\left(\sigma = \frac{\sigma_{\text{detector}}}{\sqrt{2}}\right)$

***D* = 175 μm/cm$^{1/2}$**

Better by factor 2

σ = 162 μm

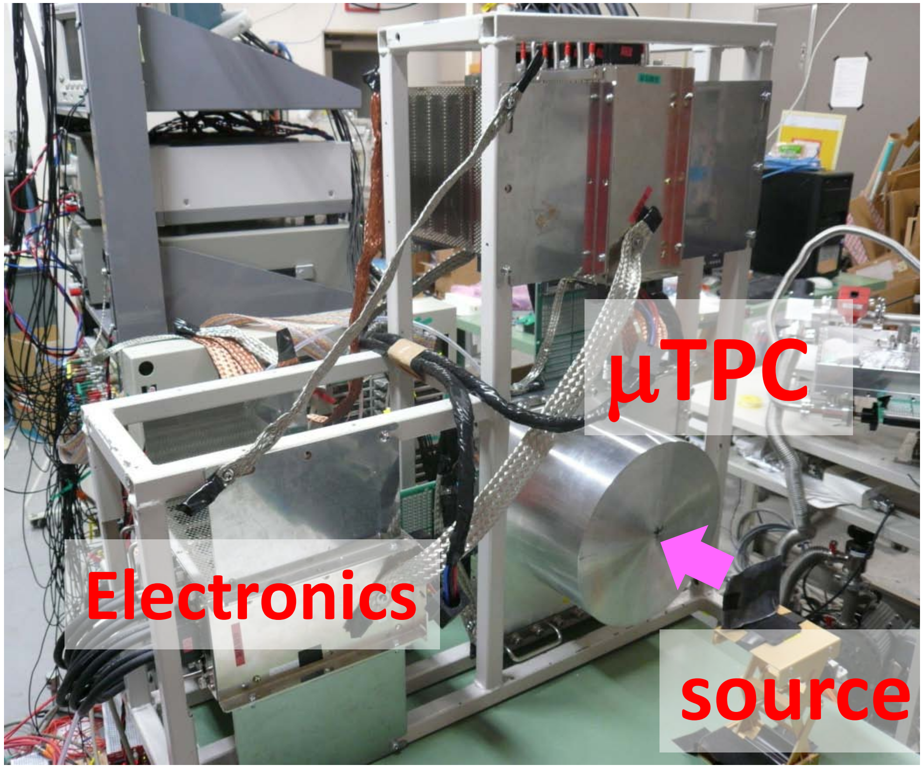
***D* = 81 μm/cm$^{1/2}$**

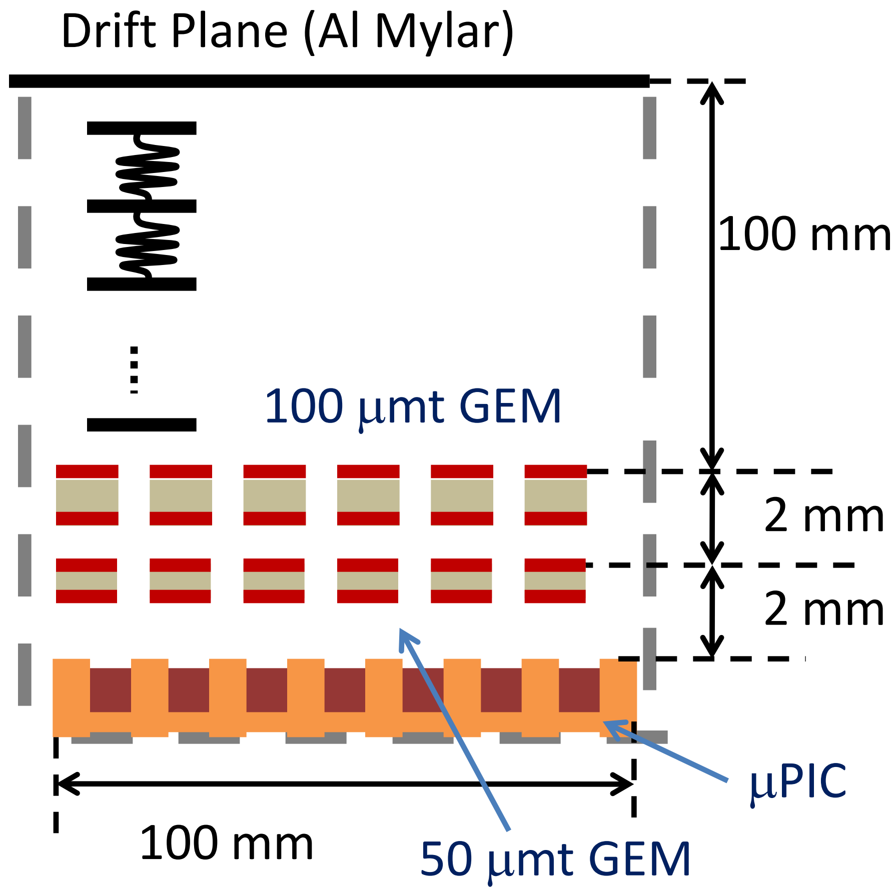


$$\sigma^2(l) = \sigma^2_{\text{detector}} + (D\sqrt{l})^2$$

l : Drift length
D : Diffusion Constant

High Pressure



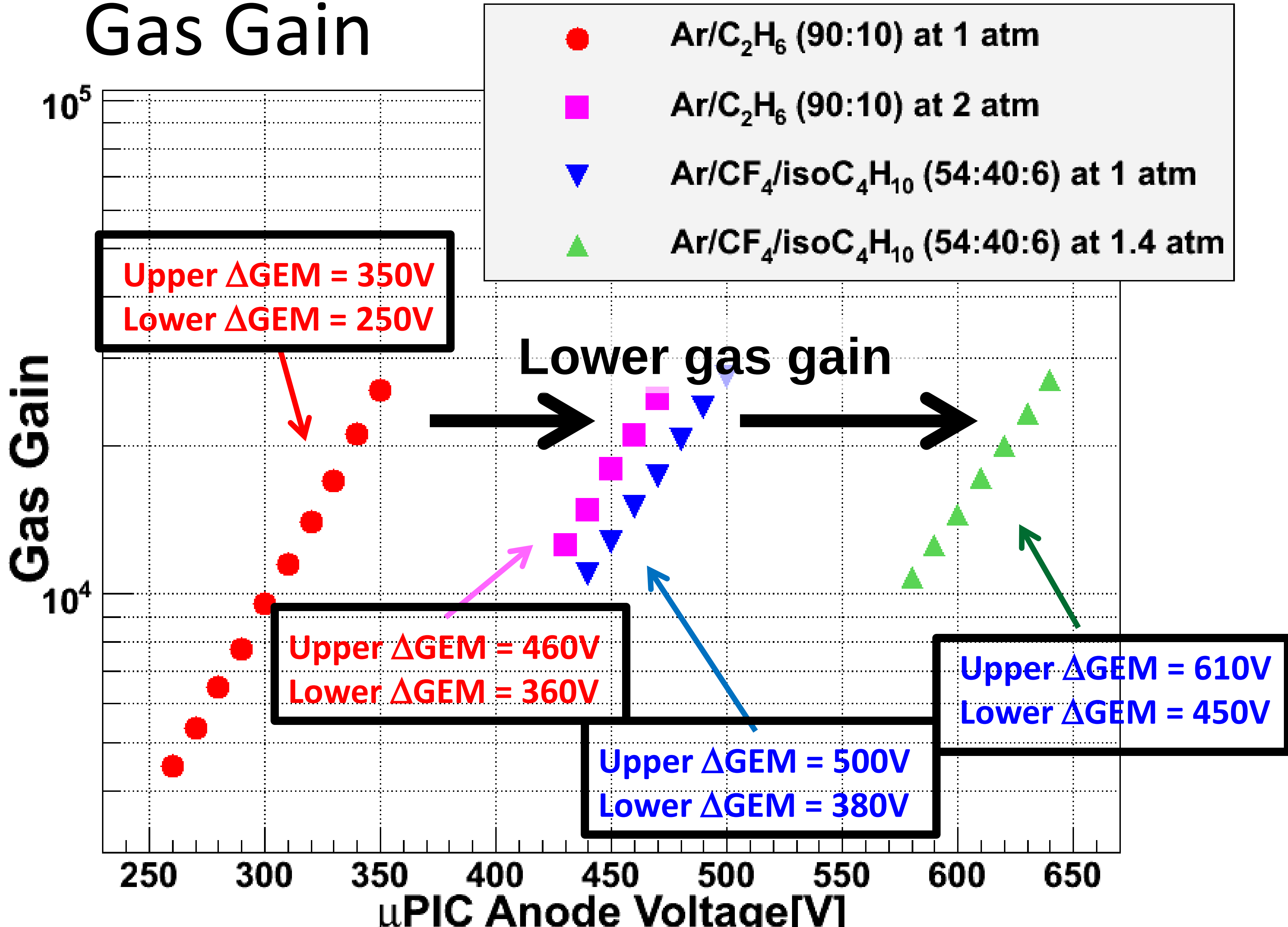


- Ar/C_2H_6 (90:10) at 1 atm
- Ar/C_2H_6 (90:10) at 2 atm
- $Ar/CF_4/isoC_4H_{10}$ (54:40:6) at 1 atm
- $Ar/CF_4/isoC_4H_{10}$ (54:40:6) at 1.4 atm

Measurement

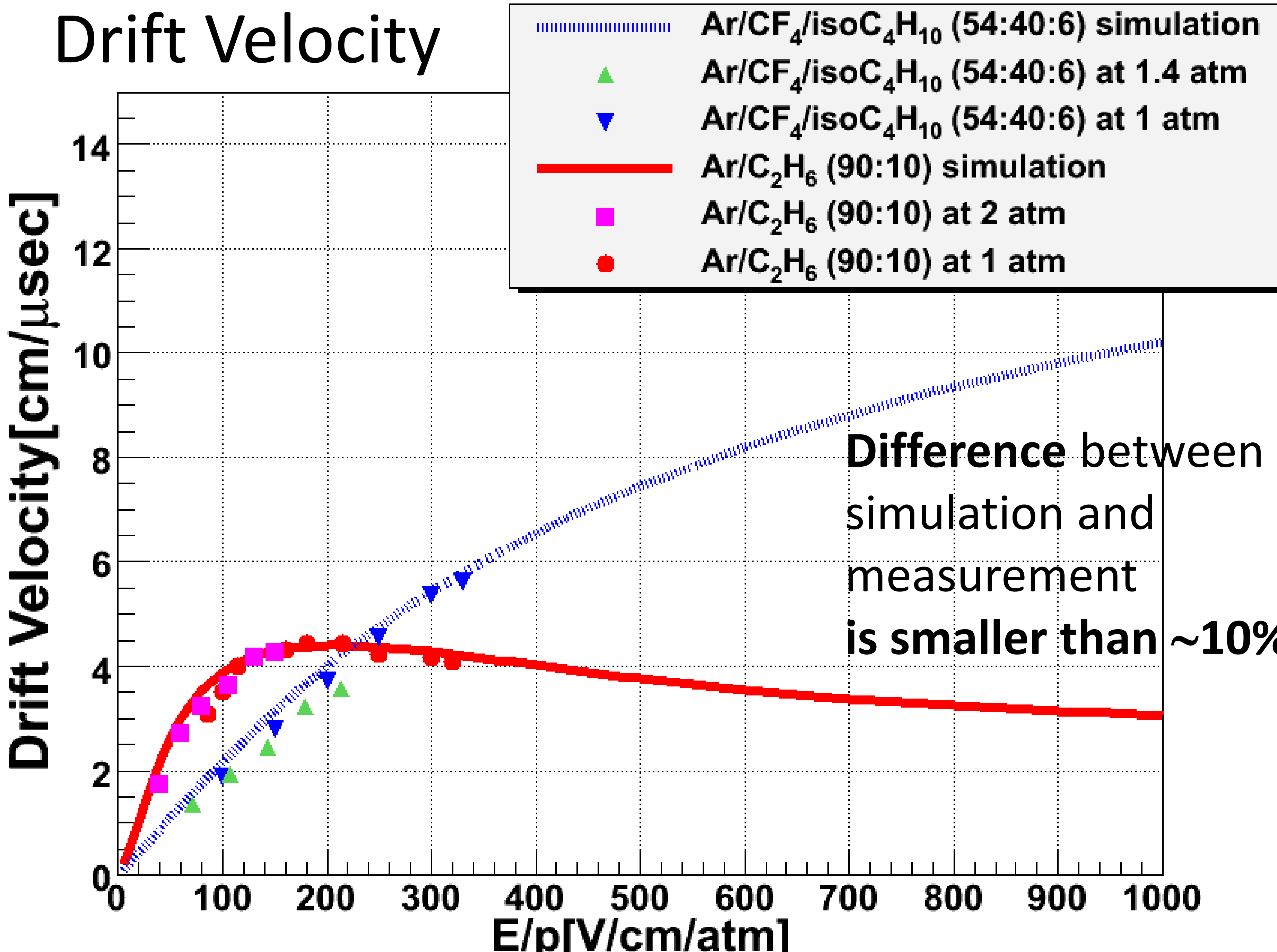
1. Gas Gain
2. Drift Velocity
3. Position Resolution
4. Energy Resolution

Gas Gain



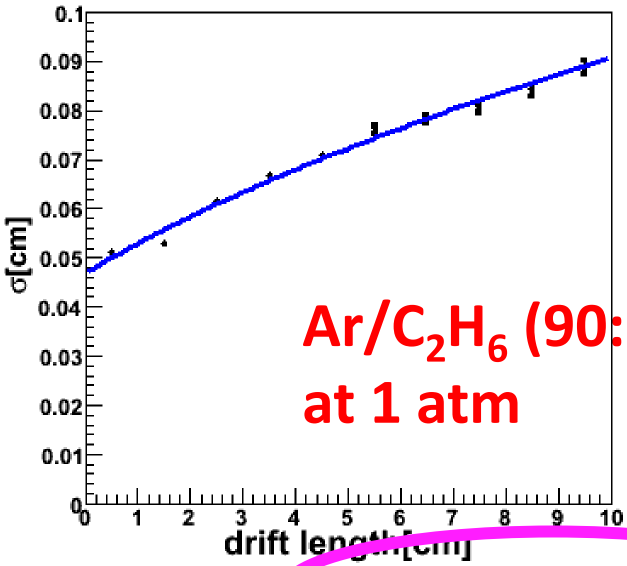
Ar/C2H6 (90:10) at 1 atm
Ar/C2H6 (90:10) at 2 atm
Ar/CF4/isoC4H10 (54:40:6) at 1 atm
Ar/CF4/isoC4H10 (54:40:6) at 1.4 atm
Upper ΔGEM = 350V
Lower ΔGEM = 250V
Lower gas gain
Upper ΔGEM = 460V
Lower ΔGEM = 360V
Upper ΔGEM = 500V
Lower ΔGEM = 380V
Upper ΔGEM = 610V
Lower ΔGEM = 450V
Gas Gain
μPIC Anode Voltage[V]
10^5
10^4
250
300
350
400
450
500
550
600
650

Drift Velocity



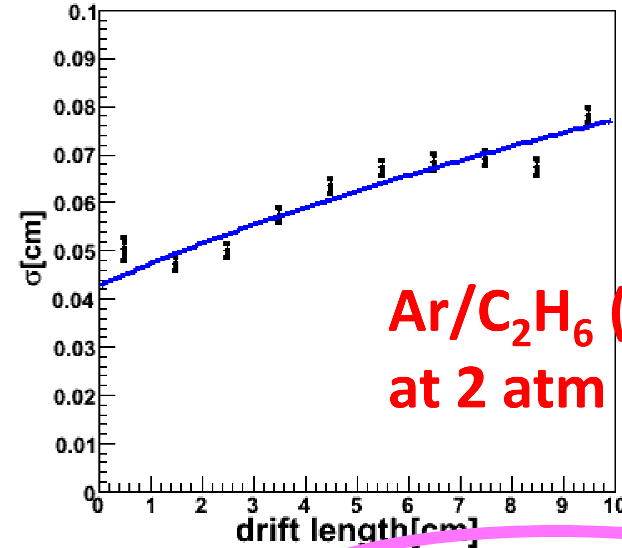
Difference between simulation and measurement **is smaller than ~10%**

Position Resolution



Ar/C_2H_6 (90:10) at 1 atm

σ = 332 μm, D = 246 μm/cm$^{1/2}$

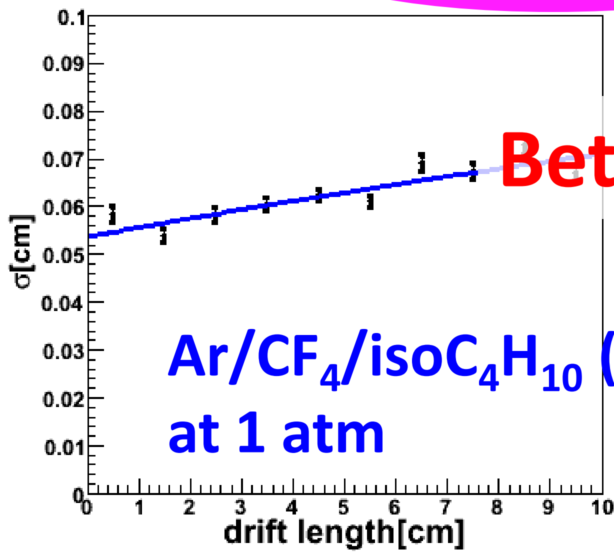


Ar/C_2H_6 (90:10) at 2 atm

σ = 302 μm, D = 204 μm/cm$^{1/2}$

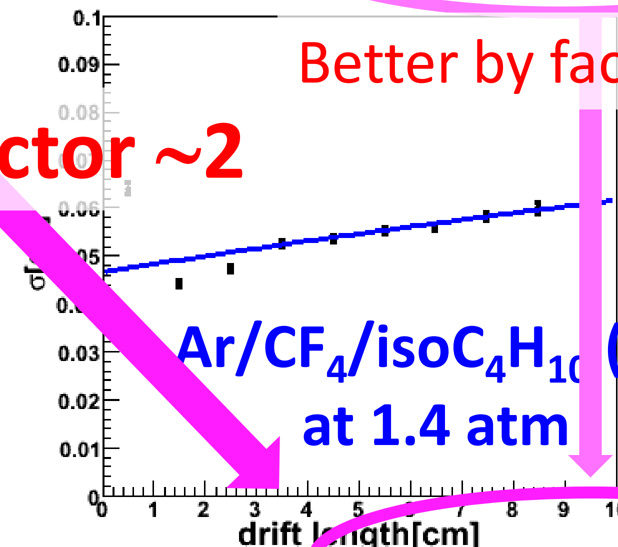
Better by factor ~2

Better by factor ~1.6



$Ar/CF_4/isoC_4H_{10}$ (54:40:6) at 1 atm

σ = 378 μm, D = 147 μm/cm$^{1/2}$

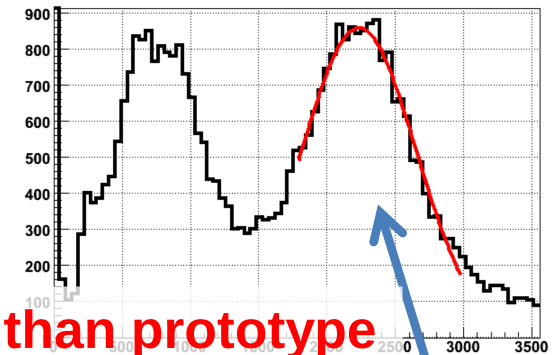


$Ar/CF_4/isoC_4H_{10}$ (54:40:6) at 1.4 atm

σ = 330 μm, D = 128 μm/cm$^{1/2}$

Energy Resolution
31 keV X-ray from ^{133}Ba (31 keV)

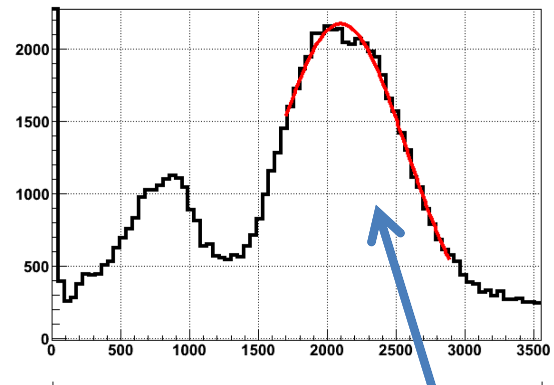
Ar/C_2H_6 (90:10) at 1 atm



Worse than prototype

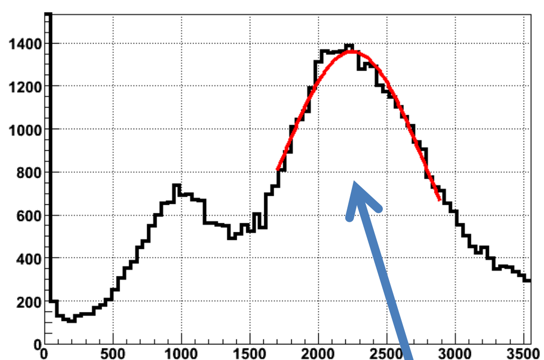
43.8% (FWHM) @31 keV

Ar/C_2H_6 (90:10) at 2 atm



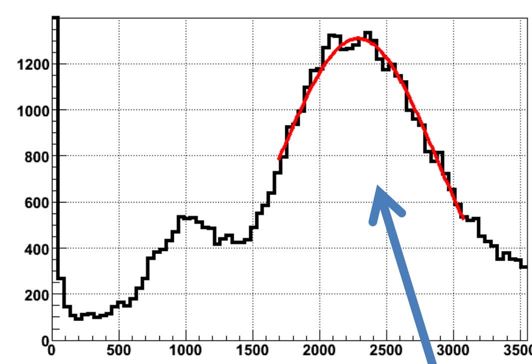
53.1% (FWHM) @31 keV

Ar/CF_4/isoC_4H_{10} (54:40:6) at 1 atm



56.1% (FWHM) @31 keV

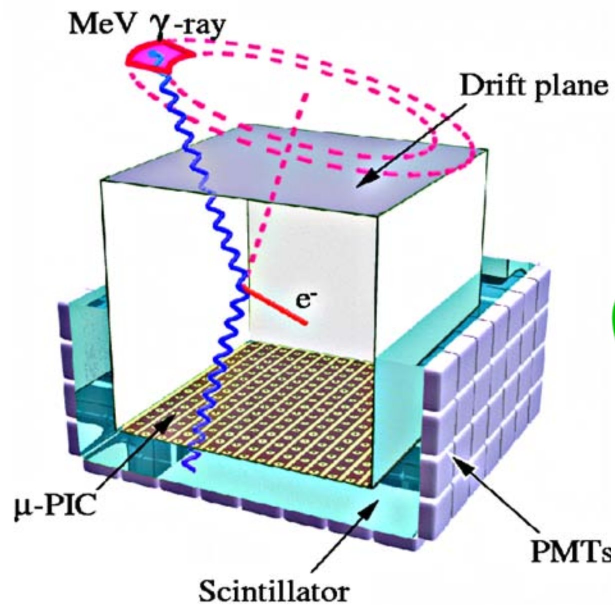
Ar/CF_4/isoC_4H_{10} (54:40:6) at 1.4 atm



60.0% (FWHM) @31 keV

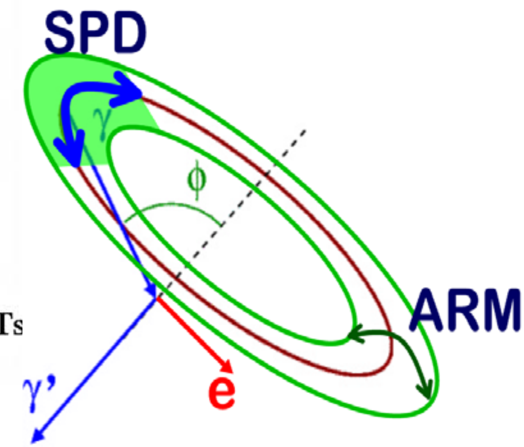
Imaging with ETCC

gamma-ray from ^{133}Ba (356 keV, 800 kBq)



ARM : Angular Resolution Measure

SPD : Scatter Plane Deviation



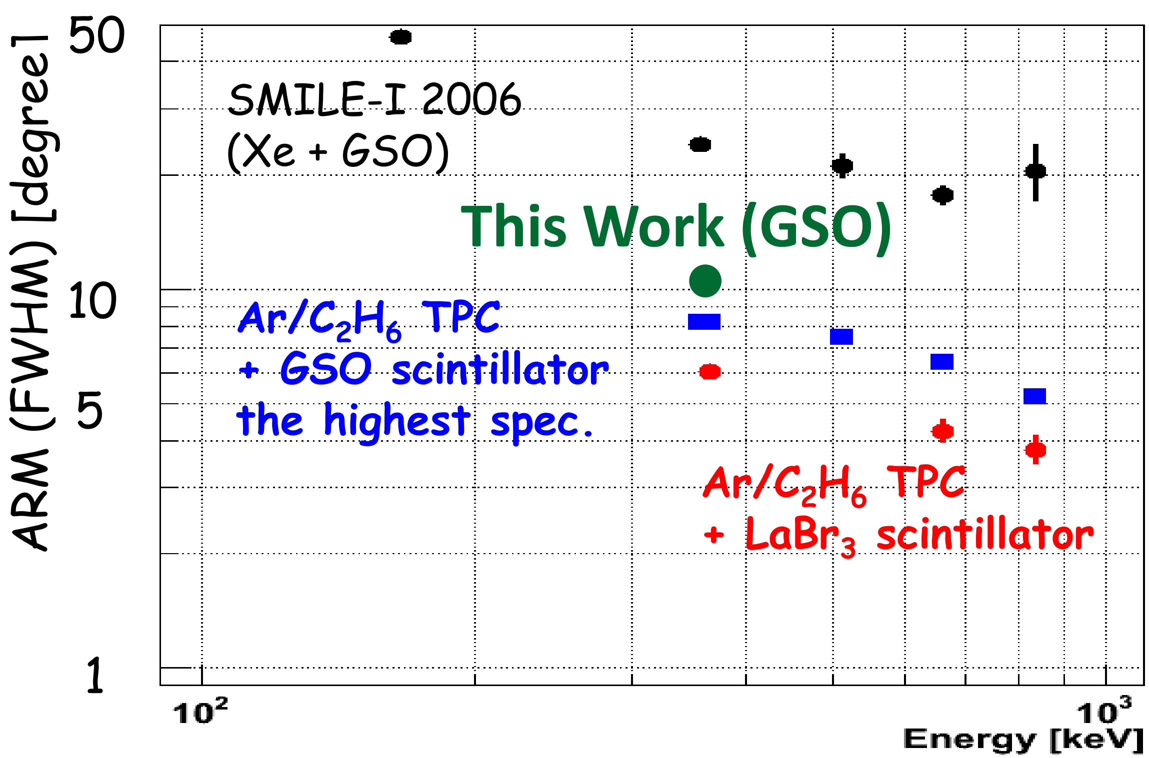
Measurement

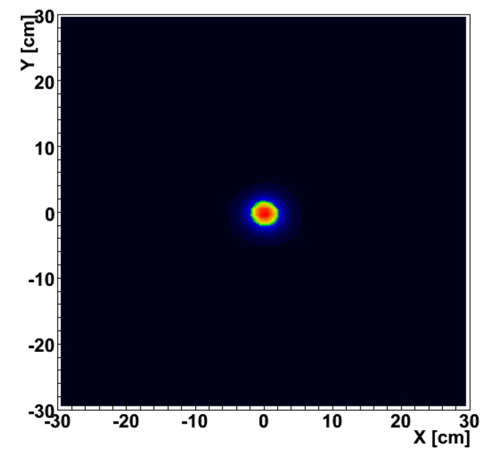
1. Efficiency
2. Angular resolution (ARM and SPD)

Efficiency and Angular Resolution (^{133}Ba 356 keV)

Gas	Pressure	Efficiency	ARM (FWHM)	SPD (FWHM)
Ar/C_2H_6 (90:10)	**1** atm	**1.81×10^{-5}**	**10.4°**	**114.8°**
Ar/C_2H_6 (90:10)	2 atm	3.55×10^{-5}	11.1°	105.1°
Ar/CF_4/isoC_4H_{10} (54:40:6)	1 atm	2.44×10^{-5}	11.7°	117.9°
Ar/CF_4/isoC_4H_{10} (54:40:6)	**1.4** atm	**3.51×10^{-5}**	**11.2°**	**119.1°**

better by factor 1.94





Ar/CF_4/isoC_4H_{10} (54:40:6)
at 1.4 atm
Imaging of ^{133}Ba
15 cm away from top of μTPC

Summary

- In order to improve the efficiency of the ETCC, we have optimized the **gas mixture** and **pressure** sealed in the μTPC.
- The highest ratio of CF_4 gas with steady gas gain of ~ 20,000 is $Ar/CF_4/isoC_4H_{10}$ (54:40:6).
- The diffusion constant of $Ar/CF_4/isoC_4H_{10}$ (54:40:6) is **2 times better** than that of Ar/C_2H_6 (90:10), so the position resolution is improved.
- The efficiency for the ETCC using $Ar/CF_4/isoC_4H_{10}$ (54:40:6) at 1.4 atm is **2 times higher** than that using Ar/C_2H_6 (90:10) at 1 atm, and those ARMs are comparable (~11° at 356 keV (FWHM)).

Thank you
for your attention